Gamma-ray lines from dark matter

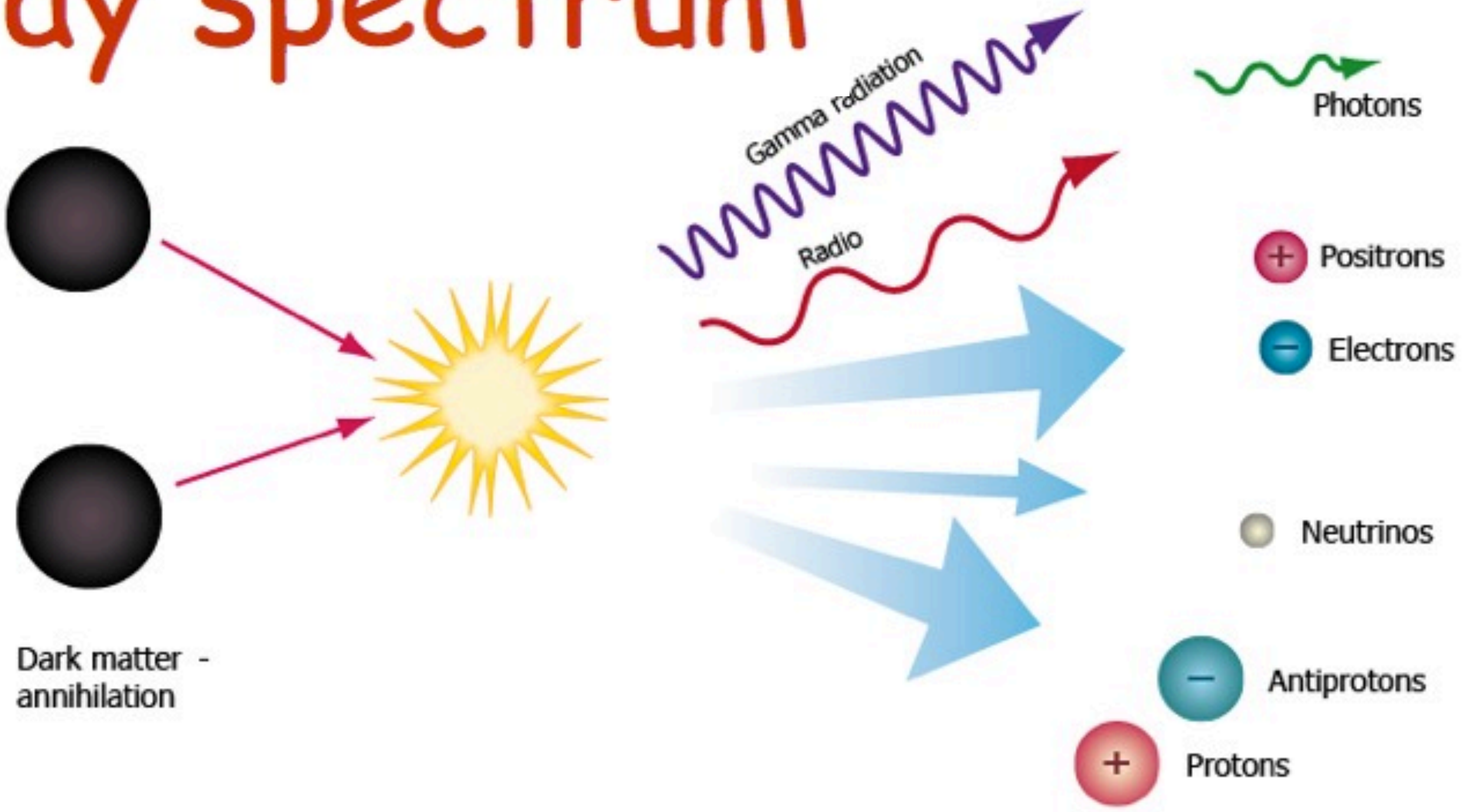
Michael Gustafsson
INFN/Padova

GGI work shop on Dark Matter. Florence, May 13, 2010

Outline

- Gamma-ray spectrum from dark matter
- Backgrounds
- When are gamma-lines significant?
  ... specific dark matter models
- Observational constraints/possibilities

DM gamma-ray spectrum



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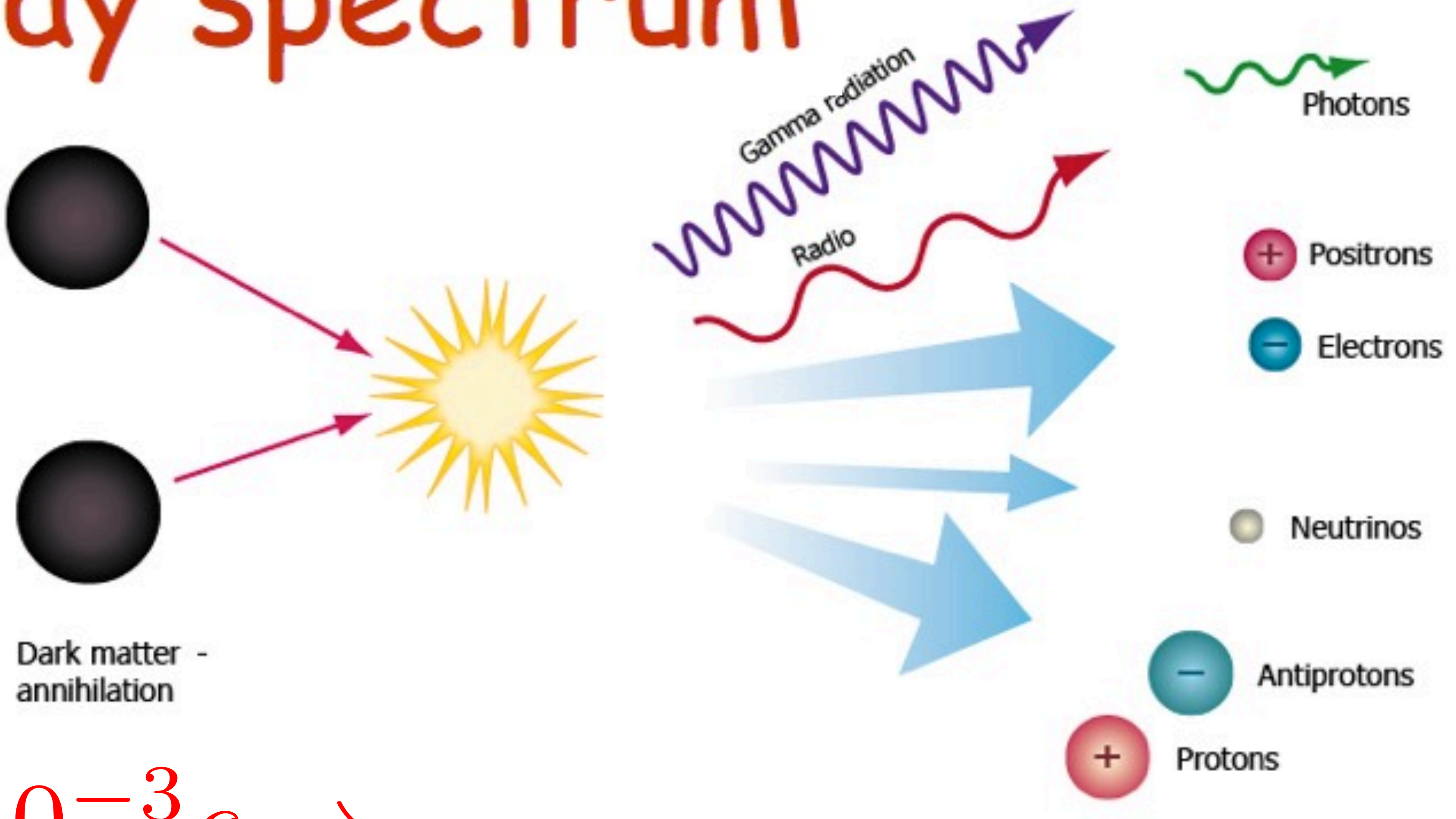

velocity $v \lesssim 10^{-3}c \Rightarrow$

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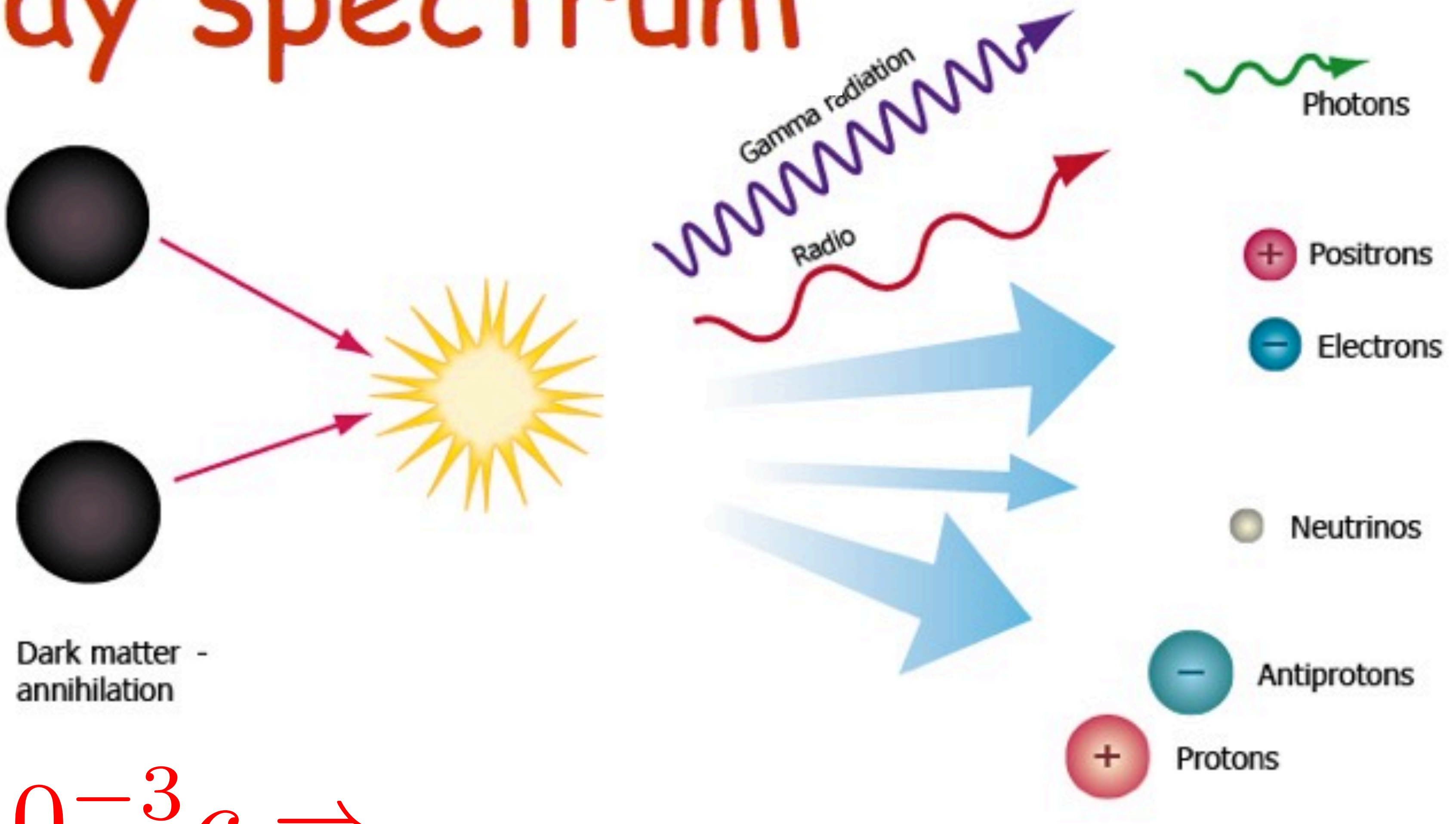

velocity $v \lesssim 10^{-3} c \Rightarrow$

$$\text{Energy injection} \approx \begin{array}{ll} 2 \times m_{DM} & \text{(annihilation)} \\ 1 \times m_{DM} & \text{(decay)} \end{array}$$

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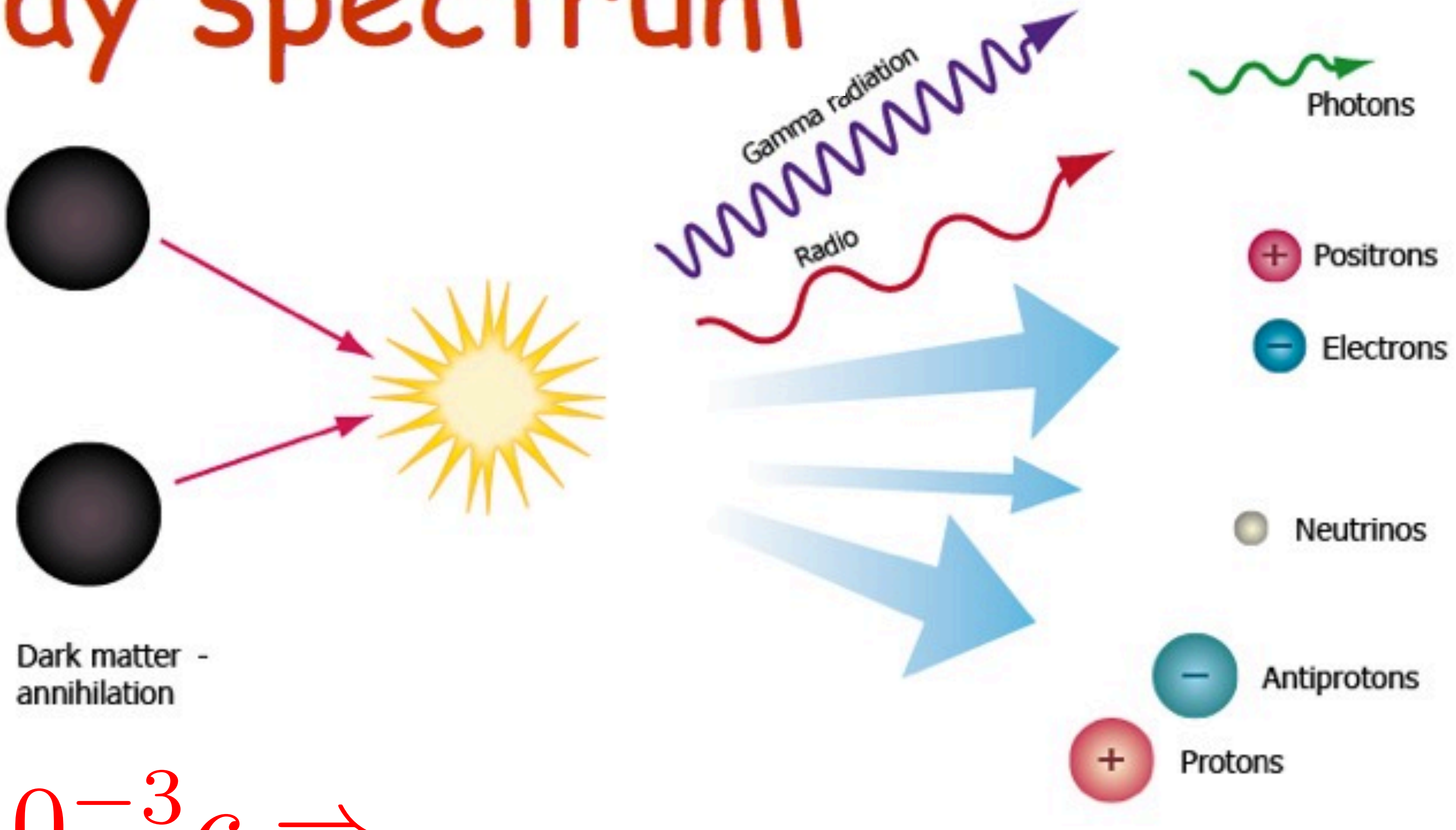

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Energy injection $\approx$ $2 \times m_{DM}$ (annihilation)

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Energy correction $\sim m_{DM} v^2$ in center-of-mass

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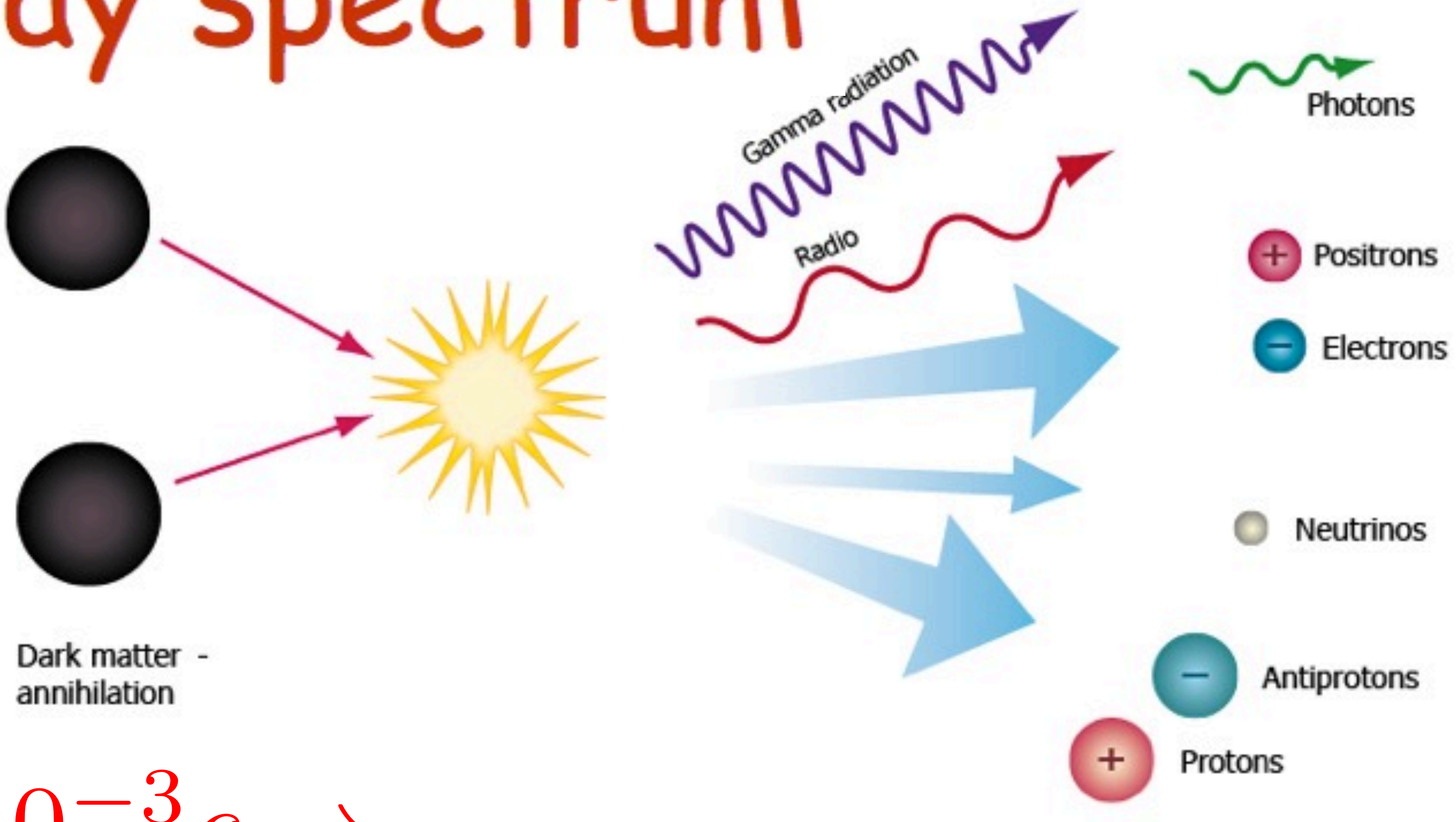

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Energy smearing $\sim m_{DM}v/c$ (doppler shift)

DM gamma-ray spectrum

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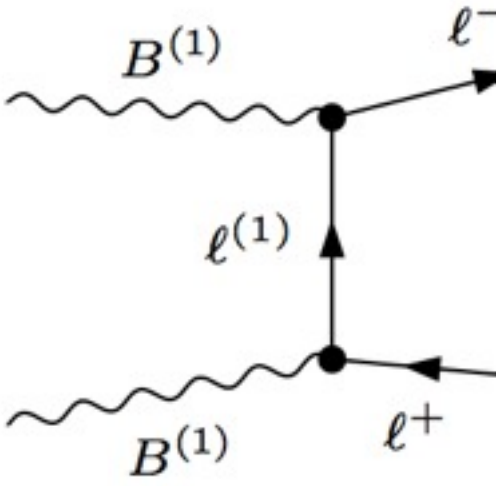
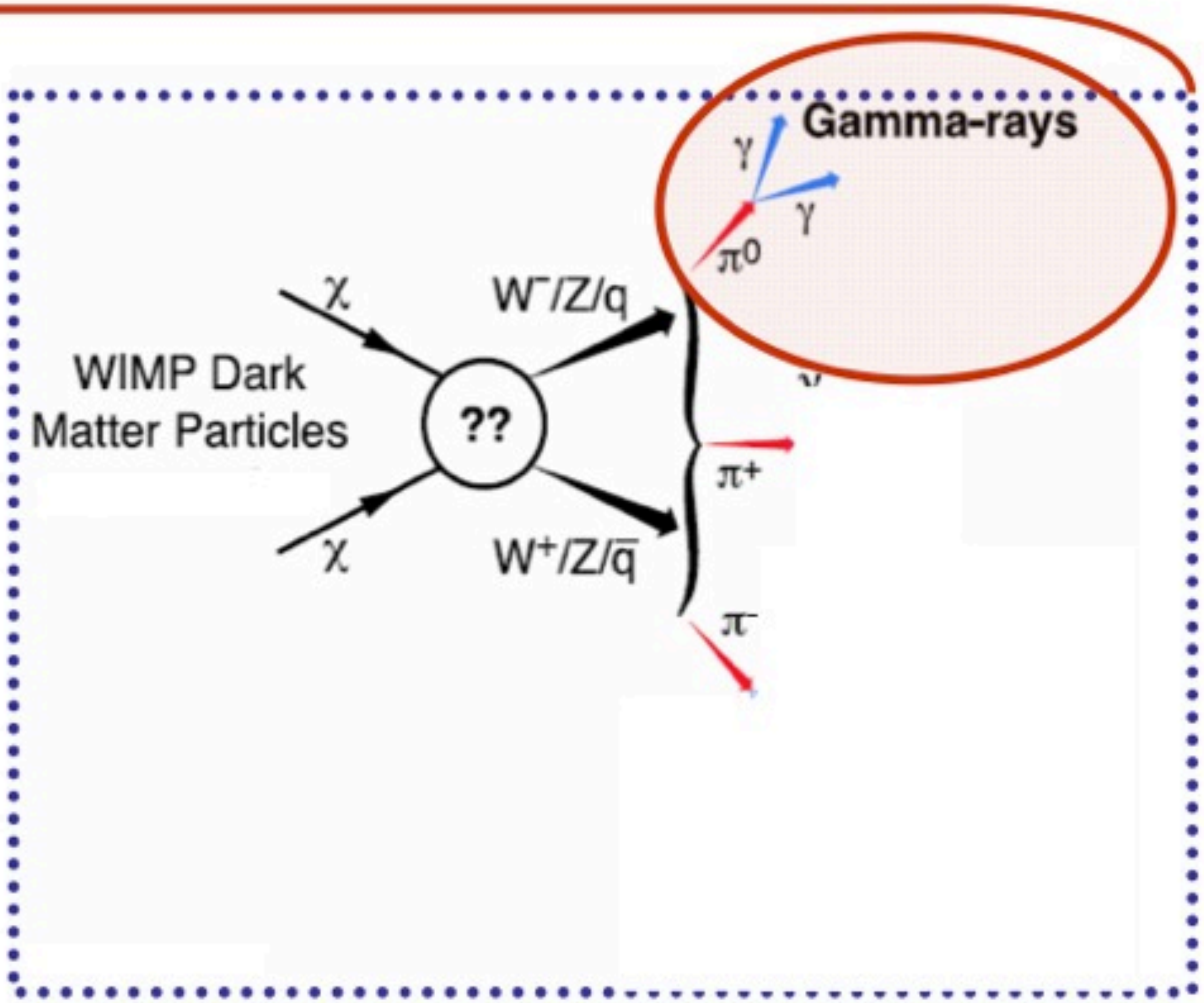
- lowest order $\mathcal{O}(1)$
- and subsequent pion decay

$$\pi^0 \rightarrow \gamma + \gamma$$





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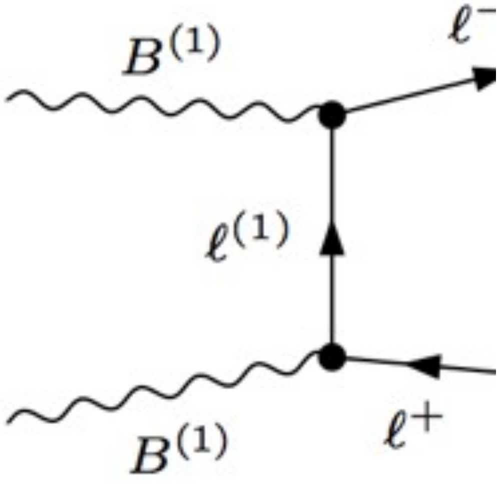

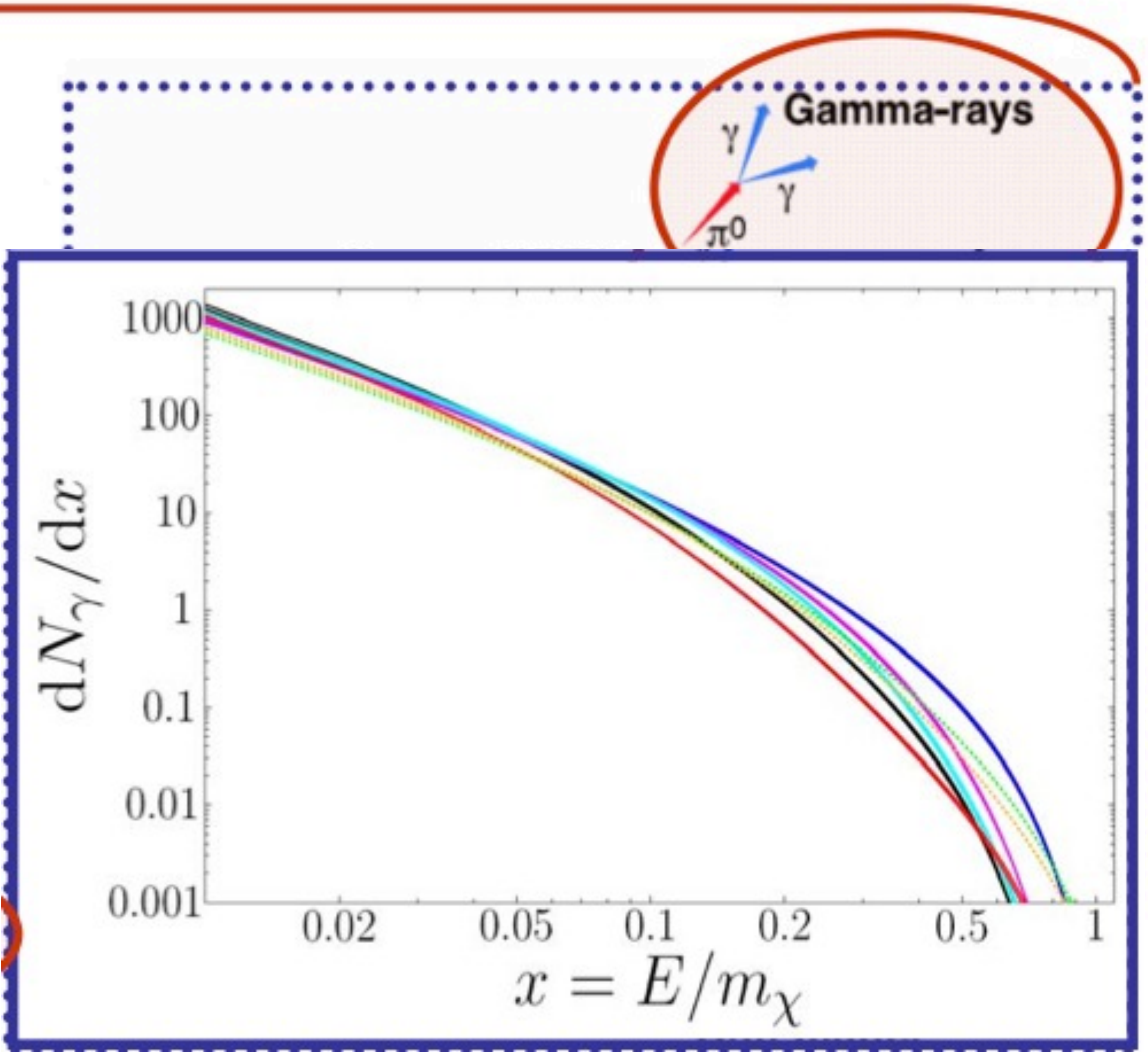

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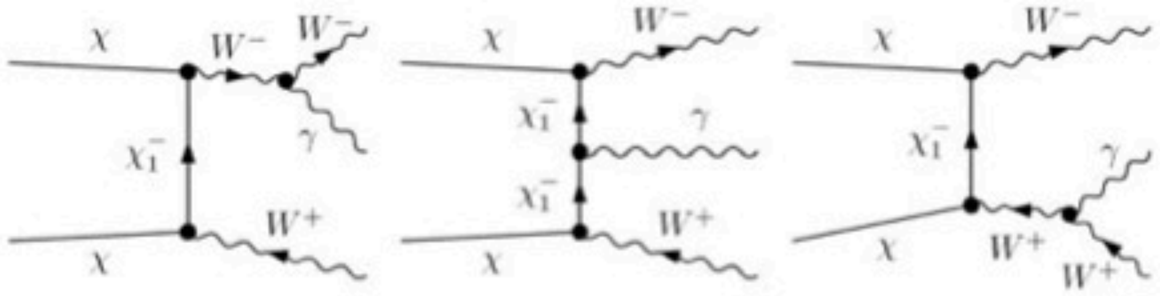
- vertex suppressed, i.e. $\mathcal{O}(\alpha)$



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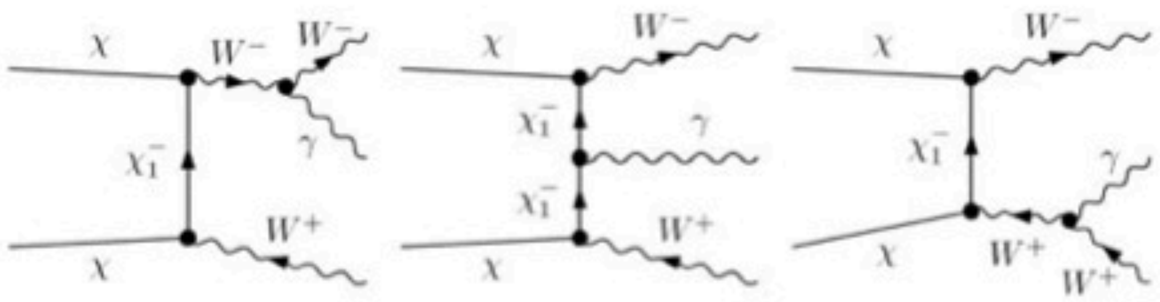

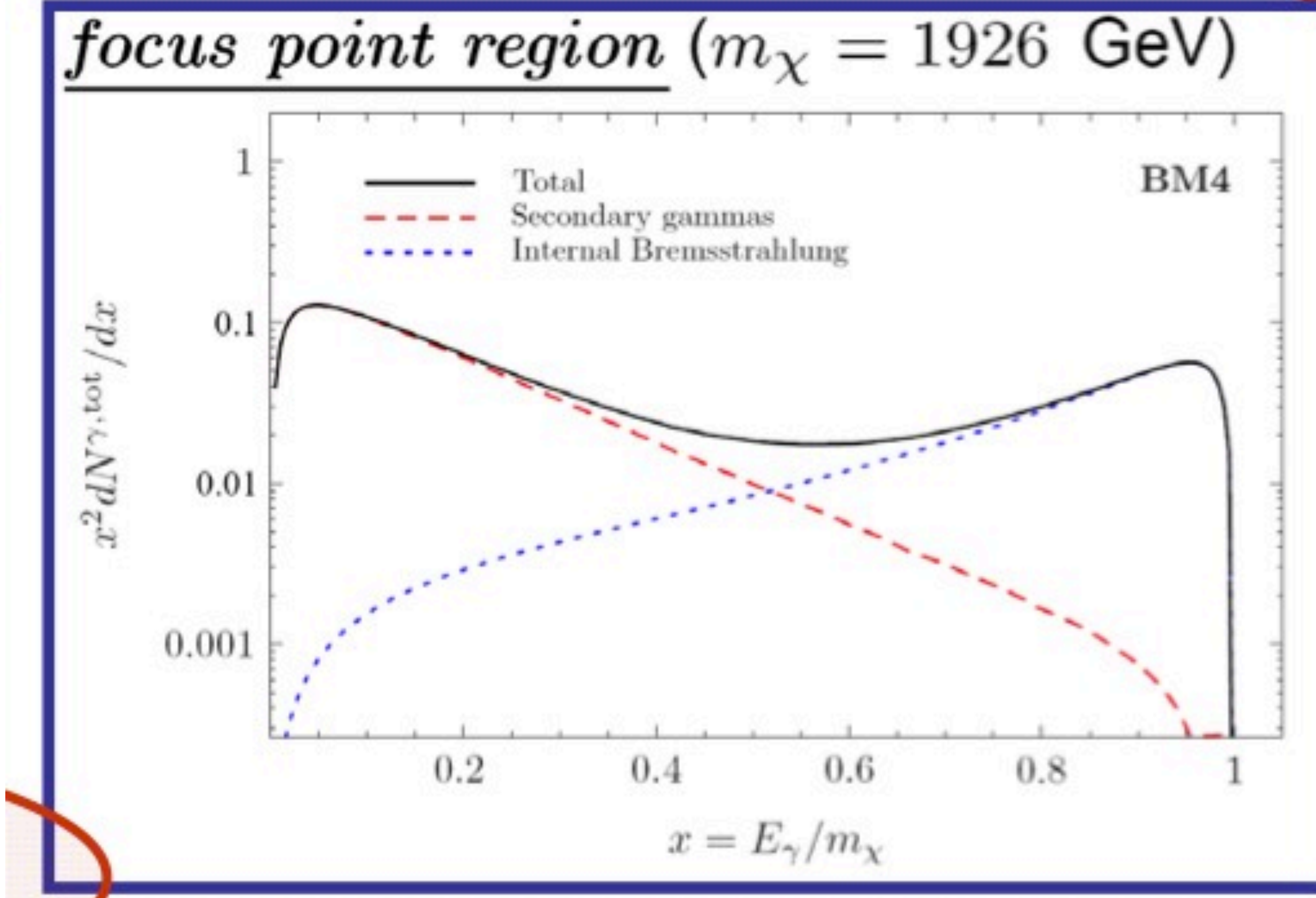
focus point region ($m_\chi = 1926$ GeV)

Bergström, Bringmann, MG & Eriksson '04
Bringmann, Bergström & Edsjö '08
Bergström '89

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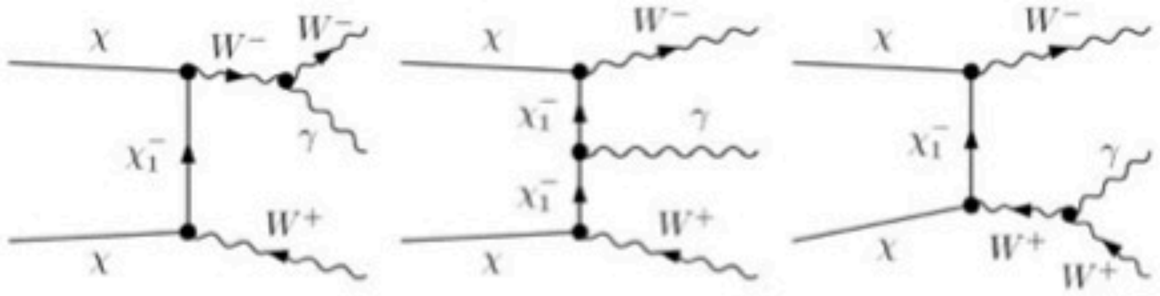

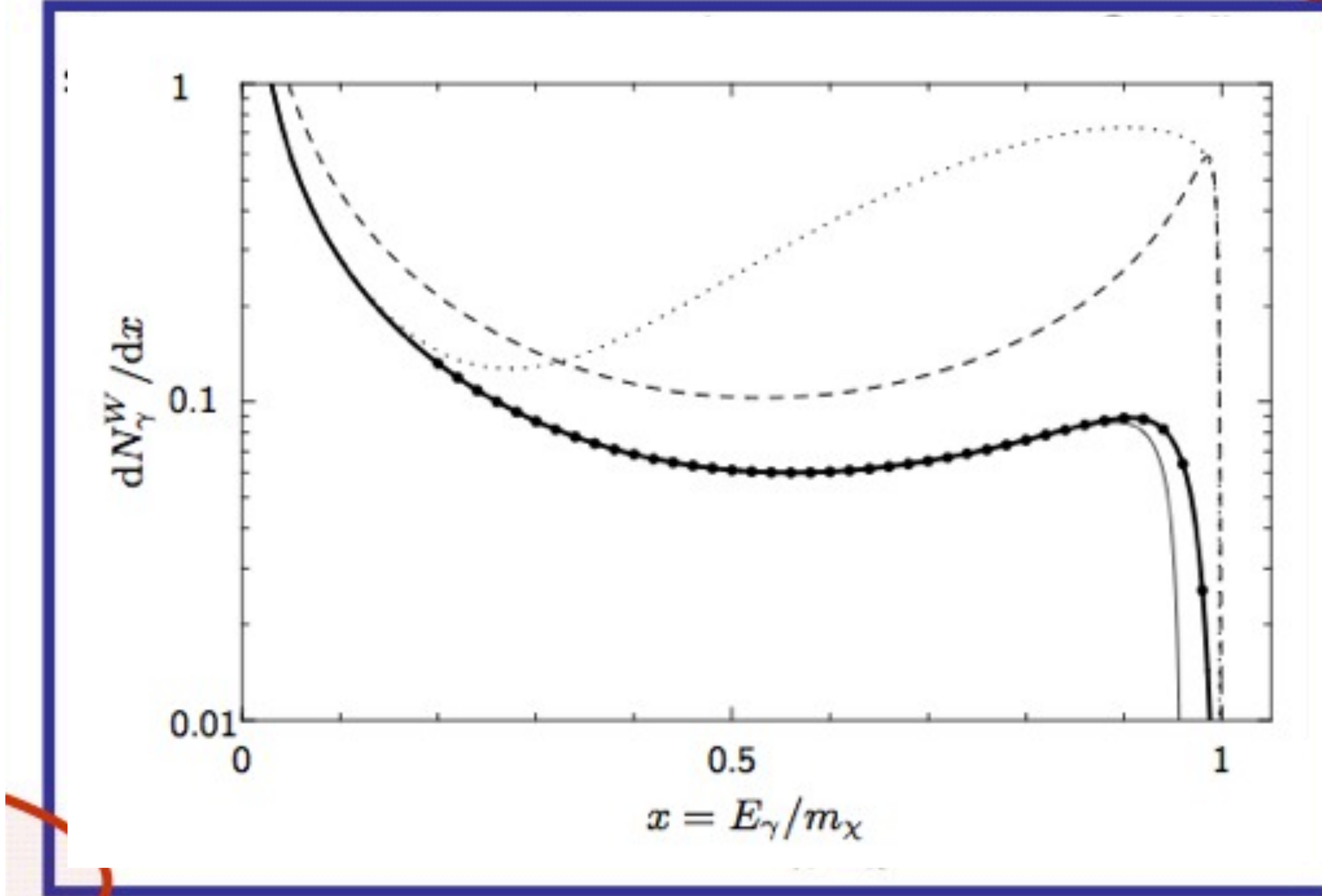

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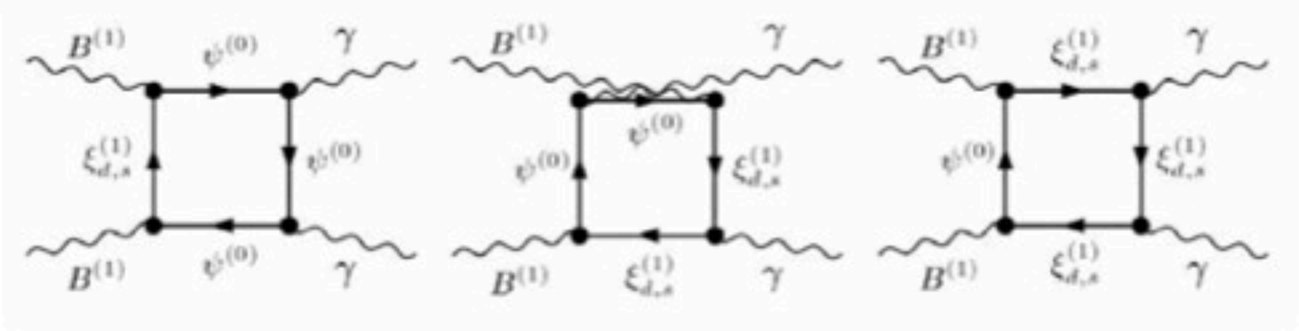
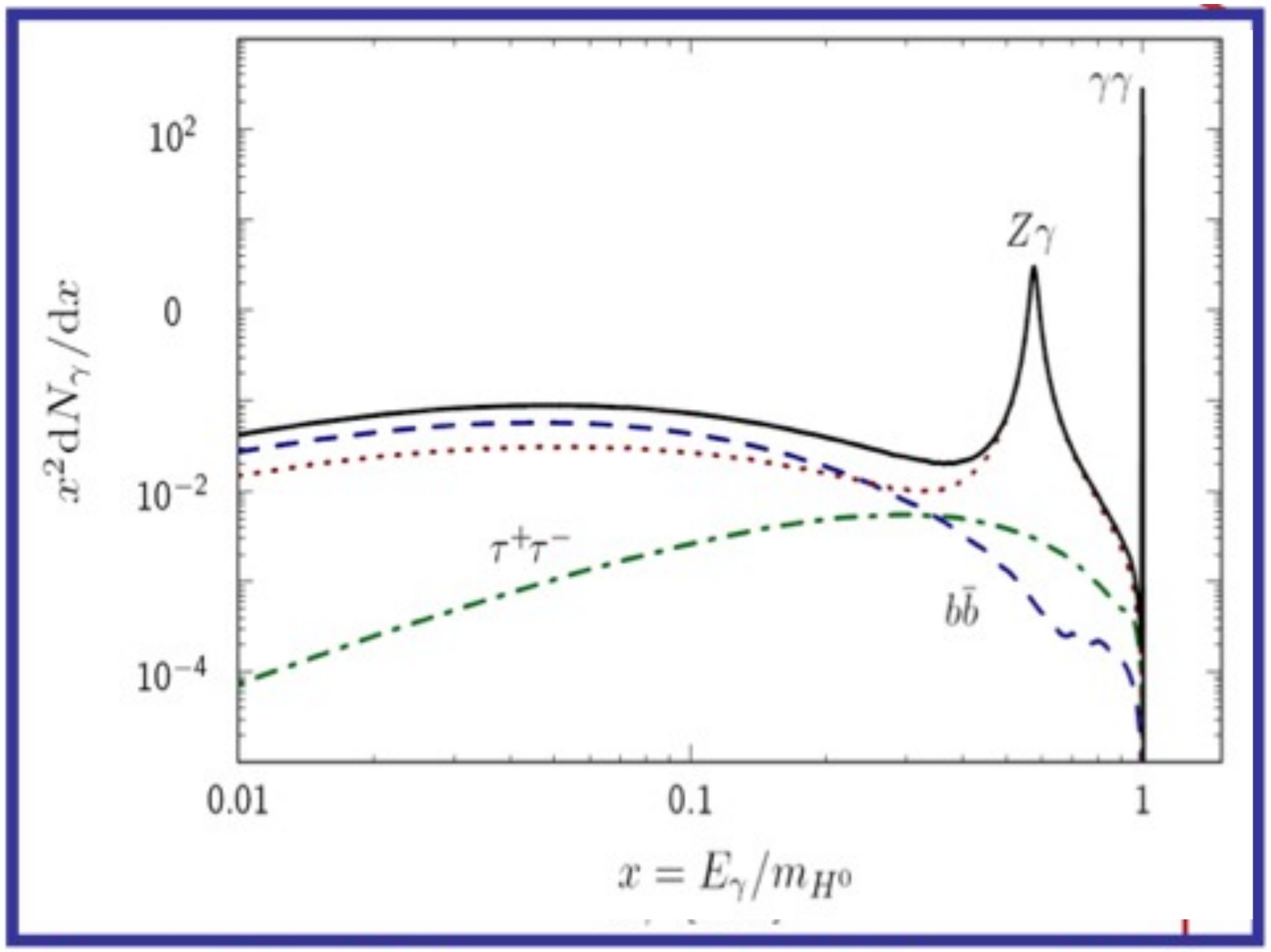
3) Monoenergetic line(s):
- loop suppressed, i.e. $\mathcal{O}(\alpha^2)$

