Stefano Profumo

UC Santa Cruz
Santa Cruz Institute for Particle Physics
T.A.S.C. [Theoretical Astrophysics, Santa Cruz]

Fundamental Physics with GeV Gamma Rays

Based on: Kamionkowski & SP, 0810.3233 (subm. to PRL)
Jeltema & SP, 0808.2641 (JCAP in press)
Jeltema & SP, 0805.1054 (ApJ)
SP, 0801.0740 (PRD)
Colafrancesco, SP & Ullio, astro-ph/0607073 (PRD) and 0507575 (A&A)

KICP – October 27, 2008, Chicago, IL

1. “ 1 / v ” WIMP Models

2. Fermi and Dark Matter
   Particle Properties

3. Beyond Gamma Rays:
   the Multi-wavelength Perspective

Detectable WIMP indirect detection signals typically imply some "**boost factor**" of the annihilation Cross Section expected in the Early Universe

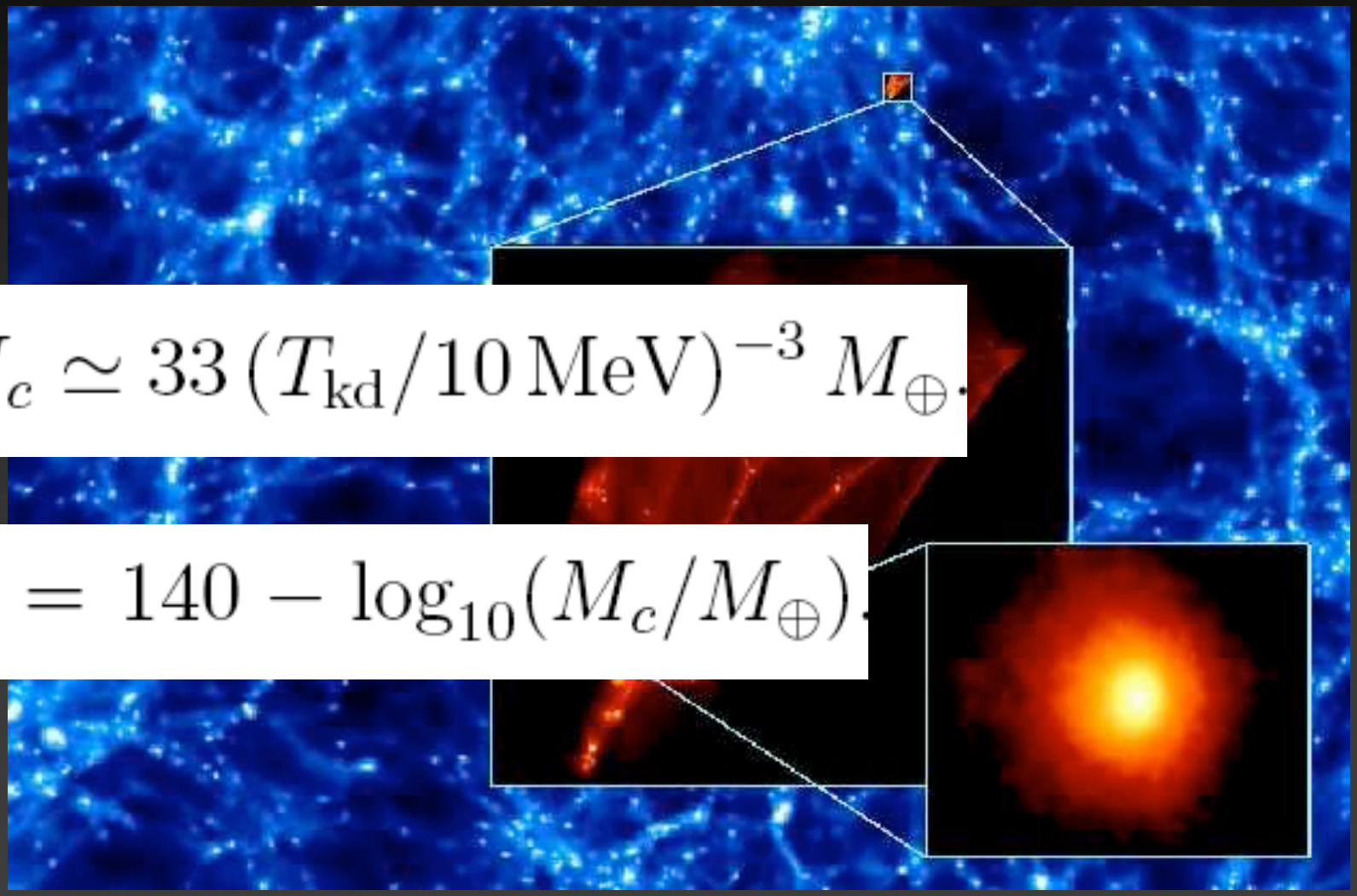
One possibility: **1/v WIMP** models

$$\sigma v \sim 3 \times 10^{-26}\ \mathrm{cm}^3/\mathrm{s}\ \sigma_{26}\ (c / v)$$

- Right Relic Abundance ($v \sim c/2$)
- $\sim 10^3$ Enhancement Today ($v \sim 150$ km/s)

Models that can lead to a 1/v cross section include e.g. the case of **Sommerfeld** enhanced Dark Matter Cross Section, with a light interaction carrier, or **SUSY**, with $m_\chi \sim \alpha_{EW} m_W$

After chemical decoupling ("freeze-out"),
WIMPs **kinematically** decouple at $T \sim T_{kd}$ from the relativistic thermal bath, and **protohalos** start to collapse



$$M_c \simeq 33\,(T_{\rm kd}/10\,{\rm MeV})^{-3}\,M_\oplus.$$

$$z_c = 140 - \log_{10}(M_c/M_\oplus).$$

Diemand et al, astro-ph/0501589

Velocity Dispersion: $v \sim R/t,$

Dynamical Time: $t \sim (G\rho)^{-1/2}$

Size : $R \sim (M/\rho)^{1/3}$

$$v \sim M^{1/3} G^{1/2} \rho^{1/6}.$$

$$(v/c) \sim 6.0 \times 10^{-9} \, (M_c/M_\oplus)^{1/3} (z_c/200)^{1/2}.$$

Kamionkowski & Profumo, 0810.3233 [astro-ph]

WIMP **annihilation rate** in the first collapsed halos:

$$\Gamma = 2.2 \times 10^{-17} \left(\frac{M_c}{M_\oplus}\right)^{-1/3} \sigma_{26} B_{2.6} \left(\frac{z_c}{200}\right)^{2.5} \left(\frac{m_\chi}{\mathrm{TeV}}\right)^{-1} \mathrm{s}.$$

where $B \equiv \frac{\int \rho^2 dV}{V \rho_v^2} = \frac{c_v^3 g(c_v)}{3[f(c_v)]^2}$, accounts for "**clumpiness**"

Fraction of Dark Matter particles that annihilate in the first halos:

$$f \simeq \Gamma t \simeq 0.44 \left(\frac{M_c}{M_\oplus}\right)^{-1/3} \sigma_{26} B_{2.6} \left(\frac{z_c}{200}\right)^{2.5} \left(\frac{m_\chi}{\mathrm{TeV}}\right)^{-1}$$

f<<1 already provide **constraints**… (we want DM today, and CMB implies a matter density at recombination within 10% of its value today…)

Kamionkowski & Profumo, 0810.3233 [astro-ph]

Two astrophysical **constraints** from annihilation in the first **protohalos**:

- Diffuse radiation Background
- IGM Heating and Ionization outside transparency window

Diffuse Radiation Background Limit

$$\sigma_{26} \lesssim 6 \times 10^{-6}\, B_{2.6}^{-1} \left(\frac{M_c}{M_\oplus}\right)^{1/3} \left(\frac{z_c}{100}\right)^{-1.5} \left(\frac{E_\gamma}{\mathrm{GeV}}\right)^{-1.11} \left(\frac{m_\chi}{\mathrm{TeV}}\right)$$

IGM Heating and Ionization Limit

$$\sigma_{26} \lesssim 6 \times 10^{-7} \left(\frac{M_c}{M_\oplus}\right)^{1/3} B_{2.6}^{-1} \left(\frac{z_c}{100}\right)^{-2.5} \left(\frac{m_\chi}{\mathrm{TeV}}\right)$$

