Status of DM and DF

Natalia Toro

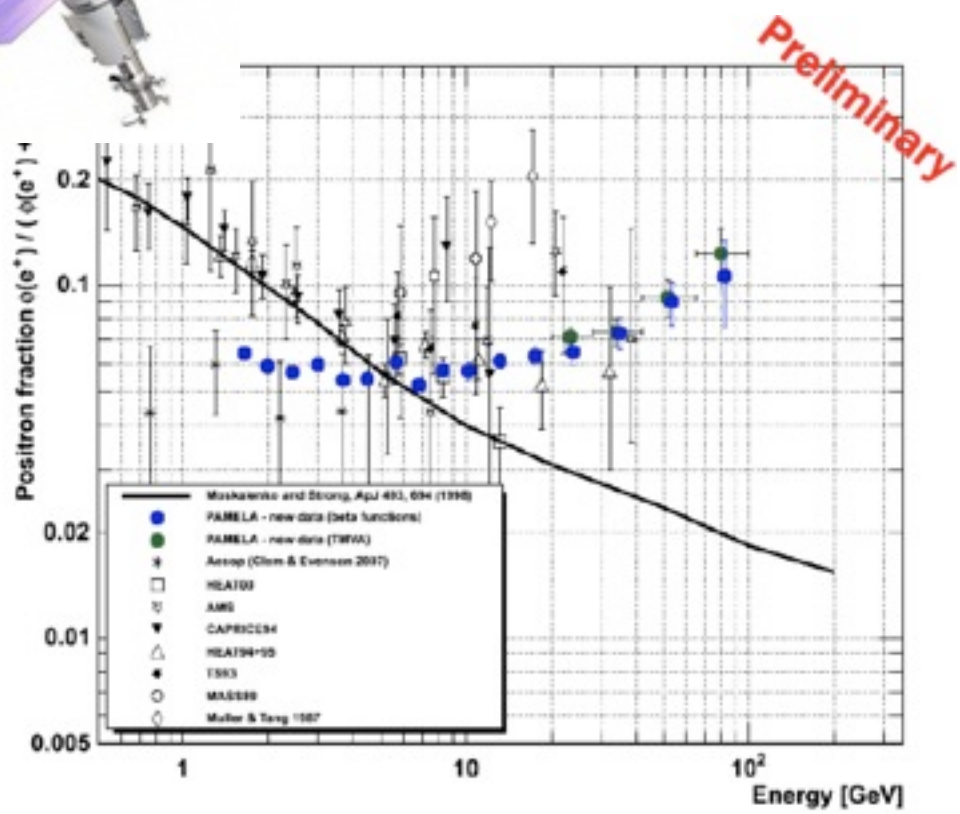
thanks to R. Essig
T. Slatyer and N. Weiner

Outline

- DM Motivation
- Constraints
- Uncertainties

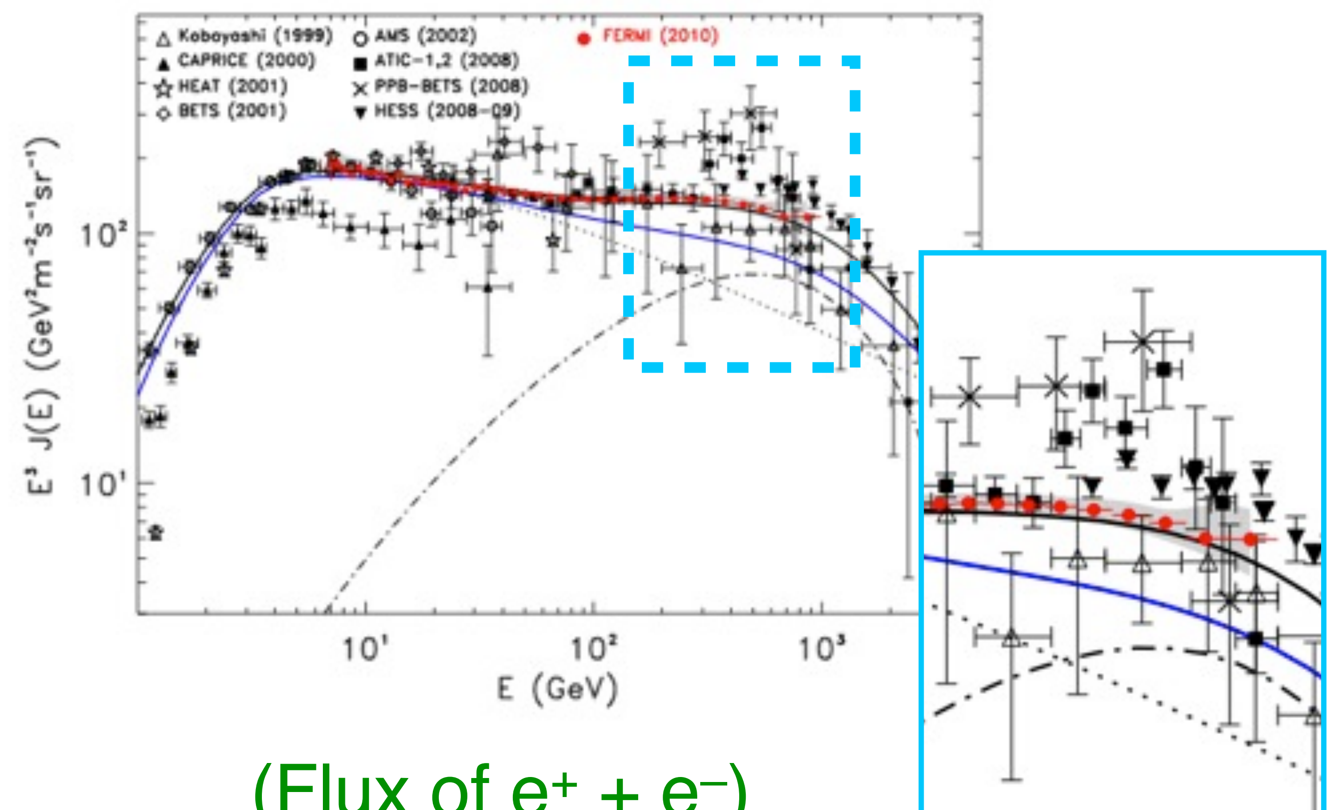
Indirect detection: 2010

PAMELA



(Flux of e^+)/(Flux of e^-)

Fermi 1008.3999

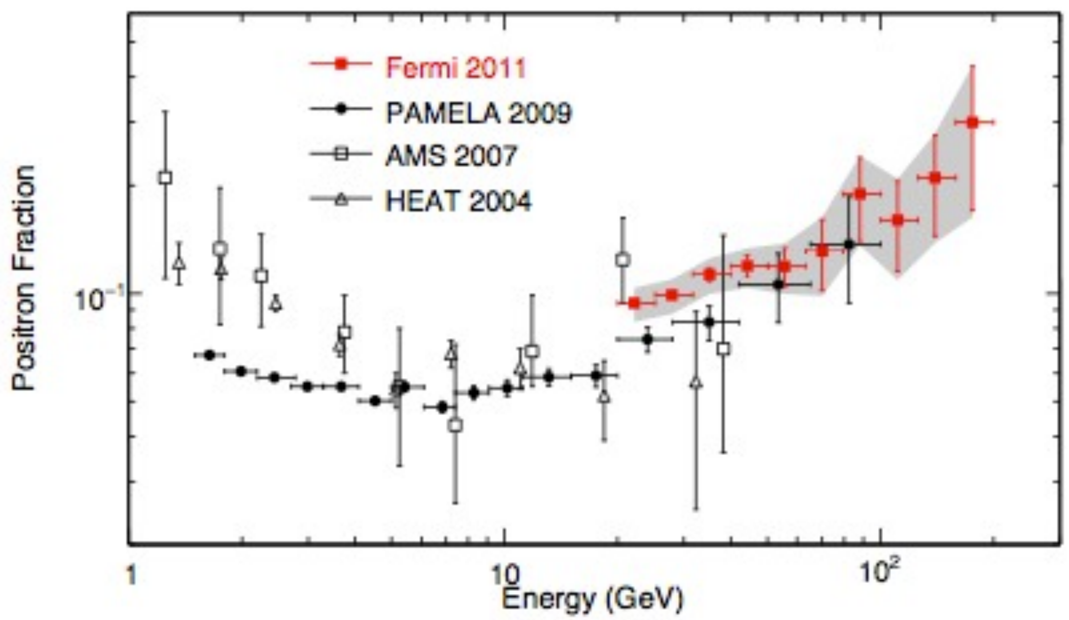


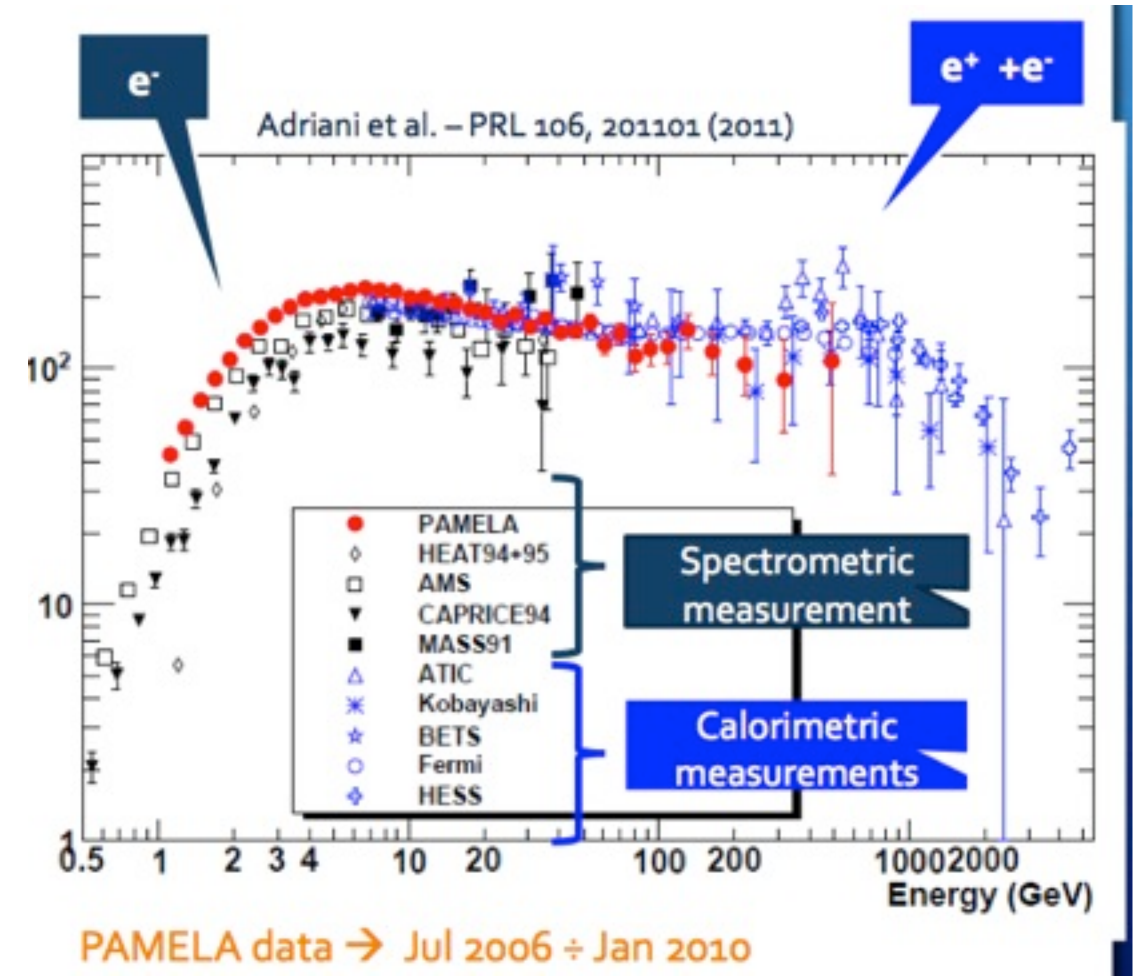
(Flux of e^+ + e^-)

New era of precision cosmic-ray physics!