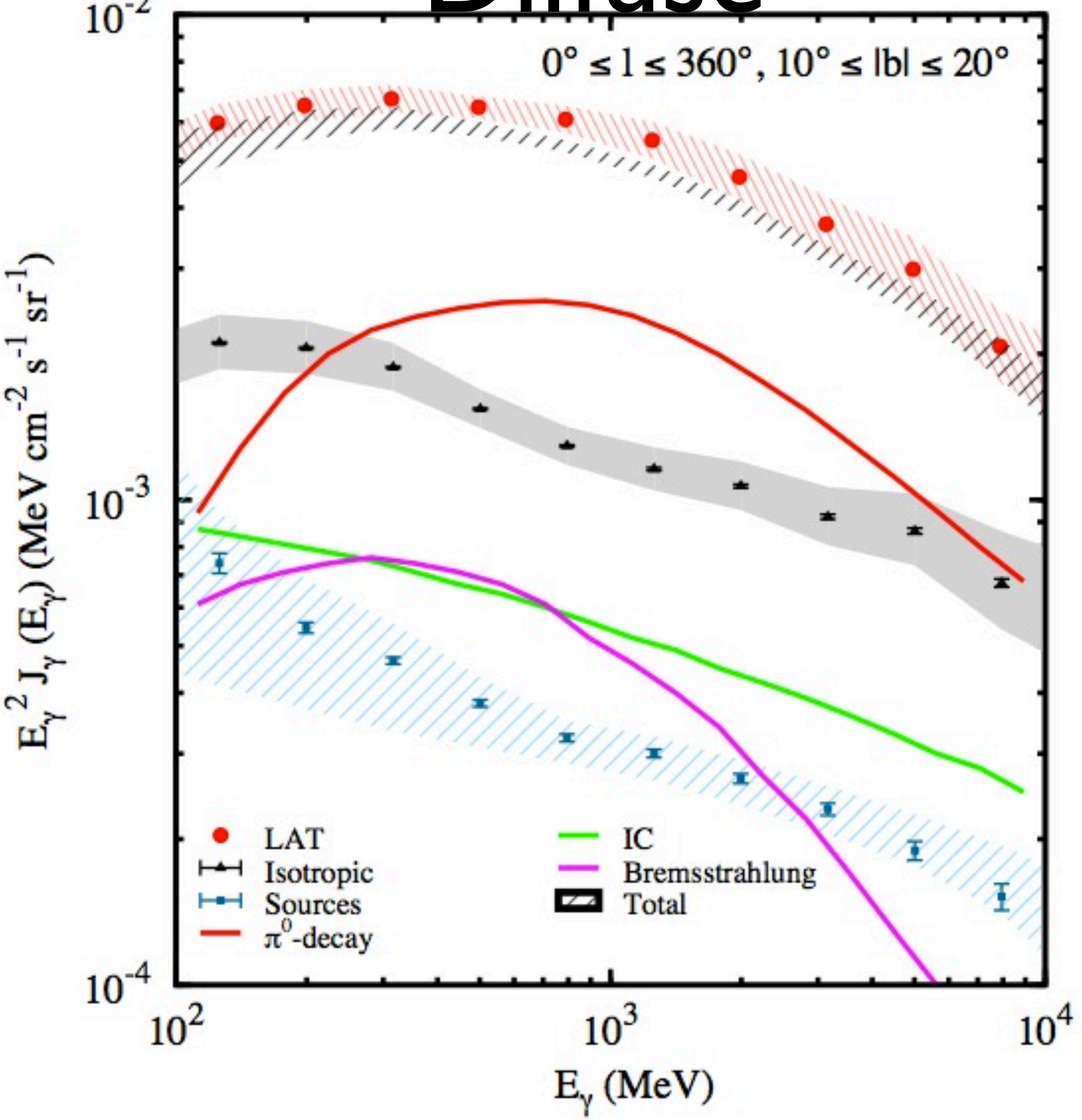




Bergström, Bringmann, MG & Eriksson '04

Dark matter Backgrounds

Diffuse



$0° \le l \le 360°$, $10° \le |b| \le 20°$
$E_\gamma^2 J_\gamma(E_\gamma)$ (MeV cm^{-2} s^{-1} sr^{-1})
E_γ (MeV)
10^{-2}
10^{-3}
10^{-4}
10^{2}
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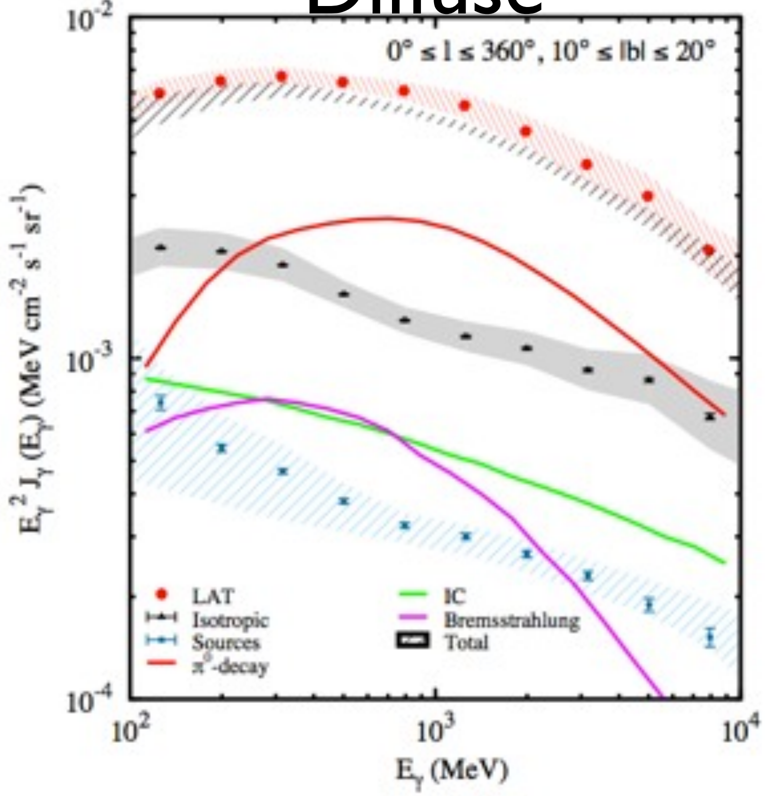
LAT
Isotropic
Sources
π^0-decay
IC
Bremsstrahlung
Total

Diffuse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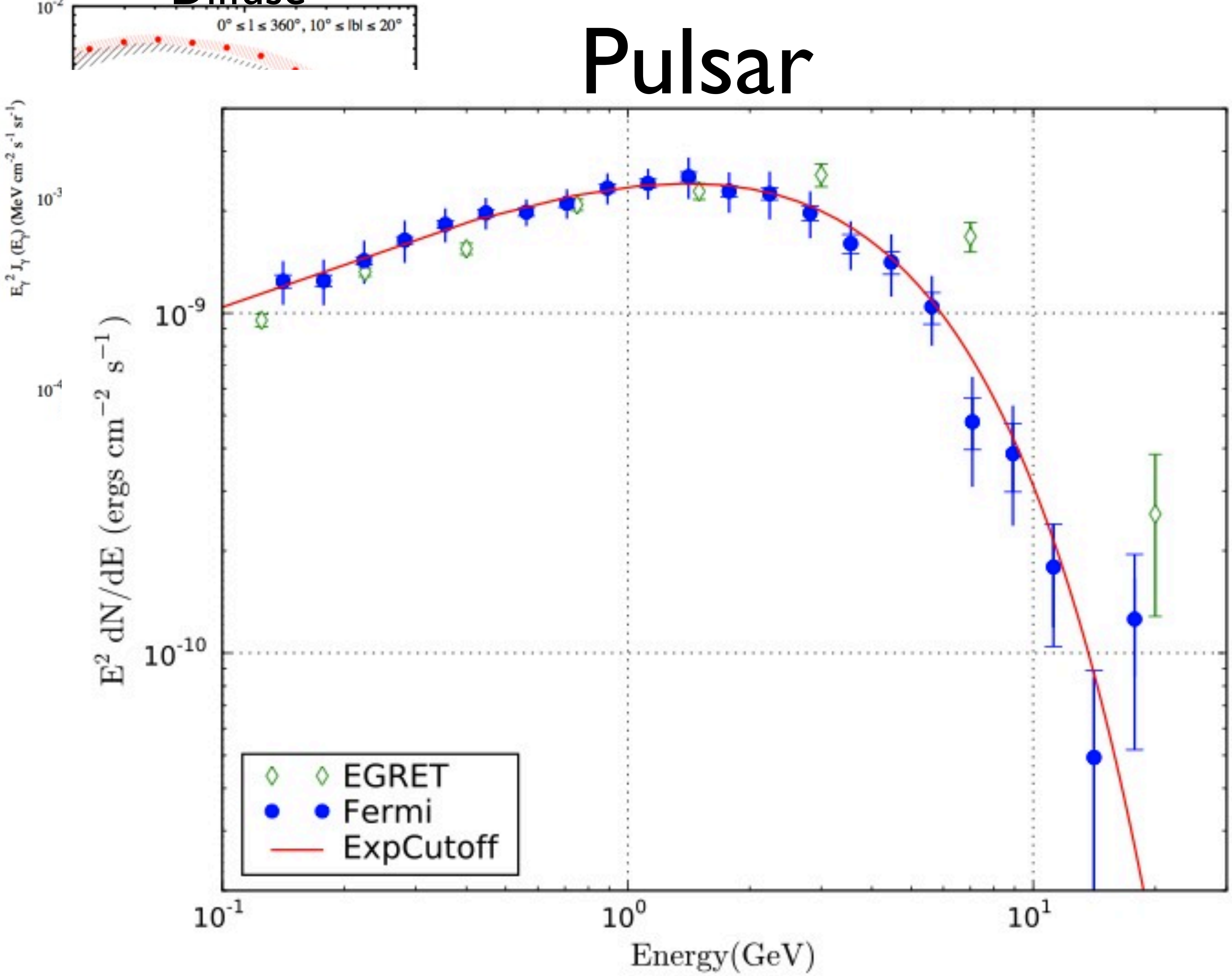
Pulsar



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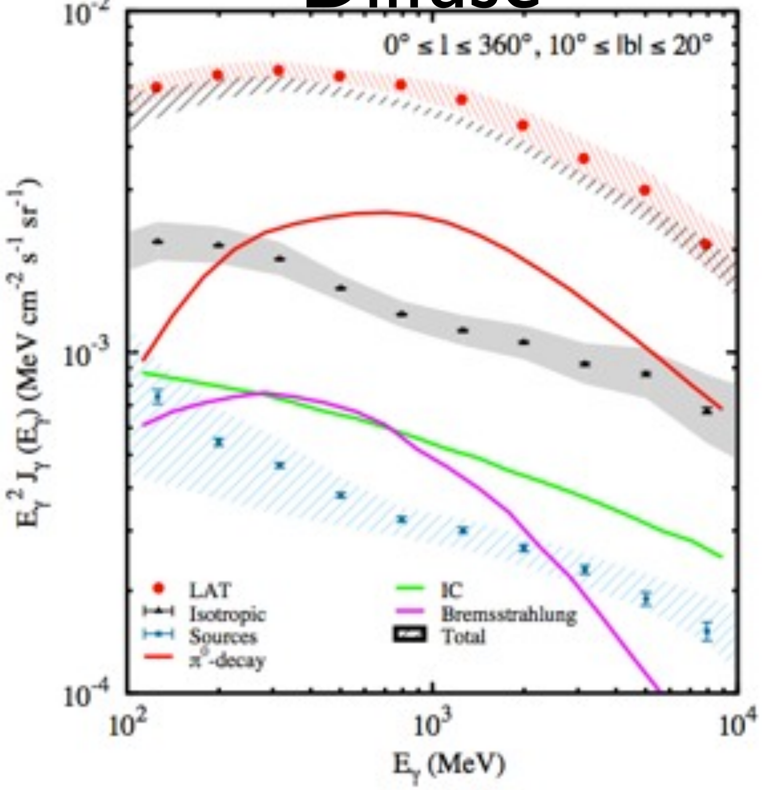

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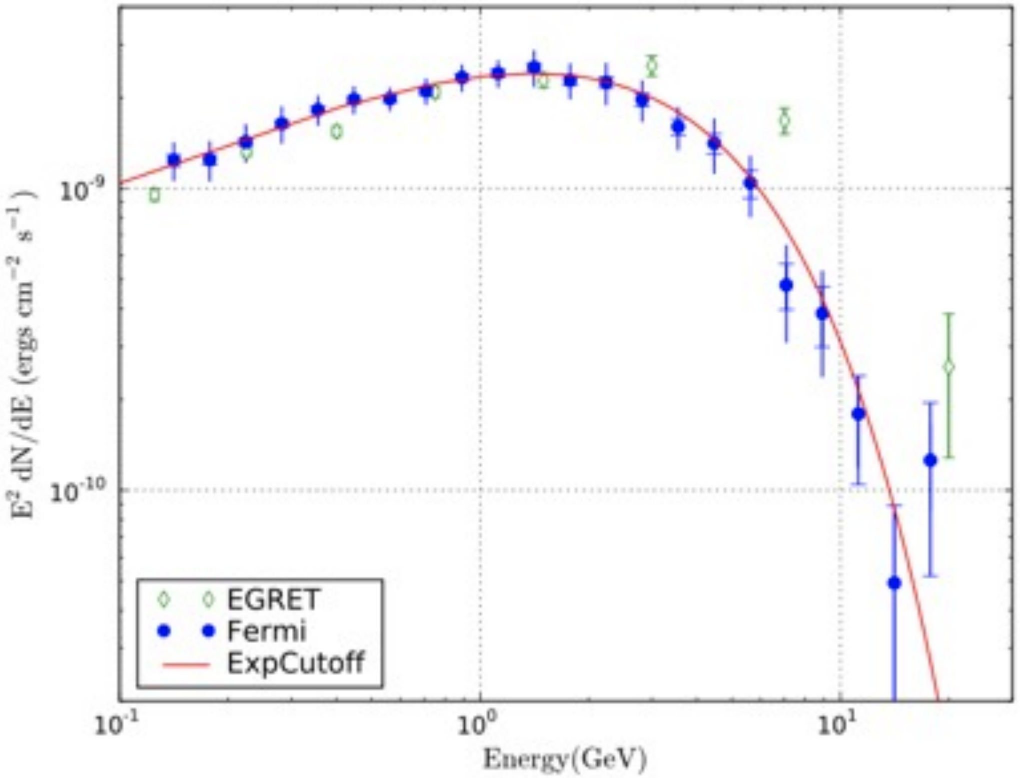
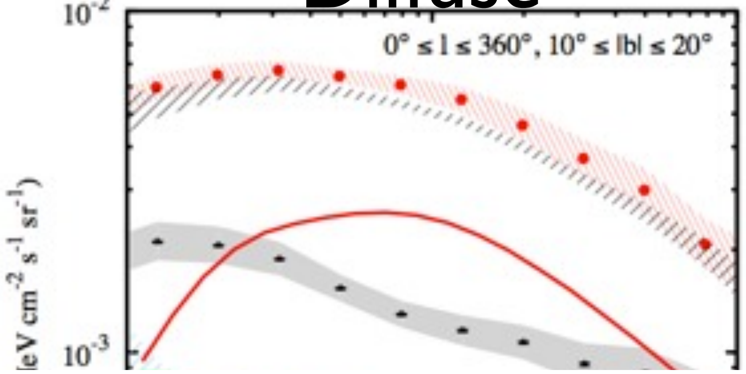


Galactic center

Diffuse



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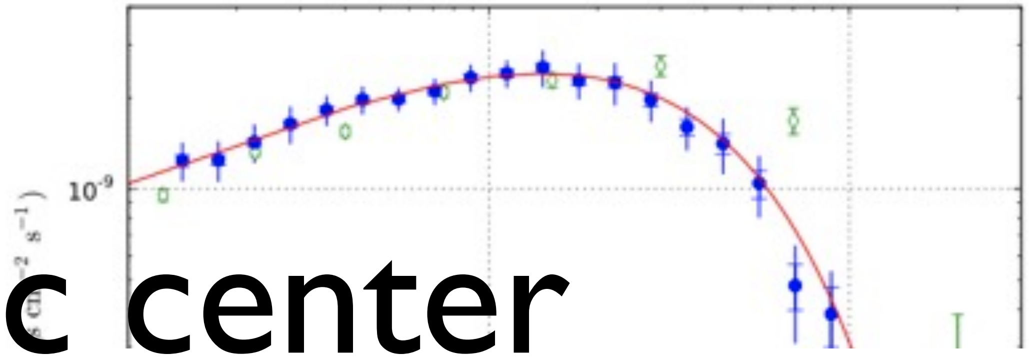

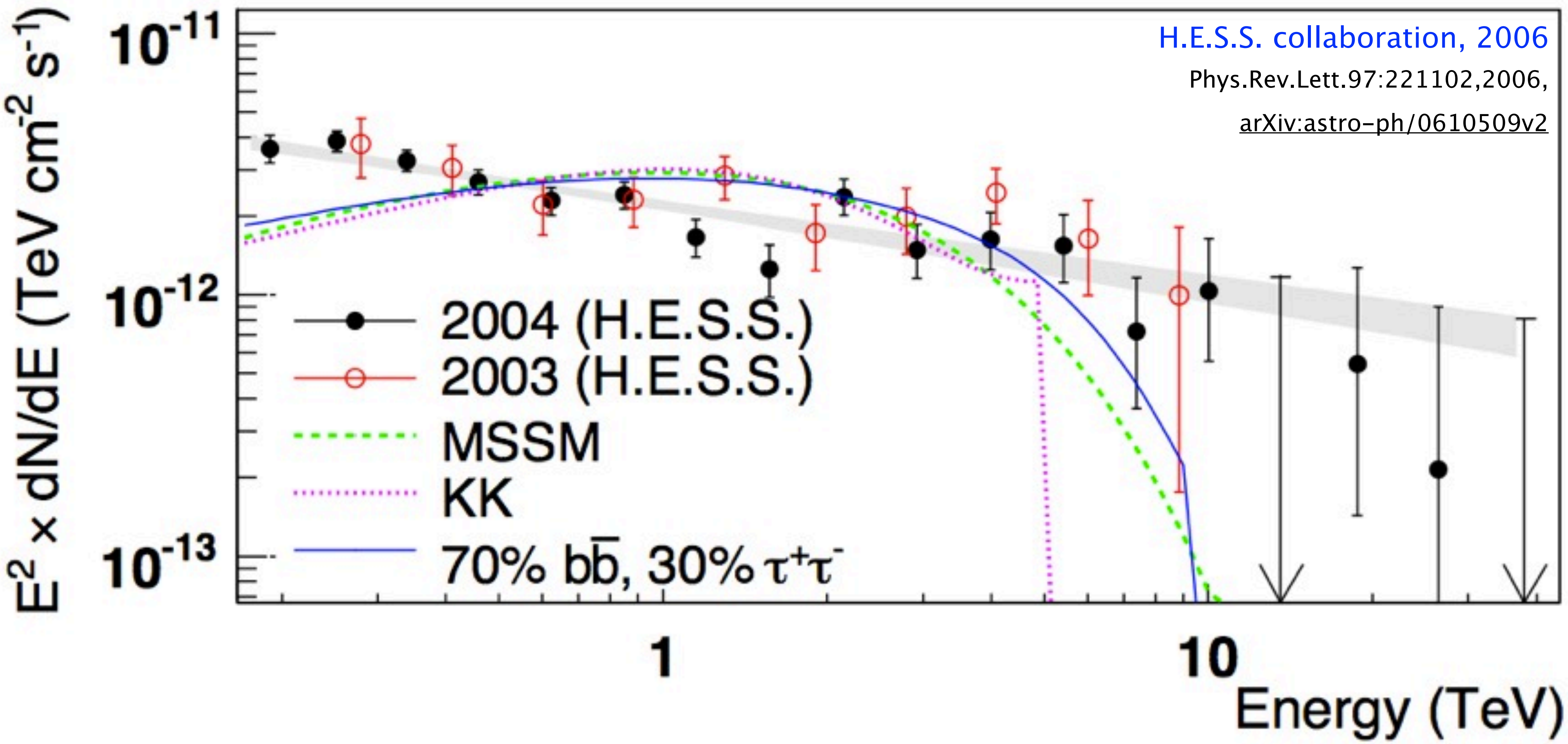

H.E.S.S. collaboration, 2006

Phys.Rev.Lett.97:221102,2006,

arXiv:astro-ph/0610509v2

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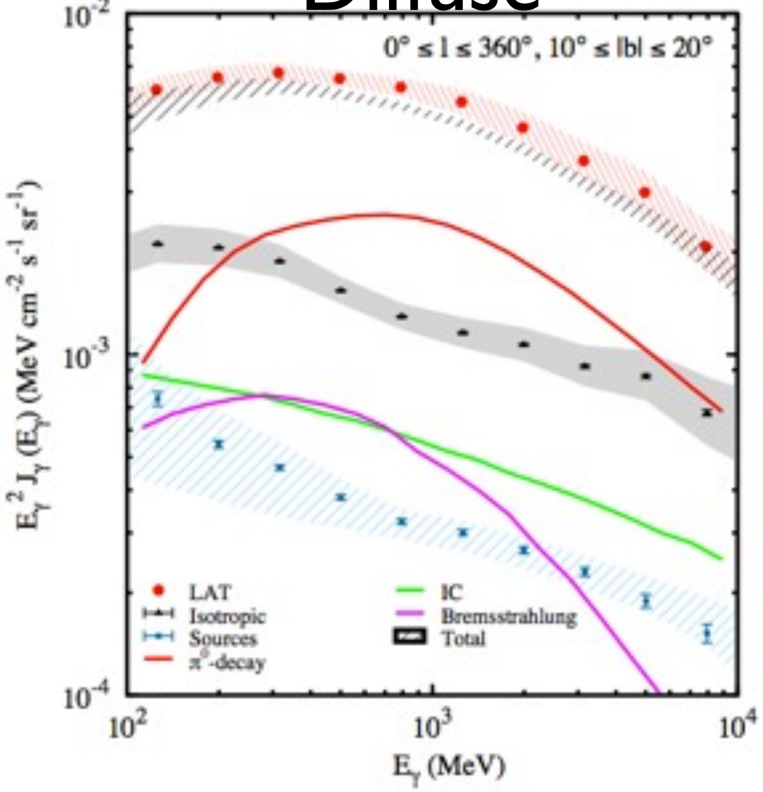

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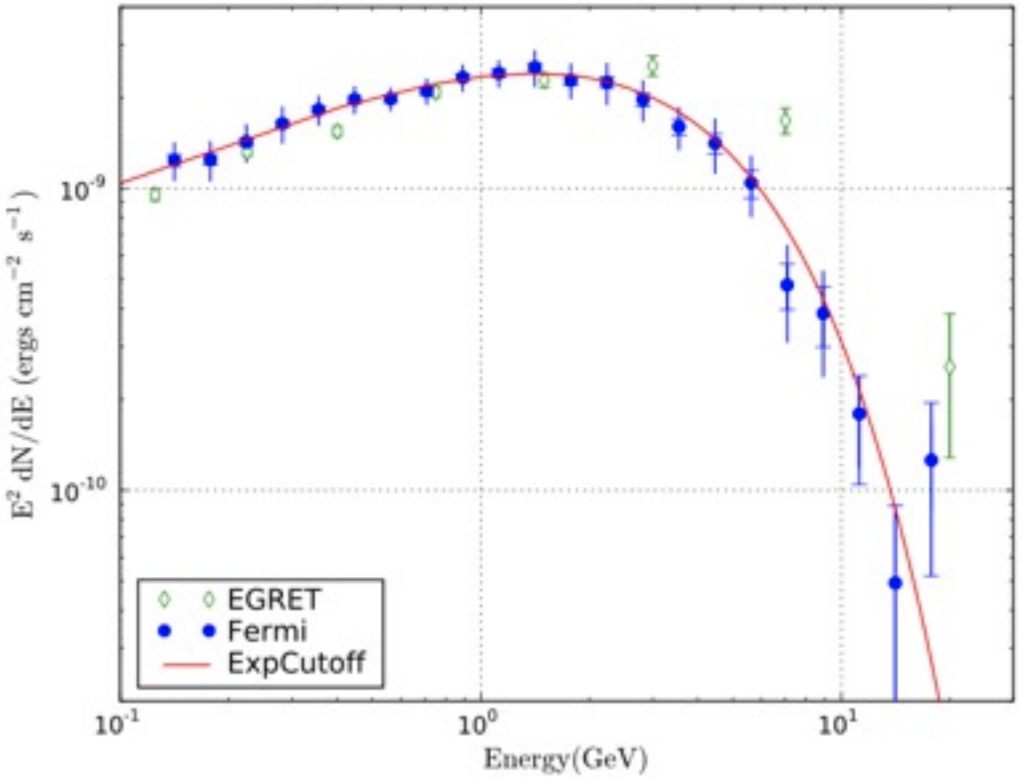

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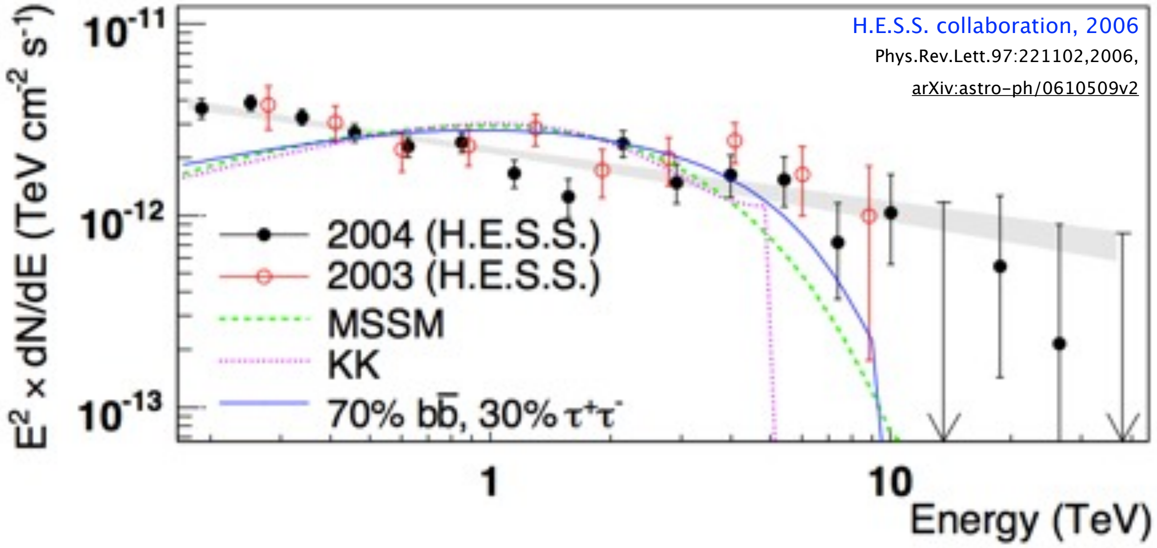
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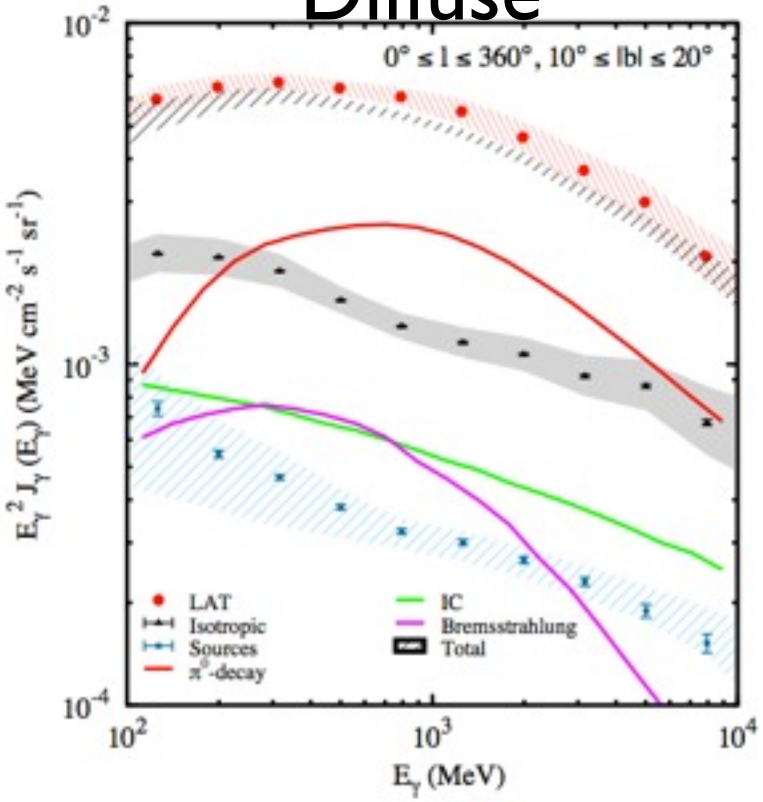

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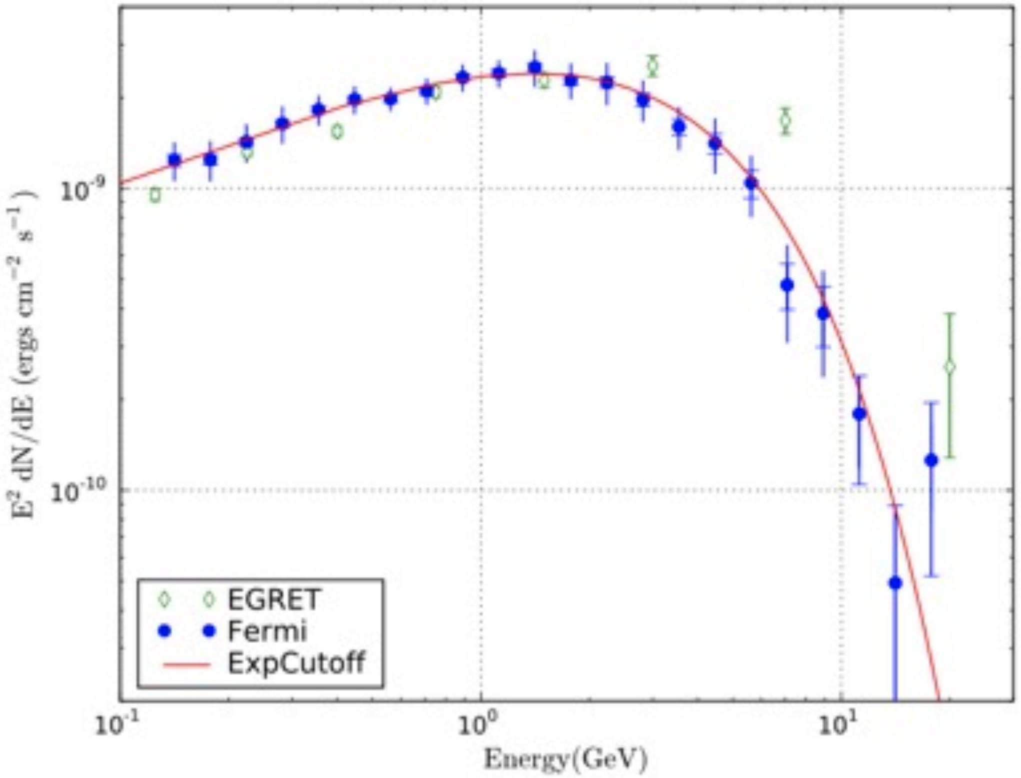

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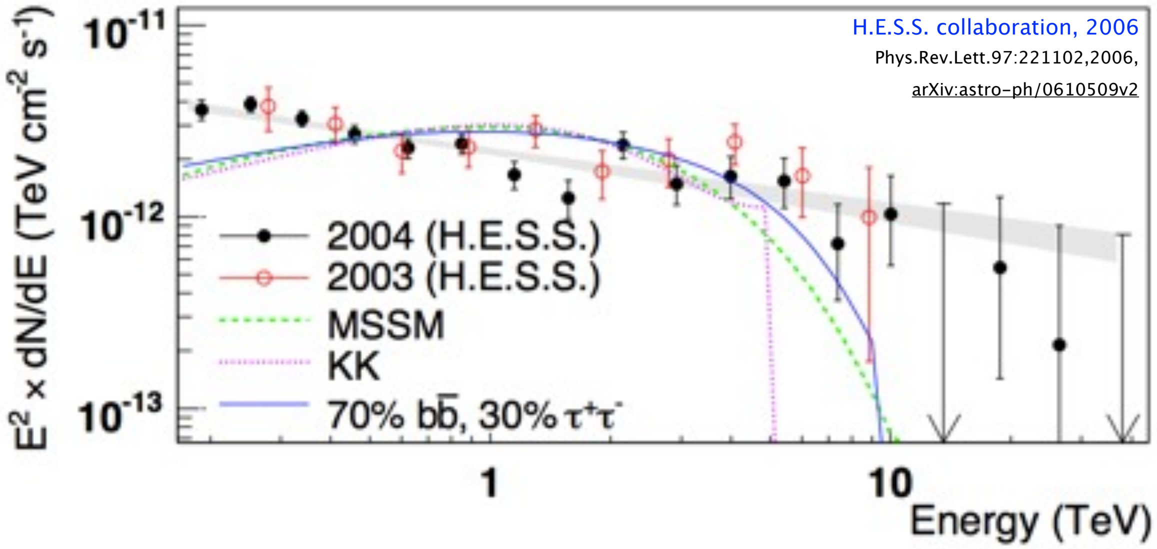

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Backgrunds:

“feutureless” spectra

⇒ no gamma-ray lines expected

The DM gamma-ray line dream...

