Dirac neutrino dark Matter and topphilic Z'

Géraldine SERVANT, CERN-TH

based on:

- C. Jackson, G. Servant, G. Shaughnessy, T. Tait & M.Taoso. To appear.
- Belanger, Servant, Pukhov '07
- Agashe, Servant '04

Dark Matter and the Fermi scale

Fraction of the universe's energy density stored in a stable massive thermal relic:

$$\boxed{\Omega_{DM} \approx \frac{0.2\ \text{pb}}{\sigma_{anni}}}$$

→ a particle with a typical Fermi-scale cross section $\sigma_{anni} \approx 1$ pb leads to the correct dark matter abundance.

a compelling coincidence (the "WIMP miracle")

Which particle? How to test this hypothesis?

New symmetries at the TeV scale and Dark Matter

to cut-off quadratically divergent quantum corrections to the Higgs mass

→

New TeV scale physics needed

↓

tension with precision tests of the SM in EW & flavor sector (post-LEP "little hierarchy pb")

↓

introduce new discrete symmetry P

R-parity in SUSY, KK parity in extra dim, T parity in Little Higgs ...

↓

Lightest P-odd particle is stable

↓

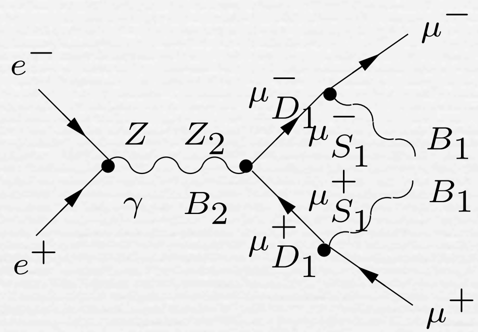
DM candidate

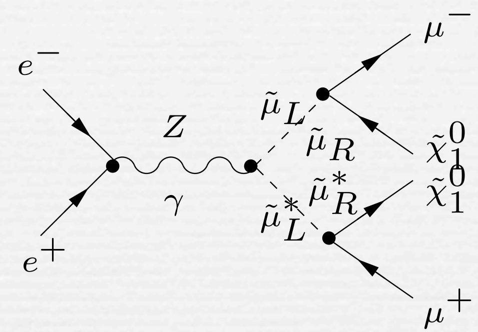
Dark Matter Candidates

	M_{EW}/M_{Pl} hierarchy adressed	little hierarchy adressed(∼TeV cutoff)	Hierarchy pb ignored
SPIN 0			
- axion (not wimps)	×		×
- radion	?		
- branon	?		
- singlet scalar			×
- adjoint scalar (=spinless photon)		×	
SPIN 1/2			
- Dirac neutrino	× (in RS)		
- SU(2) p-uplet			×
- neutralino	×		
- axino	×		
SPIN 1			
- Heavy photon (KK or B-partner in Little Higgs)		×	
SPIN 3/2			
- Gravitino	×		
SPIN 2			
- KK Graviton		× (in UED)	

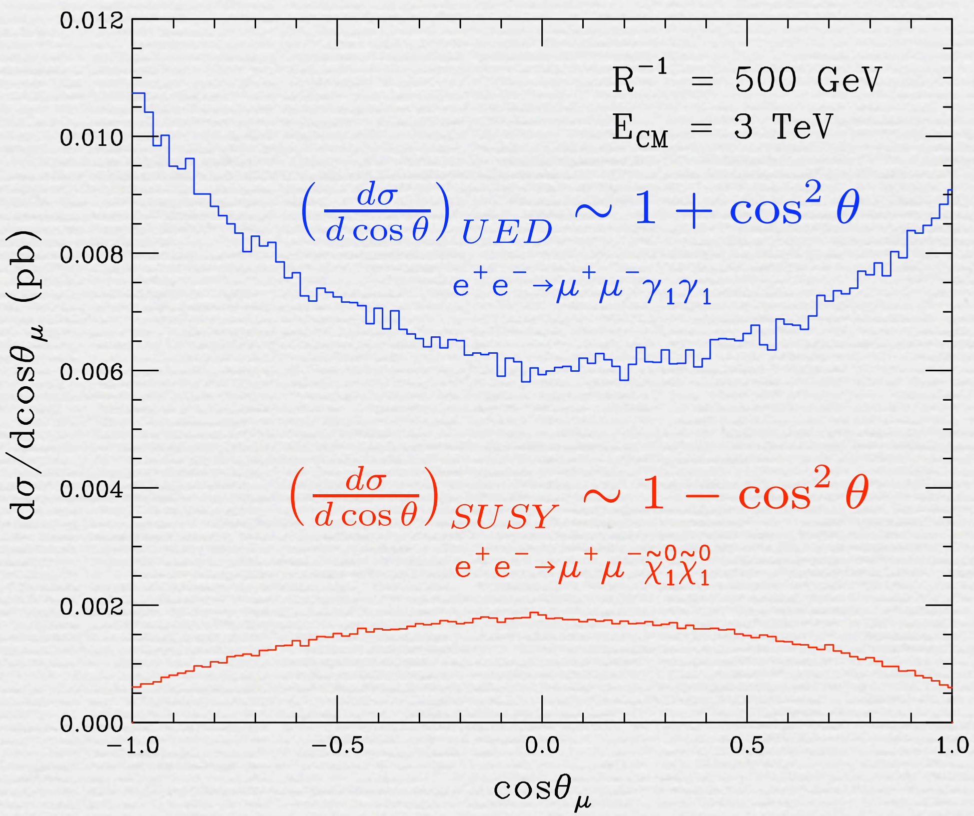
SUSY vs UED at LC in $\mu^+\mu^- + \not{E}_T$ channel

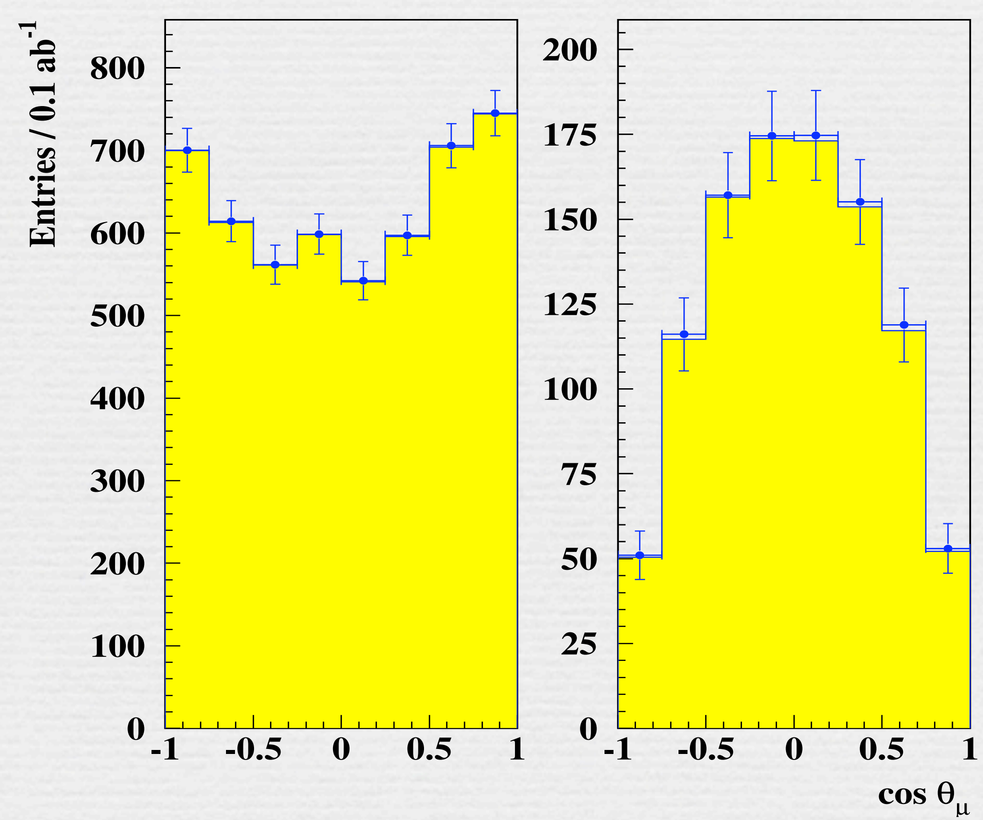
(Battaglia, Datta, De Roeck, Kong, Matchev, hep-ph/0502041)





Angular Distribution





A Dark Matter - Top Quark Connection

A very simple effective theory

see also Belanger-Pukhov-Servant '07

The WIMP is a Dirac fermion, ν, singlet under the SM, charged under a new spontaneously broken U(1)'.

$$\mathcal{L} = \mathcal{L}_{SM} - \frac{1}{4} F'_{\mu\nu} F'^{\mu\nu} + M_{Z'}^2 Z'_\mu Z'^\mu + i\bar{\nu}\gamma^\mu D_\mu \nu + g_R^t \bar{t}\gamma^\mu P_R Z'^\mu t + \frac{\chi}{2} F'_{\mu\nu} F_Y^{\mu\nu}$$

$$D^\mu \equiv \partial_\mu - i\left(g_R^\nu P_R + g_L^\nu P_L\right) Z'^\mu$$

The only SM particle charged under the Z' is the top quark

There is no SM state the WIMP can decay into: ν is stable.

