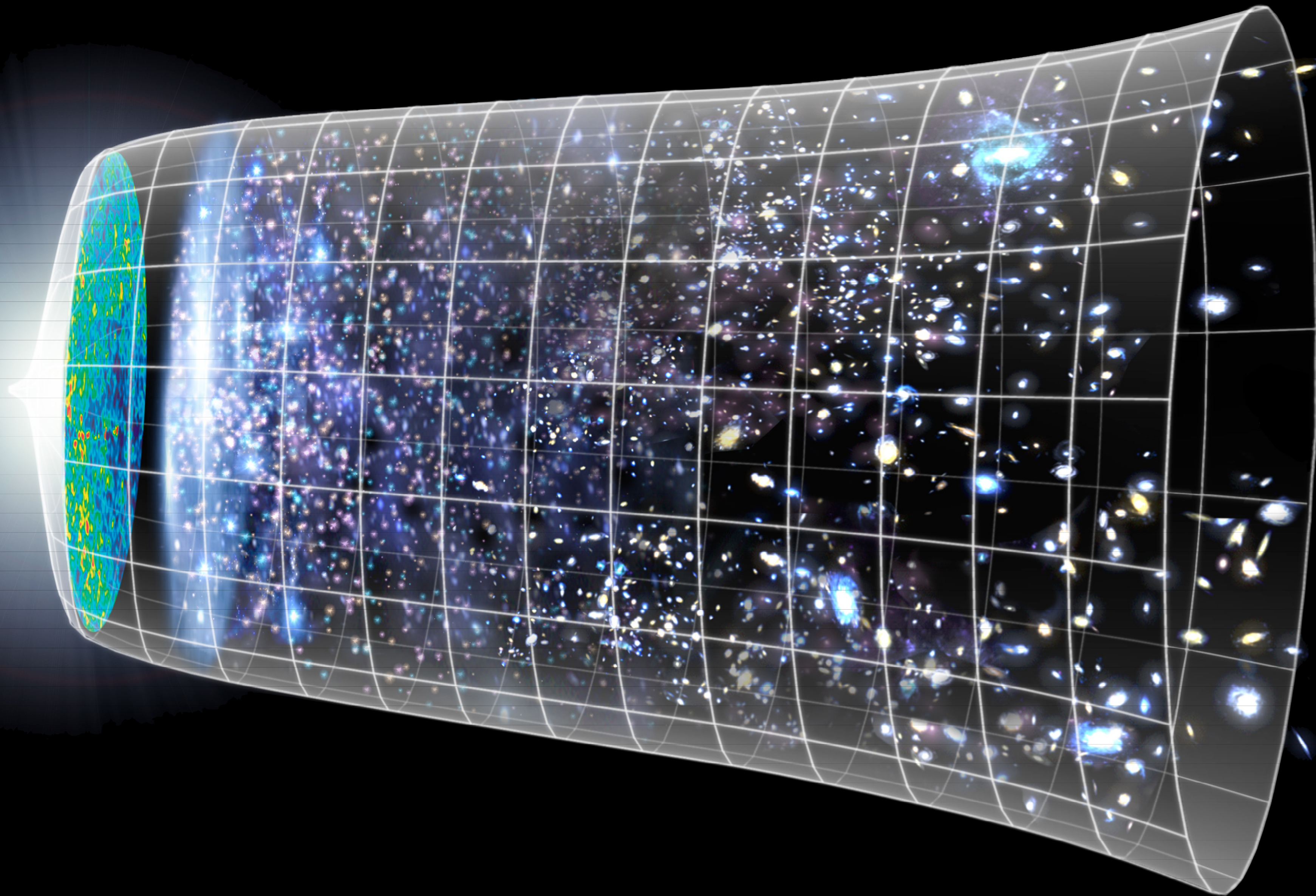
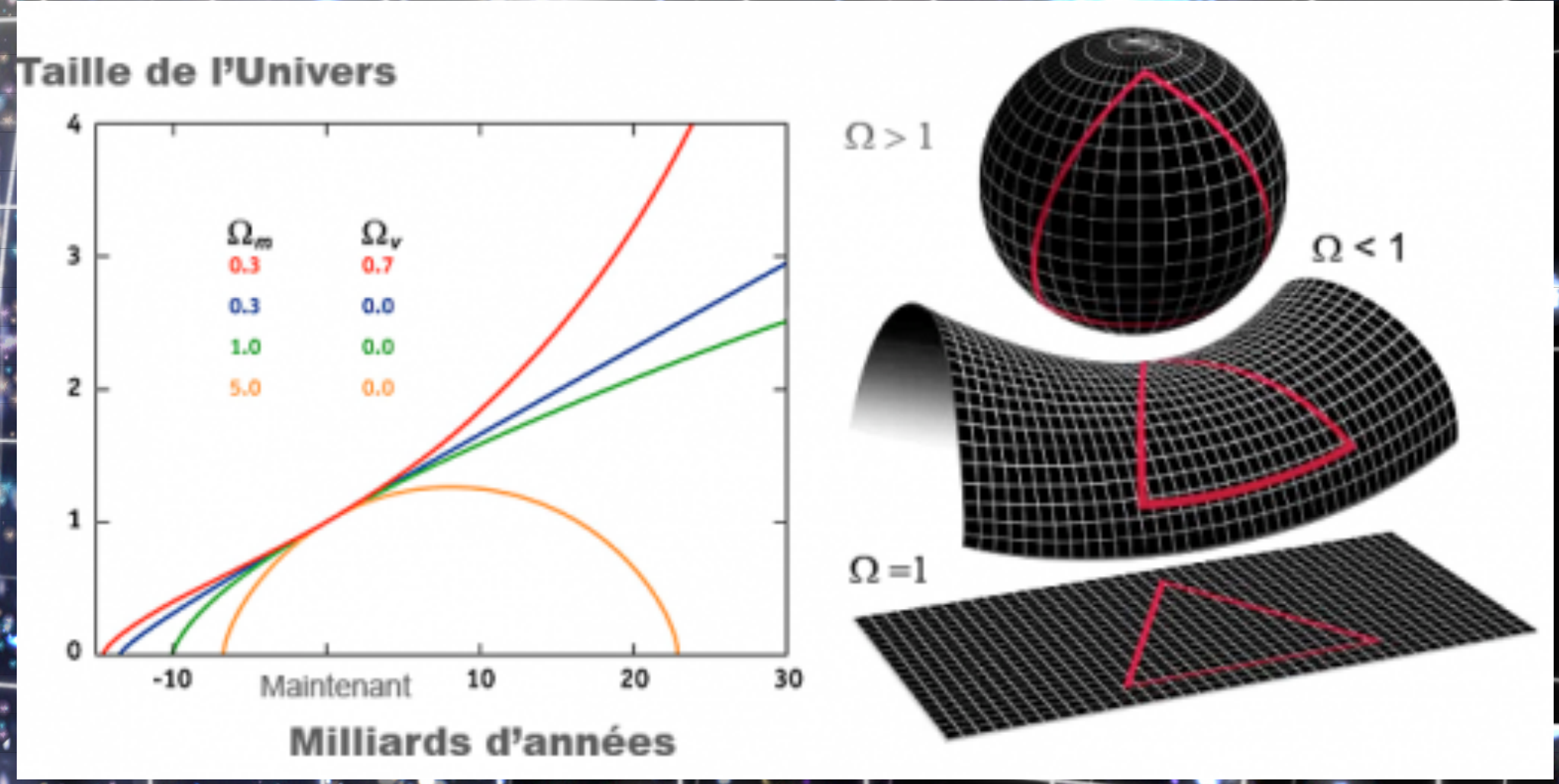
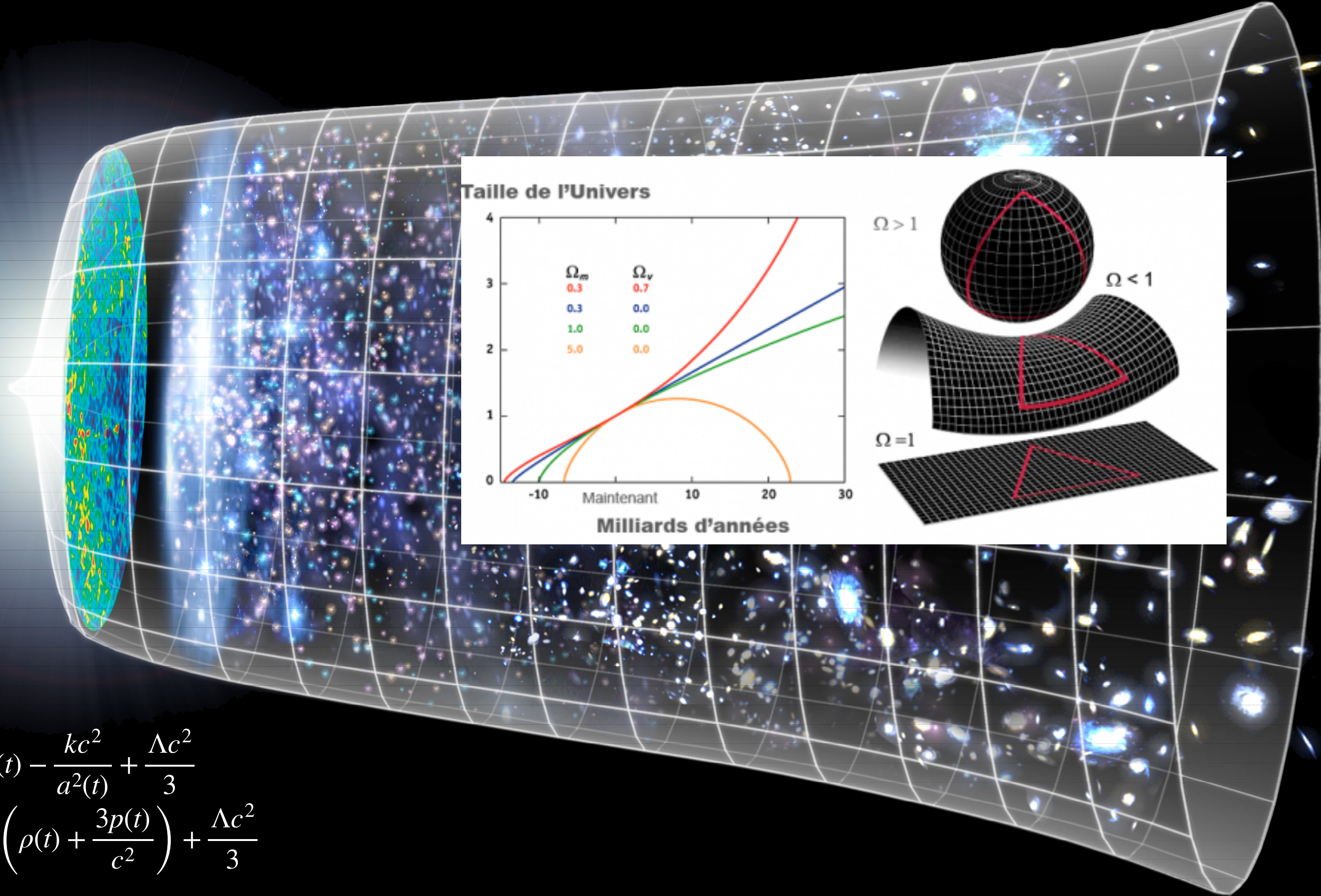


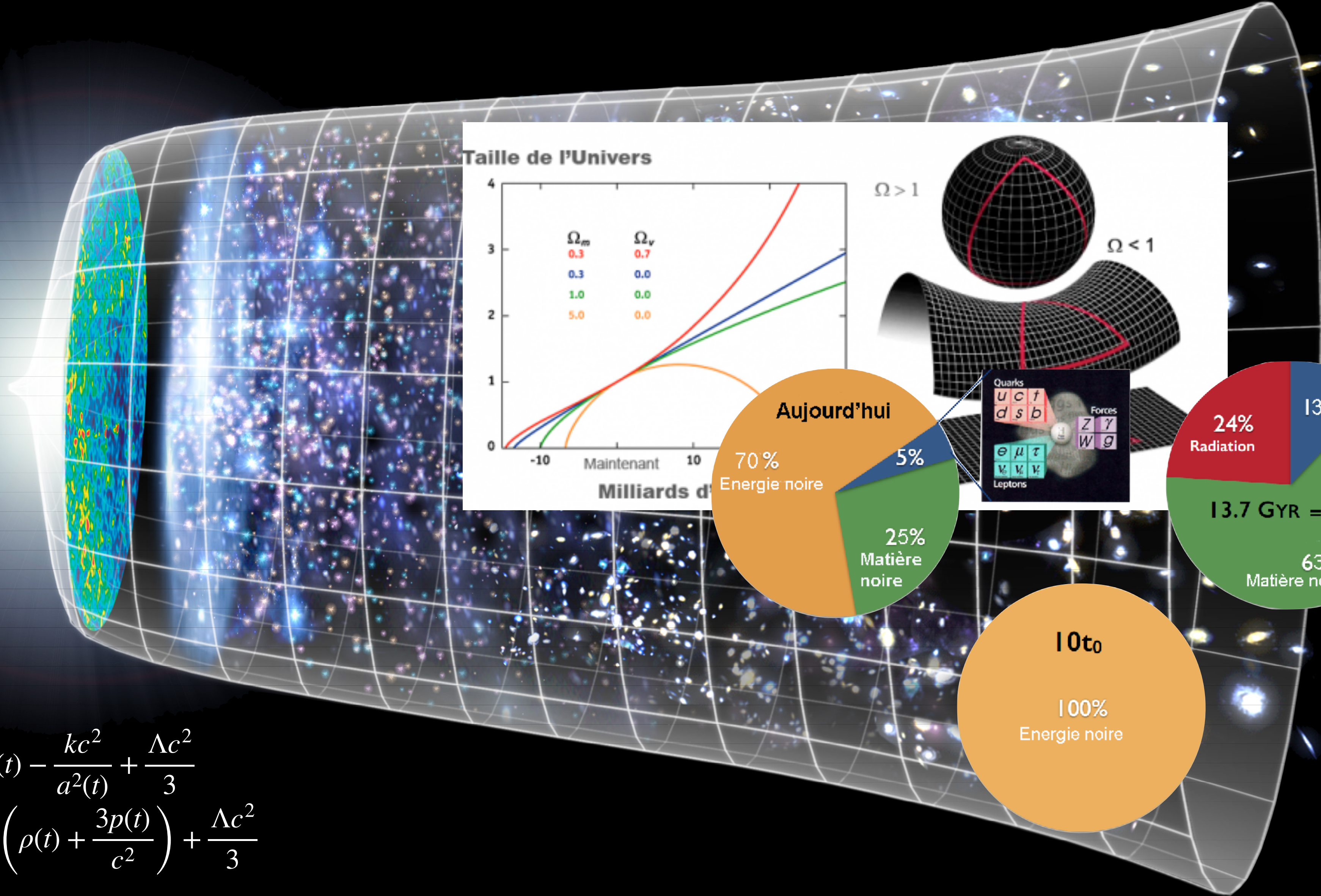
La cosmologie à Sorbonne Université



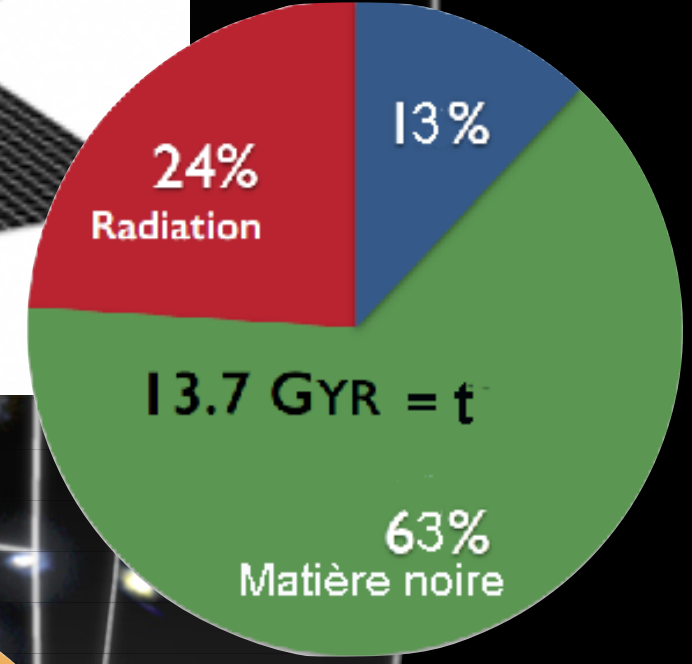
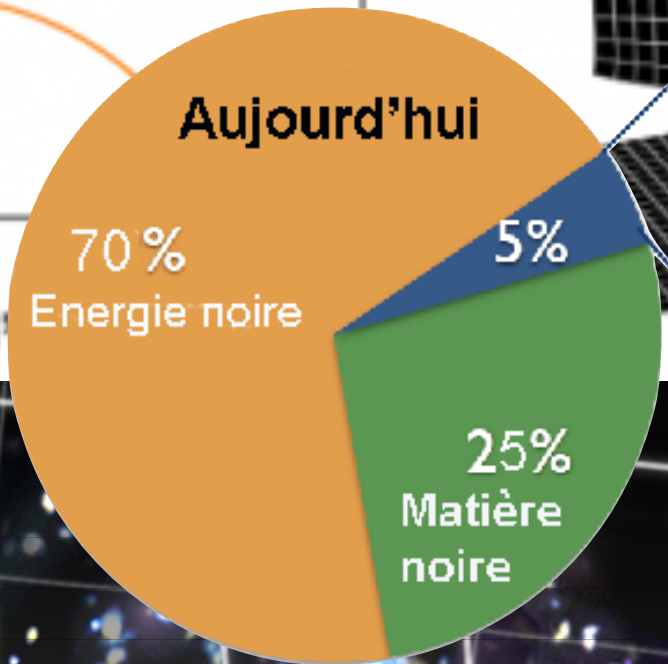
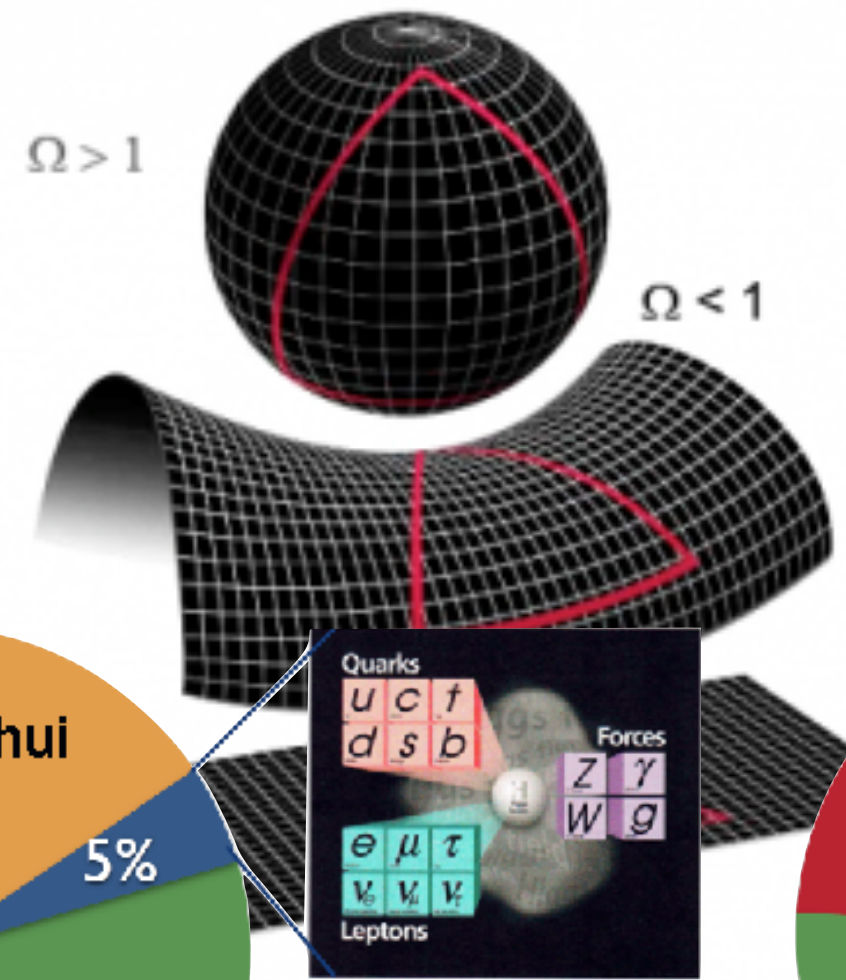
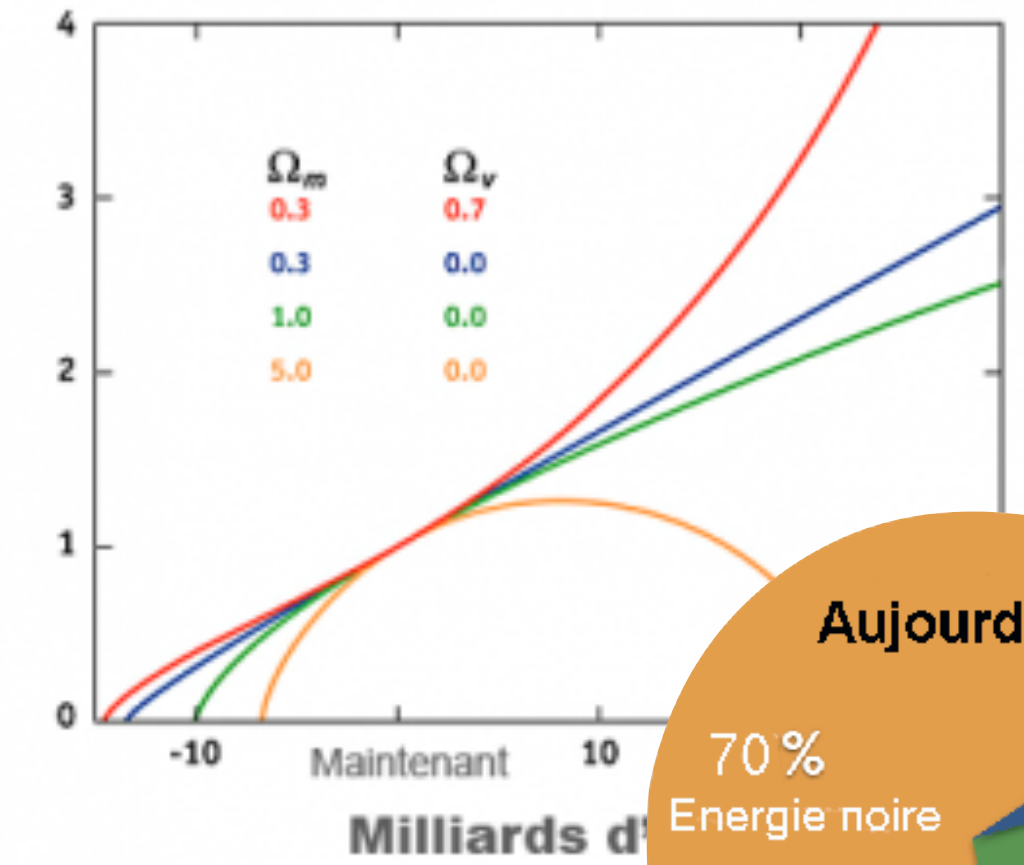


$$H^2(t) = \frac{8\pi G}{3c^2} \rho(t) - \frac{kc^2}{a^2(t)} + \frac{\Lambda c^2}{3}$$

$$\frac{\ddot{a}(t)}{a(t)} = -\frac{4\pi G}{3c^2} \left(\rho(t) + \frac{3p(t)}{c^2} \right) + \frac{\Lambda c^2}{3}$$



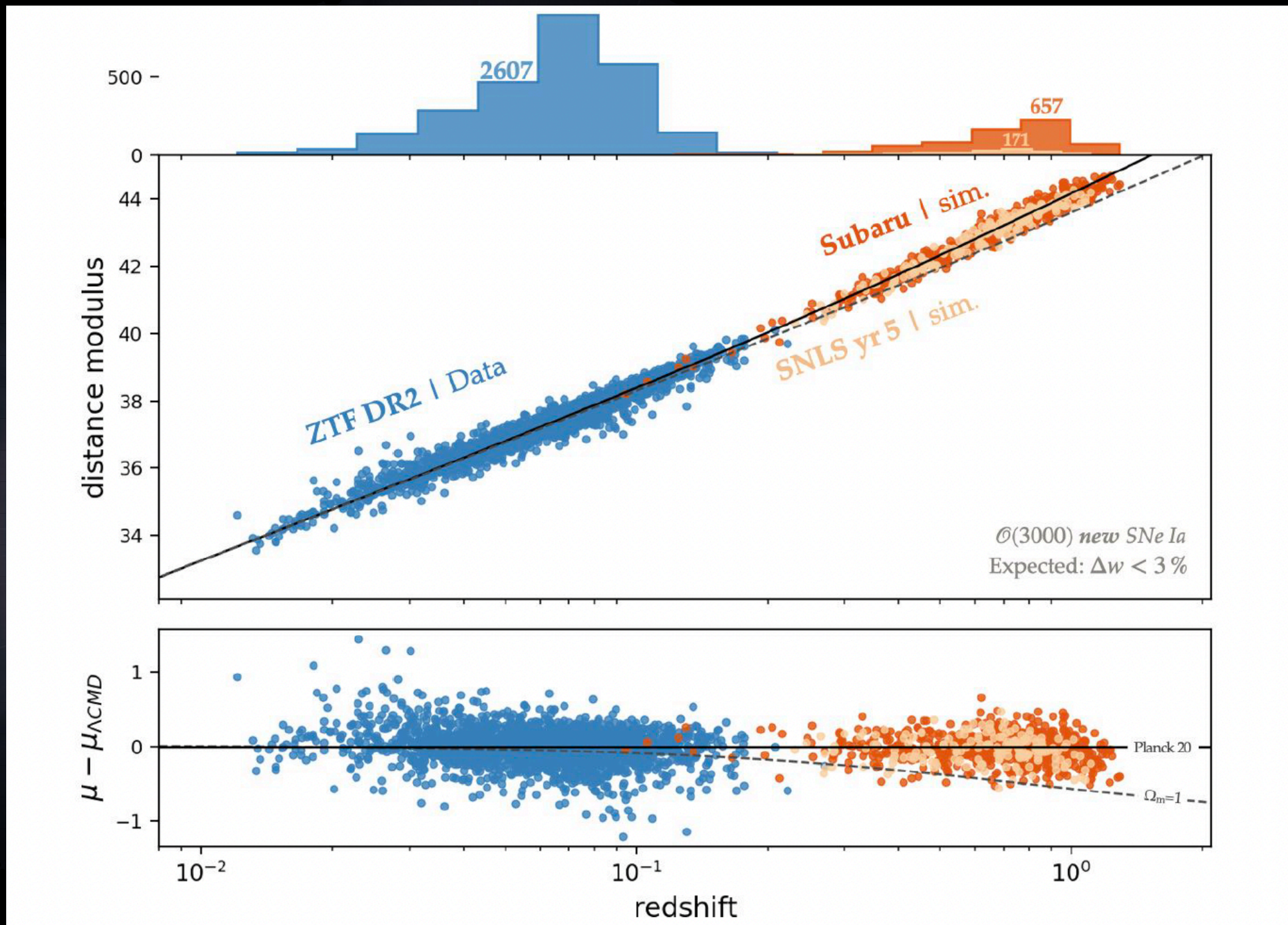
Taille de l'Univers



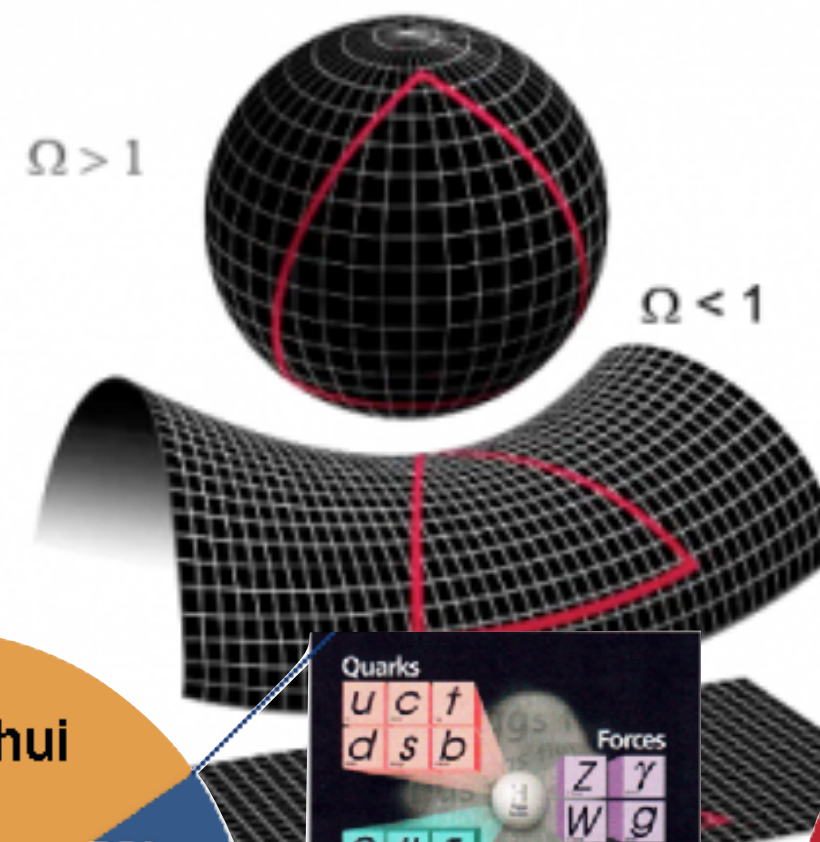
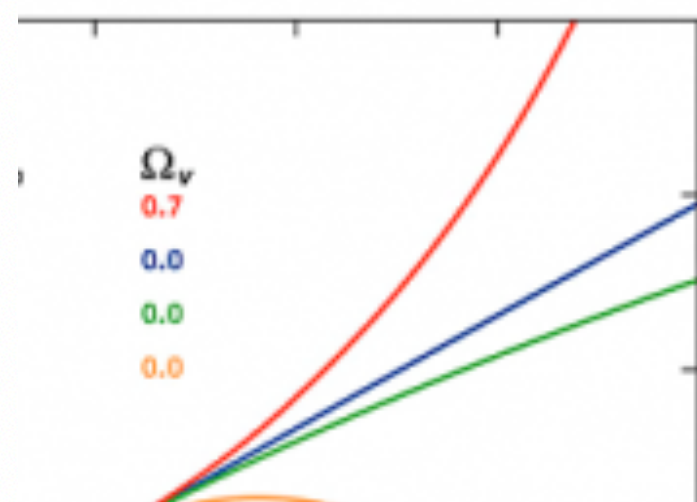
Quarks	Forces
u c t	Z γ
d s b	W g
Leptons	
e μ τ	
ν e ν μ ν τ	

$$H^2(t) = \frac{8\pi G}{3c^2} \rho(t) - \frac{kc^2}{a^2(t)} + \frac{\Lambda c^2}{3}$$

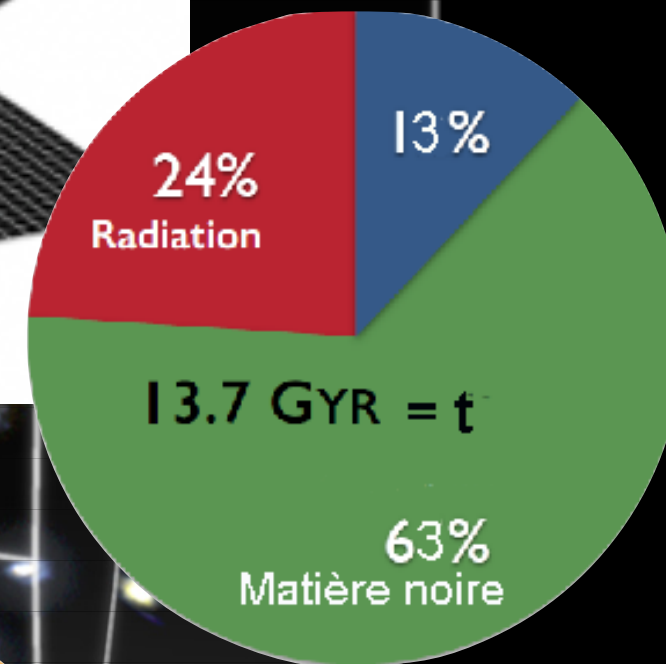
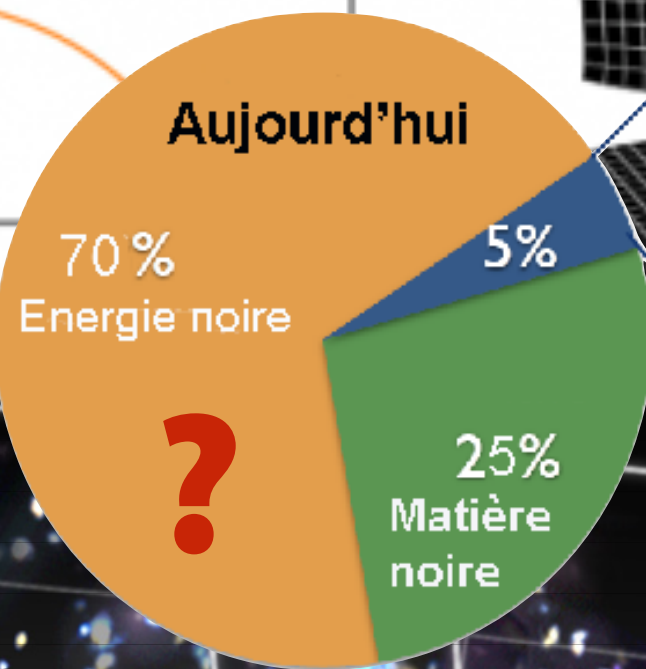
$$\frac{\ddot{a}(t)}{a(t)} = -\frac{4\pi G}{3c^2} \left(\rho(t) + \frac{3p(t)}{c^2} \right) + \frac{\Lambda c^2}{3}$$



univers

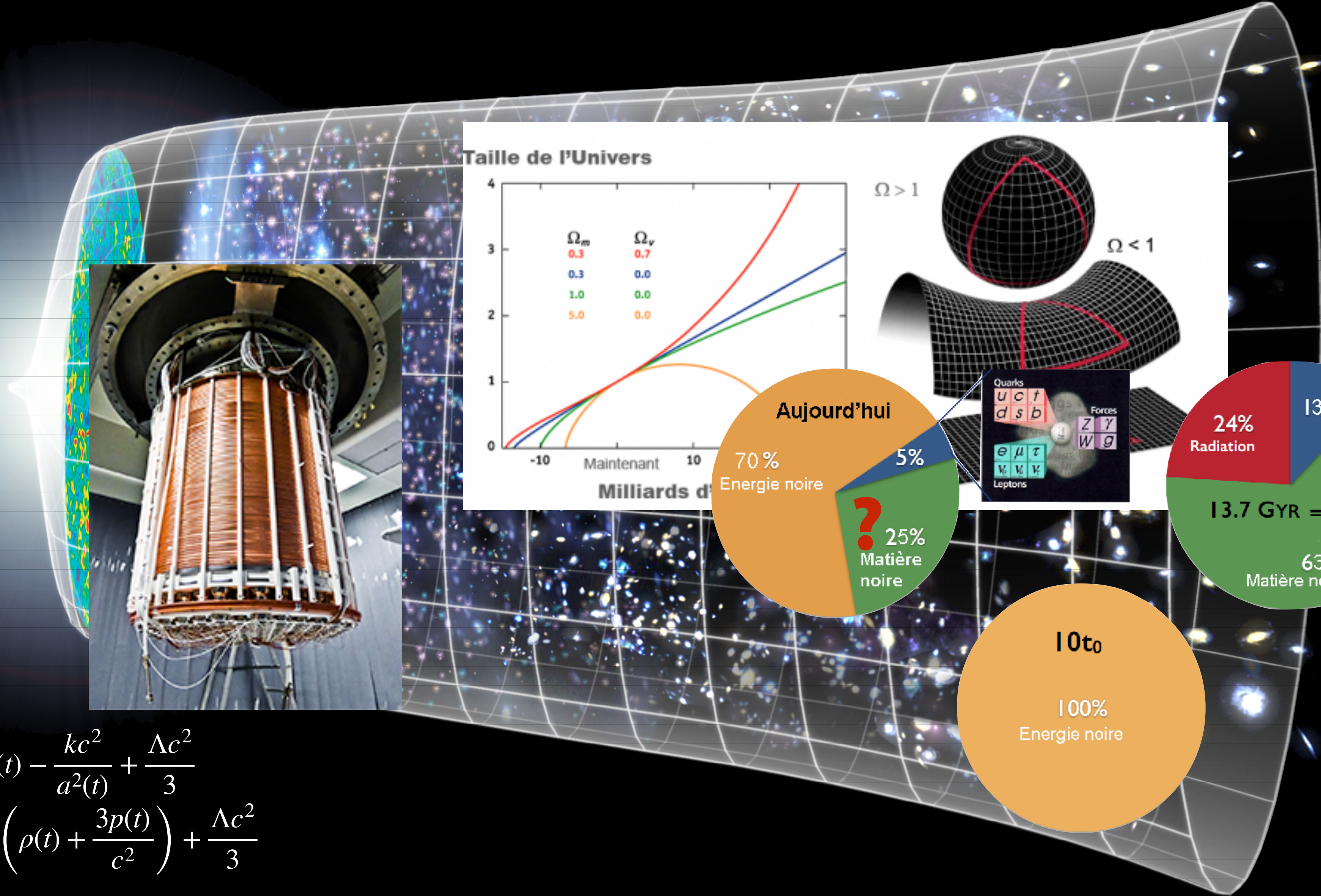


Maintenant 10
Milliards d'

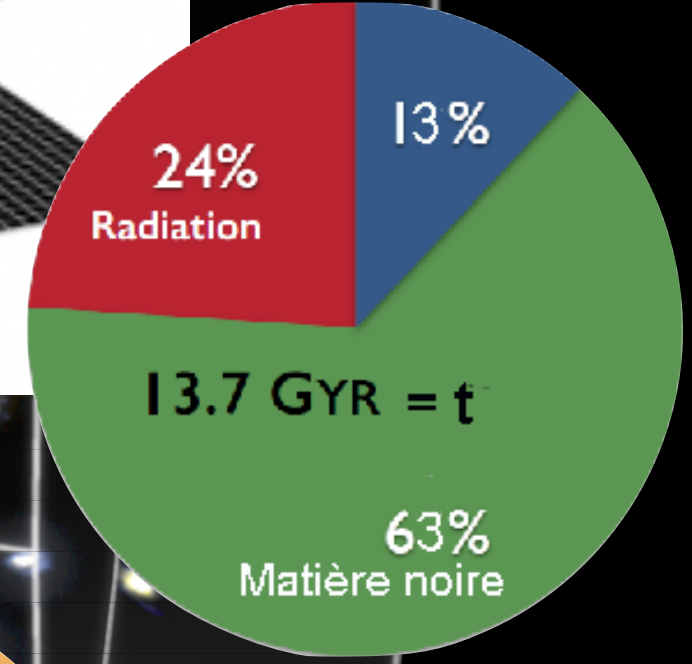
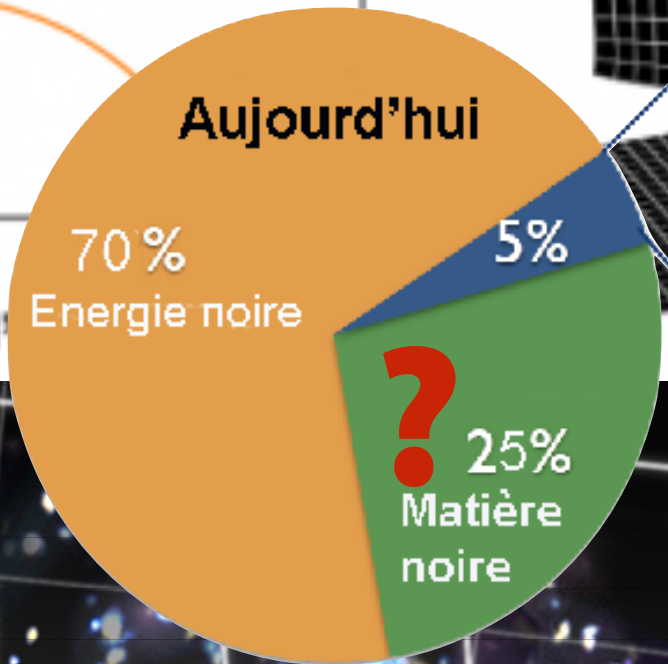
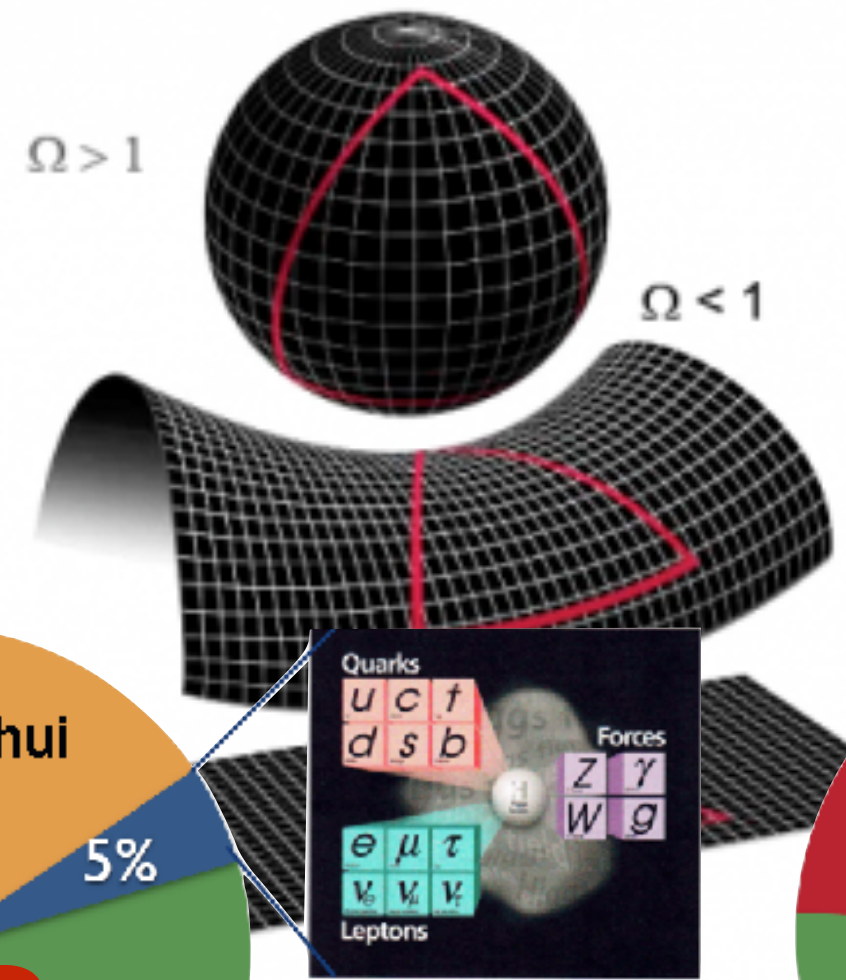
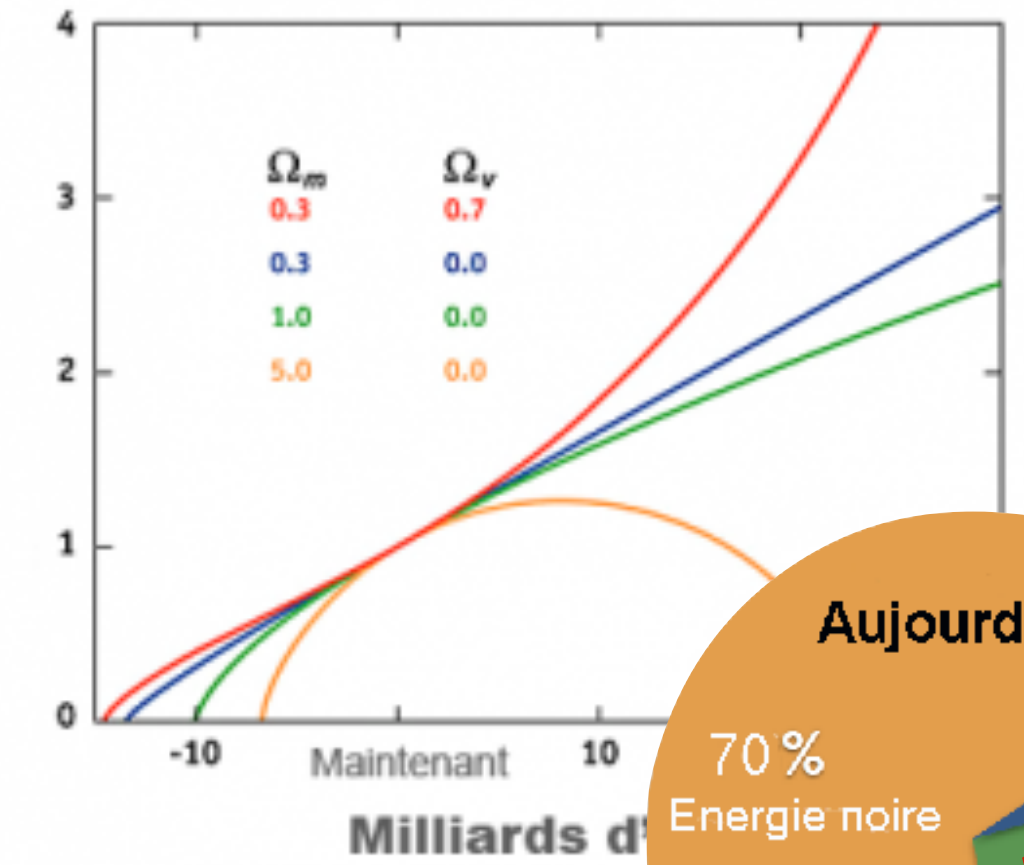


$$H^2(t) = \frac{8\pi G}{3c^2} \rho(t) - \frac{kc^2}{a^2(t)} + \frac{\Lambda c^2}{3}$$

$$\frac{\ddot{a}(t)}{a(t)} = -\frac{4\pi G}{3c^2} \left(\rho(t) + \frac{3p(t)}{c^2} \right) + \frac{\Lambda c^2}{3}$$



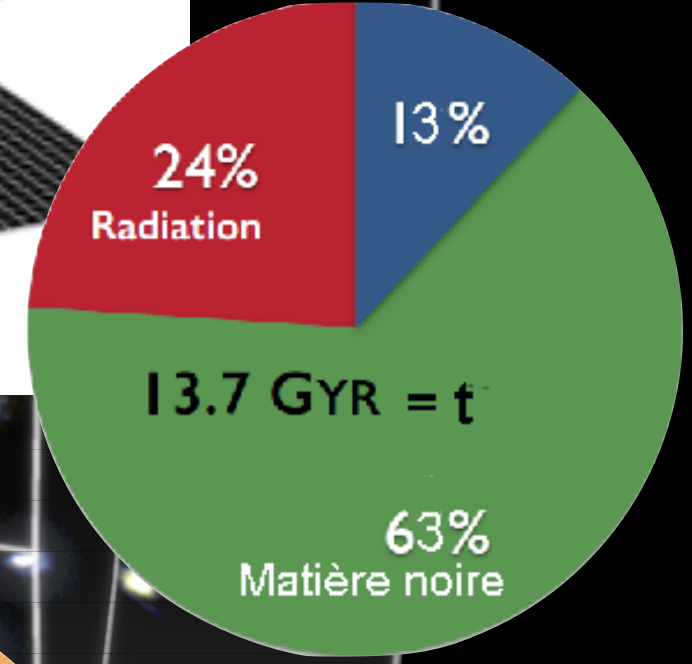
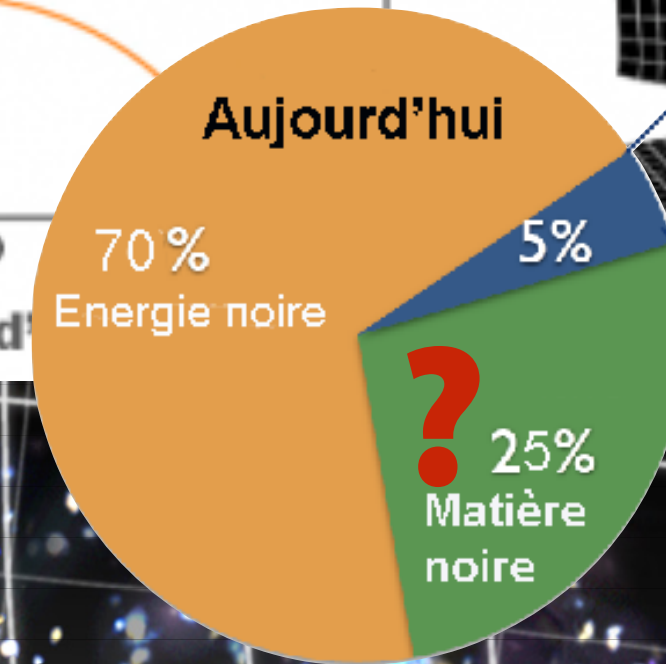
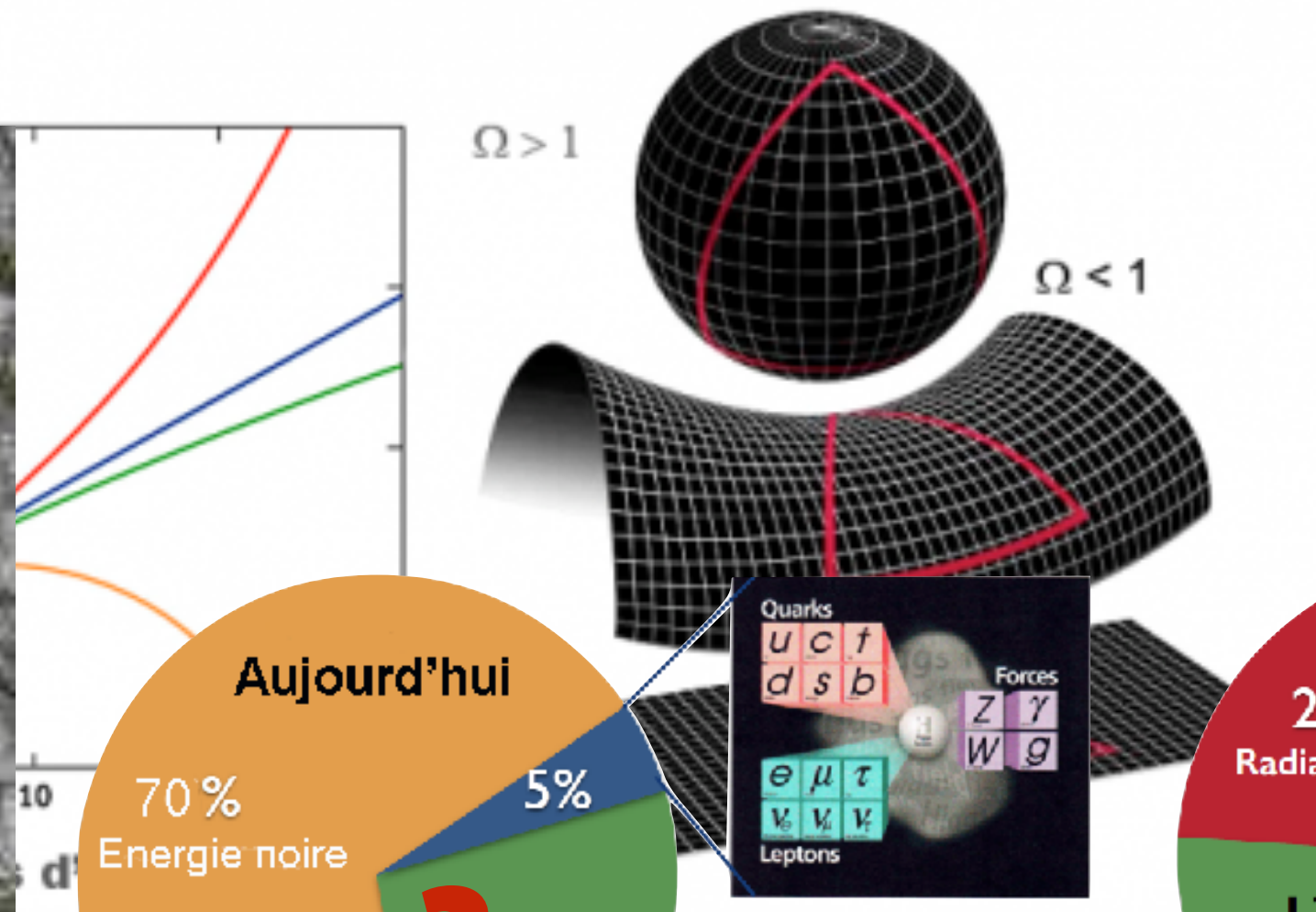
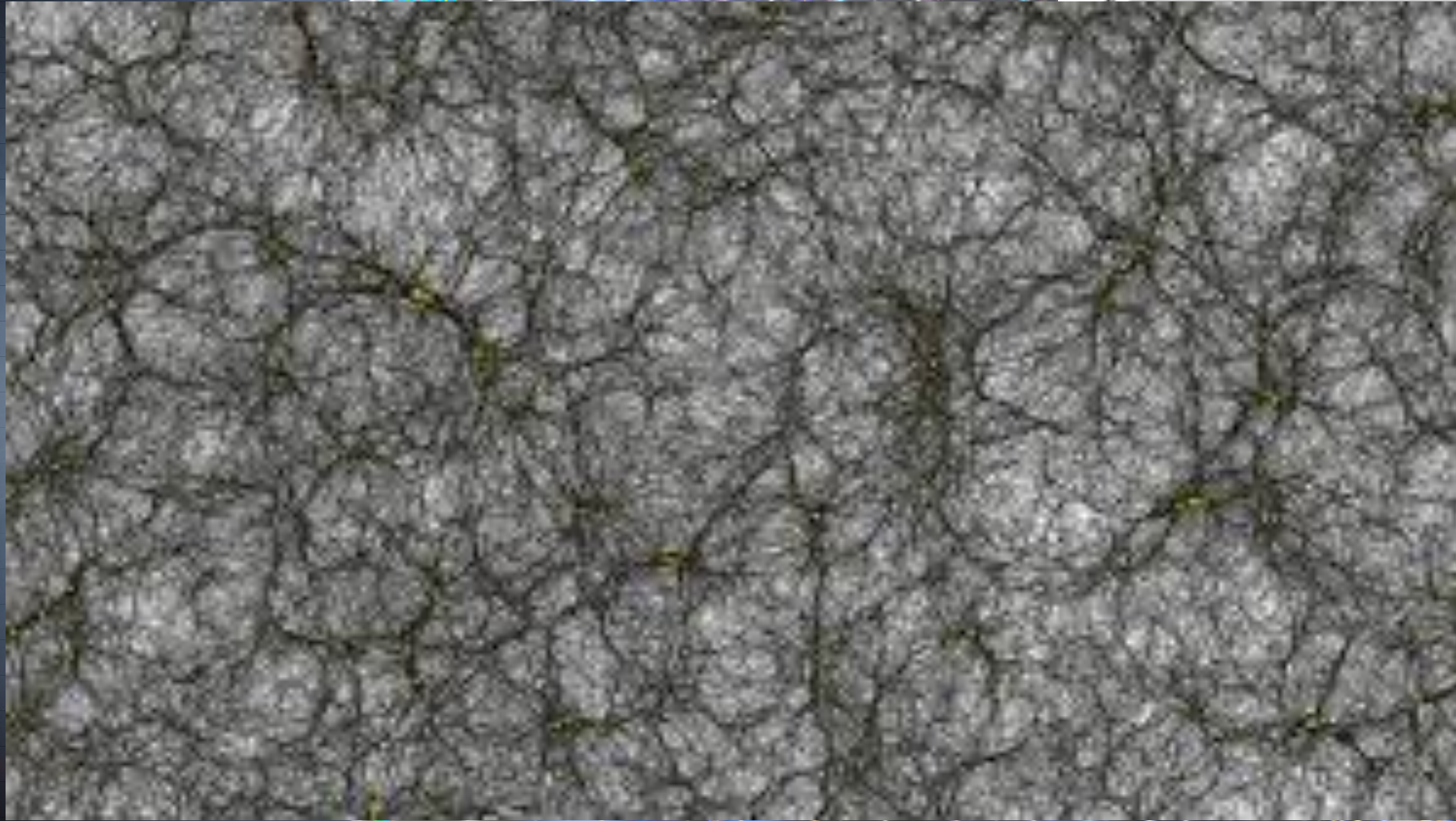
Taille de l'Univers



$$H^2(t) = \frac{8\pi G}{3c^2} \rho(t) - \frac{kc^2}{a^2(t)} + \frac{\Lambda c^2}{3}$$

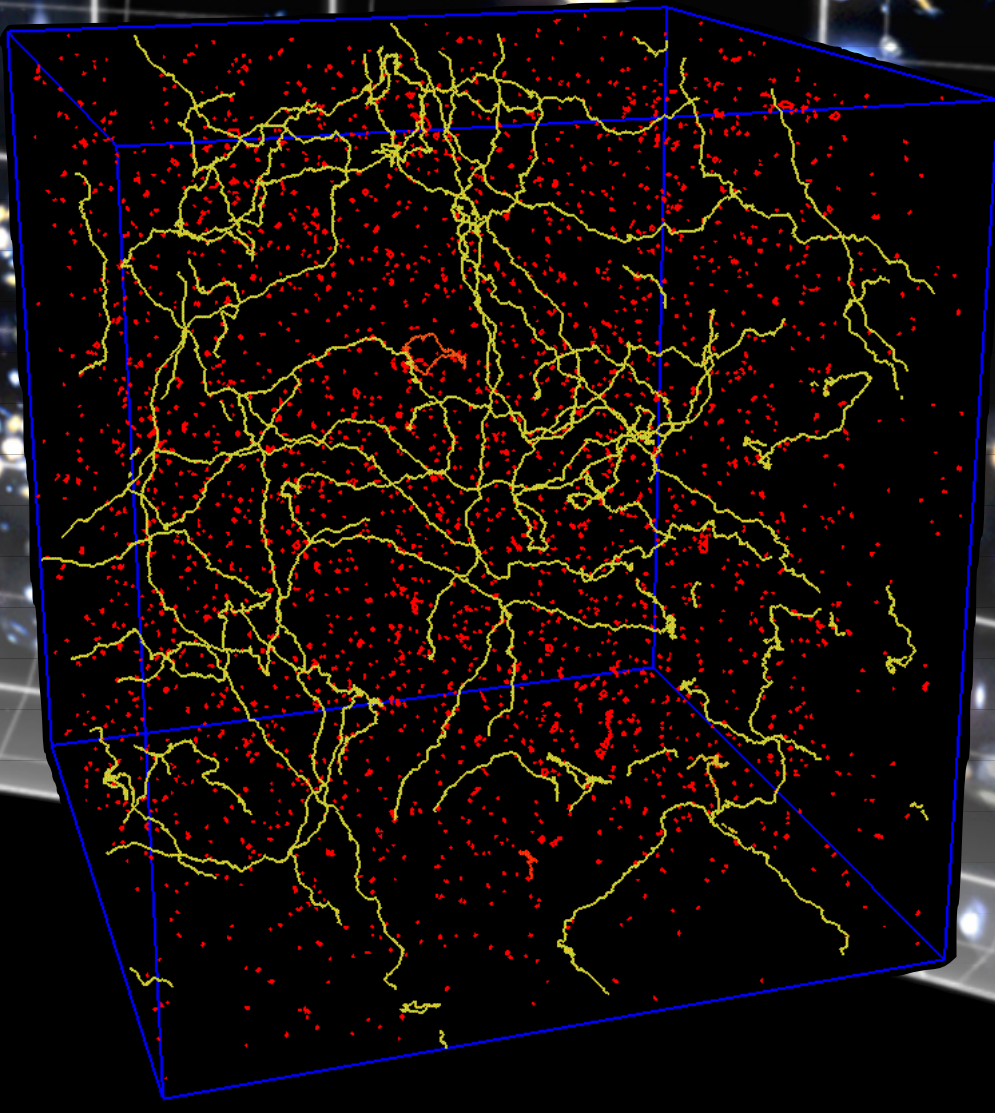
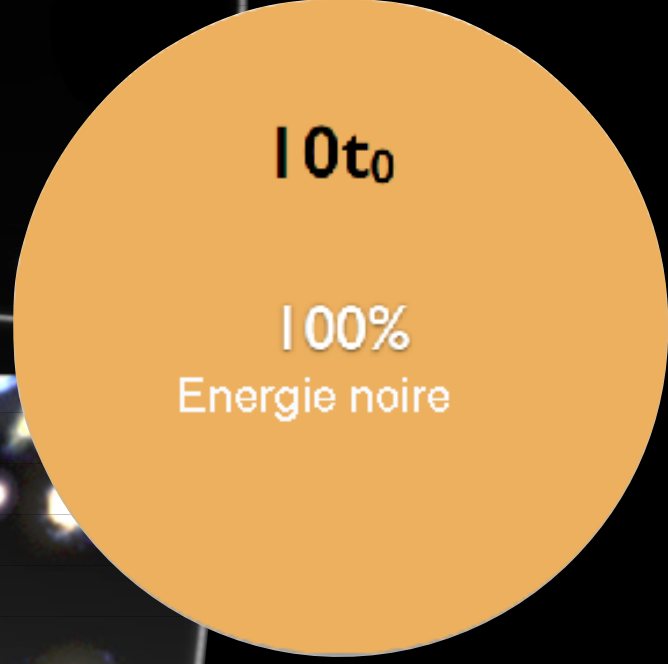
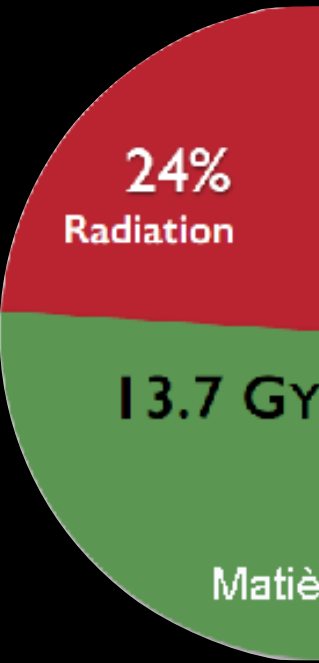
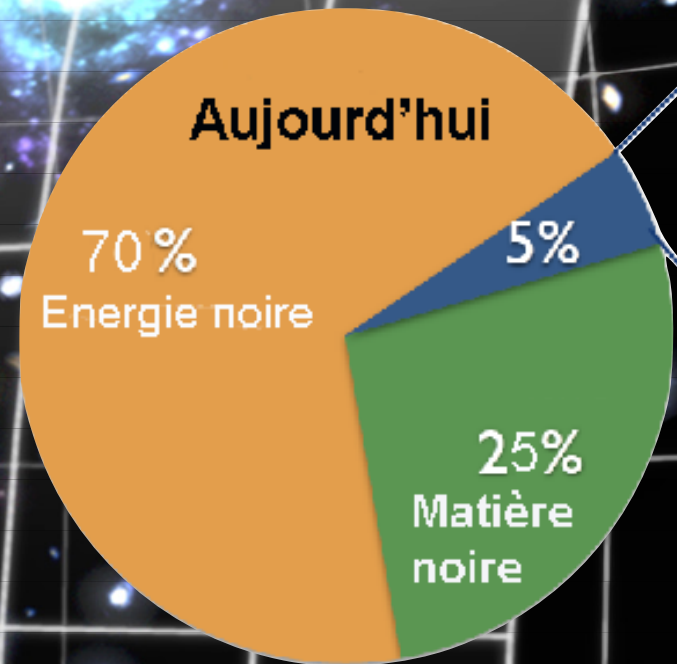
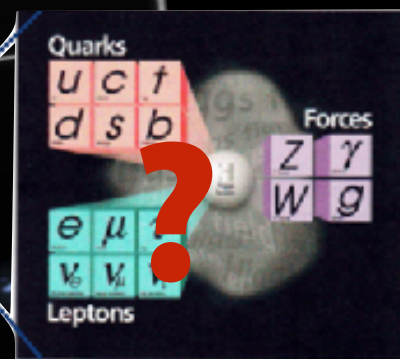
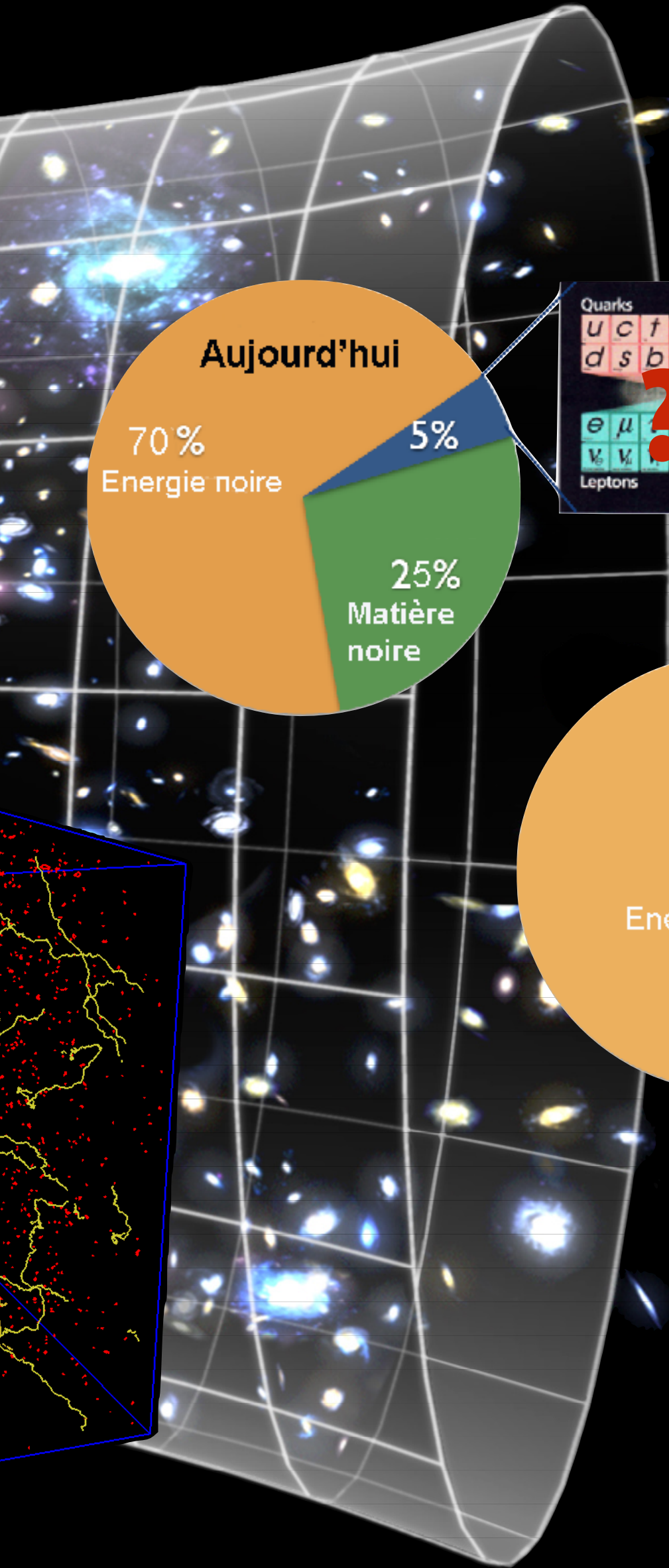
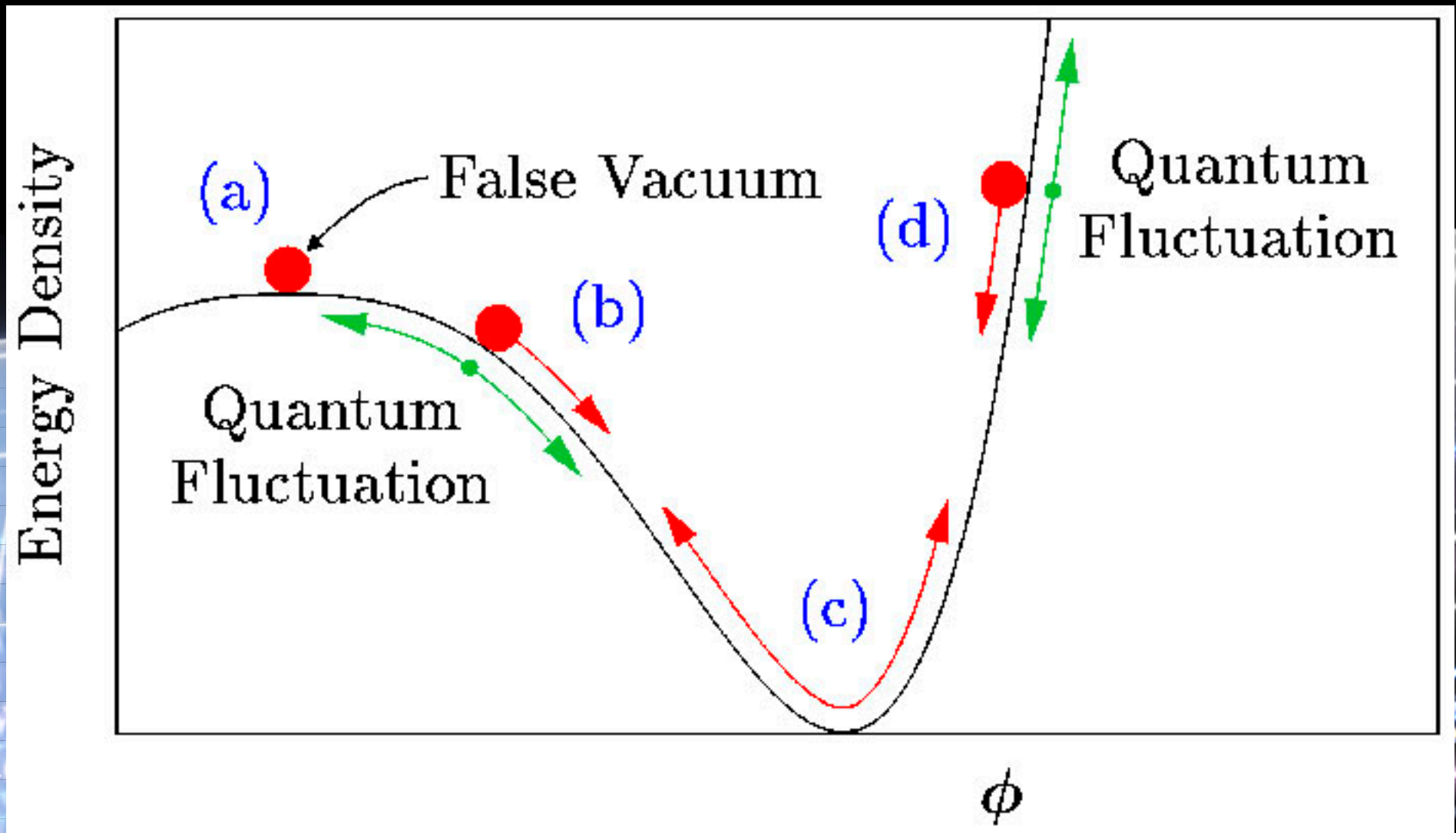
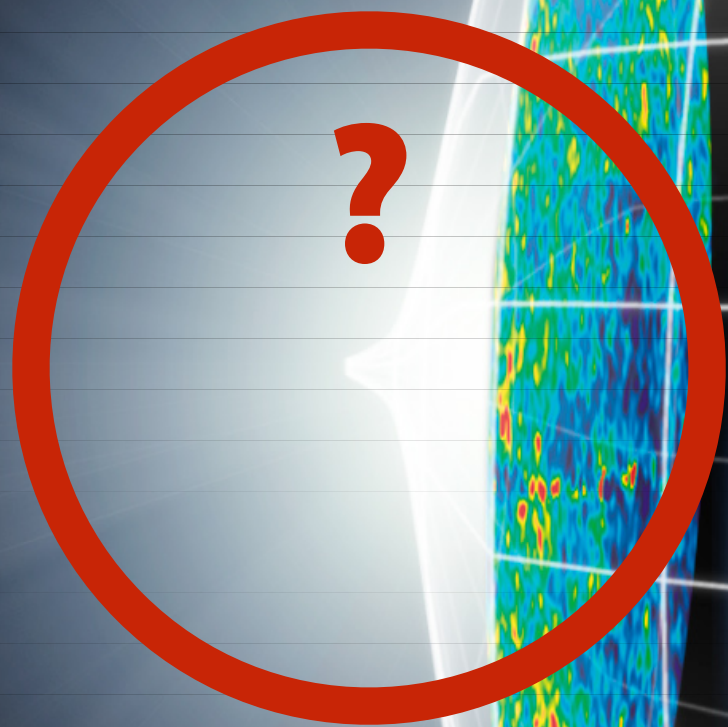
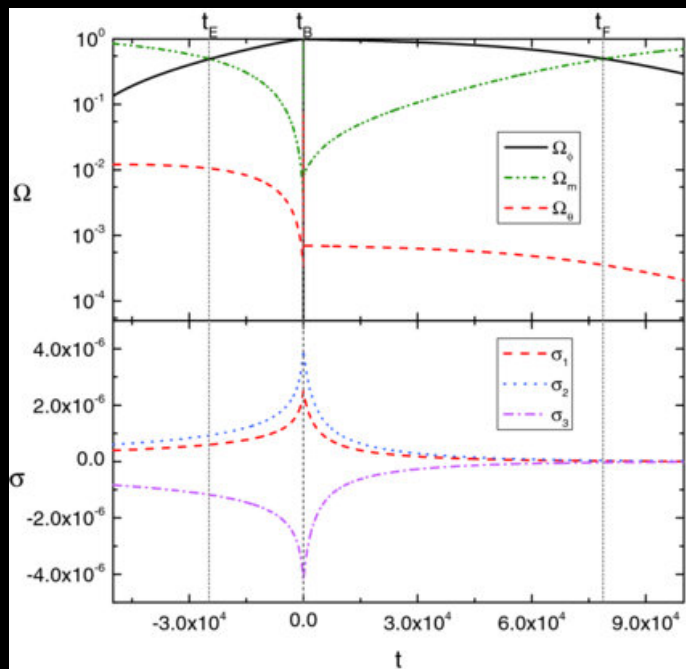
$$\frac{\ddot{a}(t)}{a(t)} = -\frac{4\pi G}{3c^2} \left(\rho(t) + \frac{3p(t)}{c^2} \right) + \frac{\Lambda c^2}{3}$$

Taille de l'Univers



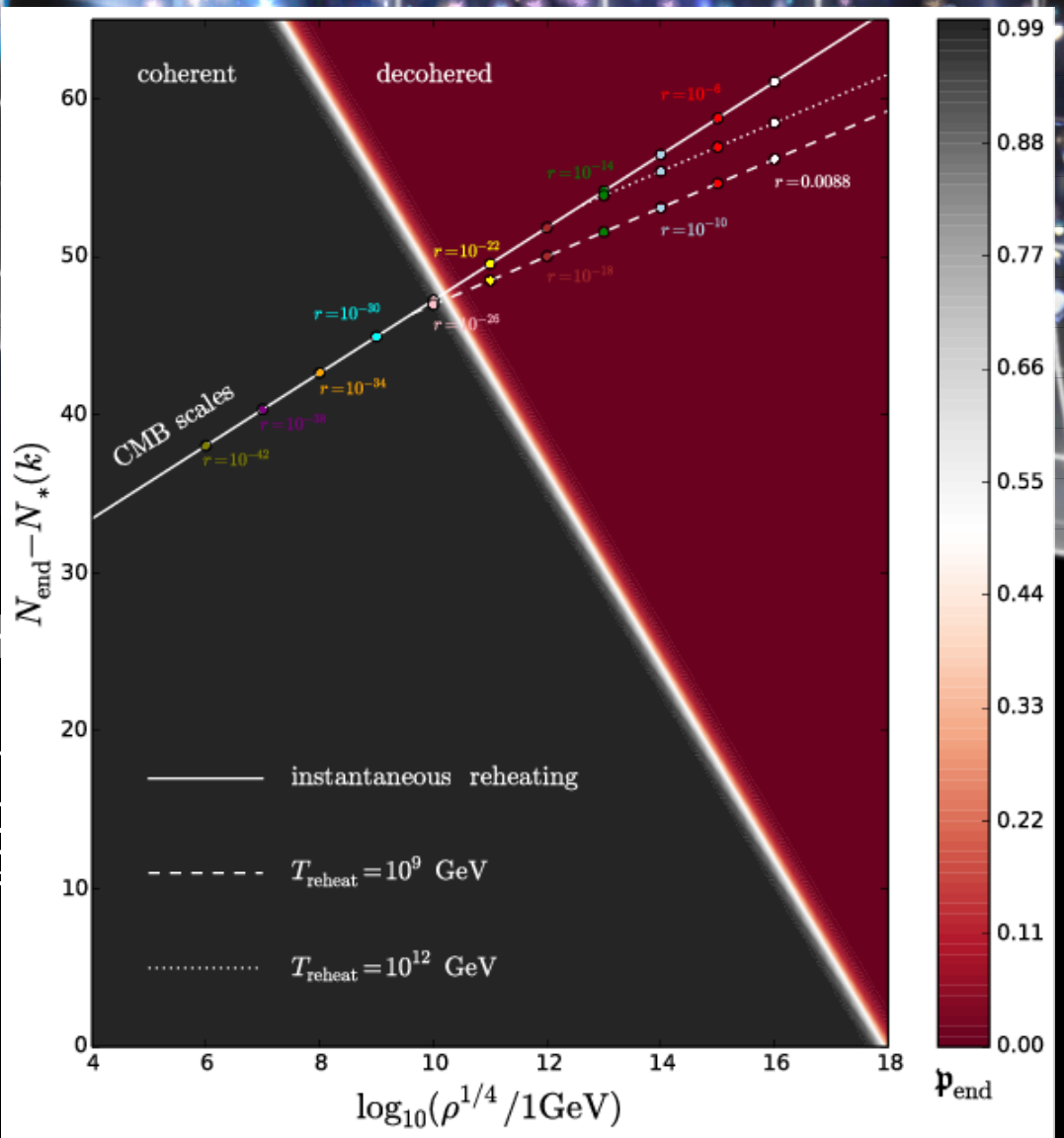
$$H^2(t) = \frac{8\pi G}{3c^2} \rho(t) - \frac{kc^2}{a^2(t)} + \frac{\Lambda c^2}{3}$$

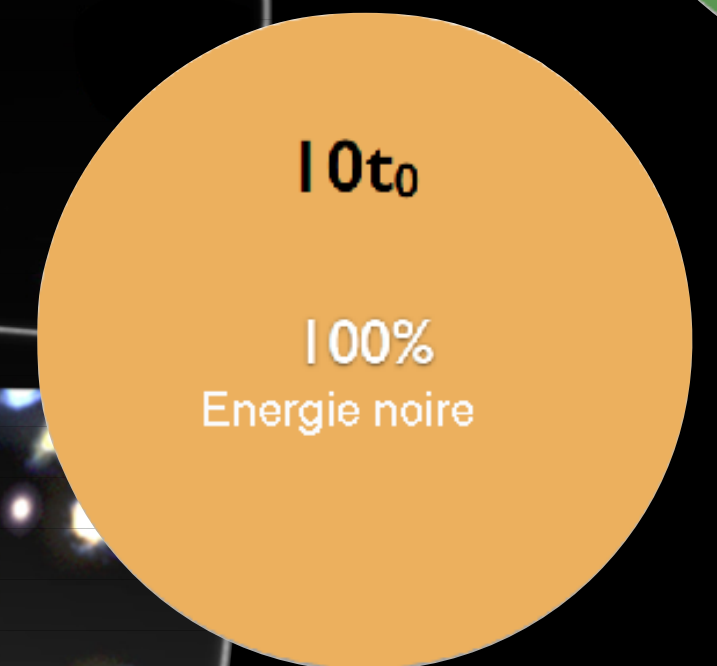
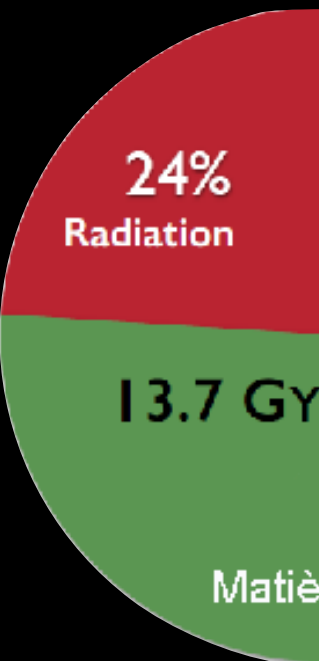
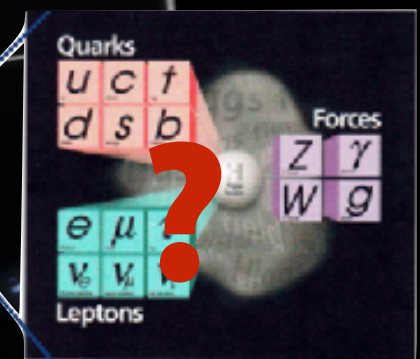
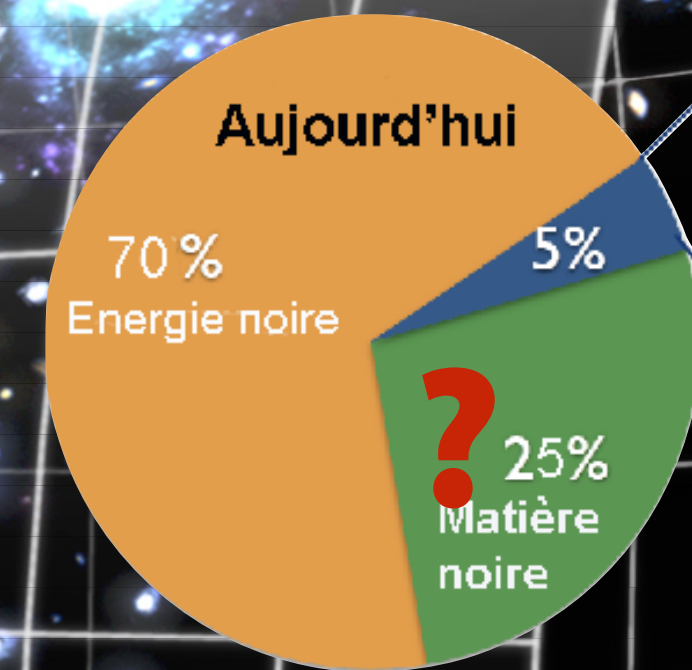
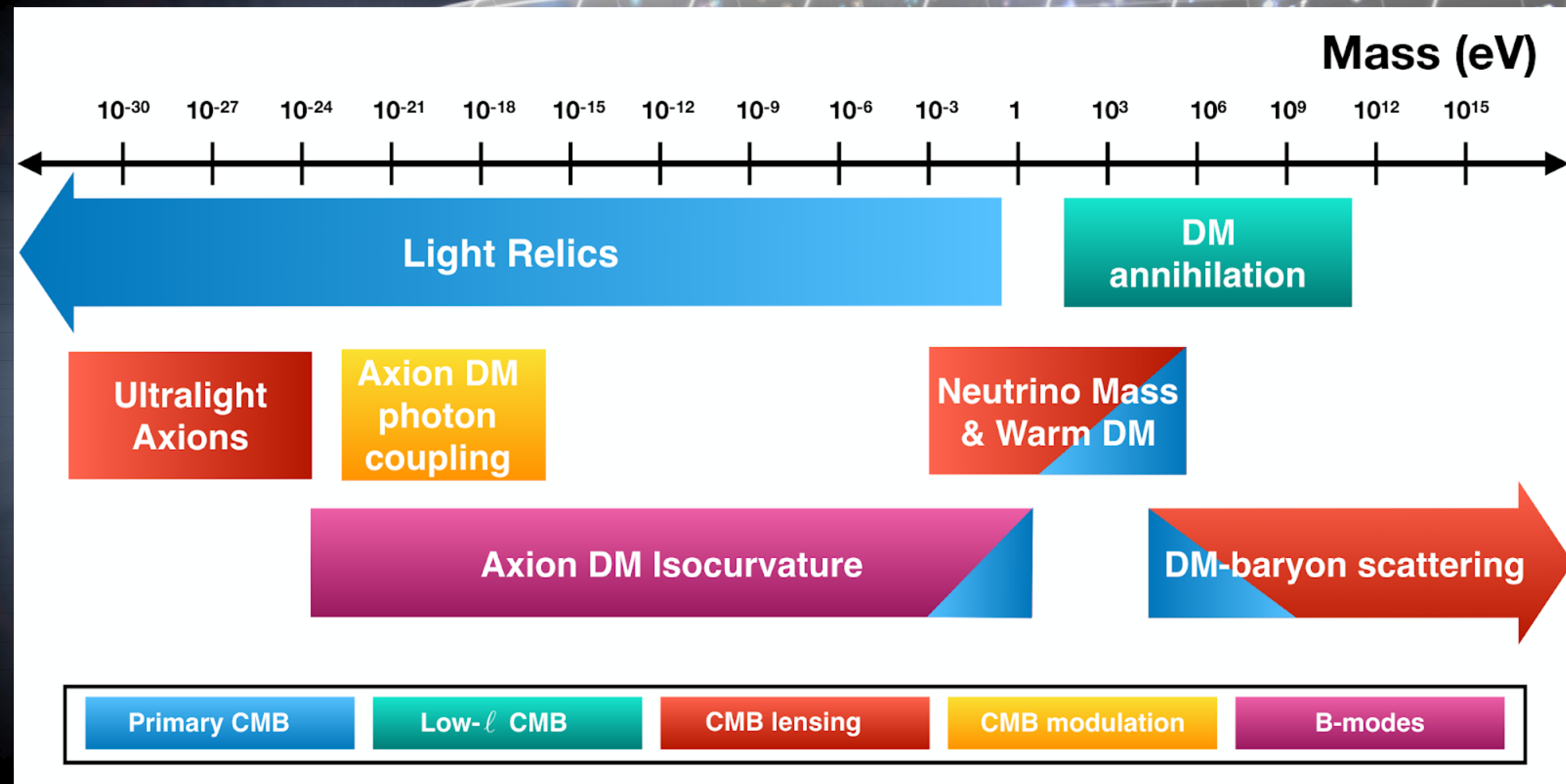
$$\frac{\ddot{a}(t)}{a(t)} = -\frac{4\pi G}{3c^2} \left(\rho(t) + \frac{3p(t)}{c^2} \right) + \frac{\Lambda c^2}{3}$$



$$H^2(t) = \frac{8\pi G}{3c^2} \rho(t) - \frac{kc^2}{a^2(t)}$$

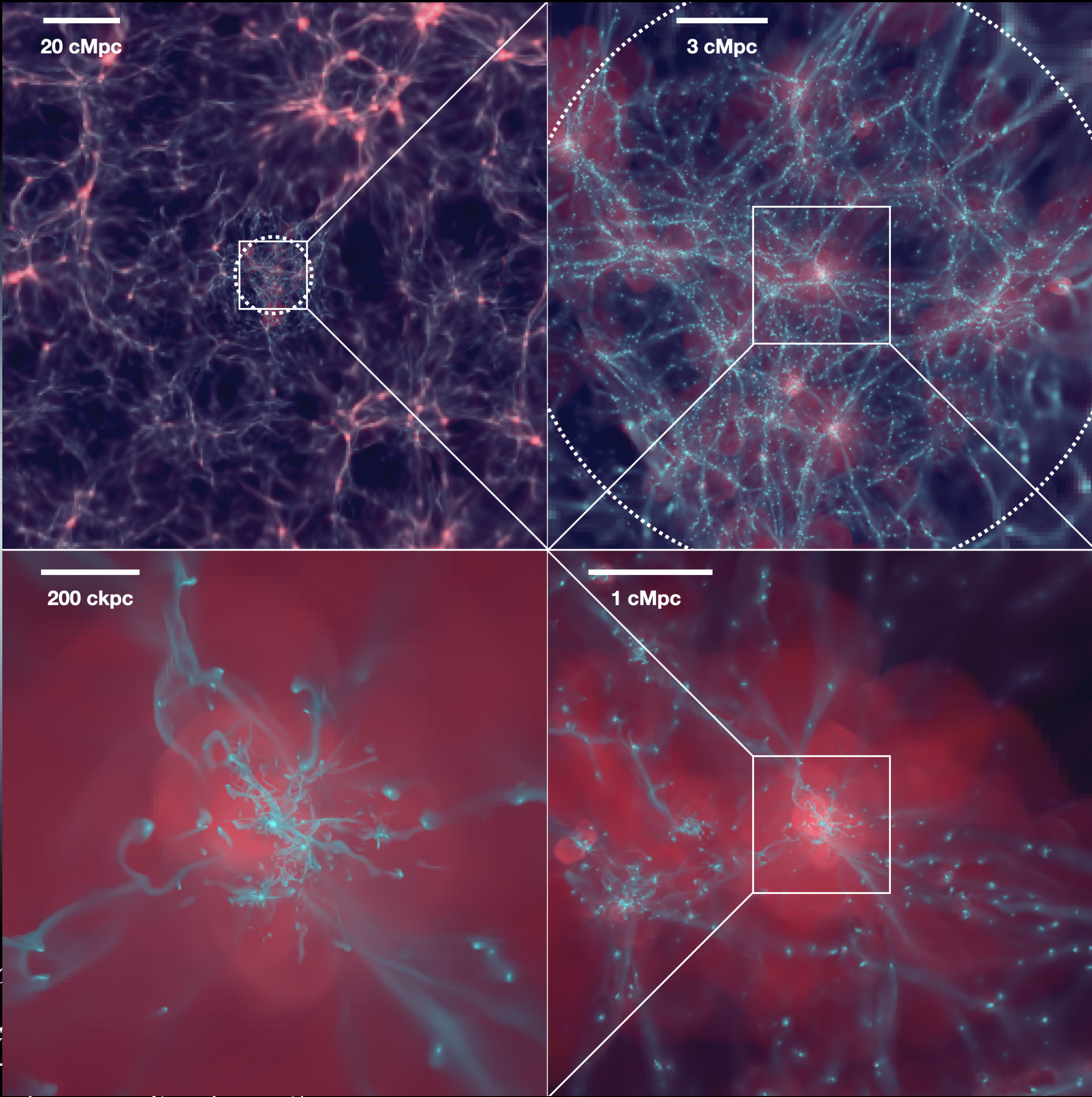
$$\frac{\ddot{a}(t)}{a(t)} = -\frac{4\pi G}{3c^2} \left(\rho(t) + \frac{3p(t)}{c^2} \right)$$





