Higgs in Space !

Géraldine SERVANT, CERN-TH

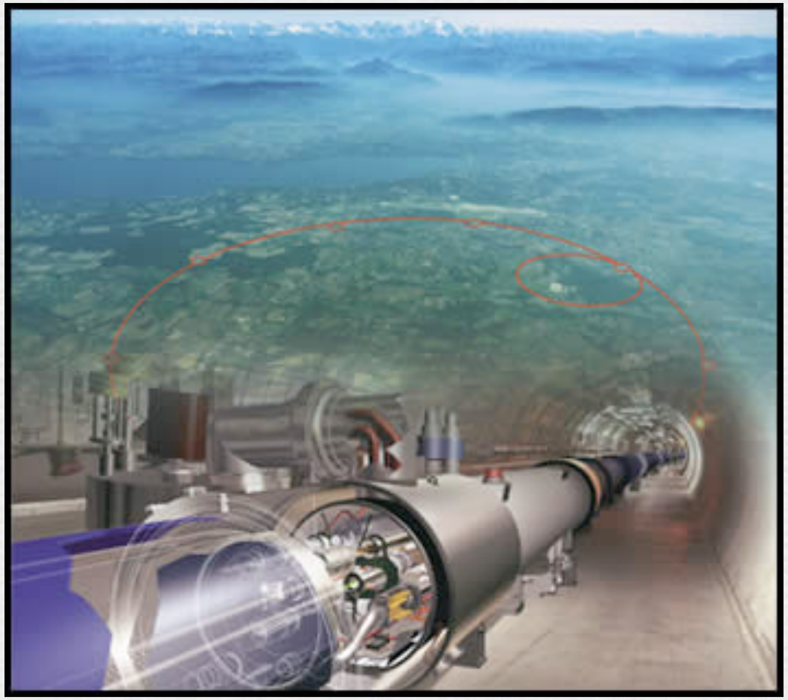
based on:

- C. Jackson, G. Shaughnessy (U. Northwestern & Argonne), T. Tait (U. Irvine) & M. Taoso (U. Valencia), 0912.0004
- Bélanger, Servant, Pukhov '07
- Agashe, Servant '04

The 2 main races of the next several years:

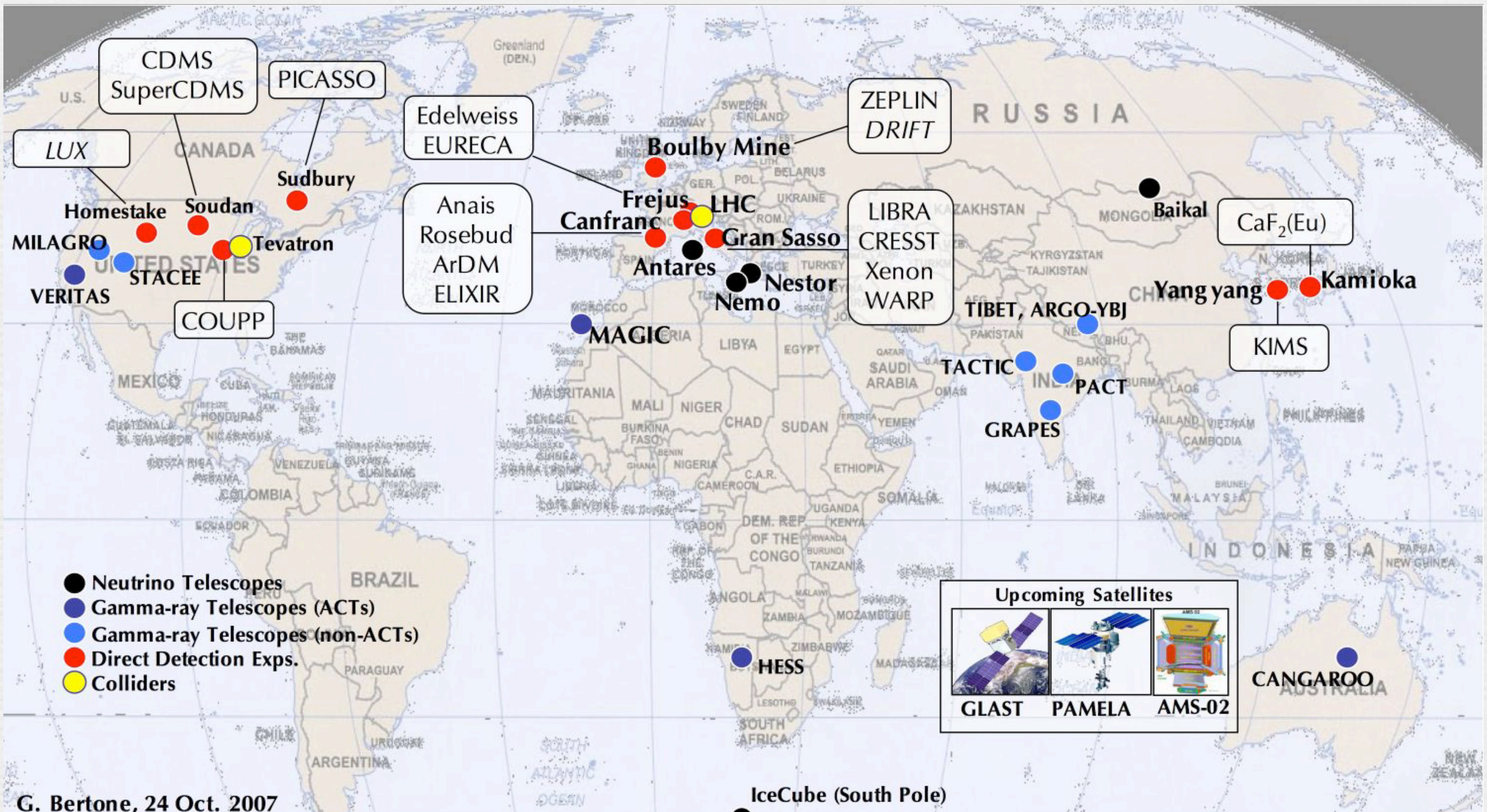
the searches for the Higgs Boson and Dark Matter

Huge experimental effort towards the identification of the Higgs boson



Huge experimental effort towards the identification of Dark Matter

Indirect	Direct	Collider experiments
Antimatter Neutrinos Gamma Rays — Signature of Annihilation in space	Elastic Scattering signature in underground labs	Missing Energy signature in high energy accelerators



Dark Matter and the Fermi scale

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

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

→ 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")

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

↓

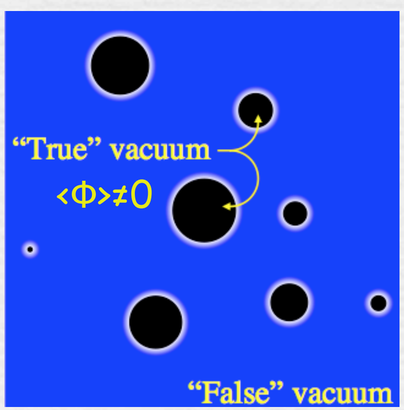
DM candidate

Can the Higgs be searched for outside of colliders?

Indirect probes of the Higgs in space. I

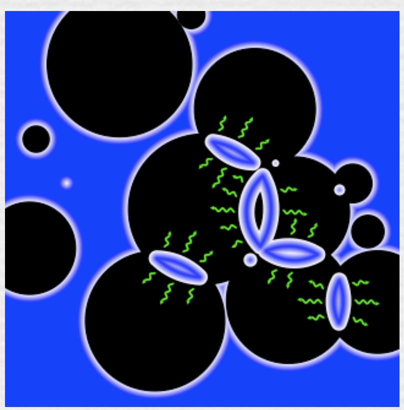
Discovery of a stochastic background of gravity waves peaked in the MilliHertz would be an indication of a first-order phase transition at temperatures ~ 100 GeV-10 TeV -> Indirect probe of the Higgs potential or of TeV scale physics responsible for EW sym. breaking

Bubble nucleation



<Φ>=0

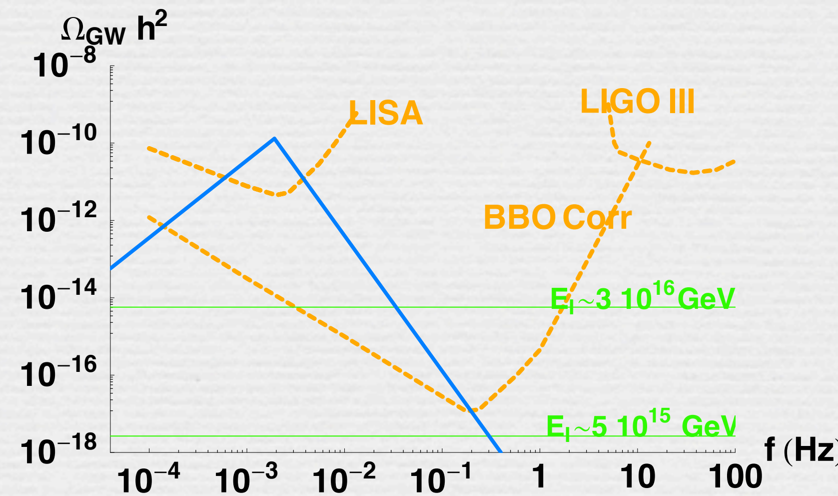
Bubble percolation



Fluid flows

Magnetic fields

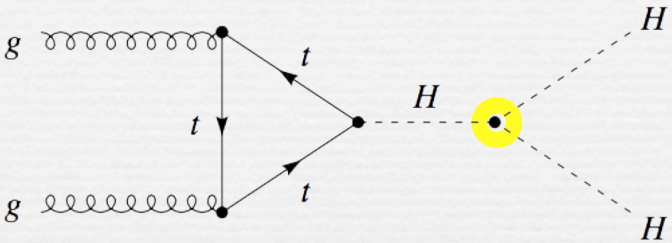
Stochastic background of gravitational radiation



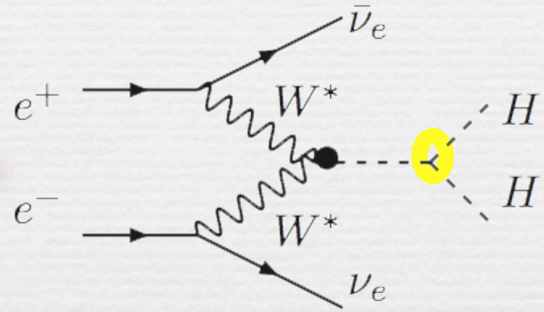
e.g. Caprini, Durrer, Servant '08,'09
Huber & Konstandin '08

Experimental tests of the Higgs self-coupling

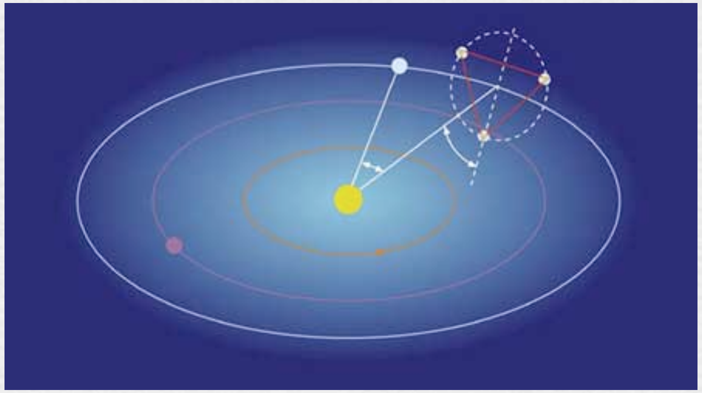
at a Hadron Collider

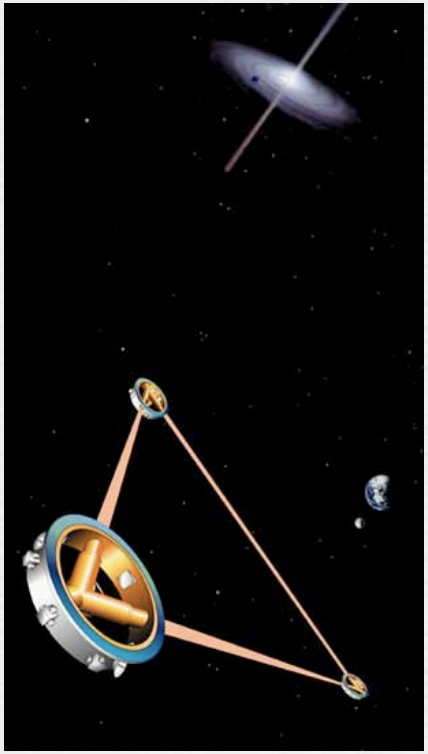


at an $e^+ e^-$ Linear Collider



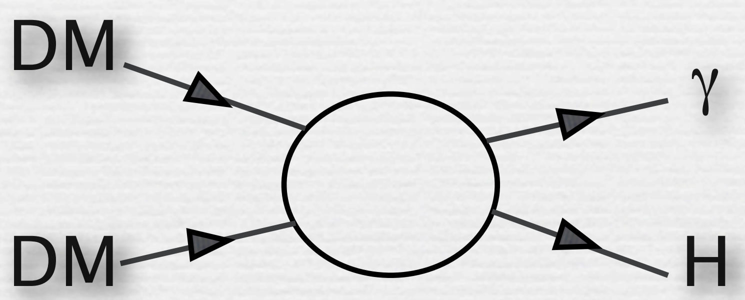
... or at the gravitational wave detector LISA

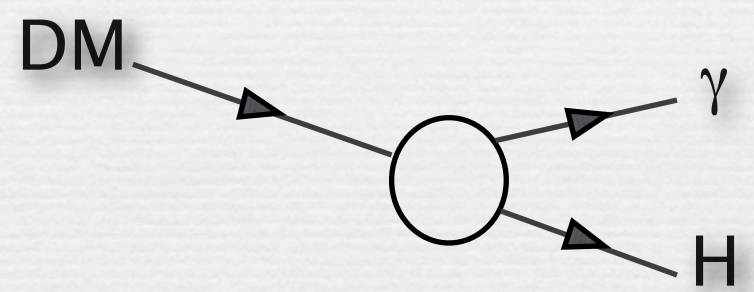




The LHC may not be the only place in the universe
where the Higgs is being produced today

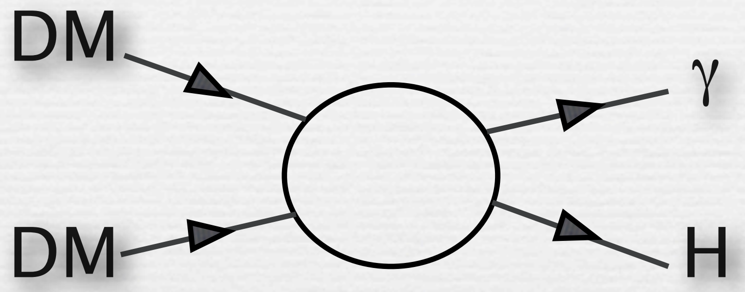
What about Higgs production today in
Dark Matter annihilations or Dark Matter decays?