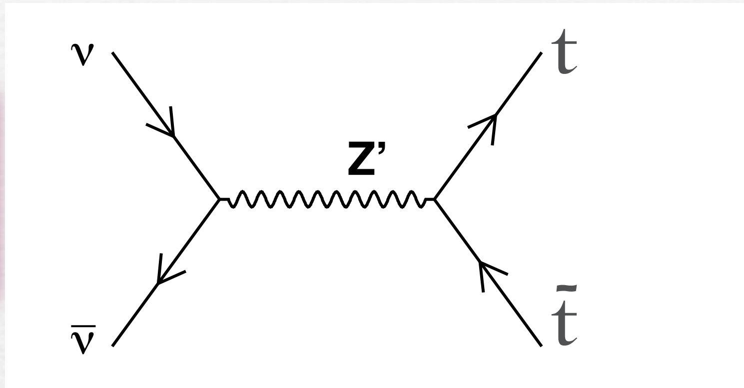
This model can be UV completed as an SO(10) RS model Agashe-Servant '04

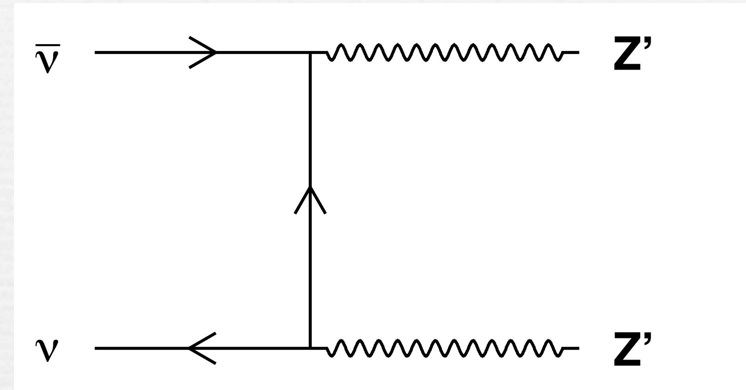
More generally, in models where top quark is composite, natural to expect that only the top couples to a new strongly interacting sector.

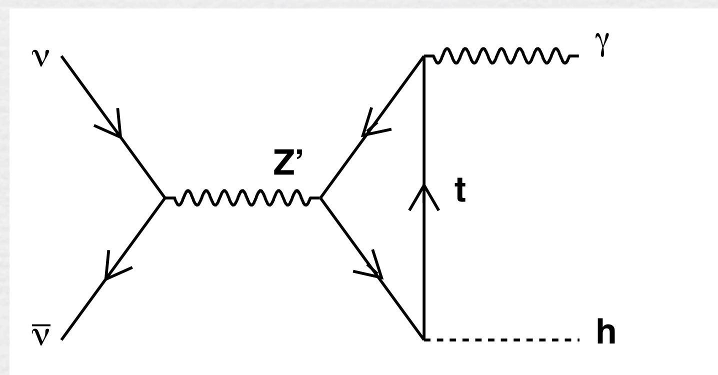
Relic density calculation

(assuming no $\nu\,\bar{\nu}$ asymmetry)