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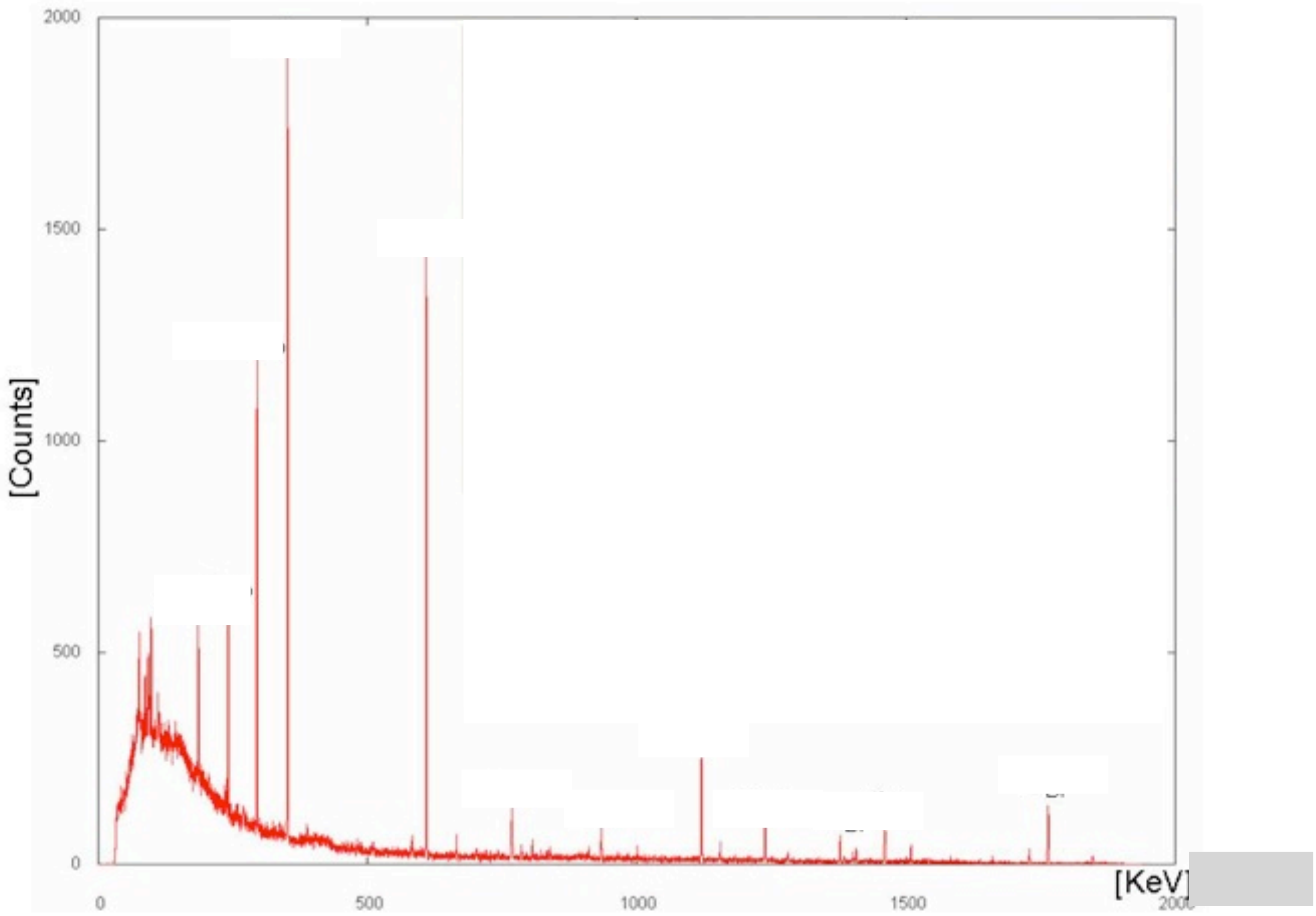

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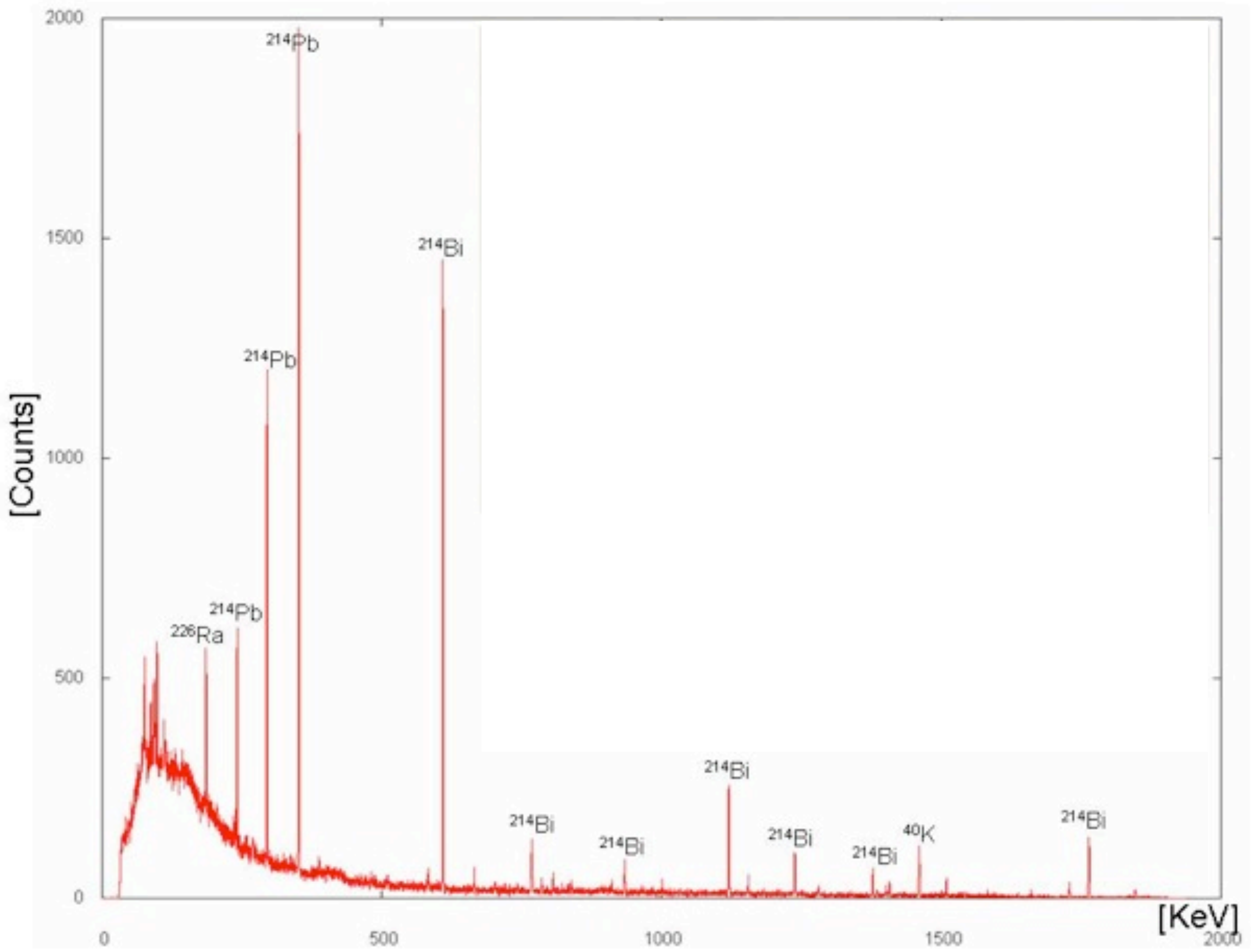

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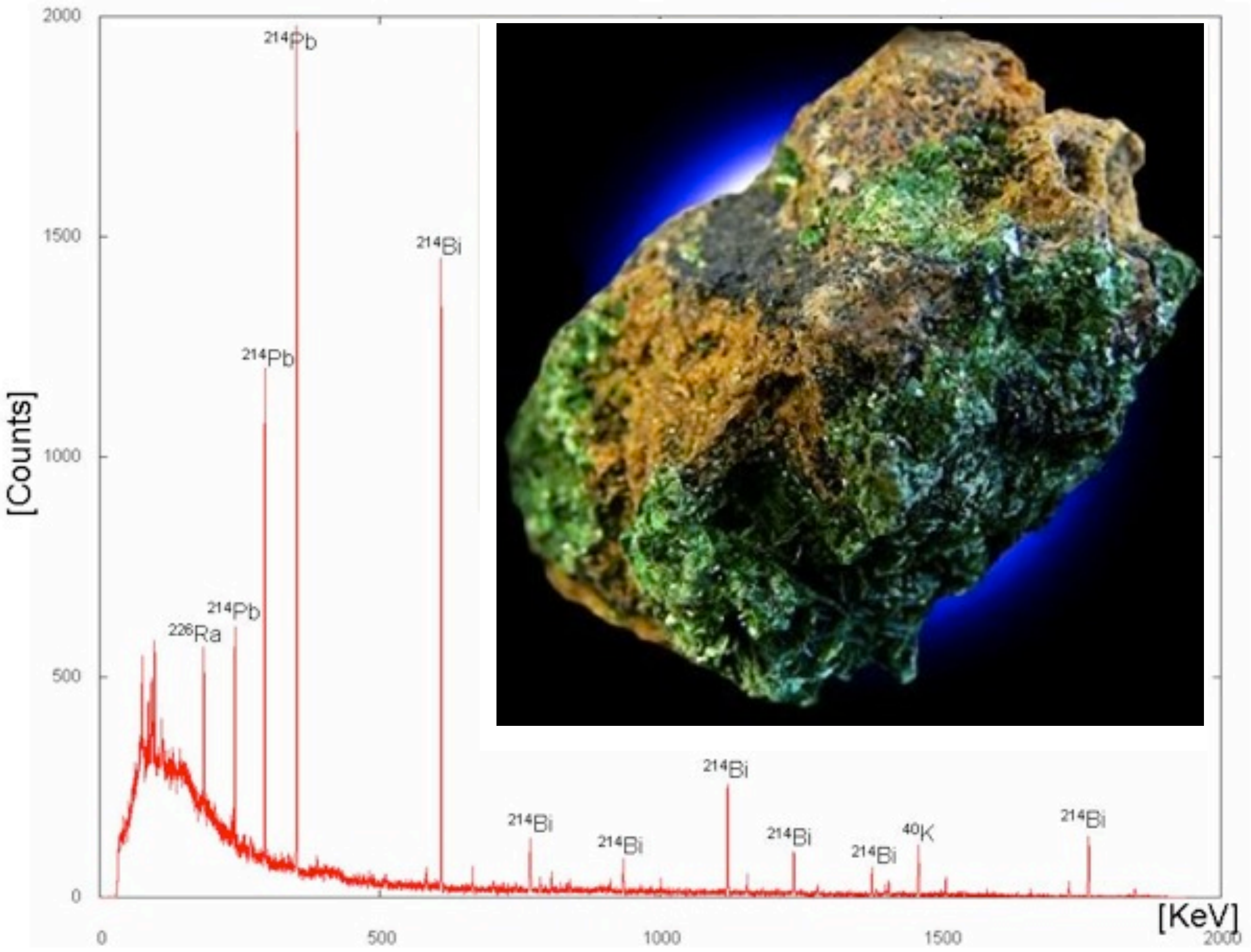

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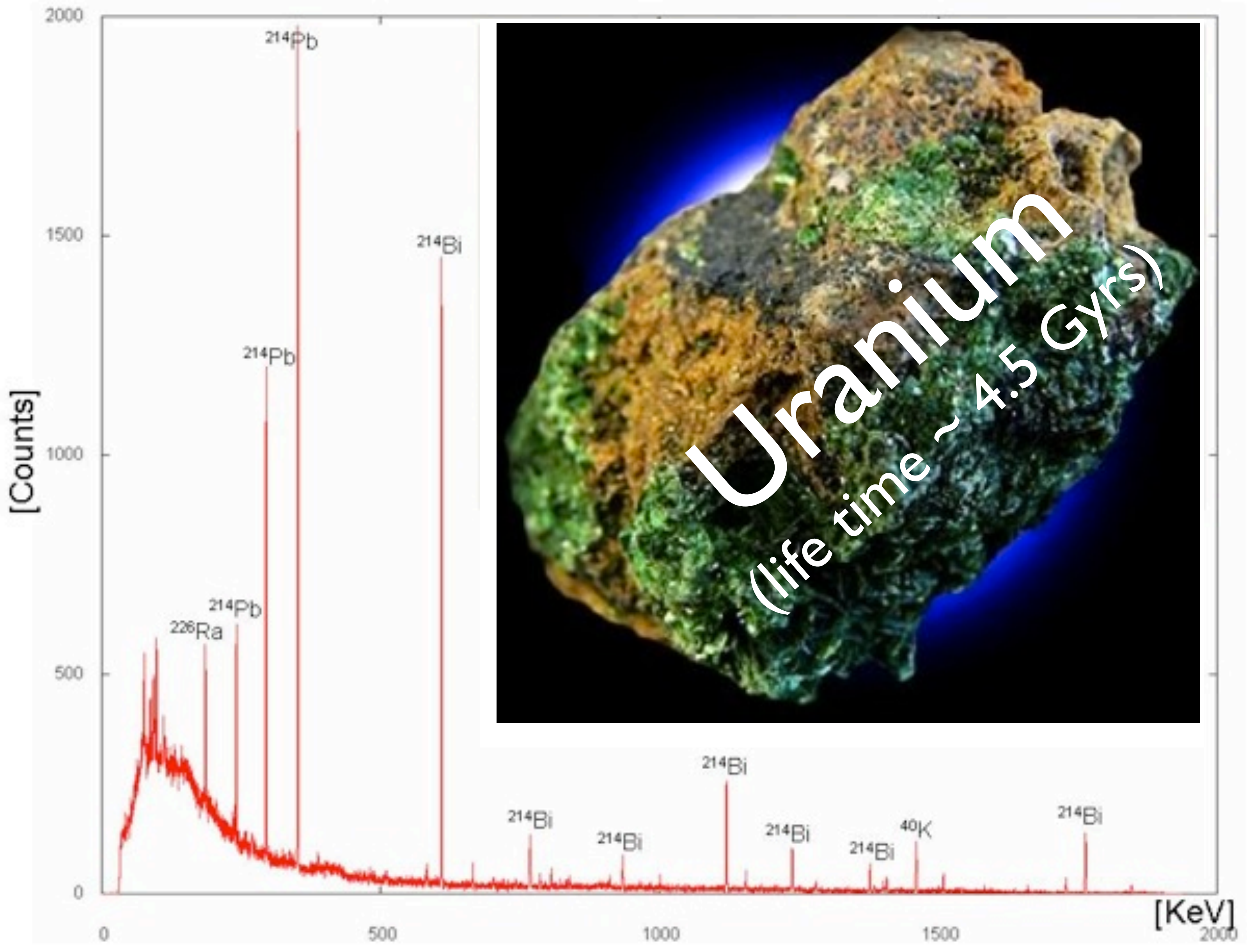


Uranium
(life time ~ 4.5 Gyrs)

When can the DM line be prominent spectral feature?

- Cross section into a gamma-ray line is large
  (but neutral DM ⇒ loop suppressed)

- The continuum is low
  (but low absolute flux ⇒ boost needed)

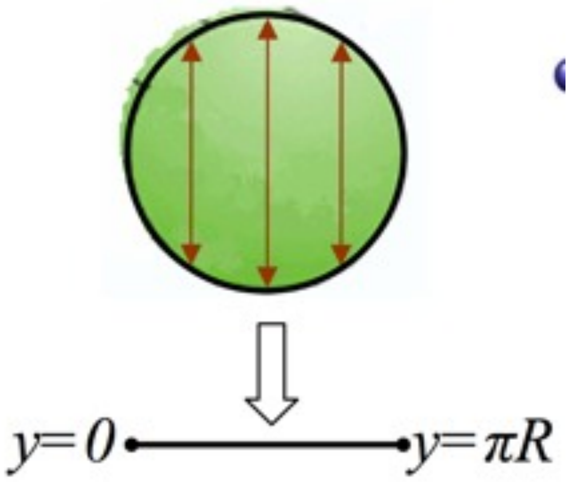
- FSR/Internal Bremsstrahlung
  (Can mimic a line feature)

- Decaying DM
  (from symmetry breaking operator)

Specific DM models

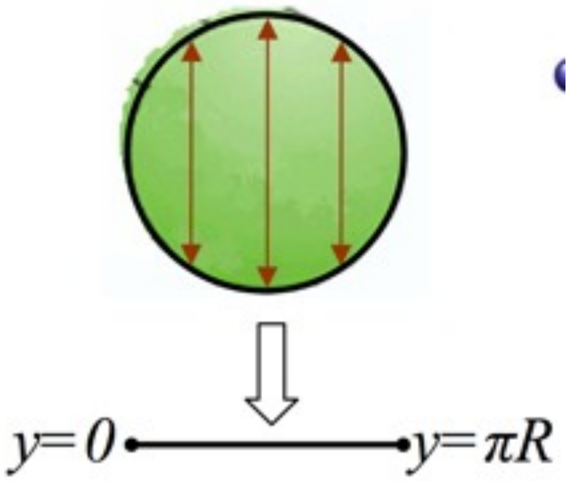
- Extra dimensions
- Supersymmetry
- Inert doublet model
- Z’ models, e.g. Higgs in space
- Decaying dark matter
- ...

Universal
Extra Dimensions



Kaluza-Klein tower of more massive states: $m_n^2 = \dfrac{n^2}{R^2}$

$\Rightarrow$ KK parity $(-1)^n$ conserved



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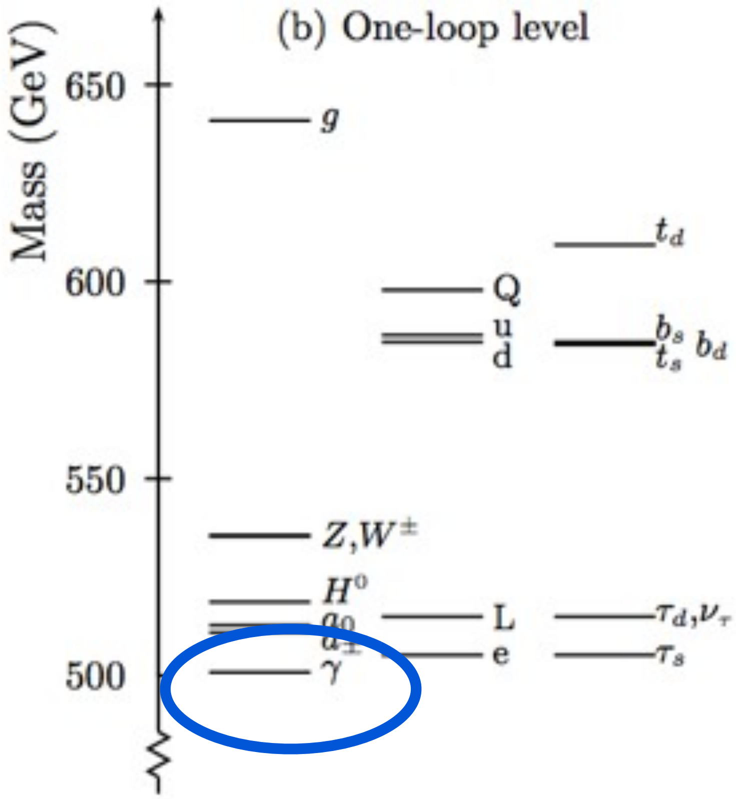
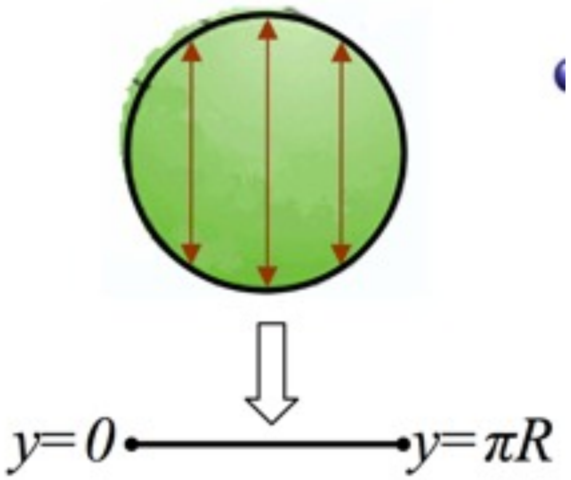


Lightest KK state of the ‘photon’



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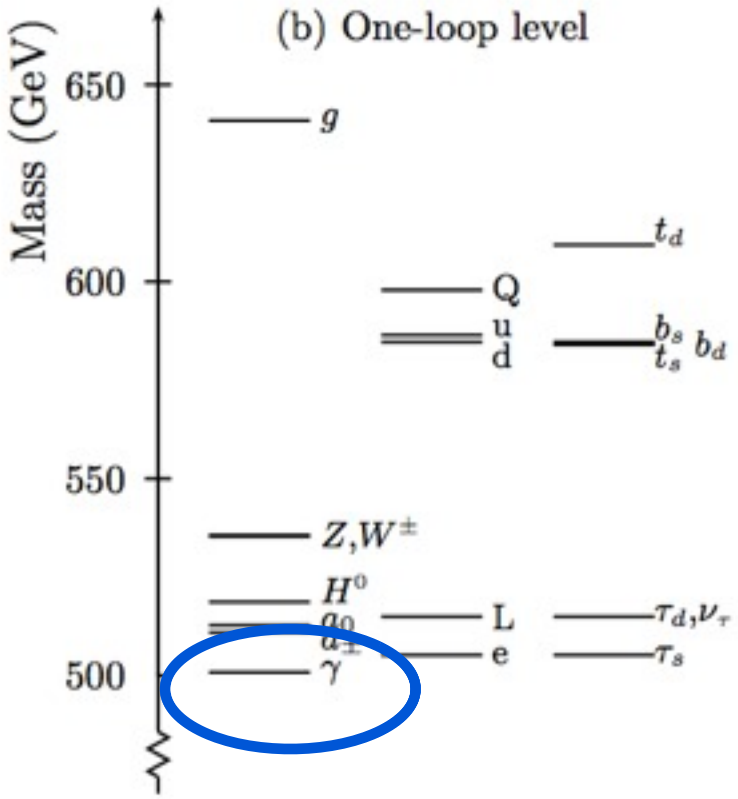
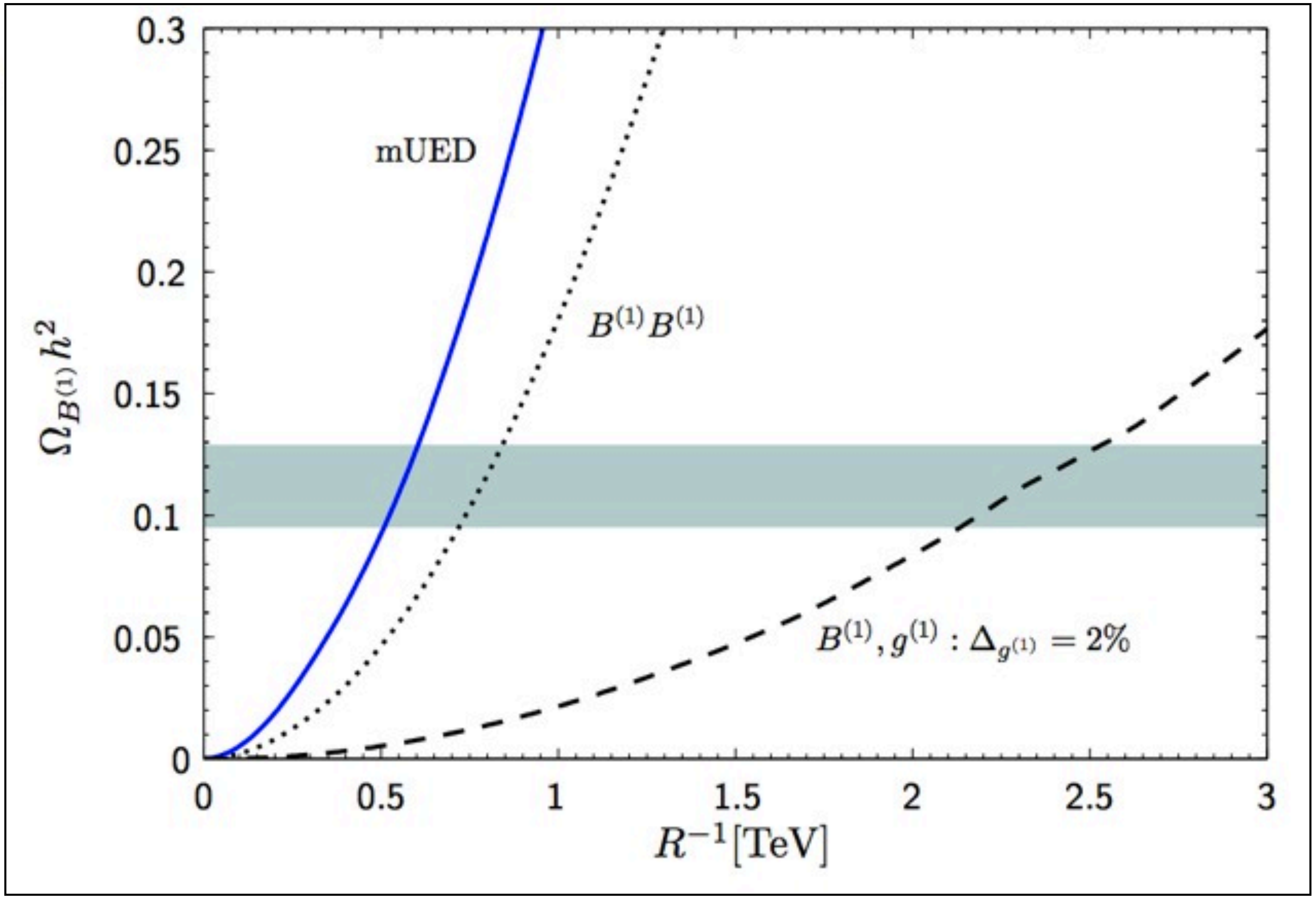
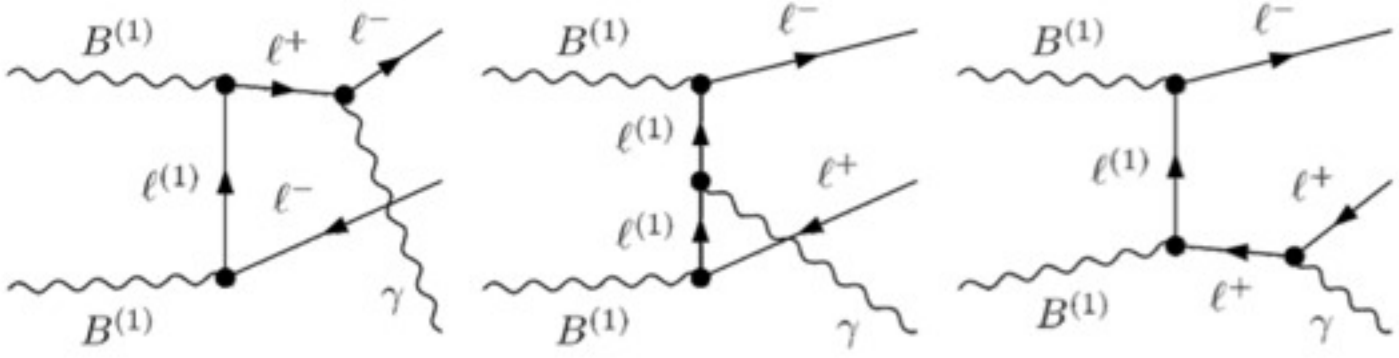


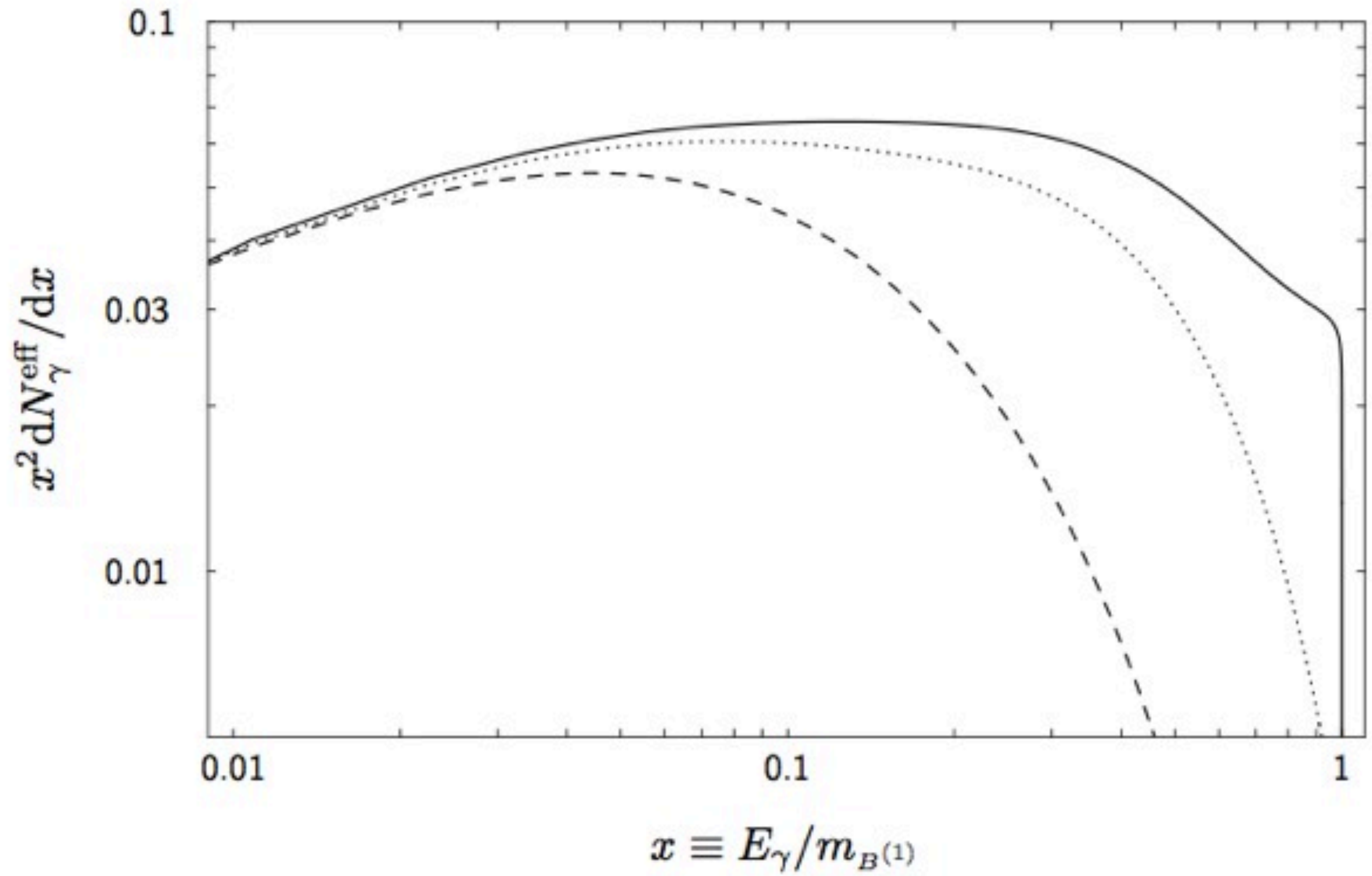


Lightest KK state of the ‘photon’

- Branching ratios: $\ell^+\ell^- \sim 59\%,\ q\bar{q} \sim 35\%,\ \nu\bar{\nu} \sim 4\%,$
  $W^+W^- \sim 1\%,\ ZZ \sim 0.5\%,\ HH \sim 0.5\%$

Final state radiation:





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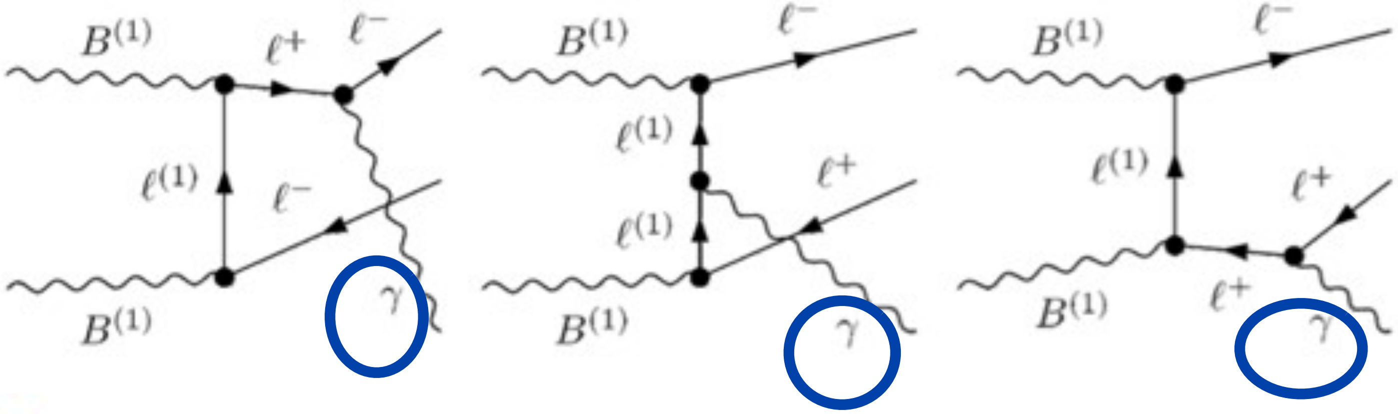

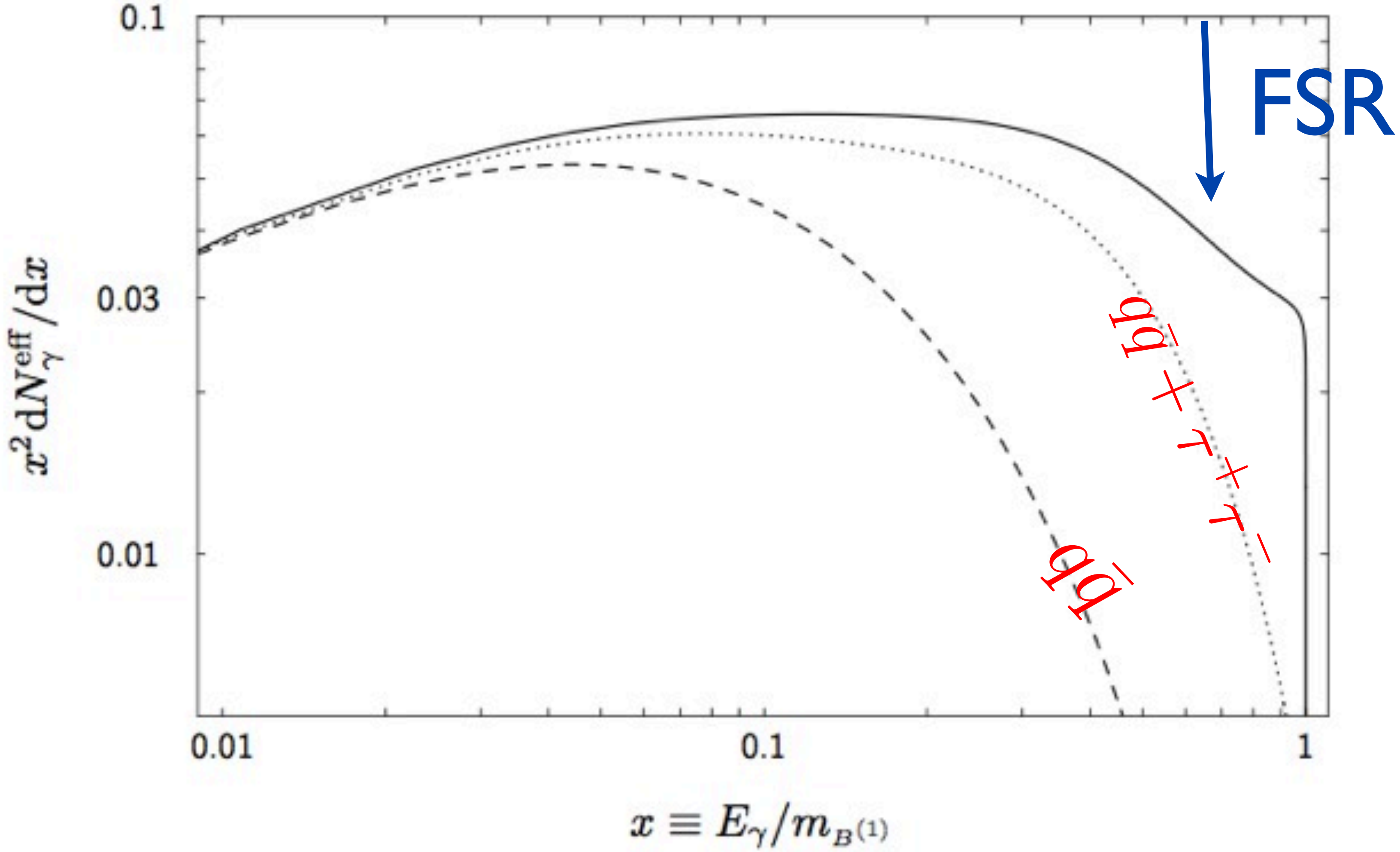

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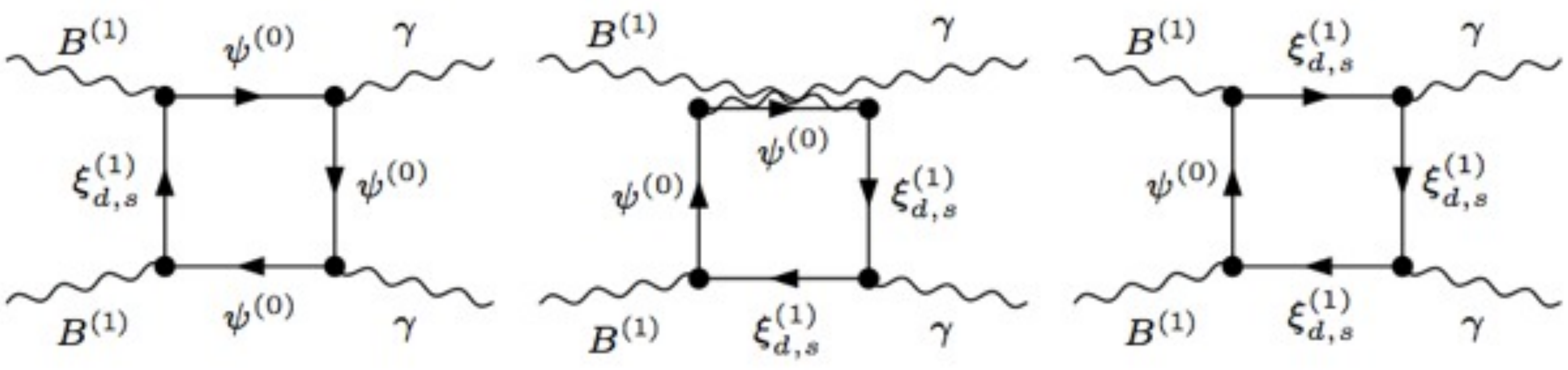
Monochromatic gammas:



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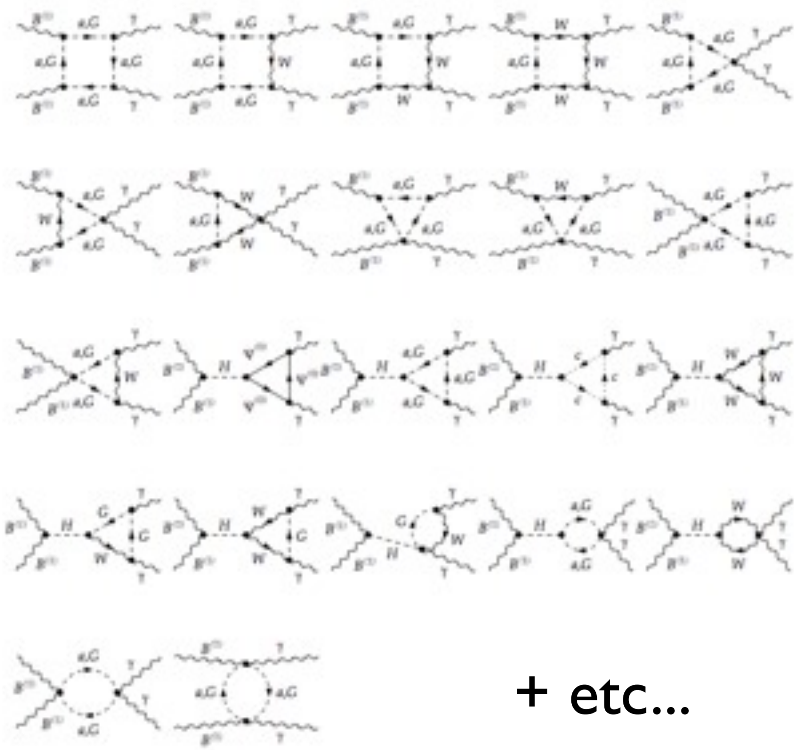

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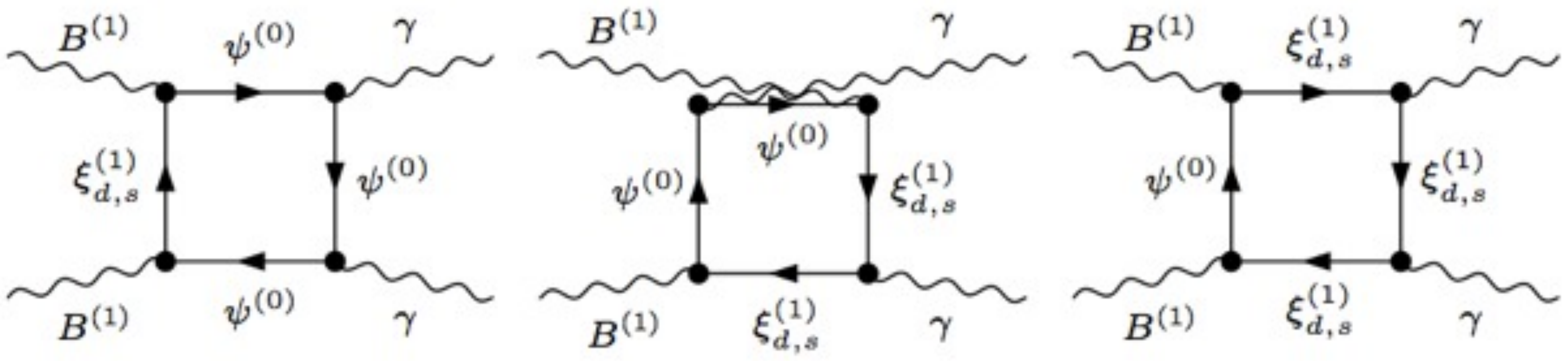

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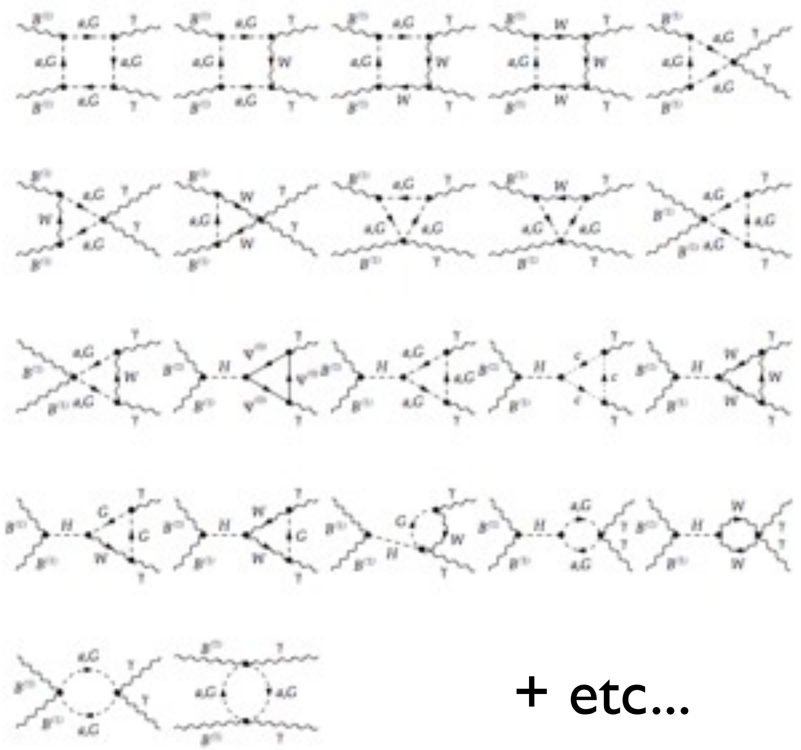

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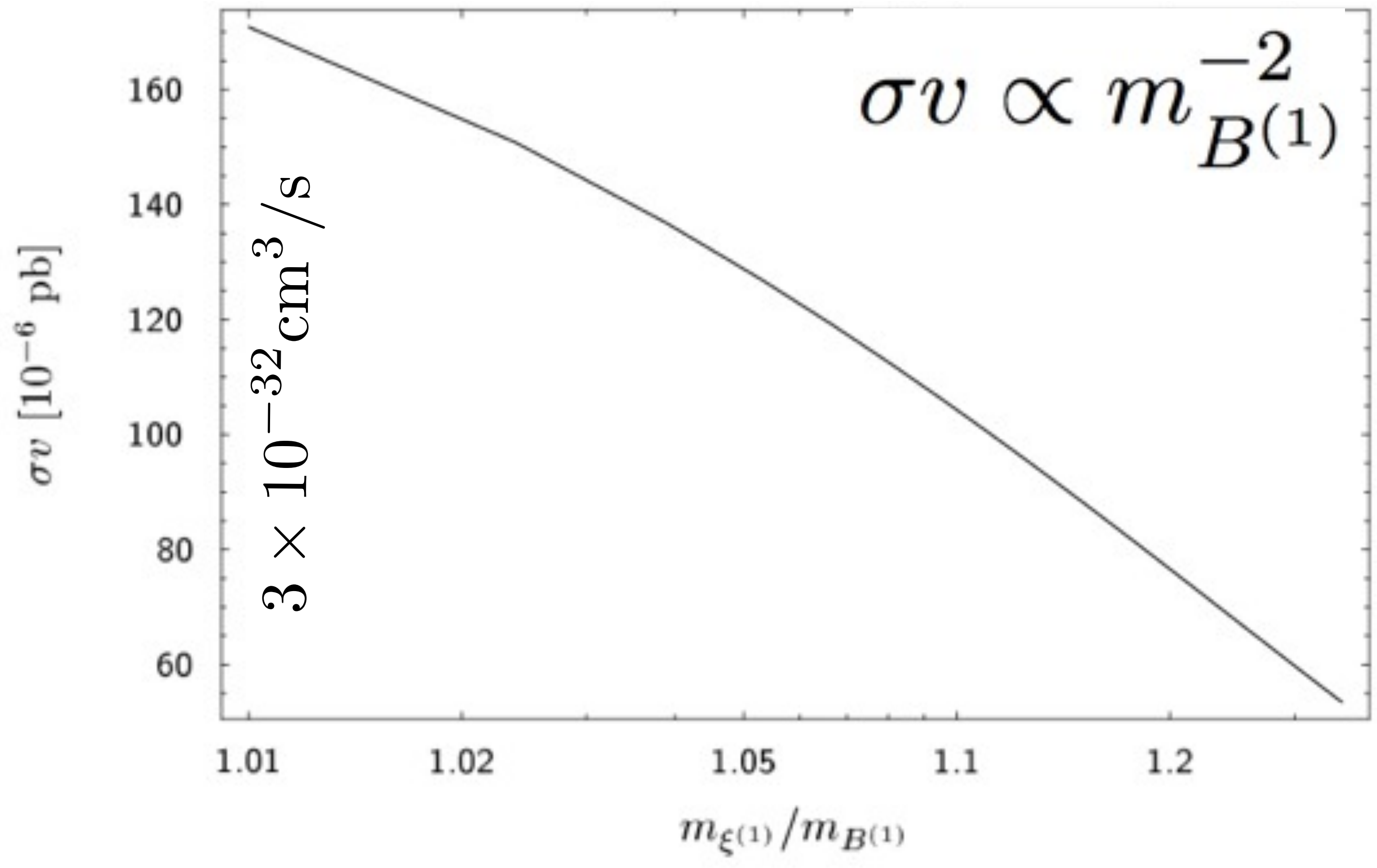