Indirect probes of the Higgs in space. II

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

if the WIMP hypothesis is correct: likely to be connected to the physics of EW symmetry breaking and may have enhanced couplings to massive states

Seeing the light from Dark Matter

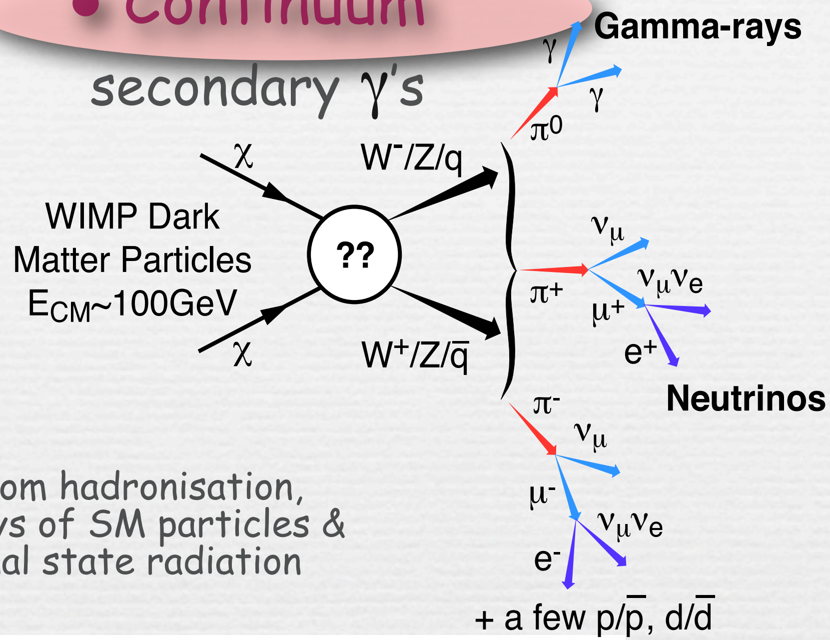
- photons travel undeflected and point directly to source
- photons travel almost unattenuated and don't require a diffusion model
- detected from the ground (ACTs) and from above (FERMI)

Seeing the light from Dark Matter

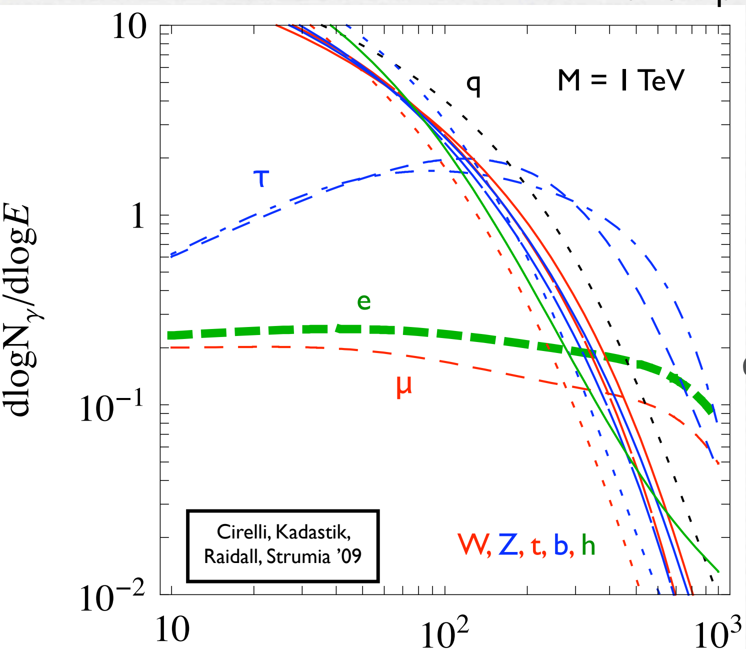
γ's from DM annihilations consist of 2 components

• Continuum

secondary γ's



from hadronisation,
decays of SM particles &
final state radiation



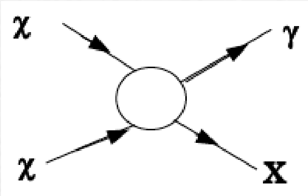
GeV

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

Bergstrom, Ullio, Buckley '98

Seeing the light from Dark Matter

- What if the nature of DM is such that production of "direct" photons can be large?
- The position and strength of lines can provide a wealth of information about DM:

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

→ $\gamma\gamma$ 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]

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 $\Delta\Omega=10^{-5}$

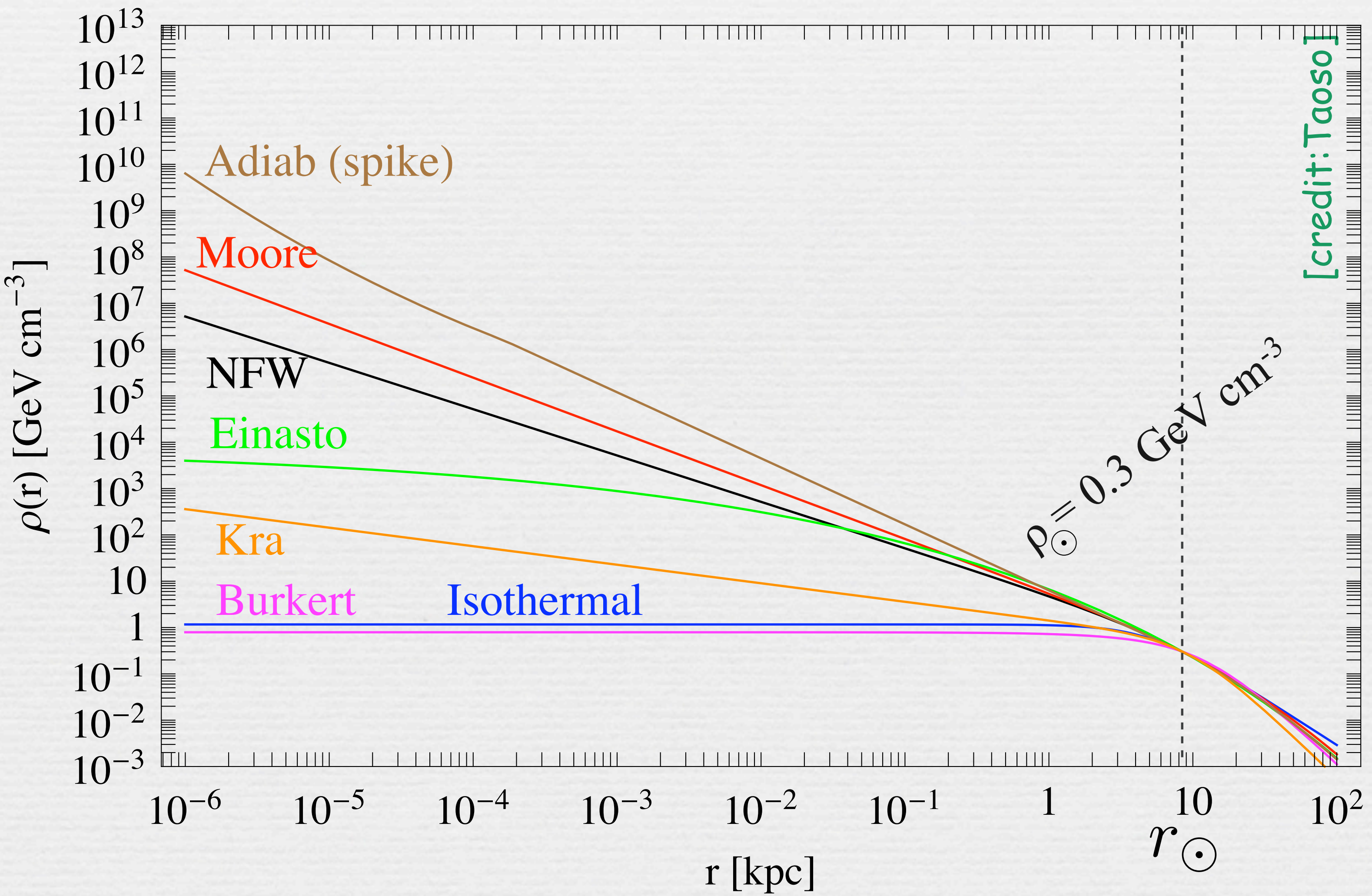
for DM decay:

* $\frac{\langle \sigma v \rangle}{4M_{DM}^2} \rightarrow \frac{1}{\tau M_{DM}}$
* $\rho^2 \rightarrow \rho$

$$\frac{d\Phi}{dE} \propto \int \rho^2$$

Searches focus on regions of the sky where DM clumps: Galactic Center, dwarf galaxies...

Astrophysical uncertainties on the DM density profile



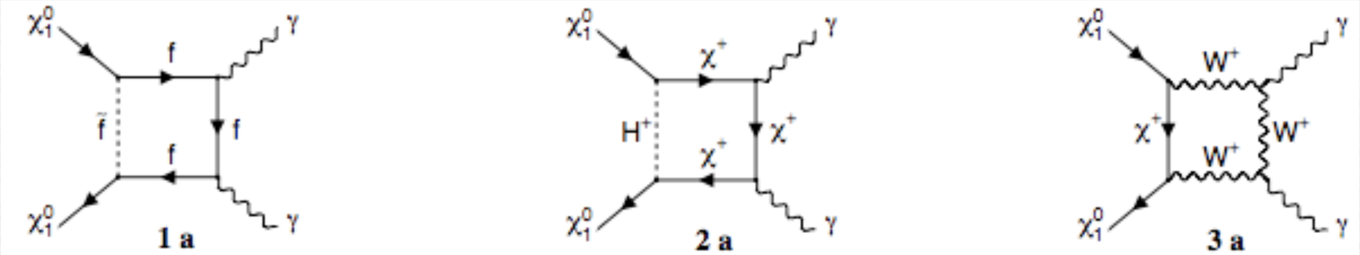
γ -lines from DM

Past results

SUPERSYMMETRY

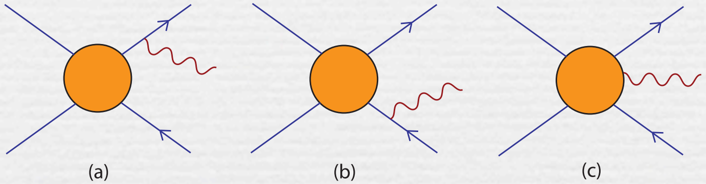
Bergstrom, Ullio, Buckley' 98
Bringmann, Bergstrom & Edsjo '08
...

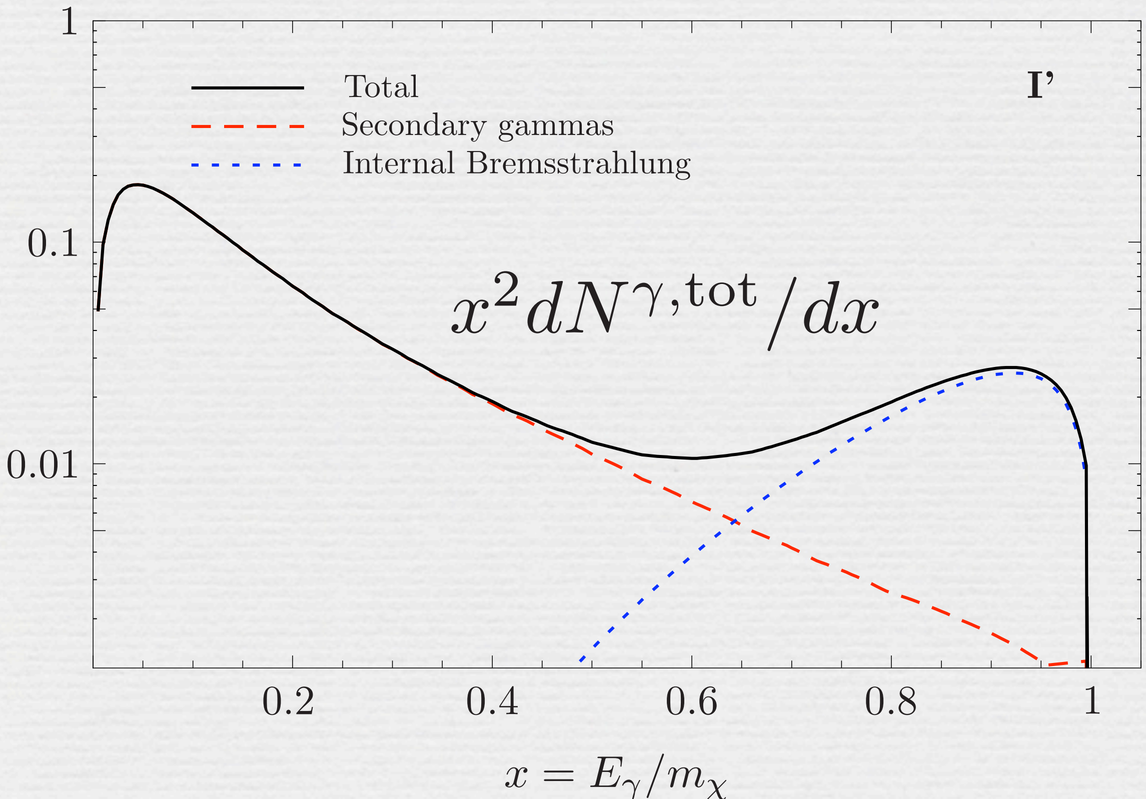
annihilations into γ γ & γ Z :



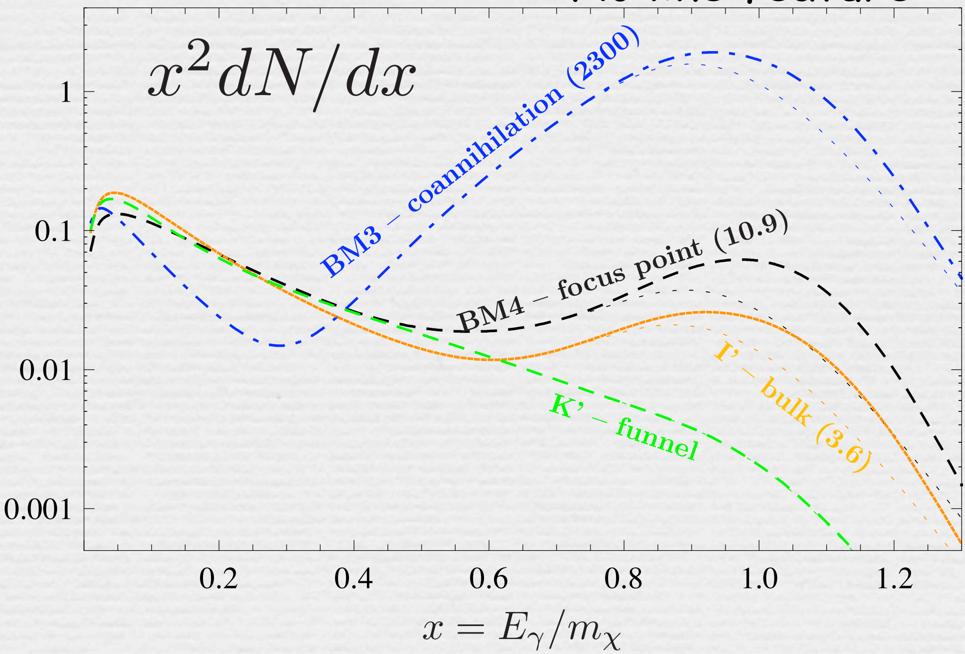
"Standard"Continuum suppressed by Majorana nature of WIMP
(light fermion states chirally suppressed)

However, as recently reexamined: large enhancements from internal bremsstrahlung





No line feature



The Inert Doublet Model (IDM)

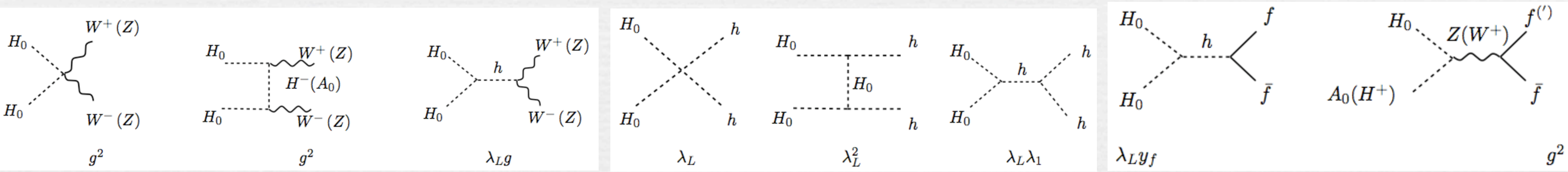
Deshpande-Ma'78; Barbieri-Hall-Rychkov 06; Lopez Honorez-Nezri-Oliver-Tytgat 06; Gerard-Herquet'07 ; Hambye, Tytgat 07 .....