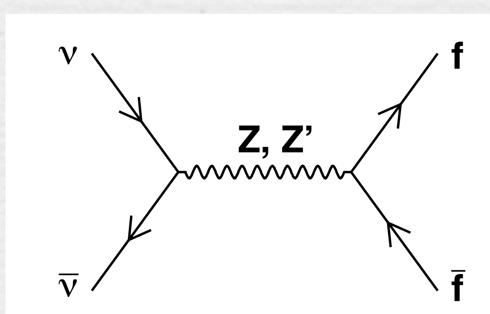
dominant channels

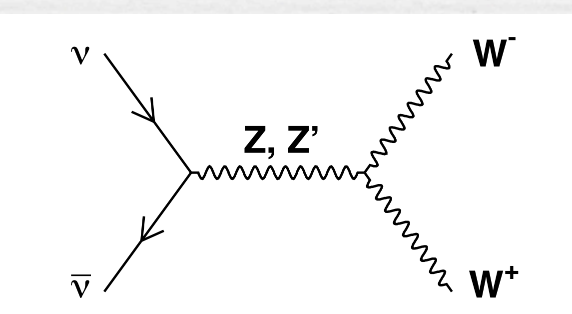


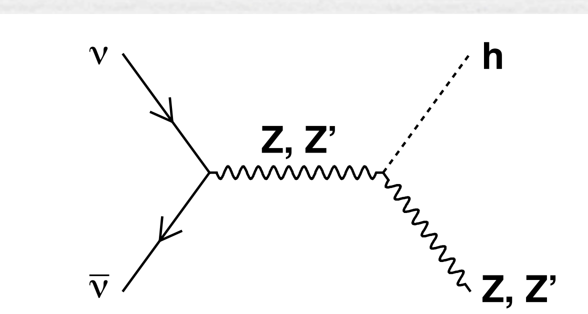




suppressed channels

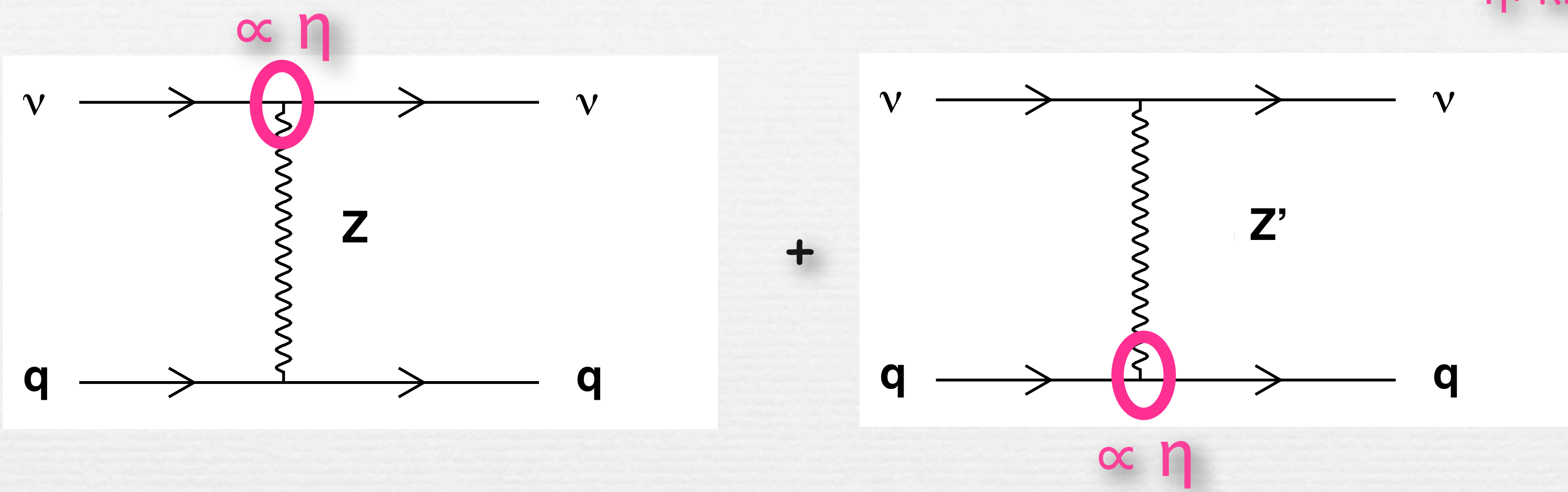






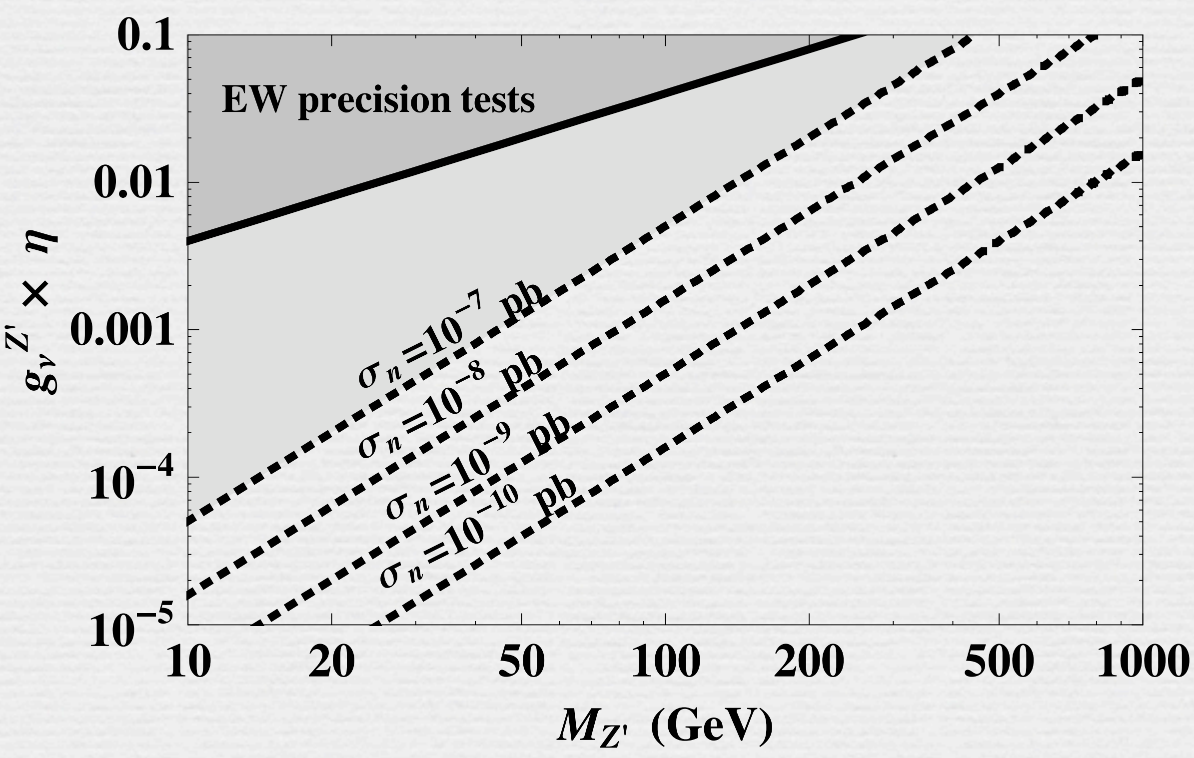
Direct detection constraints

η: kinetic mixing

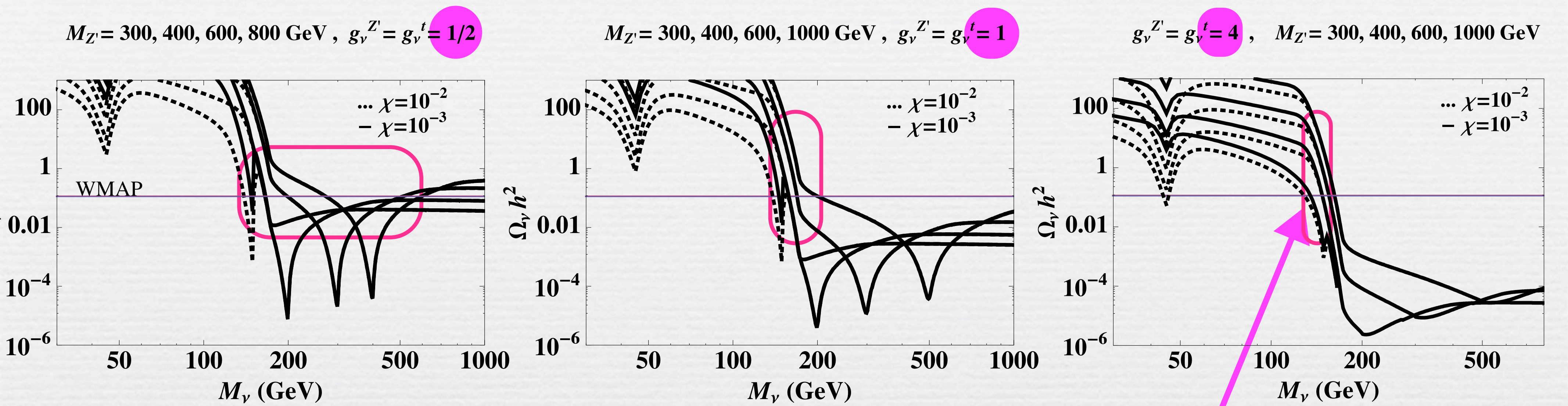


→ σ∝ η²

ν-nucleon elastic scattering cross section contours



Dark matter mass from relic density calculation



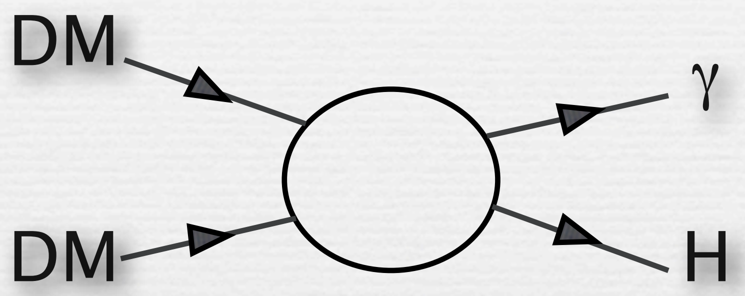
M_{DM} ~ 150 GeV

as the Z' coupling to top and ν increases, the prediction for M_{DM} gets narrower -> M_{DM} ~ 150 GeV

for $g_\nu^{Z'}, g_t^{Z'} \gtrsim 1$

Indirect probes of the Higgs in space.

Discovery of a gamma-ray line produced by WIMP annihilations in space and whose energy reflects the mass of the Higgs (and the WIMP)



could even allow the first direct observation of a Higgs production process

Tevatron and LHC scooped by FERMI

Seeing the light from Dark Matter

- photons travel undeflected and point directly to source
- photons travel almost unattenuated and don't require a diffusion model
- detected from the ground (ACTs) and from above (FERMI)

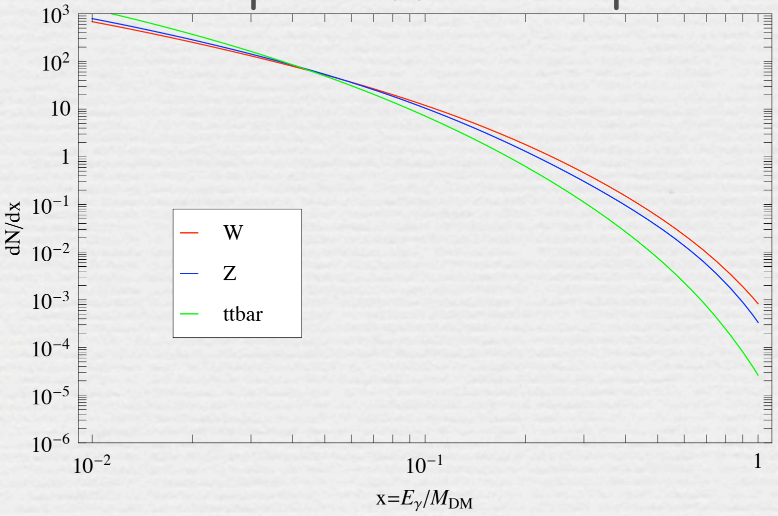
γ's from DM annihilations consist of 2 components

• Continuum

secondary γ's

from hadronisation and decays of SM particles, final state radiation of charged particles

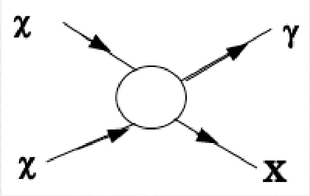
almost featureless but with sharp cutoff at Wimp mass



• Lines

primary γ's

loop-level annihilation into γ+X



-> mono energetic lines superimposed onto continuum at

$$E_\gamma = M_{DM}\left(1 - \frac{M_X^2}{4M_{DM}^2}\right)$$

☺ -> striking spectral feature, SMOKING GUN signature of Dark Matter

☹ lines are usually small (loop-suppressed) compared to continuum

Seeing the light from Dark Matter

- What if the nature of DM is such that continuum emission is suppressed while production of "direct" photons can be large?

