Dark Matter & Electroweak Symmetry Breaking

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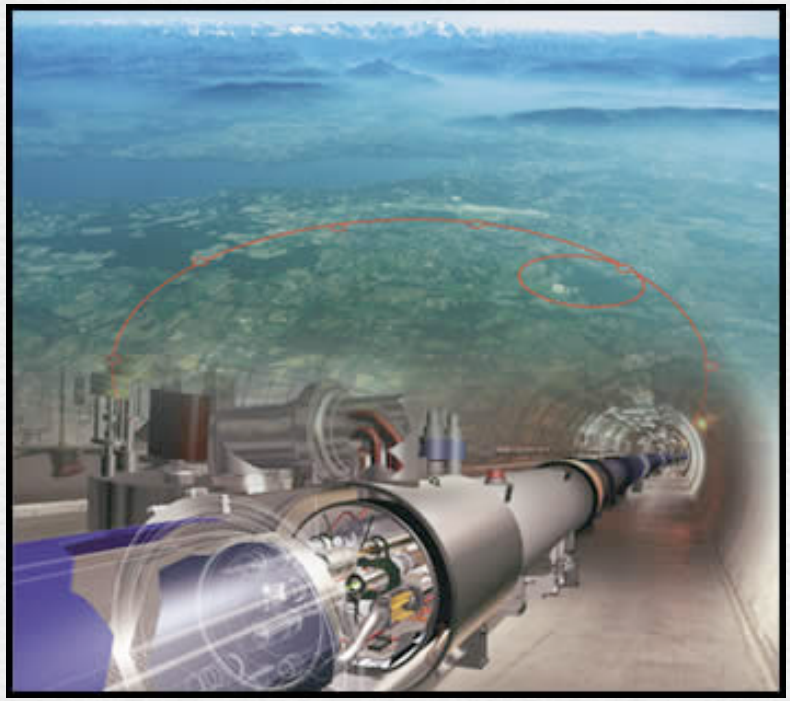
The 2 main races of the next several years:

the searches for the Higgs Boson and Dark Matter

Huge experimental effort towards the identification of the Higgs boson



2010: First collisions at the LHC

Direct exploration of the Fermi scale starts.

main physics goal:

What is the mechanism of Electroweak Symmetry breaking ?

Huge experimental effort towards the identification of Dark Matter

Indirect

Antimatter
Neutrinos
Gamma Rays

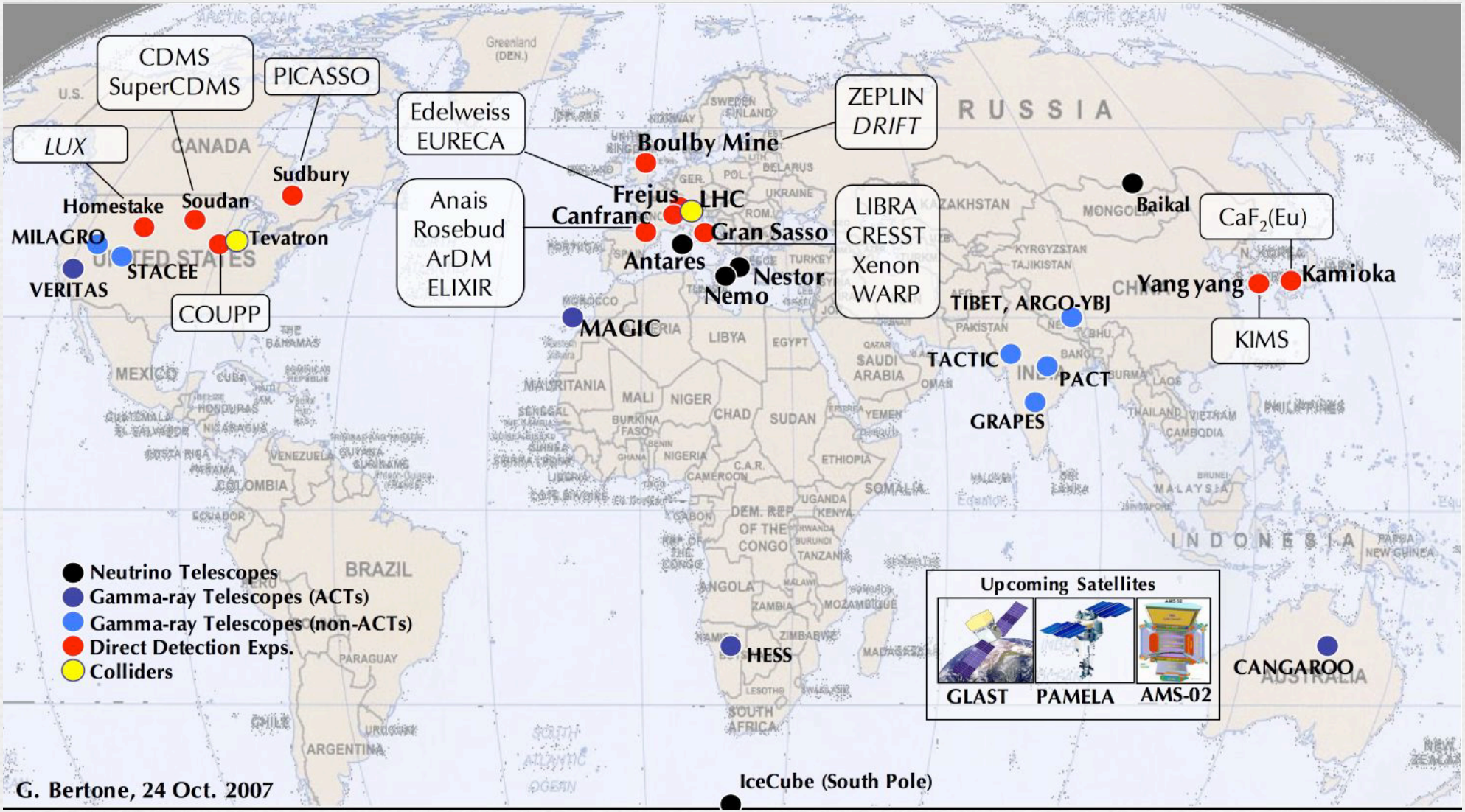
Signature of Annihilation in space

Direct

Elastic Scattering signature in underground labs

Collider experiments

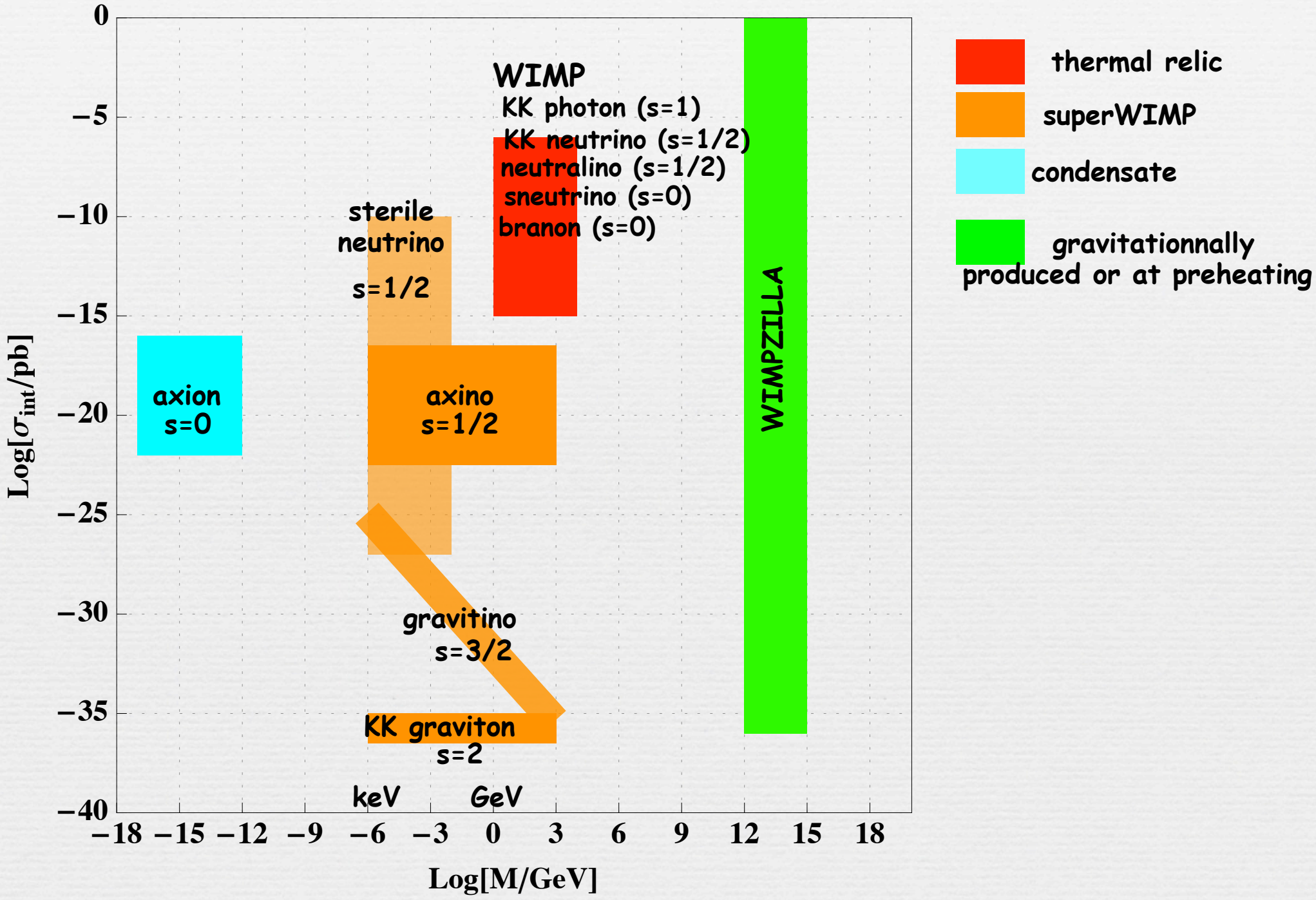
Missing Energy signature in high energy accelerators



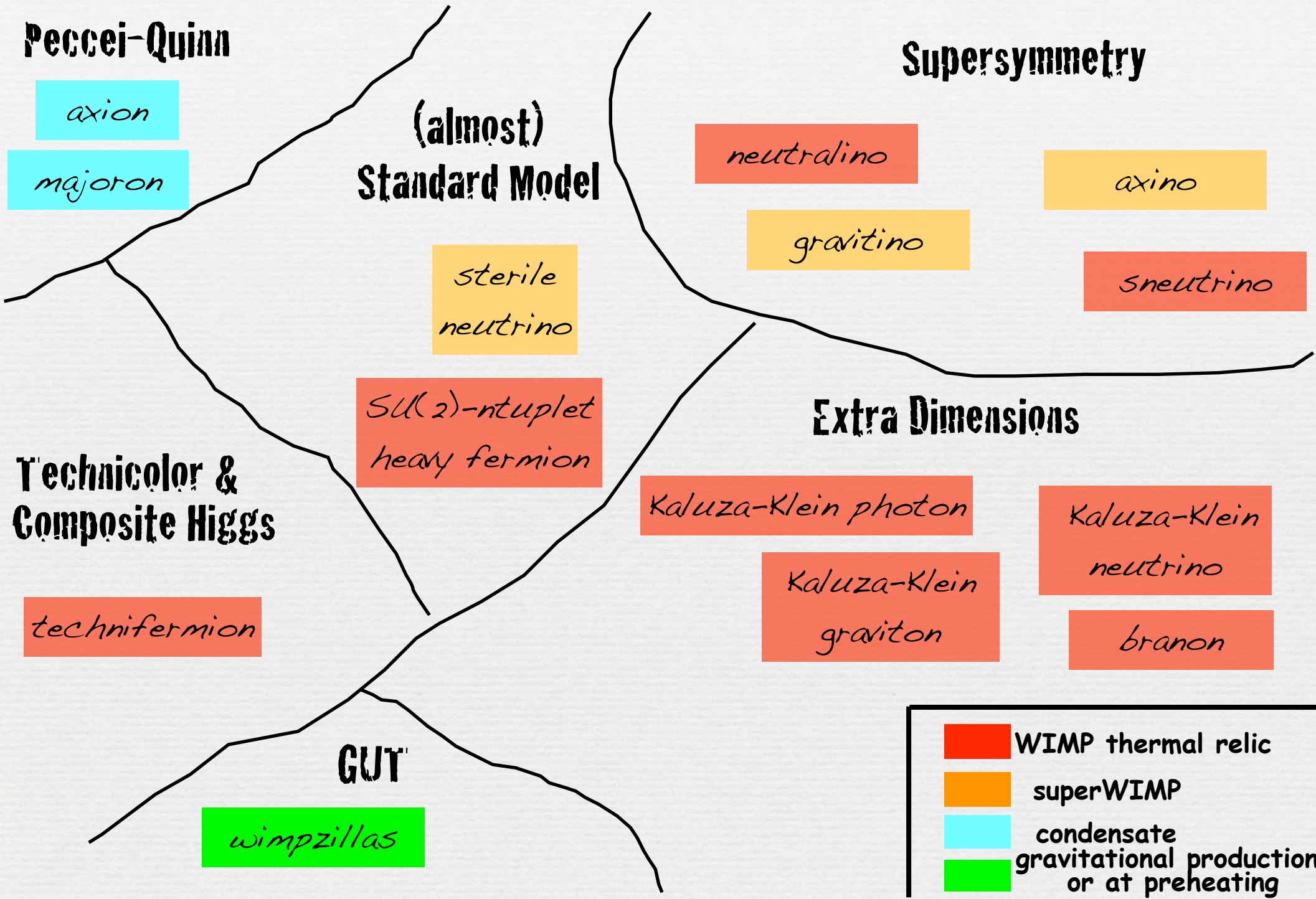
Most of DM experiments rely on the assumption that DM is a WIMP

Are DM and electroweak symmetry breaking related?