A two-Higgs extension of the SM with an unbroken Z_2 symmetry

$H_1 \rightarrow H_1$ and $H_2 \rightarrow -H_2$ (and all SM fields are even)

$$V = \mu_1^2|H_1|^2 + \mu_2^2|H_2|^2 + \lambda_1|H_1|^4 + \lambda_2|H_2|^4 + \lambda_3|H_1|^2|H_2|^2 + \lambda_4|H_1^\dagger H_2|^2 + \frac{\lambda_5}{2}\left[(H_1^\dagger H_2)^2 + h.c.\right]$$

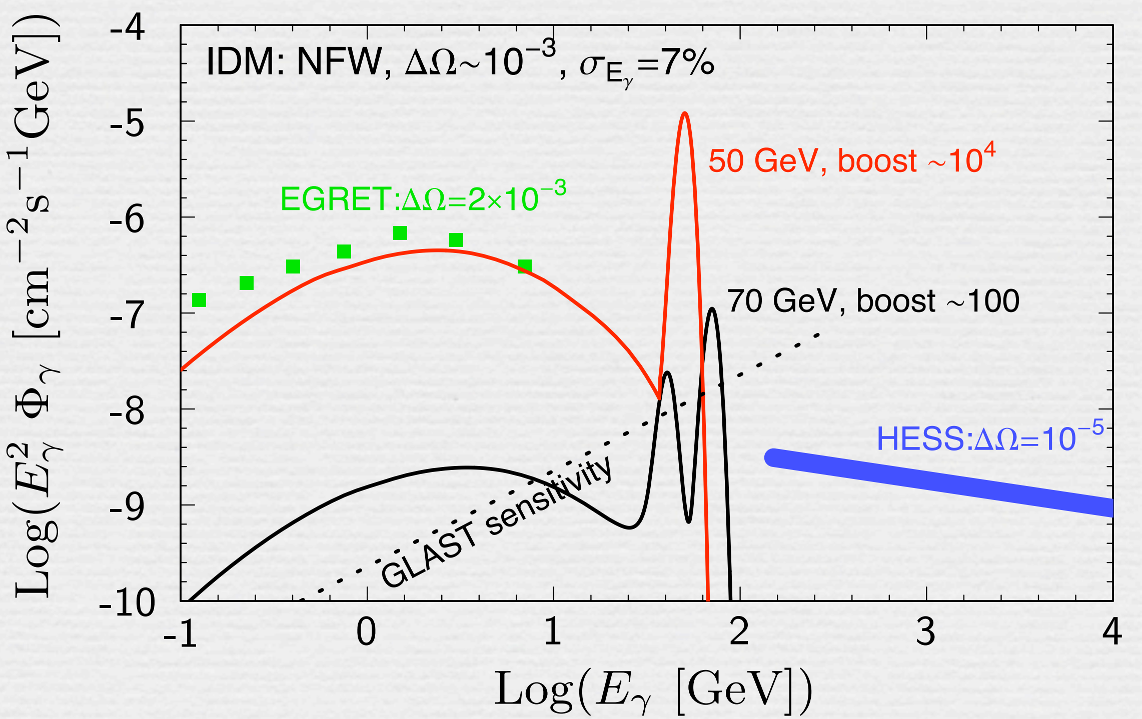
Scalar WIMP with $M_{DM} \sim M_W$



annihilations into $\gamma\gamma$ & γZ mainly through loops of W

Gustaffsson et al. '07

virtual W nearly on-shell threshold enhancement

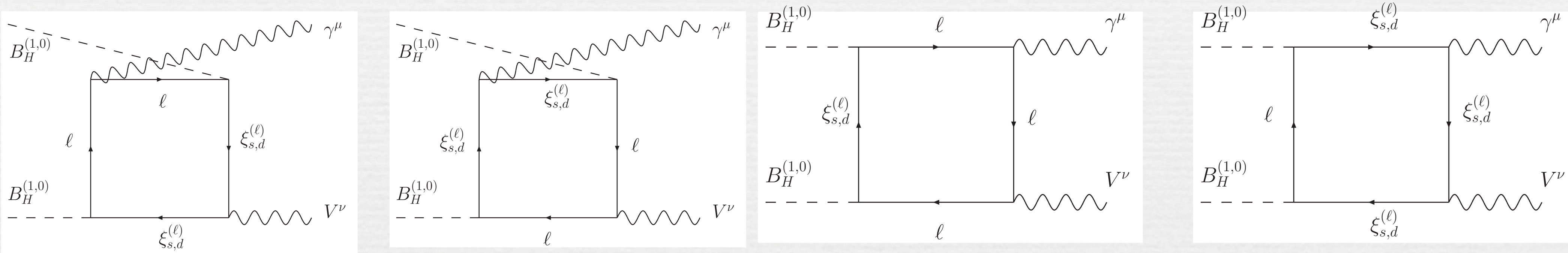


Lines from 6D Universal Extra Dimensions (the "Chiral square")

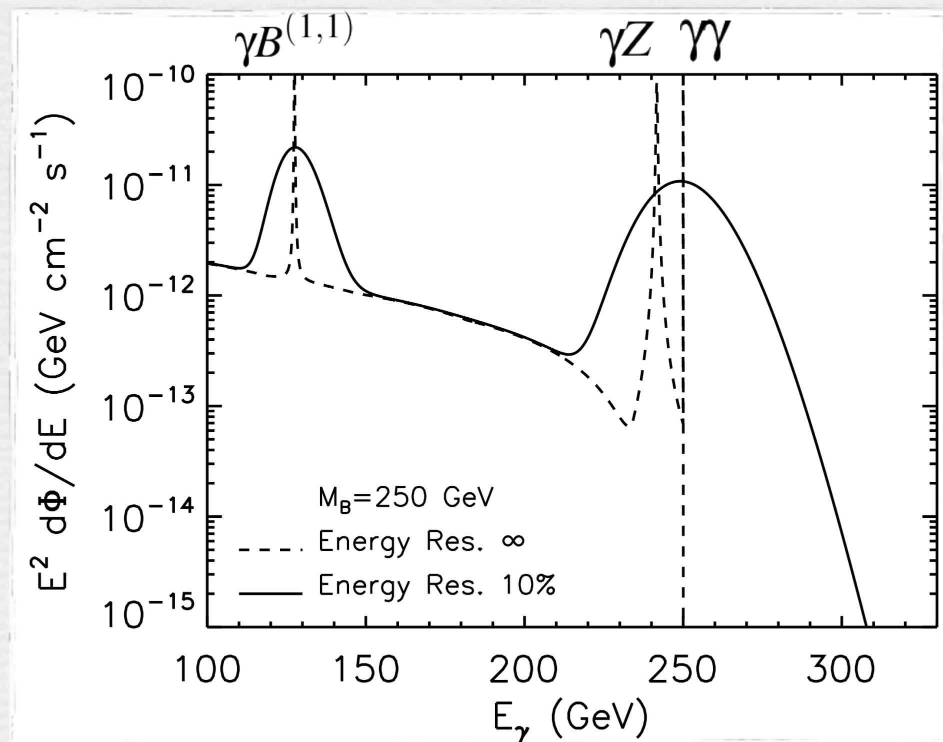
WIMP=scalar B_H ("spinless photon") with M~200-500 GeV

Burdman, Dobrescu, Ponton'05
Dobrescu, Hooper, Kong, Mahbubani '07

$B_H B_H \to \gamma V$ where V= γ, Z and $B^{(1,1)}$



Bertone, Jackson, Shaughnessy, Vallinotto, Tait. '09



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)

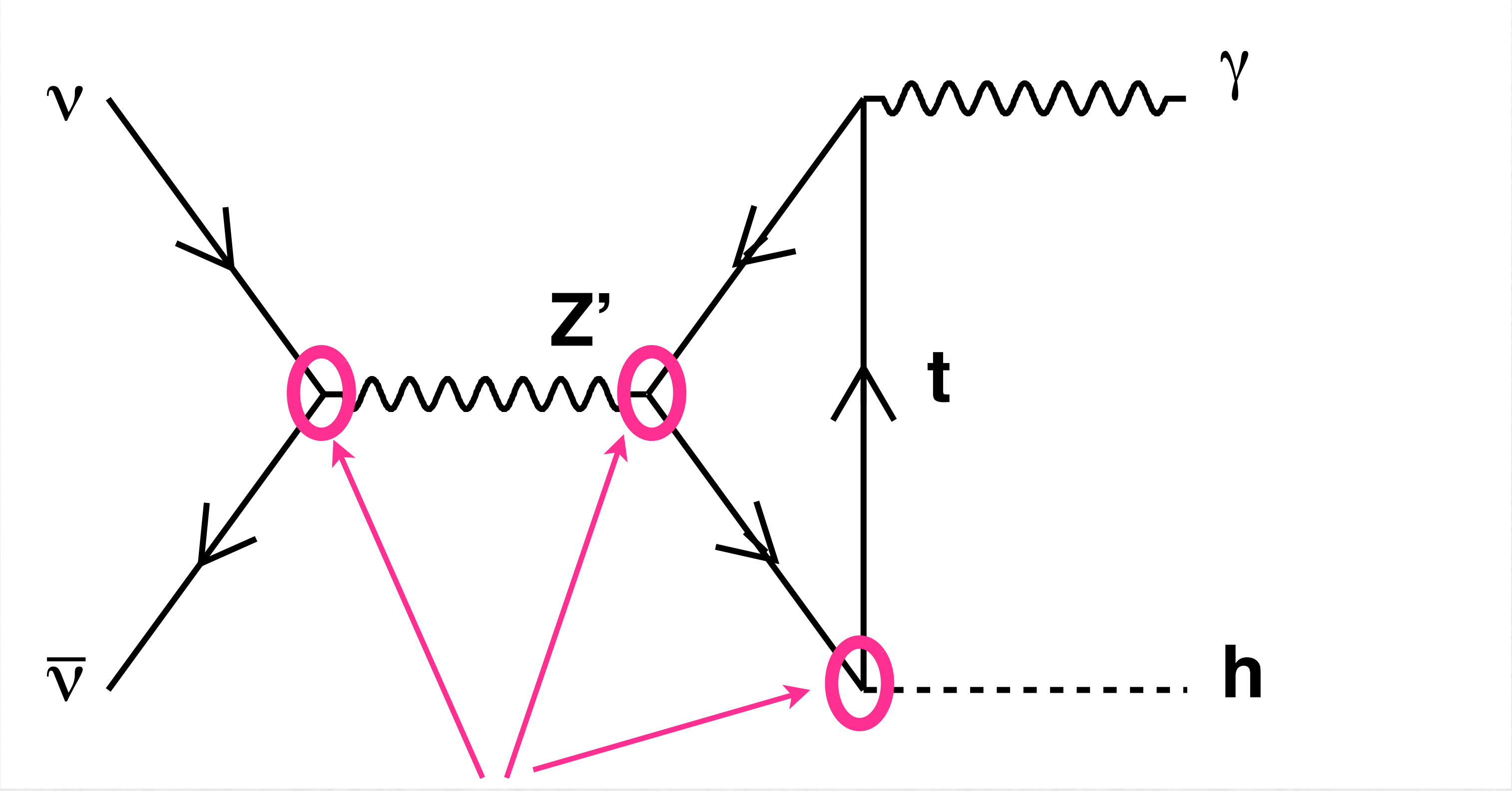
Vector DM e.g. KK photon in 5D UED, heavy photon in Little Higgs models

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)

→ **need for Dirac Fermion DM**

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

Dirac fermion annihilation into γ H



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 of partial fermion compositeness, natural to expect that only the top couples sizably to a new strongly interacting sector.

Proton stability & Stable GUT partner in Warped GUTs

Agashe-Servant'04

DM is RH neutrino from 16 of SO(10)

$$\begin{pmatrix} Q'_L \\ u^c_R \\ d^c_R \\ L'_L \\ e'^c_R \\ \nu'^c_R \end{pmatrix}$$

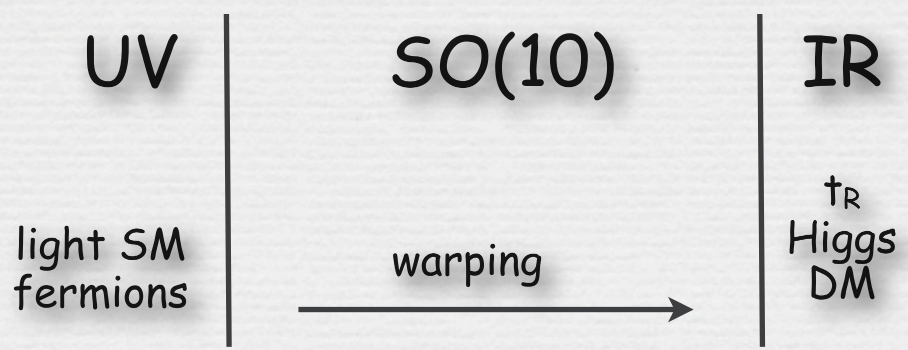
multiplet has B=1/3

bulk fermion with (-+) BC -> light!

number of color indices

stable under $Z_3 : \Phi \longrightarrow \Phi \; e^{2\pi i \left[B - \frac{\alpha - \overline{\alpha}}{3}\right]}$

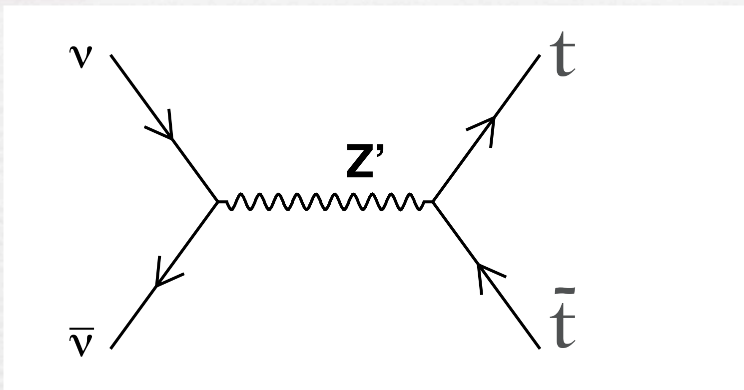
Has enhanced couplings to TeV KK modes (such as Z') and top quark

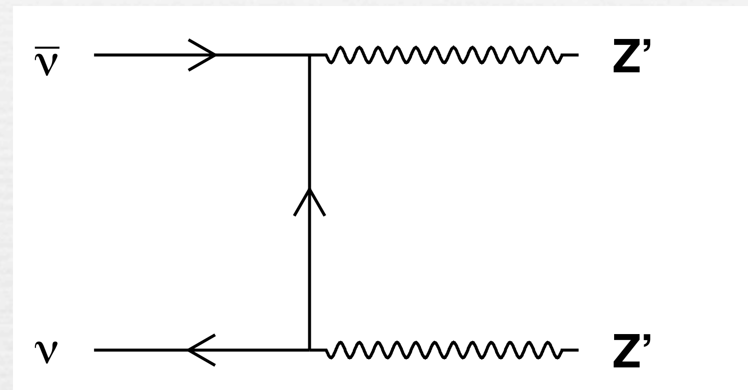


Relic density calculation

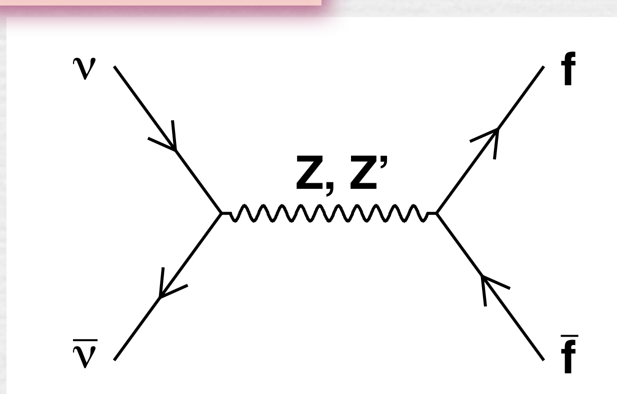
(assuming no ν ν̄ asymmetry)