Order-of-magnitude more precise & consistent than past data

Cross-Checks + Extensions





Fermi checks, extends PAMELA e+ fraction

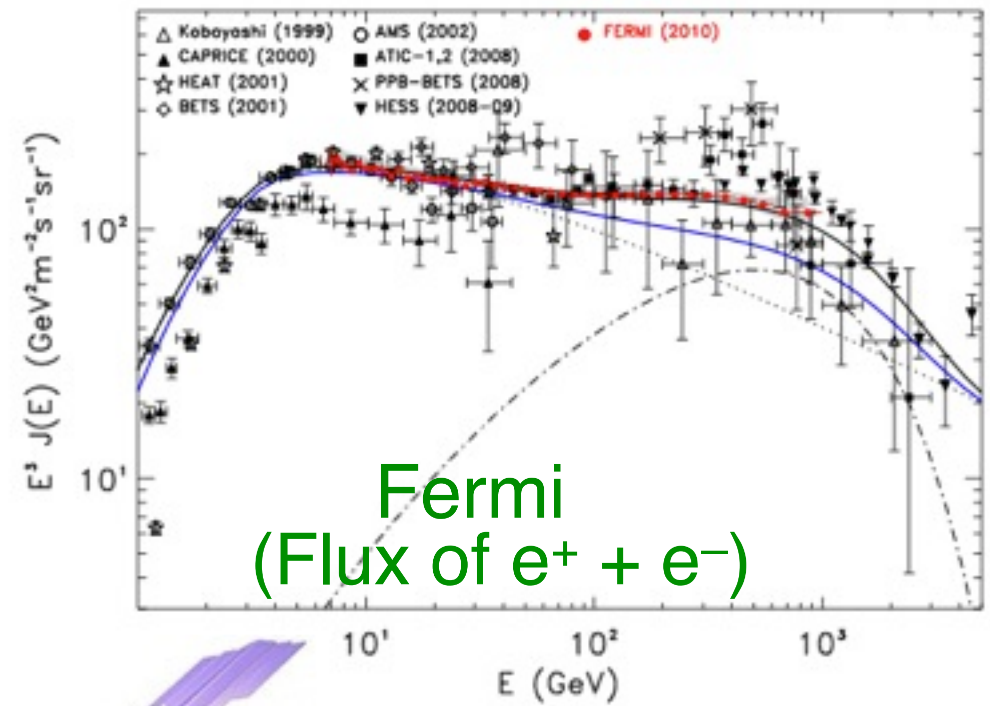
[1109.0521]

PAMELA checks Fermi/HESS e⁻ flux

[Adriani, EPS2011]

new limits from Fermi on anisotropy, solar component, ...

What's the new source of positrons?

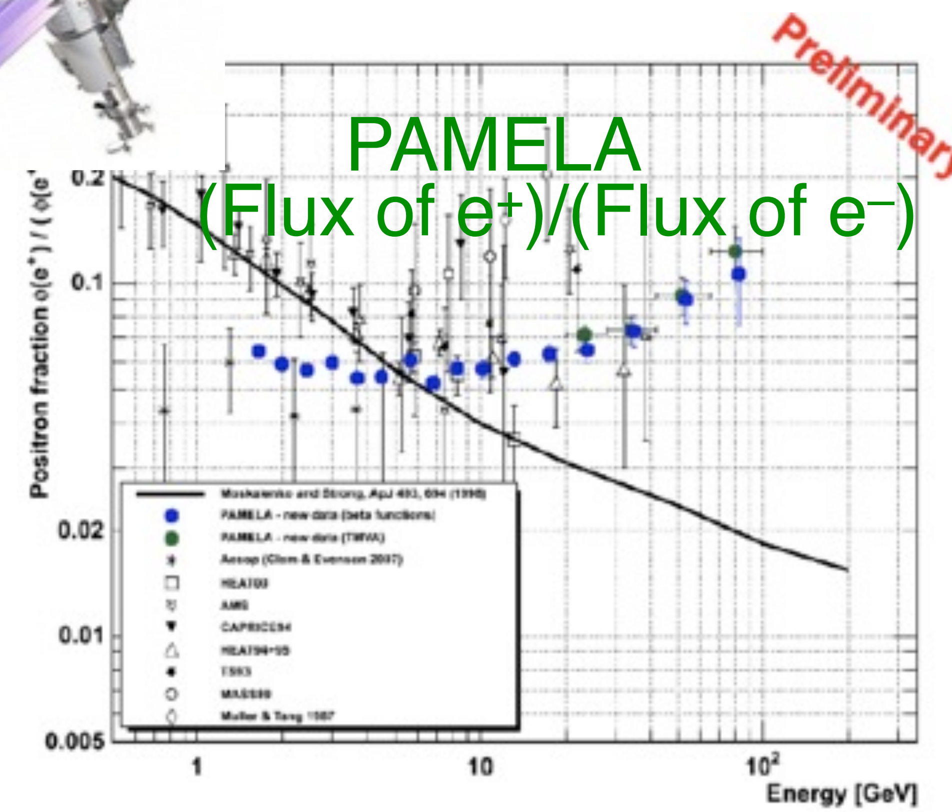


Qualitative features

1. Comparable new e^+ and e^- fluxes
2. No similar rise in anti-protons (nor gamma-ray signals)

   $\Rightarrow$ decays to hadrons, W, Z (low-mass source)

3. Rate is a few hundred times larger than expected for annihilation of a 100-1000 TeV thermal WIMP



Candidate explanations

1. Local(ish) astrophysical sources

   e.g. pulsars
2. New propagation effects
3. Dark matter annihilation, but not a vanilla thermal WIMP in vanilla halo

WIMP annihilation through dark forces

[Arkani-Hamed, Finkbeiner, Slatyer, Weiner; Pospelov and Ritz]

Qualitative features

1. Comparable e^+ and e^- fluxes at high E

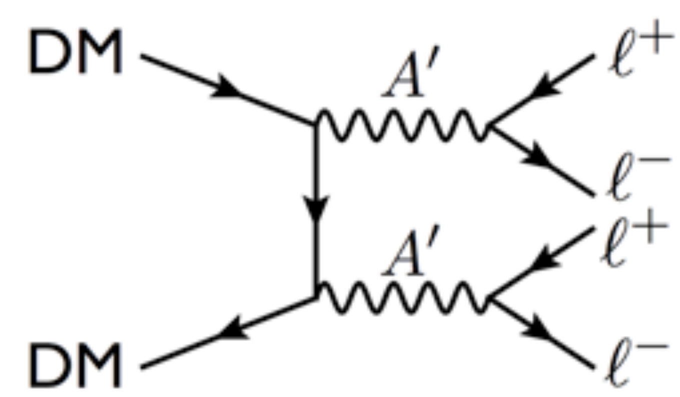
   This is the easy part for DM – symmetric annihilation

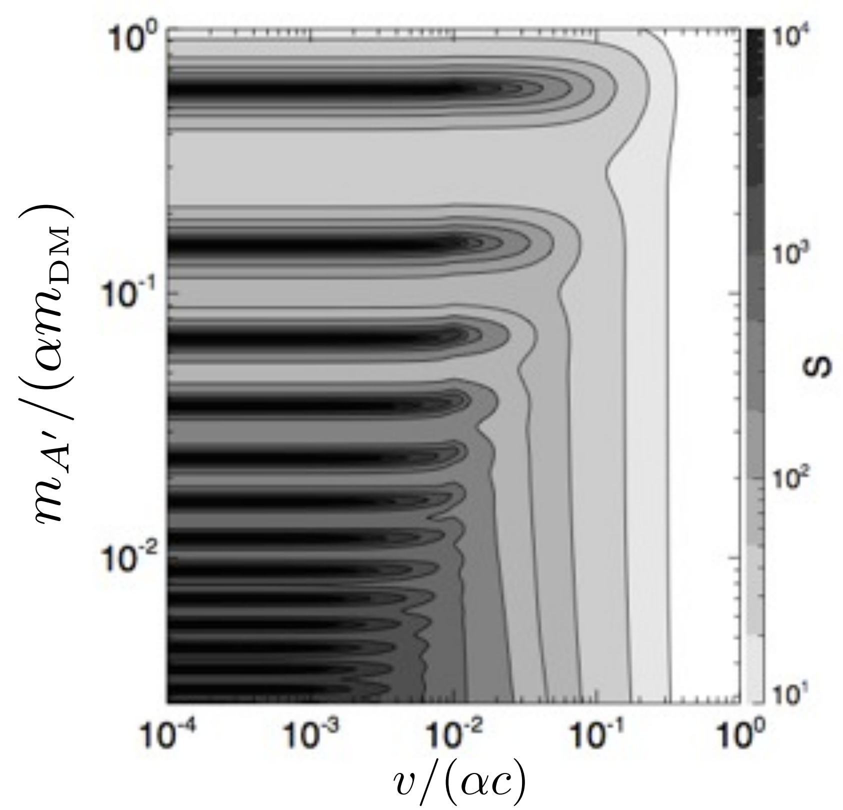
2. No similar rise in anti-protons (nor gamma-ray signals)

   Kinematically constrained decays to charged particles lighter than $m_{A'}/2$

3. Rate is a few hundred times larger than expected for annihilation of a 100-1000 TeV thermal WIMP

   Long-range attractive force mediated by A' $\Rightarrow$ Sommerfeld enhancement to annihilation rate





[Slatyer 2009]

Outline

- DM Motivation
- Constraints
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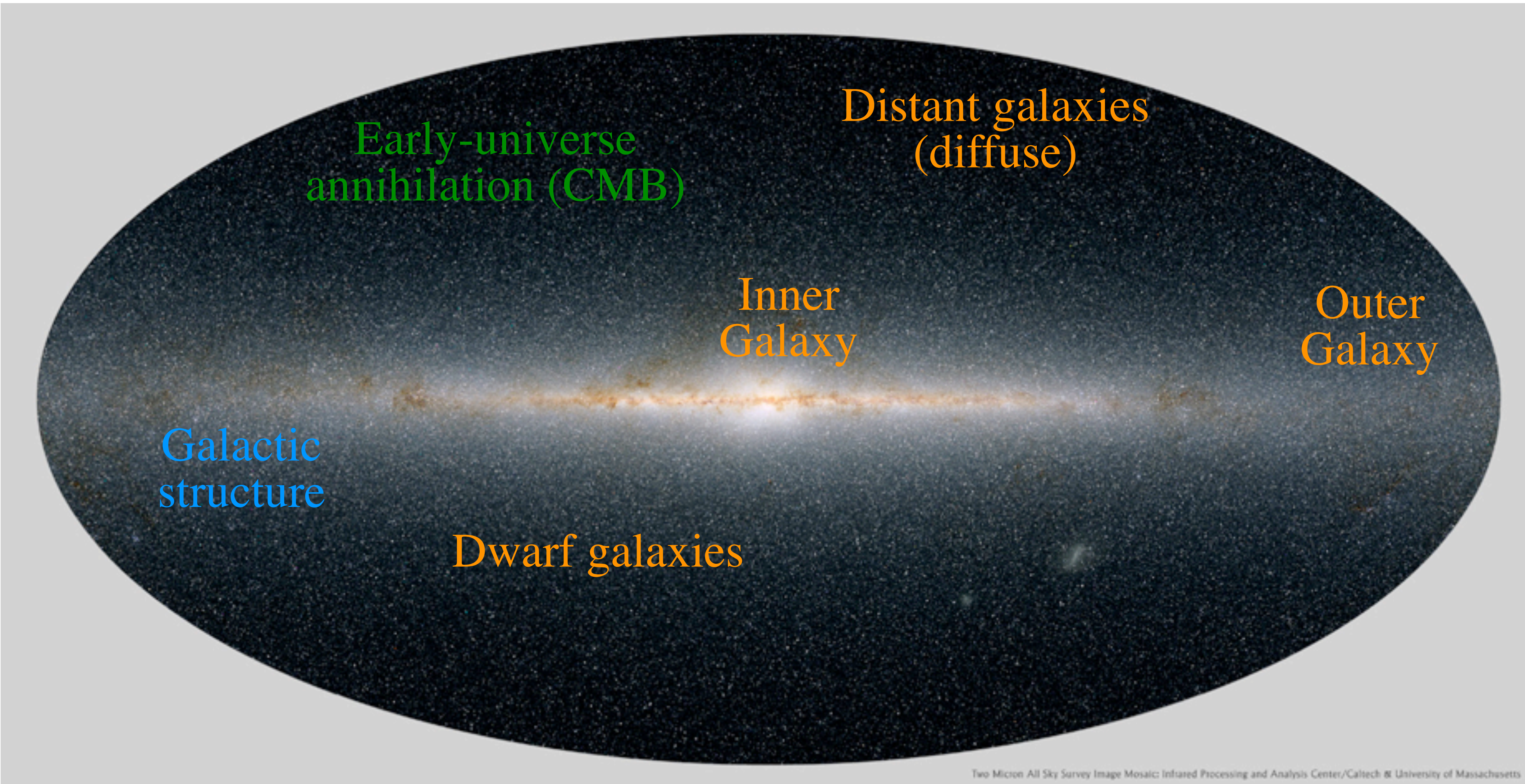
Testing the Light-Mediator Hypothesis



Dark matter is everywhere, and signals should be too!