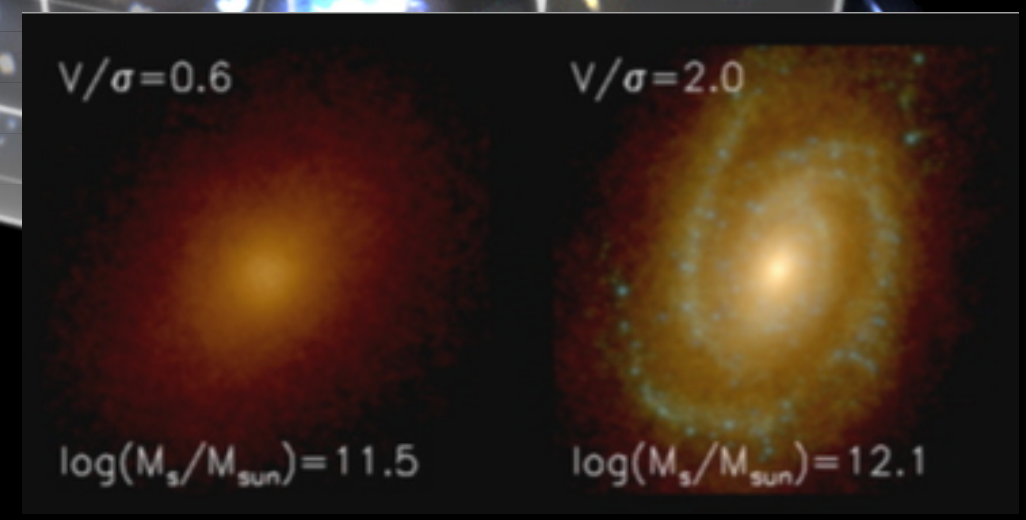
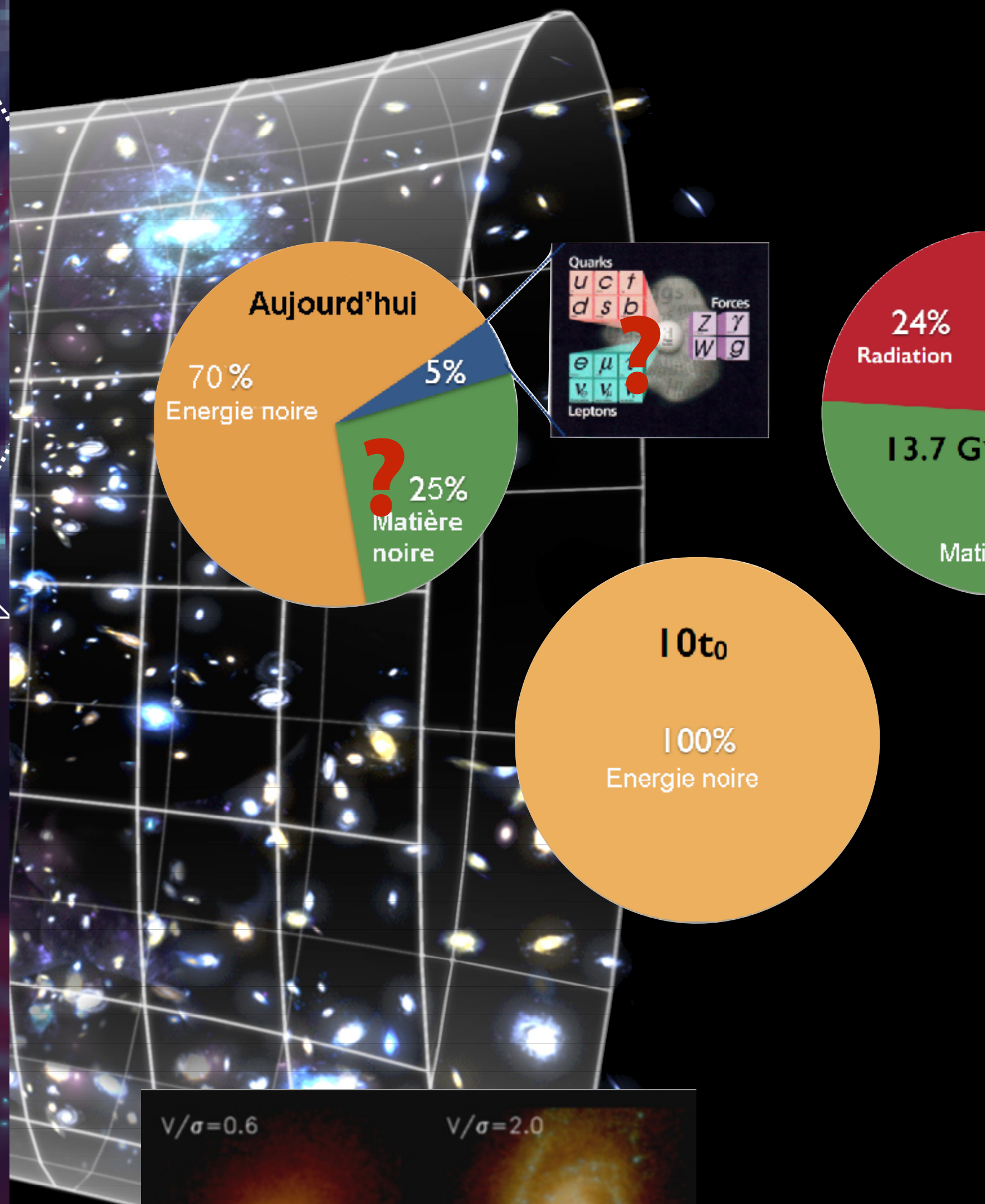
$$H^2(t) = \frac{8\pi G}{3c^2} \rho(t) - \frac{kc^2}{a^2(t)} + \frac{\Lambda c^2}{3}$$

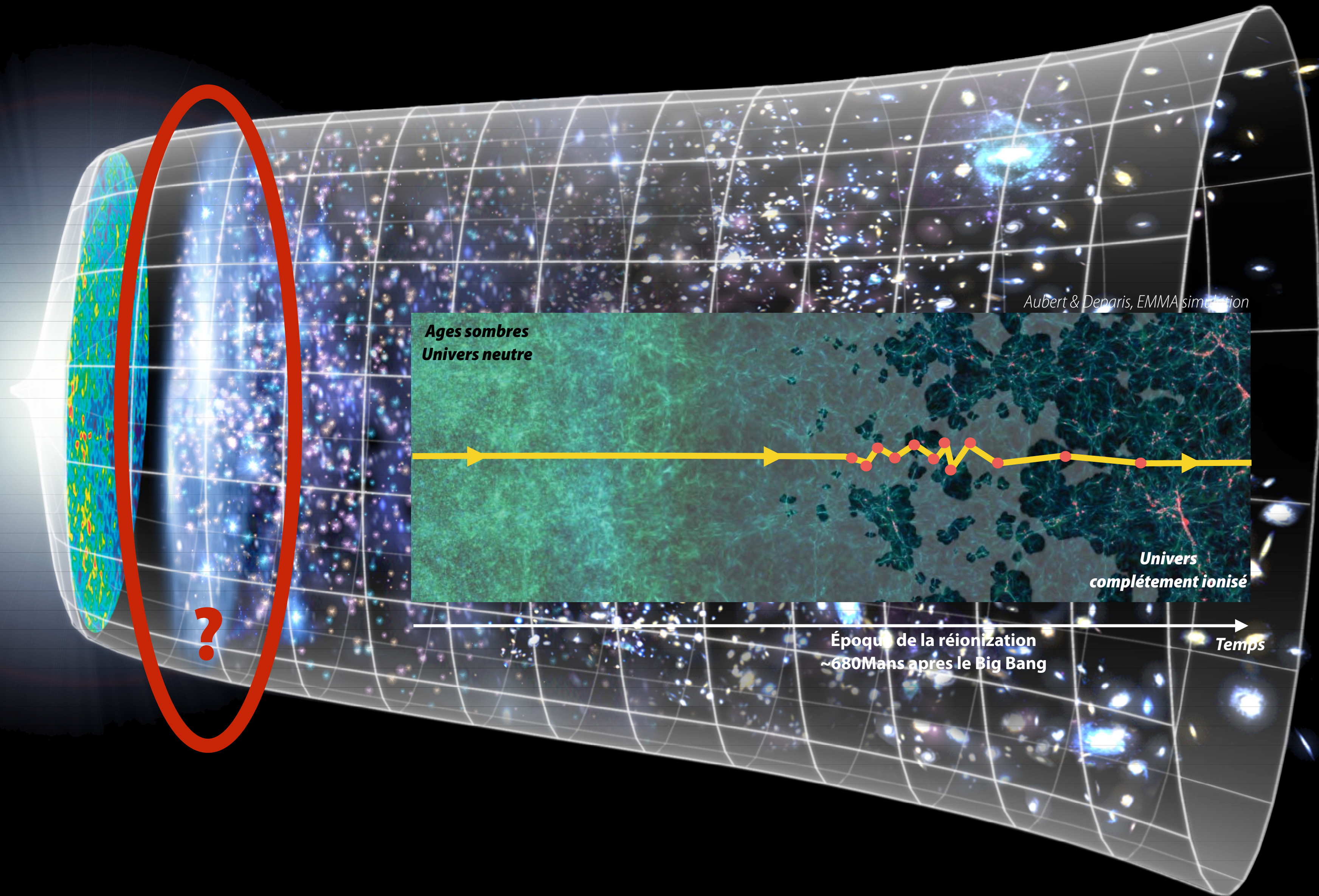
$$\frac{\ddot{a}(t)}{a(t)} = -\frac{4\pi G}{3c^2} \left(\rho(t) + \frac{3p(t)}{c^2} \right) + \frac{\Lambda c^2}{3}$$

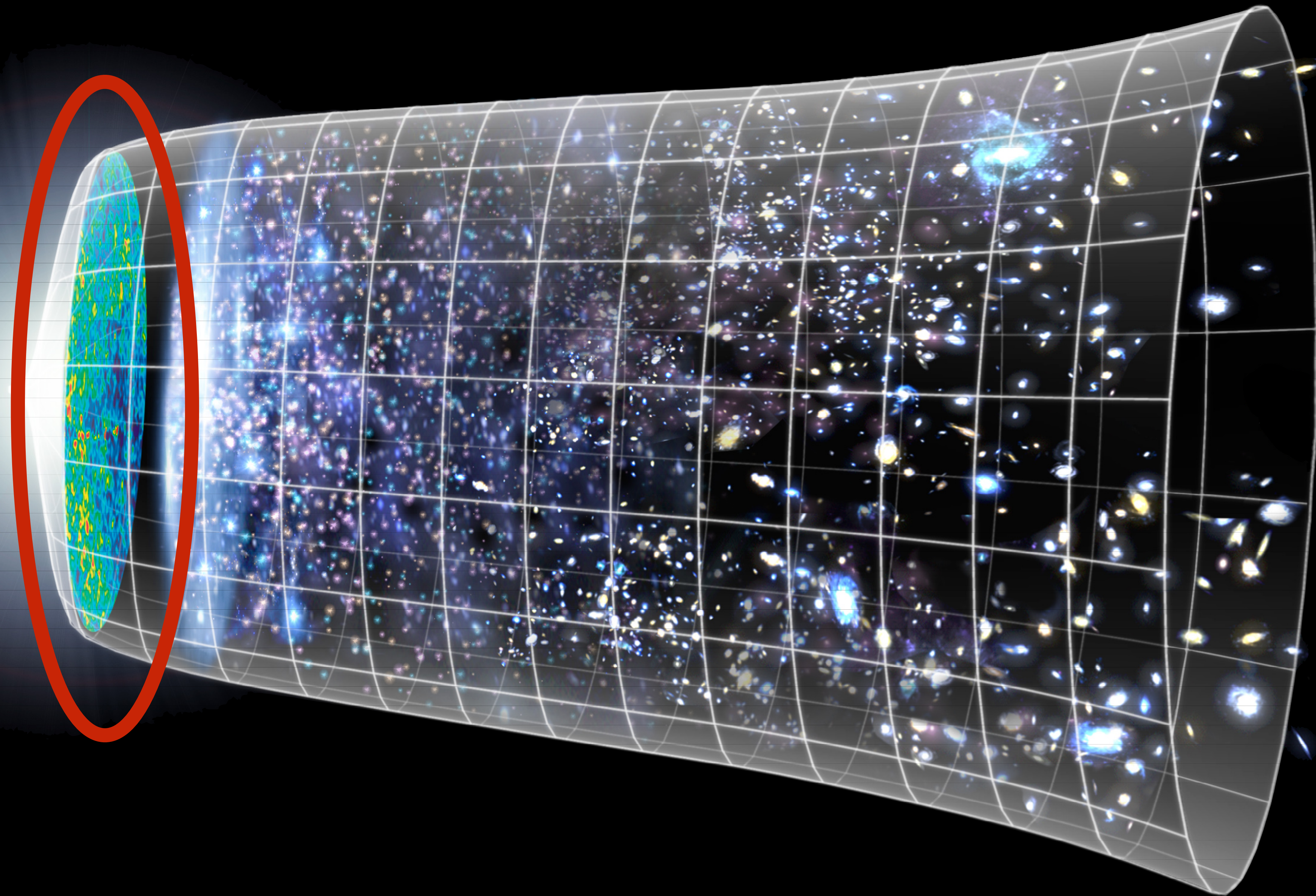


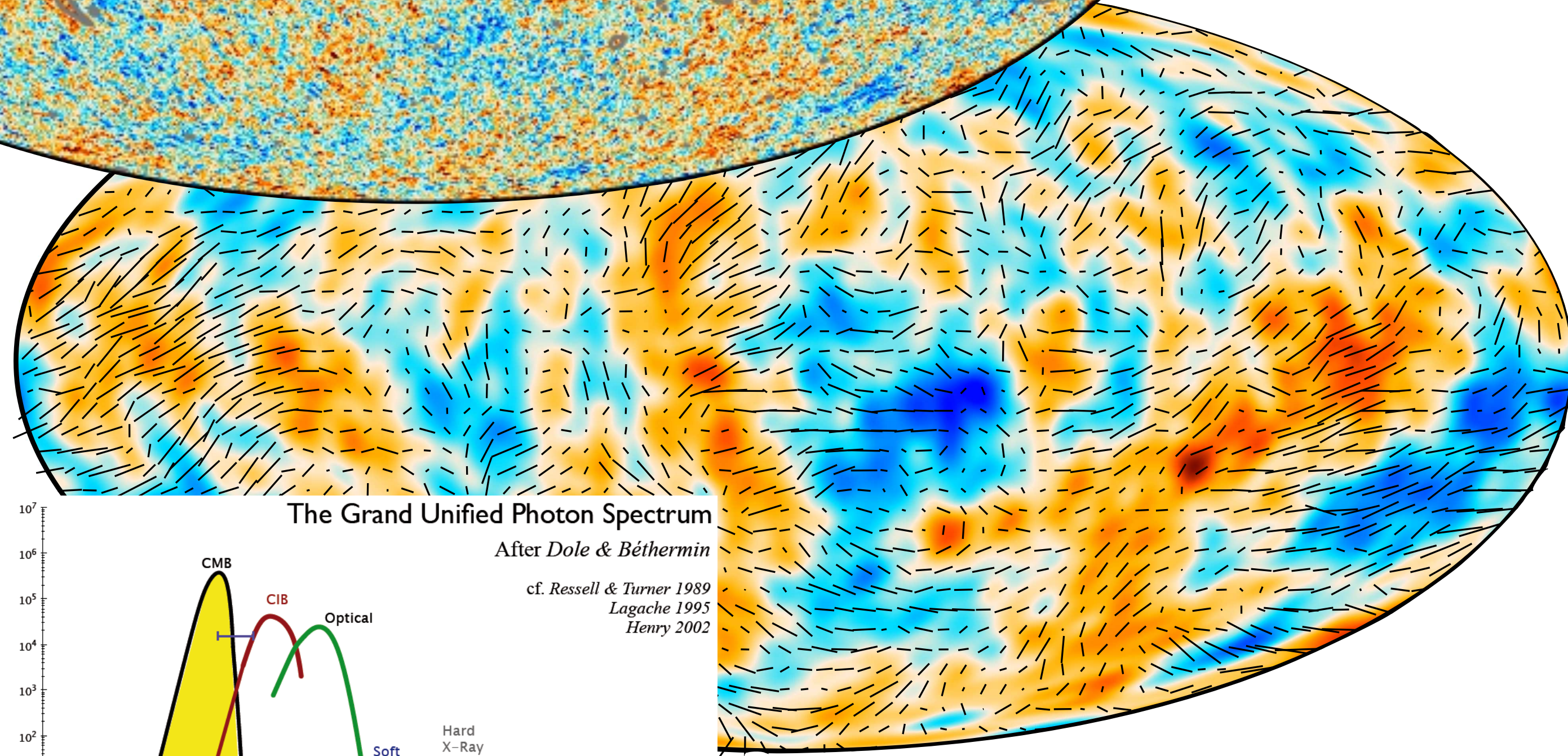
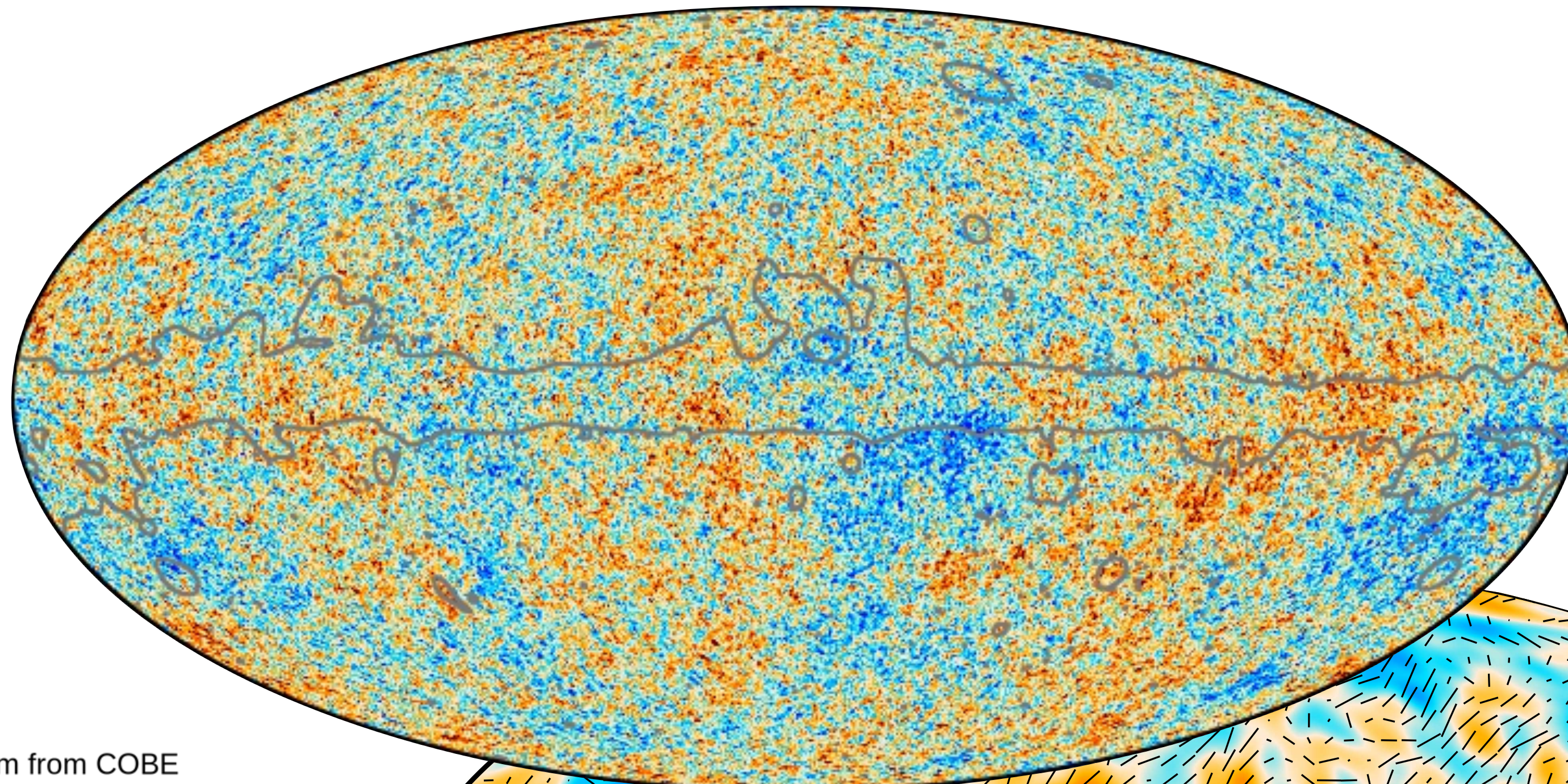
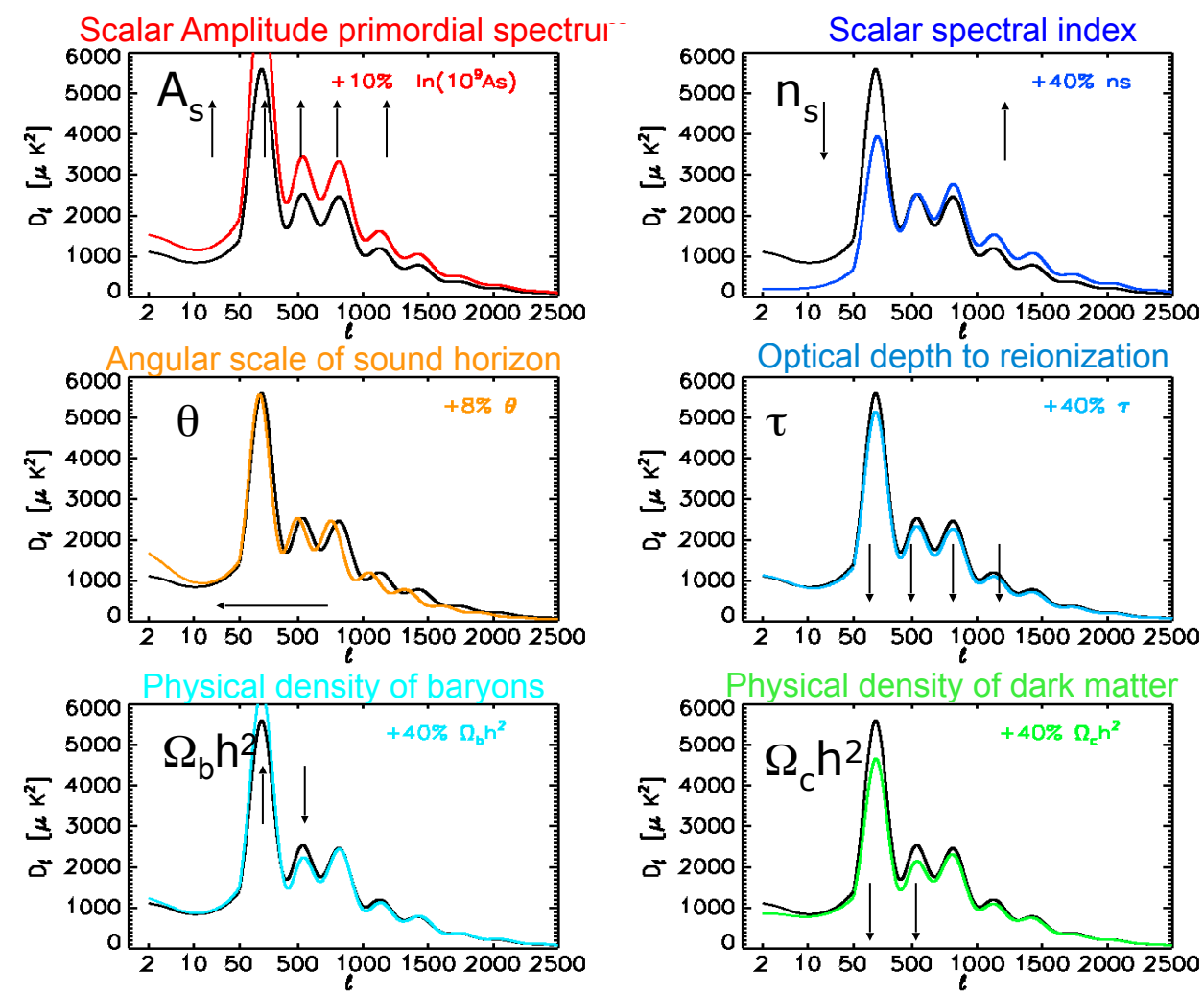
$$H^2(t) = \frac{8\pi G}{3c^2} \rho$$

$$\frac{\ddot{a}(t)}{a(t)} = -\frac{4\pi G}{3c^2} \rho$$

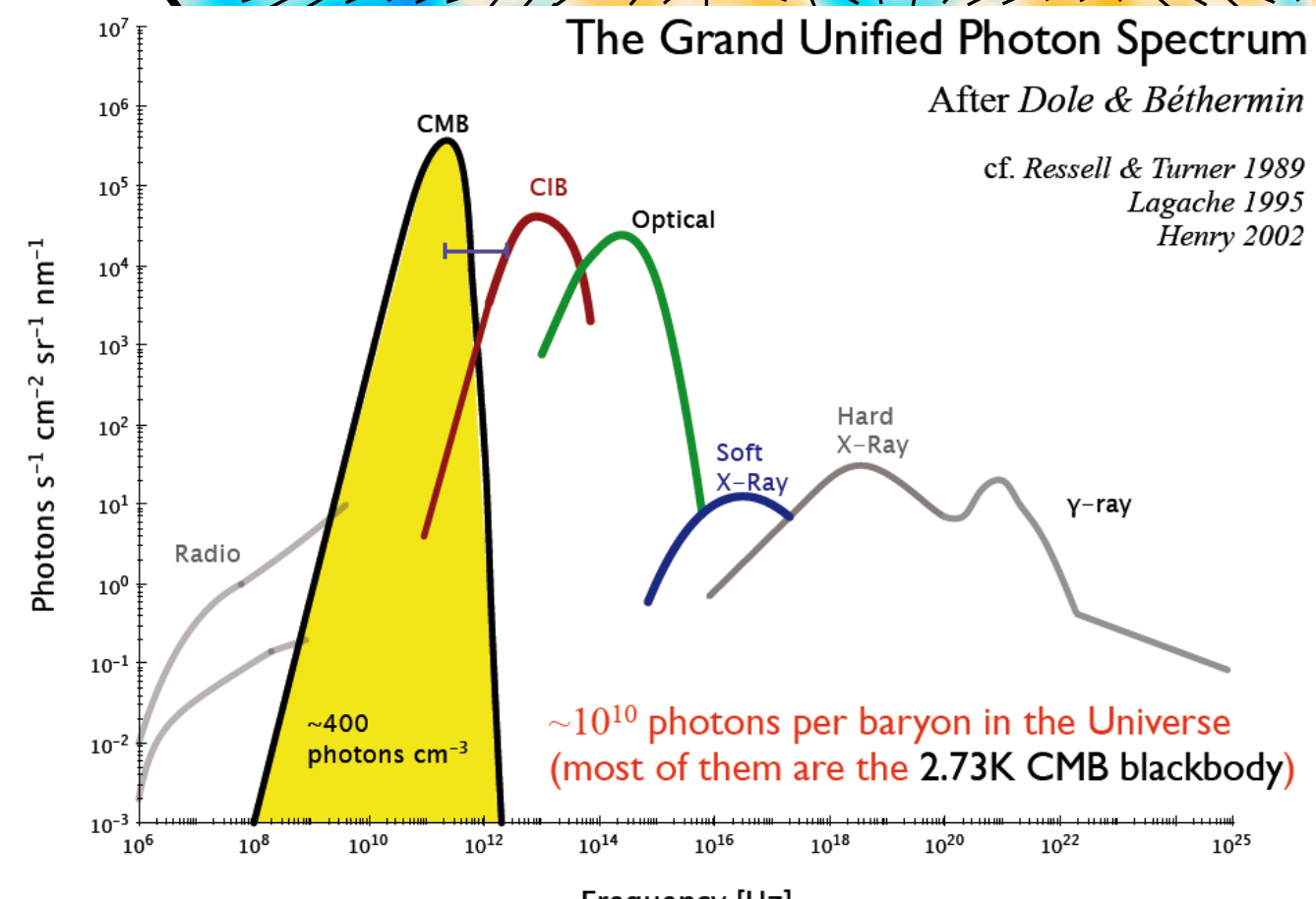
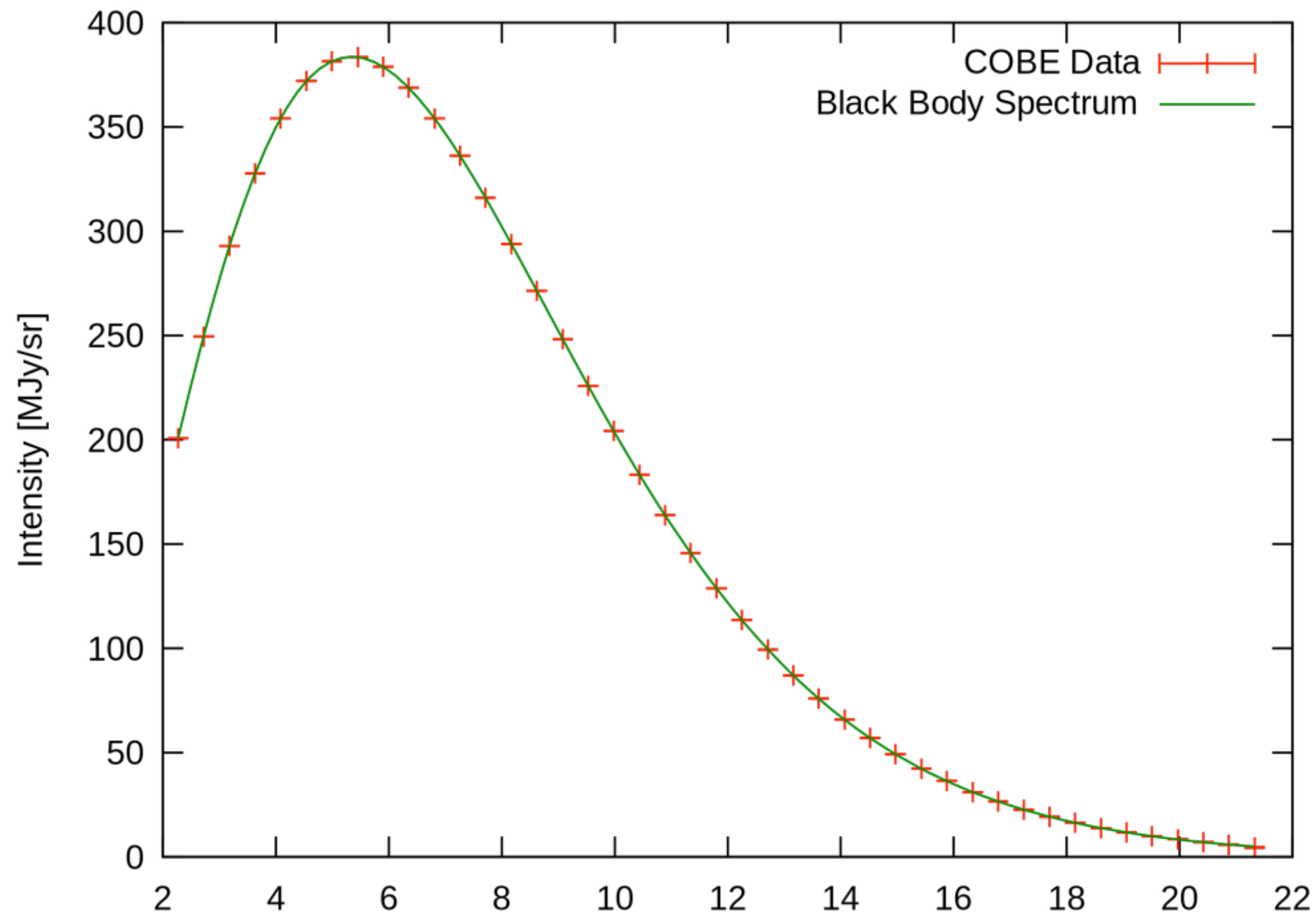


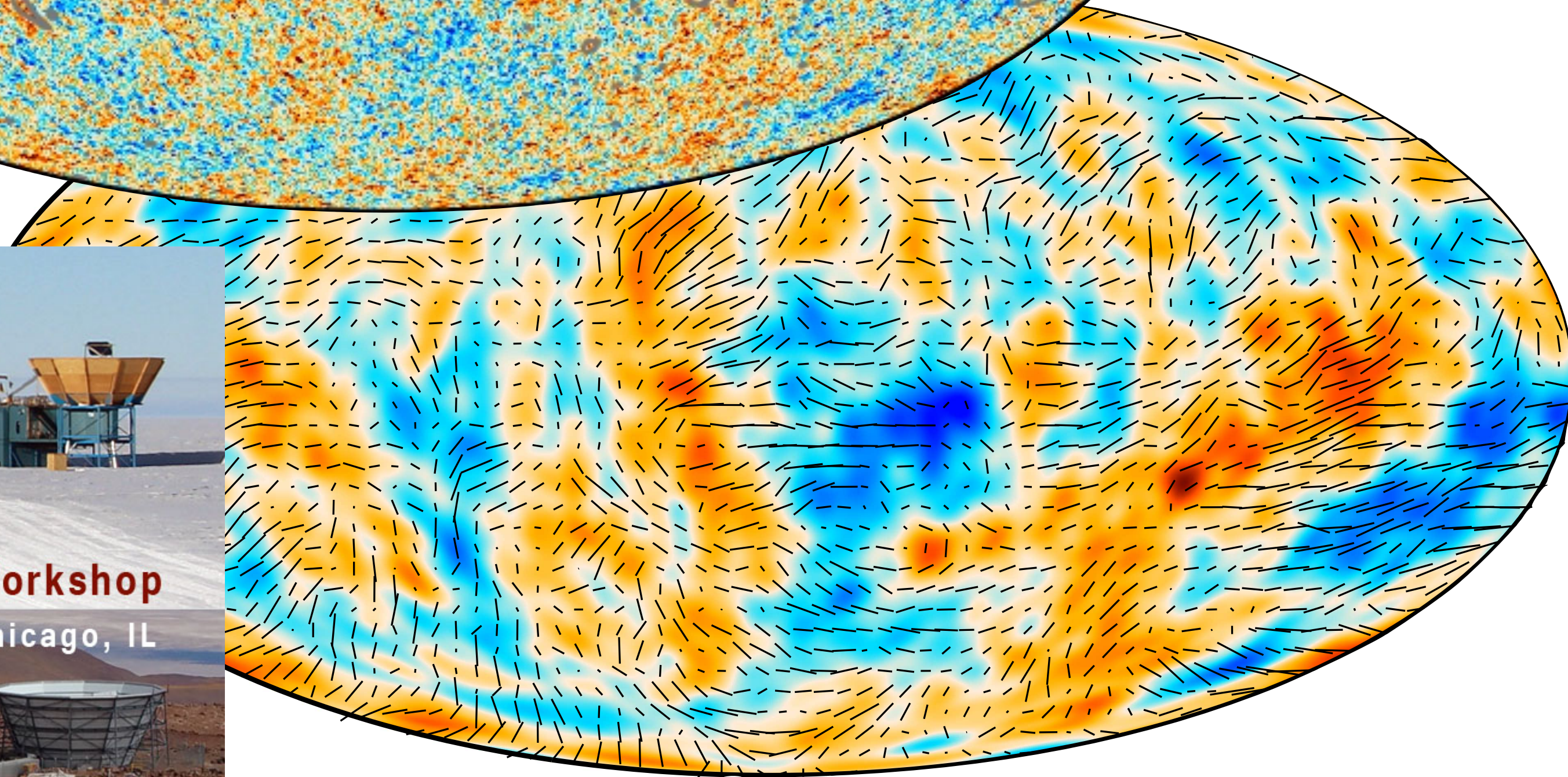
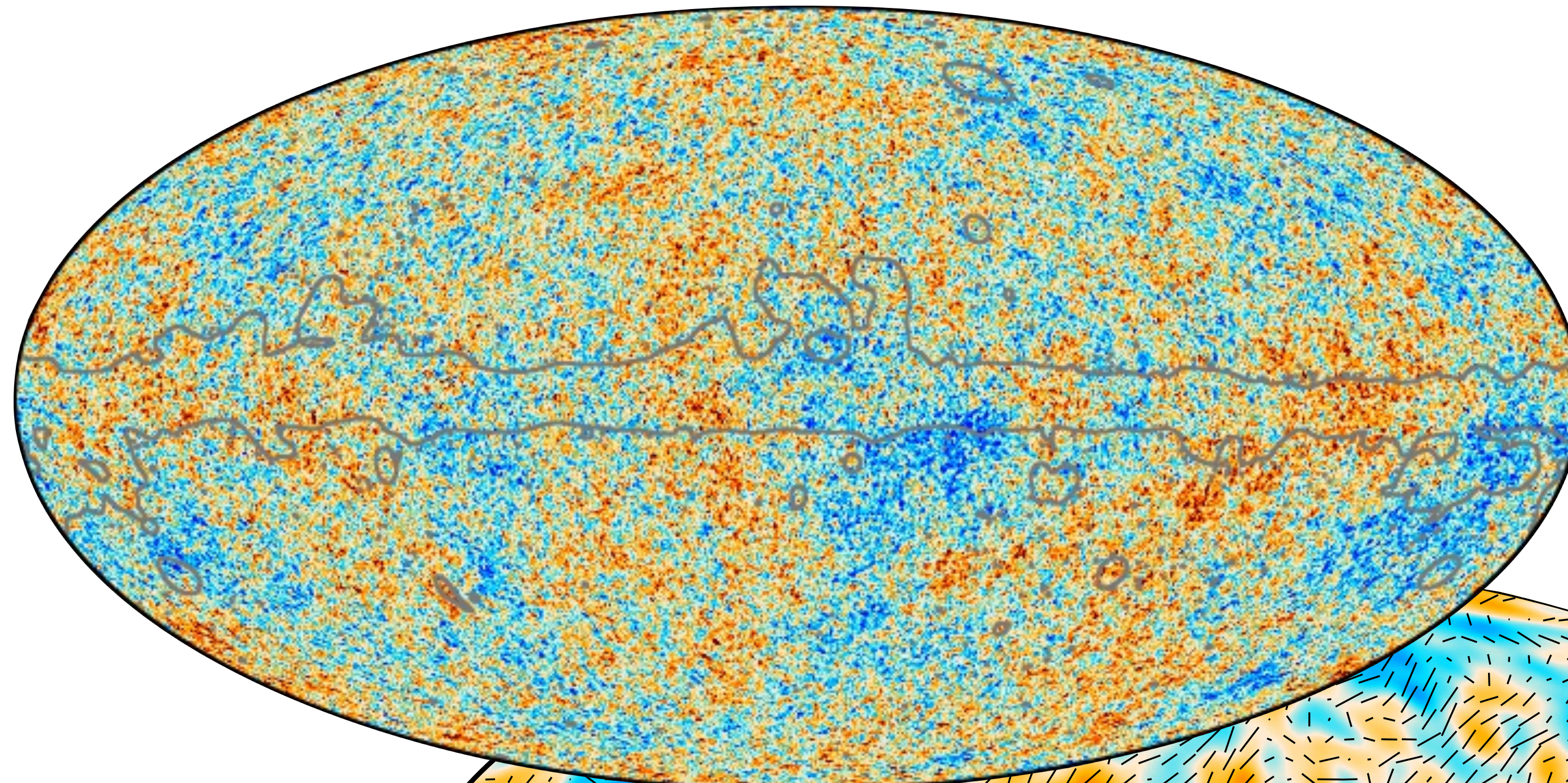






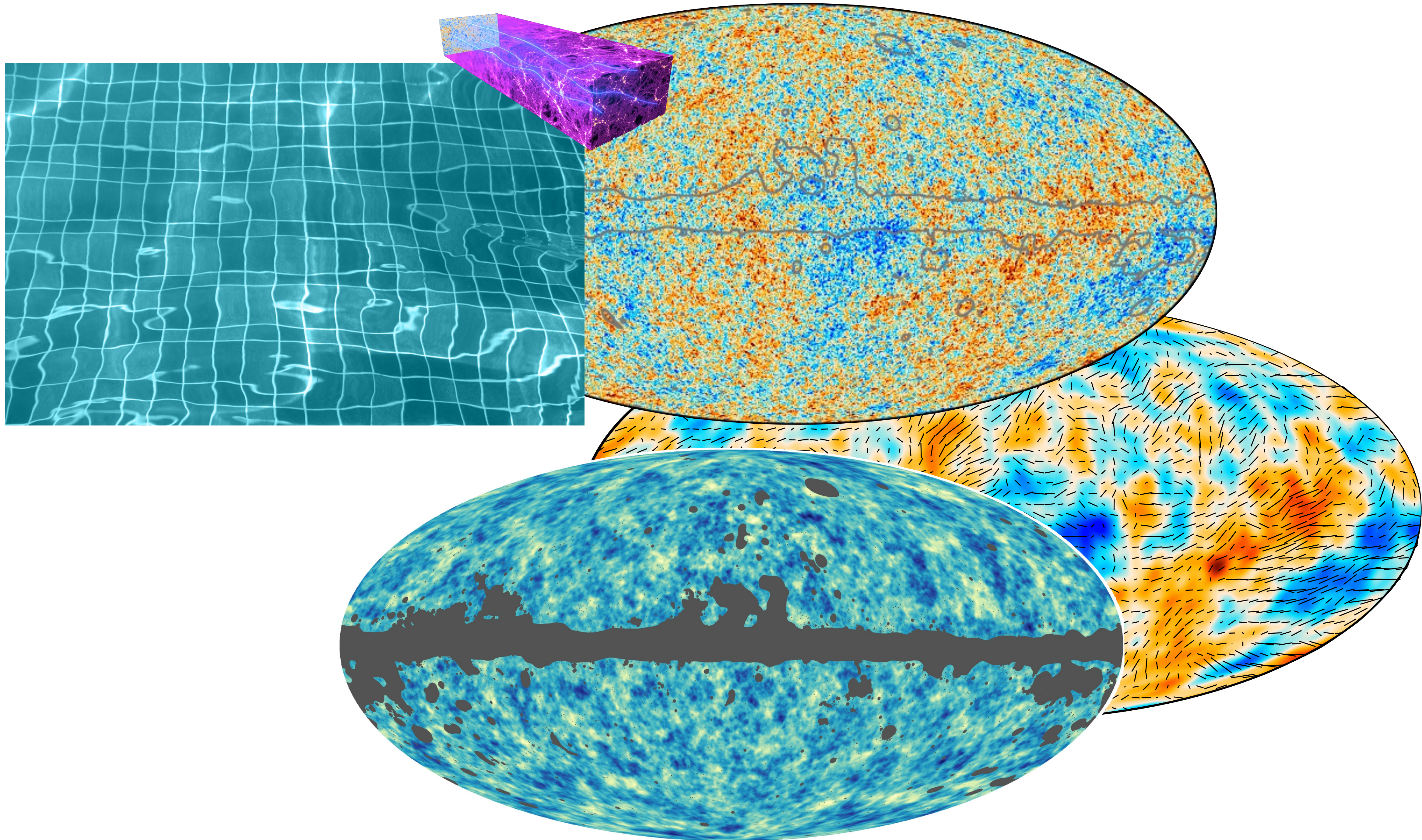
Cosmic Microwave Background Spectrum from COBE

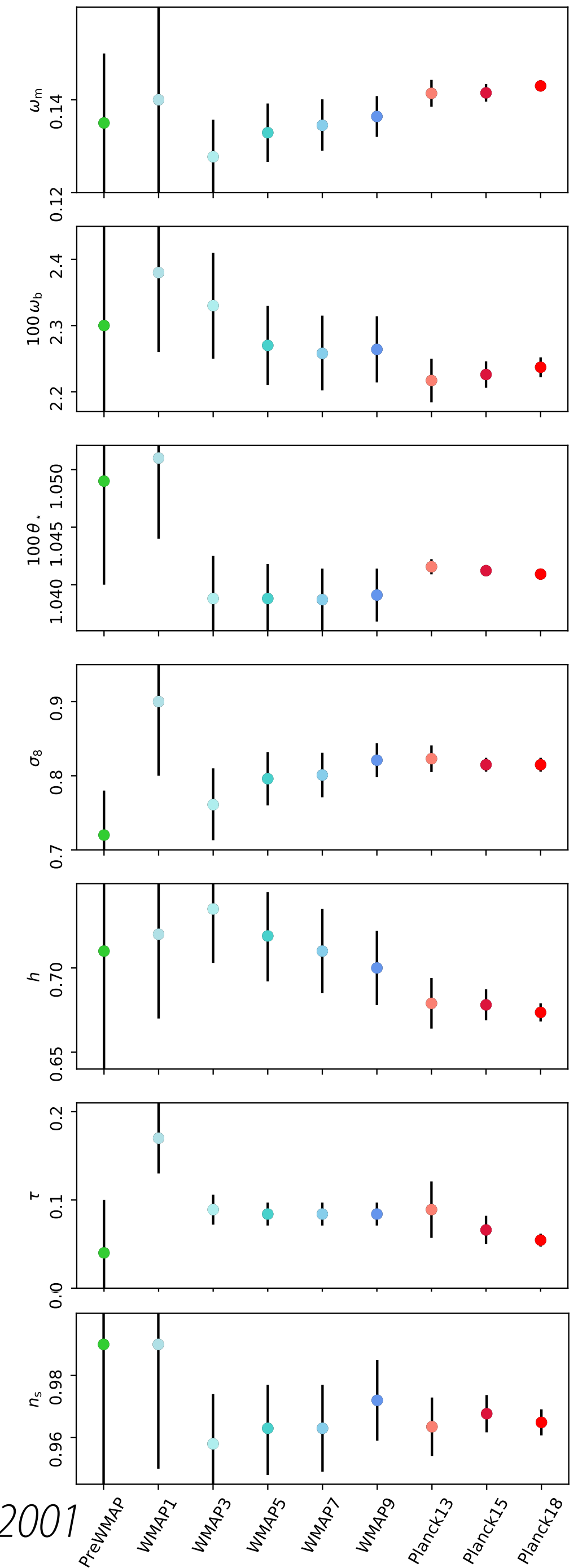
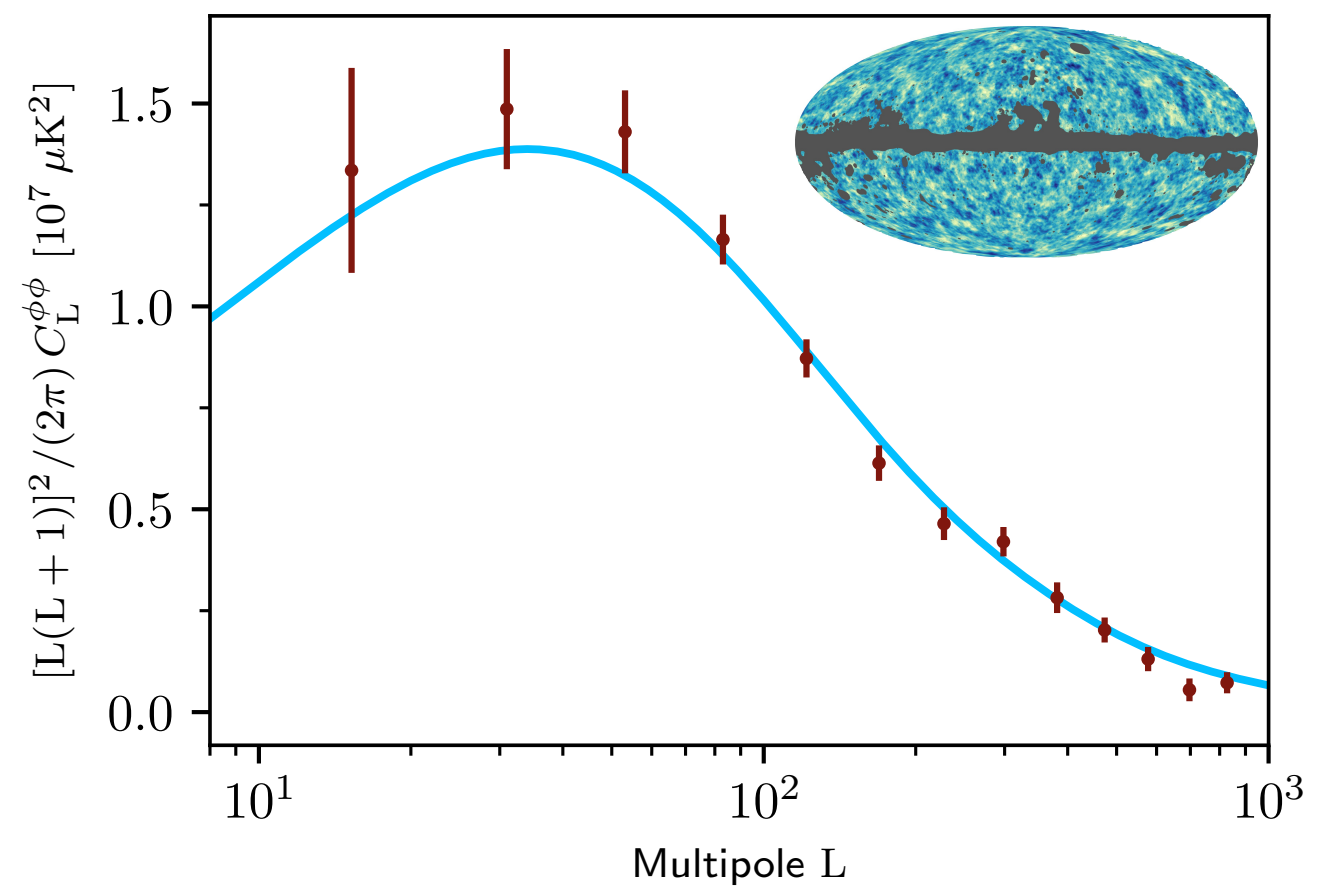
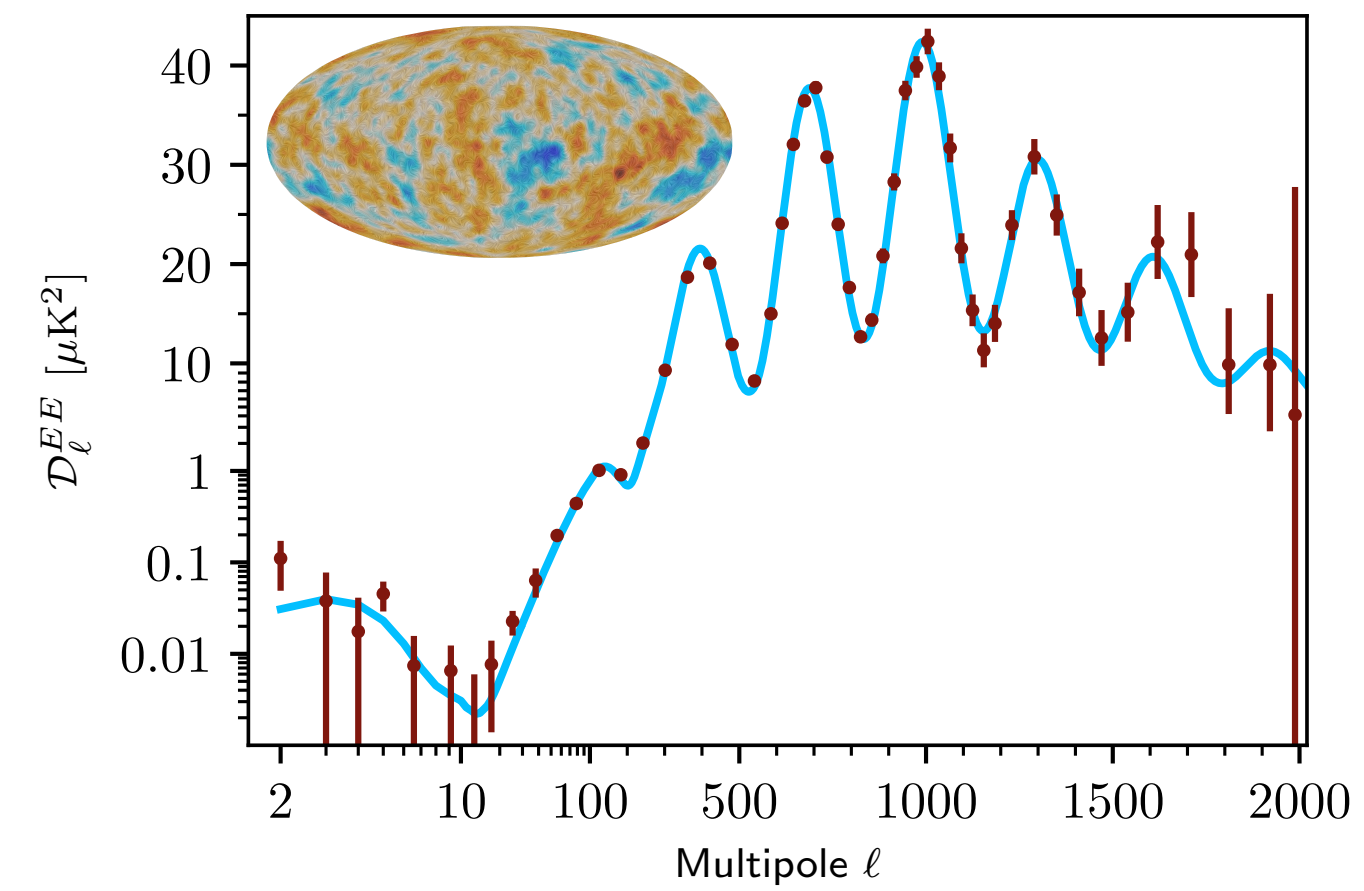
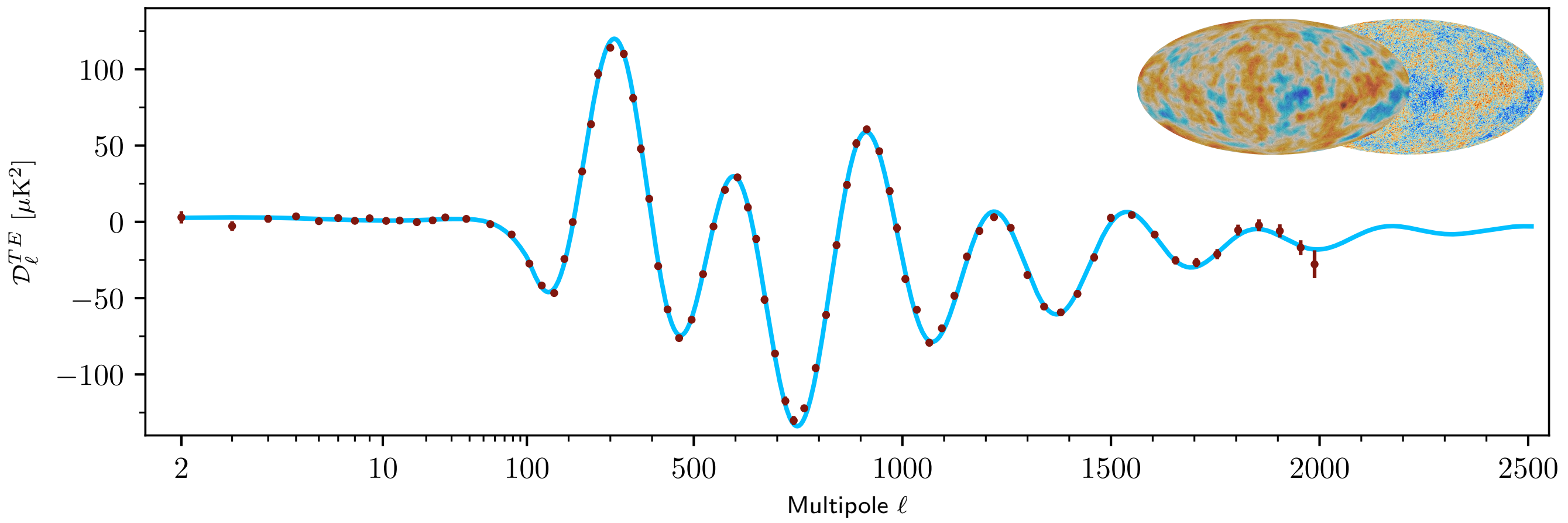
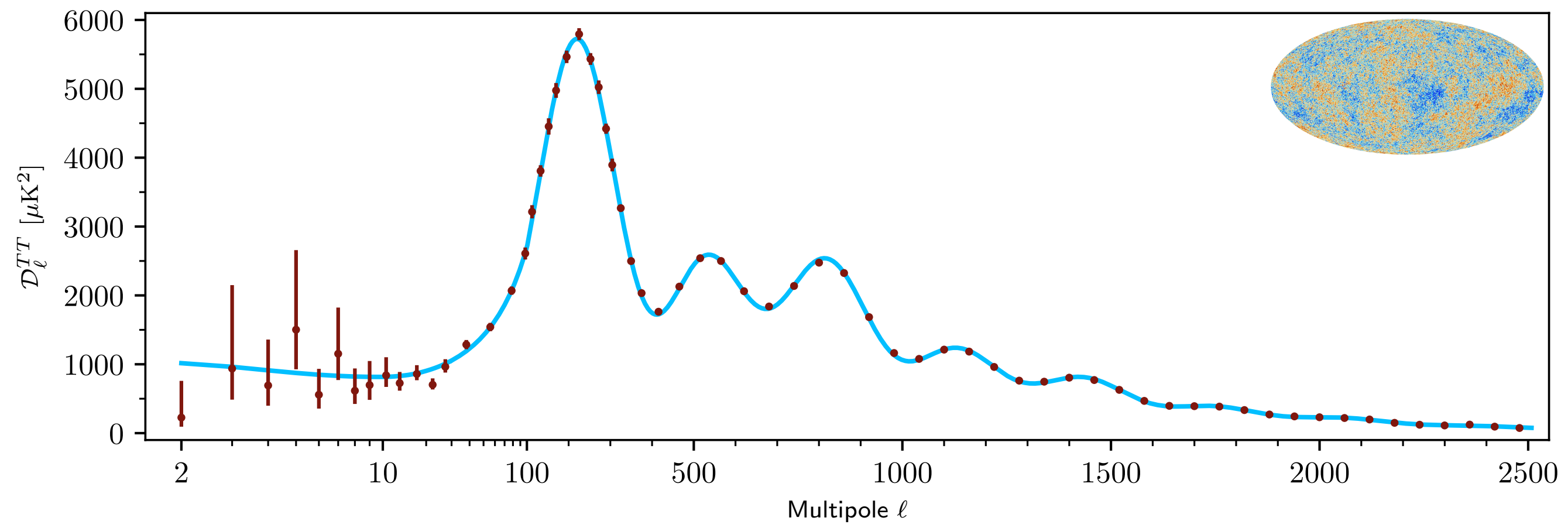




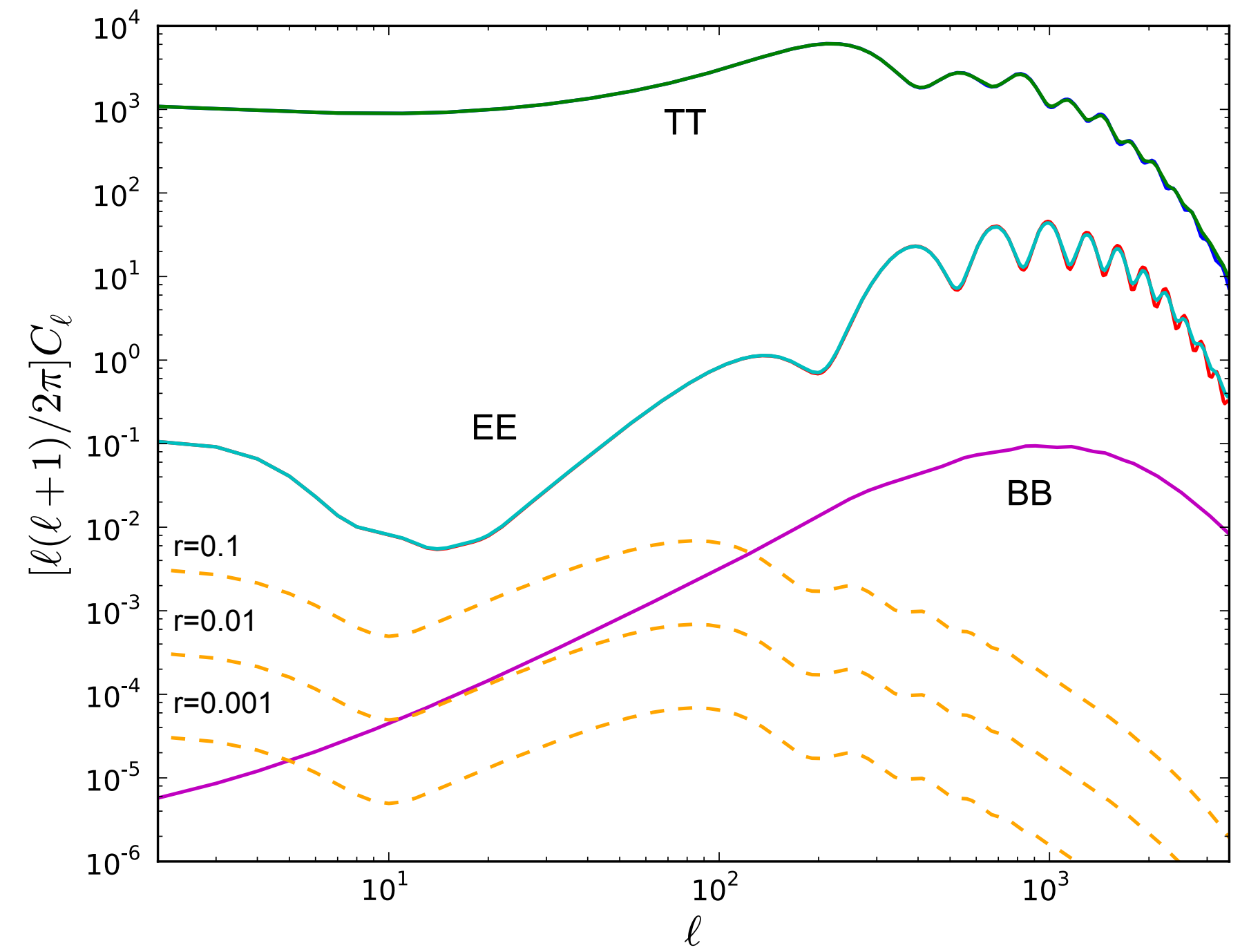
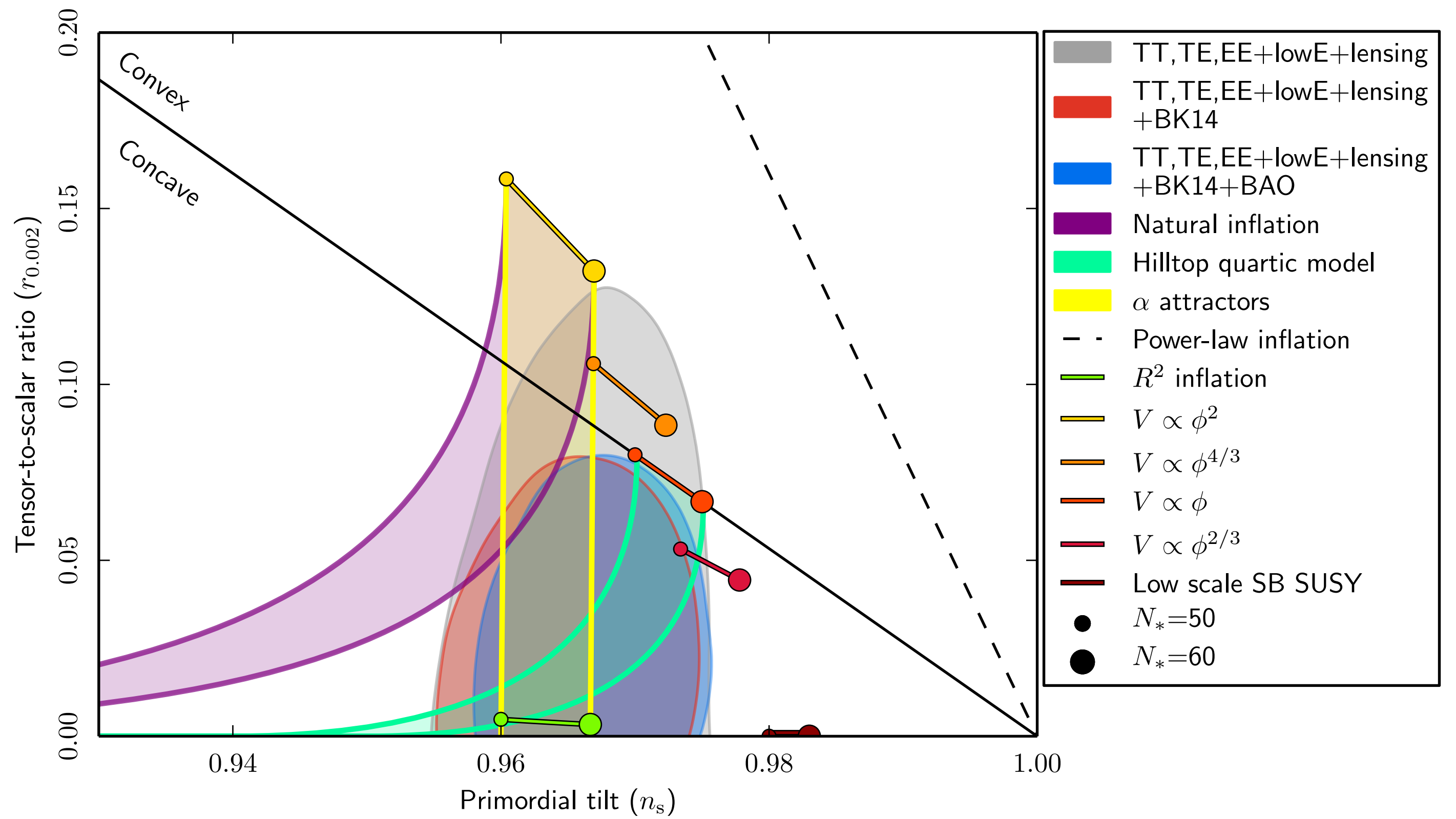
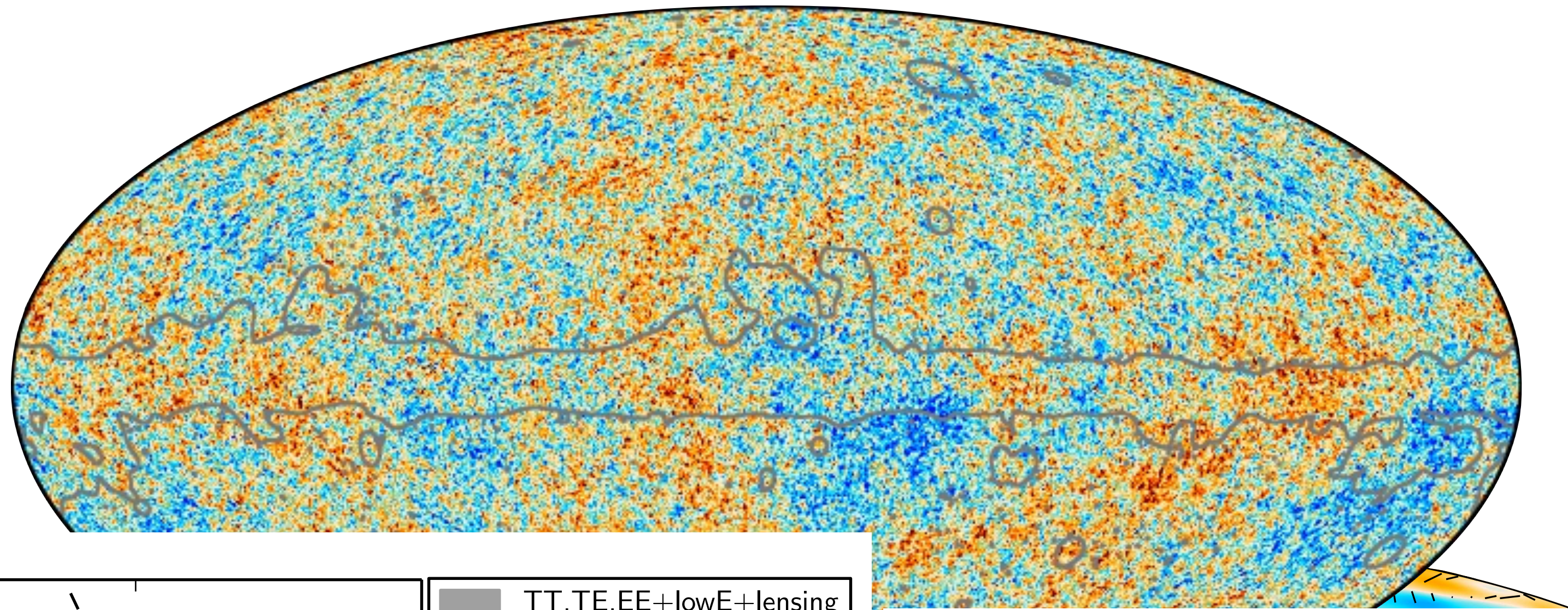
CMB-S4
Next Generation CMB Experiment

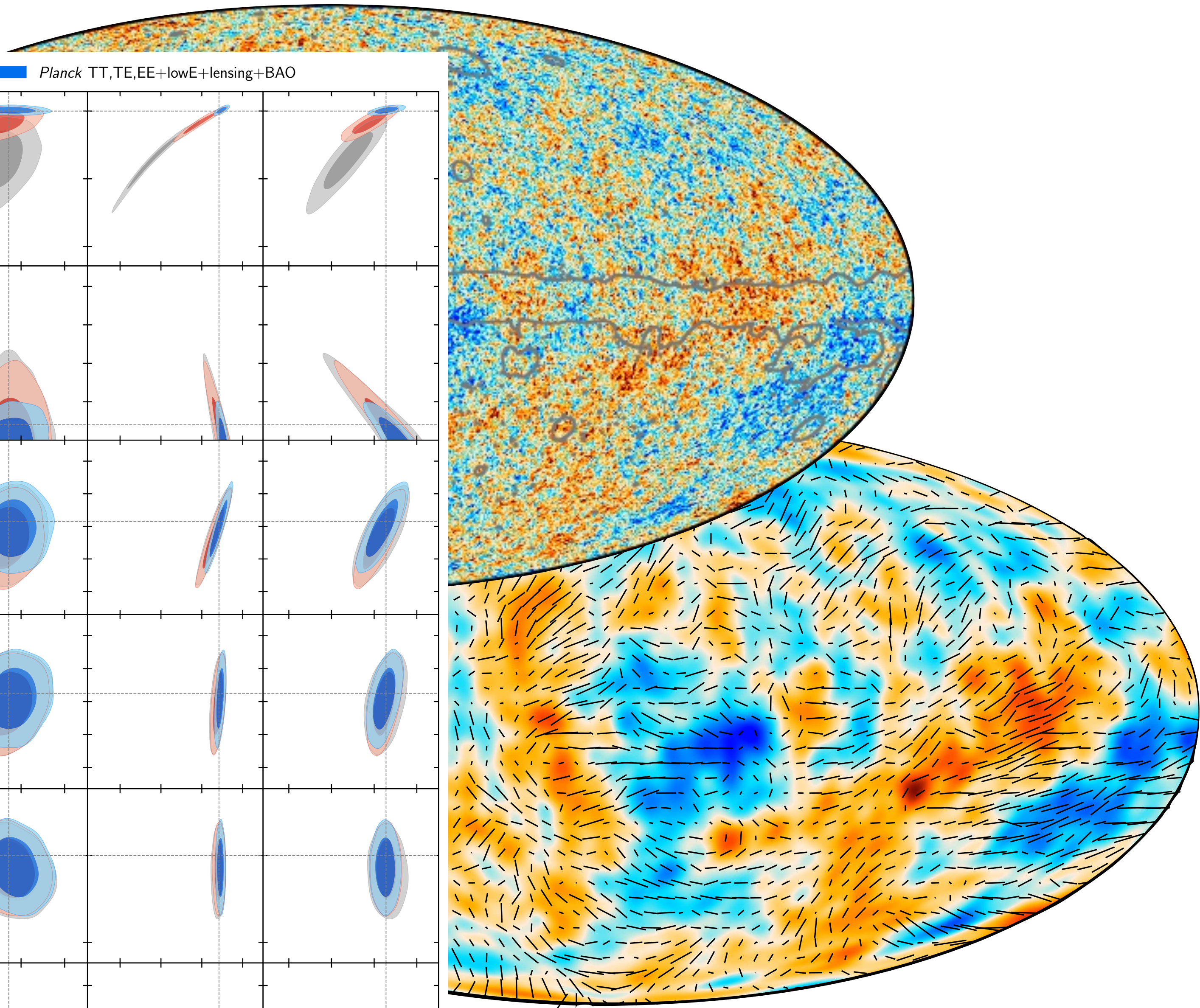
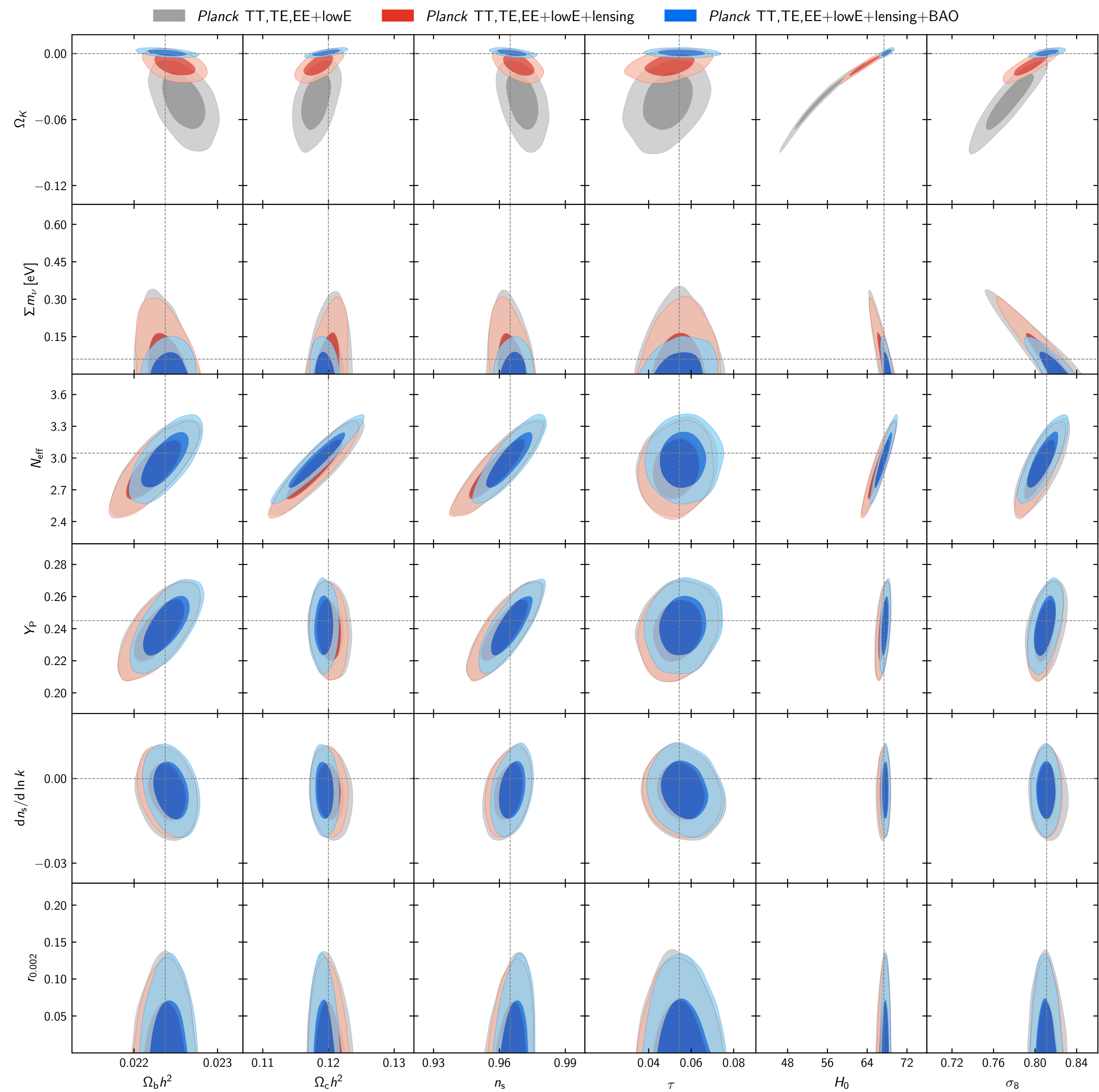
CMB-S4 Collaboration Workshop
September 19-21, 2016 • Chicago, IL

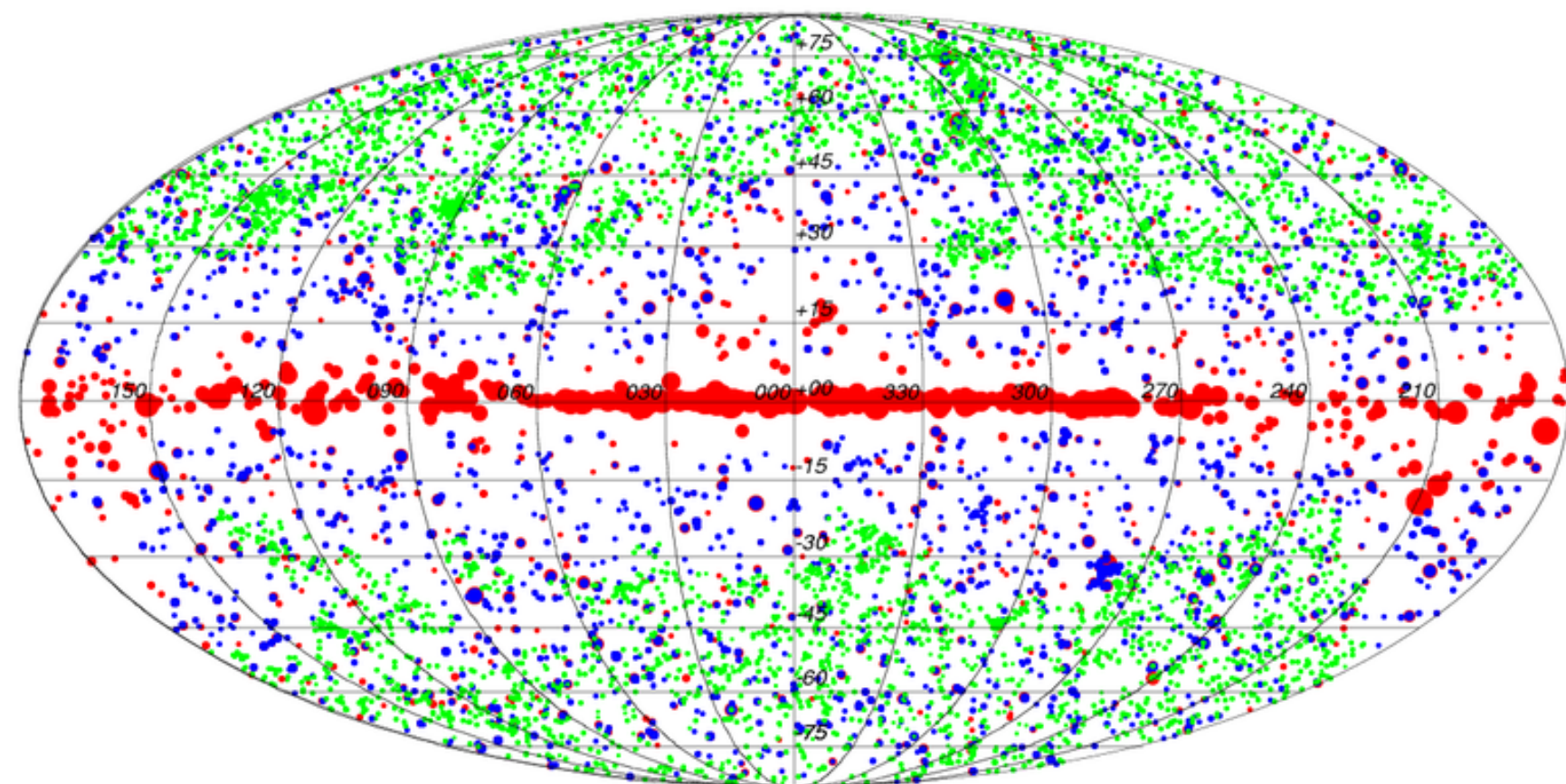
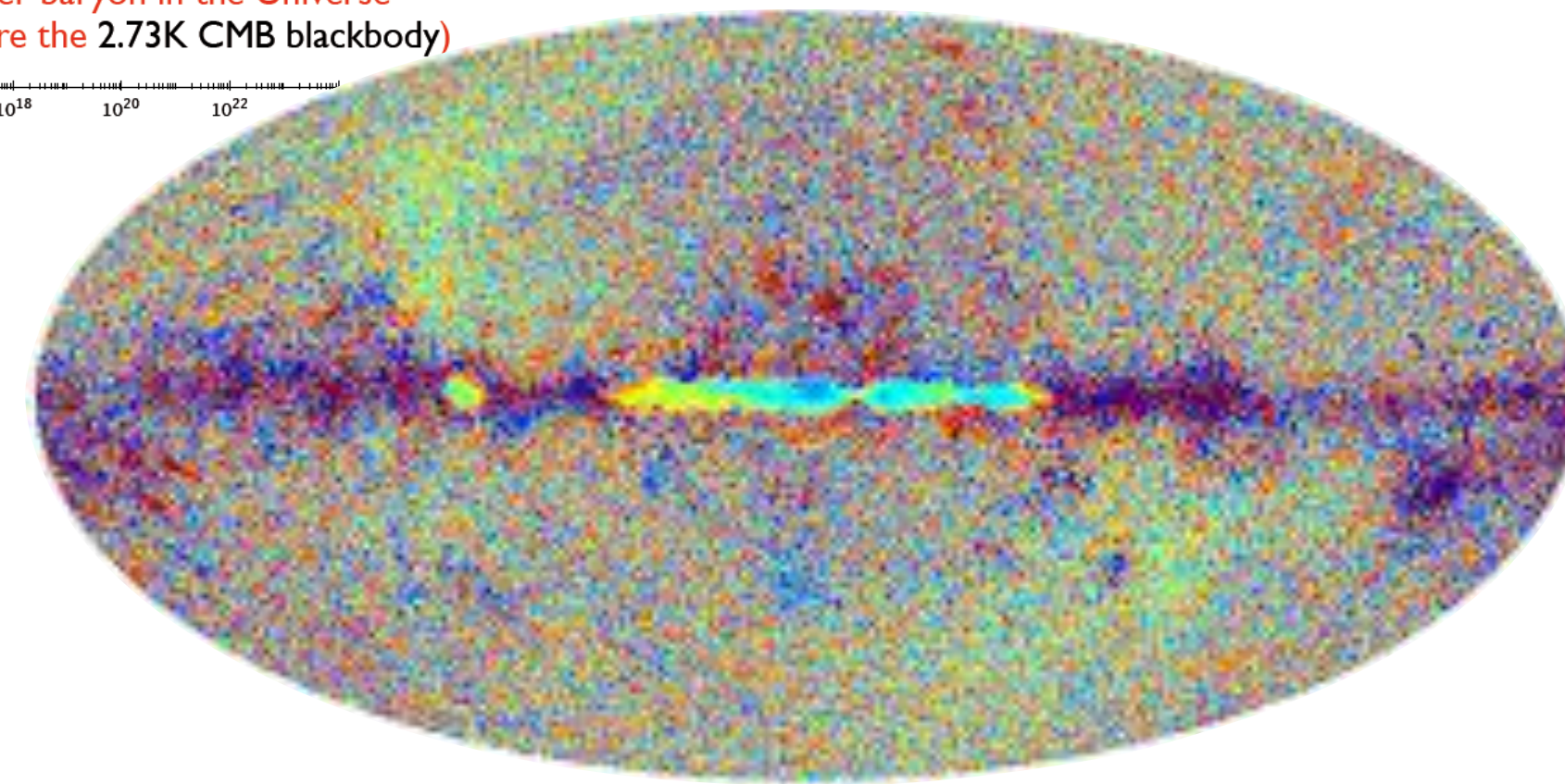
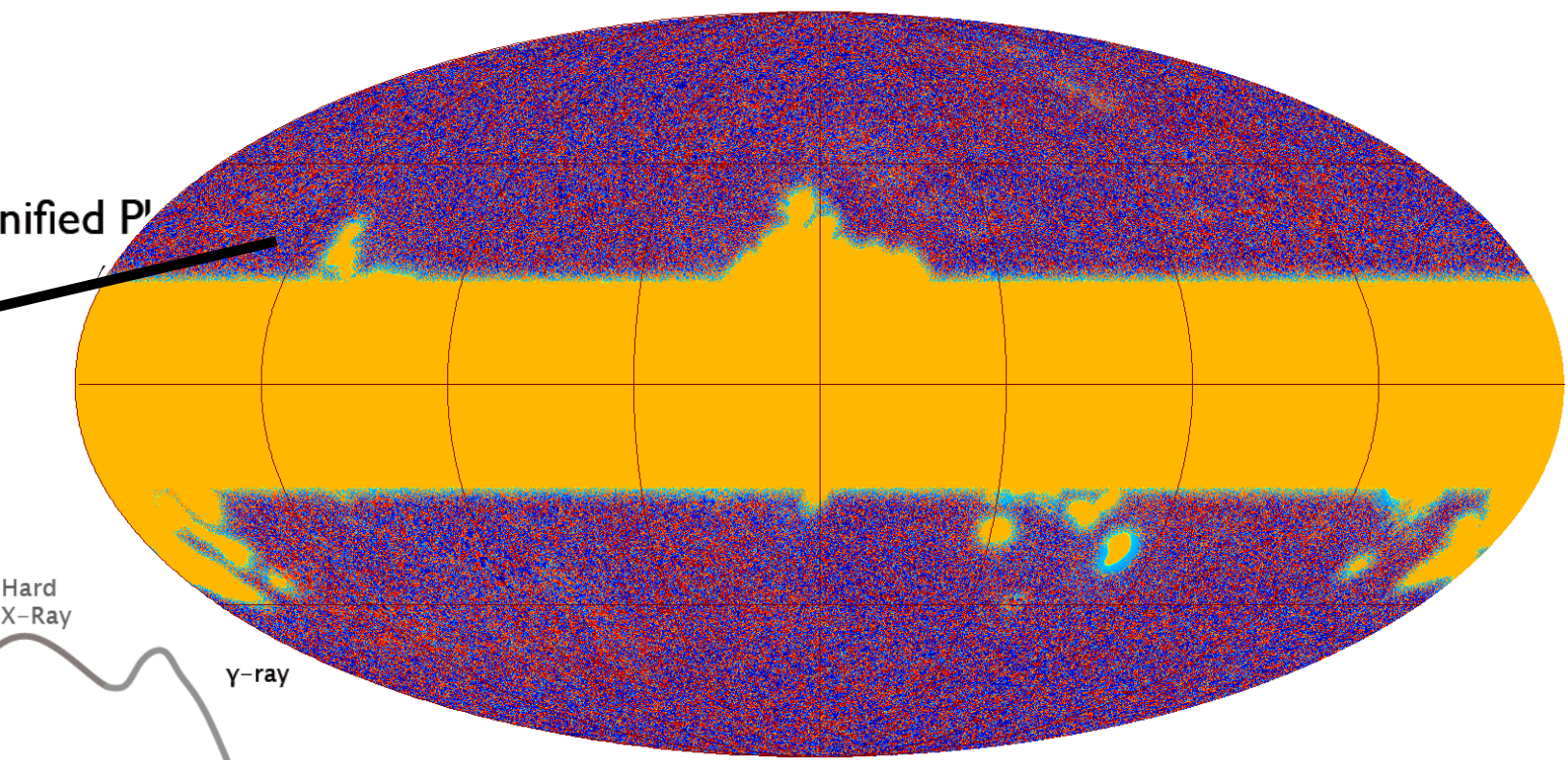
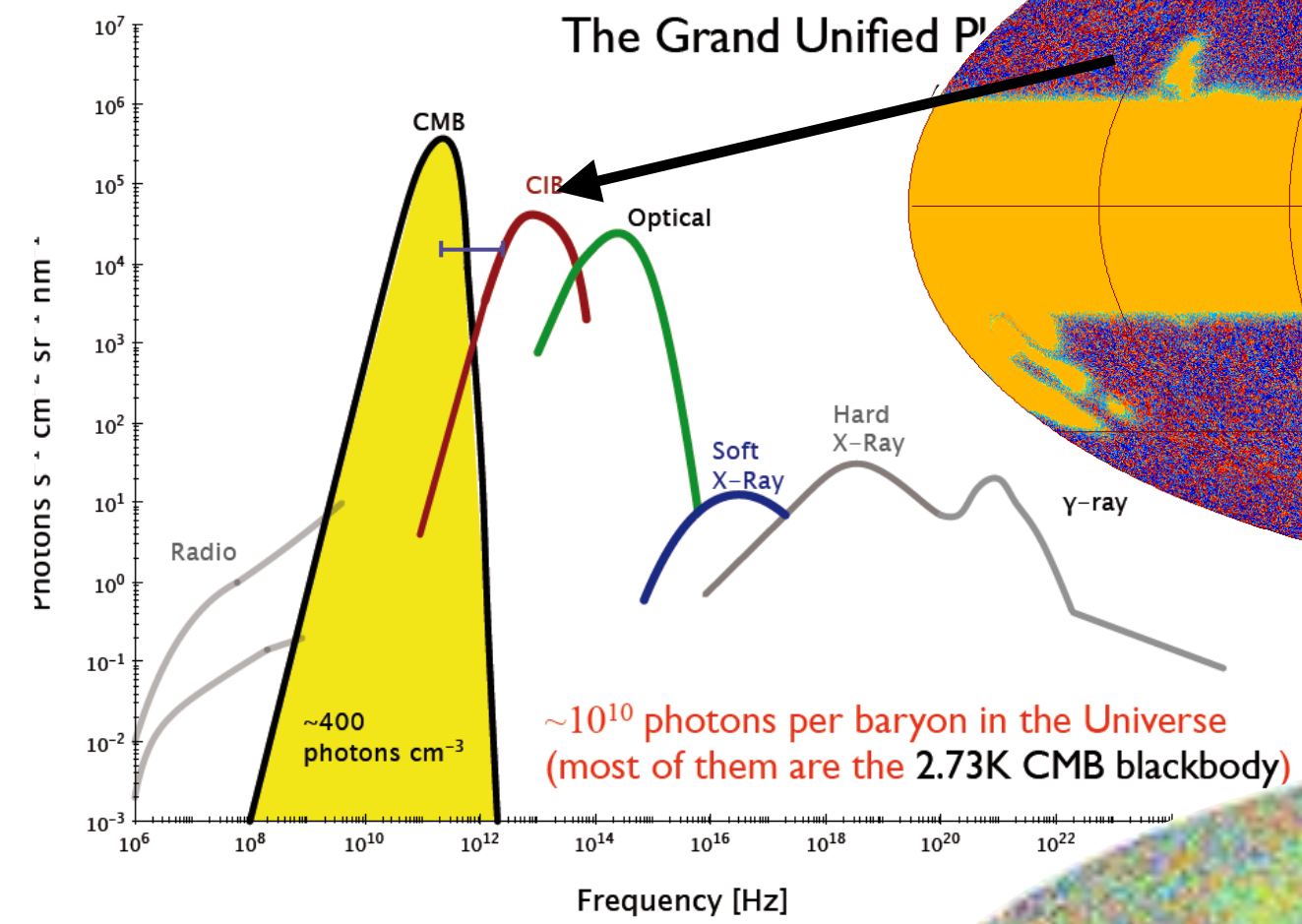
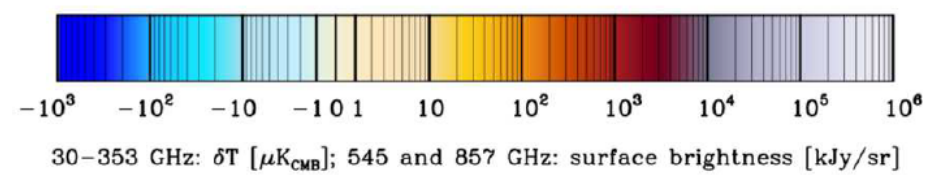
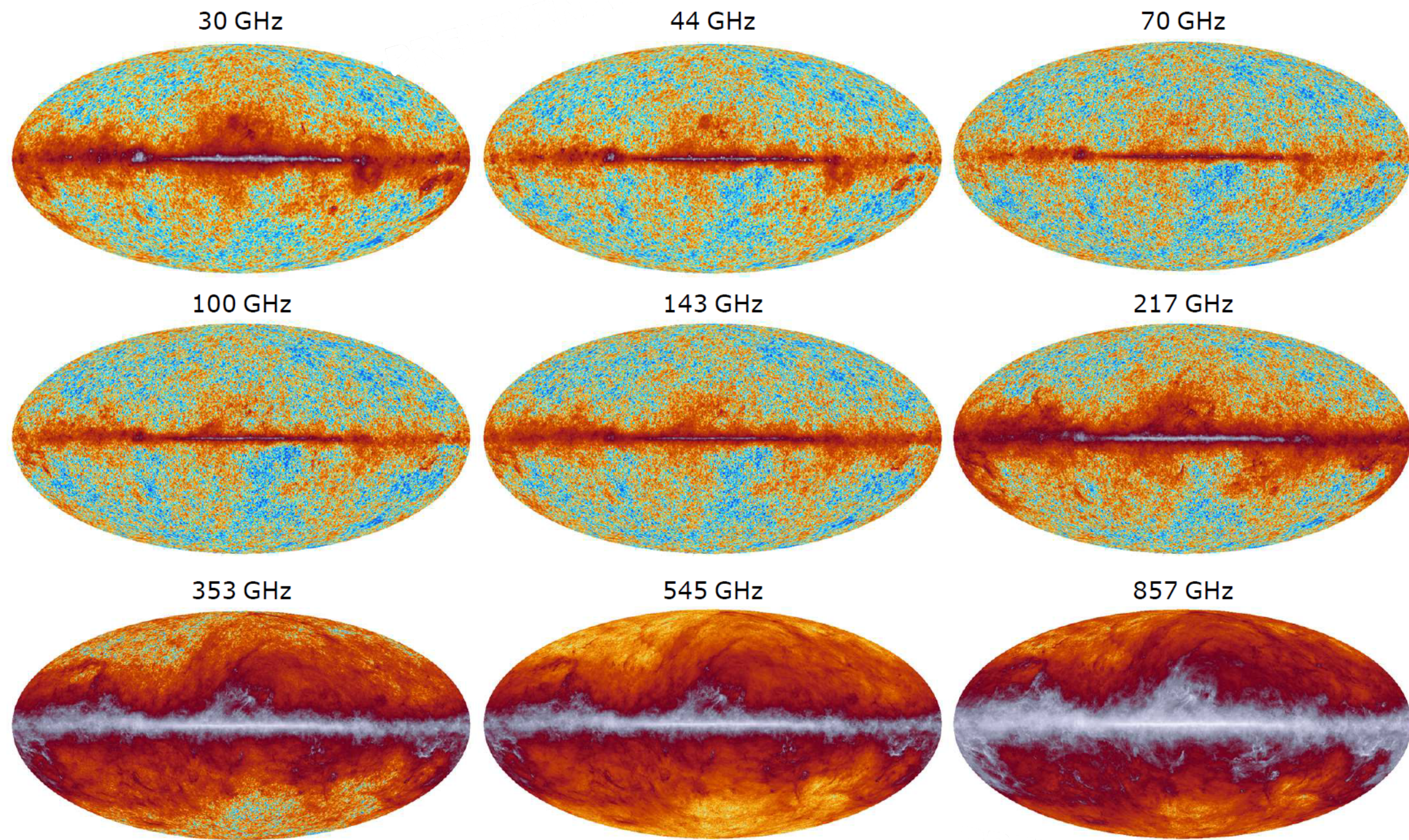