- The position and strength of lines can provide a wealth of information about DM:

$$\boxed{E_\gamma = M_{DM}\left(1 - \frac{M_X^2}{4M_{DM}^2}\right)}$$

→ $\gamma\gamma$ line measures mass of DM

→ relative strengths between lines provides info on WIMP couplings

→ observation of γH would indicate WIMP is not scalar or Majorana fermion

→ if other particles in the dark sector, we could possibly observe a series of lines

[the "WIMP forest", Bertone et al. '09]

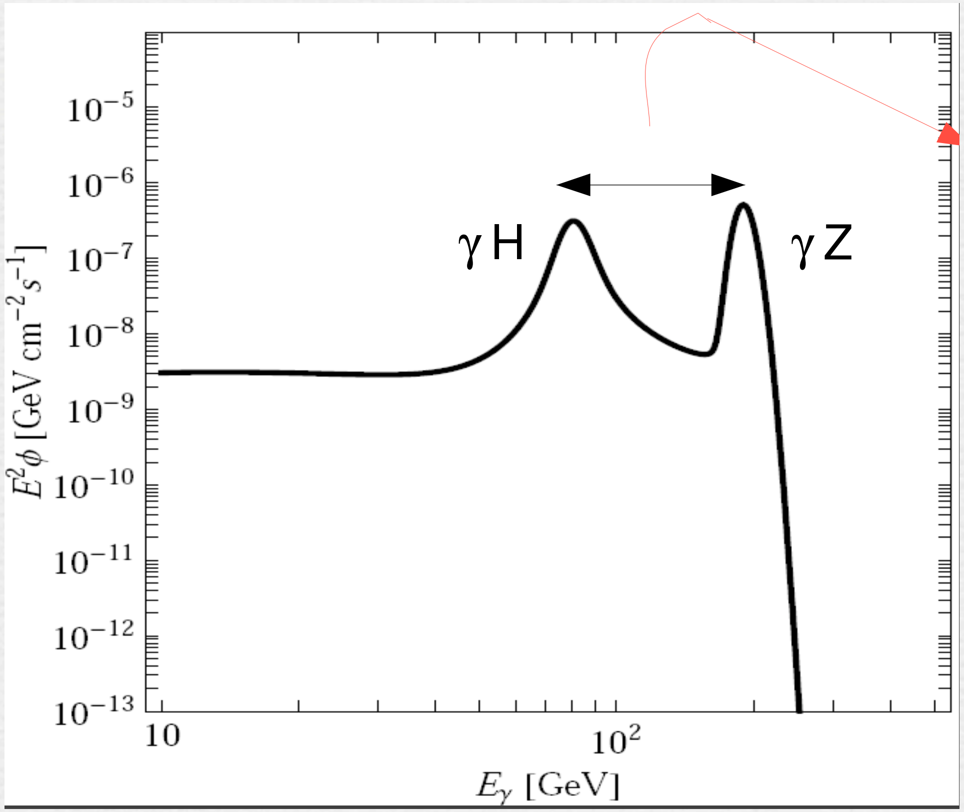
Probing the Higgs in Seeing the light from Dark Matter

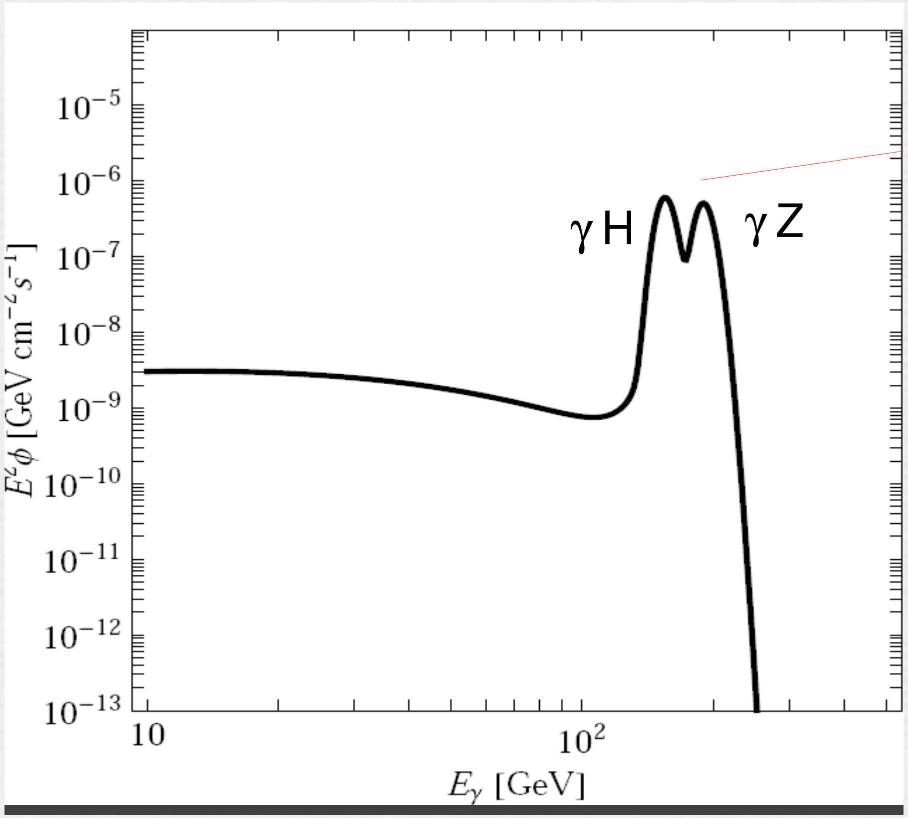
What about DM annihilations into γ H ?

$$E_\gamma = M_{DM}\left(1 - \frac{M_H^2}{4M_{DM}^2}\right)$$

$$E_\gamma = M_{DM}\left(1 - \frac{M_Z^2}{4M_{DM}^2}\right)$$

lines well separated for heavy Higgs





Annihilations into γ H?

Scalar DM ☹ e.g. "Chiral Square" (6D UED model), Inert Doublet Model ...

Non-relativistic scattering of 2 scalars ⇛ The initial state angular momentum is zero

OK if 2 vectors in the final state but vector+scalar final state
requires initial state orbital angular momentum ⇛ higher order in v^2

Majorana fermion DM ☹ e.g. neutralino in SUSY

Must also annihilate at higher order in v^2 (initial state S=0)

→ **Vector DM** ☺

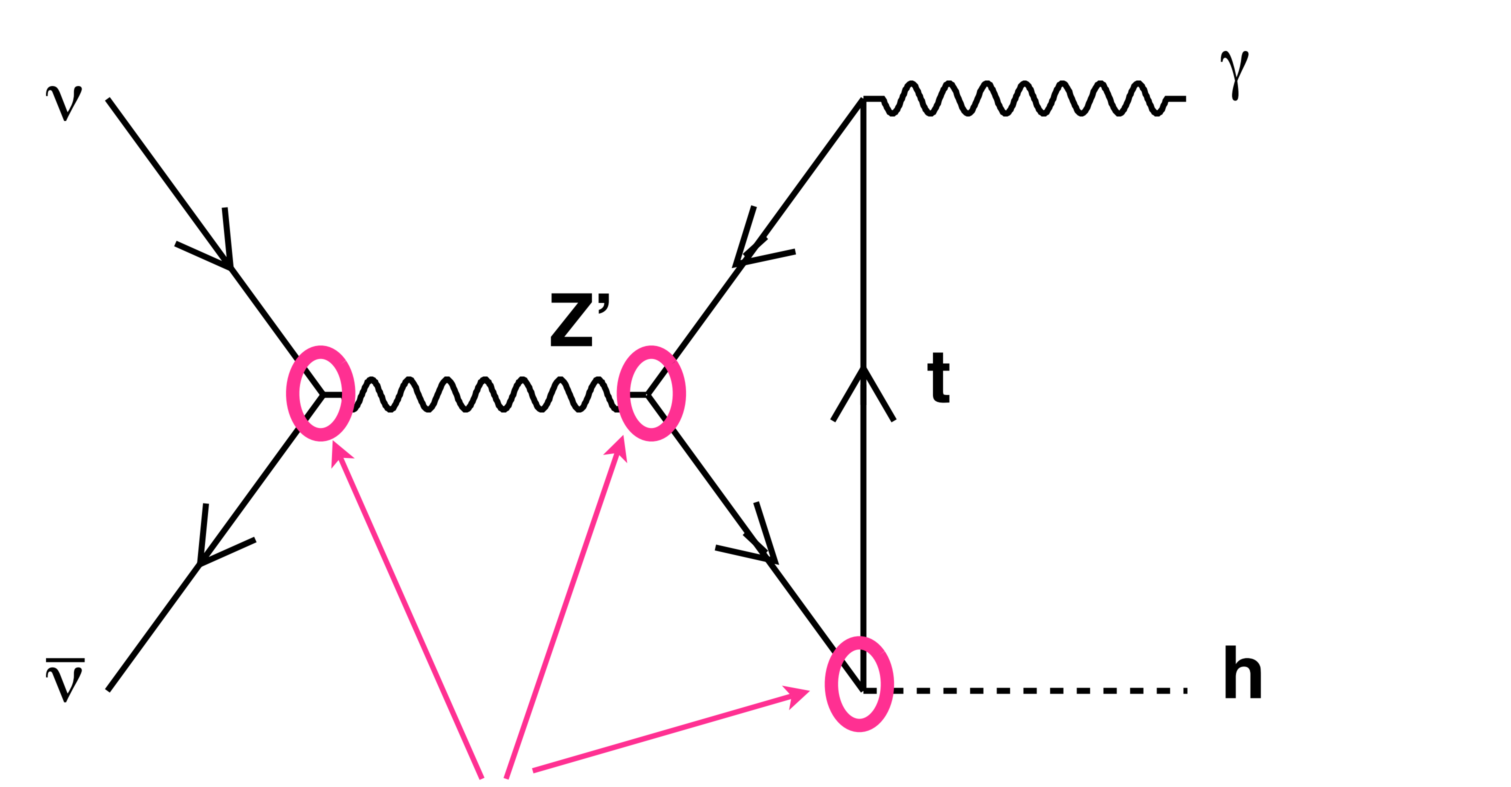
e.g. KK photon in 5D UED, heavy photon in Little Higgs models