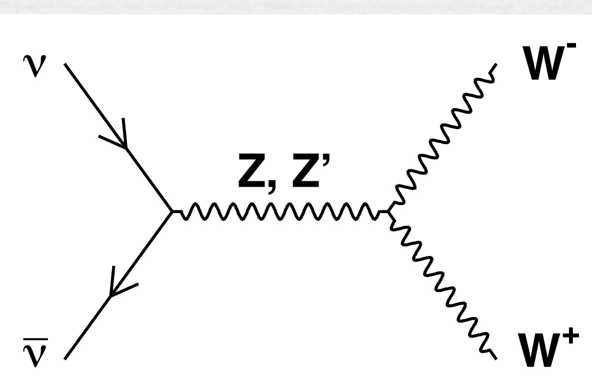
dominant channels

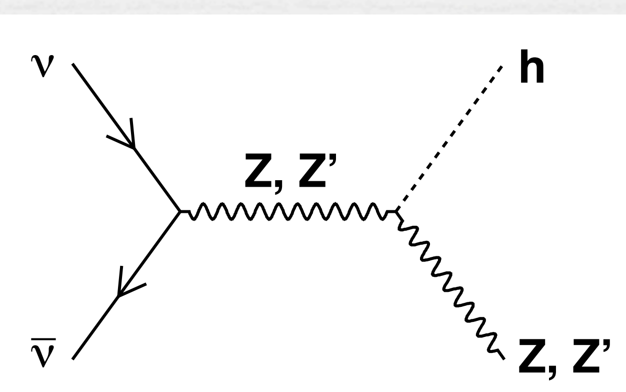




suppressed channels

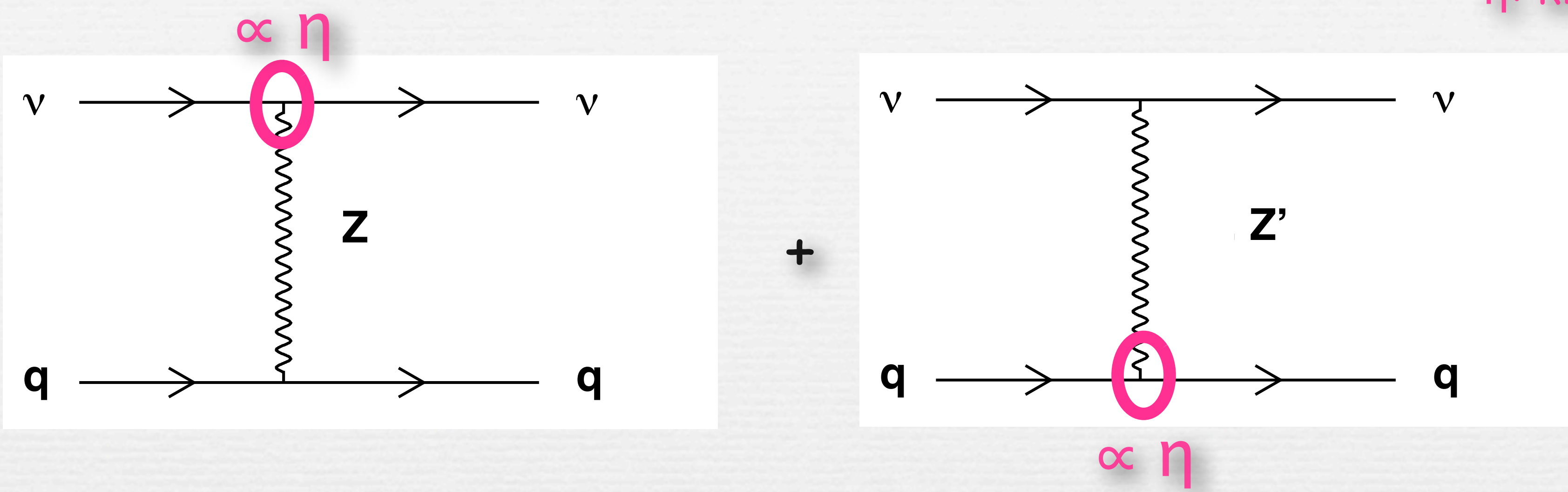






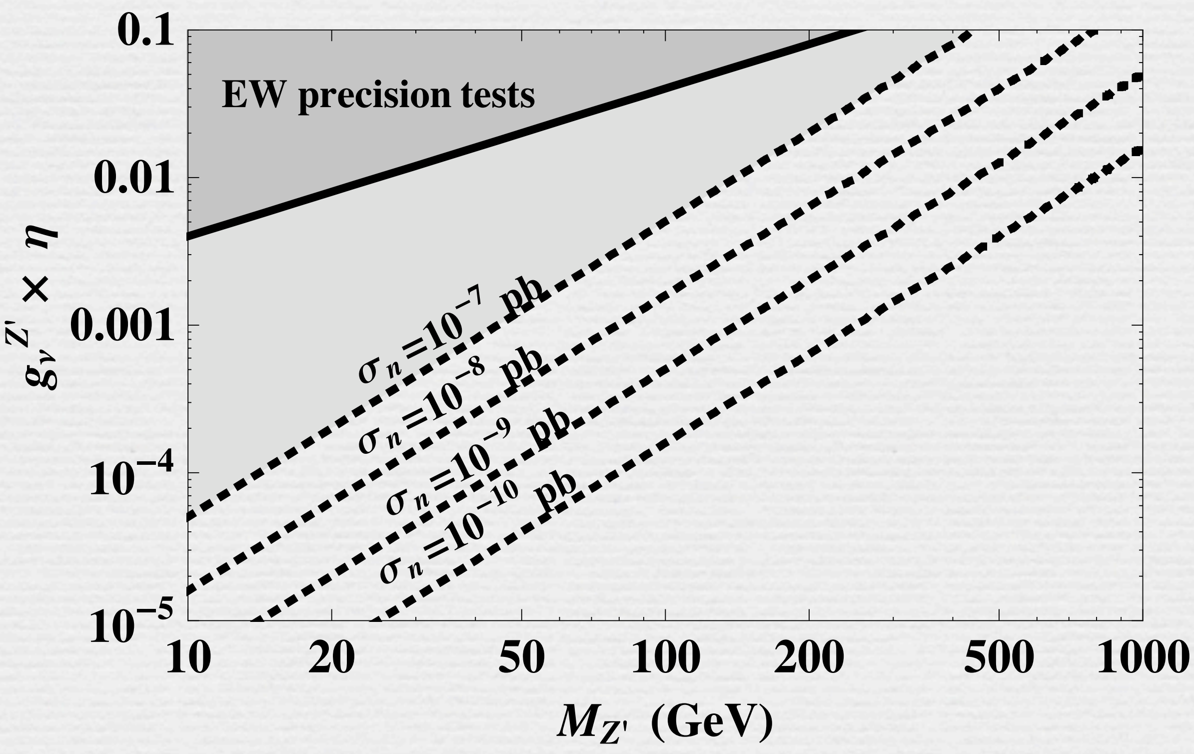
Direct detection constraints

η: kinetic mixing

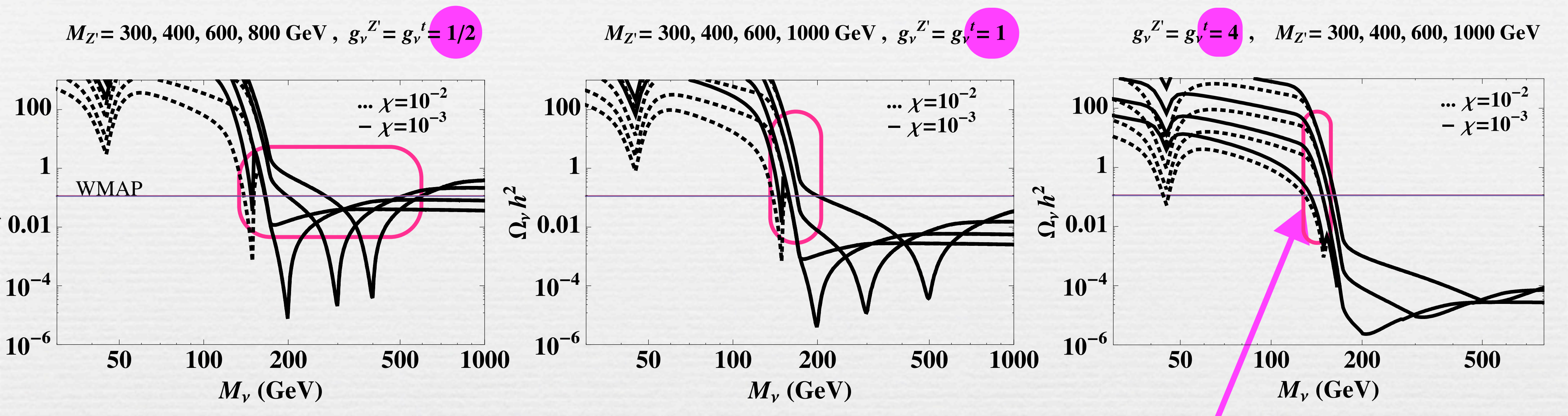


→ $\sigma \propto \eta^2$

ν-nucleon elastic scattering cross section contours



Dark matter mass from relic density calculation

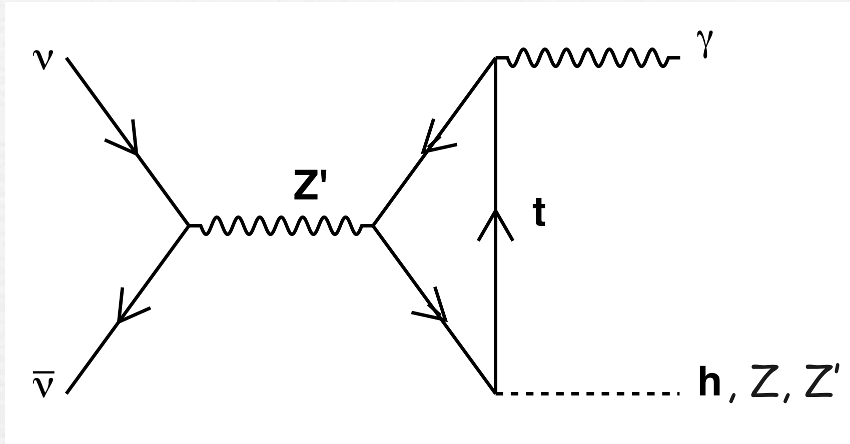


M_{DM} ~ 150 GeV

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

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

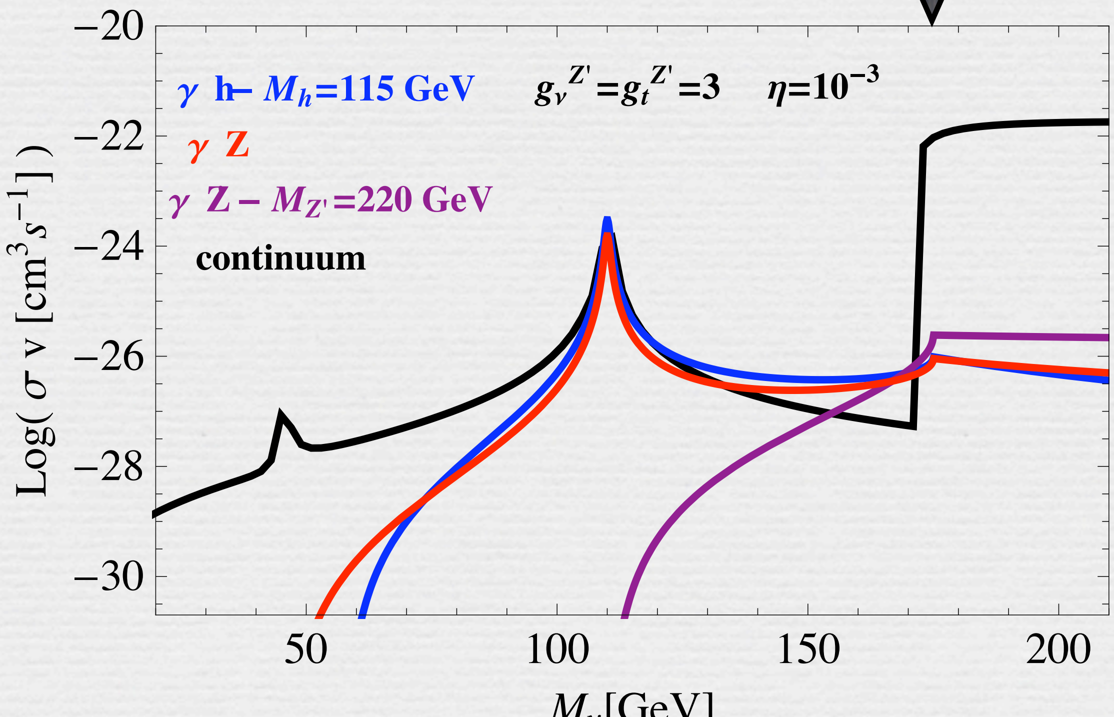
γ signal from ν annihilation



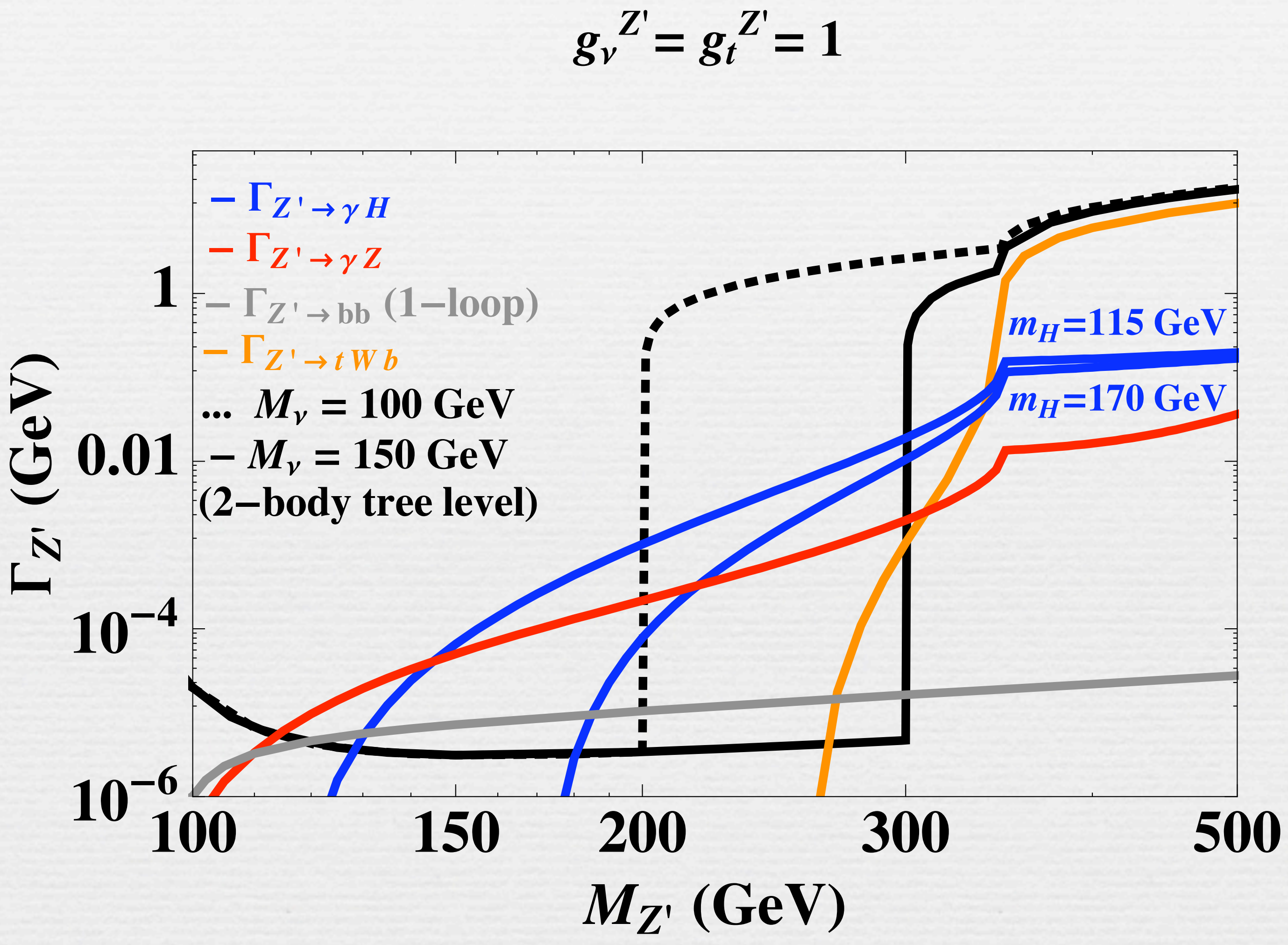
Note: no γγ line as dictated by Landau-Yang theorem (Z' being the sole portal from the wimp sector to the SM)