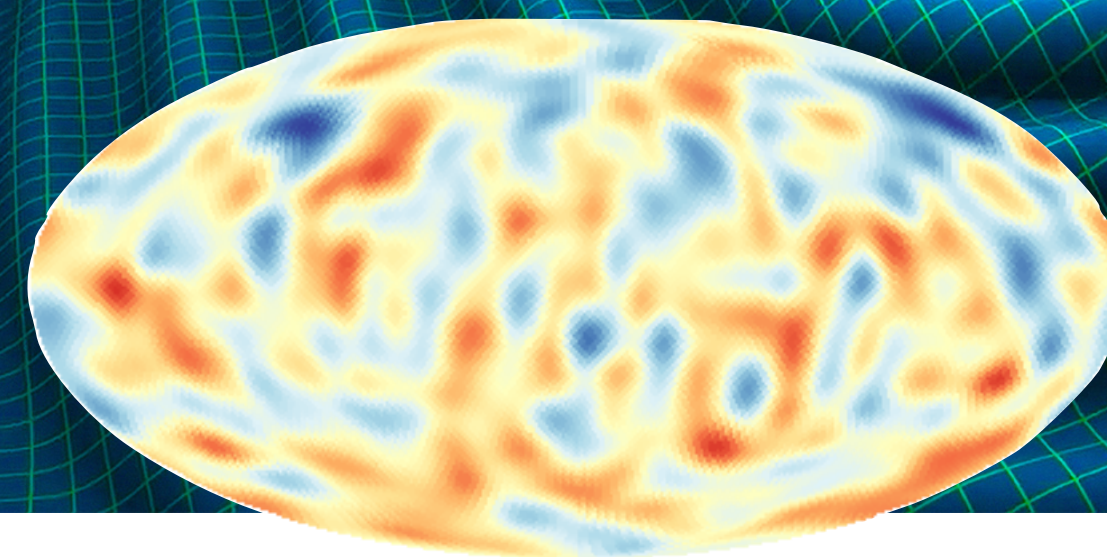
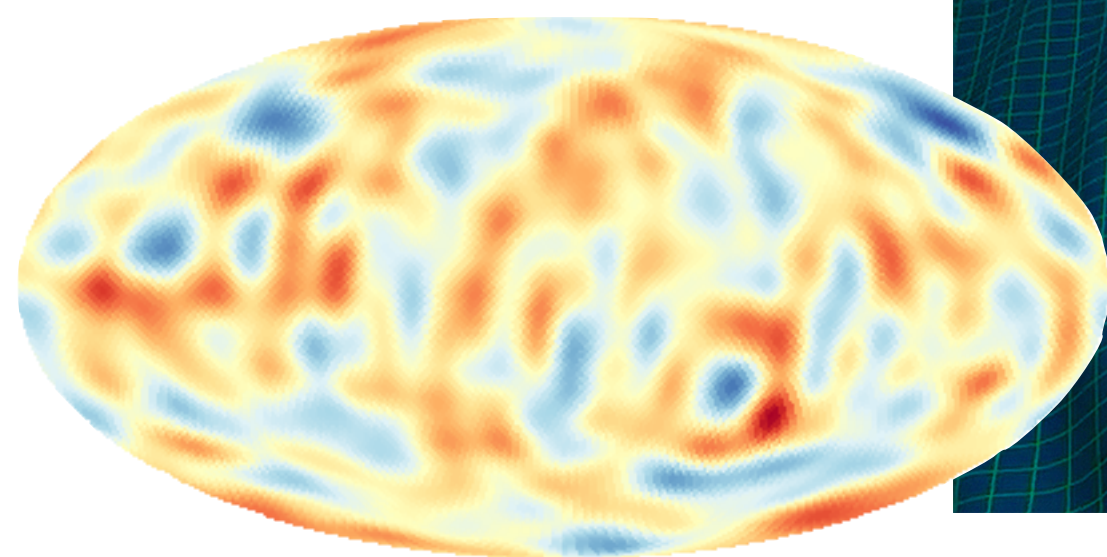
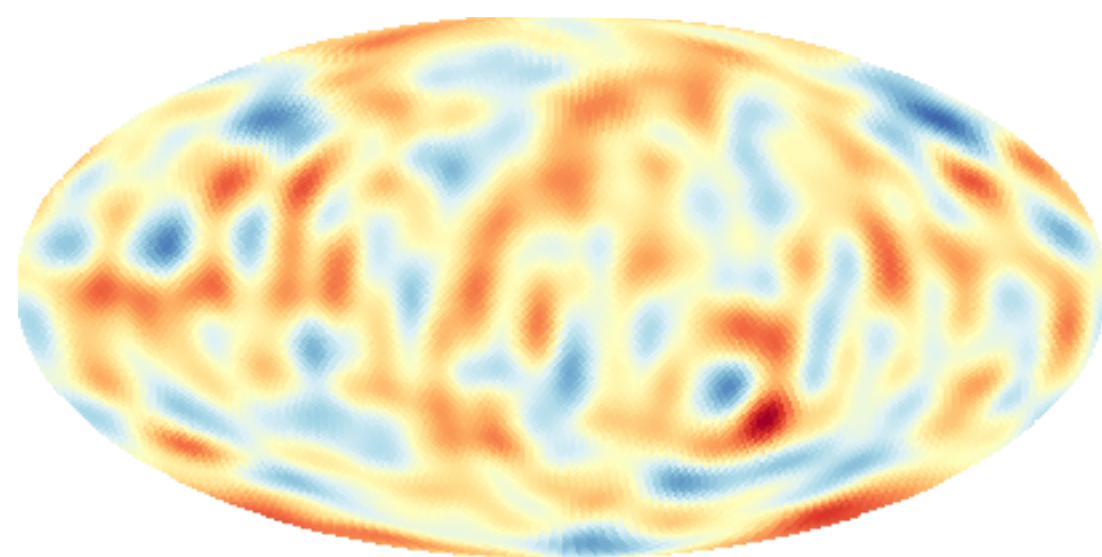
2001 Pre-WMAP WMAP1 WMAP3 WMAP5 WMAP7 WMAP9 Planck13 Planck15 Planck18 2019



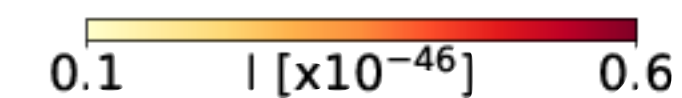
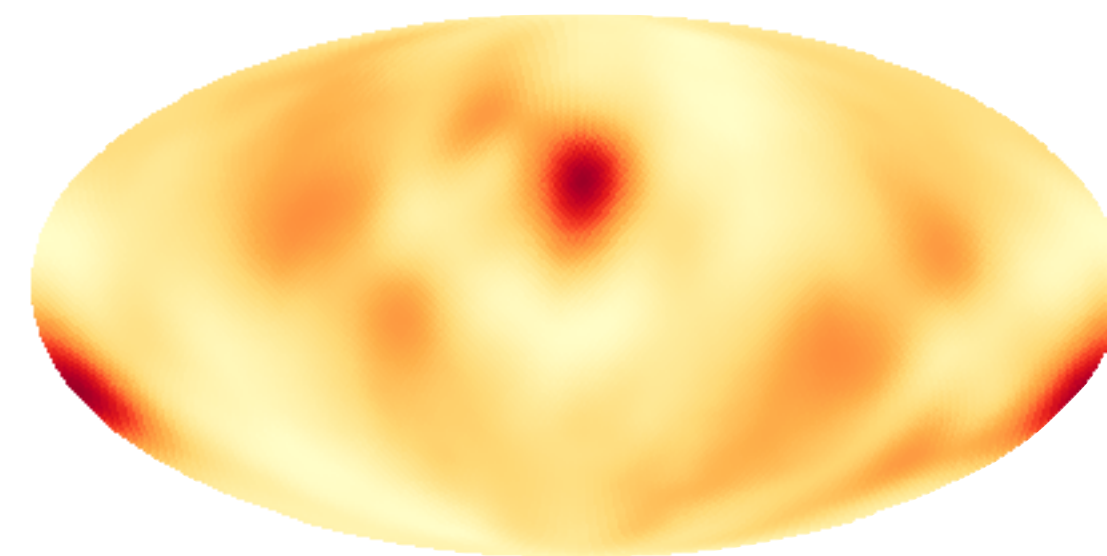
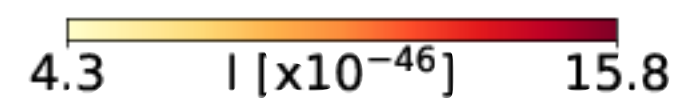
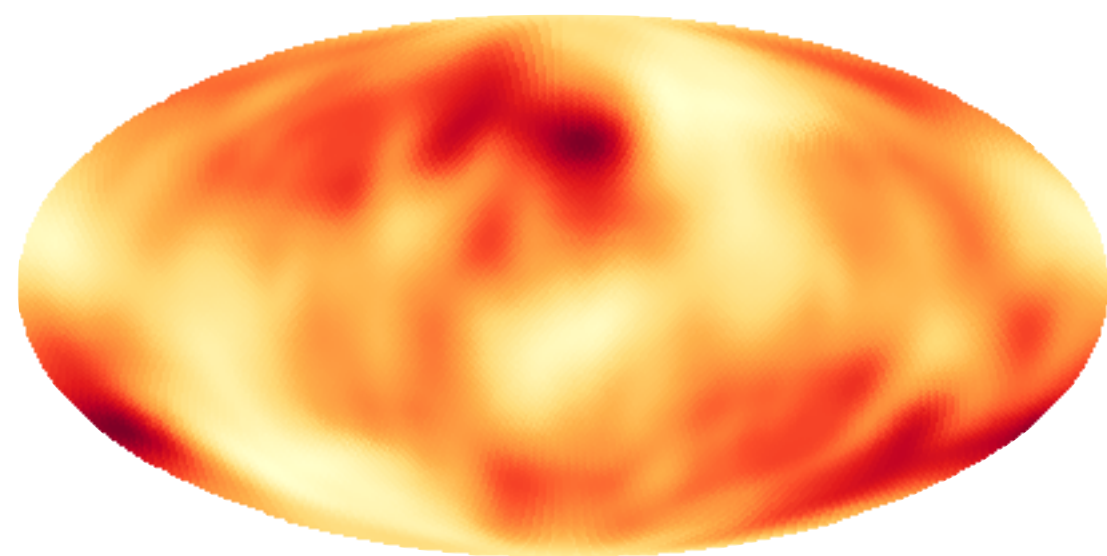
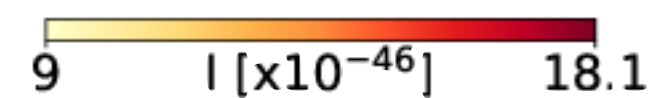
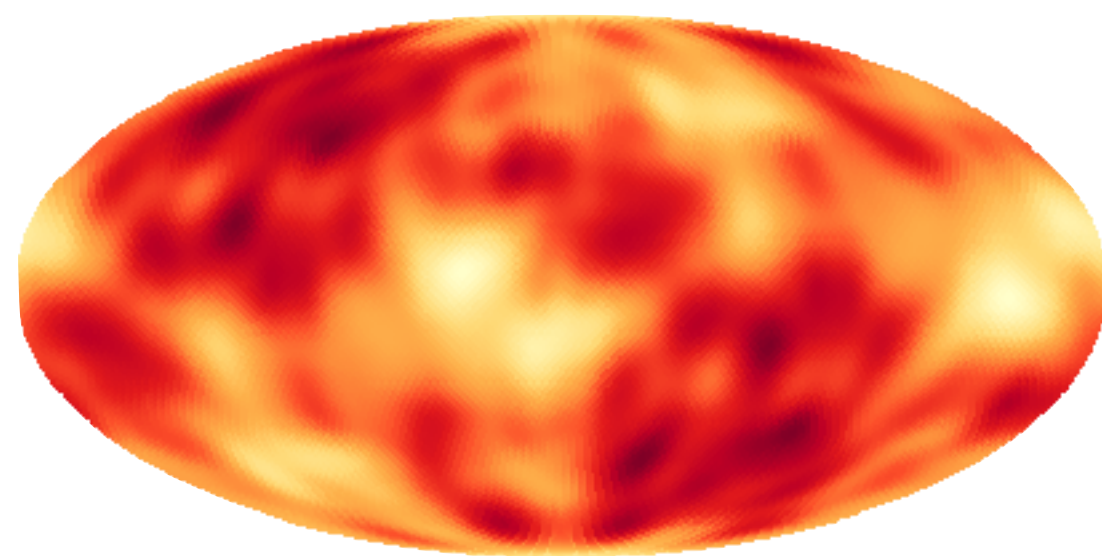




S/N



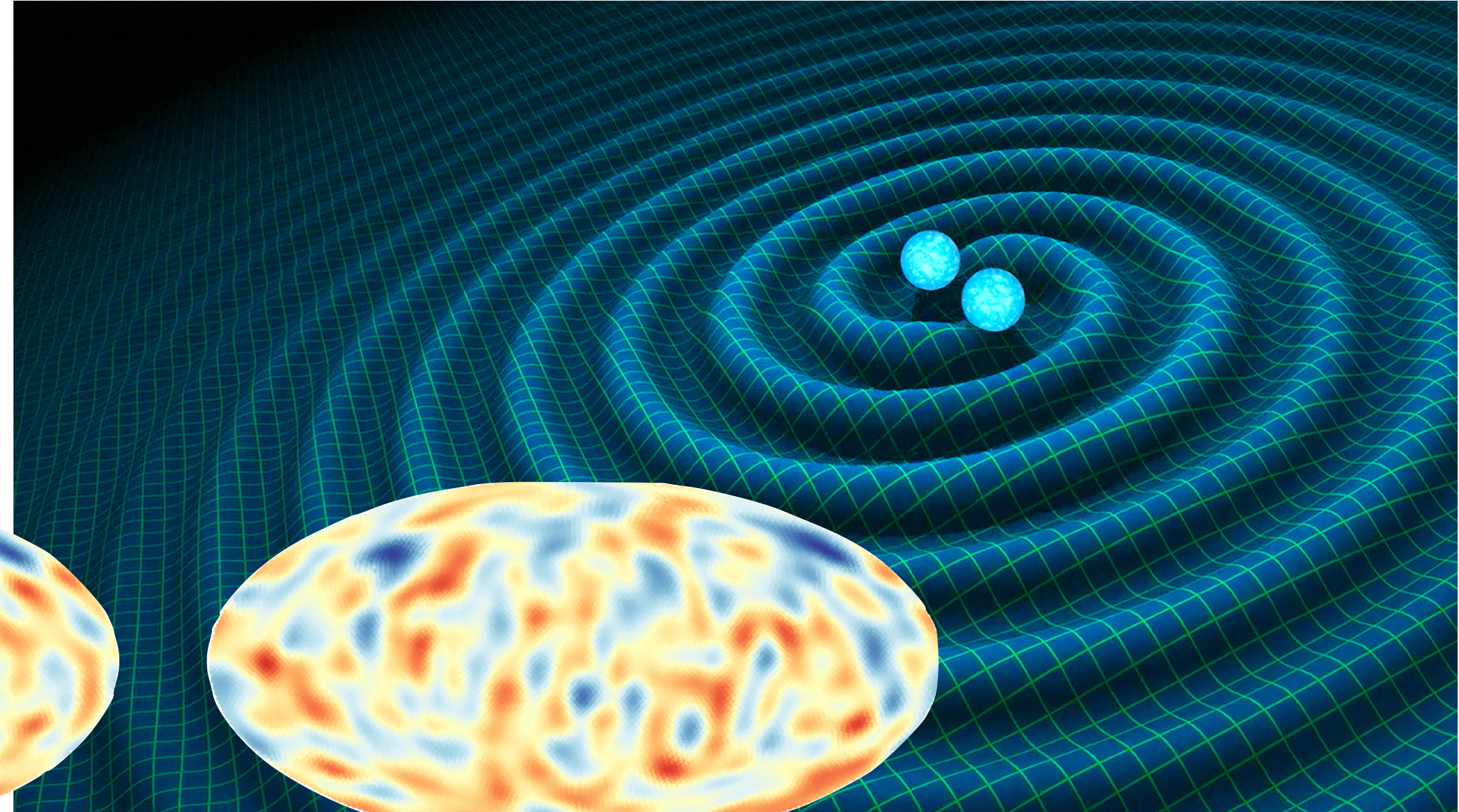
Noise

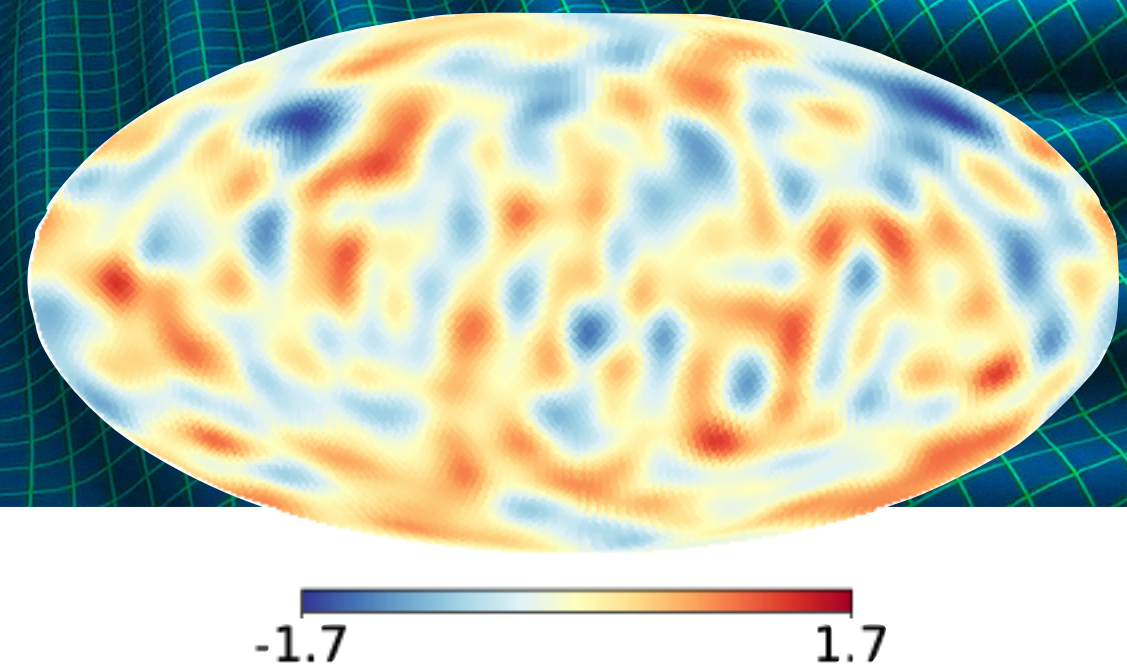
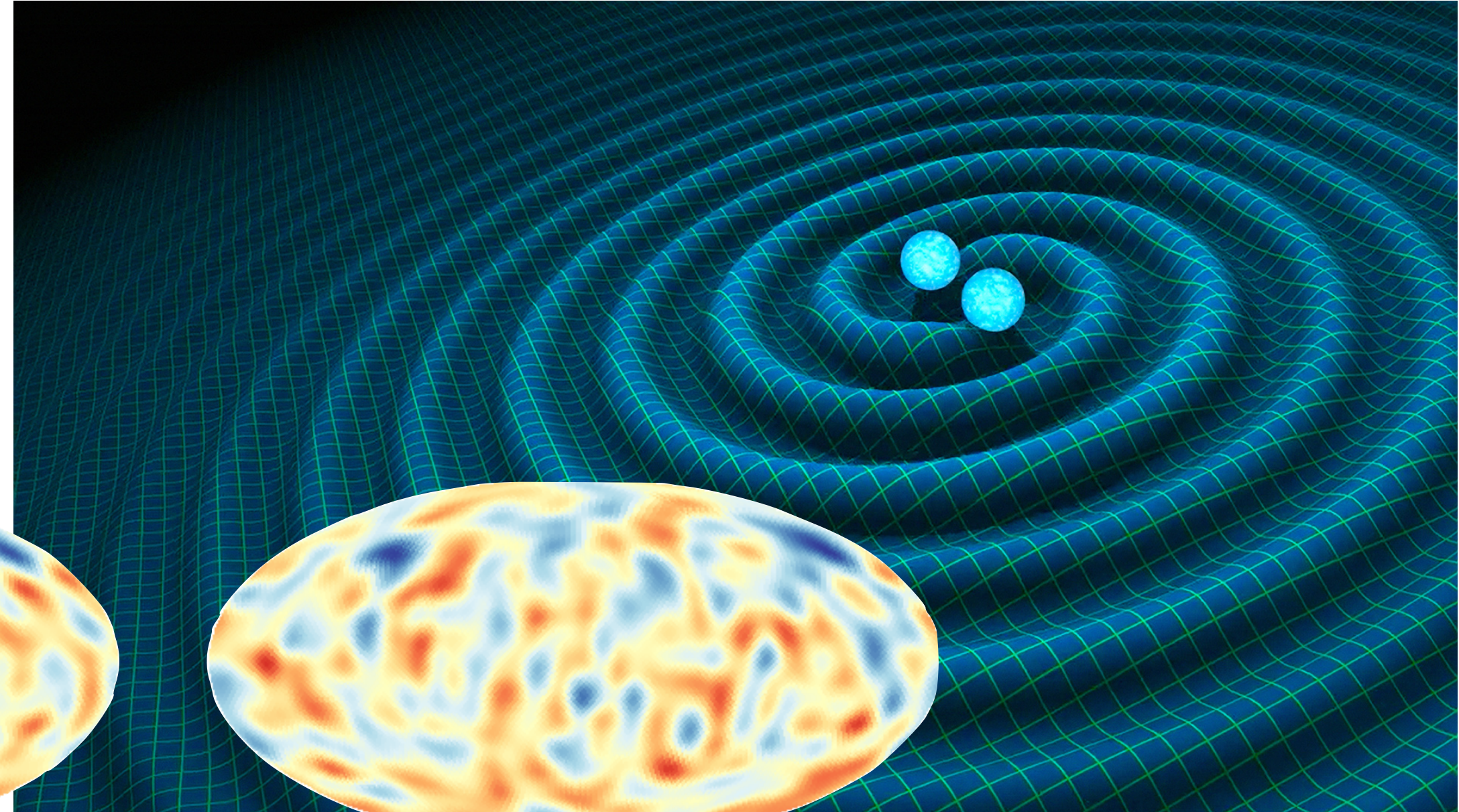
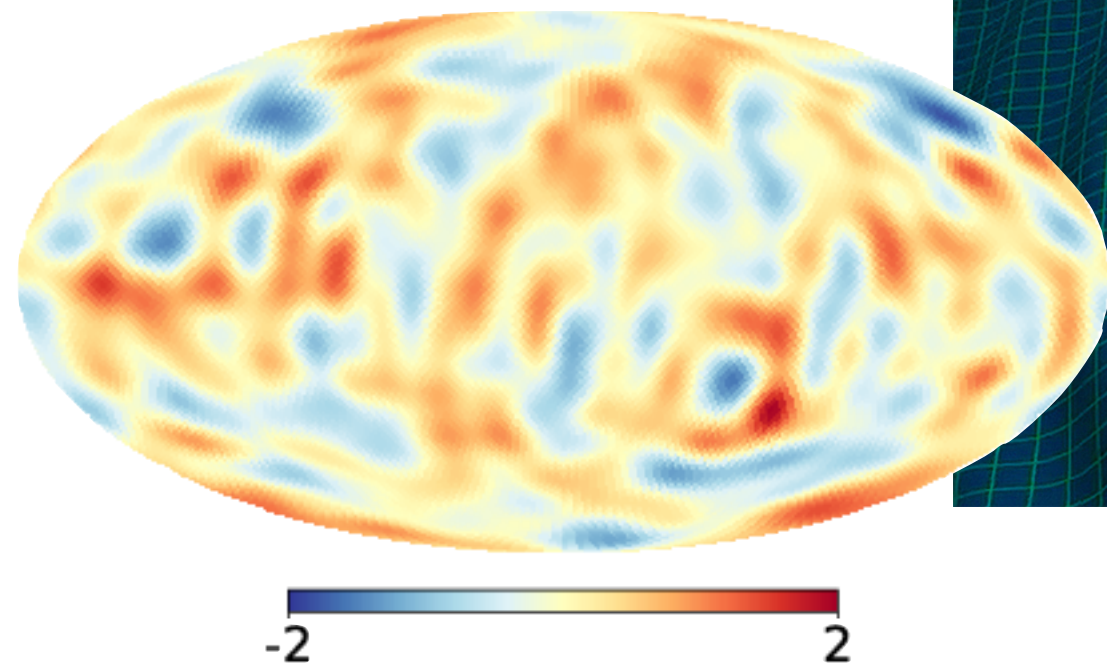
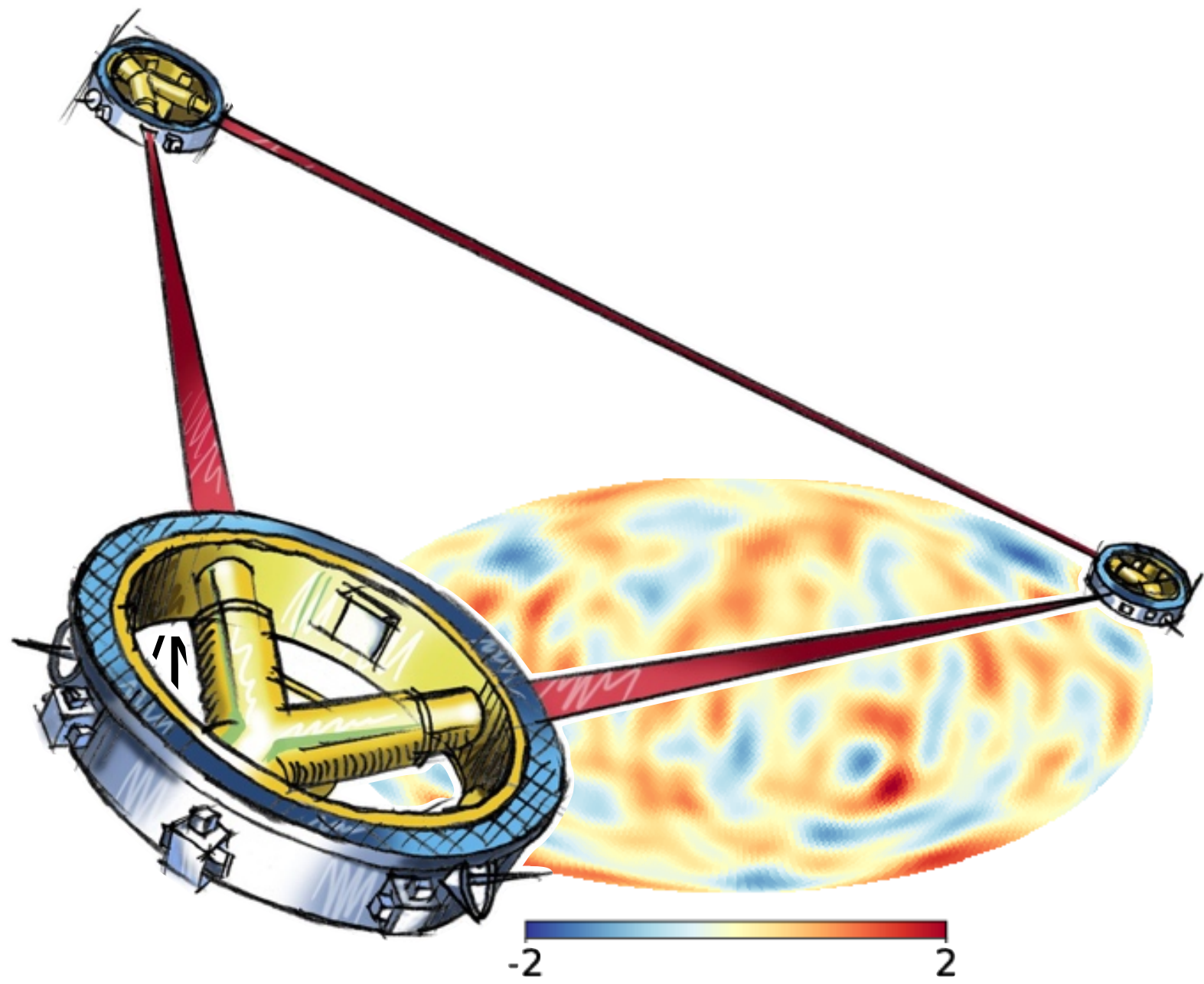


Primordial

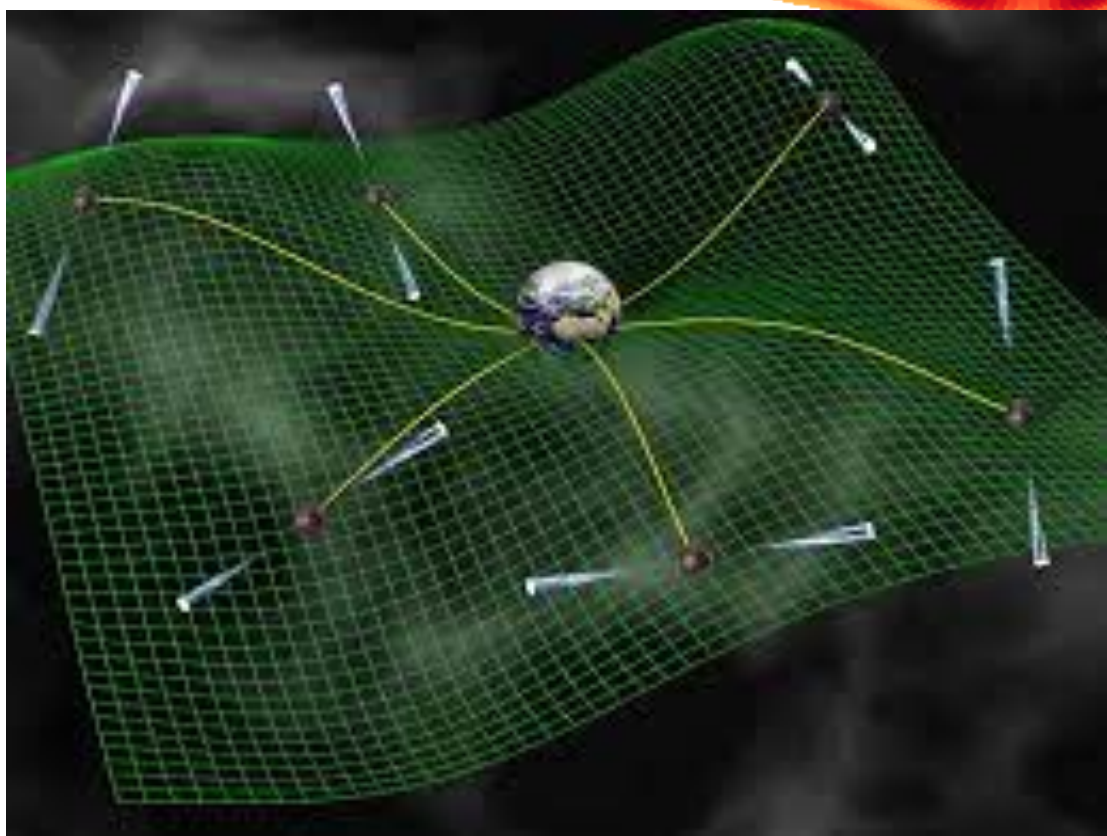
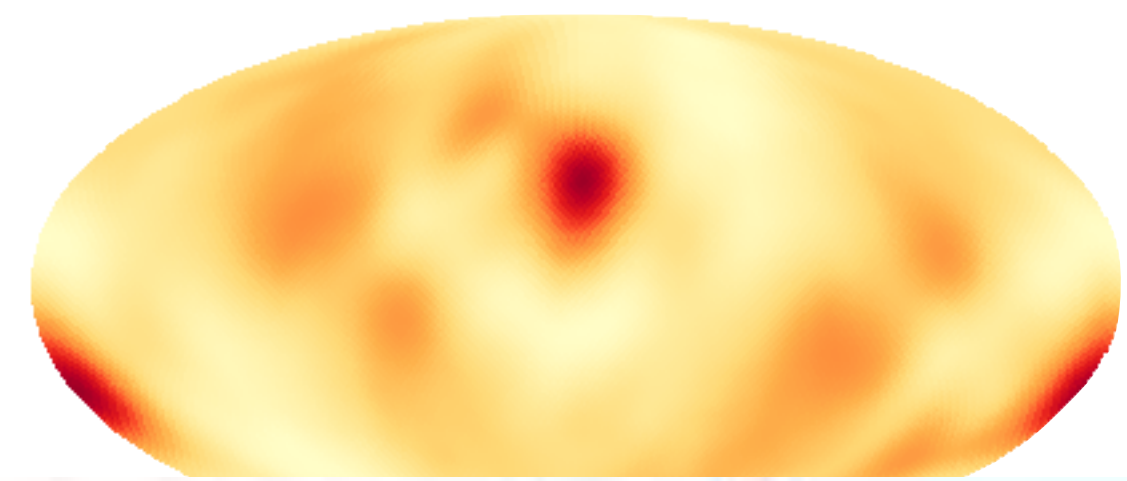
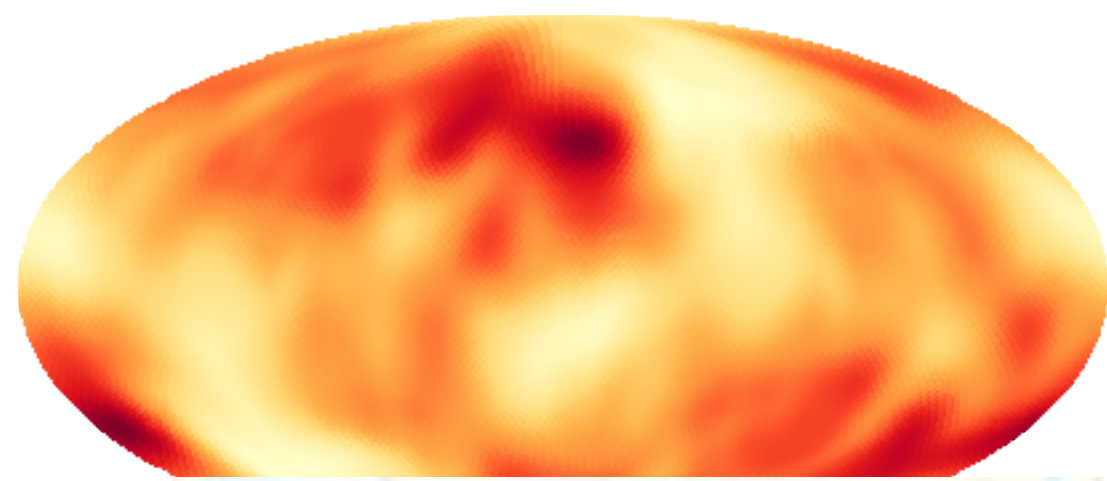
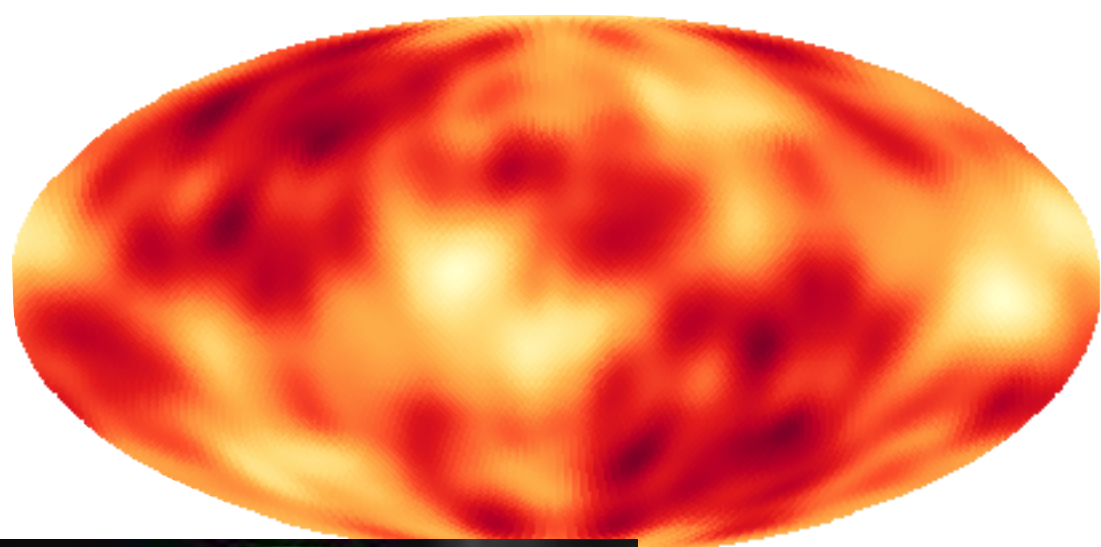
object collapse $\alpha = 2/3$

$\alpha = 3$





Noise



radial

obj



GRAND AT A GLANCE 简介

Objectives 目标

By the 2030s, in its complete configuration, GRAND will reach a sensitivity that will enable the detection of neutrinos with energies above 10^6 eV. Thanks to its sub-degree angular resolution, it will launch ultra-high-energy neutrino astronomy. Already by 2025, GRAND will be able to make the first discovery of these neutrinos. GRAND will be the largest experiment for the detection of ultra-high-energy cosmic rays and photons. Moreover, GRAND will uniquely explore fundamental neutrino physics, the astrophysics of fast radio bursts, and the epoch of reionization.

GRAND预计在2030年完成建设。完整的GRAND将达到前所未有的灵敏度，将实现超高能中微子天文学。早在2025年，GRAND就能实现首次发现。GRAND将是探测超高能宇宙射线和光子的最大实验。此外，GRAND还将独特地探索基本中微子物理、快速射电暴的天体物理学以及再电离时代。

How does GRAND work? GRAND如何工作?

The strategy of GRAND is to detect air showers above 10^6 eV that are induced by the interaction of high-energy particles in the atmosphere or underground, through its associated coherent radio-emission in the 30-300 MHz range.

超高能宇宙射线在大气中或地下与初级粒子相互作用，产生级联粒子。这些级联粒子在30-300 MHz频段产生相干无线电辐射。GRAND通过探测这种无线电辐射来探测超高能宇宙射线。

Why now? 为什么是现在?

With the first detection of very high-energy neutrinos and gravitational waves, we stand today at the threshold of a multi-messenger era. Many high-precision high-energy astroparticle experiments are projected (CTA, IceCube-Gen2, LHAASO, GRAND) completes the picture at the highest energy front. Radio-detection of astroparticles is experiencing a renaissance, with drastic technological, theoretical and numerical advances. Now is the time to develop the radio technique further and join the exciting momentum of high-energy Astroparticle physics!

随着中微子和引力波的首次探测，我们正站在多信使天文学时代的门槛上。许多高精度的超高能天体粒子实验正在规划中（CTA, IceCube-Gen2, LHAASO, GRAND）完成了最高能前沿的拼图。无线电探测天体粒子正在经历复兴，伴随着巨大的技术、理论和数值上的进步。现在是时候进一步发展无线电技术，并加入超高能天体物理学的激动人心的势头！

NEUTRINOS! 中微子!

Neutrinos are elementary particles that interact weakly with matter. This characteristic makes them challenging to detect and study. At the same time, neutrinos can serve as unique messengers of the extreme Universe, as they allow us to see further in the early Universe and deeper in objects. Neutrinos are unaffected by magnetic fields and are clear hadronic acceleration signatures. They are the essential ingredient for high-energy astrophysics.

中微子是一种基本粒子（费米子），它们与物质相互作用非常微弱。这一特性使得它们难以探测和研究。与此同时，中微子可以作为极端宇宙的“信使”，因为它们允许我们更深入地观察早期宇宙和天体内部。中微子不受磁场的影响，是清晰的强子加速信号。它们是高能天体物理学不可或缺的成分。

4V Electromagnetic energy unit equal to 10^6 Joules. The proton rest mass energy is equivalent to 10^9 eV. Cosmic rays charged particles mostly protons and heavier nuclei that constantly bombard the Earth. A small fraction of them (ultra-high-energy cosmic rays) are detected with colossal energy 10^{20} eV, at a rate of 3 per month with the 3000 km² Auger Observatory. Their origins are still a mystery. Cosmogenic neutrinos: neutrinos produced during the propagation of their parent ultra-high-energy cosmic rays in the intergalactic medium, via interactions with cosmic radiation. Their existence is guaranteed as ultra-high-energy cosmic rays are observed. Air-showers cascades of particles produced in the atmosphere by primary energetic particle. The electron and positrons in the cascade interact with the magnetic field of the Earth to produce radio emission.

4V电磁能单位等于10⁶焦耳。质子的静止质量能量相当于10⁹eV。宇宙射线带电粒子主要是质子和更重的原子核，它们持续不断地轰击地球。其中一小部分（超高能宇宙射线）具有巨大的能量10²⁰eV，以每月3次的频率被3000平方公里的Auger观测站探测到。它们的起源仍然是一个谜。宇宙生成中微子：在它们的母体超高能宇宙射线在星际介质中传播时，通过与宇宙辐射相互作用而产生的。它们的存在是肯定的，因为已经观测到了超高能宇宙射线。空气簇射：由高能粒子在大气中产生的粒子级联。级联中的电子和正电子与地球的磁场相互作用产生无线电辐射。

2018 2020 2025 2035

GRAND PROTO35

GOALS
- Standalone radio detection of air-showers
- Good background noise rejection

SETUP
- 35 radio antennas
- 1 x100m

BUDGET & STAGE
- 100k€ fully funded by INO-CHEP development 2018 @ Ustat

GRAND 10K

GOALS
- First GRAND sub-array, sensitivity comparable to AERA/ARIANNA on similar time scale, allowing potential 1st discovery of cosmogenic neutrinos

SETUP
- 100 radio antennas
- 1 x100m

BUDGET & STAGE
- 1000k€ fully funded by INO-CHEP development 2020 @ Ustat

GRAND

Giant Radio Array for Neutrino Detection

The Giant Radio Array for Neutrino Detection project aims to detect ultra-high-energy cosmic neutrinos, cosmic rays, and gamma rays with a radio antenna array deployed over a total area of 200 000 km² in mountainous regions, in several favorable locations around the world.

巨中微子探测阵列（GRAND）旨在通过部署在多个有利地点的总面积达20万平方公里的无线电天线阵列，探测超高能宇宙中微子、宇宙射线和伽马射线。该项目旨在实现宇宙生成中微子的首次发现。

GRAND PROTO300

GOALS
- Standalone radio detection of inclined showers (depth angle > 10°) induced by high-energy cosmic rays (10¹⁶ eV)

SETUP
- 300 Horizon Antennas over 300 km²
- Fast data acquisition system
- Solar panels (2x7) - Wifi data transfer
- Array of surface moon detectors

BUDGET & STAGE
- 13 M€ for radio only, funded by Chinese Institutes

GRAND 200K

GOALS
- Discover neutrinos of 10^6 eV and neutrino astronomy

Selection of optimal sites (mountainous, accessible, radio-quiet) worldwide for deployment of 10 000 km² hotspots

SETUP
- 200 000 antennas over 200 000 km²
- ~20 x 10 000 km² hotspots worldwide

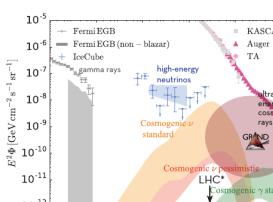
BUDGET & STAGE
Industrial scale allows to cut costs down: 500€ per unit (100M€ in total)

WHY ULTRA-HIGH-ENERGY NEUTRINOS?

Because they exist. Ultra-high-energy neutrinos are bound to be produced by the interactions of ultra-high-energy cosmic rays with the cosmic backgrounds, on their way from their sources to the Earth. Neutrinos should also be produced directly at the sources.

Because they are unique messengers. Neutrinos are produced with 5% of their parent cosmic-ray energy and travel undeflected by cosmic magnetic fields. Neutrinos with energy 10^6 eV can thus solve one of the most puzzling mysteries of our Universe: the origin of the ultra-high-energy cosmic rays.

Because they are the next energy frontier. Neutrino physics is booming with 3 recent Nobel prizes and the first detection of 10^6 eV neutrinos with the IceCube experiment. Ultra-high-energy neutrinos remain undetected. GRAND is the only projected experiment that can reach this uncharted territory.

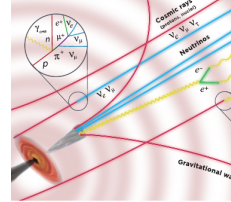


*Large Hadron Collider
Data and theoretical predictions for energy spectra of gamma rays, neutrinos and cosmic rays at the highest energies

Because multi-messenger astronomy is the way. The recent observation of neutron star merger GW170817 has definitively shown that the challenges of high-energy astronomy will be solved by combining data from a large number of multi-messenger experiments. Ultra-high-energy neutrino astronomy will be central to the quest of understanding the violent Universe.

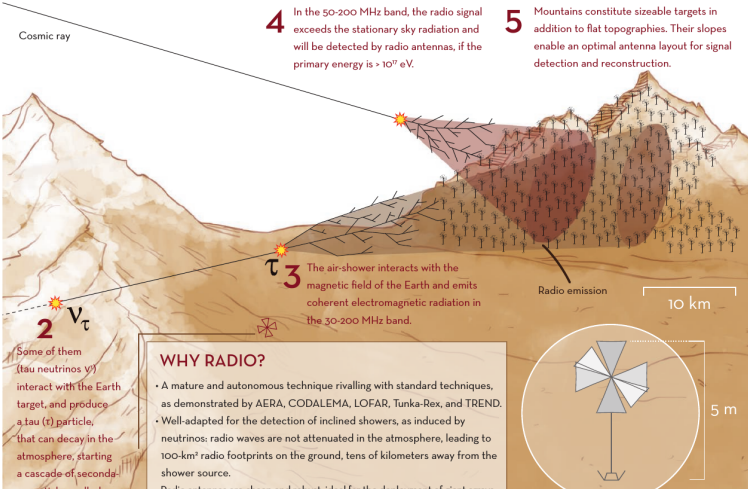
A new multi-messenger era is opening! A primary cosmic-ray and its secondary gamma rays and neutrinos are their flight from the source to the Earth.

Ultra-high-energy neutrinos produced by powerful sources reach the Earth.



1 Ultra-high-energy neutrinos produced by powerful sources reach the Earth.

DETECTION PRINCIPLE



2 The air-shower interacts with the magnetic field of the Earth and emits coherent electromagnetic radiation in the 30-300 MHz band.
3 GRAND will be an array of 200 000 antennas over 200 000 km² in mountainous and radio-quiet regions to collect hundreds of neutrinos with energy 10^6 eV with angular resolution of a fraction of degrees.
4 300 000 km² corresponds to the size of Great Britain! Several hotspots of ~10 000 km² will be deployed in several continents.
5 Mountains constitute sizeable targets in addition to flat topographies. They also enable an optimal antenna layout for signal detection and reconstruction.

ARRAY LAYOUT

GRAND will be an array of 200 000 antennas over 200 000 km² in mountainous and radio-quiet regions to collect hundreds of neutrinos with energy 10^6 eV with angular resolution of a fraction of degrees.

BURSTING RADIO ASTRONOMY

GRAND will contribute in a unique way to the measurement of fast radio bursts and giant radio pulses by collecting unprecedented statistics at low frequencies (100-200 MHz)

GRAND will not be a phased antenna array, thus taking advantage of the full antenna field of view

COSMIC DAWN

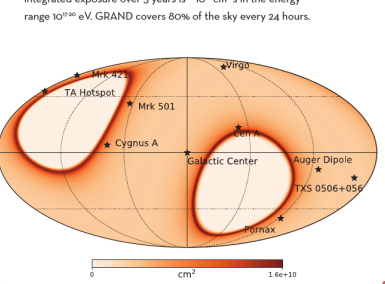
GRAND will strongly contribute to other science topics such as the measurement of the global signature of the Cosmic Dawn and of the Epoch of Reionization

By detecting neutrinos above 10^6 eV, GRAND will probe fundamental particle physics at energies that are orders of magnitude larger than in particle accelerators, allowing for stringent tests of the Standard Model and potential discovery of new physics

FUNDAMENTAL NEUTRINO PHYSICS

By detecting neutrinos above 10^6 eV, GRAND will probe fundamental particle physics at energies that are orders of magnitude larger than in particle accelerators, allowing for stringent tests of the Standard Model and potential discovery of new physics

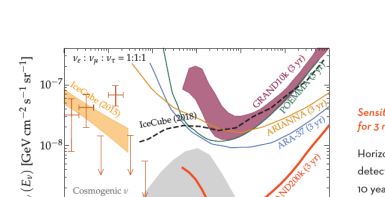
GRAND opens the possibility of observing point sources with its excellent angular resolution and sky coverage. GRAND will kick start ultra-high-energy neutrino astronomy.



GRAND field of view for 3 years

ULTRA-HIGH-ENERGY NEUTRINO ASTRONOMY

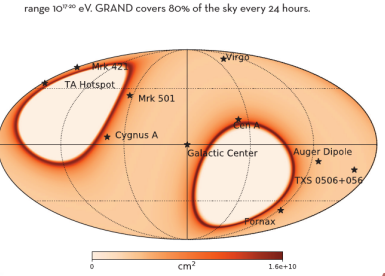
GRAND will have unrivaled sensitivity to diffuse ultra-high-energy neutrino fluxes, down to 10^{-10} GeV cm⁻² yr⁻¹ at energy 10^6 eV. This will guarantee the detection of cosmogenic neutrinos that are produced during the propagation of ultra-high-energy cosmic rays.



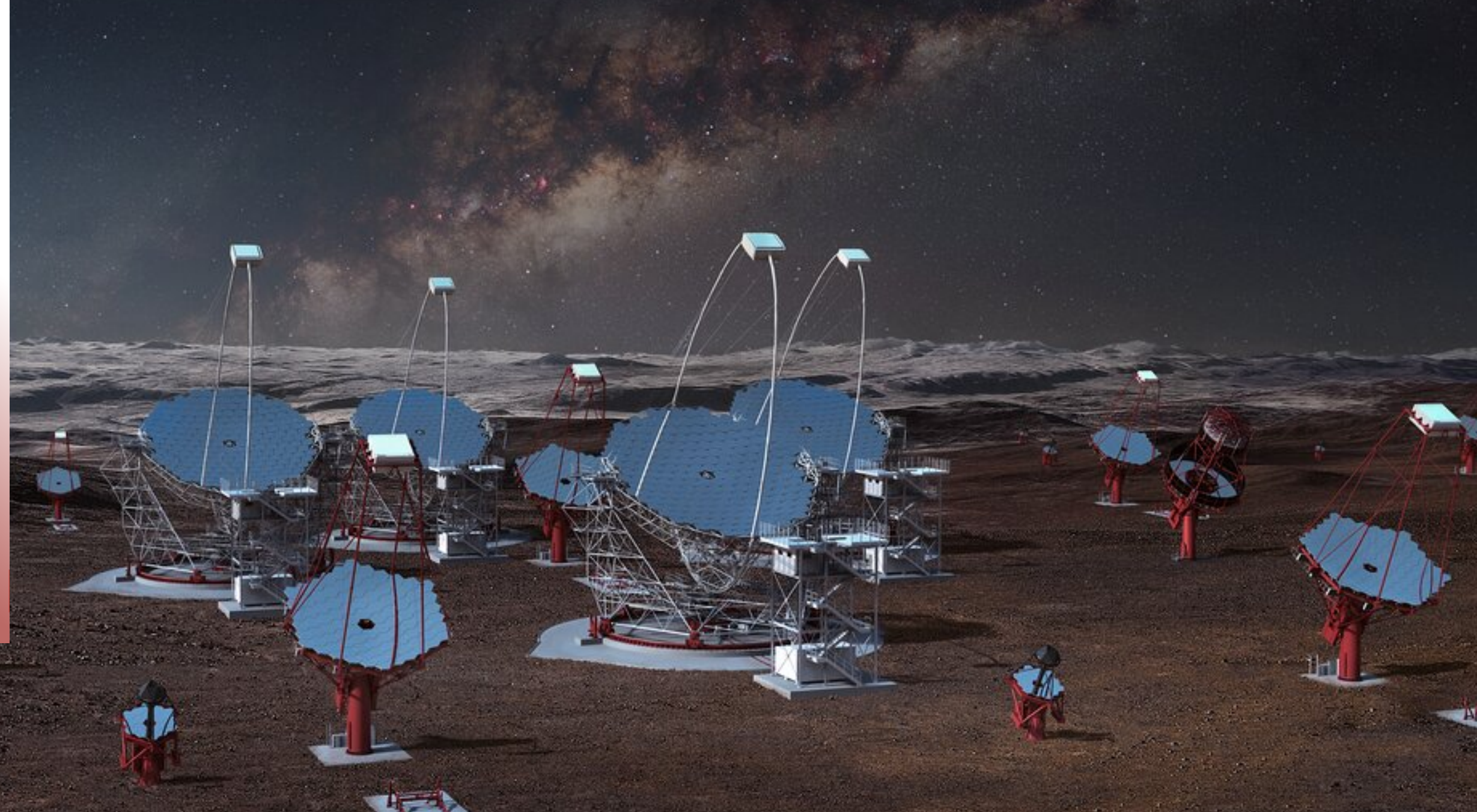
Sensitivity of GRAND and its first 10K hotspot, for 3 neutrino flavors, over 3 years.
Horizontal lines: 90% confidence level detection limit of GRAND for 3 and 10 years. Other project sensitivities for AERA, ARIANNA, POEMMA are shown for comparison with GRAND's IceCube astrophysical flux. The gray band spans possible cosmogenic neutrino fluxes in the standard and most pessimistic scenarios.
*E. Albert, B. M. de Almeida, R. Lugo, K. Kawanaka (ICAP) at Northology

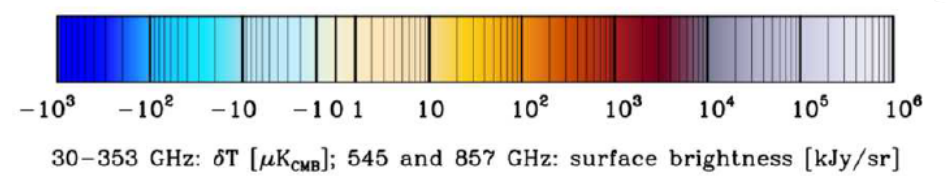
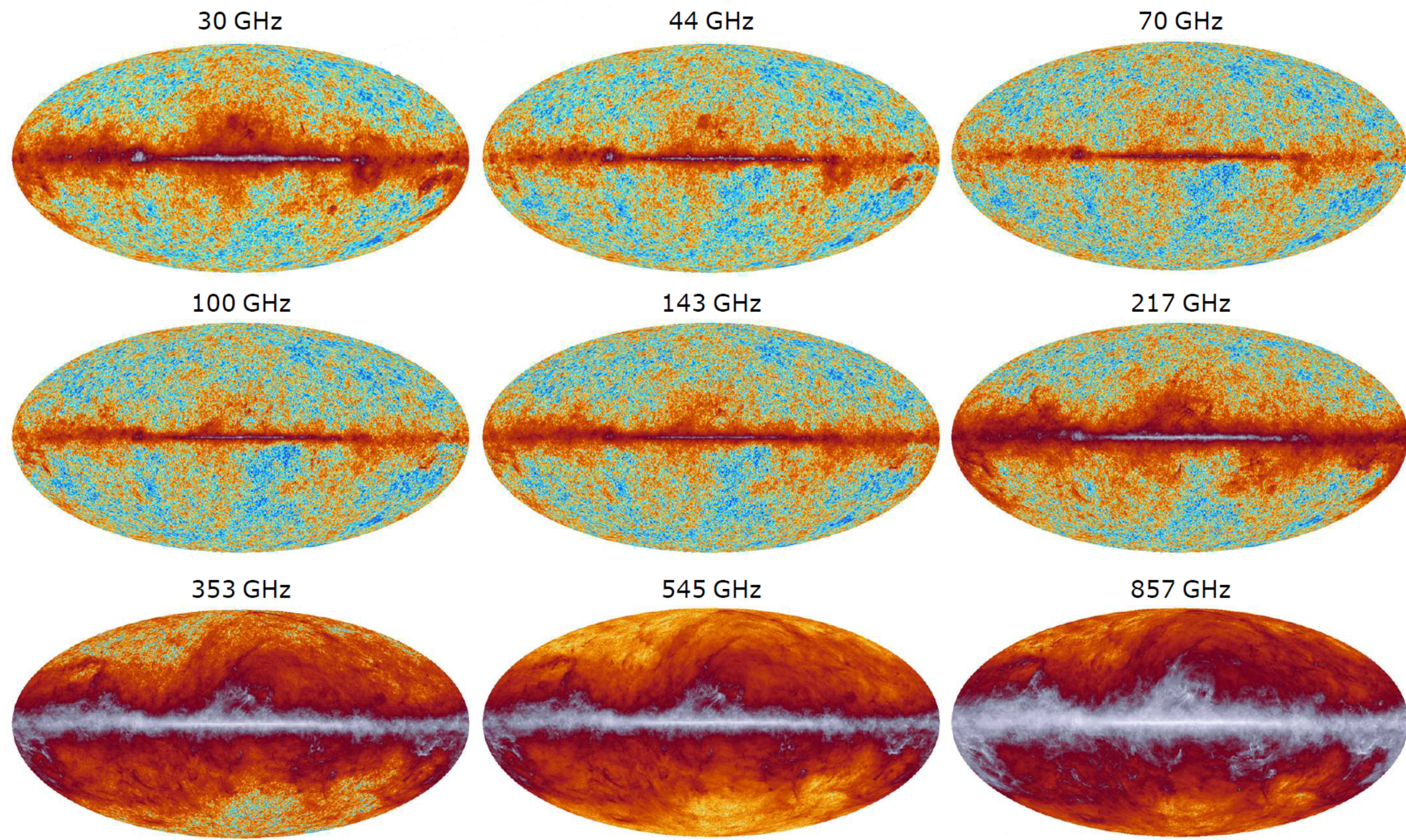
For a diffuse neutrino flux of 10^{-10} GeV cm⁻² yr⁻¹ as predicted by diverse astrophysical source models, GRAND could collect more than hundreds of events in 3 years.

With 200 000 km² at one location in Western China, the integrated exposure over 3 years is 10^7 km² yr in the energy range 10^{16} eV. GRAND covers 80% of the sky every 24 hours.

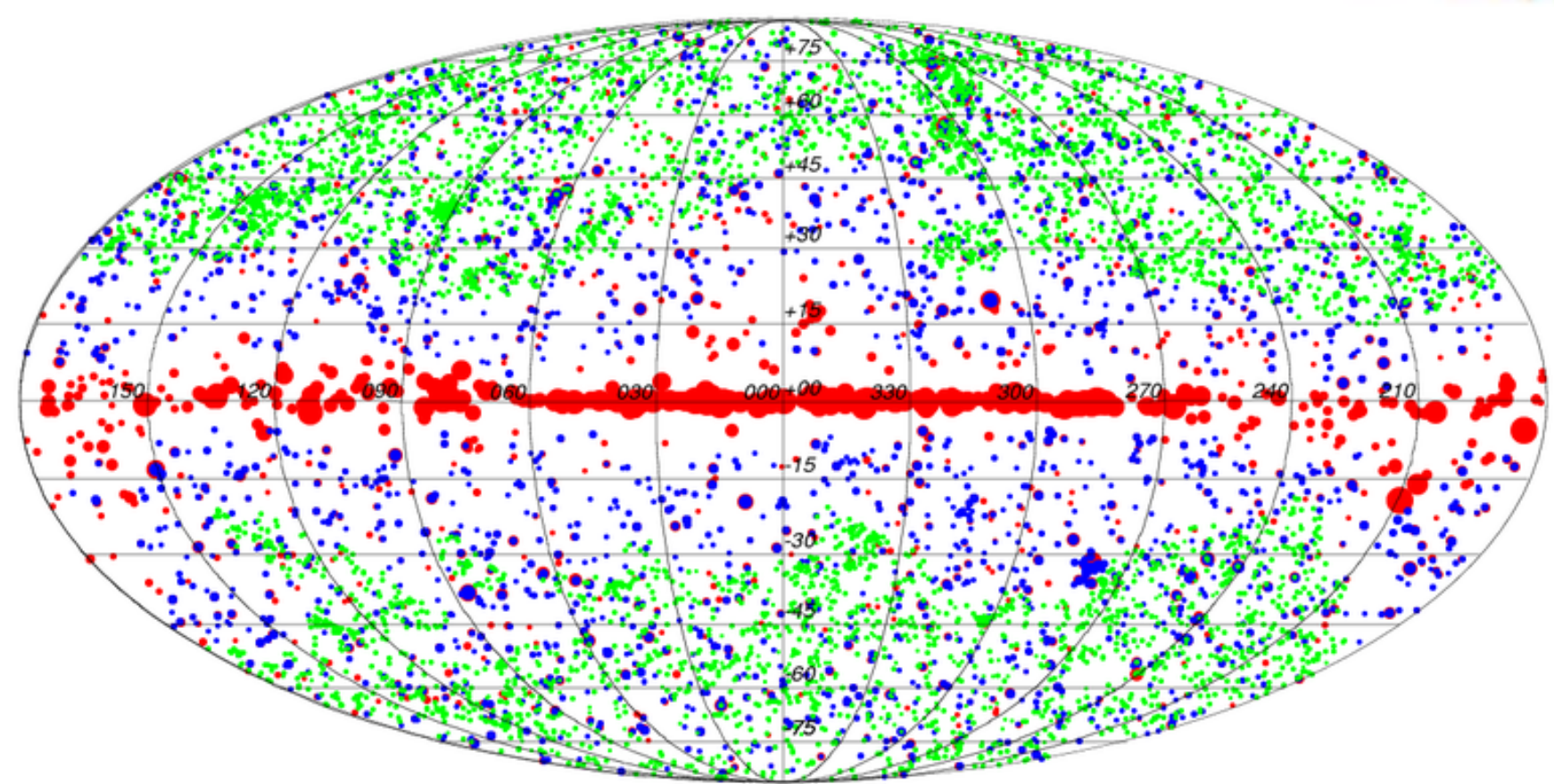
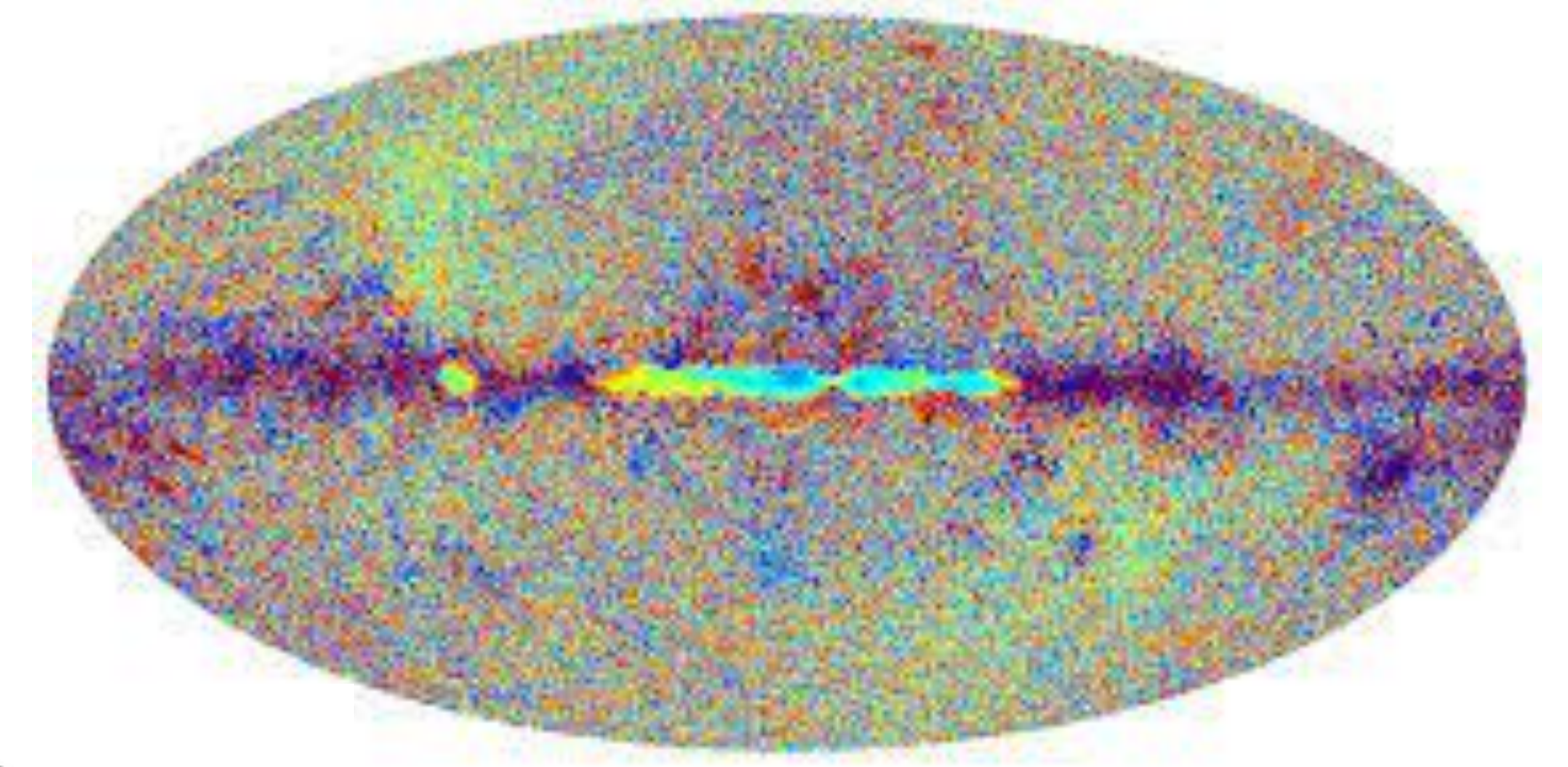
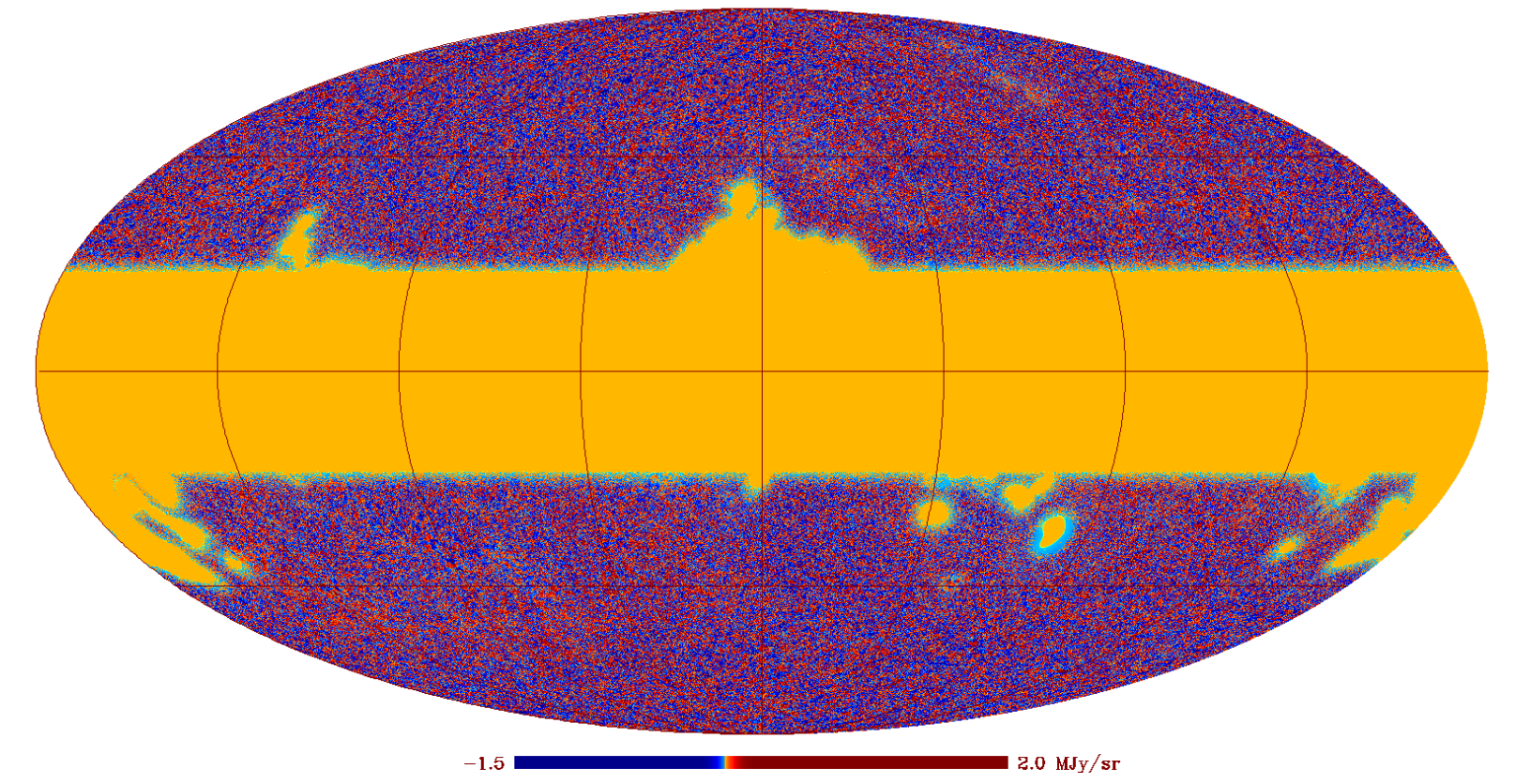


GRAND opens the possibility of observing point sources with its excellent angular resolution and sky coverage. GRAND will kick start ultra-high-energy neutrino astronomy.





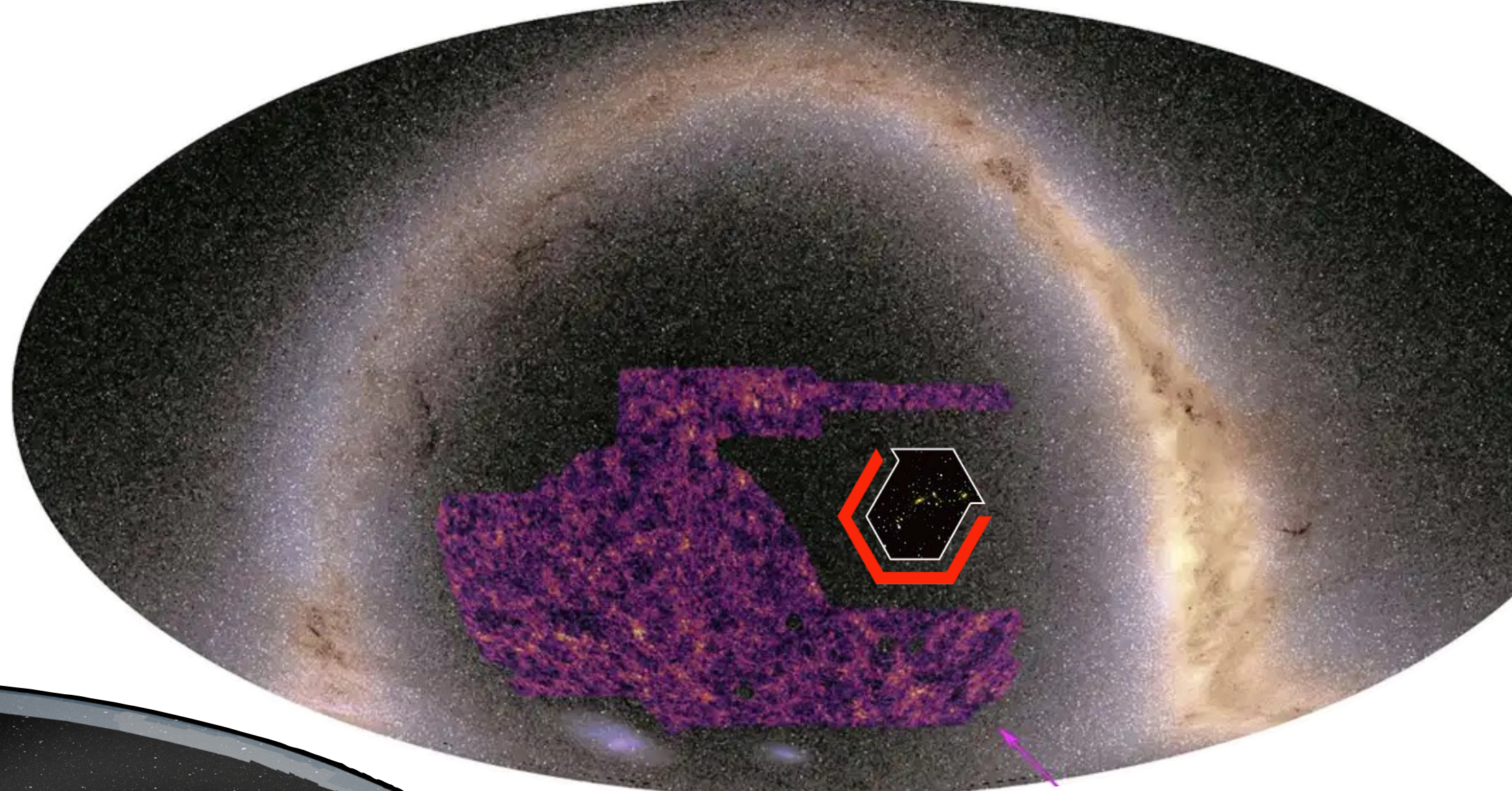
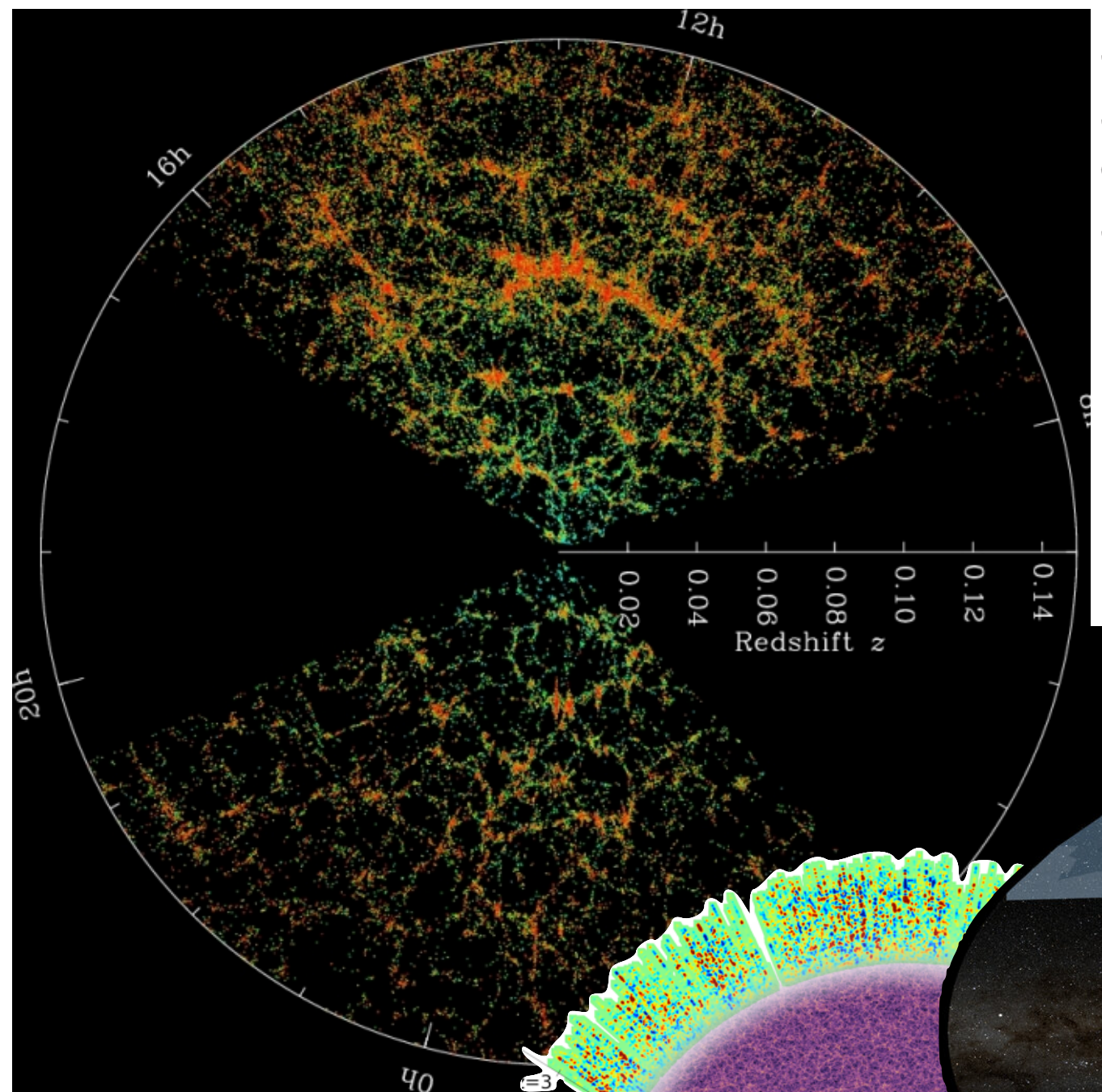
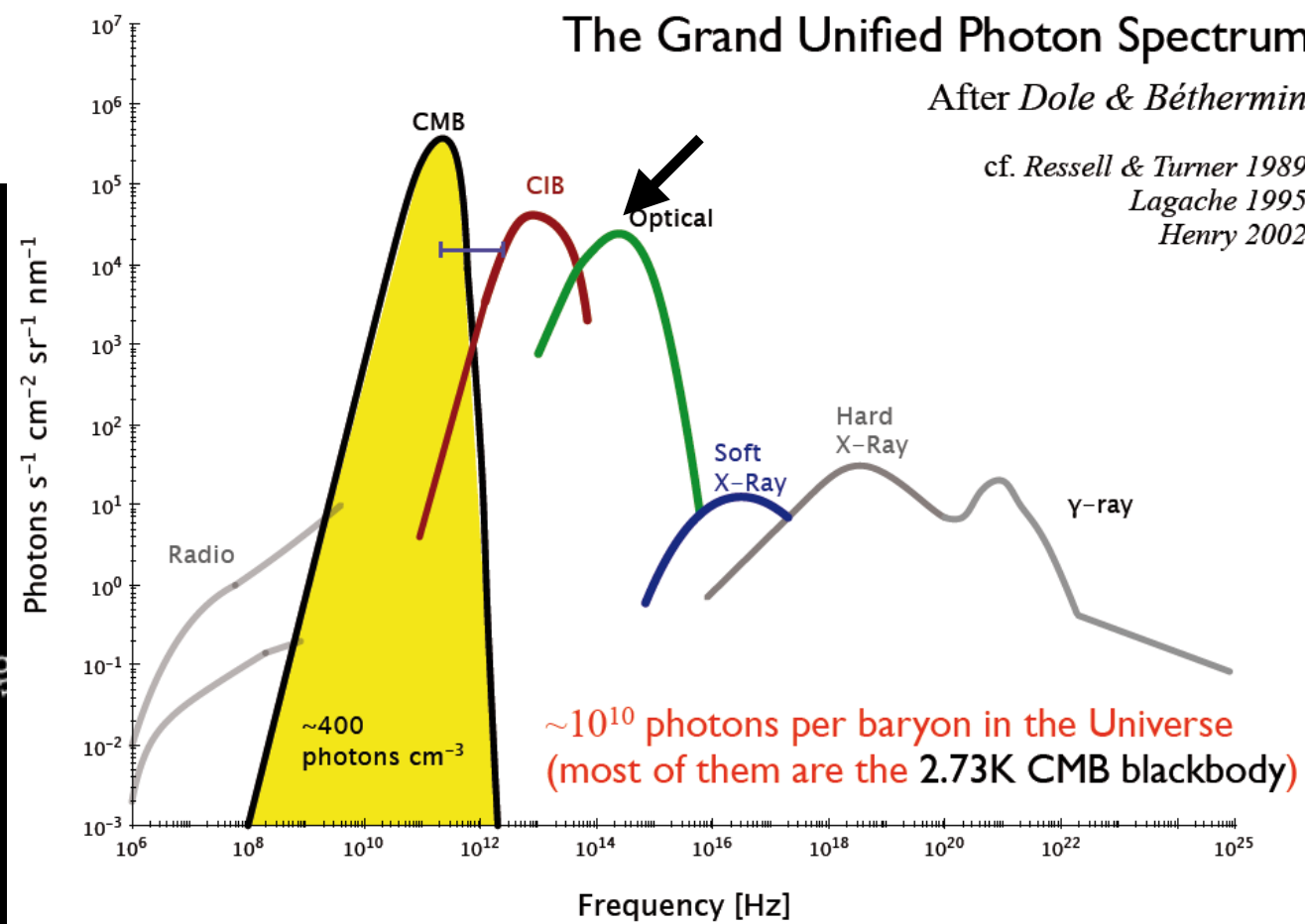
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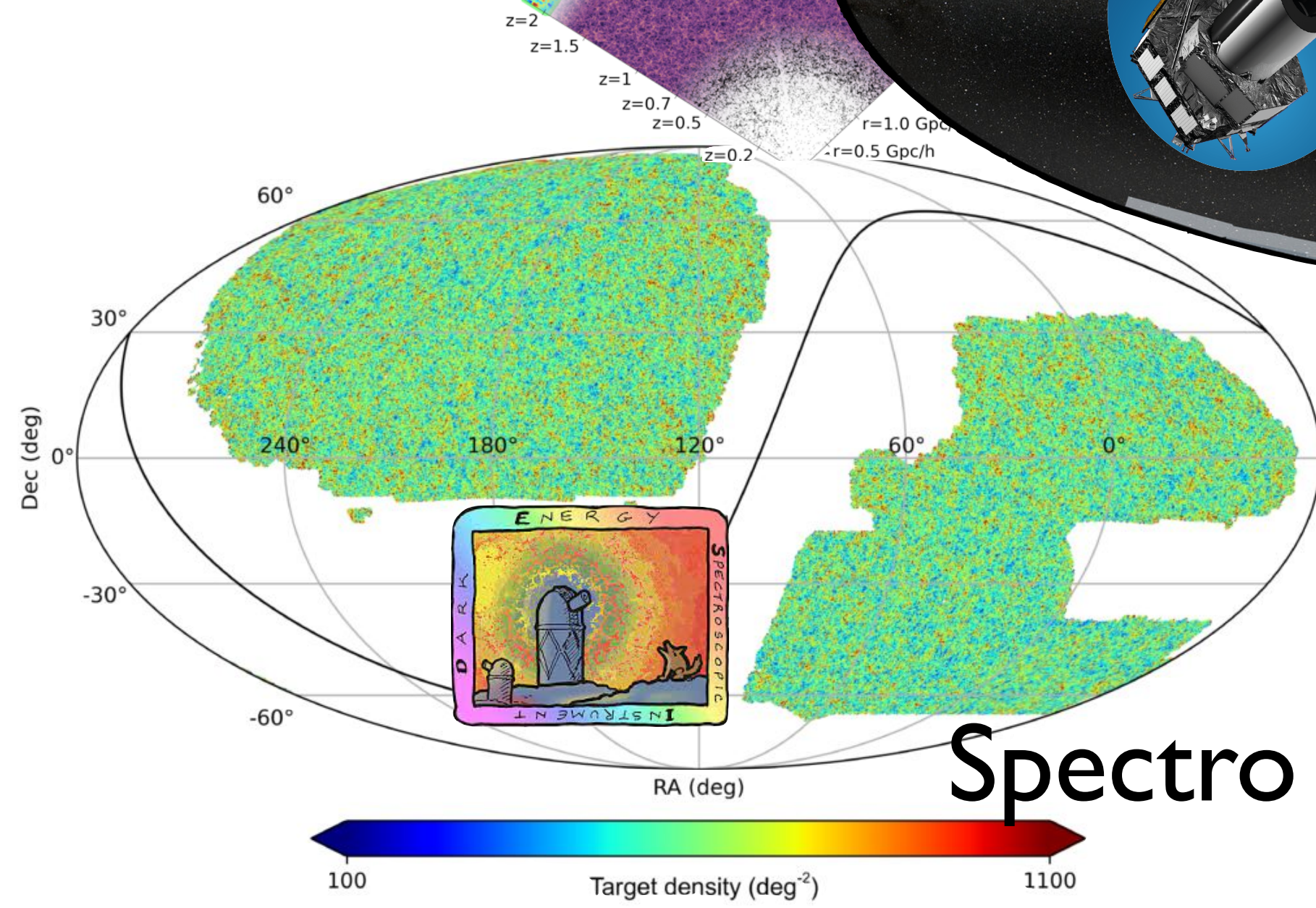
The Grand Unified Photon Spectrum