Dark Matter Candidates Ω~1



In Theory Space



Dark Matter and the Fermi scale

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

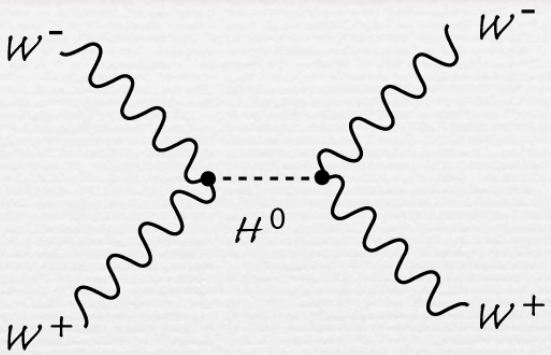
$$\Omega_{DM} \approx \frac{0.2\ \text{pb}}{\sigma_{anni}}$$

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

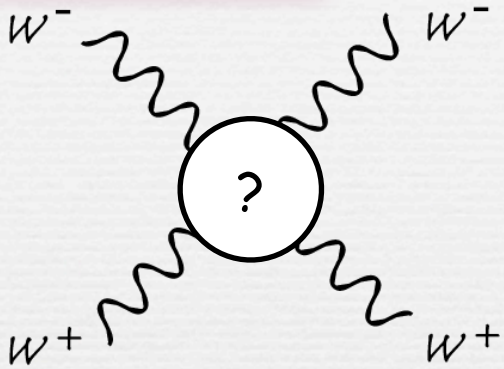
a compelling coincidence (the "WIMP miracle")

Electroweak symmetry breaking: 2 main questions

- What is unitarizing the $W_L W_L$ scattering amplitude?

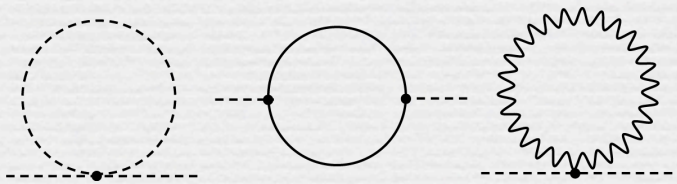


the Higgs or something else?



- What is cancelling the divergent diagrams?

(i.e what is keeping the Higgs light?)
: Hierarchy problem



$$\Rightarrow \delta M_H^2 \propto \Lambda^2$$

Λ , the maximum mass scale that the theory describes

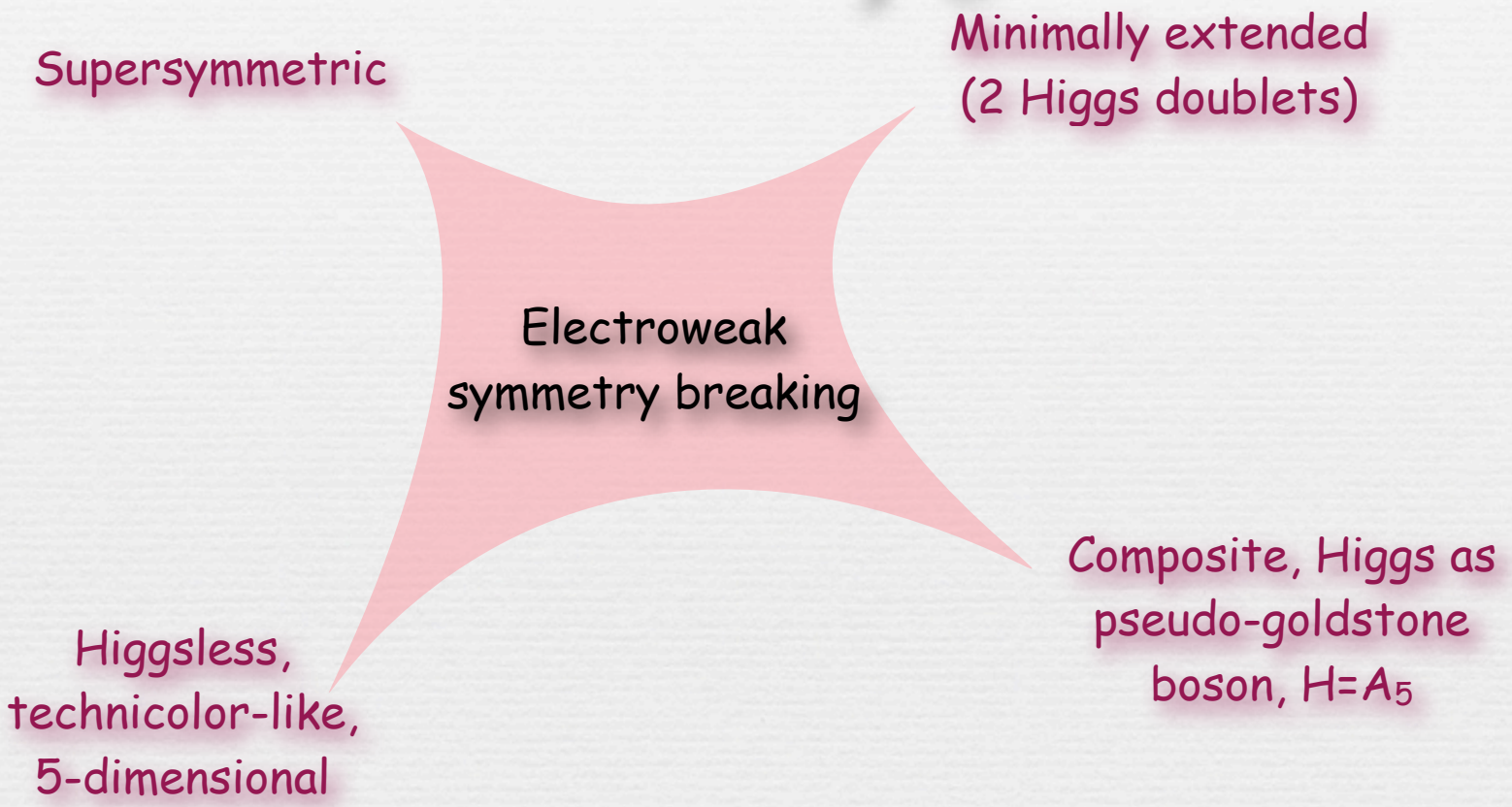
strong sensitivity on UV unknown physics

need new degrees of freedom & new symmetries to cancel the divergences

supersymmetry, gauge-Higgs unification, Higgs as a pseudo-goldstone boson...

→ theoretical need for new physics at the TeV scale

Which new physics?



In all explicit examples, without unwarranted cancellations, new phenomena are required at a scale $\Lambda \sim [3\text{-}5] \times M_{Higgs}$

Which Higgs ?

- Composite Higgs ?
- Little Higgs ?
- Littlest Higgs ?
- Intermediate Higgs ?
- Slim Higgs ?
- Fat Higgs ?
- Gauge-Higgs ?
- Holographic Higgs ?
- Gaugephobic Higgs ?
- Higgsless ?
- UnHiggs ?
- Portal Higgs ?
- Simplest Higgs ?
- Private Higgs ?
- Lone Higgs ?
- Phantom Higgs ?

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

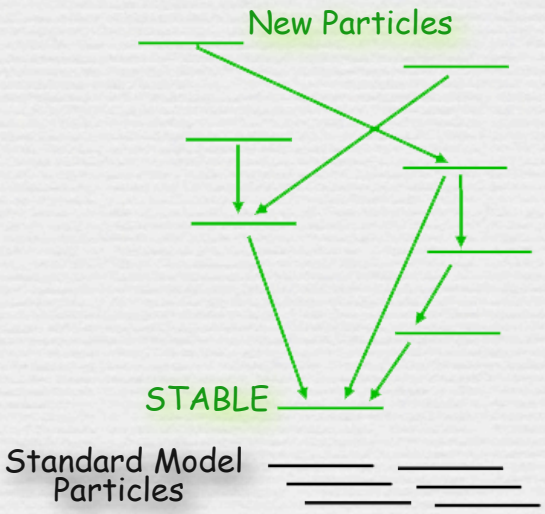
↓ DM candidate

The hunt for WIMPS: a well-defined programme

Work out properties of new degrees of freedom

The stability of a new particle is a common feature of many models

mass spectrum, interactions



dark matter candidates

relic abundance

detection signatures & rates

But honestly: None of the SM extensions on the market

(MSSM, RS, Little Higgs, Composite Higgs, UED ...)

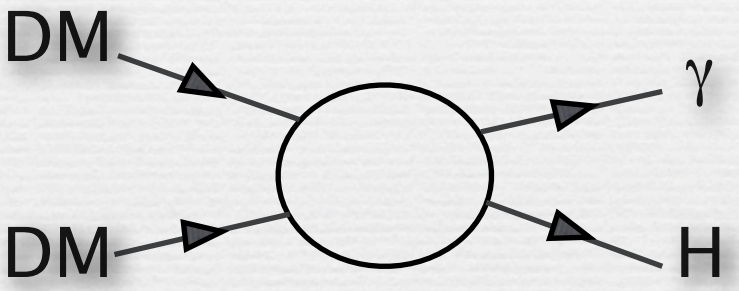
are fully satisfactory

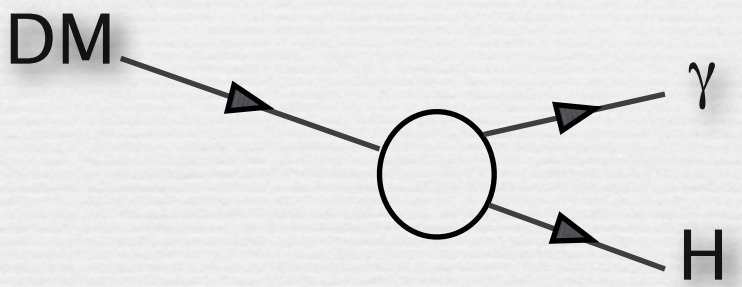
Anyhow, within 10 years, we'll test them and we'll test the WIMP hypothesis

Can the Higgs be searched for outside of colliders?

The LHC & Tevatron may not be the only places in the universe where the Higgs is being produced today

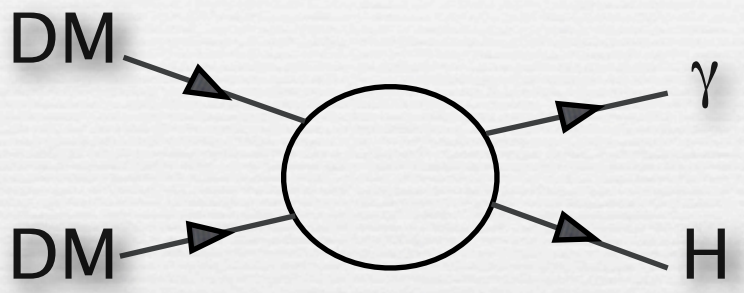
What about Higgs production today in
Dark Matter annihilations or Dark Matter decays?





Indirect probes of the Higgs in space

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

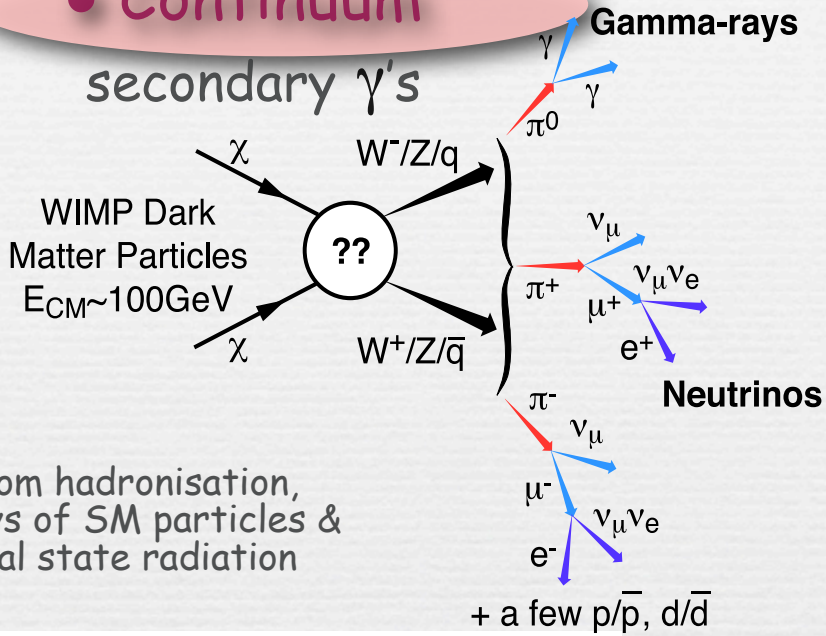
- photons travel undeflected and point directly to source
- photons travel almost unattenuated and don't require a diffusion model
- detected from the ground (ACTs) and from above (FERMI)

Seeing the light from Dark Matter

γ's from DM annihilations consist of 2 components

• Continuum

secondary γ's



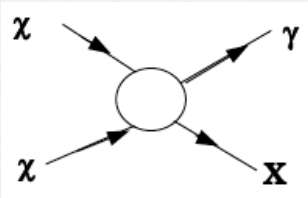
from hadronisation, decays of SM particles & final state radiation

