Constraining Dark Matter with Background Light

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Dec 5,

LANL

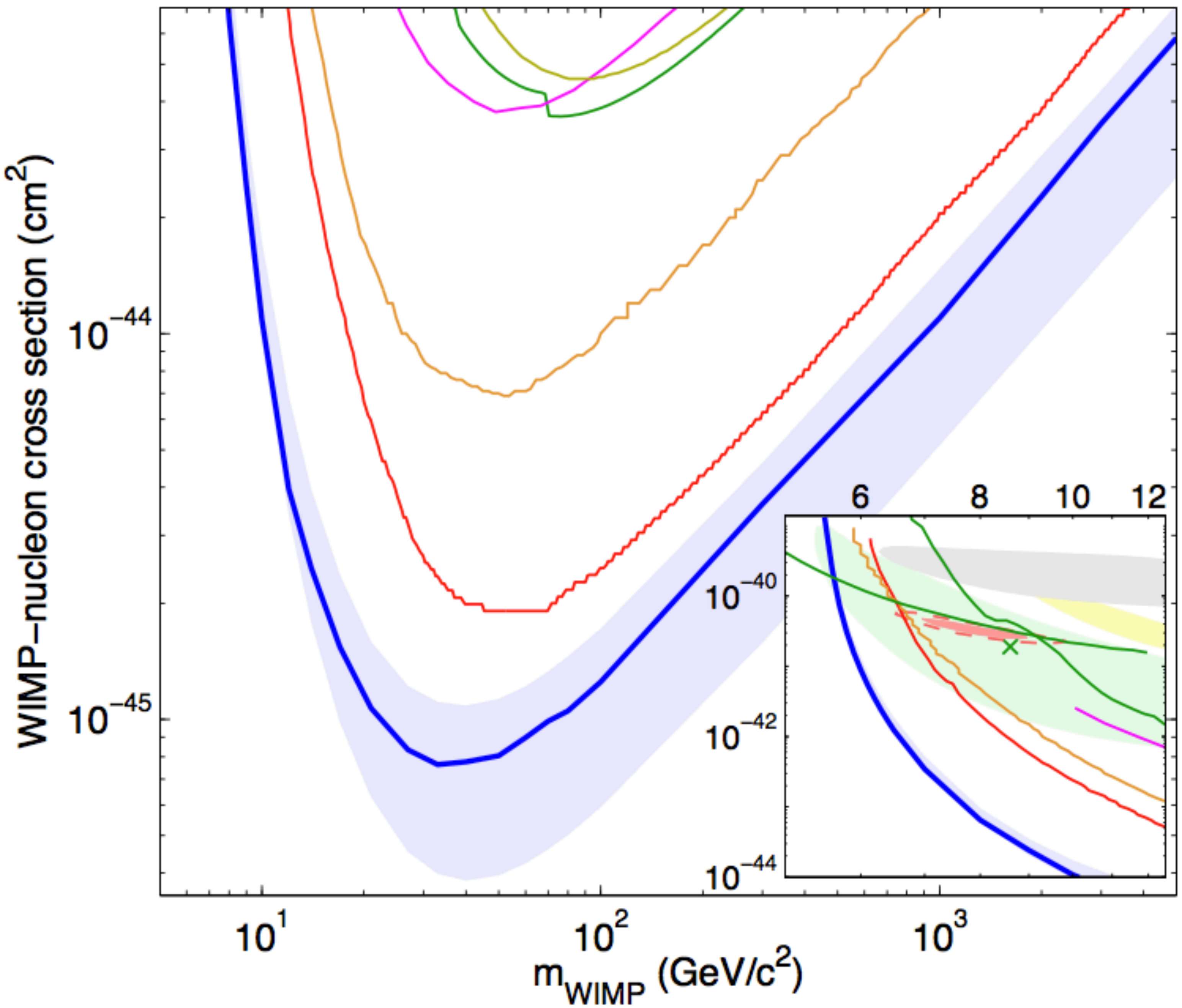
MCTP

Fermilab

from 1309.4091,
with Rouven Essig, Eric Kuflik, Tomer Volansky, and Kathryn Zurek

and 1312.0608
with Ilias Cholis and Dan Hooper

Prelude



LUX sees nothing

Is this really a big problem? See e.g.: Cirigliano, Graesser, Ovanesyan, and Shoemaker 1311. 5886; Gresham and Zurek 1311.2082

Motivation

- More and more of our favorite DM parameter space seems to be getting ruled out
- (Infinitely) large swaths of well-motivated DM parameter space are currently up for grabs
- We need complementary probes to
  - test assumptions of bounds
  - explore different parameter space
- This talk will focus on indirect detection

Motivation

- Photons (produced directly, from FSR, from cascades, etc.) are generic in DM annihilation and decay
- Data are "just sitting there" ready to use

<u>This talk</u>

two very different methods
of approaching this problem

Outline

- Light decaying dark matter:
  - models
  - statistical methodology
  - results

- “Light” annihilating dark matter:
  - isotropic gamma rays from DM
  - astrophysical backgrounds
  - results

Part I:

Light (MeV-ish) Decaying DM

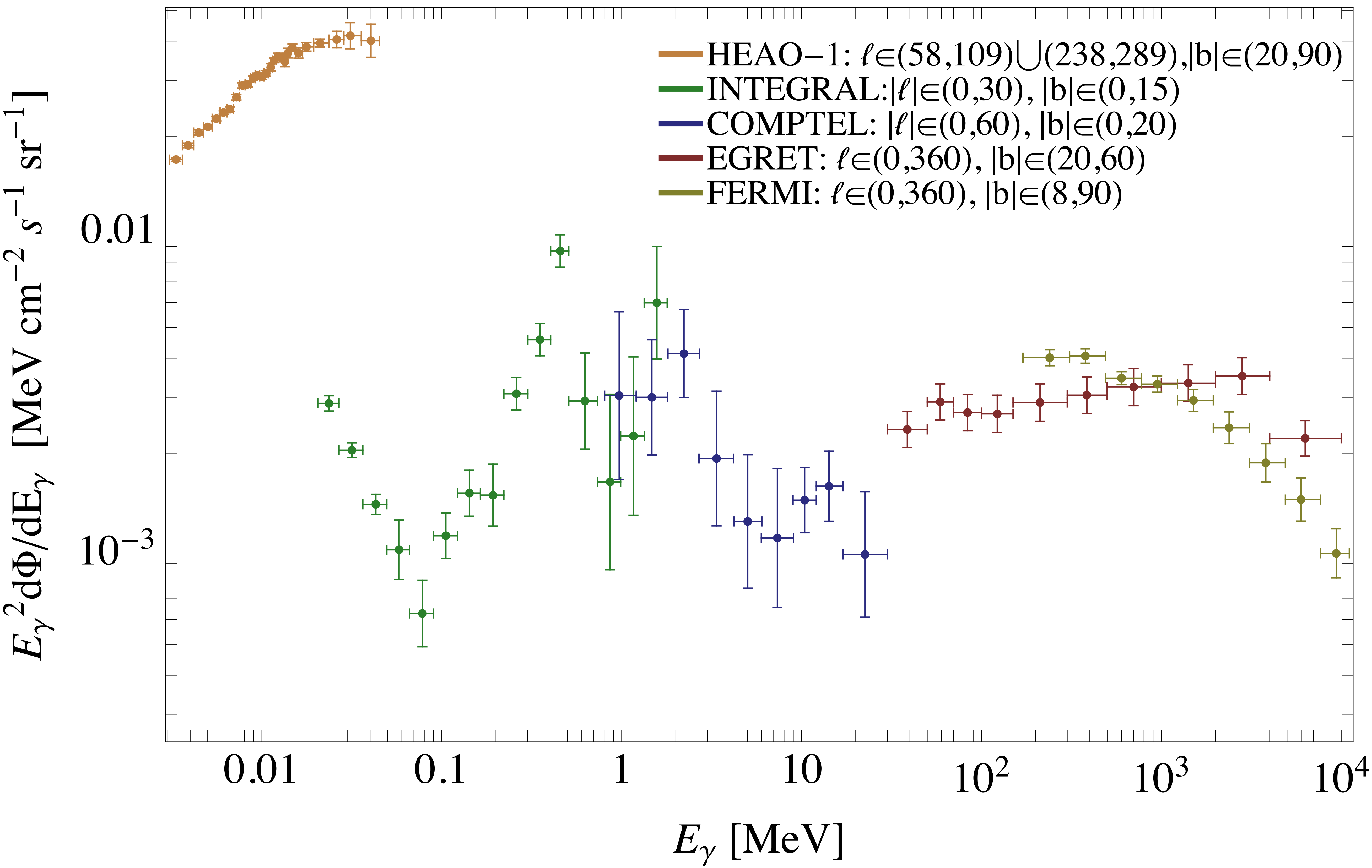
“Light” Dark Matter

- still cold
  - not warm, not an ALP that forms a galactic scale BEC, etc.
  - few keV to few GeV mass
- we assume that all (model-dependent) observables of standard cosmology are taken care of (i.e., asymmetric or thermal production where appropriate)

Data

- “Diffuse” X-Rays and Gamma-Rays
  - HEAO-1 (1977)
  - INTEGRAL (2008)
  - COMPTEL (1998)
  - EGRET (2003)
  - Fermi (2012) (21 months)
- Some observations near the galactic poles, some near the galactic center

Data



HEAO−1: ℓ∈(58,109)⋃(238,289),|b|∈(20,90)
INTEGRAL:|ℓ|∈(0,30), |b|∈(0,15)
COMPTEL: |ℓ|∈(0,60), |b|∈(0,20)
EGRET: ℓ∈(0,360), |b|∈(20,60)
FERMI: ℓ∈(0,360), |b|∈(8,90)
0.01
10^{-3}
$E_\gamma{}^2 d\Phi/dE_\gamma$ [MeV cm^{-2} s^{-1} sr^{-1}]
0.01
0.1
1
10
10^2
10^3
10^4
E_γ [MeV]

Analysis methods

- There are many different methods:
  - spectral fit plus power law in sliding energy window (cf. Weniger)
  - precise background modeling
    (cf. Siegal-Gaskins; newer work here; others)
  - "on-off" or template analyses
    (cf. Koushiappas + Geringer-Sameth; Finkbeiner + Slatyer; Hooper + Slatyer; Tempel, Hektor, + Raidal; others)

Analysis methods

requires exceptional energy resolution

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requires detailed knowledge of astrophysics over very wide ranges of position and energy space

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requires exceptional angular resolution

Analysis methods

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Our analysis (1309.4091)

- Only direct photon production and primary FSR; no ICS, synchrotron, etc.
- We simply require (for every energy bin):

$$\text{Flux}_{\text{predicted}} \leq \text{Flux}_{\text{observed}} + 2 \times \text{Error Bar}_{\text{observed}}$$

- Robust results!

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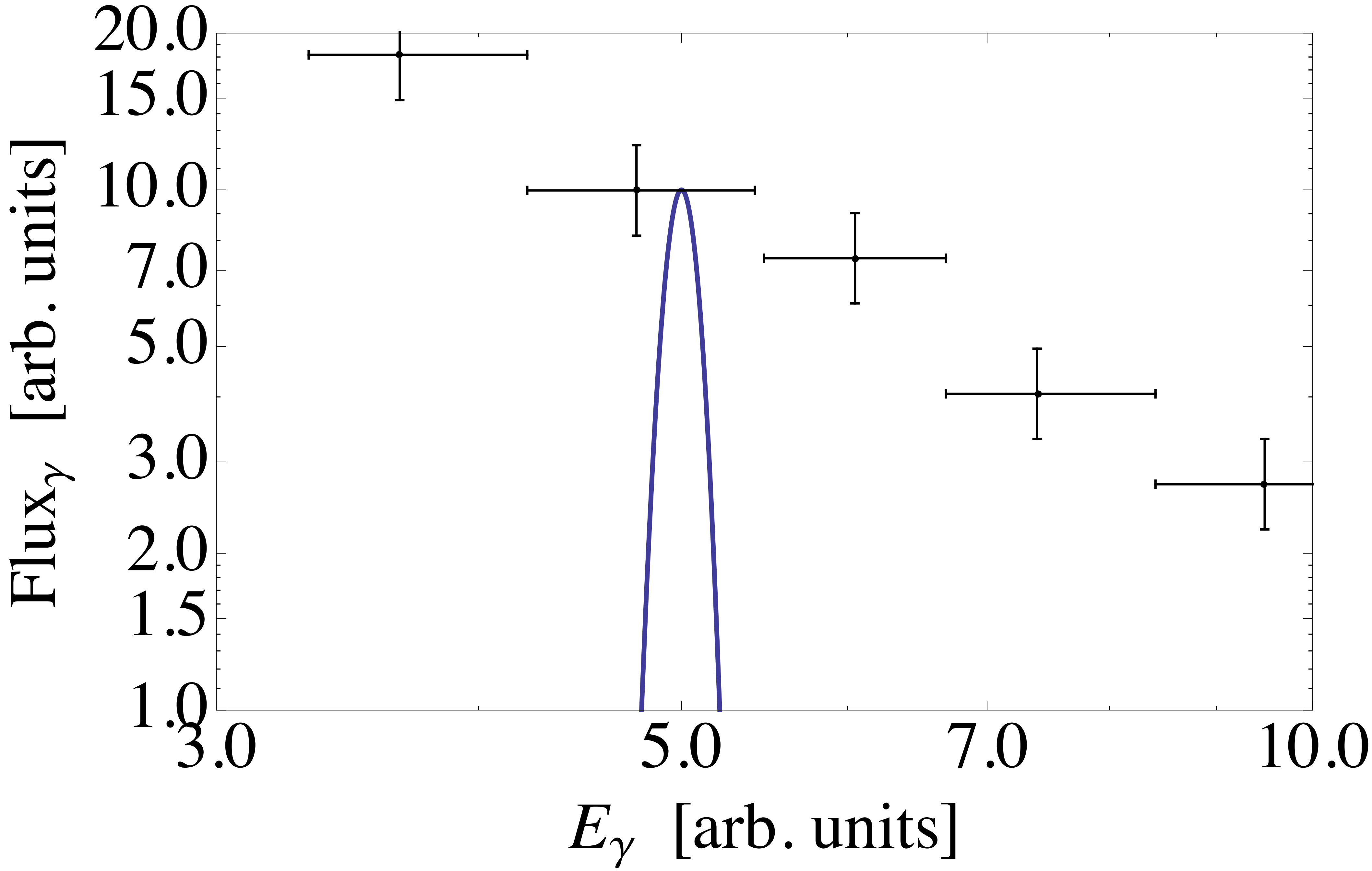
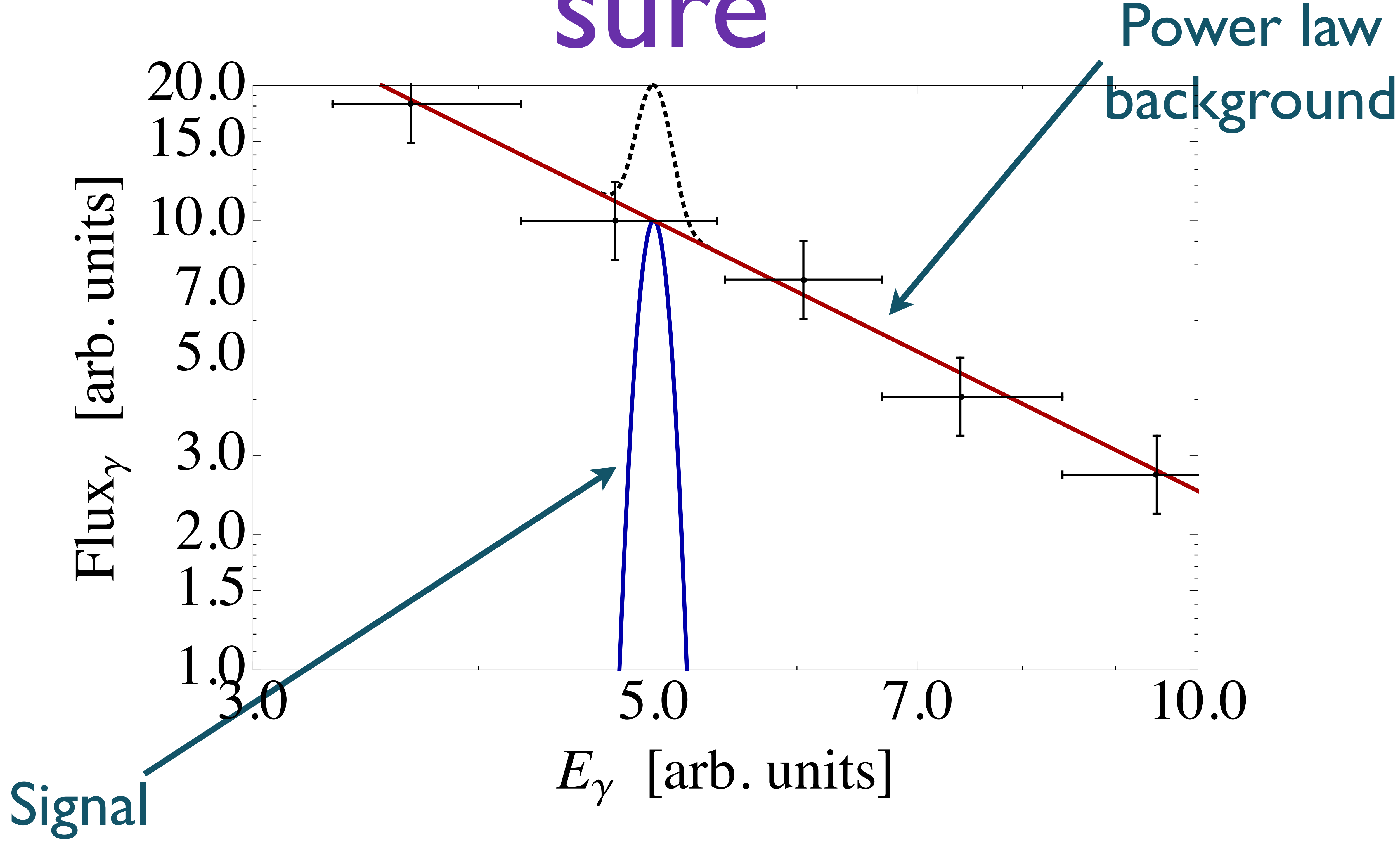
- Robust results!