OK in principle but if it annihilates via s-channel scalar exchange: still v^2 -suppressed; if t-channel (box diagrams), this is typically suppressed by couplings and masses (e.g. in UED or Little Higgs)

→ **Dirac Fermion DM** ☺

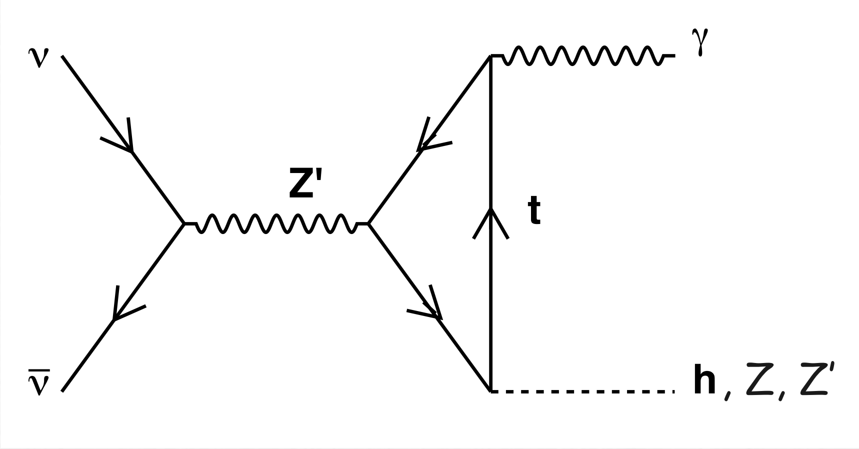
e.g. Agashe-Servant '04; Belanger-Pukhov-Servant '07

Dirac fermion annihilation into γ H



~ O(1) couplings

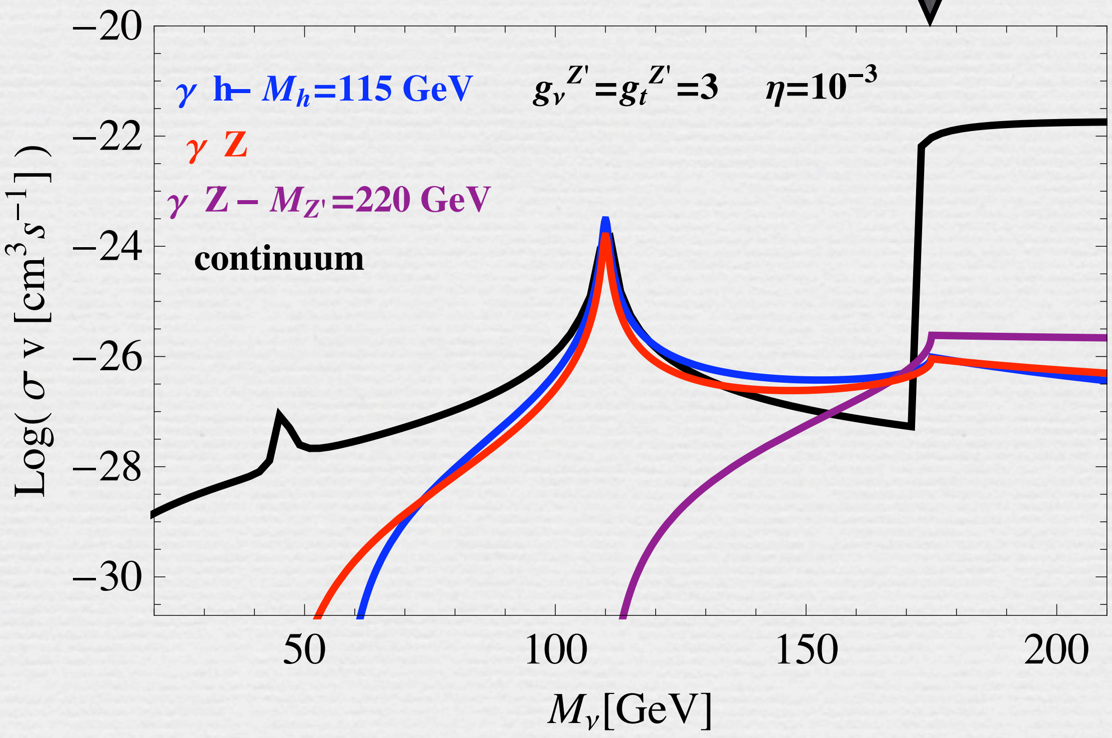
γ signal from ν annihilation



Note: no γγ line as dictated by Landau-Yang theorem (Z' being the sole portal from the wimp sector to the SM)

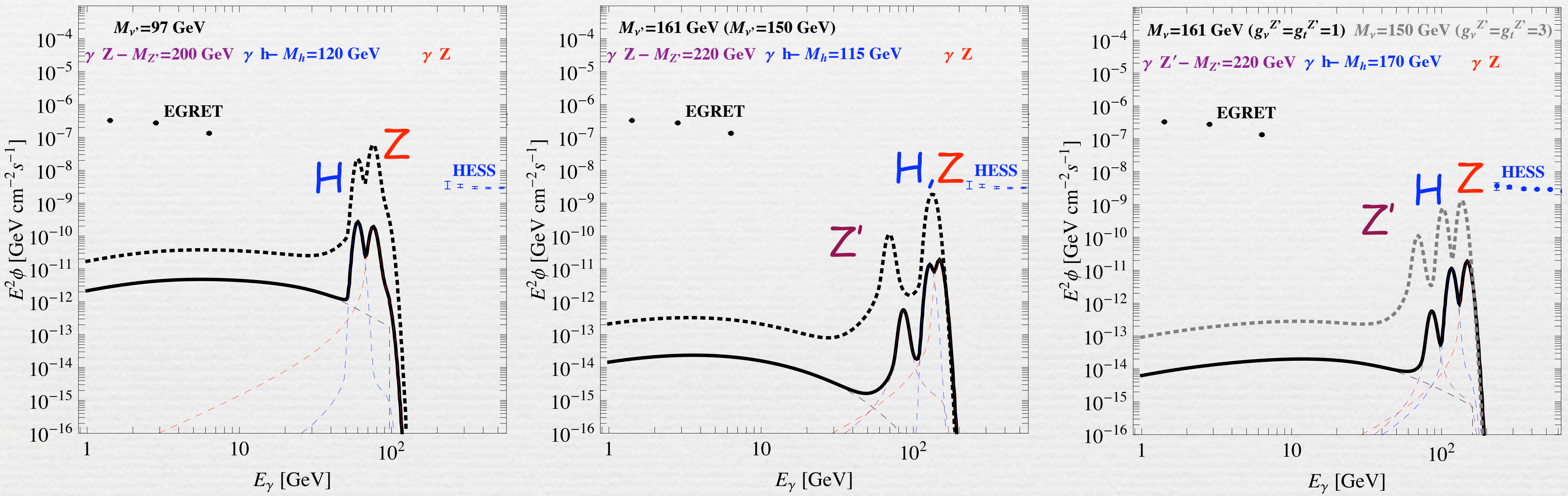
Lines not suppressed compared to continuum

continuum jumps due to opening of $t\bar{t}$ channel



γ-ray lines from the Galactic Center ΔΩ= 10^{-5} sr

Spectra for parameters leading to correct relic density and satisfying direct detection constraints



NFW profiles. No need for astro boost factors

To recap:

DM almost decouples from light fermions while still having large couplings to top

$M_{DM} < M_t$ since the strong coupling to top would otherwise give a too low relic density (for O(1) couplings).

DM mass is below kinematic threshold for top production in the zero velocity limit

Virtual top close to threshold can significantly enhance loop processes producing monochromatic photons.