+ a few p/p̄, d/d̄

• Lines

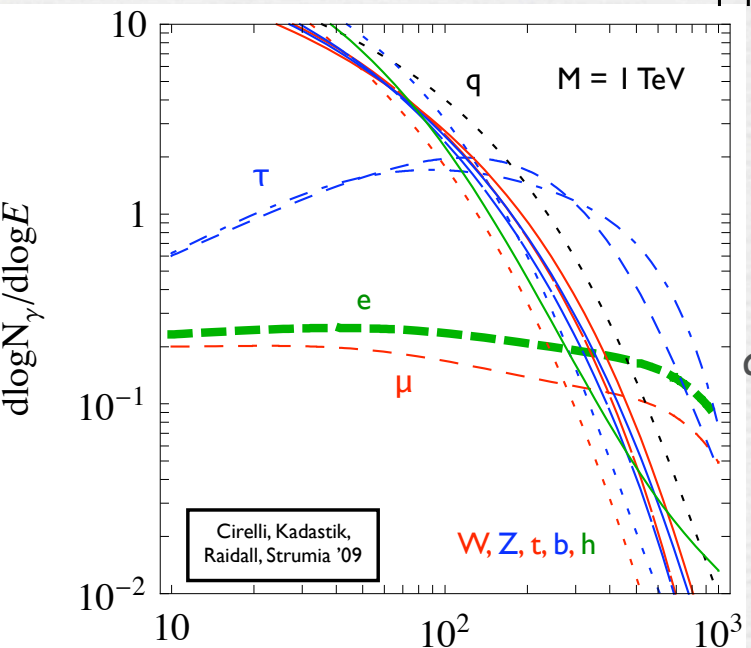
primary γ's

loop-level annihilation into γ+X



-> mono energetic lines superimposed onto continuum at

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



almost featureless but with sharp cutoff at Wimp mass

☺ -> 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 $\Delta\Omega$

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

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

includes all possible annihilation final states

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

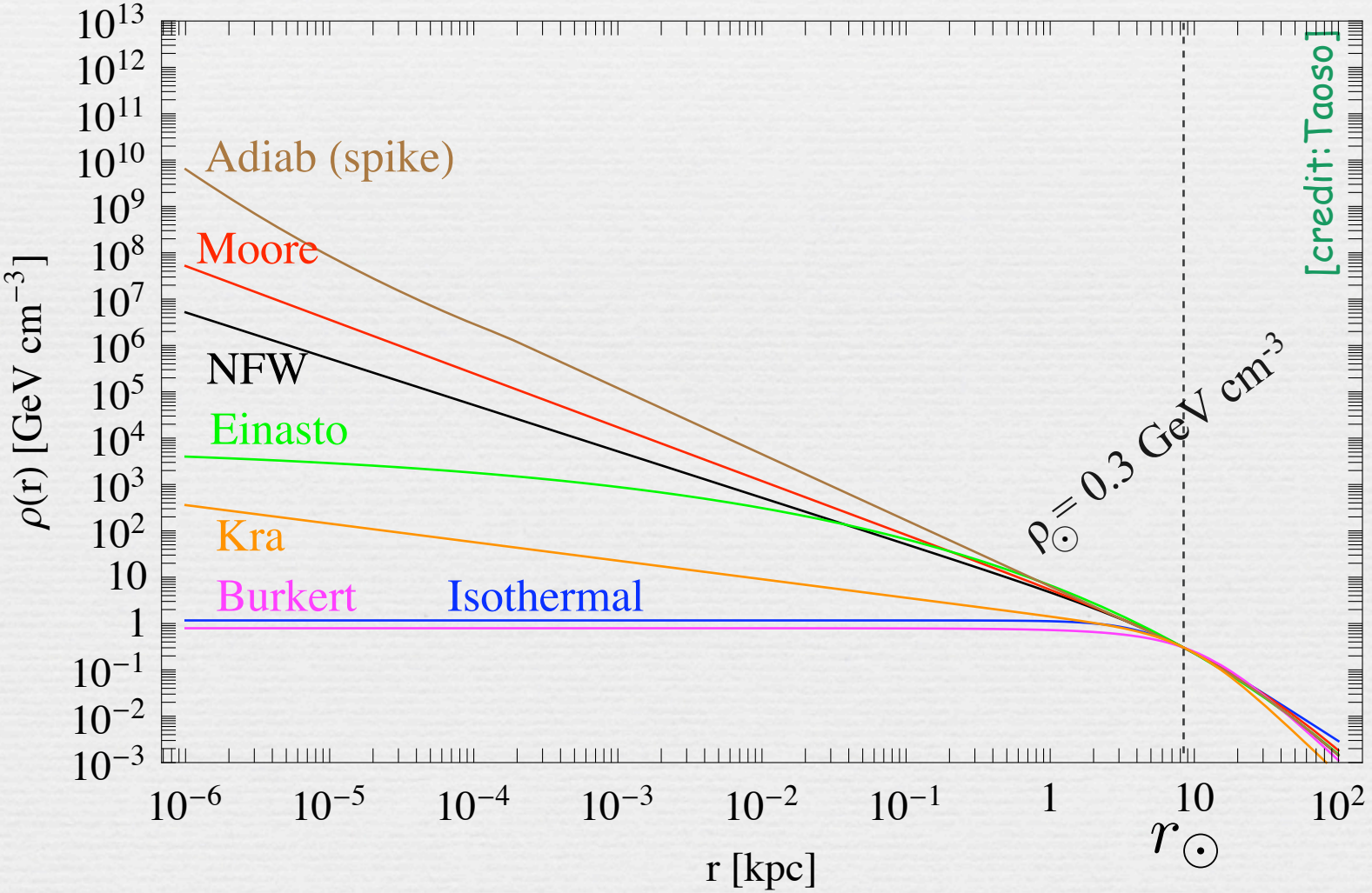
for DM decay:

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

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

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

Astrophysical uncertainties on the DM density profile



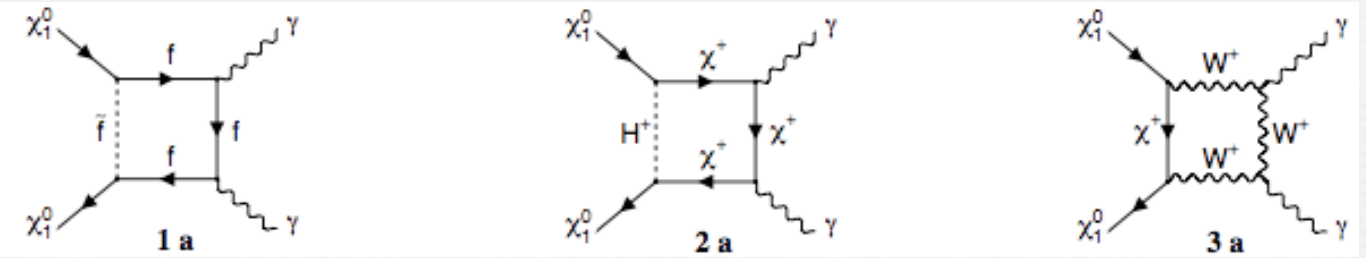
γ-lines from DM

Past results

SUPERSYMMETRY

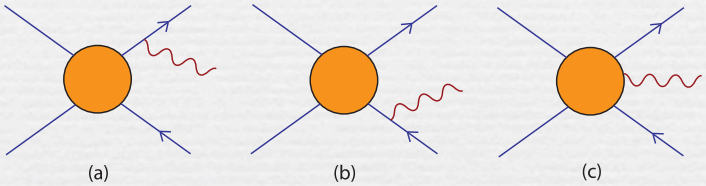
Bergstrom, Ullio, Buckley' 98
Bringmann, Bergstrom & Edsjo '08
...

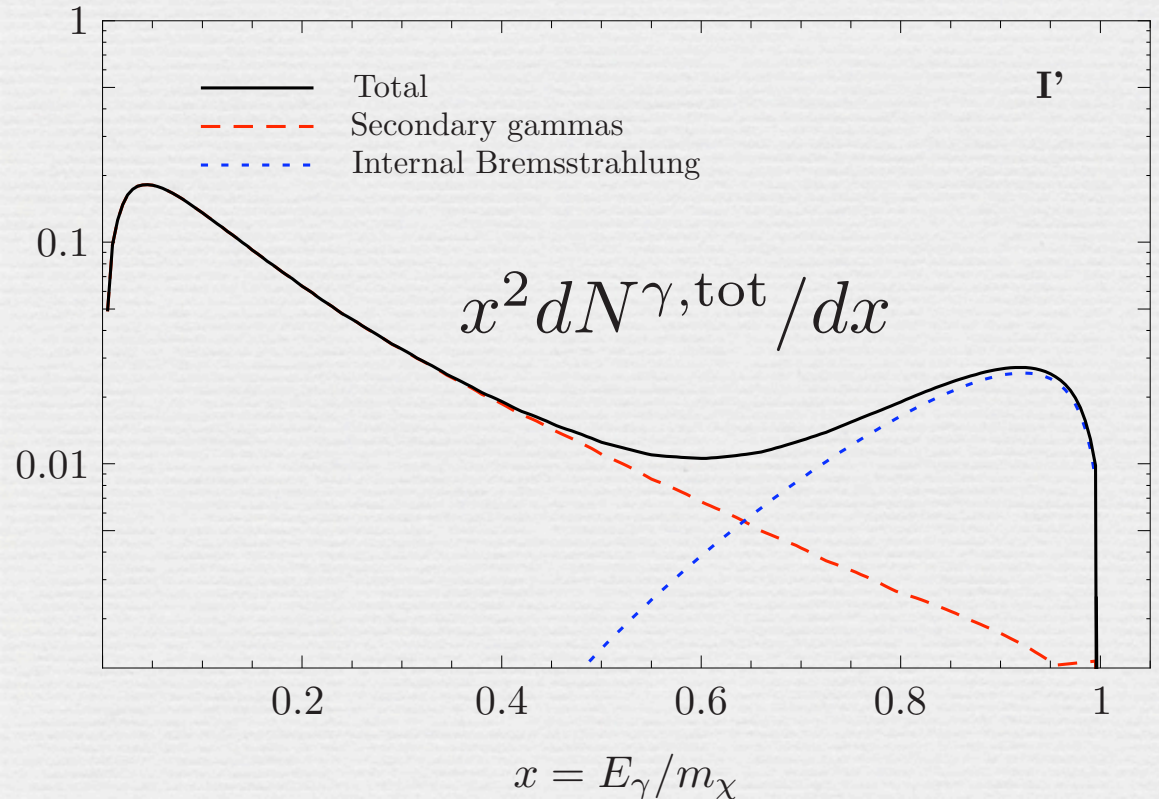
annihilations into $\gamma\gamma$ & γZ :



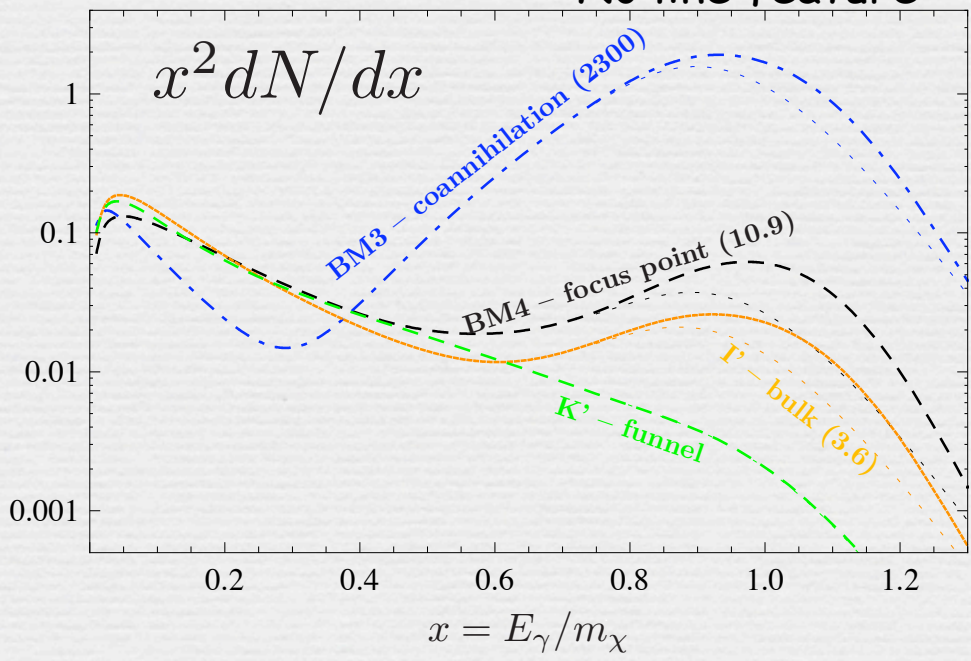
"Standard"Continuum suppressed by Majorana nature of WIMP
(light fermion states chirally suppressed)

However, as recently reexamined: large enhancements from internal bremsstrahlung





No line feature



The Inert Doublet Model (IDM)

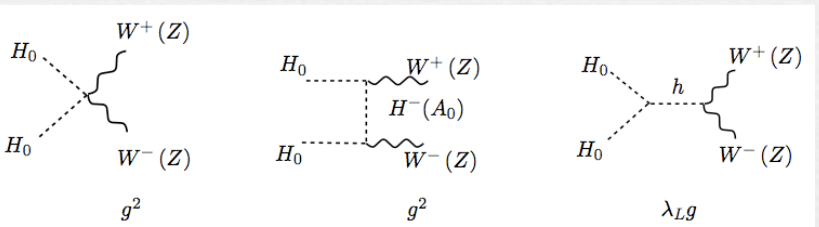
Deshpande-Ma'78; Barbieri-Hall-Rychkov 06; Lopez Honorez-Nezri-Oliver-Tytgat 06; Gerard-Herquet'07 ; Hambye, Tytgat 07 .....