After Dole & Béthermin

cf. *Ressell & Turner 1989*
Lagache 1995
Henry 2002

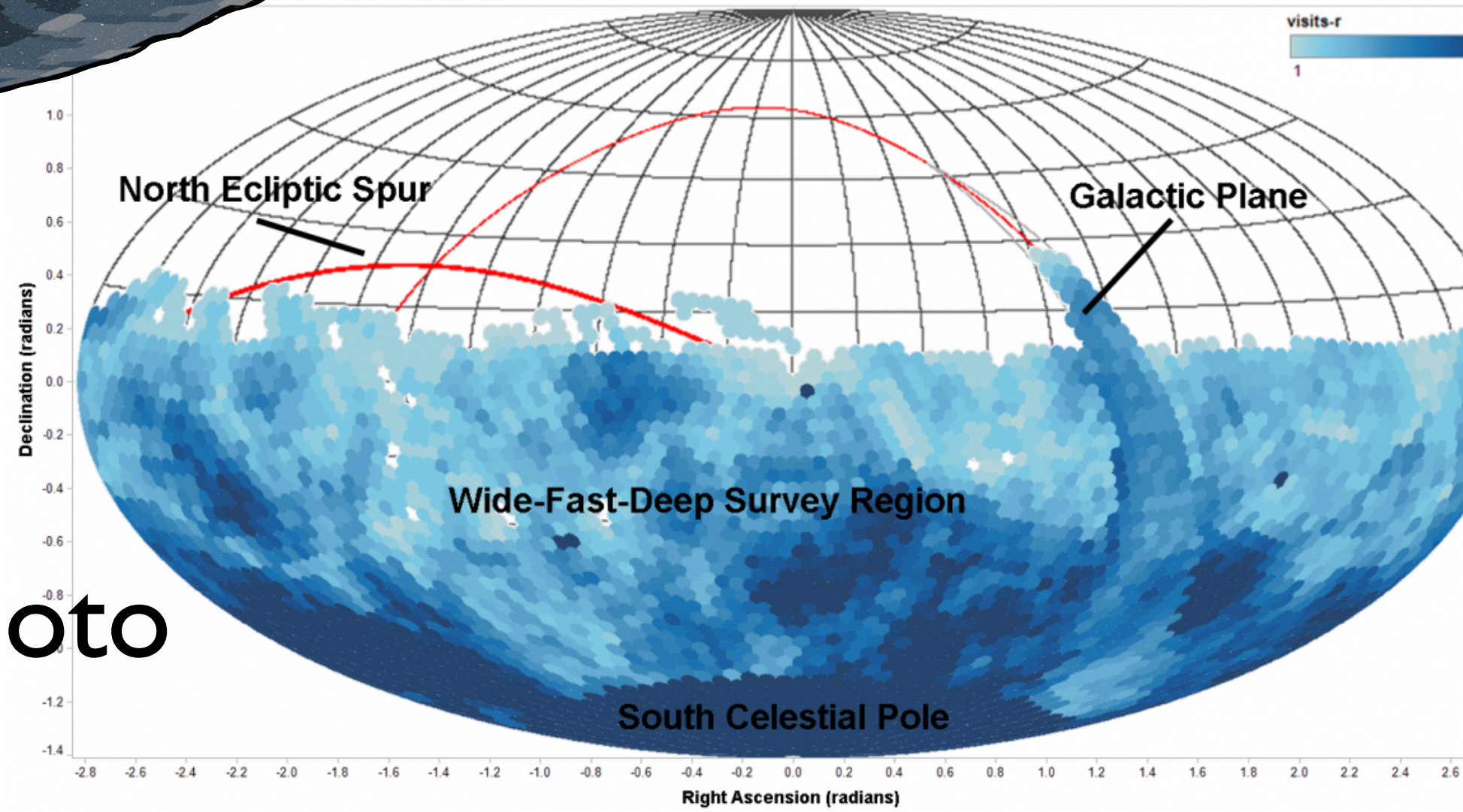


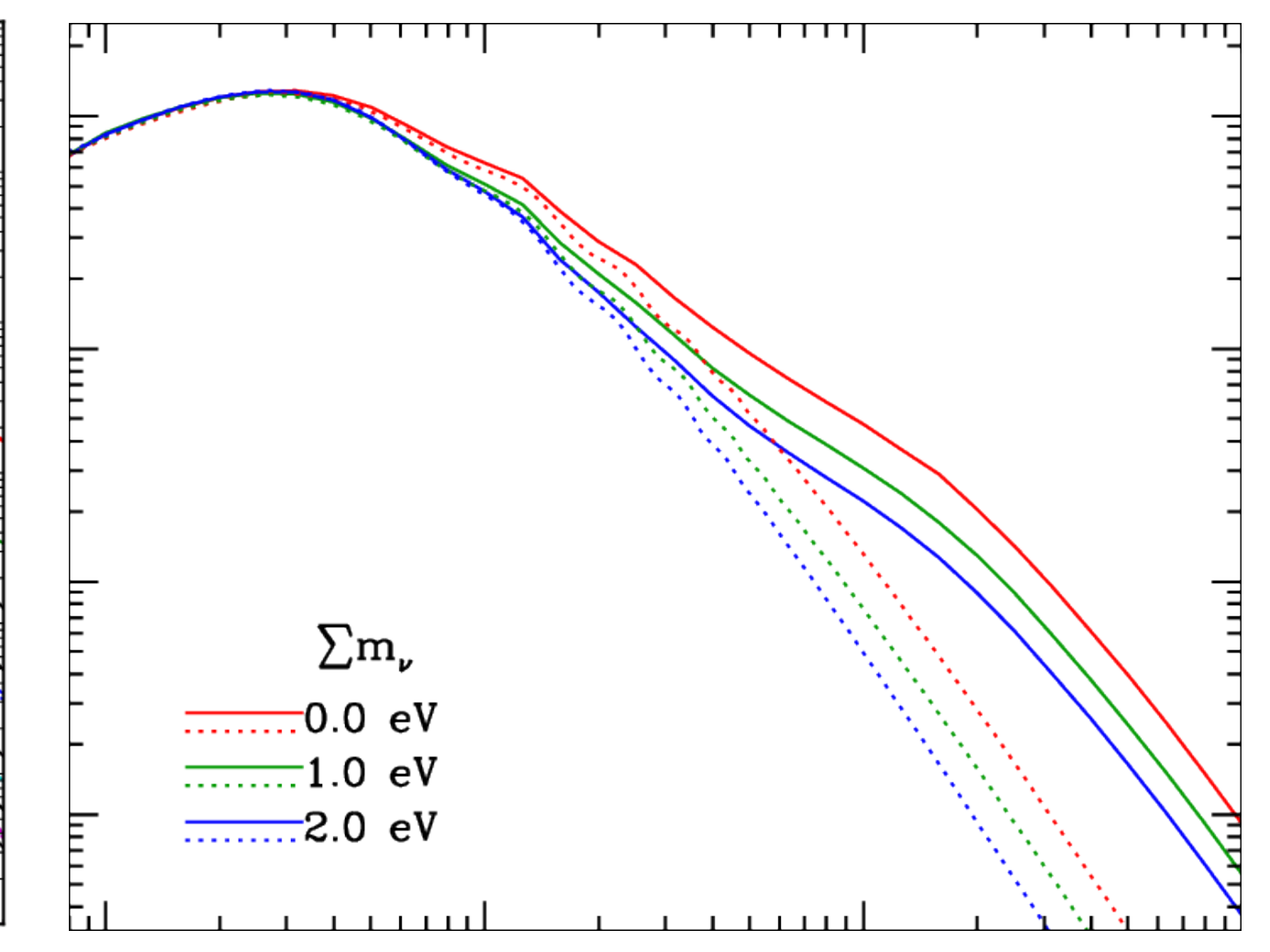
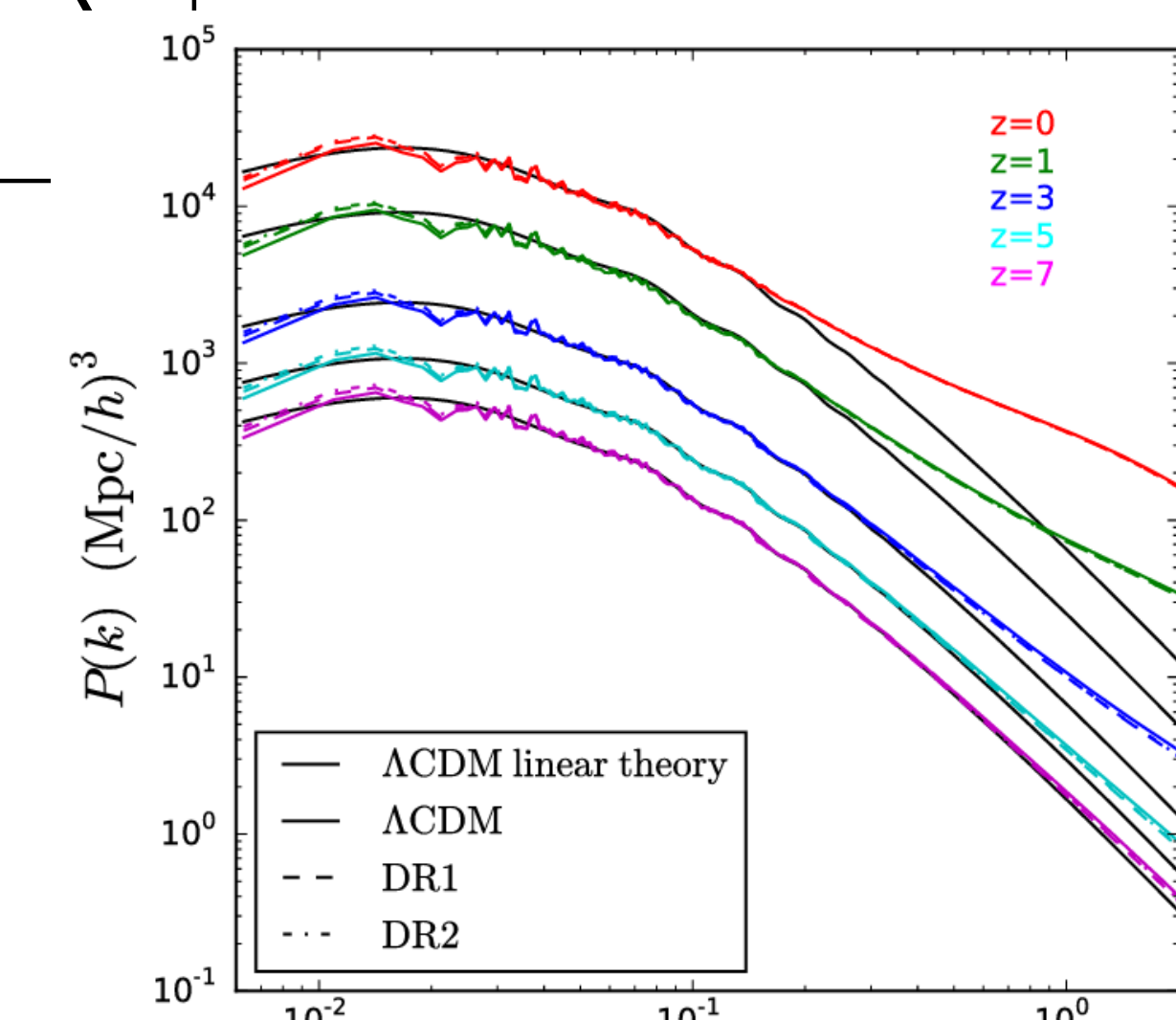
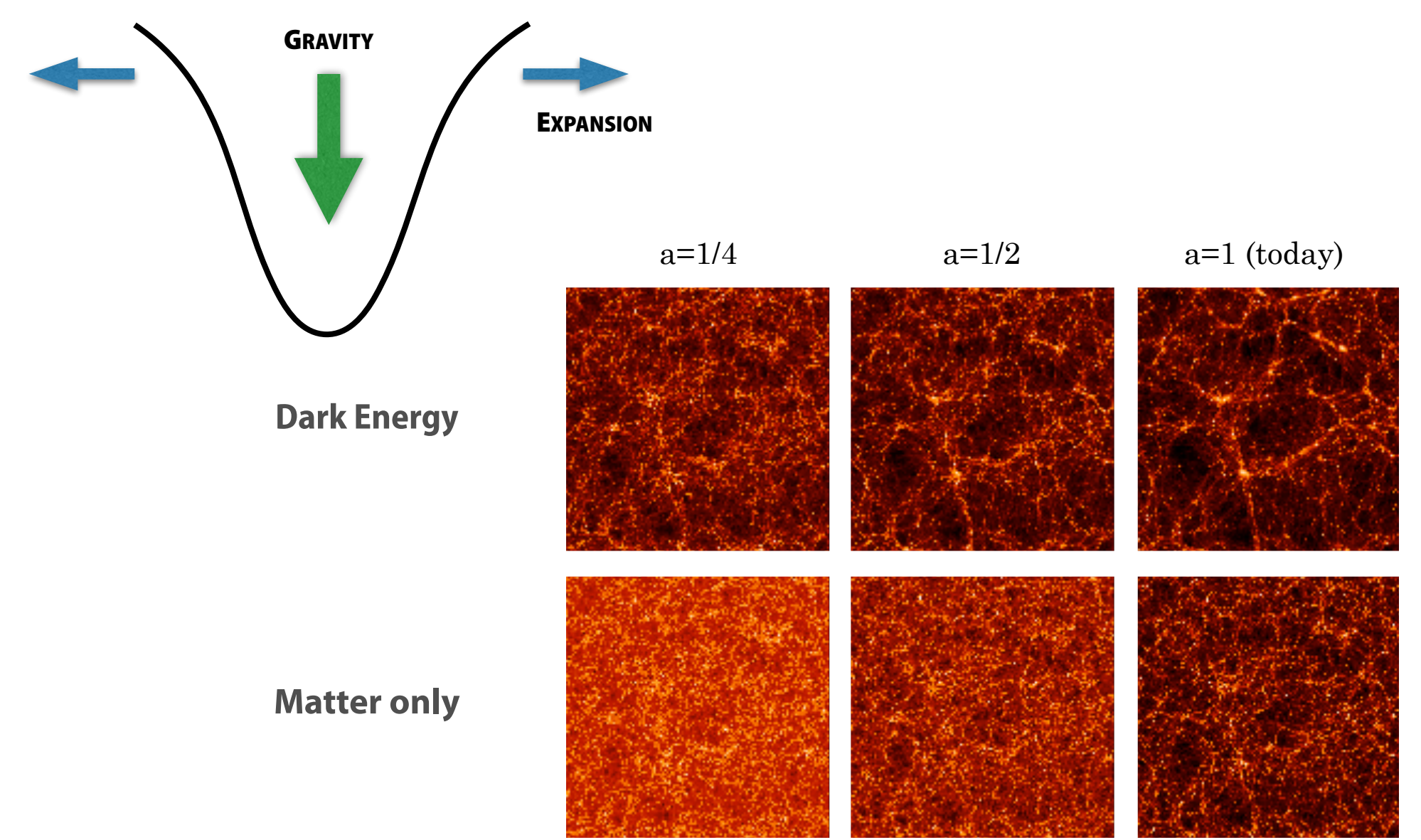
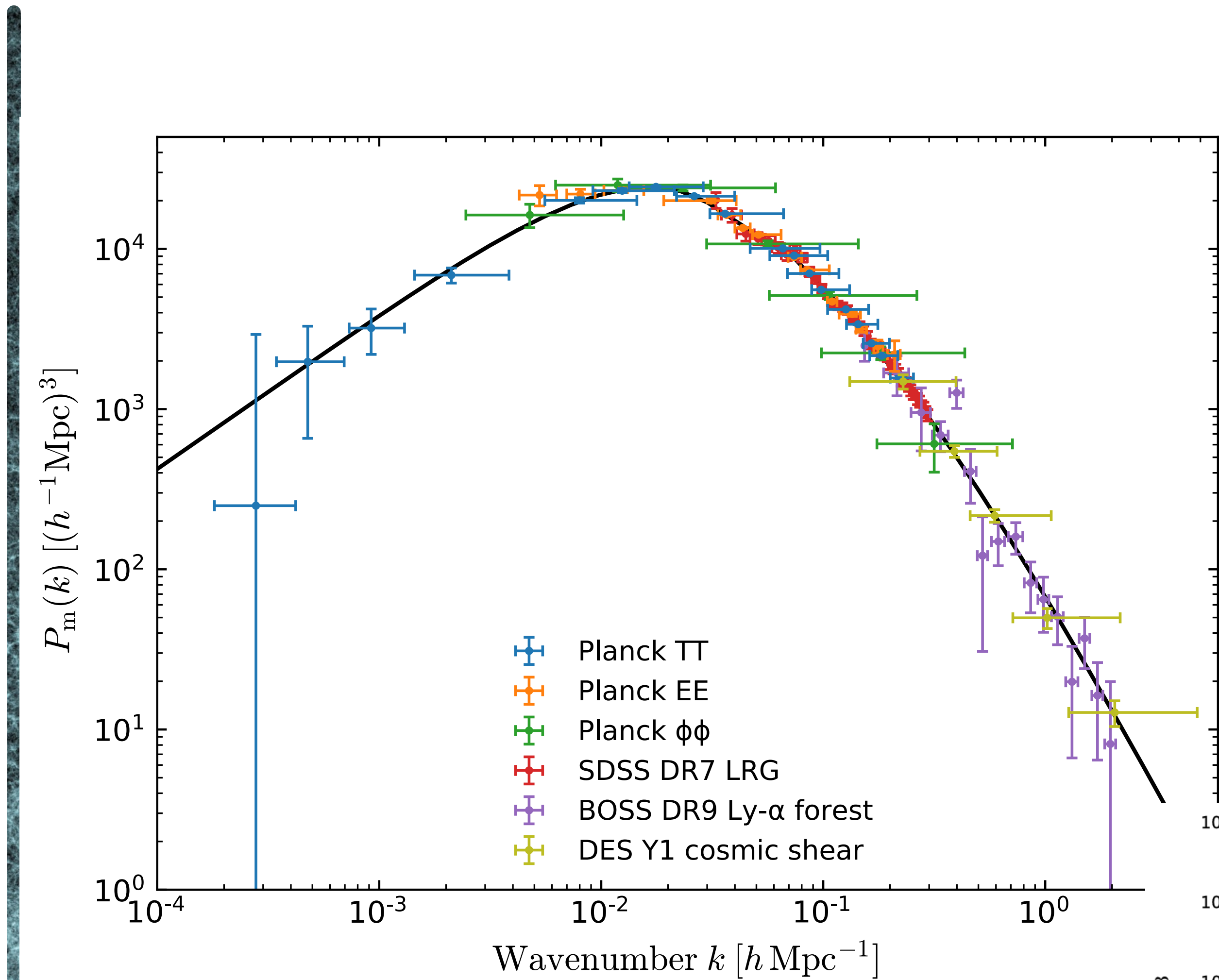
VERA C. RUBIN OBSERVATORY
LSST
Legacy Survey of Space and Time
Visits Obtained in r-filter for Year 1

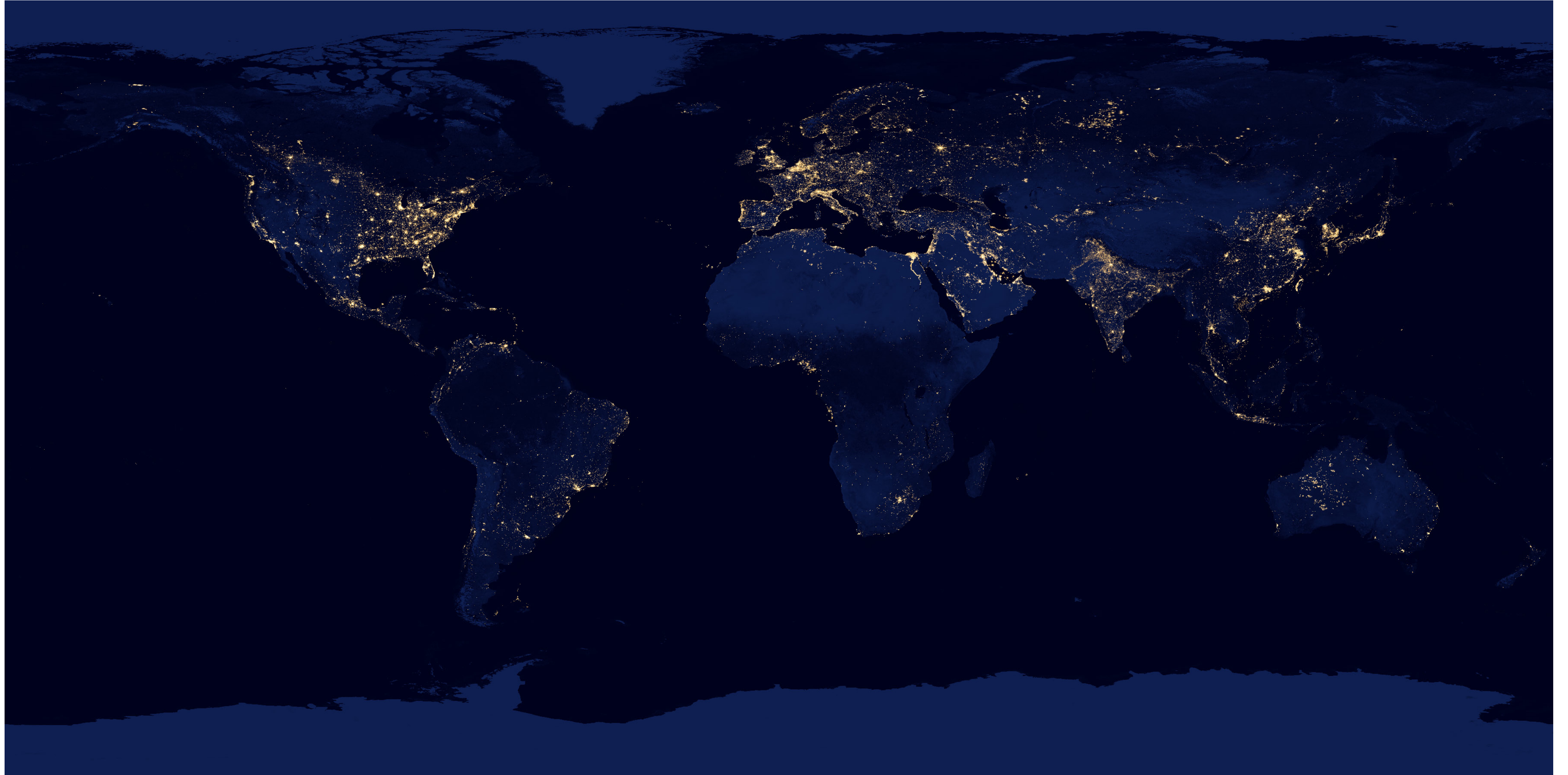


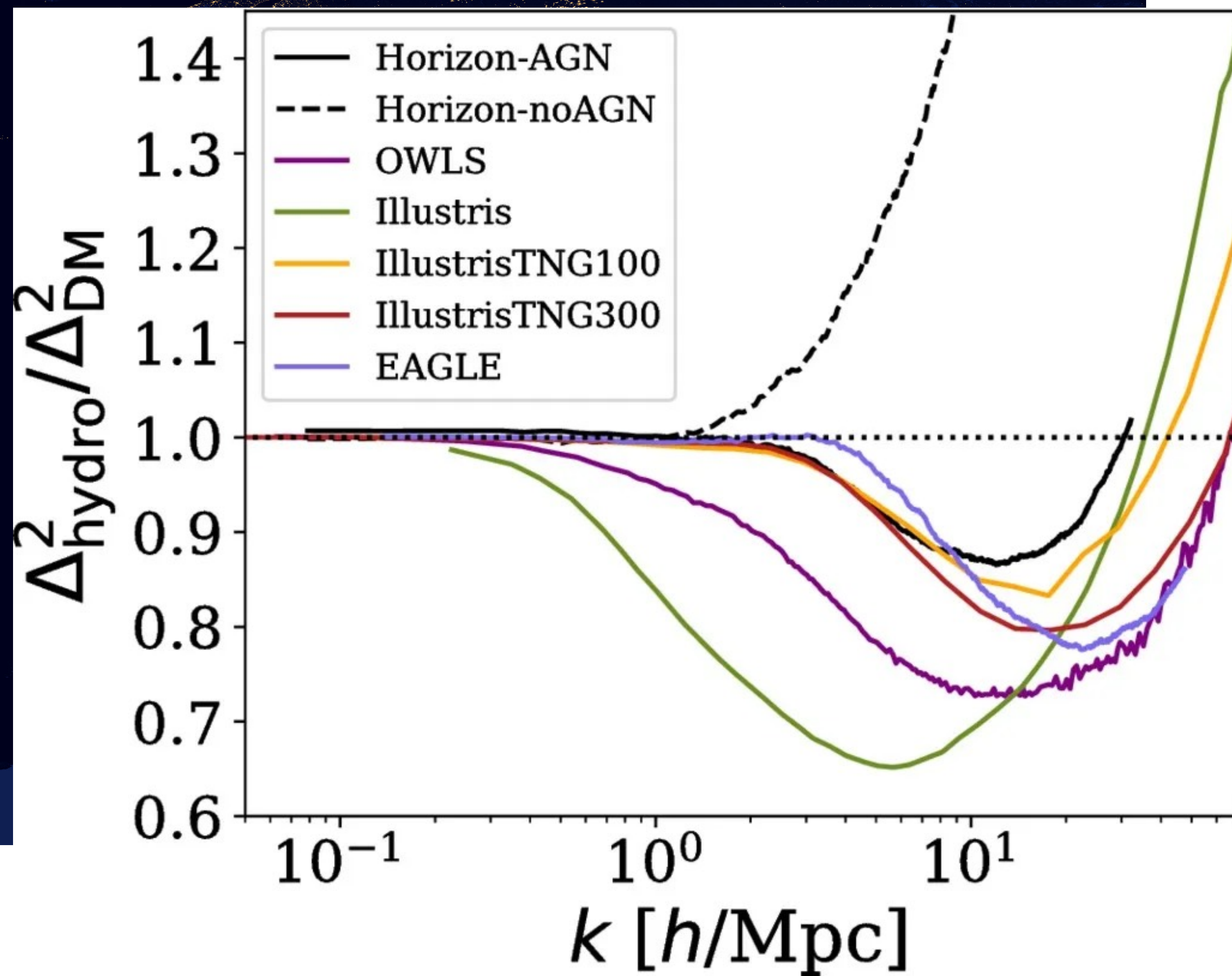
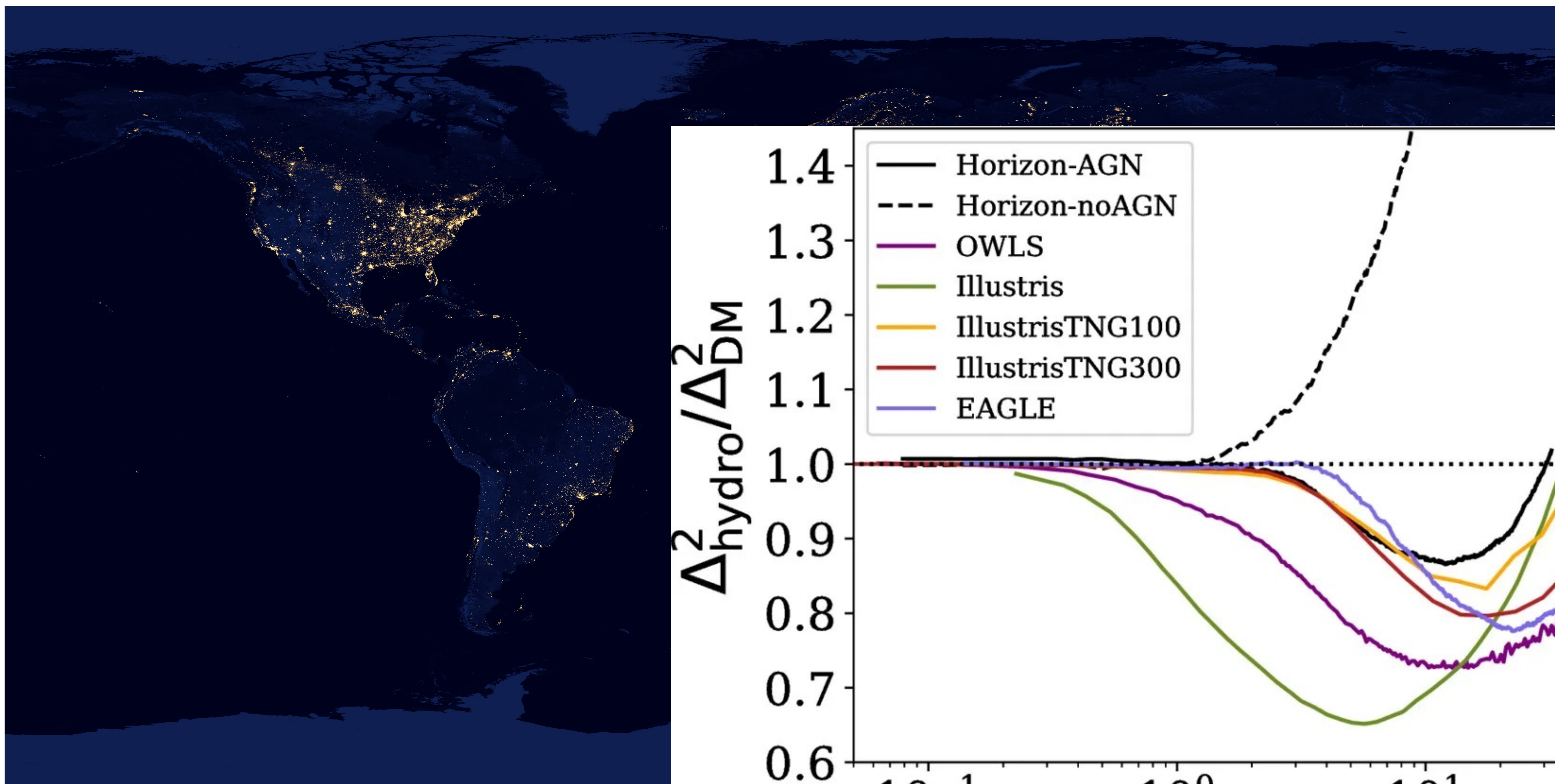
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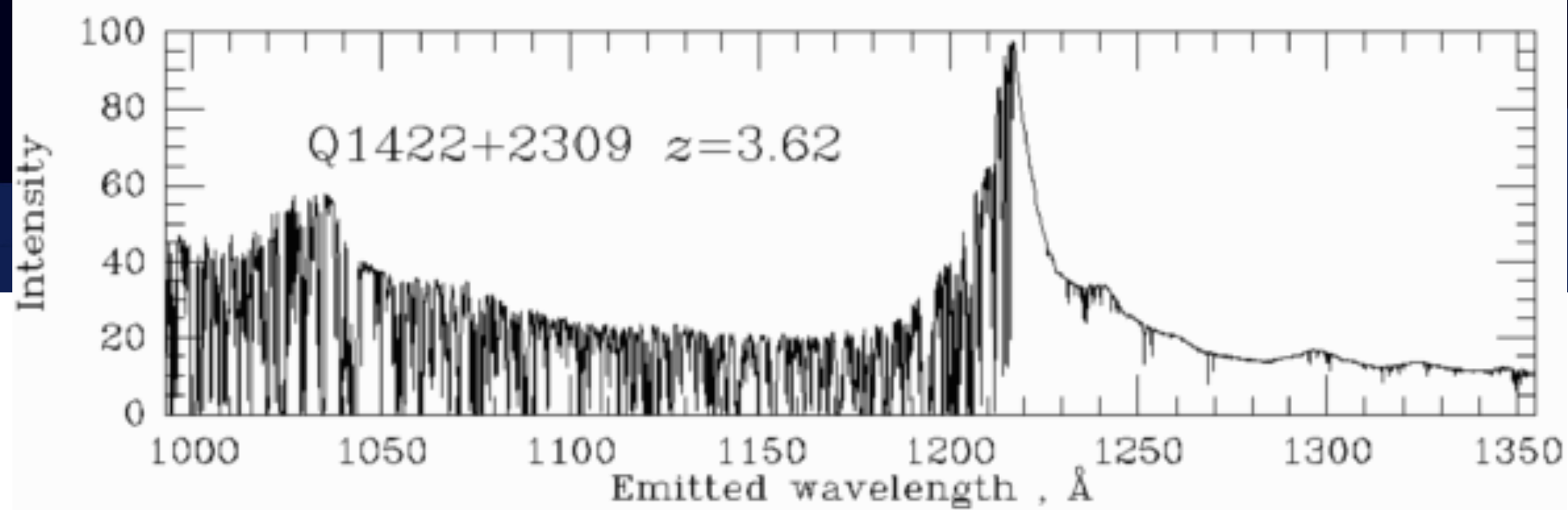
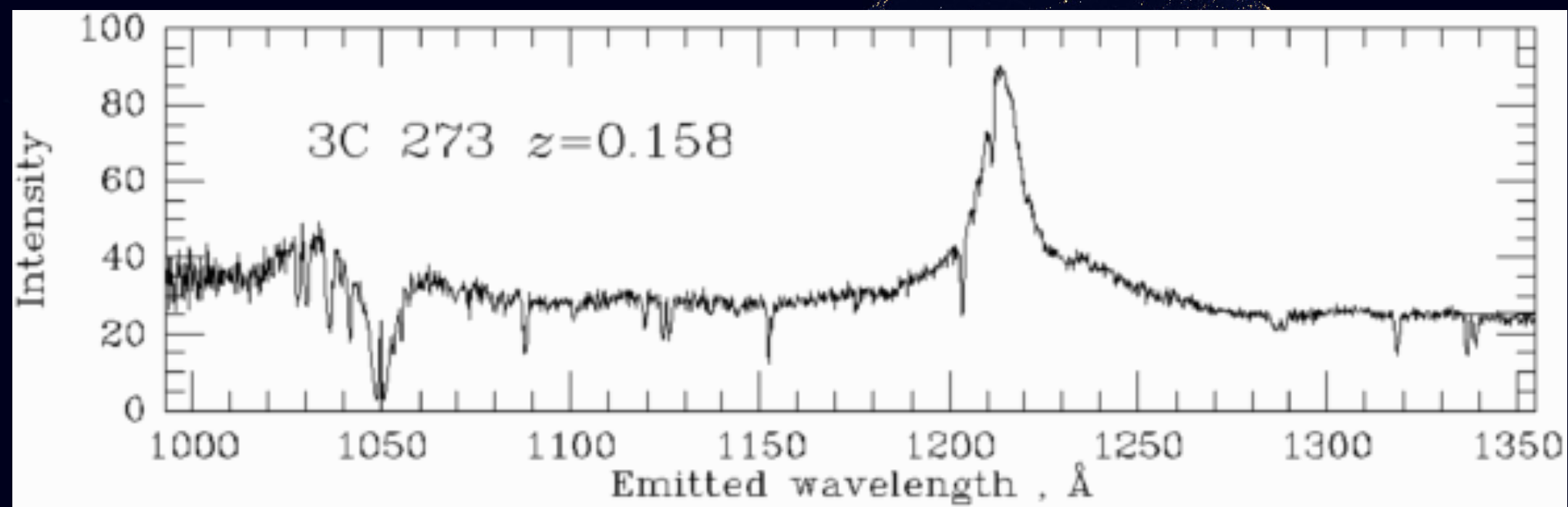
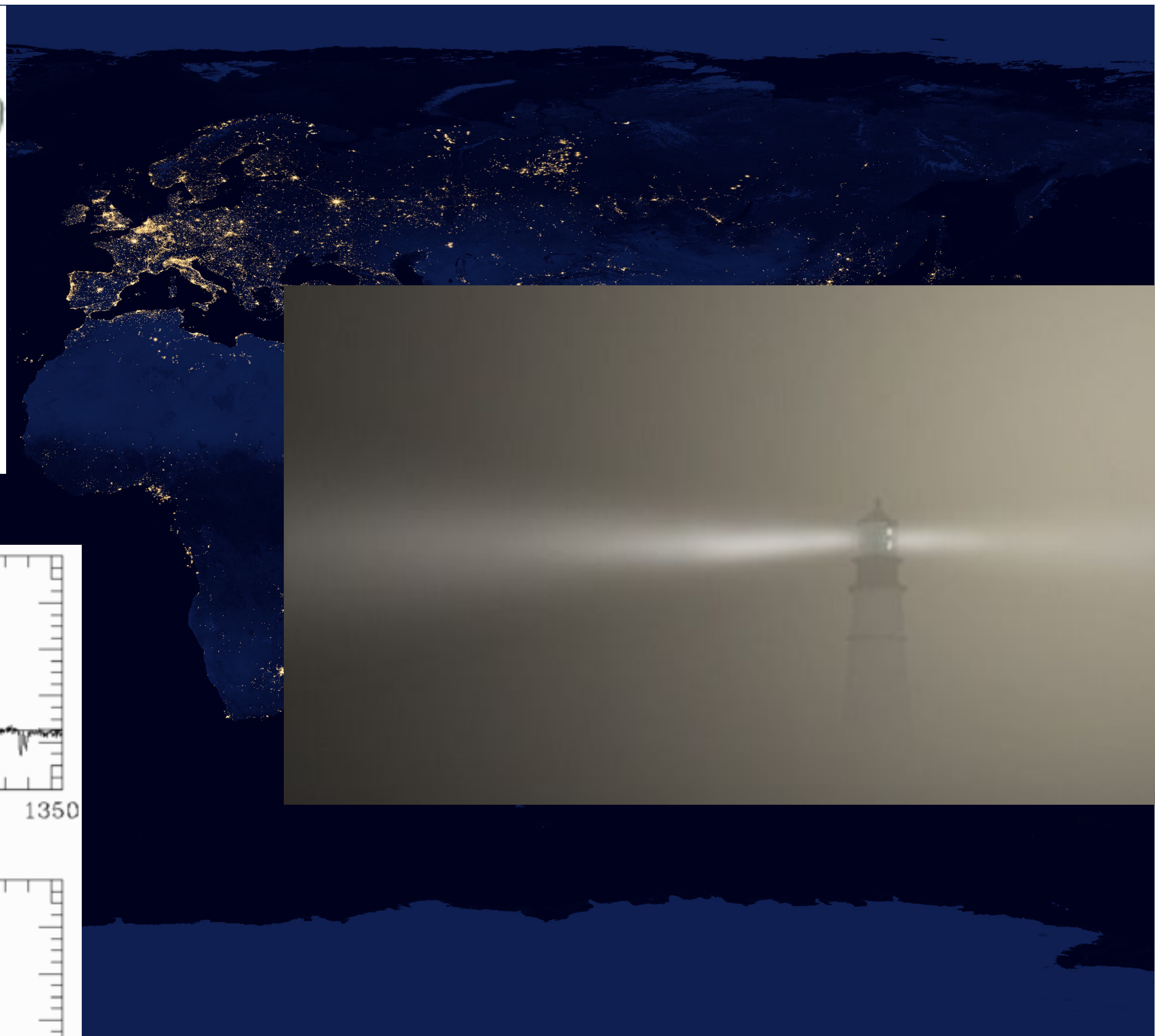
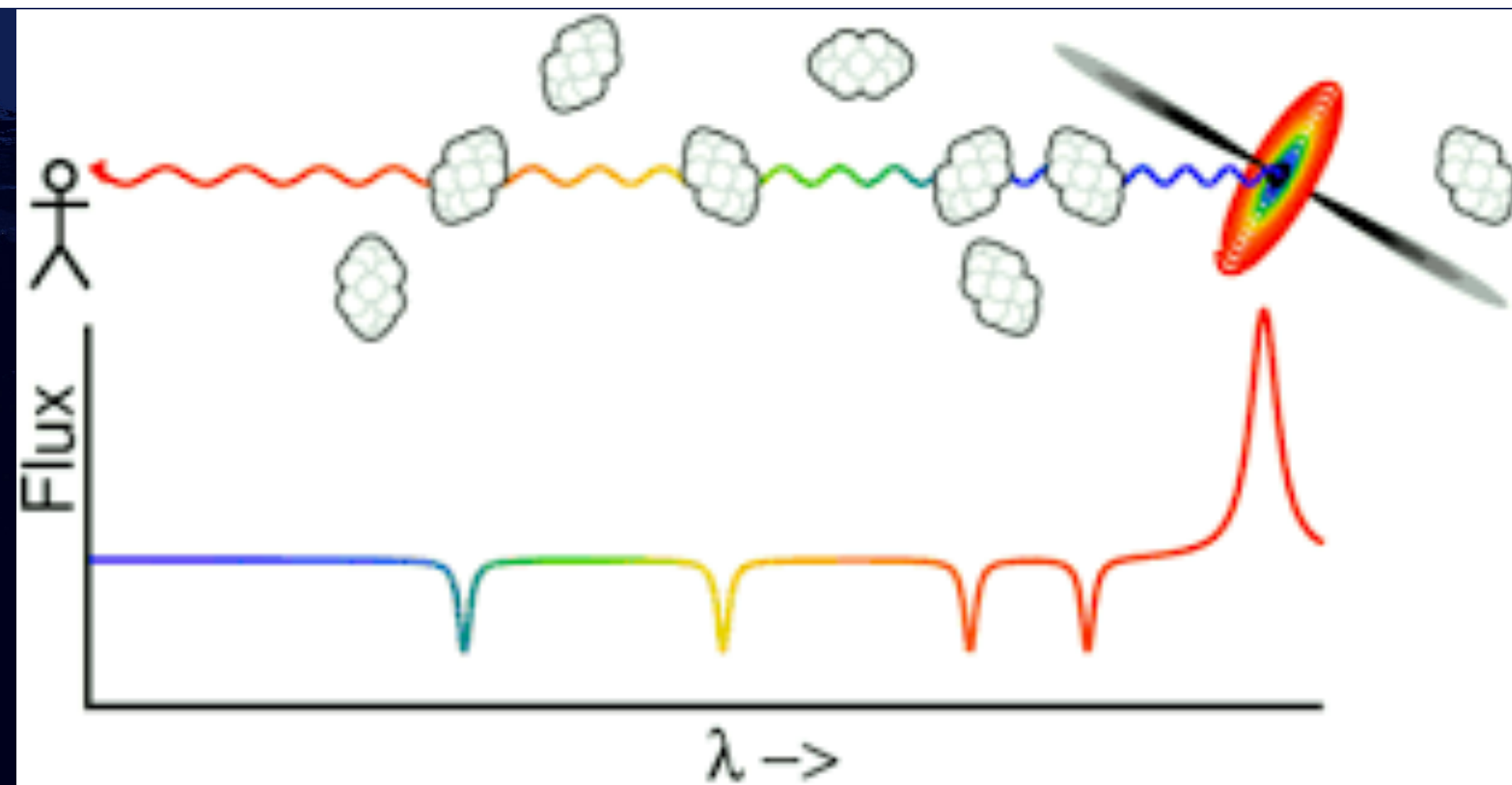
Photo



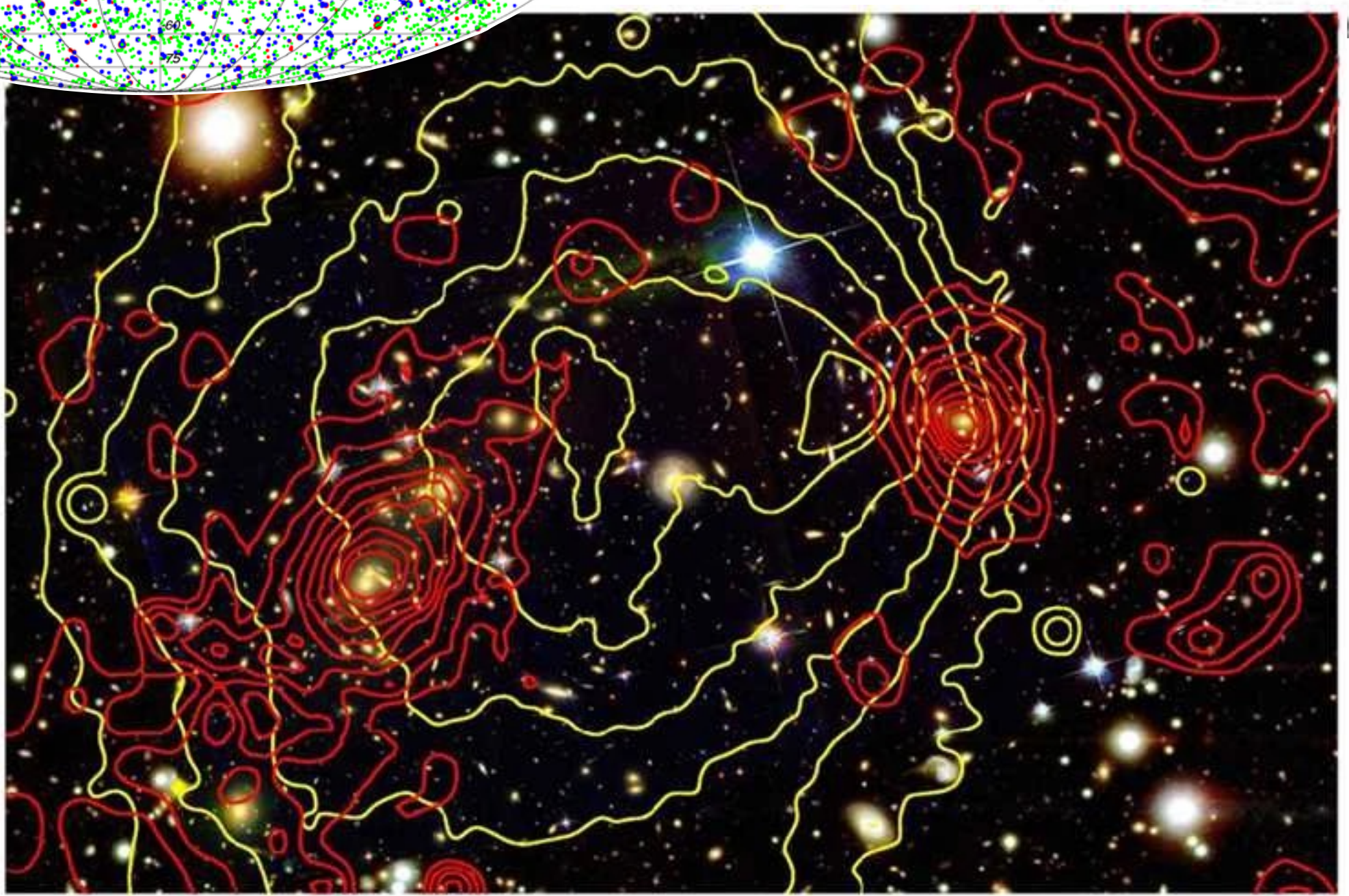
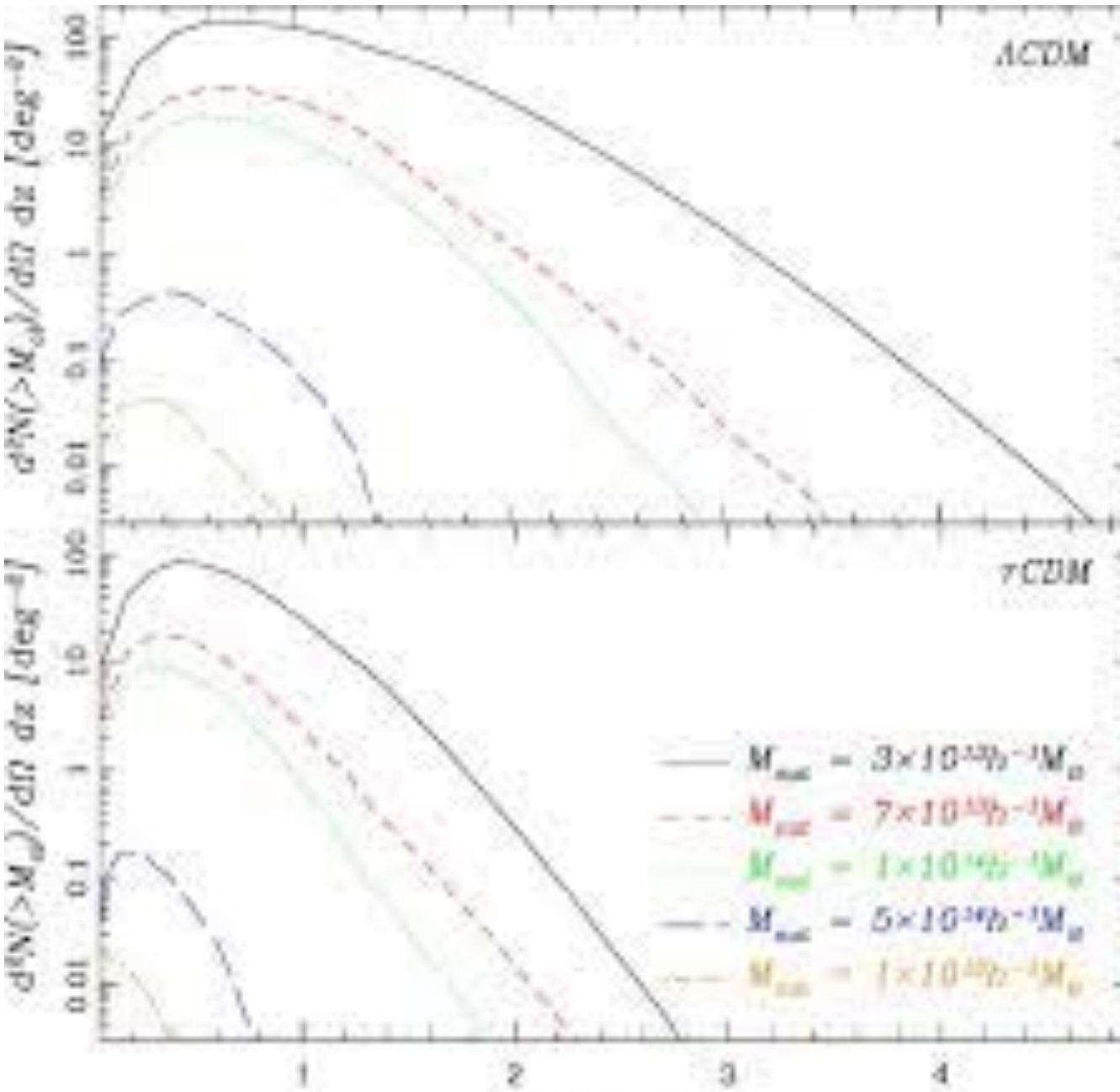
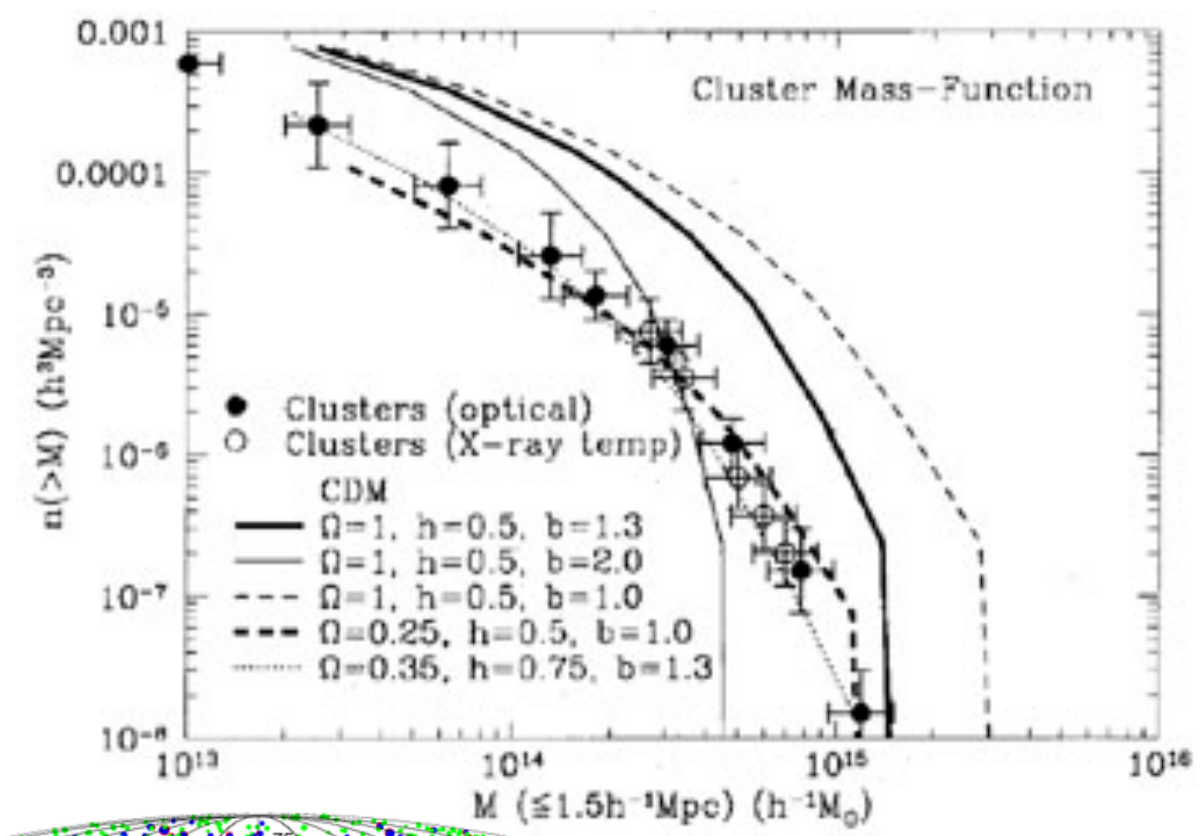
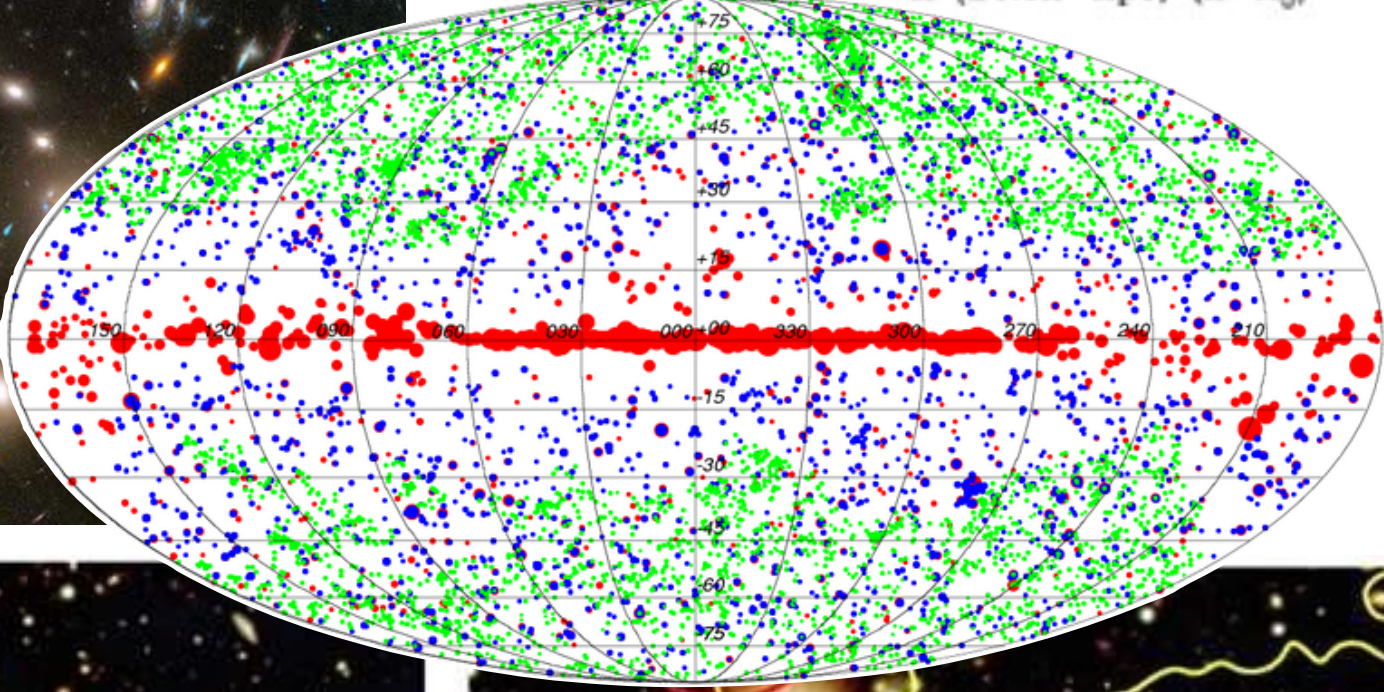
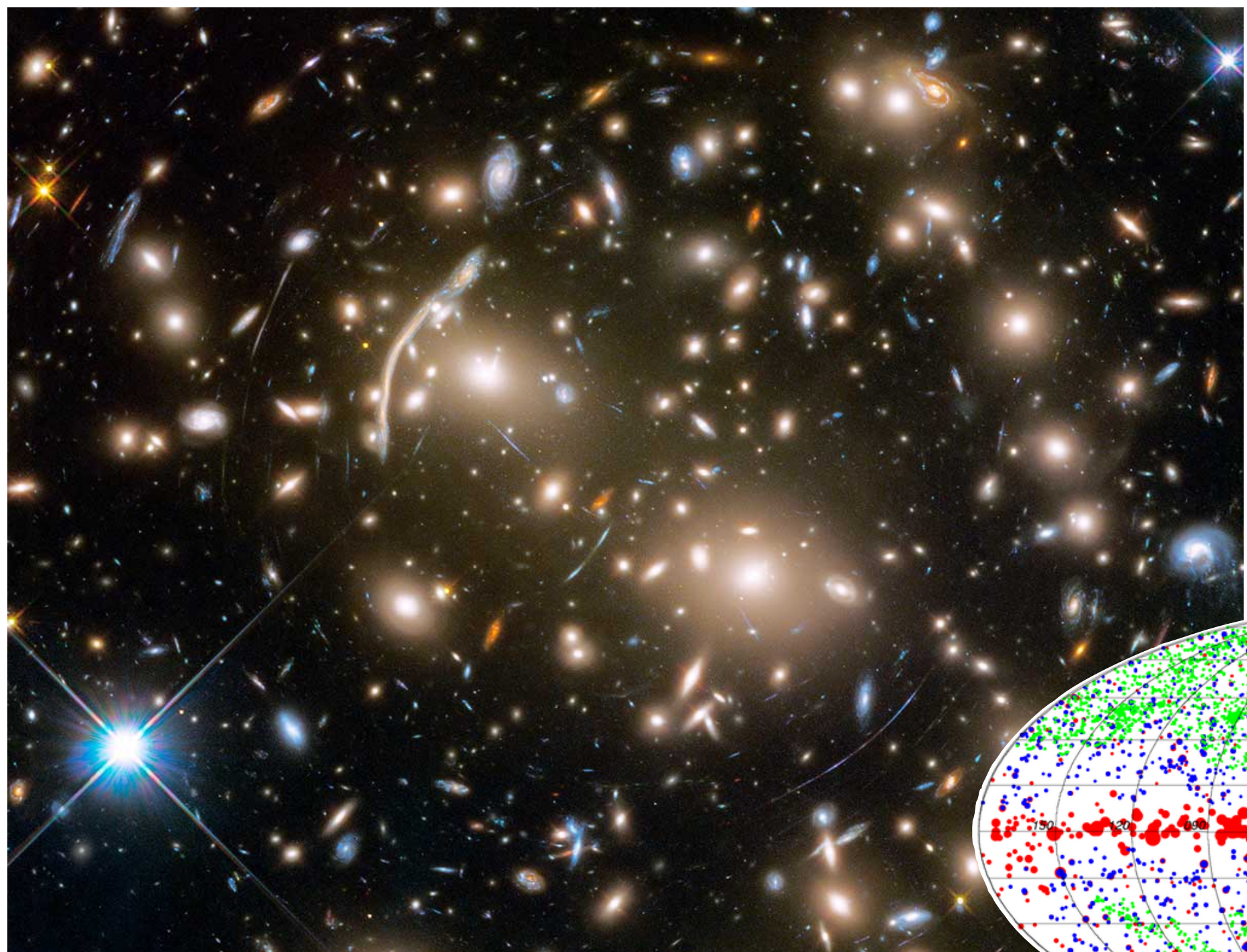




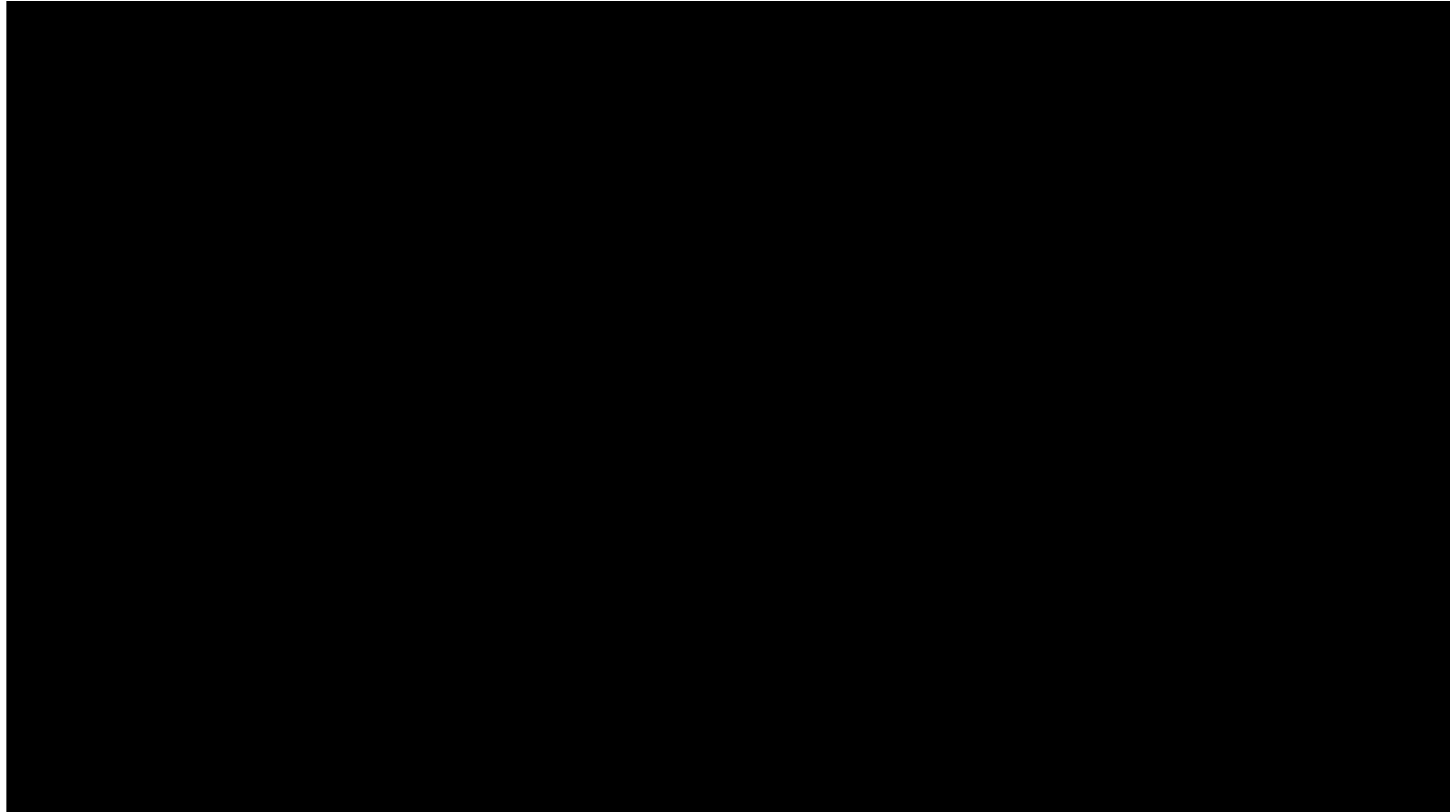


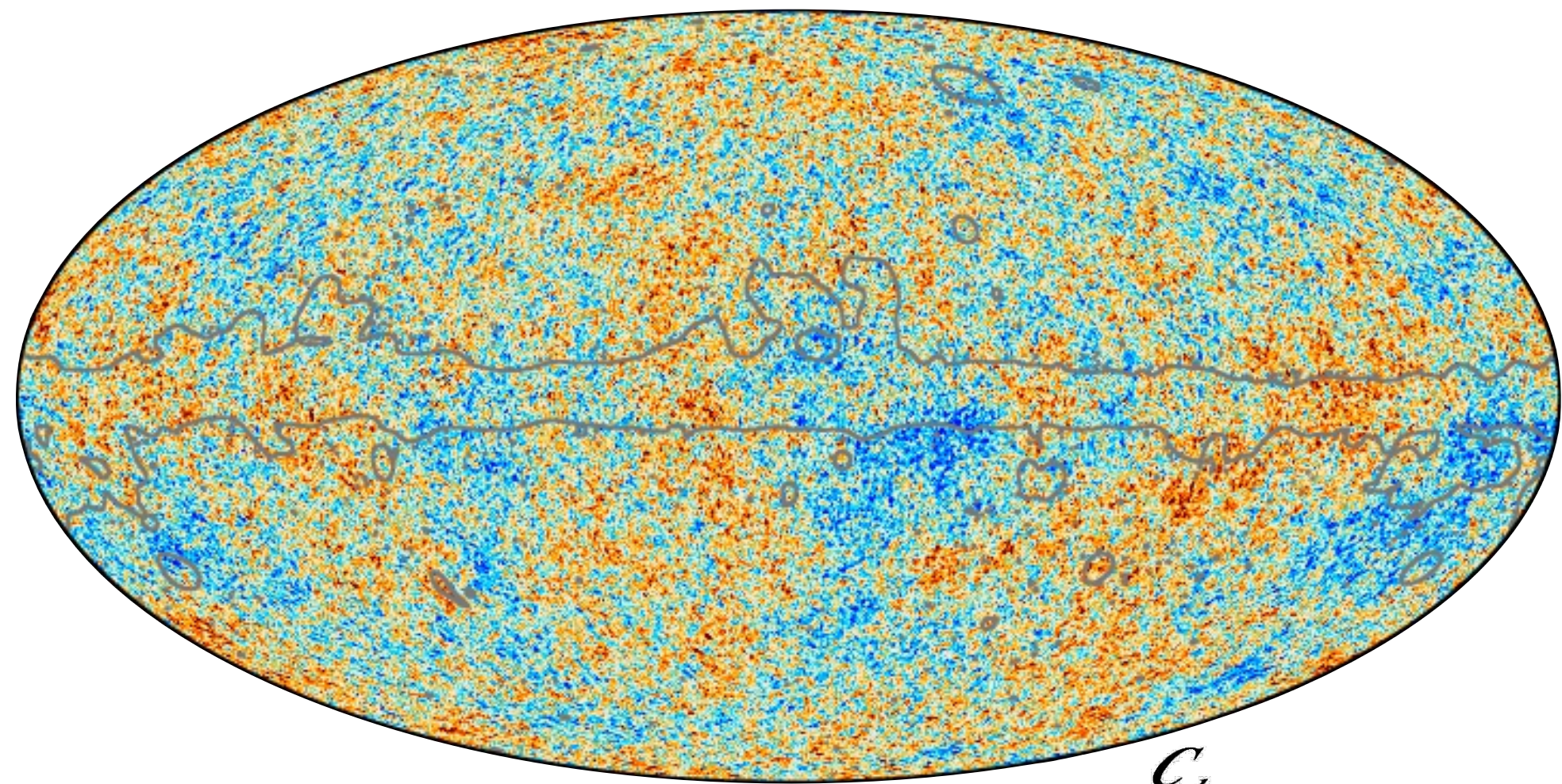




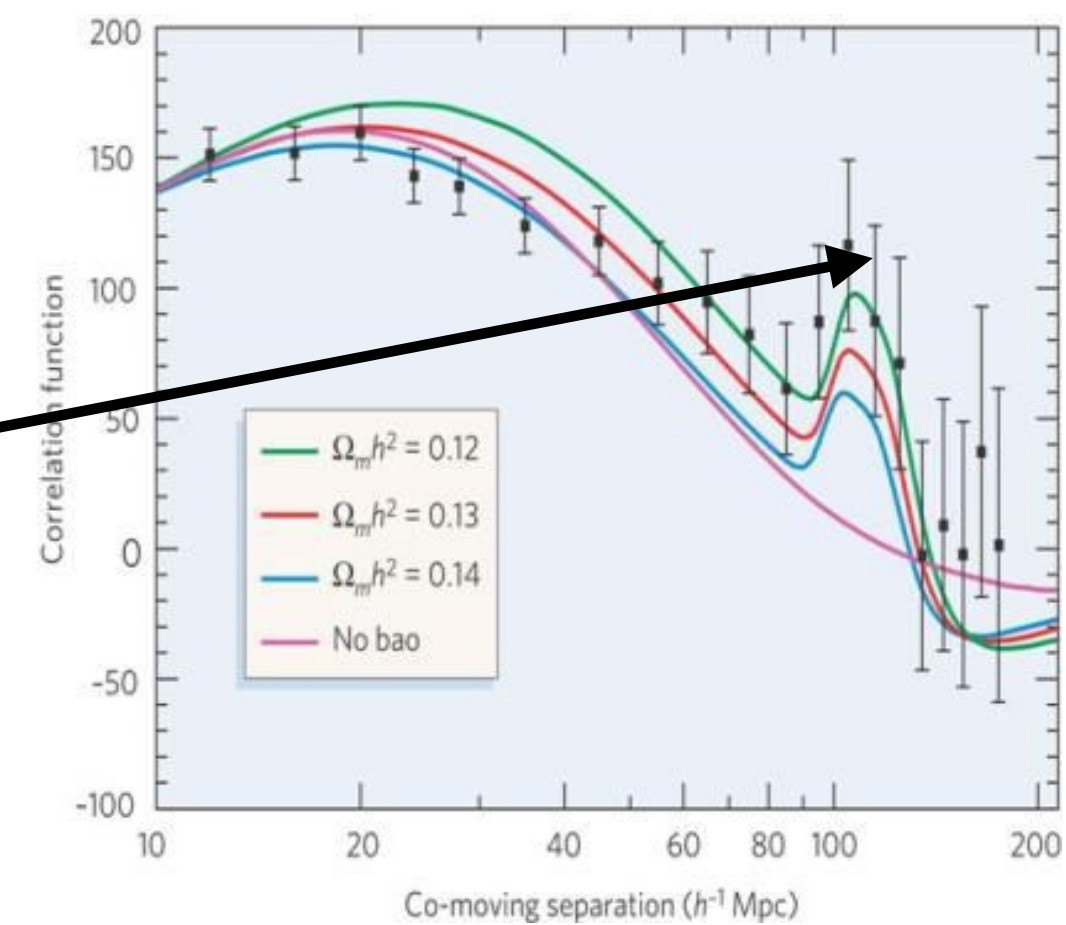
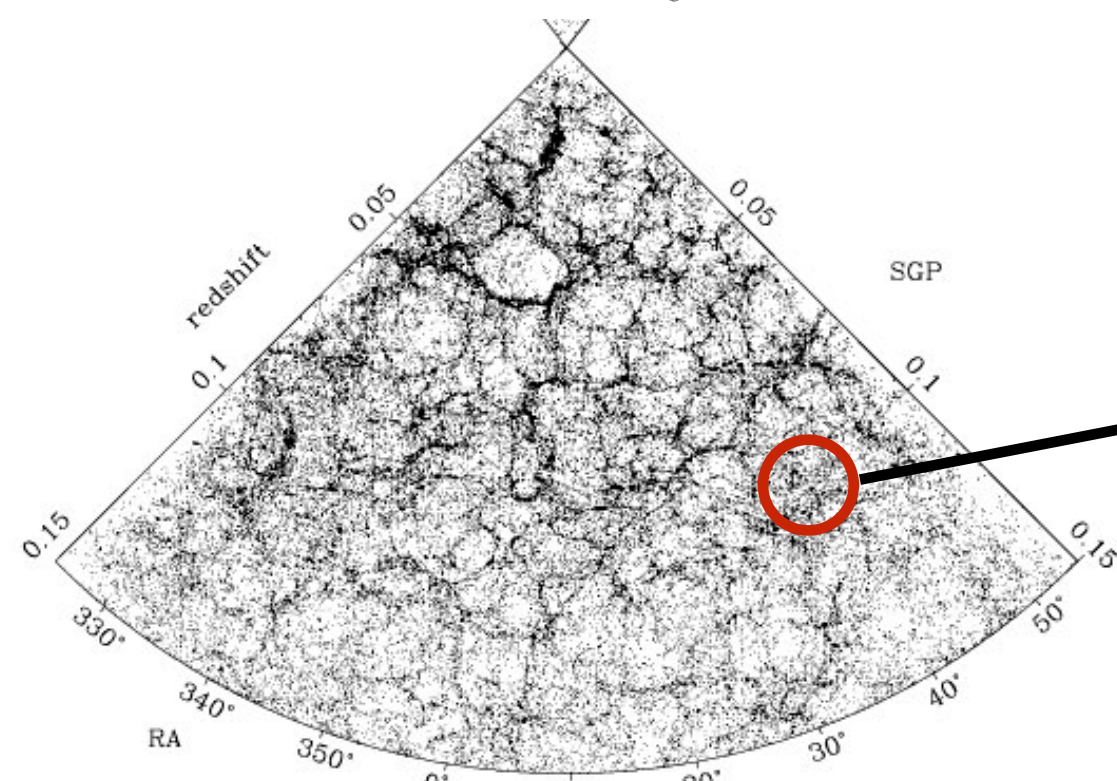
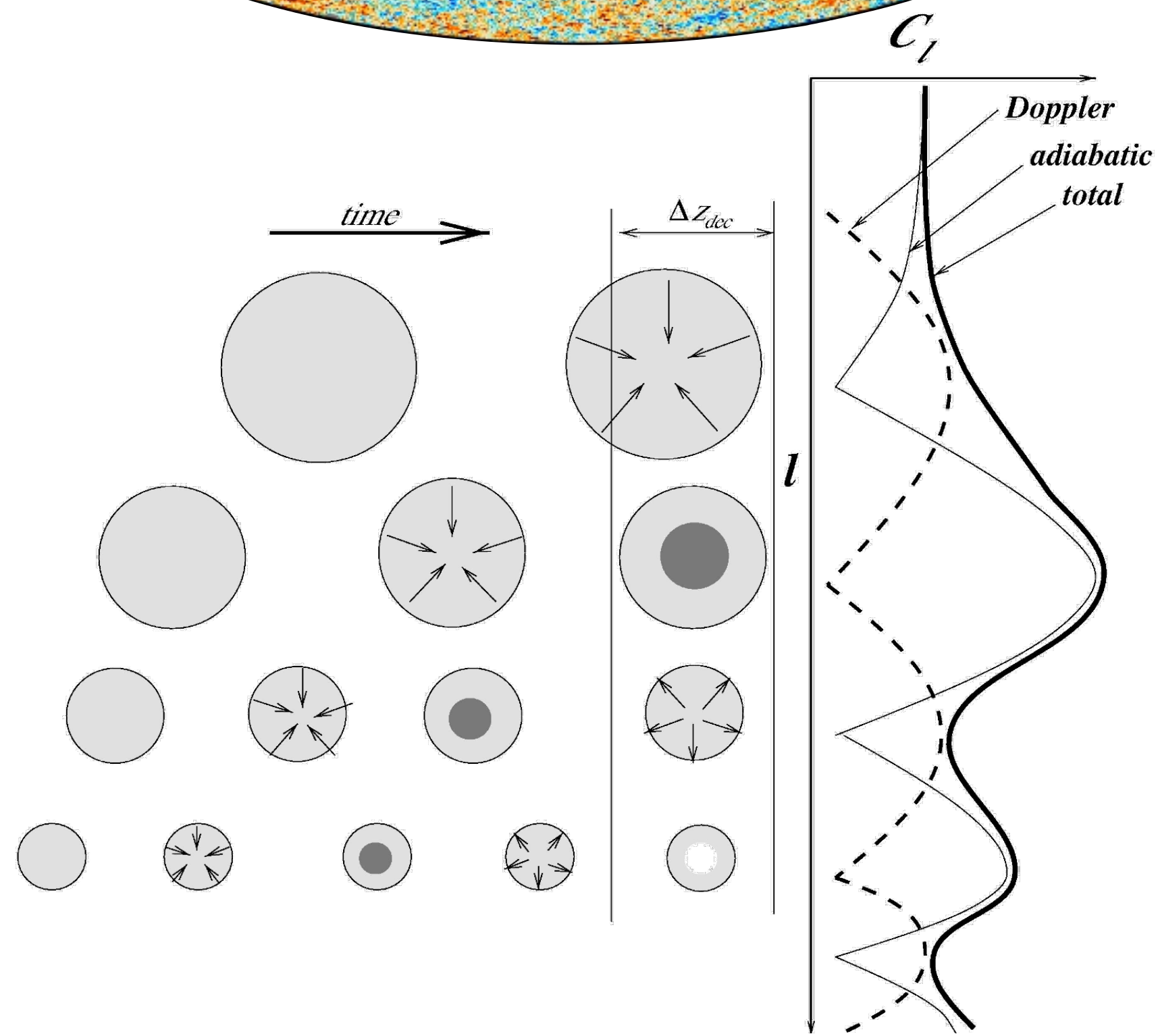
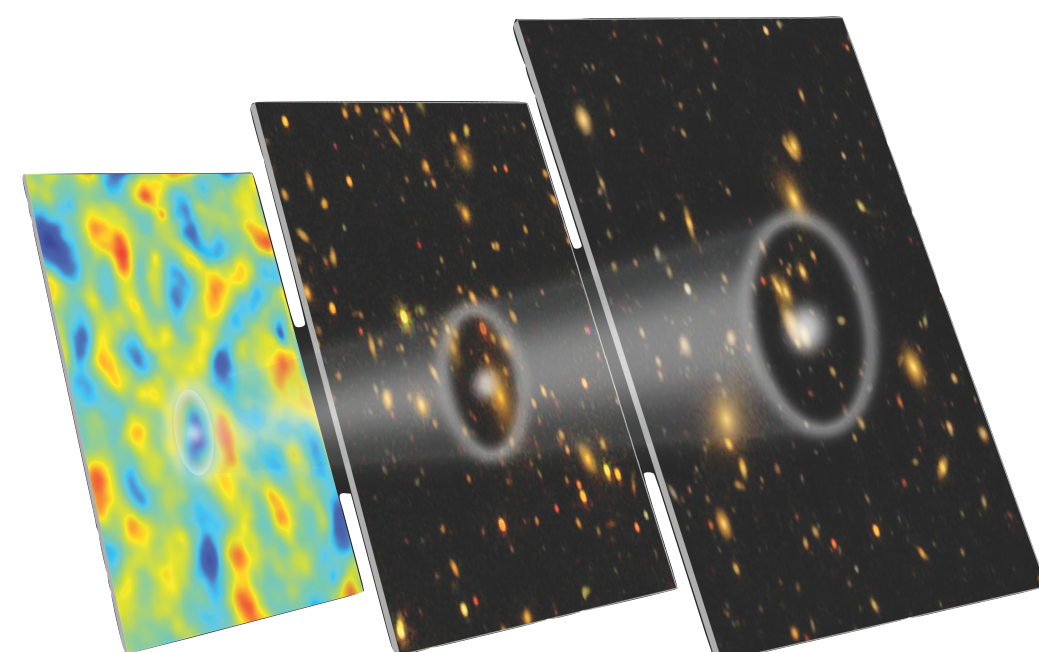
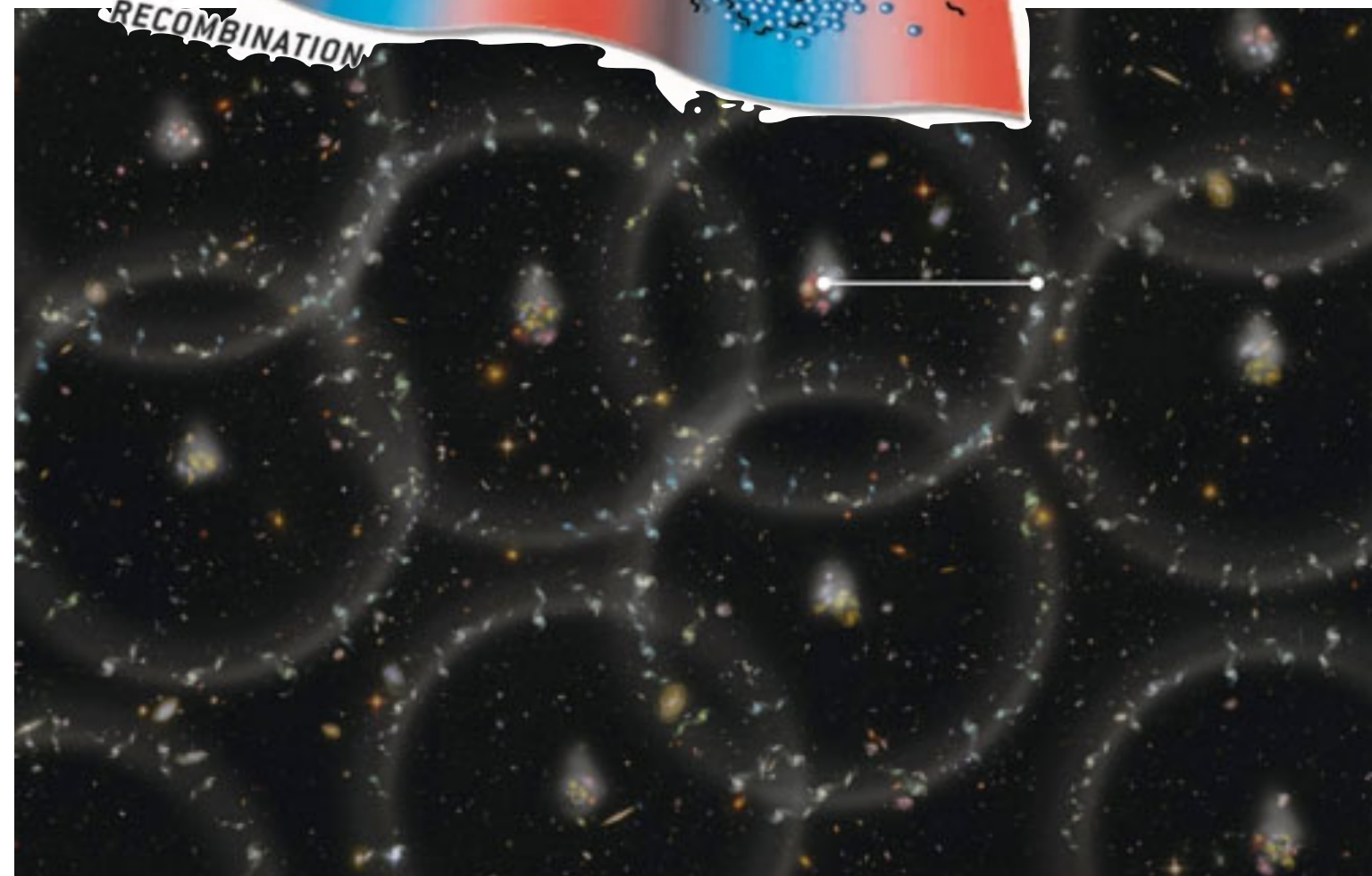
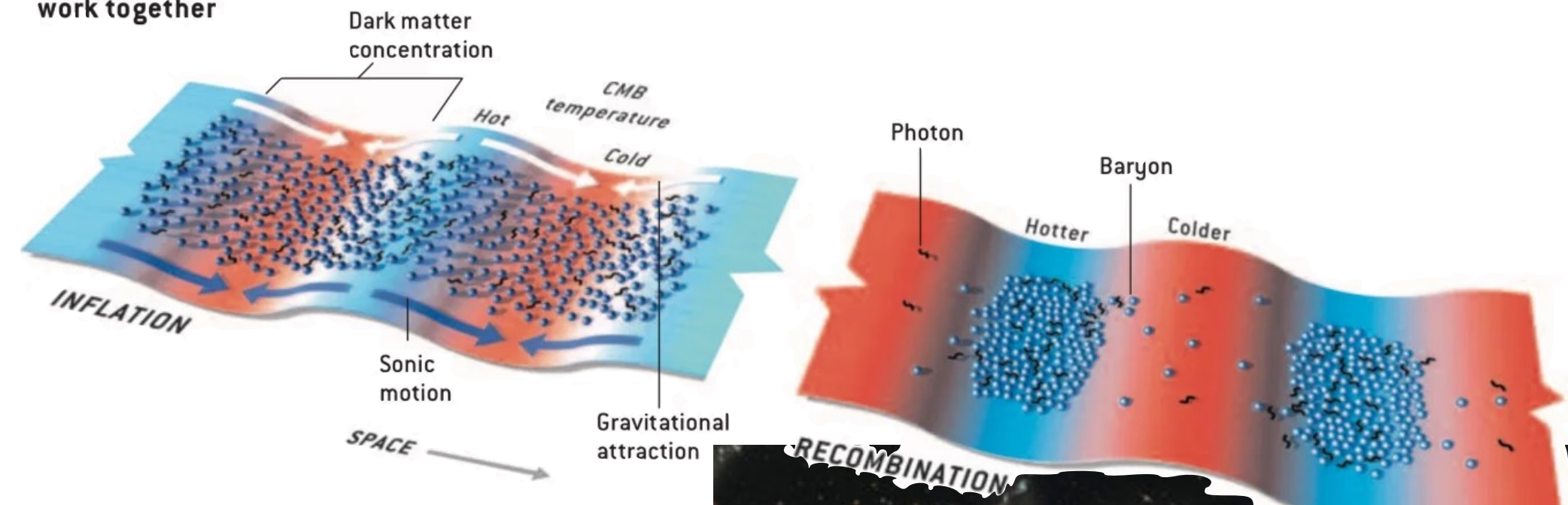


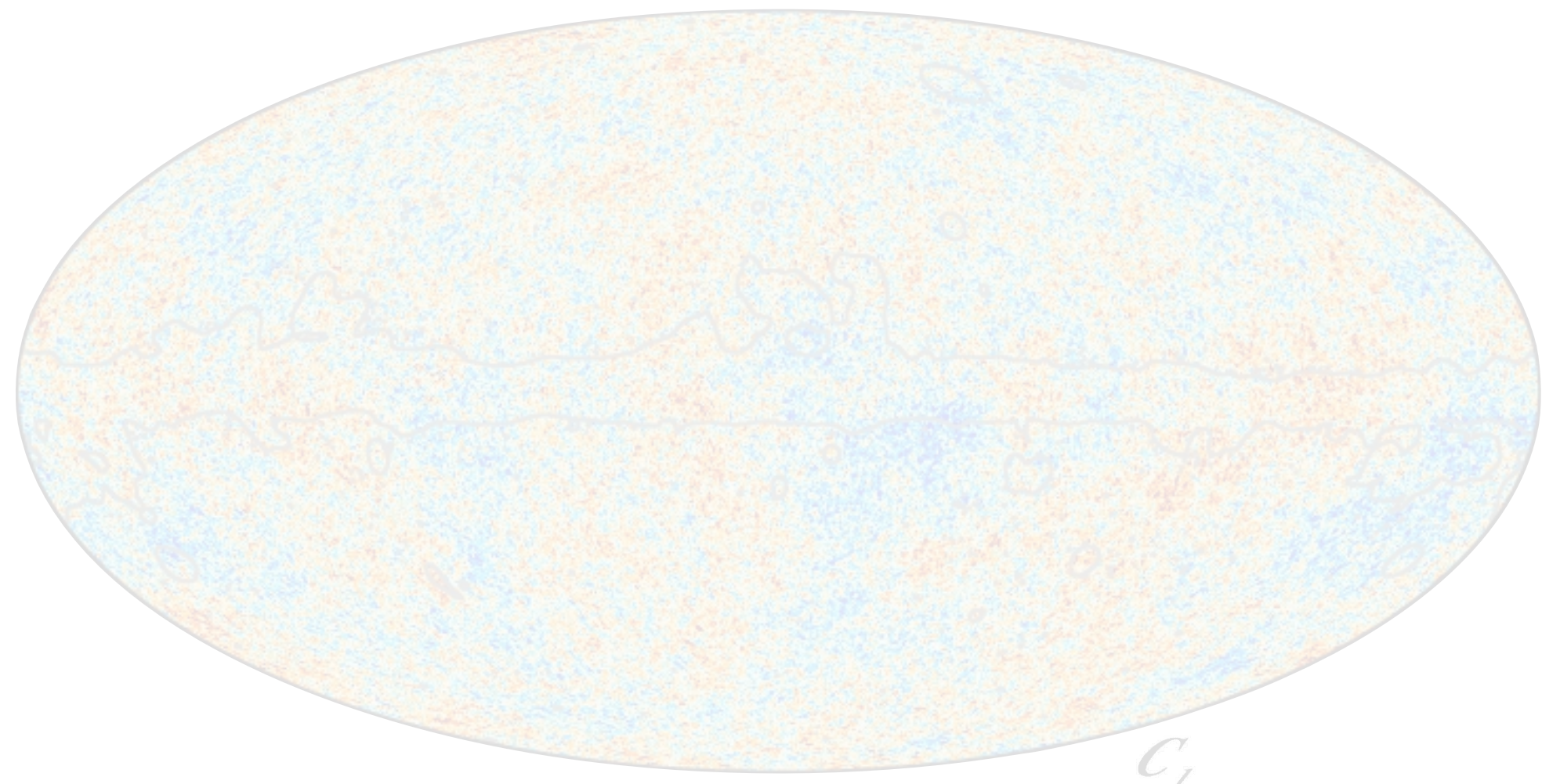
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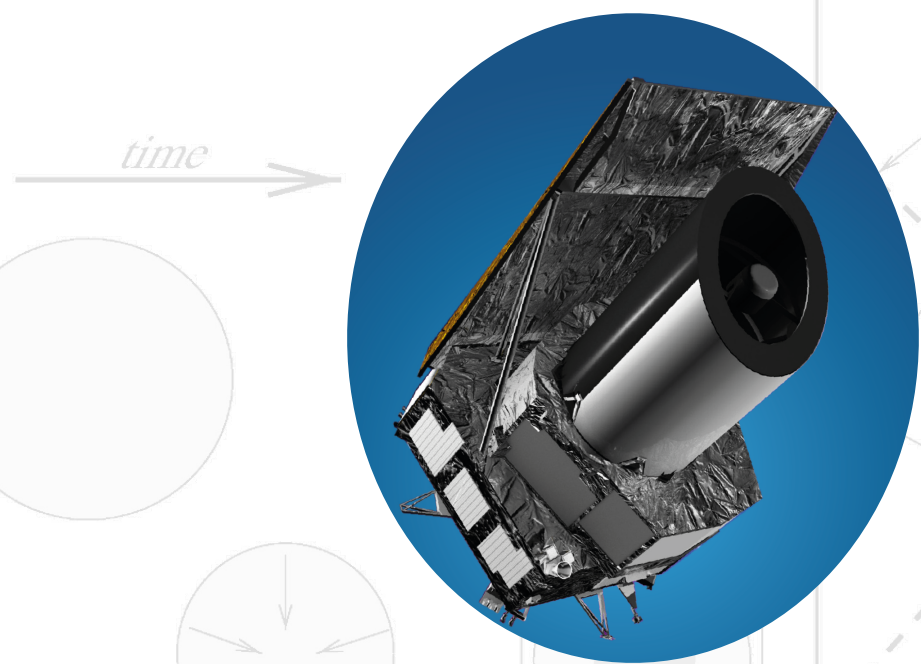
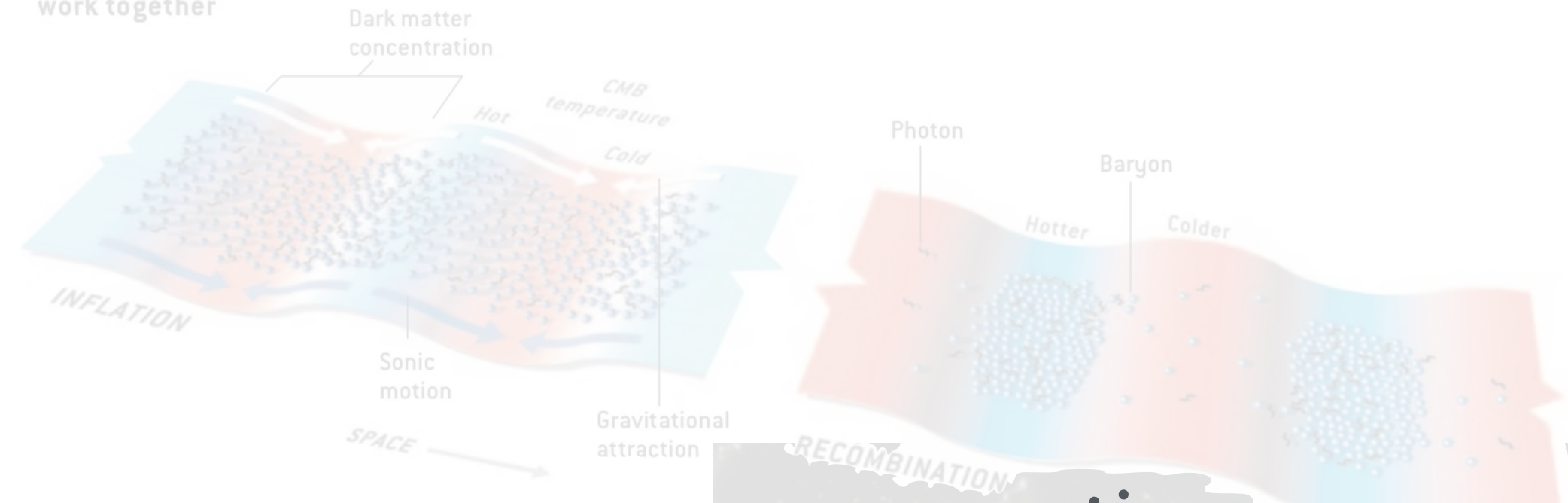