$3 \times 10^{-32}\mathrm{cm}^3/\mathrm{s}$

$\sigma v \propto m_{B^{(1)}}^{-2}$

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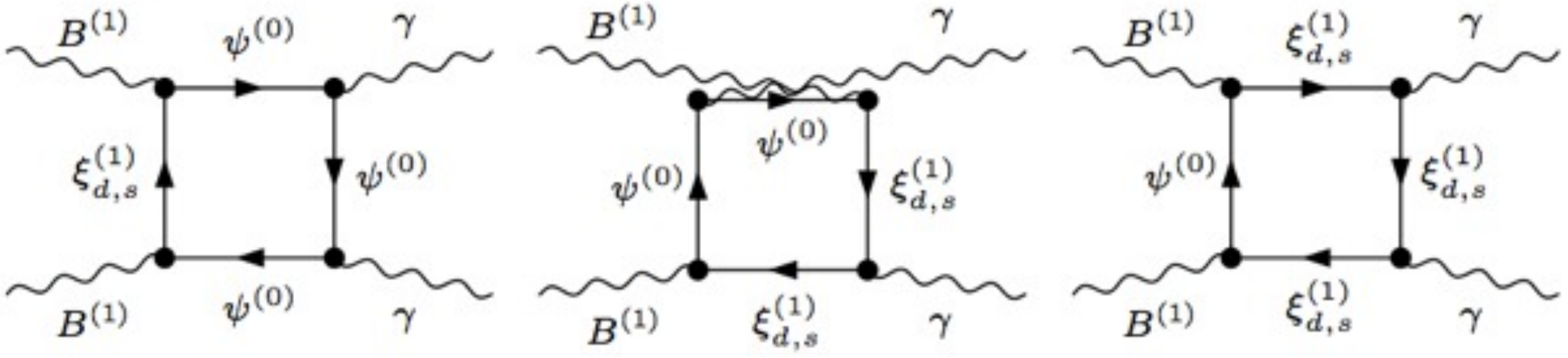

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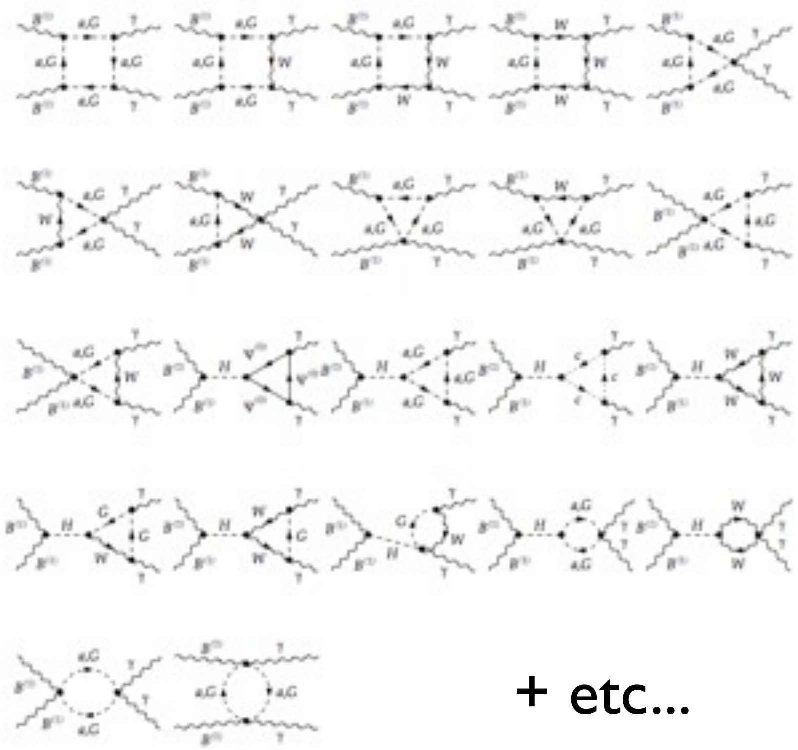
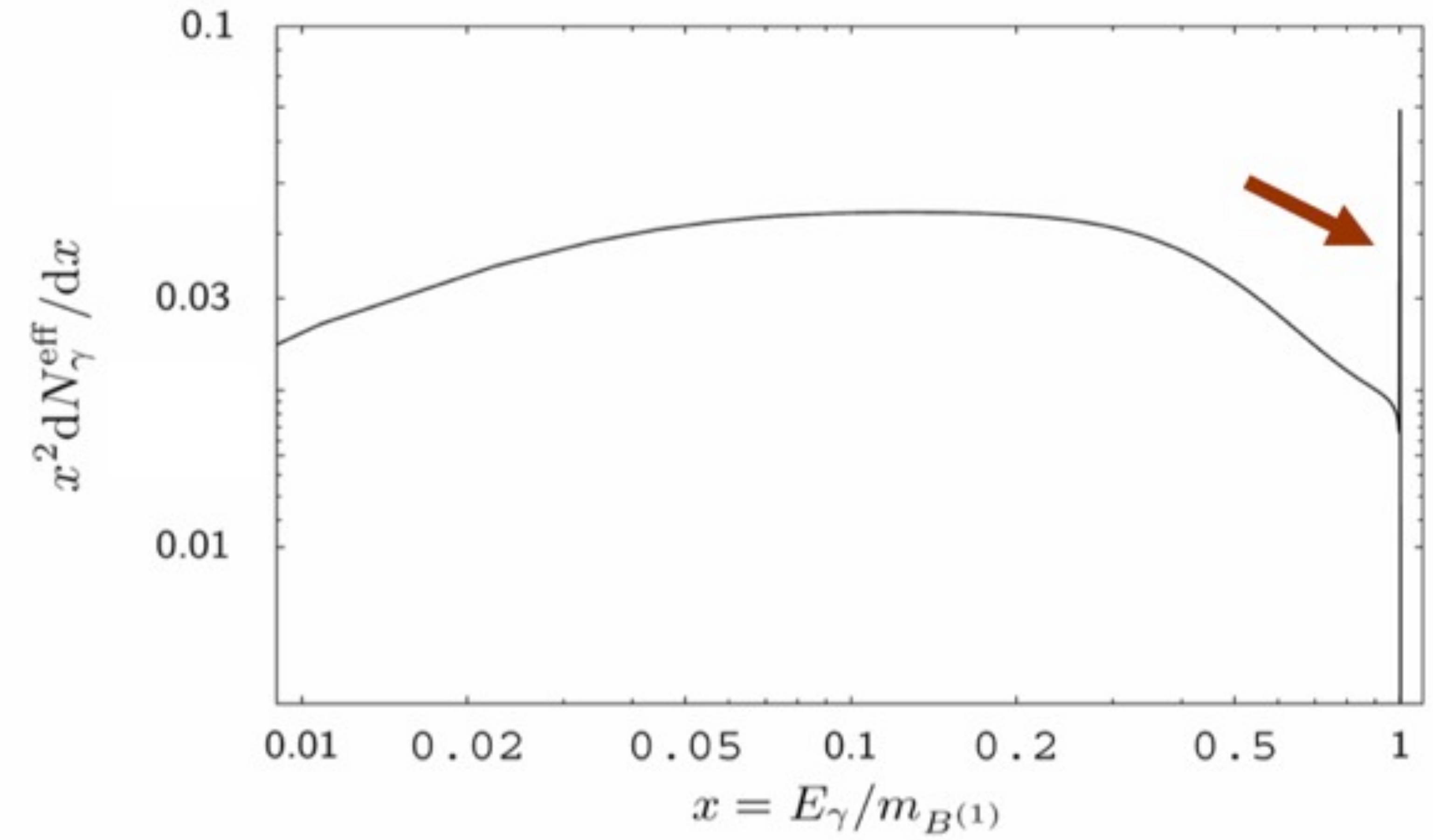
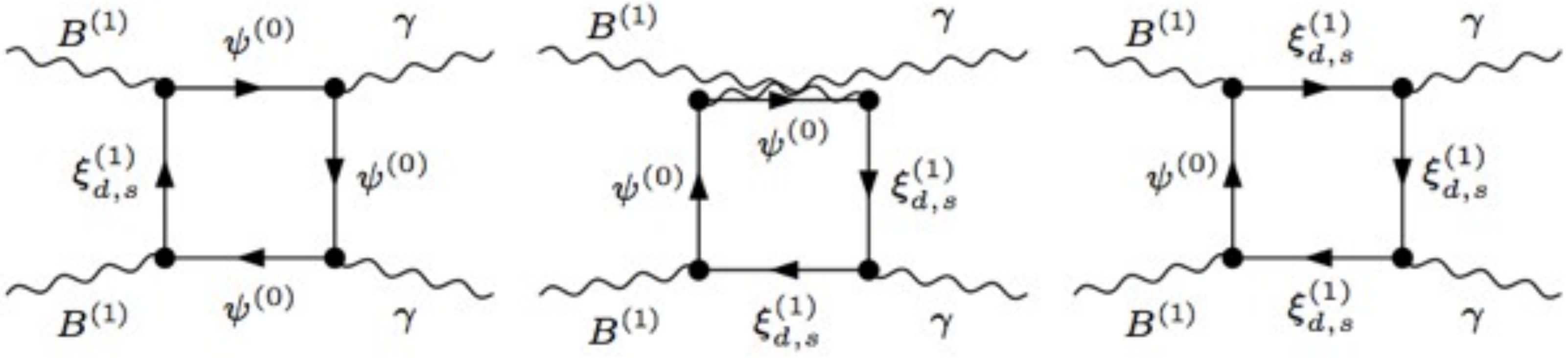


+ etc...

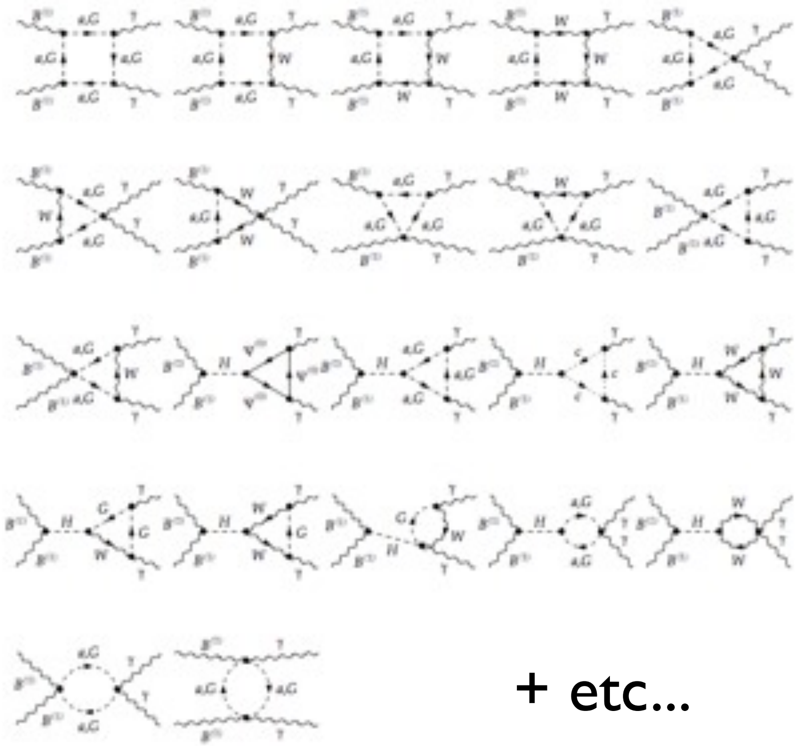


- Branching ratios: $\ell^+\ell^- \sim 59\%,\ q\bar{q} \sim 35\%,\ \nu\bar{\nu} \sim 4\%,$ $W^+W^- \sim 1\%,\ ZZ \sim 0.5\%,\ HH \sim 0.5\%$

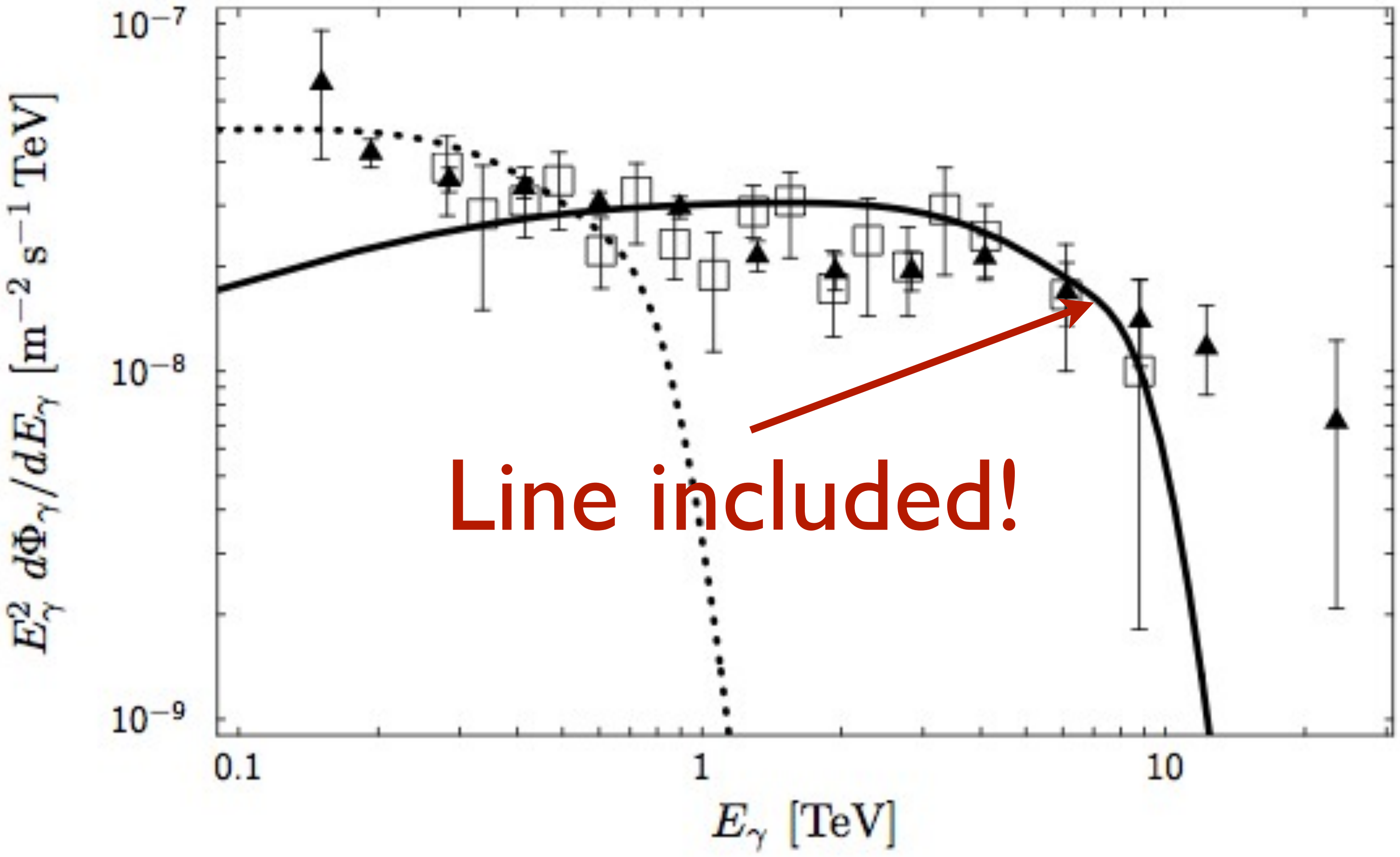
Monochromatic gammas:



+



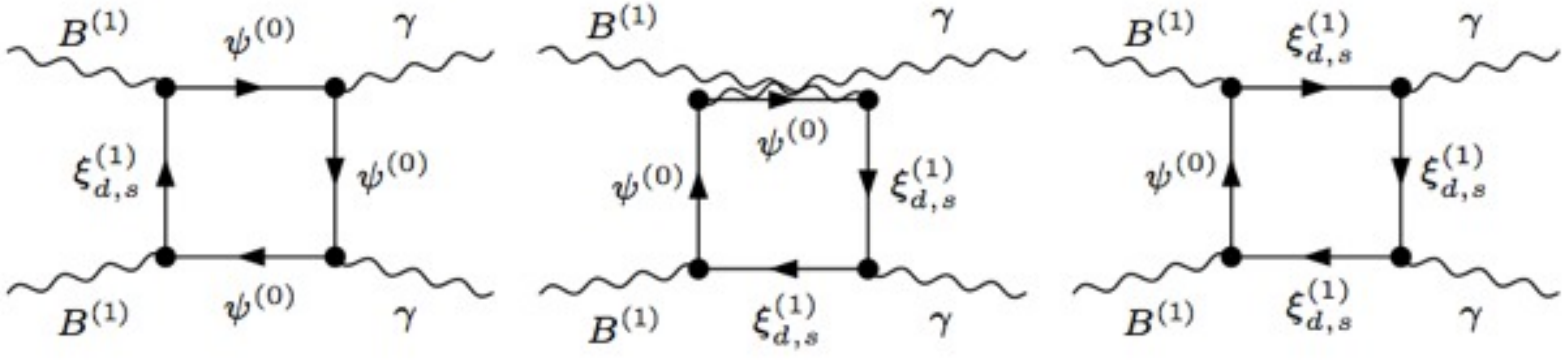
+ etc...



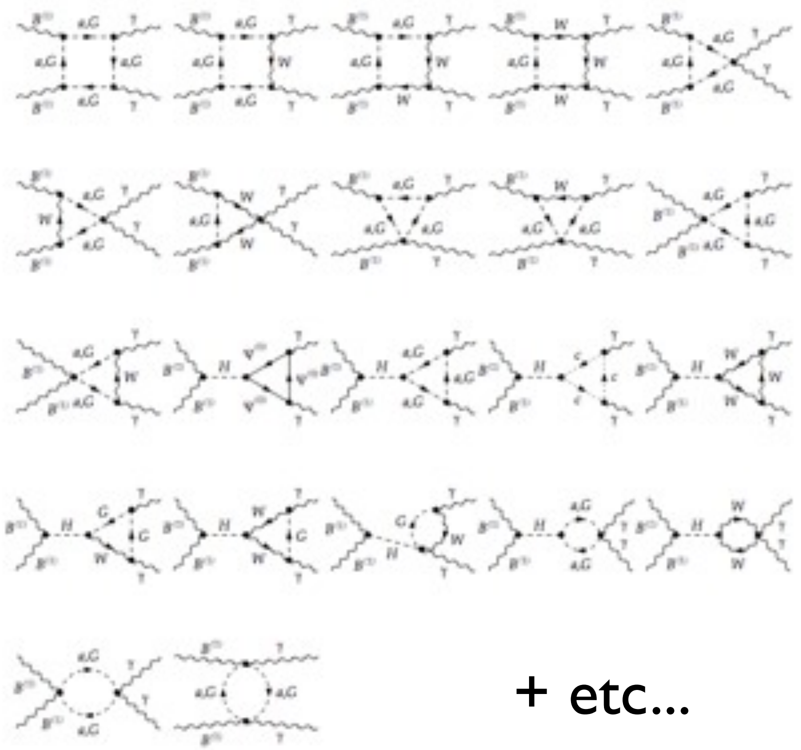
Line included!

- Branching ratios: $\ell^+\ell^- \sim 59\%,\ q\bar{q} \sim 35\%,\ \nu\bar{\nu} \sim 4\%,$ $W^+W^- \sim 1\%,\ ZZ \sim 0.5\%,\ HH \sim 0.5\%$

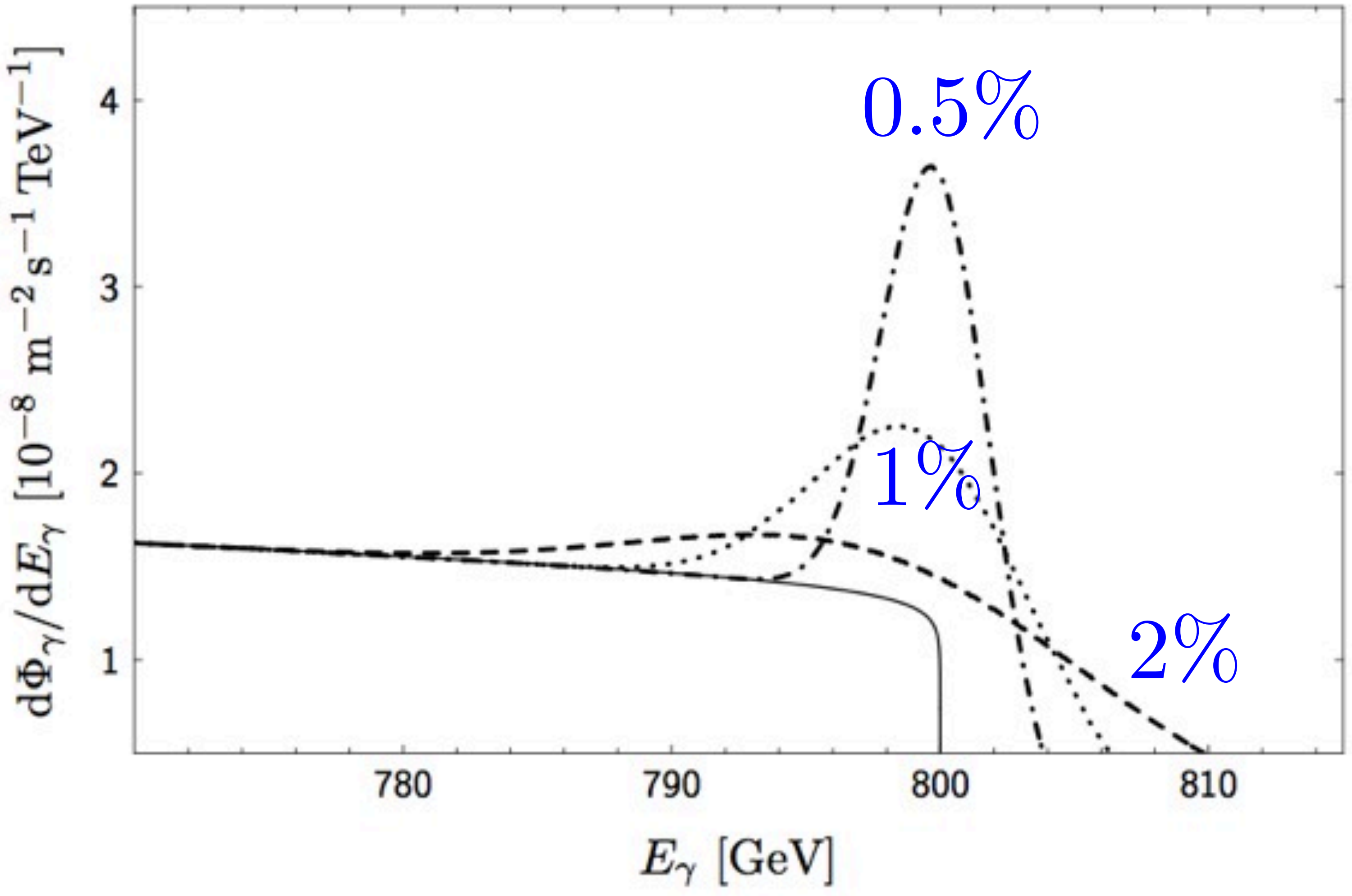
Monochromatic gammas:



+

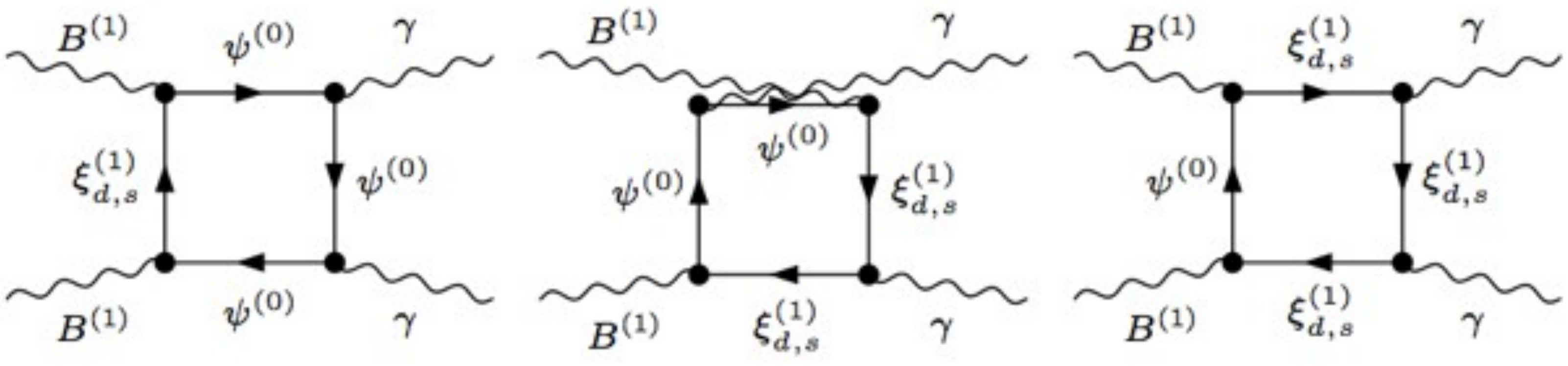


+ etc...

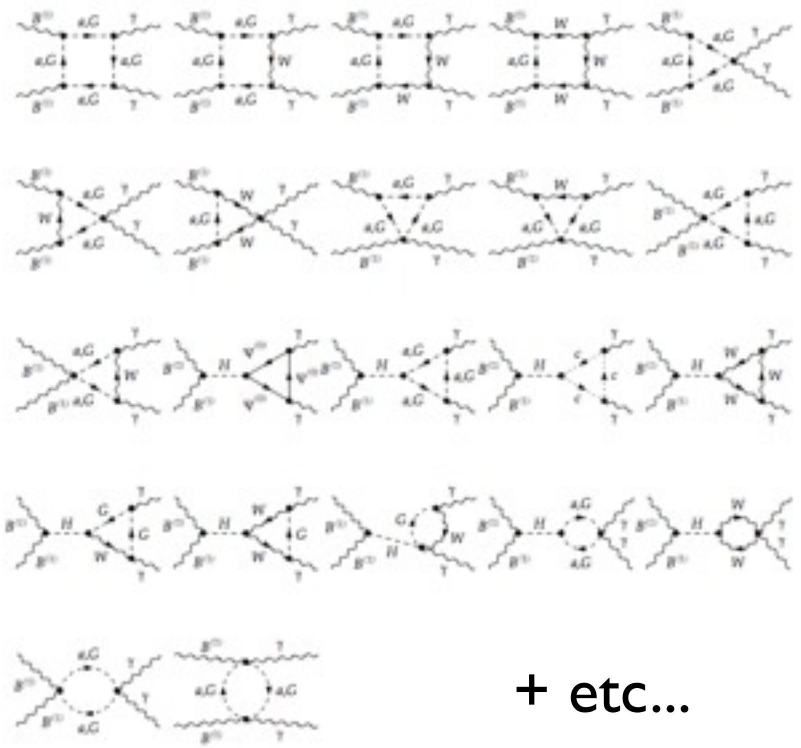


- Branching ratios: $\ell^+\ell^- \sim 59\%,\ q\bar{q} \sim 35\%,\ \nu\bar{\nu} \sim 4\%,$ $W^+W^- \sim 1\%,\ ZZ \sim 0.5\%,\ HH \sim 0.5\%$

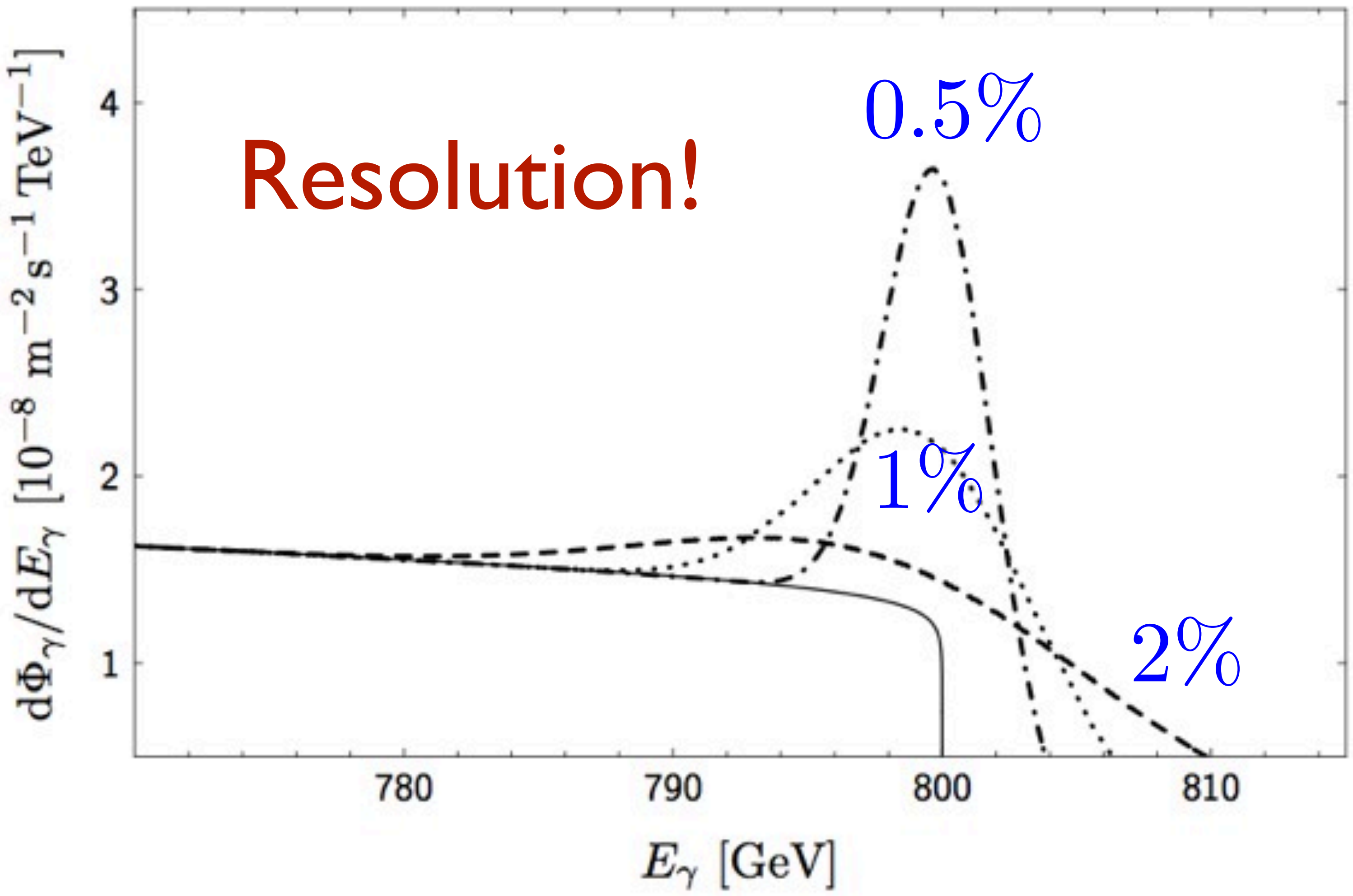
Monochromatic gammas:



+



+ etc...

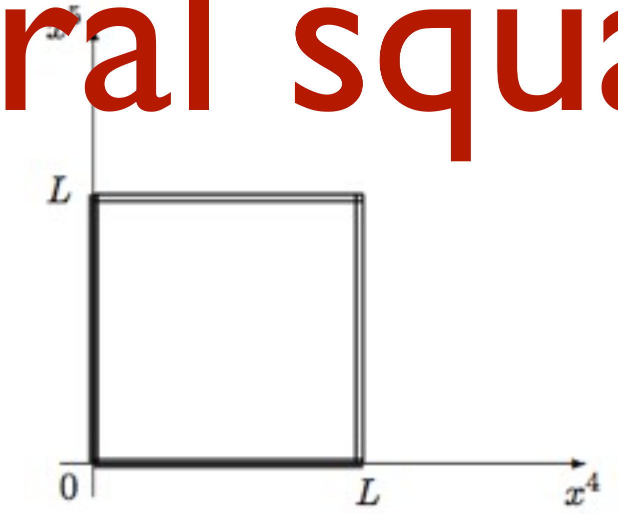


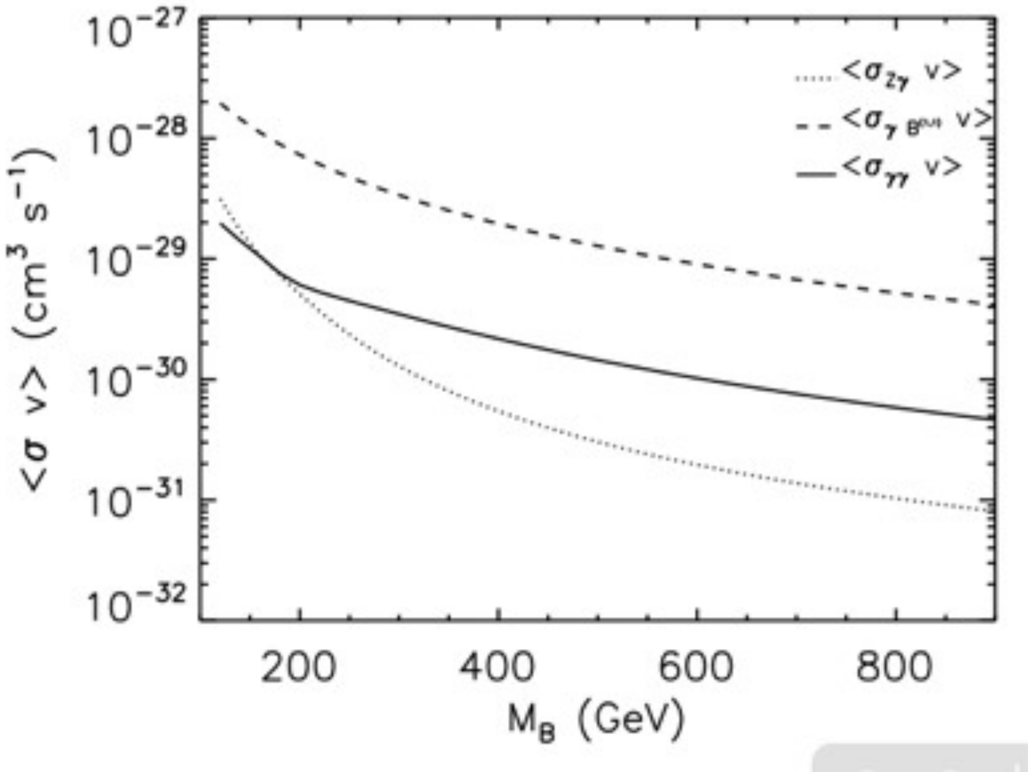
Resolution!

6D UED with a chiral square

- T^2/Z_4 compatification of the 2 ED

G. Burdman, B. A. Dobrescub and E. Ponton JHEP02(2006)033
(see also JHEP 03 (2004) 071)

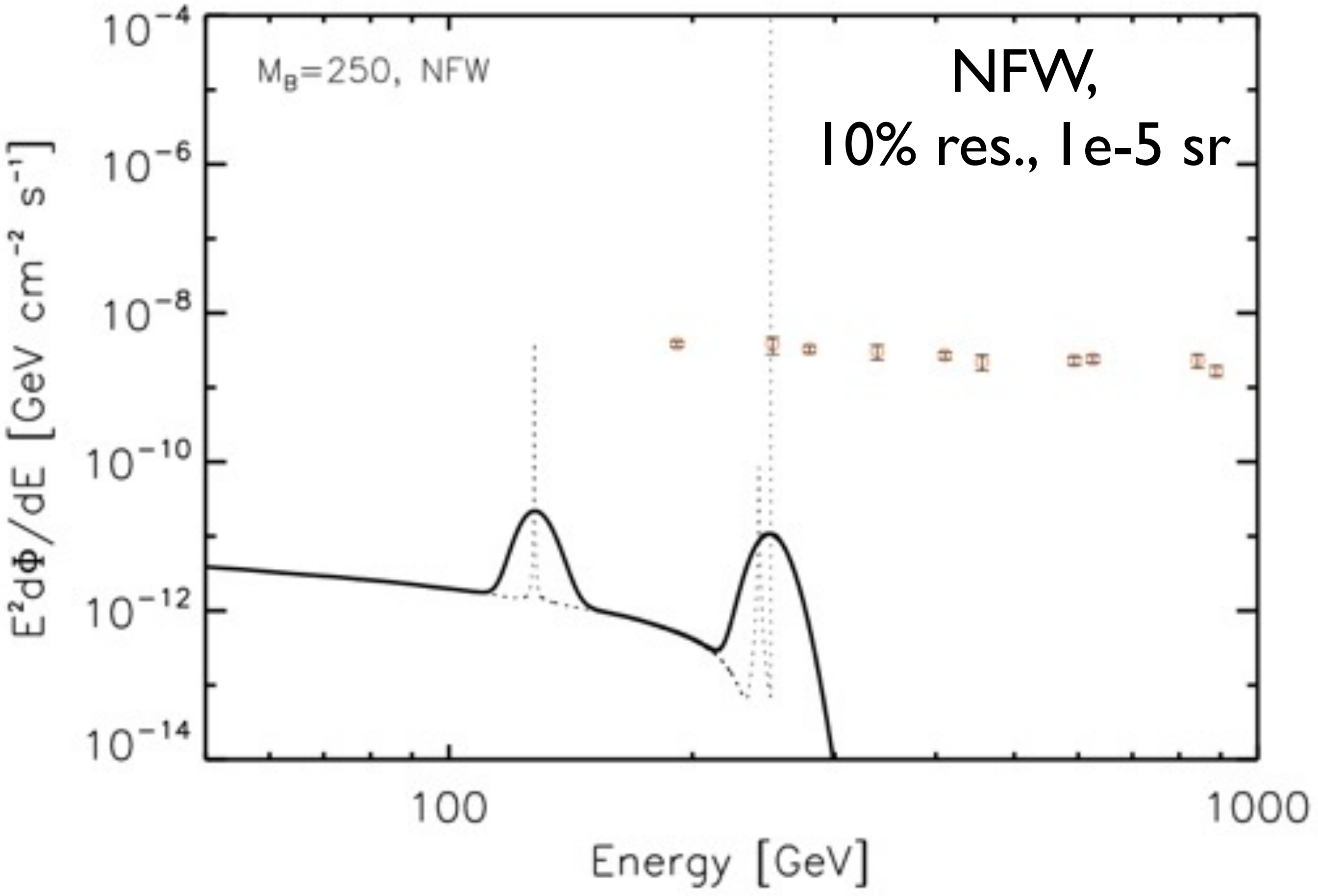




- Scalar DM from the extra component of the 6D SM U(1) gauge field.