Lines not suppressed compared to continuum

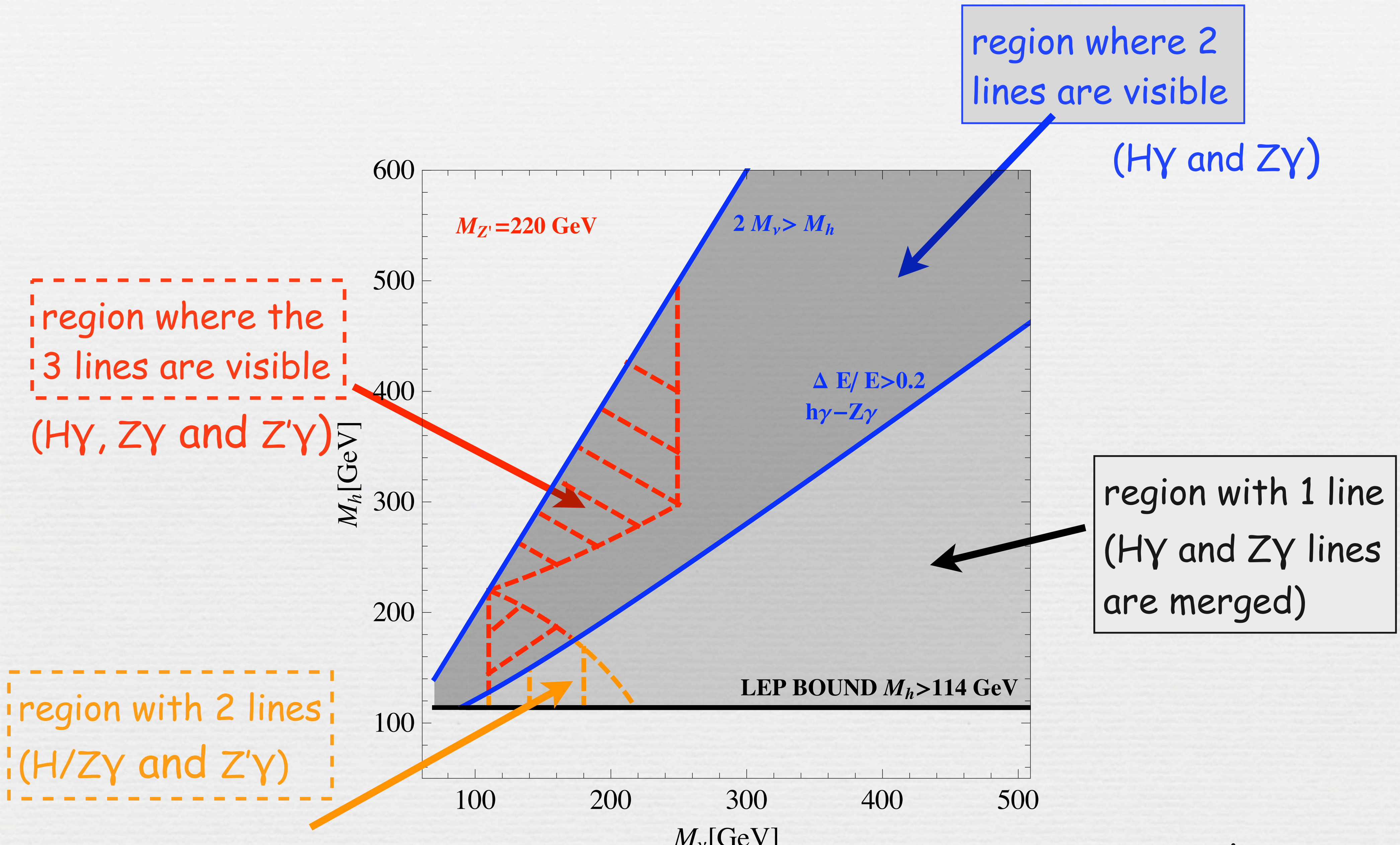
continuum jumps due to opening of $t\bar{t}$ channel



Lines not suppressed compared to continuum



How many lines?



assuming energy resolution of 10%

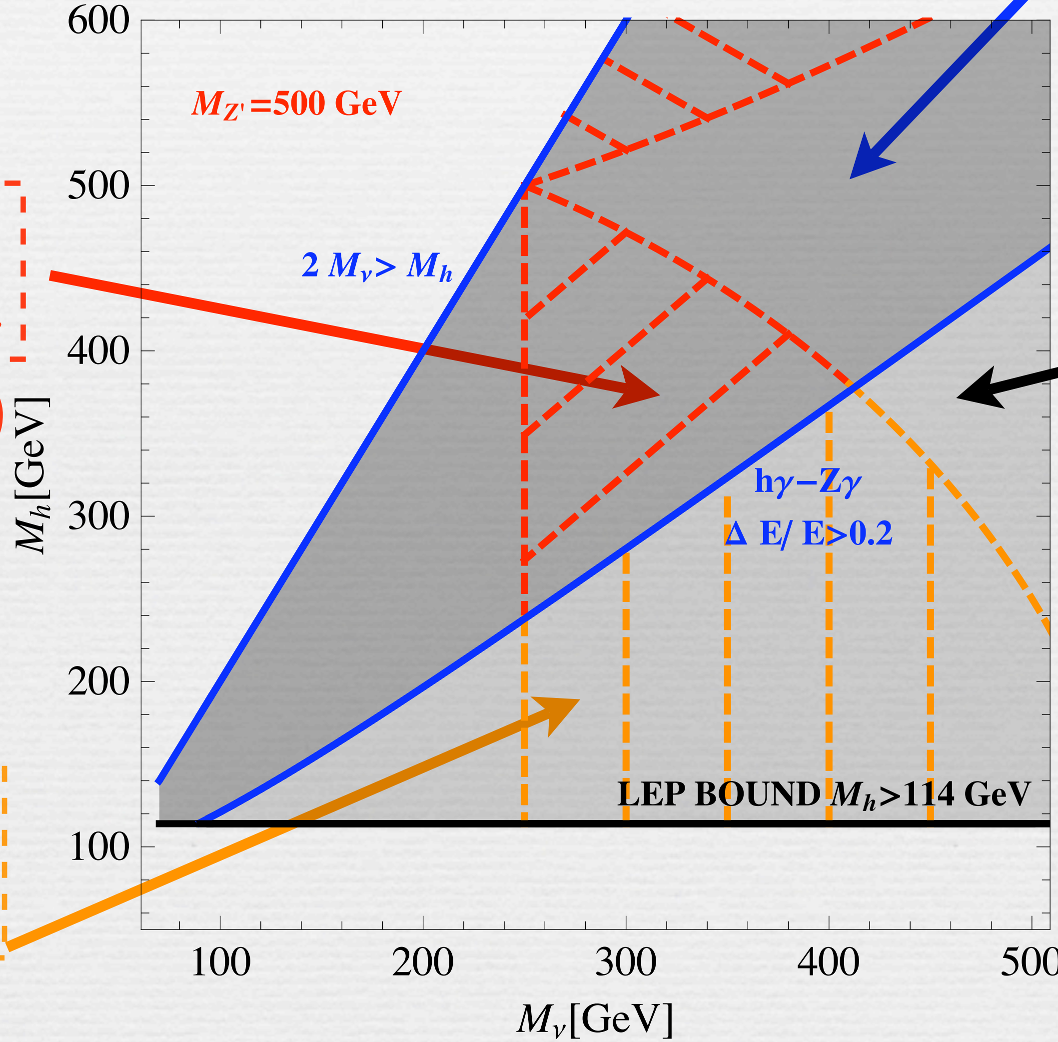
Line observability in the (M_{DM} - M_H) plane

region where 2 lines are visible

(Hγ and Zγ)

region where the 3 lines are visible

(Hγ, Zγ and Z'γ)



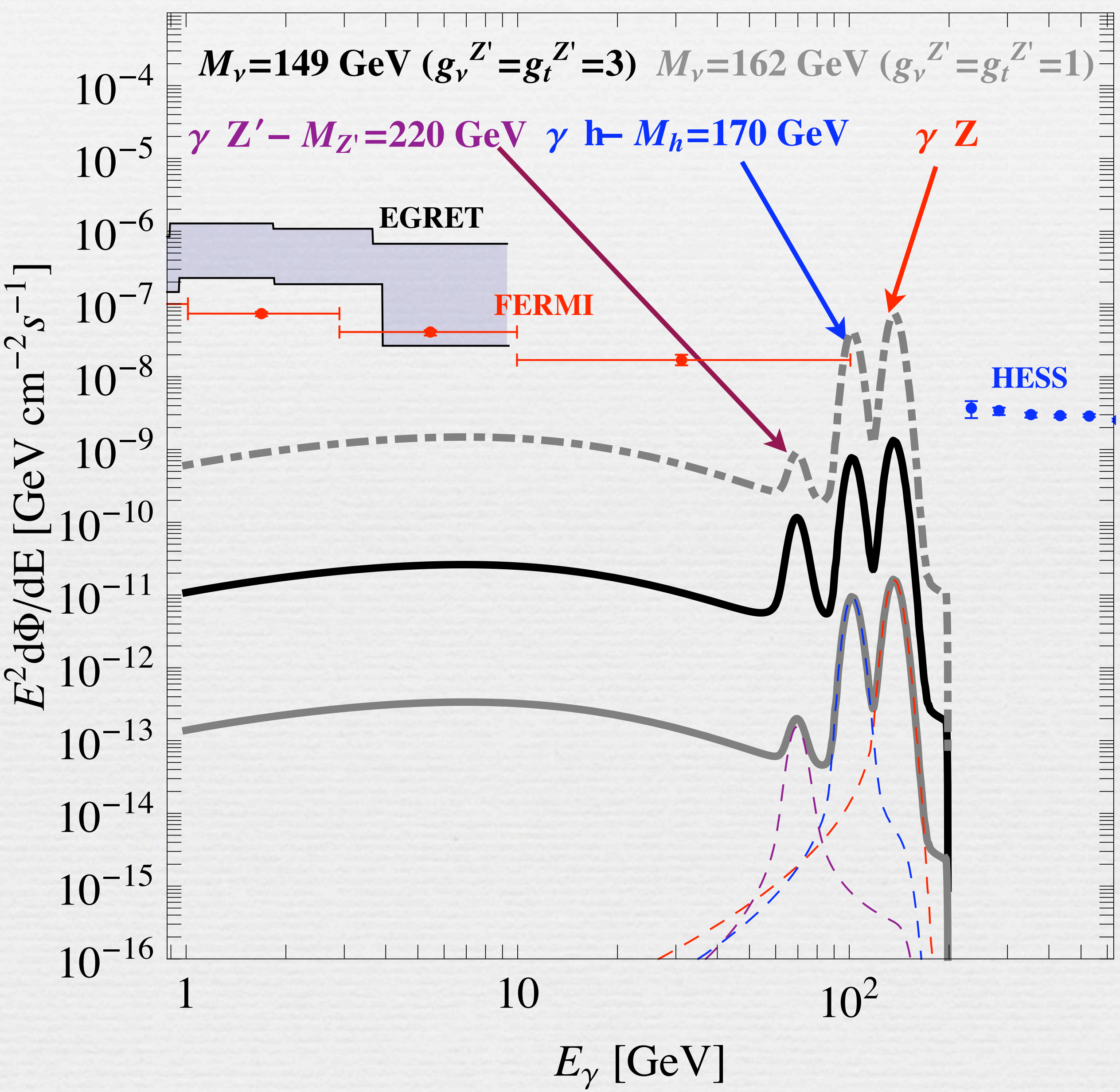
region with 1 line (Hγ and Zγ lines are merged)

region with 2 lines (H/Zγ and Z'γ)