Quantitative comparisons depend greatly on velocity-dependence of Sommerfeld enhancement, and the structure of DM halos

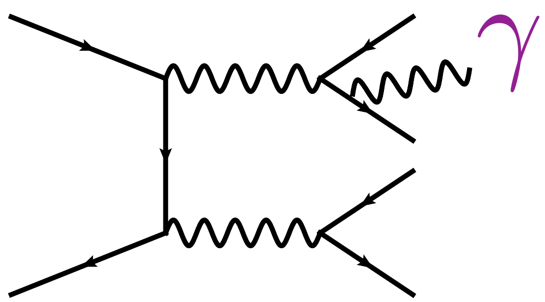
Outline

- DM Motivation
- Constraints
- Uncertainties
  - Distribution of starlight for ICS
  - Backgrounds
  - Distribution of DM:
    - halo shape
    - substructure

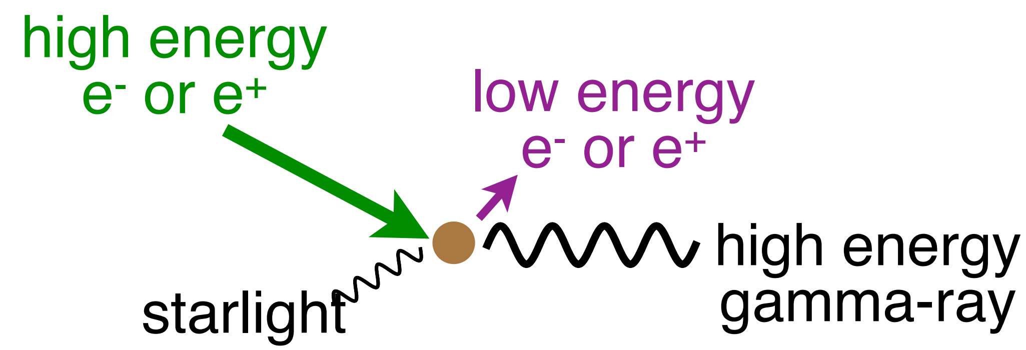
Inner Galaxy

Two sources of photons:

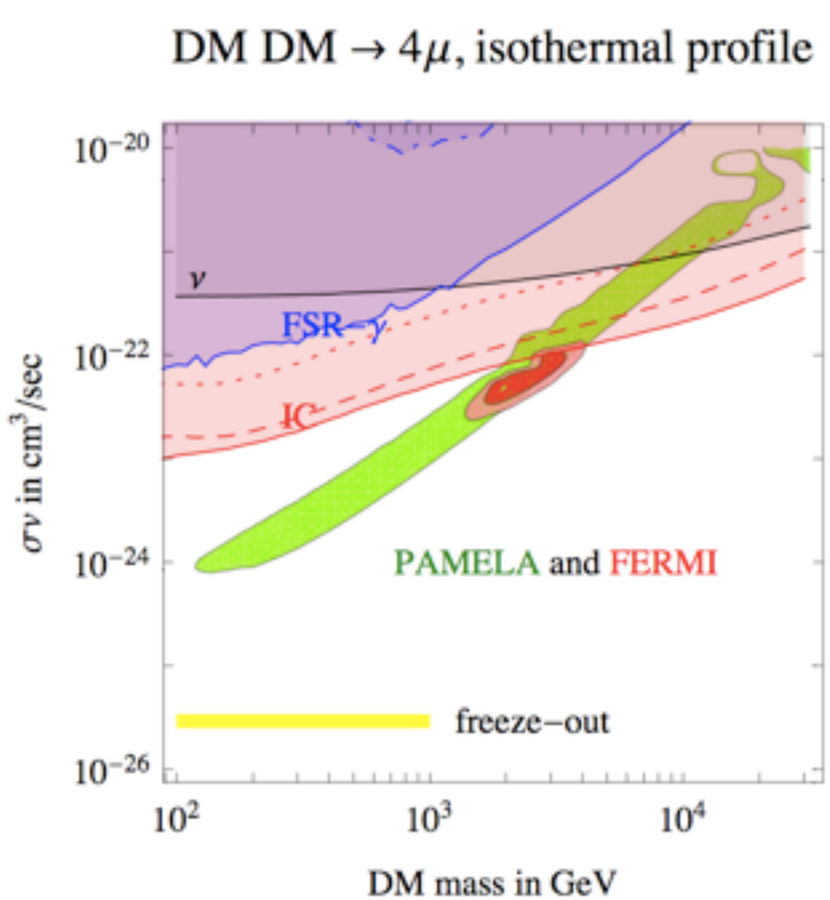
Final-state radiation (FSR)



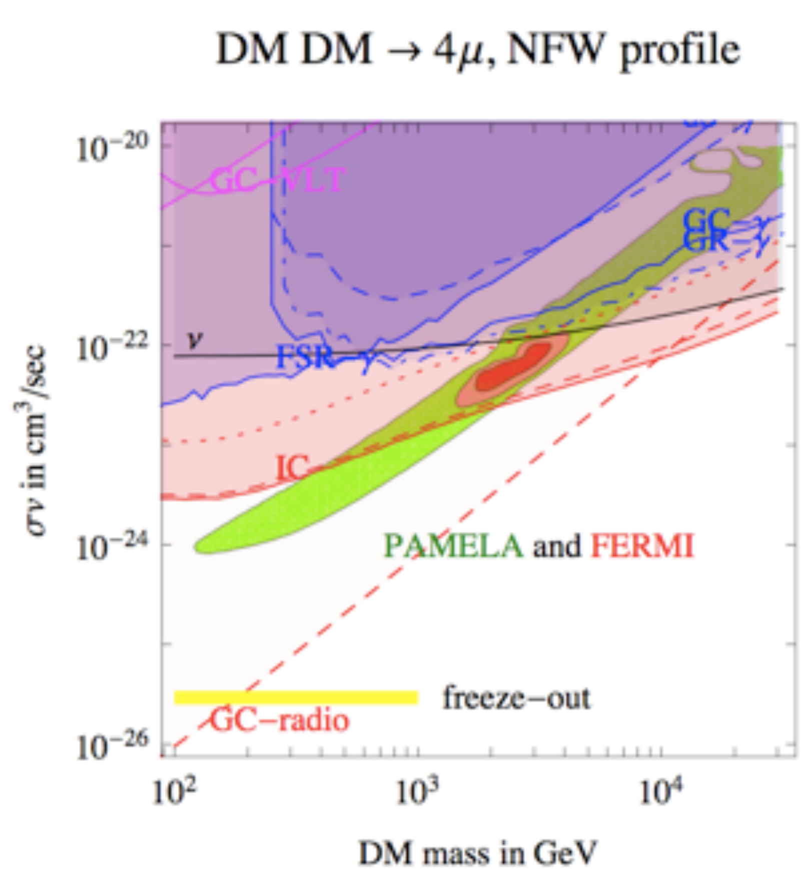
Inverse Compton-Scattering (ICS)



Constraints depend on diffusion model and halo profile

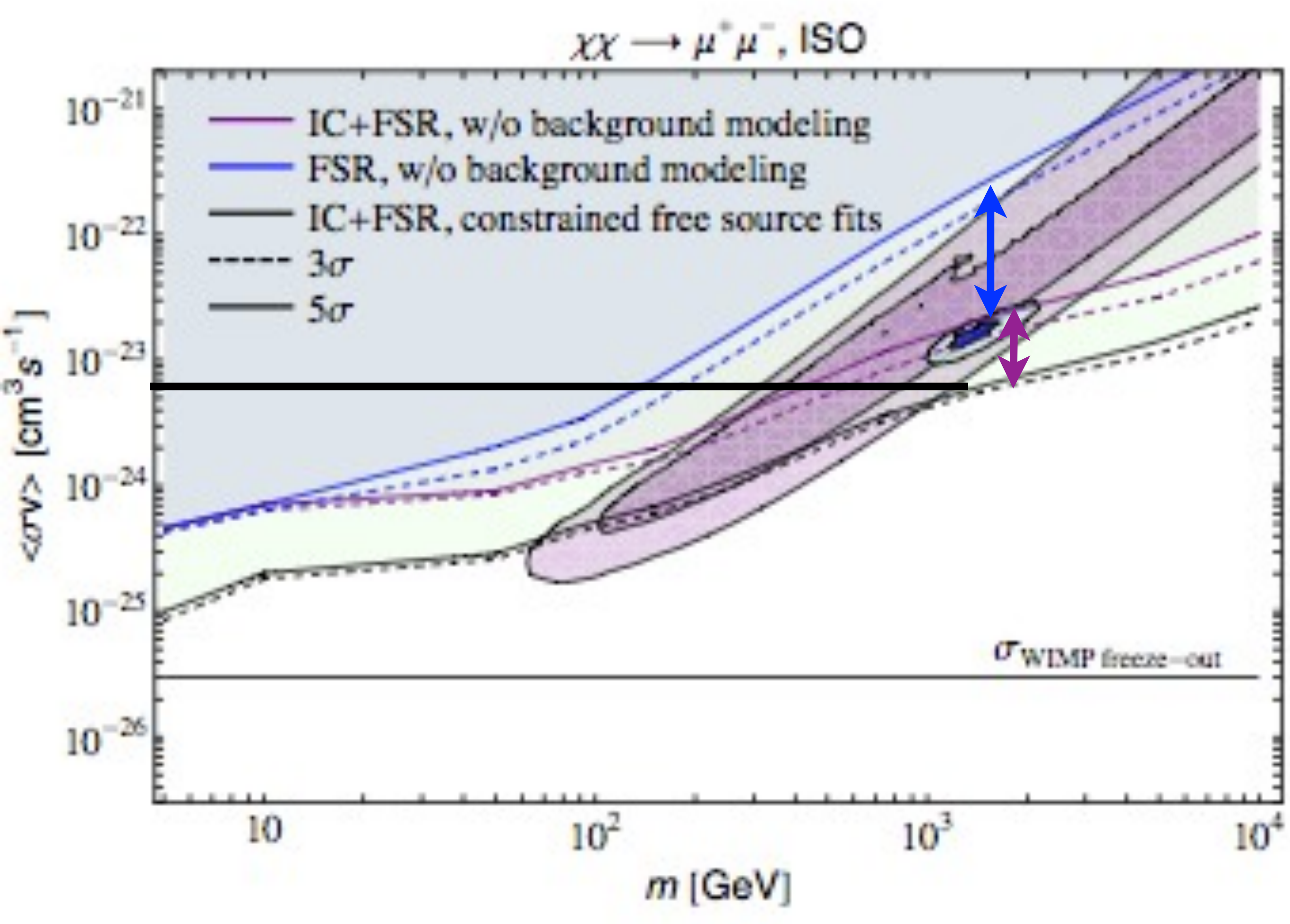


[Papucci, Strumia 2009]