- Line at $E_\gamma \approx m_{DM}$ and $= m_{DM}/2$

Dobrescu and Ponton (JHEP, 2004), Dobrescu et al. (JCAP, 2007)



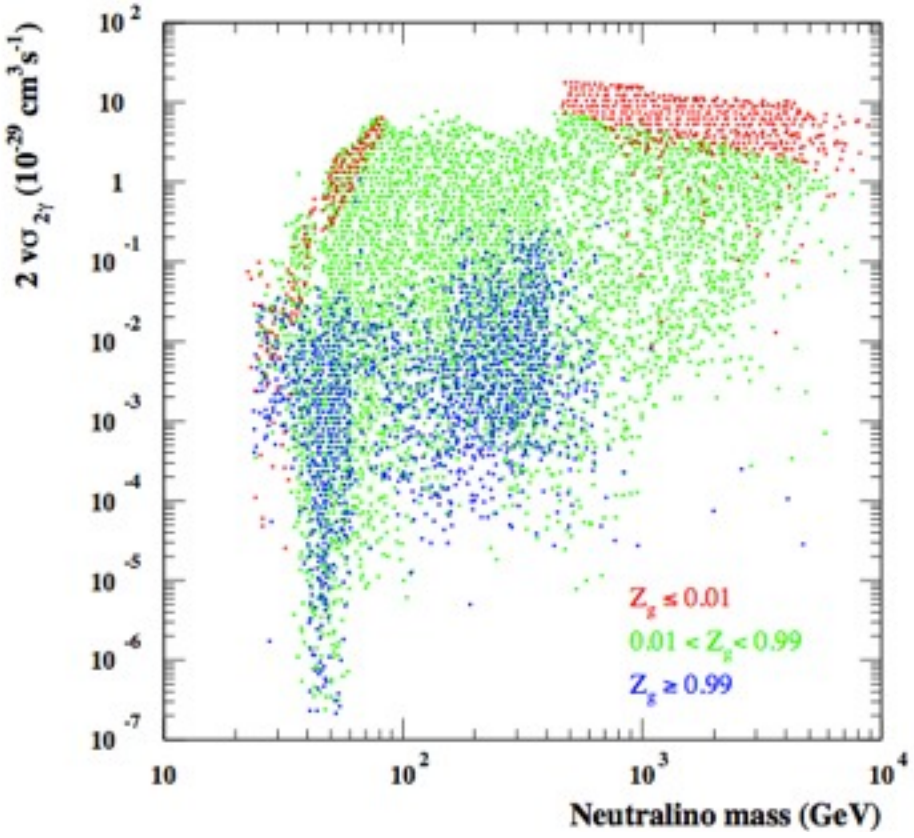
NFW,
10% res., 1e-5 sr

Supersymmetry

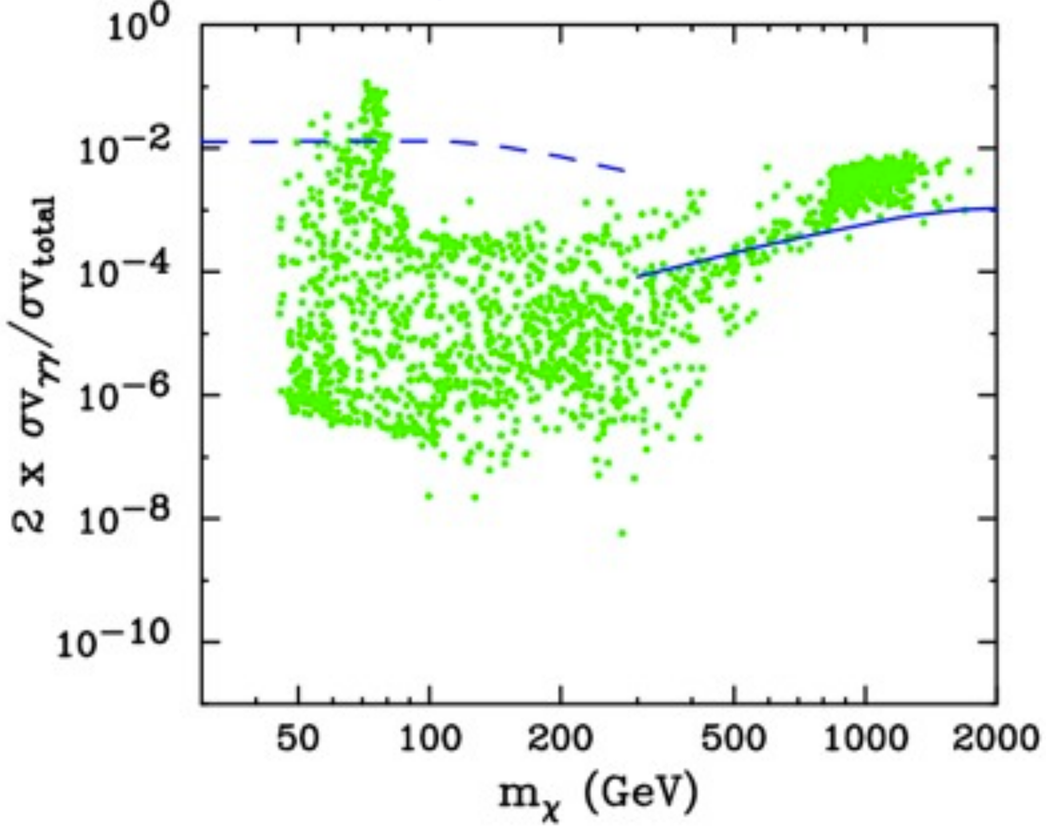
gamma lines

MSSM:

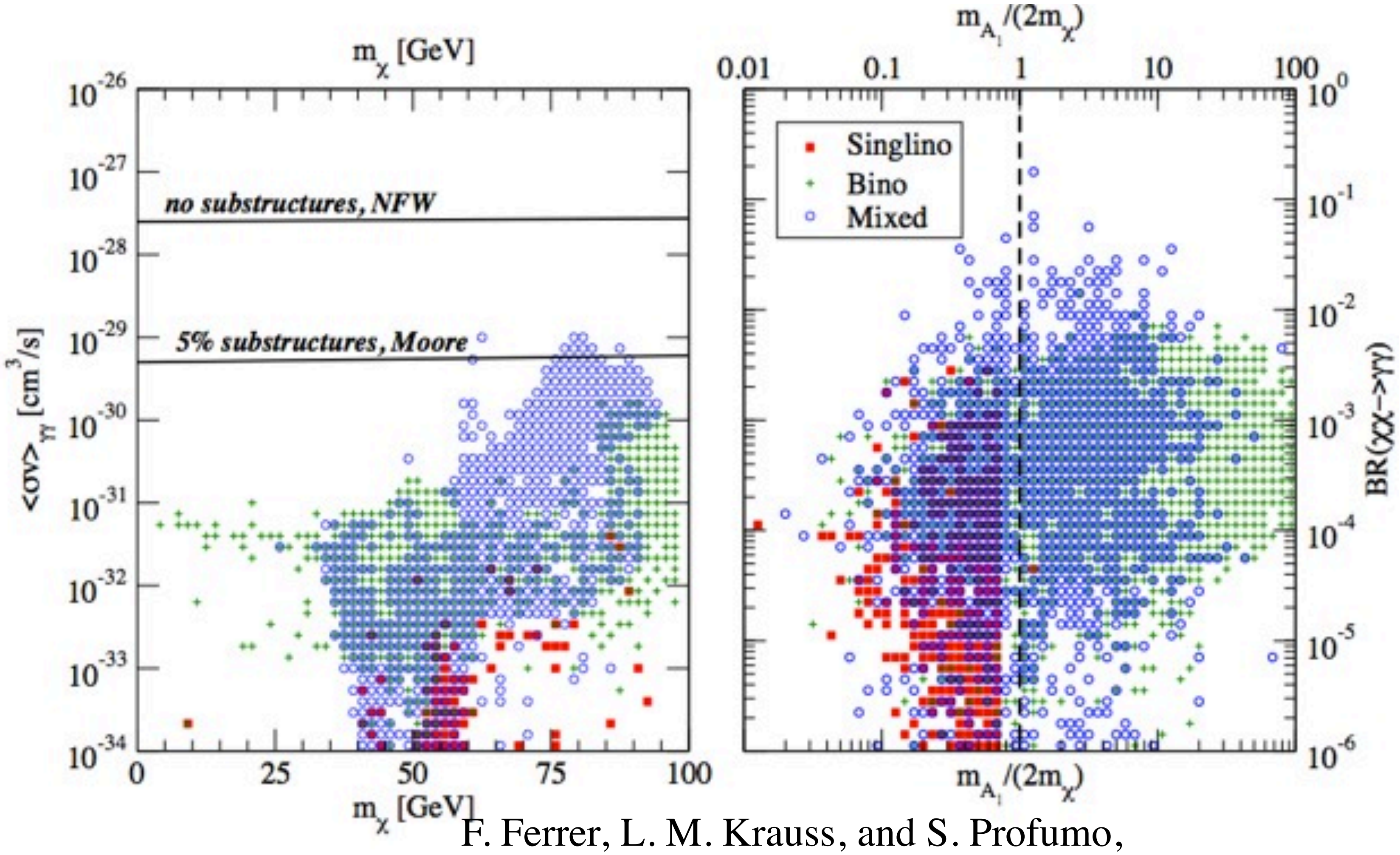
L. Bergström, P. Ullio, K. Buckley
Astropart. Phys. 9 (1998) 137-162, [arXiv:astro-ph/9712318v1]



Gabrijela Zaharijas and Dan Hooper,
Phys.Rev.D73:103501,2006
[arXiv:astro-ph/0603540v1]



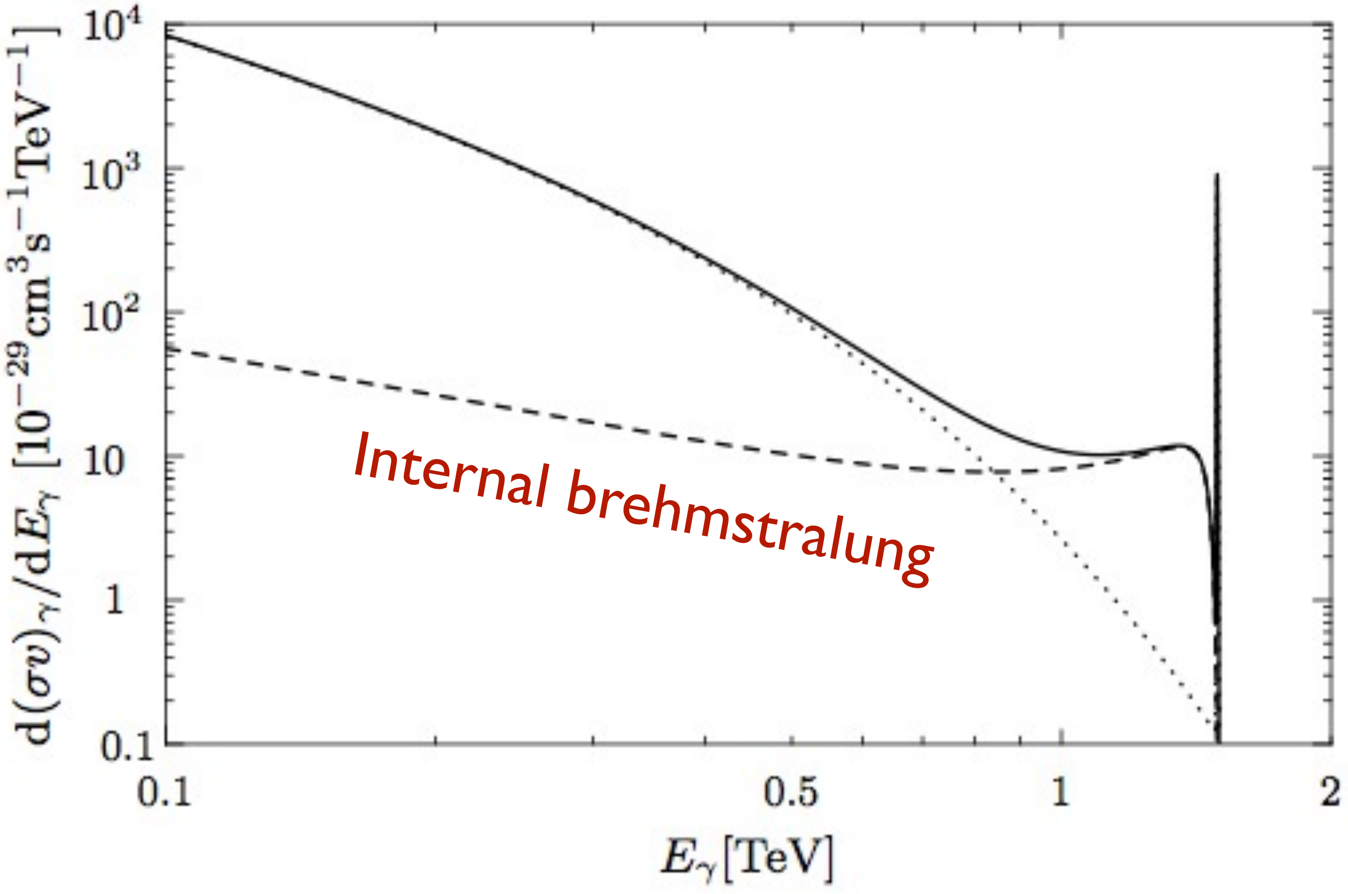
NMSSM:



F. Ferrer, L. M. Krauss, and S. Profumo,
Phys.Rev.D74:115007,2006 [arXiv:hep-ph/0609257v2]

Internal brehmstralung

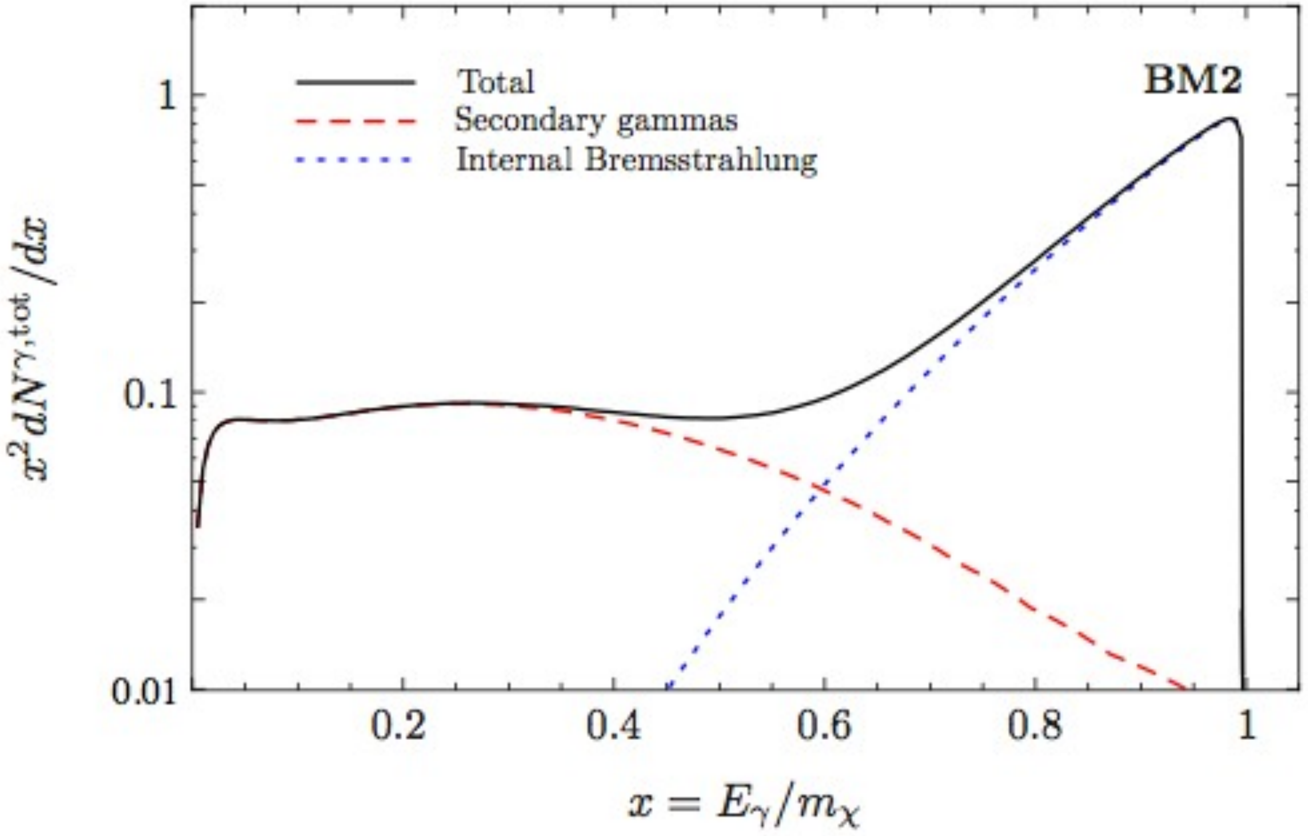
- Example: Higgsino
  - TeV mass
  - high W^+W^- b. r.



L. Bergström, T. Bringmann, M. Eriksson, M.G.,
Phys.Rev.Lett. 95 (2005) 241301 [hep-ph/0507229v2]

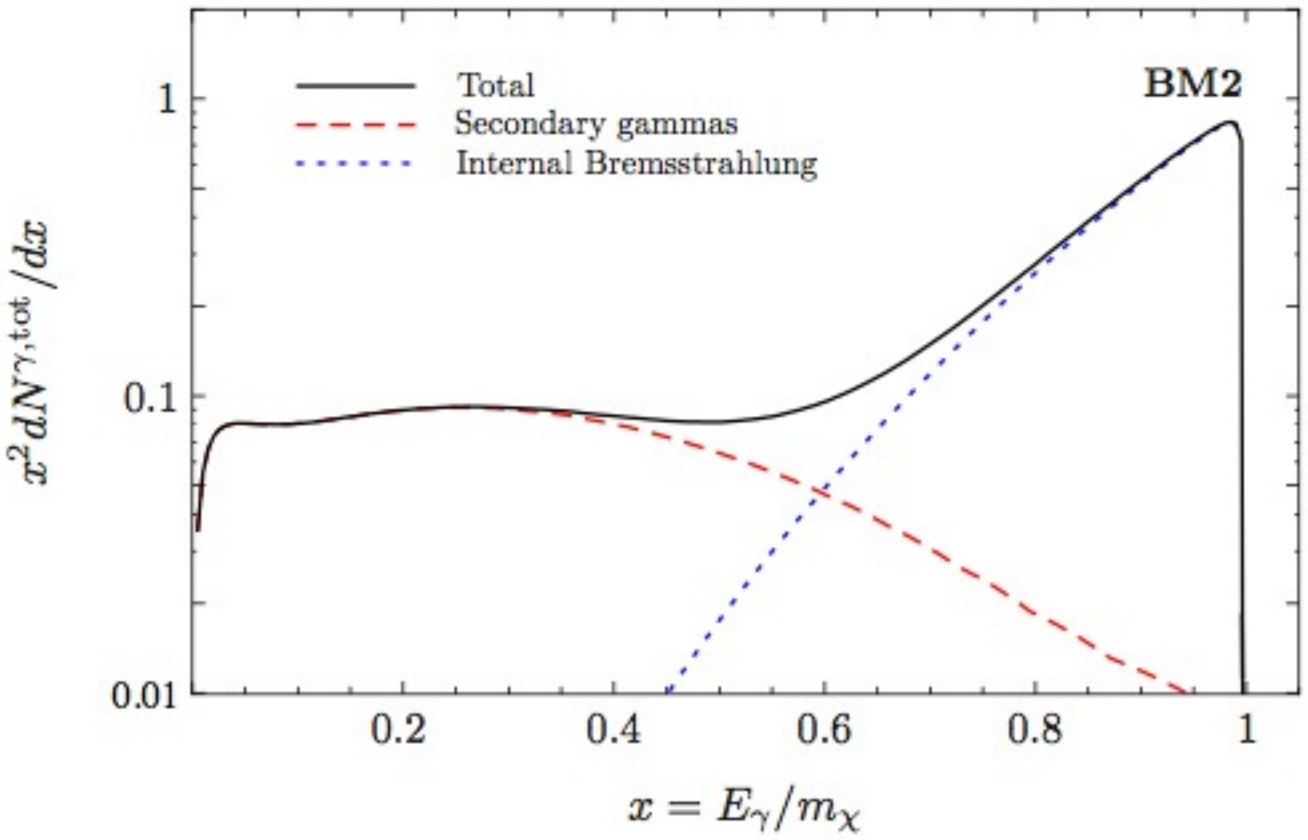
Internal brehmstralung

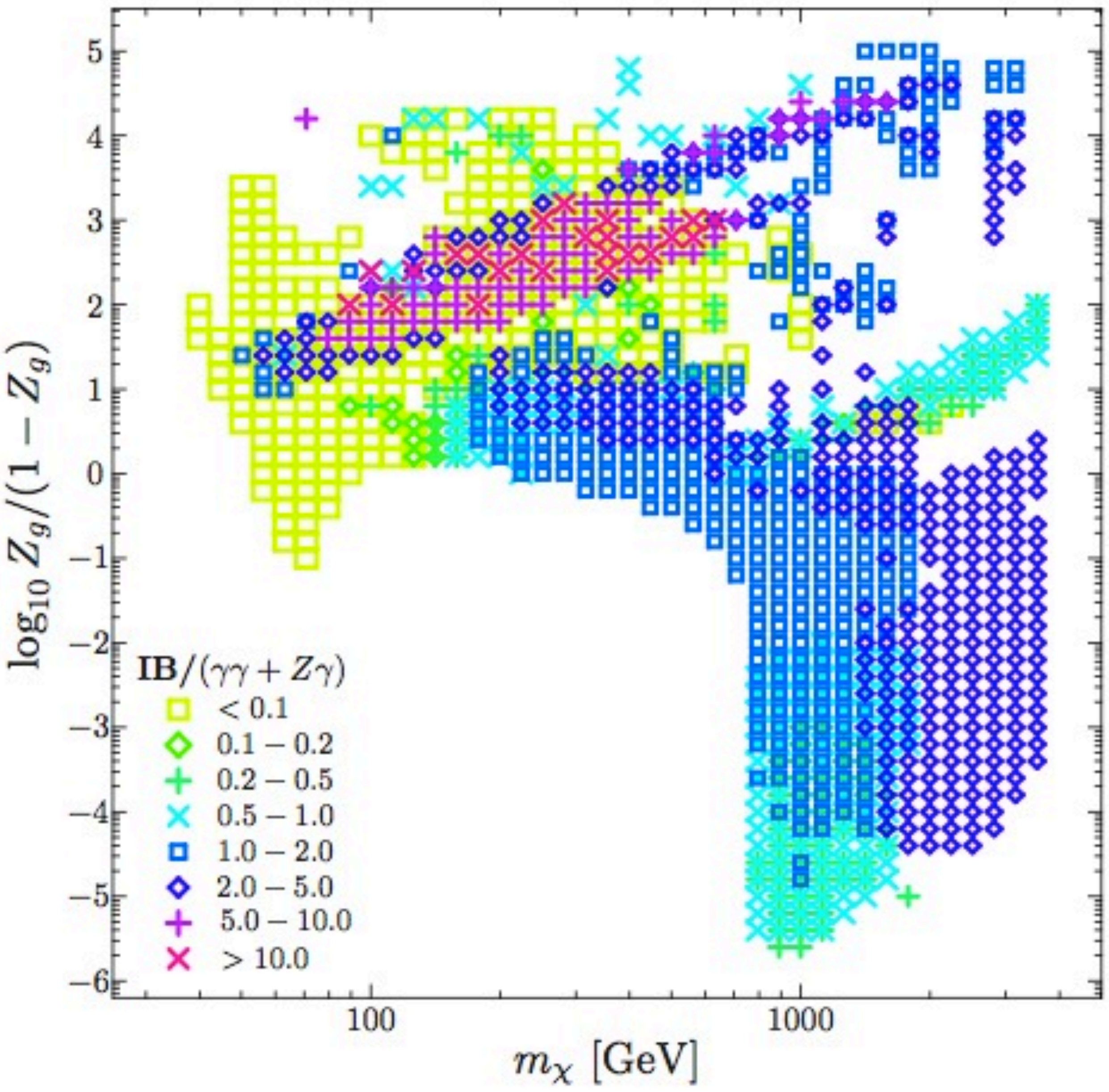
- Example: Gaugino
  - GeV mass
  - high $\tau^+\tau^-$ b. r.



Internal brehmstralung

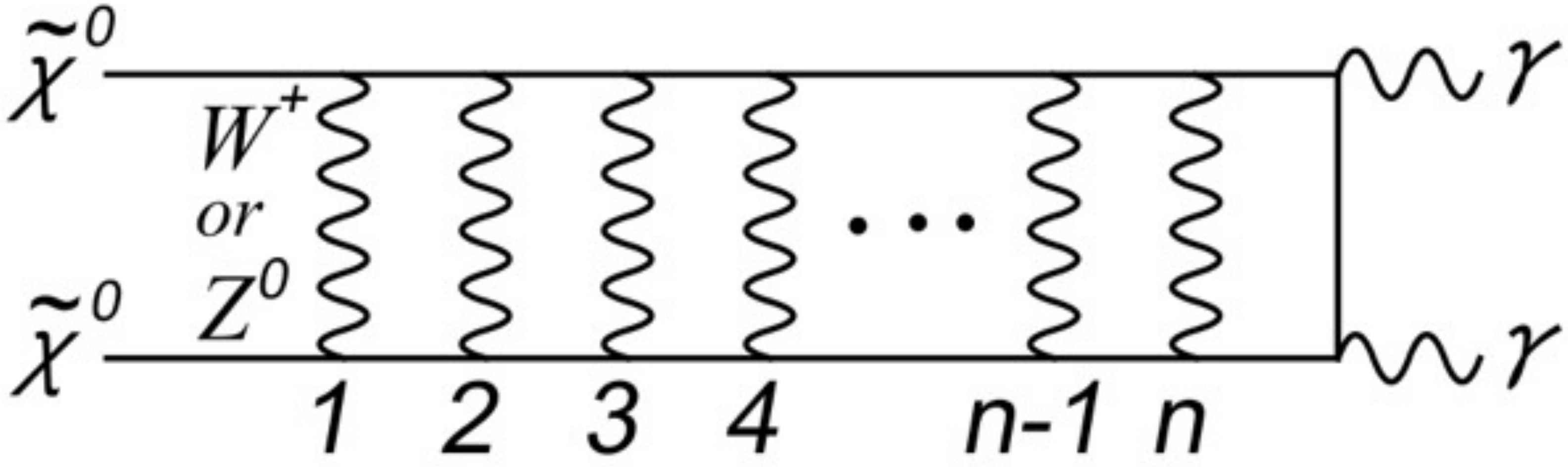
- Example: Gaugino
  - GeV mass
  - high $\tau^+\tau^-$ b. r.

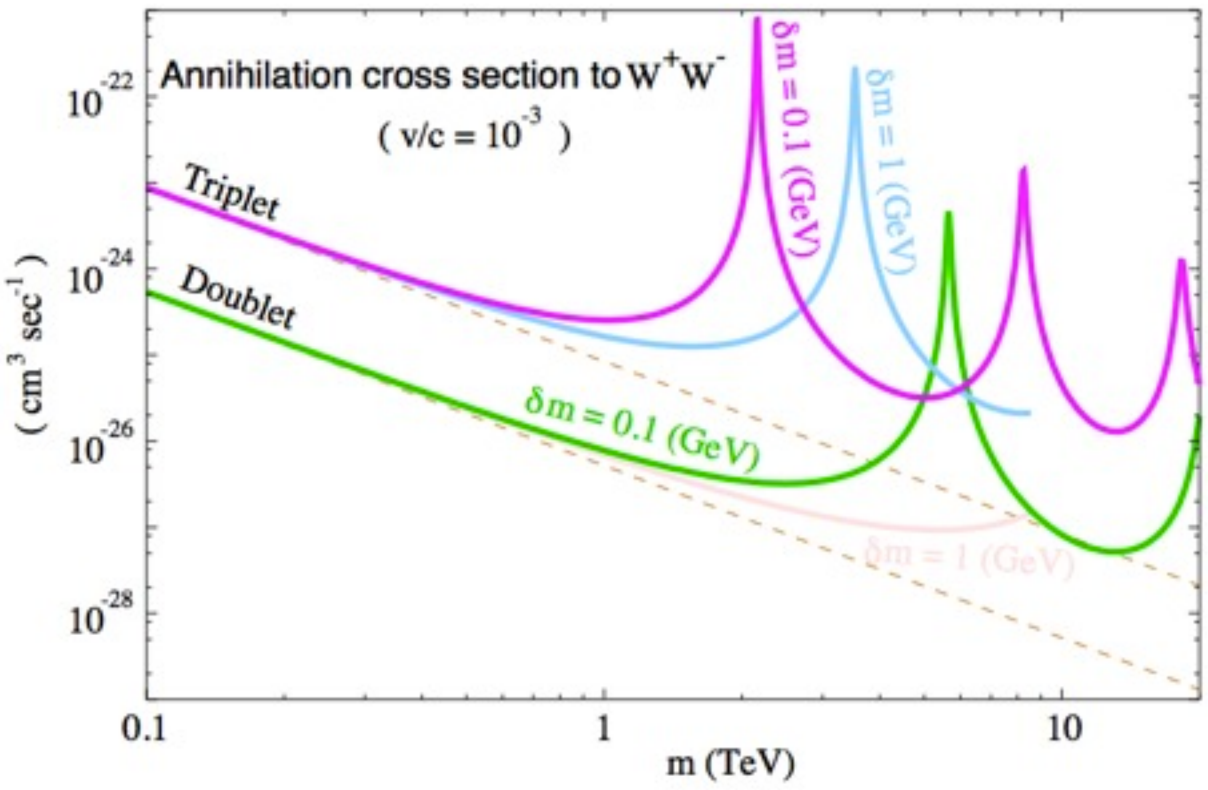


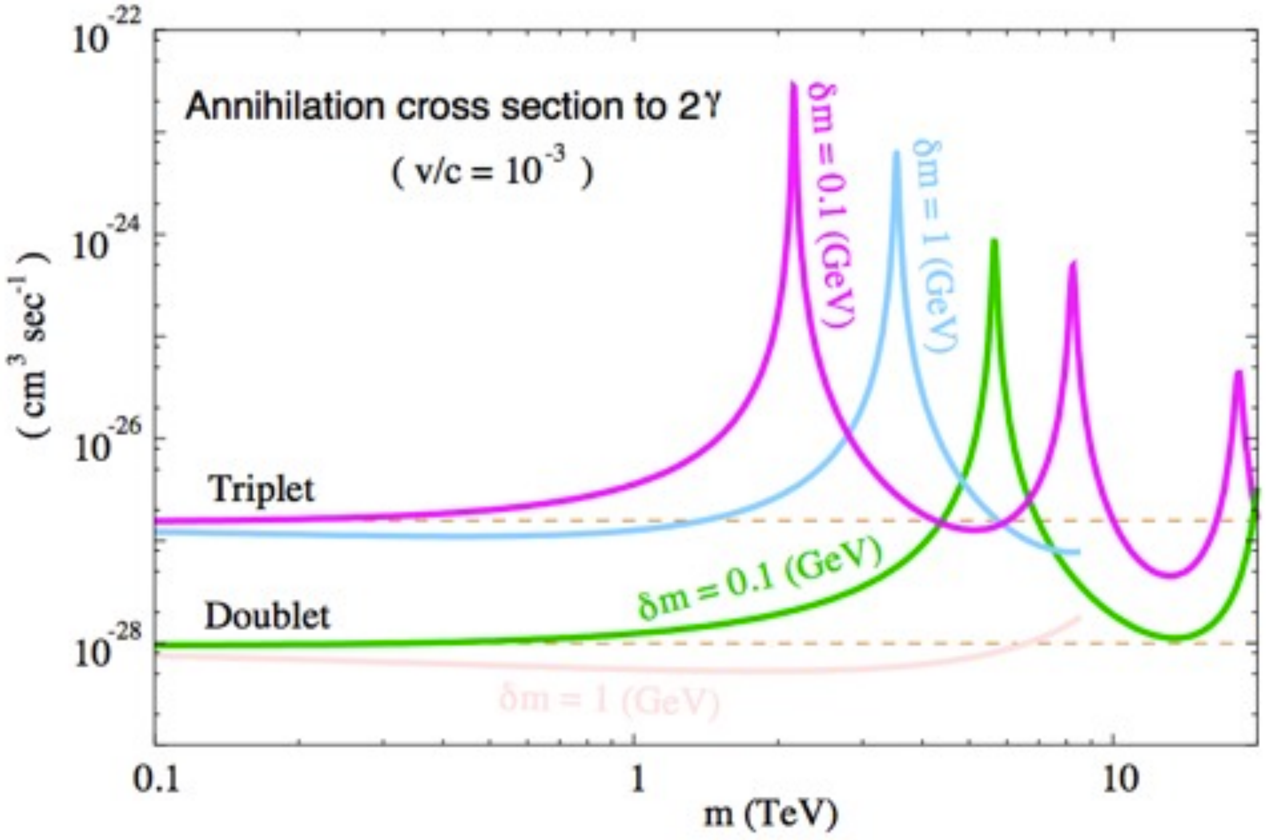


T. Bringmann, L. Bergström, J. Edsjö,
JHEP 0801:049,2008 [arXiv:0710.3169v3]

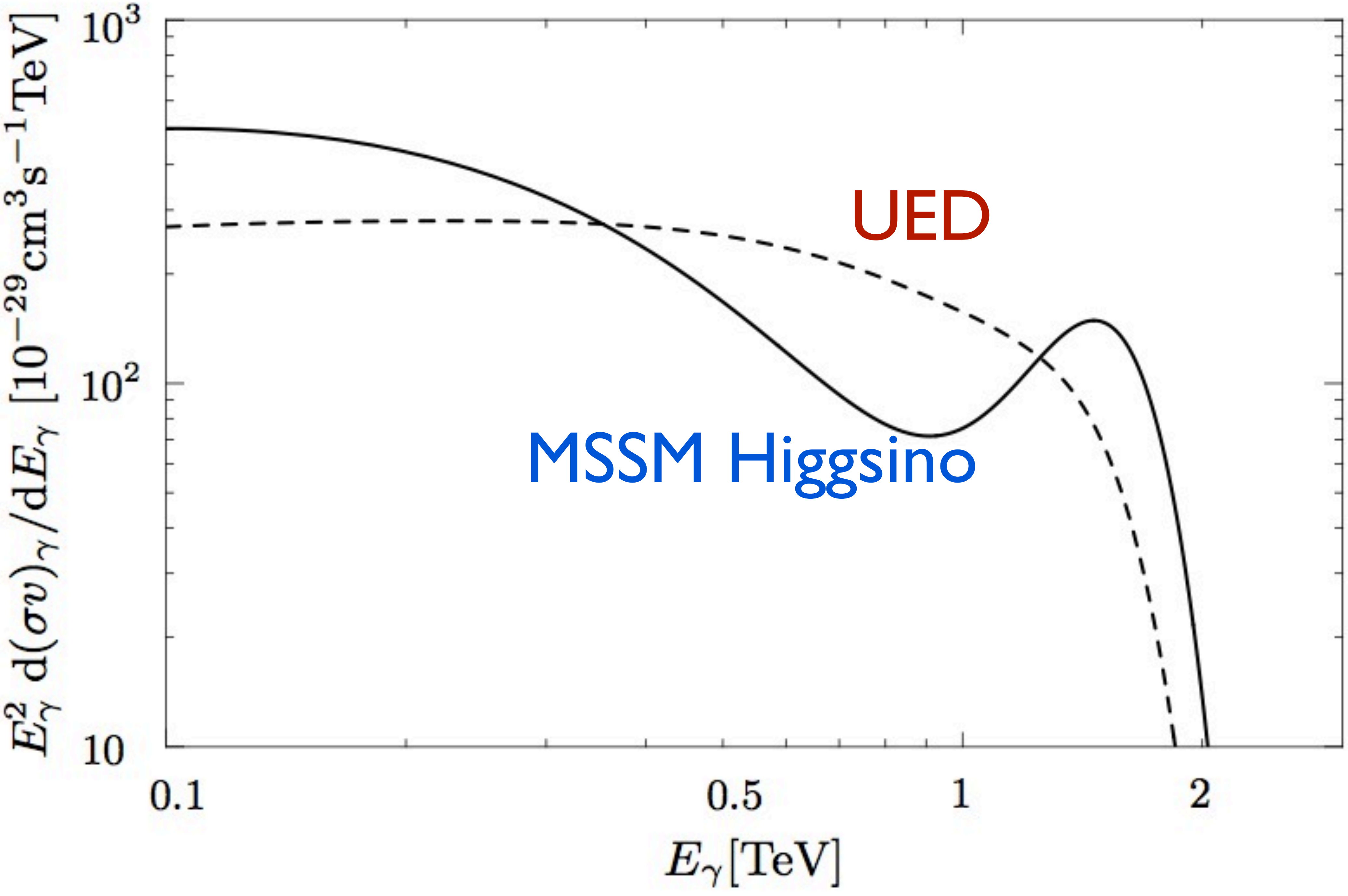
Explosive annihilation/ Sommerfeld enhancement





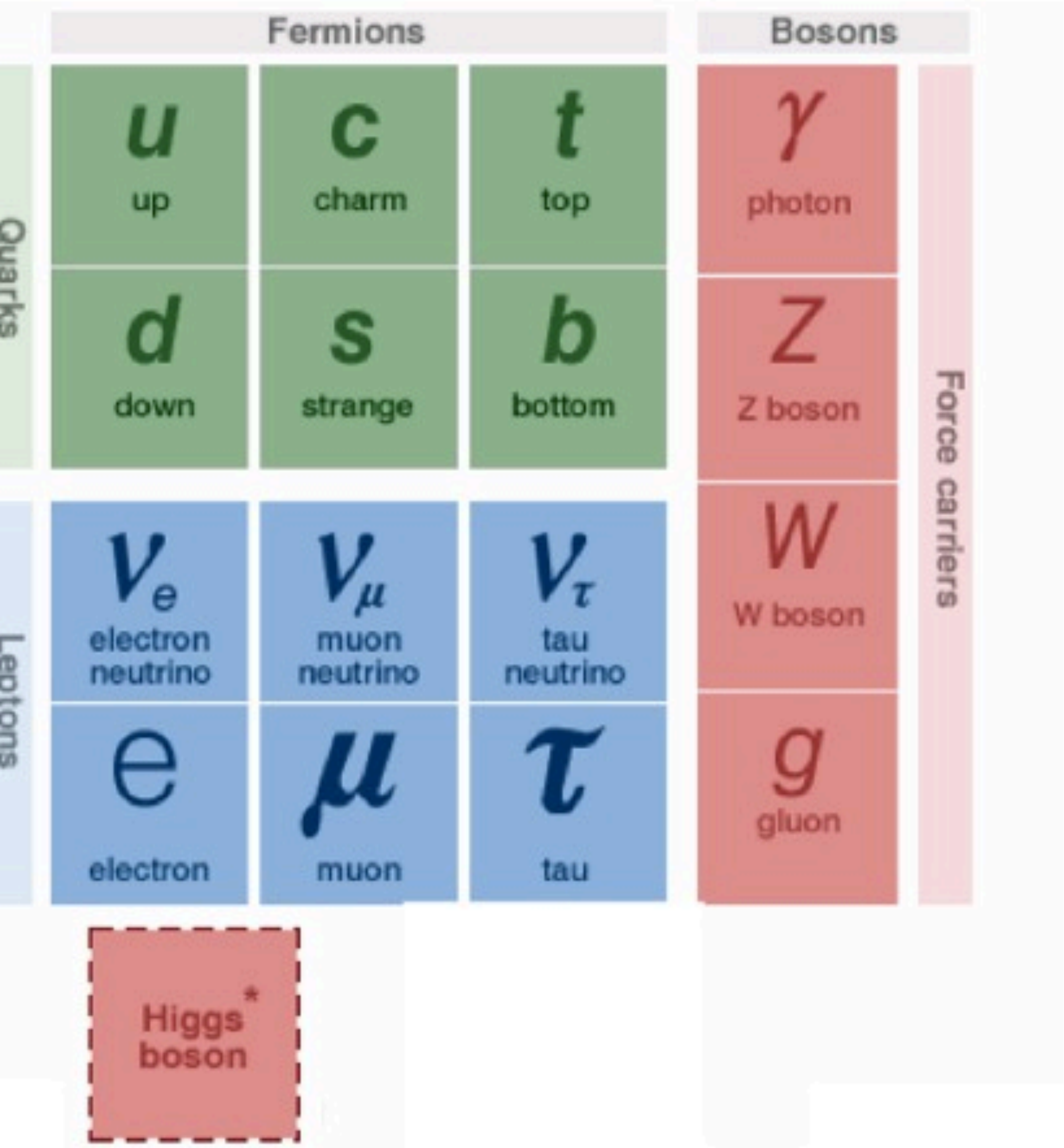


J. Hisano, S. Matsumoto and M. M. Nojiri, Phys. Rev. D 67, 075014 (2003).
[arXiv:hep-ph/0307216v1]


UED
MSSM Higgsino
$E_\gamma^2\, \mathrm{d}(\sigma v)_\gamma/\mathrm{d}E_\gamma\ [10^{-29}\mathrm{cm}^3\mathrm{s}^{-1}\mathrm{TeV}]$
10^3
10^2
10
0.1
0.5
1
2
E_γ[TeV]

Inert scalar doublet model

Standard model

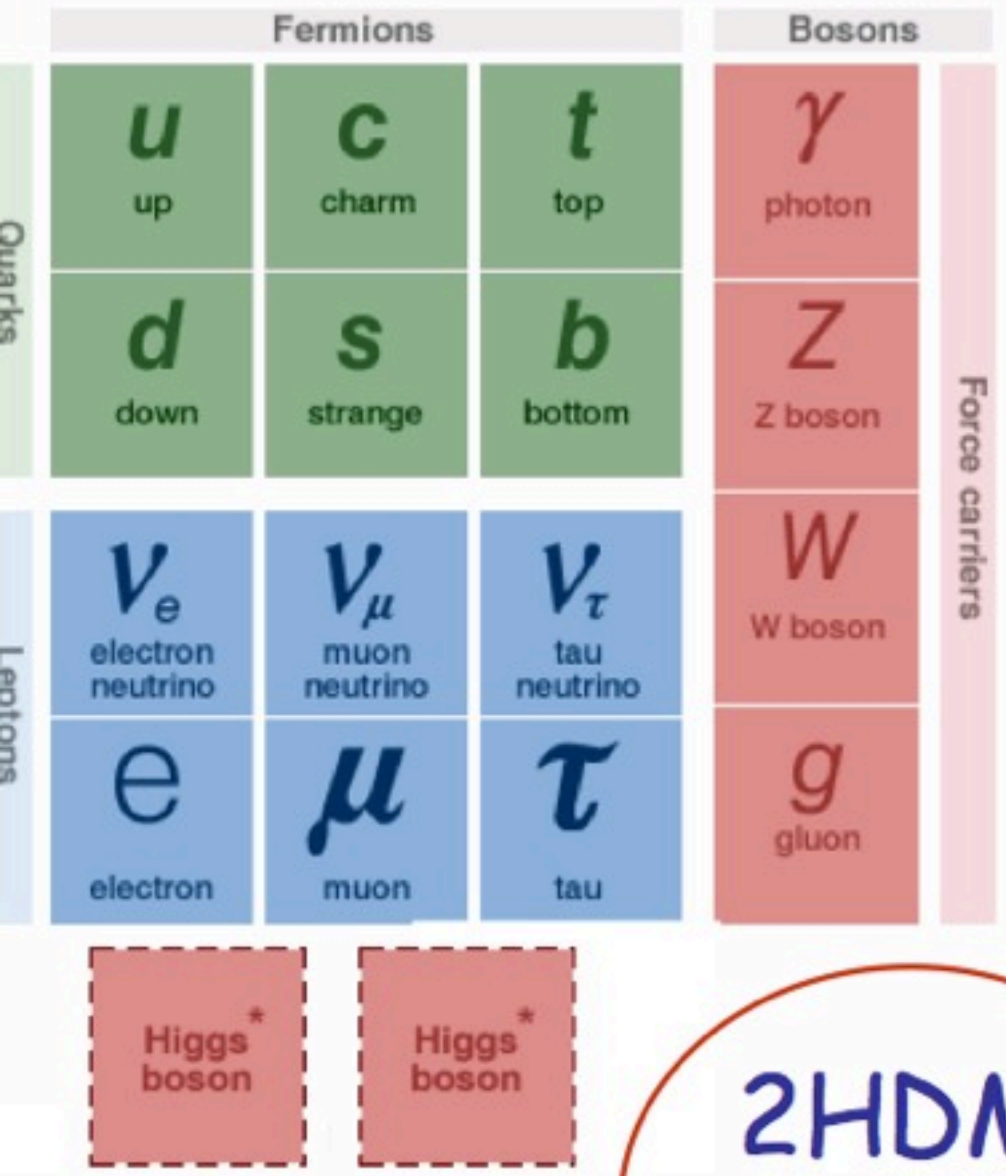


	Fermions			Bosons	
Quarks	u up	c charm	t top	γ photon	Force carriers
	d down	s strange	b bottom	Z Z boson	
Leptons	ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino	W W boson	
	e electron	μ muon	τ tau	g gluon	
	Higgs* boson				

ϕ_1

Scalar doublet

Standard model



ϕ_1 ϕ_2

Scalar doublets

2HDM

= Two Higgs doublet model

Inert Doublet model (IDM)

Deshpande & Ma 1978 , Barbieri et al. 2006

- 2HDM with an imposed

  Z_2-symmetry: $\phi_2 \rightarrow -\phi_2$

  and even Z_2-parity for all SM fields.