Kamionkowski & Profumo, 0810.3233 [astro-ph]

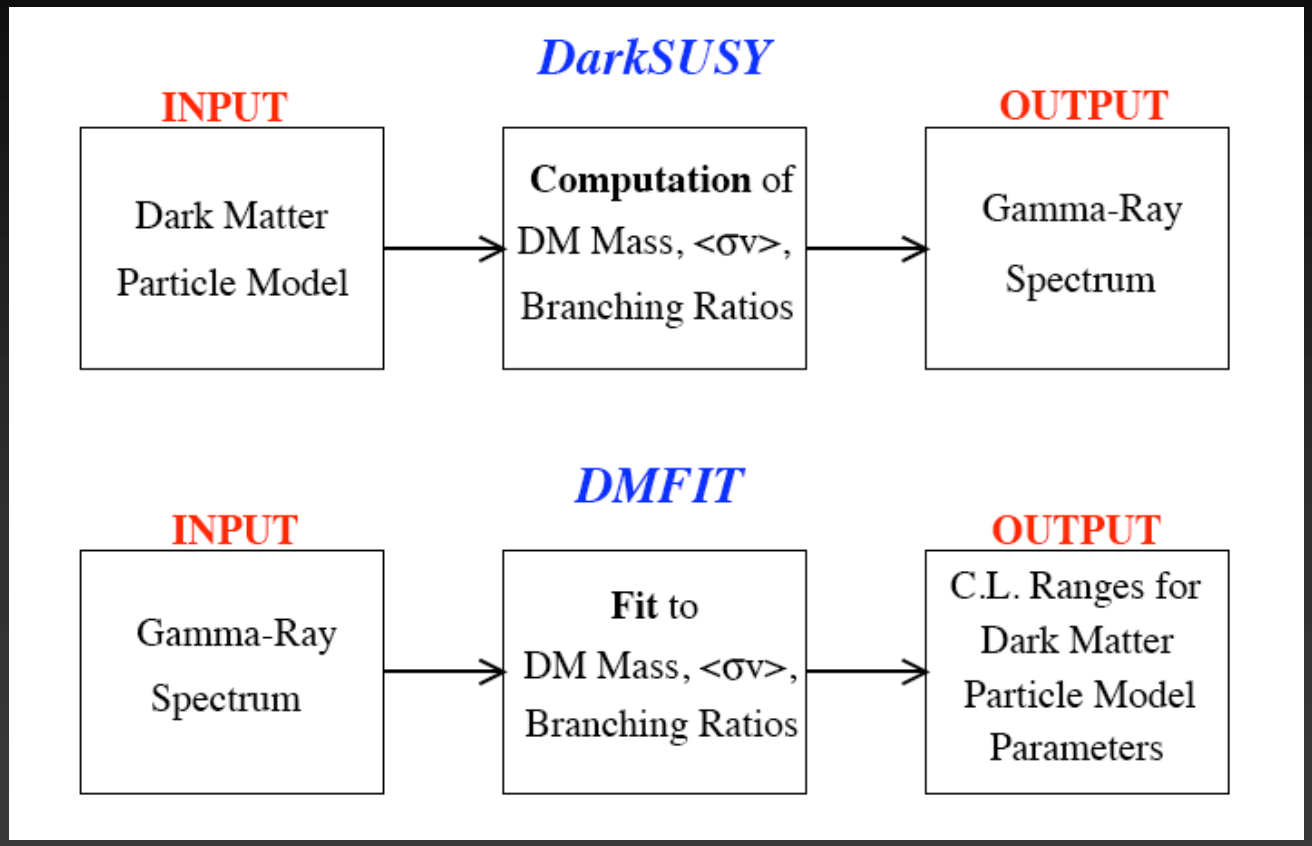
Punchline: 1/v models **violate**
one or the other constraint
by **~ 6** order of magnitude

Ways out:

- **Detect** Signature in Diffuse Galactic or Extra-Galactic Background!
- Resonant Elastic Scattering with protohalos **suppression**
- Velocity **cutoff** for the enhancement
- Larger enhancement by **minihalos today**, but something else for Relic Abundance!

Kamionkowski & Profumo, 0810.3233 [astro-ph]

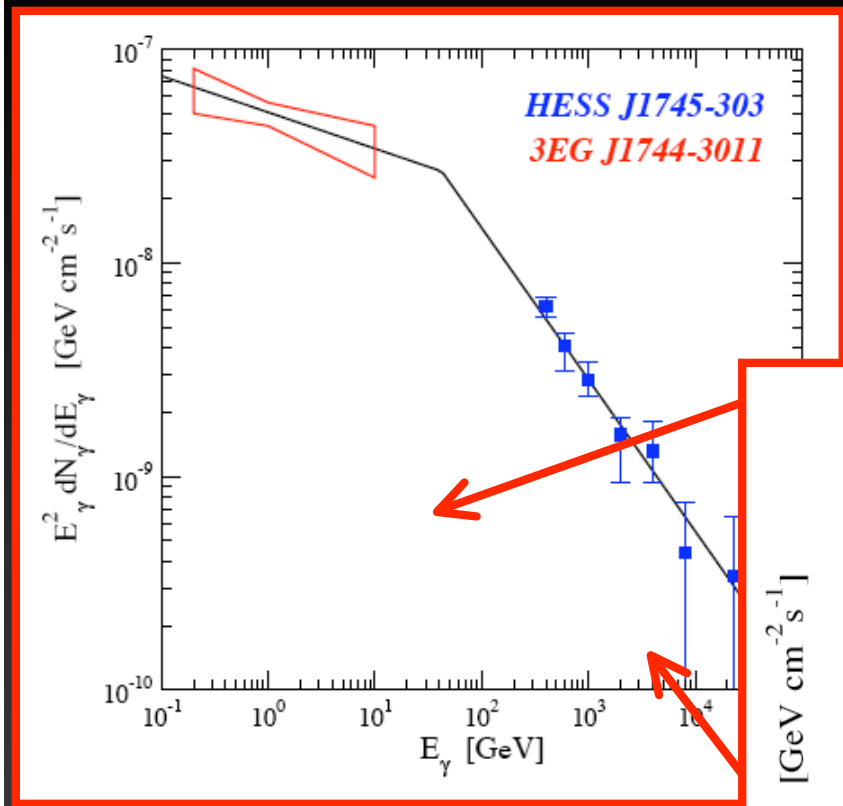
Fitting the Gamma-Ray Spectrum from Dark Matter with **DMFIT**: Fermi-LAT and the **Galactic Center** Region

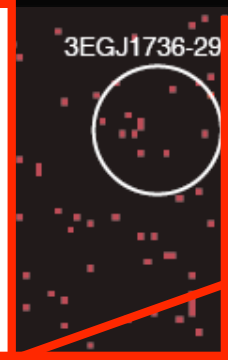


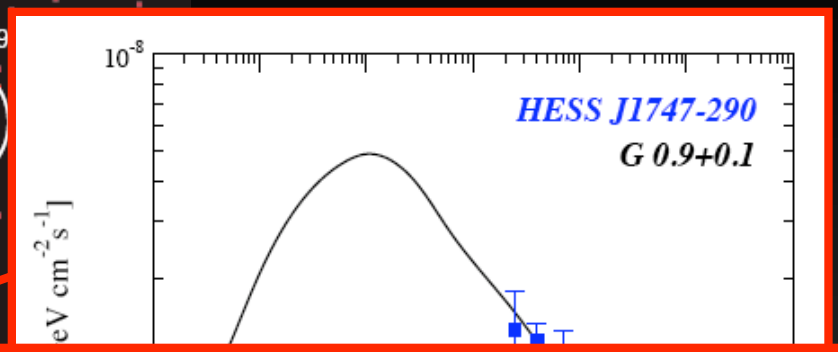
Assess which Dark Matter **particle properties** can be deduced with gamma-ray spectral analyses, and associated theoretical **systematics**