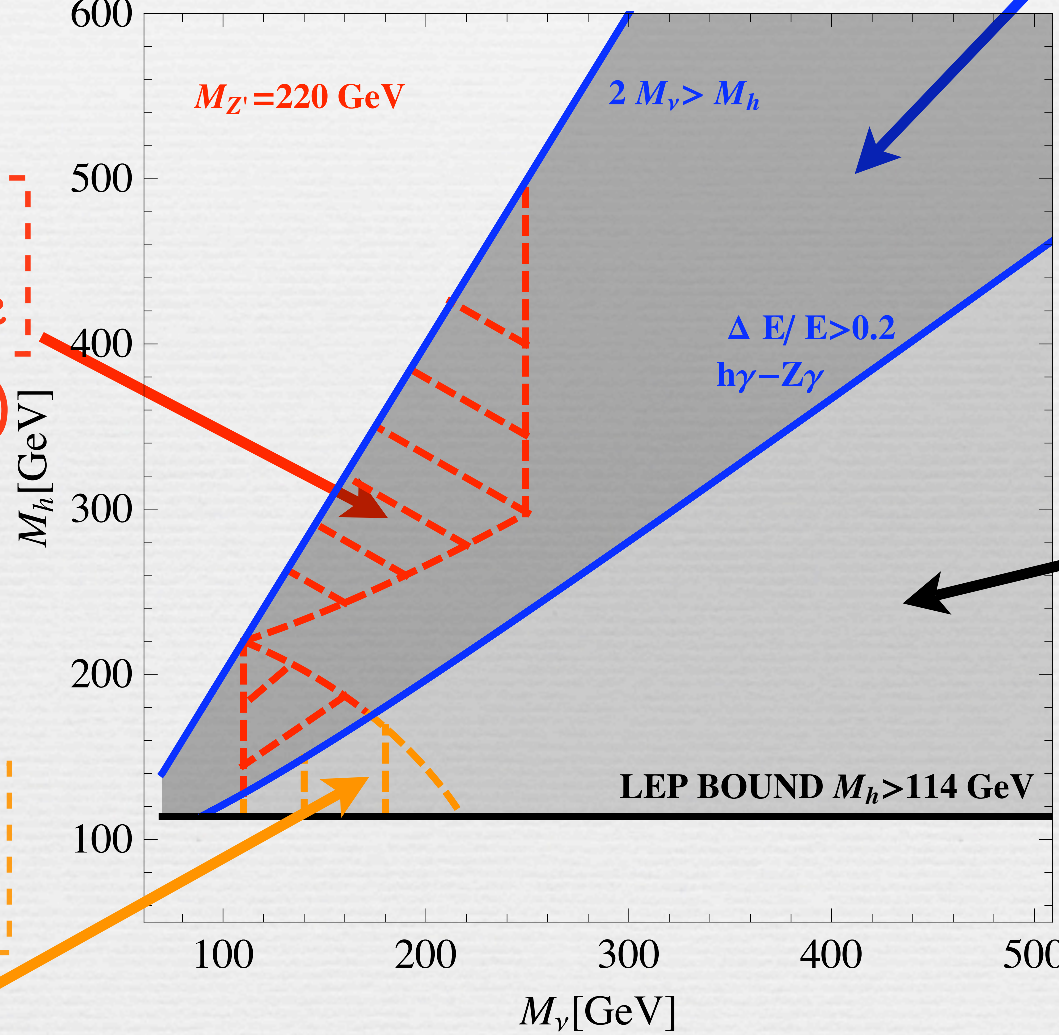
How many lines?

region where 2 lines are visible

(Hγ and Zγ)

region where the 3 lines are visible

(Hγ, Zγ and Z'γ)



region with 1 line (Hγ and Zγ lines are merged)

region with 2 lines

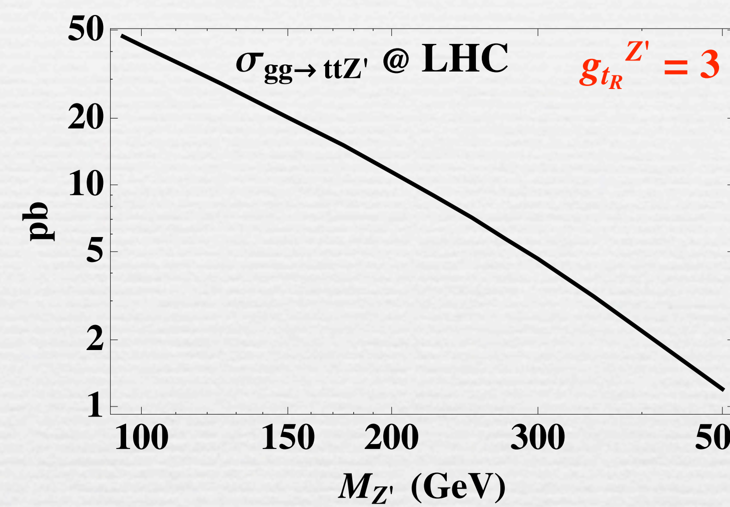
(H/Zγ and Z'γ)

assuming energy resolution of 10%

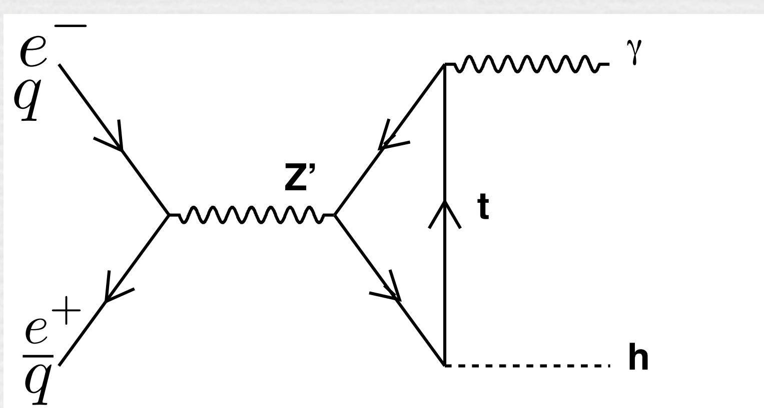
Collider signatures of a top (and DM)-philic Z′

- $f\bar{f} \to Z' \to t\bar{t}$ — light $t\bar{t}$ resonances

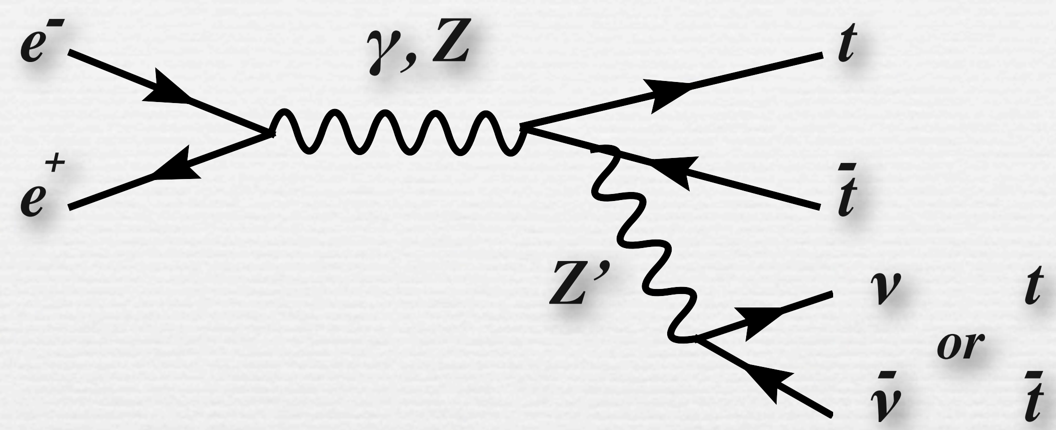
- $gg \to t\bar{t} + Z'$
  - $Z' \to \nu\bar{\nu}$: $t\bar{t} + \not{E}_T$
  - $Z' \to t\bar{t}$: $t\bar{t}t\bar{t}$