Can we exclude this?



With background model, sure



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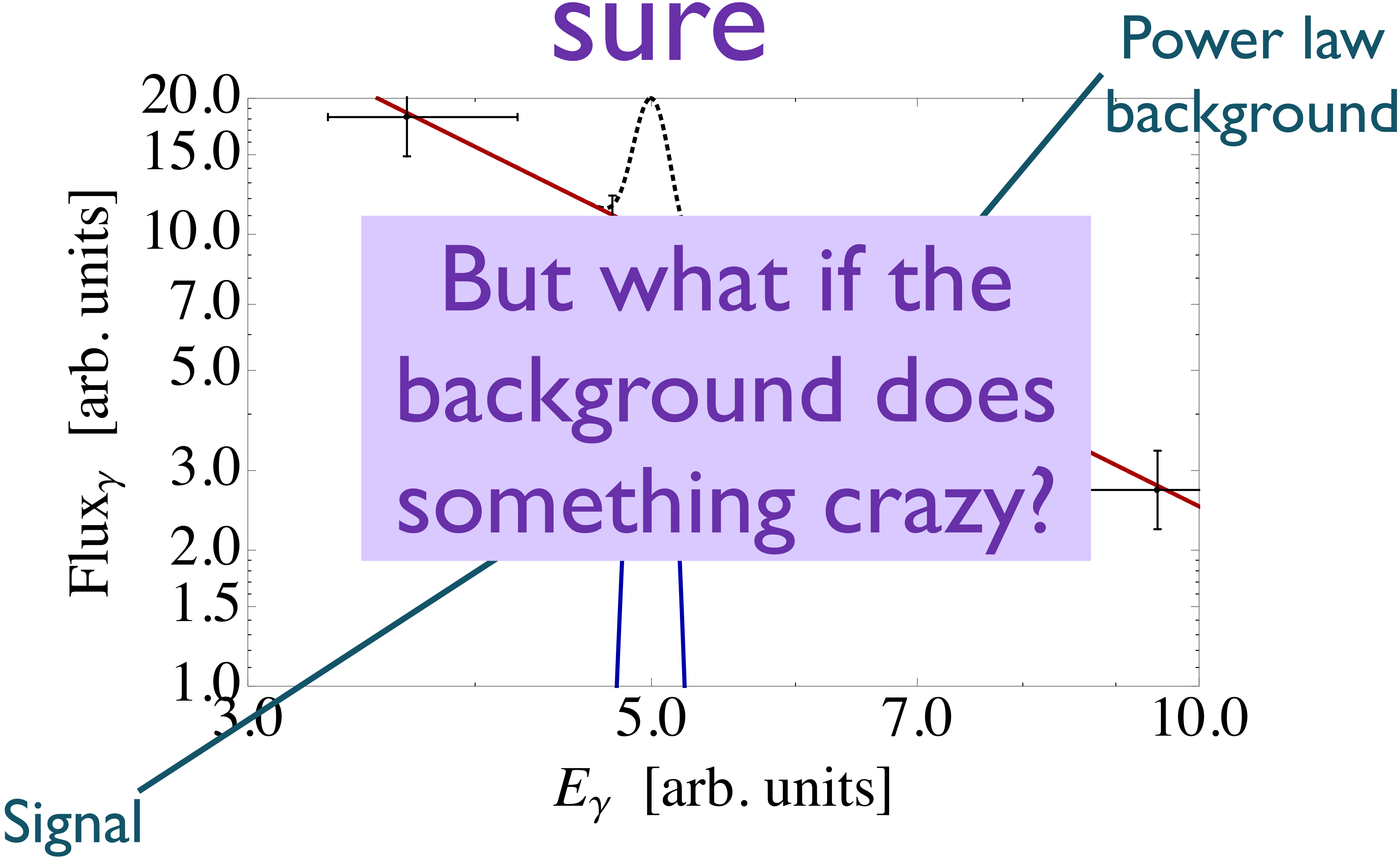
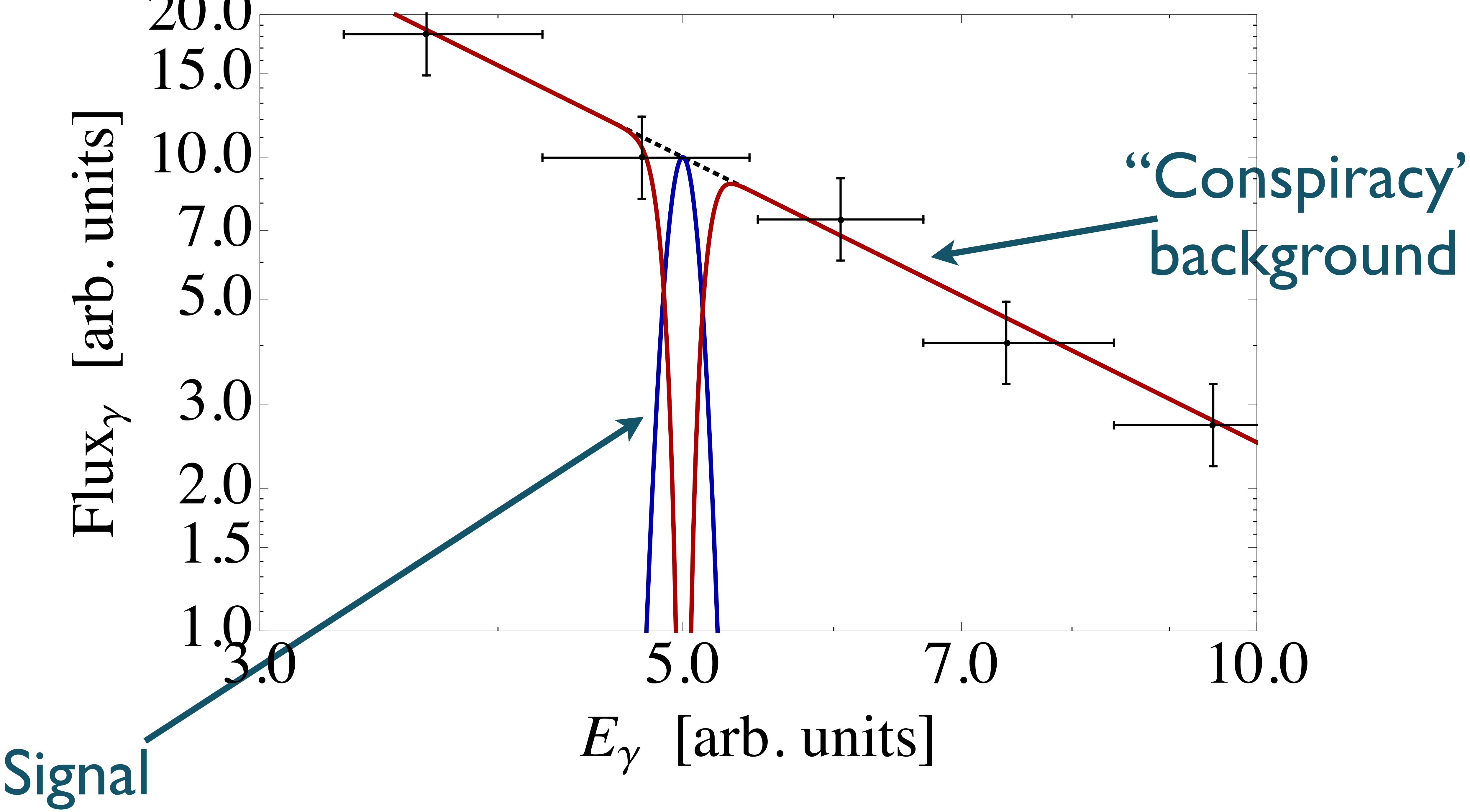


But what if the background does something crazy?

Being conservative: Not ruled out!



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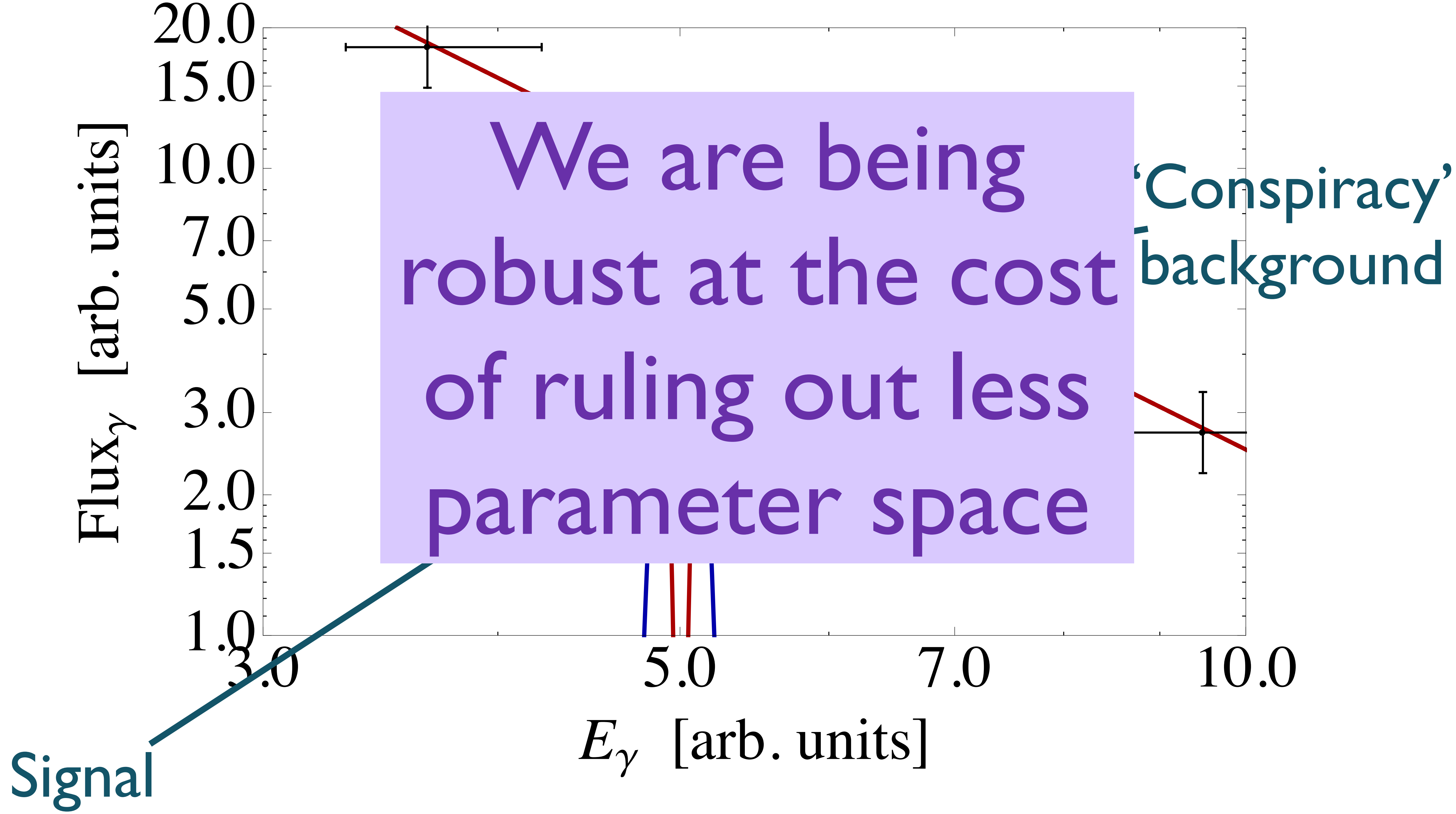


We are being robust at the cost of ruling out less parameter space

Photons from DM decays

Galactic: $$\frac{d\Phi_{\gamma,\mathrm{G}}}{dE} = \frac{r_\odot}{4\pi}\frac{\rho_\odot}{m_{\mathrm{DM}}}\Gamma\frac{dN_\gamma}{dE}J(\Omega)$$

vs. extragalactic:

$$\frac{d\Phi_{\gamma,EG}}{dE} = \frac{\Omega}{4\pi}\frac{\Gamma\Omega_{\mathrm{DM}}\rho_c}{m_{\mathrm{DM}}a_0H_0}\int_0^\infty dz\,\frac{dN}{dE(z)}\frac{1}{\sqrt{\Omega_\Lambda+\Omega_m(1+z)^3}}$$

Galactic dominates, marginally:

$$\rho_\odot r_\odot J(\Omega) \simeq \mathcal{O}(10^{-5}\ \mathrm{GeV}^3) \quad \text{vs.} \quad \rho_{\mathrm{DM}}/H_0 \simeq 5\times 10^{-6}\ \mathrm{GeV}^3$$

but same order of magnitude

Models of decaying DM

- Hidden Photino – SUSY + hidden U(1). [Higgs a hidden U(1); break SUSY with messengers from SM; hidden photon/photino with small mass splitting; kinetically mix hidden photon and photon of U(1)EM. Decays involving SM possible if there is a light gravitino. Topology depends on relative masses of hidden photon/photino.]
- Sterile Neutrino – long-lived sterile neutrino
- RPV Gravitino – neutrino/photino mixing. [Planck-scale suppression gives a naturally small rate for gravitino decays. Fastest decay is gravitino > photon + neutrino.]
- Plus dipole DM, dark scalar, dark pseudoscalar

So the name of the game is...