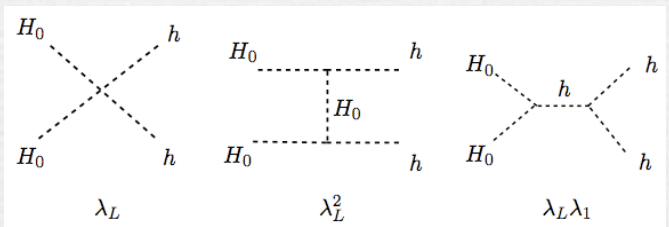
A two-Higgs extension of the SM with an unbroken Z_2 symmetry

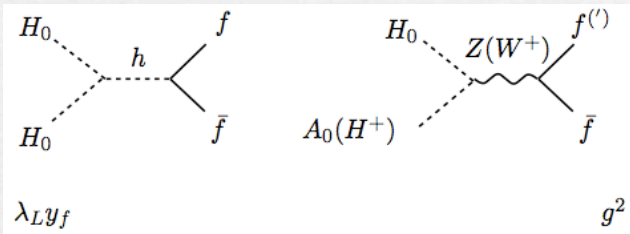
$H_1 \to H_1$ and $H_2 \to -H_2$ (and all SM fields are even)

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

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



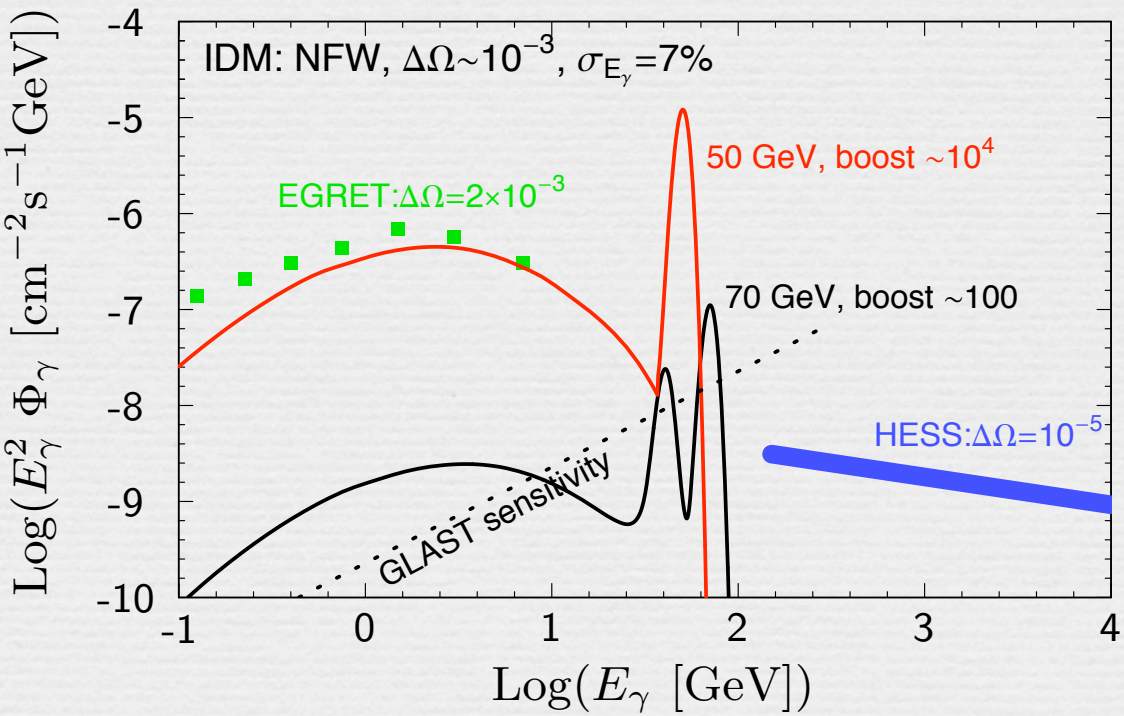




annihilations into $\gamma\gamma$ & γZ mainly through loops of W

Gustaffsson et al. '07

virtual W nearly on-shell threshold enhancement

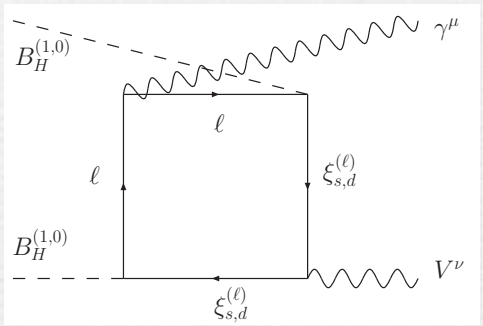


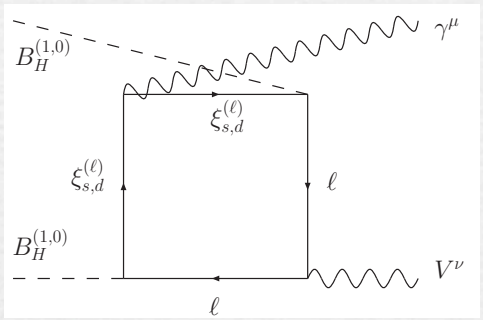
Lines from 6D Universal Extra Dimensions (the "Chiral square")

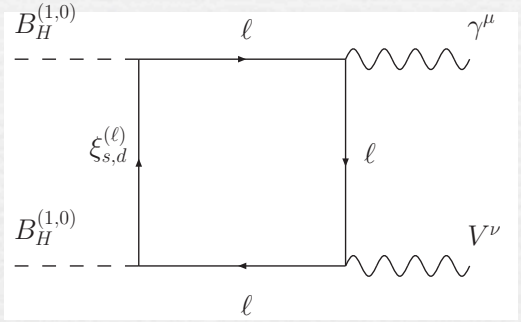
WIMP=scalar B_H ("spinless photon") with M~200-500 GeV

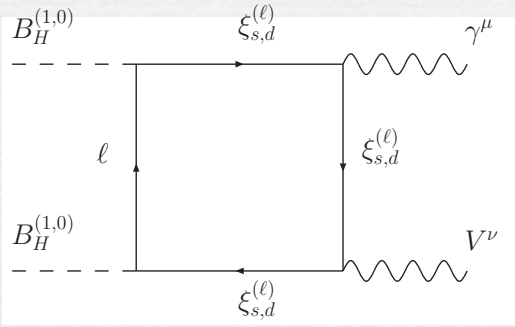
Burdman, Dobrescu, Ponton'05
Dobrescu, Hooper, Kong, Mahbubani '07

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

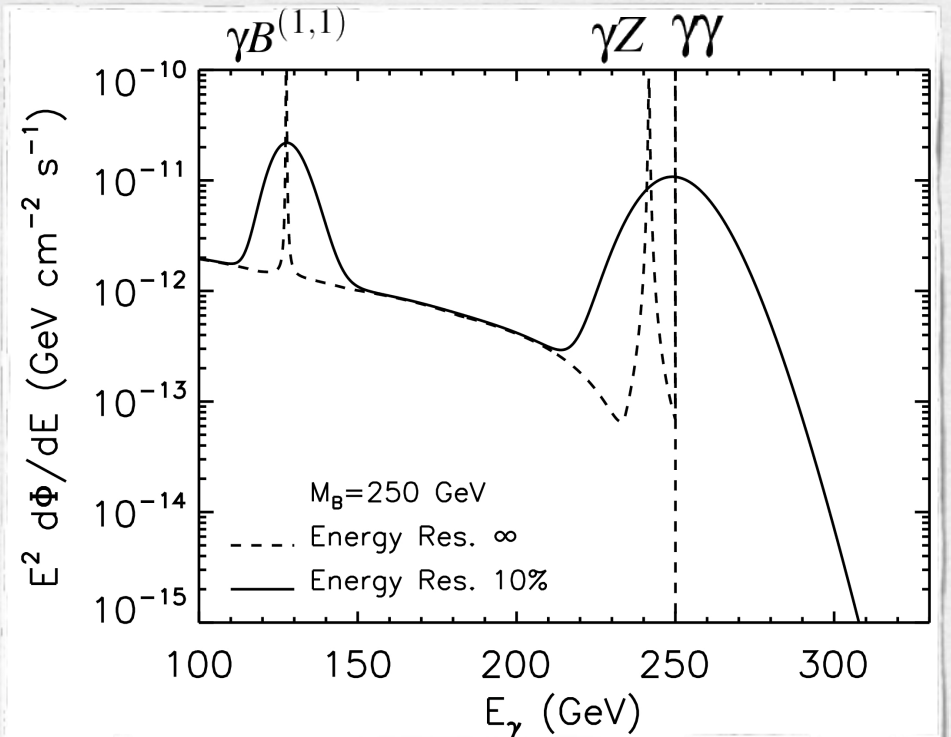








Bertone, Jackson, Shaughnessy, Vallinotto, Tait. '09



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)

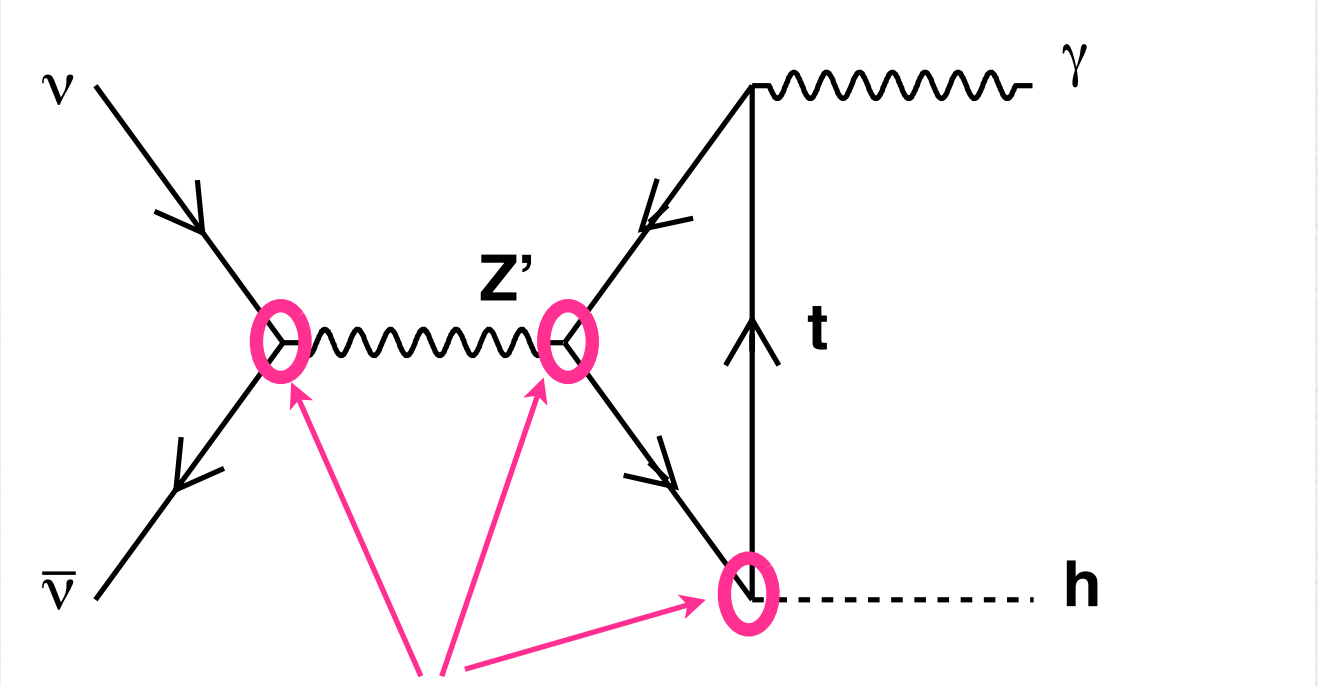
→ **Dirac Fermion DM** ☺

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

The top quark-Dark Matter connection

Jackson, Servant, Shaughnessy,Tait, Taoso,'09

Dirac Dark Matter annihilation into γ H



~ O(1) couplings

A very simple effective theory

Jackson, Servant, Shaughnessy,Tait, Taoso,'09
Agashe-Servant '04; Belanger-Pukhov-Servant '07

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

The only SM particle with a large coupling to the Z' is the top quark

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

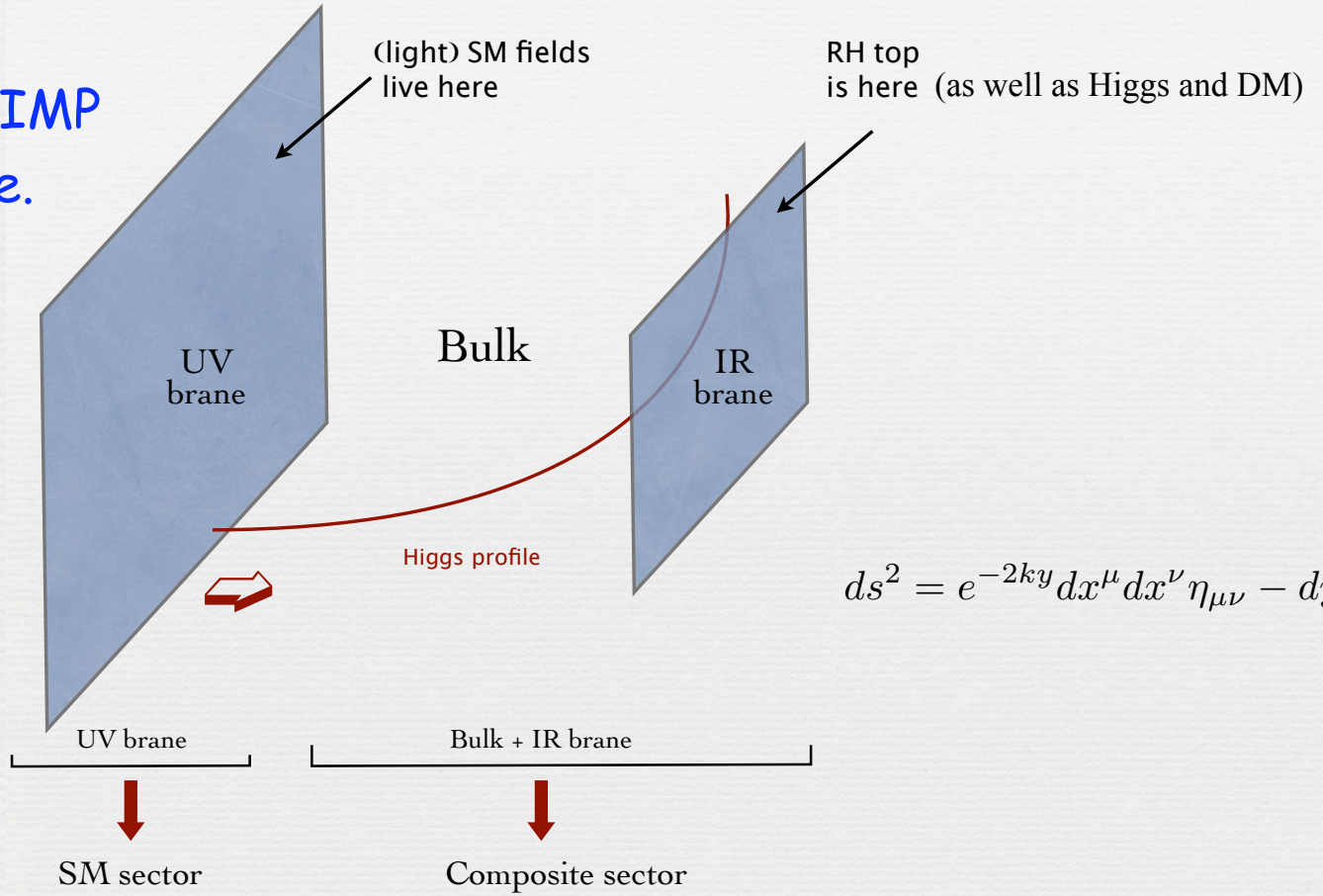
DM

$$D^\mu \equiv \partial_\mu - i\left(g^\nu_R P_R + g^\nu_L P_L\right) Z'^\mu$$

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

This model is inspired by the Randall-Sundrum setup (warped extra dimension):