- Implications for ϕ_2 :

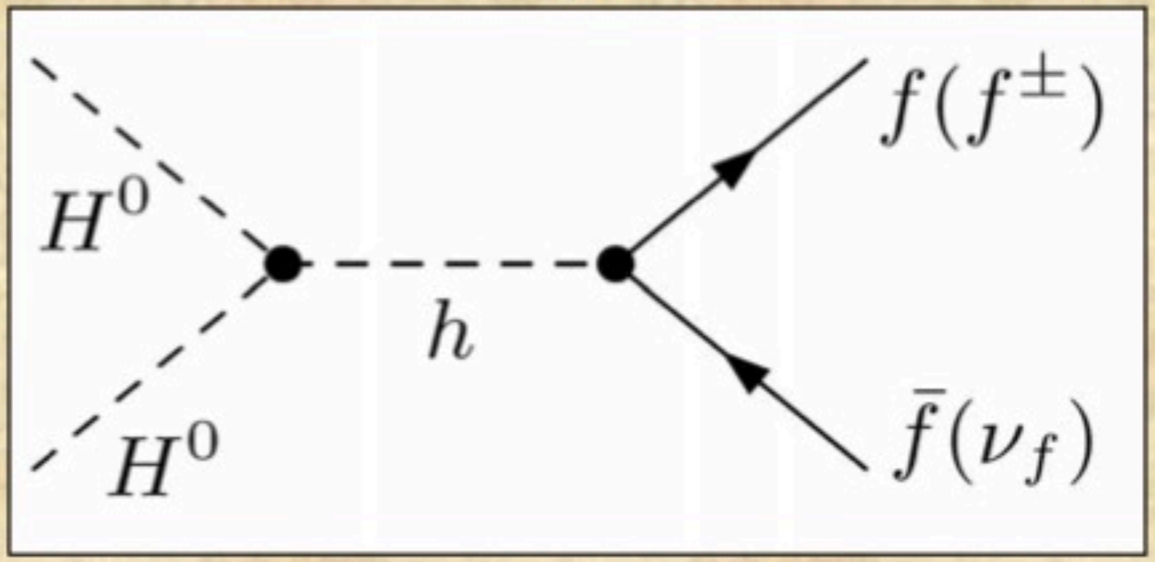
  - No direct couplings to fermions, i.e. **inert**
  - Allows for a **heavy SM Higgs**, up to about 500 GeV
  - Provide a **dark matter** candidate H^0 with a mass ~ 50 – 80 GeV

    (without fine tuning)

IDM gamma-ray spectrum

Inert Doublet Model

$$\frac{dN_\gamma}{dE_\gamma} = \underbrace{\frac{dN^{sec}}{dE_\gamma} + \frac{dN^{IB}}{dE_\gamma}} + \frac{dN^{line}}{dE_\gamma}$$



$$\sigma v \propto \frac{\lambda_L \alpha^2 m_f^2}{(4m_{H^0}^2 - m_h^2)^2}$$

Three-level annihilation are typically very weak for this dark matter candidate in the halo.

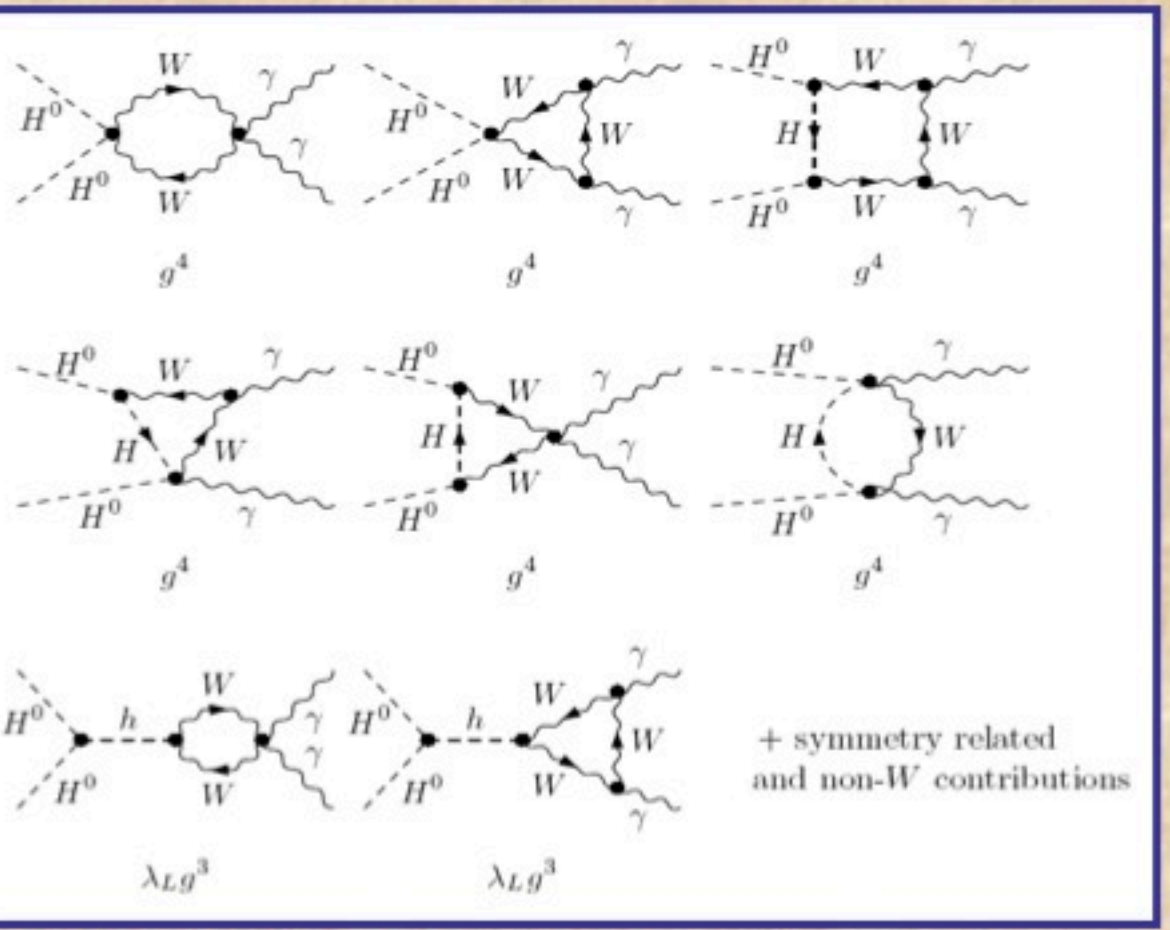
⇨ Low continuum spectra

(especially for heavy SM Higgs)

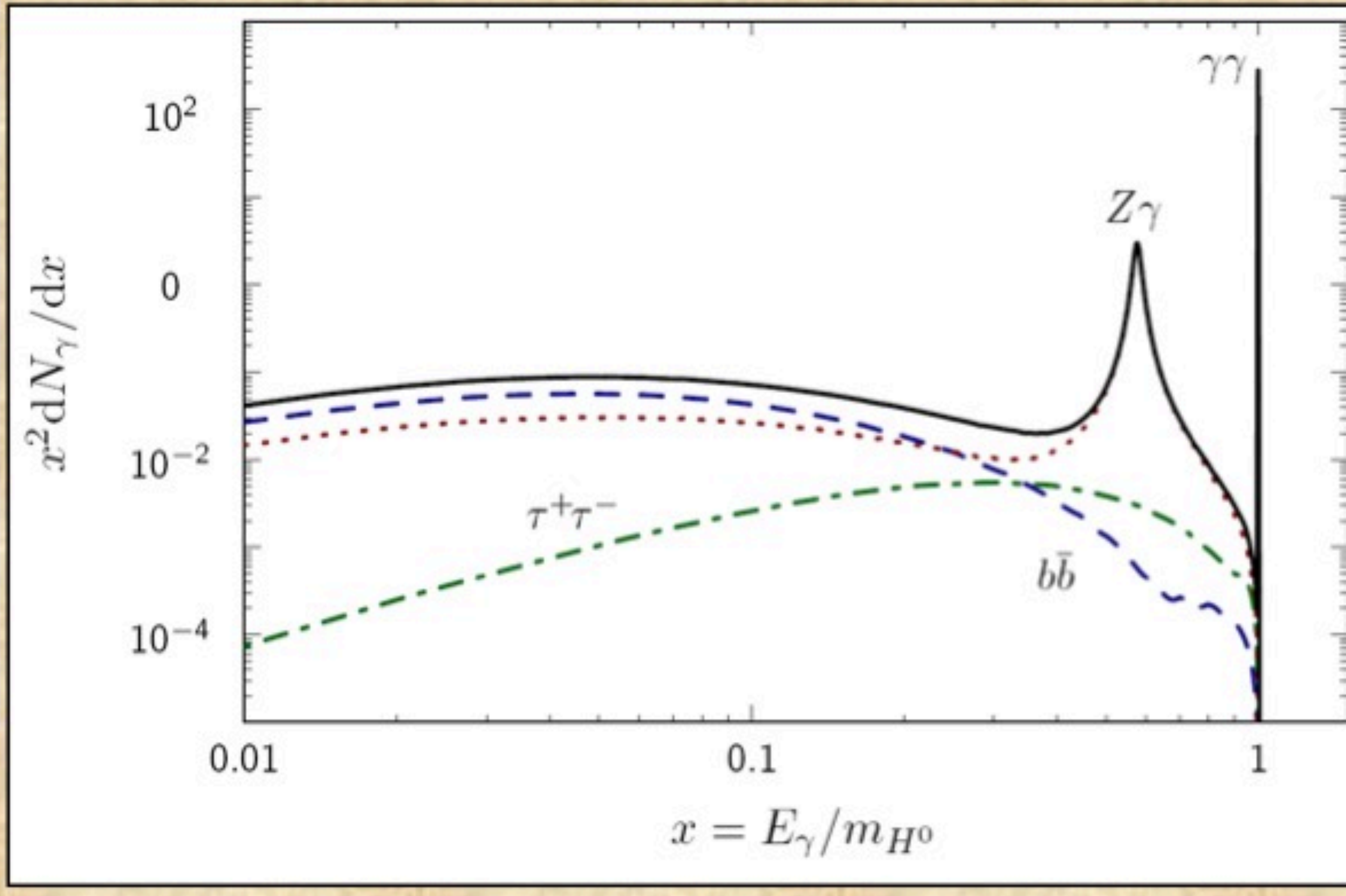
IDM gamma-ray spectrum

Inert Doublet Model

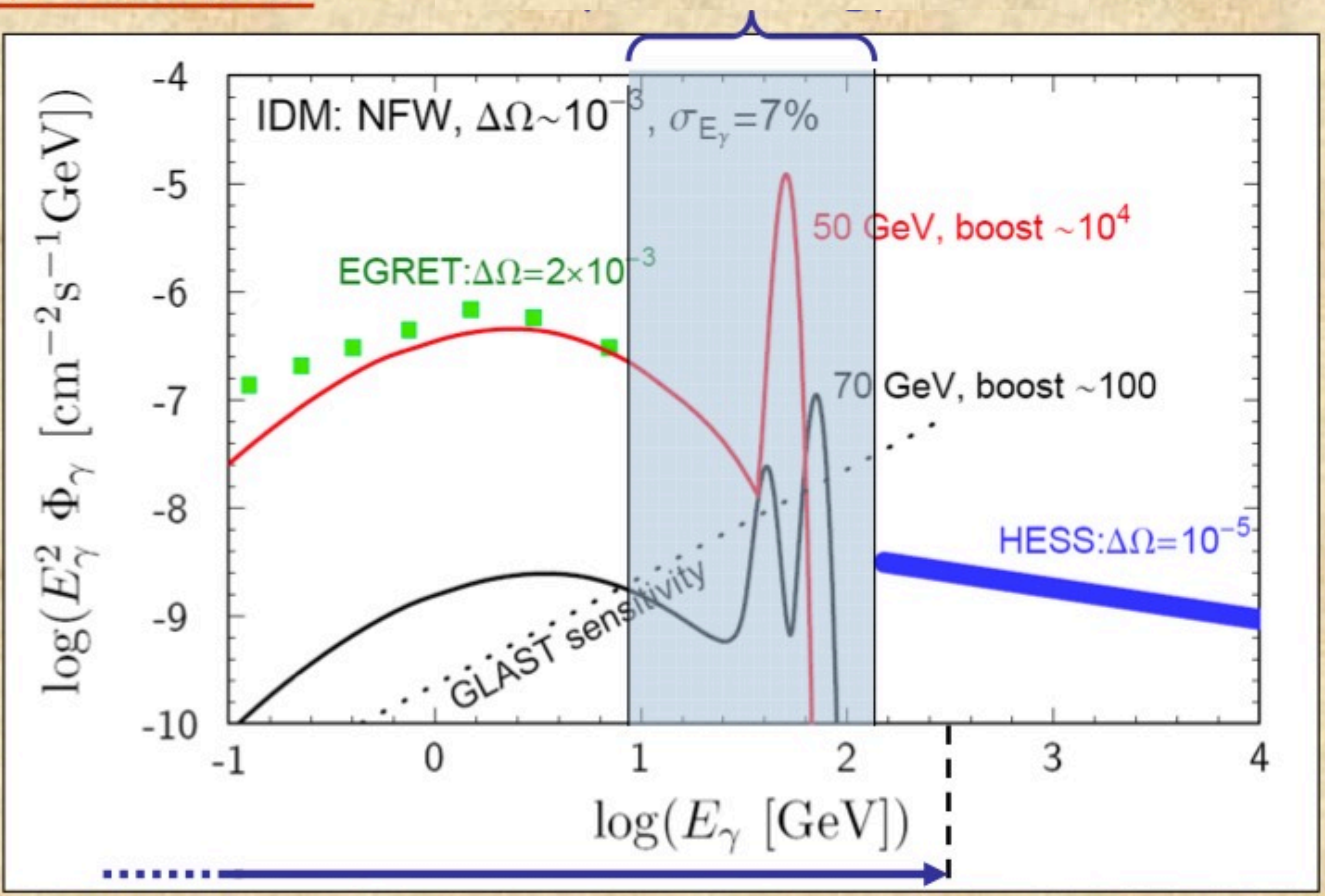
$$\frac{dN_\gamma}{dE_\gamma} = \frac{dN^{sec}}{dE_\gamma} + \frac{dN^{IB}}{dE_\gamma} + \underbrace{\frac{dN^{line}}{dE_\gamma}}_{}$$



M.G., Lundström, Bergström, Edjö '07



Inert Doublet Model



Energy range for the Fermi satellite

Z’ models

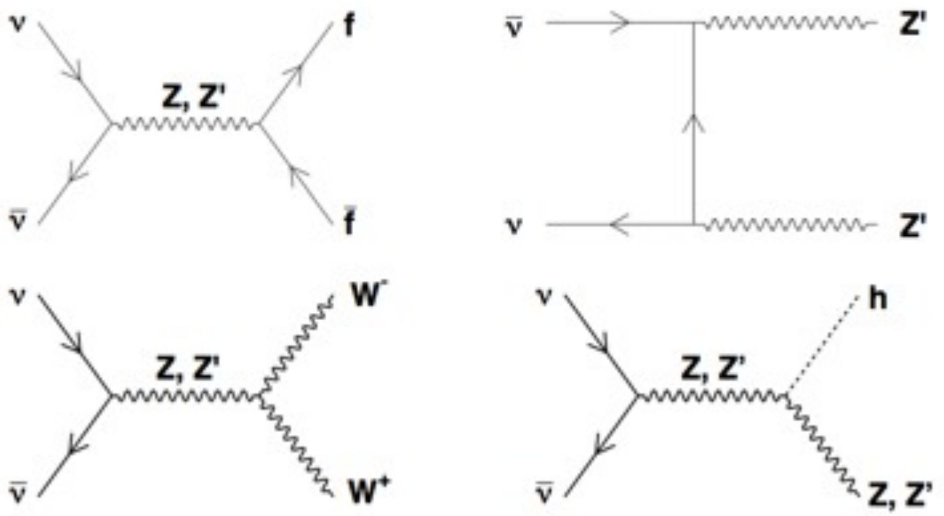
Higgs in space

C. B. Jackson, G. Servant, G. Shaughnessy, T. Taita, and M. Taoso,
JCAP 1004:004,2010 arXiv:0912.0004v2

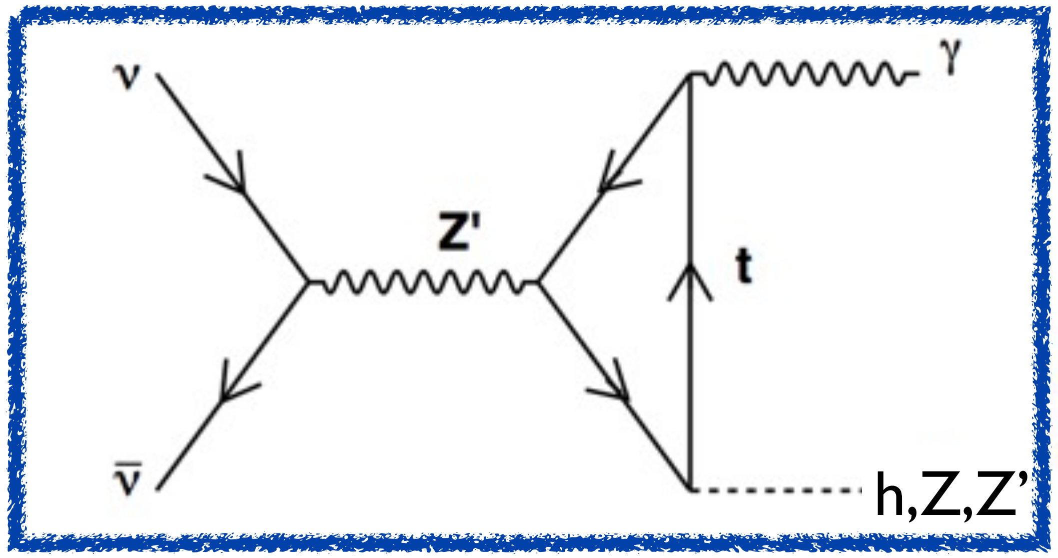
[See e.g. also: (In)visible Z′ and dark matter byE. Dudas1,2, Y. Mambrini2, S. Pokorski3 and A. Romagnoni JHEP 0908:014,2009 arXiv:0904.1745v2]

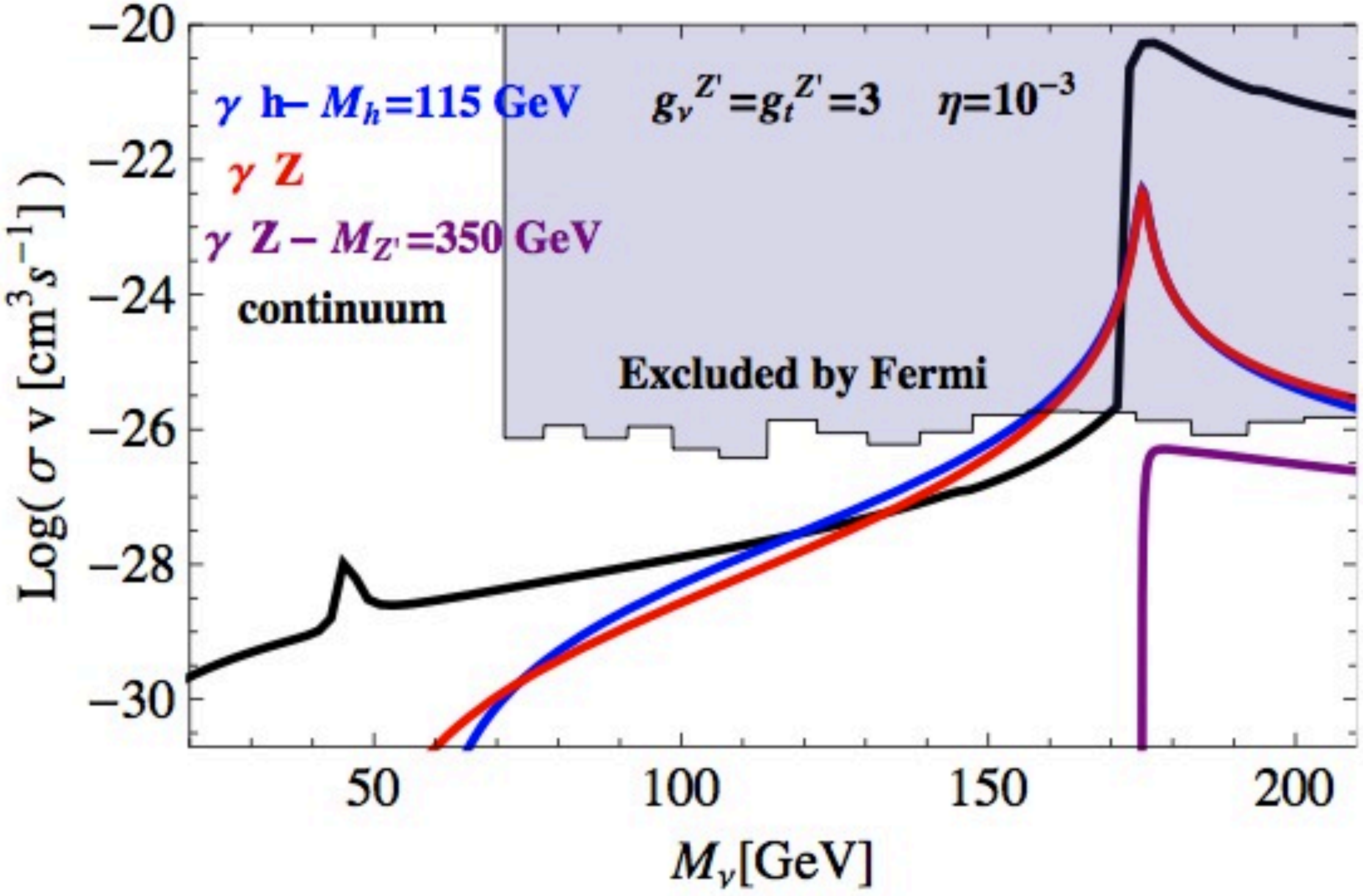
- New Z’ gauge boson, U(1)’
- DM Dirac fermion couples only to Z’
- Z’ couples to SM right handed top quark
- plus kinetic mixing Z-Z’, $\frac{\chi}{2}\hat{F}'_{\mu\nu}\hat{F}_Y^{\mu\nu}$

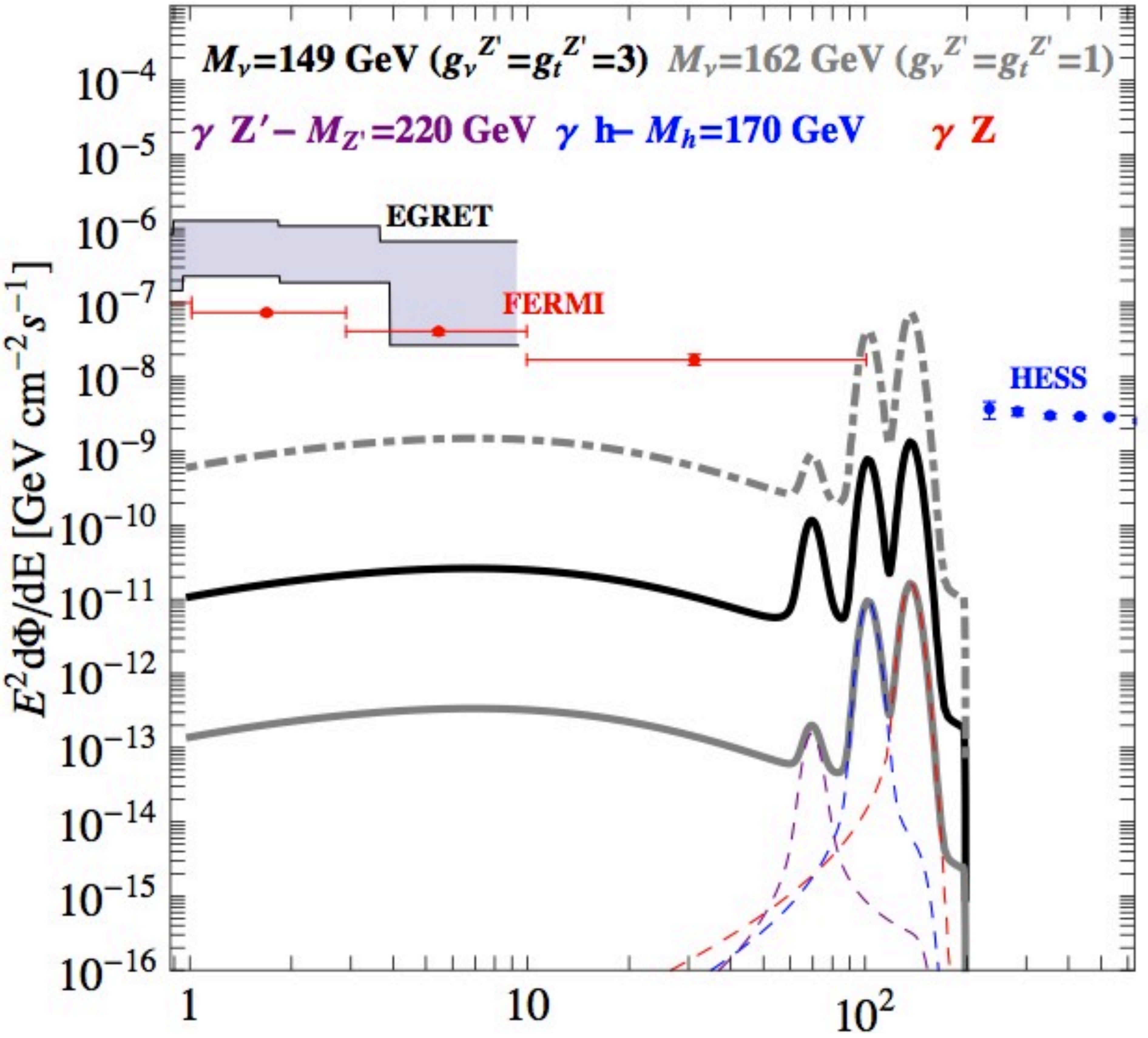
- Tree level (low up to top mass)



- Loop level (strong via top-loop)







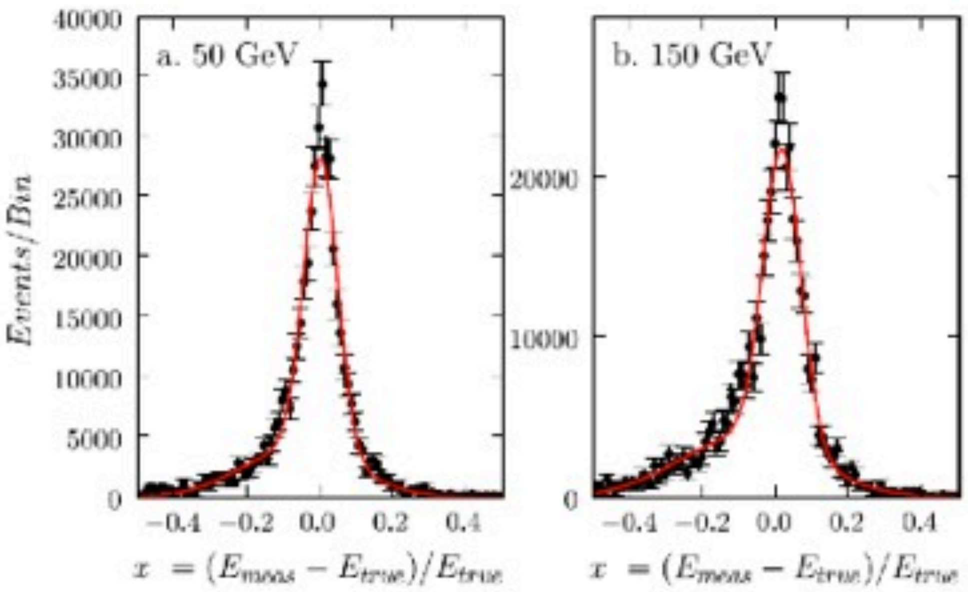
Einasto, NFW and Adiabatic contracted ~ boost 1E4, ΔΩ = 1E−5

Limits on gamma-ray lines from Fermi

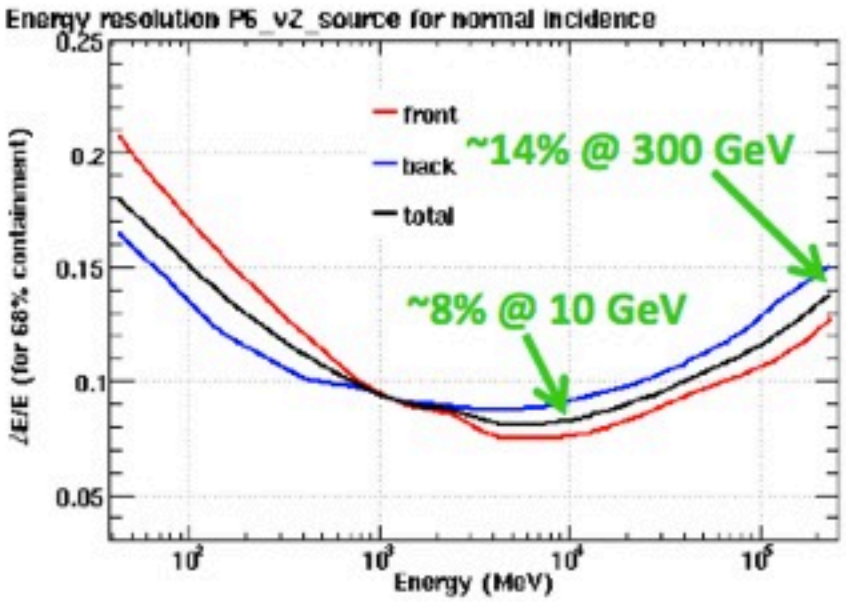
Fermi-LAT performance

- Energy resolution of the LAT varies between 8 and 14% at high energies
- Energy dispersion is therefore energy dependent

E.A. Baltz, et al., JCAP, 07 (2008) 013, arXiv:0806.2911v2 [astro-ph]



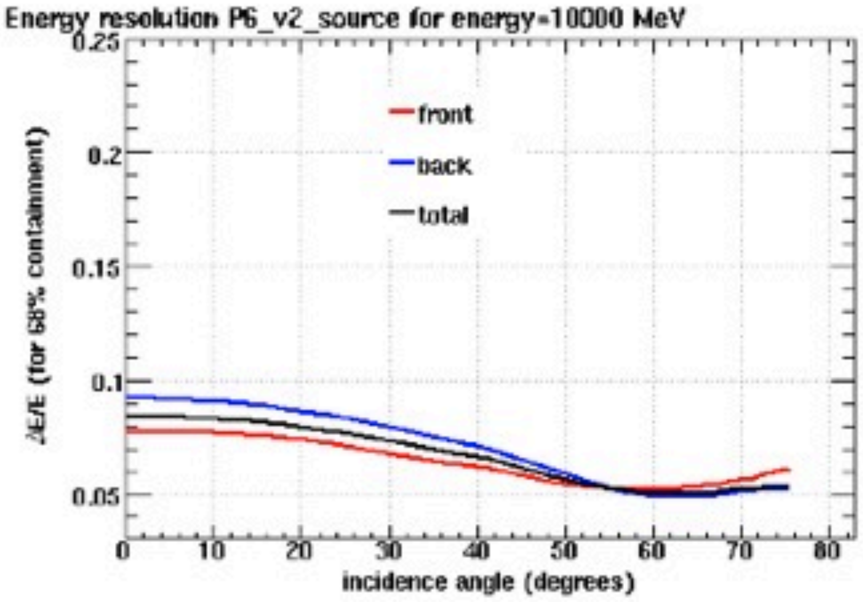
Energy resolution P6_v2_source for normal incidence



~14% @ 300 GeV

~8% @ 10 GeV

Energy resolution P6_v2_source for energy=10000 MeV

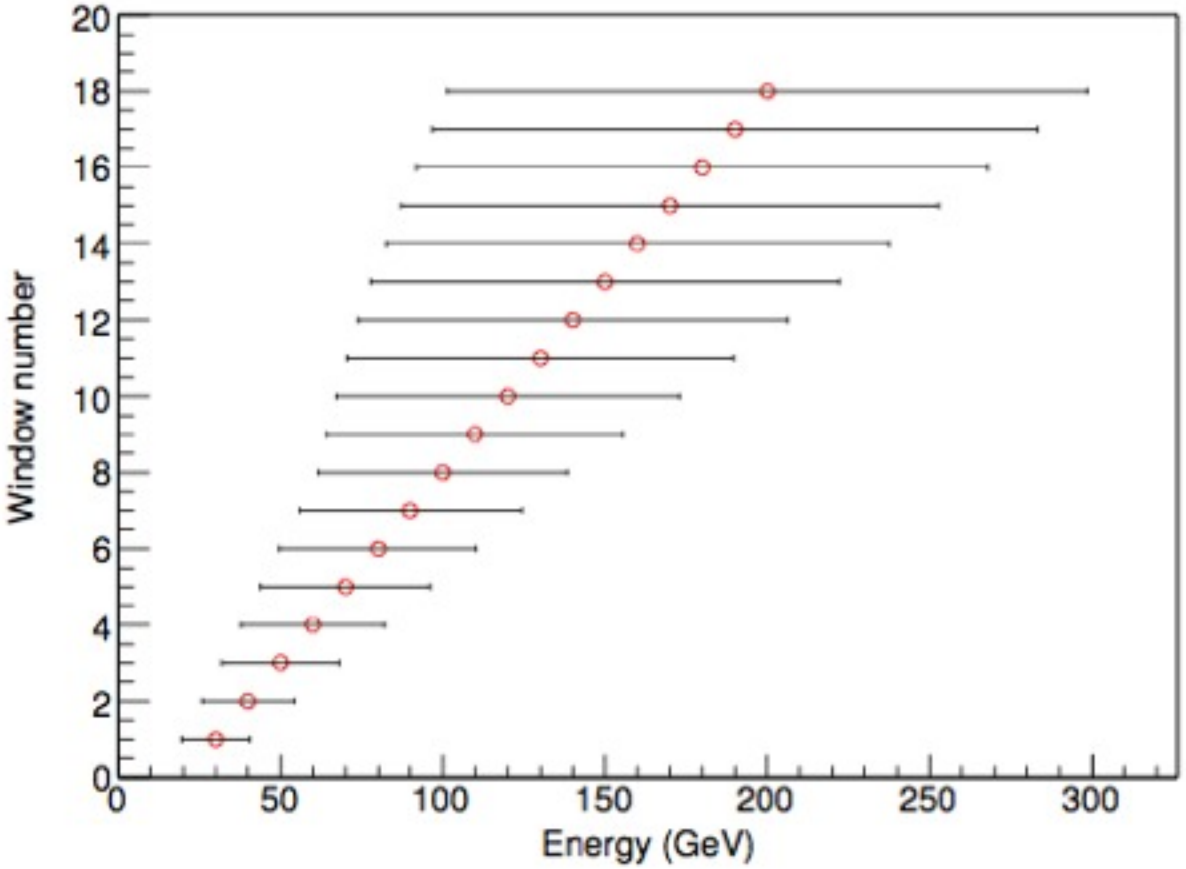


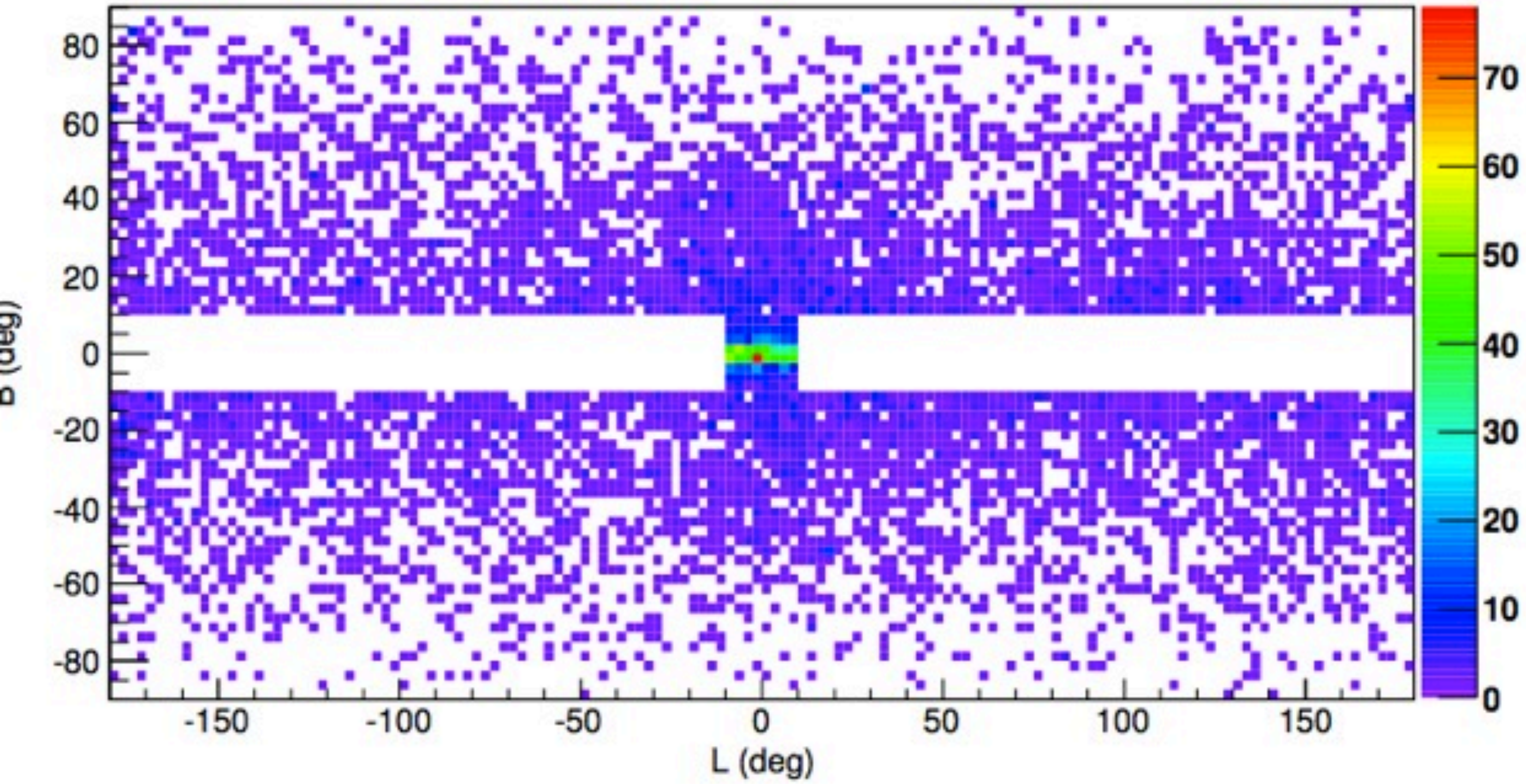
NB: Pass 6 IRFs
(currently Pass 7)