Ignore the astro/cosmology stuff (be conservative)

Particle physics enters through Γ and dN/dE_γ only:

dN/dE_γ is fixed by decay topology

Γ is fixed by the model

Dark photino model

MeV scale comes out naturally:

$$m^2_{\widetilde{\gamma}_d} = \epsilon \cdot g_d \left\langle D_Y \right\rangle \simeq (5 \text{ MeV})^2 \left(\frac{\epsilon}{10^{-8}}\right) \left(\frac{g_d}{0.2}\right) \left(\frac{\sqrt{\langle D_Y \rangle}}{50 \text{ GeV}}\right)^2$$

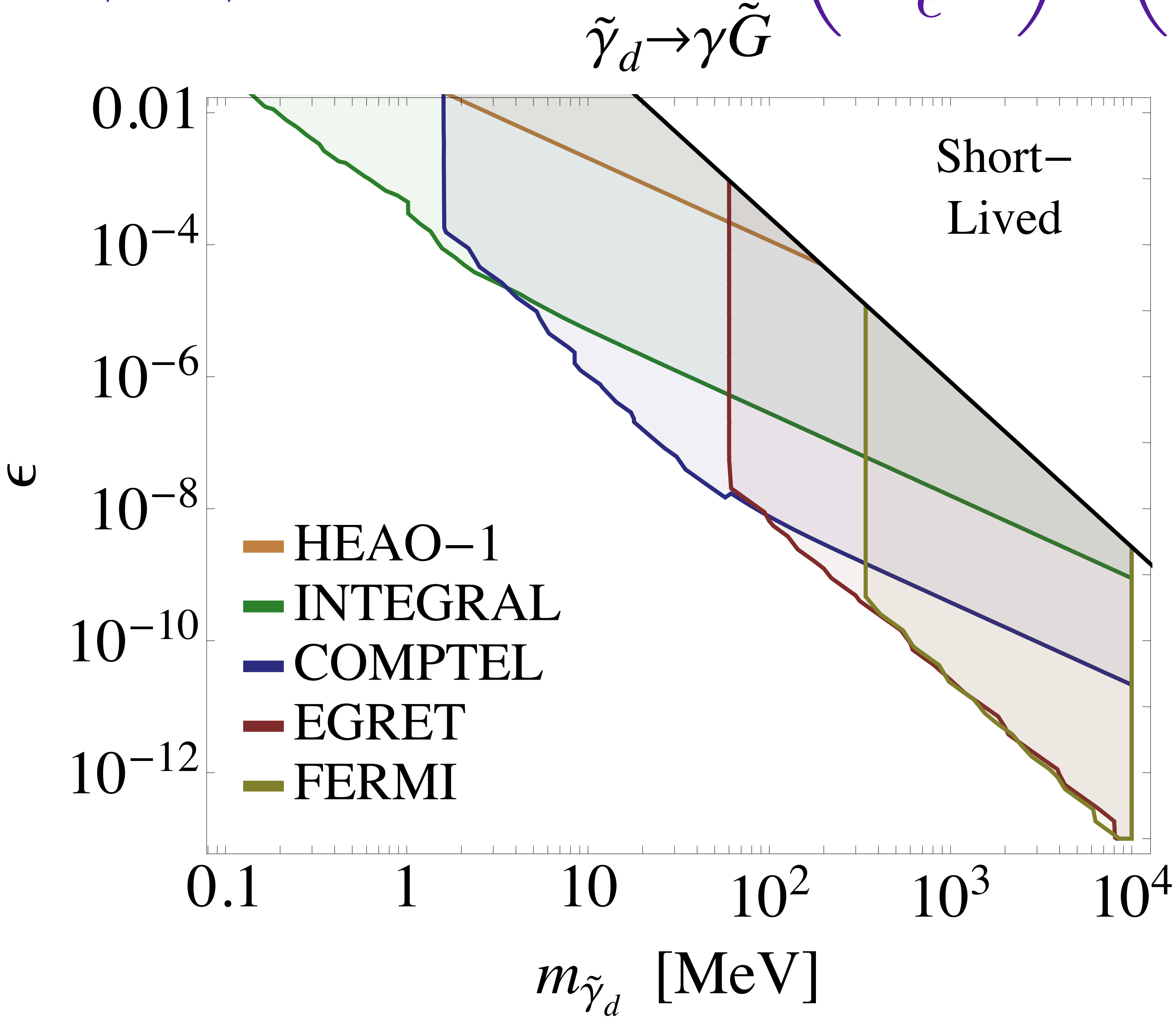
Two different decays, depending on whether the dark photon or dark photino is more massive:

$$\tau_{\widetilde{\gamma}_d \to \gamma \widetilde{G}} \simeq 3 \times 10^{23} \text{ sec} \left(\frac{10^{-8}}{\epsilon}\right)^2 \left(\frac{10 \text{ MeV}}{m_{\widetilde{\gamma}_d}}\right)^5 \left(\frac{\sqrt{F}}{100 \text{ TeV}}\right)^4$$

$$\tau_{\widetilde{\gamma}_d \to \gamma_d \widetilde{G}} \simeq 3 \times 10^{20} \text{ sec} \left(\frac{1 \text{ MeV}}{m_{\widetilde{\gamma}_d}}\right)^5 \left(\frac{\sqrt{F}}{10^4 \text{ TeV}}\right)^4 \left(1 - \frac{m^2_{\gamma_d}}{m^2_{\text{DM}}}\right)^{-4}$$

Dark photino DM, $m_{\tilde{\gamma}_d} < m_{\gamma_d}$

$$\tau_{\tilde{\gamma}_d \to \gamma \tilde{G}} \simeq 3 \times 10^{23} \text{ sec} \left(\frac{10^{-8}}{\epsilon}\right)^2 \left(\frac{10 \text{ MeV}}{m_{\tilde{\gamma}_d}}\right)^5 \left(\frac{\sqrt{F}}{100 \text{ TeV}}\right)^4$$

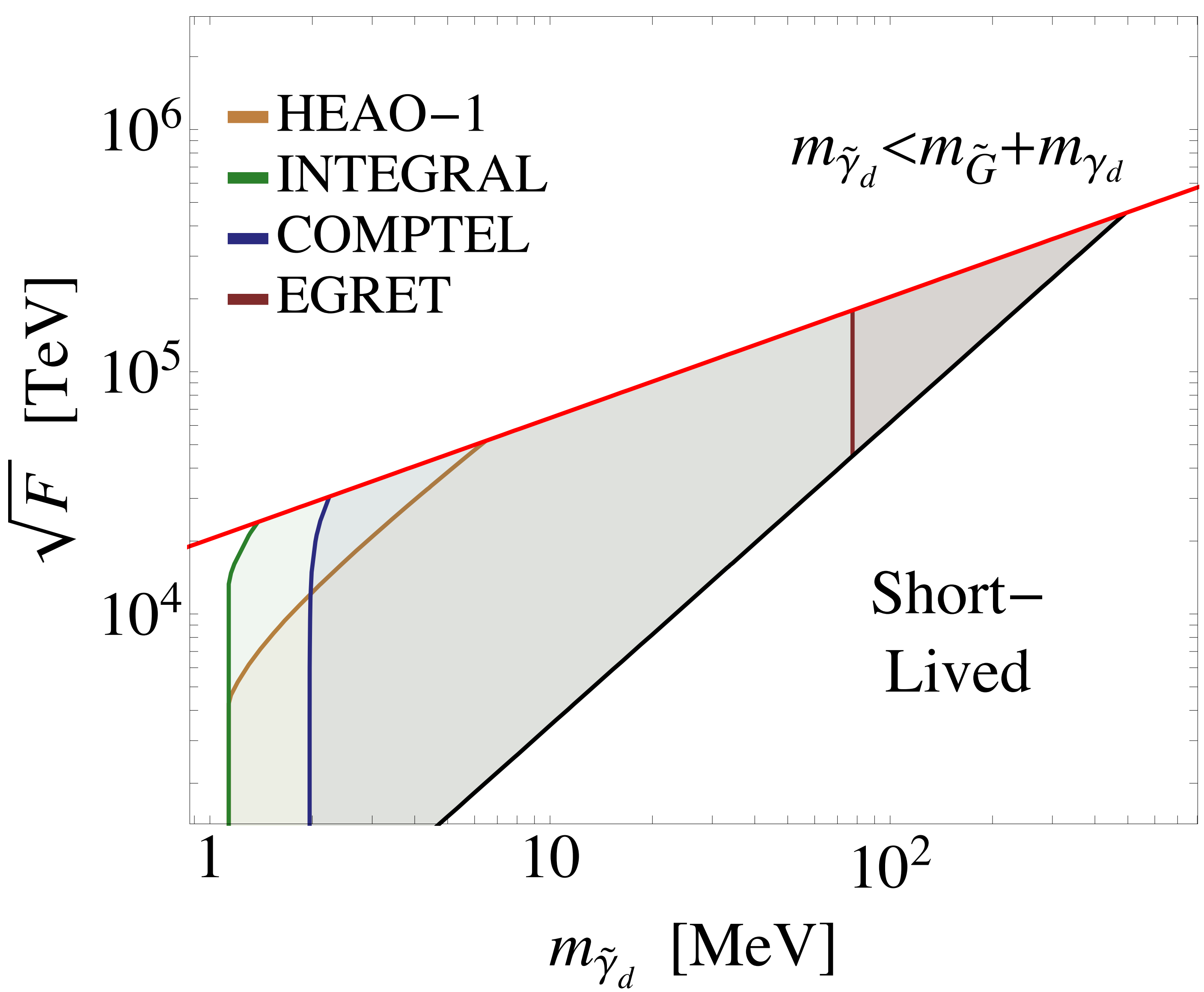


$$\sqrt{F} = 10^4 \text{ TeV}$$

Dark photino DM, $m_{\tilde{\gamma}_d} > m_{\gamma_d}$

$$\tau_{\tilde{\gamma}_d \to \gamma_d \tilde{G}} \simeq 3 \times 10^{20}\ \text{sec} \left(\frac{1\ \text{MeV}}{m_{\tilde{\gamma}_d}}\right)^5 \left(\frac{\sqrt{F}}{10^4\ \text{TeV}}\right)^4 \left(1 - \frac{m_{\gamma_d}^2}{m_{\text{DM}}^2}\right)^{-4}$$

$\tilde{\gamma}_d \to \gamma_d \tilde{G} \to f^+ f^- \tilde{G}$



Sterile neutrino DM

Three-body and radiative decays contribute to photon background at similar levels:

mixing angle between ν_s and ν_e

$$\tau_{\nu_s \to \nu\gamma} \simeq 7.2 \times 10^{17} \text{ sec} \left(\frac{10 \text{ MeV}}{m_\chi}\right)^5 \left(\frac{\sin^2 2\theta}{10^{-8}}\right)^{-1}$$

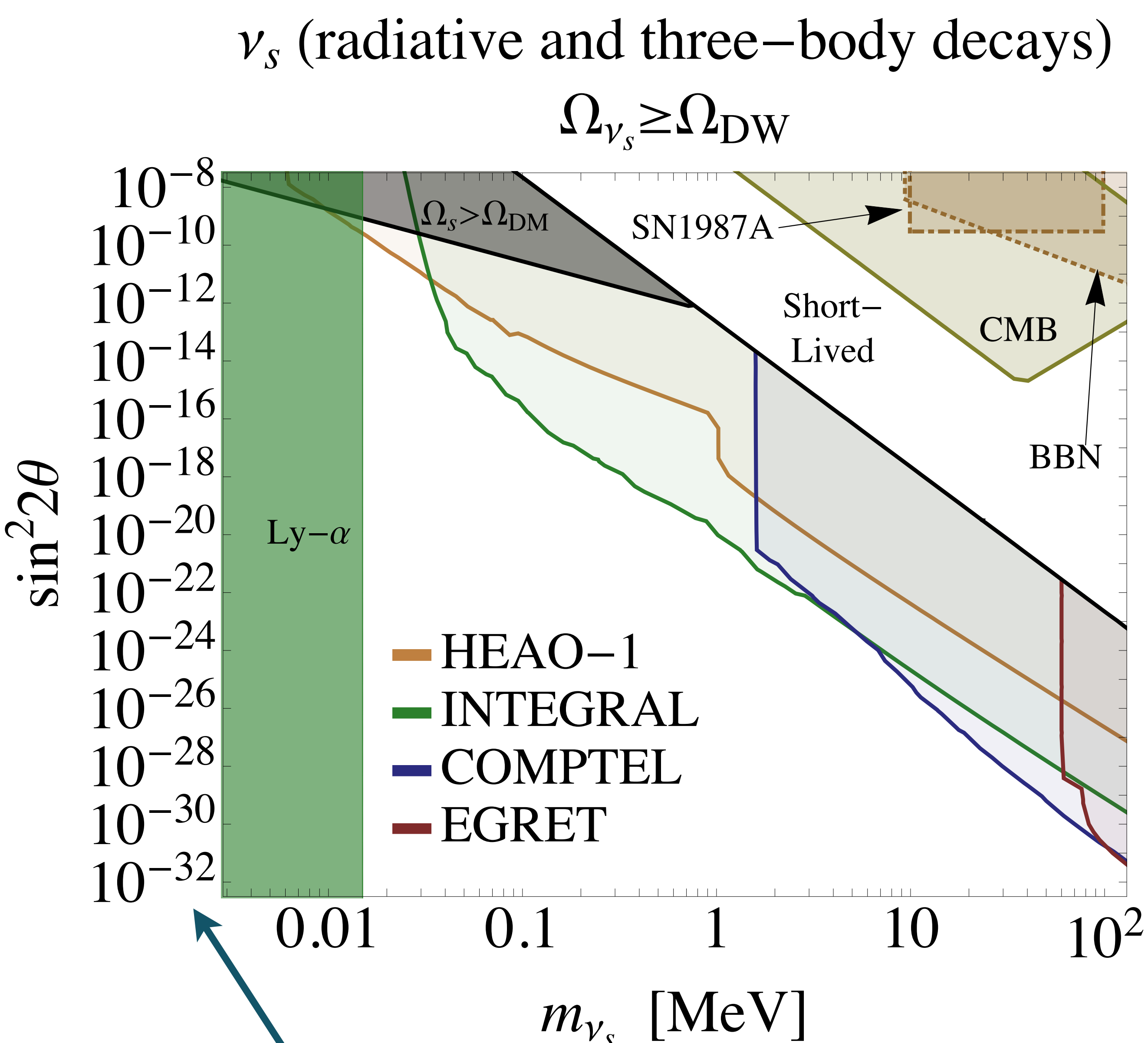
$$\tau_{\nu_s \to \nu_\alpha e^+ e^-} \simeq 9.6 \times 10^{15} \text{ sec} \left(\frac{10 \text{ MeV}}{m_\chi}\right)^5 \left(\frac{\sin^2 2\theta}{10^{-8}}\right)^{-1}$$