“Whole-sky”

Optimized generalization of inner-galaxy studies: assume a halo profile, and optimize constraint. **But still driven by the “inner” part**



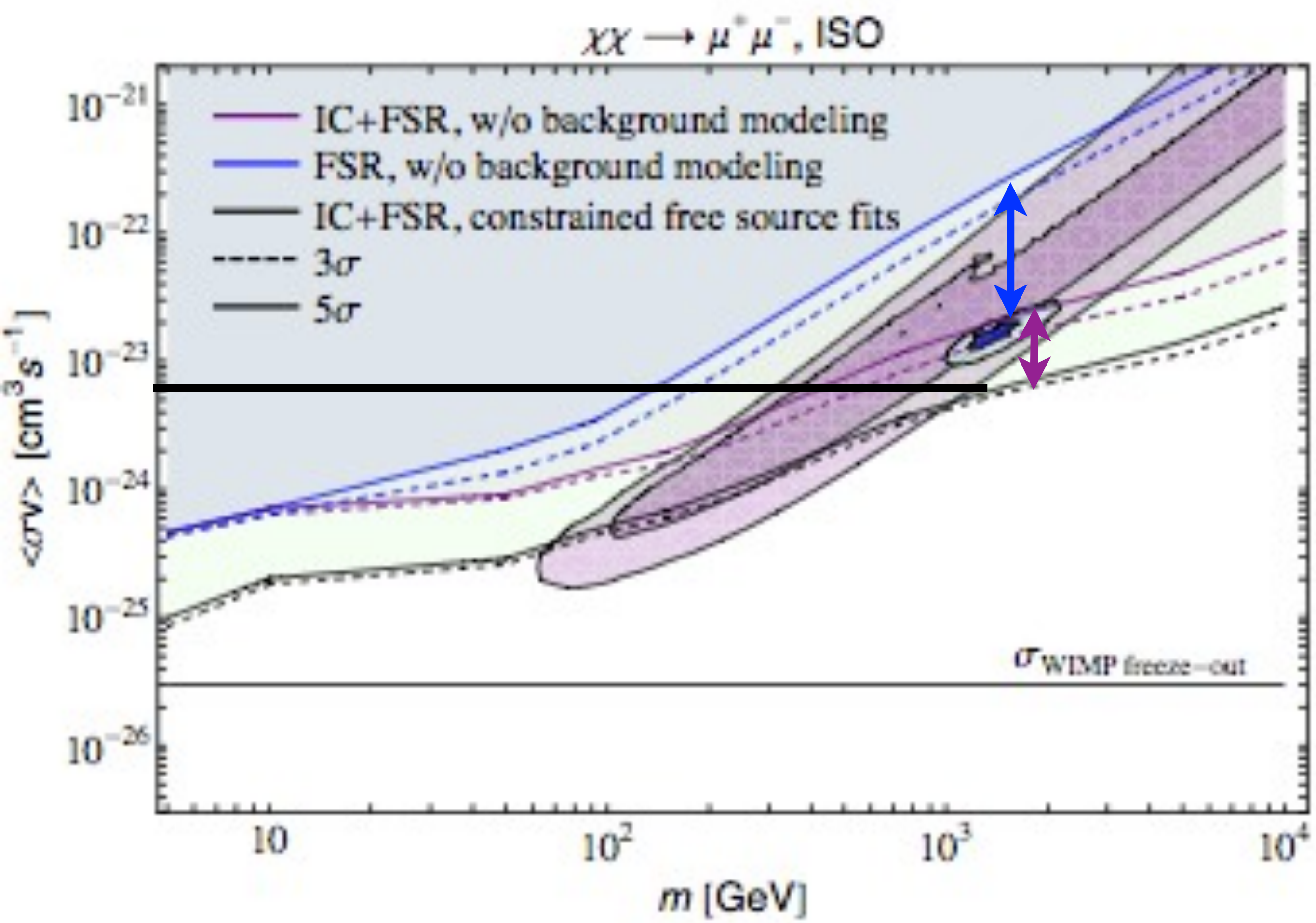
1205.6474

10x more light from ICS (but more uncertain)

Background model → factor of 4 reduction

“Whole-sky”

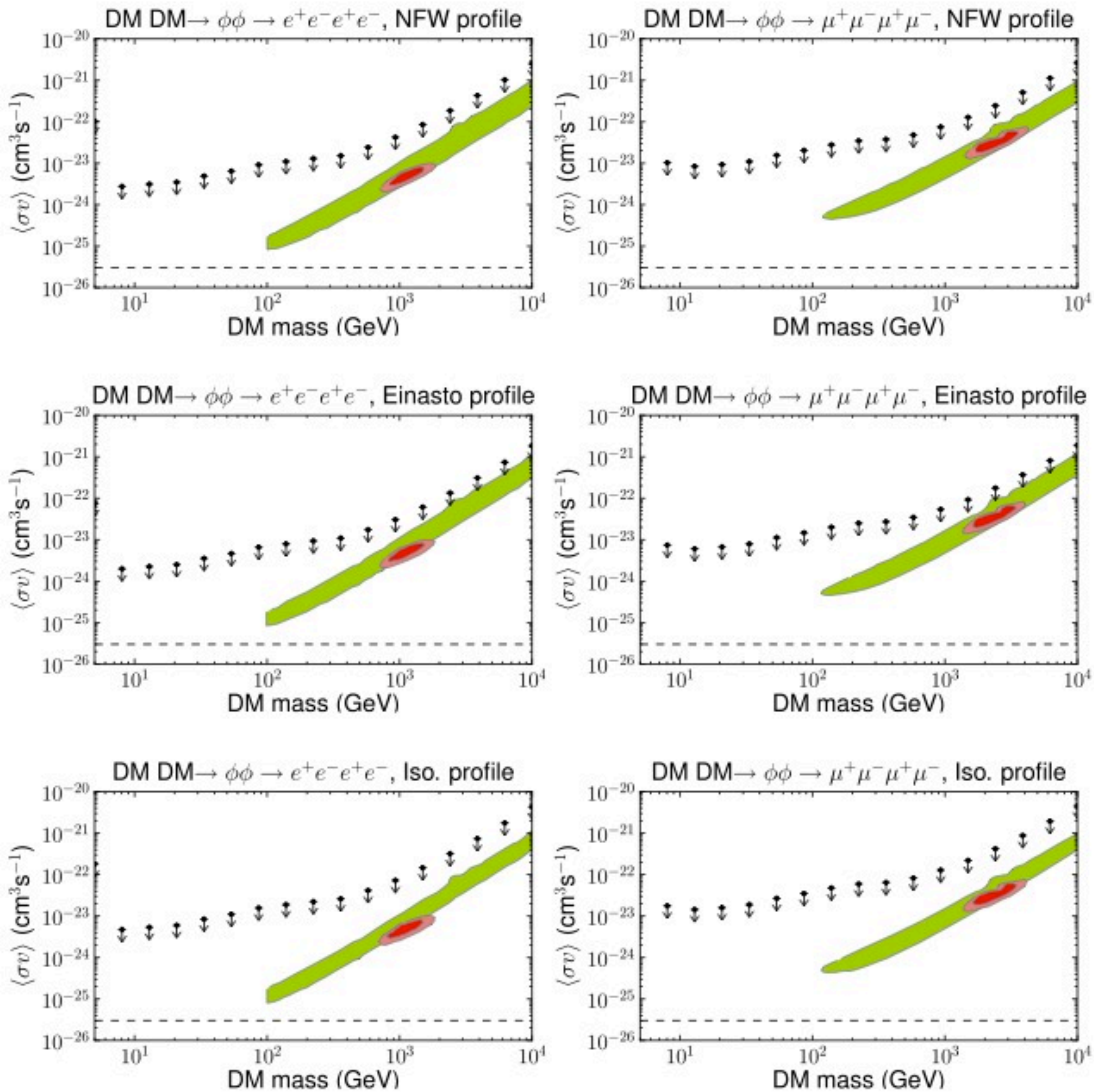
Optimized generalization of inner-galaxy studies: assume a halo profile, and optimize constraint. **But still driven by the “inner” part**



1205.6474

More whole-sky results [1205.2739]

These are analogous to the weakest of the 3 lines in the previous plots (no background fit, and no ICS $\Rightarrow$ most conservative)



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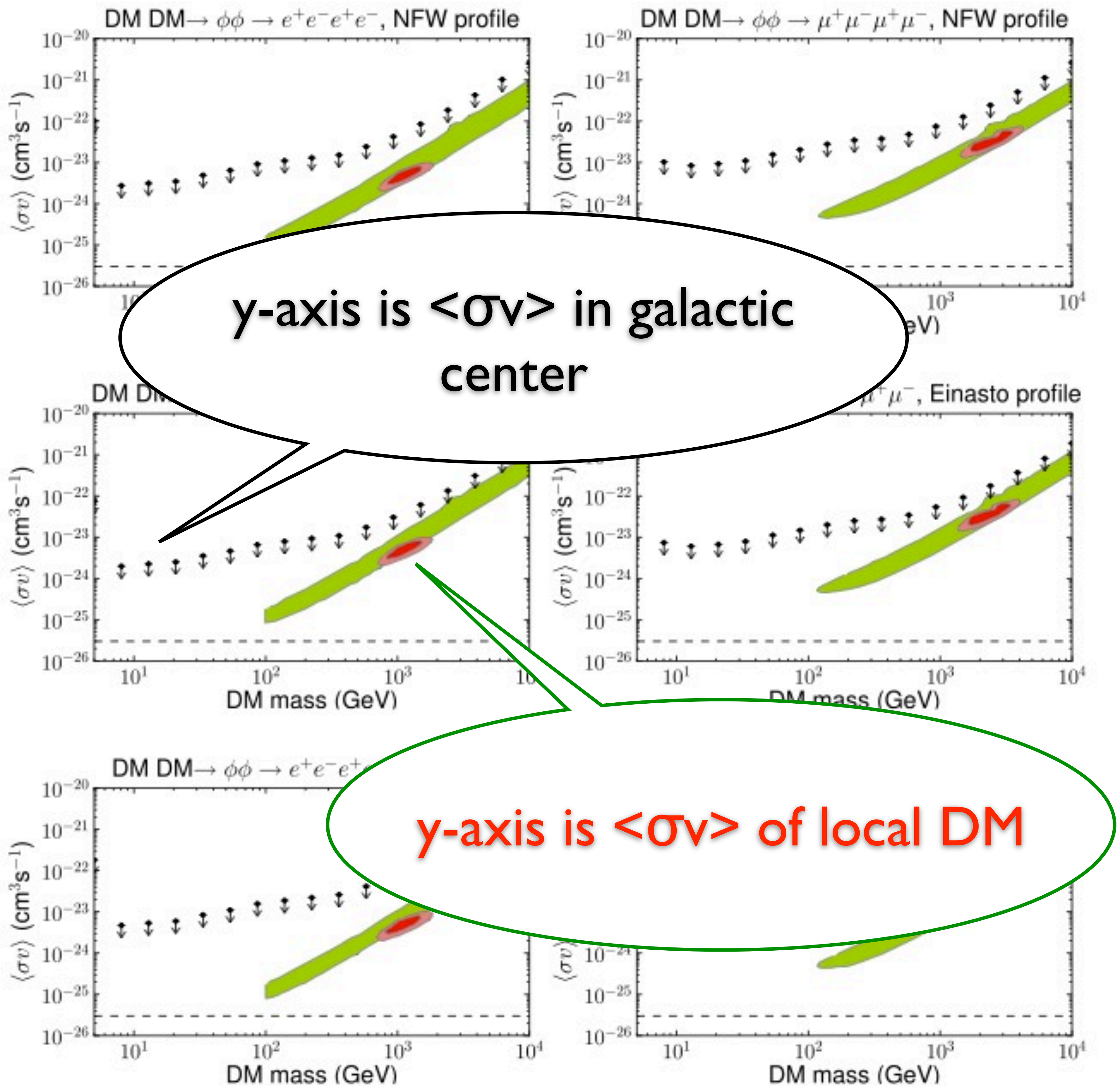
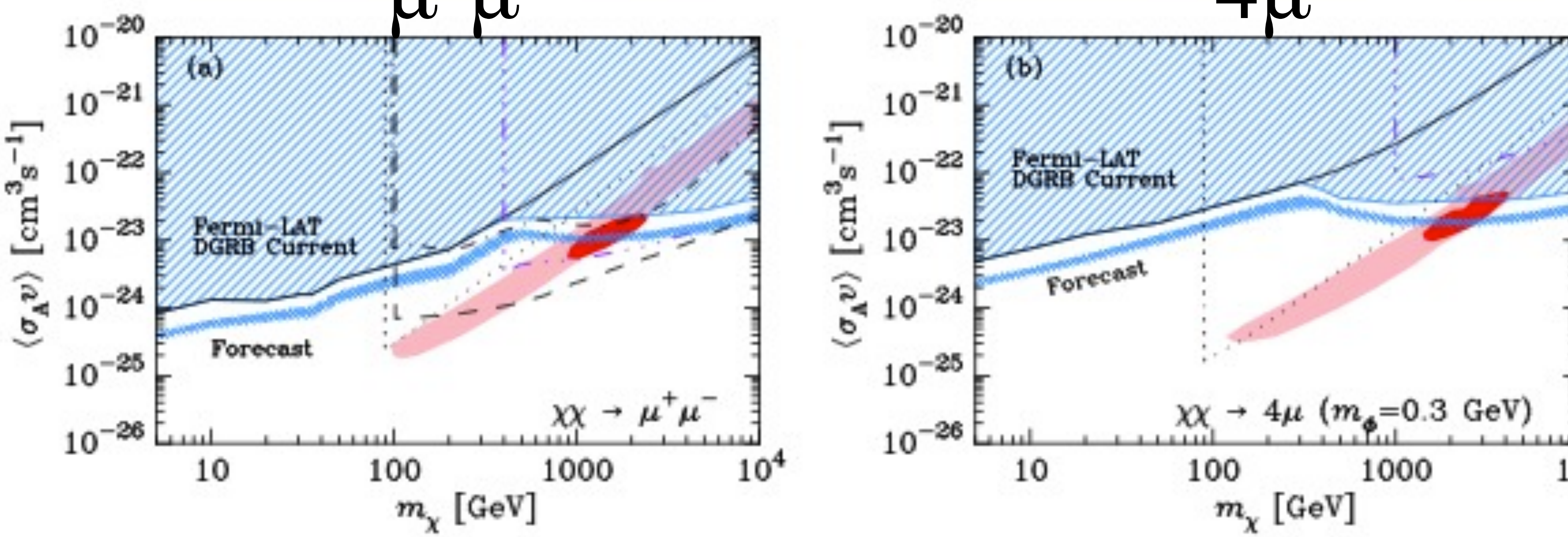