assuming energy resolution of 10%

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

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

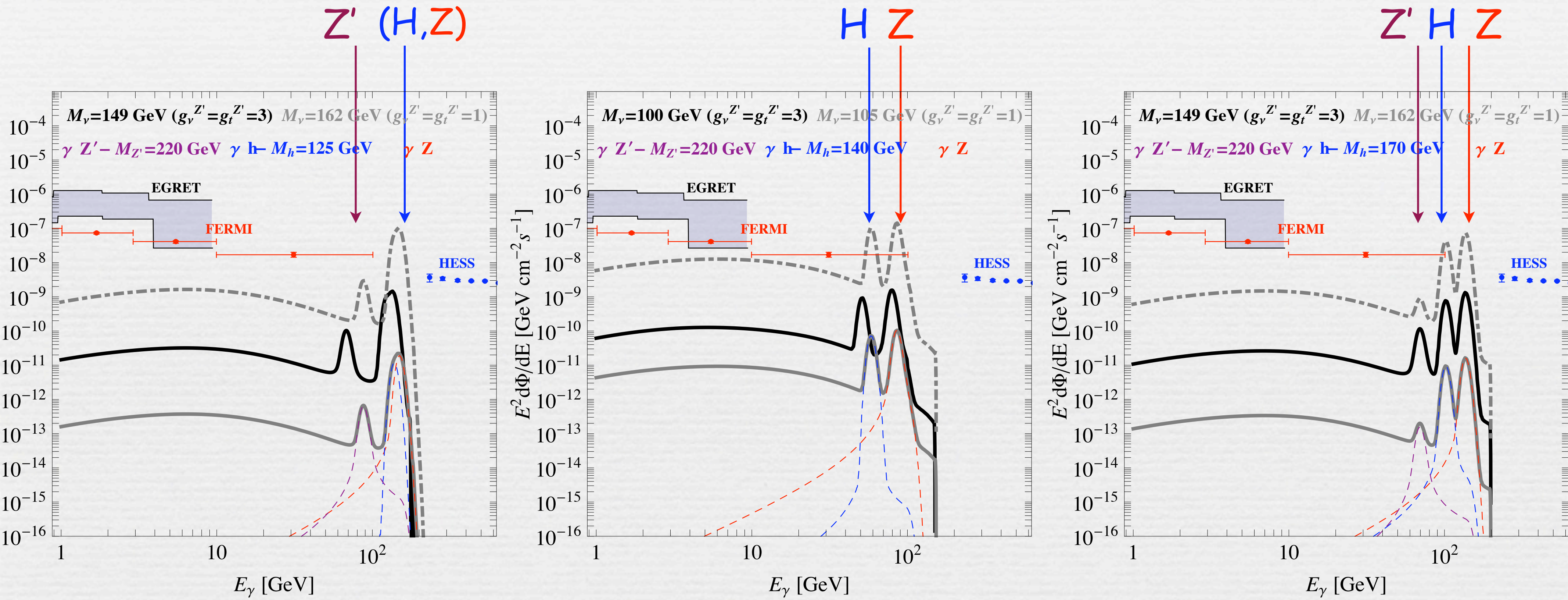


NFW profile

adiabatically contracted

γ-ray lines from the Galactic Center $\Delta\Omega = 10^{-5}$ sr

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

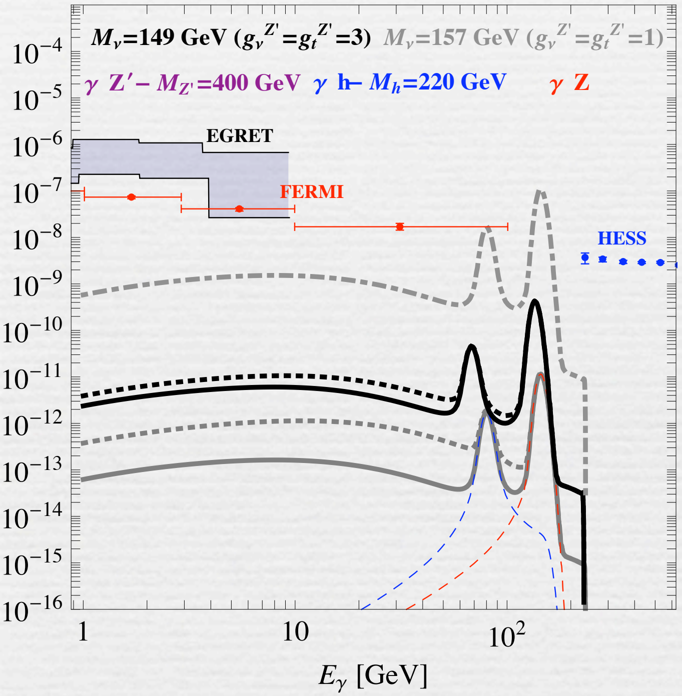


NFW profile

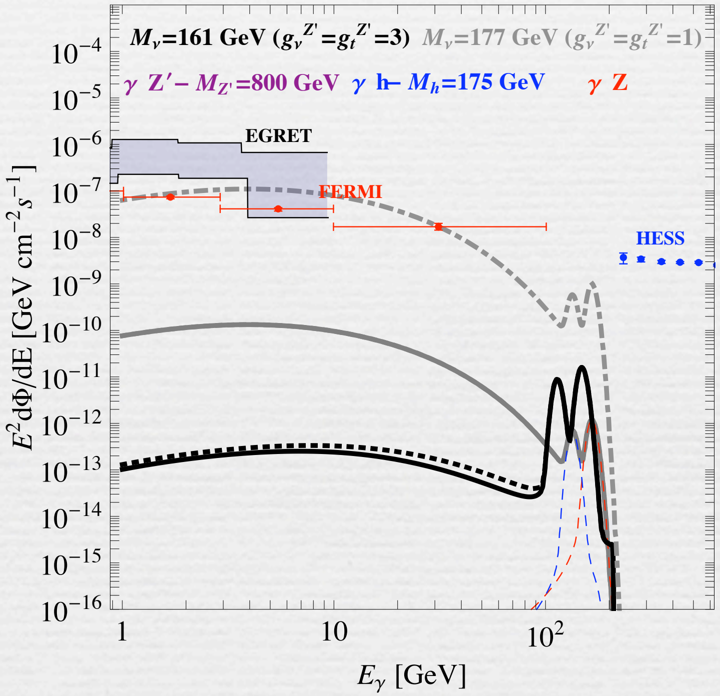
adiabatically contracted

Increasing $M_{Z'}$

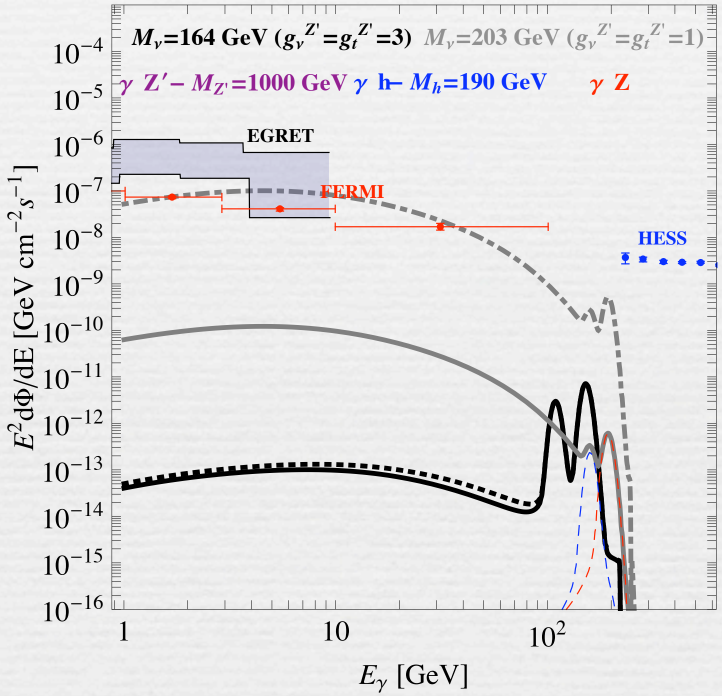
$M_{Z'}$ = 400 GeV



$M_{Z'}$ = 800 GeV



$M_{Z'}$ = 1 TeV



To recap:

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

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

ν 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.

A simple 4d UV completion

All SM fermions are uncharged under U(1)'

in addition to ν, add $\tilde{T}$ (vector-like) charged under U(1)'
with same gauge SM quantum numbers as t_R

to realize coupling of top quark to Z' and h:

$$y H \overline{Q}_3 t_R + \mu \overline{\tilde{T}}_L \tilde{T}_R + Y \Phi \overline{\tilde{T}}_L t_R$$

higgs of U(1)' (↑ Φ)

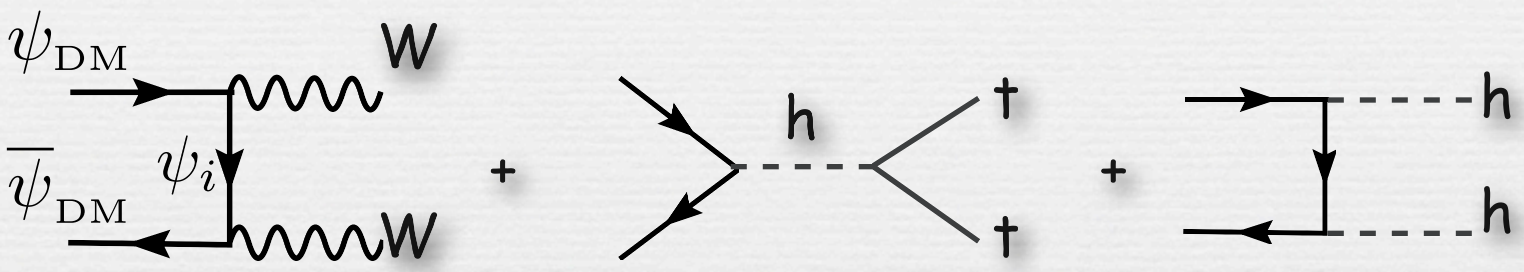
the light mass eigen state identified with top
quark is an admixture of t and $\tilde{T}$

Models of Gauge-Higgs unification

DM is part of a 5_0 multiplet under $SO(5) \times U(1)_X$

Carena et al, Haba et al '09

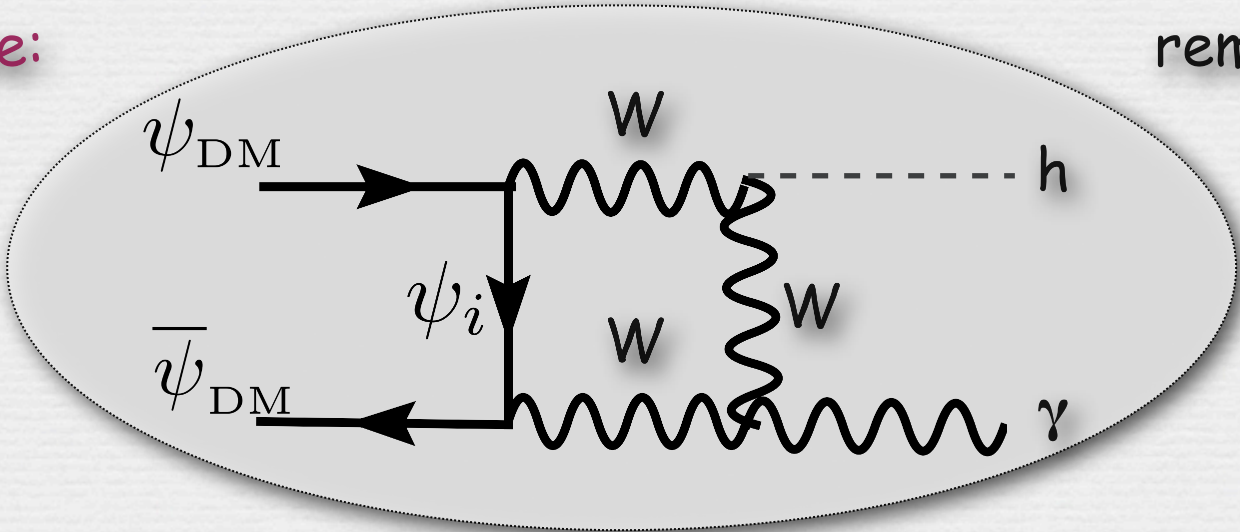
→ DM couples either to higgs or W, annihilation into heavy states of the SM favored



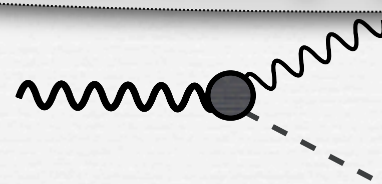
+ coannihilations

→ γh line:

remains to be done



γh line from decaying vector dark matter



Arina, Hambye, Ibarra, Weniger 0912.4496

hidden sector non-abelian group $SU(2)_{HS}$ broken by ϕ

$$\mathcal{L} = \mathcal{L}^{SM} - \frac{1}{4}F^{\mu\nu} \cdot F_{\mu\nu} + (\mathcal{D}_\mu\phi)^\dagger(\mathcal{D}^\mu\phi) - \lambda_m\phi^\dagger\phi H^\dagger H - \mu_\phi^2\phi^\dagger\phi - \lambda_\phi(\phi^\dagger\phi)^2$$

A_i^μ : stable because of accidental SO(3)

stability broken by non-renormalizable operators:

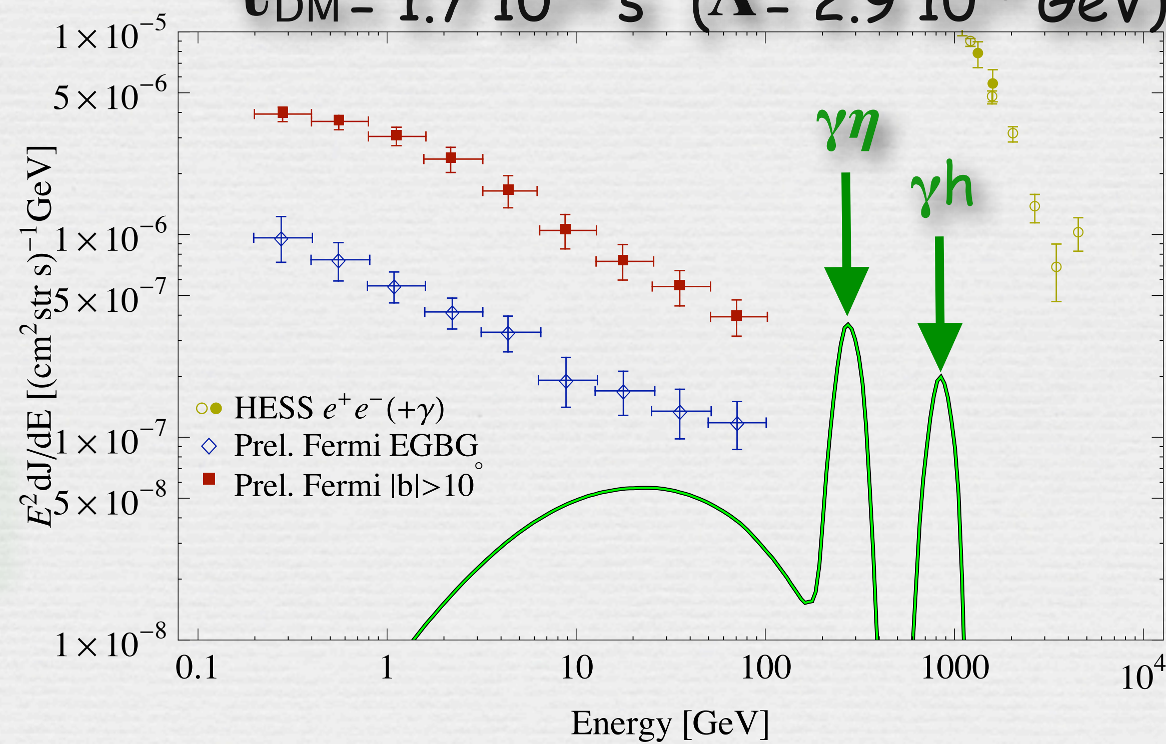
$$\frac{1}{\Lambda^2}\,\mathcal{D}_\mu\phi^\dagger\phi\;\mathcal{D}_\mu H^\dagger H \qquad \frac{1}{\Lambda^2}\,\mathcal{D}_\mu\phi^\dagger\mathcal{D}_\nu\phi\;F^{\mu\nu Y}$$

$$\frac{1}{\Lambda^2}\,\mathcal{D}_\mu\phi^\dagger\phi\;H^\dagger\mathcal{D}_\mu H \qquad \frac{1}{\Lambda^2}\,\phi^\dagger F^a_{\mu\nu}\frac{\tau^a}{2}\phi F^{\mu\nu Y}$$

late decay of DM → γh & γη lines :

(η: hidden sector scalar)

$\tau_{DM} = 1.7\ 10^{28}$ s ($\Lambda = 2.9\ 10^{15}$ GeV)



Gamma rays from Dark Matter decays

De Rujula, Glashow'80
Bertone, Buchmuller, Covi, Ibarra'07
Ibarra, Tran'08; Ibarra, Tran, Weniger'09
Boyarsky, Neronov, Ruchayskiy, Shaposhnikov, Tkachev'06 .....
(X-rays)

Different strategy

signal also depends on DM profile — but only $\propto \rho$ rather than $\propto \rho^2$

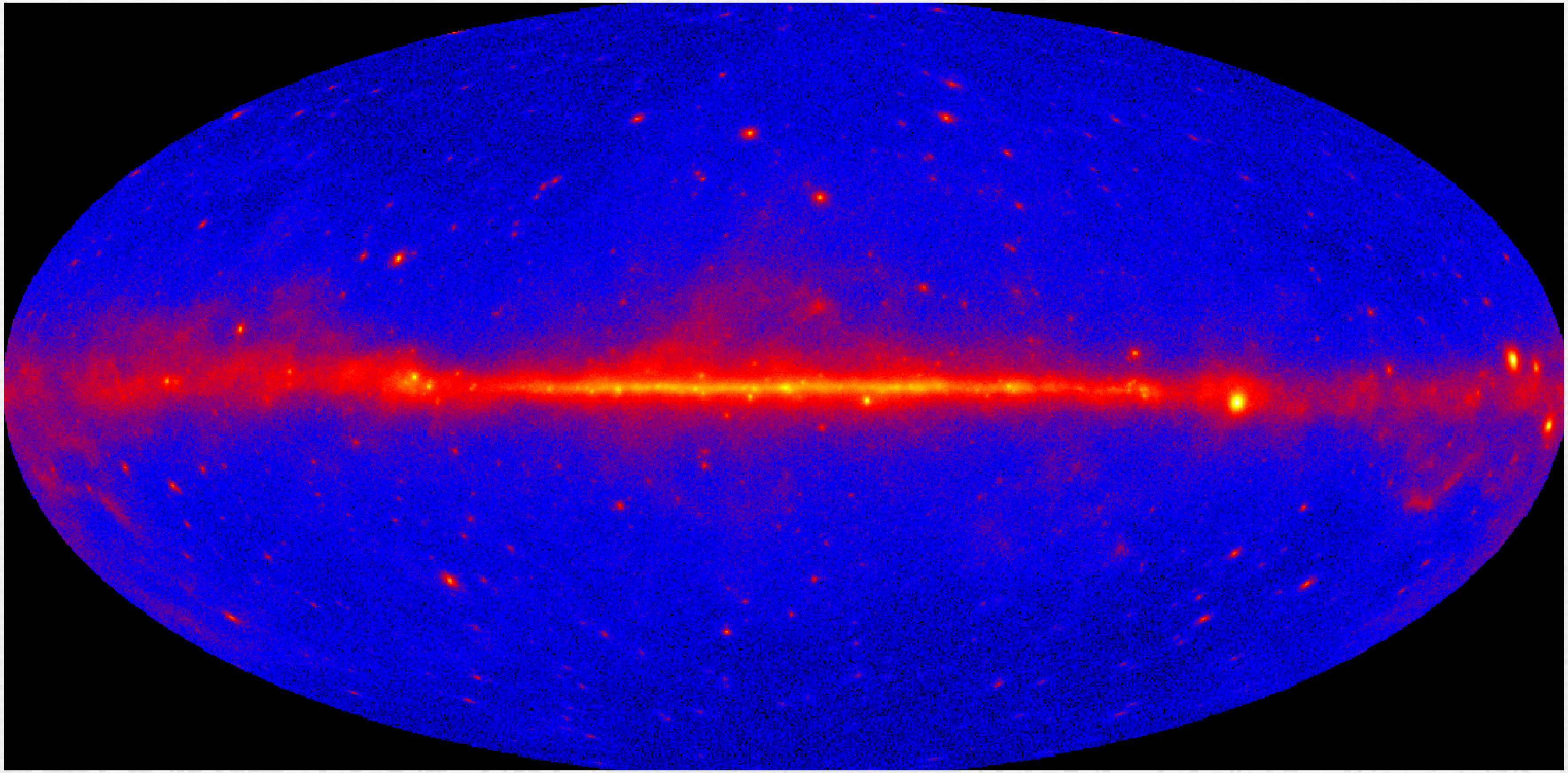
however not focussed on the GC -> less background

two components :

galactic	extragalactic
flux at earth exhibits 20% dipole-like anisotropy due to the off-set between the Sun and galactic center	isotropic