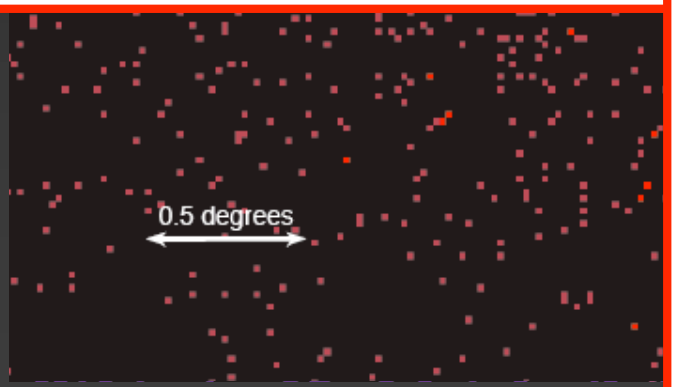
Jeltema & Profumo, 0808.2641 [astro-ph]

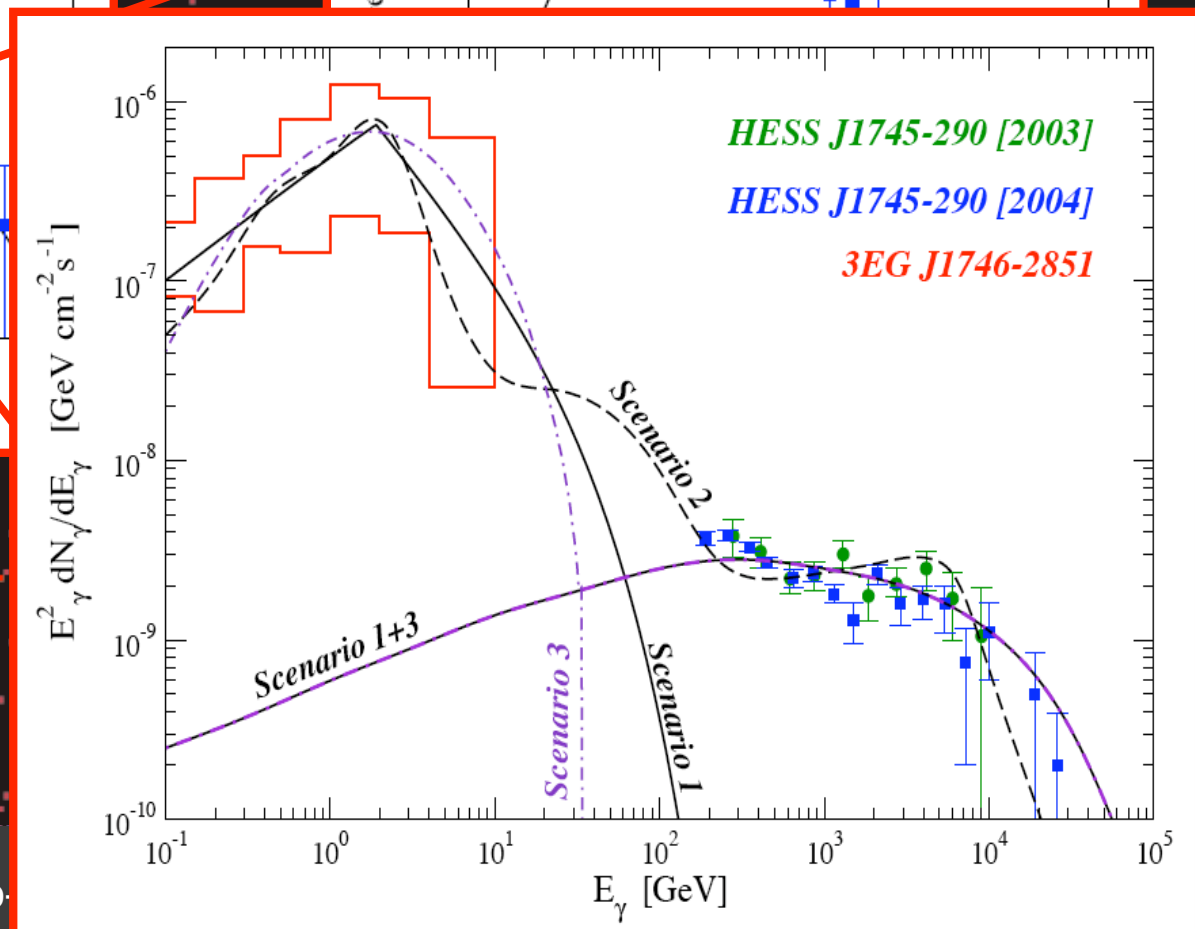
Fermi Science Tools **simulation** of the gamma-ray sky in the GC region