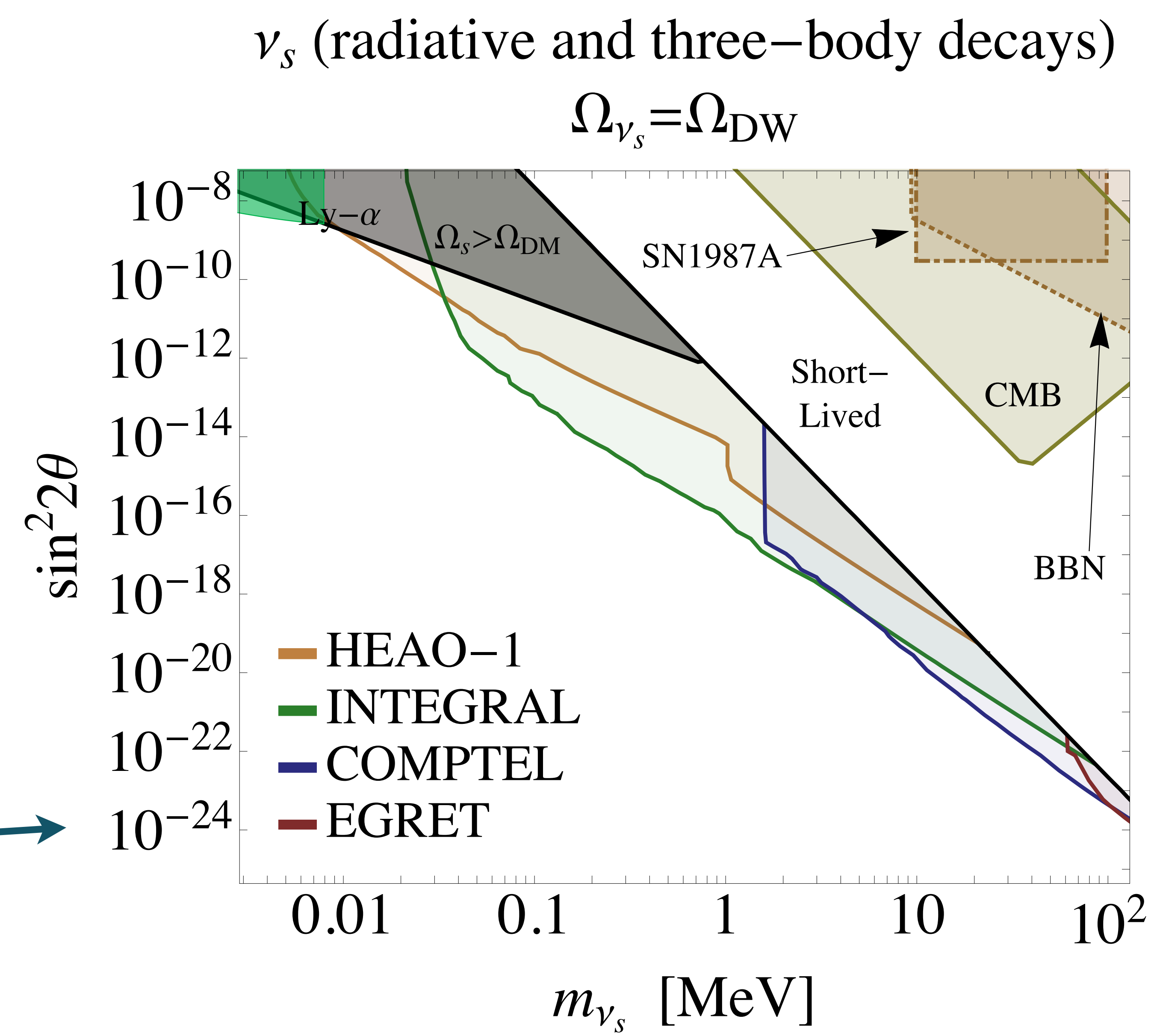
Sterile neutrino DM

Relic abundance is model-dependent, but a UV-insensitive contribution comes from late-time oscillations (Dodelson-Widrow mechanism)

Bounds are different depending on whether $\Omega_{\nu_s} = \Omega_{\rm DW}$ or $\Omega_{\nu_s} \geq \Omega_{\rm DW}$

Sterile neutrino DM

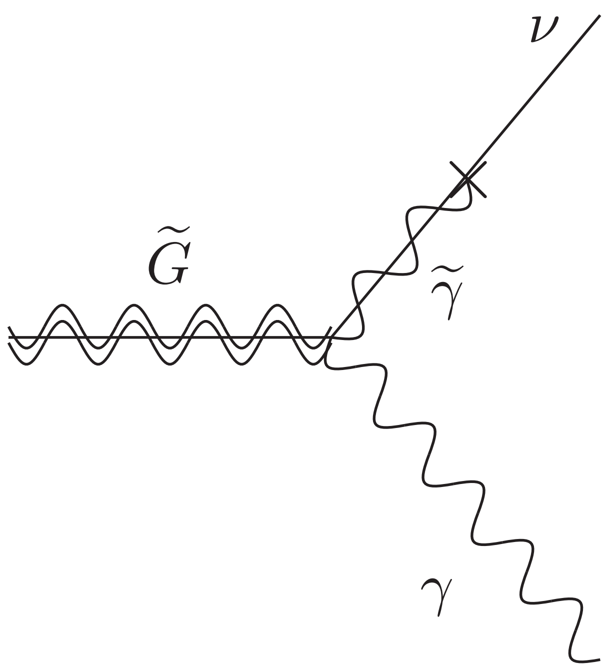


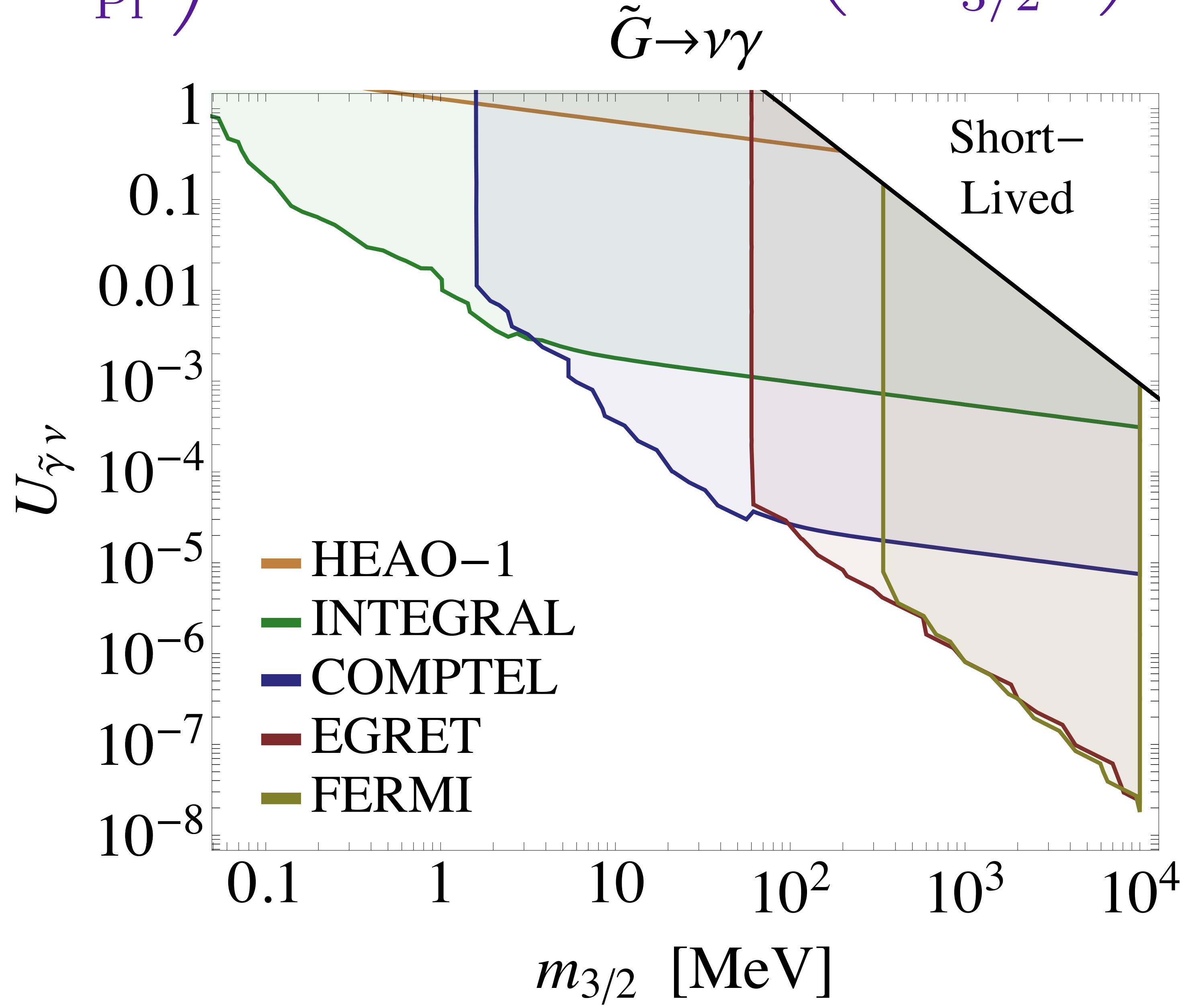


very strong!

RPV gravitino DM

$$\tau_{\widetilde{G}\to\nu\gamma} = \left(\frac{1}{32\pi}\,|U_{\widetilde{\gamma}\nu}|^2\,\frac{m_{3/2}^3}{m_{\rm Pl}^2}\right)^{-1} \simeq 3.8\times 10^{28}\ \sec\left(\frac{10\ \rm MeV}{m_{3/2}}\right)^3\left(\frac{10^{-4}}{U_{\widetilde{\gamma}\nu}}\right)^2$$



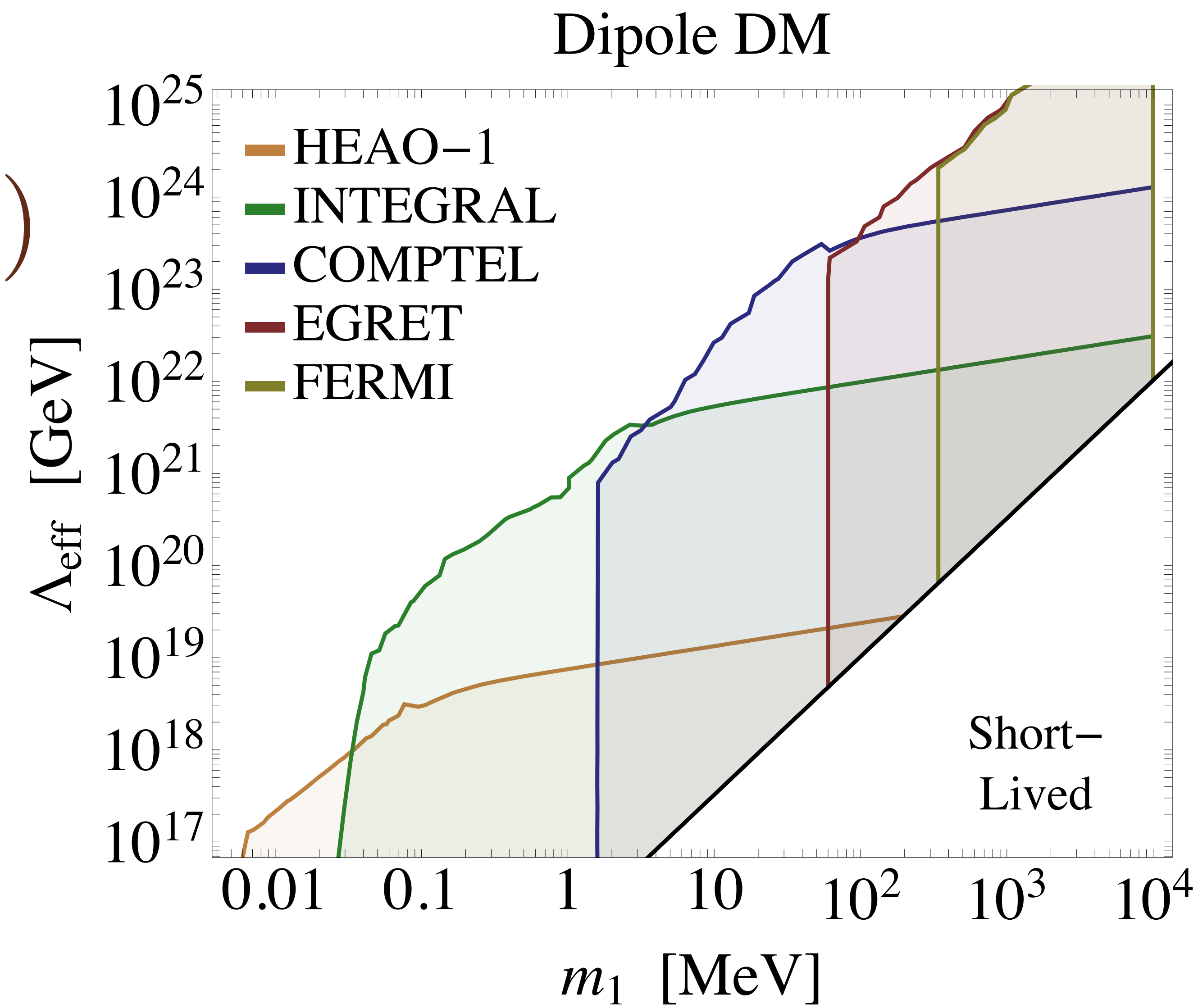


Dipole DM

$$\mathcal{L} \supset \frac{\lambda}{\Lambda}\bar{\chi}_2\sigma^{\mu\nu}\chi_1 F_{\mu\nu}$$

$$\tau_{\rm dipole} \simeq 4.1\times 10^{20}\ \text{sec}\left(\frac{10\ \text{MeV}}{m_1}\right)^3\left(\frac{\Lambda_{\rm eff}}{10^{19}\ \text{GeV}}\right)^2$$