TeV KK modes (such as Z') have enhanced couplings to RH top quark



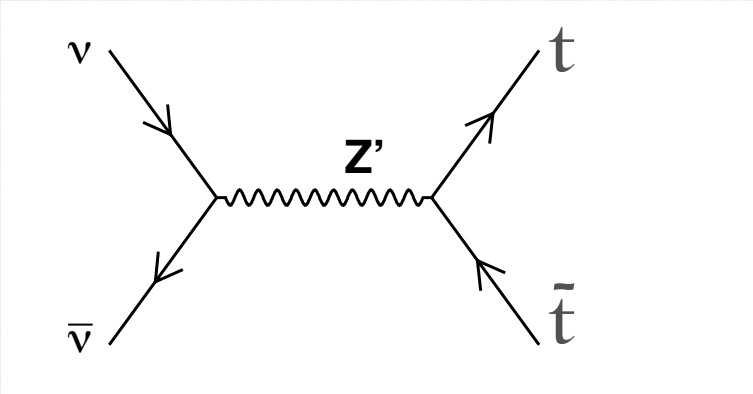
$$ds^2 = e^{-2ky}dx^\mu dx^\nu \eta_{\mu\nu} - dy^2$$

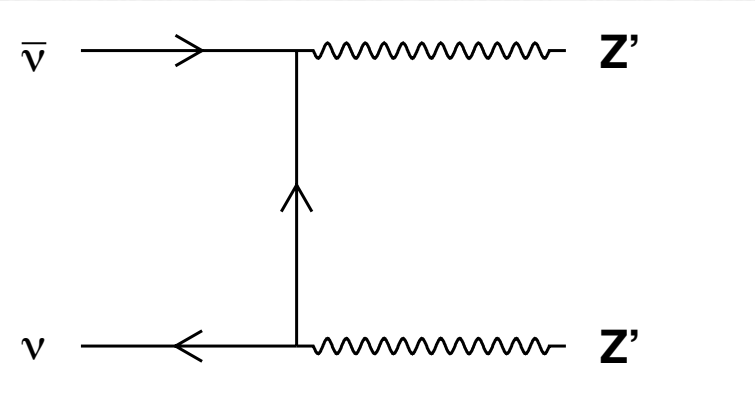
More generally, in models of partial fermion compositeness, natural to expect that only the top couples sizably to a new strongly interacting sector.

Relic density calculation

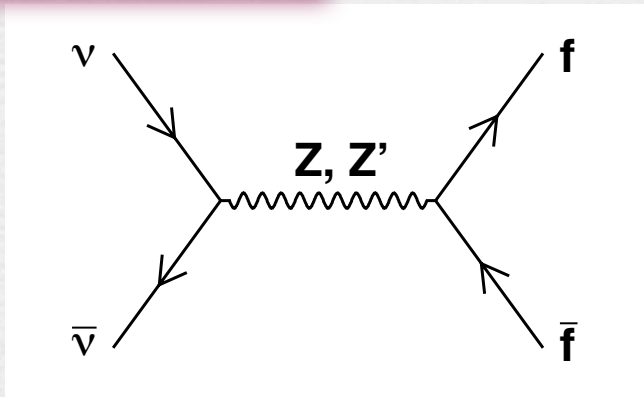
(assuming no ν $\bar{\nu}$ asymmetry)