FIRST PEAK
Gravity and sonic motion work together

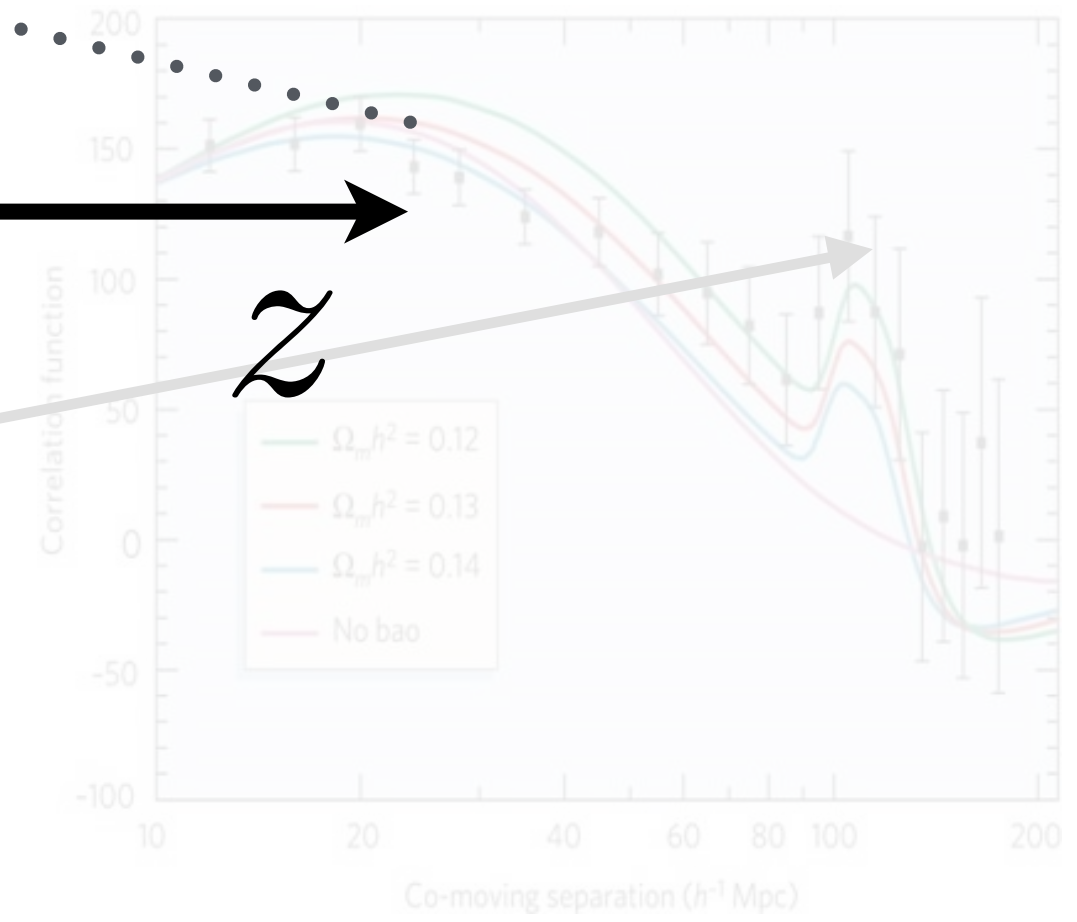
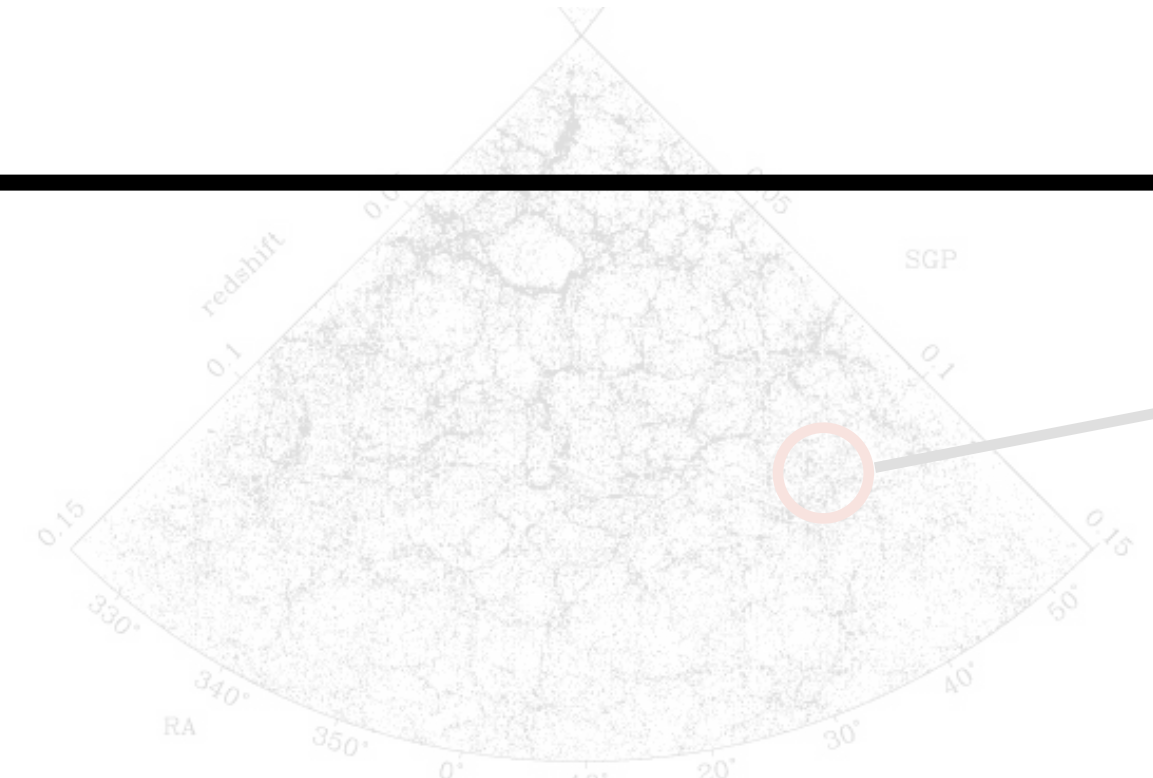
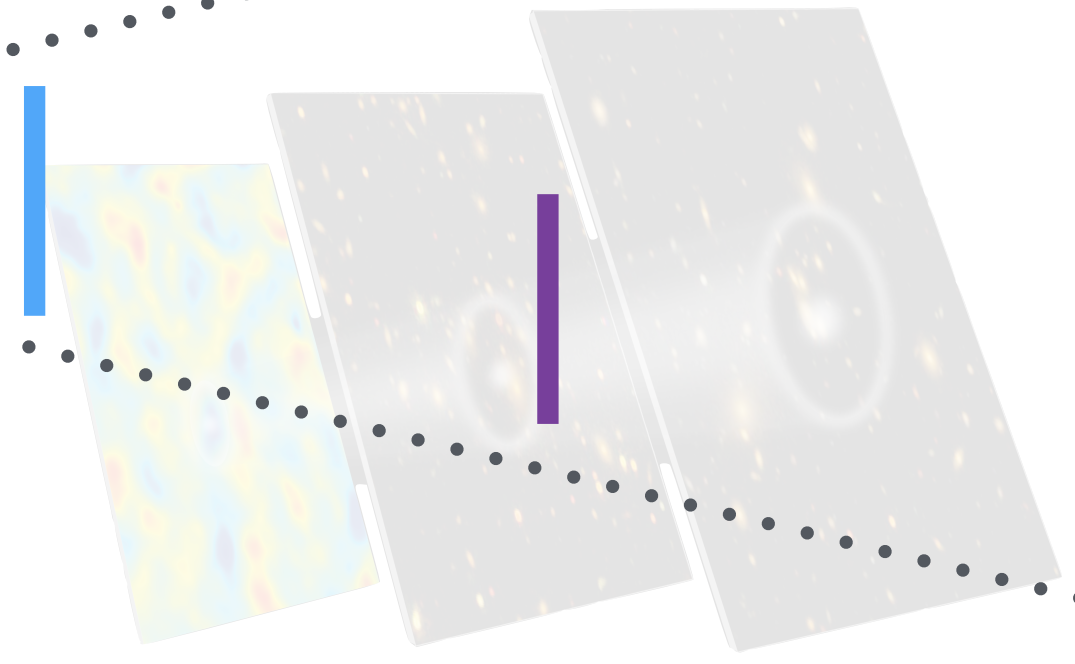


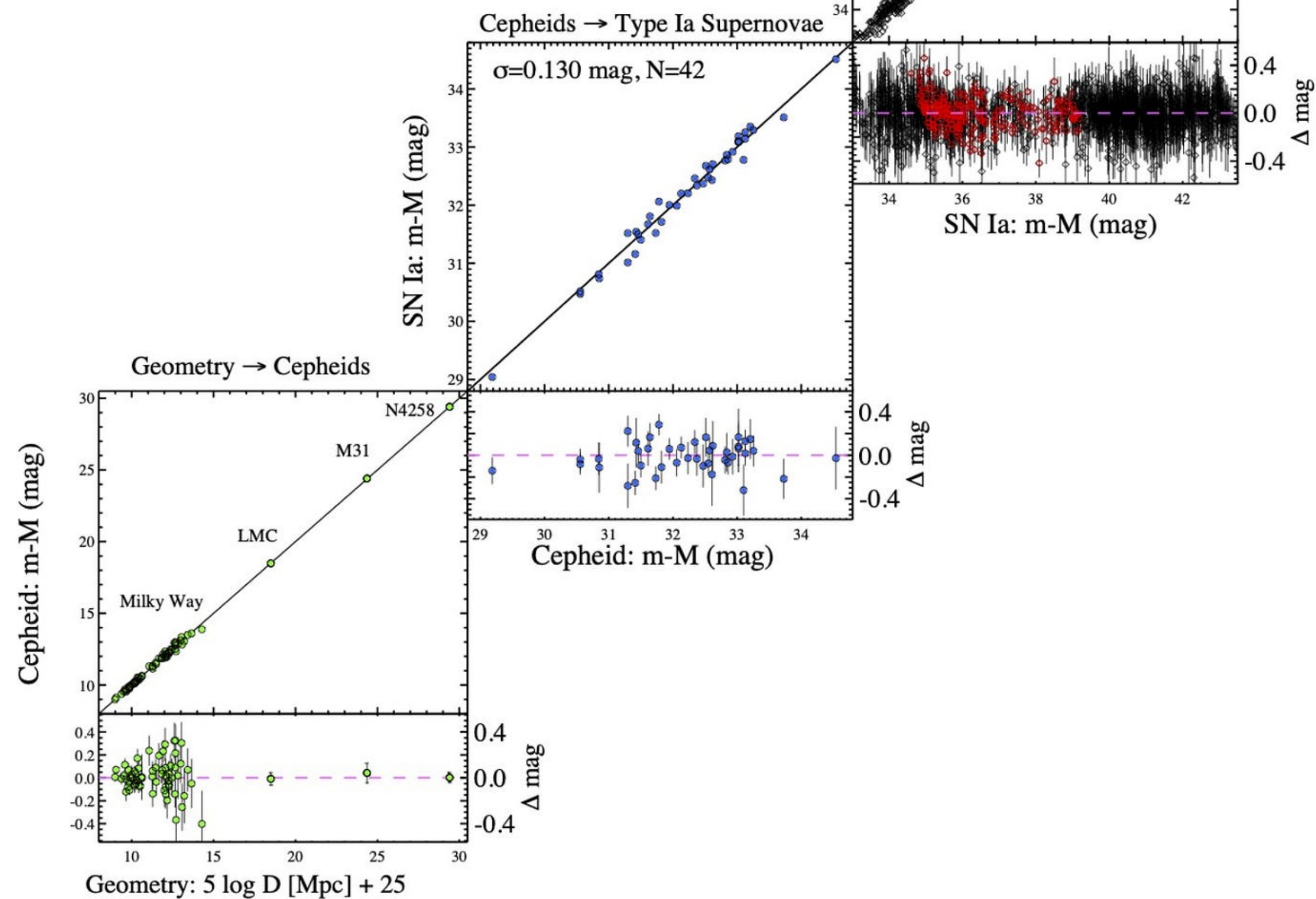
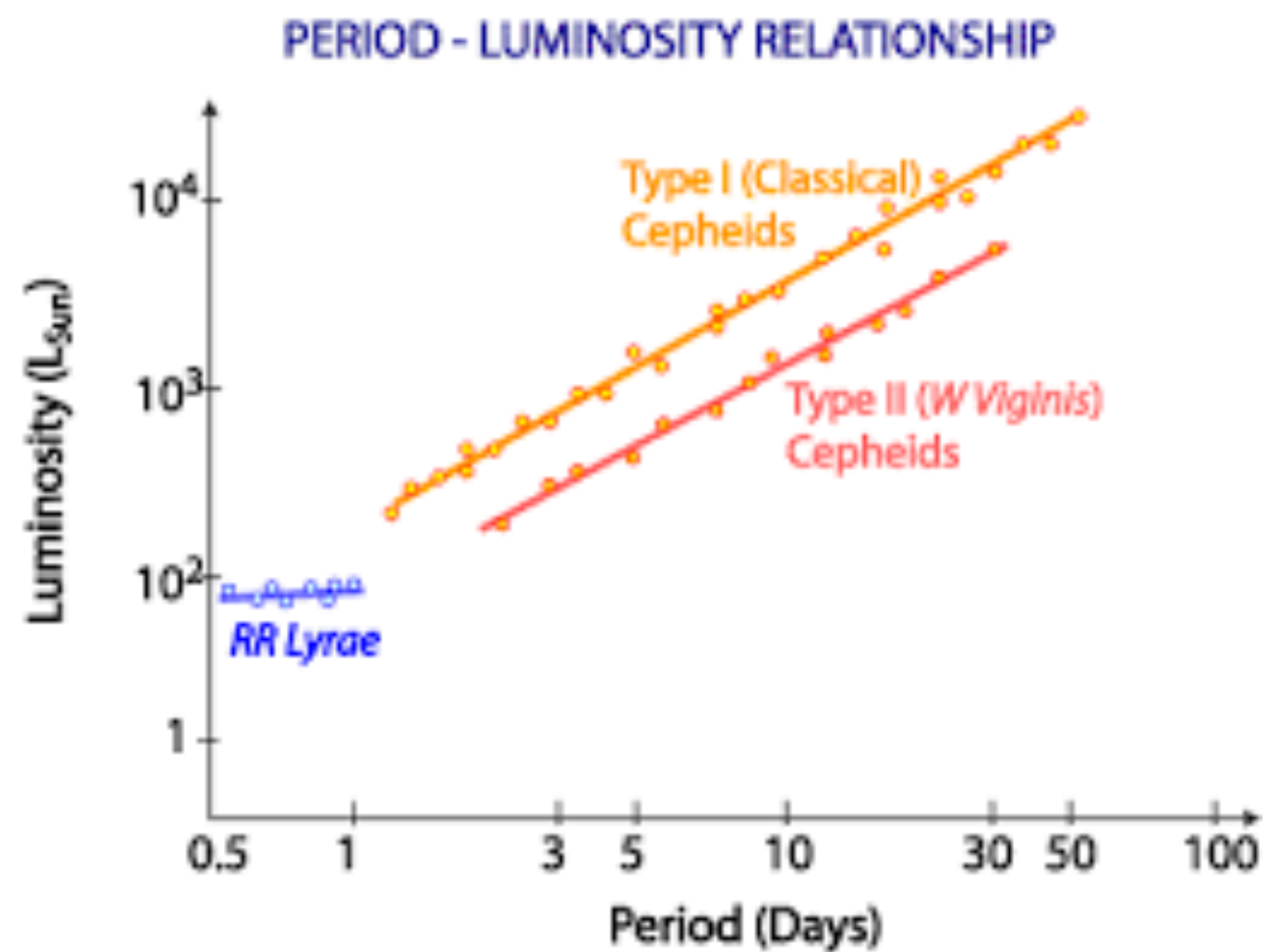
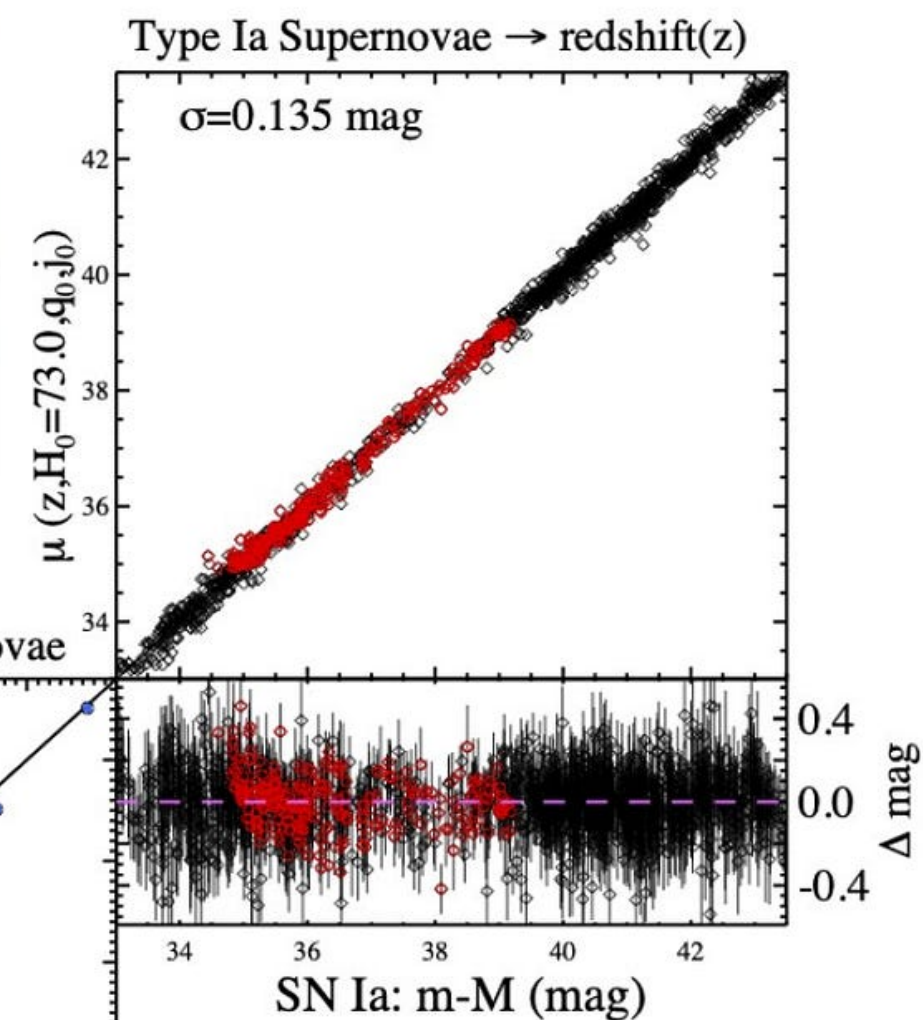
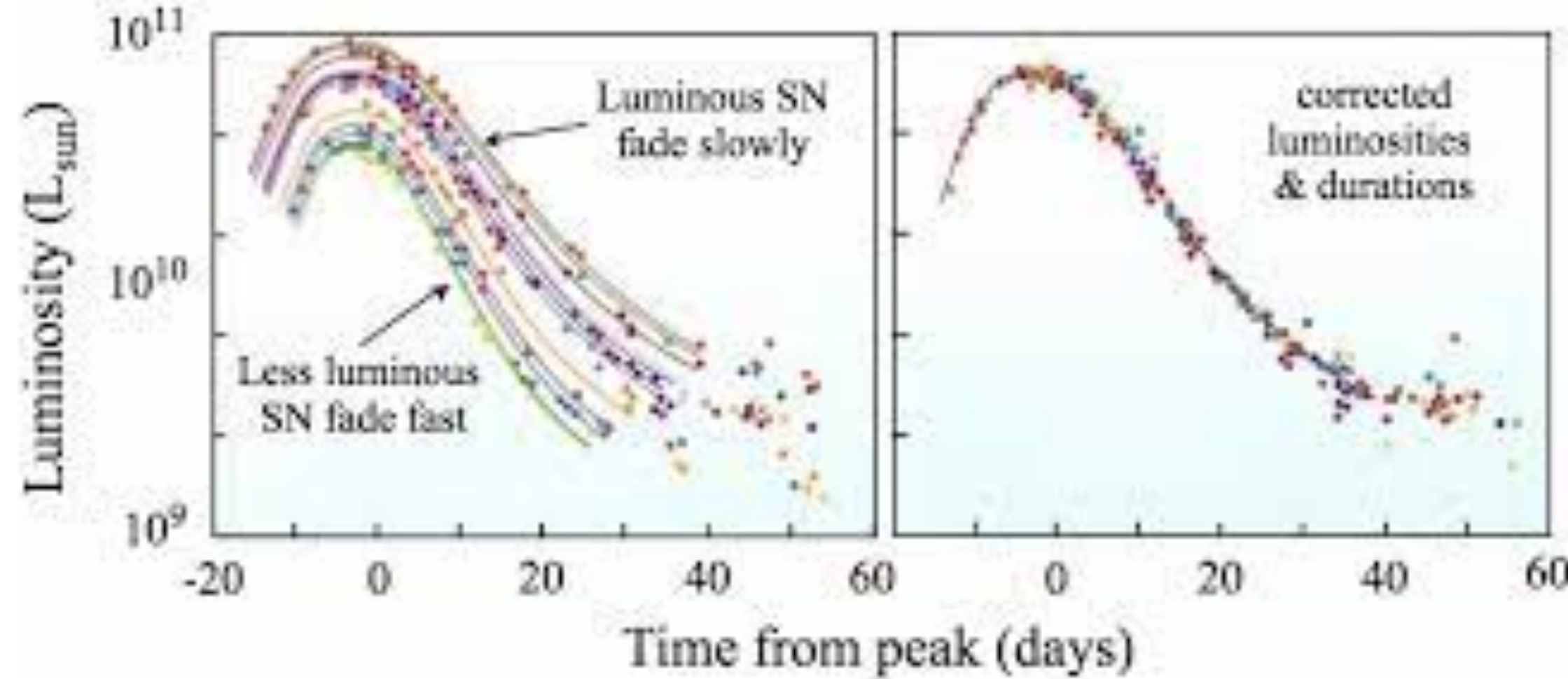
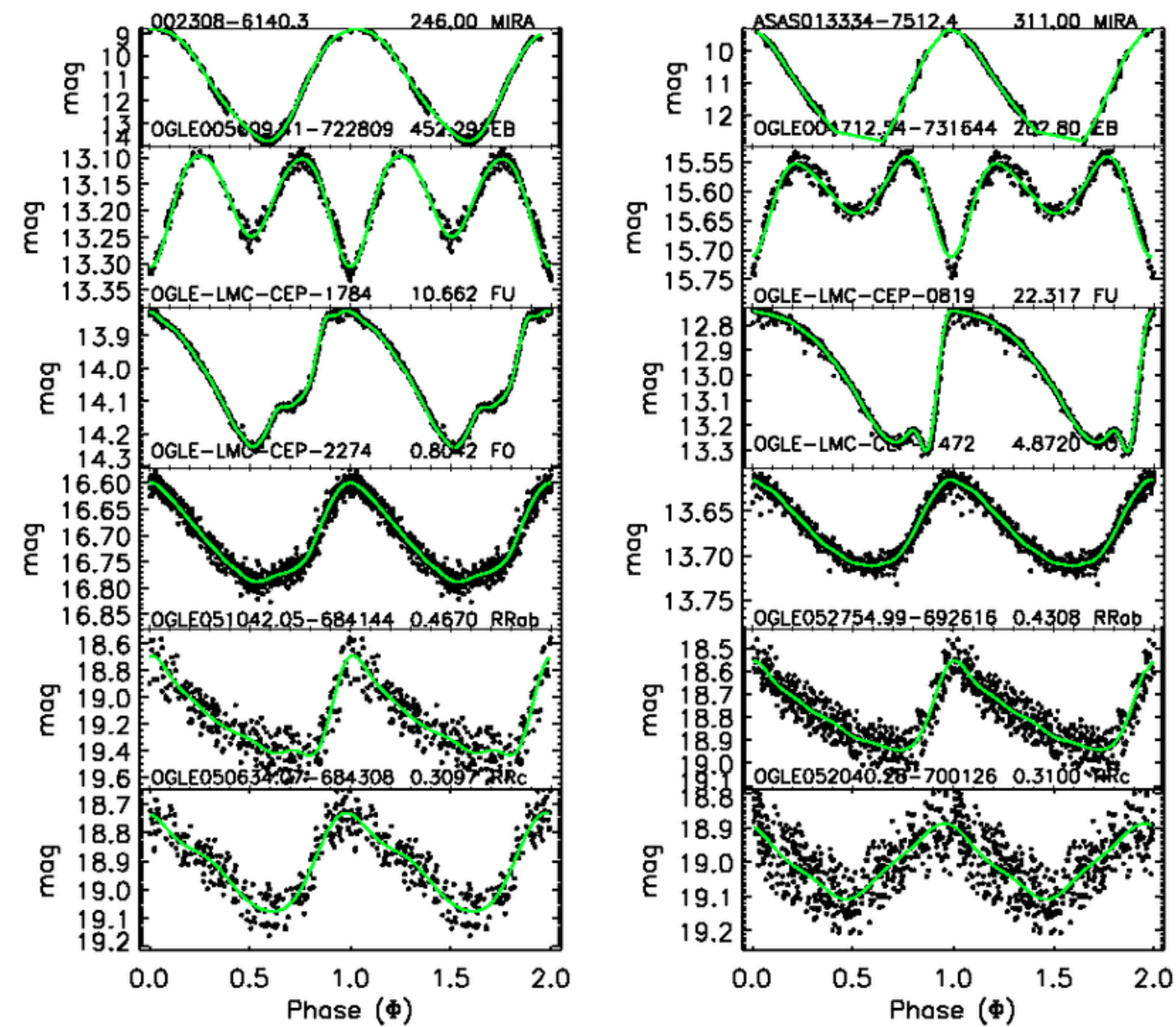


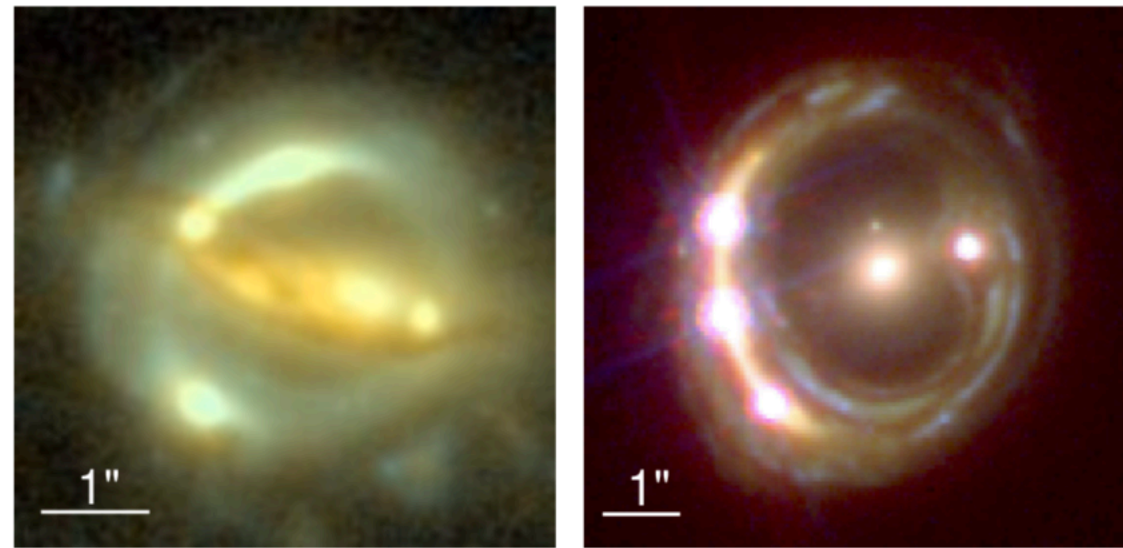
FIRST PEAK
Gravity and sonic motion
work together



C_l
Doppler
adiabatic
total

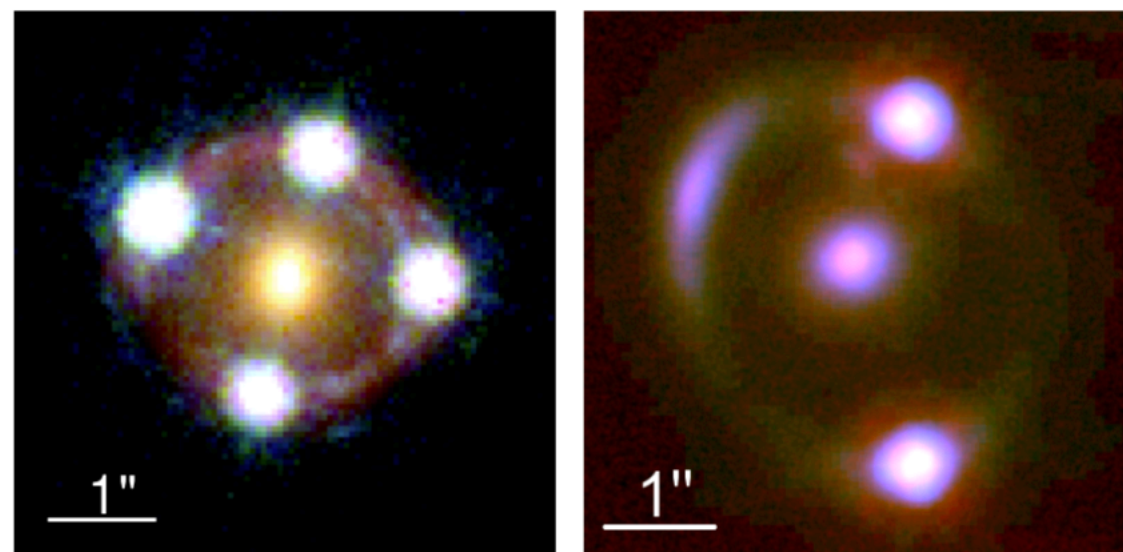






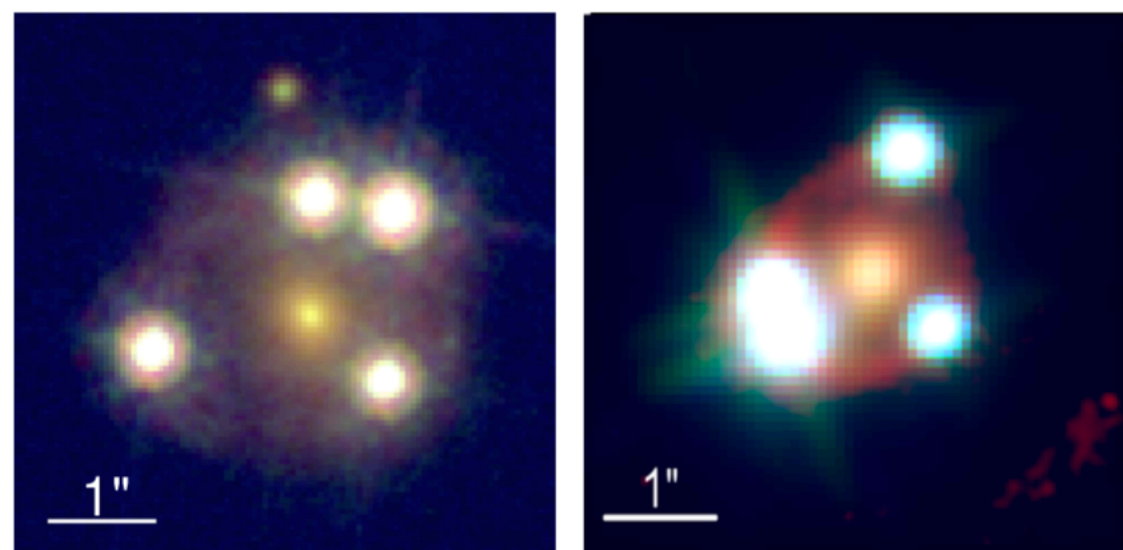
(a) B1608+656

(b) RXJ1131-1231



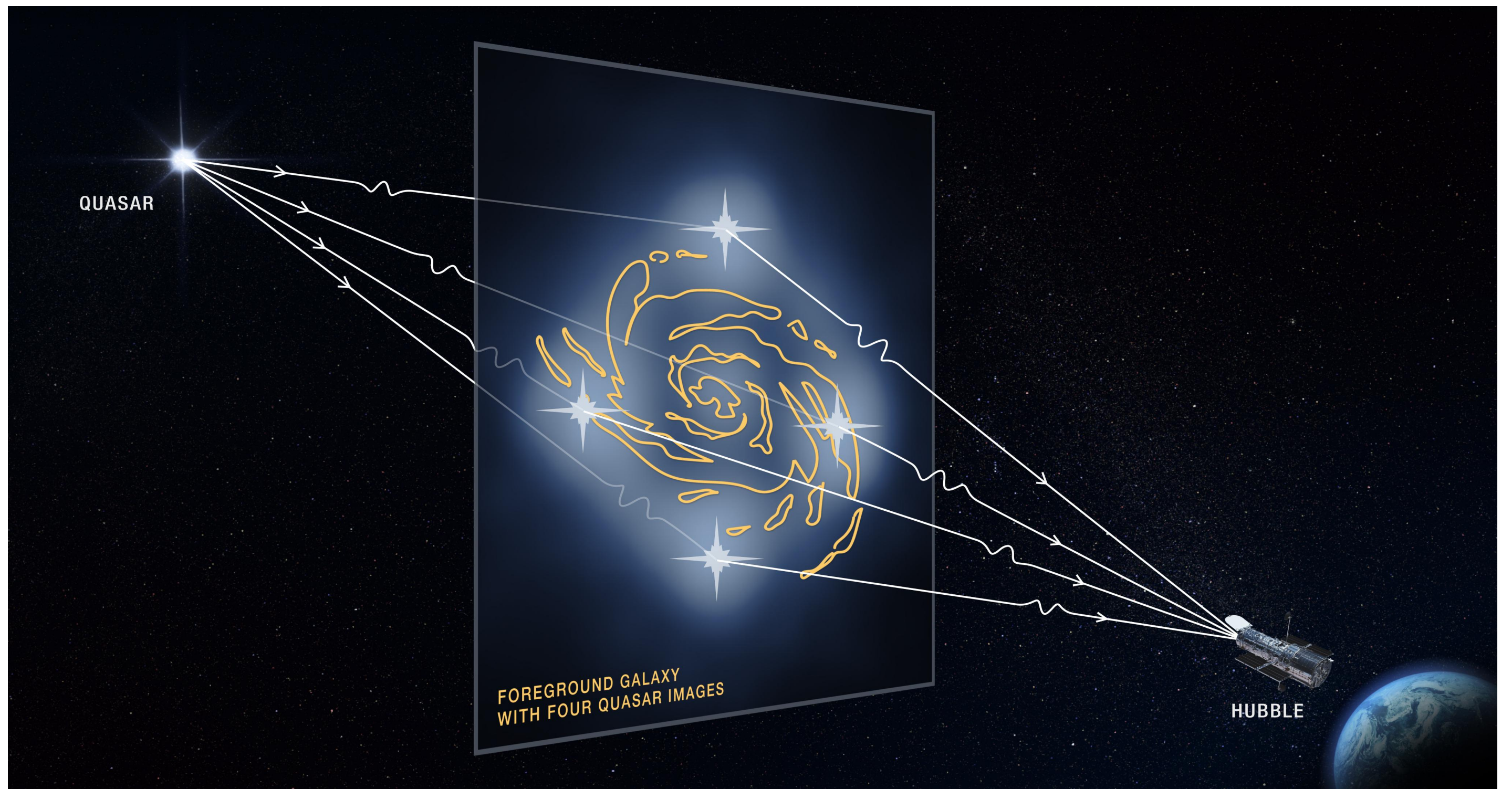
(c) HE 0435-1223

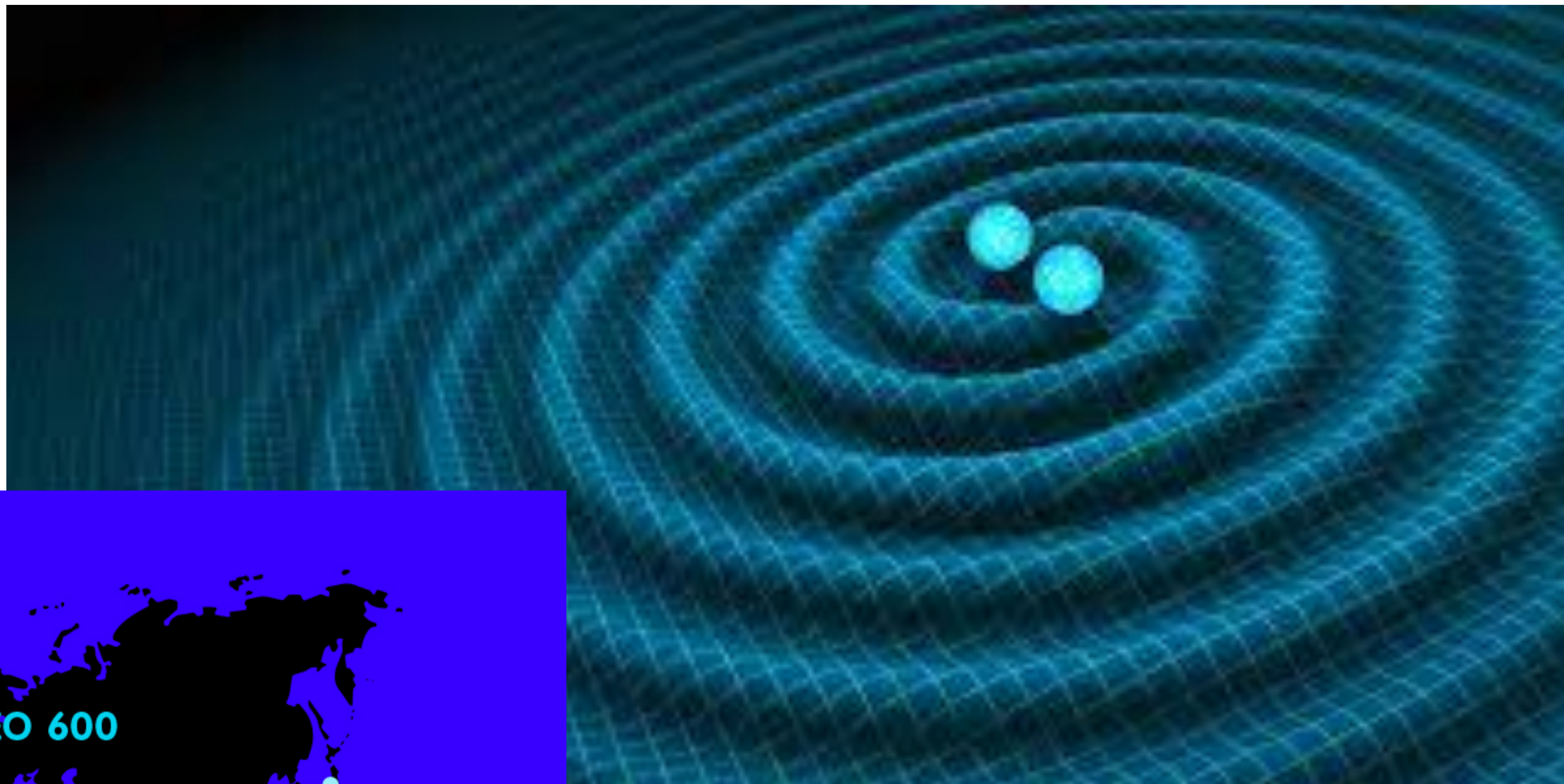
(d) SDSS 1206+4332



(e) WFI2033-4723

(f) PG 1115+080

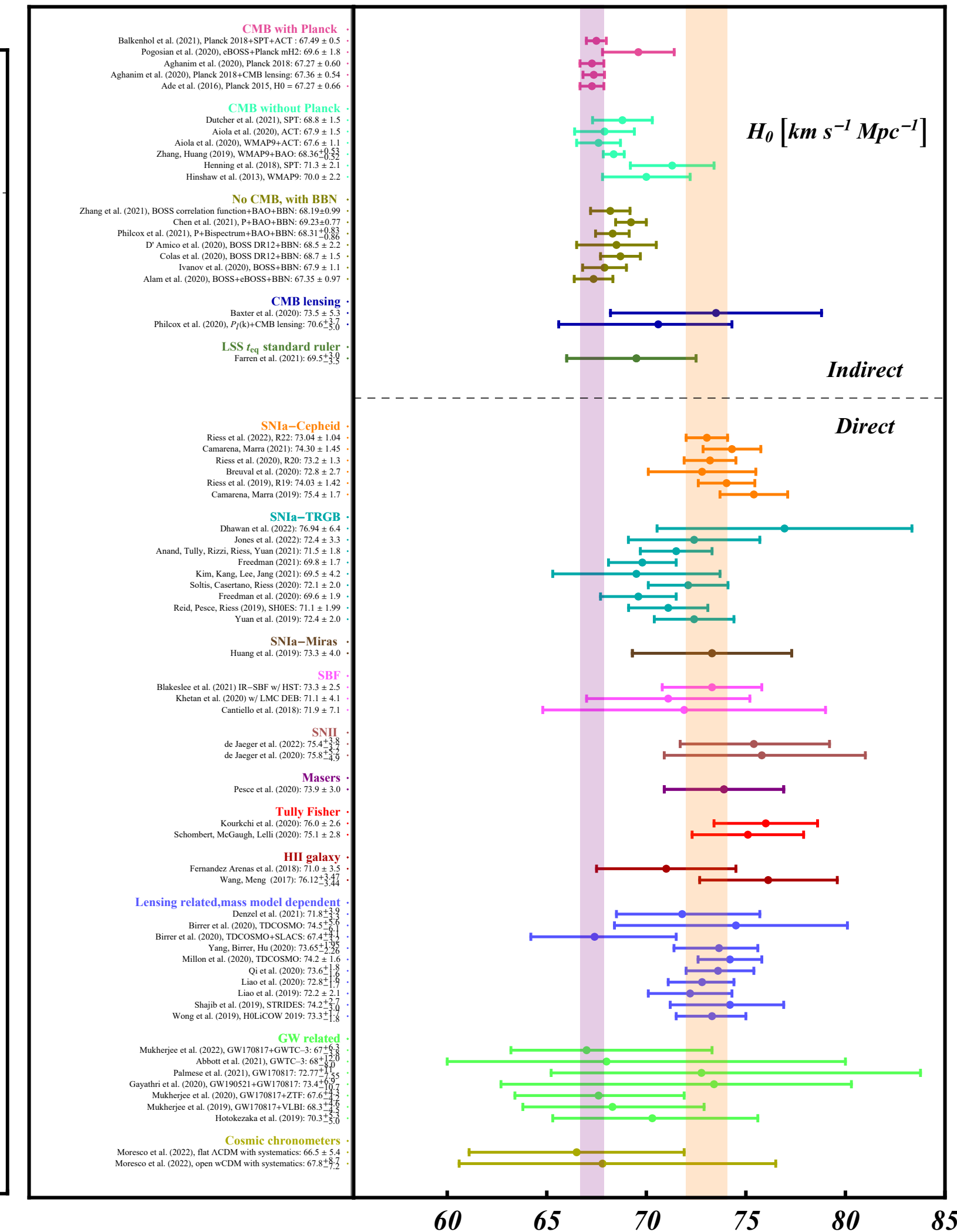
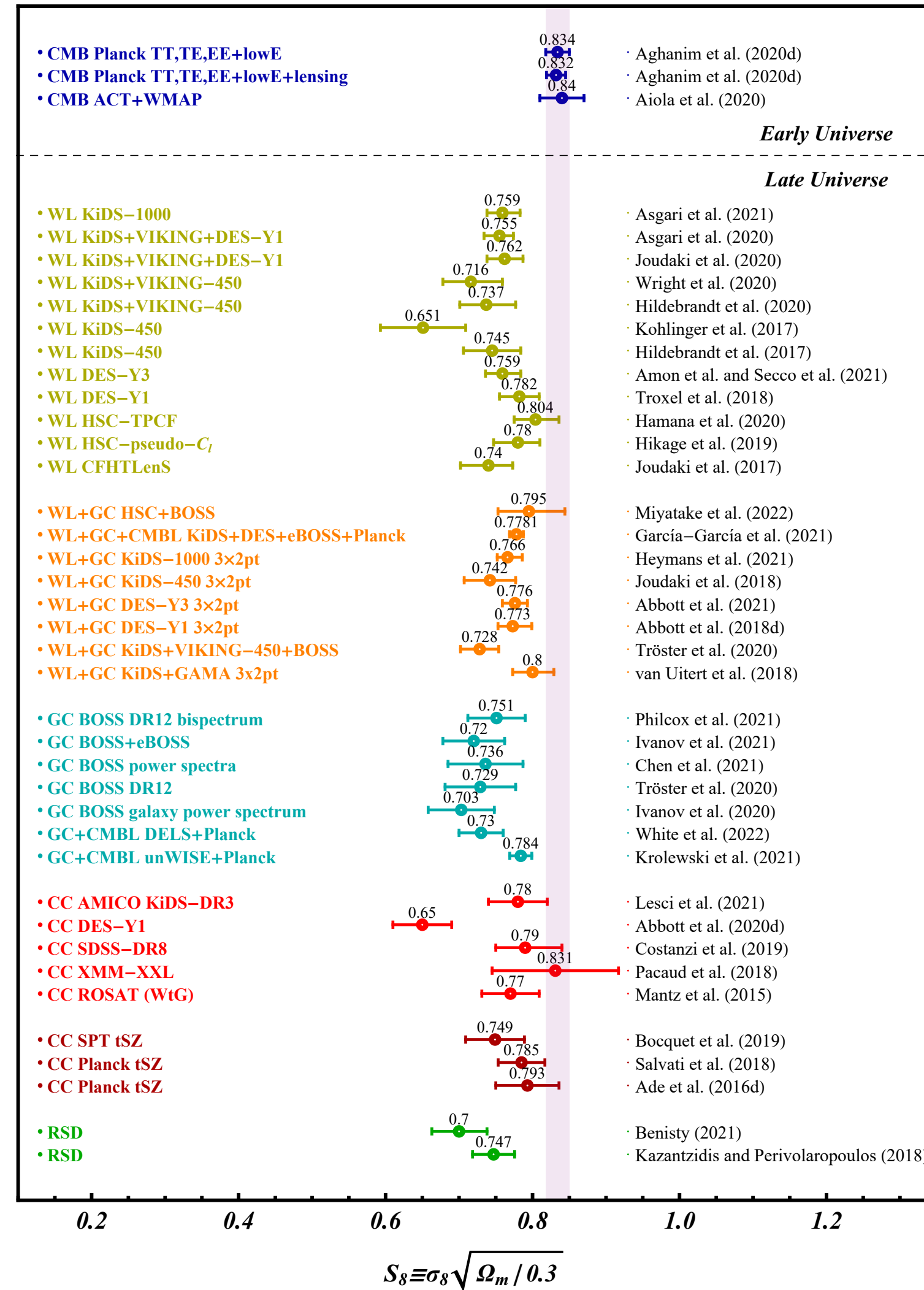




Cosmologie quelques grandes questions

- Quelle est l'histoire de formation et d'évolution de l'Univers ?
 - Quelle est la nature de l'Inflation et est-ce le meilleur modèle pour expliquer les perturbations primordiales ?
 - Quelle est la nature de l'énergie noire et est-ce le meilleur modèle pour expliquer l'accélération apparente tardive ?
- Quel est son contenu ?
 - Quelle est la nature de la matière noire ?
 - Combien y a-t-il de familles de neutrinos, quelle sont leurs masses et leur propriétés, y a-t-il d'autres reliques ?
- Comment s'organise la matière dans l'Univers ?
 - Quelle est l'influence des processus baryoniques sur la distribution de matière aux grandes échelles
 - Comment la matière se structure-t-elle dans les objets, galaxies et amas et quelle est l'histoire de formation des galaxies ?

Notre modèle est-il complet ?



Structuration de la communauté

- **CNRS**

- INSU
 - Programme Nationaux : PNCG, PNGRAM, PNHE
- IN2P3
 - Astroparticule et cosmologie, ondes gravitationnelles, neutrinos
- INP
- *GDR CoPHY*

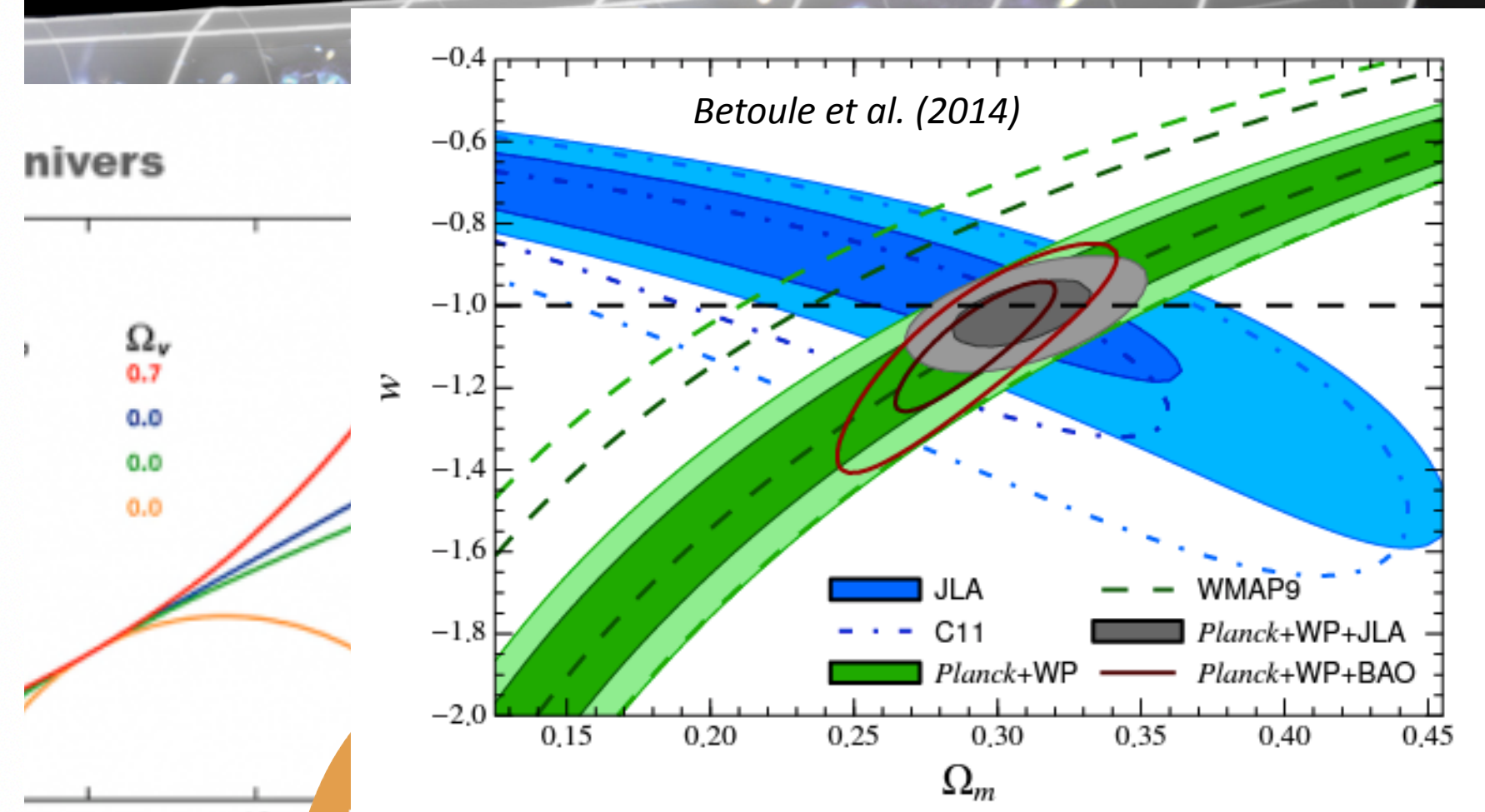
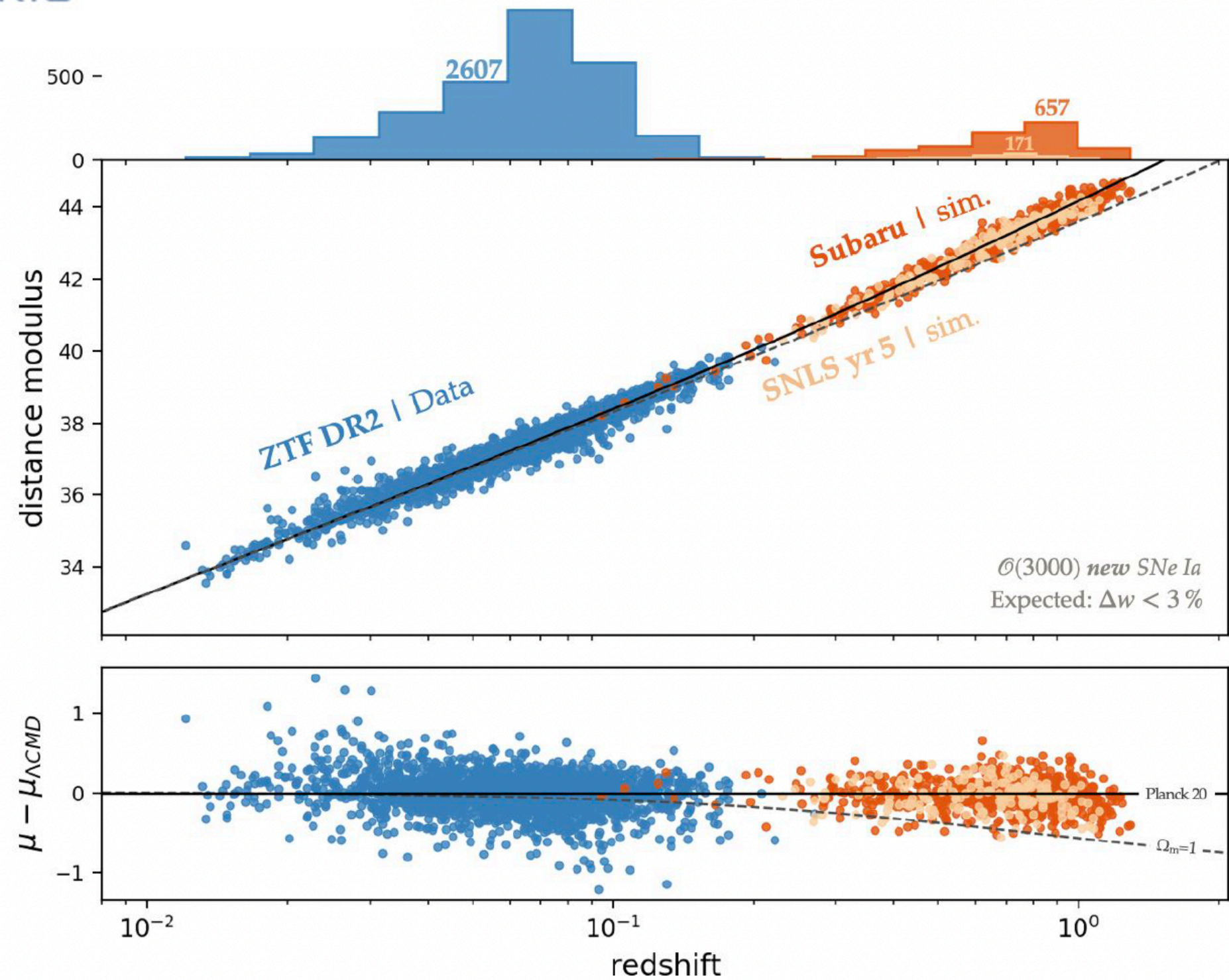
- **CNU 34 & 29**

- **à Sorbonne Université**

- IAP, LPNHE, LPTHE, LERMA, LESIA, LPENS, SYRTE, LKB
 - *IAP, LPNHE, LPTHE, L3@Obs, L2@Obs, LPENS, L1@Obs, LKB*
- Enseignement
 - 1 module L3 + 1PAD ~40 étudiants
 - 2 modules M1 (dont un anglais) + 1 PAD ~30 étudiants
 - M2 AAIS, M2 NPAC
 - ED A&A (1/3 soutenances cosmo, i.e. 3/an), ED PIF (+ ED Step'Up)

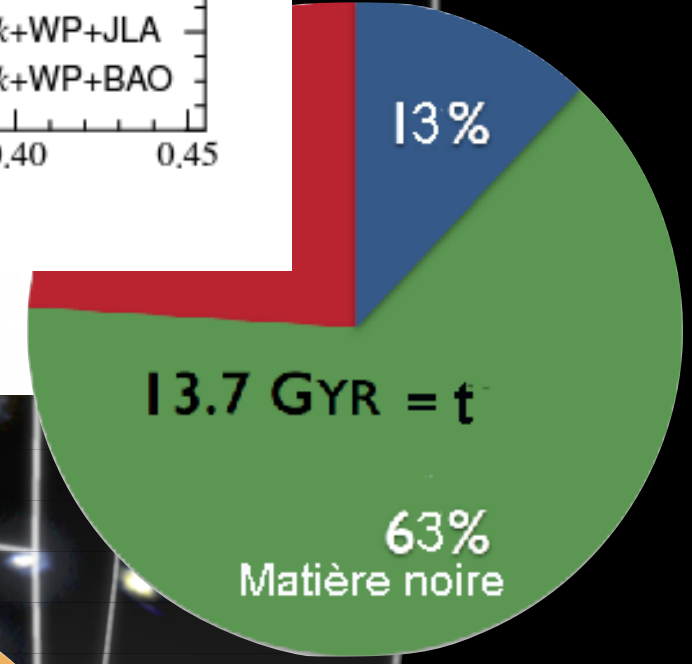
- **Ressources**

- classiques : ERC, ANR, CNRS, PN...
- CNES, pour les projets spatiaux
- DIM-ACAV, DIM-Origines
- ILP, IPI



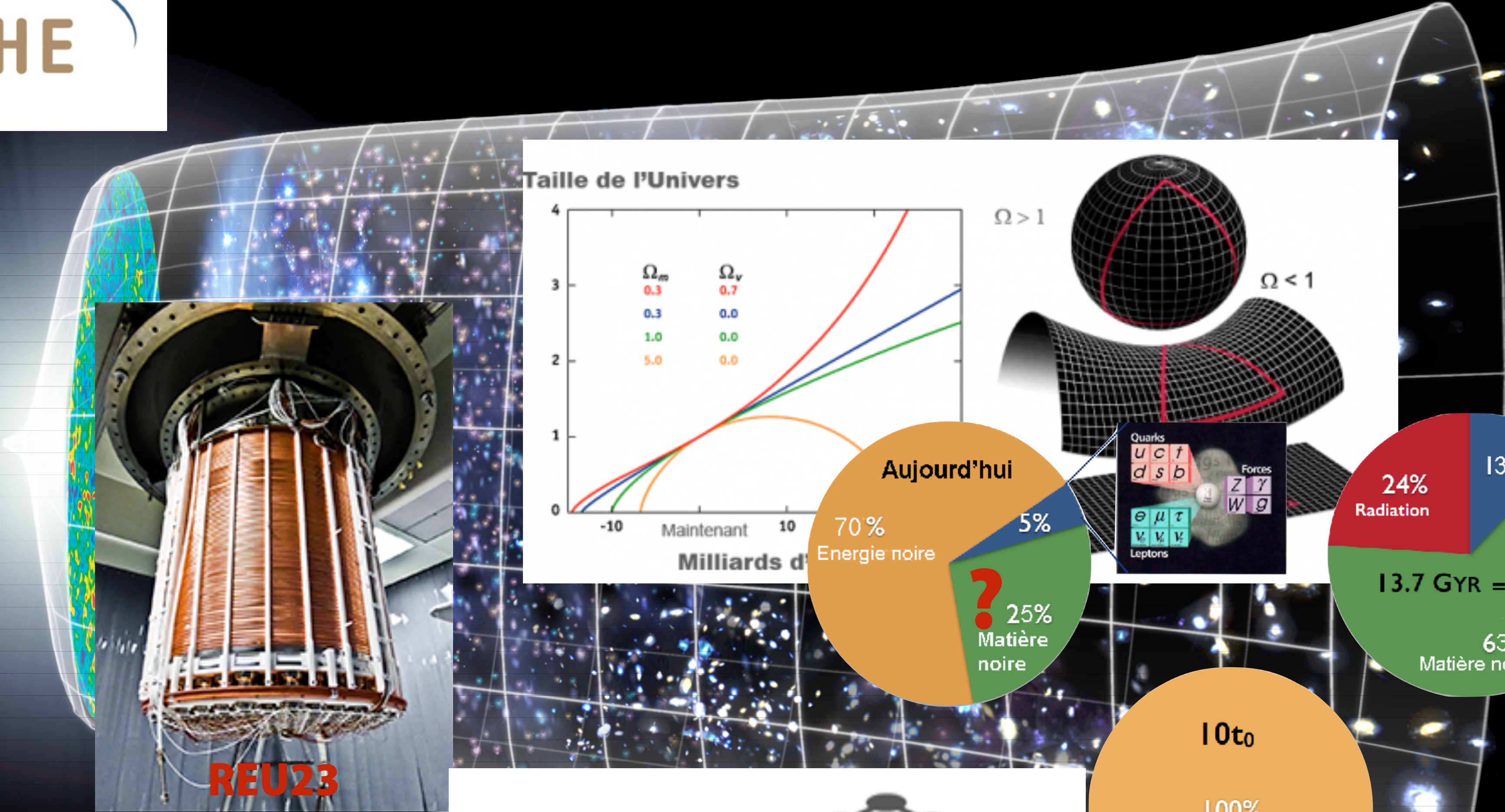
Maintenant 10 milliards d'années

Leptons

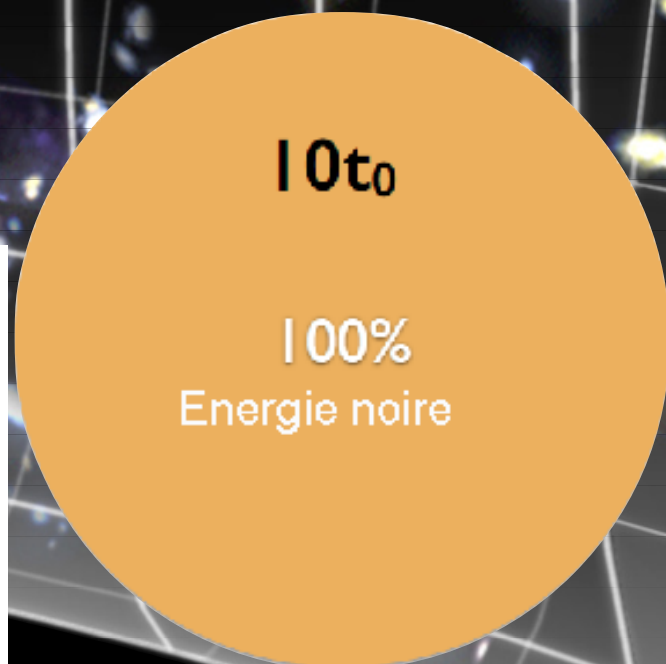
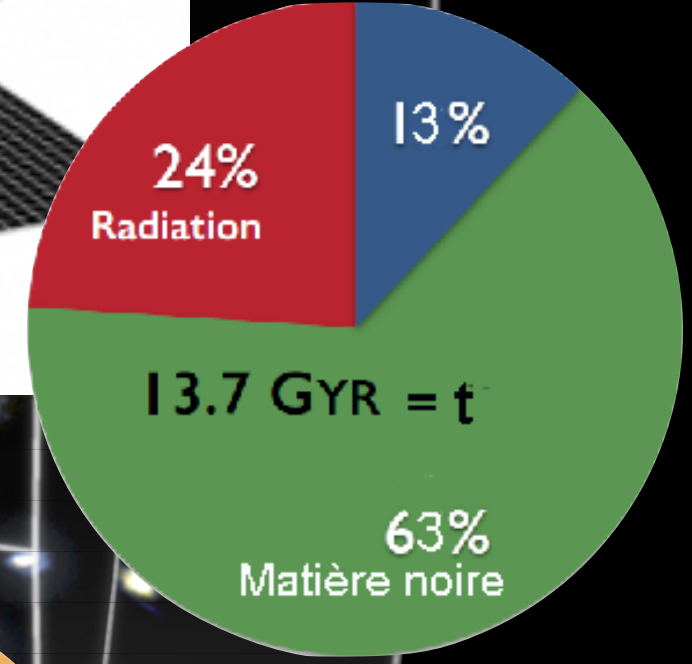
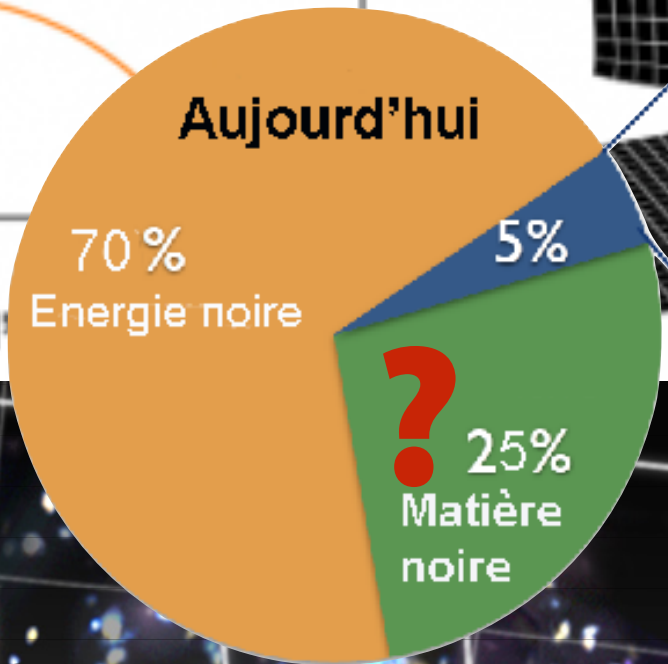
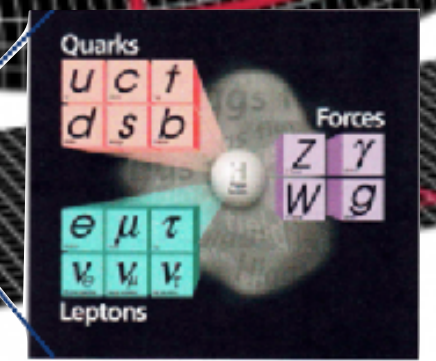
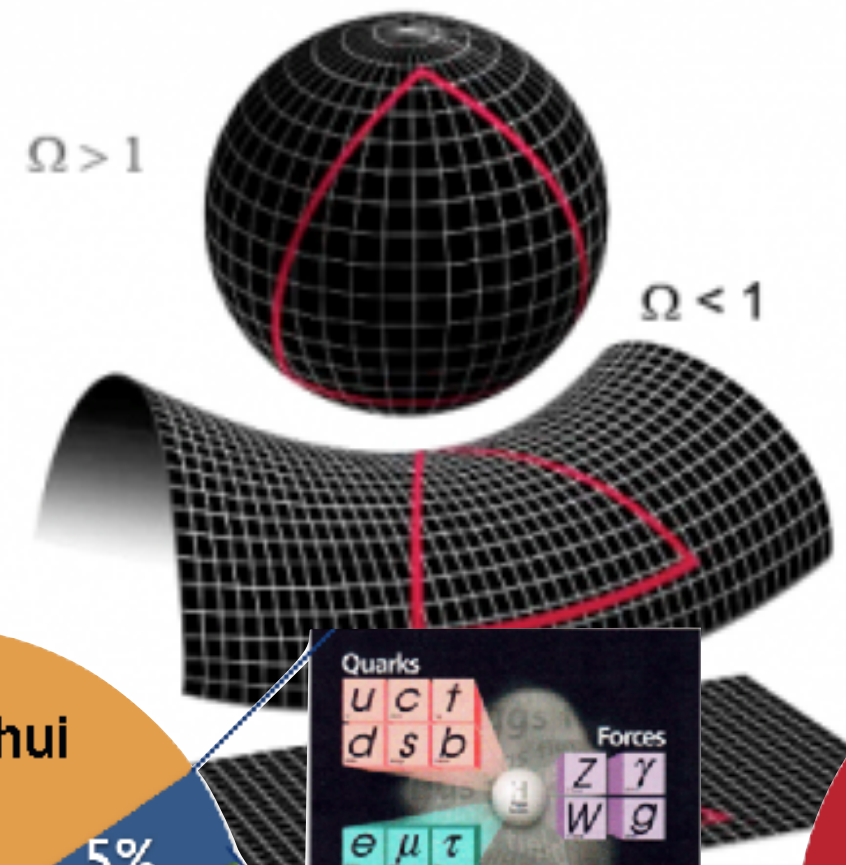
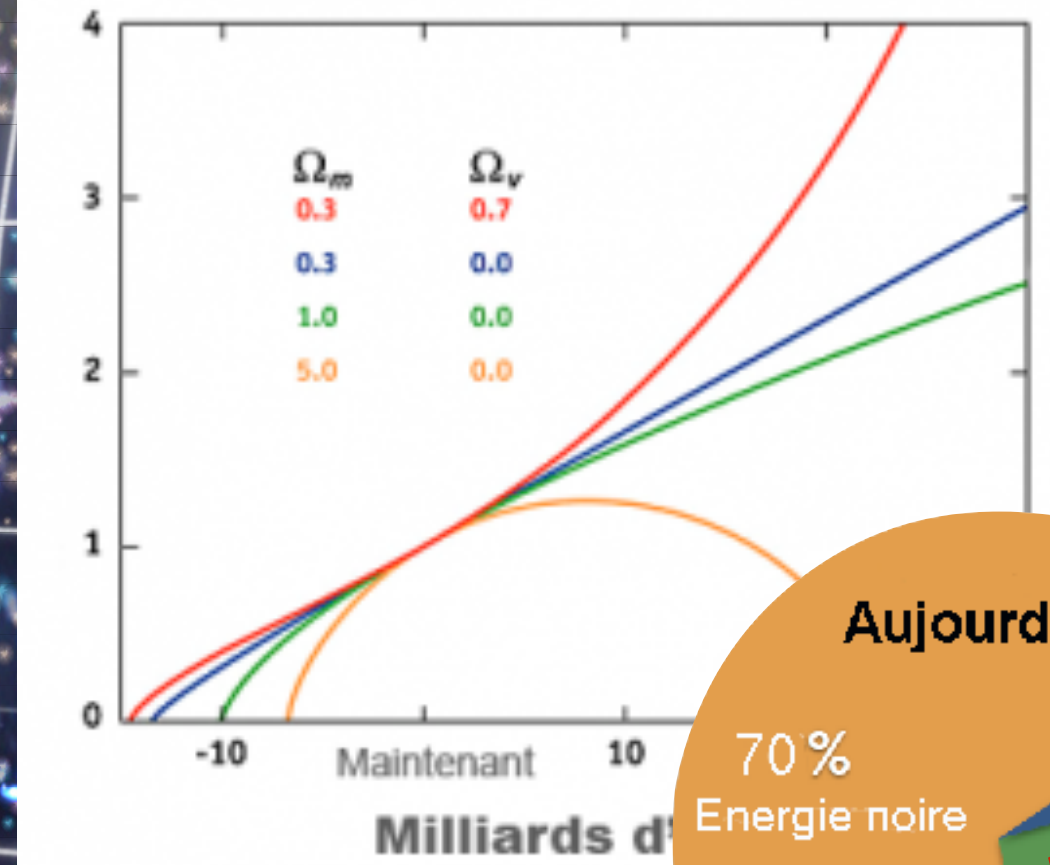


$$H^2(t) = \frac{8\pi G}{3c^2} \rho(t) - \frac{kc^2}{a^2(t)} + \frac{\Lambda c^2}{3}$$

$$\frac{\ddot{a}(t)}{a(t)} = -\frac{4\pi G}{3c^2} \left(\rho(t) + \frac{3p(t)}{c^2} \right) + \frac{\Lambda c^2}{3}$$



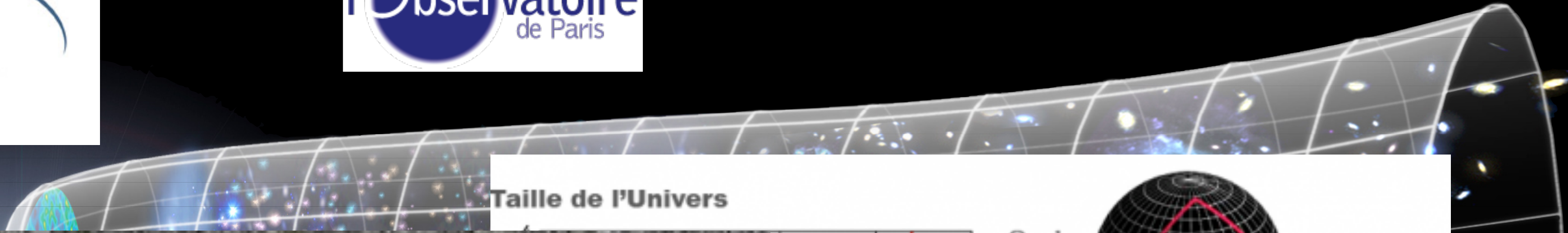
Taille de l'Univers



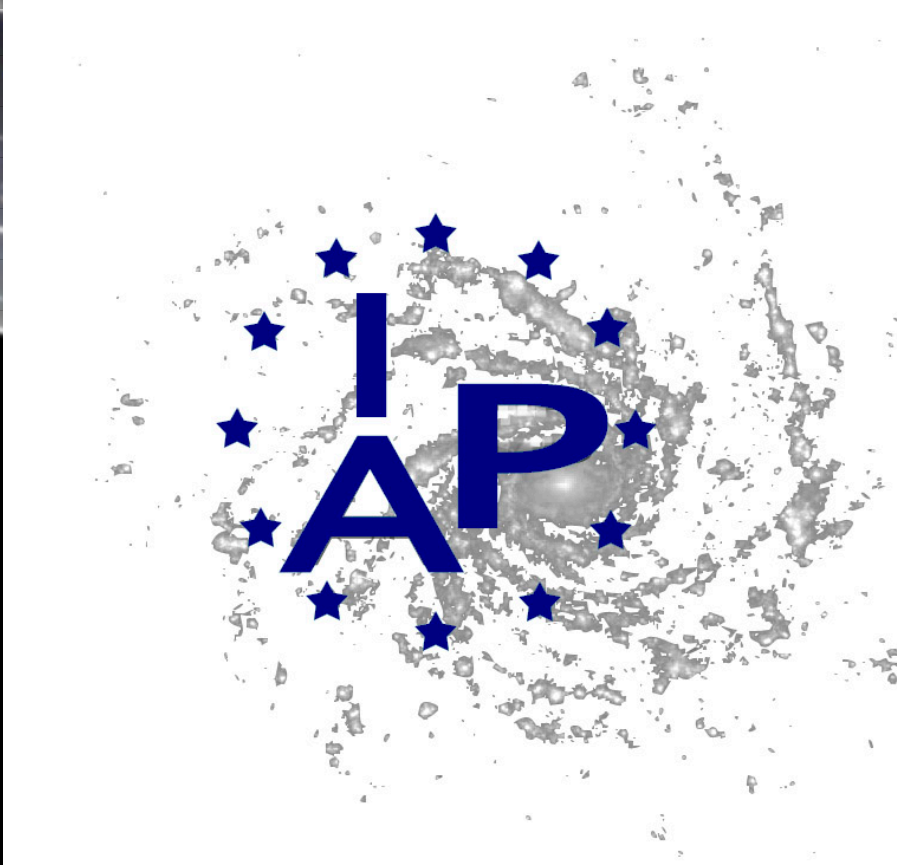
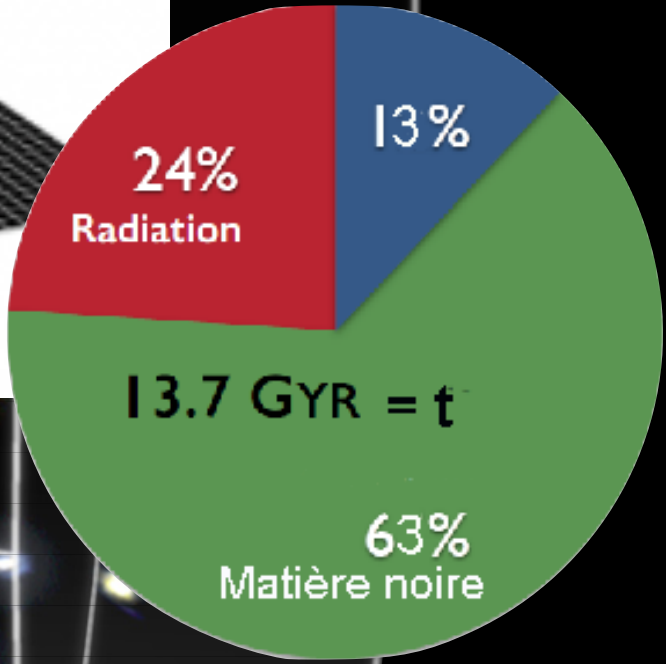
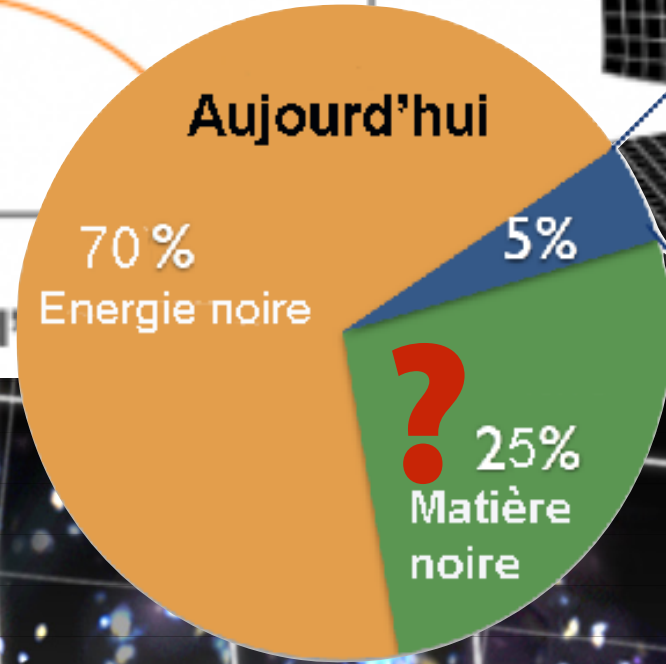
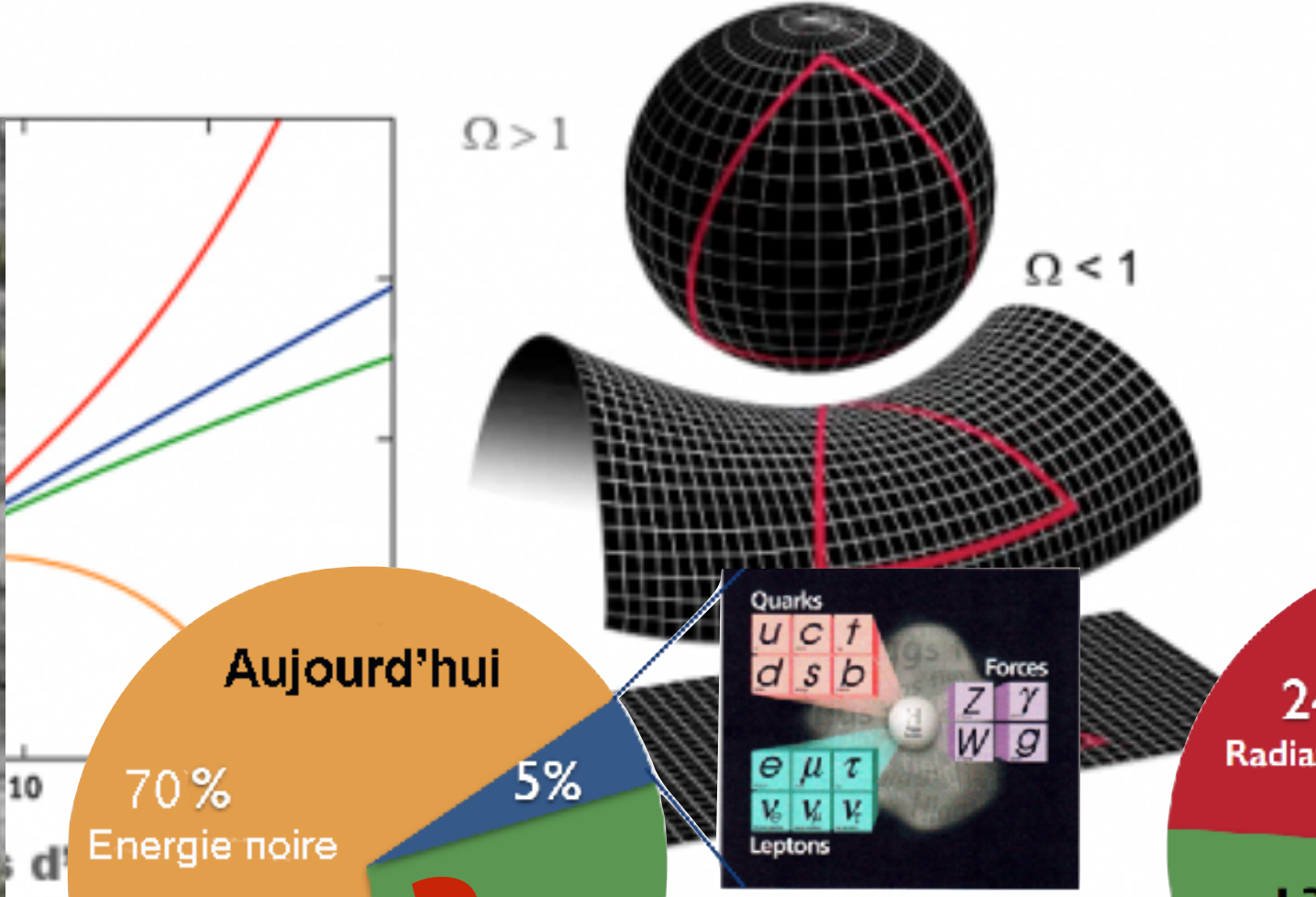
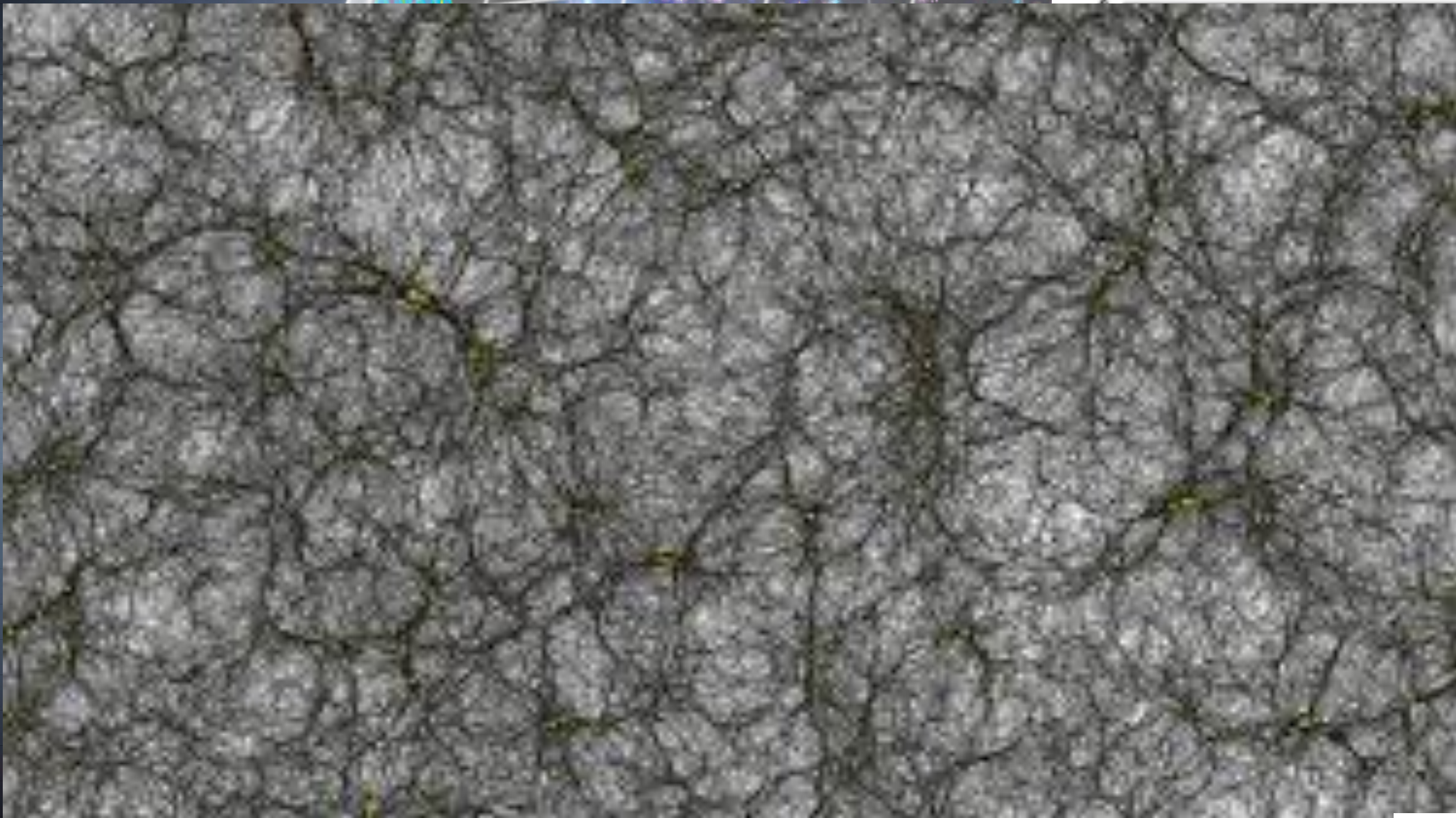
$$H^2(t) = \frac{8\pi G}{3c^2} \rho(t) - \frac{kc^2}{a^2(t)} + \frac{\Lambda c^2}{3}$$

$$\frac{\ddot{a}(t)}{a(t)} = -\frac{4\pi G}{3c^2} \left(\rho(t) + \frac{3p(t)}{c^2} \right) + \frac{\Lambda c^2}{3}$$