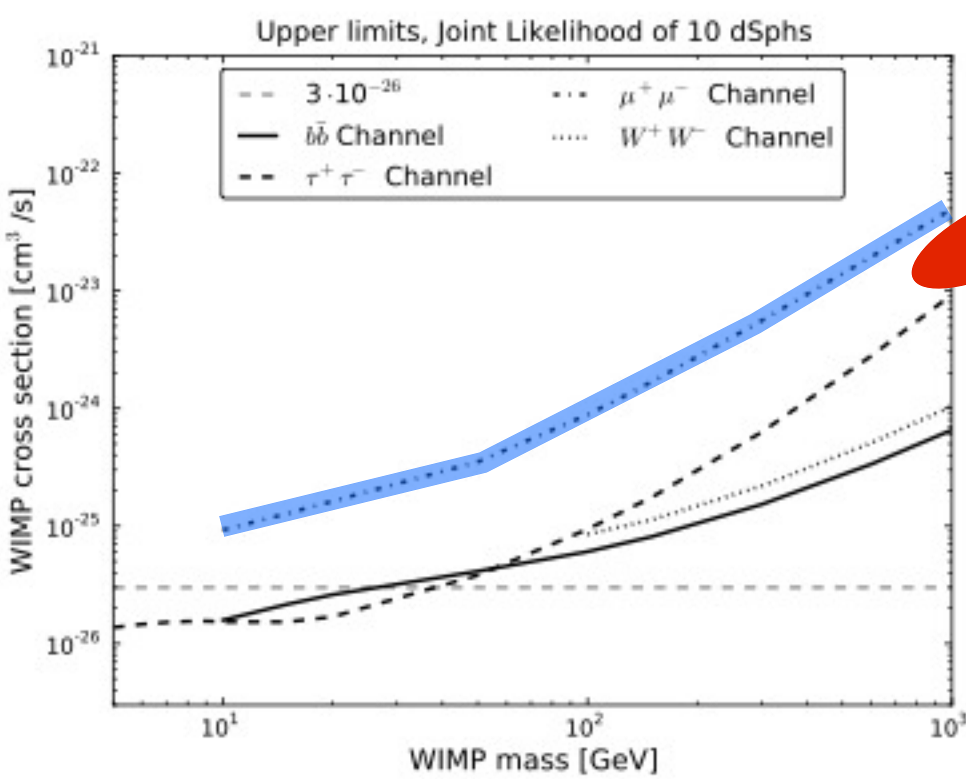
Diffuse γ Rays
(from outer Milky Way halo)

$\mu^+\mu^-$ $\quad$ 4μ

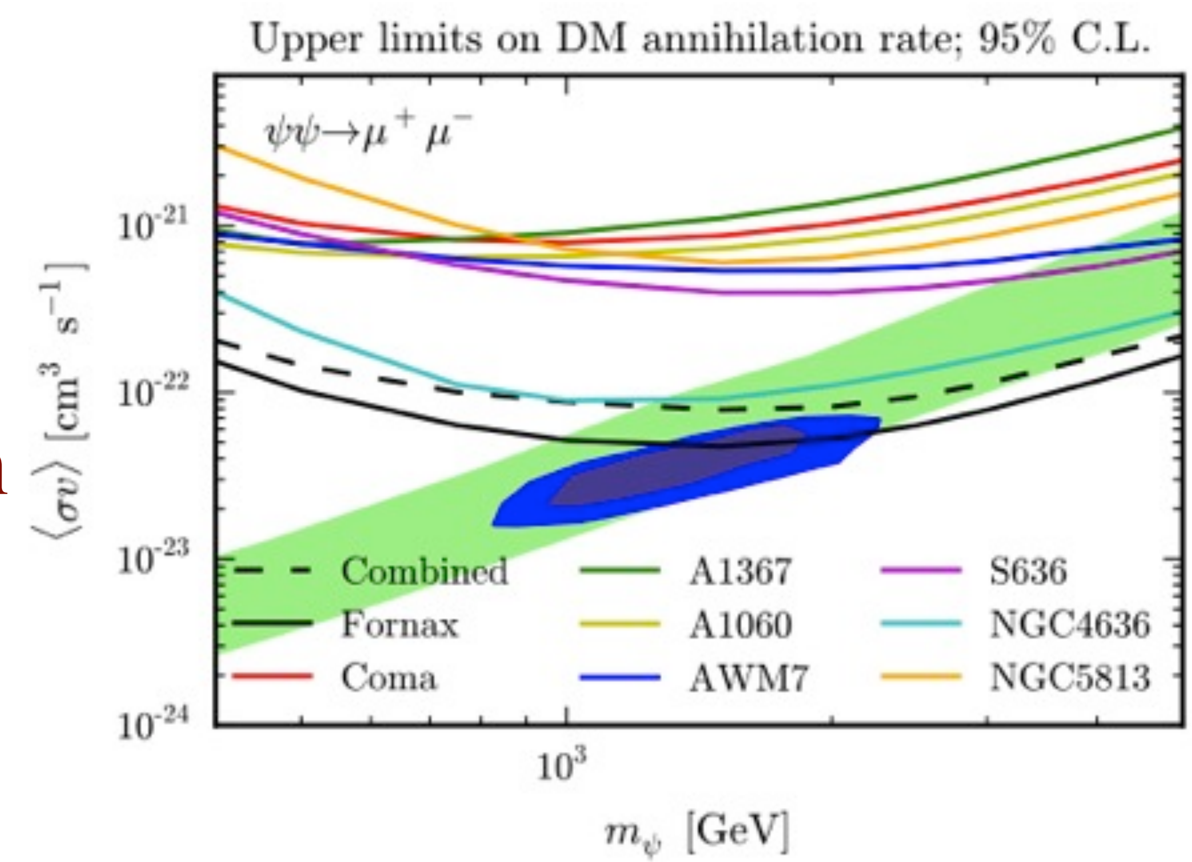
1011.5090



Annihilation in
Dwarf Galaxies and Nearby Clusters



Fermi ROI
(annihilation
to $\mu^+\mu^-$)

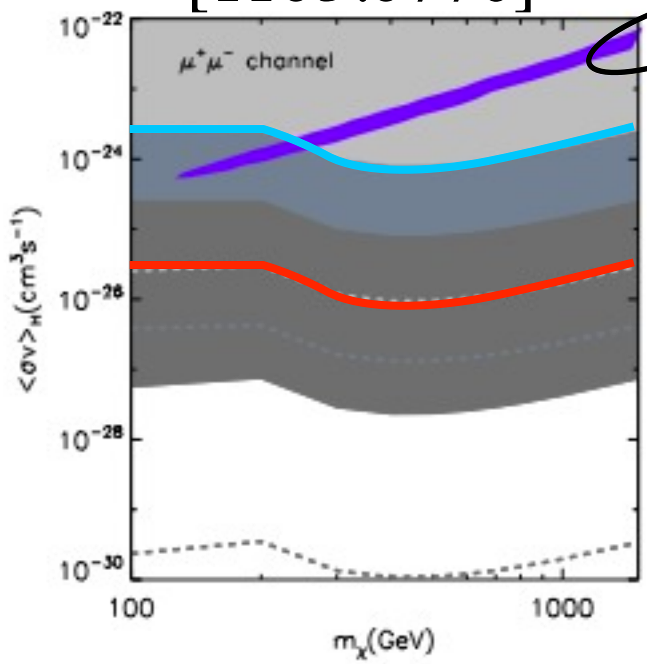


1108.3546
(Limit from stacked γ signals
from 10 dwarph spheroidal
galaxies)

1110.1529
(Limit from combined
γ-ray signals from 8 nearby
clusters)

Diffuse γ Rays
(from unresolved distant galaxies)

[1103.0776]

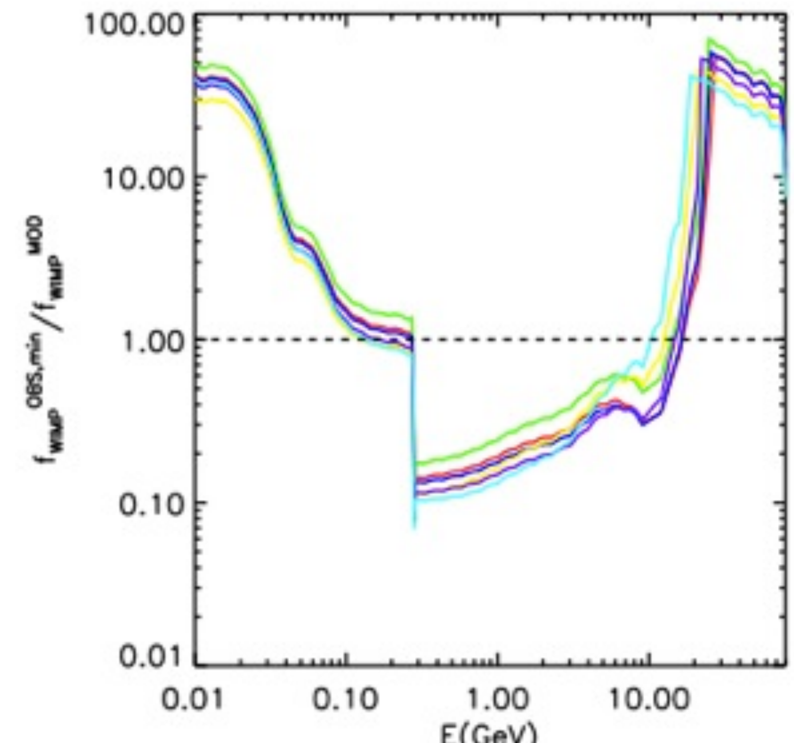


Fermi ROI

Limit (low-substructure)