Slide From Tomi Ylinen

Line search regions

Sliding energy window →



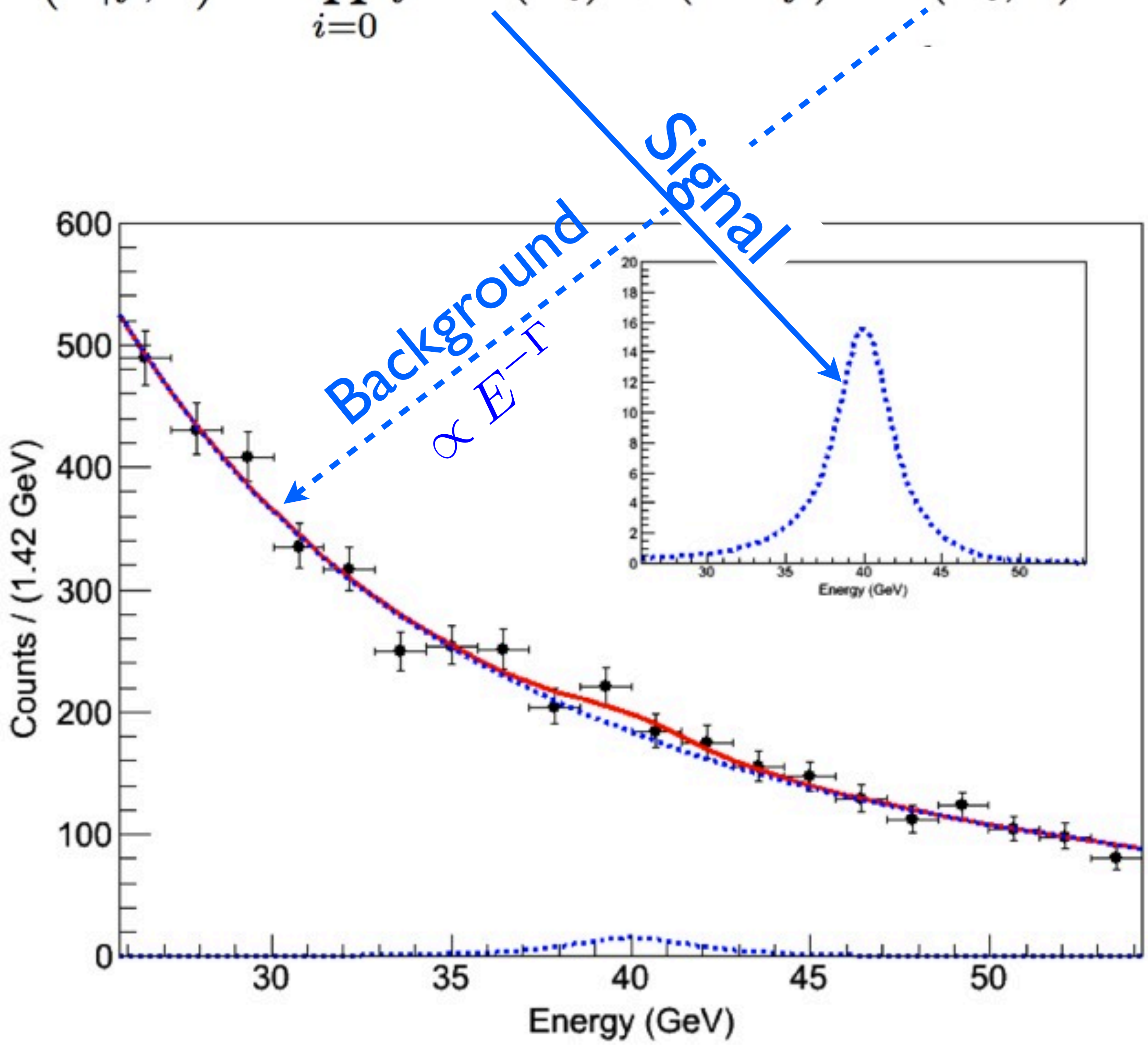


← Region of interest

b>10° + G.C. 20°x 20°

Likelihood analysis

$$L\left(\bar{E}|f,\Gamma\right) = \prod_{i=0}^{n_{tot}} f \cdot S\left(E_i\right) + (1-f) \cdot B\left(E_i,\Gamma\right)$$

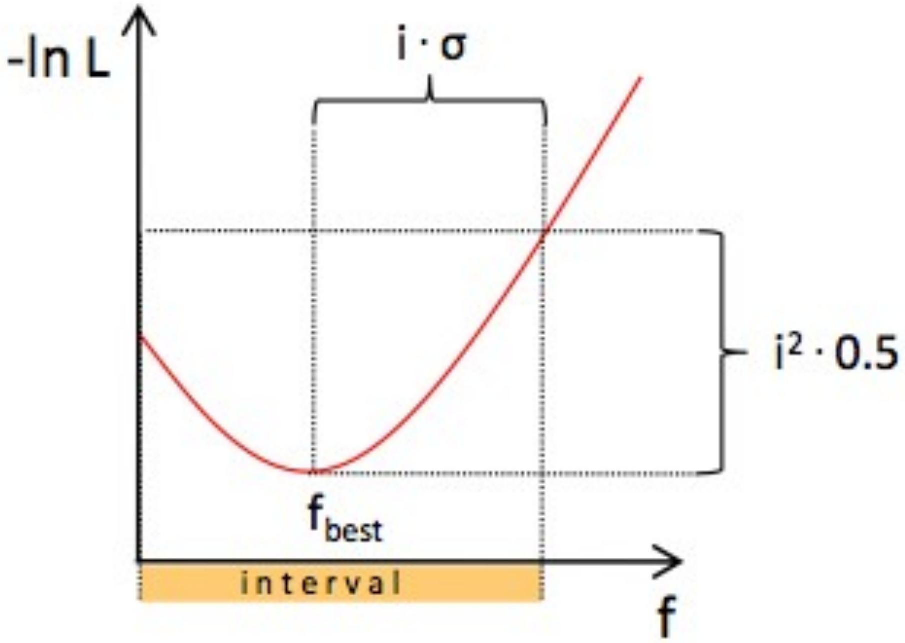


Likelihood analysis

$$L\left(\bar{E}|f,\Gamma\right) = \prod_{i=0}^{n_{tot}} f \cdot S\left(E_i\right) + (1-f) \cdot B\left(E_i,\Gamma\right)$$

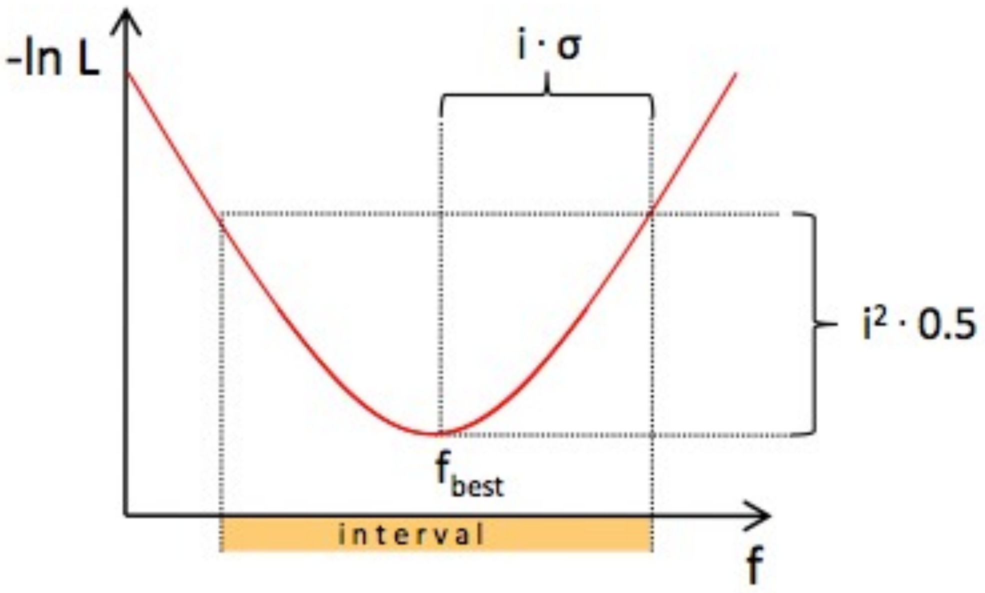
- The minimized and evaluated -ln (L) can be used for both upper limits (non-detection) on f and for detection

upper limit



f = 0 **IS** included in interval

detection

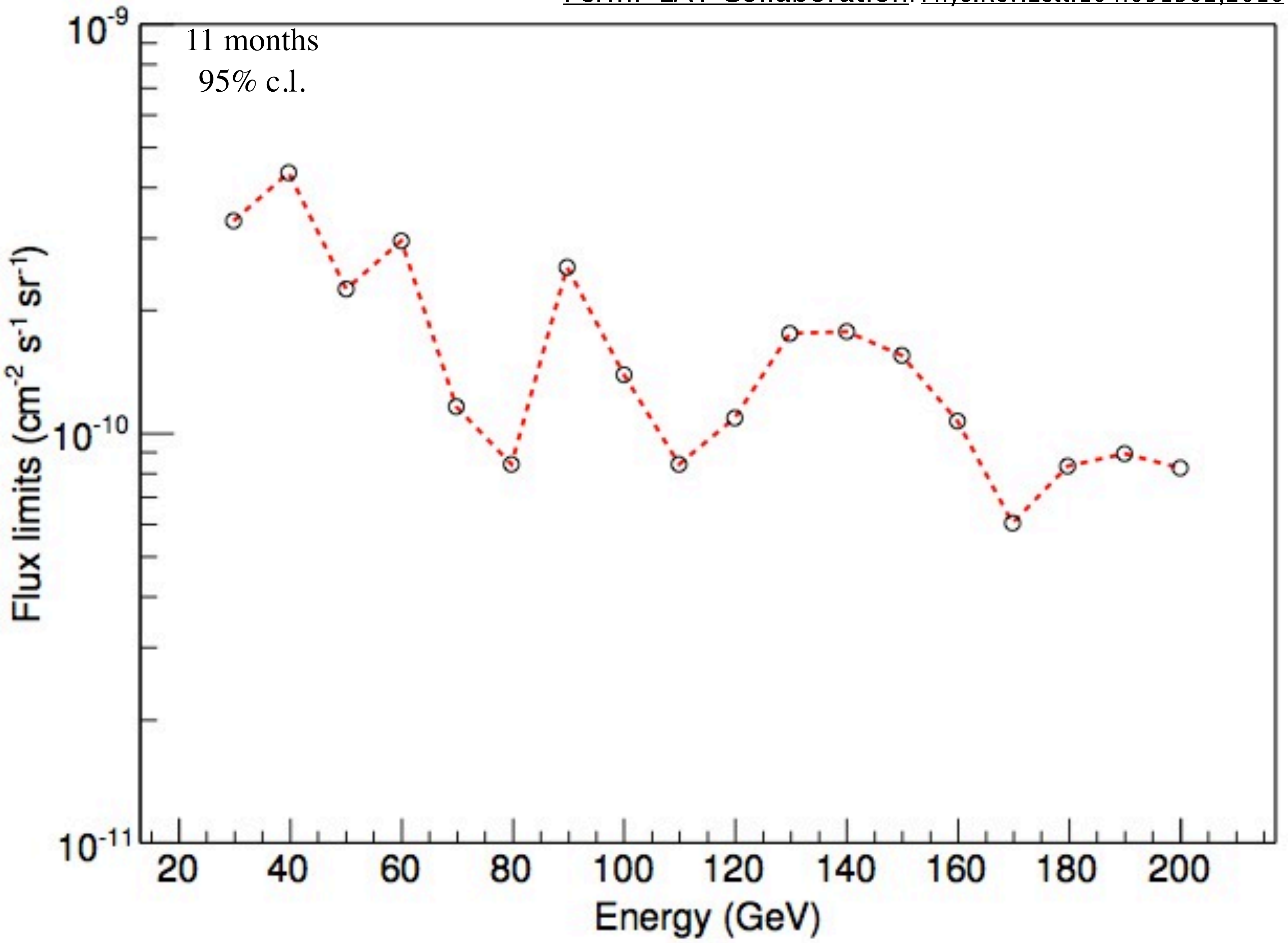


f = 0 **IS NOT** included in interval

Figures from Tomi Ylinen

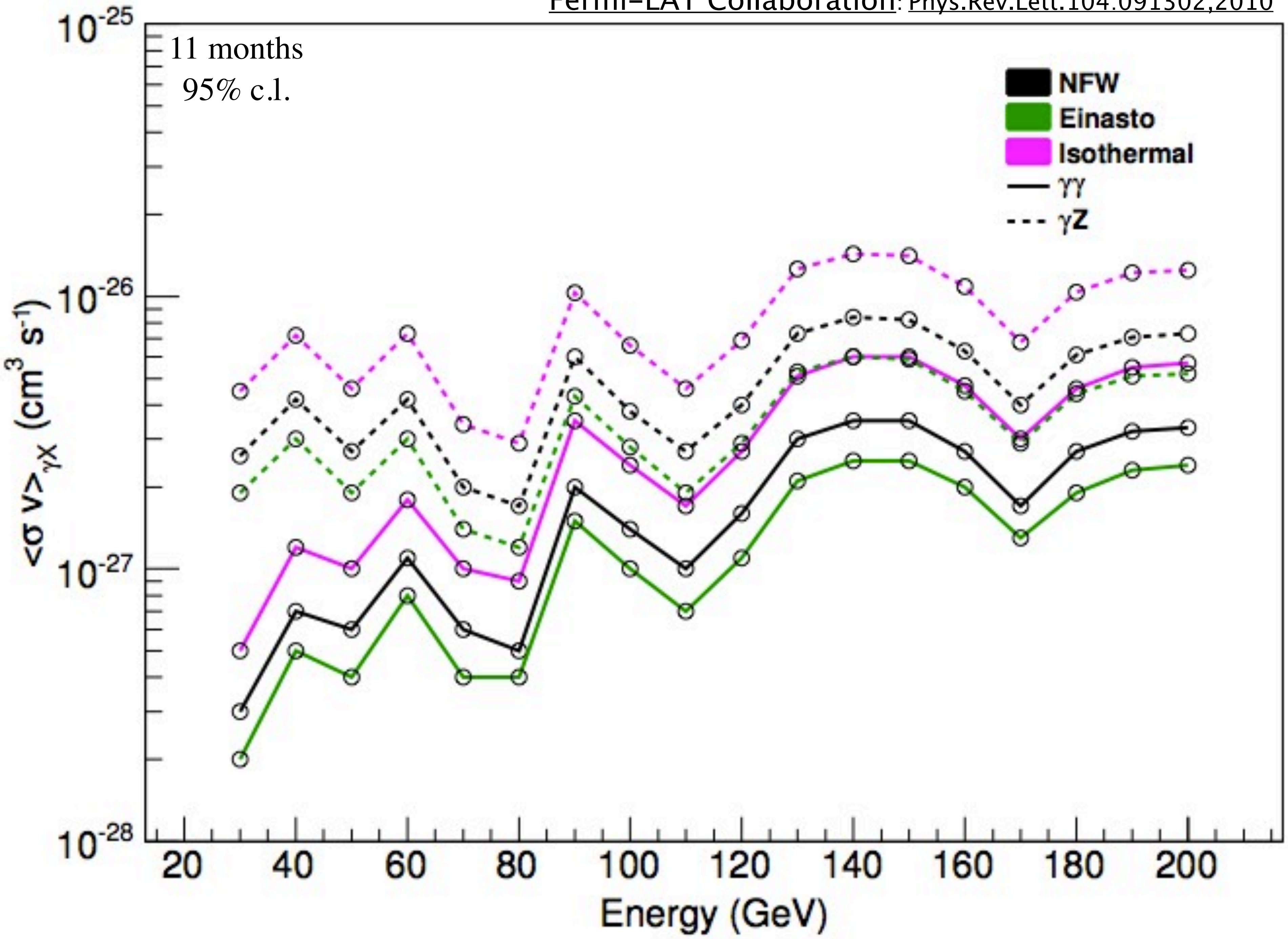
Line-fluxes upper limits

Fermi-LAT Collaboration: Phys.Rev.Lett.104:091302,2010



Cross-section upper limits

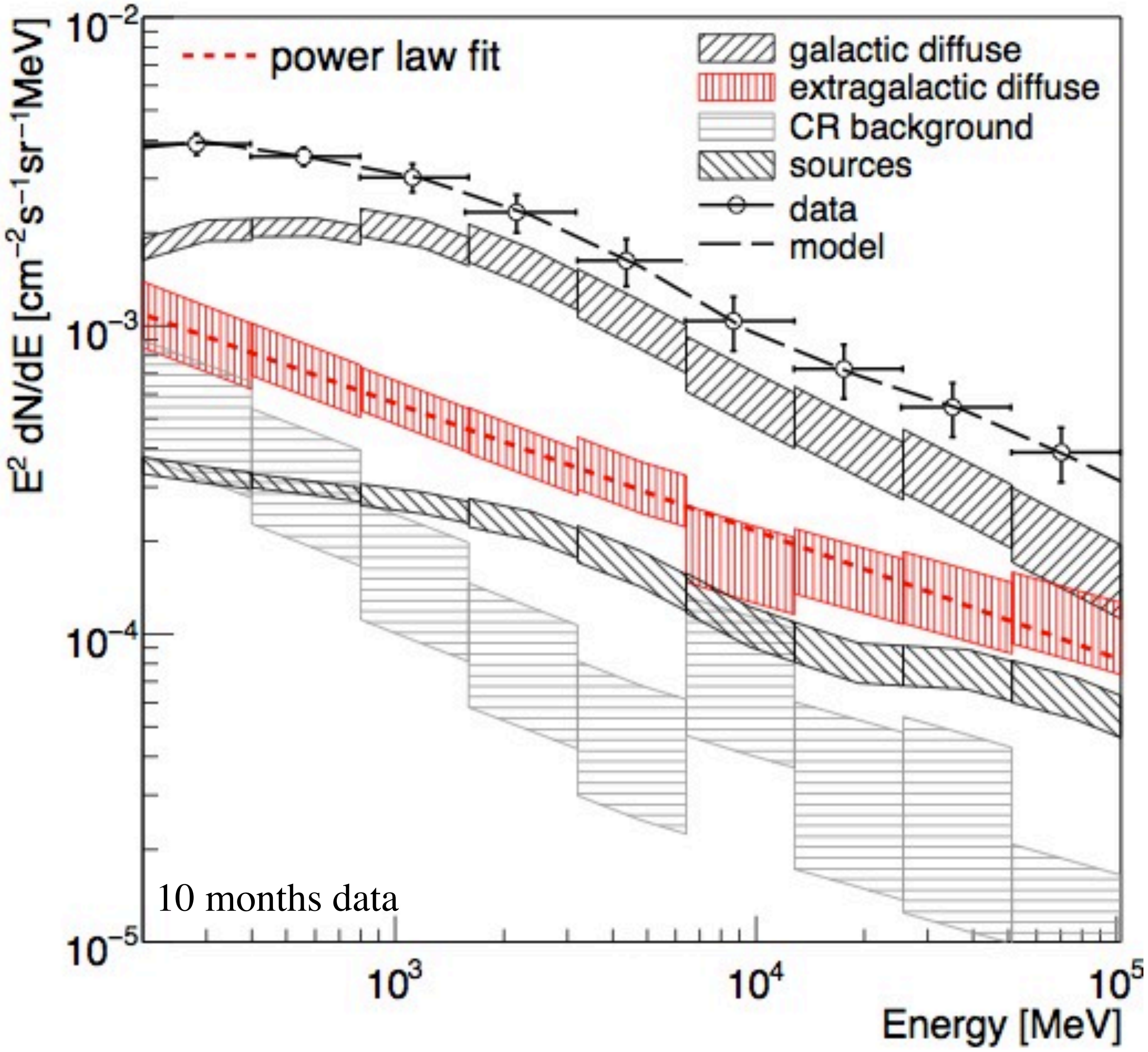
Fermi-LAT Collaboration: Phys.Rev.Lett.104:091302,2010



$$\langle\sigma v\rangle^{m_{\rm DM}}_{\gamma {\rm X,limit}} = 2\frac{m^2_{\rm DM}}{m'^2_{\rm DM}} \times \langle\sigma v\rangle^{m'_{\rm DM}}_{\gamma\gamma,{\rm limit}}\,, \quad \text{where } m'_{\rm DM} = \frac{m_{\rm DM}}{2}\left(1+\sqrt{1+\frac{m^2_{\rm X}}{m^2_{\rm DM}}}\right).$$

Cosmological
dark matter line

Cosmological/isotropic gamma-ray measurement

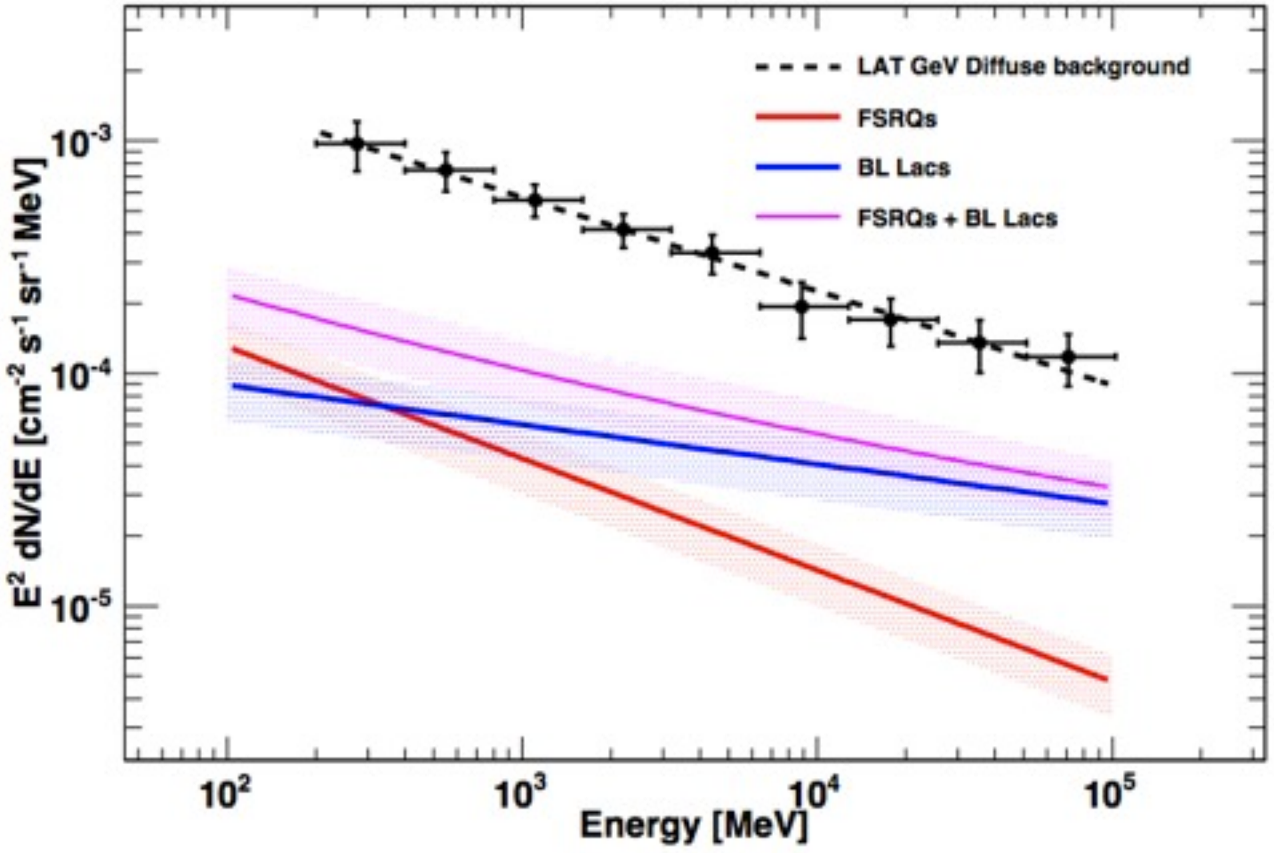


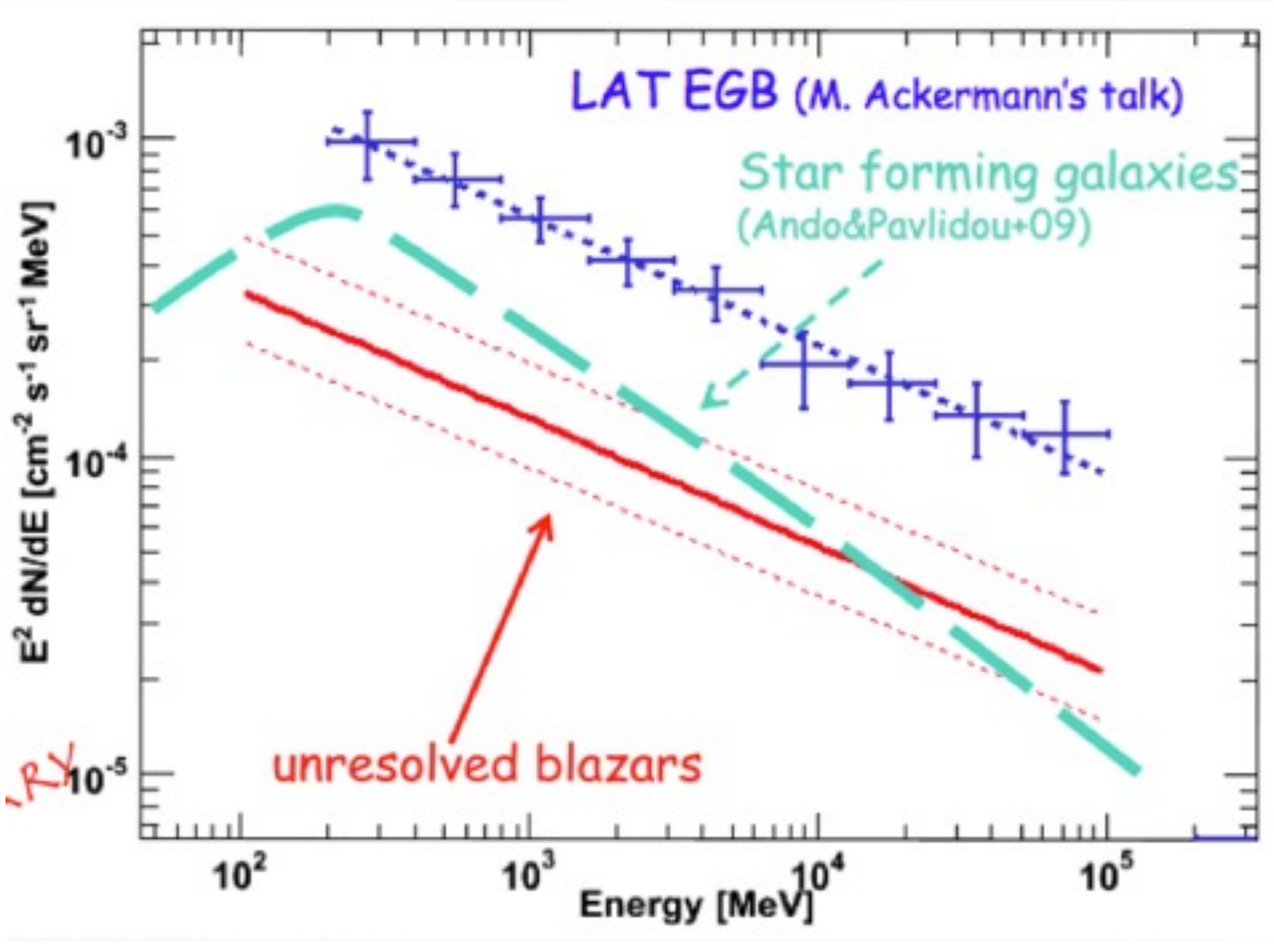
Fermi-LAT Collaboration
Phys.Rev.Lett.104:101101,2010
arXiv:1002.3603

Cosmological diffuse sources

Blazars: 16 ±1.8±10 % of the GeV isotropic diffuse background.

Fermi-LAT Collaboration: The Fermi-LAT high-latitude Survey: Source Counts Distributions and the Origin of the Diffuse Background arXiv:1003.0895v1



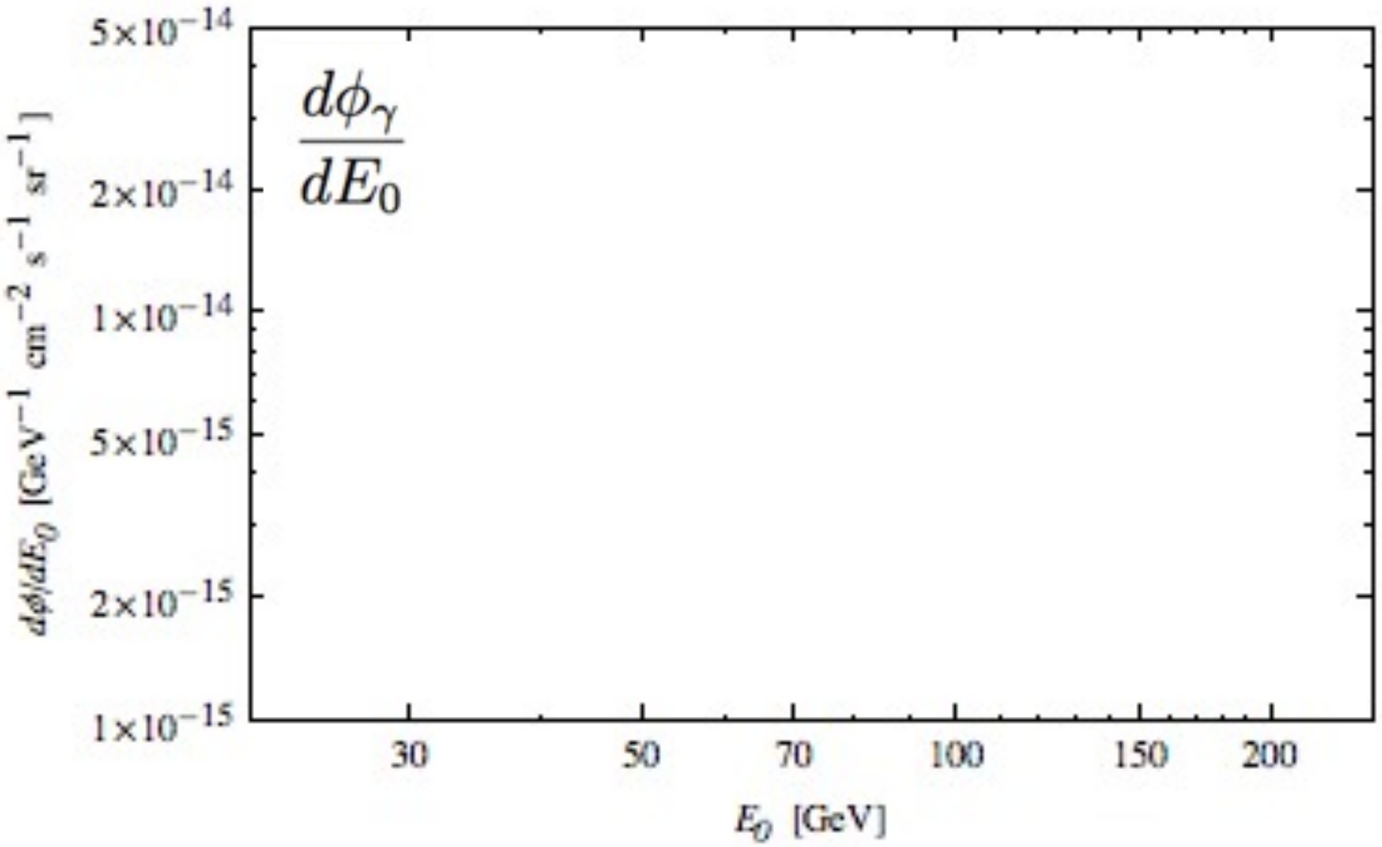


Star forming galaxies?

Cosmological DM line

$$\frac{d\phi_\gamma}{dE_0} = \frac{\langle\sigma v\rangle}{8\pi}\frac{c}{H_0}\frac{\bar{\rho}_0^2}{m_{DM}^2}\int dz(1+z)^3\frac{\Delta^2(z)}{h(z)}\underline{\frac{dN_\gamma(E_0(1+z))}{dE}}e^{-\tau(z,E_0)}$$

$$\frac{dN_\gamma}{dE} \propto \delta(E_\gamma - m_{DM})$$



Cosmological DM line

$$\frac{d\phi_\gamma}{dE_0} = \frac{\langle\sigma v\rangle}{8\pi}\,\frac{c}{H_0}\,\frac{\bar{\rho}_0^2}{m_{DM}^2}\int dz(1+z)^3\,\frac{\Delta^2(z)}{h(z)}\,\underline{\frac{dN_\gamma(E_0(1+z))}{dE}}\,e^{-\tau(z,E_0)}$$

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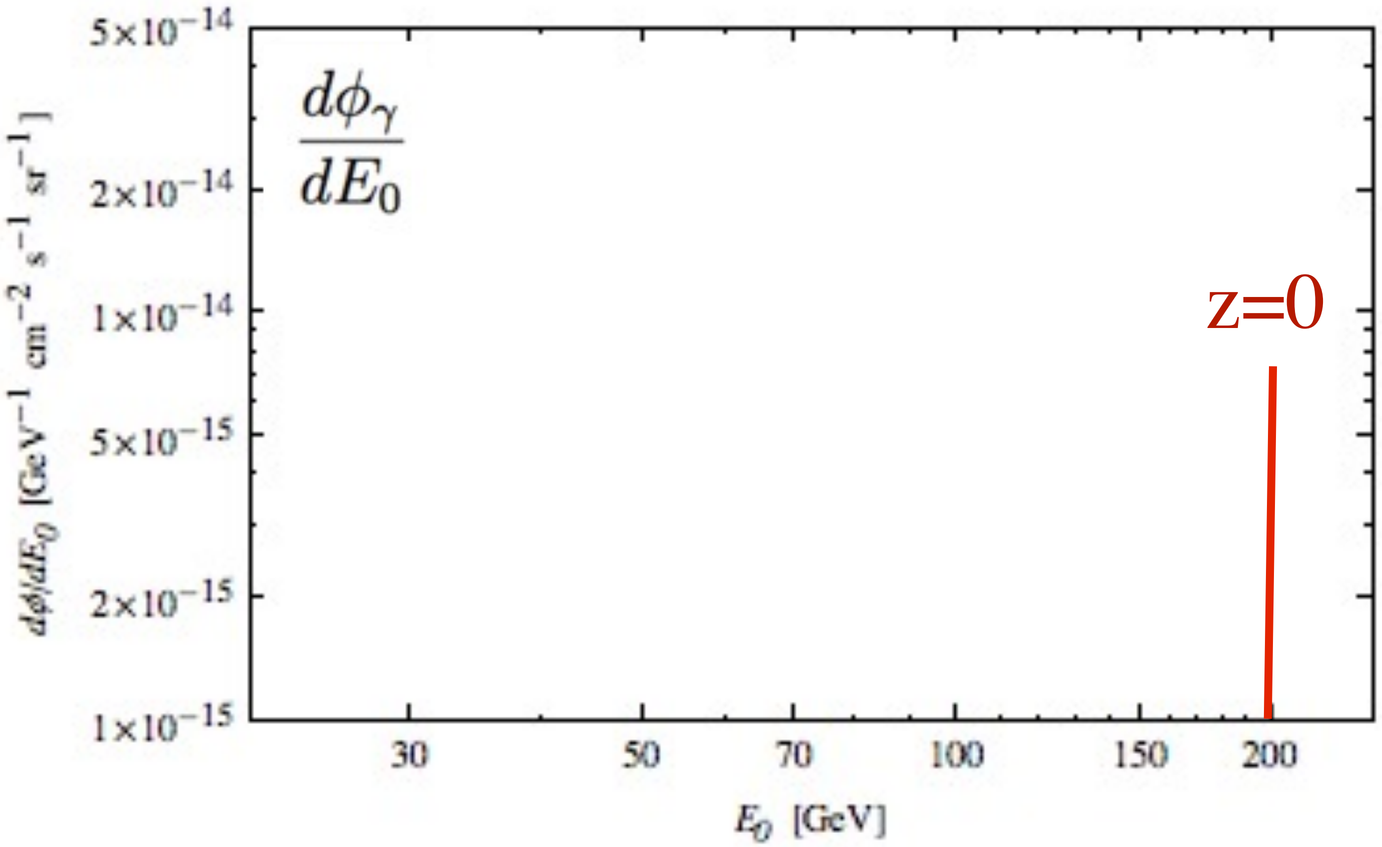
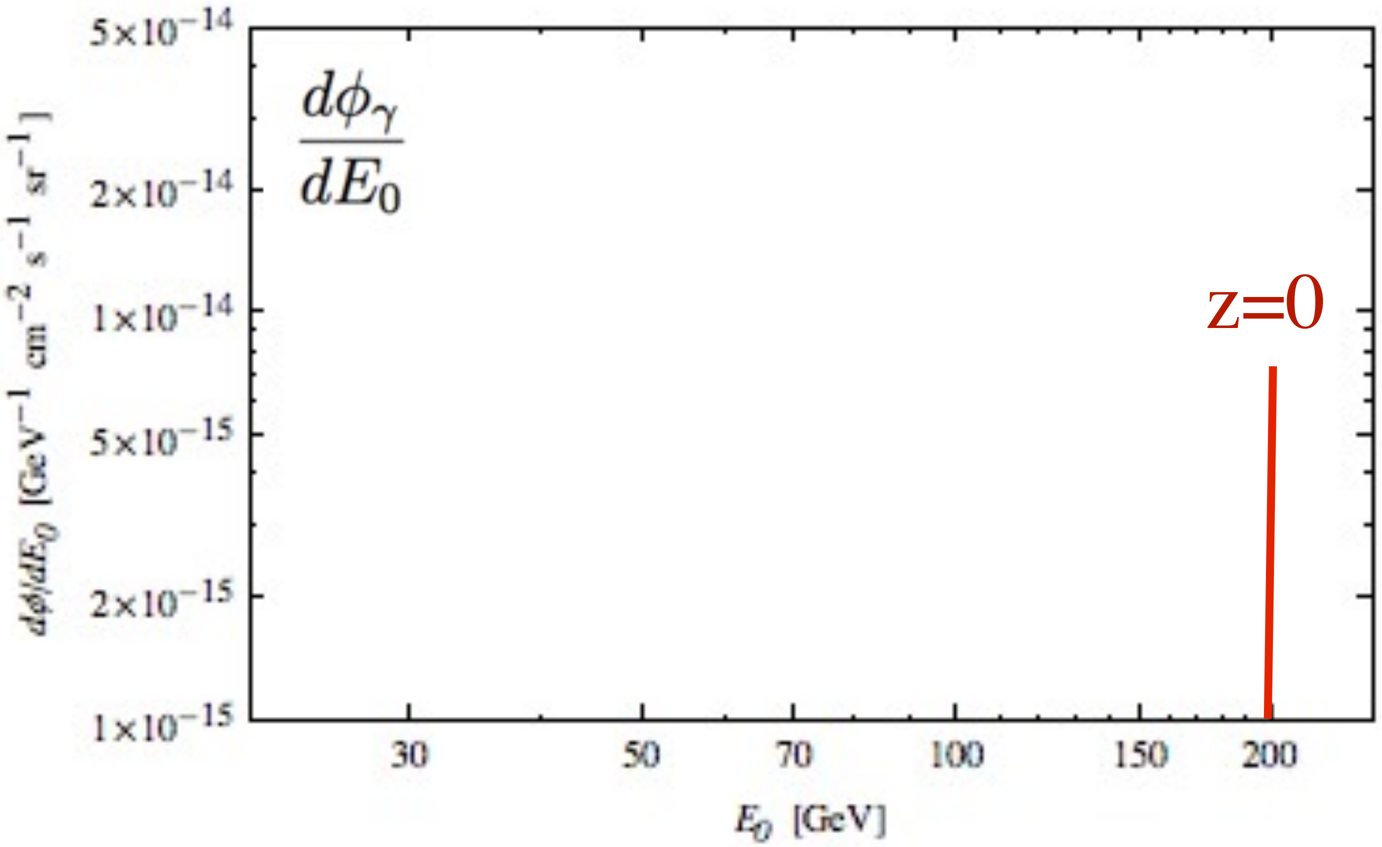


Cosmological DM line

$$\frac{d\phi_\gamma}{dE_0} = \frac{\langle \sigma v \rangle}{8\pi} \frac{c}{H_0} \frac{\bar{\rho}_0^2}{m_{DM}^2} \int dz (1+z)^3 \frac{\Delta^2(z)}{h(z)} \underline{\frac{dN_\gamma(E_0(1+z))}{dE}} e^{-\tau(z,E_0)}$$

$$\begin{aligned} \frac{dN_\gamma}{dE} &\propto \delta(E_\gamma - m_{DM}) \\ &= \frac{\delta(E_0(1+z) - m_{DM})}{1+z} \end{aligned}$$



Cosmological DM line

$$\frac{d\phi_\gamma}{dE_0} = \frac{\langle \sigma v \rangle}{8\pi} \frac{c}{H_0} \frac{\bar{\rho}_0^2}{m_{DM}^2} \int dz (1+z)^3 \frac{\Delta^2(z)}{h(z)} \frac{dN_\gamma(E_0(1+z))}{dE} e^{-\tau(z,E_0)}$$