$$(\Lambda_{\rm eff} \equiv \Lambda/\lambda)$$

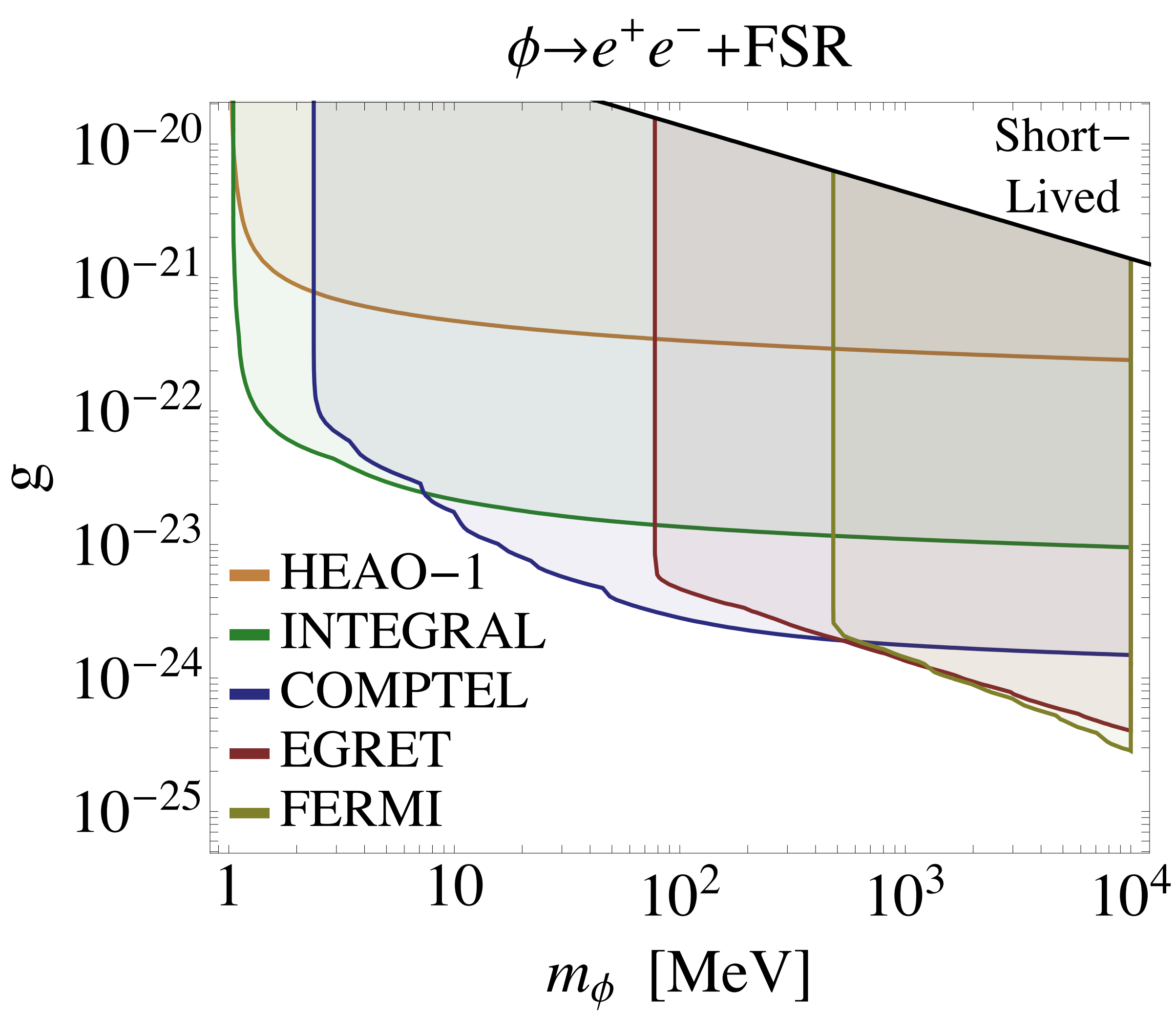


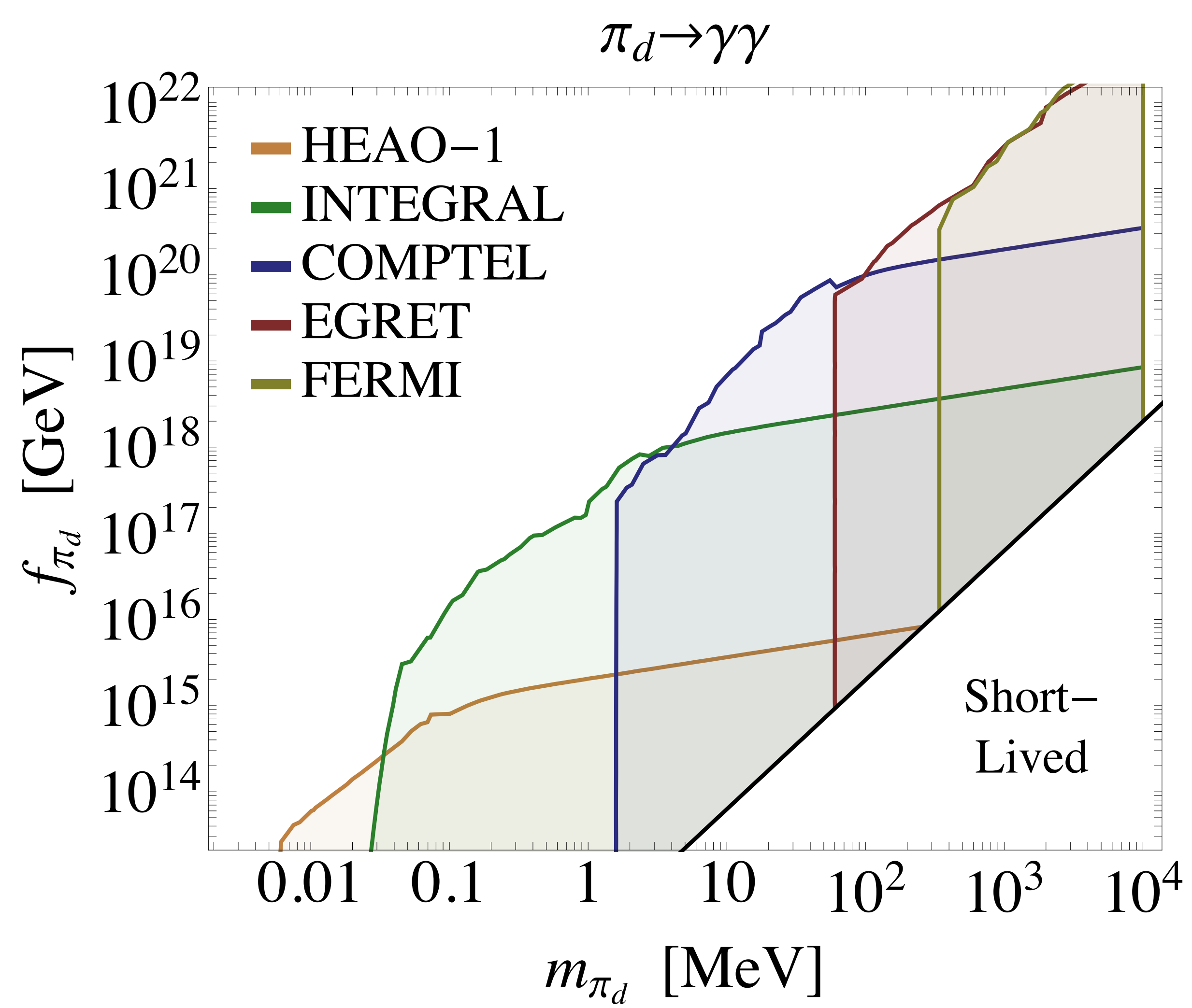
dimension 5 operator
can be strongly constrained

Dark (pseudo)scalars

$$\tau_{\phi \to e^+ e^-} \simeq 8.3 \times 10^{18} \text{ sec} \frac{10 \text{ MeV}}{m_\phi} \left(\frac{10^{-20}}{g_a} \right)^2$$

$$\tau_{\pi_d \to \gamma\gamma} \simeq 1.1 \times 10^{20} \text{ sec} \left(\frac{10 \text{ MeV}}{m_{\pi_d}} \right)^3 \left(\frac{f_{\pi_d}}{10^{15} \text{ GeV}} \right)^2$$



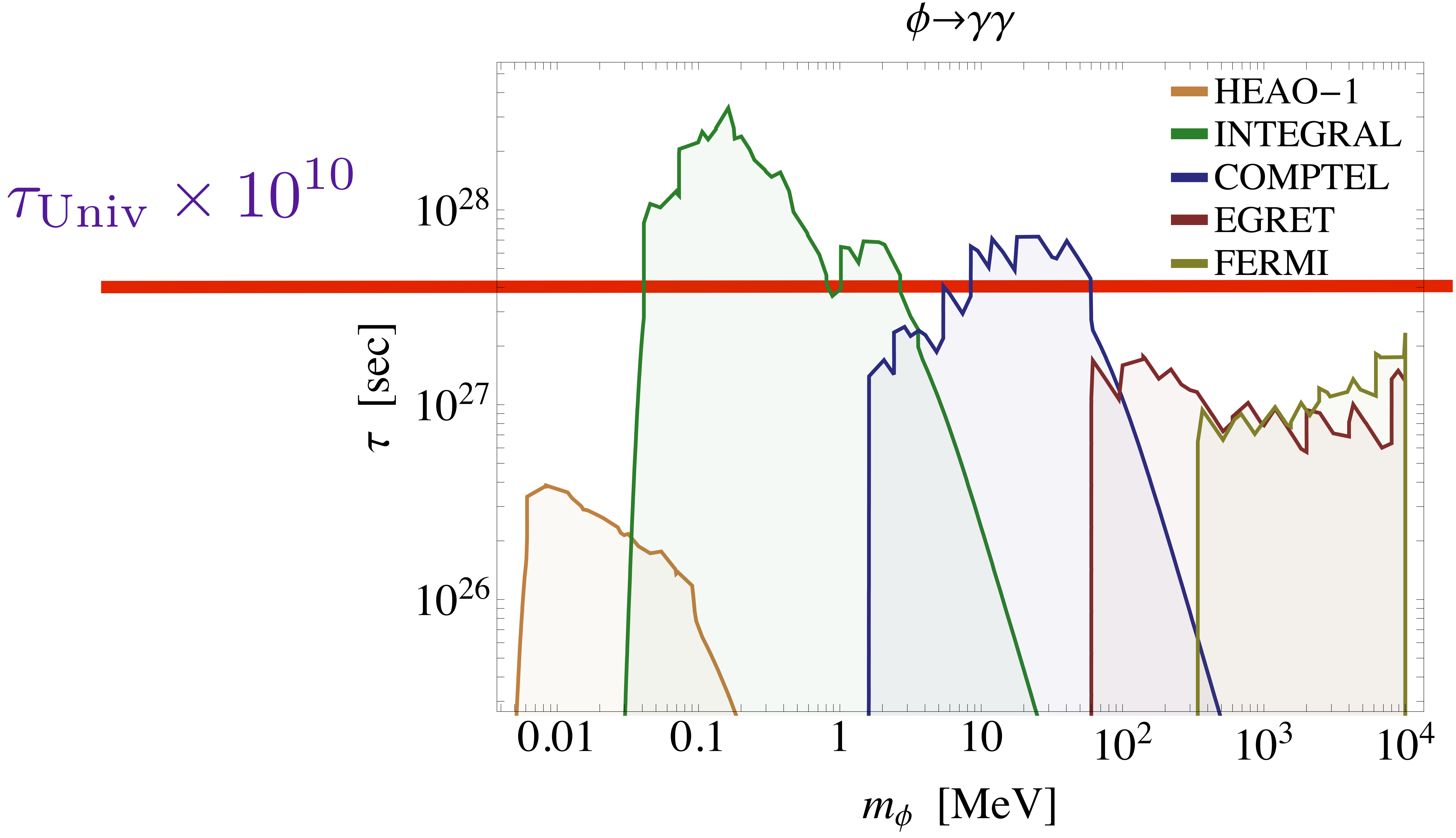


Part 1 Halftime

- Those were the model-dependent bounds
  - bounds on model-specific parameters (mixing angles, decay constants, etc.)
  - very strong for dimension<6, non-Planck-suppressed operators

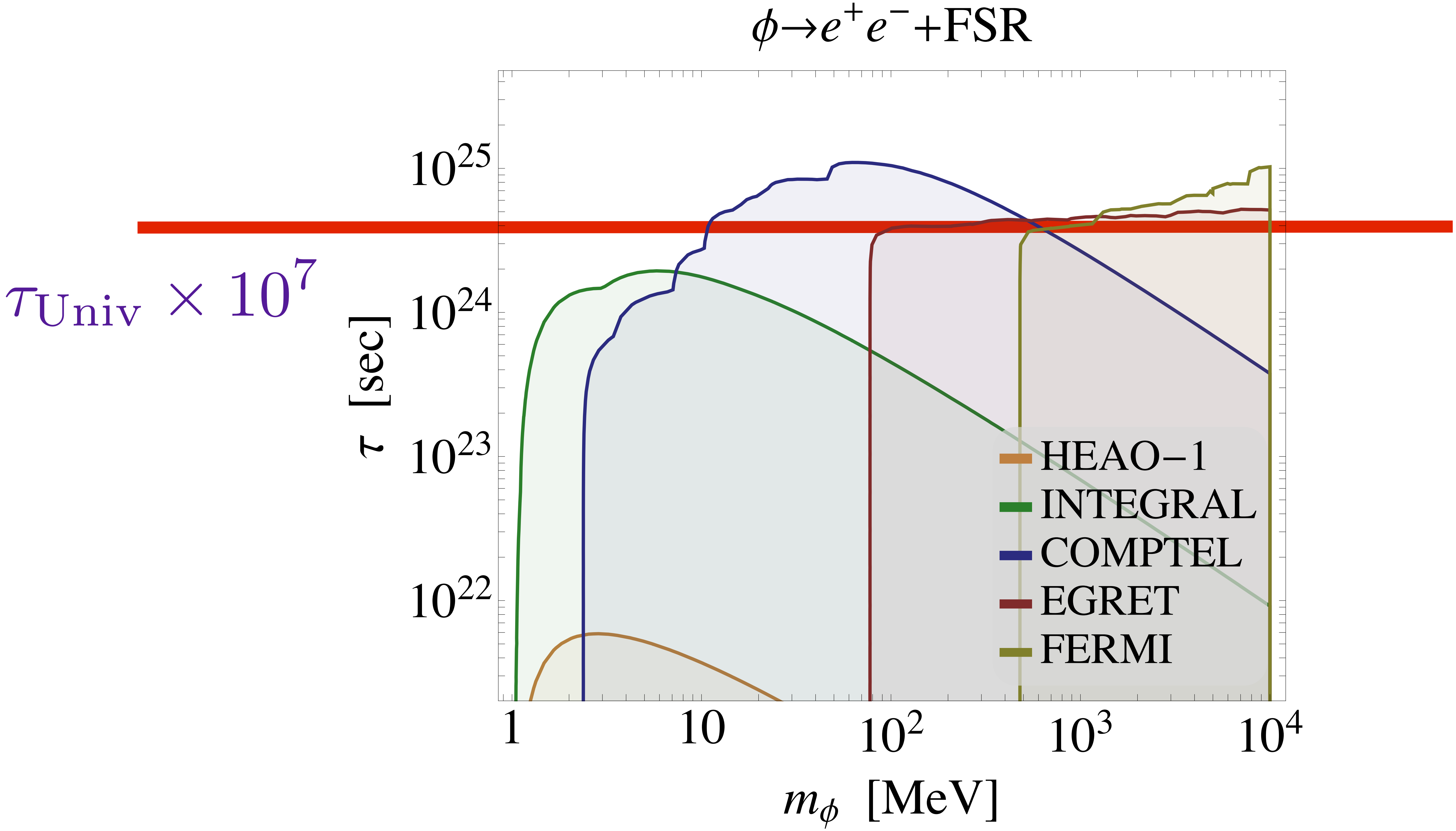
- About to show model-independent bounds
  - just the lifetime – mass plane from now on
  - lifetime bounds from 6 (FSR photons) to 10 (direct photons) orders of magnitude stronger than 1/H0

Photon line



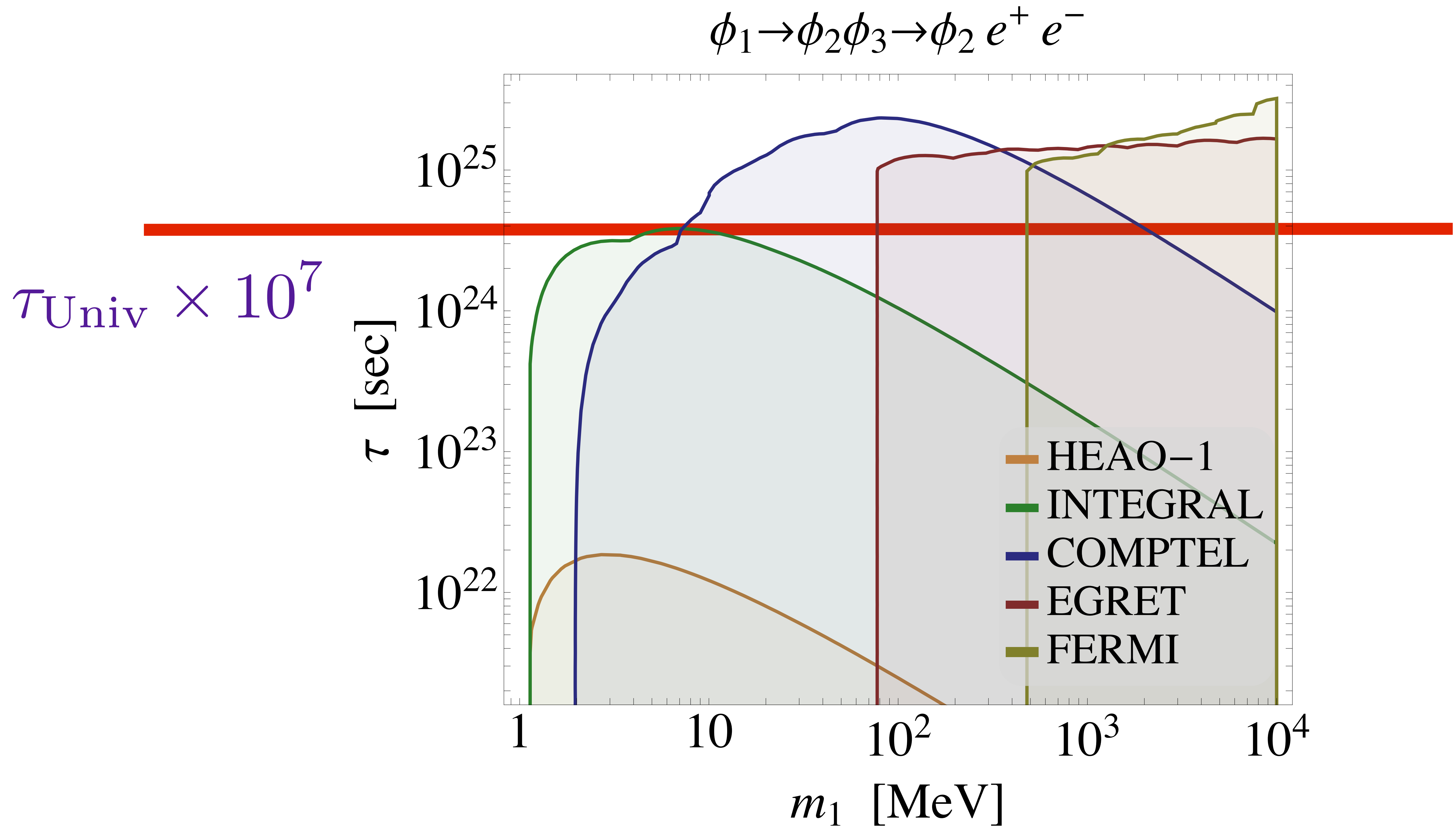
$\phi \to \gamma\gamma$
$\tau_{\rm Univ} \times 10^{10}$
HEAO−1
INTEGRAL
COMPTEL
EGRET
FERMI
10^{28}
10^{27}
10^{26}
τ [sec]
0.01
0.1
1
10
10^2
10^3
10^4
m_ϕ [MeV]

e+ e- (FSR)