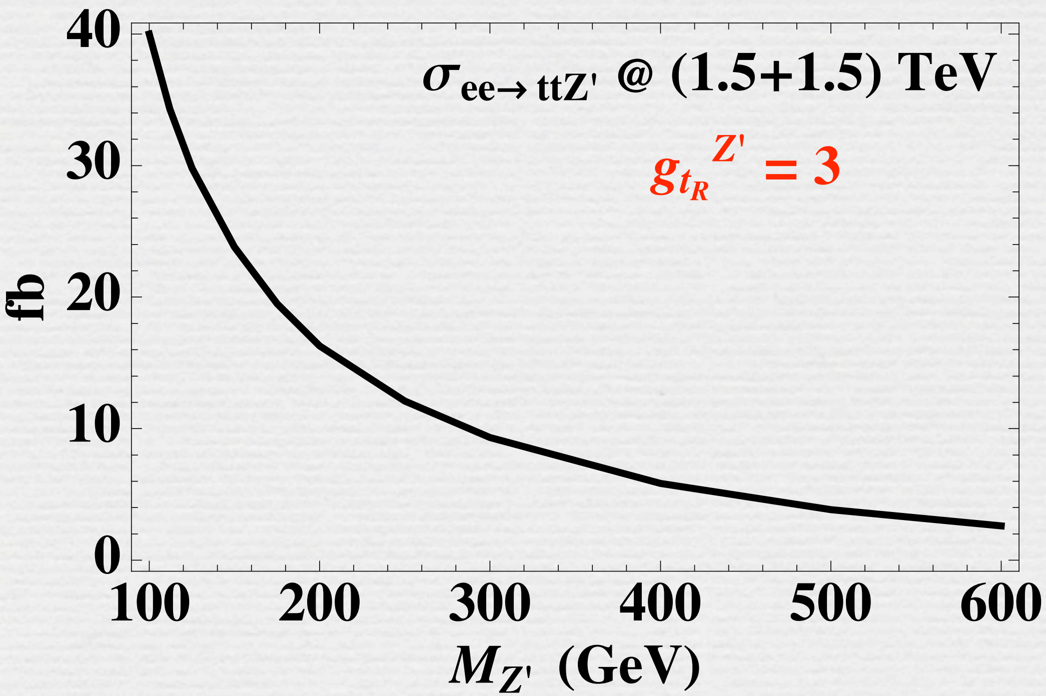


- $f\bar{f} \to Z' \to \gamma H$ — energetic monochromatic γ

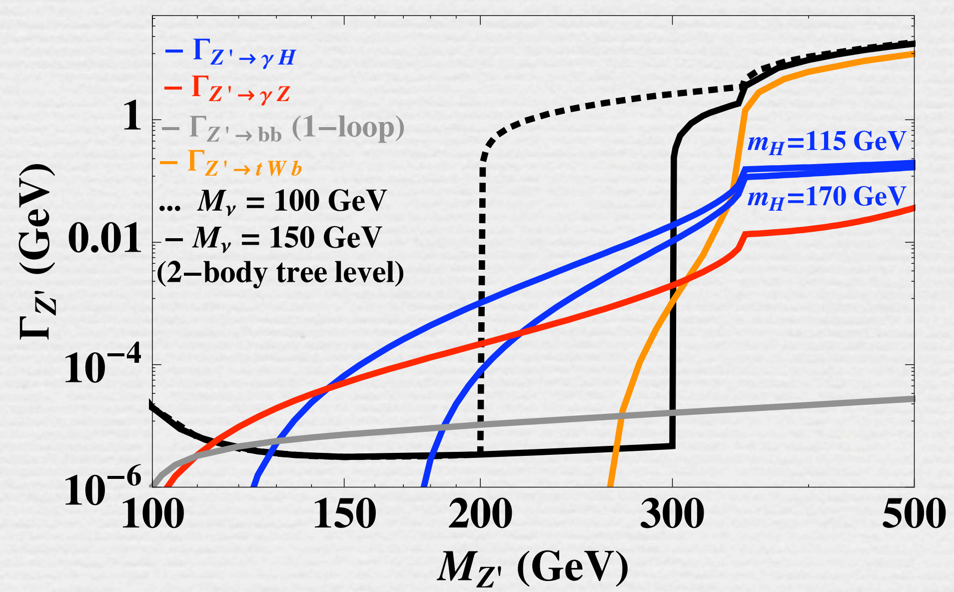


$e^+ e^- \to t\ \bar{t} + Z'$ @ CLIC

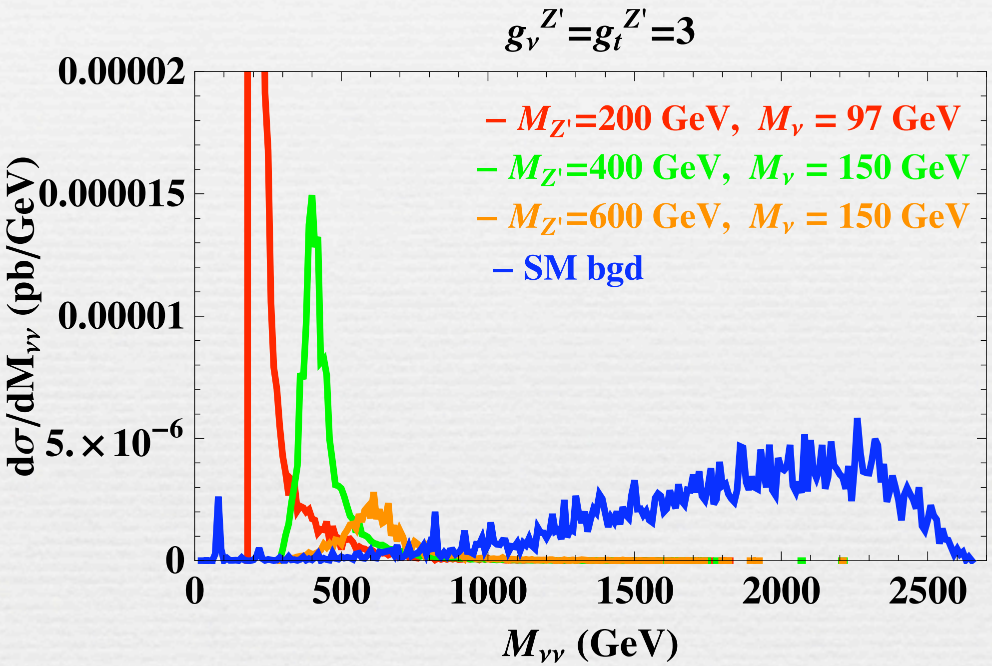




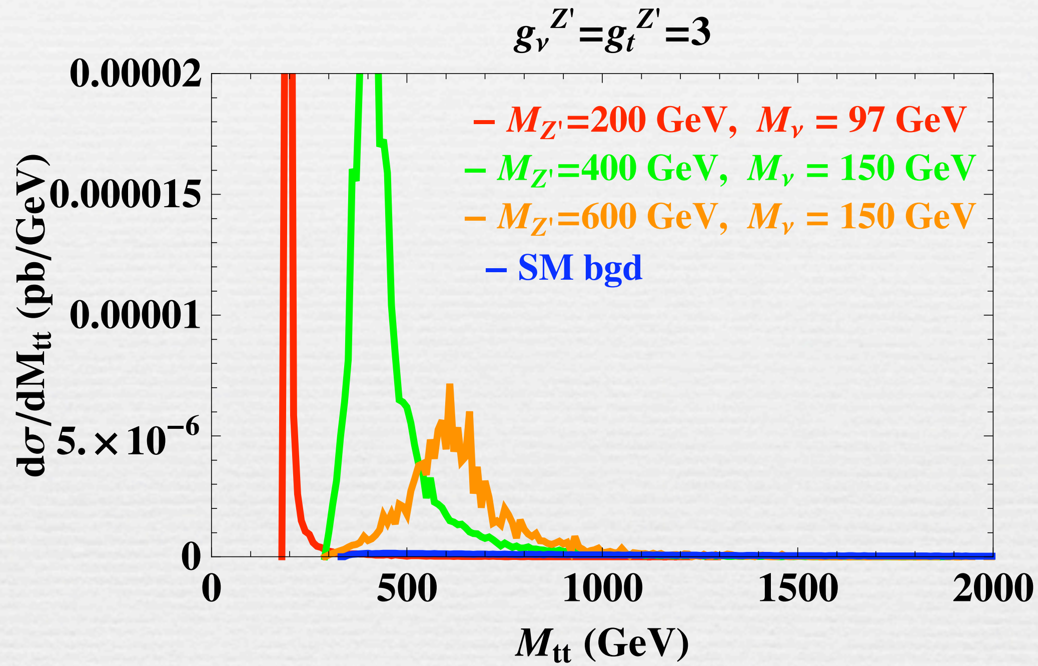
$g_\nu^{Z'} = g_t^{Z'} = 1$



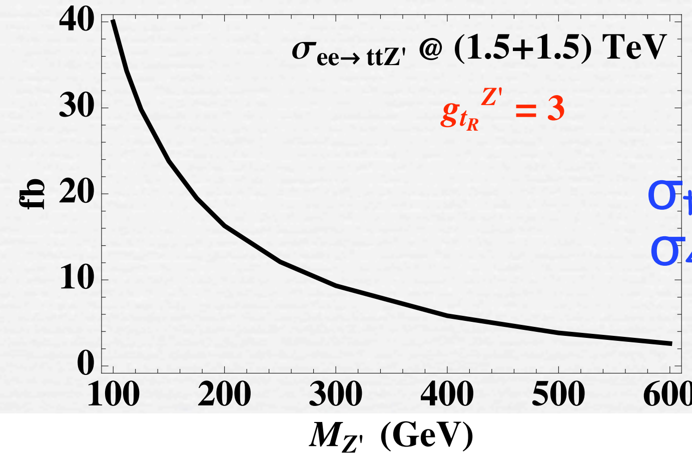
$e^+ e^- \to t\bar{t} + \not{E}_T$ @ (1.5 + 1.5) TeV