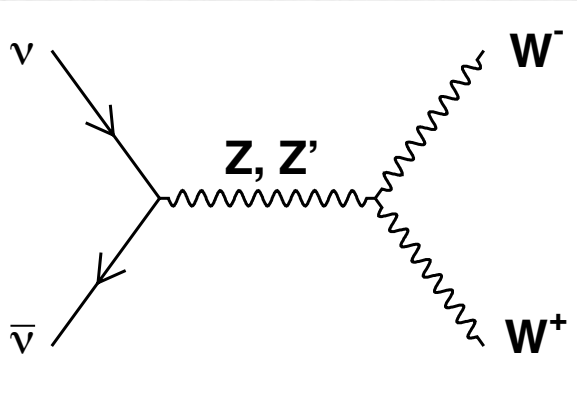
dominant channels

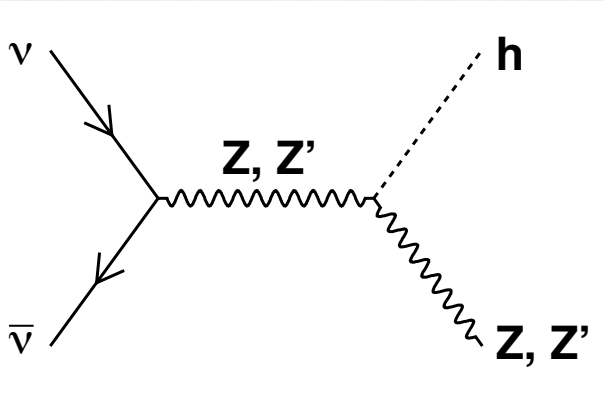




suppressed channels

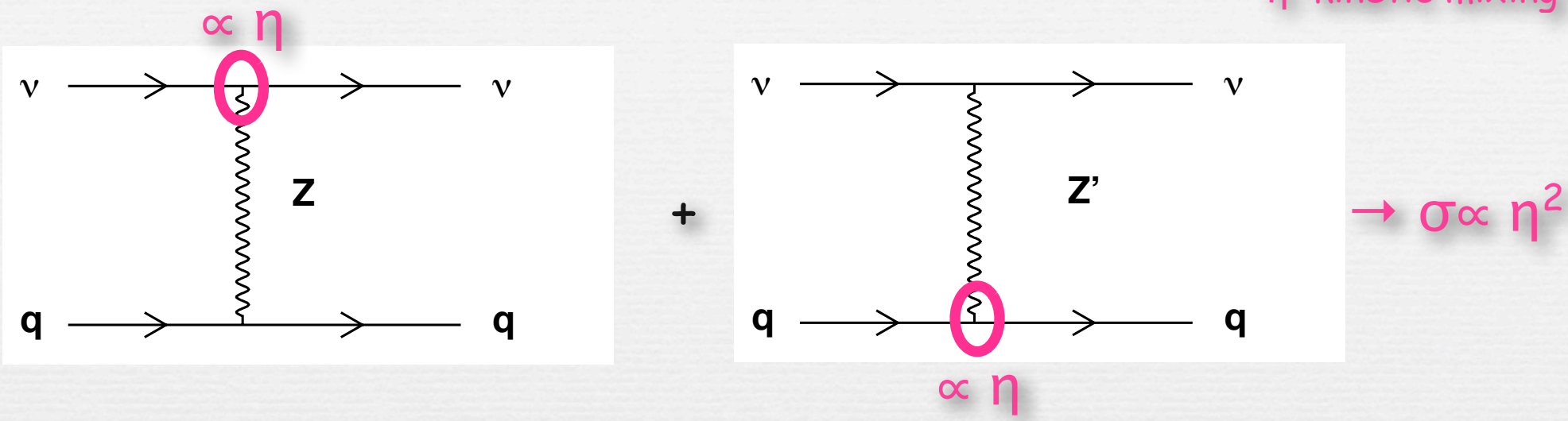




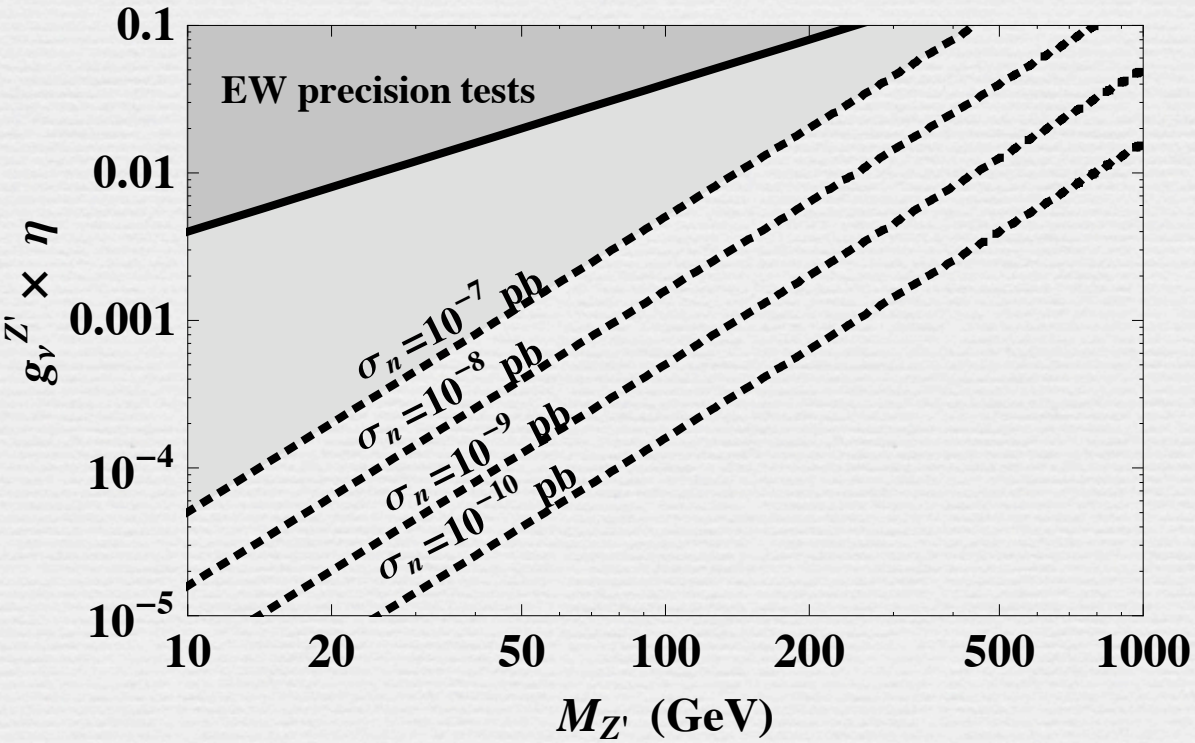


Direct detection constraints

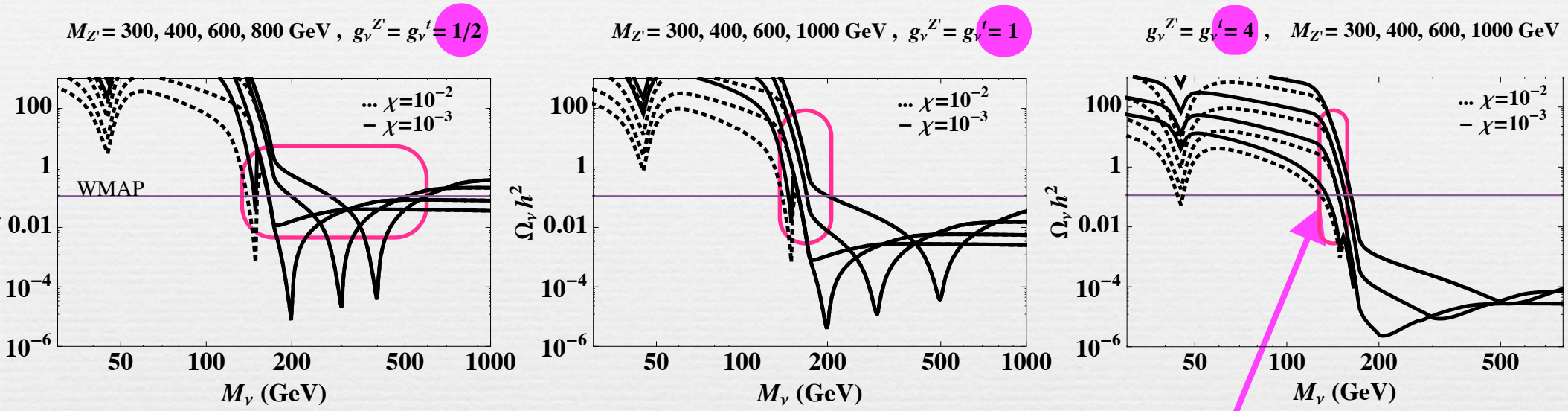
η: kinetic mixing



ν-nucleon elastic scattering cross section contours



Dark matter mass from relic density calculation

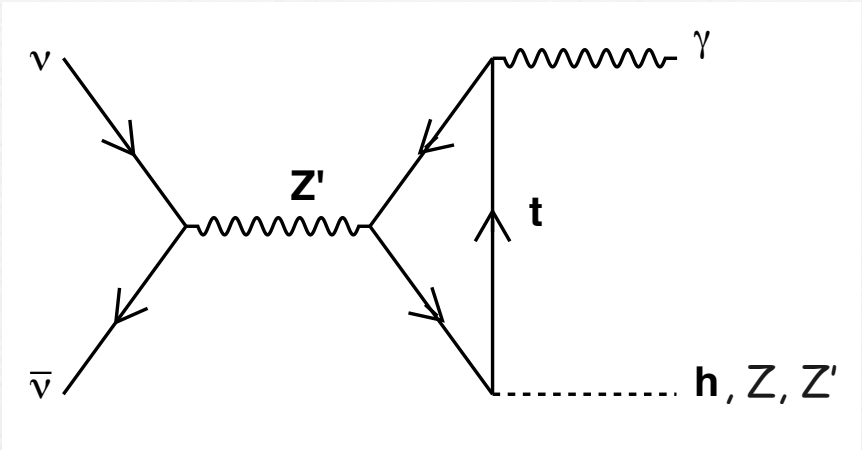


M_{DM} ~ 150 GeV

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

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

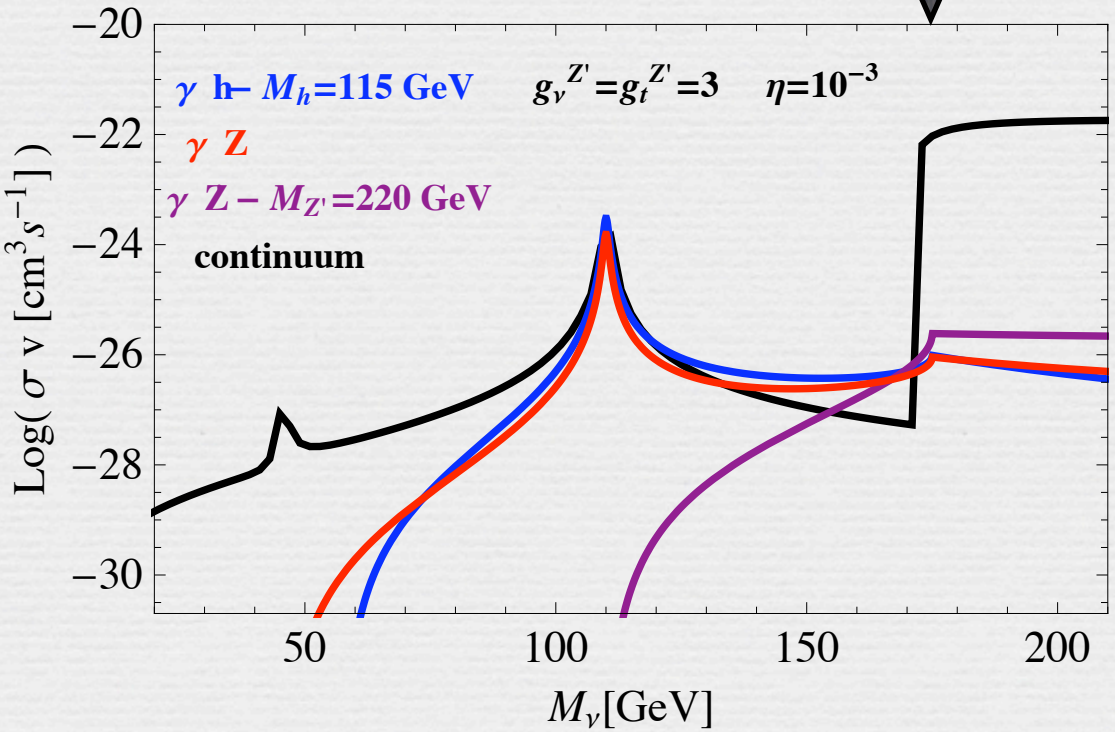
γ signal from ν annihilation



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



How many lines?

region where 2 lines are visible

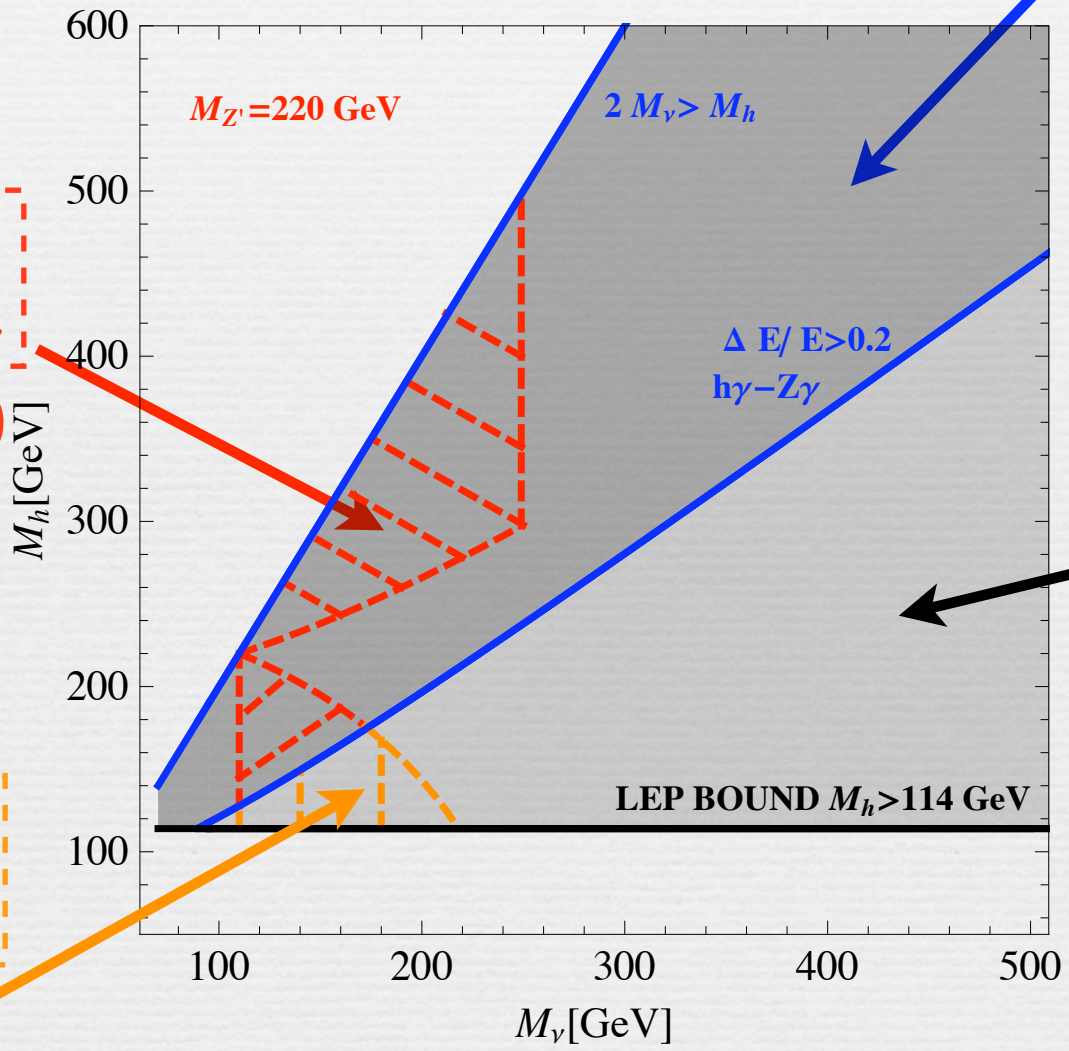
(HY and ZY)

region where the 3 lines are visible

(HY, ZY and Z'Y)

region with 1 line (HY and ZY lines are merged)

region with 2 lines (H/ZY and Z'Y)



assuming energy resolution of 10%

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

region where 2 lines are visible

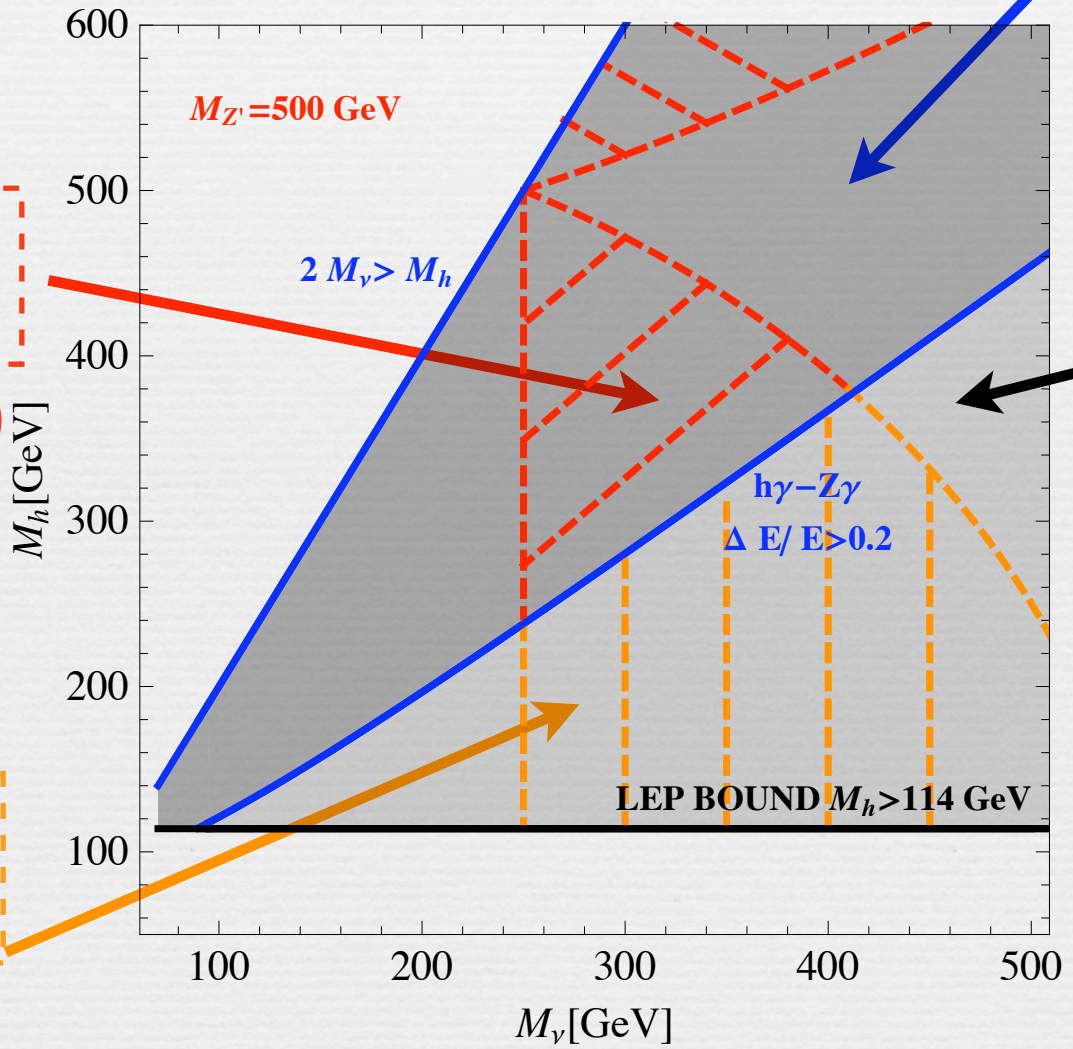
(Hγ and Zγ)

region where the 3 lines are visible

(Hγ, Zγ and Z'γ)

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

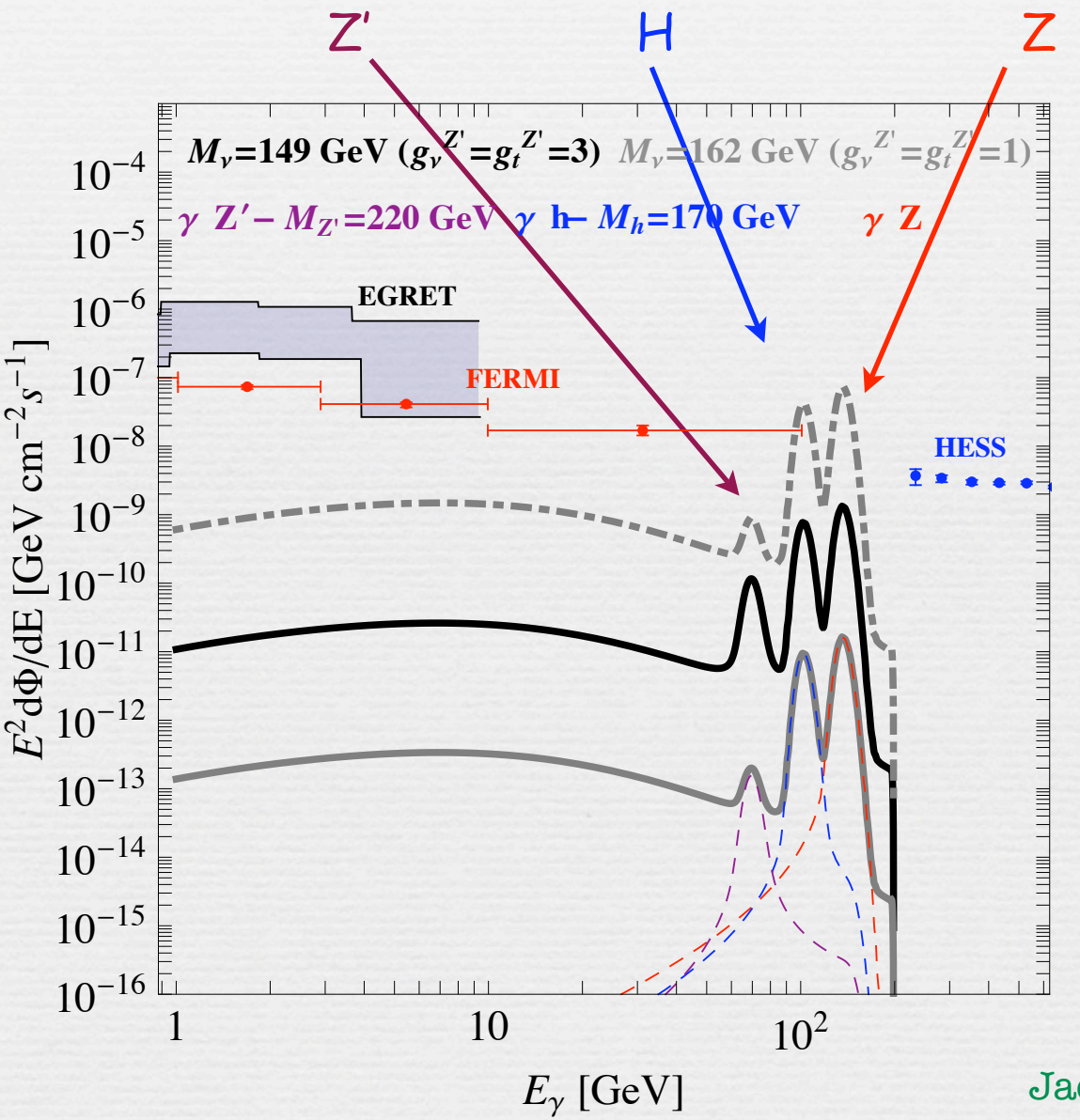
region with 2 lines (H/Zγ and Z'γ)



assuming energy resolution of 10%

Higgs in Space!