REU23

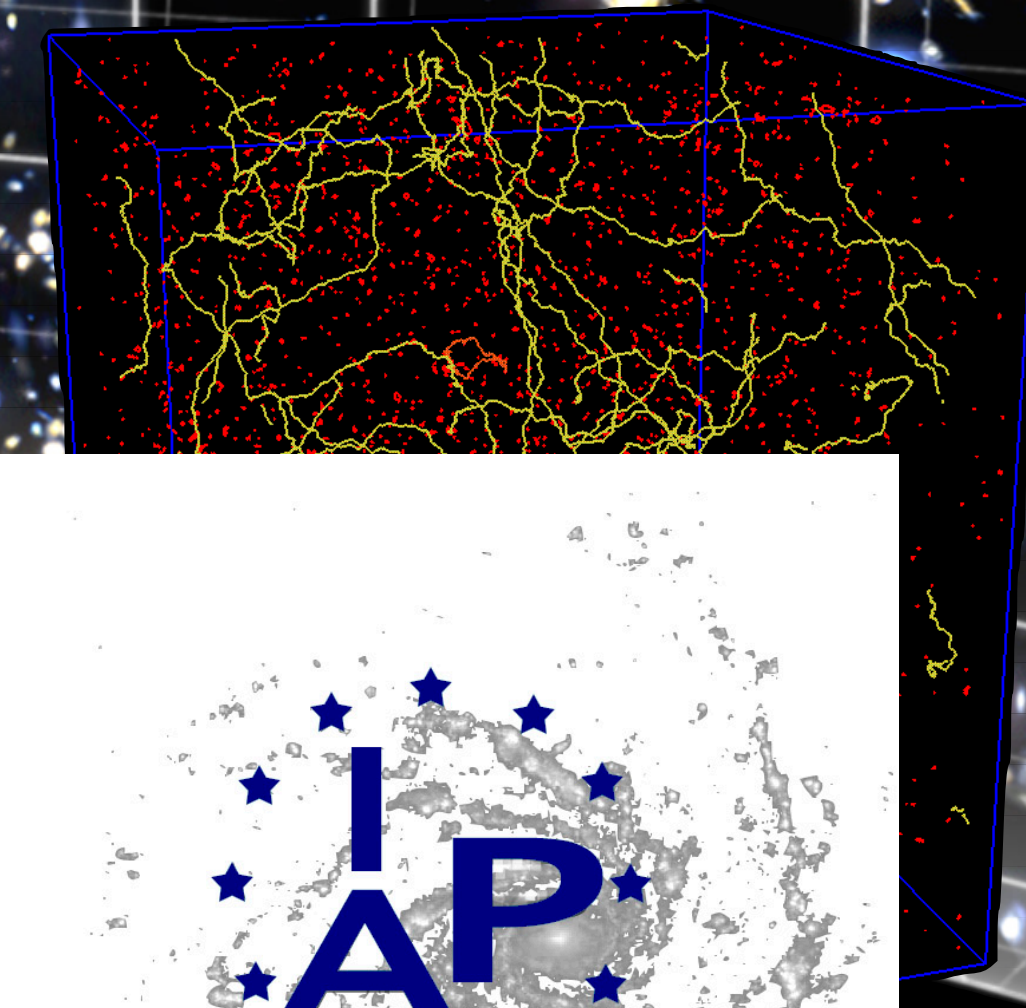
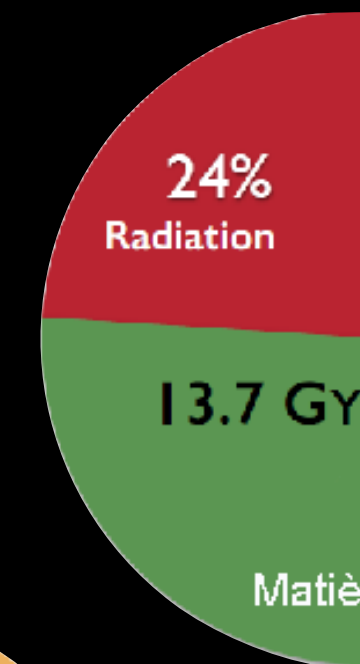
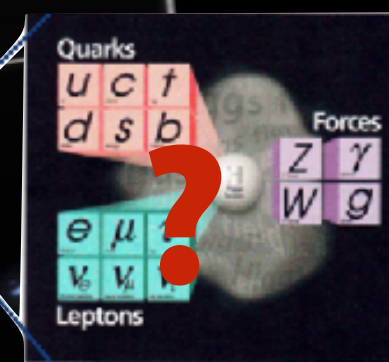
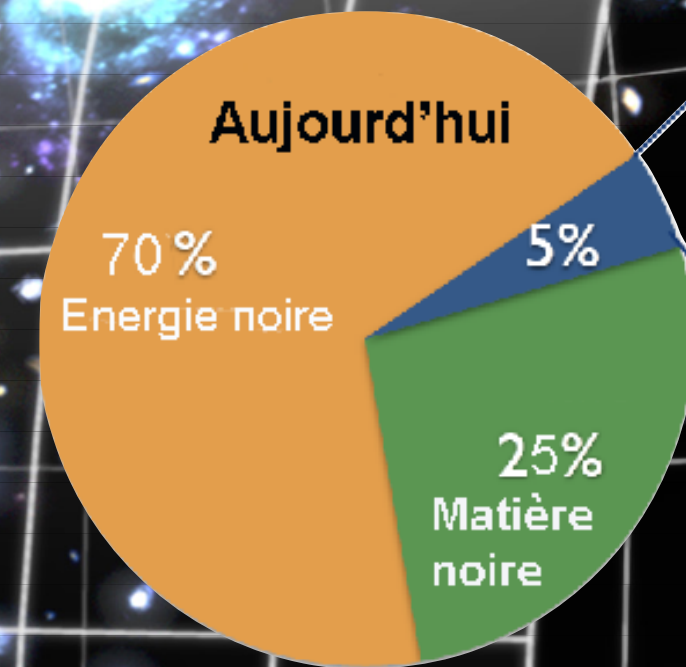
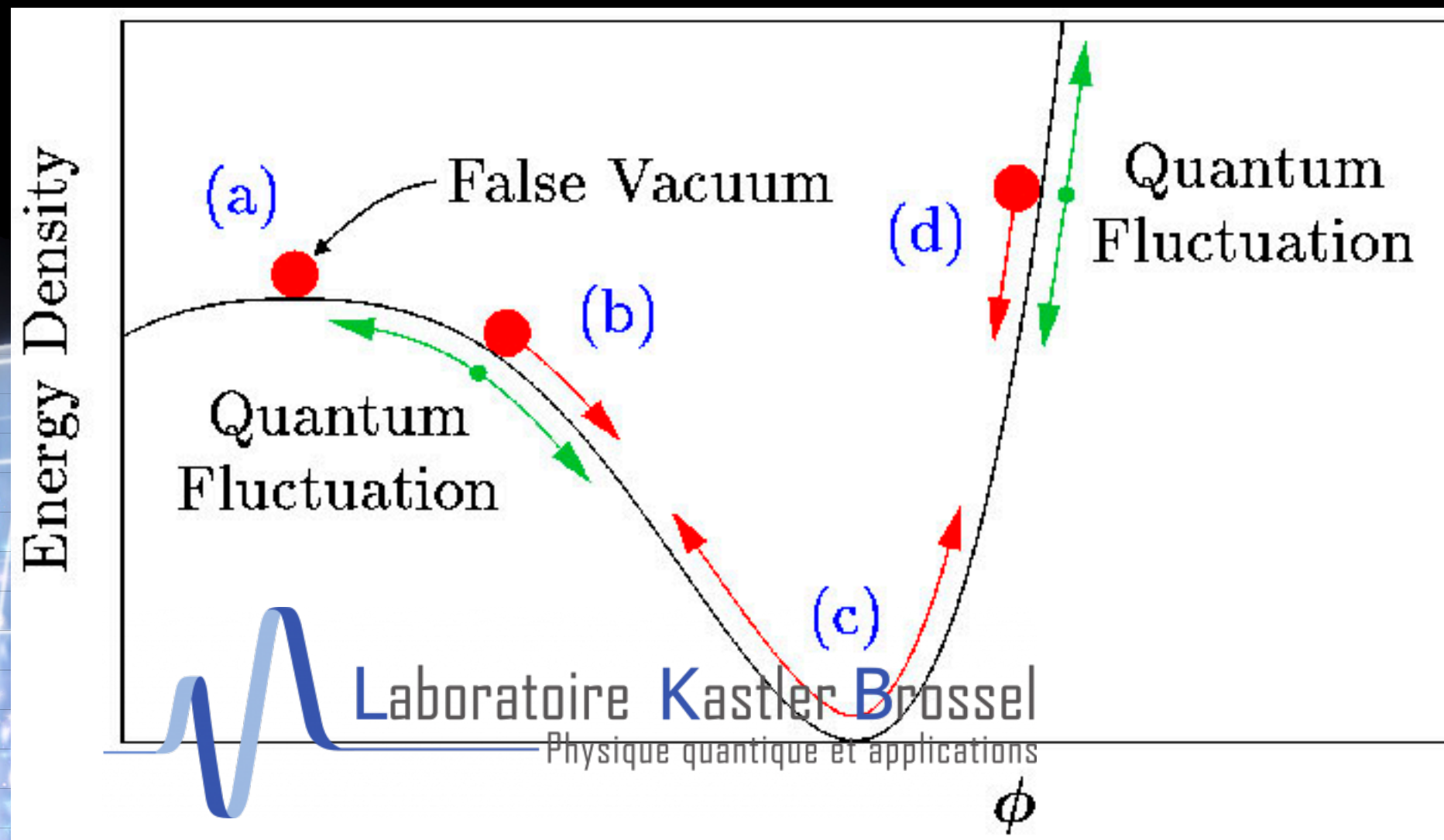
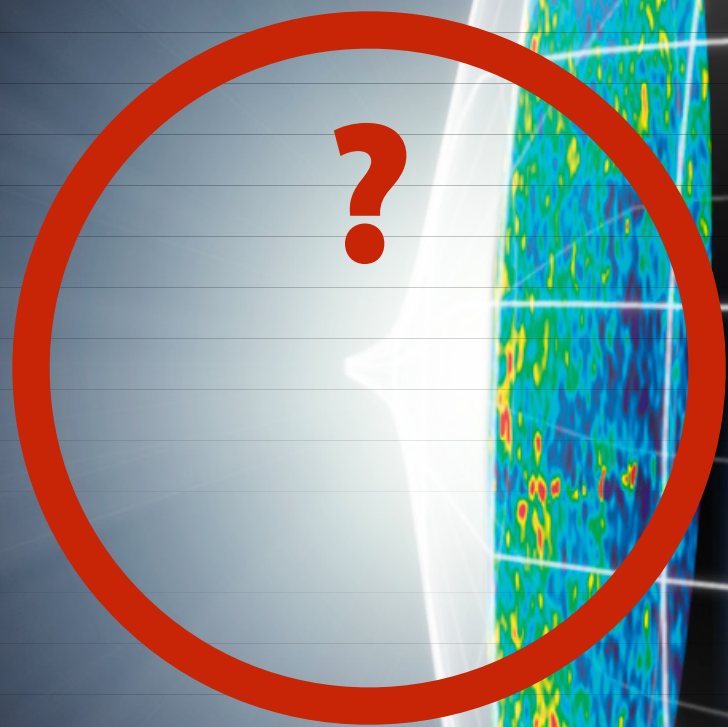
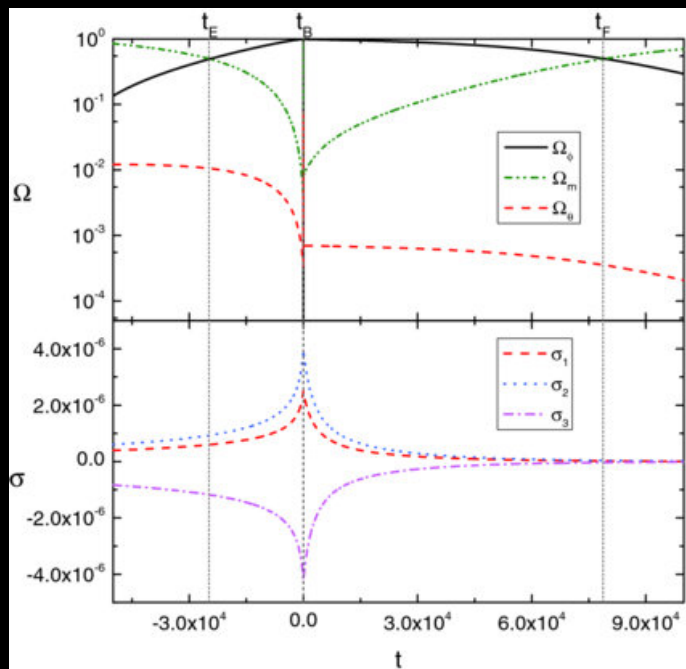


Taille de l'Univers



$$H^2(t) = \frac{8\pi G}{3c^2} \rho(t) - \frac{kc^2}{a^2(t)} + \frac{\Lambda c^2}{3}$$

$$\frac{\ddot{a}(t)}{a(t)} = -\frac{4\pi G}{3c^2} \left(\rho(t) + \frac{3p(t)}{c^2} \right) + \frac{\Lambda c^2}{3}$$

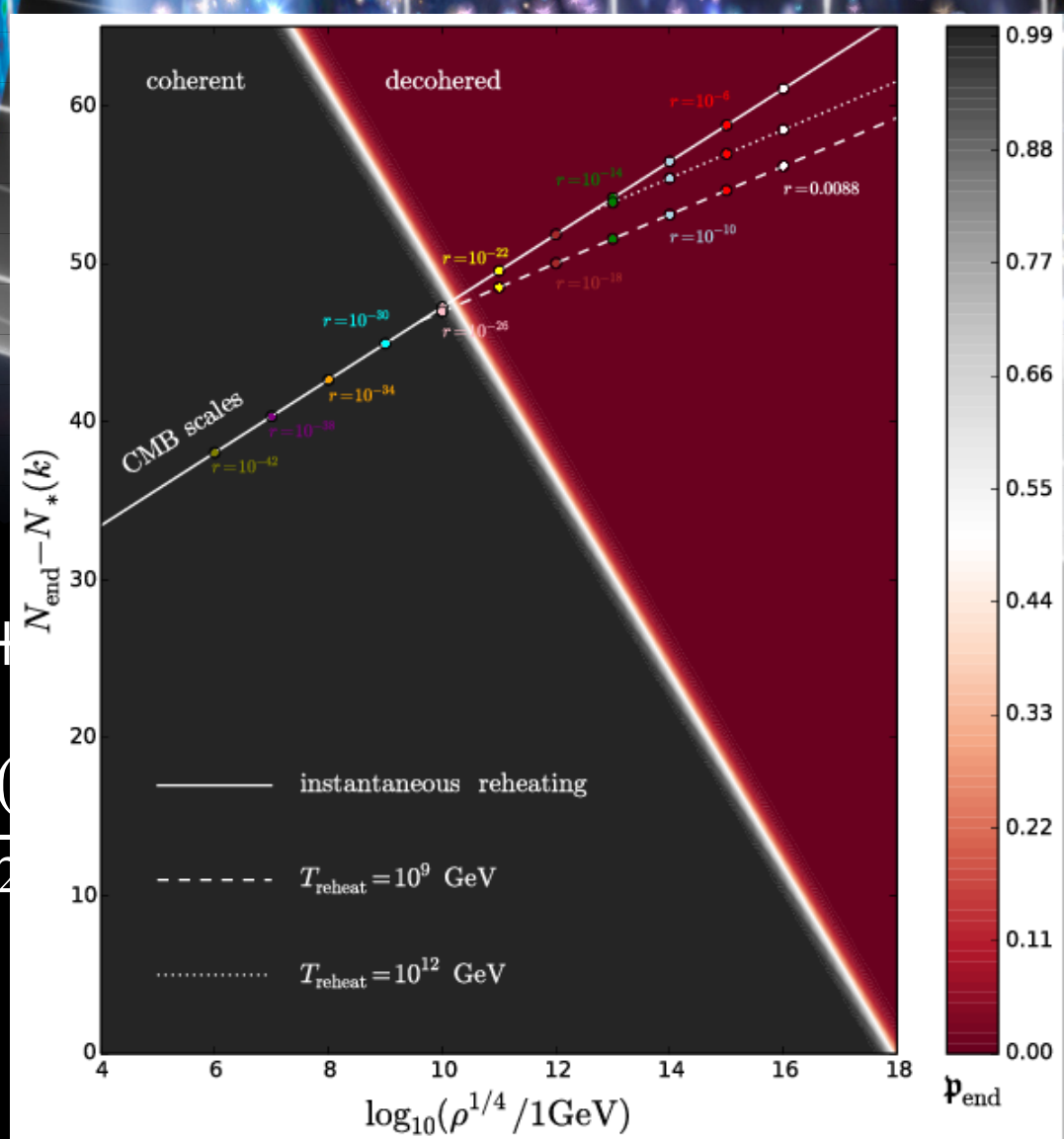


LPENS

LABORATOIRE DE PHYSIQUE DE L'ÉCOLE NORMALE SUPÉRIEURE

$$H^2(t) = \frac{8\pi G}{3c^2} \rho(t) - \frac{kc^2}{a^2(t)}$$

$$\frac{\ddot{a}(t)}{a(t)} = -\frac{4\pi G}{3c^2} \left(\rho(t) + \frac{3p(t)}{c^2} \right)$$



LPTHE
LABORATOIRE DE PHYSIQUE THEORIQUE ET HAUTES ENERGIES



LPENS

LABORATOIRE DE PHYSIQUE DE L'ÉCOLE NORMALE SUPÉRIEURE

Light Relics

Mass (eV)

10⁻³⁰ 10⁻²⁷ 10⁻²⁴ 10⁻²¹ 10⁻¹⁸ 10⁻¹⁵ 10⁻¹² 10⁻⁹ 10⁻⁶ 10⁻³ 1 10³ 10⁶ 10⁹ 10¹² 10¹⁵

Ultralight Axions

Axion DM photon coupling

Neutrino Mass & Warm DM

Axion DM Isocurvature

DM-baryon scattering

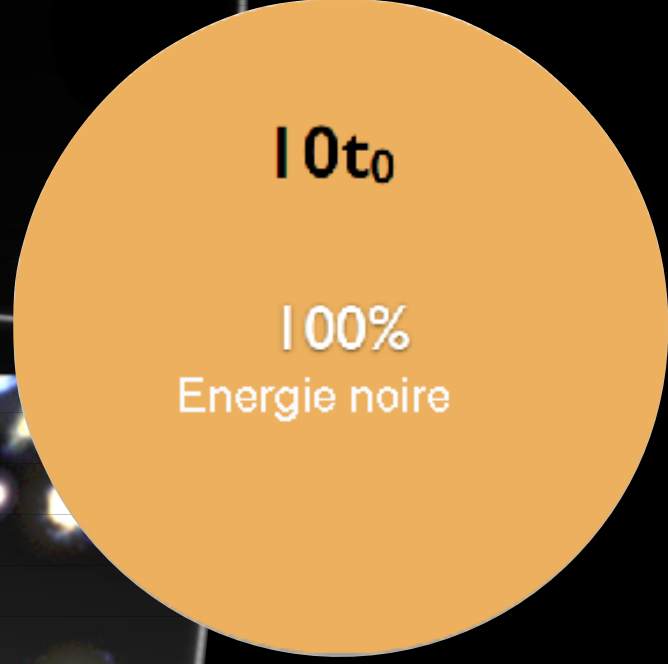
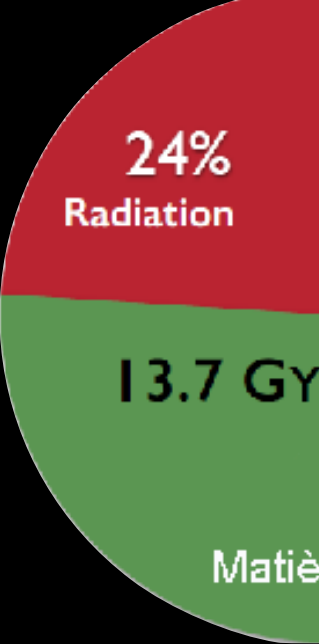
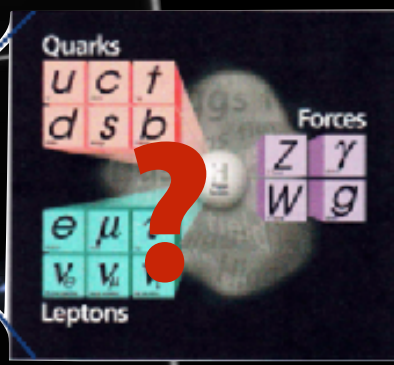
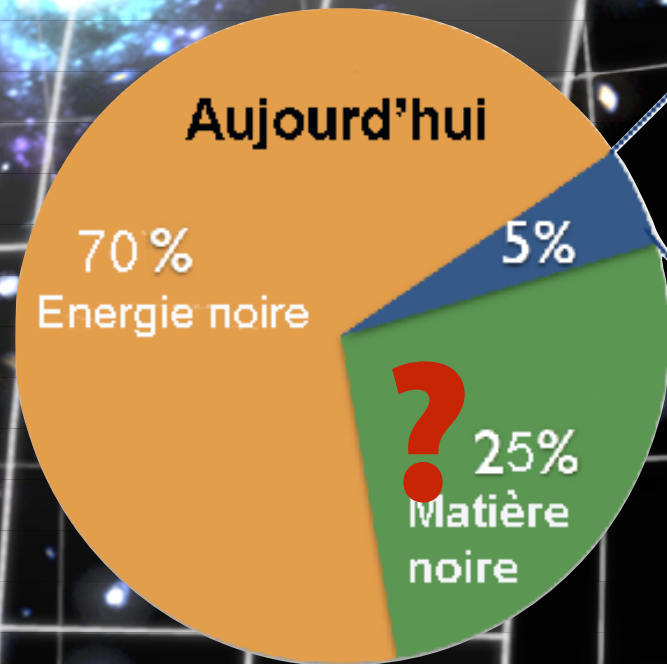
Primary CMB

Low-*l* CMB

CMB lensing

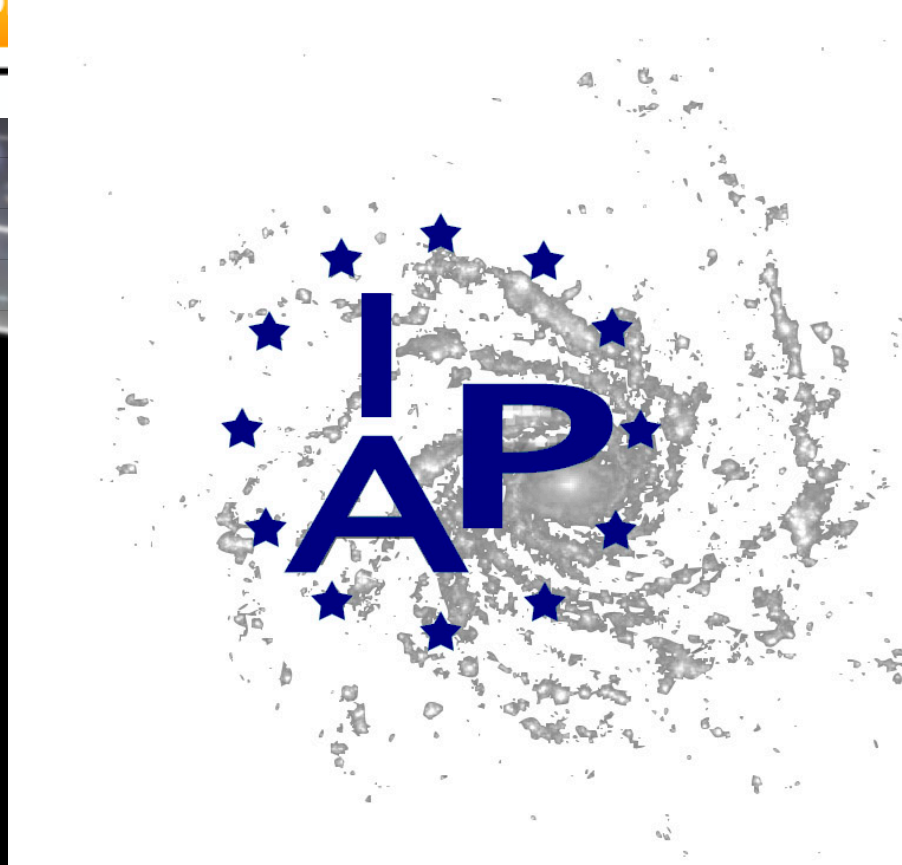
CMB modulation

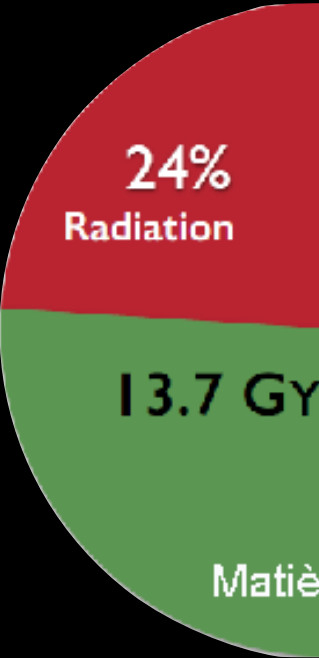
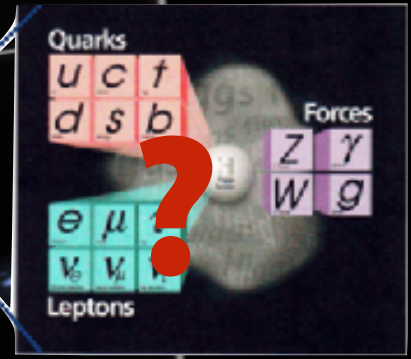
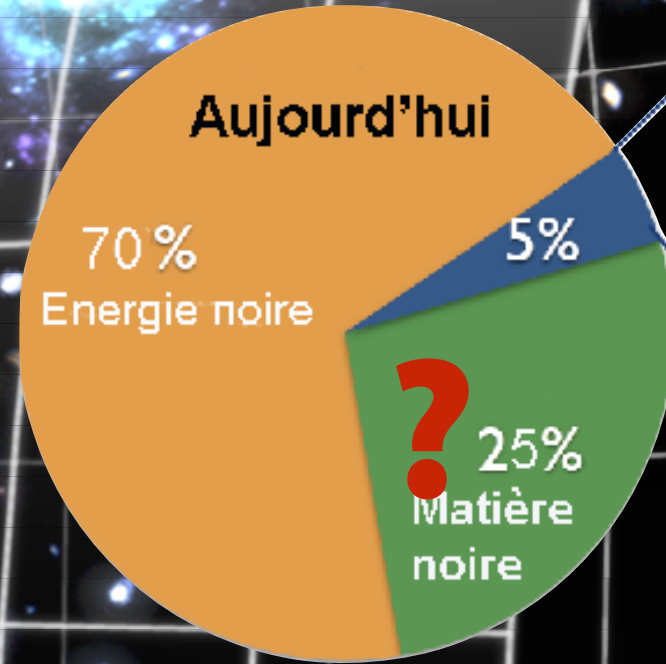
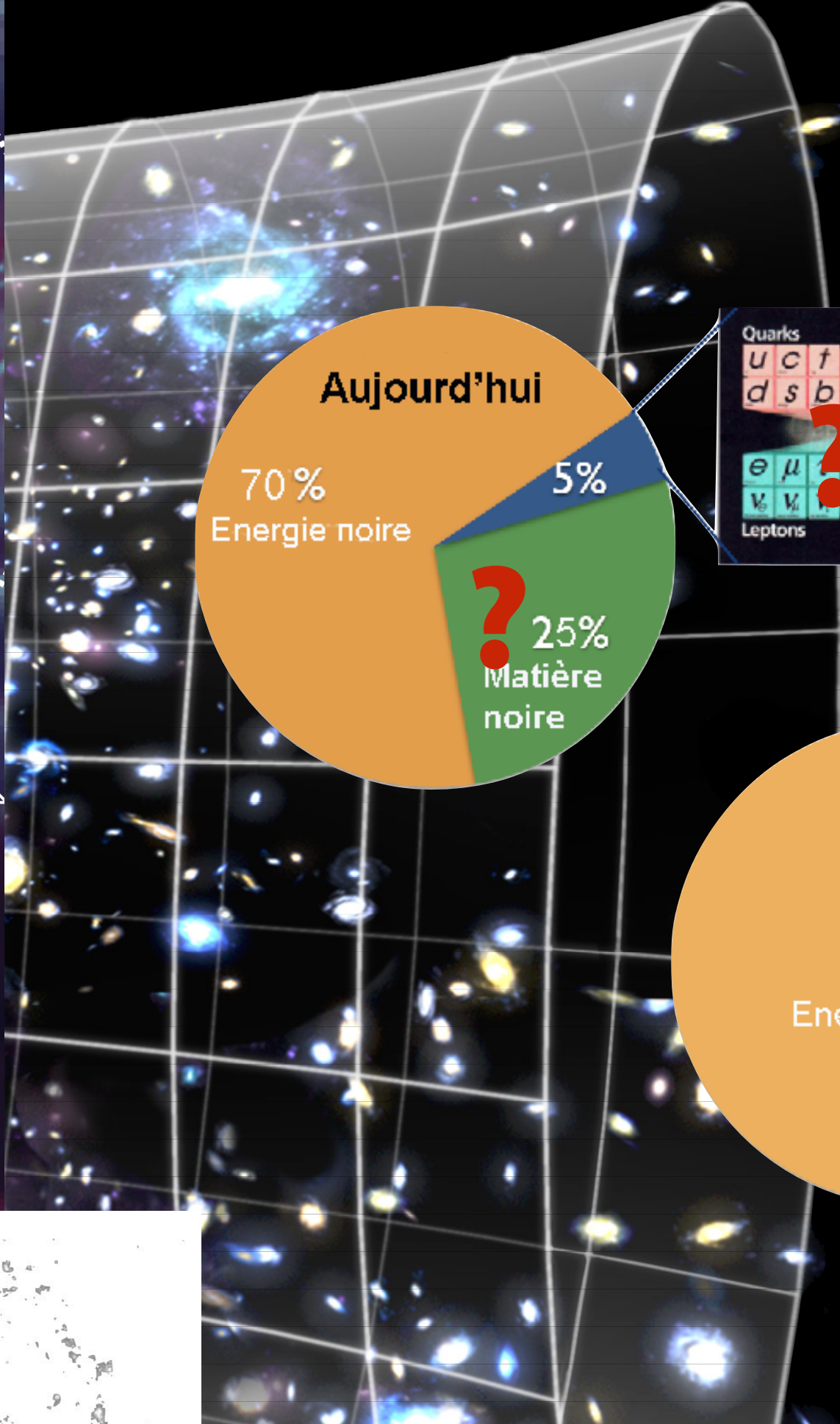
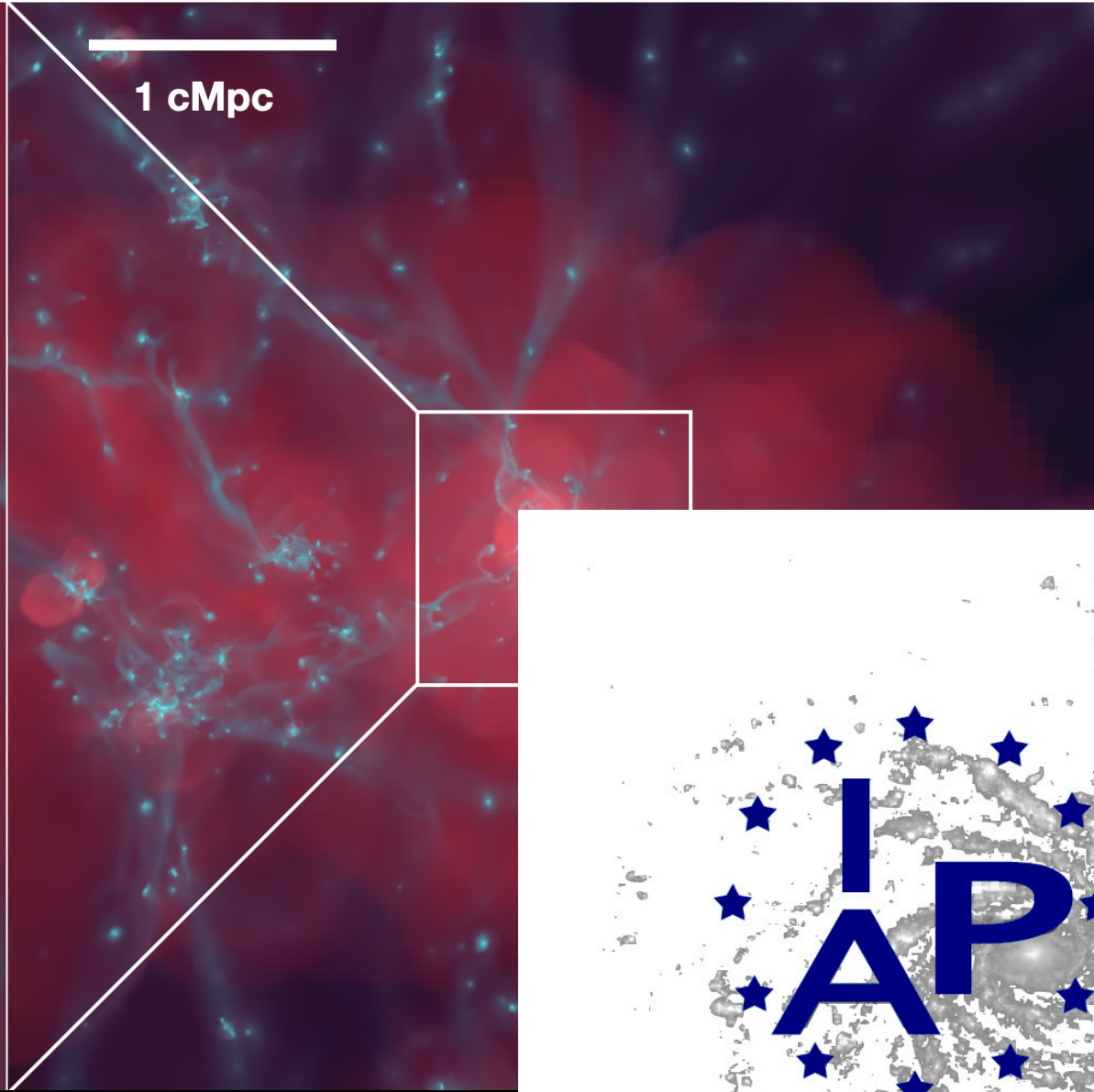
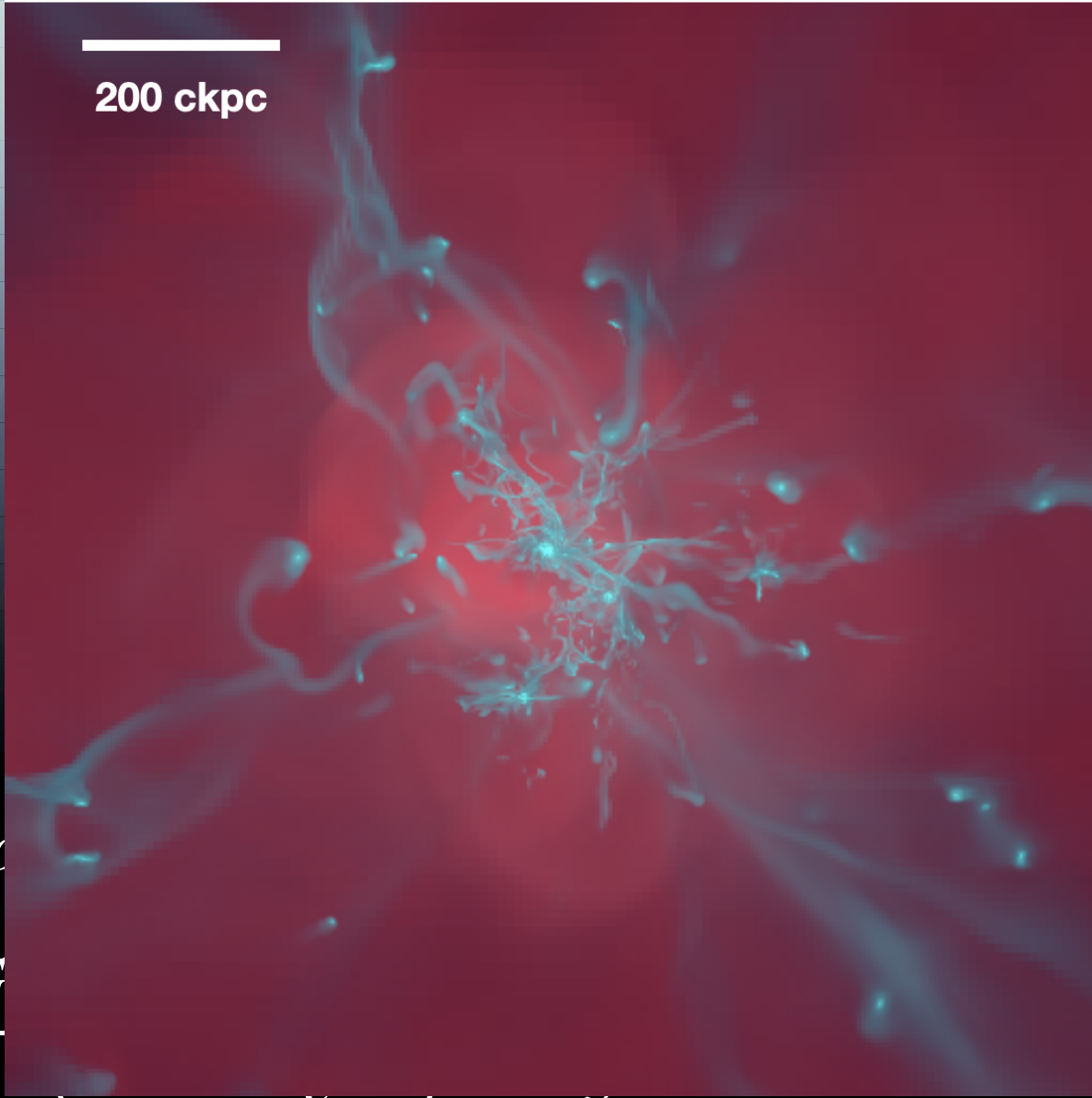
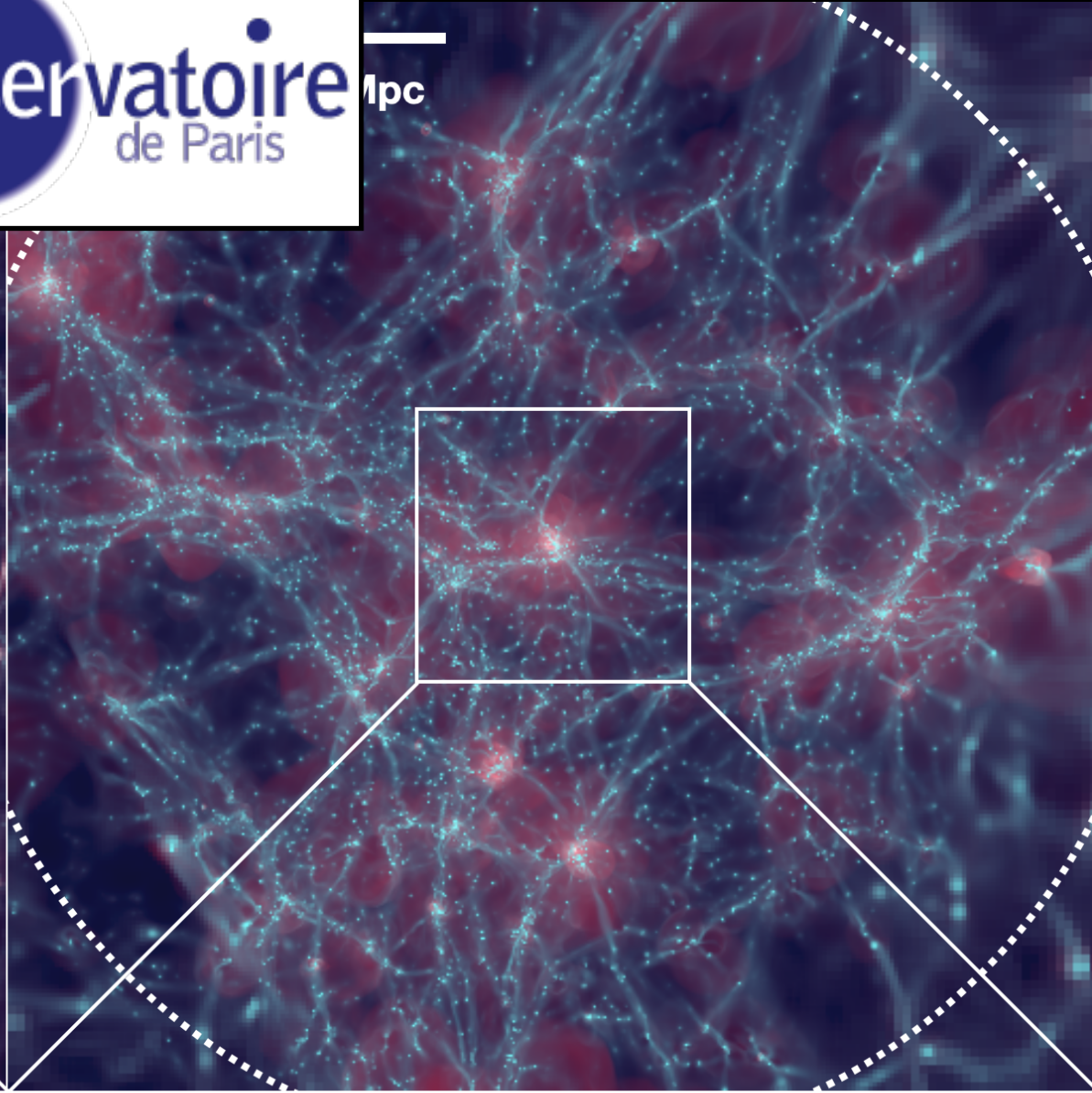
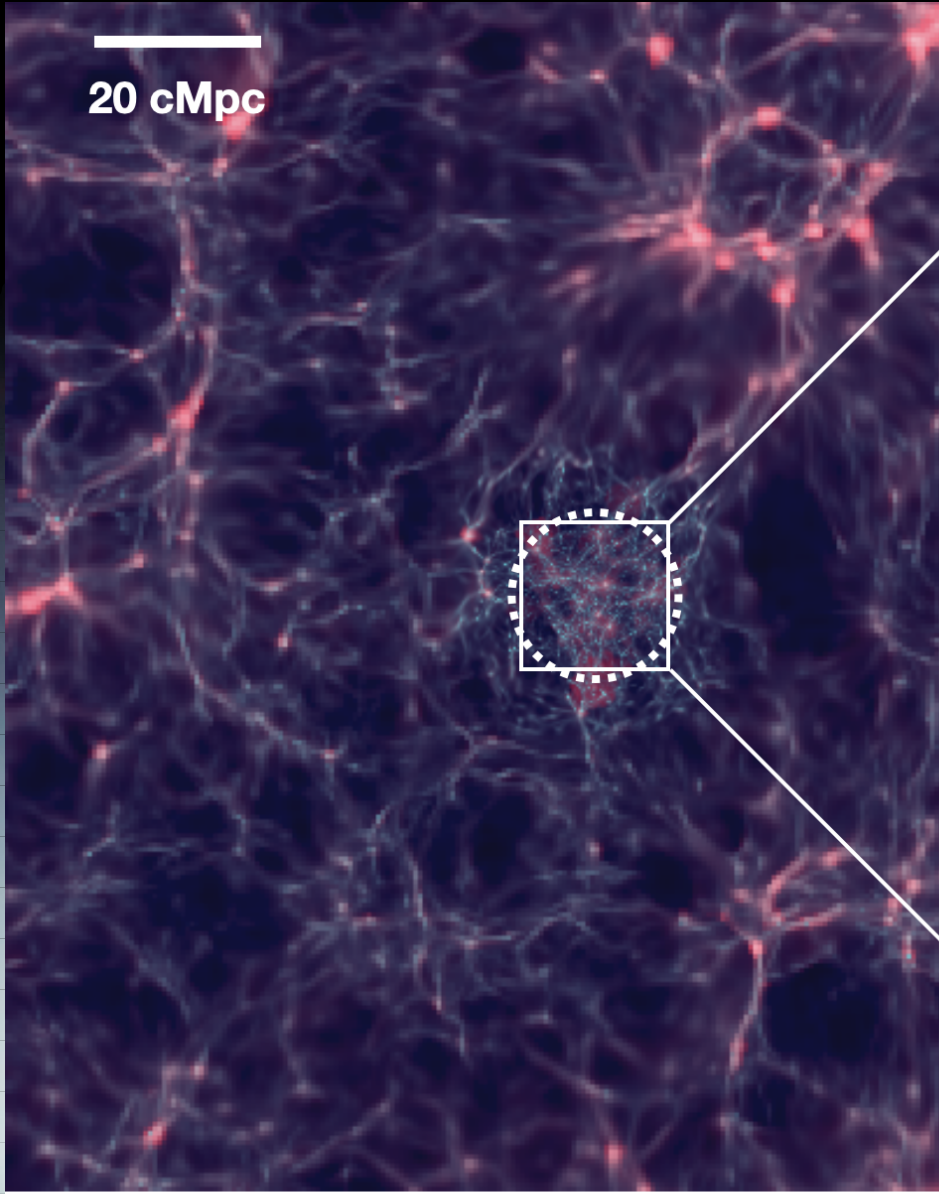
B-modes



$$H^2(t) = \frac{8\pi G}{3c^2} \rho(t) - \frac{kc^2}{a^2(t)} + \frac{\Lambda c^2}{3}$$

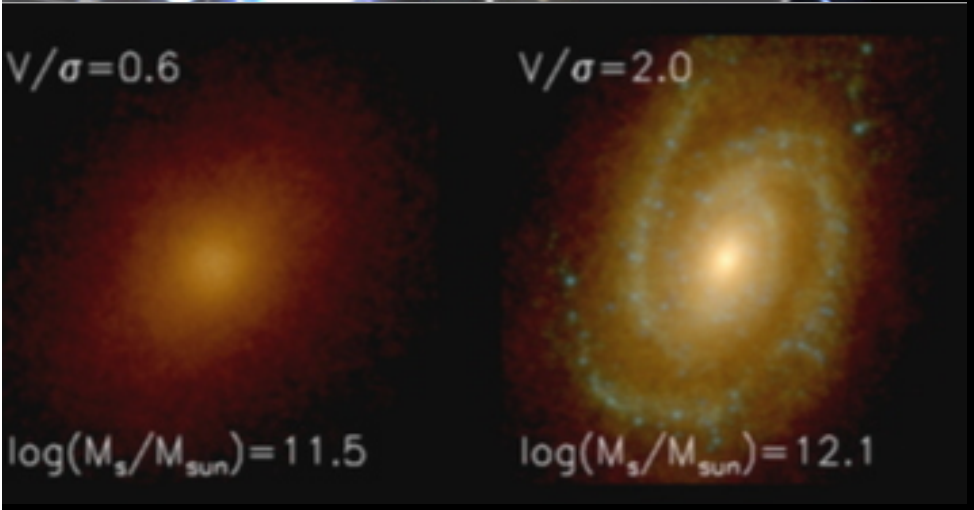
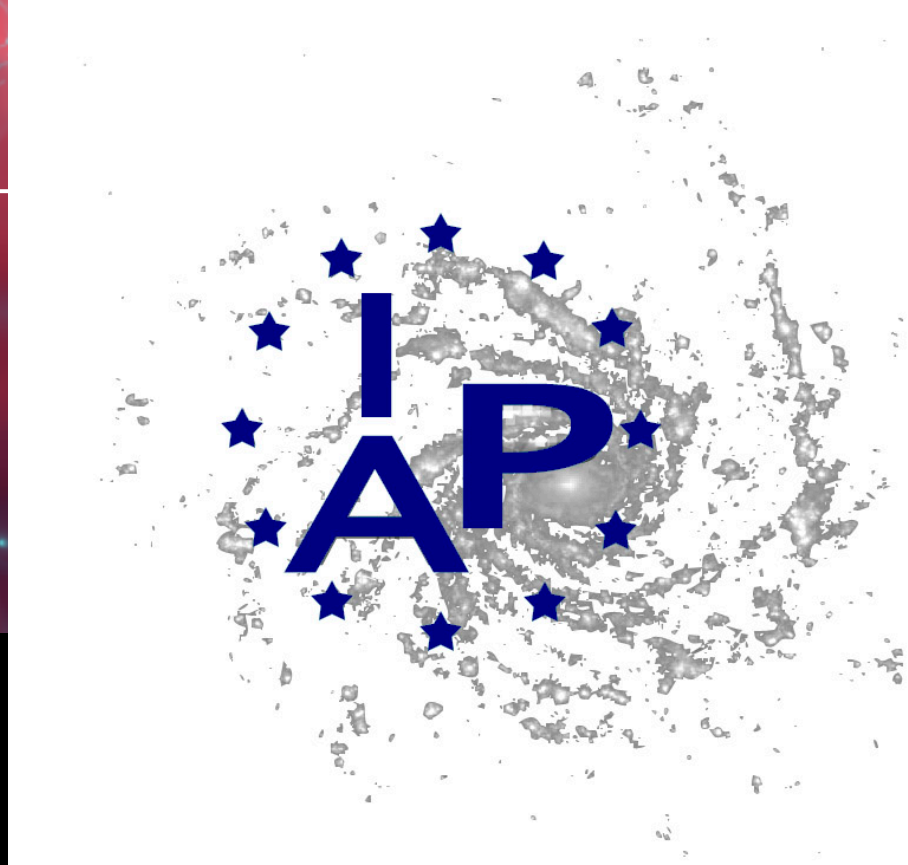
$$\frac{\ddot{a}(t)}{a(t)} = -\frac{4\pi G}{3c^2} \left(\rho(t) + \frac{3p(t)}{c^2} \right) + \frac{\Lambda c^2}{3}$$





$$H^2(t) = \frac{8\pi G}{3c^2} \rho$$

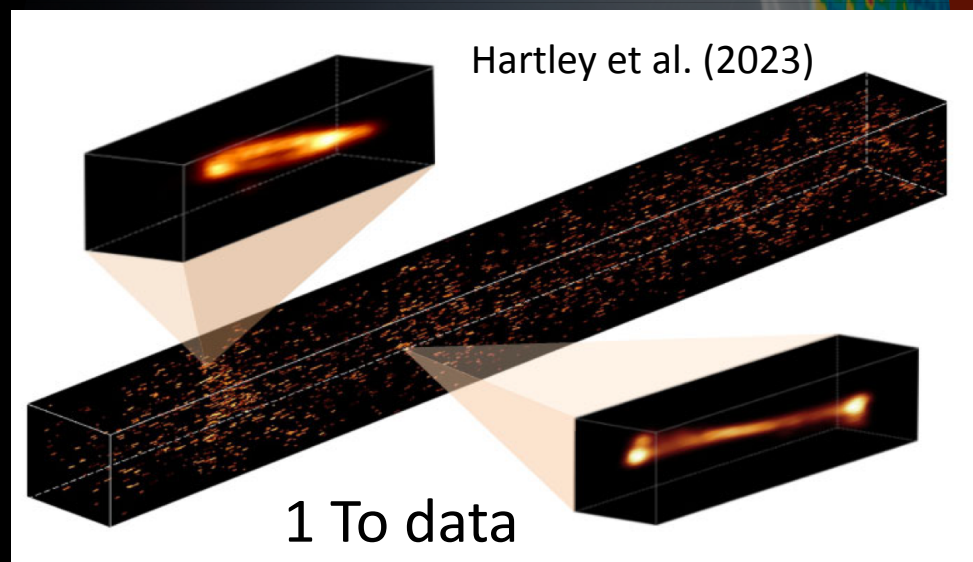
$$\frac{\ddot{a}(t)}{a(t)} = -\frac{4\pi G}{3c^2} \rho$$



Aubert & Deparis, EMMA simulation

Implication dans les SKA data challenges

SDC 2: détecter/caractériser sources HI



Equipe MINERVA (PI D. Cornu) 1iere place

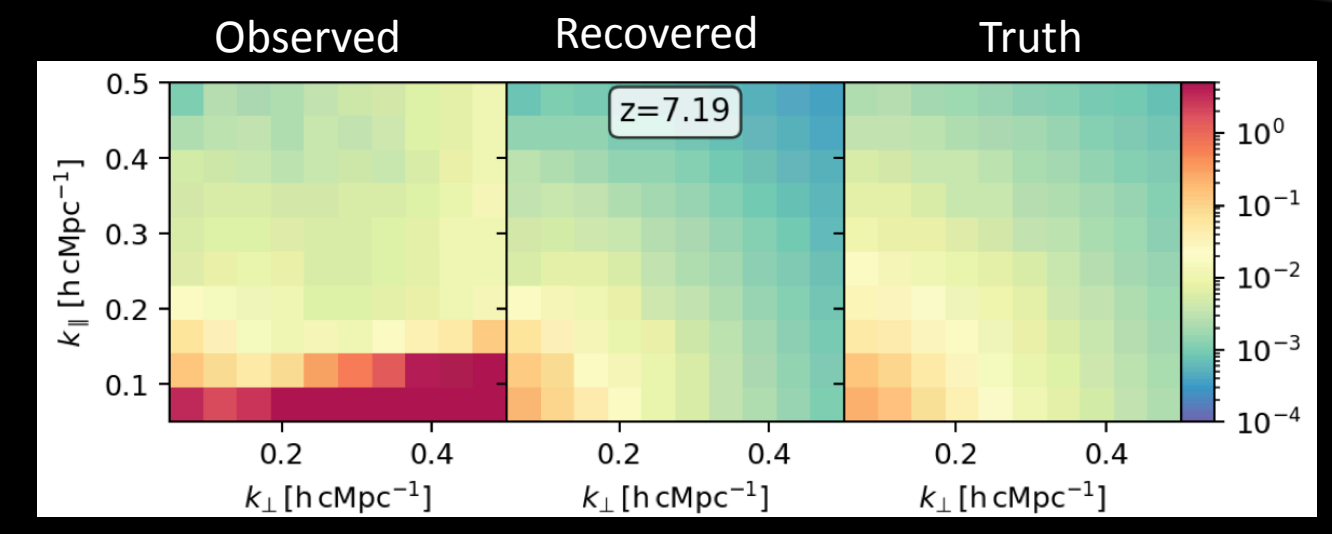
YOLO-CIANNA (Cornu et al. 2024)

Team name	Score	N_d	N_m	R	C	A
MINERVA	23 254	32 652	30 841	0.945	0.132	0.81
FORSKA-Sweden	22 489	33 294	31 507	0.946	0.135	0.77
Team SOFIA	16 822	24 923	23 486	0.942	0.101	0.78
NAOC-Tianlai	14 416	29 151	26 020	0.893	0.112	0.67
HI-FRIENDS	13 903	21 903	20 828	0.951	0.089	0.72

SDC 3: spectre de puissance du 21-cm EoR

2ième place
DOTSS-21
Equipe Fr-NI
(PI F. Mertens)

Notre approche:
Soustraire sources compactes
Modéliser et soustraire fond diffus Galactique
Extraire le signal 21-cm avec ML-GPR
Produire le spectre de puissance

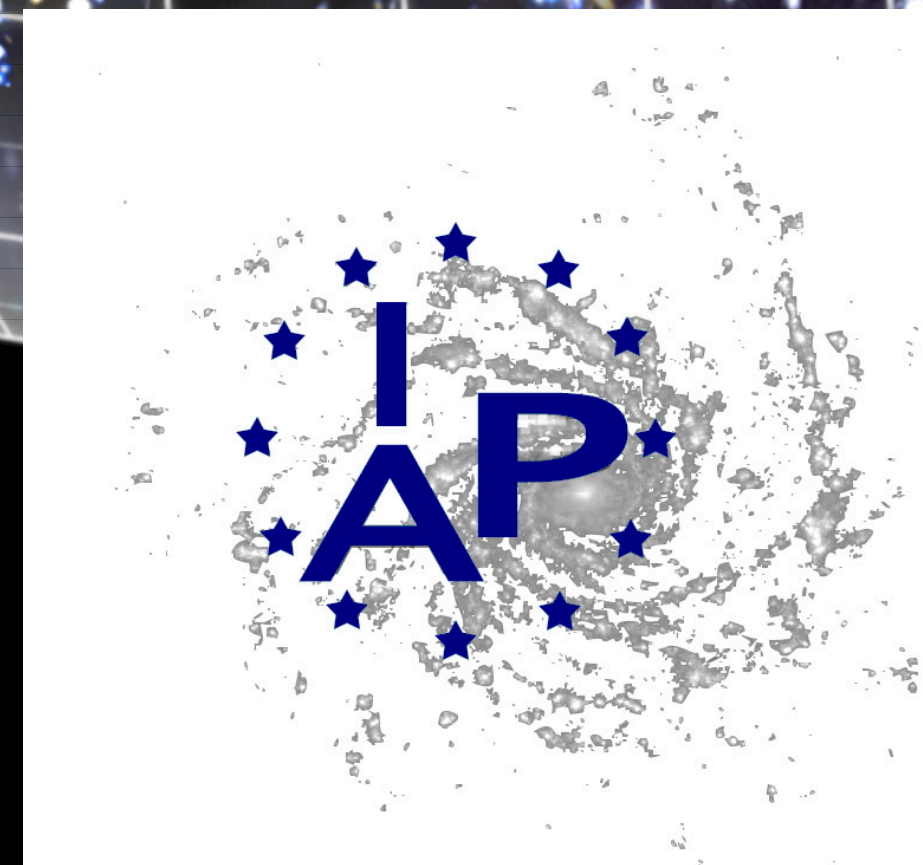
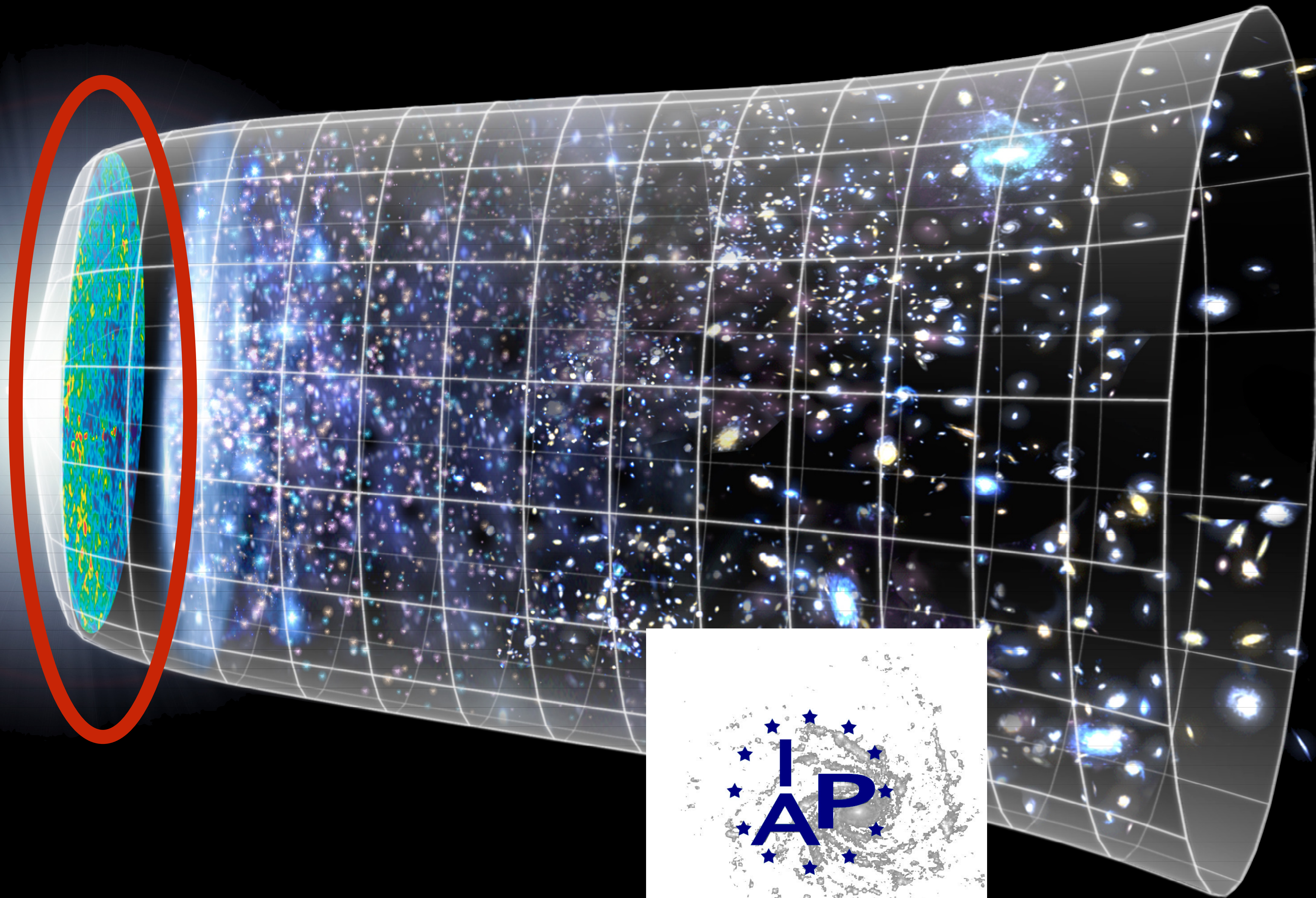


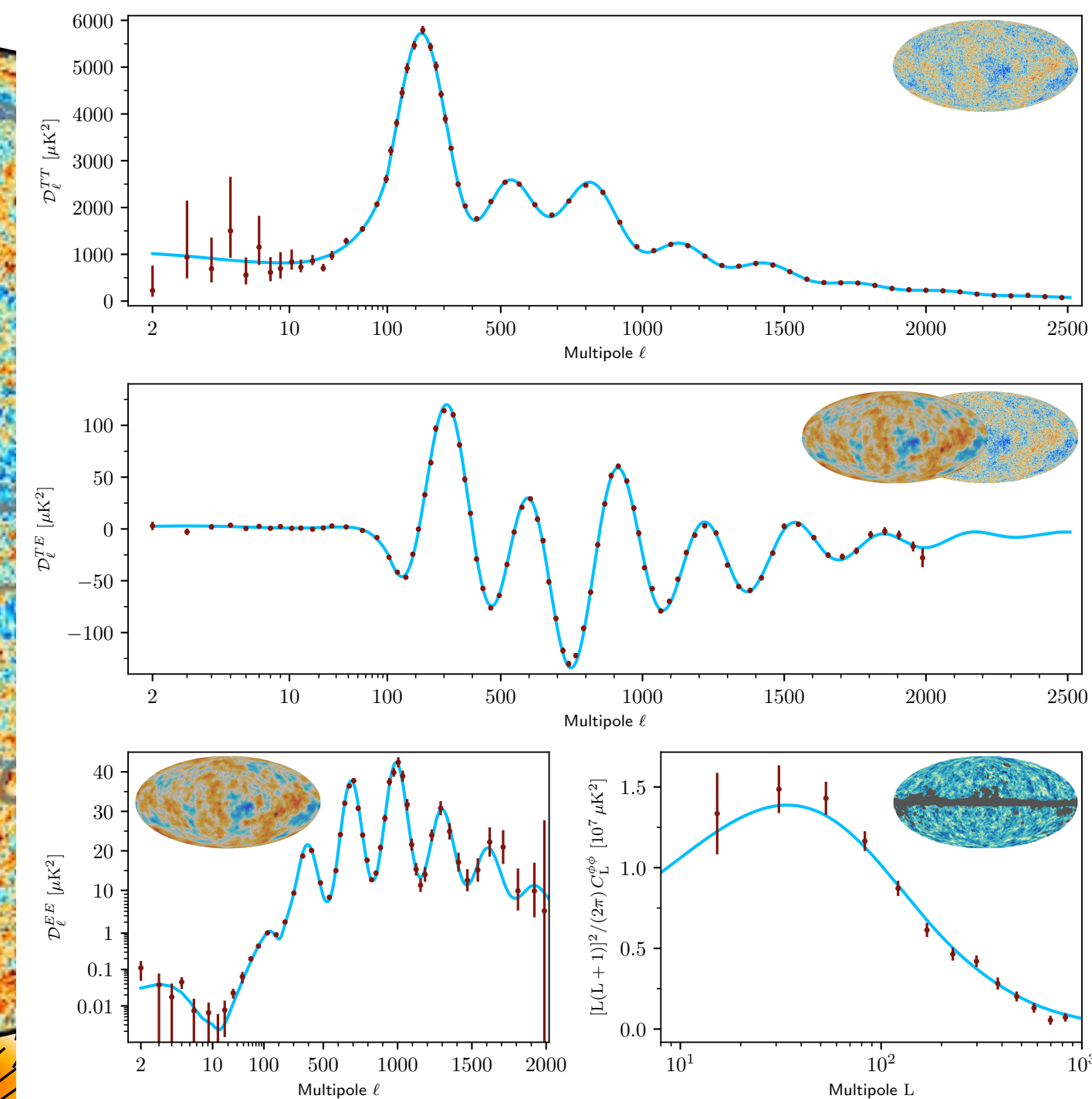
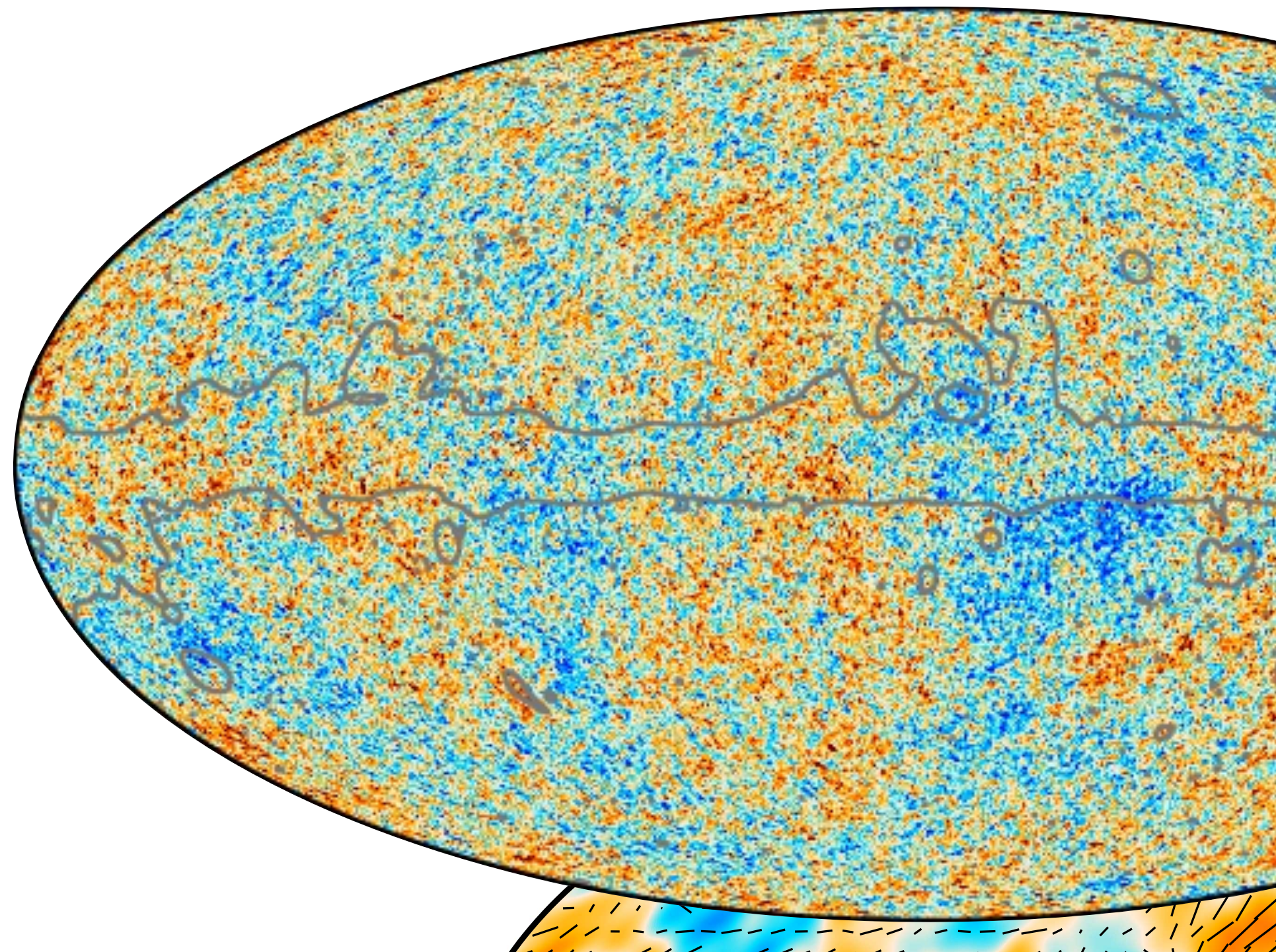
Ages sombres
Univers neutre

Univers
complètement ionisé

Époque de la réionisation
~680Mans après le Big Bang

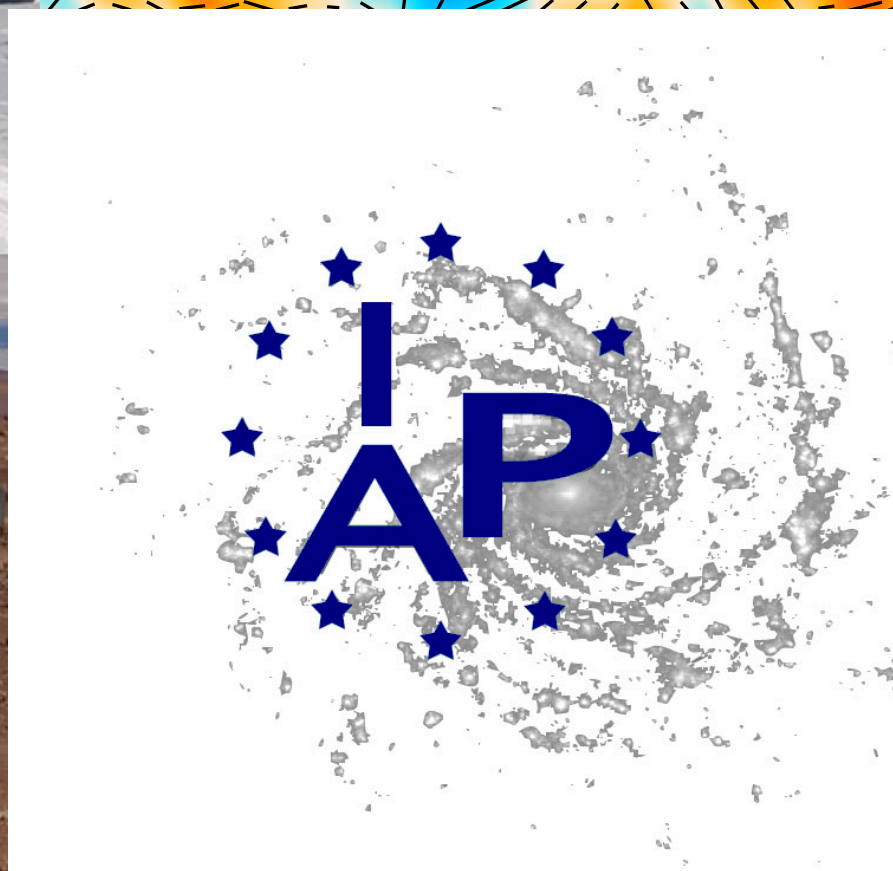
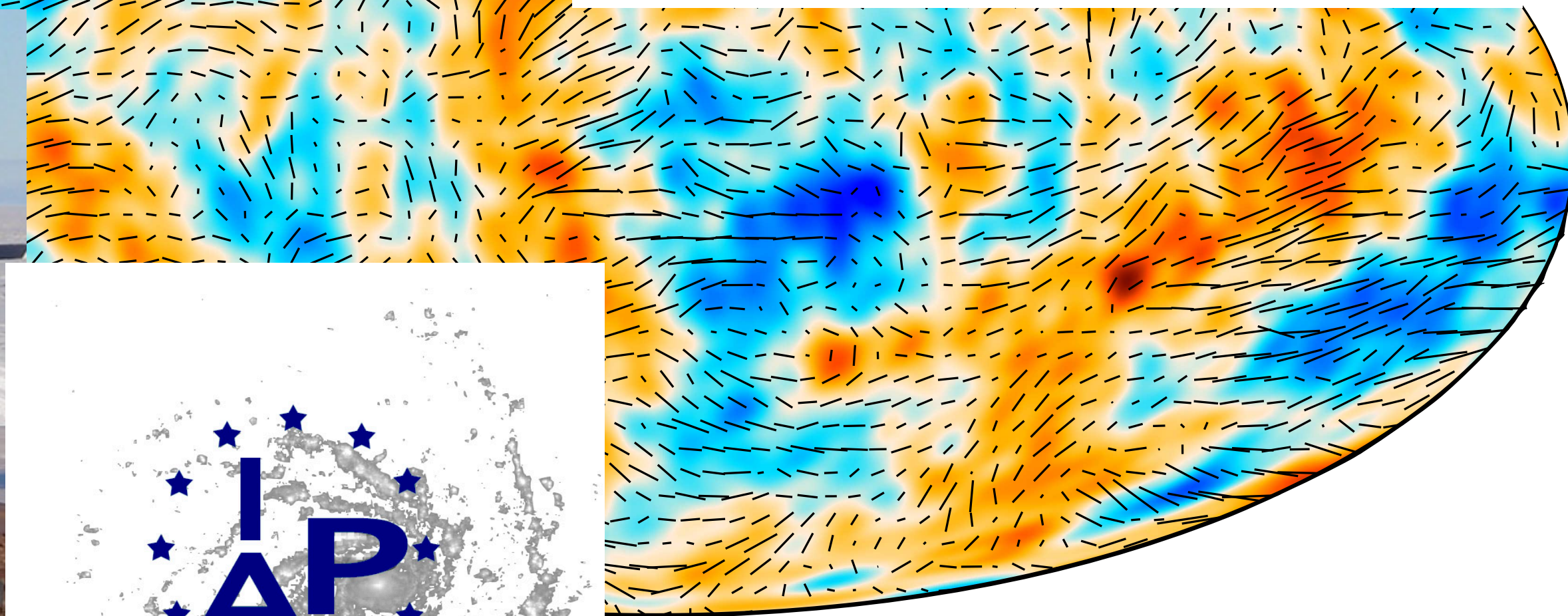
Temps

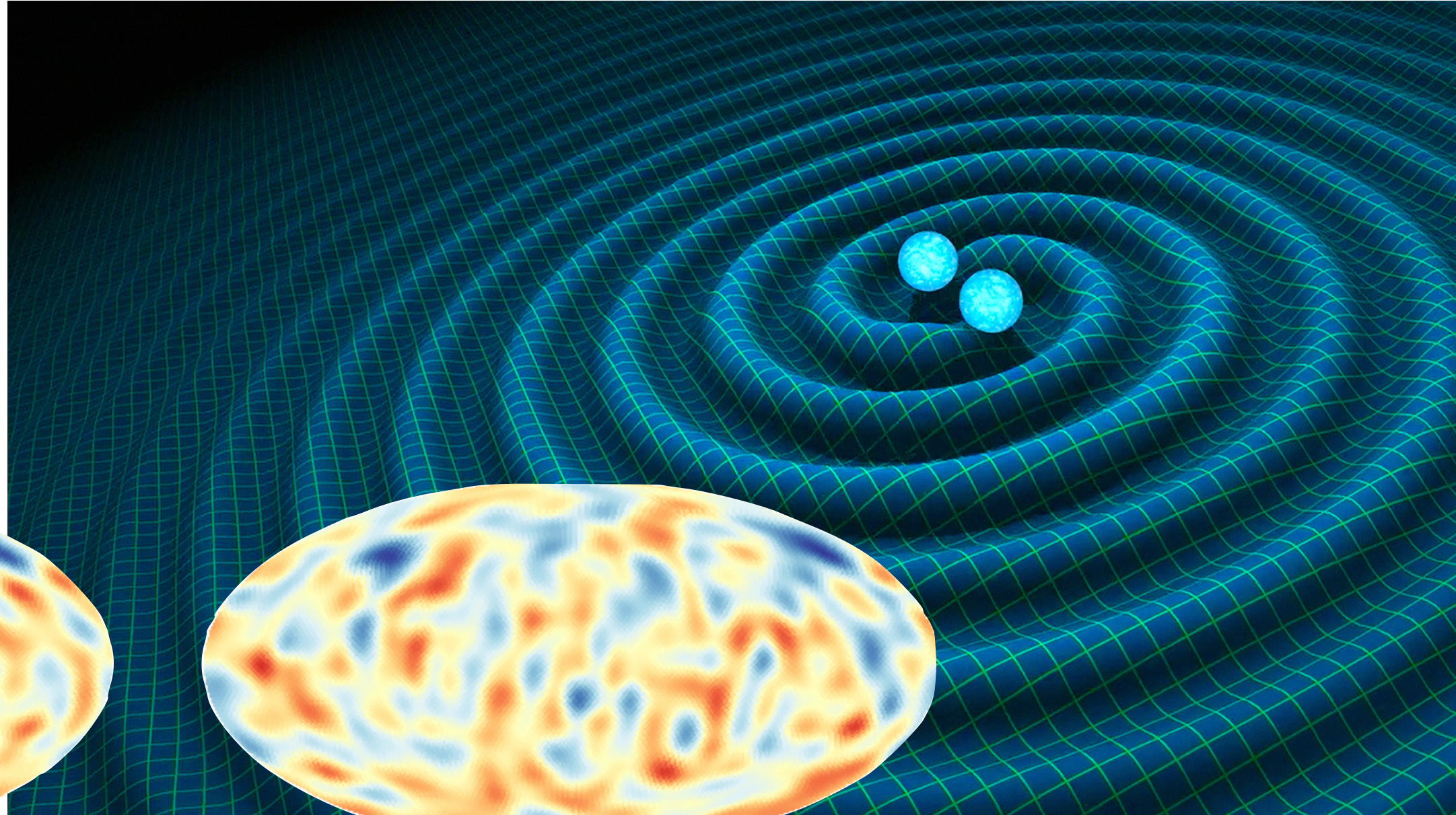




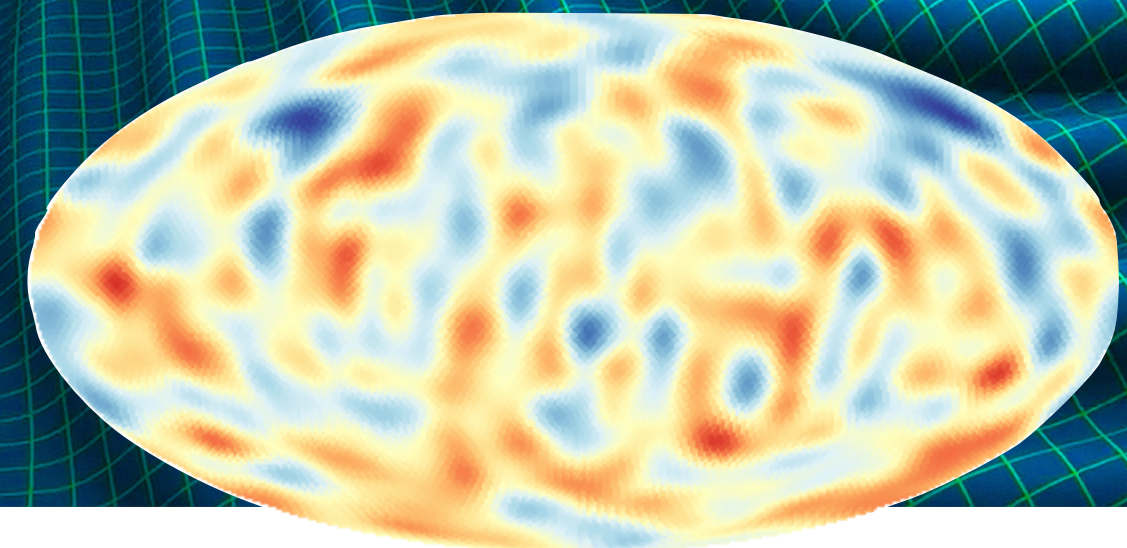
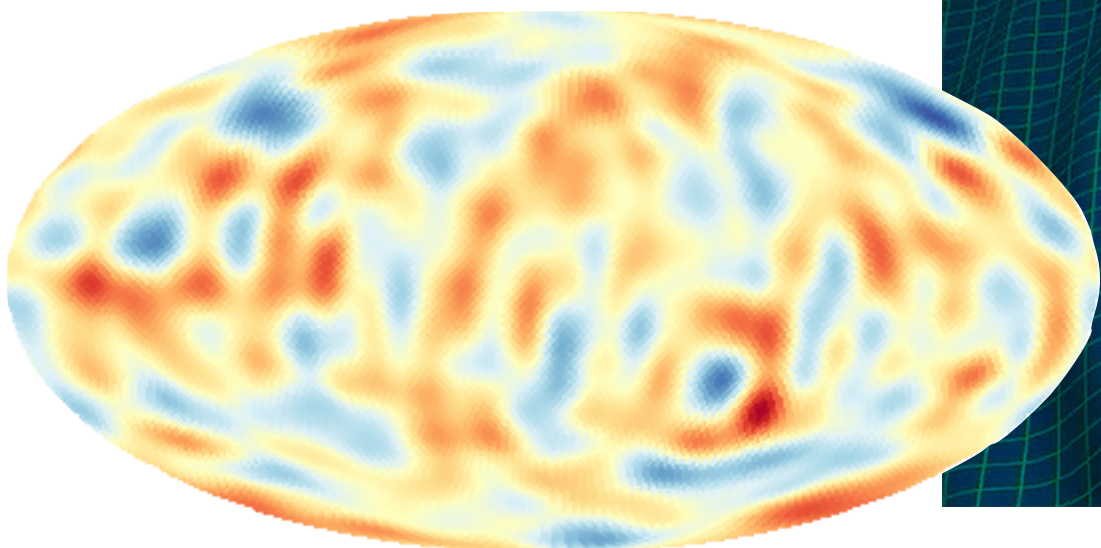
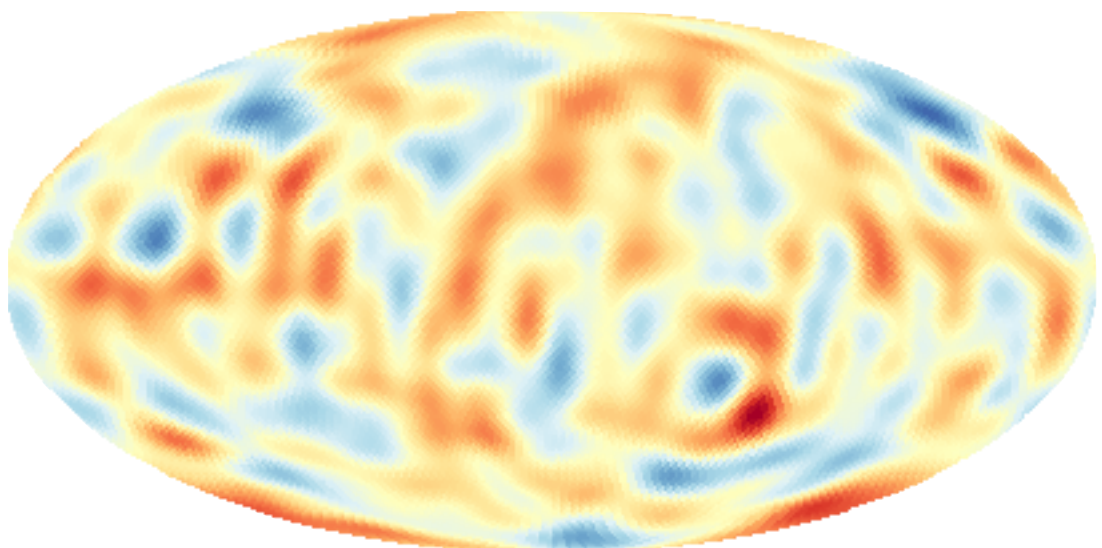
CMB-S4
Next Generation CMB Experiment

CMB-S4 Collaboration Workshop
September 19-21, 2016 • Chicago, IL

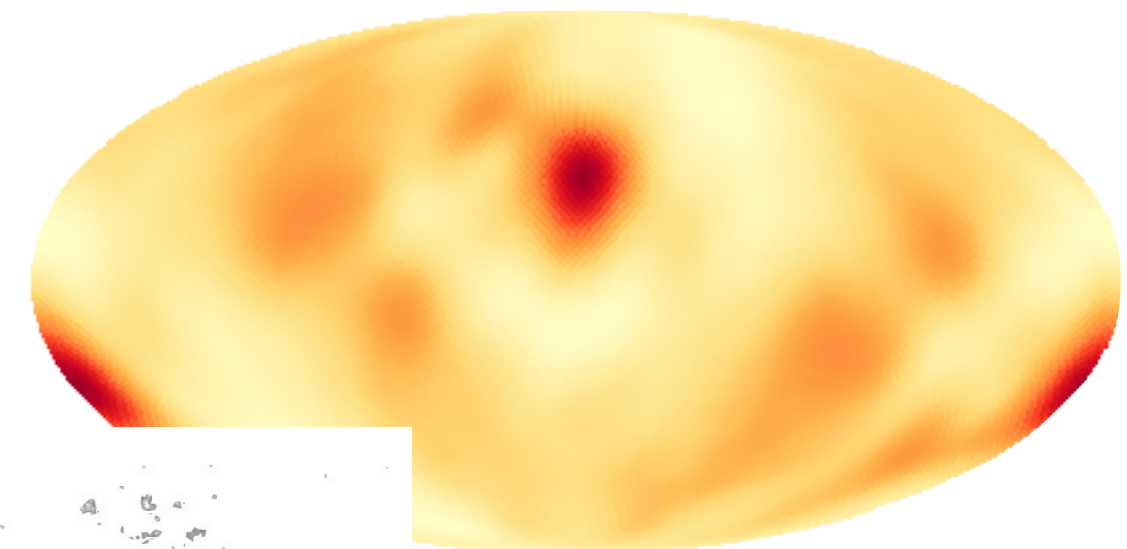
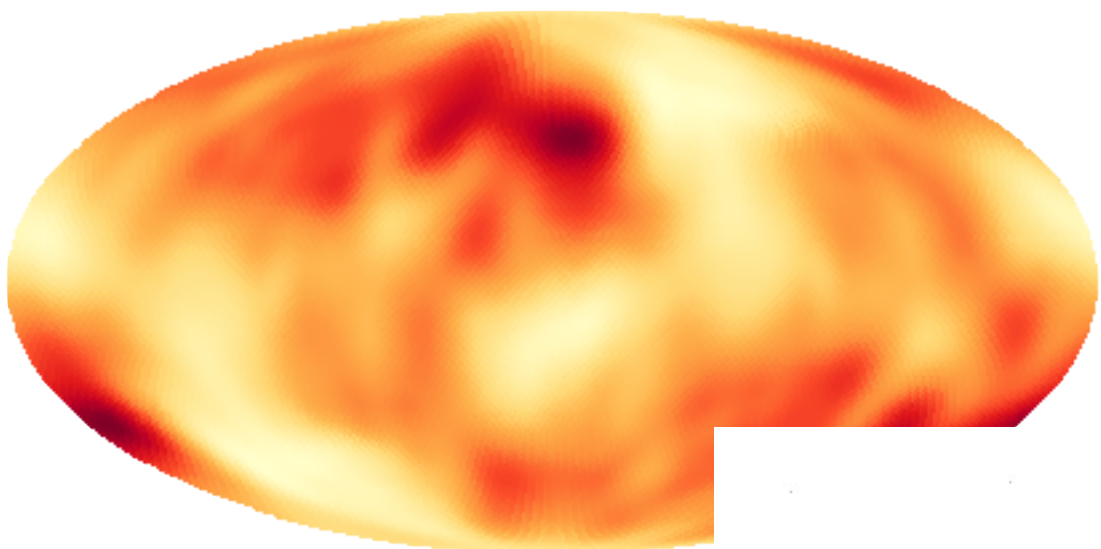
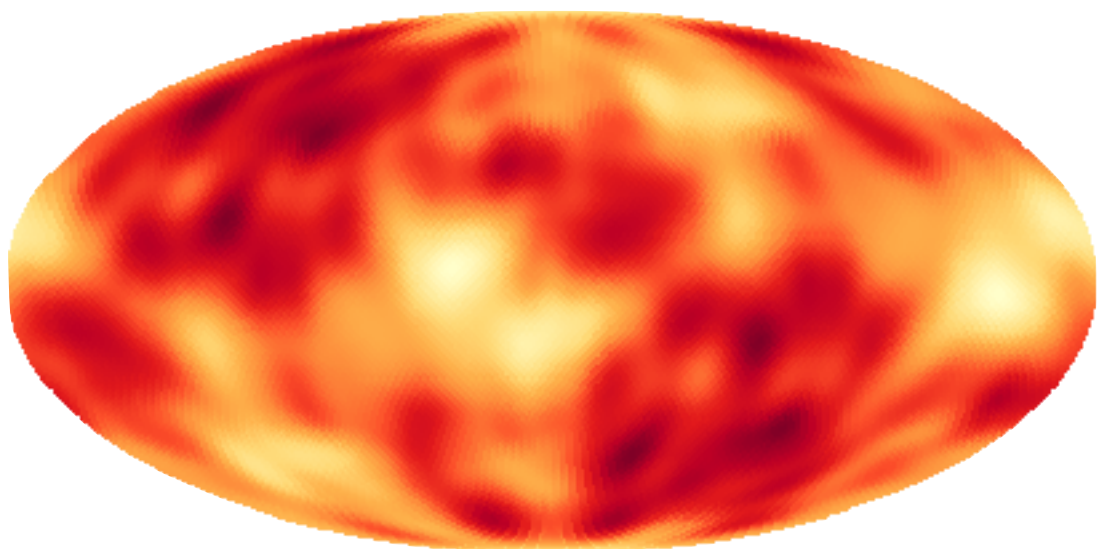




S/N



Noise

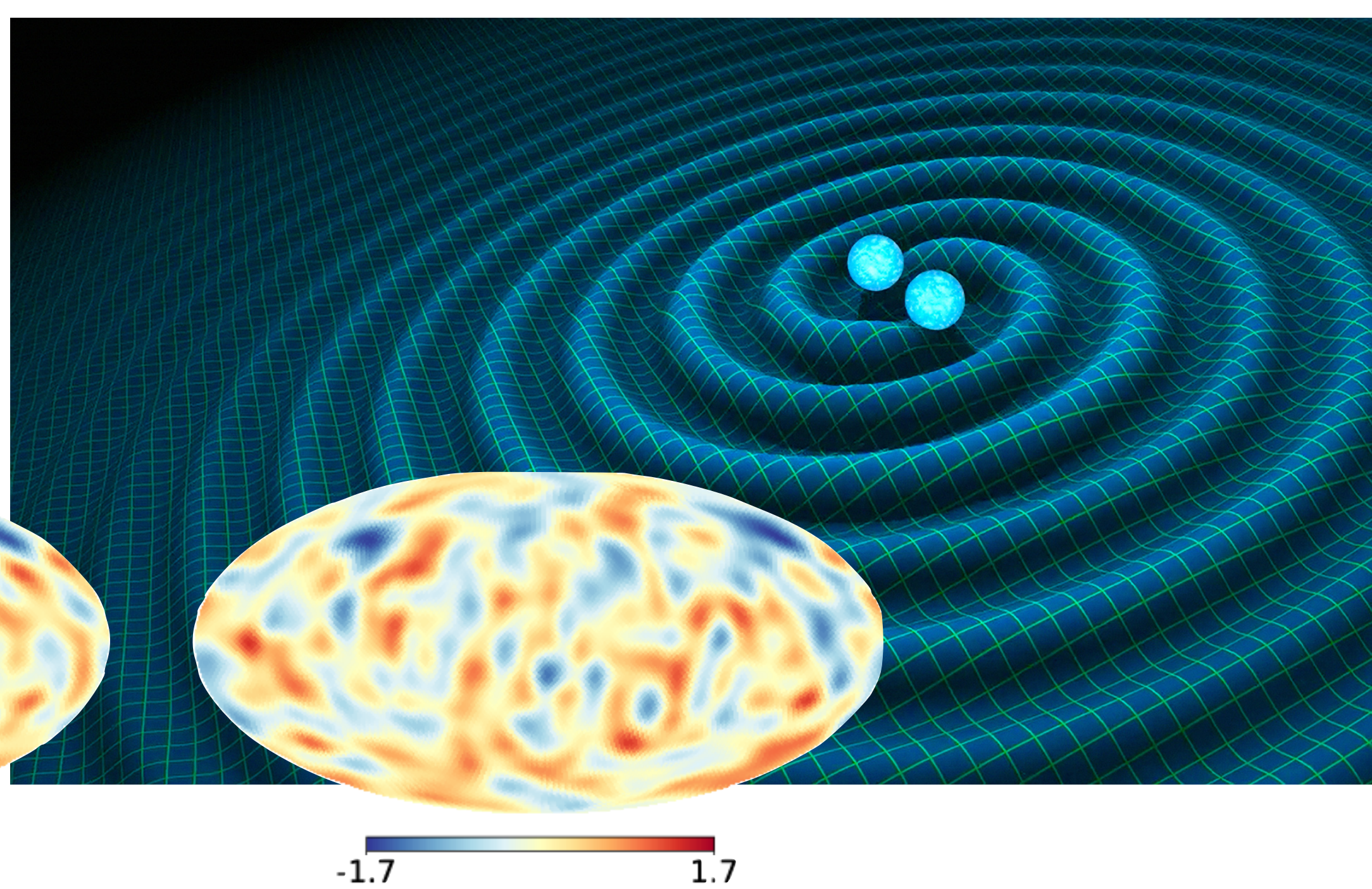
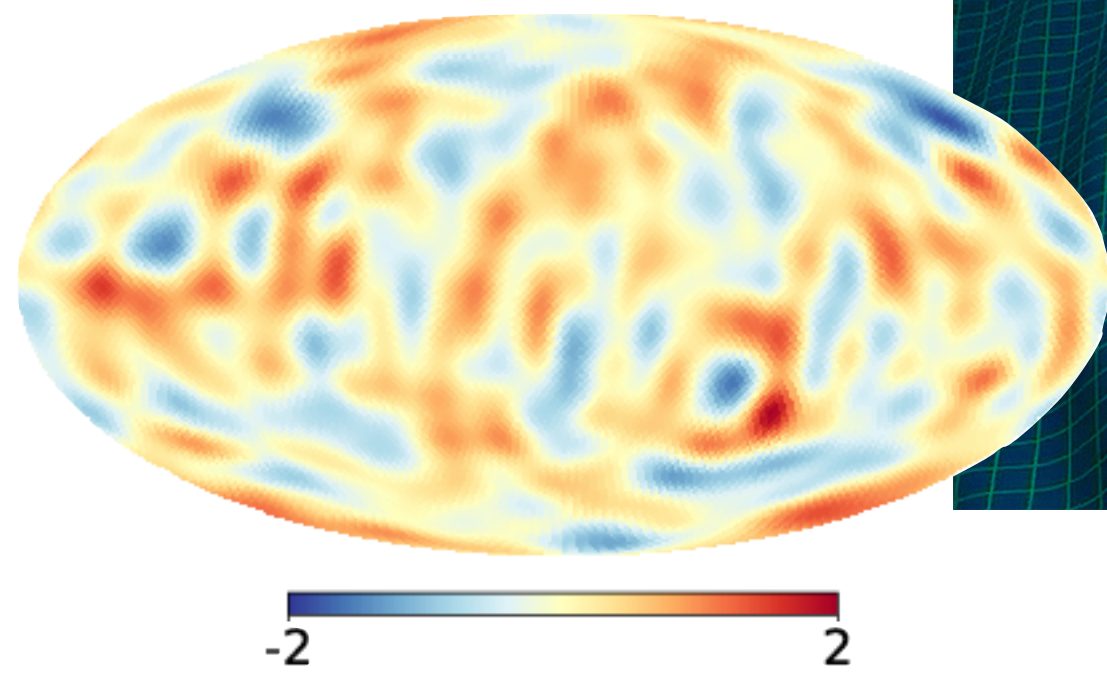
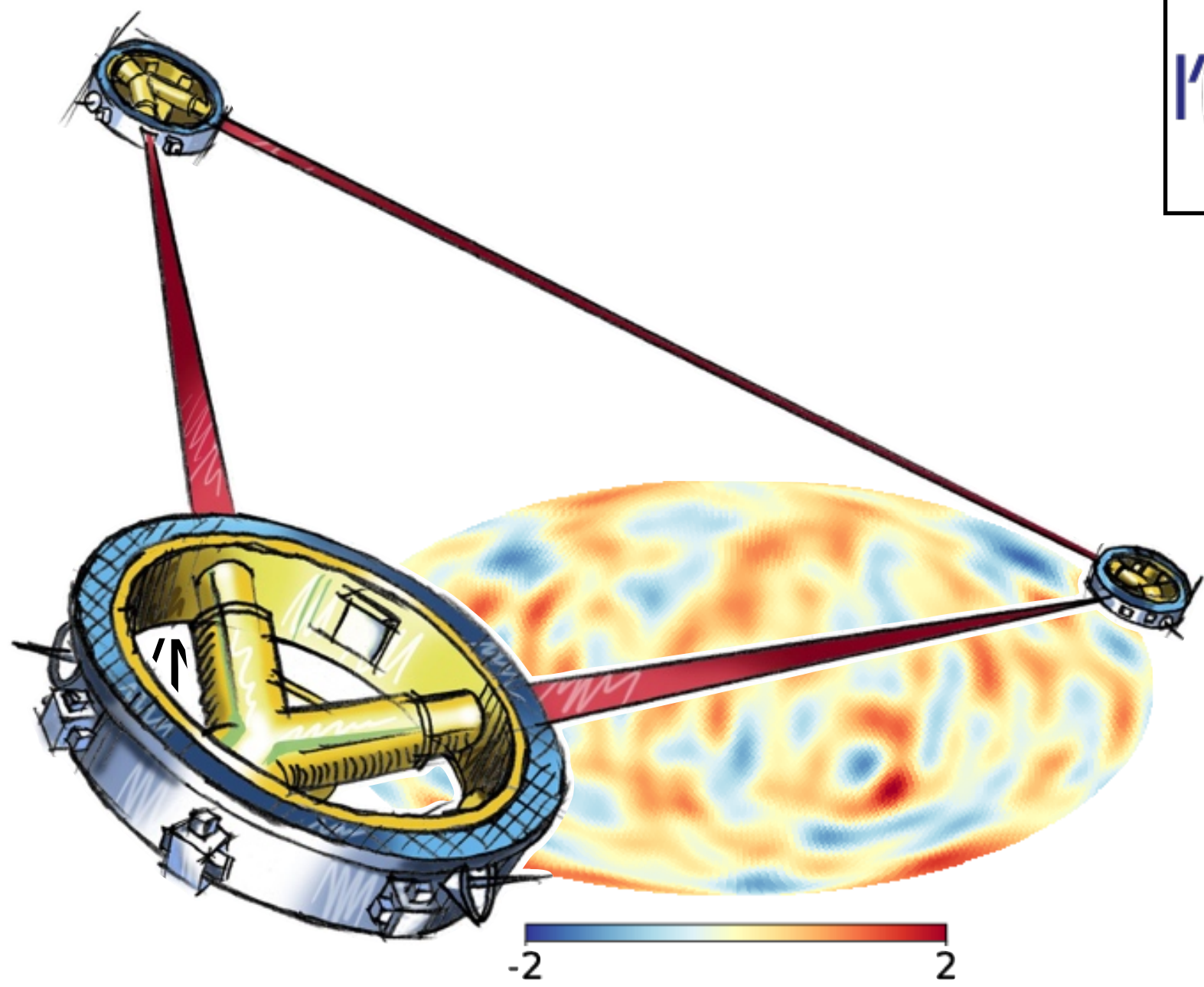


Primordial

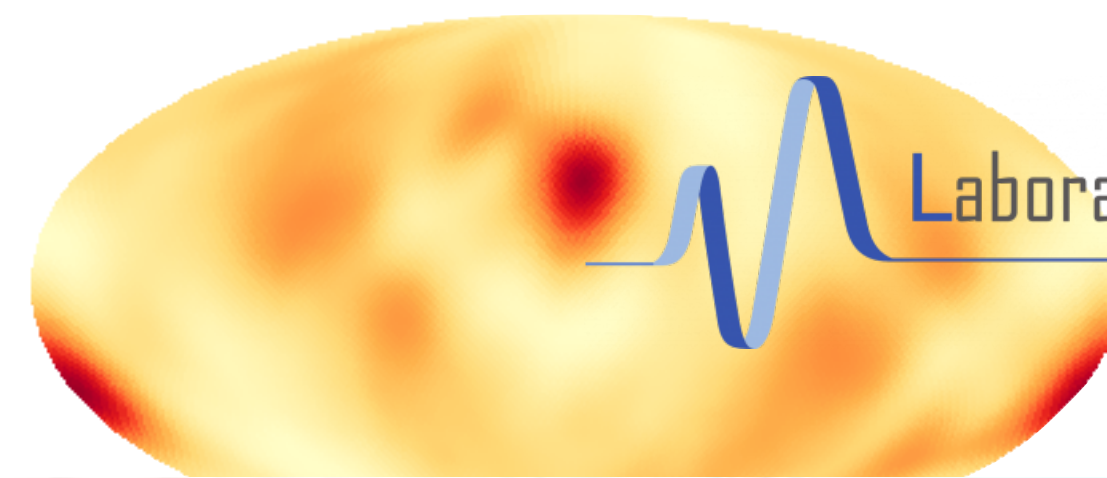
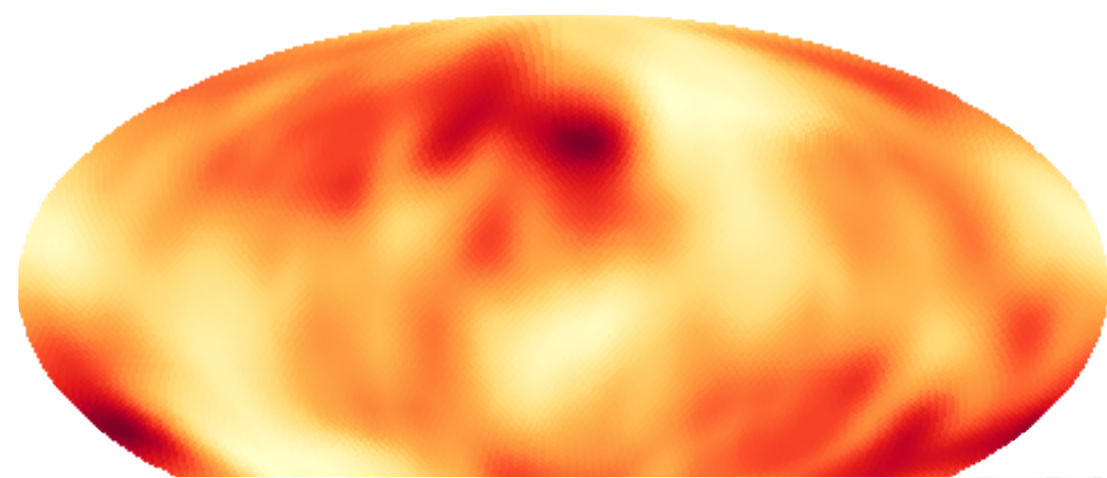
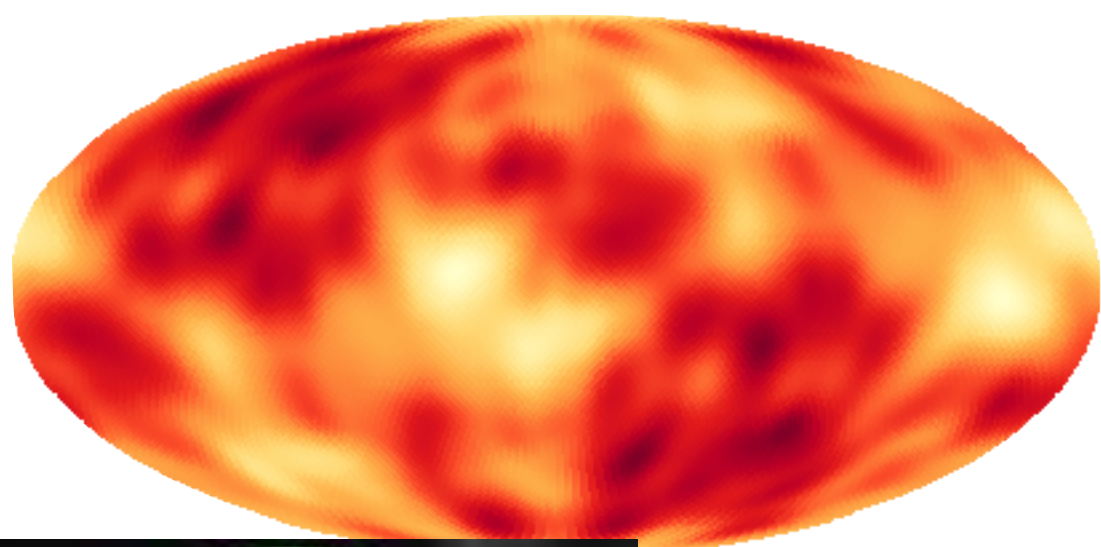
object collapse

$\alpha = 3$

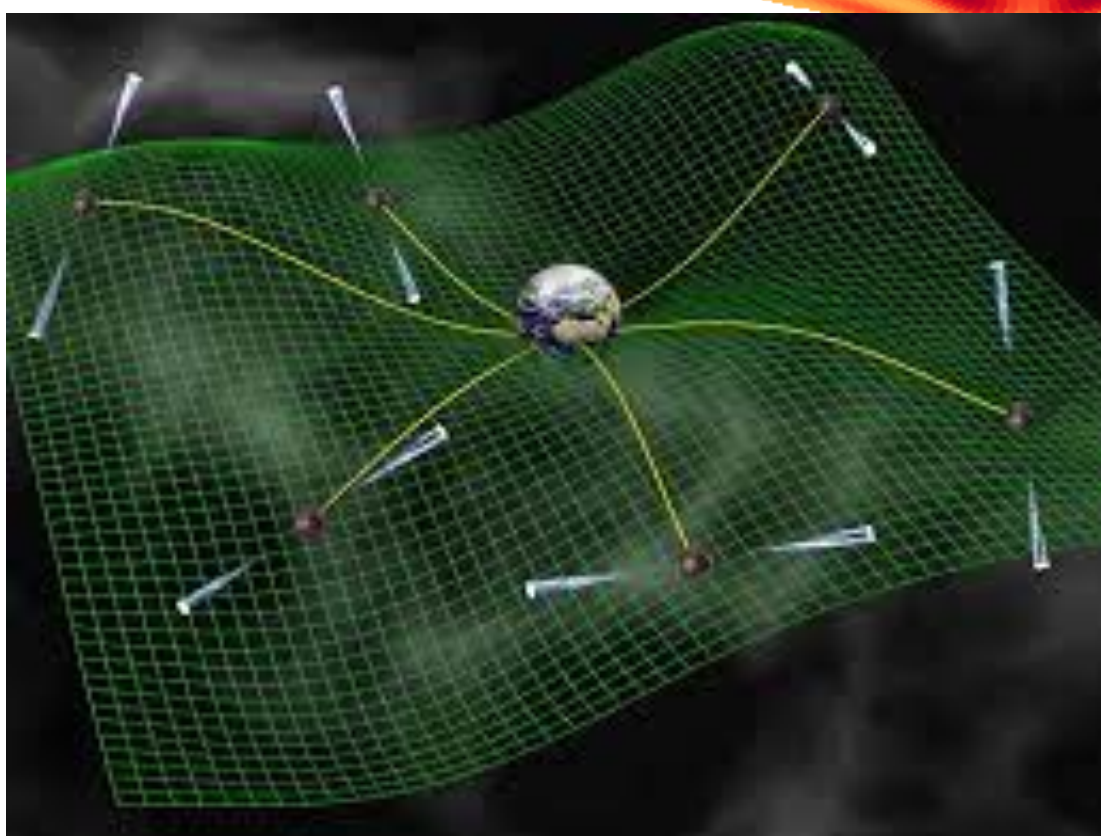




Noise



Laboratoire Kastler Brossel
Physique quantique et applications



radial

obj



GRAND AT A GLANCE 简介

Objectives 目标

By the 2030s, in its complete configuration, GRAND will reach a sensitivity that will enable the detection of neutrinos with energies above 10^6 eV. Thanks to its sub-degree angular resolution, it will launch ultra-high-energy neutrino astronomy. Already by 2025, GRAND will be able to make the first discovery of these neutrinos. GRAND will be the largest experiment for the detection of ultra-high-energy cosmic rays and photons. Moreover, GRAND will uniquely explore fundamental neutrino physics, the astrophysics of fast radio bursts, and the epoch of reionization.