Limit (high-substructure)

[1103.0776]



(γ flux limit)/ (Expected flux)

Caveats:

– relies on modeling of blazar and star-forming galaxies (86% of flux)

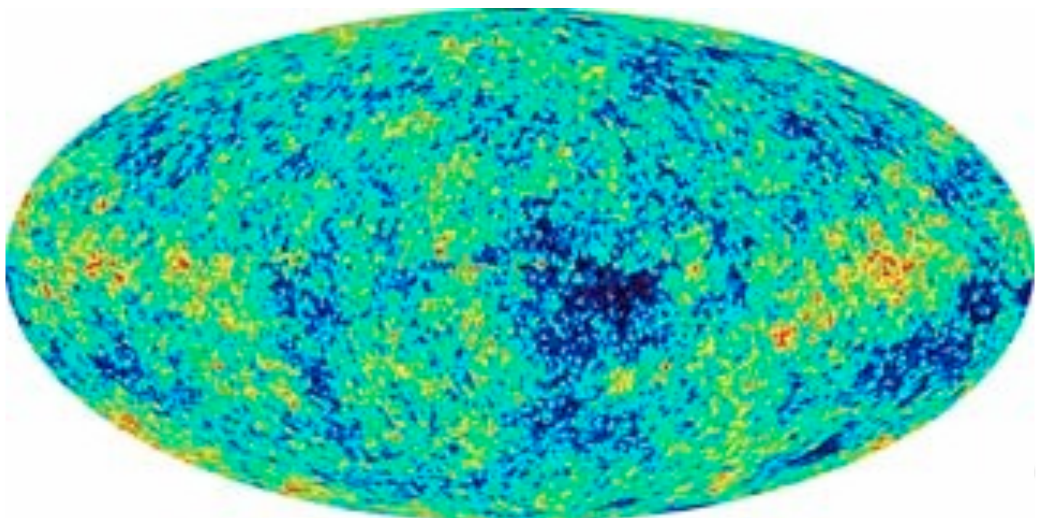
– Relies on extrapolating Millenium II simulation from $10^9\ M_\odot$ resolution to $10^{-6}\ M_\odot$ halos ***and*** subhalos $\Rightarrow$ large uncertainty in ~*log*^{2} enhancement

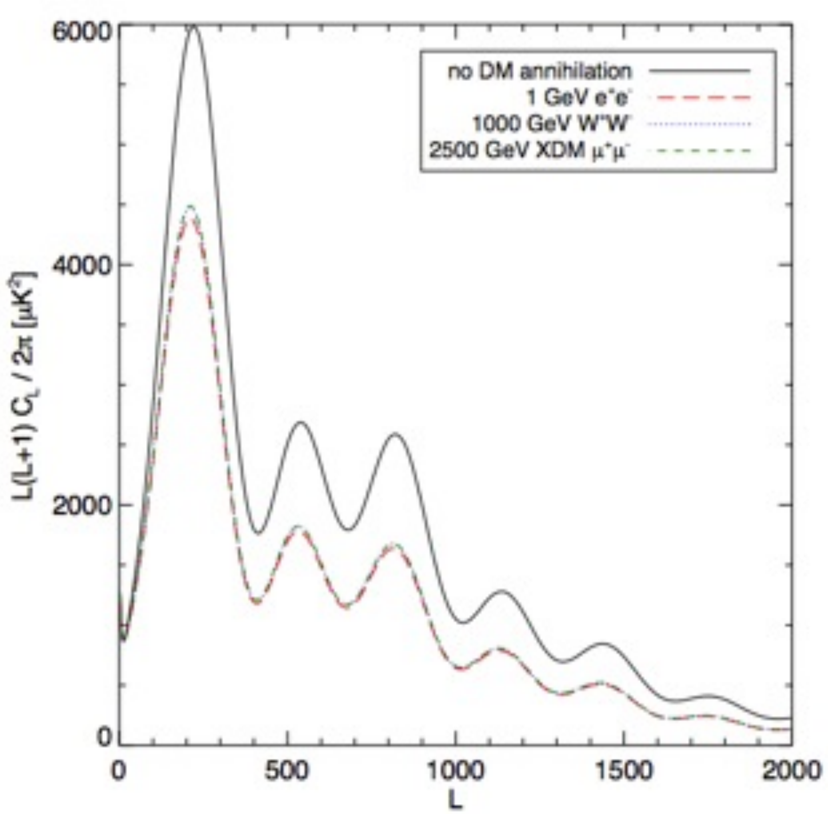
CMB

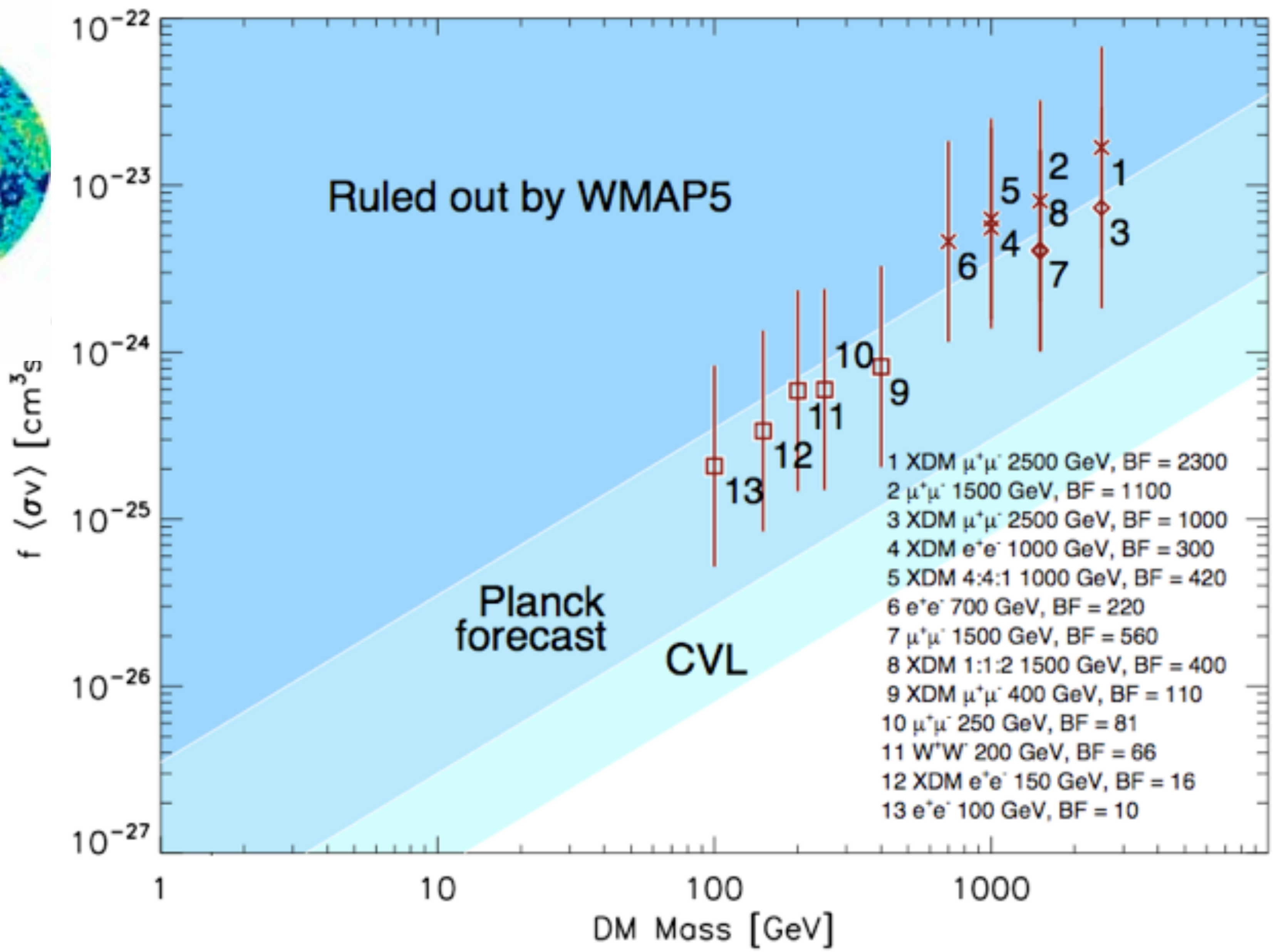
DM annihilation after recombination

⇒ modified power spectrum (somewhat degenerate with n_s)

Before structure formation, so no substructure uncertainties!

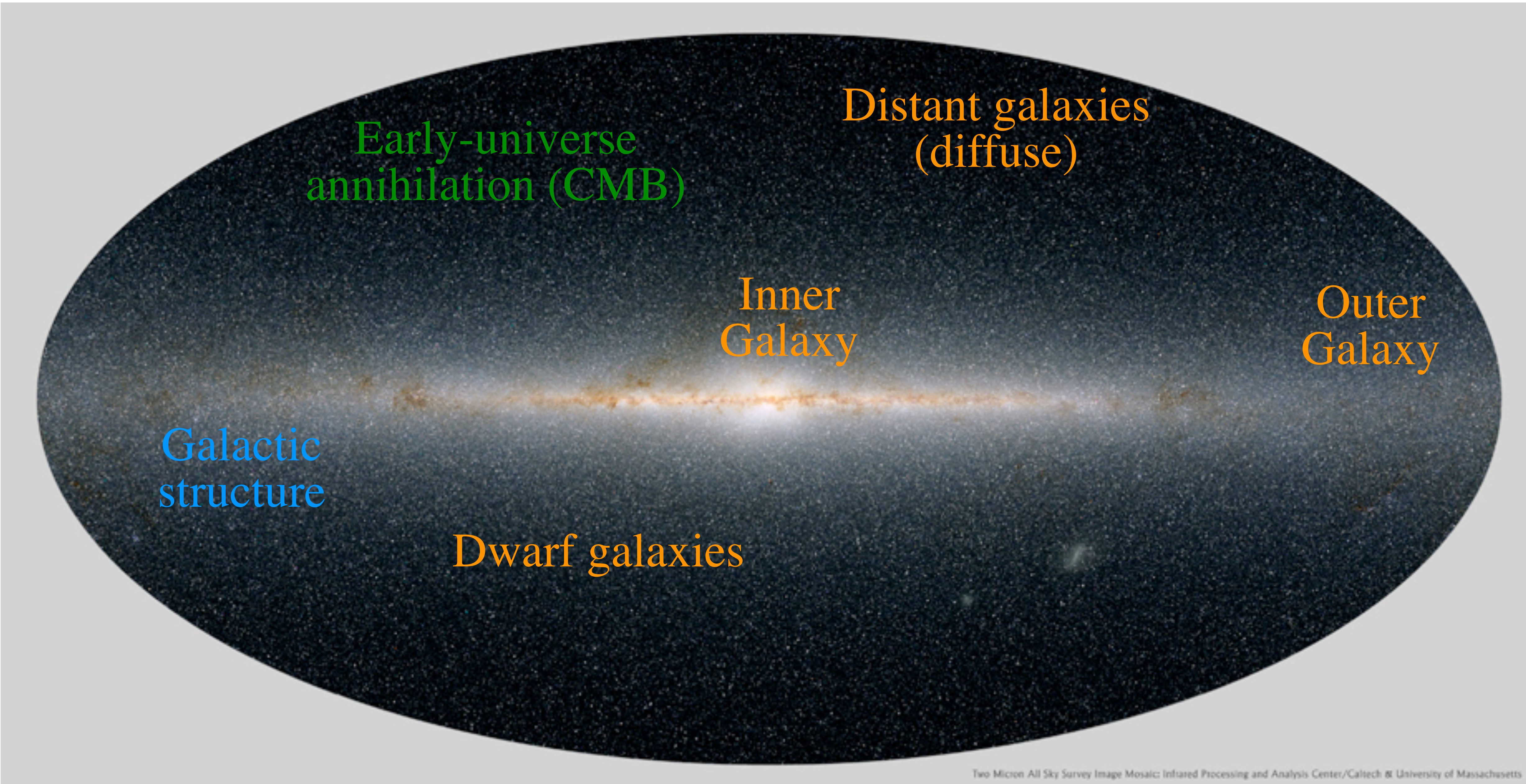






Padmanabhan, Finkbeiner / Galli, Iocco, Bertone, Melchiorri/
Slatyer, Padmanabhan, Finkbeiner

Testing the Light-Mediator Hypothesis



Dark matter is everywhere, and signals should be too!