$e^+ e^- \to t\bar{t}t\bar{t}$ @ (1.5 + 1.5) TeV

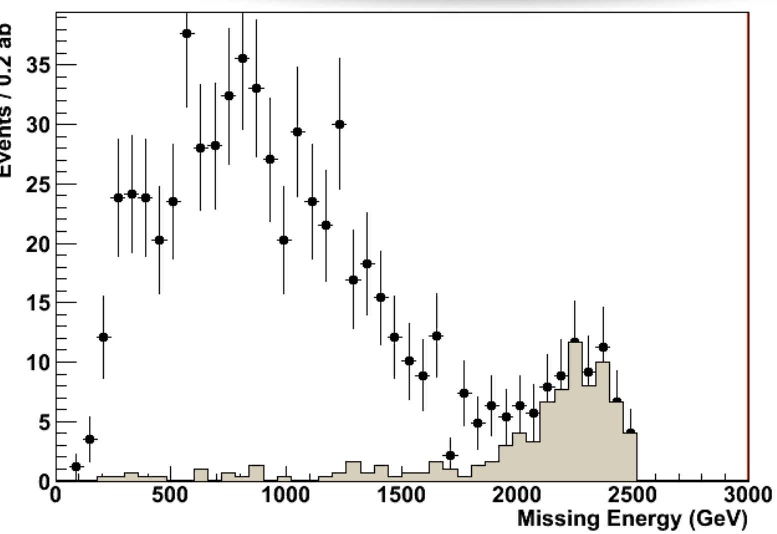


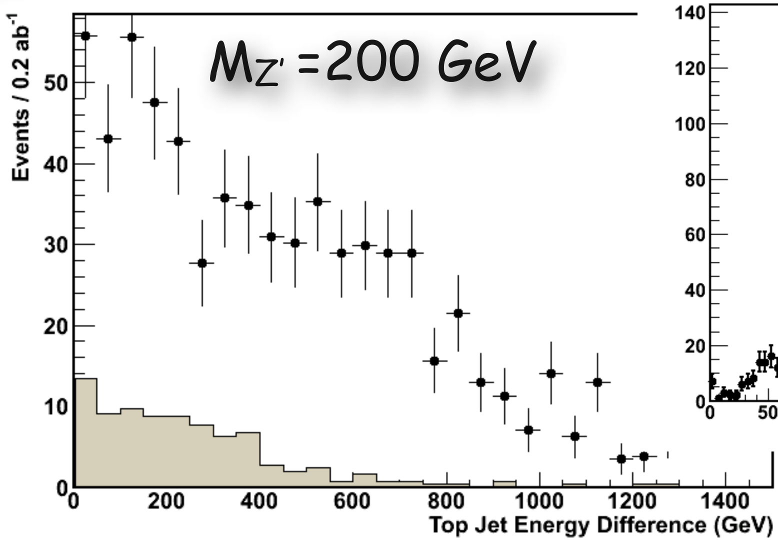
$M_{Z'}$ = 200 GeV, M_ν=97 GeV:	$\sigma_{tt\nu\nu}$ =16.5 fb	σ_{4t} = 0.9 fb
$M_{Z'}$ = 400 GeV, M_ν=150 GeV:	$\sigma_{tt\nu\nu}$ =1.6 fb	σ_{4t} = 3.3 fb
$M_{Z'}$ = 600 GeV, M_ν=150 GeV:	$\sigma_{tt\nu\nu}$ =0.5 fb	σ_{4t} = 1.3 fb
SM =	$\sigma_{tt\nu e\nu e}$ =4.1 fb	σ_{4t} = 0.03 fb

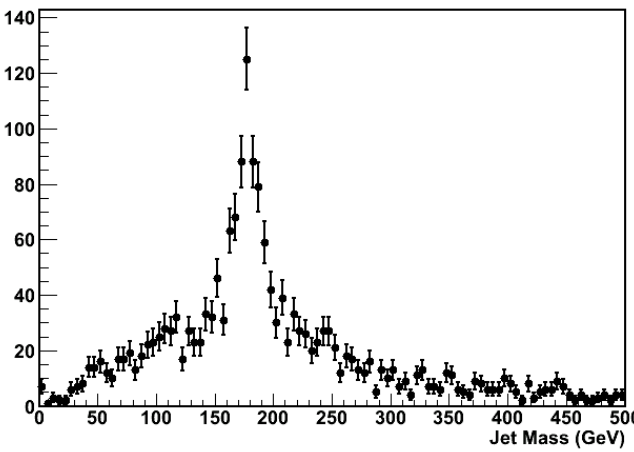


σ_{ttveve} = 4.1 fb
$\sigma_{4t \text{ in SM}}$ = 0.03 fb

$e^+ e^- \to t\bar{t} + \not{E}_T$ @ 3 TeV CLIC

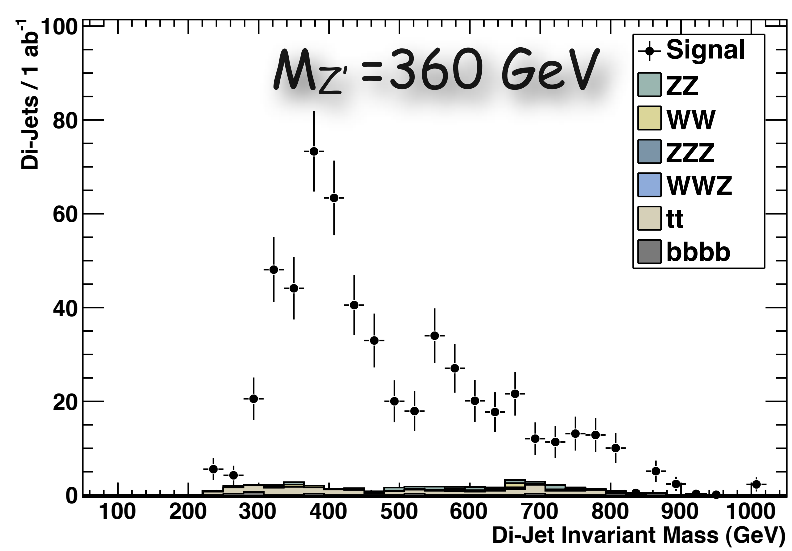






0.2 ab^{-1}

$e^+ e^- \to t\bar{t}t\bar{t}$ @ 3 TeV CLIC



Battaglia-Servant in progress

Summary

Are DM and EW symmetry breaking related ? If so, wimps may have enhanced couplings to massive states, top, W/Z, H etc.

DM-Top quark connection (RS and composite Higgs inspired)

Signals of a Higgs from γ rays

Observation of ΥH would indicate that the WIMP is not a scalar nor a Majorana fermion but most likely a Dirac fermion

Collider studies in progress

Y(T): abundance of DM

$$\frac{dY}{dT} = \sqrt{\frac{\pi g_*(T)}{45}} M_p < \sigma v > (Y(T)^2 - Y_{eq}(T)^2)$$

$\langle\sigma v\rangle$: relativistic thermally averaged annihilation cross section

$$< \sigma v >= \frac{\sum_{i,j} g_i g_j \int_{(m_i+m_j)^2} ds \sqrt{s} K_1(\sqrt{s}/T) p_{ij}^2 \sum_{k,l} \sigma_{ij;kl}(s)}{2T\Big(\sum_i g_i m_i^2 K_2(m_i/T)\Big)^2}$$

Photon flux produced by DM annihilations

and collected from a region of angular size ΔΩ

$$\frac{d\Phi}{dE} = \frac{1}{4\pi} \frac{r_\odot \rho_\odot^2}{4M_{DM}^2} \sum_f \langle \sigma v \rangle_f \frac{dN_\gamma^f}{dE} \int_{\Delta\Omega} d\Omega \int_{los} \frac{dl}{r_\odot} \left(\frac{\rho(r(l,\psi))}{\rho_\odot} \right)^2$$

includes all possible annihilation final states

$\equiv \bar{J}(\Delta\Omega)$

microphysics

astrophysics (halo profile)

Astrophysical uncertainties on the DM density profile

MW halo model	r_s in kpc	ρ_s in GeV/cm^3	$\bar{J}$ (10^{-5})
NFW [20]	20	0.26	$15 \cdot 10^3$
Einasto [21]	20	0.06	$7.6 \cdot 10^3$
Adiabatic[22]			$4.7 \cdot 10^7$

for observation of the galactic center region with angular acceptance $\Delta\Omega = 10^{-5}$

A common signature:

$$t\,\bar{t} + \text{large } \not{E}_T$$

from pair-production of top partners that decay into DM

scalar

Majorana fermion

SUSY: $\tilde{t} \longrightarrow \chi_0\ t$

Little Higgs $T \longrightarrow A_H\ t$

Gauge bosons

Universal extra dimensions $t^{(1)} \longrightarrow B^{(1)}\ t$

Randall-Sundrum GUTs $t^{(1)'} \longrightarrow \nu^{(1)'}\ \overline{\nu}^{(1)'}\ t$

Dirac fermions