GRAND预计在2030年建成。完整的GRAND将能够达到探测能量高于 10^6 eV的中微子。得益于其亚度角分辨率，它将开启超高能中微子天文学。从2025年起，GRAND将能够首次发现这些中微子。GRAND将是探测超高能宇宙射线和光子的最大实验。此外，GRAND还将独特地探索基本中微子物理、快速射电暴的天体物理学以及再电离时代。

How does GRAND work? GRAND如何工作?

The strategy of GRAND is to detect air showers above 10^6 eV that are induced by the interaction of high-energy particles in the atmosphere or underground, through its associated coherent radio emission in the 30-300 MHz range.

策略是在探测由大气中高能粒子相互作用产生的能量高于 10^6 eV的宇宙射线空气簇射。通过其在30-300 MHz频段的相干无线电发射实现探测。

Why now? 为什么是现在?

With the first detection of very high-energy neutrinos and gravitational waves, we stand today at the threshold of a multi-messenger era. Many high-precision high-energy astroparticle experiments are projected (CTA, IceCube-Gen2, LHAASO, GRAND) completes the picture at the highest energy front. Radio-detection of astroparticles is experiencing a renaissance, with drastic technological, theoretical and numerical advances.

随着首个超高能中微子和引力波的首次探测，我们今天站在多信使时代的门槛上。许多高精度的高能天体粒子实验正在规划中（CTA, IceCube-Gen2, LHAASO, GRAND）完成了最高能前沿的拼图。天体粒子的无线电探测正在经历复兴，伴随着巨大的技术、理论和数值上的进步。

NEUTRINOS! 中微子!

Neutrinos are elementary particles that interact weakly with matter. This characteristic makes them challenging to detect and study.

中微子是基本粒子，与物质相互作用极弱。这一特性使得它们难以探测和研究。

AV Electromagnetic energy unit equal to 10^6 Joules. The proton rest mass energy is equivalent to 10^9 eV. Cosmic rays charged particles mostly protons and heavier nuclei that constantly bombard the Earth. A small fraction of them (ultra-high-energy cosmic rays) are detected with colossal energy 10^{20} eV, at a rate of 2 per month with the 3000 km² Auger Observatory. Their origins are still a mystery.

1 eV电磁能单位等于 10^6 焦耳。质子的静止质量能量相当于 10^9 eV。宇宙射线带电粒子主要是质子和更重的原子核，它们不断地轰击地球。其中一小部分（超高能宇宙射线）的能量高达 10^{20} eV，在3000平方公里的Auger观测站每两个月探测到2次。它们的起源仍然是一个谜。

Why now? 为什么是现在?

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GRAND PROTO35

GOALS
- Standard radio detection of air showers
- Good background noise rejection

SETUP
- 35 radio antennas
- 1 scientist

BUDGET & STAGE
- 100k€
- NANO-RED deployment 2018 @ Ustat

GRAND 10K

GOALS
- First GRAND sub-array, sensitivity comparable to AERA/ARIANNA on similar time scale, allowing potential "discovery of cosmogenic neutrinos"

SETUP
- 1000 radio antennas
- 100 scientists

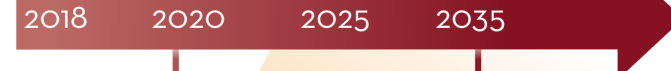
BUDGET & STAGE
- 10M€
- fully funded by NANO-RED deployment 2025 @ Ustat

GRAND

Giant Radio Array for Neutrino Detection

The Giant Radio Array for Neutrino Detection project aims to detect ultra-high-energy cosmic neutrinos, cosmic rays, and gamma rays with a radio antenna array deployed over a total area of 200 000 km² in mountainous regions, in several favorable locations around the world.

巨中微子探测阵列（GRAND）旨在在20万平方公里的山区部署无线电天线阵列，以探测超高能宇宙中微子、宇宙射线和伽马射线。该项目将在全球多个有利地点进行。



GRAND PROTO300

GOALS
- Standard radio detection of inclined showers (depth angle > 60°) induced by high-energy cosmic rays (10^{18} eV)

SETUP
- 300 Horizon Antennas over 300 km²
- Fast data acquisition system
- Solar panels (2x7) - WiFi data transfer

BUDGET & STAGE
- 13 M€ for radio only, funded by Chinese Institutes

GRAND 200K

GOALS
- Discover neutrinos of 10^6 eV and neutrino astronomy

SETUP
- 200 000 antennas over 200 000 km²
- > 20 x 10 000 km² hotspots worldwide

BUDGET & STAGE
- Industrial scale allows to cut costs down: 500€ per unit (150M€ in total)

WHY ULTRA-HIGH-ENERGY NEUTRINOS?

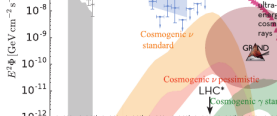
Because they exist. Ultra-high-energy neutrinos are bound to be produced by the interactions of ultra-high-energy cosmic rays with the cosmic background, on their way from their sources to the Earth. Neutrinos should also be produced directly at the sources.

因为它们存在。超高能中微子必然由超高能宇宙射线在传播过程中与宇宙背景辐射的相互作用产生。此外，中微子也可能在源处直接产生。

Because they are unique messengers. Neutrinos are produced with 5% of their parent cosmic-ray energy and travel undeflected by cosmic magnetic fields. Neutrinos with energy 10^6 eV can thus solve one of the most puzzling mysteries of our Universe: the origin of the ultra-high-energy cosmic rays.

因为它们独特的信使。中微子携带其母宇宙射线能量的5%传播，不受宇宙磁场的偏转。能量 10^6 eV的中微子可以解开宇宙起源之谜：超高能宇宙射线的来源。

Because they are the next energy frontier. Neutrino physics is booming with 2 recent Nobel prizes and the first detection of 10^6 eV neutrinos with the IceCube experiment. Ultra-high-energy neutrinos remain undetected. GRAND is the only projected experiment that can reach this uncharted territory.



*Large Hadron Collider
Data and theoretical predictions for energy spectra of gamma rays, neutrinos and cosmic rays at the highest energies

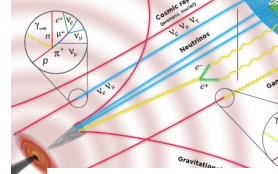
Because multi-messenger astronomy is the way.

The recent observation of neutron star merger GW170817 has brilliantly shown that the challenge of high-energy astronomy will be solved by combining data from a large number of multi-messenger experiments. Ultra-high-energy neutrino astronomy will be central to the quest of understanding the violent Universe.

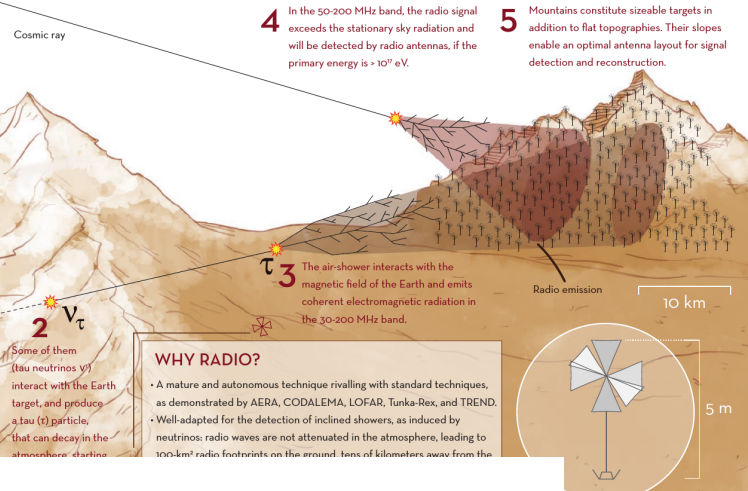
多信使天文学是解决问题的关键。GW170817的观测表明，高能天文学的挑战将通过结合大量多信使实验的数据来解决。超高能中微子天文学将是理解狂暴宇宙的核心。

A new multi-messenger era is opening!

A primary cosmic-ray and its secondary gamma rays and neutrinos as they flight from the source to the Earth.



DETECTION PRINCIPLE



1 Cosmic ray

2 V_c

3 The air-shower interacts with the magnetic field of the Earth and emits coherent electromagnetic radiation in the 30-300 MHz band.

4 In the 30-200 MHz band, the radio signal exceeds the stationary sky radiation and will be detected by radio antennas. If the primary energy is $> 10^6$ eV.

5 Mountains constitute sizeable targets in addition to flat topographies. They allow an optimal antenna layout for signal detection and reconstruction.

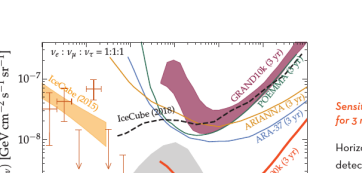
6 WHY RADIO?
- A mature and autonomous technique rivaling with standard techniques, as demonstrated by AERA, CODALEMA, LOFAR, Tunka-Rex, and TRECND.
- Well-adapted for the detection of inclined showers, as induced by neutrinos: radio waves are not attenuated in the atmosphere, leading to 100 km² radio footprints on the ground two of kilometers away from the antenna.

7 size of Great Britain! will be deployed in

ULTRA-HIGH-ENERGY NEUTRINO ASTRONOMY

GRAND will have unrivaled sensitivity to diffuse ultra-high-energy neutrino flux at energy 10^6 eV. This will guarantee the detection of cosmogenic neutrinos the propagation of ultra-high-energy cosmic rays.

GRAND将拥有无与伦比的灵敏度，探测 10^6 eV的弥散超高能中微子通量。这将确保宇宙生成中微子的探测，从而验证超高能宇宙射线的传播。

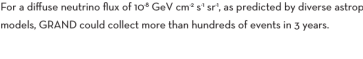


* Alex Belikov, S. M. de Almeida, B. Lago, K. Kawanaka (ICAP) at Astrobiology

For a diffuse neutrino flux of 10^6 GeV cm⁻² s⁻¹ sr⁻¹, as predicted by diverse astrophysical source models, GRAND could collect more than hundreds of events in 3 years.

With 200 000 km² at one location in Western China, the integrated exposure over 3 years is $> 10^6$ km² s in the energy range 10^{17} - 10^{21} eV. GRAND covers 80% of the sky every 24 hours.

GRAND opens the possibility of observing point sources with its excellent angular resolution and sky coverage. GRAND will kick start ultra-high-energy neutrino astronomy.



GRAND field of view for 3 years

A ROBUST, RICH AND VERS.

ULTRA-HIGH-ENERGY COSMIC RAYS ANI
- GRAND will observe ultra-high-energy cosmic rays that are more than 10 times larger than the Pierre Auger Observatory. The high statistics and reconstruction performances will resolve small-scale anisotropies, the chemical composition and features near the end of the cosmic-ray spectrum.

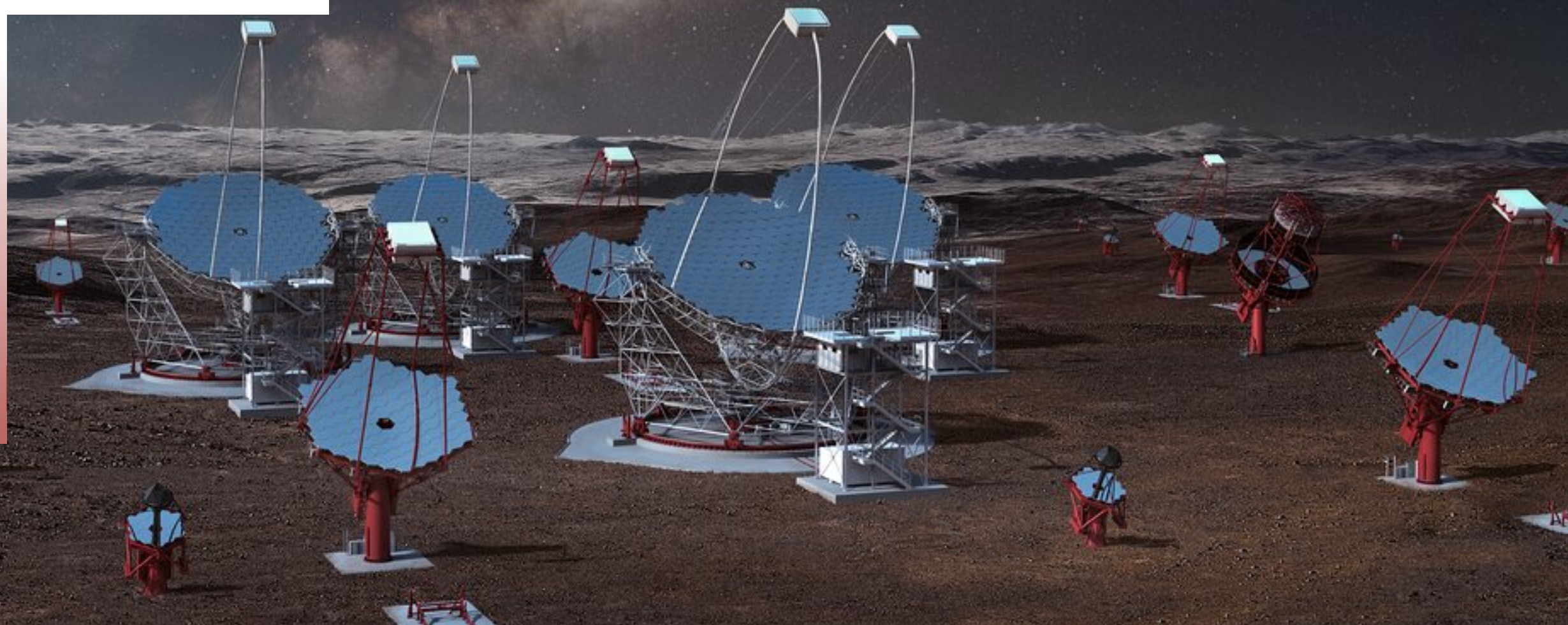
GRAND将观测到比Pierre Auger观测站大10倍的超高能宇宙射线。高统计量和重建性能将解析小尺度各向异性、化学成分和谱尾特征。

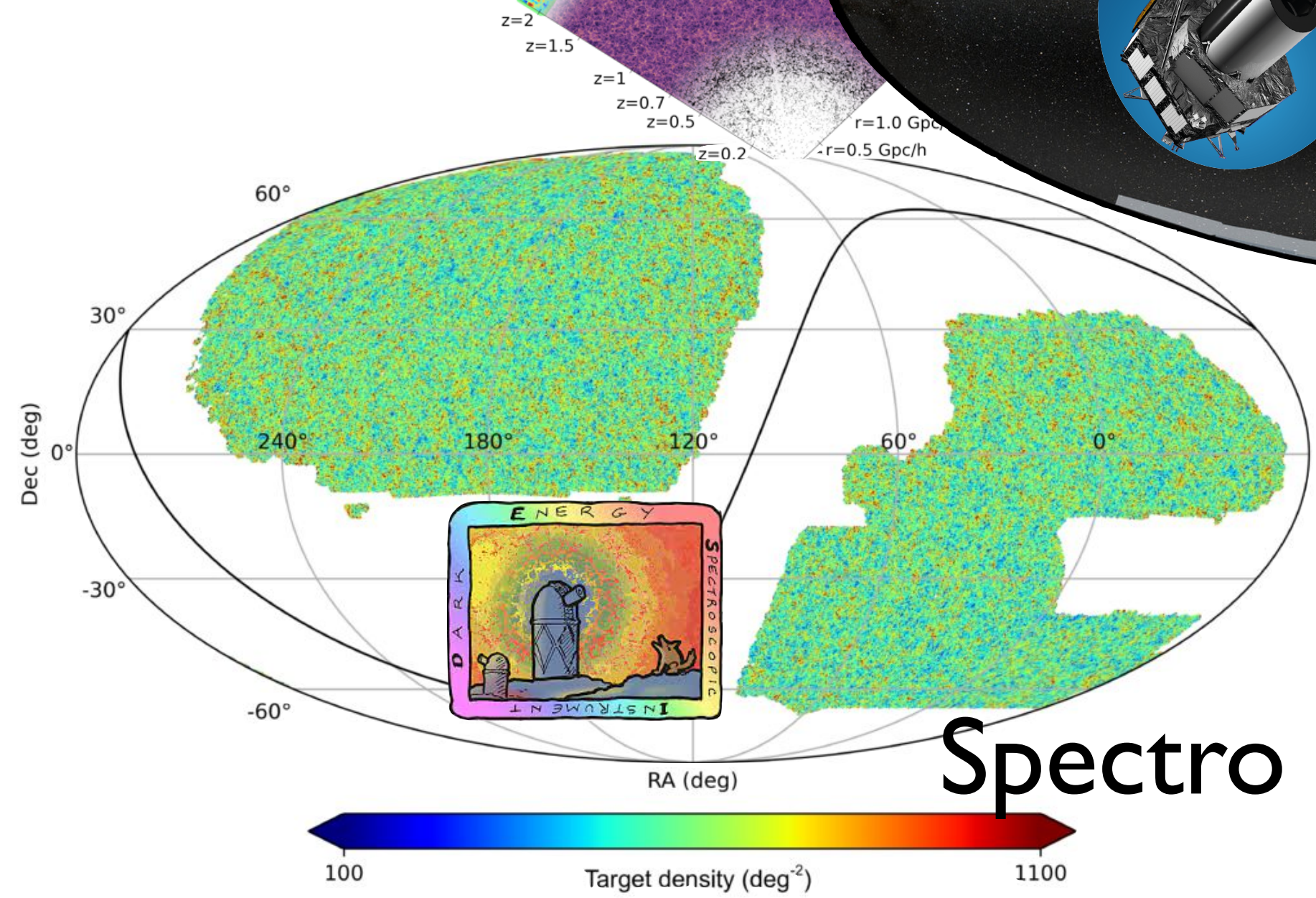
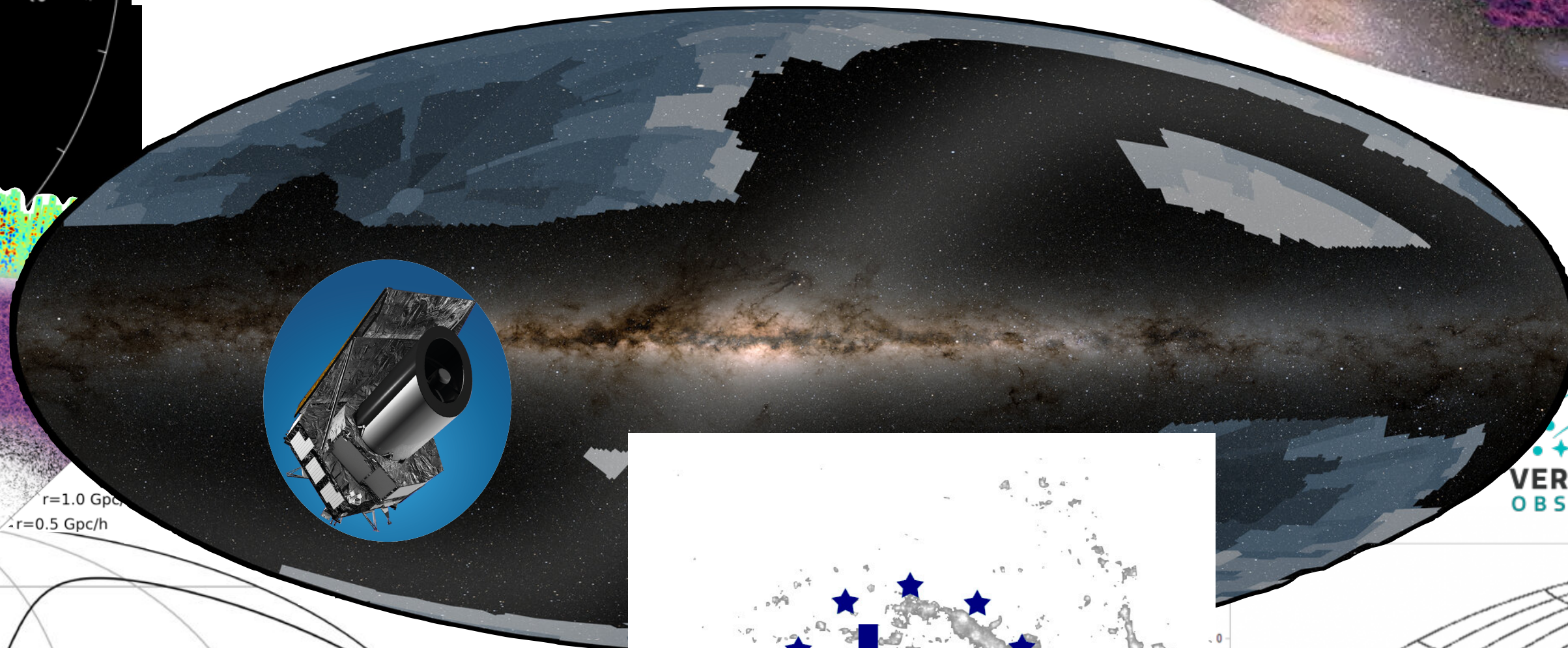
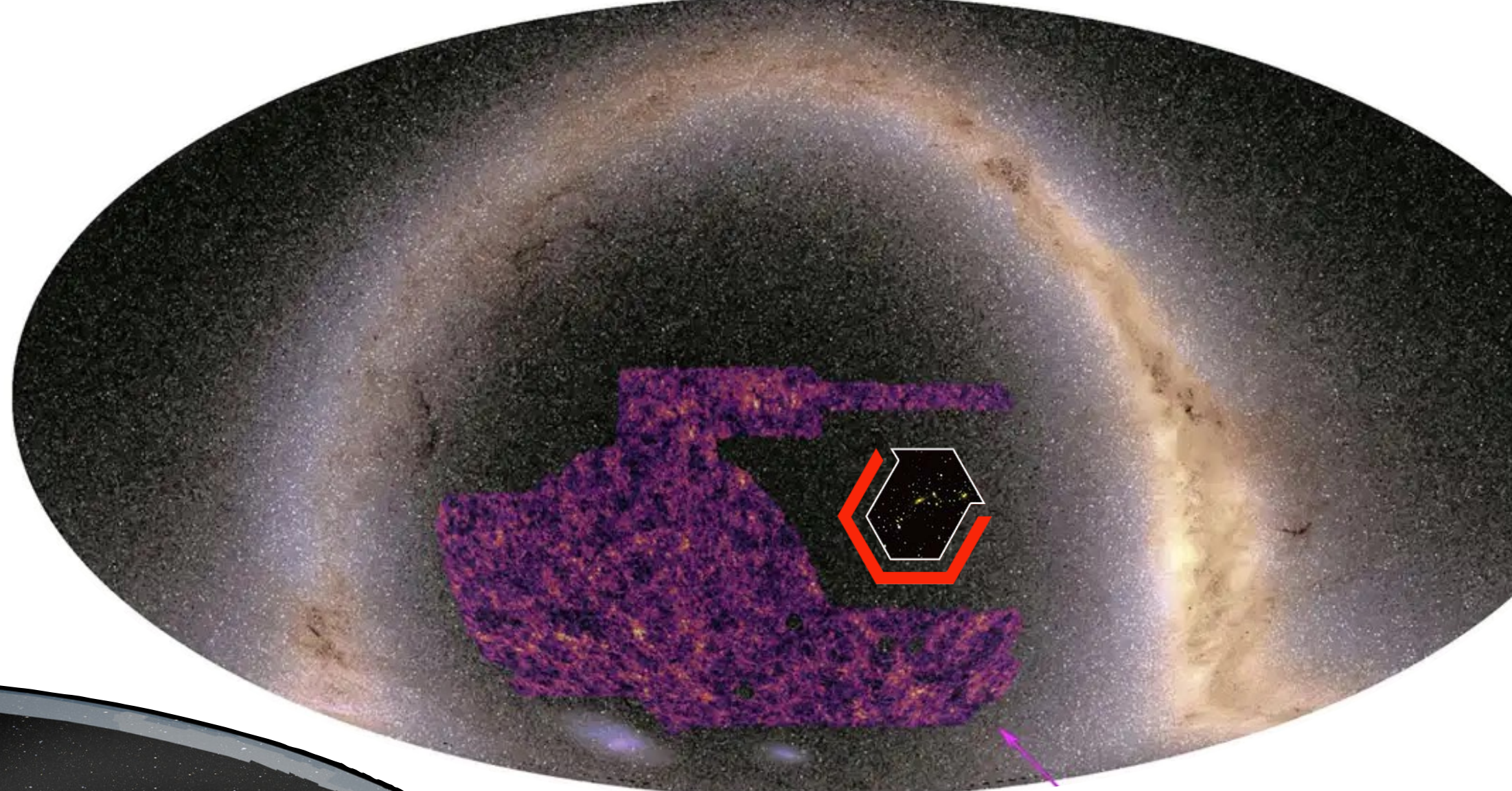
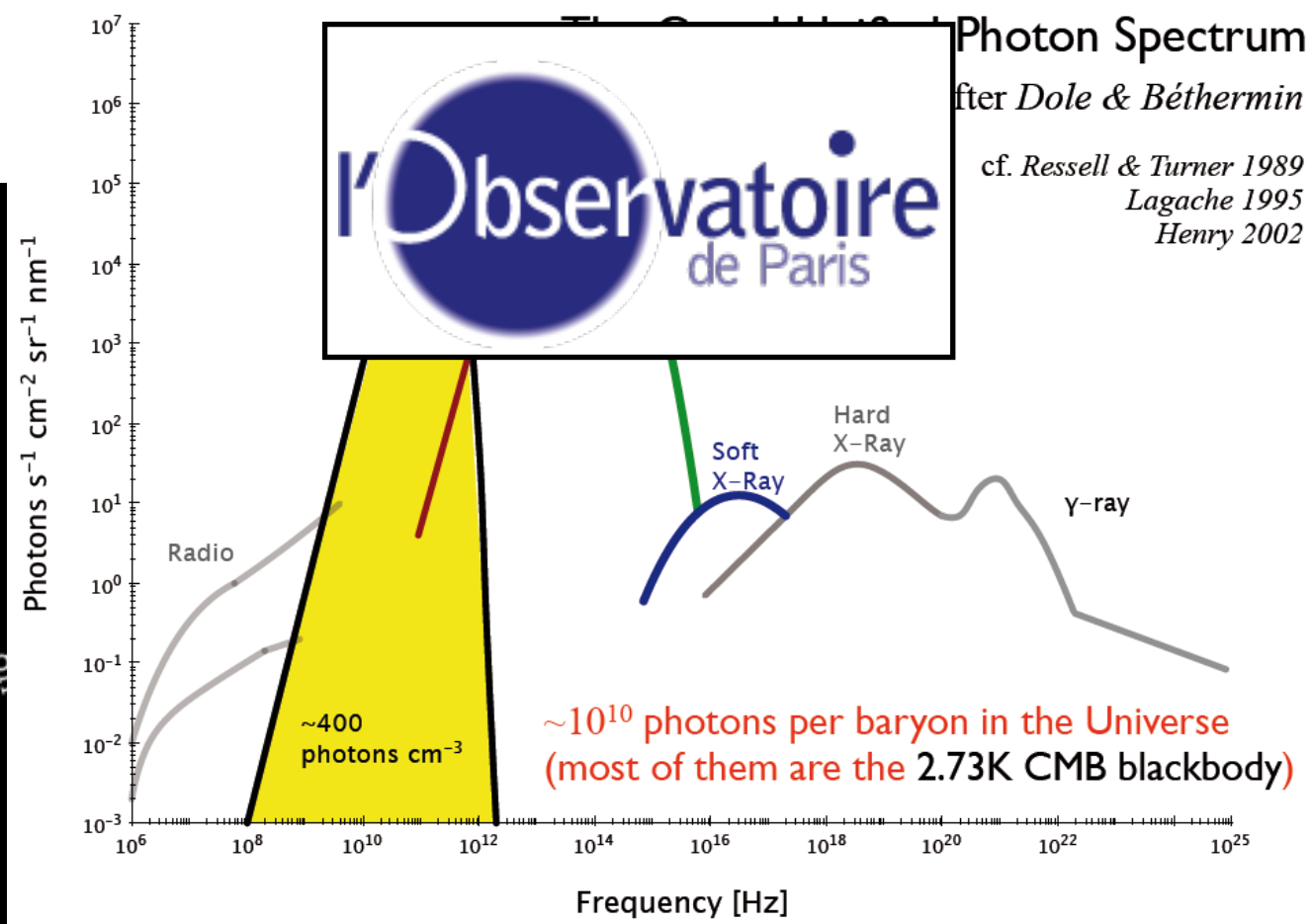
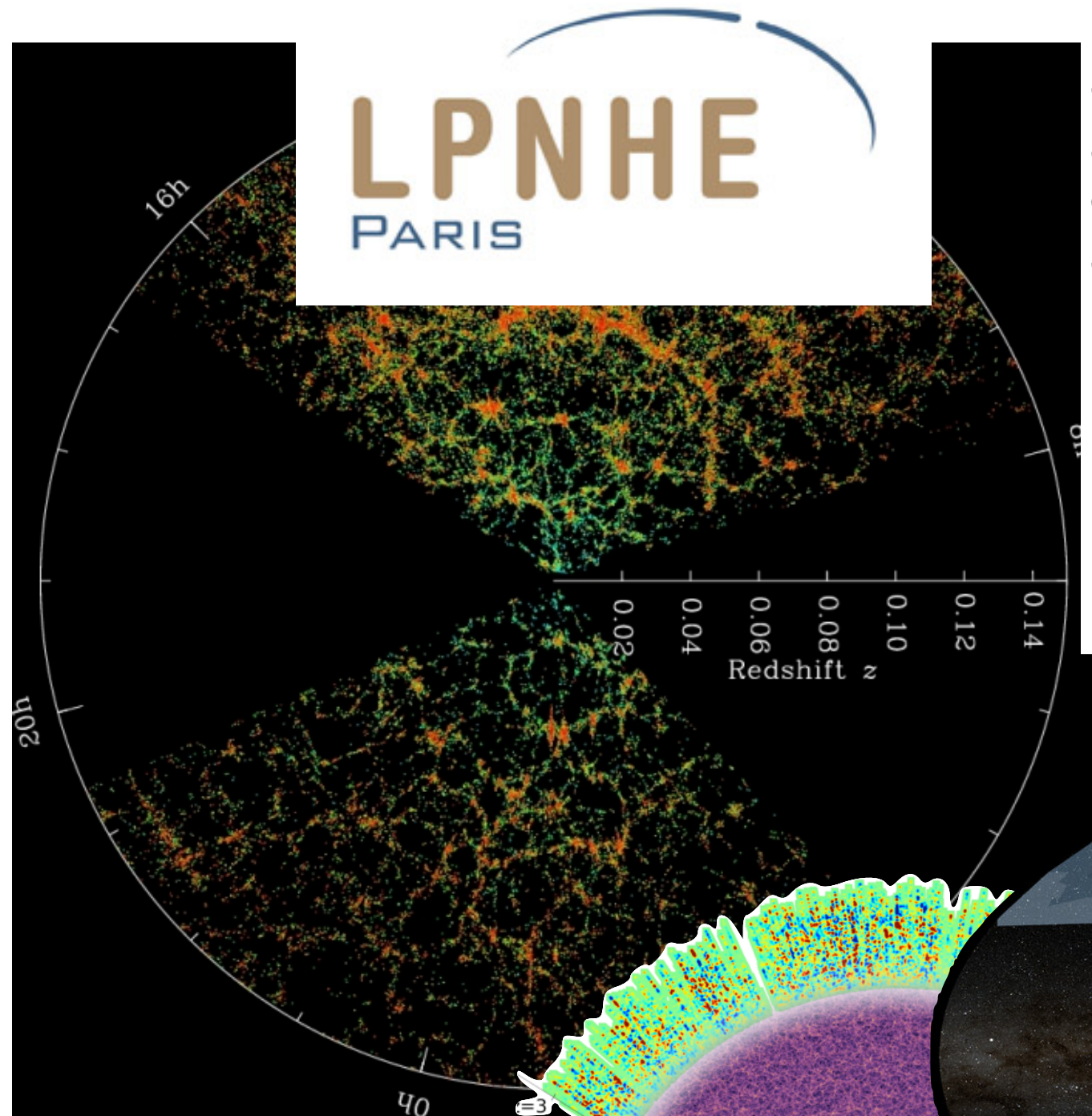


NEUTRINO PHYSICS

Neutrino physics at a scale of magnitude larger acceleration, allowing for the Standard Model and beyond.

在标准模型及超越标准模型的能量尺度上，中微子物理将得到前所未有的加速研究。

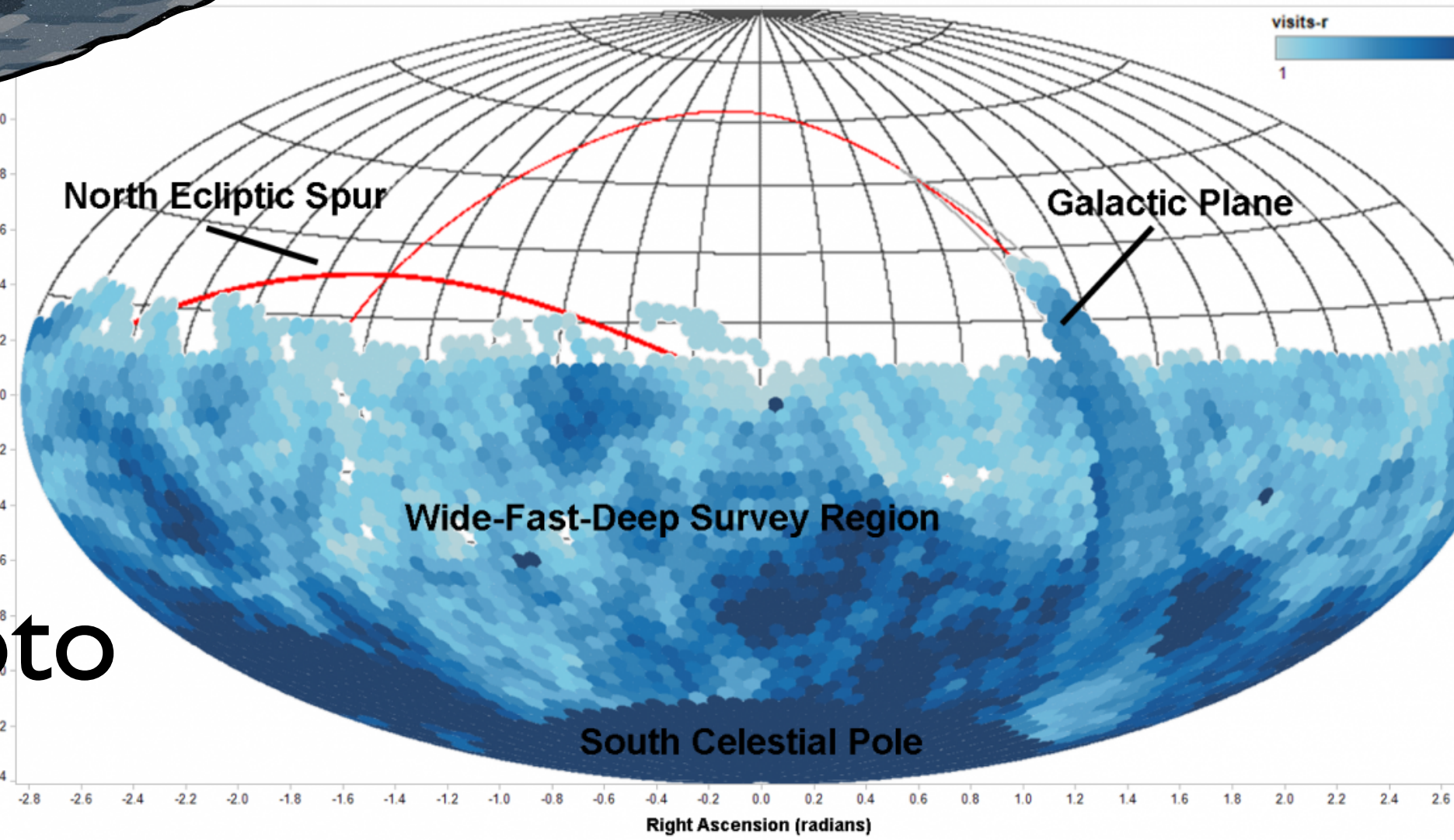




Spectro



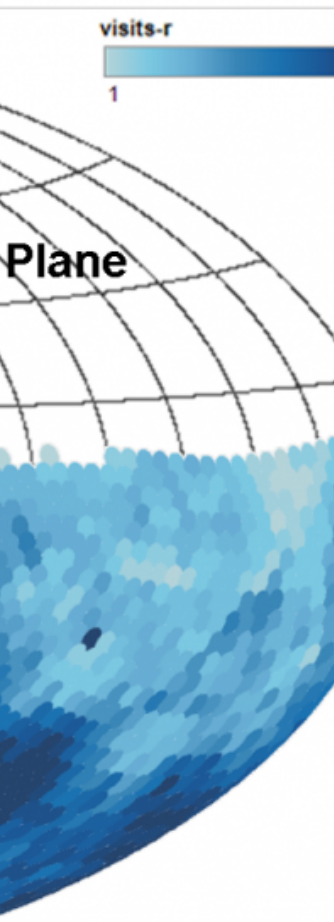
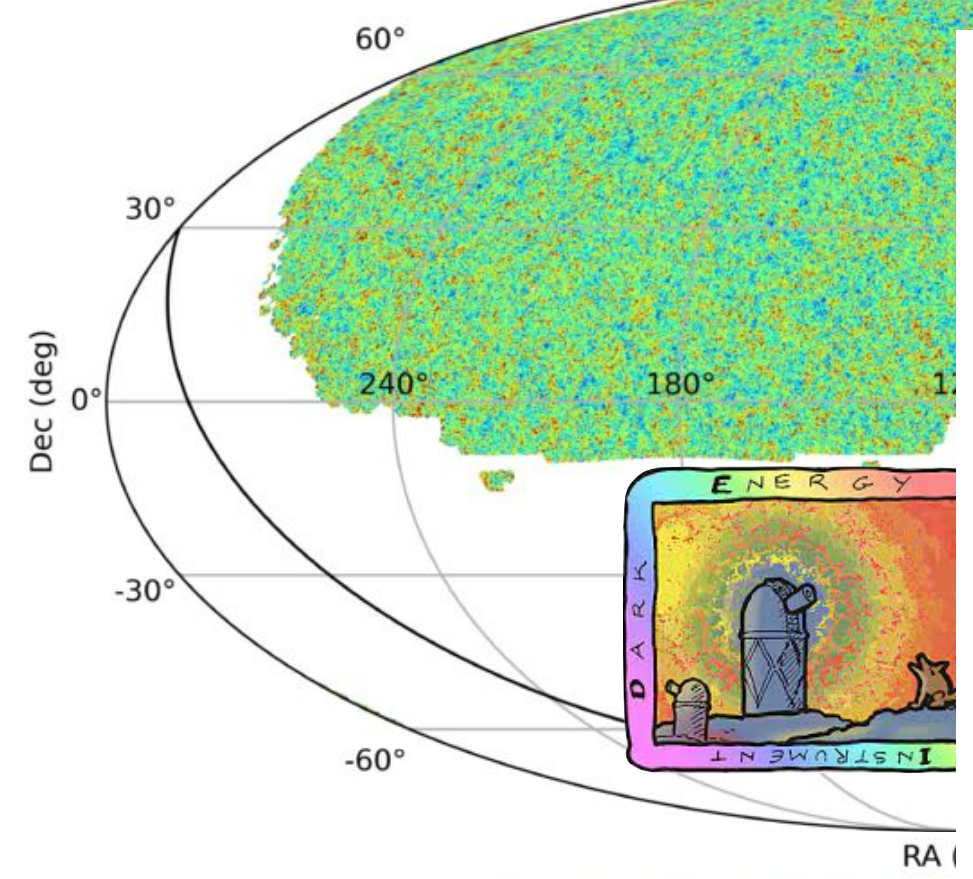
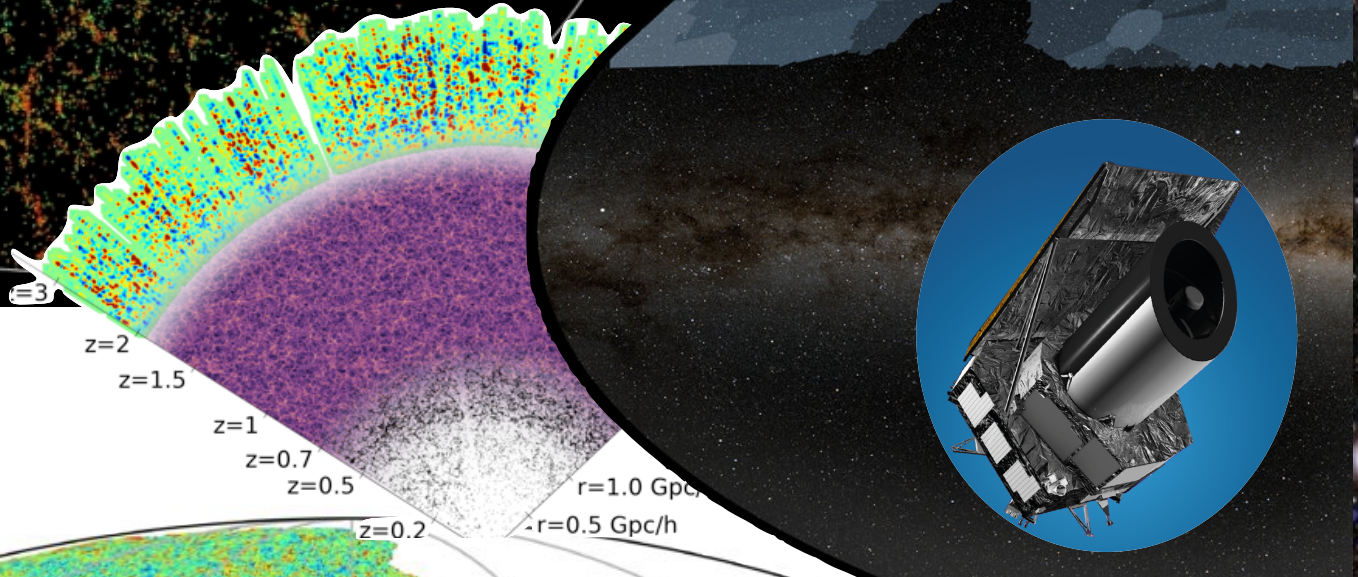
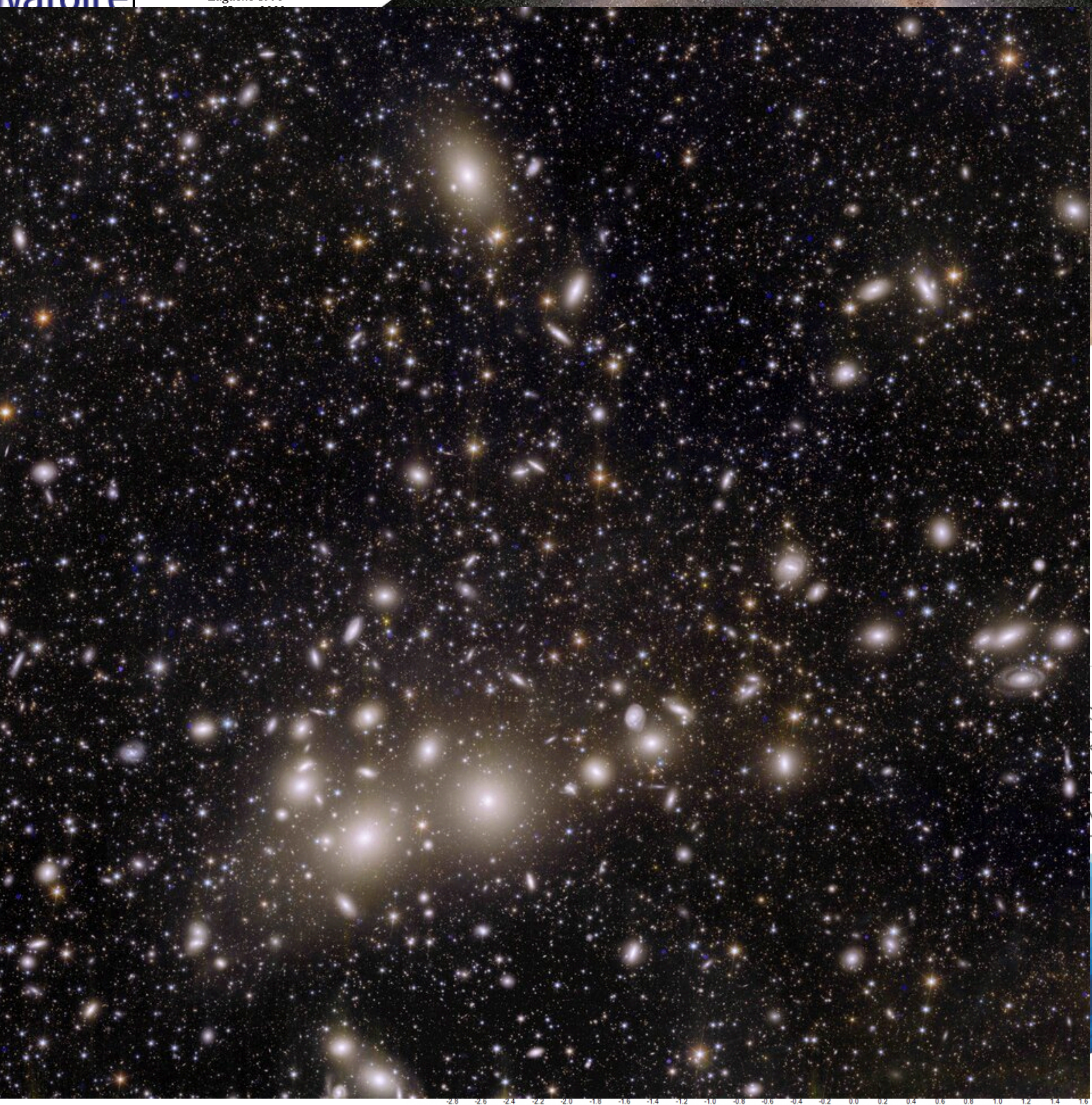
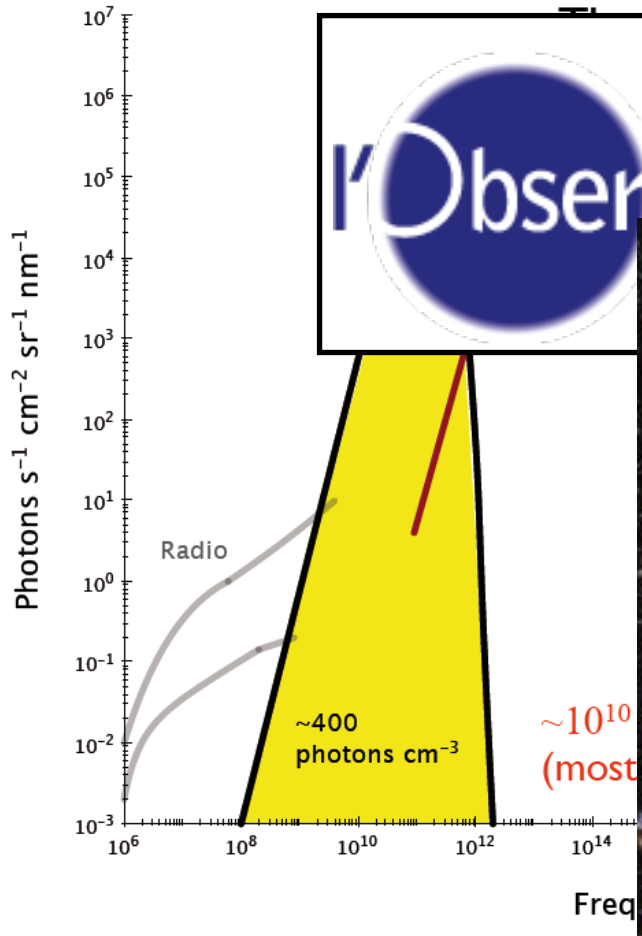
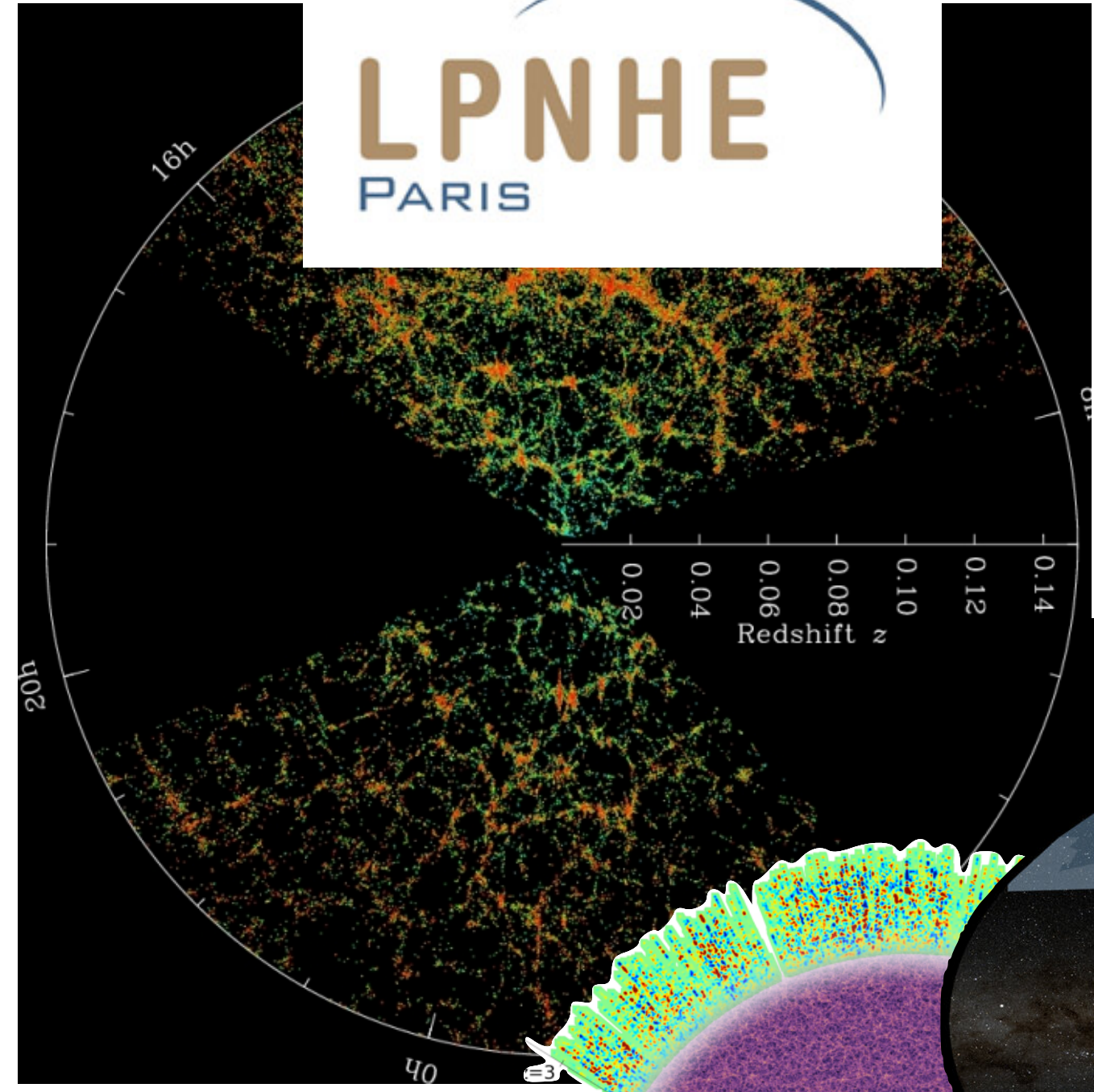
VERA C. RUBIN OBSERVATORY
LSST
 Legacy Survey of Space and Time
 Visits Obtained in r-filter for Year 1



Photo



Photon Spectrum
after Dole & Béthermin
cf. Ressel & Turner 1989
Lagache 1995

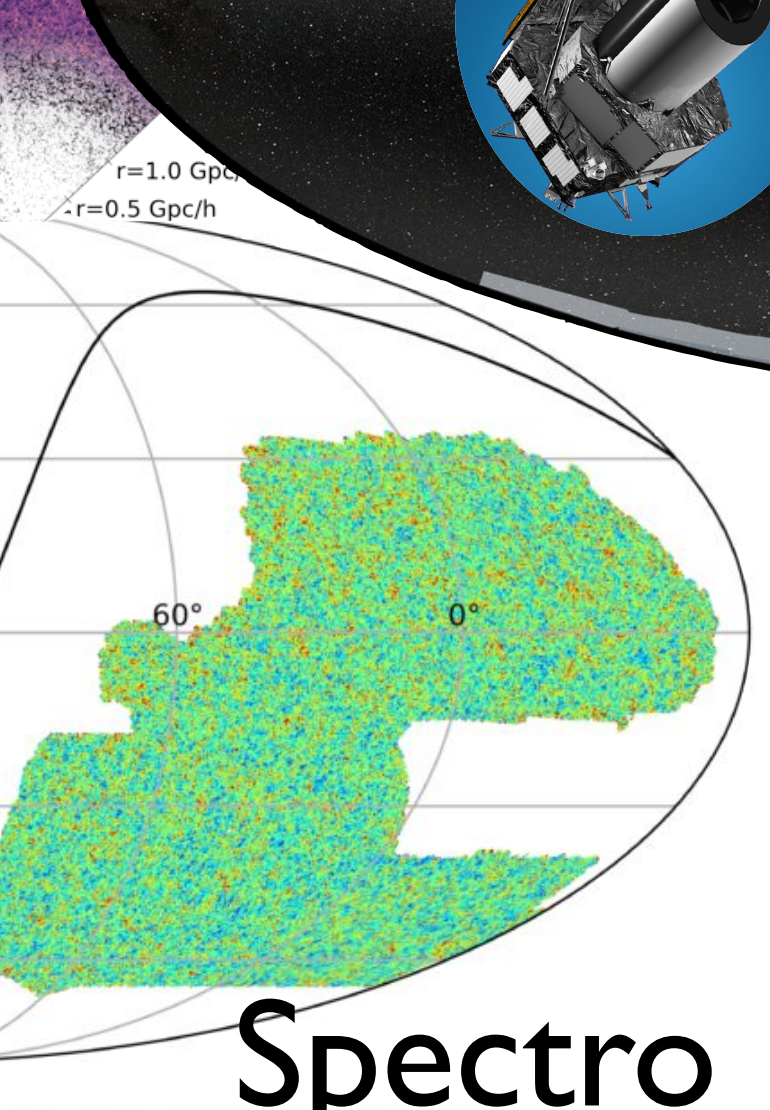
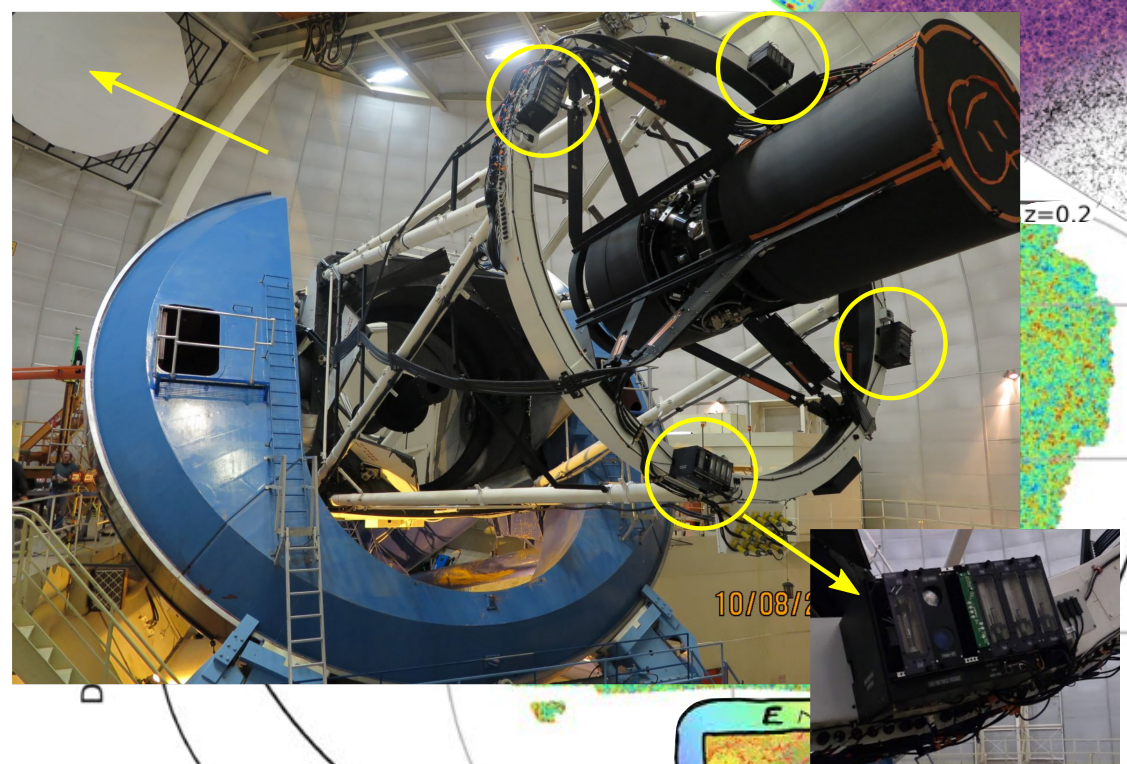
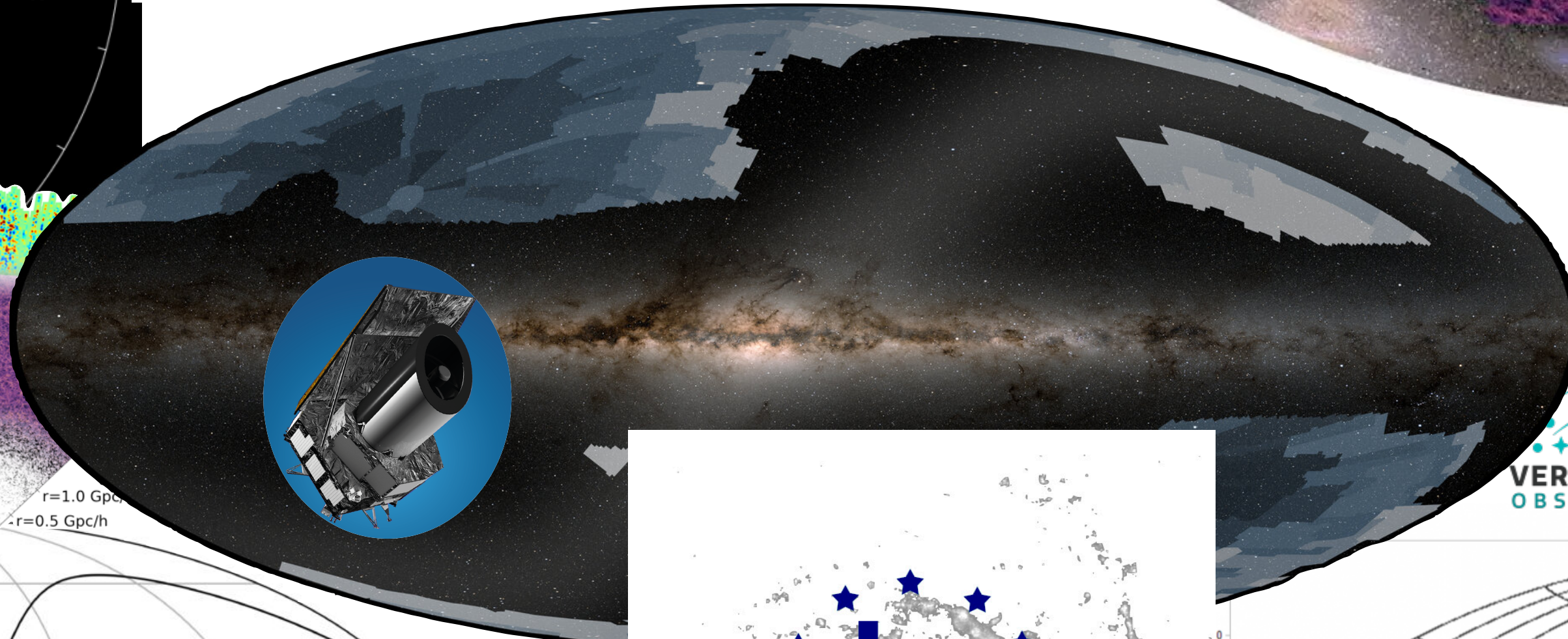
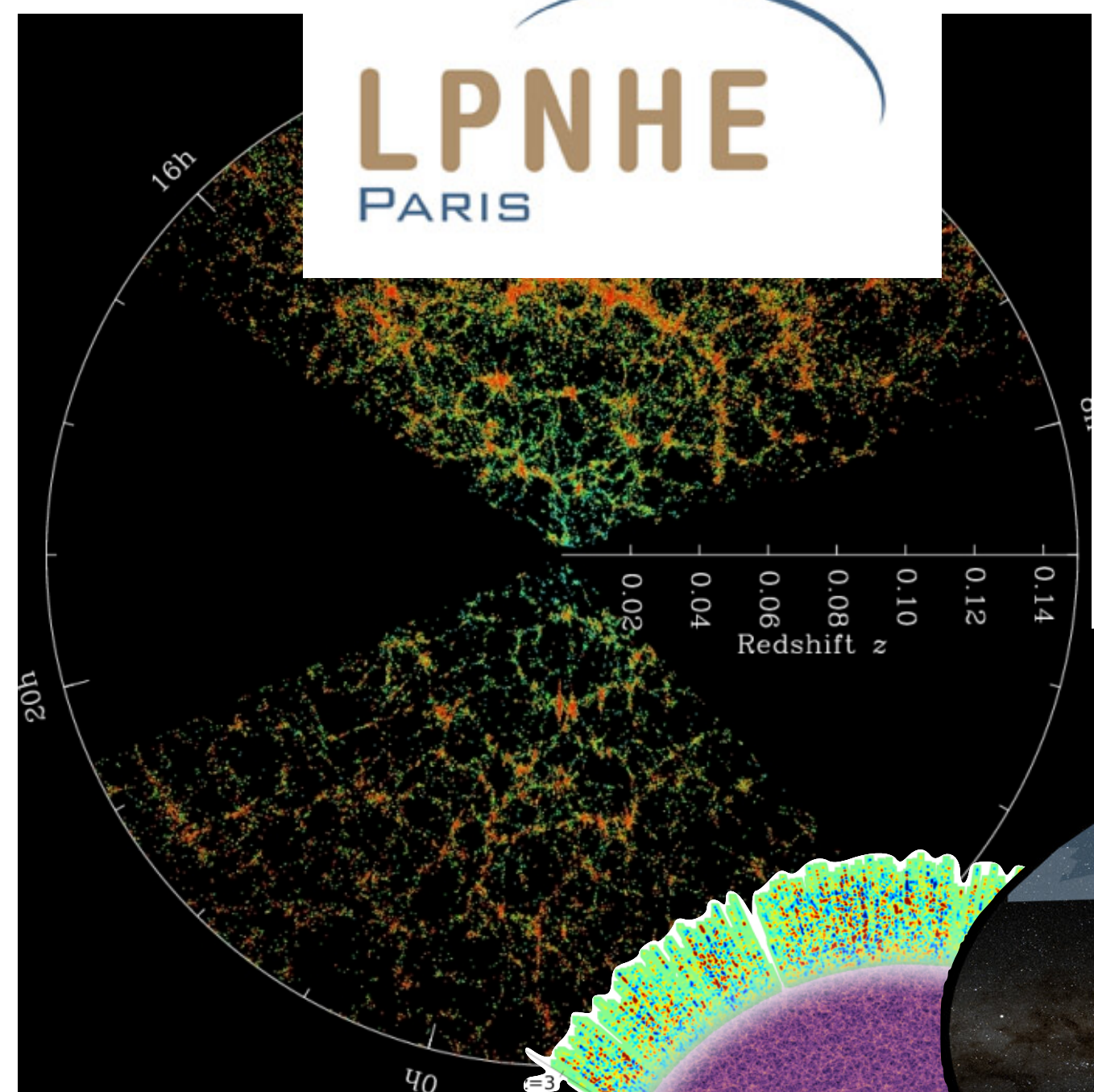
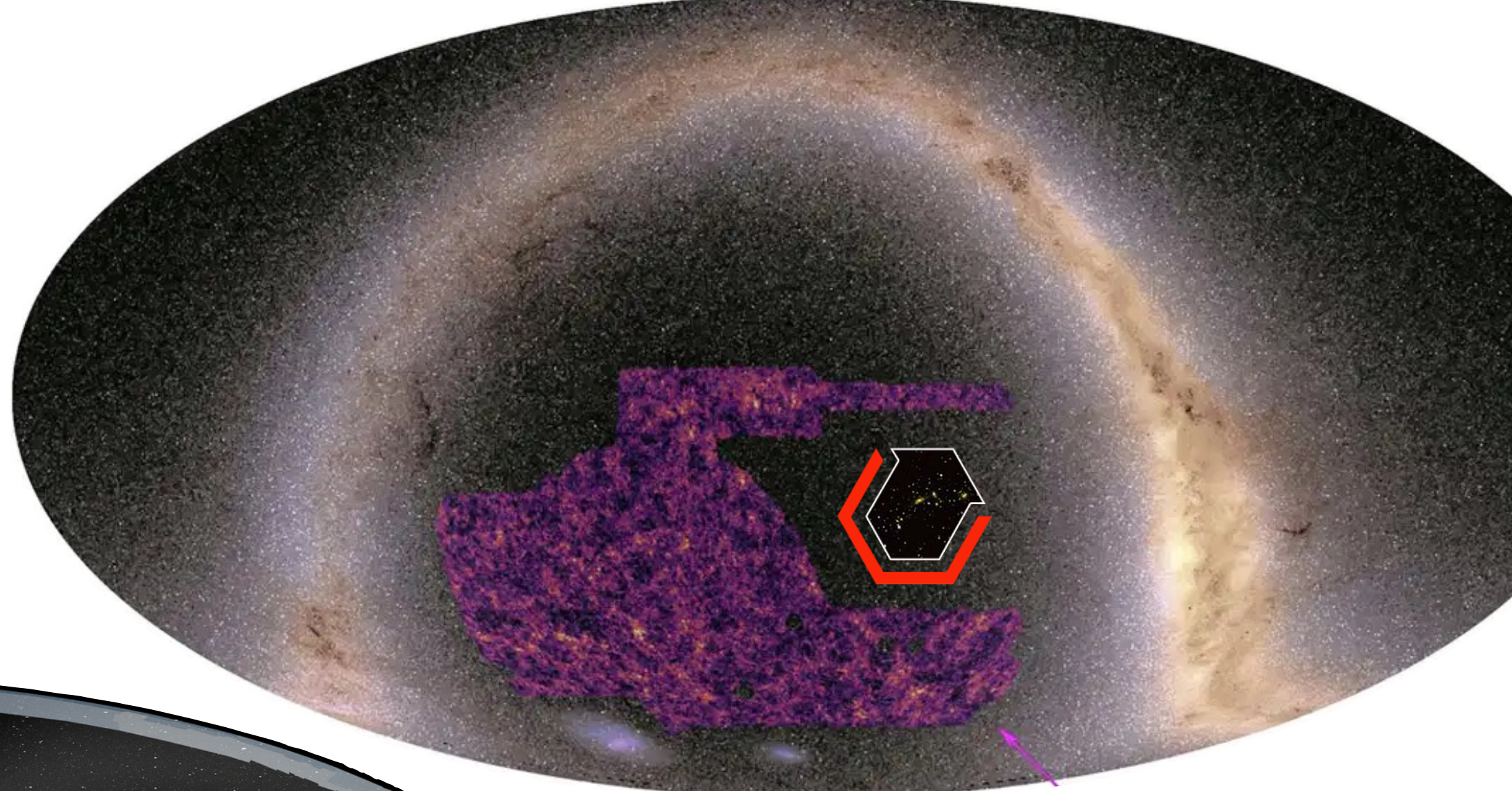
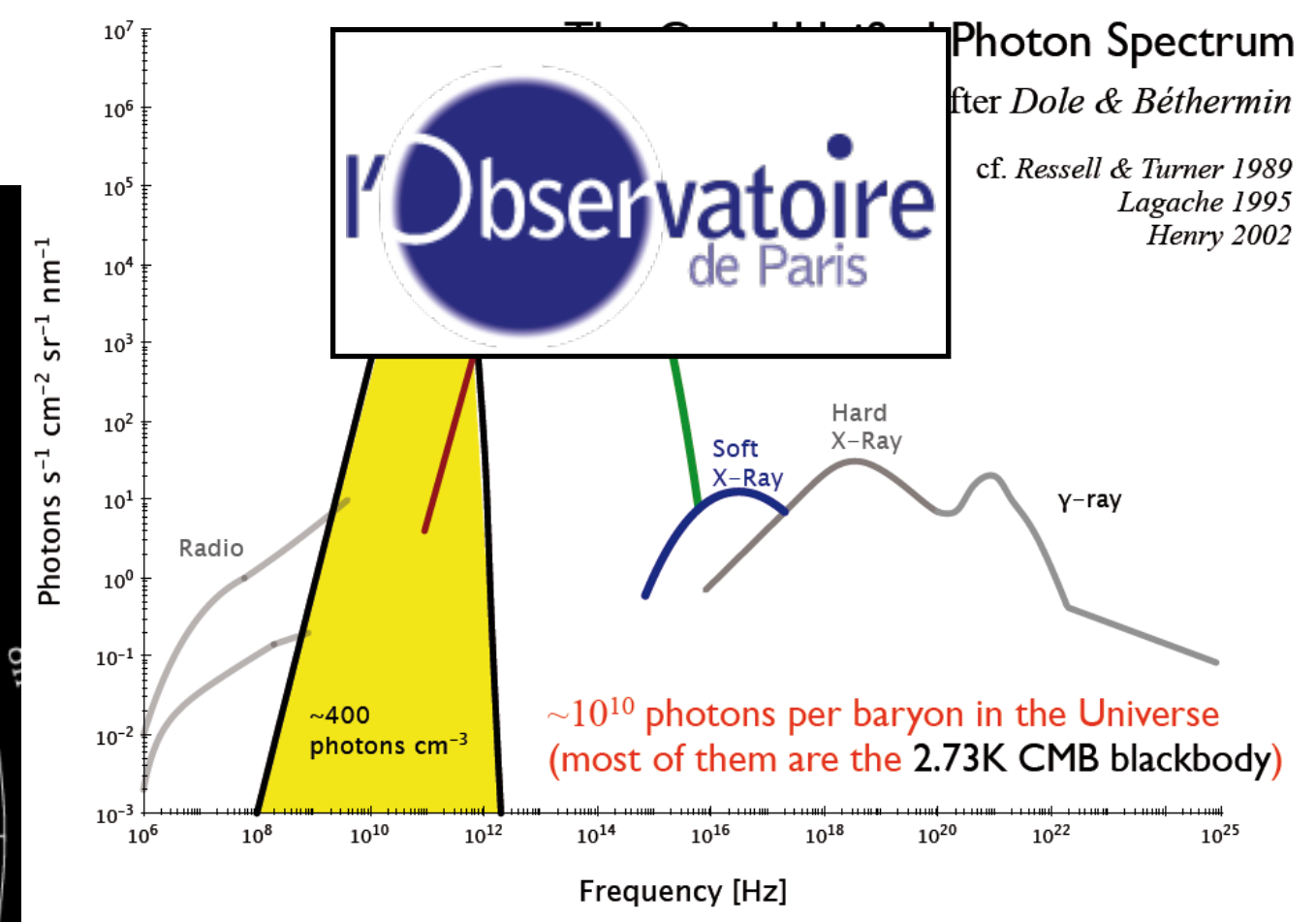


Right Ascension (radians)

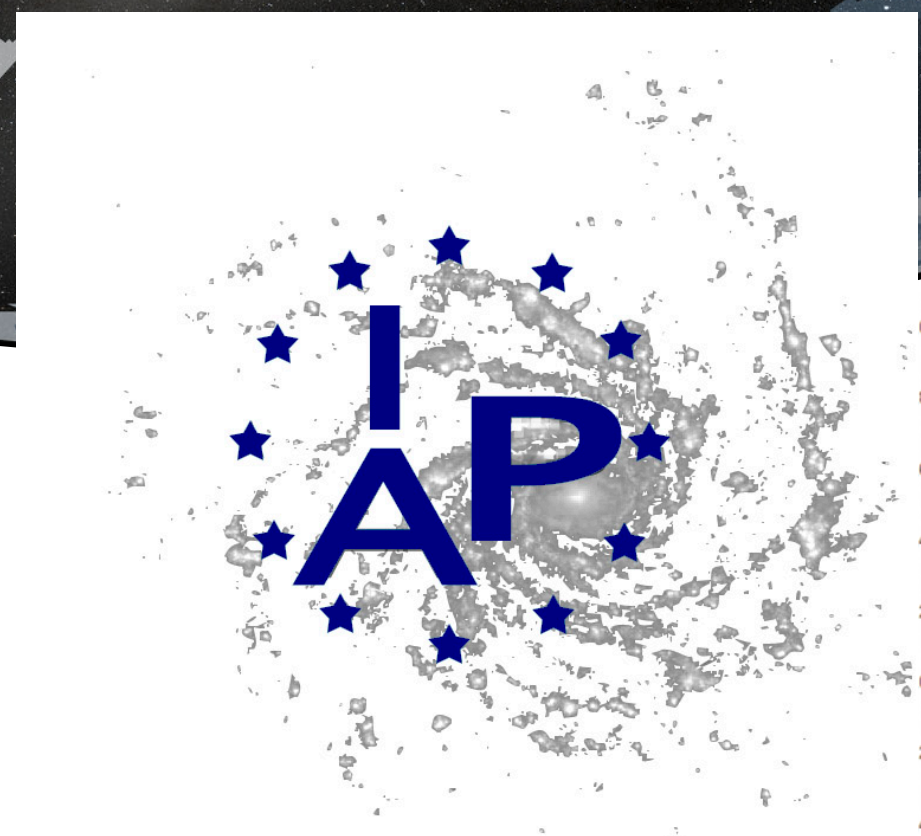
LPNHE
PARIS



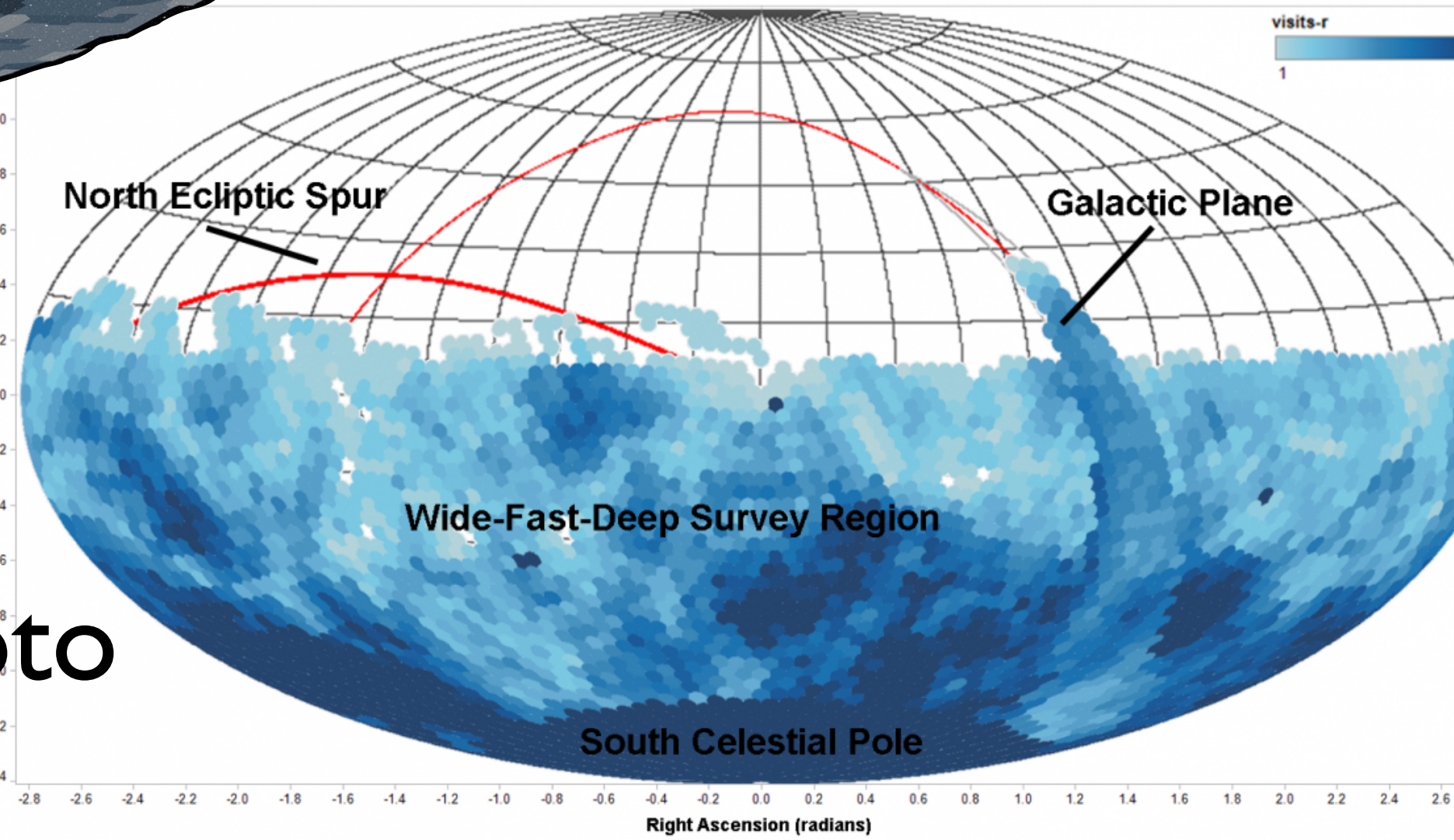
Photon Spectrum
after Dole & Béthermin
cf. Ressler & Turner 1989
Lagache 1995
Henry 2002



Spectro



VERA C. RUBIN OBSERVATORY
LSST
Legacy Survey of Space and Time
Visits Obtained in r-filter for Year 1



Photo

Contribution au Plan focal de LSST

- Début de l'implication dans les ASICs du plan focal : fev 2007
- 2 labos (LPNHE , IJCLab) impliqués dans ces développements ASICS
- En plus au LPNHE : interaction CCD-vendeur , Optimisation lecture CCD & contrib. design readout , micro-code du plan focal
- Au LPNHE : un banc test CCD LSST dédié à l'optimisation de la lecture & études fines CCD
- Plan Focal au LPNHE: 35 ETP ITA (0.2 ETP ITA en 2023) pour un total IN2P3 ~3 M€ > 50 ETP ITA
- Participation au commissioning

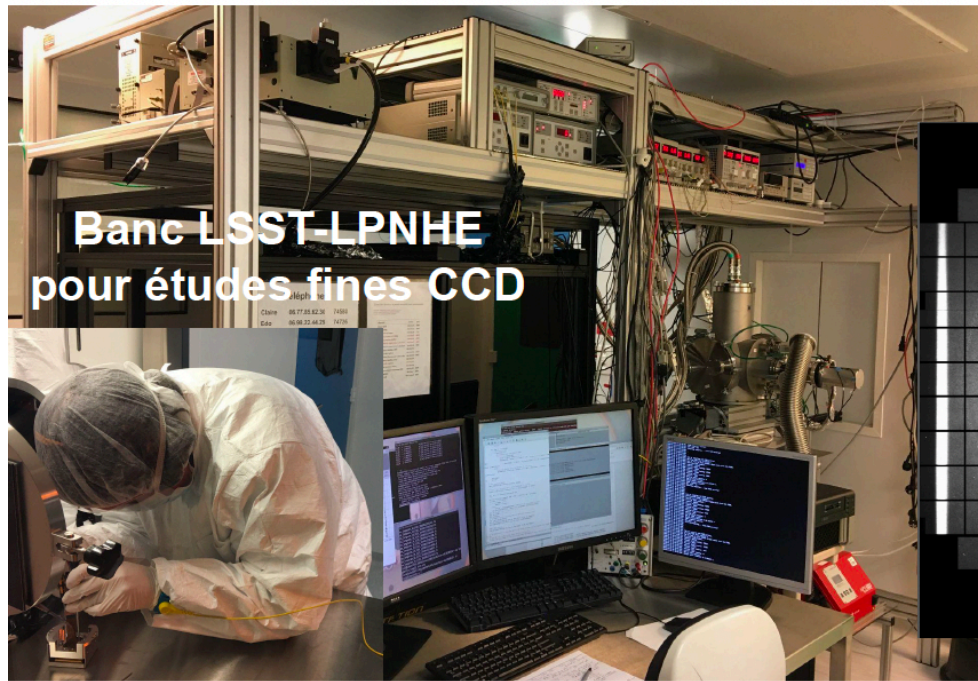
C.Juramy , Cristal 2020 pour son travail sur les CCD dans le cadre du Plan focal de LSST

Photon Spectrum

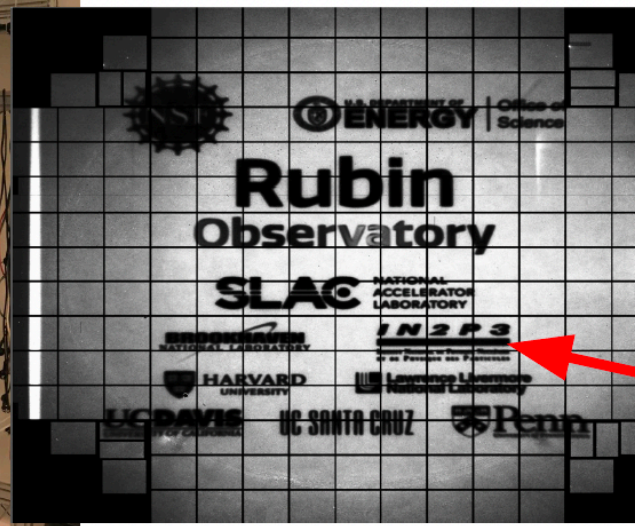
Le Changeur de Filtre de la caméra de LSST

- 1ère études fin 2006 (carousel au LPNHE)
- 5 labos de l'IN2P3 impliqués
- un cout total à l'IN2P3 de 2.3 M€ + > 100 FTE
- Au LPNHE: ~ 40 ETP ITA (dont ~0.7 ETP en 2023)

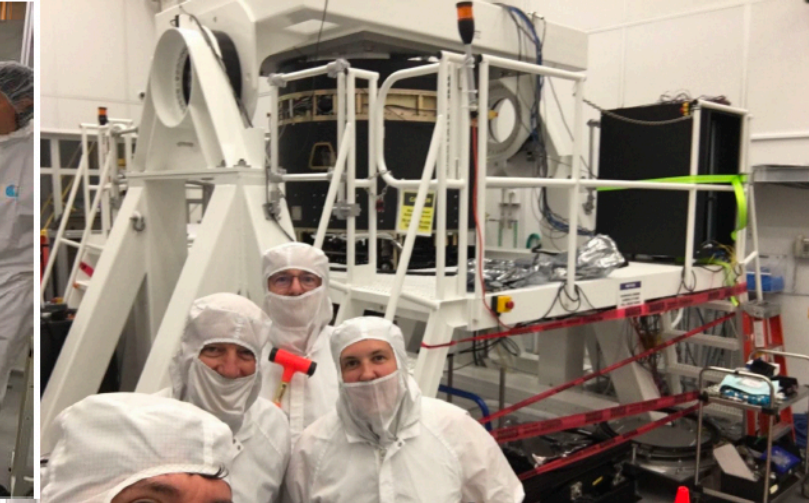
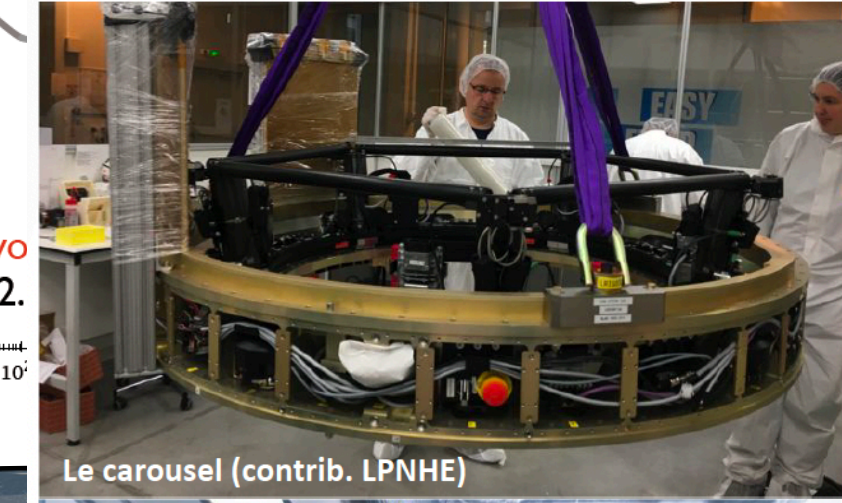
11 ITA des labos du changeur de filtre (APC,CCPM,LPC,LPNHE,LPSC) (dont 4 du LPNHE) ont reçu le Cristal Collectif 2021 !!!