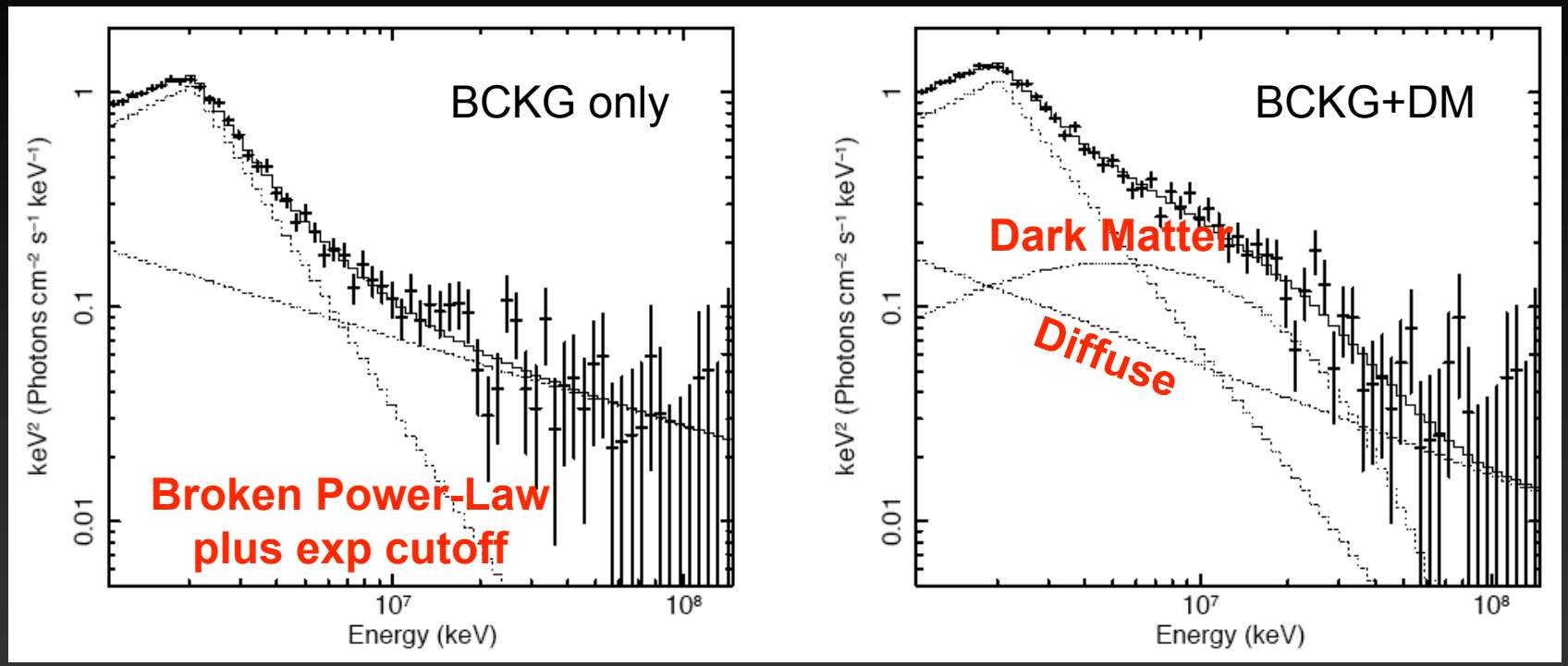






Jeltema & Profumo, 0808.2641 [astro-

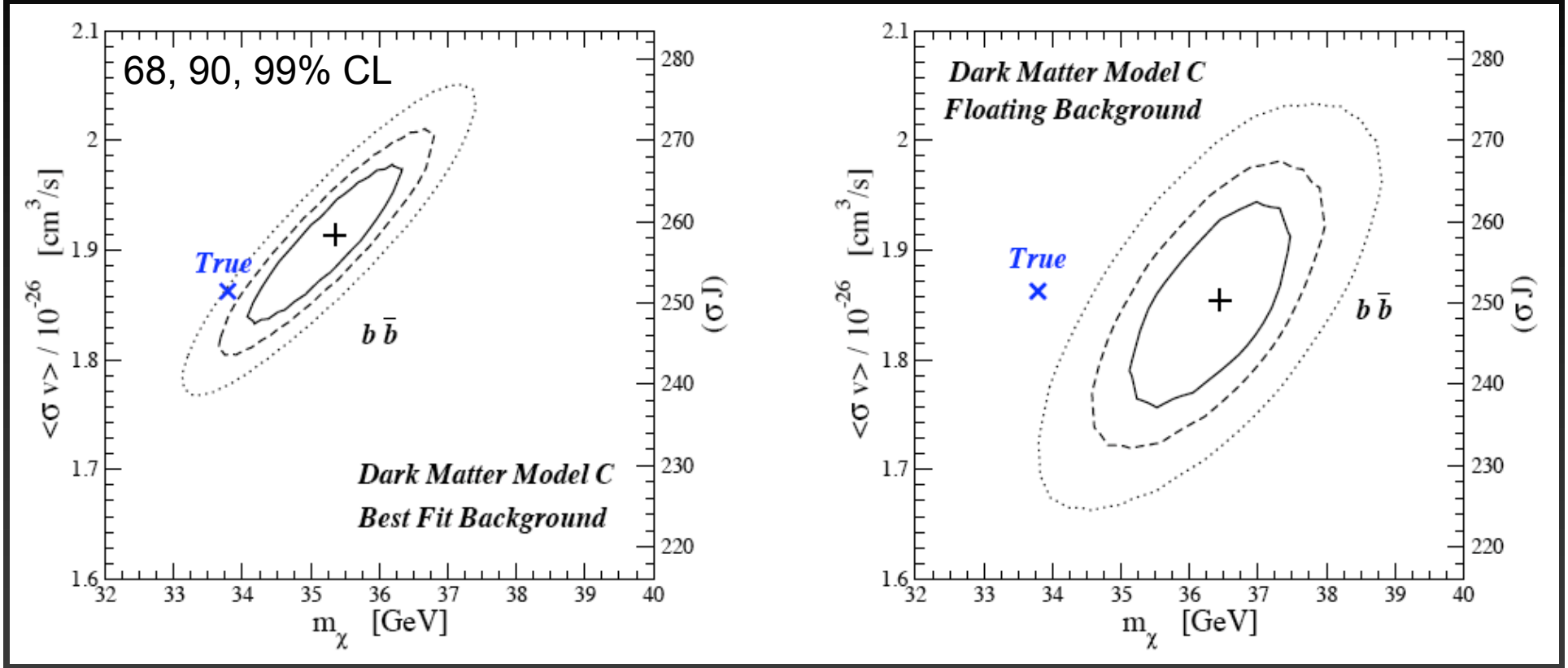
Use **XSPEC** to fit background and Dark Matter signal with **DMFIT**



Bkgd Model	DM Model	DM Mass	Bkgd Only Spectrum	Bkgd + DM Spectrum: bkgd spec.	bkgd spec. + DMFIT	bkgd spec. (fixed) + DMFIT
1	A	167.5	1.22	1.20	1.10 $[144^{+30}_{-40}]$	1.09 $[173^{+16}_{-8}]$
1	B	92.8	1.22	**2.86**	1.36 $[81.8^{+3.4}_{-8.7}]$	1.39 $[90.6^{+2.0}_{-2.0}]$
2	A	167.5	0.99	1.24	0.946 $[274^{+56}_{-58}]$	0.891 $[208^{+16}_{-16}]$
2	B	92.8	0.99	**1.56**	1.29 $[109^{+8}_{-16}]$	1.21 $[92.4^{+2.0}_{-2.0}]$

Jeltema & Profumo, 0808.2641 [astro-ph]

Mass & **Annihilation Rate** estimates, for a bright DM source at the GC with and without best fit to **background** alone

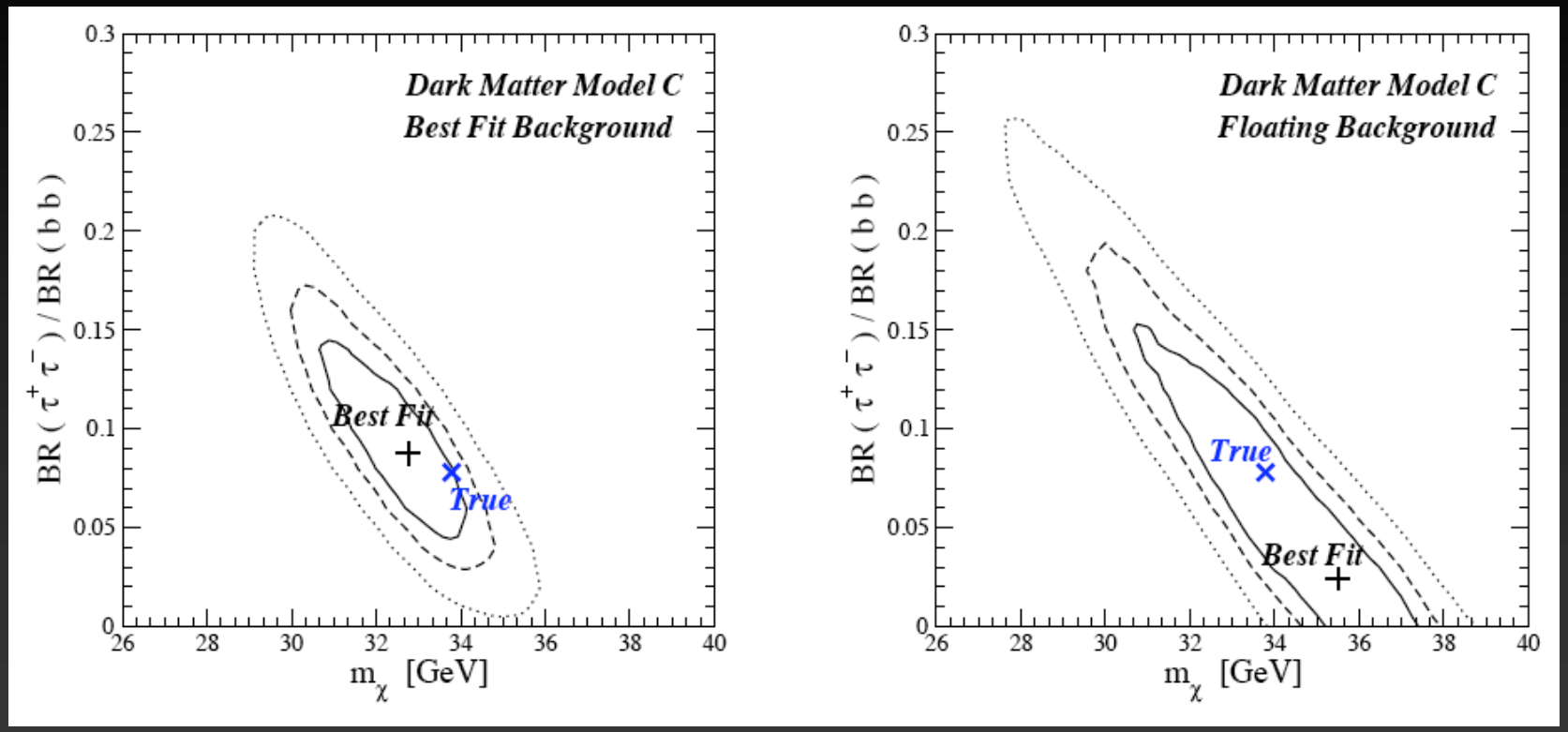


The Dark Matter model has a significant (15%) $\tau^+\tau^-$ component

This causes a **bias** in the mass extraction towards larger values!