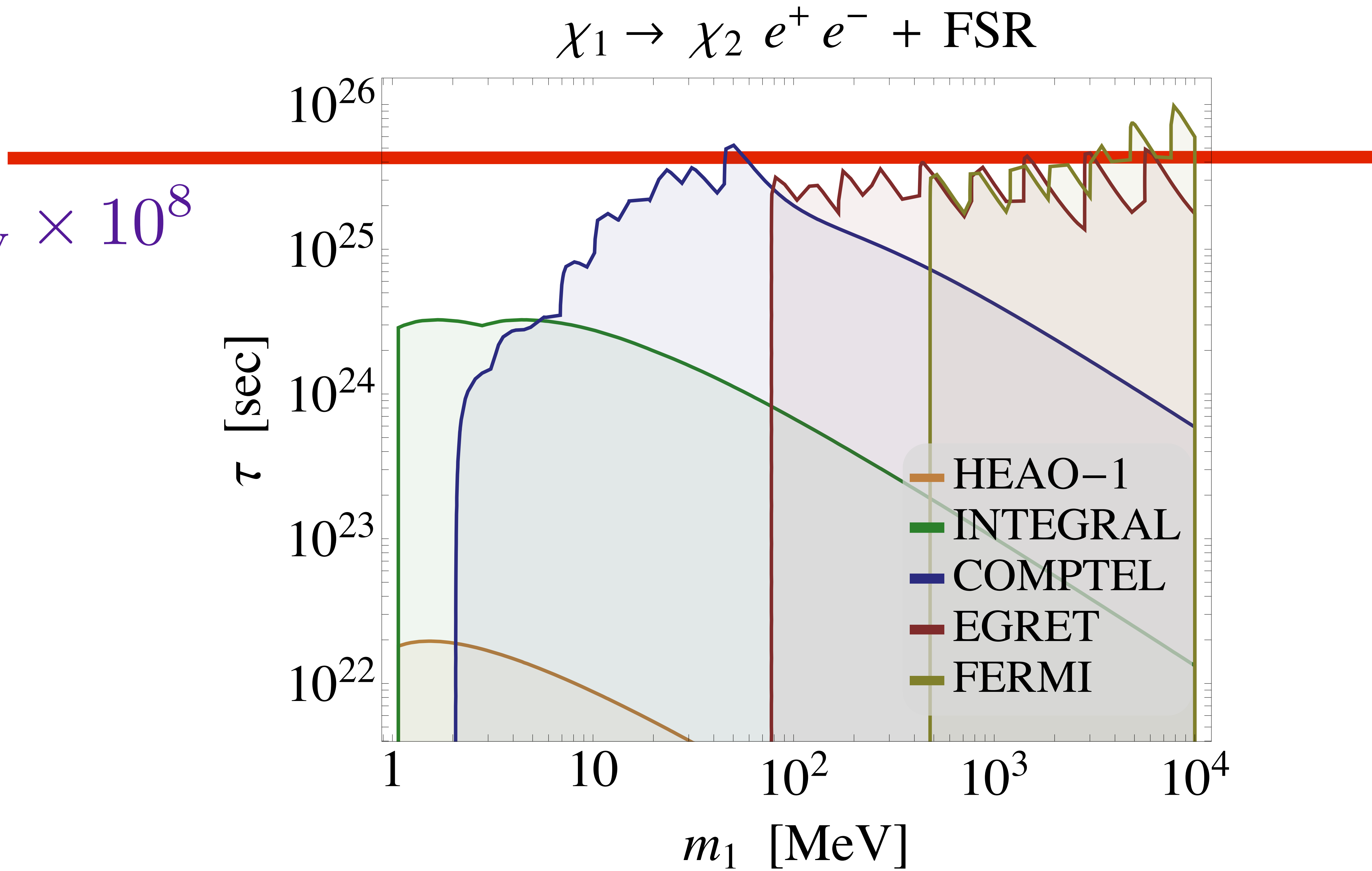


$\phi \to e^+ e^- + \text{FSR}$
$\tau_{\text{Univ}} \times 10^7$
τ [sec]
10^{25}
10^{24}
10^{23}
10^{22}
1
10
10^2
10^3
10^4
m_ϕ [MeV]
HEAO−1
INTEGRAL
COMPTEL
EGRET
FERMI

e+ e- (FSR), boosted

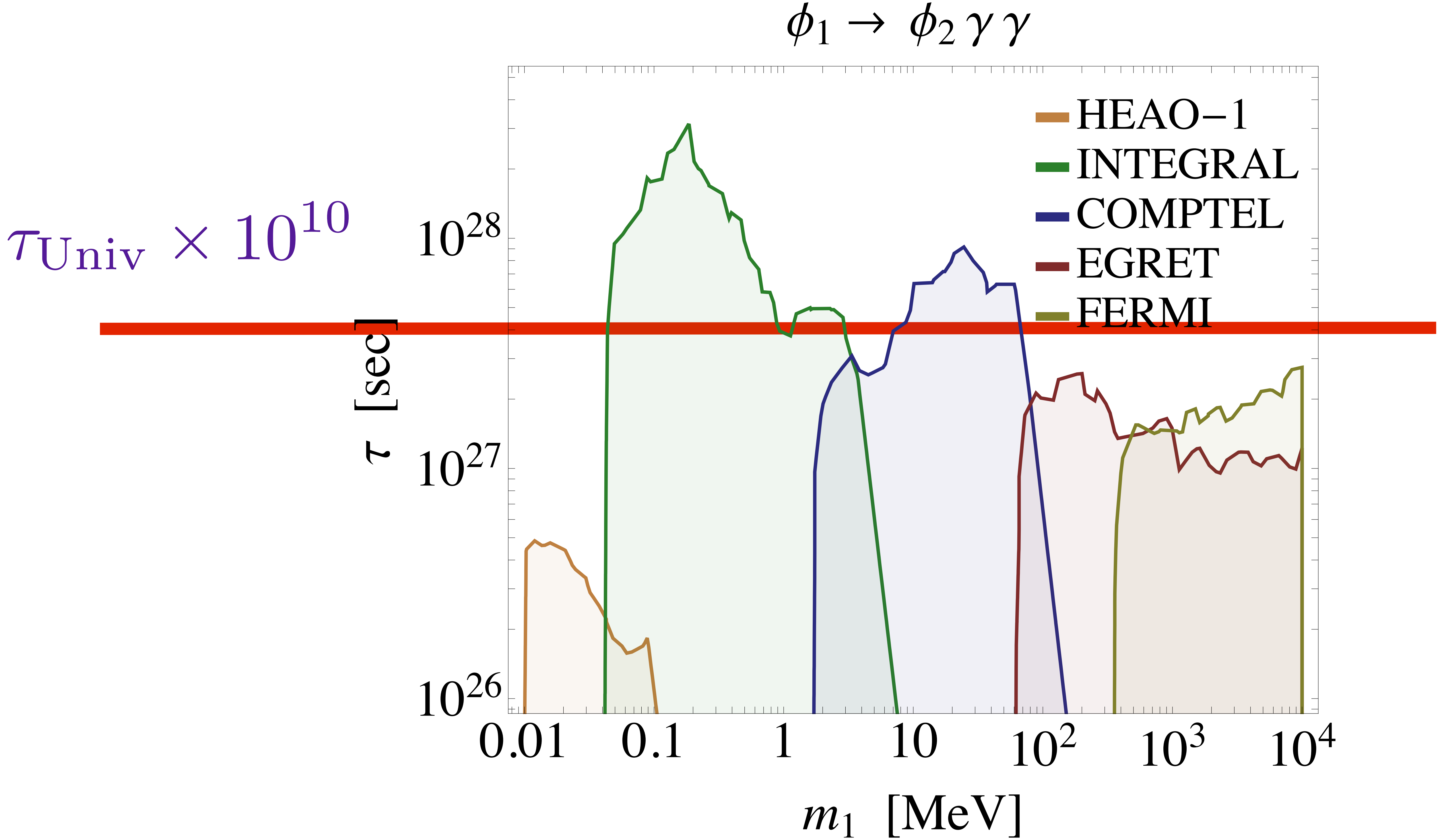


e+ e- (FSR), three-body



$\tau_{\mathrm{Univ}} \times 10^8$

three-body, with photons



Part 1, Recap

- The decaying DM bounds:
  - model-specific parameters
  - model-independent parameters (lifetime, mass)
  - (very robust)

Part II:

“Light” (GeV-ish) Annihilating DM

Part II, Outline

Annihilating DM:

- effect of structure on DM annihilations
- relative contributions
- astrophysical backgrounds
- results

Where does DM annihilate?

smooth galactic: $\rho_s^2 r_s \simeq \mathcal{O}(10^{-47}\ \mathrm{GeV}^7)$

vs.

smooth extragalactic: $\rho_{\mathrm{DM}}^2 / H_0 \simeq \mathcal{O}(10^{-52}\ \mathrm{GeV}^7)$

First guess: mostly in the MW halo

Structure

Structures (overdensities) dramatically change this picture because the rate of annihilations scales quadratically with density (not linearly, as for decays)

Where the DM is
matters for annihilations!

Structure

Critical density with which a sphere collapses instead of growing indefinitely: $\rho_{\rm crit} \simeq 5.5 \times \rho_{\rm av}$

Final density after virializing: $\rho_f = 32 \times \rho_i$

$$\delta \equiv \rho_{\rm structure}/\rho_{\rm av} \simeq 32 \cdot 5.5 \simeq 178$$

Improved estimate:

$$\rho_{\rm eg}^2 \simeq \delta^2 \rho_{\rm DM}^2 / H_0 \simeq \mathcal{O}(\text{few} \times 10^{-48}\ \text{GeV}^7) \simeq \rho_s^2 r_s$$

Different contributions

- The smooth galactic and clumpy extragalactic intensities are roughly similar in magnitude
  - this makes sense: the MW is (mostly) a DM halo!
- But there is additional structure:
  - clusters at all redshifts have subclusters (analogously: the MW has subhalos)
- Add it all up!

Milky Way

(from smooth distribution) $$\frac{dI_{\rm sm}}{dE} = \frac{\langle \sigma v \rangle}{2m_\chi^2}\frac{dN_\gamma}{dE}\int_{V_{\rm obs}} dV_{\rm MW}\frac{\rho^2(s,b,\ell)}{4\pi s^2}$$

$$\frac{dI_{\rm sat}}{dE} = \frac{\langle \sigma v \rangle}{2m_\chi^2}\frac{dN_\gamma}{dE}\int dV_{\rm MW}\ dM\,\frac{1}{4\pi s^2}\times$$

$$\times\ \frac{dn_{\rm sat}(s,b,\ell,M)}{dM}\int dV_{\rm sat}\,\rho^2_{\rm sat}(M)$$

(from satellites)

satellite mass function (uncertain)

Extragalactic

$$\frac{dI_{\rm eg}}{dE} = \frac{\langle\sigma v\rangle}{2m_\chi^2}\int dz\,\frac{dN_\gamma[E(1+z)]}{dE}\,\frac{\bar{\rho}^2(z)}{4\pi}\times$$

$$\times\,\frac{(1+z)^3}{H(z)}\,e^{-\tau[E(1+z),z]}$$

$$\bar{\rho}^2(z) = \int dM\,\frac{dn(M,z)}{dM}\,[1+b_{\rm sh}(M)]\times$$

$$\times\int dV\,\rho^2_{\rm host}(r,M)$$

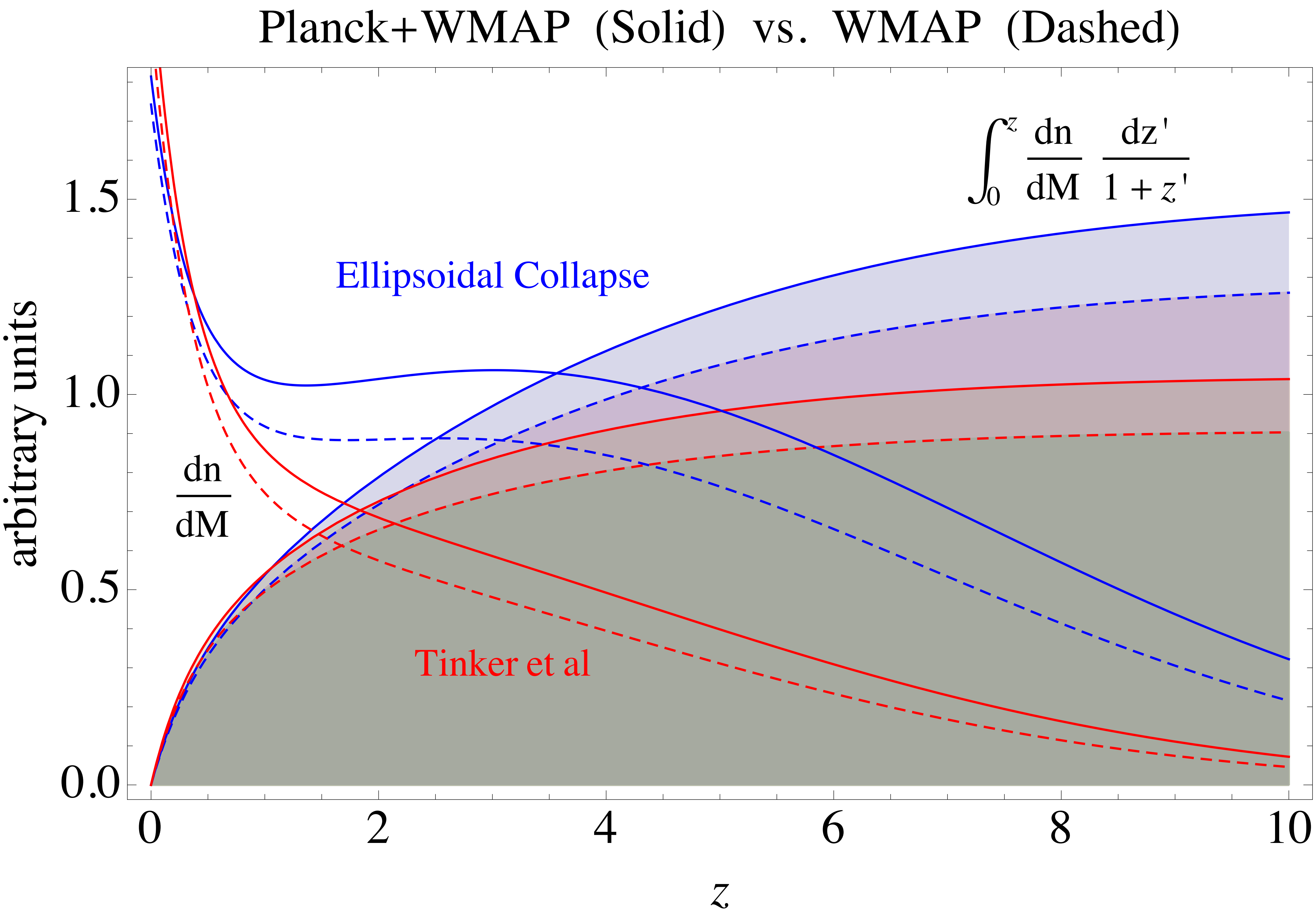
halo mass function (uncertain)

boost from substructure (uncertain)