Quantitative comparisons depend greatly on velocity-dependence of Sommerfeld enhancement, and the structure of DM halos

Sommerfeld Enhancement

Origin: long-range attractive force between non-relativistic particles.

At low velocity, attractive potential enhances annihilation rate by $S(v) \approx \pi\alpha_D/v$

Mass of mediator shuts off force at large distances, regulates low-velocity boost: $S_{v\to 0} \approx \pi\alpha_D \frac{m_{A'}}{m_{DM}}$

Changes form at $v/c \sim m_{A'}/m_{DM} \sim 10^{-3} - 10^{-4}$

Bound states near zero energy give parametrically large contribution to annihilation $\Rightarrow$ resonance "spikes"
[important only at factor-of-few level for most parameter space]

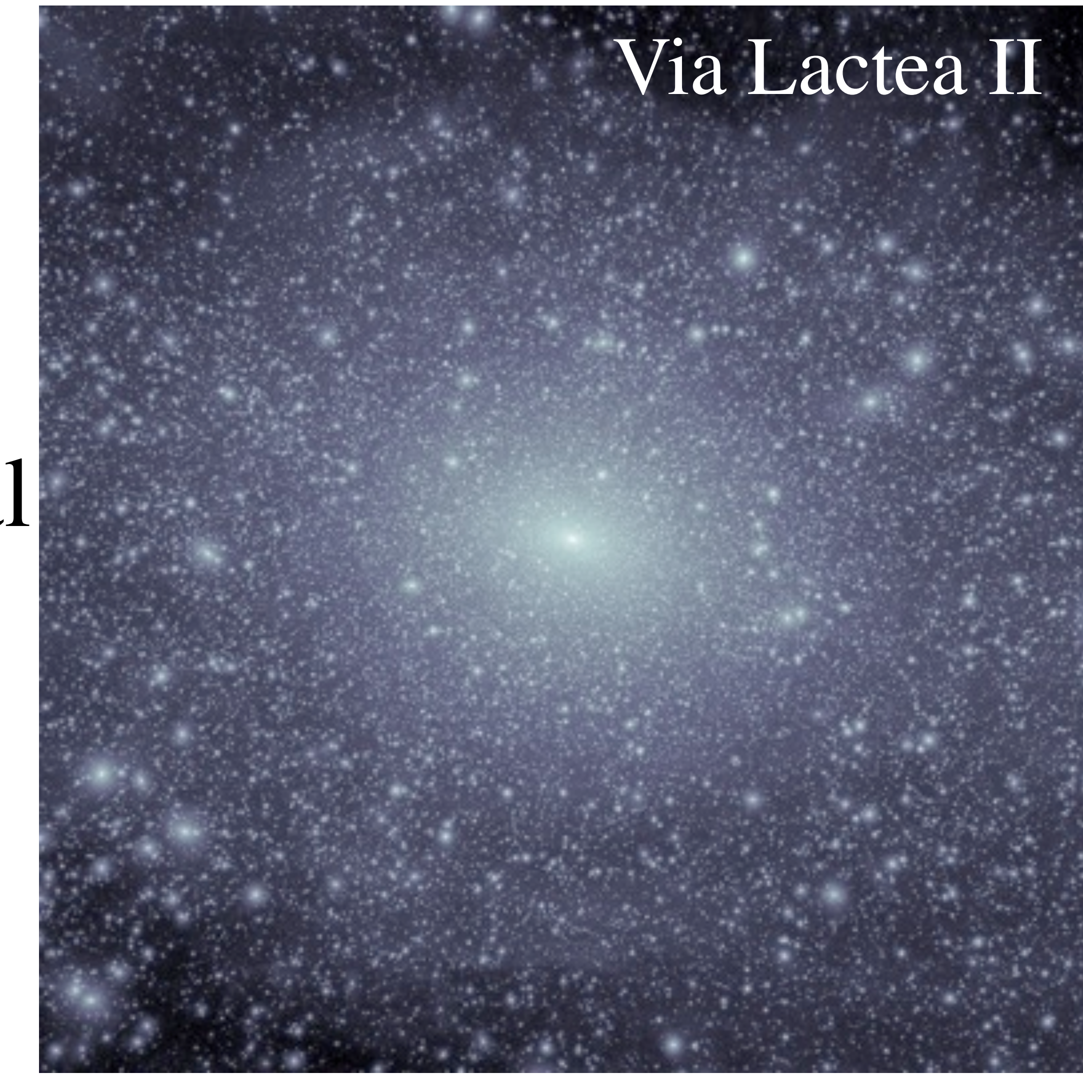
Substructure in Milky Way

Galaxy simulations (VL II, Aquarius) resolve $>10^6\ M_\odot$ subhalos

Fraction of dark matter in subhalos is only $\langle\rho_{sub}\rangle/\langle\rho\rangle \sim 10^{-3}$, but what matters for annihilation is ρ^2.

Because subhalos are very dense, local $\Delta = \langle\rho^2{}_{sub}\rangle/\langle\rho^2\rangle{\sim}1$ is possible.
Kamionkowski, Koushiappas, Kuhlen 2010, VL2

DM in subhalos is slow-moving
⇒ larger Sommerfeld enhancement.



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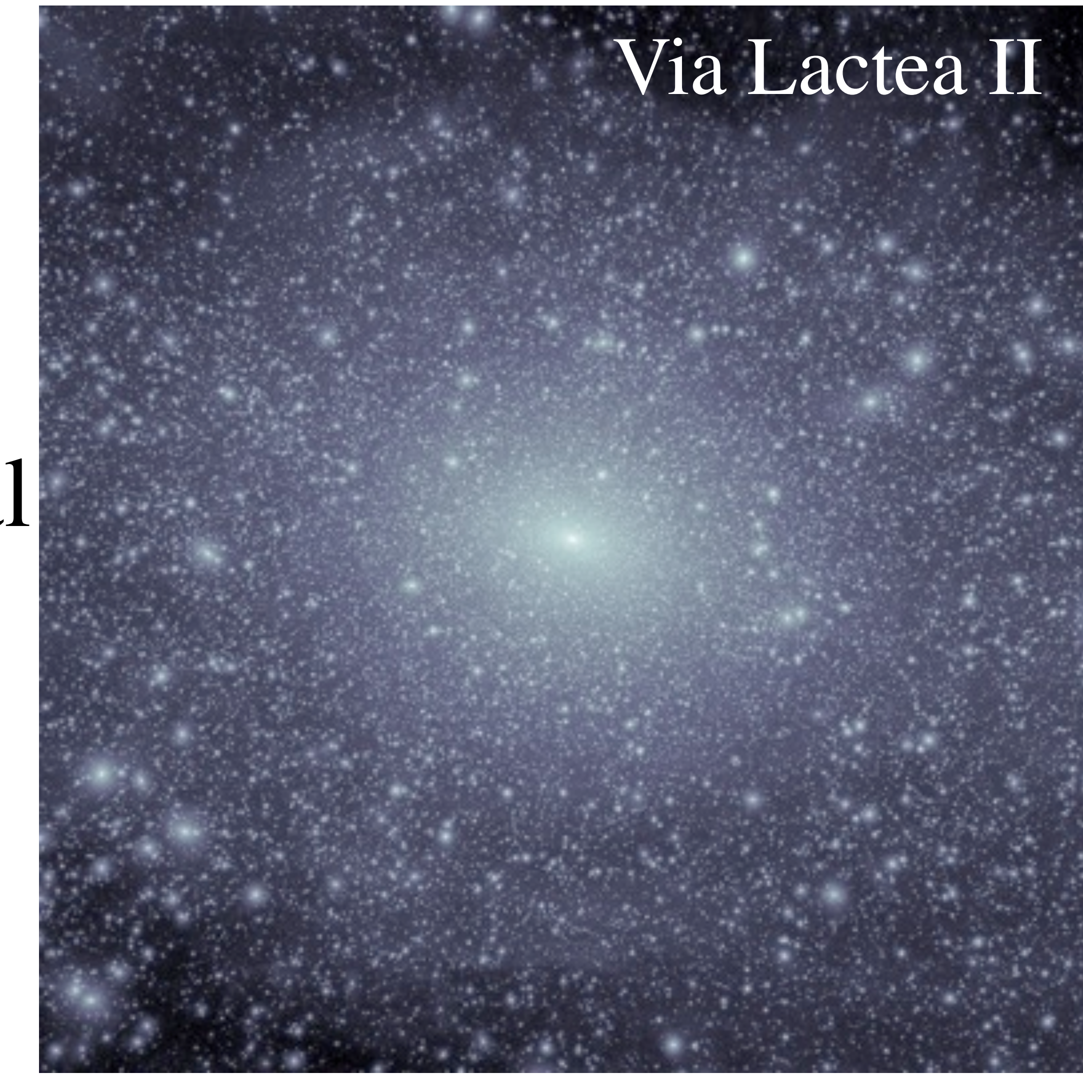

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DM in subhalos is slow-moving
$\Rightarrow$ larger Sommerfeld enhancement.