Jeltema & Profumo, 0808.2641 [astro-ph]

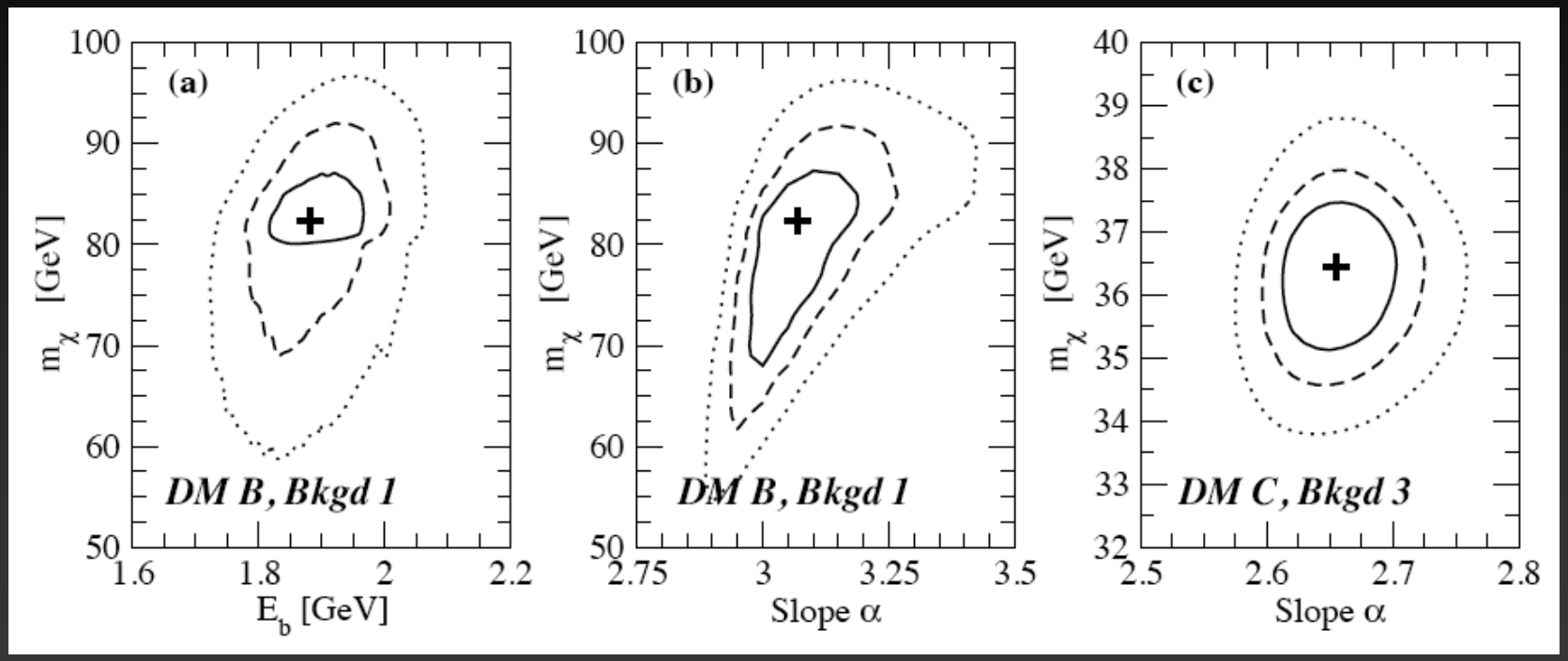
Similar approach, but studying the relative **branching ratio** contribution



- With background under control, the **existence** of a second (15%) annihilation mode is pinned down at the 99% CL!
- Including a second annihilation channel, the **artificial bias** in the mass disappears

Jeltema & Profumo, 0808.2641 [astro-ph]

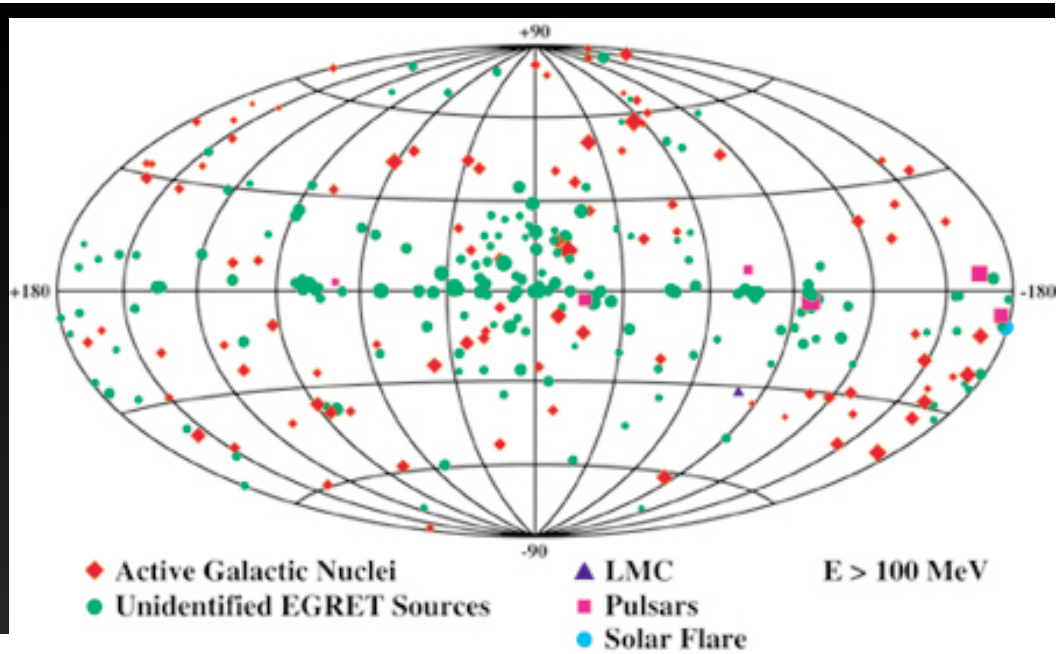
The simultaneous fit to **Background** also yields a systematic effect in the determination of particle Dark Matter properties



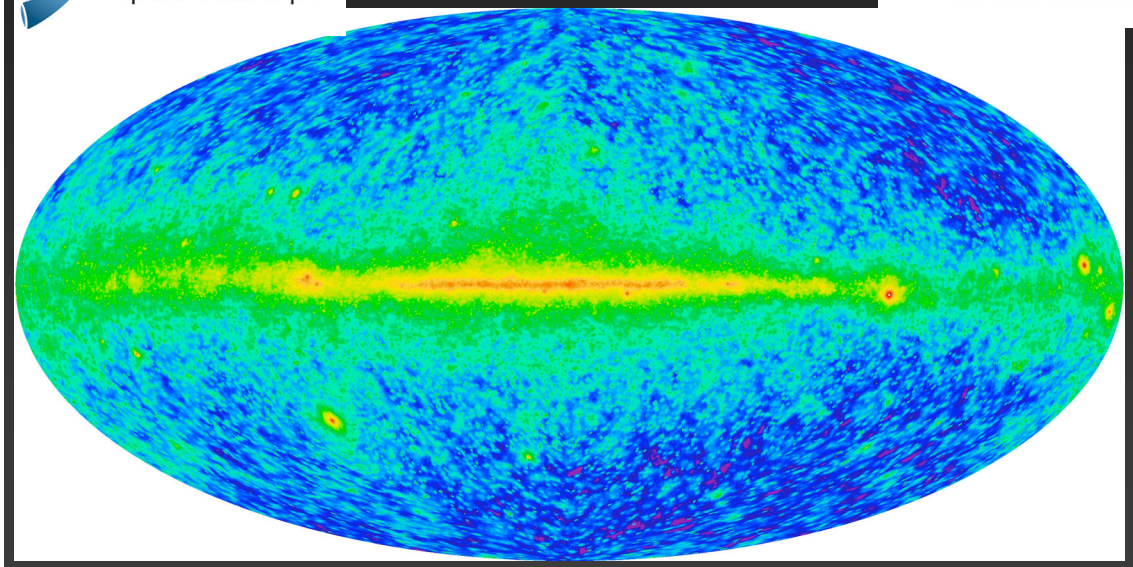
Power law slope **correlates** with mass in some cases, and so does the power-law break energy

Jeltema & Profumo, 0808.2641 [astro-ph]