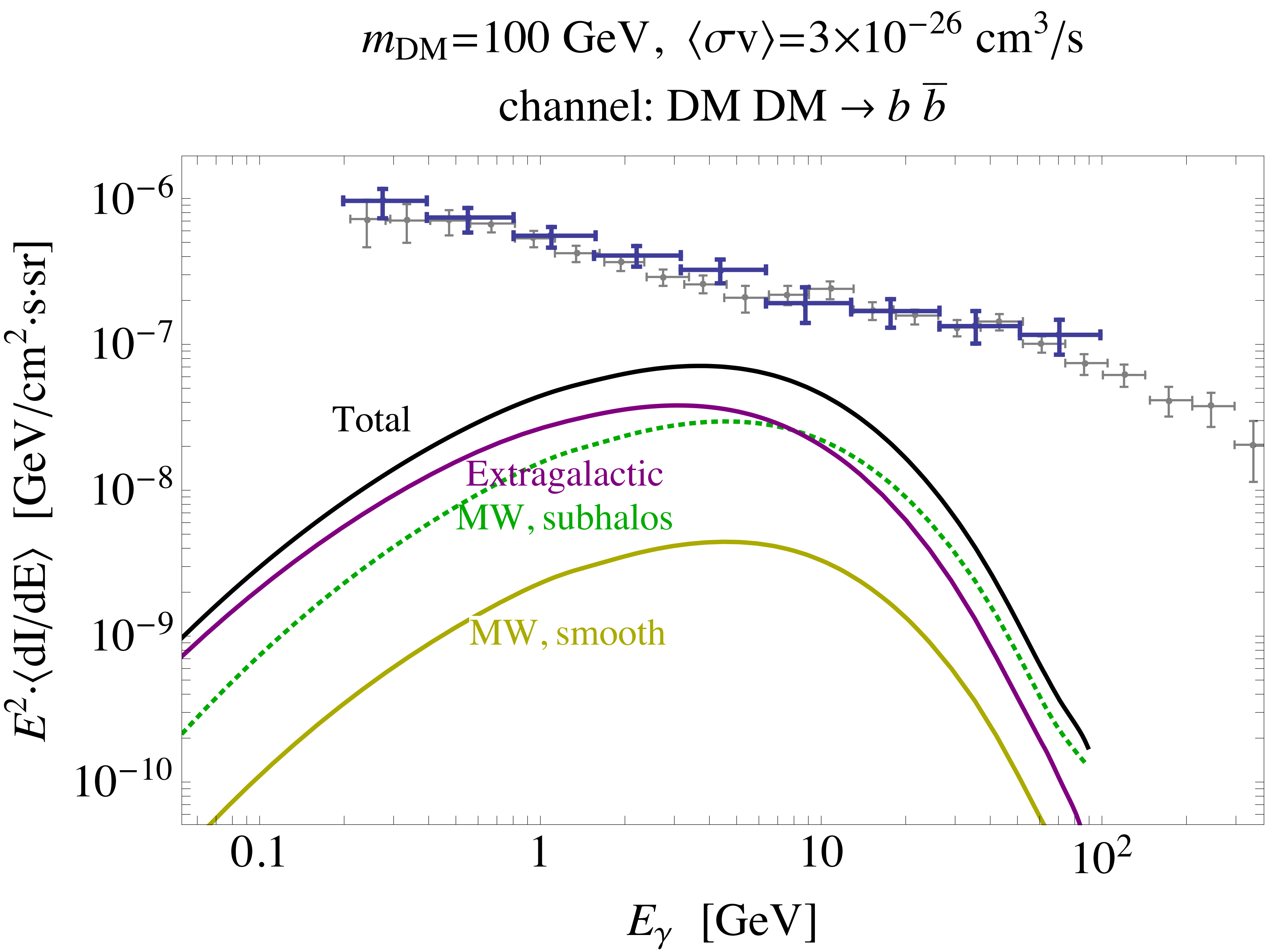
Uncertainties

- dN/dE from PPPC DM ID (Pythia+EW corrections)
- optical depth from semi-analytic modeling (Gilmore, Primack, et al)
- halo mass function and subhalo boost factor
  - semi-analytic fits (Phoenix simulation)
  - Anderhalden and Diemand

for example...

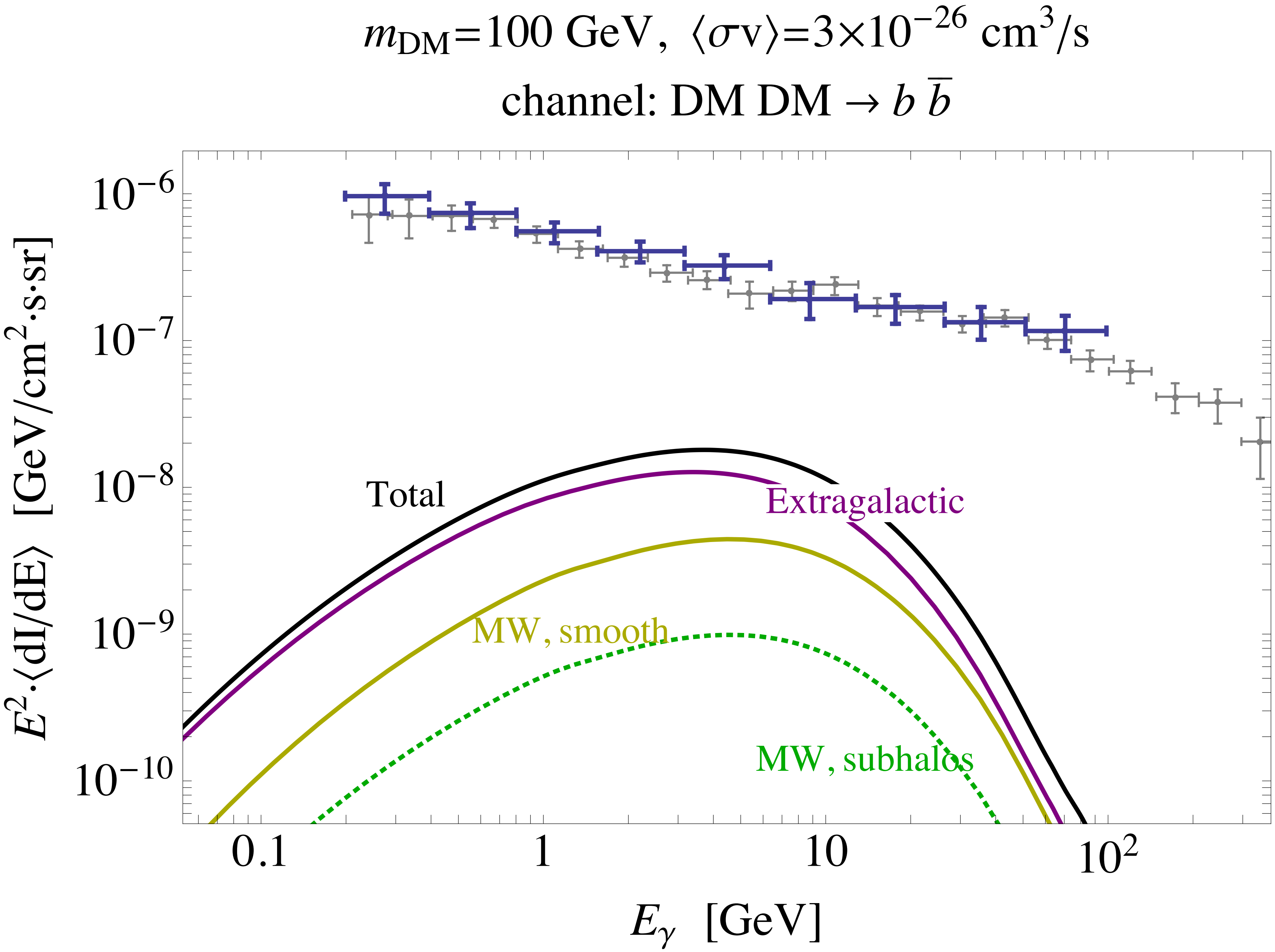

Planck+WMAP (Solid) vs. WMAP (Dashed)
$\int_0^z \frac{dn}{dM} \frac{dz'}{1+z'}$
Ellipsoidal Collapse
$\frac{dn}{dM}$
Tinker et al
arbitrary units
1.5
1.0
0.5
0.0
0
2
4
6
8
10
z