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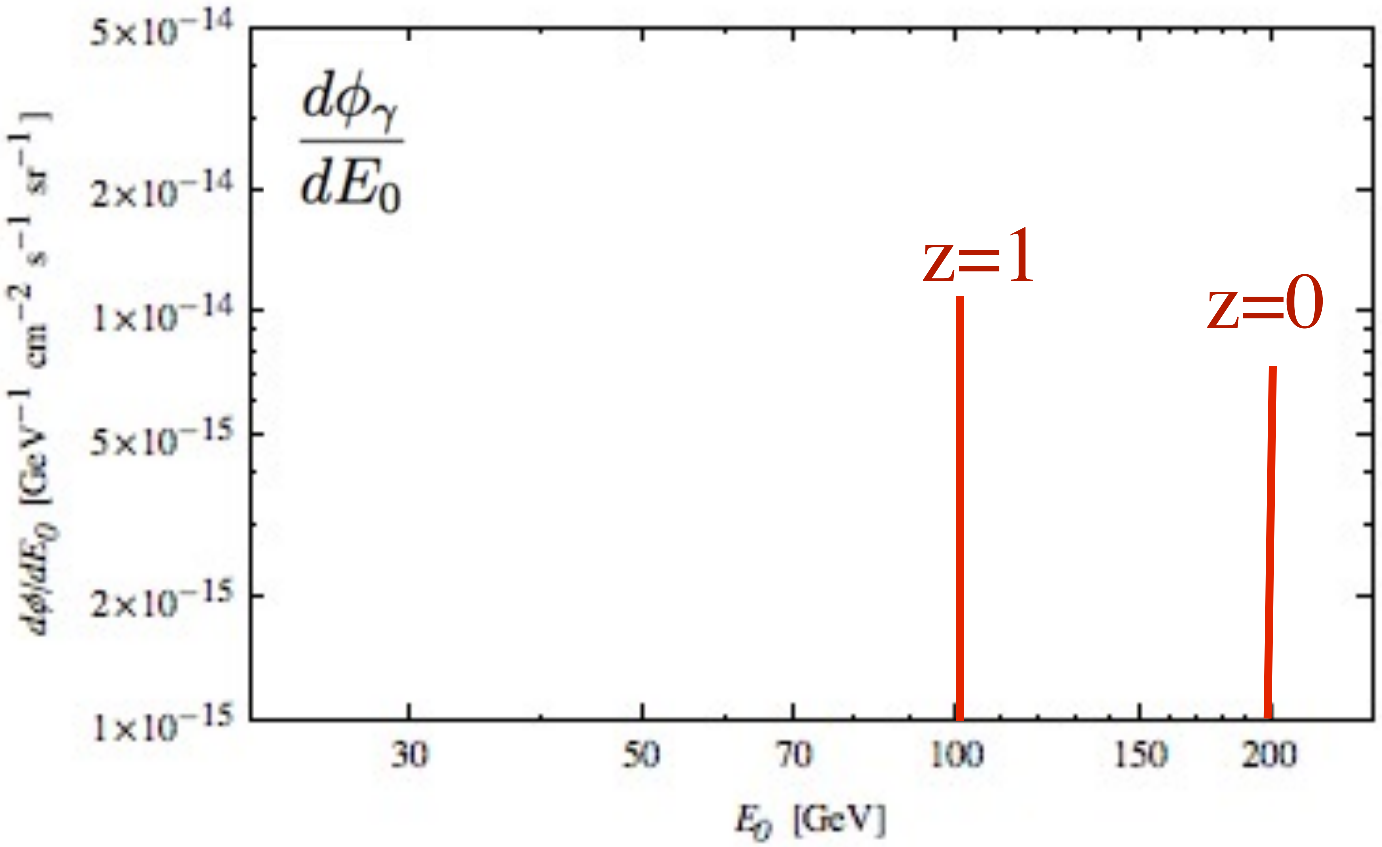

Cosmological DM line

$$\frac{d\phi_\gamma}{dE_0} = \frac{\langle\sigma v\rangle}{8\pi}\,\frac{c}{H_0}\,\frac{\bar{\rho}_0^2}{m_{DM}^2}\int dz(1+z)^3\,\frac{\Delta^2(z)}{h(z)}\,\frac{dN_\gamma(E_0(1+z))}{dE}\,e^{-\tau(z,E_0)}$$

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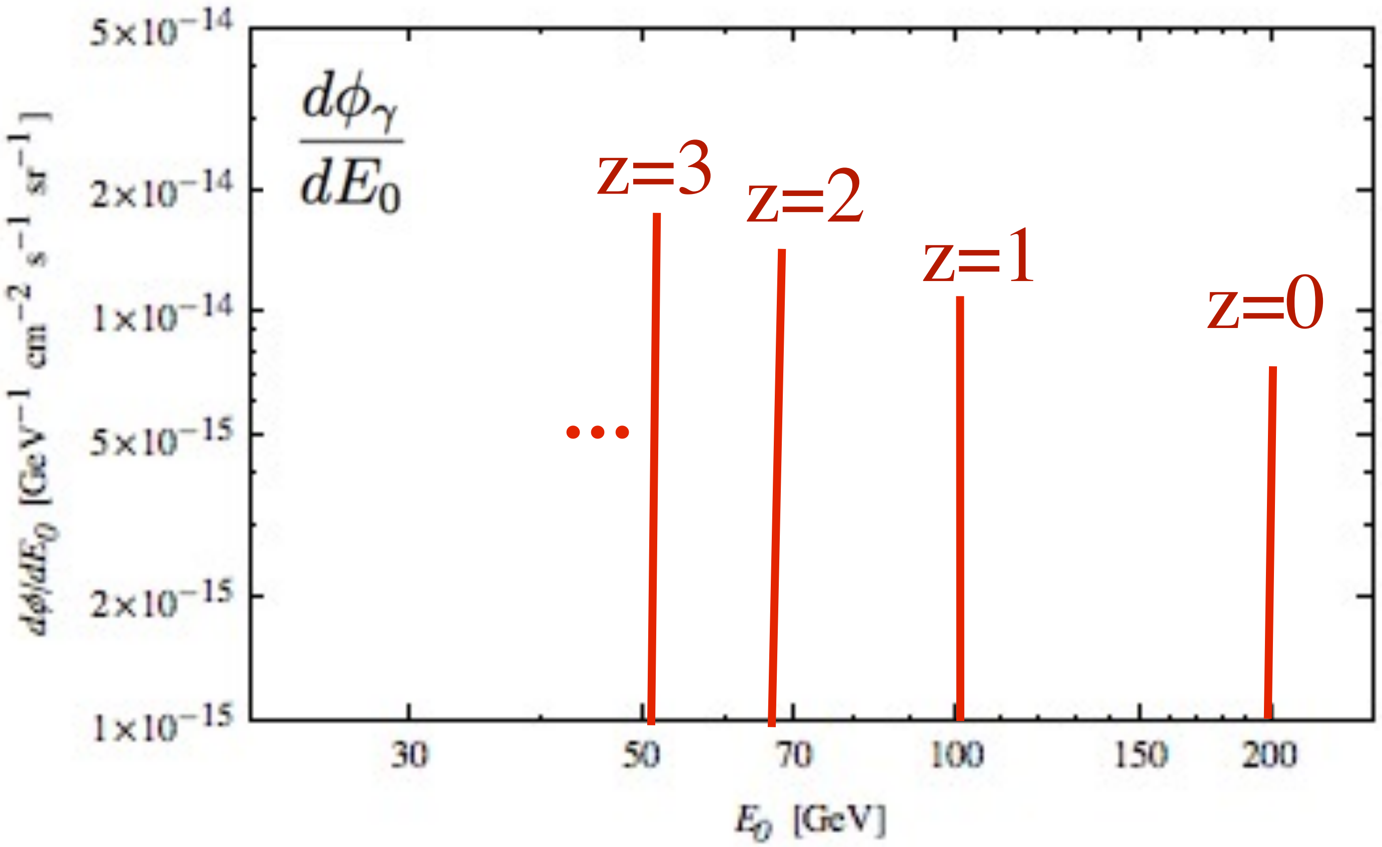

Cosmological DM line

$$\frac{d\phi_\gamma}{dE_0} = \frac{\langle\sigma v\rangle}{8\pi}\,\frac{c}{H_0}\,\frac{\bar{\rho}_0^2}{m_{DM}^2}\int dz(1+z)^3\,\frac{\Delta^2(z)}{h(z)}\,\frac{dN_\gamma(E_0(1+z))}{dE}\,e^{-\tau(z,E_0)}$$

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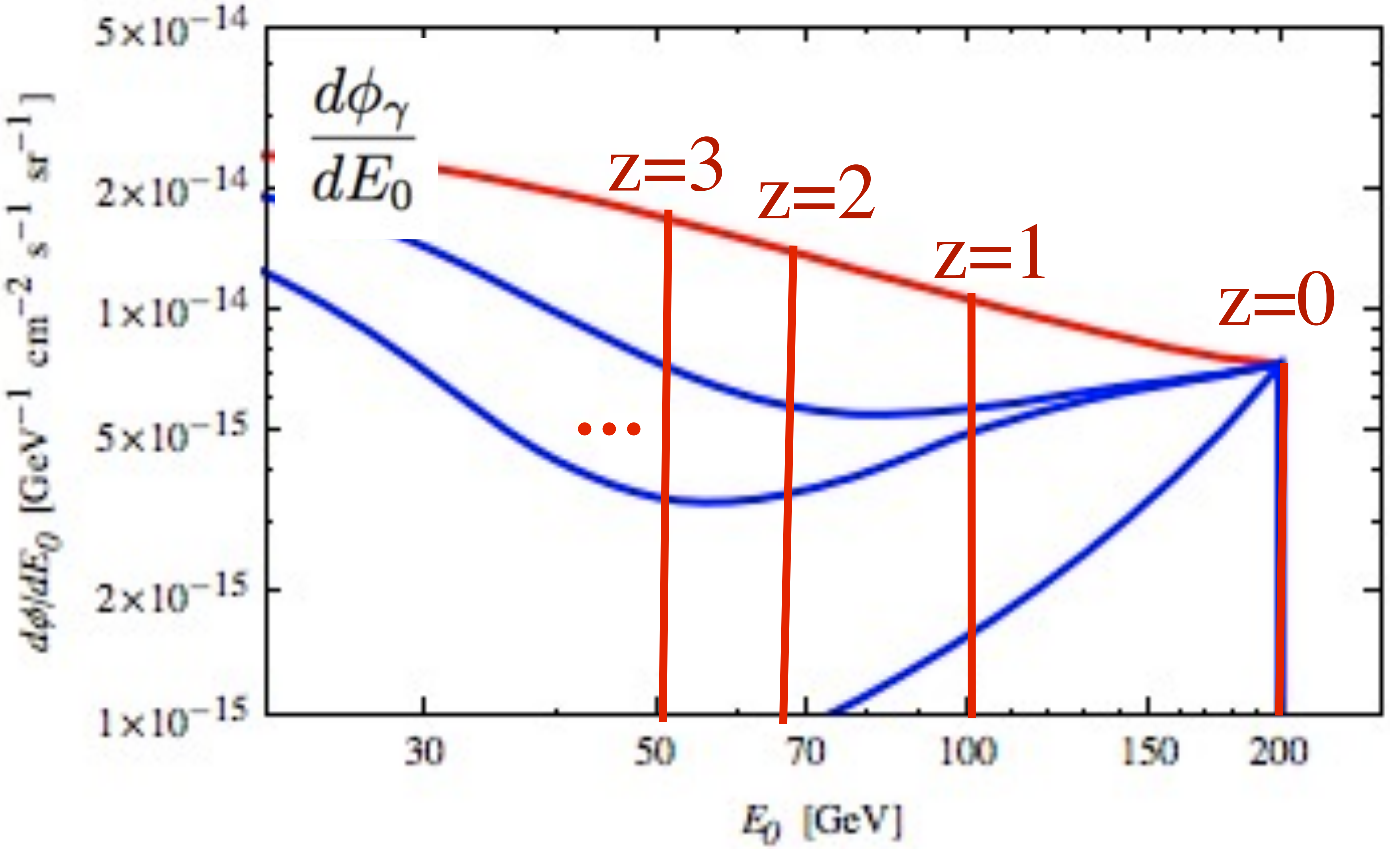

Cosmological DM line

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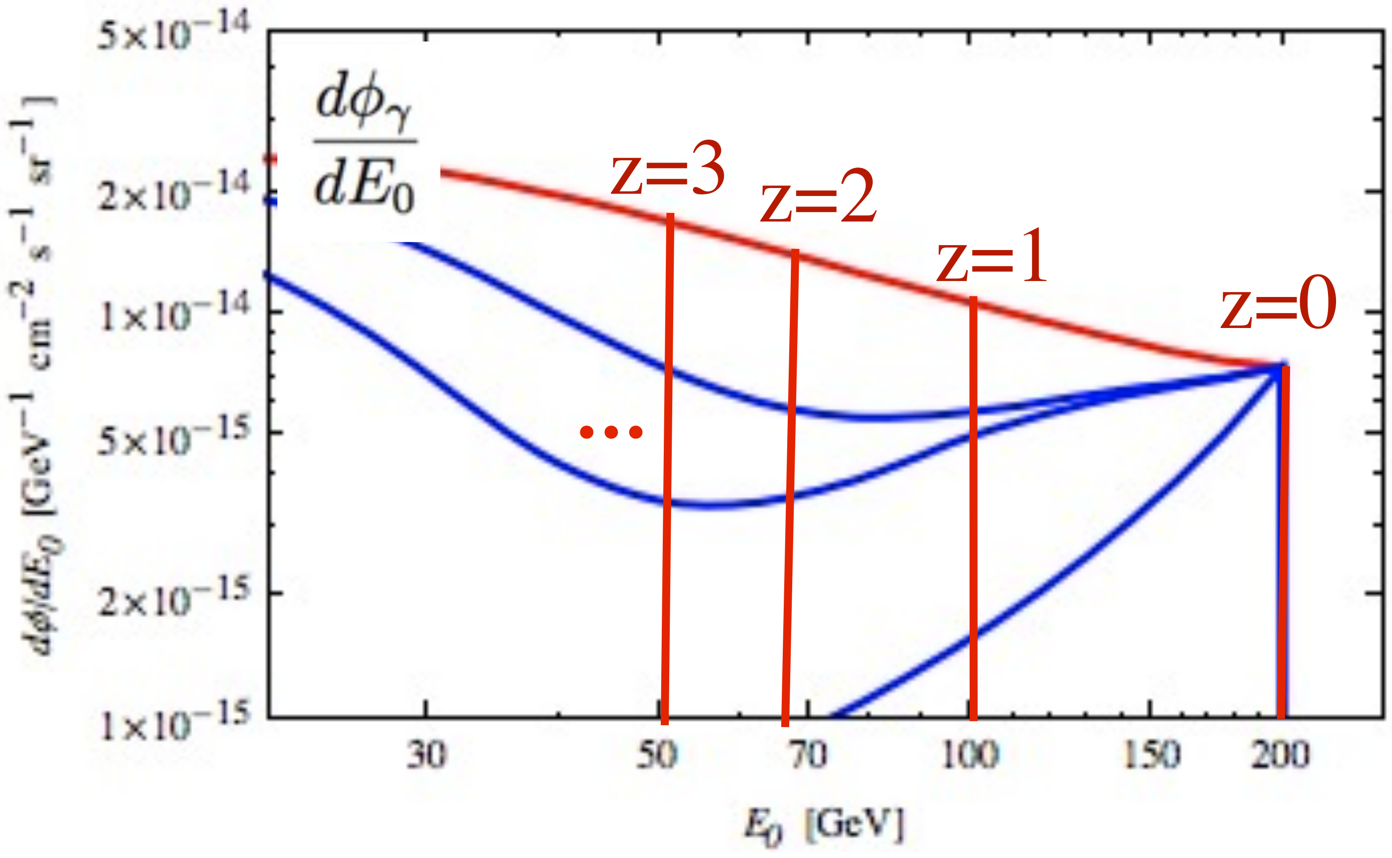
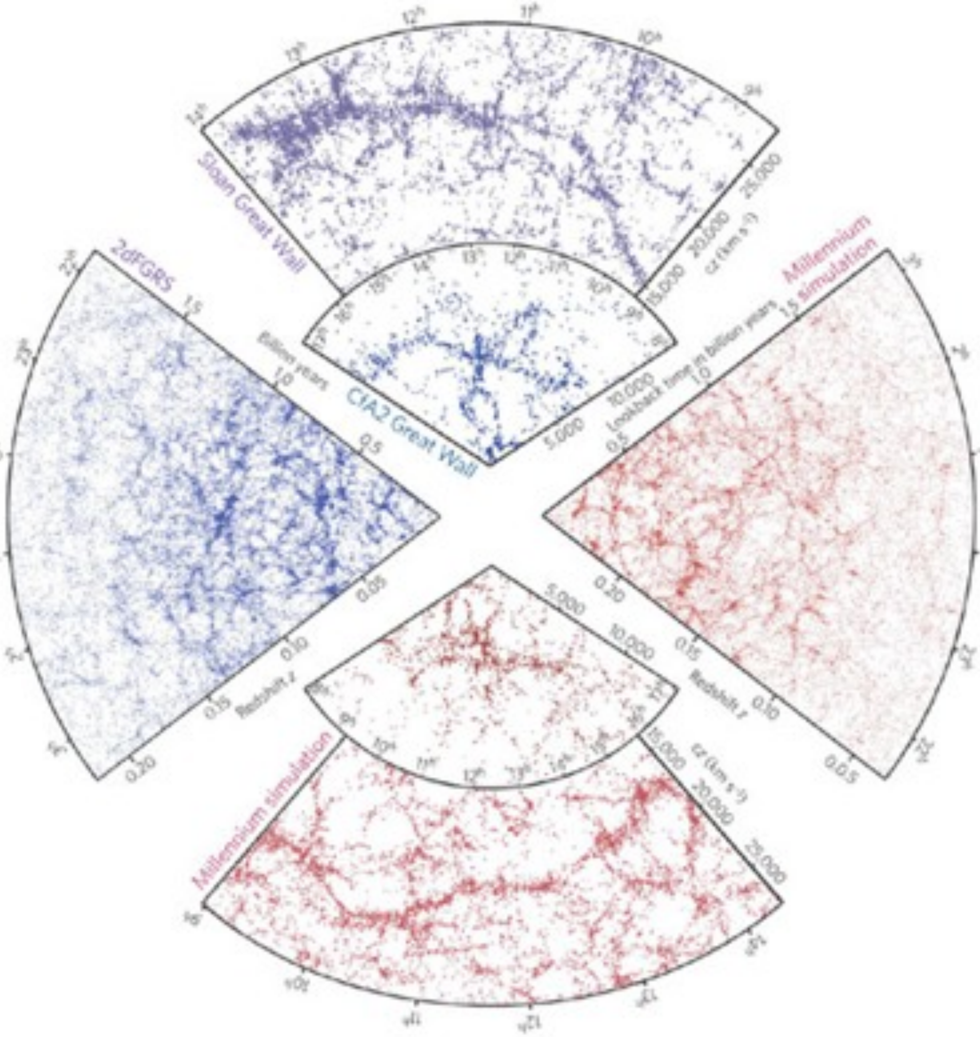
$$\begin{aligned}\frac{dN_\gamma}{dE} &\propto \delta(E_\gamma - m_{DM})\\ &= \frac{\delta(E_0(1+z) - m_{DM})}{1+z}\\ &= \frac{\delta(z - m_{DM}/E_0 + 1)}{m_{DM}}\end{aligned}$$

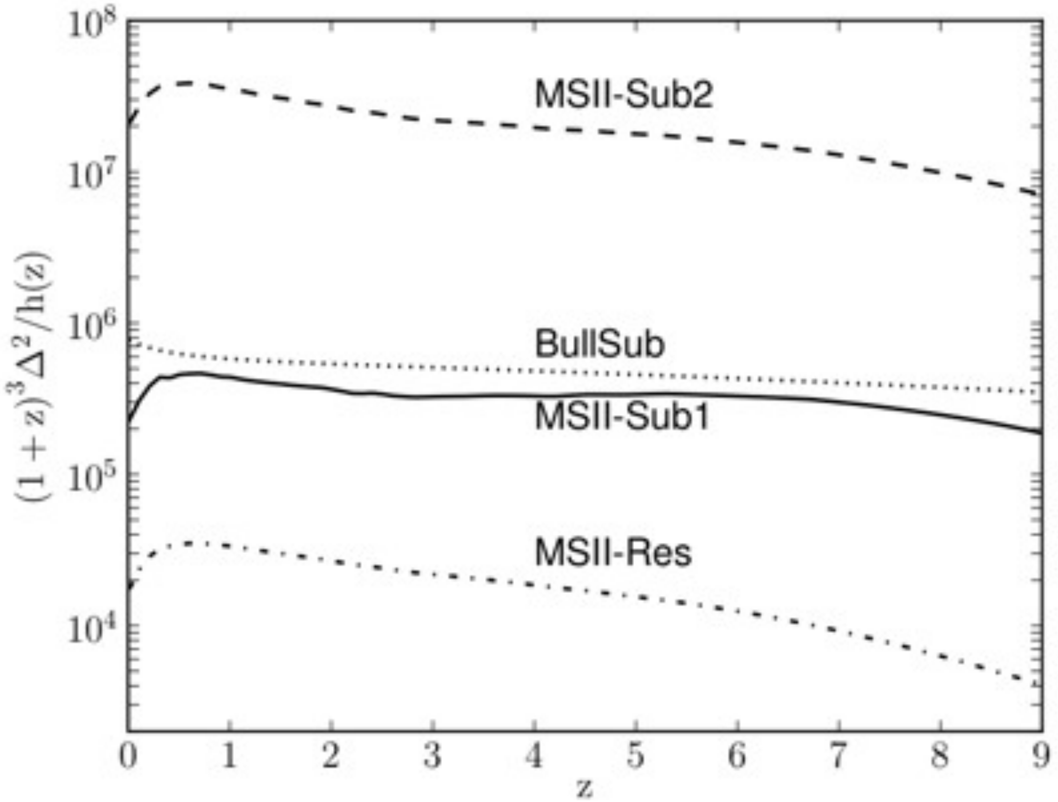


Cosmological DM line

$$\frac{d\phi_\gamma}{dE_0} = \frac{\langle \sigma v \rangle}{8\pi} \frac{c}{H_0} \frac{\bar{\rho}_0^2}{m_{DM}^2} \int dz \underline{(1+z)^3 \frac{\Delta^2(z)}{h(z)}} \frac{dN_\gamma(E_0(1+z))}{dE} e^{-\tau(z,E_0)}$$

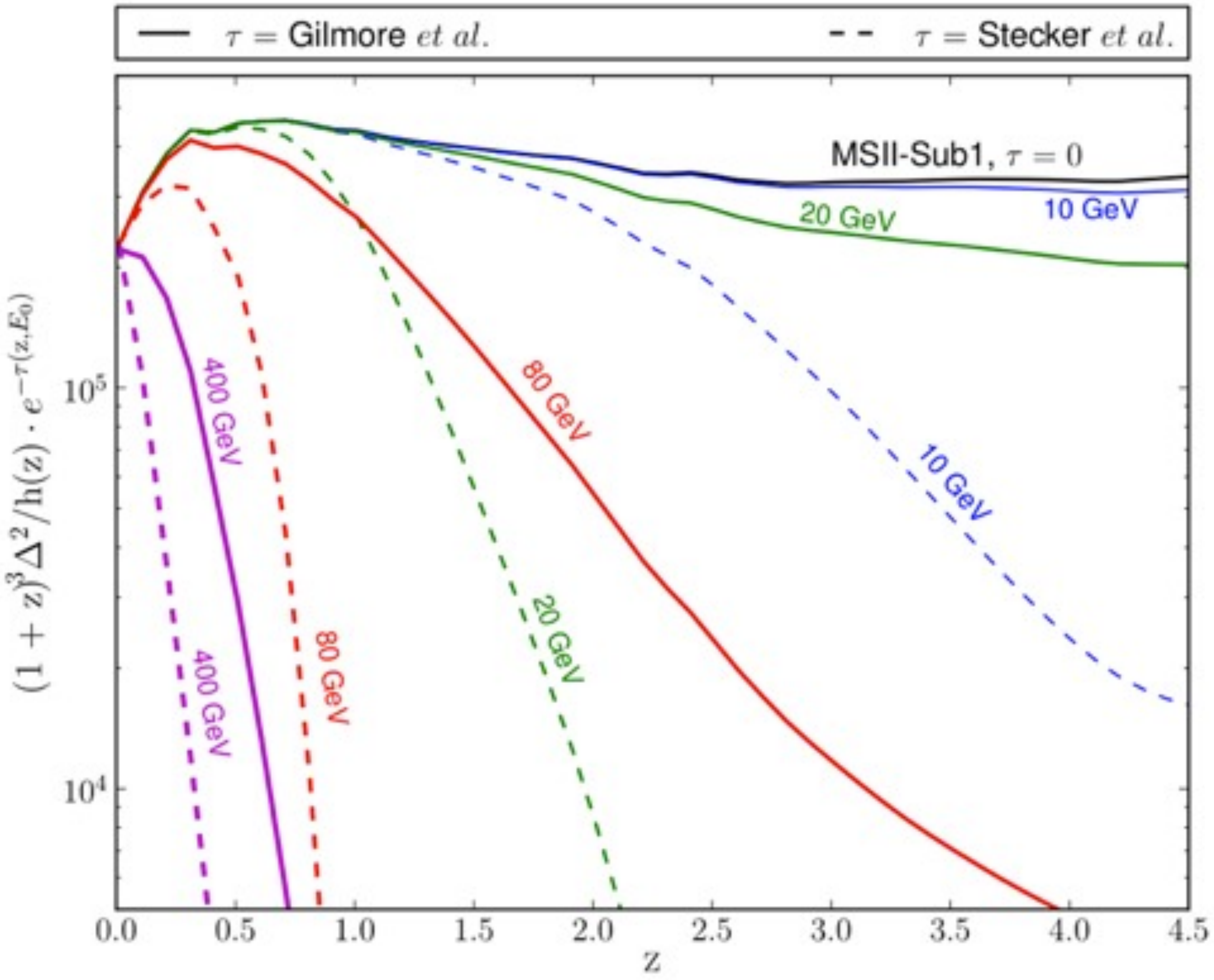


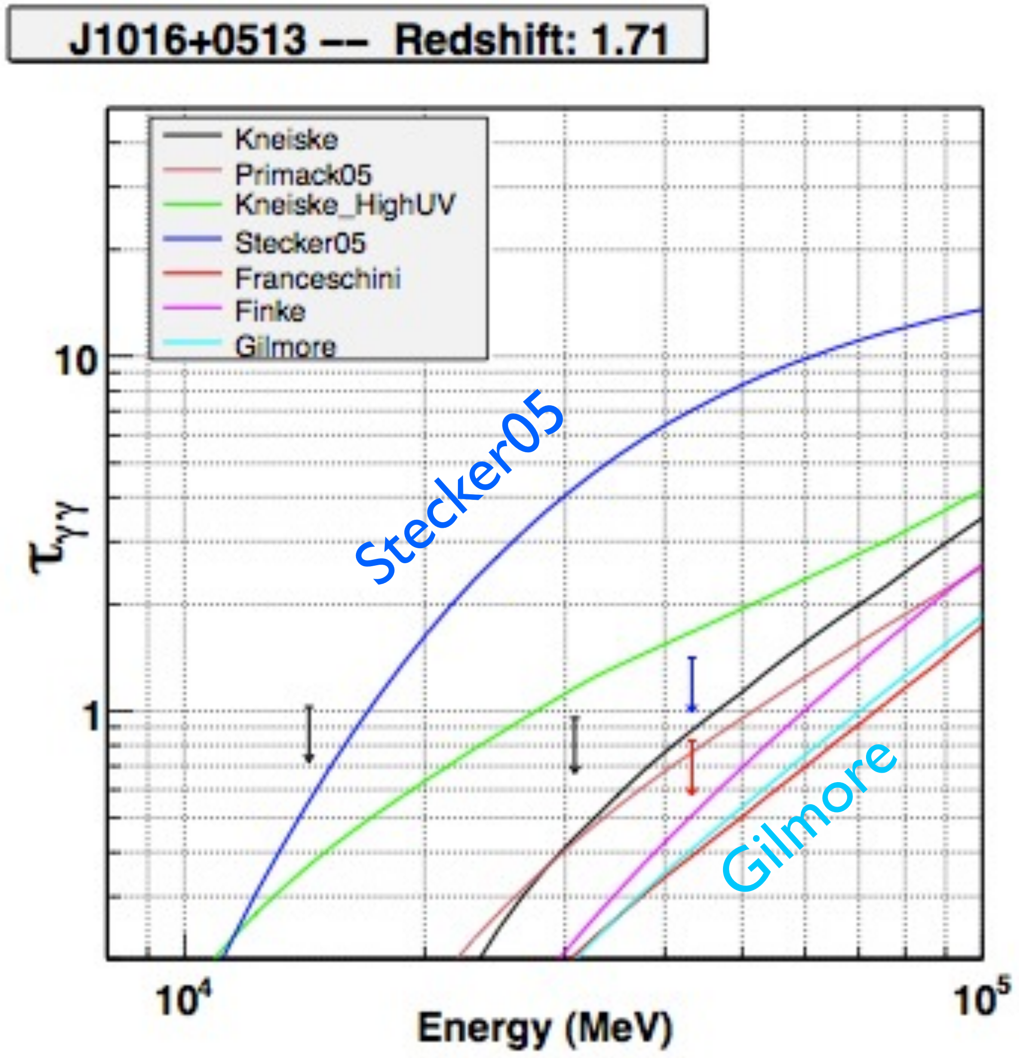
$$\Delta^2(z) = \int dM \frac{dn}{dM} \int dc\, P(c) \frac{\langle \rho^2(M,c) \rangle}{\bar{\rho}(z)^2}$$



Cosmological DM line

$$\frac{d\phi_\gamma}{dE_0} = \frac{\langle \sigma v \rangle}{8\pi} \frac{c}{H_0} \frac{\bar{\rho}_0^2}{m_{DM}^2} \int dz (1+z)^3 \frac{\Delta^2(z)}{h(z)} \frac{dN_\gamma(E_0(1+z))}{dE} e^{-\tau(z,E_0)}$$

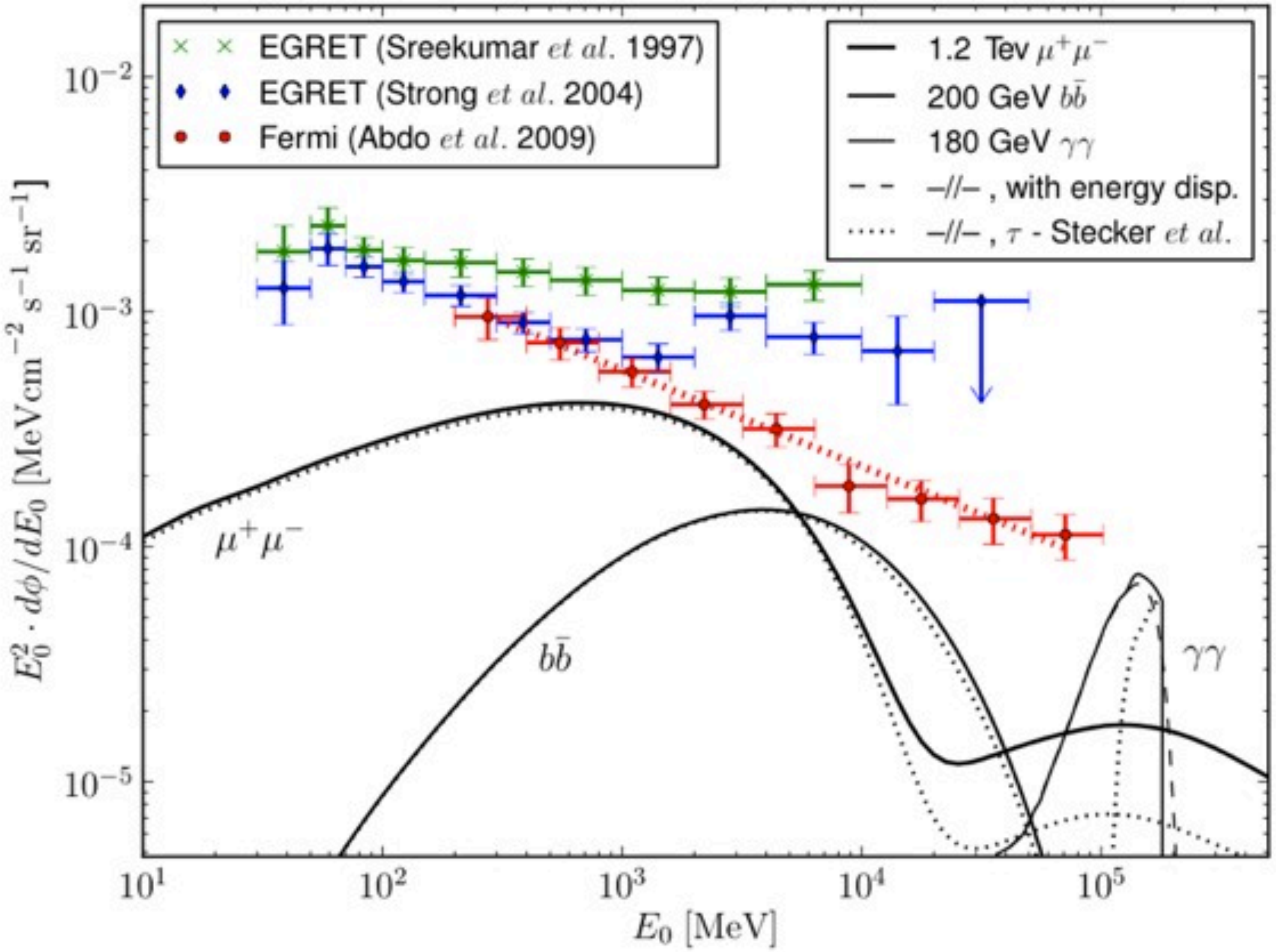




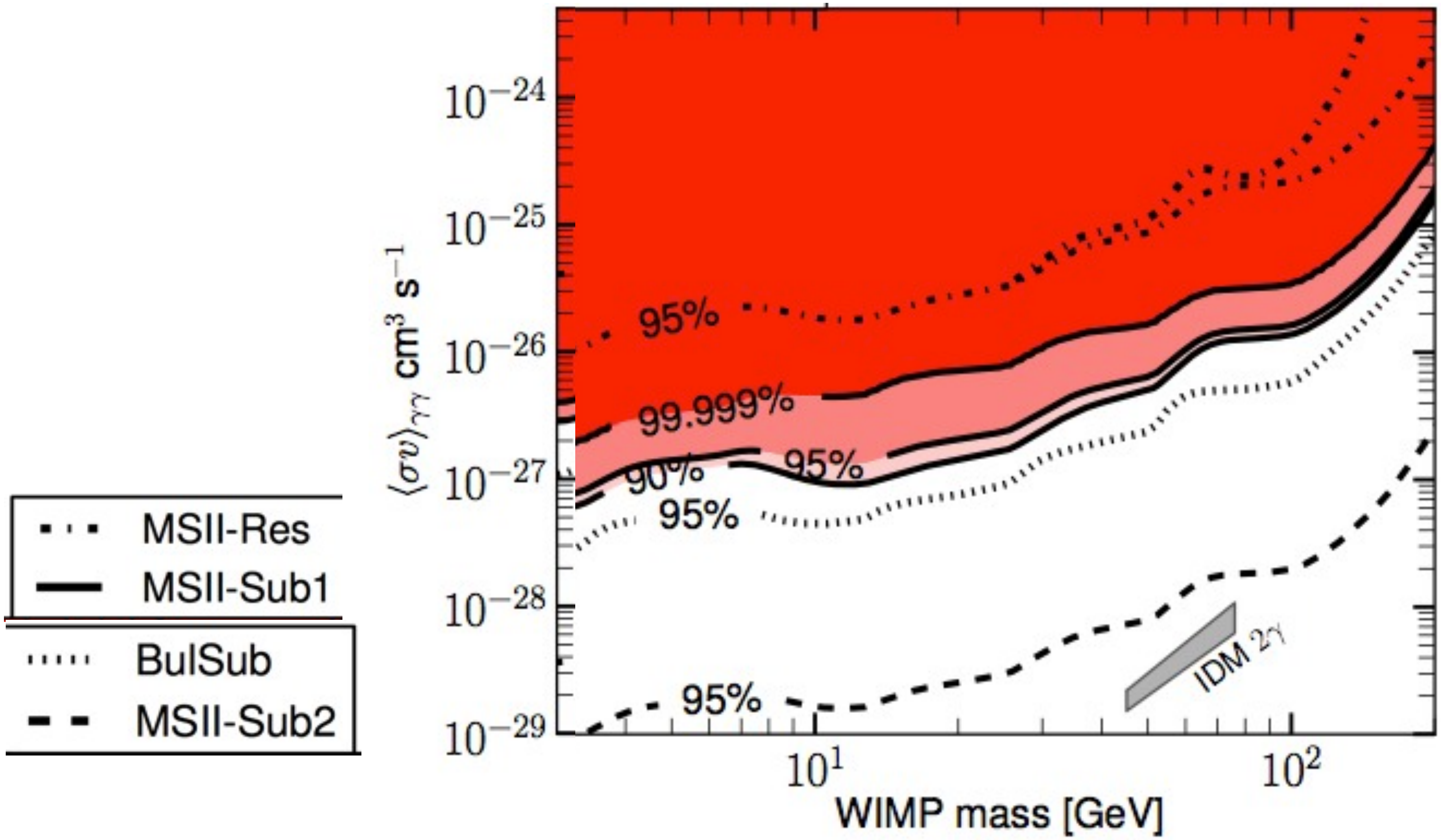
Fermi collaboration: arXiv:1005.0996v1

Cosmological DM line

$$\frac{d\phi_\gamma}{dE_0} = \frac{\langle\sigma v\rangle}{8\pi}\,\frac{c}{H_0}\,\frac{\bar{\rho}_0^2}{m_{DM}^2}\int dz(1+z)^3\,\frac{\Delta^2(z)}{h(z)}\,\frac{dN_\gamma(E_0(1+z))}{dE}\,e^{-\tau(z,E_0)}$$



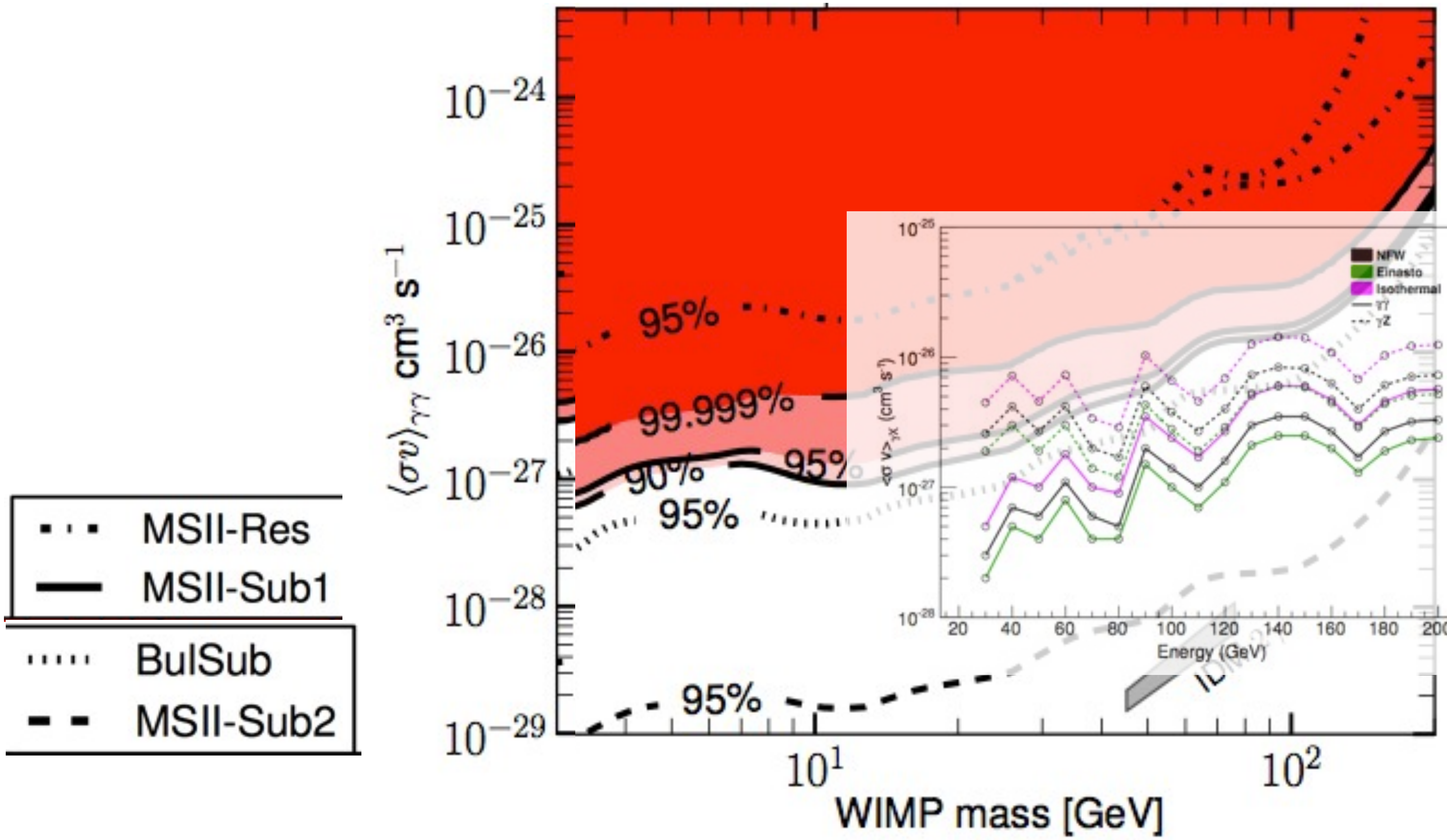
Cosmological DM line x-section limits



Fermi–LAT Collaboration: JCAP 1004:014,2010

If gamma + X: $\langle\sigma v\rangle^{m_{\rm DM}}_{\gamma X,\rm limit} = 2\frac{m^2_{\rm DM}}{m'^2_{\rm DM}} \times \langle\sigma v\rangle^{m'_{\rm DM}}_{\gamma\gamma,\rm limit}\,,\quad \text{where } m'_{\rm DM} = \frac{m_{\rm DM}}{2}\left(1+\sqrt{1+\frac{m^2_{\rm X}}{m^2_{\rm DM}}}\right)$

Cosmological DM line x-section limits



Fermi–LAT Collaboration: JCAP 1004:014,2010

If gamma + X: $\langle\sigma v\rangle^{m_{\rm DM}}_{\gamma{\rm X,limit}} = 2\frac{m_{\rm DM}^2}{m'^2_{\rm DM}} \times \langle\sigma v\rangle^{m'_{\rm DM}}_{\gamma\gamma,{\rm limit}}$, where $m'_{\rm DM} = \frac{m_{\rm DM}}{2}\left(1+\sqrt{1+\frac{m_{\rm X}^2}{m_{\rm DM}^2}}\right)$.