EGRET
Unidentified
Sources



Fermi
Gamma-ray
Space Telescope

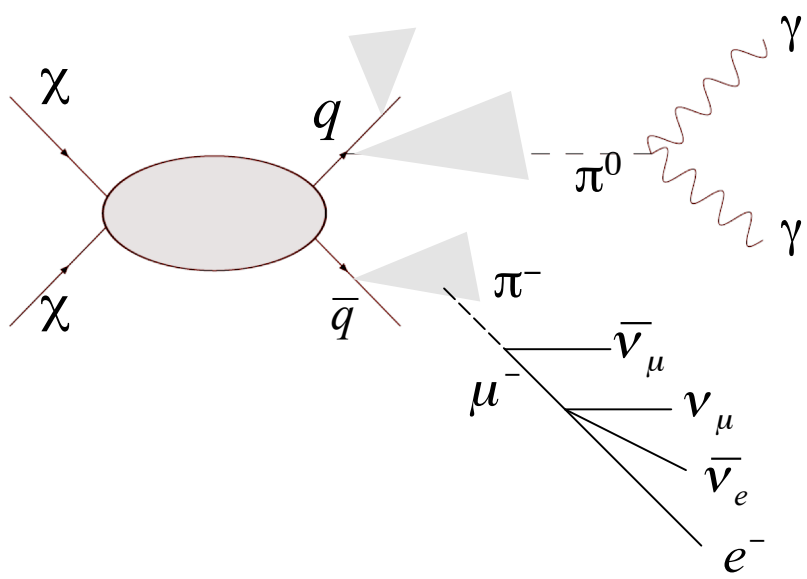


Fermi-LAT Sky after 4 days (!)

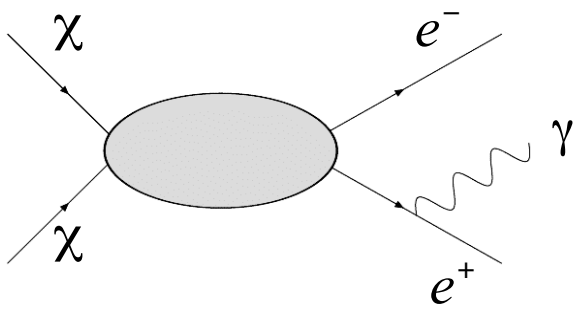
Expect several 100's of
unidentified sources!!

Will be able to conclusively state that an **unidentified** source is **associate** to **Dark Matter** annihilation?

One handle: look beyond gamma rays into other **wavelengths**!



π decays from the hadronization of quark-antiquark, W^+W^- final states



Prompt lepton pair production

DM **annihilations** produce Gamma Rays as well as energetic **electrons/positrons**, with peculiar injection spectra

Electrons and Positrons diffuse and loose energy

Inverse Compton off CMB and starlight photons,
Bremsstrahlung and **Synchrotron** emission
produce radiation from radio to gamma-ray frequencies

1. Source Term

$$Q(E,\vec{x}) \propto \frac{\rho_{\mathrm{DM}}^2(\vec{x})}{m_{\mathrm{DM}}^2}\left\langle \sigma_{\chi\chi}\ \mathrm{v}_{\mathrm{rel}} \right\rangle \frac{dN_e(E)}{dE}$$

2. Transport Equation

$$\frac{\partial}{\partial t}\frac{dn_e}{dE} = \nabla\left[D(E,\vec{x})\nabla\frac{dn_e}{dE}\right] + \frac{\partial}{\partial E}\left[b(E,\vec{x})\frac{dn_e}{dE}\right] + Q(E,\vec{x})$$

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$$b = b_{\mathrm{IC}} + b_{\mathrm{Coul}} + b_{\mathrm{Syn}} + b_{\mathrm{Brem}}$$

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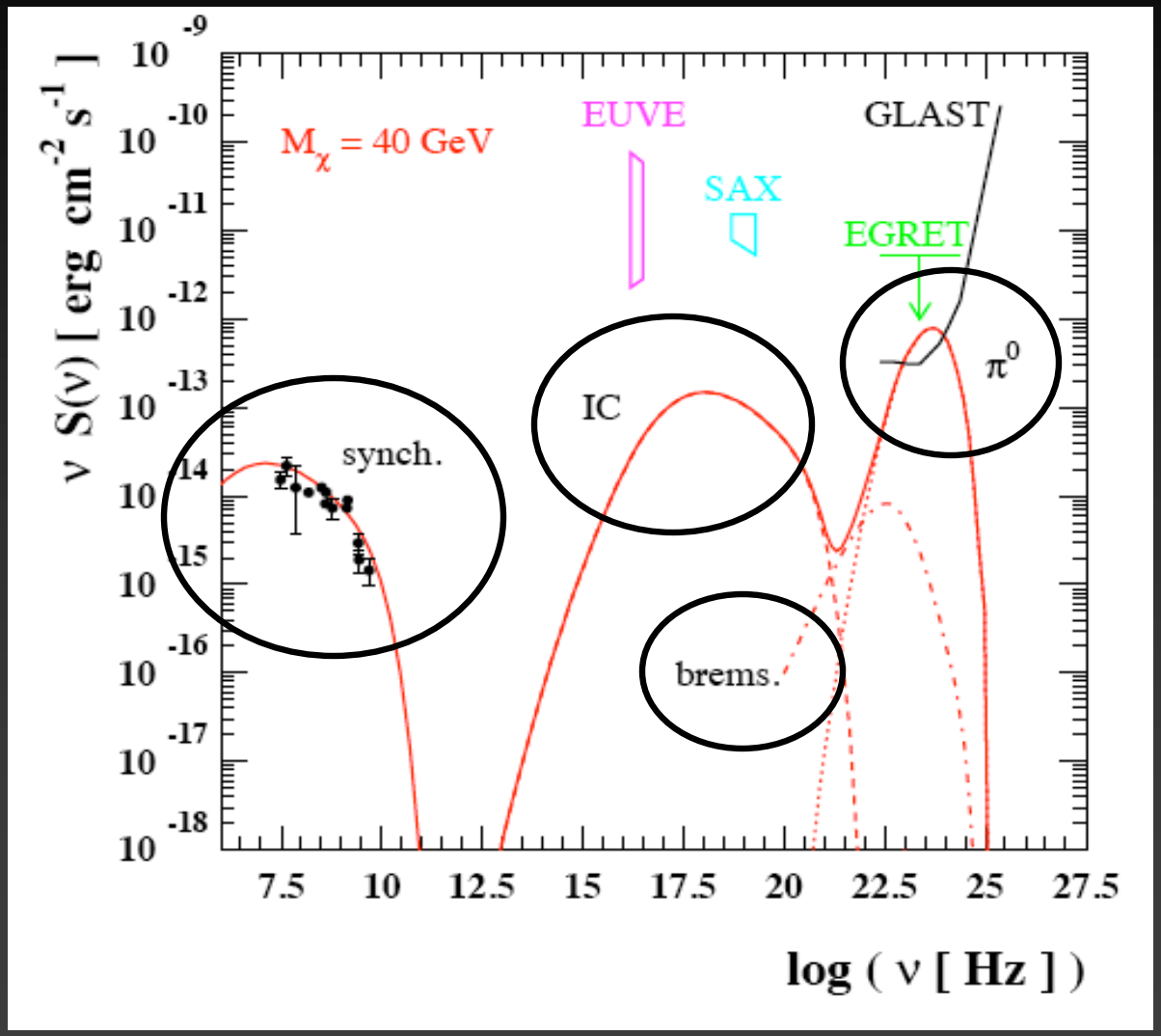
3. Compute the Signals
(*IC off CMB/starlight, Synchrotron emission,…***)**

$$n_e^{\rm EQ}(E,\vec{x})$$

The **multi-wavelength spectrum** expected from a 41 GeV “bino” annihilating in the Coma cluster