Detectability

Fermi-LAT 1 year Gamma-Ray Skymap



E_γ =100 MeV-300 GeV

~ 80% of gamma-rays produced by cosmic ray interactions with interstellar gas and radiation field

to assess upper limit on contribution from DM, need a very accurate bgd model

Gamma background:

- diffuse emission of our galaxy modeled using GALPROP

Strong, Moskalenko, Reimer '00

in agreement with Fermi-LAT data at mid-latitudes

due to interactions of cosmic rays with galactic gas

-bremsstrahlung

-π_0 decay

-inverse Compton

depends on location in the sky

strongest in galactic disk

- For the GC center analysis, the dominant background will be from sources in the vicinity of the GC.

many different kinds of objects whose spectra and distributions are not well understood

signal extraction from background in GC:challenging

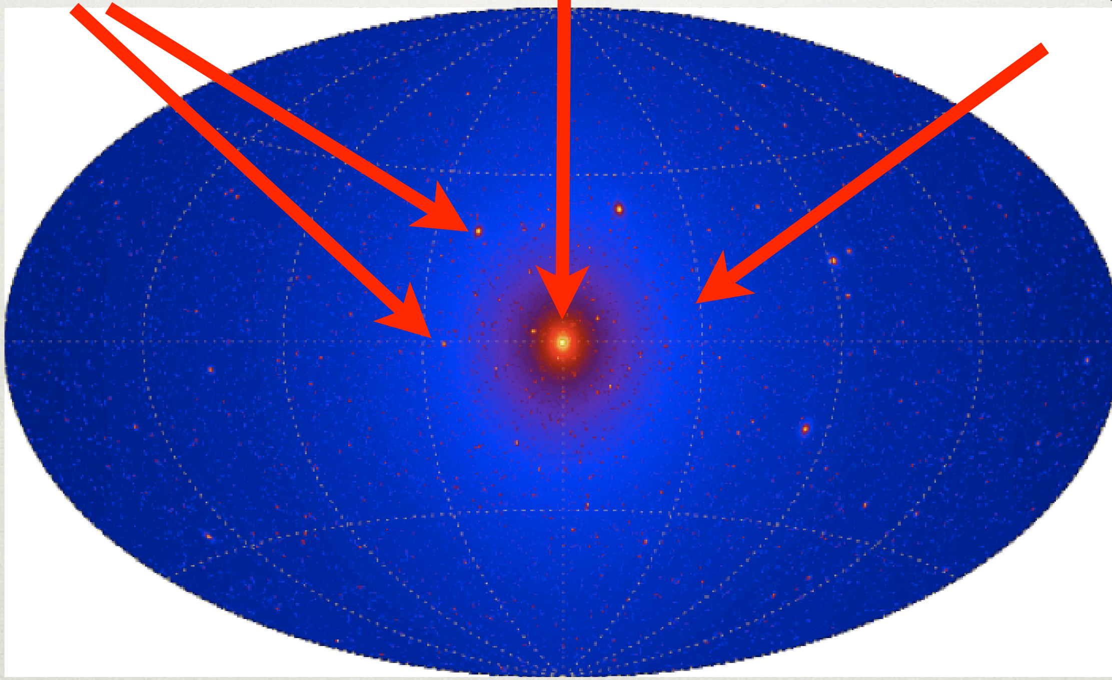
Search Strategies

[Credit: S. Murgia, Fermi Symposium ‘Nov 09]

Satellites:
Low background and good source id, but low statistics

Galactic center:
Good statistics but source confusion/diffuse background

Milky Way halo:
Large statistics but diffuse background



All-sky map of gamma rays from DM annihilation arXiv:0908.0195 (based on Via Lactea II simulation)

And electrons!

Anisotropies

Spectral lines:
No astrophysical uncertainties, good source id, but low statistics

Galaxy clusters:
Low background but low statistics

Extra-galactic:
Large statistics, but astrophysics, galactic diffuse background

Pre-launch sensitivities published in Baltz et al., 2008, JCAP 0807:013 [astro-ph/0806.2911]

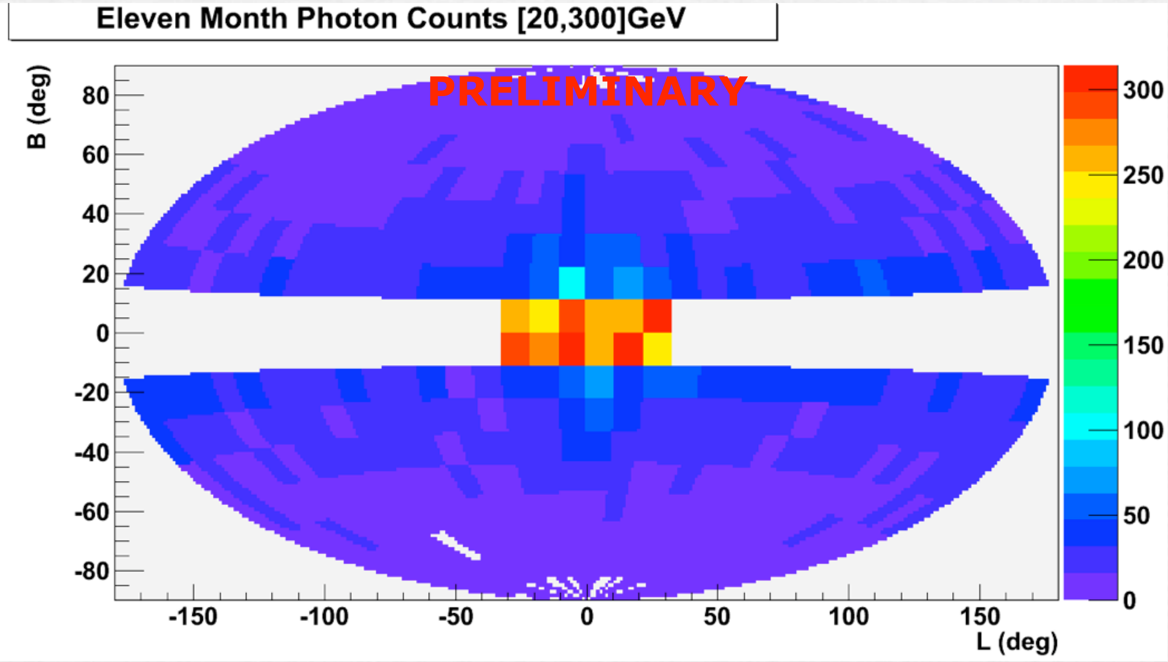
What’s best?
See discussions in

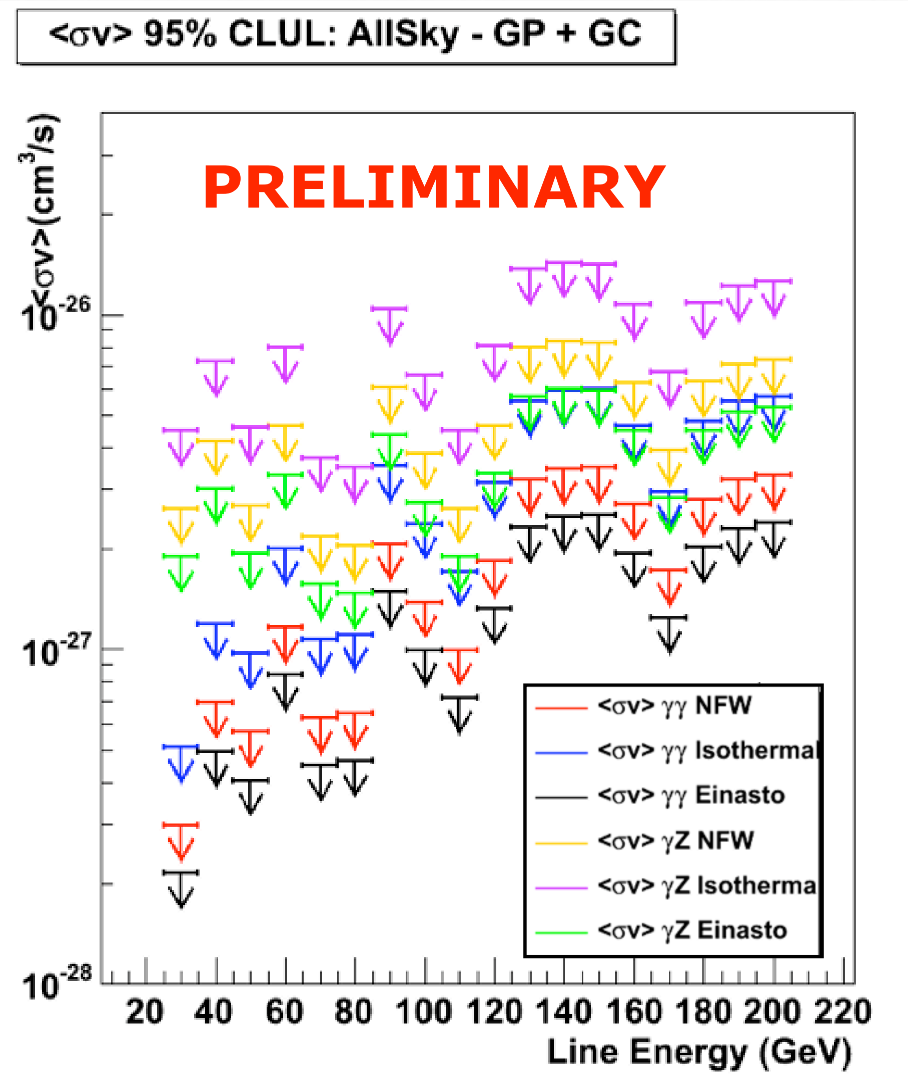
Dodelson, Hooper, Serpico’07; Serpico, Zaharijas’08
Dodelson, Belikov, Hooper, Serpico’09; Serpico, Hooper’09 ....

Fermi Line Search

Fermi/GLAST has searched for lines in the gamma ray spectrum with energies between 30-200 GeV in a shape analysis

Search region includes |b|>10° and 30° around the galactic center

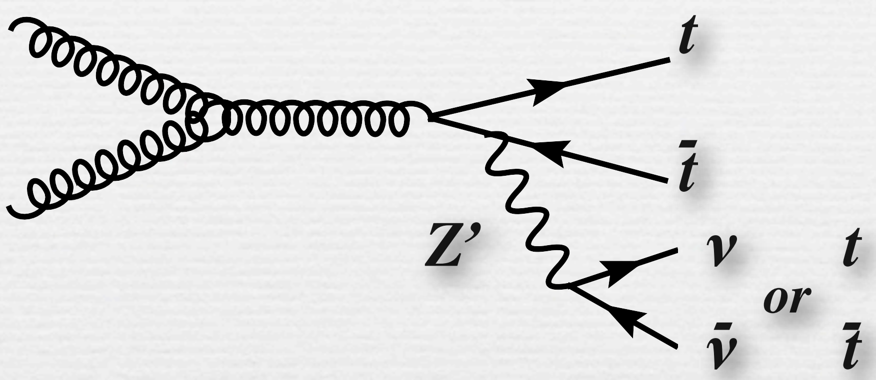




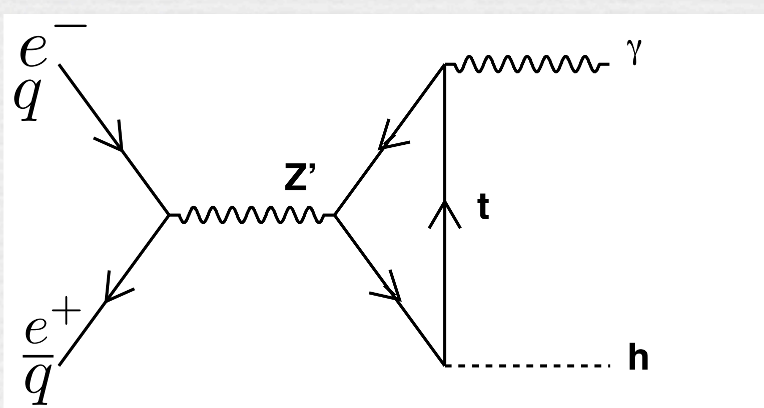
Collider signatures of a top (and DM)-philic Z'