Relative intensities



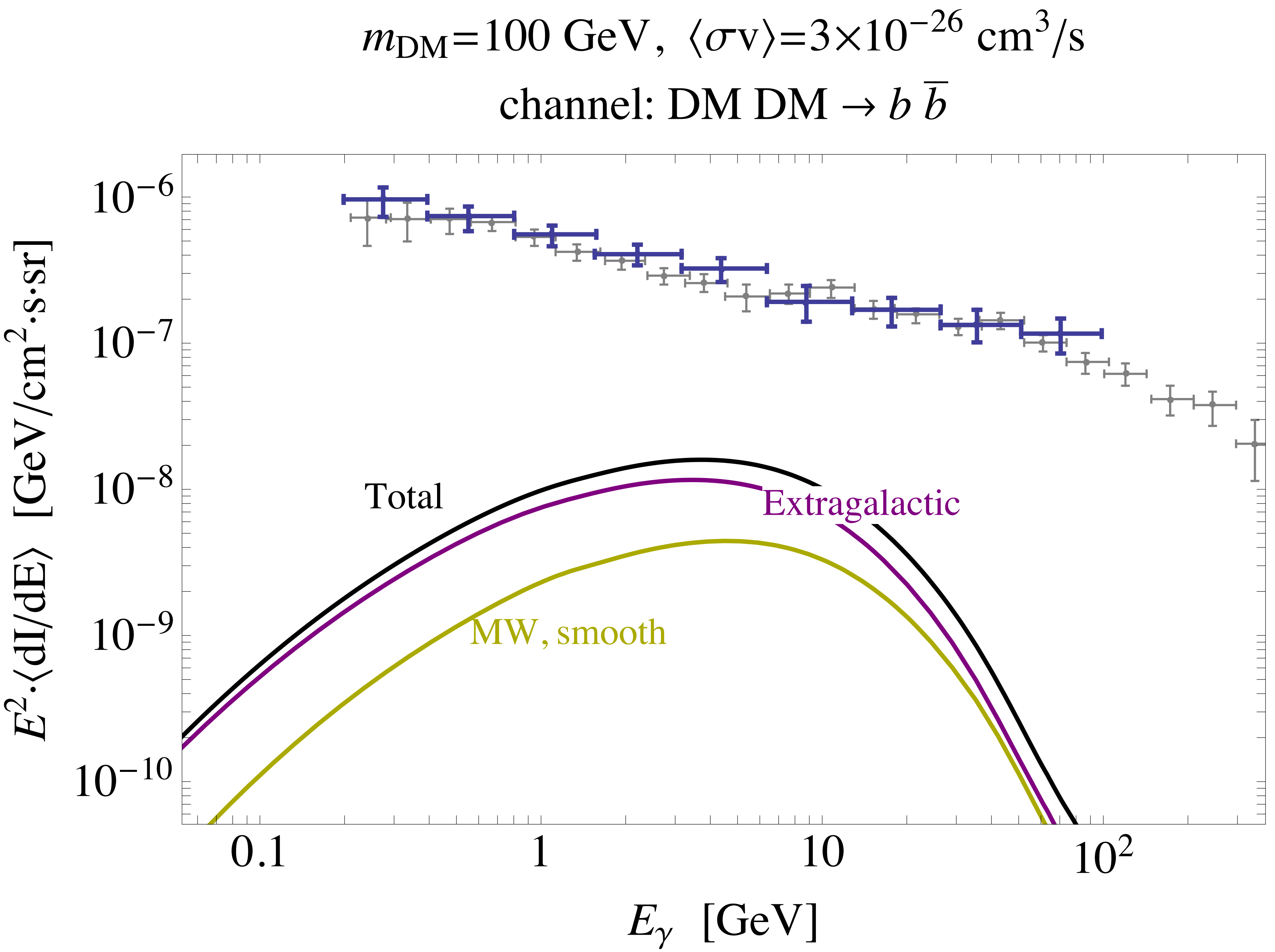
default substructure calculation

Relative intensities



conservative substructure calculation

Relative intensities

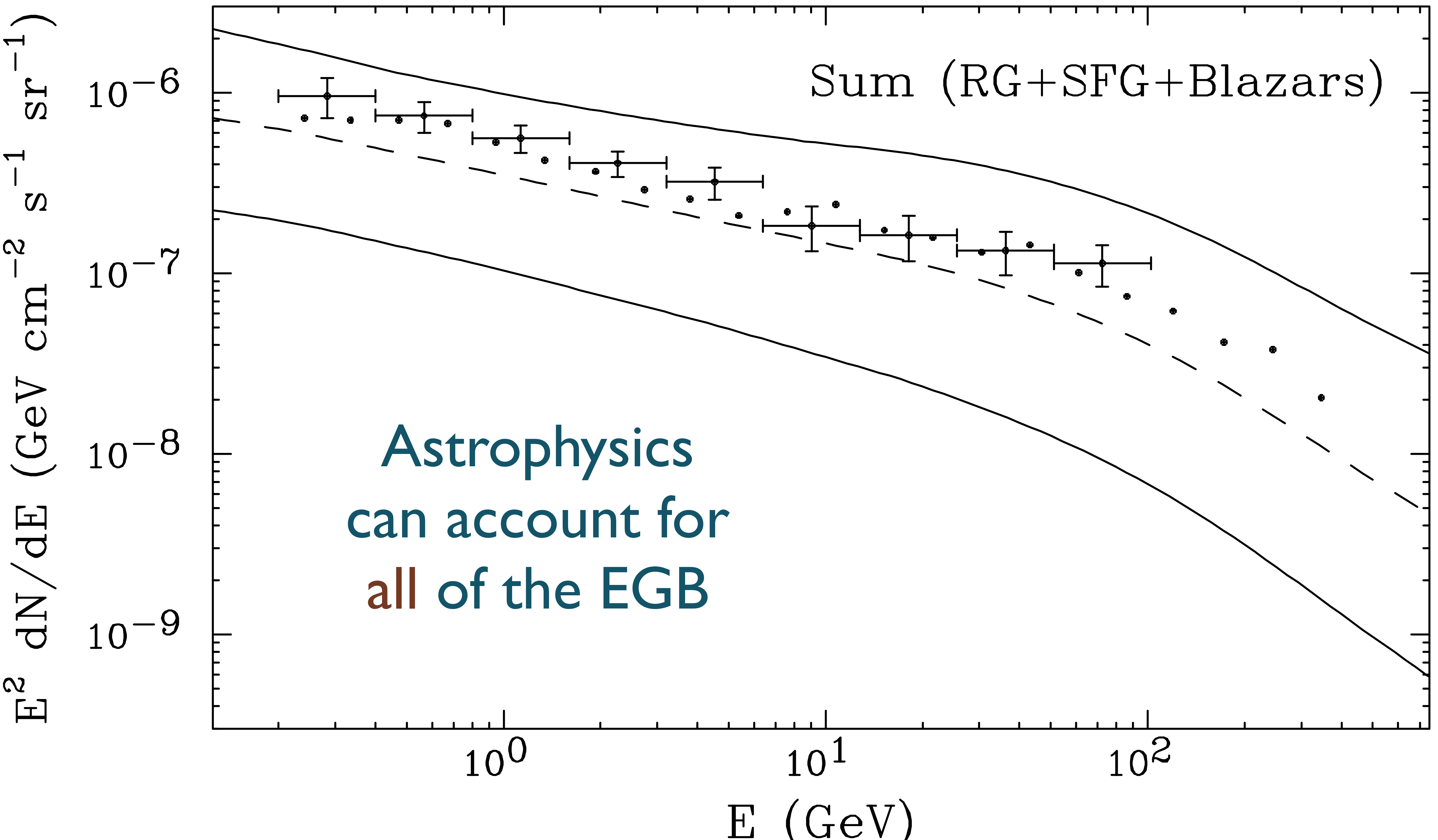


NO substructure

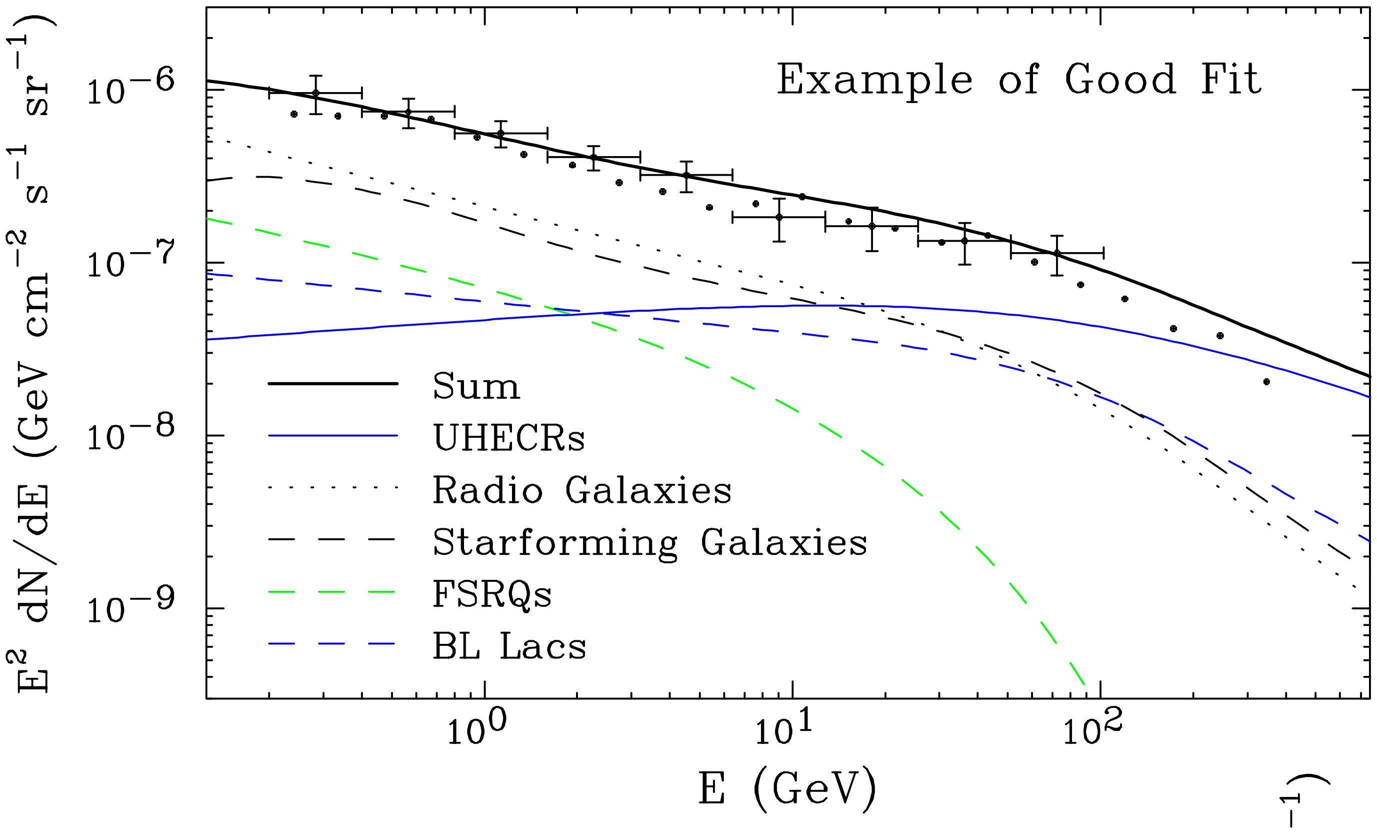
Many backgrounds

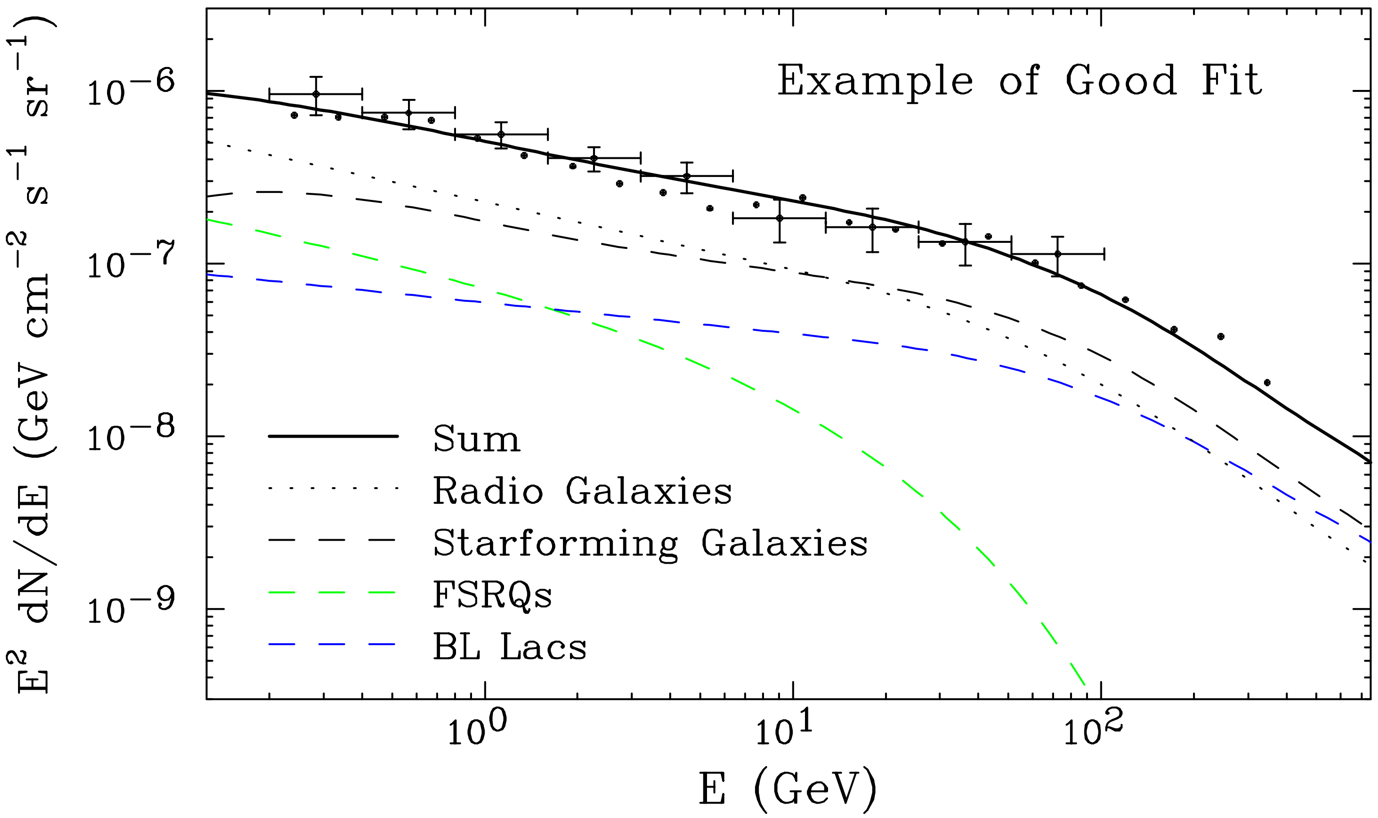
- star forming galaxies
- blazars (resolved and unresolved)
    - radio galaxies (BL Lactaea objects, FSRQs, etc.)
- ultra-high energy cosmic rays
- millisecond pulsars (...)

Backgrounds

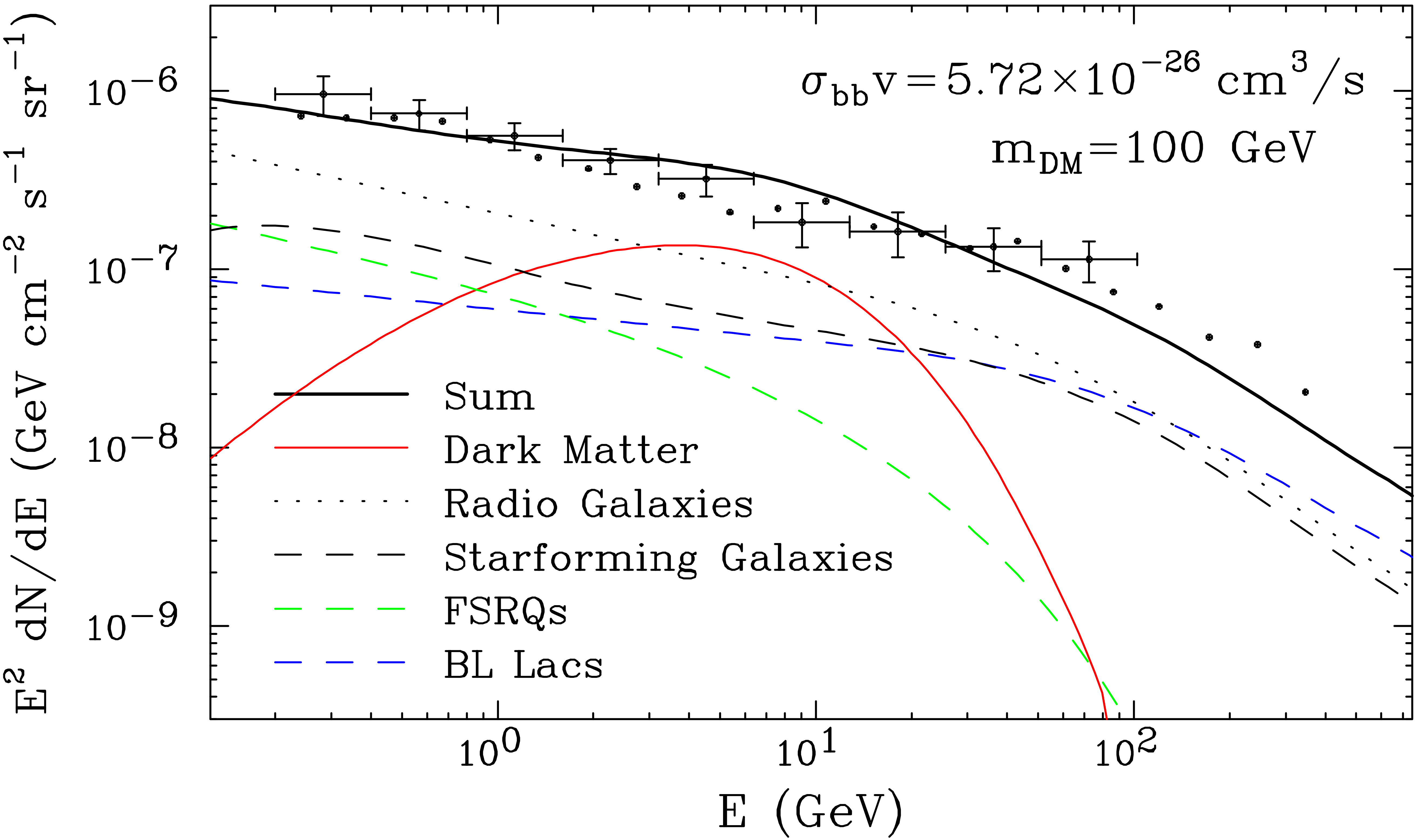


Fits without DM

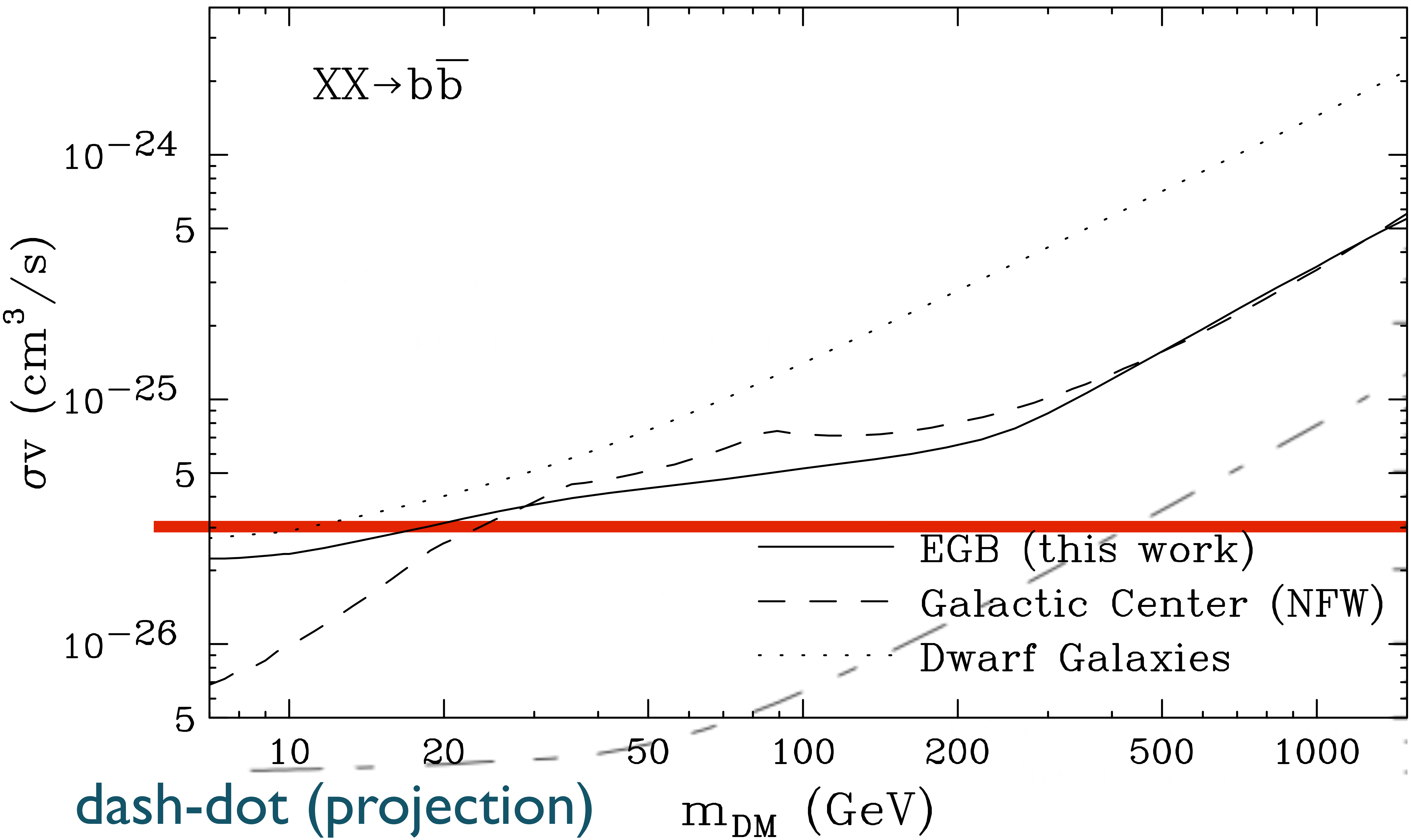




Example fit with DM



Cross-section bounds



dash-dot (projection)

Important probe

- Complementary to observations of stacked dwarf spheroidals, galactic center, ... (similarly strong or stronger, with very different systematics)
- Very strong bounds!
  - currently bounds thermal DM up to ~ 20 GeV
  - Projected to be the strongest bound by end of the Fermi mission
  - can bound thermal DM up to ~ 400 GeV

Conclusions

- Bounds on light decaying DM from the galactic diffuse background are strong (and robust!) even though observations are not DM-centric

- Looking outside the galaxy is a promising method for putting strong constraints on more massive annihilating DM

Thank you!

Other in-progress projects I'm excited to talk about:

- thoughts on relic neutrino detection
- new work related to DM direct detection
- extensions of work on DM in neutron stars
- collider phenomenology of a light Higgs partner