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

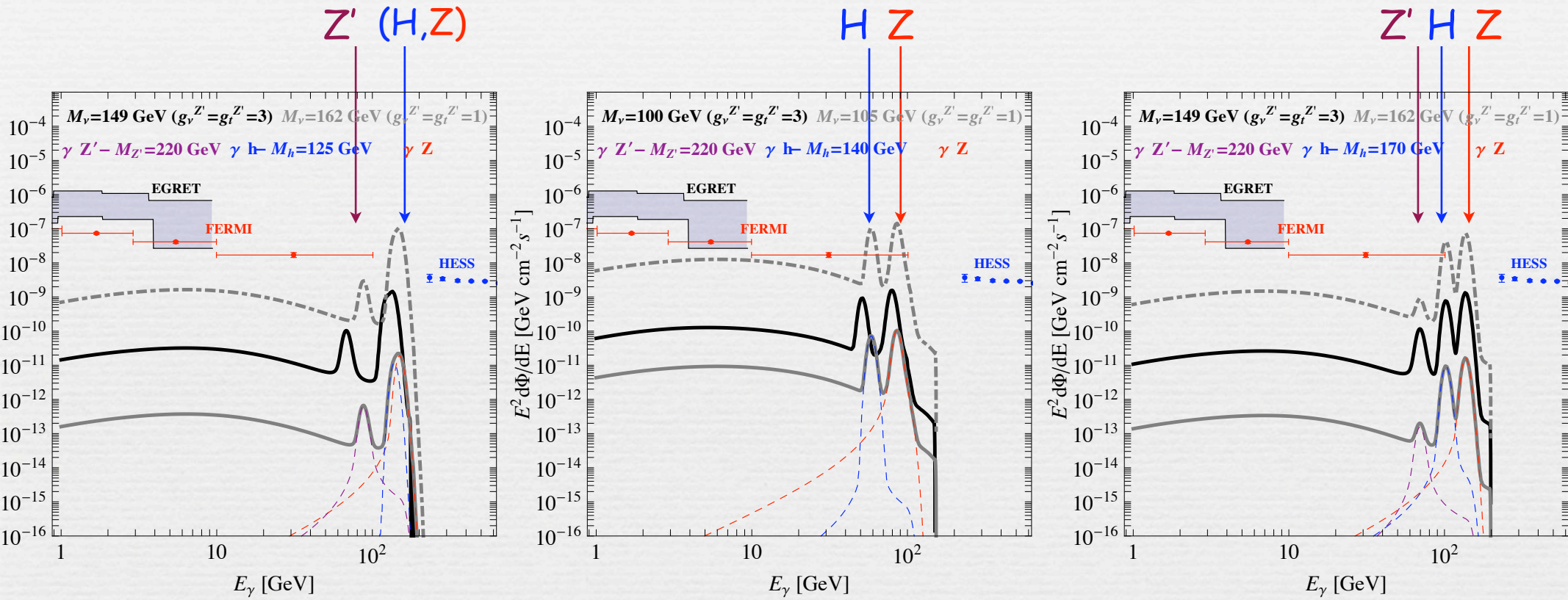
NFW profile

adiabatically contracted

Jackson, Servant, Shaughnessy,Tait, Taoso,'09

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

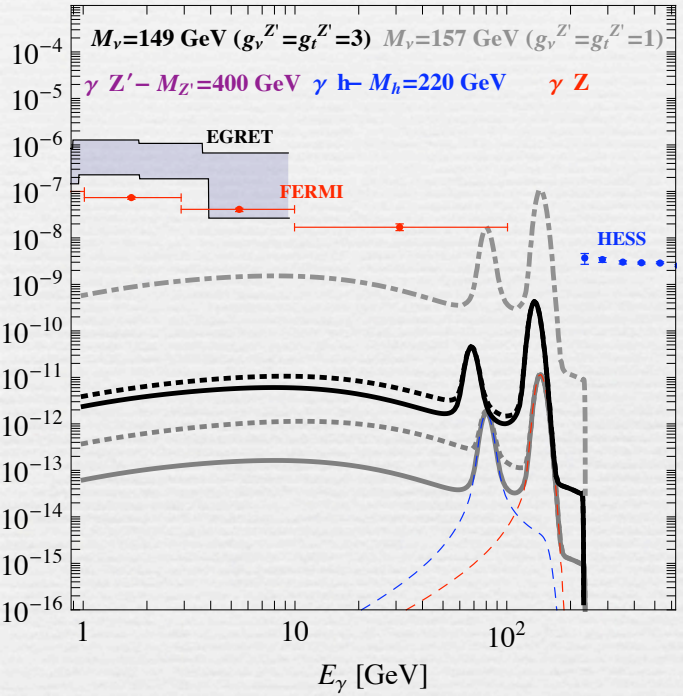


NFW profile

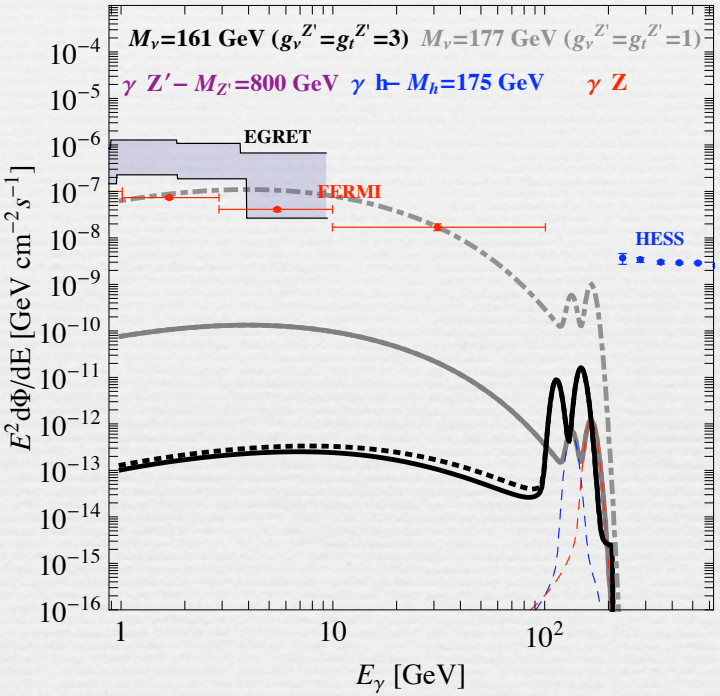
adiabatically contracted

Increasing $M_{Z'}$

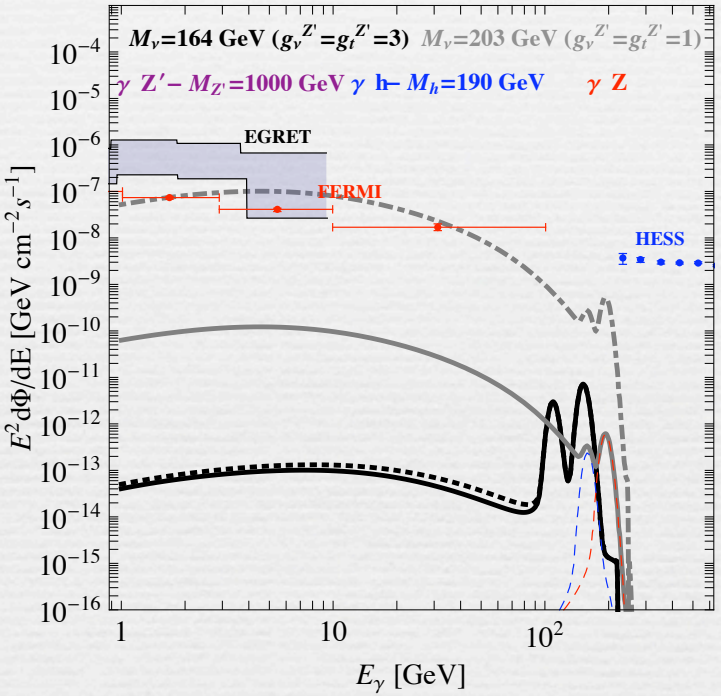
$M_{Z'}$ = 400 GeV



$M_{Z'}$ = 800 GeV



$M_{Z'}$ = 1 TeV



To recap:

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.

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:

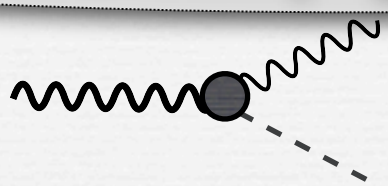
$$yH\overline{Q}_3 t_R + \mu\overline{\tilde{T}}_L\tilde{T}_R + Y\Phi\overline{\tilde{T}}_L t_R$$

higgs of U(1)'

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

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:

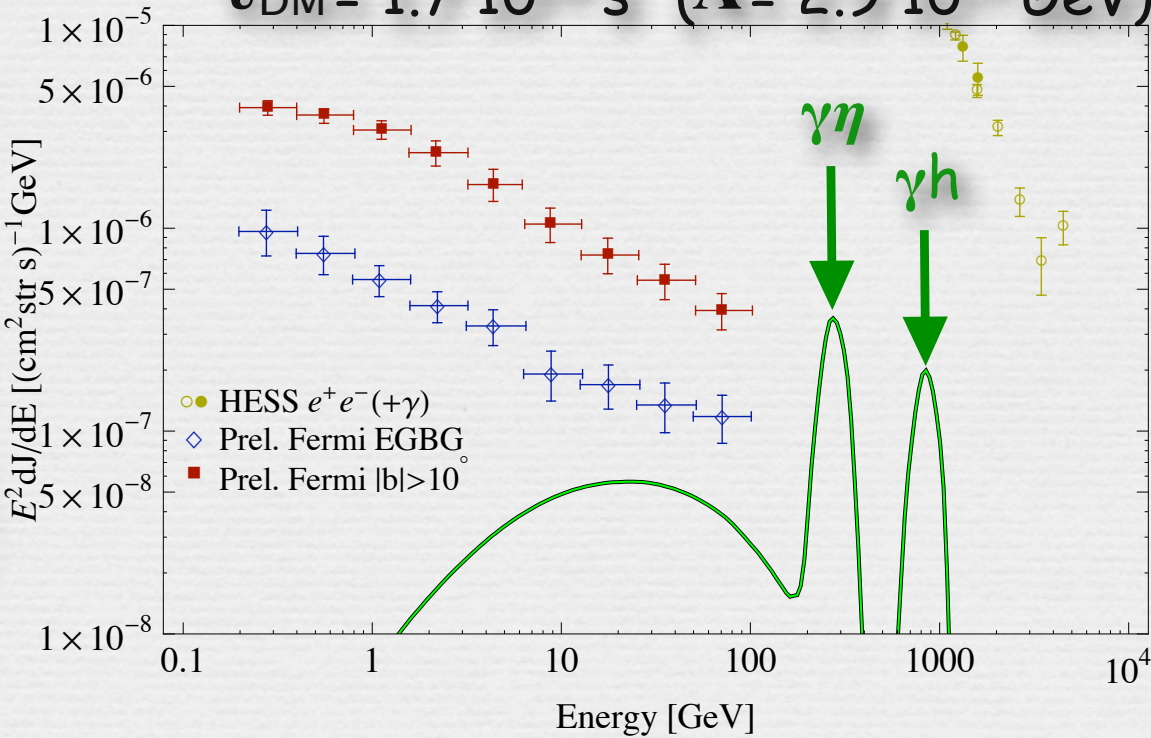
$$\frac{1}{\Lambda^2}\, \mathcal{D}_\mu \phi^\dagger \phi\, \mathcal{D}_\mu H^\dagger H \qquad \frac{1}{\Lambda^2}\, \mathcal{D}_\mu \phi^\dagger \mathcal{D}_\nu \phi\, F^{\mu\nu Y}$$

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

late decay of DM → γh & γη lines :

(η:hidden sector scalar)