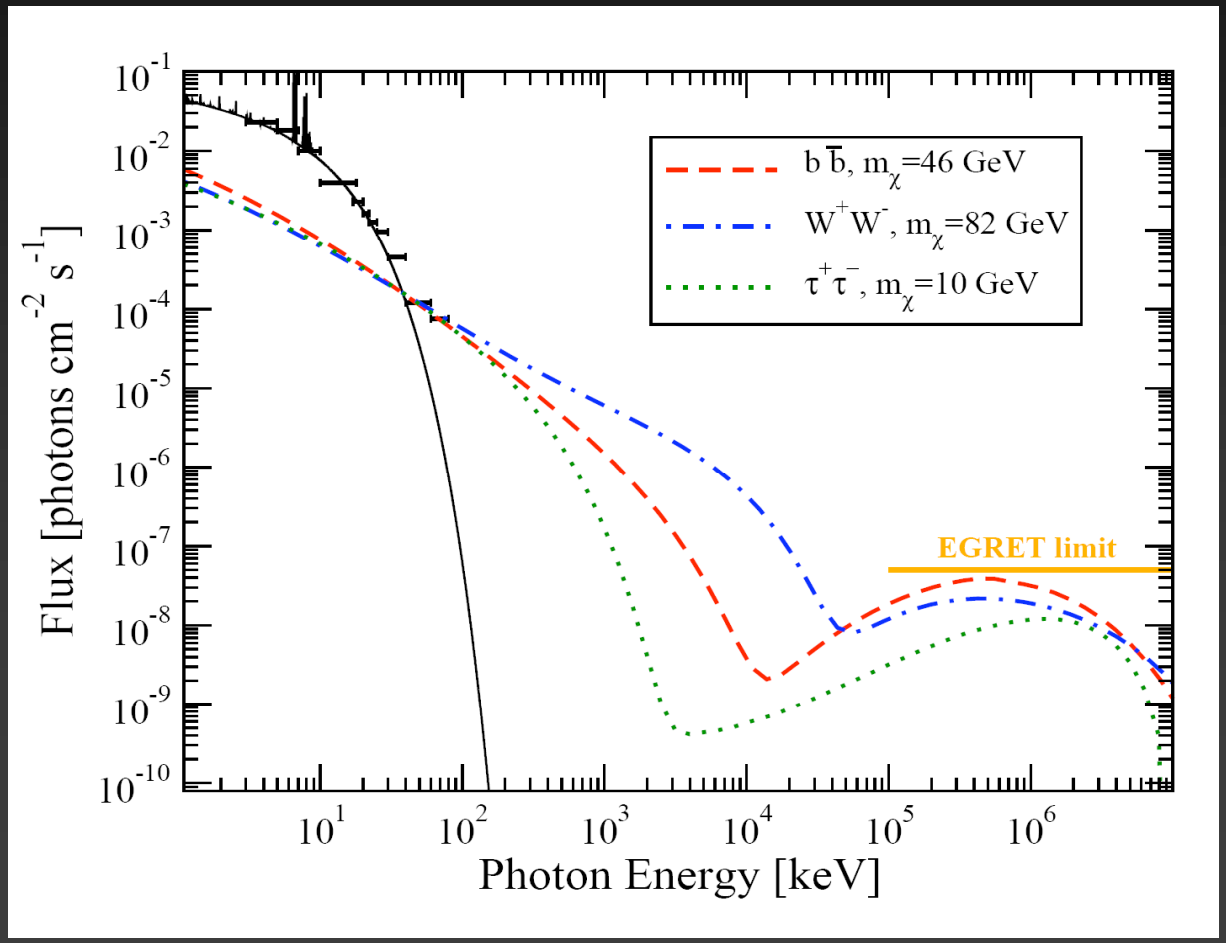
Colafransceo, Profumo & Ullio, astro-ph/0507575

Hard X-ray emission: generic feature of **DM** multi-wavelength spectra

Significant **differences** at lower/higher energies

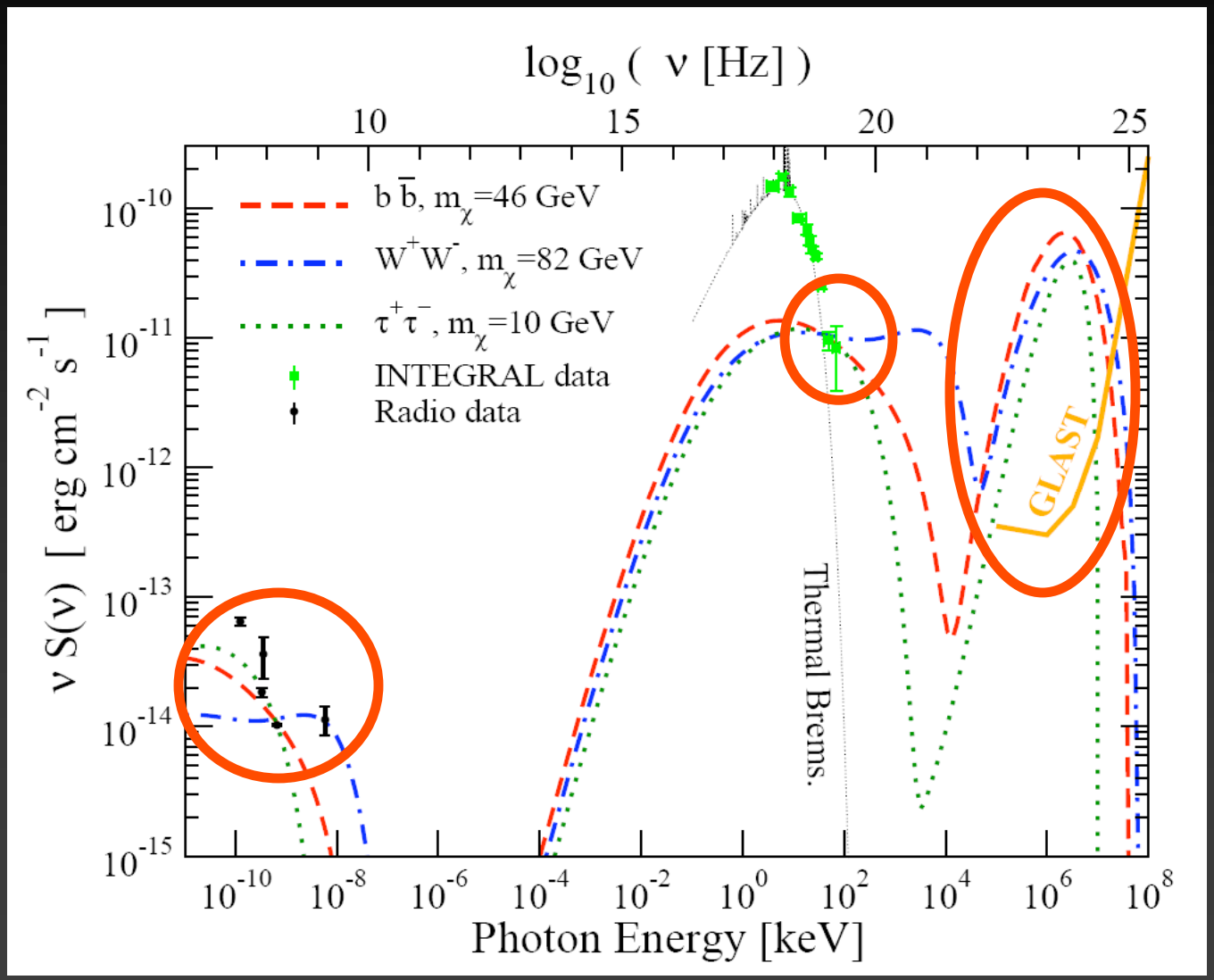
Fit the Hard X-ray emission from the **Ophiuchus** Cluster with Dark Matter

Compatible with **EGRET** limit on gamma ray emission (no detection from Oph.)



Profumo, 0801.0740 [astro-ph]

One Possibility: **Hard X-ray** emission is ascribed to **Dark Matter** Annihilation producing e+e- and IC scattering…



Fermi-LAT will conclusively test this scenario!

Radio follow-ups also crucial!

Profumo, 0801.0740 [astro-ph]

Down-side: Clusters host other sources of **non-thermal** activity!