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

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

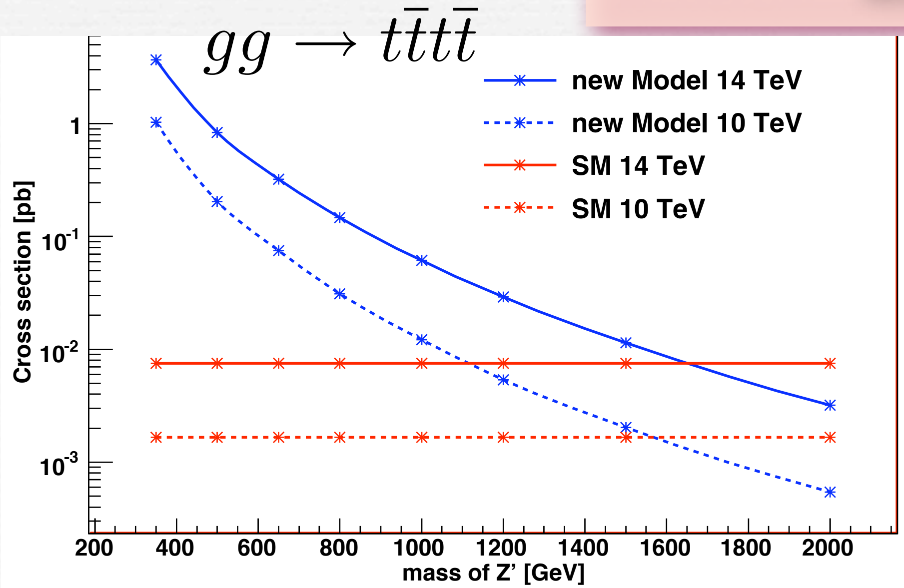


- $f\overline{f} \to Z' \to \gamma H$ — energetic monochromatic γ



four-top events from a top-philic Z' @LHC in same-sign dilepton channel

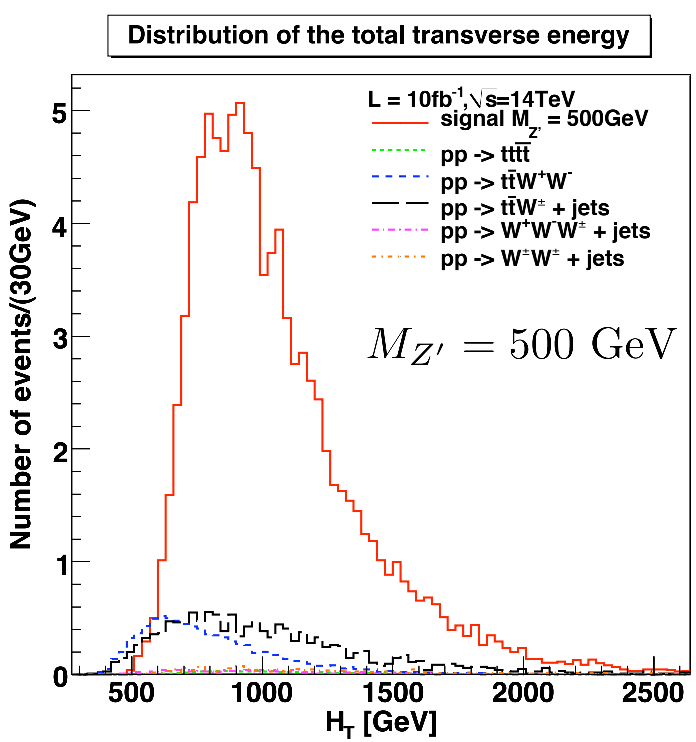
Gauthier-Servant
in progress

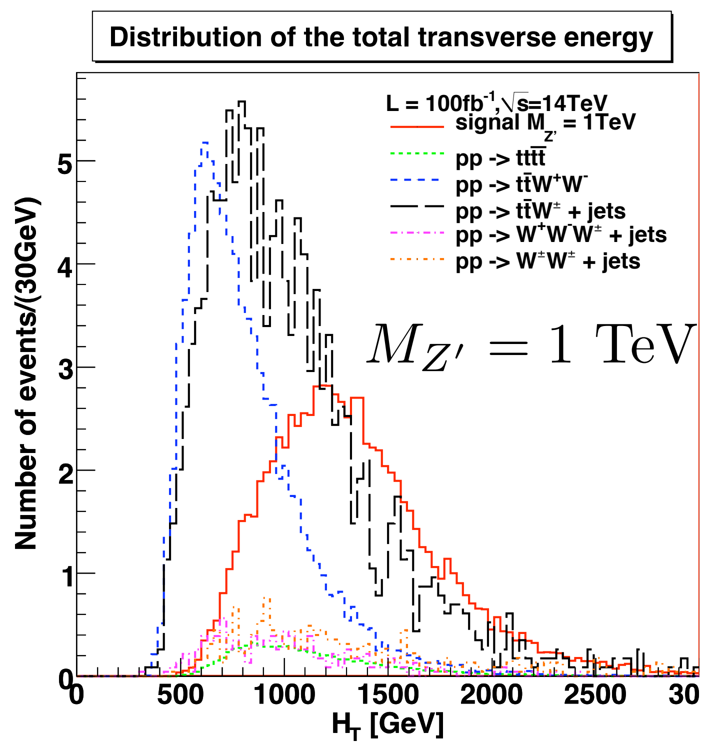


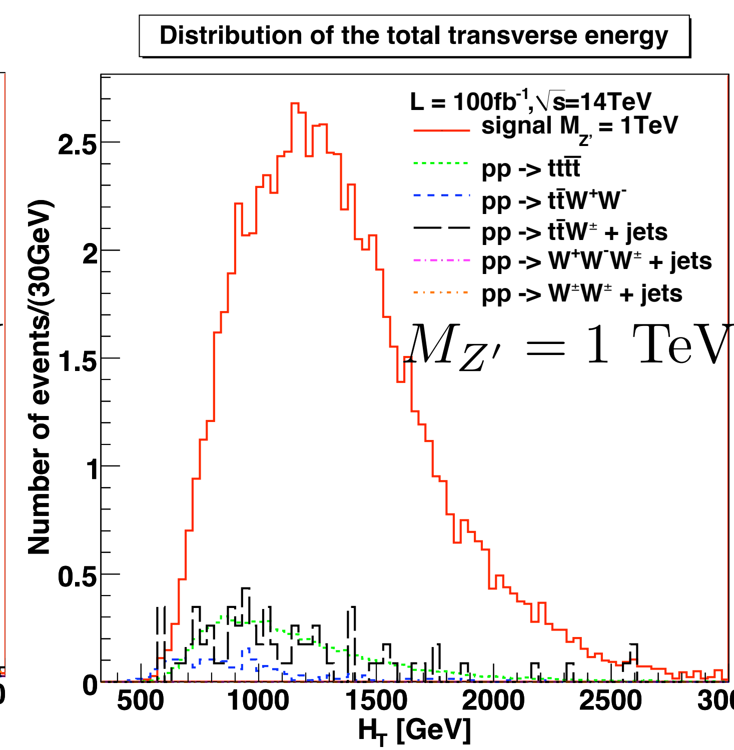
$$n_{\text{jets}} \gtrsim 6$$
$$p_T(\text{jets}) \gtrsim 30 \text{ GeV}$$

preliminary

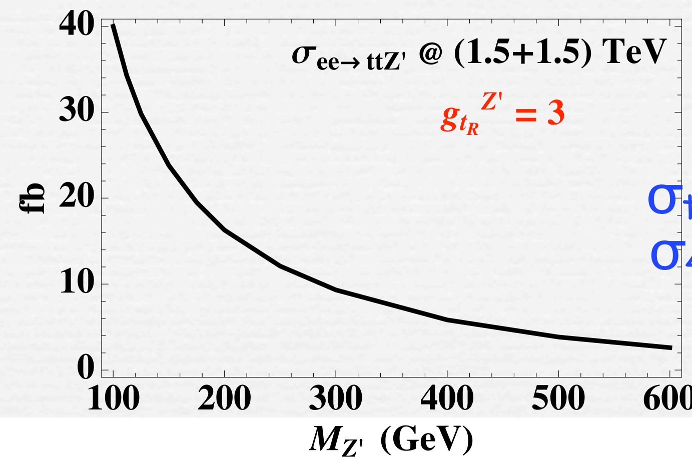
$$n_{\text{b jets}} \gtrsim 3$$



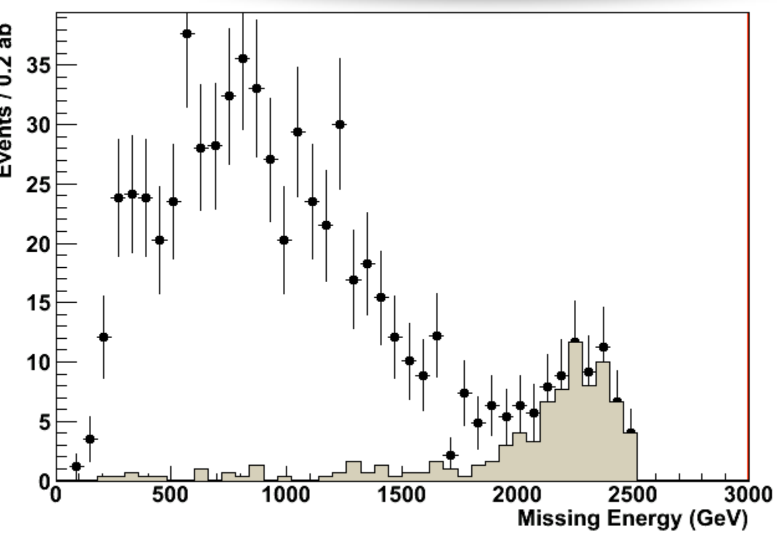


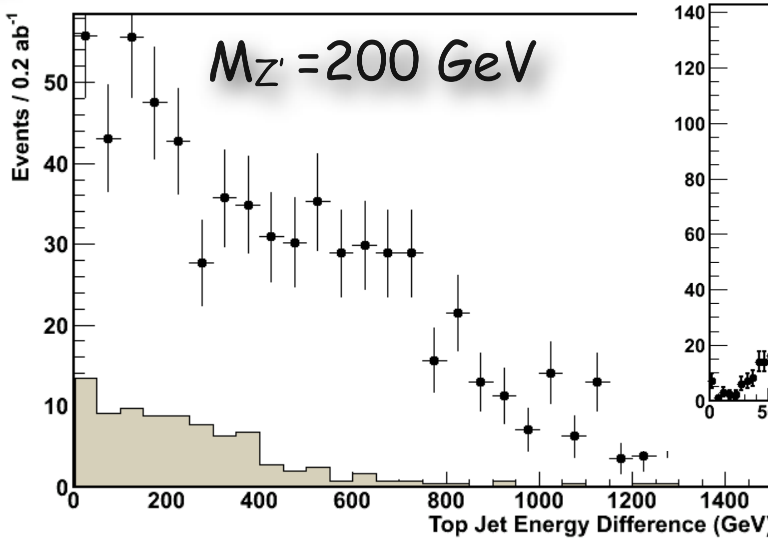


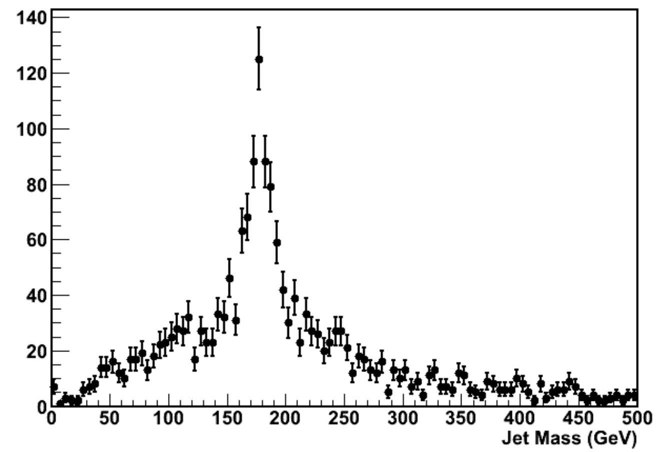
$e^+ e^- \to t\bar{t} + \not{E}_T$ @ 3 TeV CLIC



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

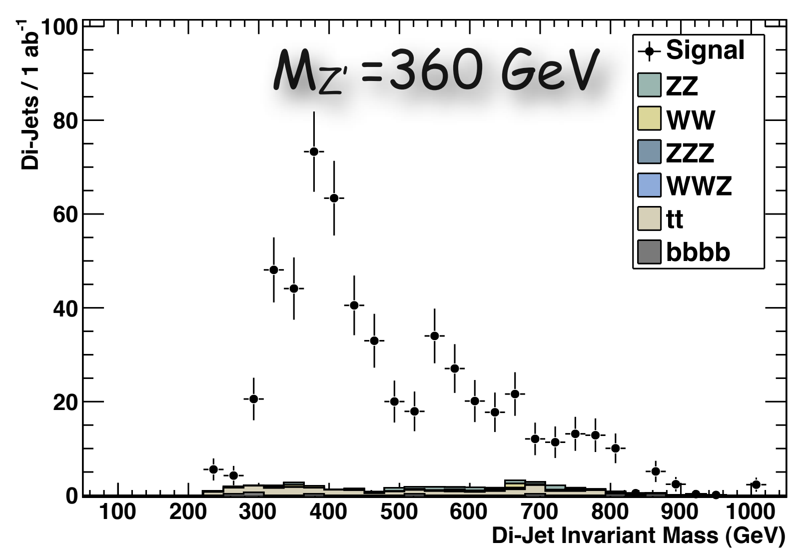






0.2 ab^{-1}

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

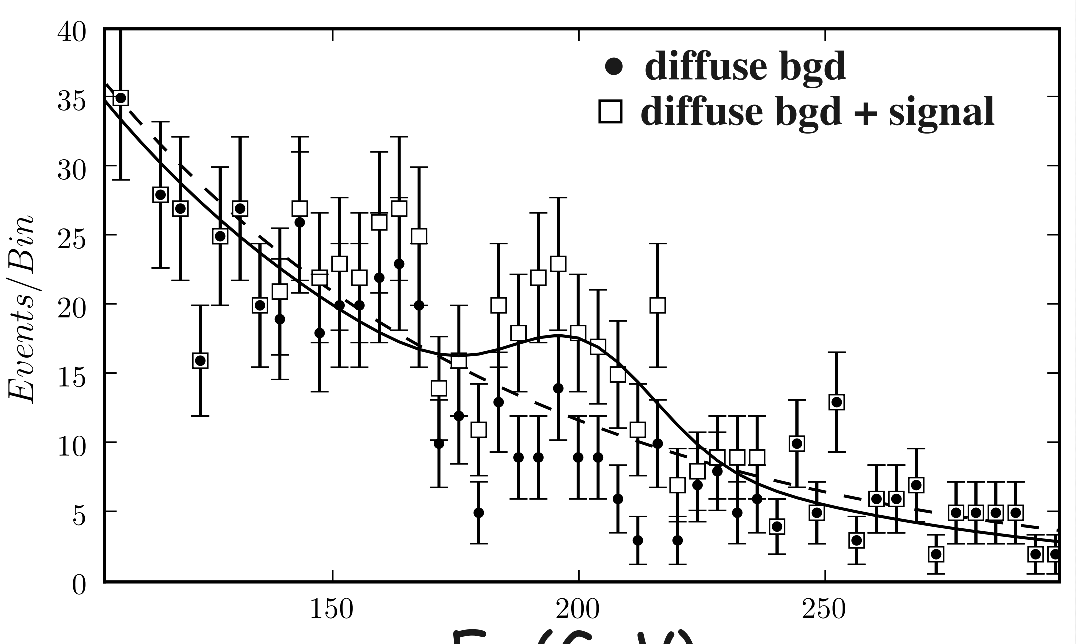
Observation of γ H would indicate that the WIMP is not a scalar nor a Majorana fermion but most likely a Dirac fermion or a vector

Worth checking whether Higgs is hiding in gamma-ray telescope's data

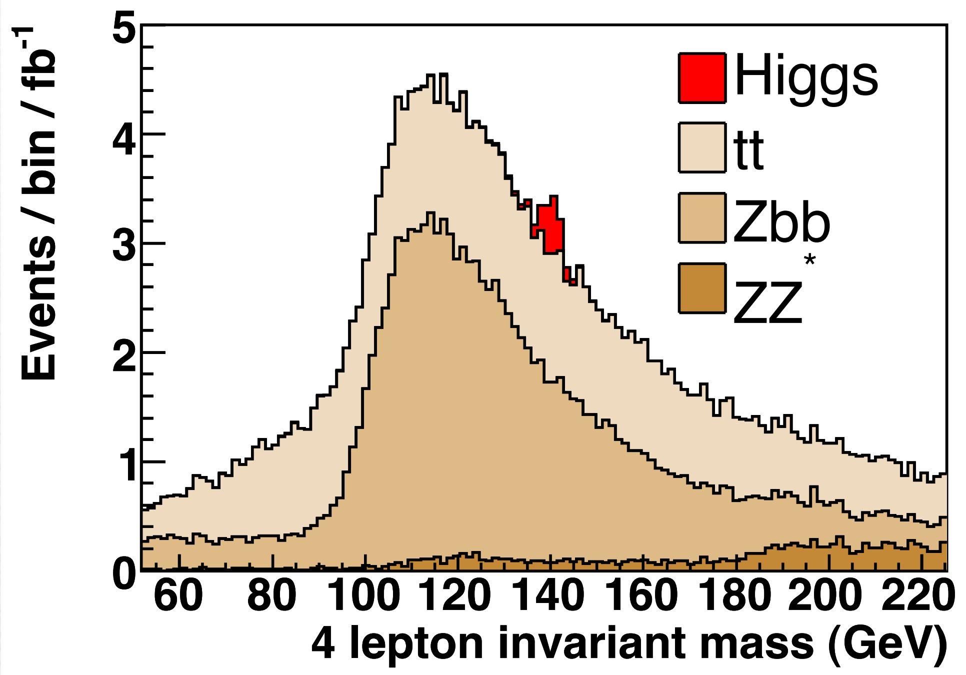
Complementary Collider studies in progress

Who will see it first?

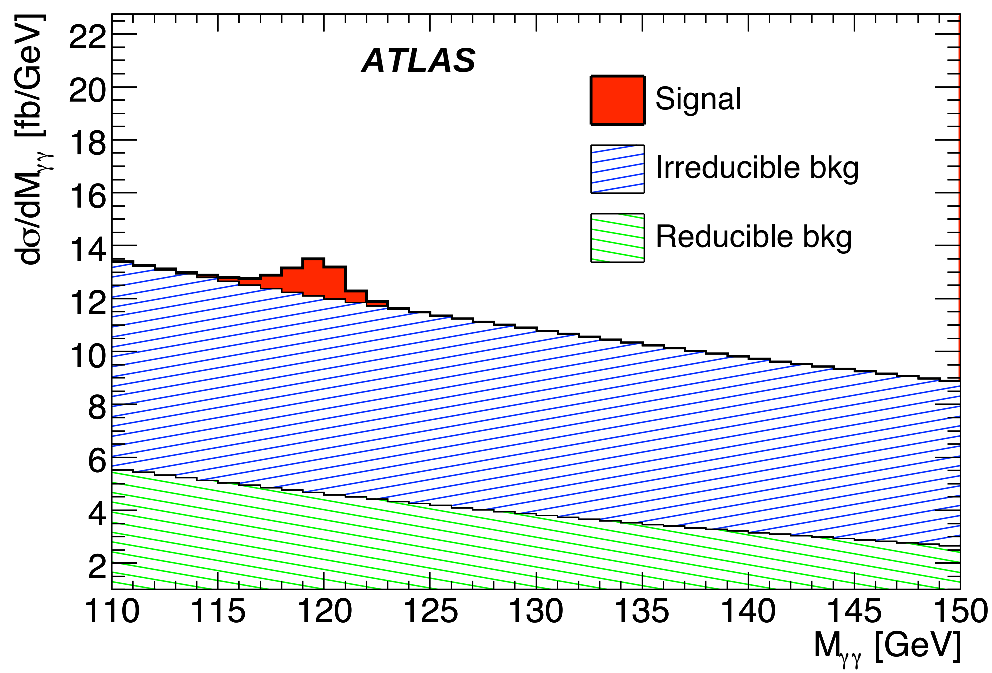
Fermi ? or CMS ?



E_γ (GeV)



or ATLAS ?



Annex

Large γ line signals compatible with low p̄ and e⁺ fluxes