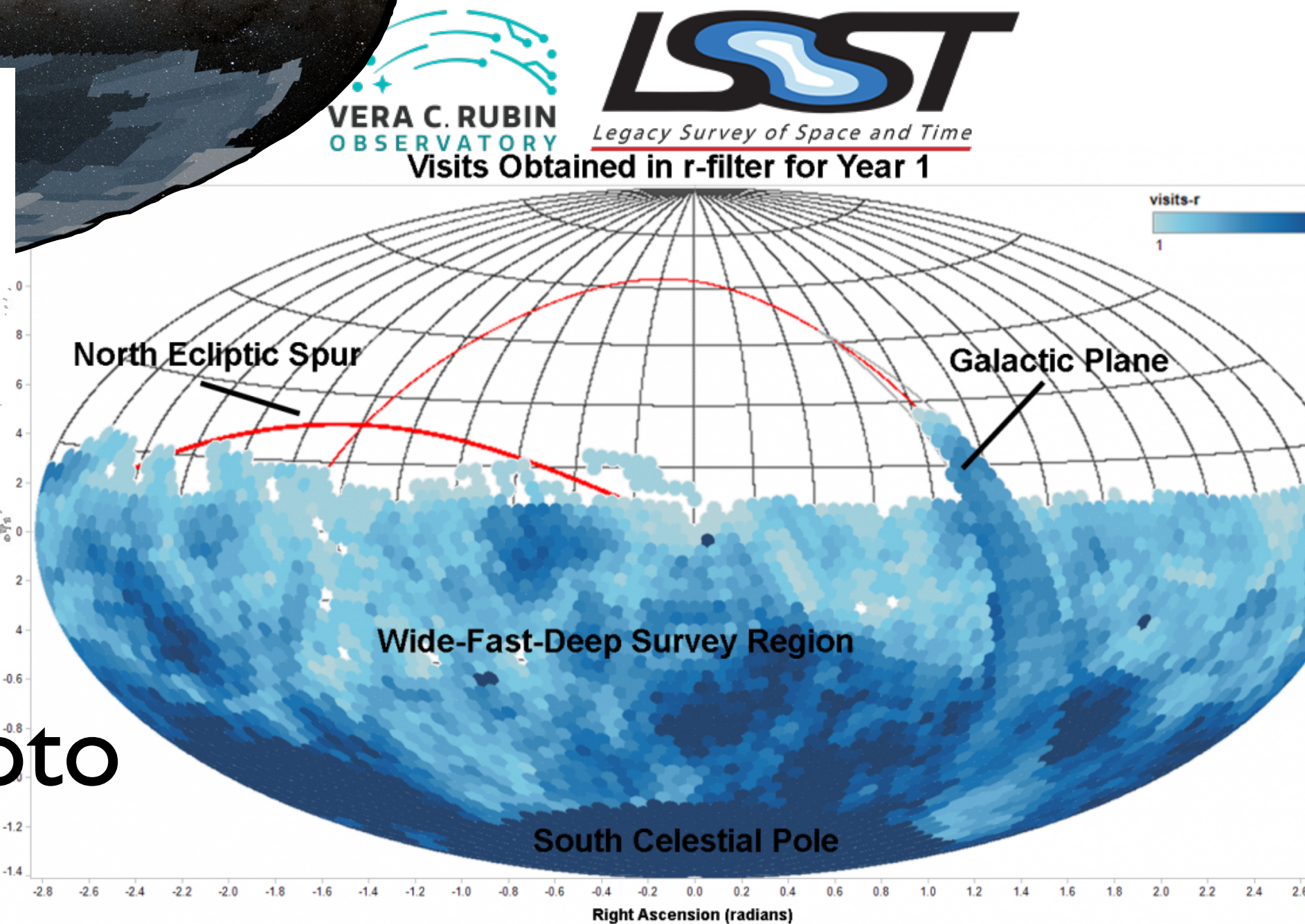
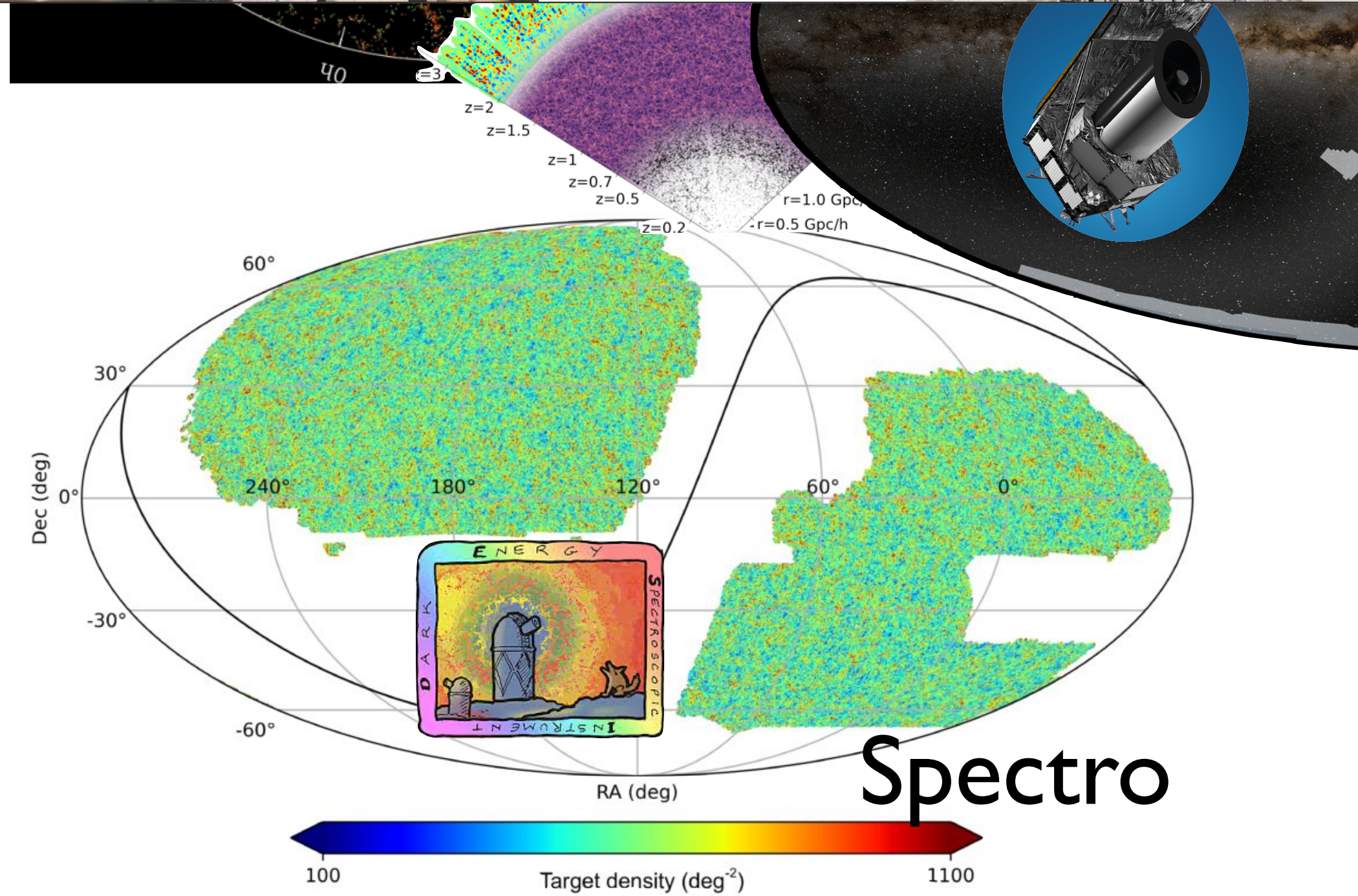
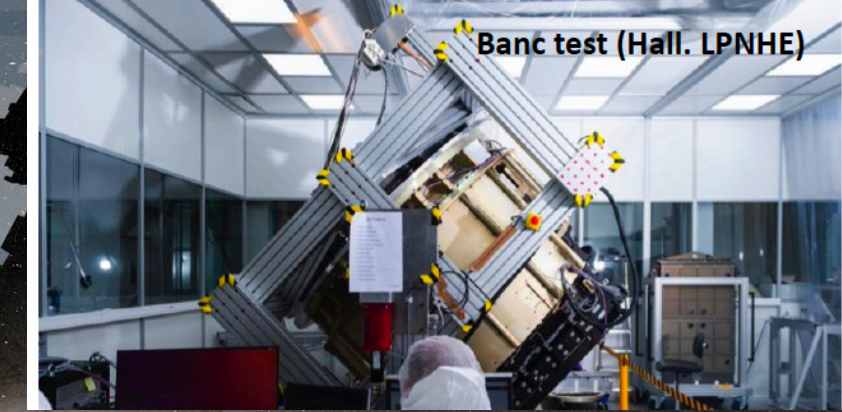
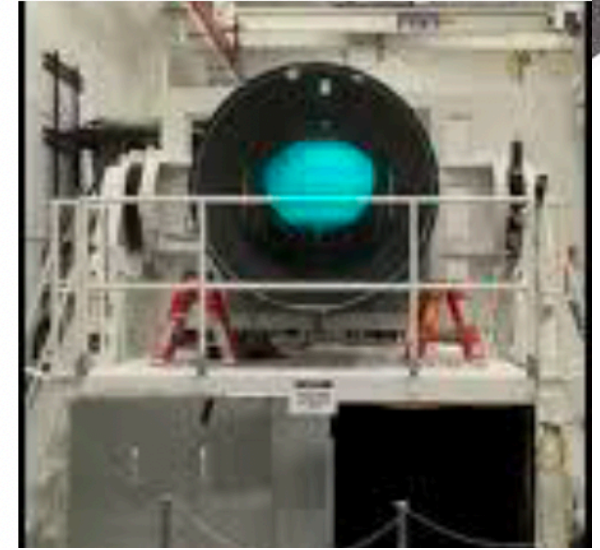
Première image 18 août 2020



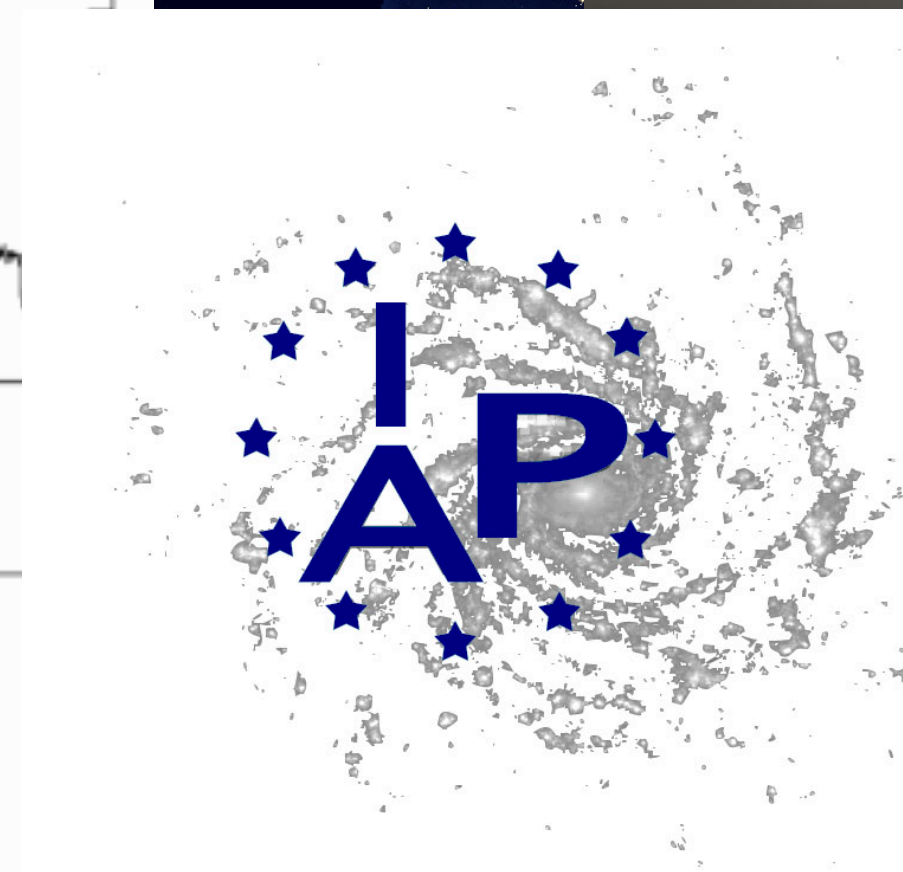
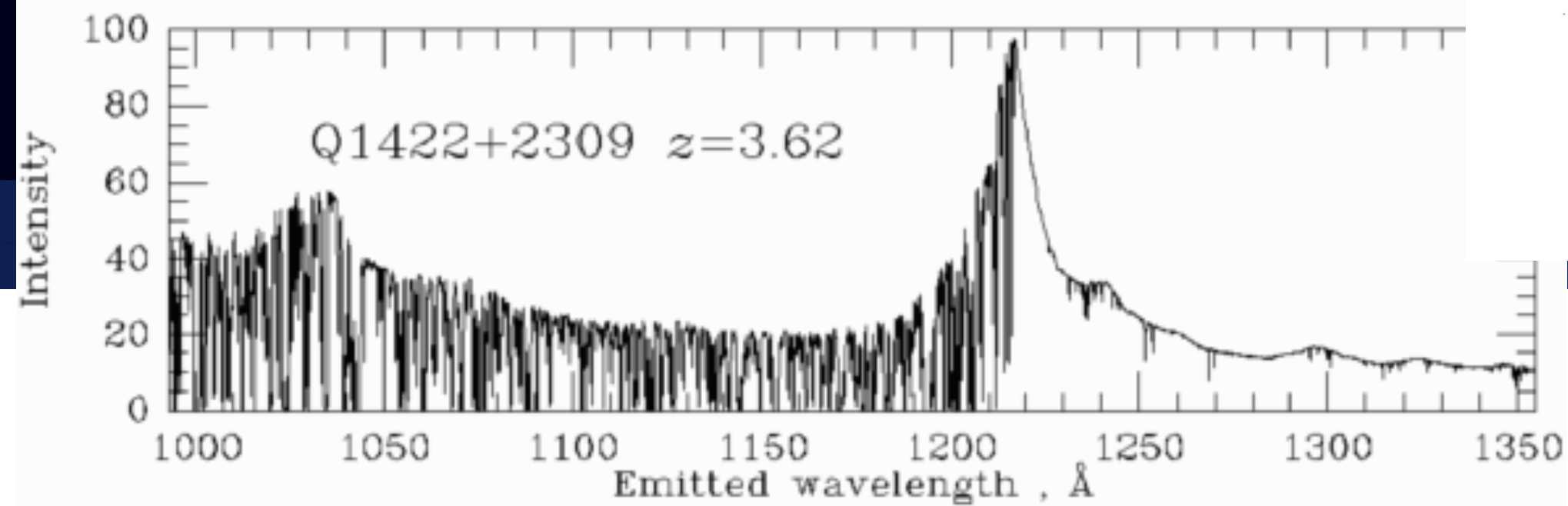
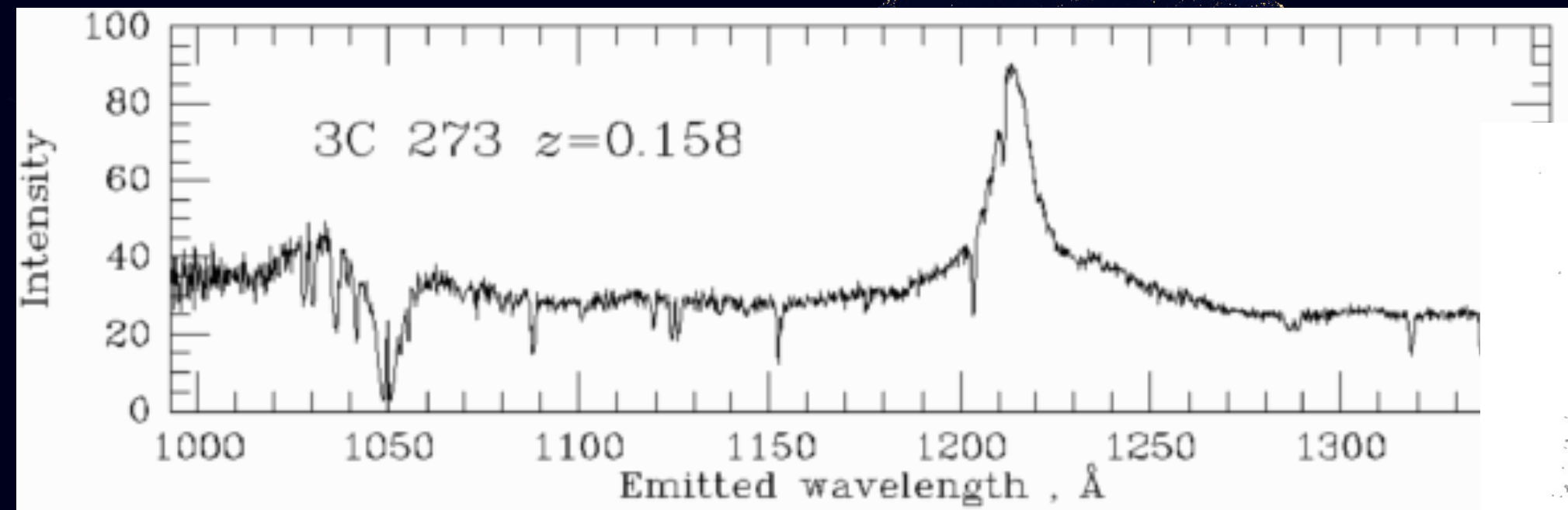
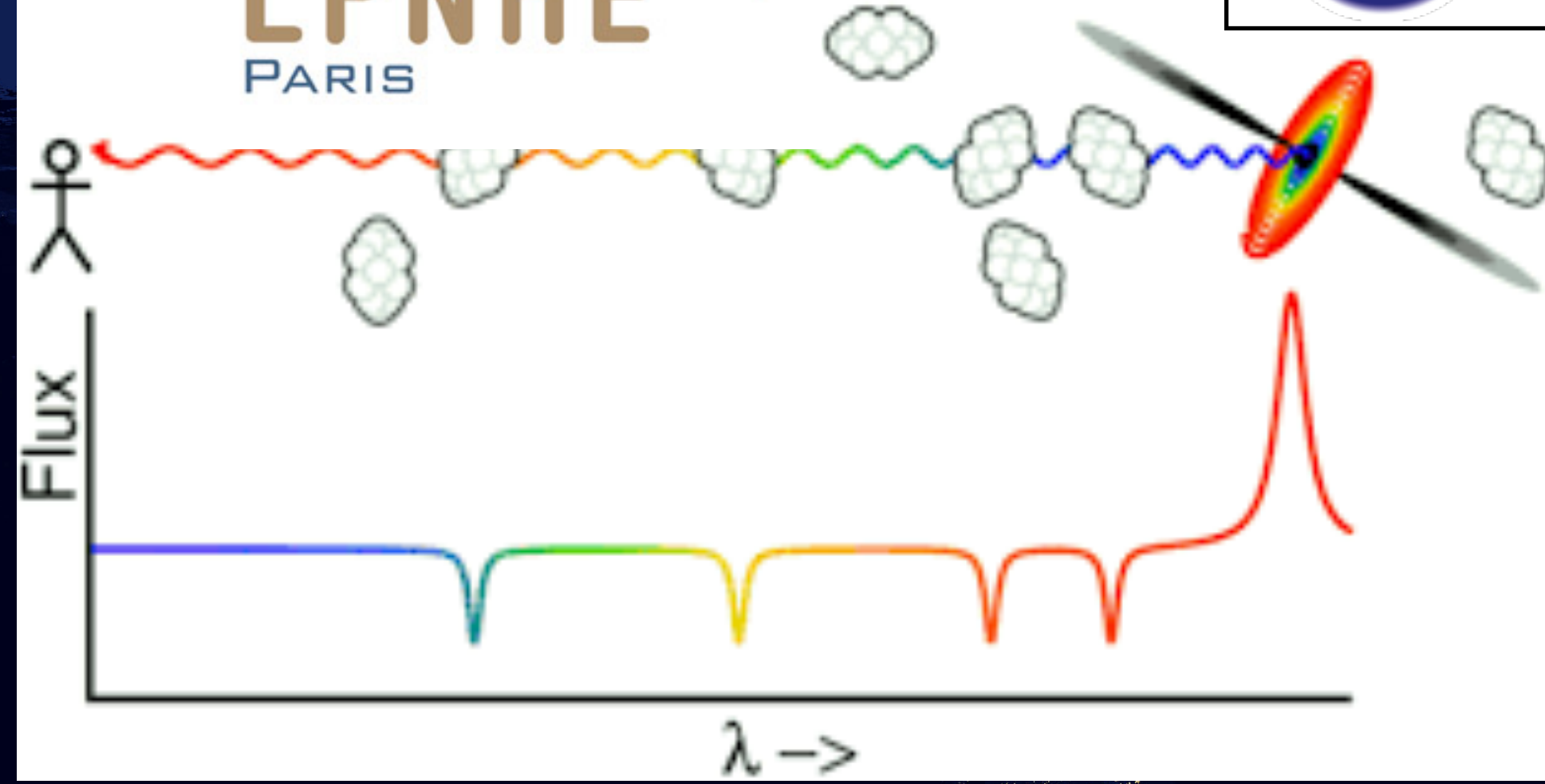
Sep 2022 : caméra + plan focal complets



Changeur de filtre installé à SLAC depuis fin 2019 : 100% opérationnel aujourd'hui

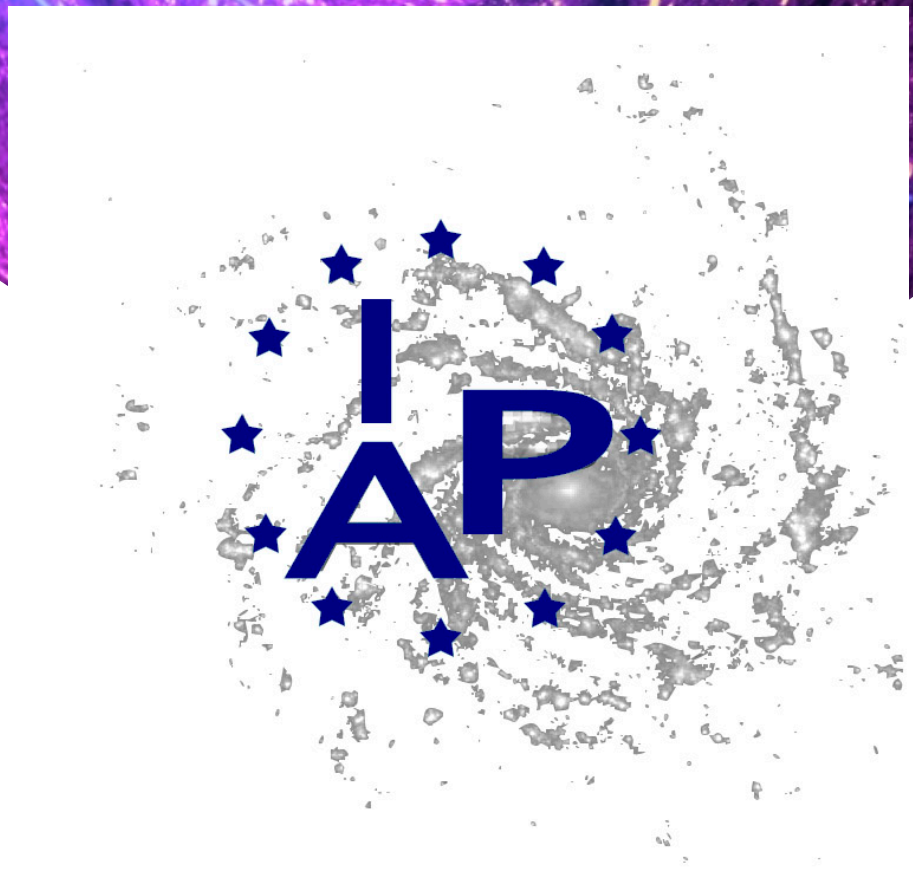
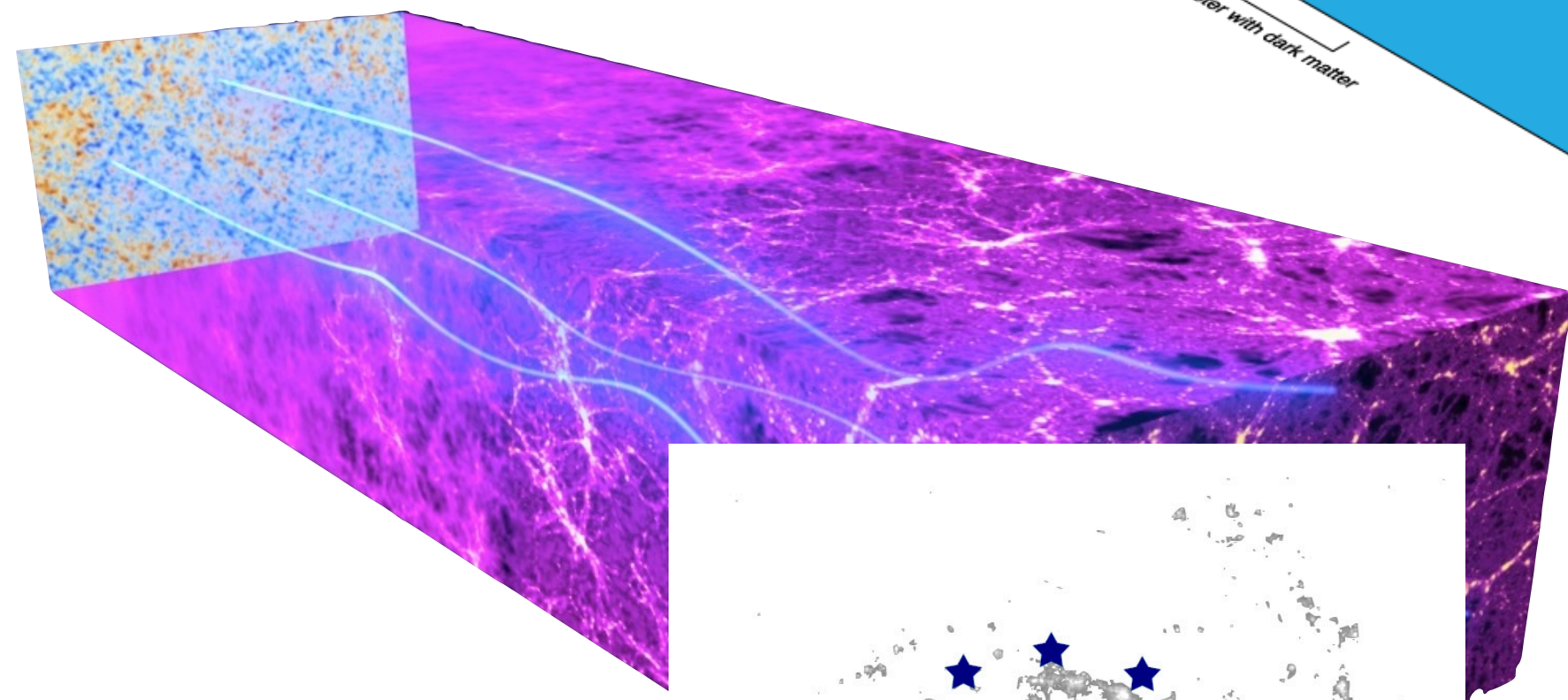
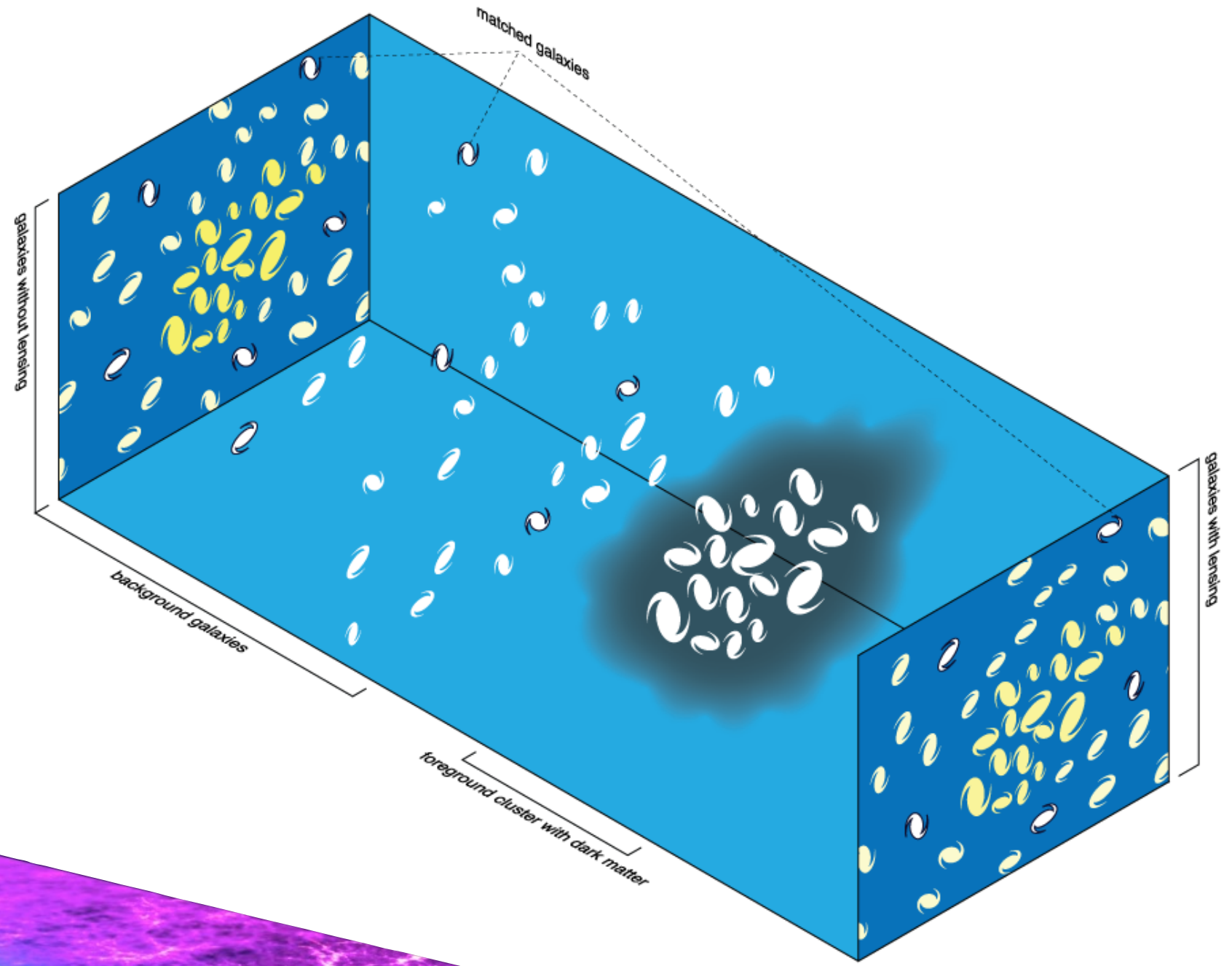
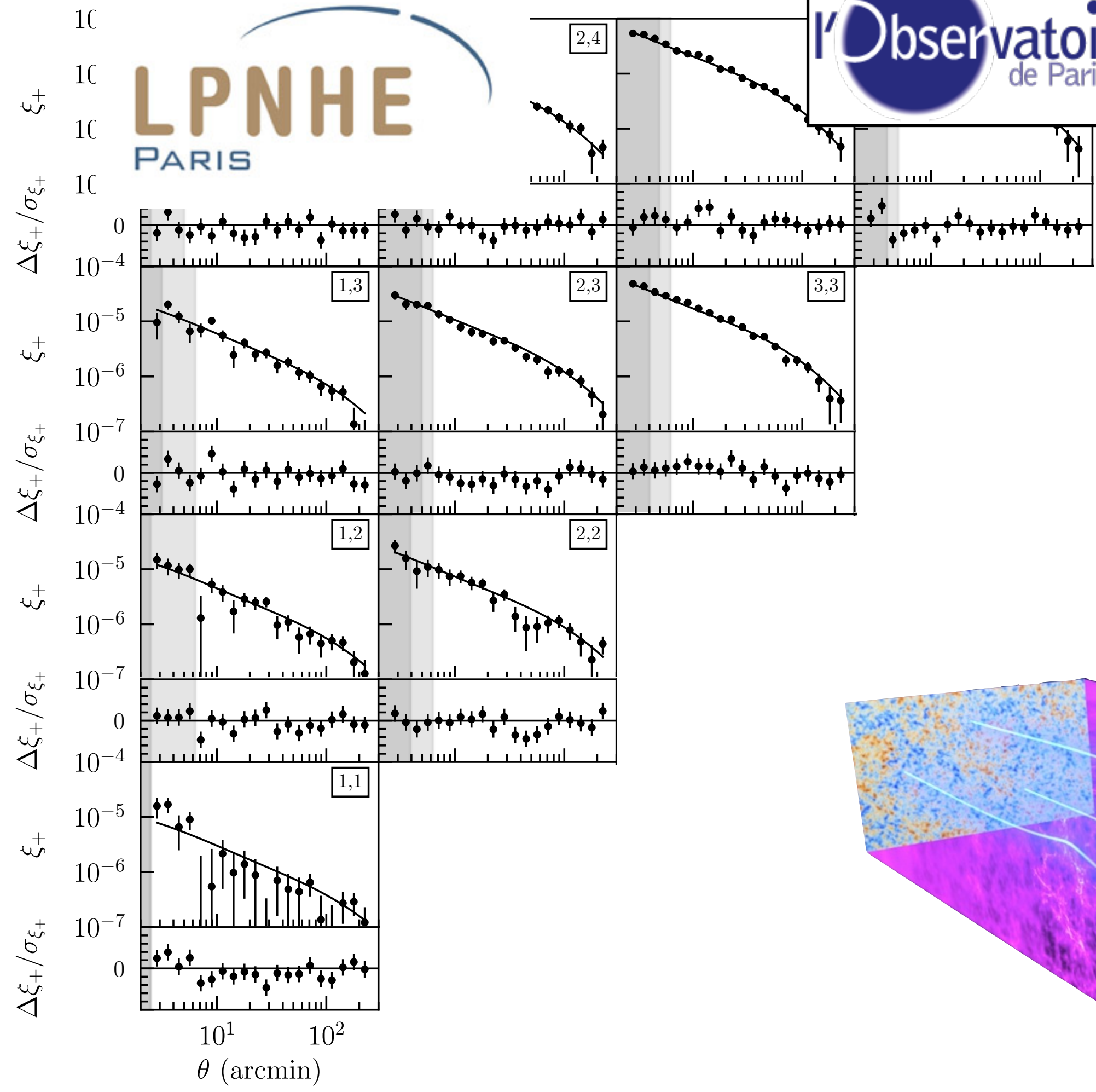


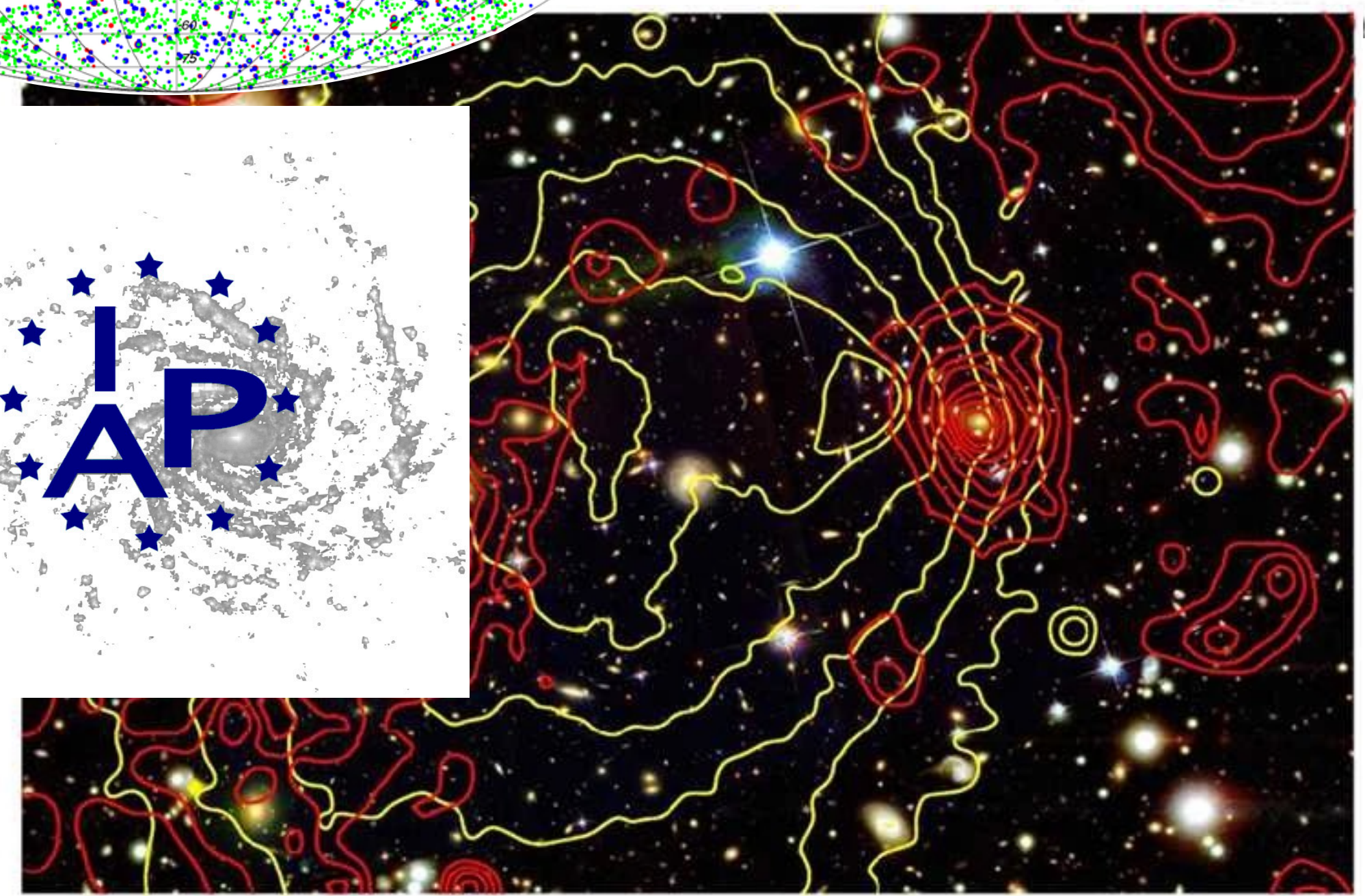
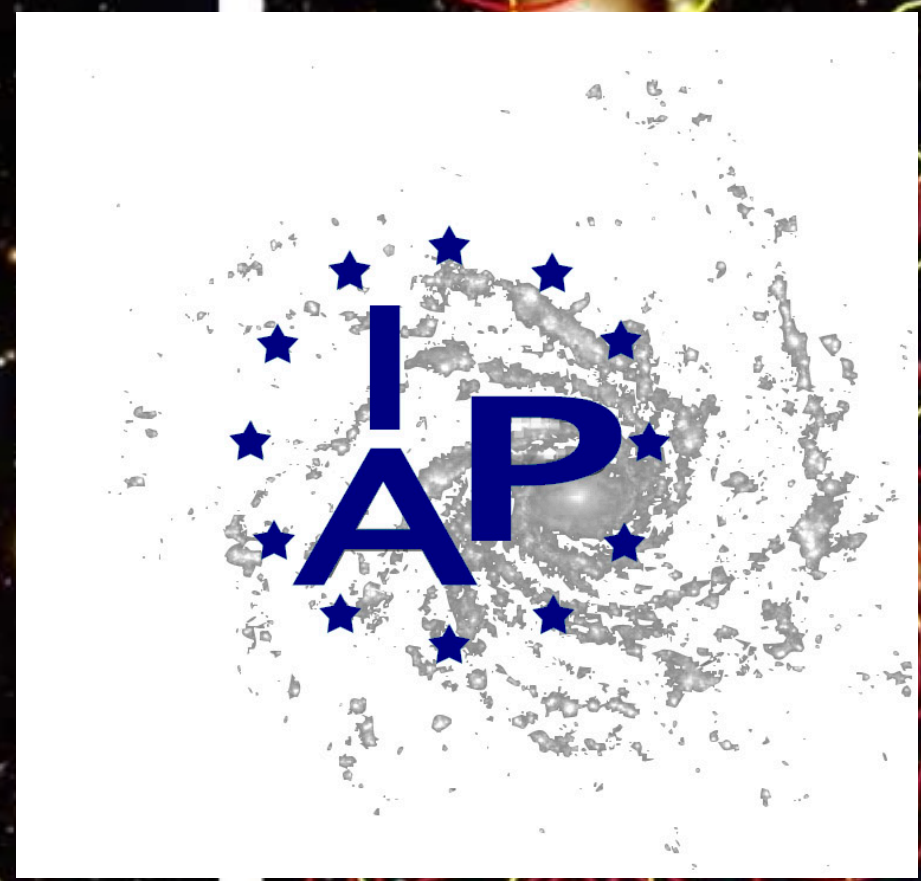
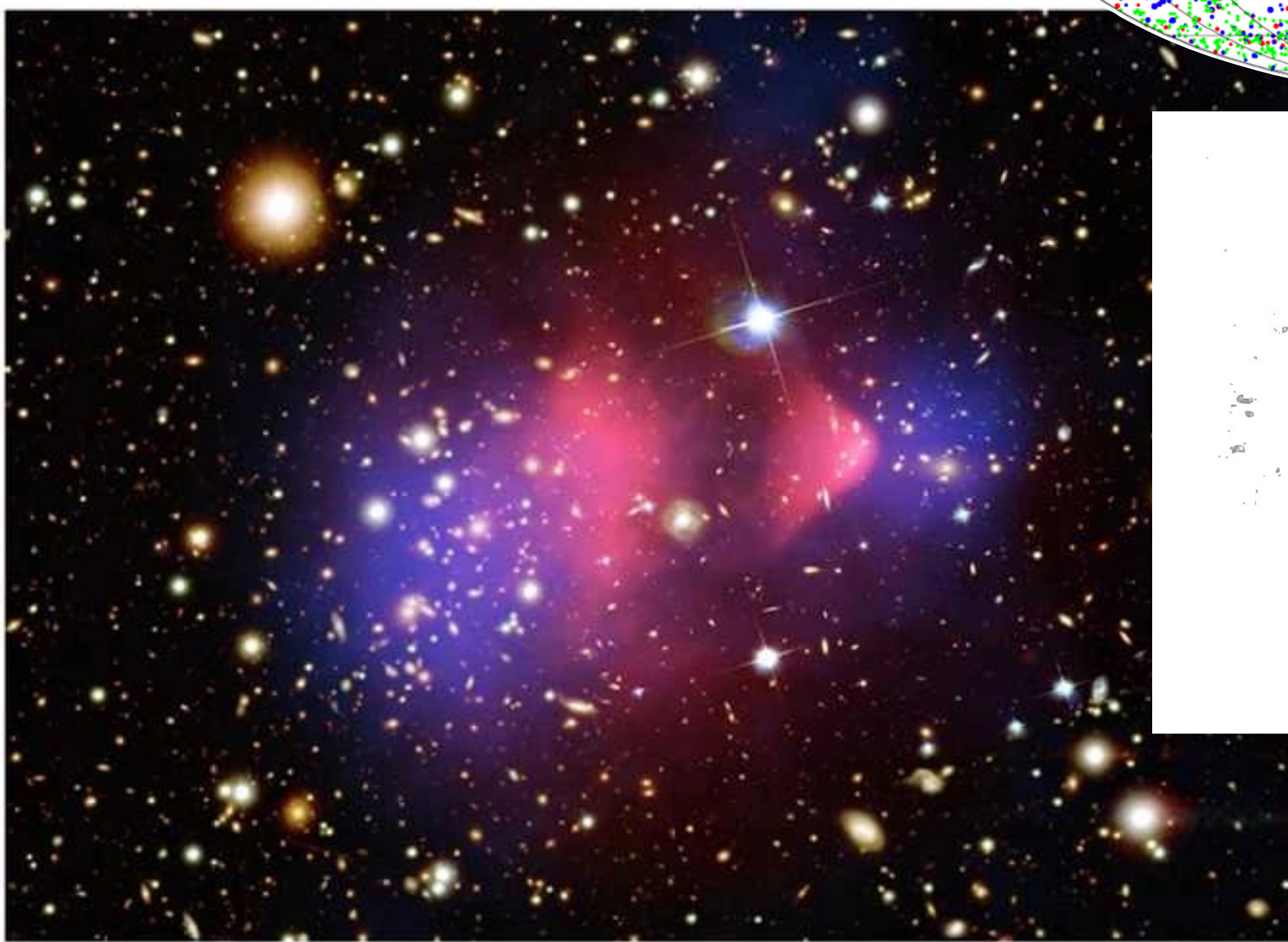
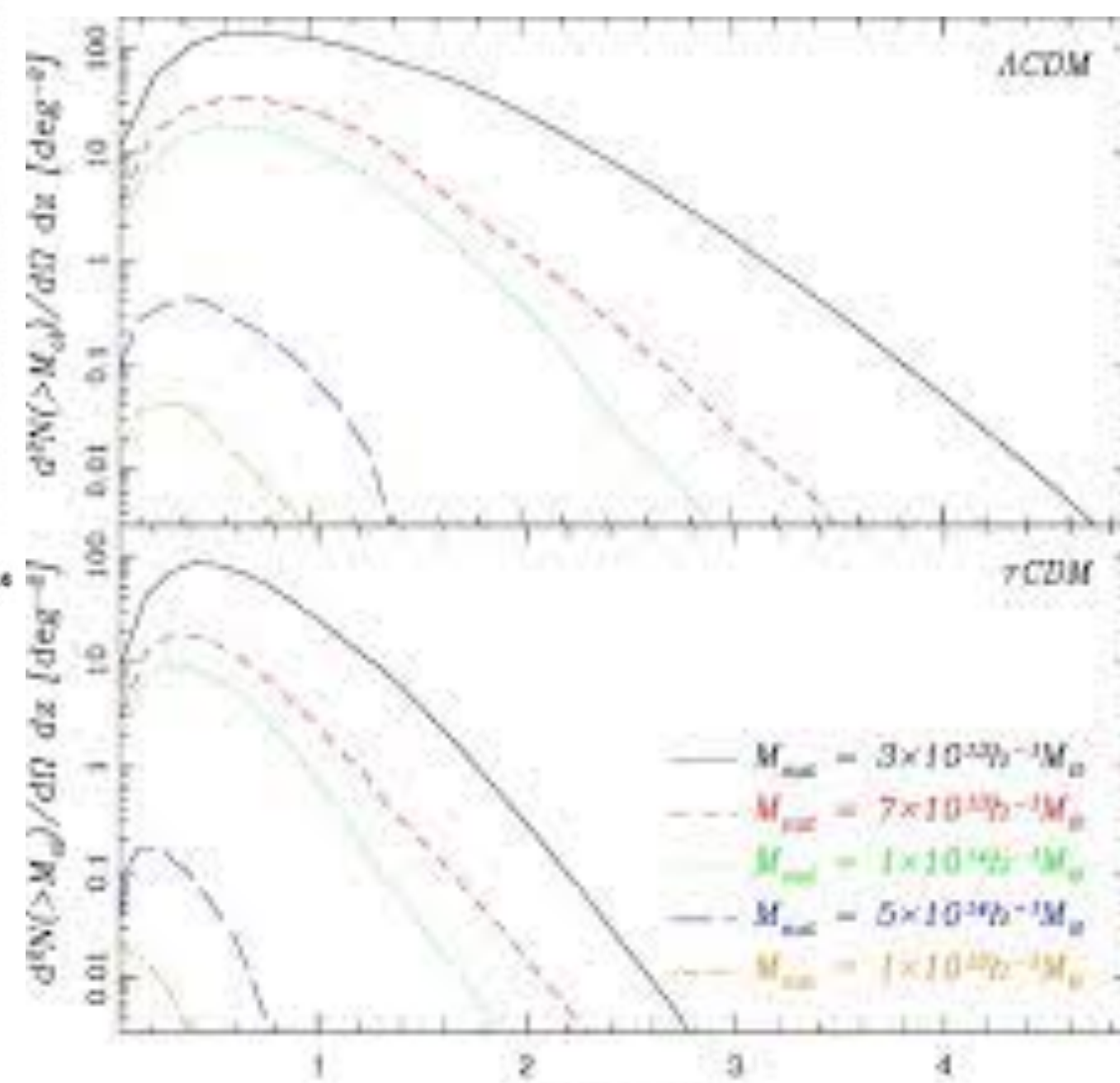
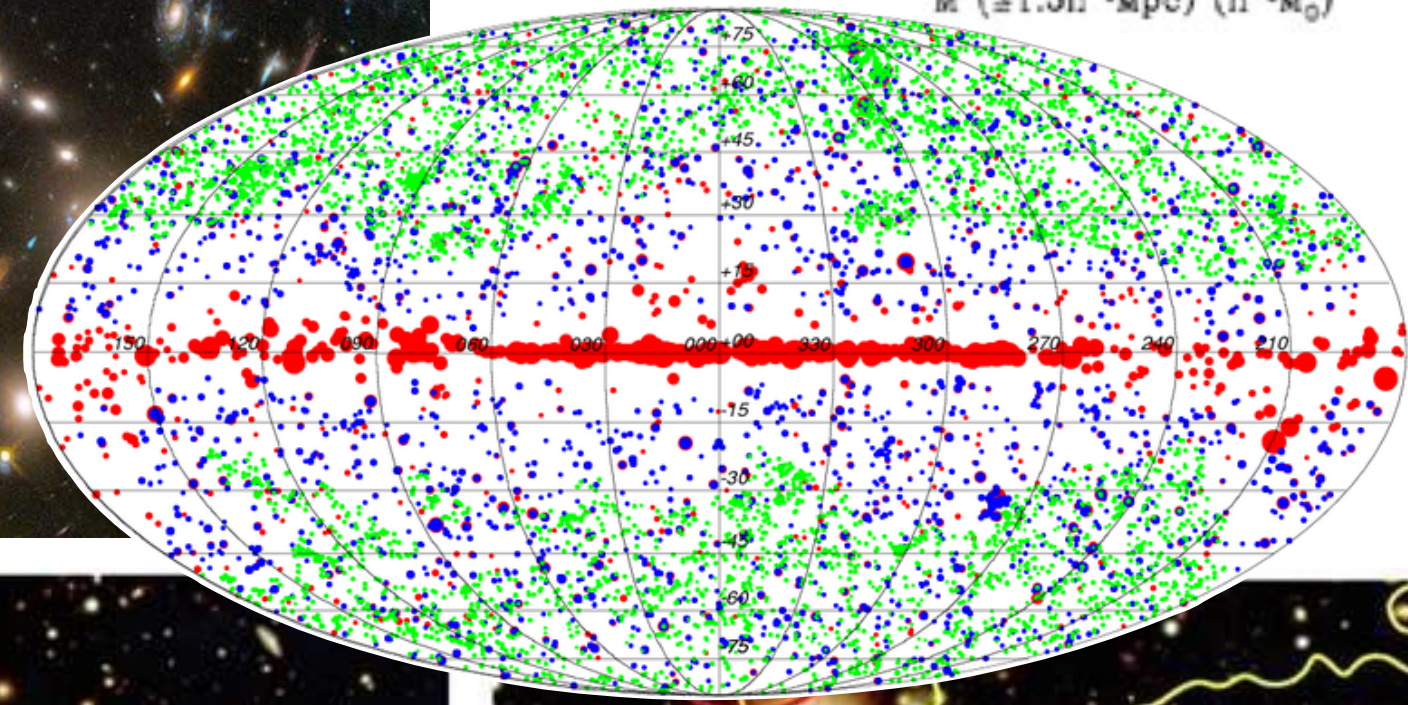
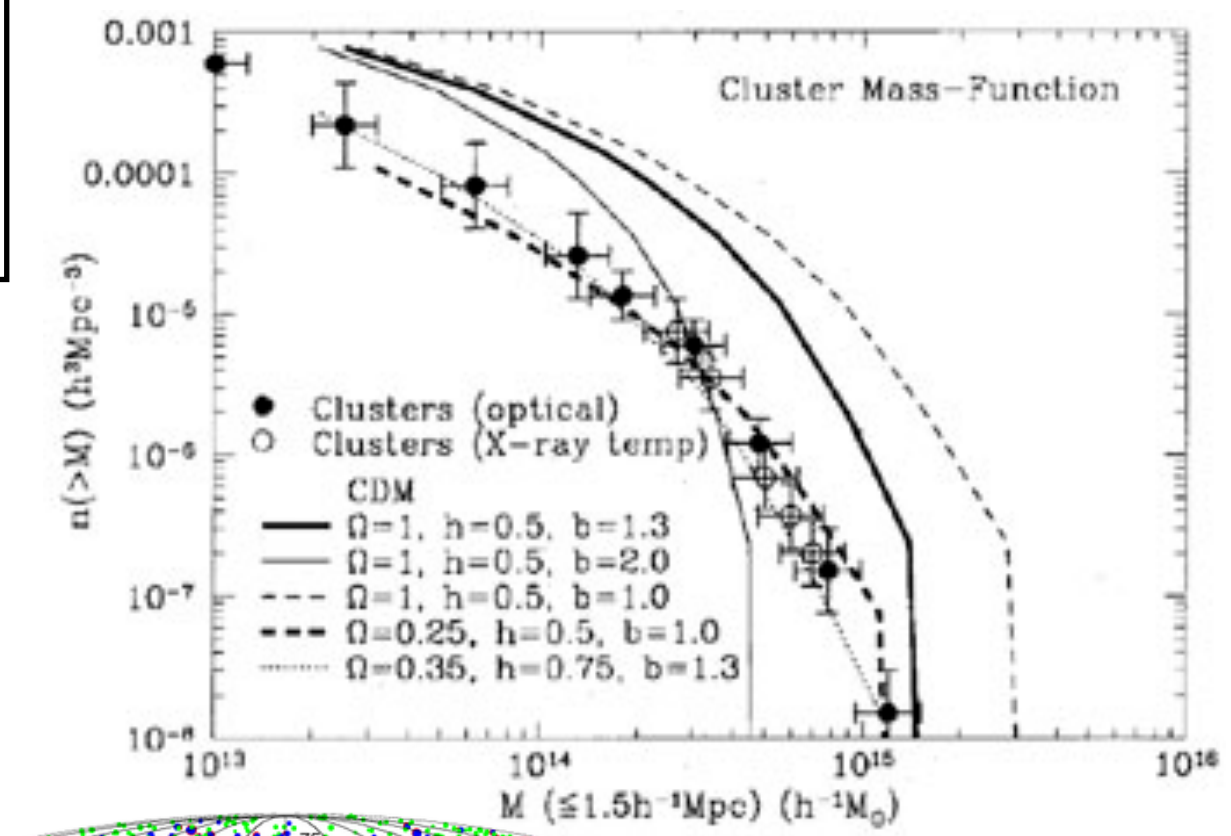
LPNHE
PARIS

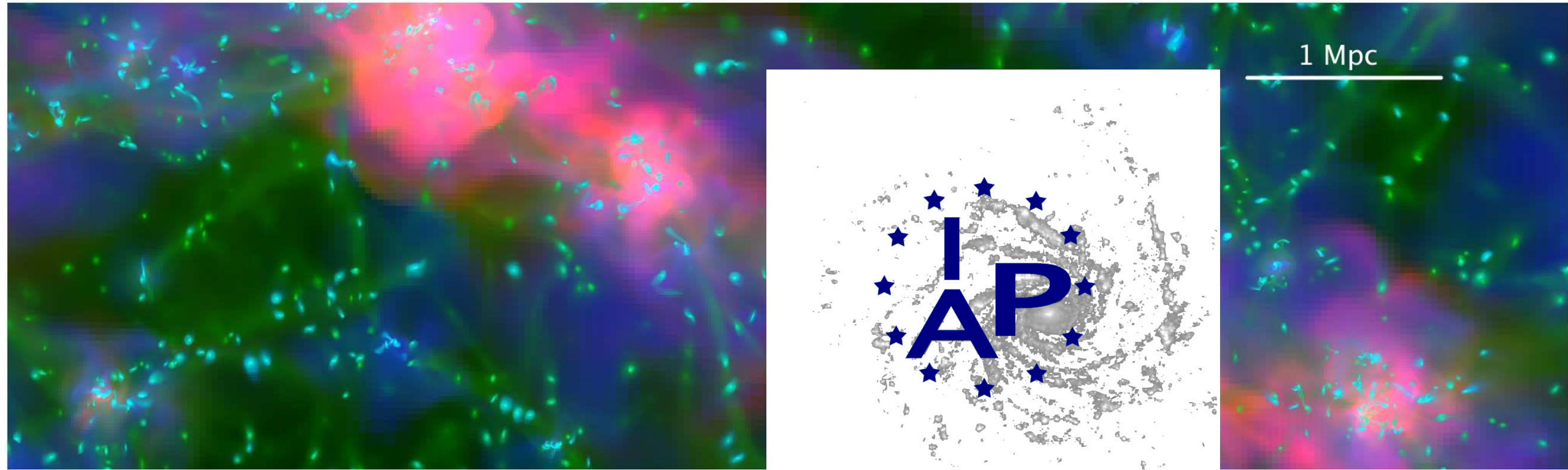
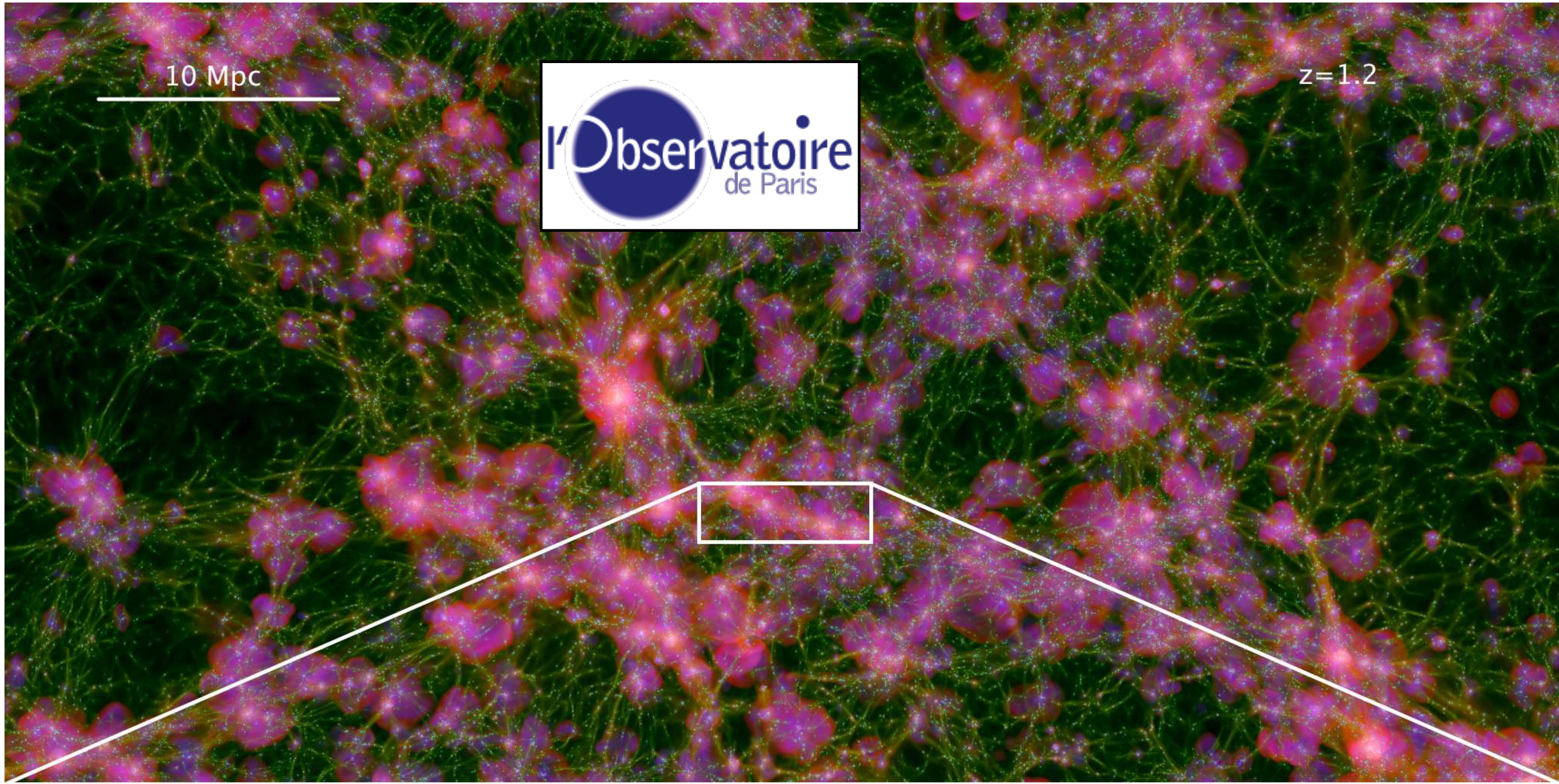




LPNHE
PARIS

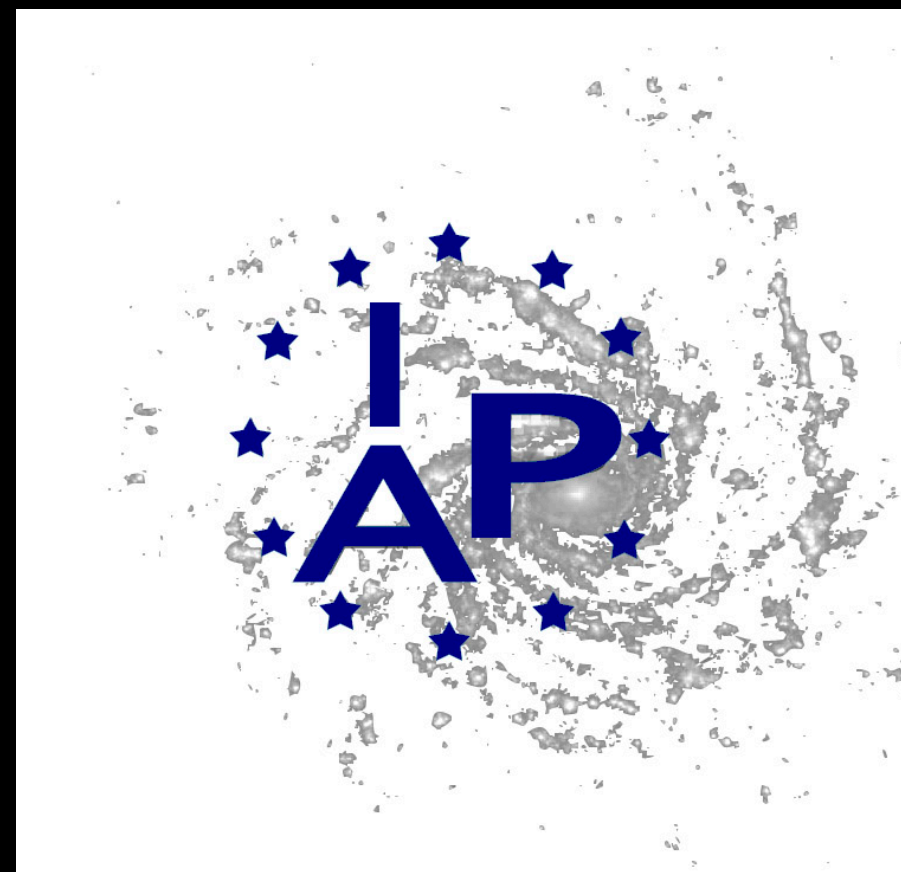


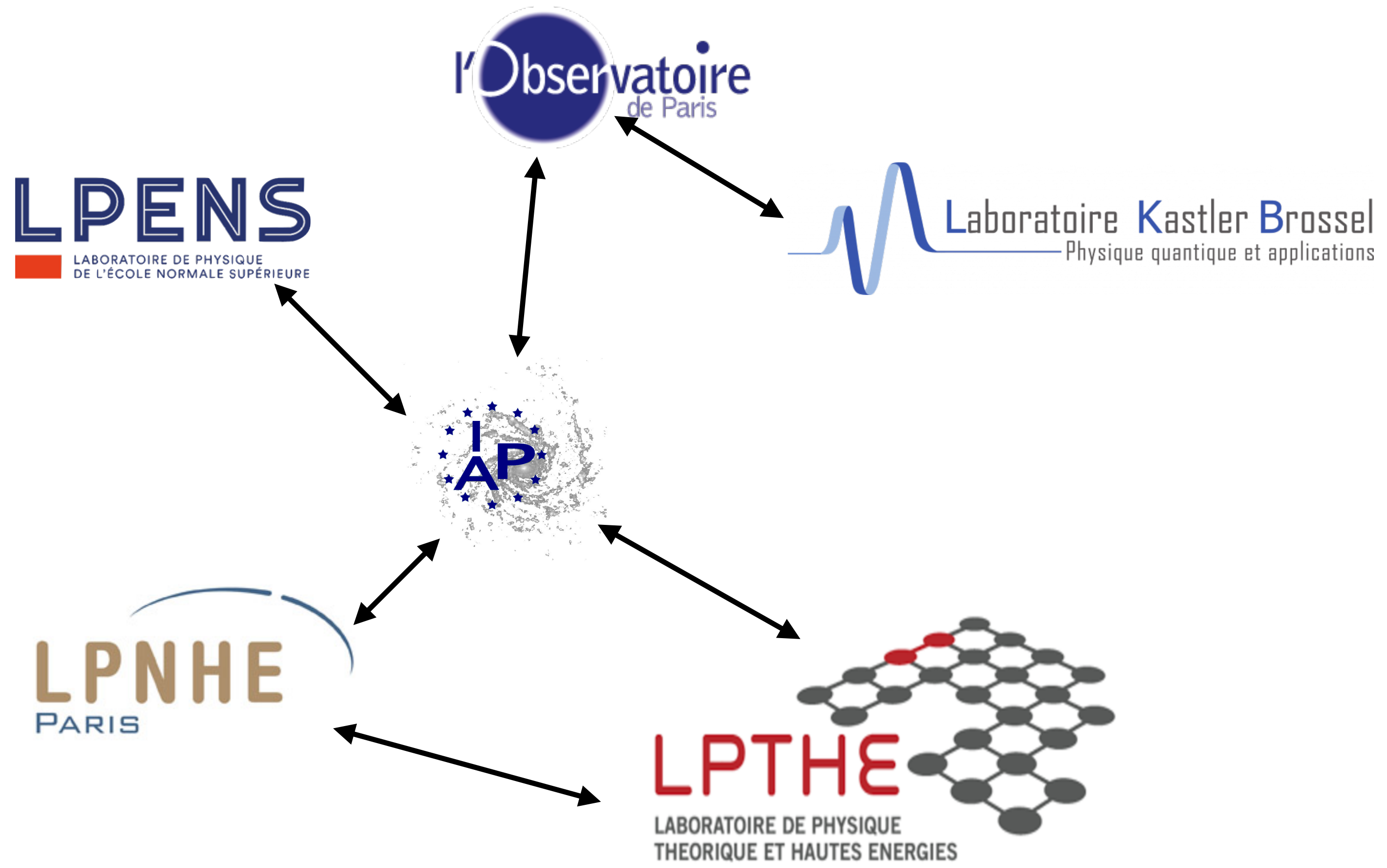


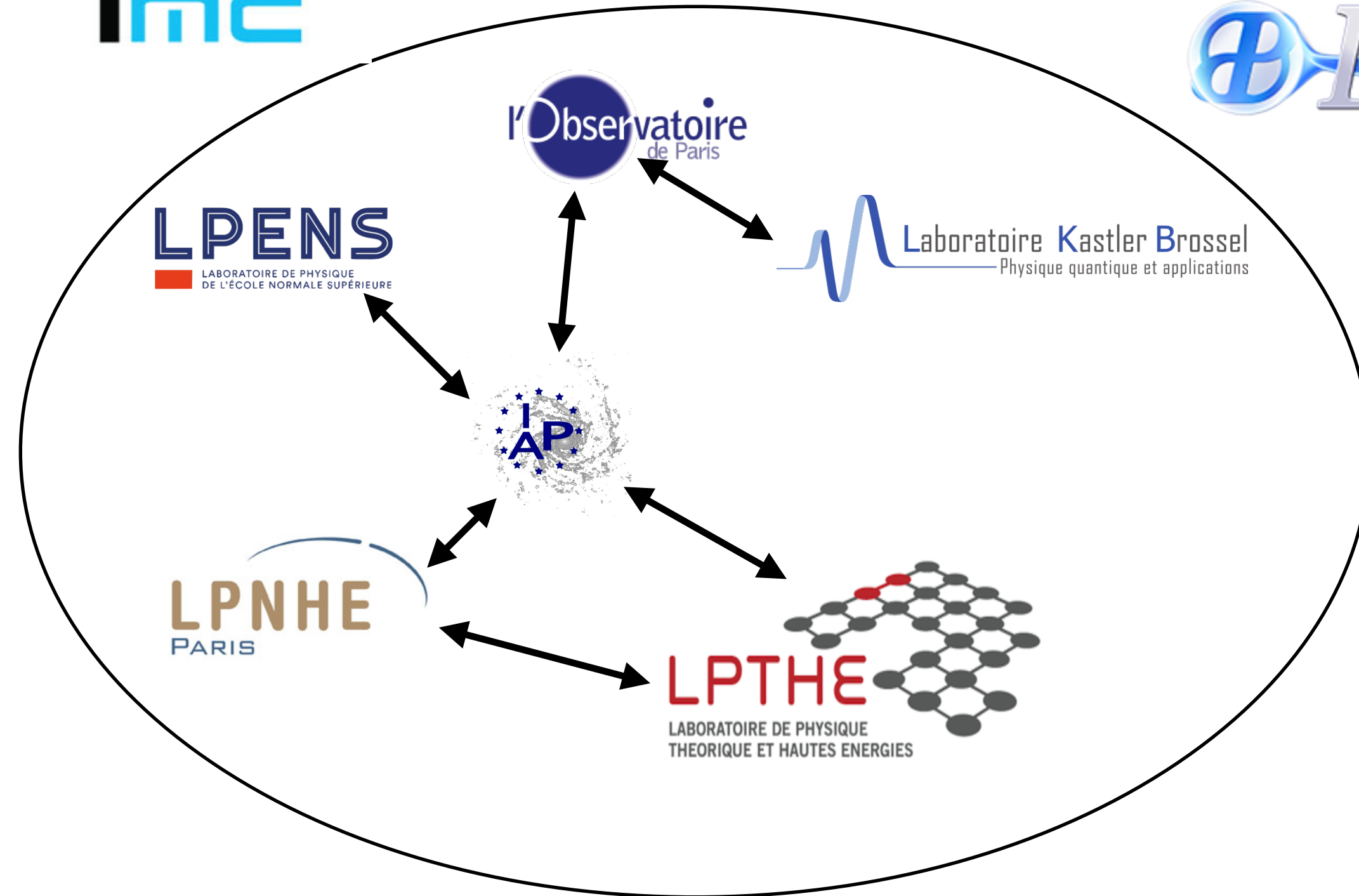


<https://www.youtube.com/watch?v=N-1GQVpevAc>

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PARIS







LPENS
LABORATOIRE DE PHYSIQUE
DE L'ÉCOLE NORMALE SUPÉRIEURE

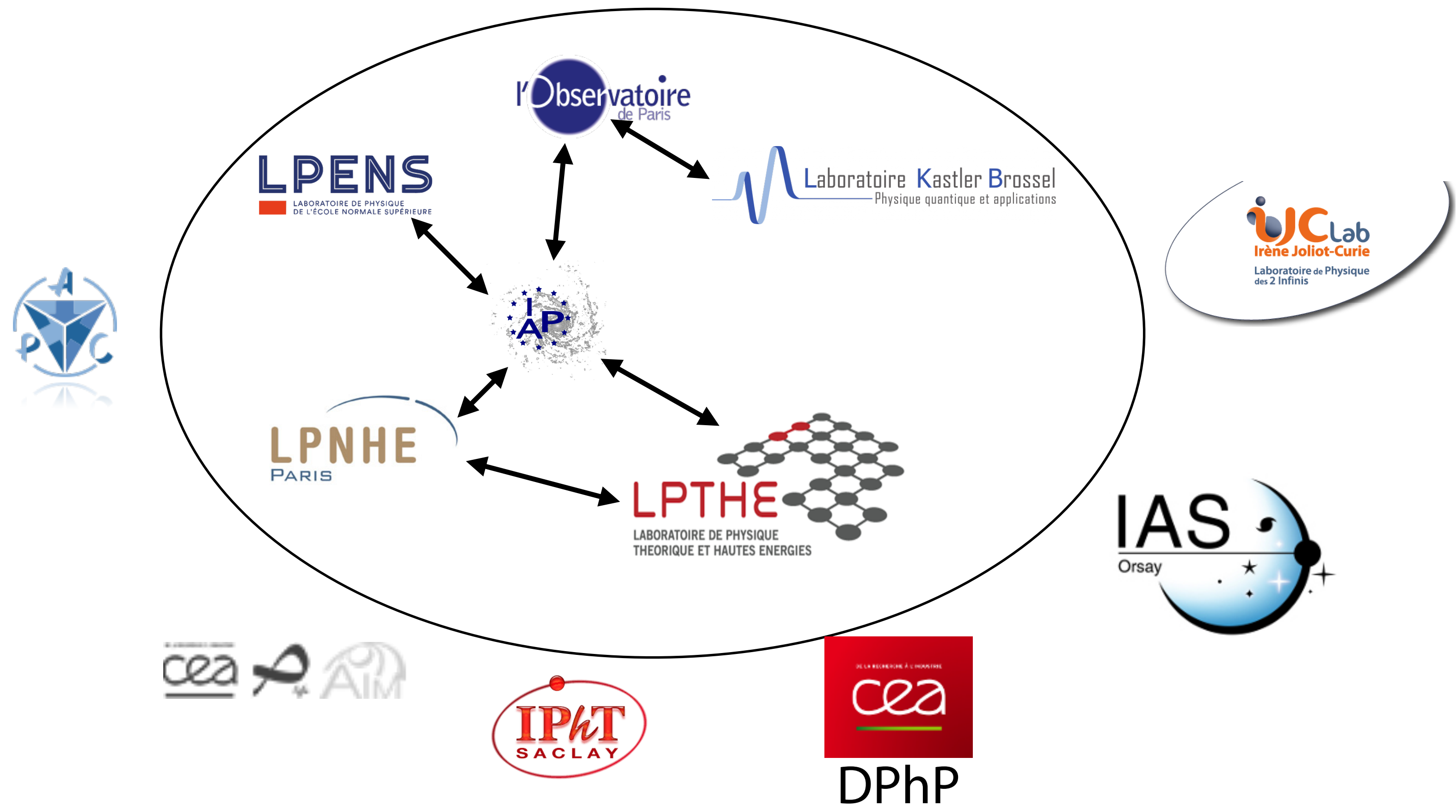
l'Observatoire
de Paris

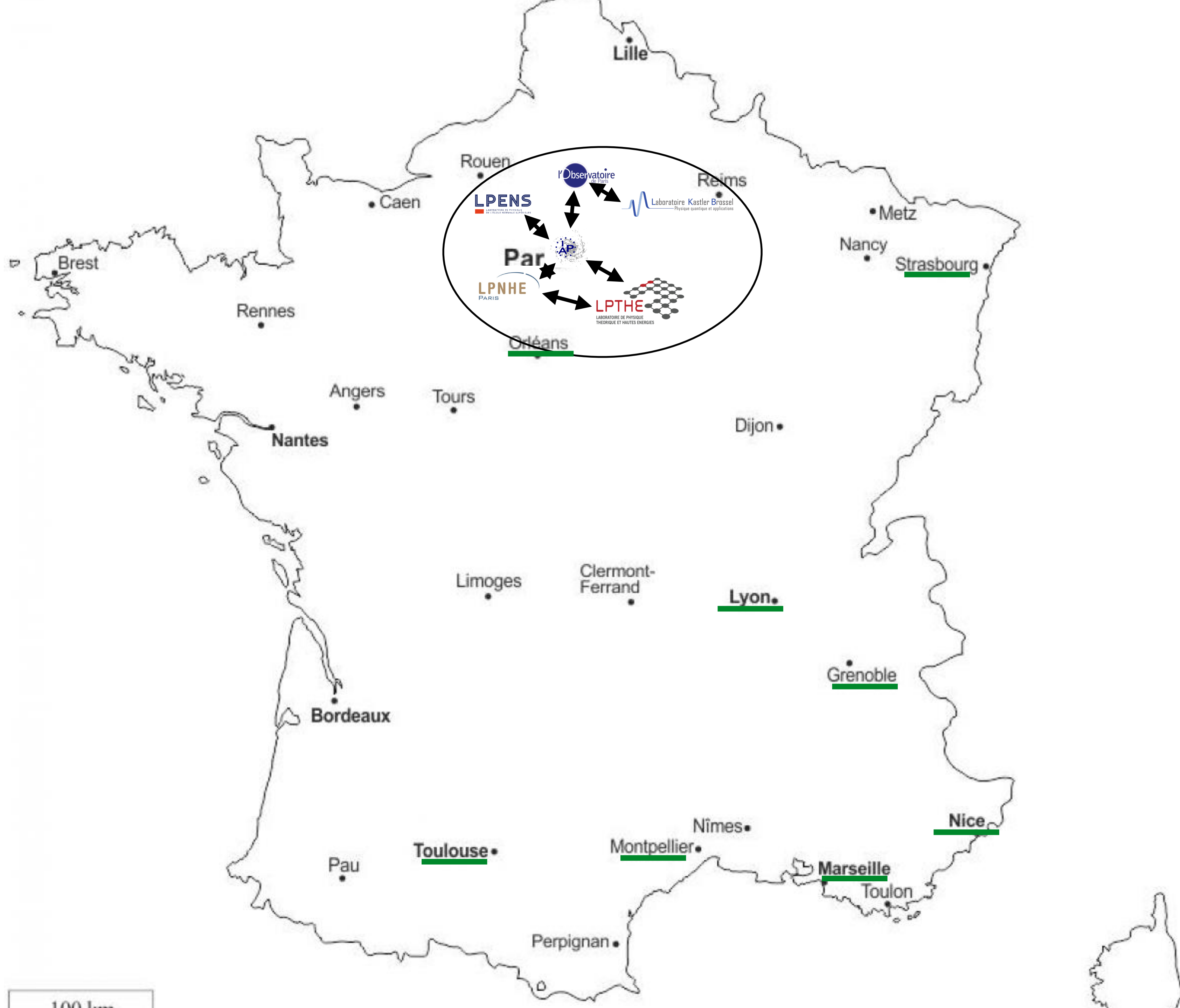
Laboratoire Kastler Brossel
Physique quantique et applications

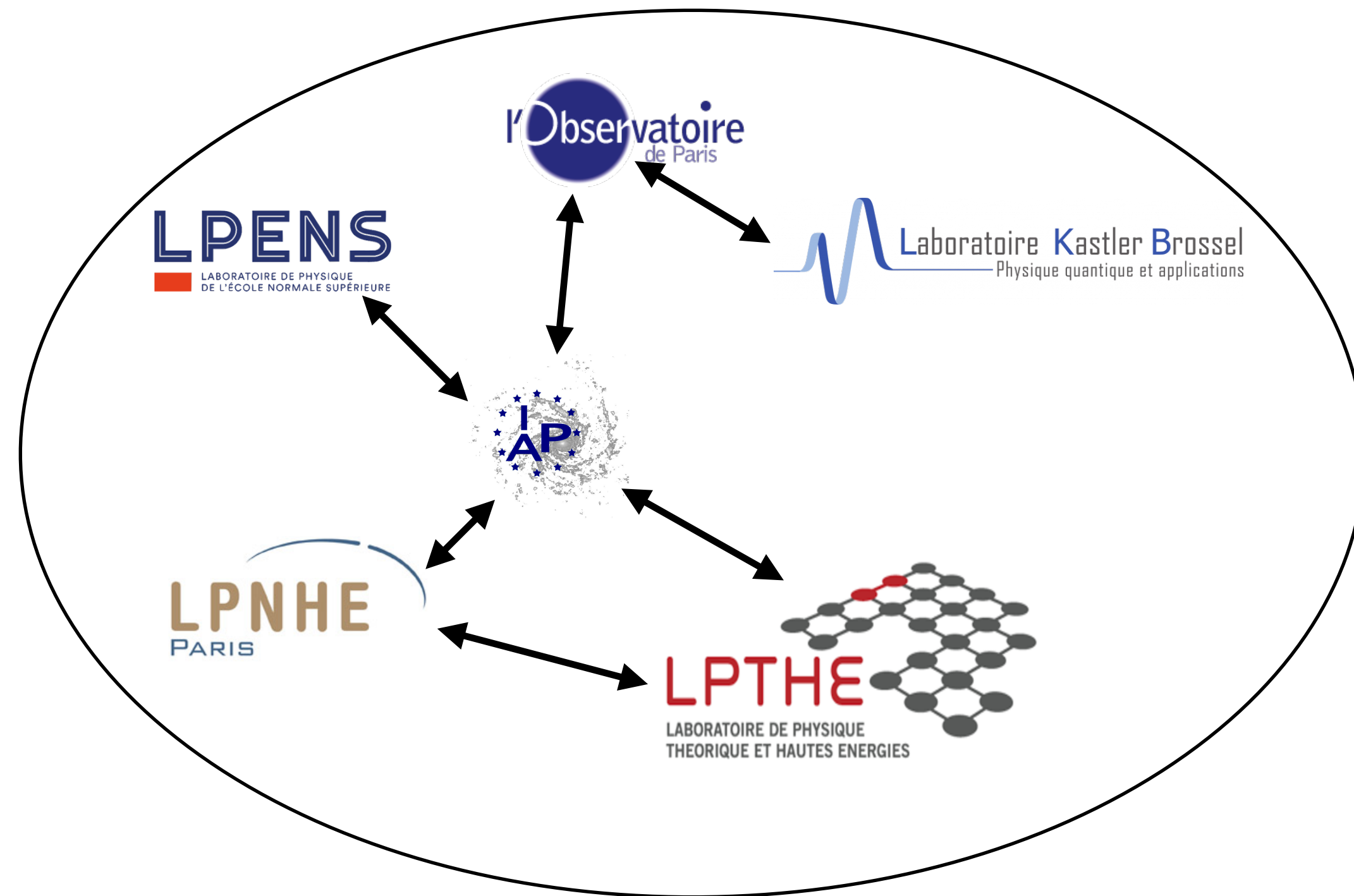
IAP

LPNHE
PARIS

LPTHE
LABORATOIRE DE PHYSIQUE
THÉORIQUE ET HAUTES ENERGIES







Combien de divisions ?

- **Evaluation parcellaire...**
- **IAP : Theorie : CNRS 6/4, Cosmologie : CNRS 5/3, SU 1/0, CNAP 3/3, Hautes Energies & Galaxies : CNRS 4/2, SU 0/3, CNAP 1/2 -> 37**
- **LPNHE : CNRS 3/3, SU 3/3 -> 12**
- **LPTHE : CNRS 3 SU 1 -> 4**
- **LKB : 2**
- **LPENS : 2**
- **Observatoire : Univers 12, Grandes Structures 17, Galaxies formation/evolution 21, Galaxies structure interne 21 -> 50 (dont 25 nouveaux arrivants)+21**

Structuration interne et besoins

- **Doctorants**
 - **Déjà très structurés avec les ED**
 - **mais : Bourses en particulier pour cotutelles entre labos SU**
- **Post Doc**
 - **Bourses !!!!!**
- **Soutien aux projets communs au sein de SU**
 - *simplification admin... Problème des budgets CNRS/SU/autres...*
 - **IPI était aussi une source de support important pour les conférences**
- **Séminaires communs**
 - **déjà très structuré et organisé (ICAP, journal club IAP vidéodiffusé, séminaire GRECO, etc...)**



- **Domaine riche avec de VRAIS résultats (grml !)**

- *Seule une fraction des observables « simples » (i.e. linéaires) est exploitée*
- *De réels progrès sur les choses plus complexes*
- *Encore de beaux mystères à éclaircir*
- *Investissement observationnel important : de nombreux nouveaux résultats majeurs dans les 10 prochaines années*

- **Thème de recherche très visible à l'international et avec un grand intérêt societal**

- *l'Île de France est un réel poids lourd dans la discipline, avec une densité de chercheurs importante (mais c'est sans doute vrai de la plupart des thématiques...)*
 - *SU est collectivement l'acteur le plus important d'IdF et porte des thématiques fortes et très visibles*
 - *aussi un acteur majeur des projets observationnels majeurs des 10 prochaines années*
- **Domaine très éclaté : 3 instituts, 2 CNU, multi labo...**
 - *Outils de structuration critiques pour faire fructifier la position forte de SU*
 - *Intérêt pour SU à valoriser, à reconnaître et à faire connaître cette pépite !*
 - *au même titre que de nombreuses autres !*