Ideal environment for a multi-wavelength Dark Matter search campaign:

Nearby **Dwarf** Galaxies

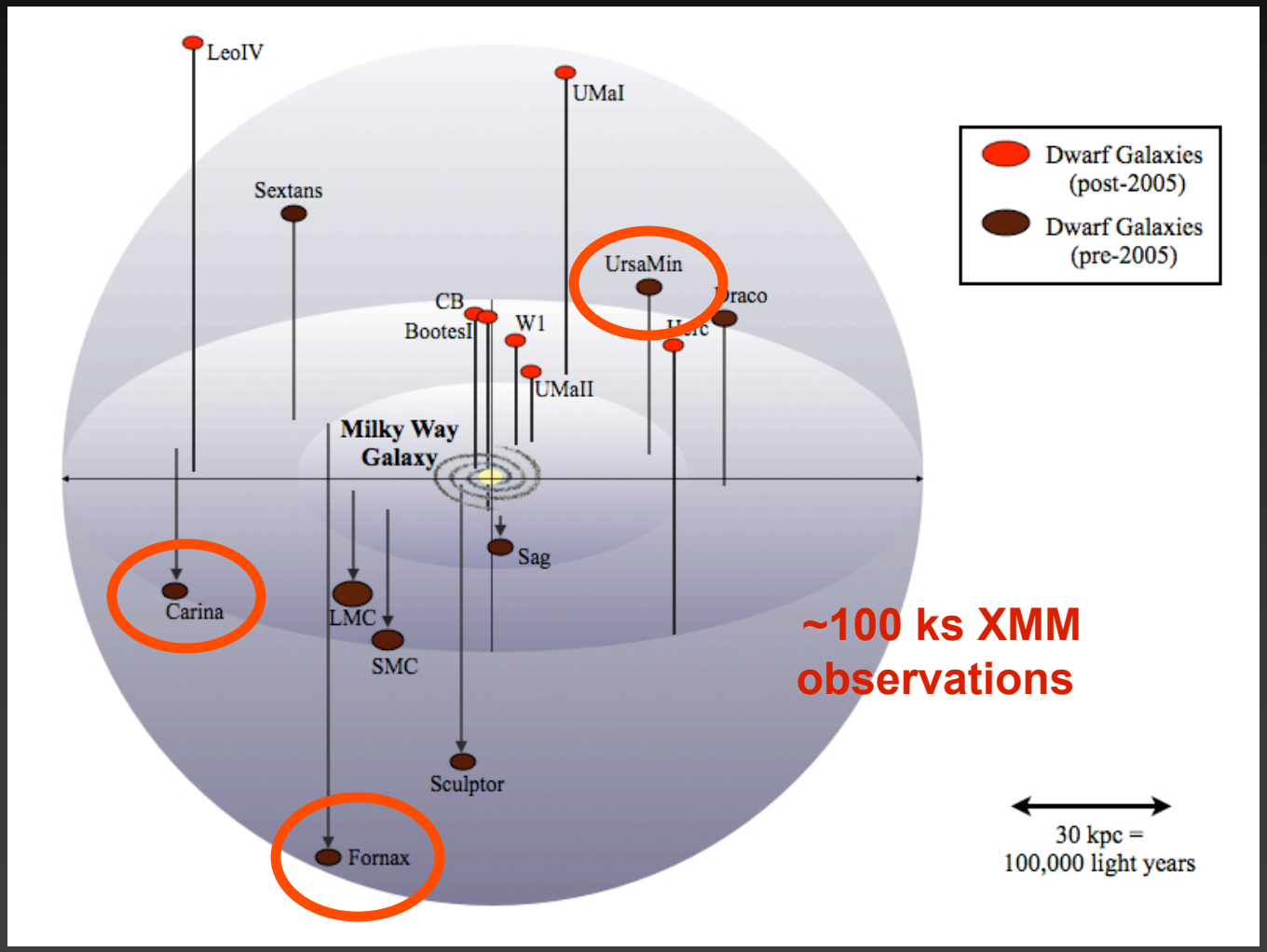
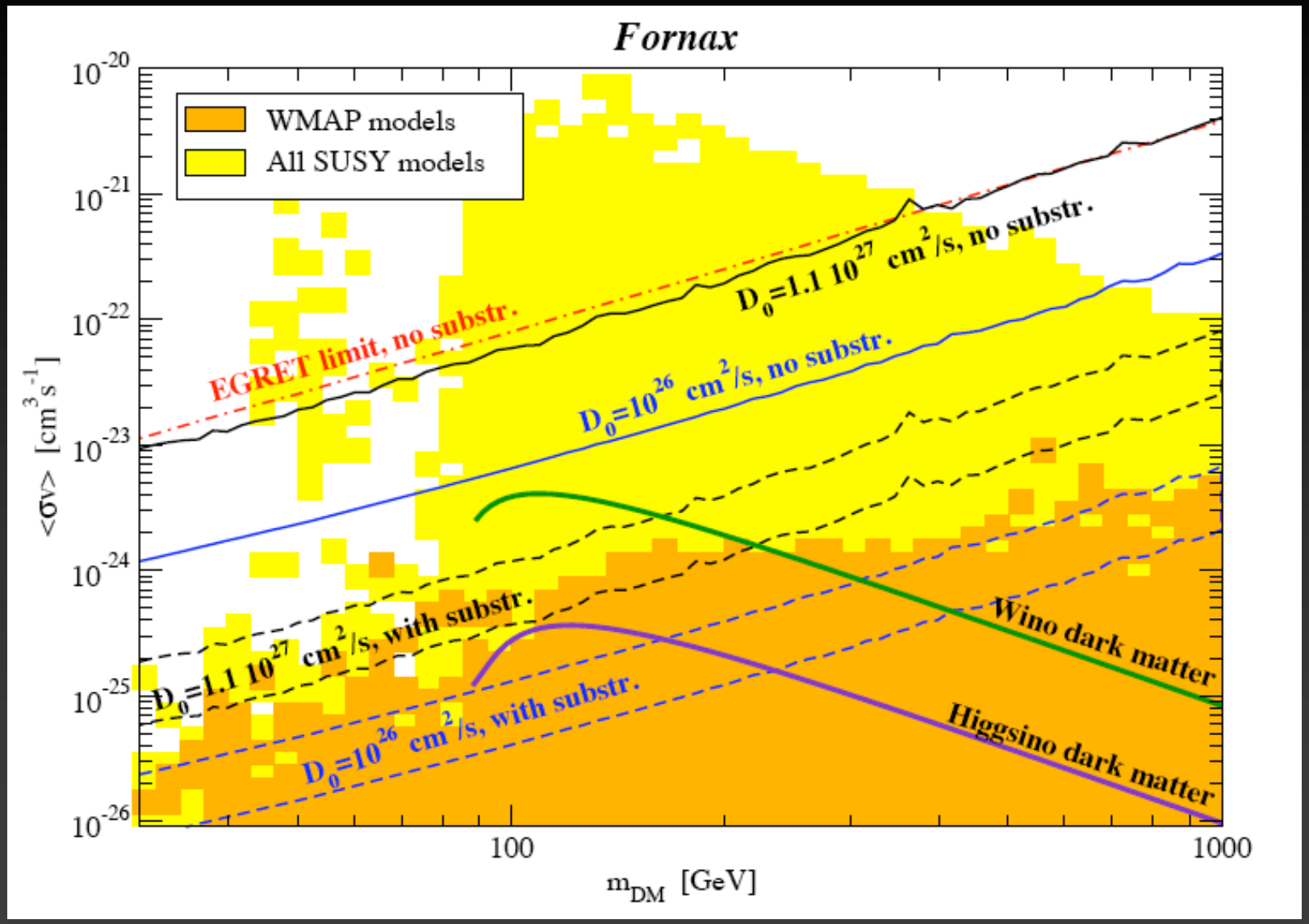


Image credit: Marla Geha

Sensitivity of **current X-ray** detectors (with ~100ks) comparable to **EGRET**



Uncertain **Diffusion** Model, but comparable sensitivity in X and gamma ray!

- **Modifications** to the Annihilation Cross Section (e.g. ~1/v) are strongly constrained by diffuse radiation from the first **protohalos**

- **Gamma-Ray** spectra (and fits to them) can yield important information on the **fundamental** nature of dark matter (e.g. **annihilation modes**, mass)

- Gamma-Ray Indirect **searches** for dark matter annihilation can be enhanced by **multi-wavelength** observational campaigns