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



Detectability

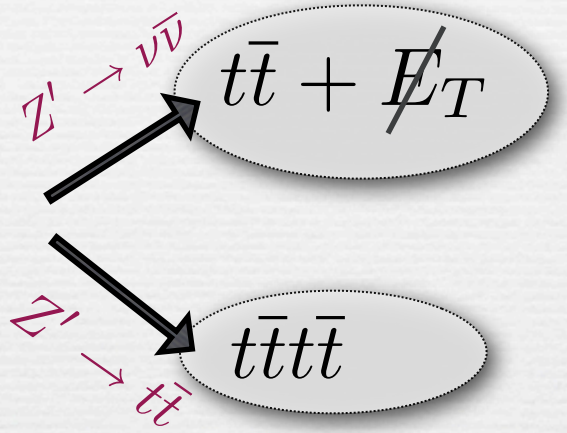
see D. Horns and L.Strigari's talks

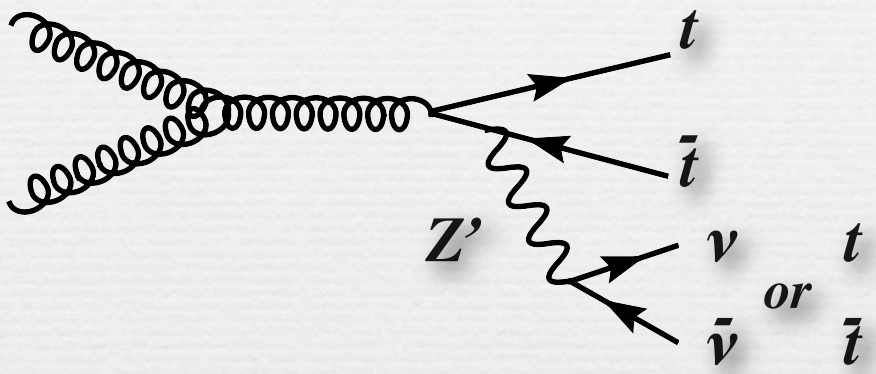
Collider signatures of a top (and DM)-philic Z'

- $f\bar{f} \to Z' \to t\bar{t}$

Z' has suppressed couplings to light quarks
-> no observable $t\bar{t}$ resonances

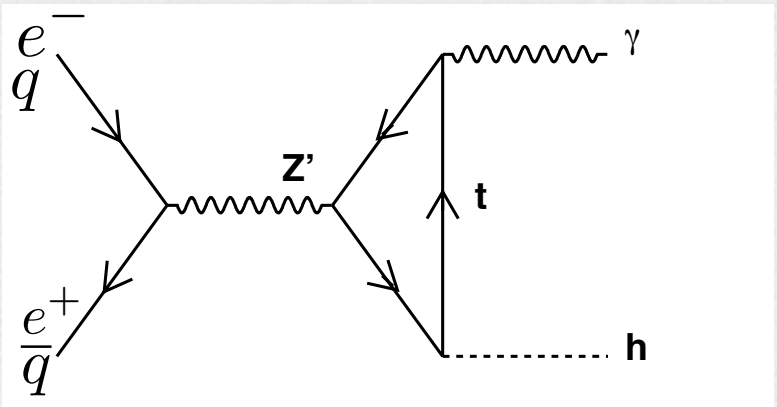
- $gg \to t\bar{t} + Z'$



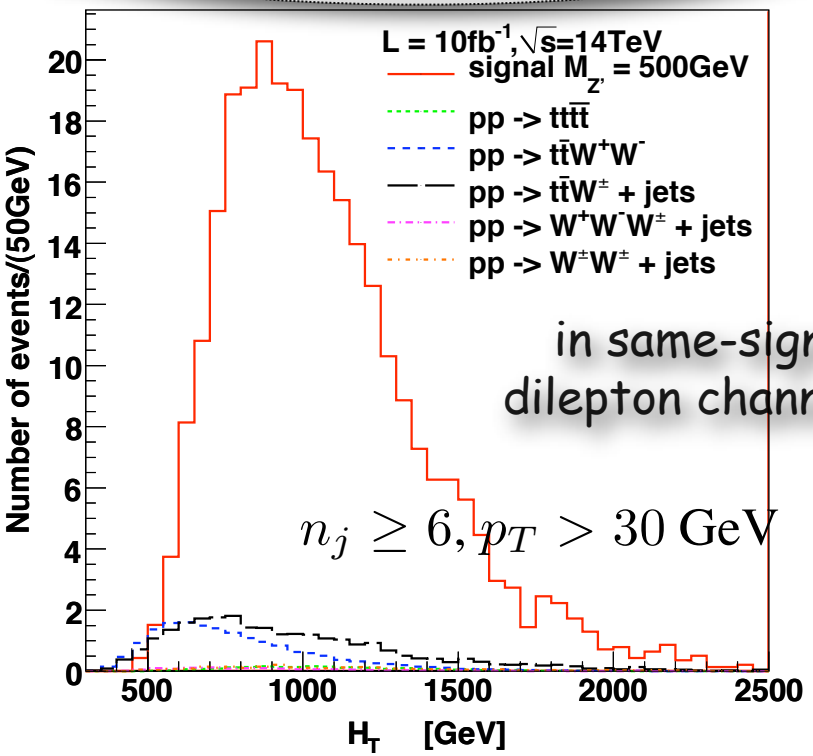


- $f\bar{f} \to Z' \to \gamma H$

energetic monochromatic γ



$pp \to t\bar{t}t\bar{t}$ @ 14 TeV LHC

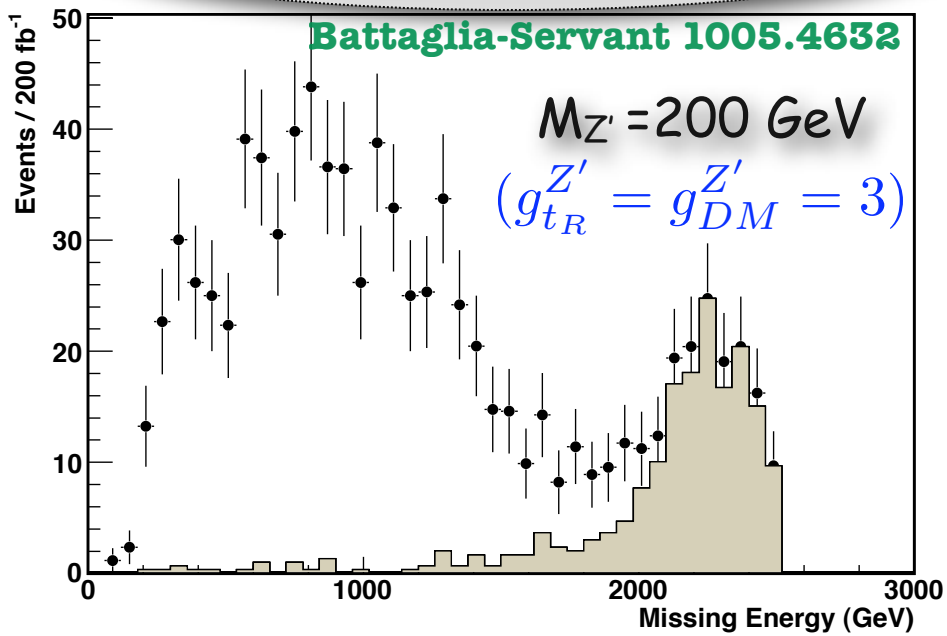


in same-sign dilepton channel

$n_j \geq 6, p_T > 30$ GeV

Gauthier-Servant

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



SM: σ_{ttveve} = 4.1 fb

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

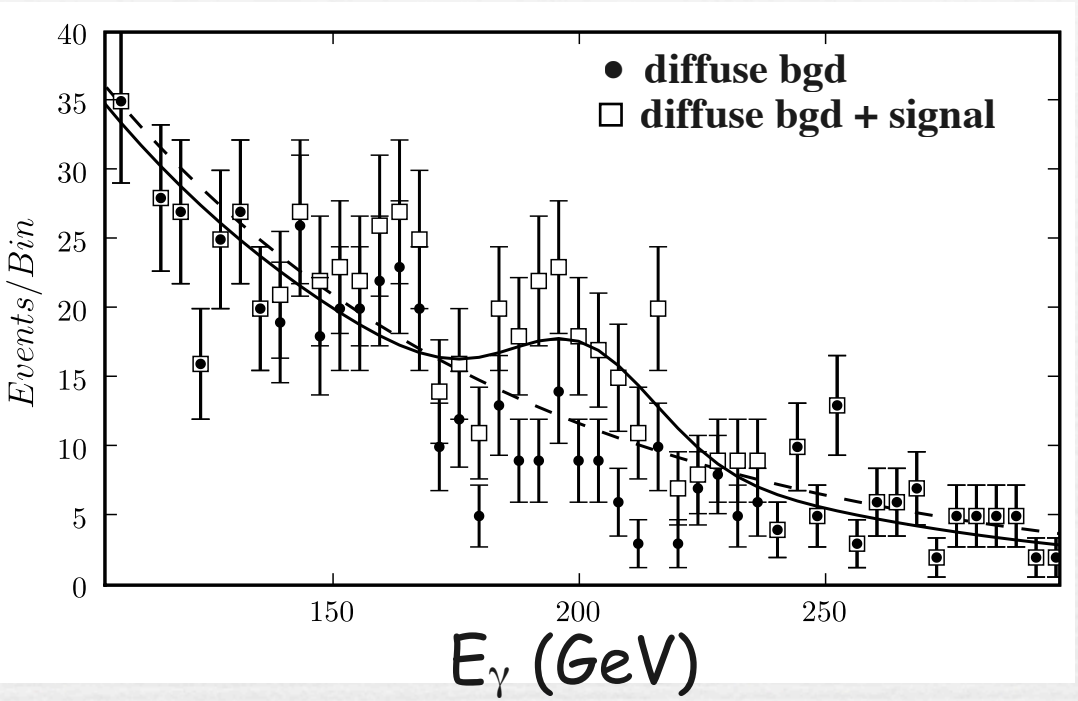
Observation of γ H would indicate that the WIMP is not a scalar nor a Majorana fermion but most likely a Dirac fermion or a vector

Worth checking whether Higgs is hiding in gamma-ray telescope's data (Fermi, Magic, Hess, Cangaroo, Veritas...)

Complementary Collider signatures (four-top events, under study)

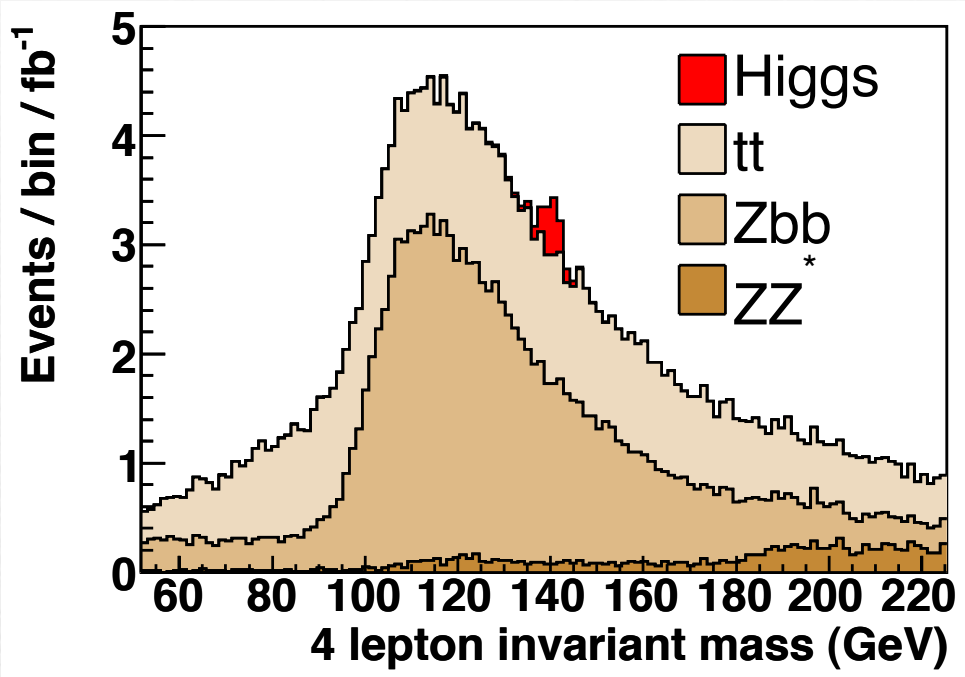
Who will see it first?

Fermi ?

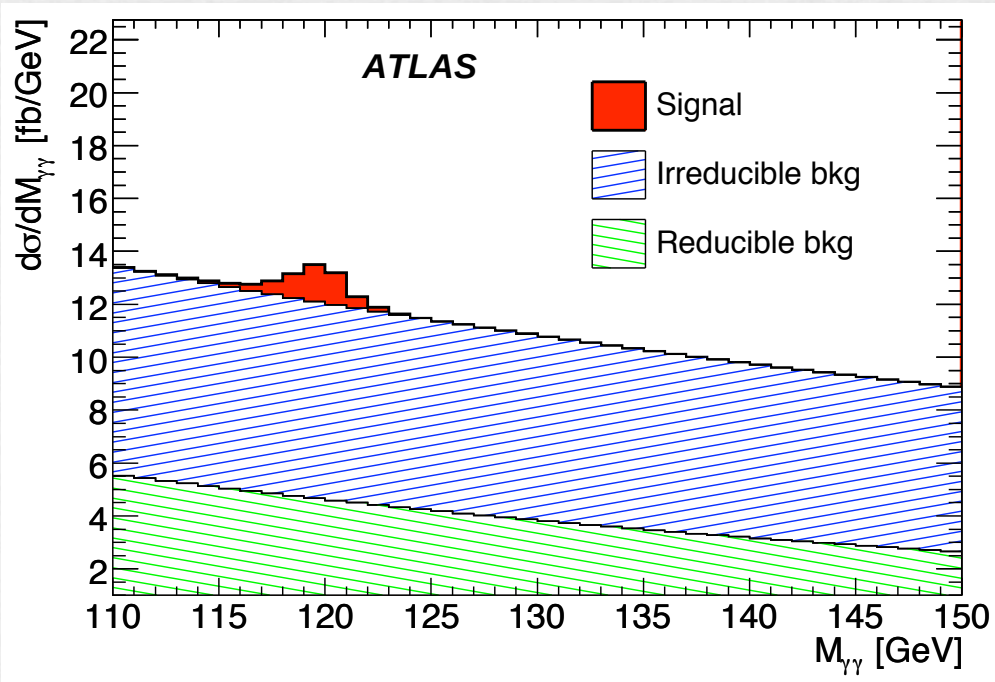


or

CMS ?



or ATLAS ?



Annexes

Large γ line signals compatible with low $\bar{p}$ and e^+ fluxes