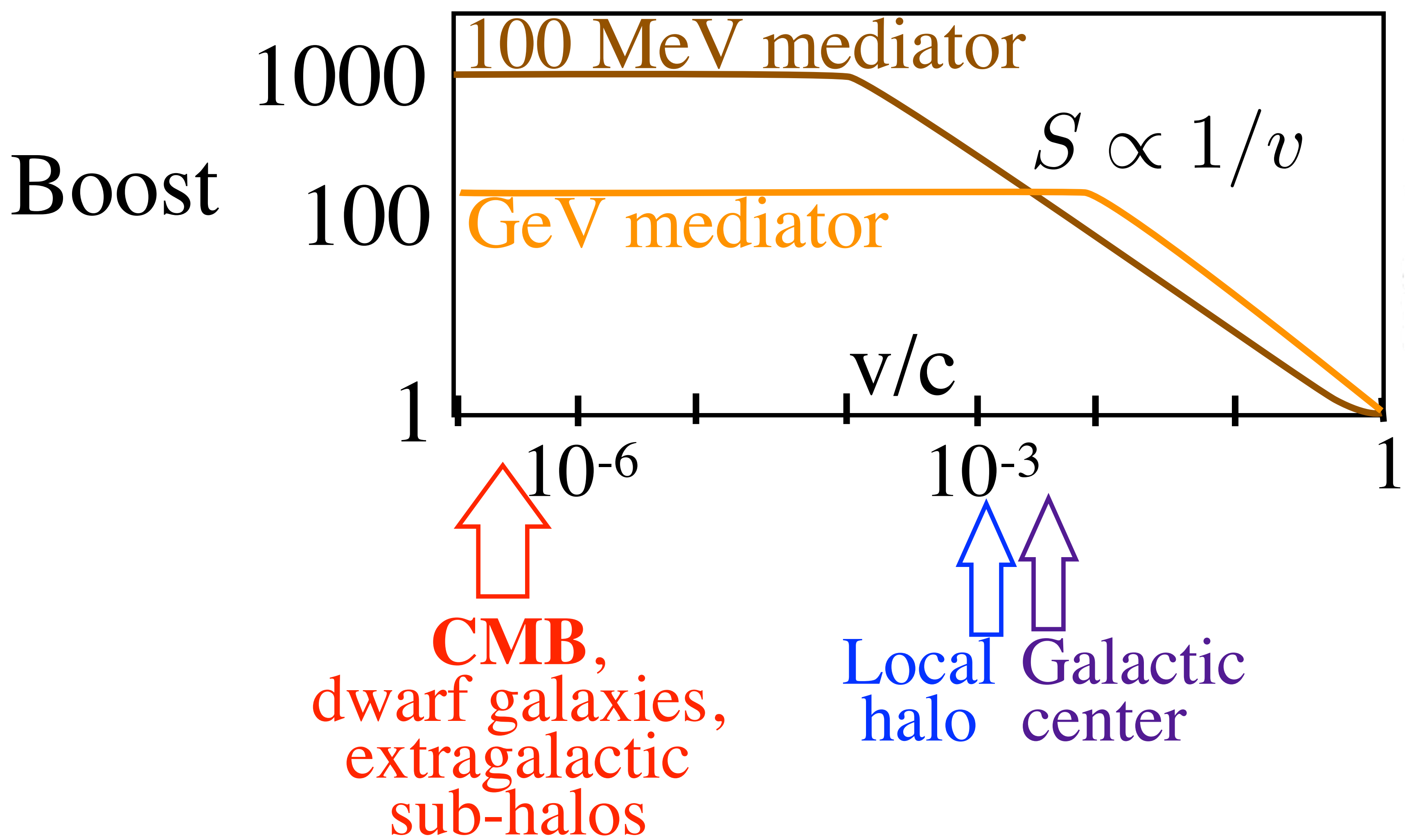
Δ depends on:

- fraction of DM in subhalos
- mass distribution of subhalos
- radial distribution of subhalos

large extrapolation from simulation

- minimum size of subhalos — *~10^{-6} (but depends on dark matter interactions)*
- tidal disruption of subhalos — *baryonic physics, not well simulated by some estimates, not important locally*

When local substructure is discounted, these results particularly disfavor low mediator masses, where the Sommerfeld effect in low-v systems is **much larger** than in the local halo

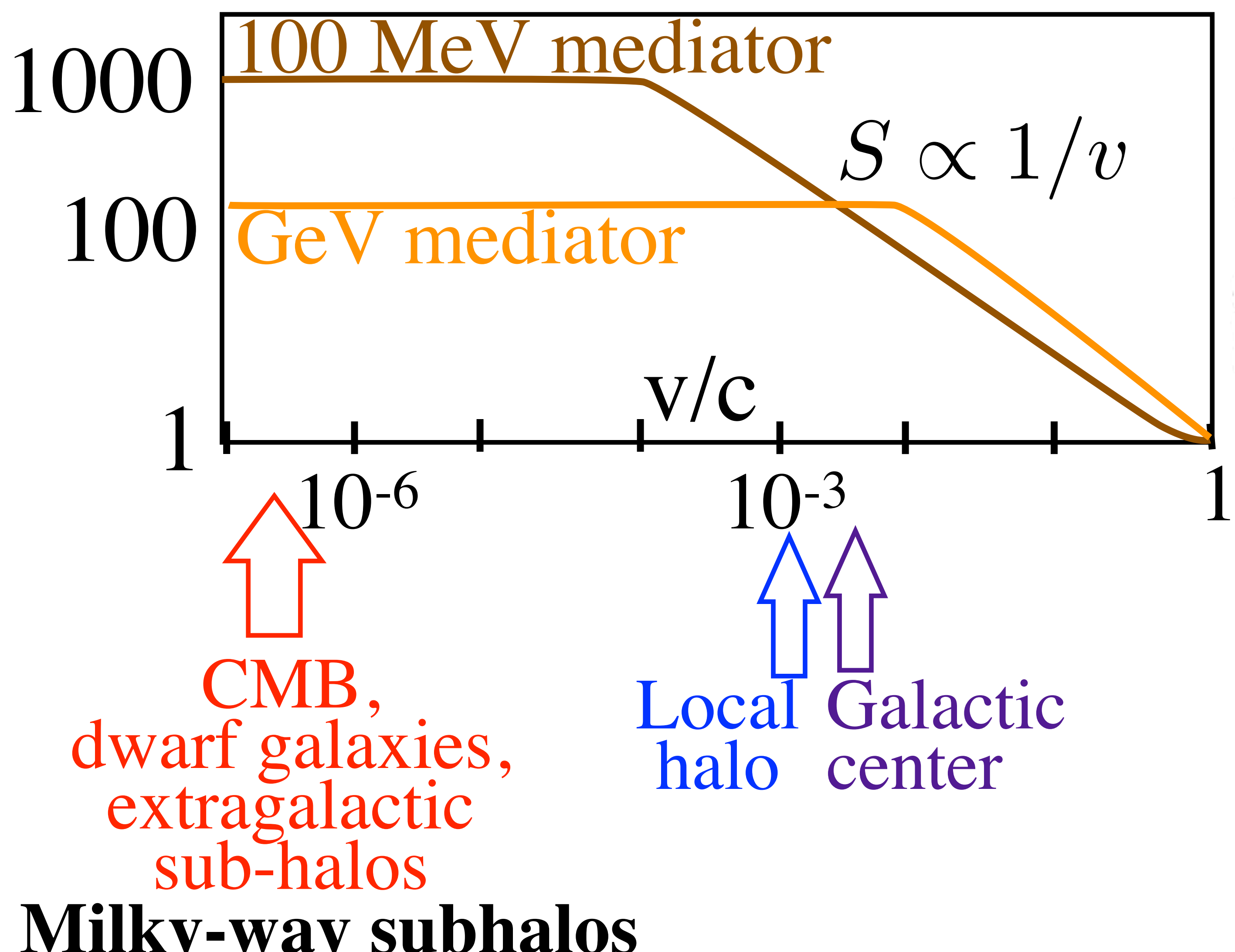


$$\frac{S_{\rm now}}{S_{\rm sat}} \sim \frac{m_\phi}{m_\chi v} \sim \frac{m_\phi}{\rm GeV}$$

Constraints on $\langle\sigma v\rangle_{\rm sat}$ imply much **tighter** constraints on $\langle\sigma v\rangle_{\rm local}$ if mediator is light

Preferred Dark-Photon Masses?

But….what if signals come from sub-halos in the Milky Way?



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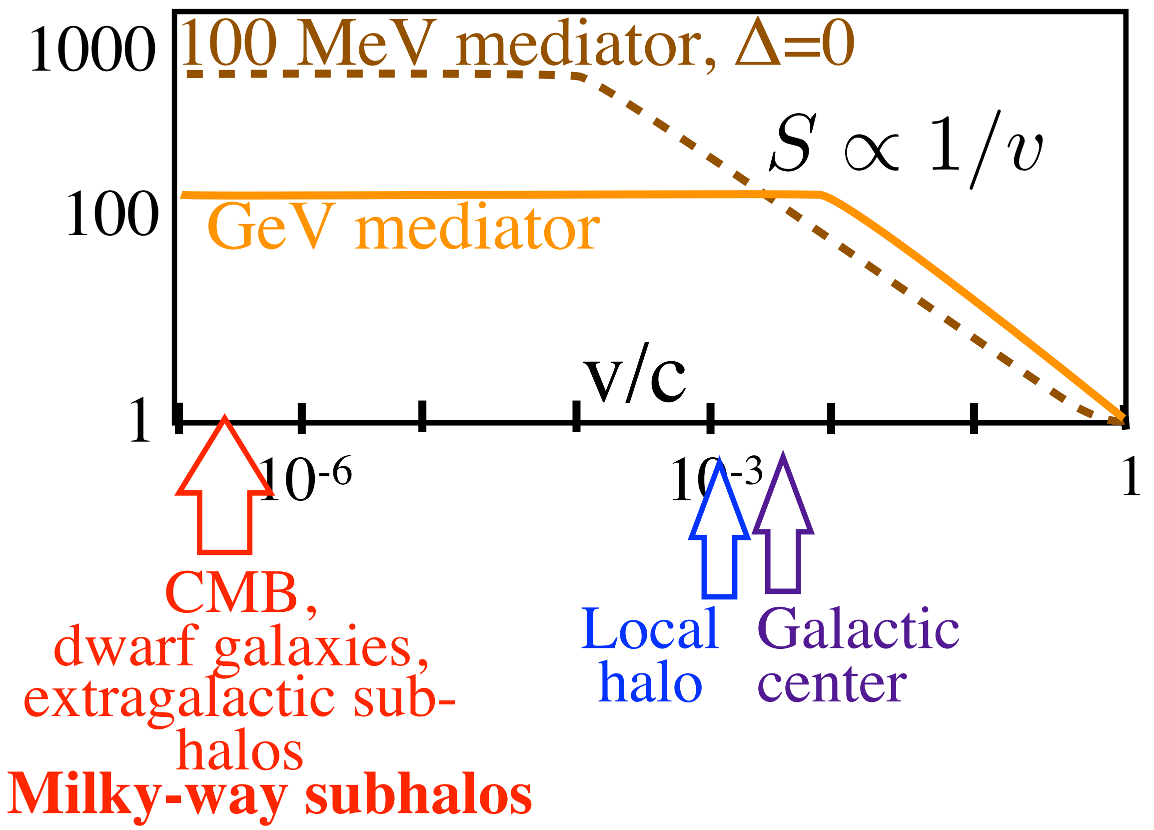
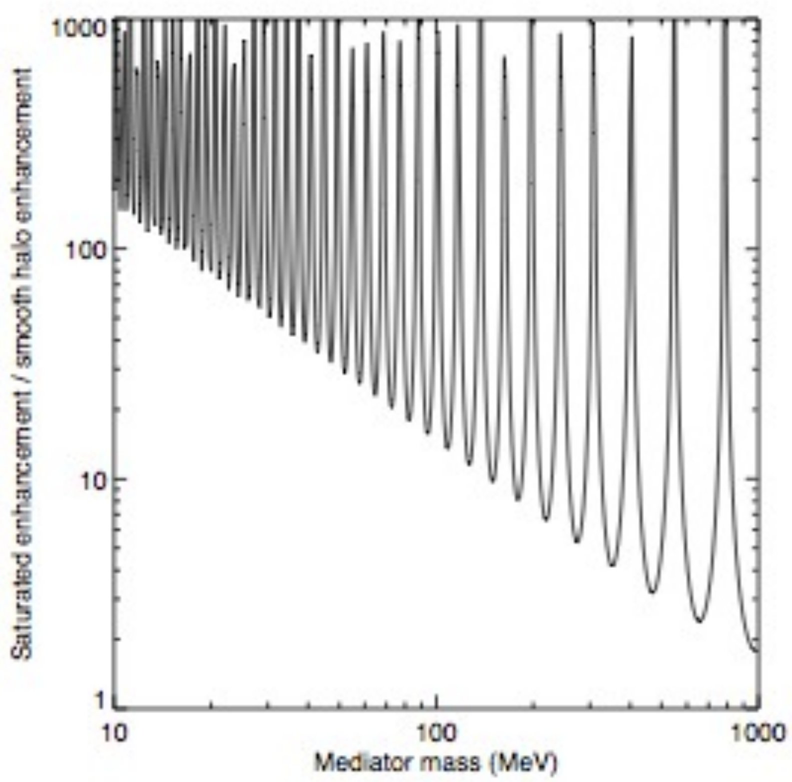
Sommerfeld DM with Substructure

If Δ=1, then the <ρ^2> from sub-halos is as large as from the smooth Milky Way halo…

...but the Sommerfeld boost factor might be 10x larger!





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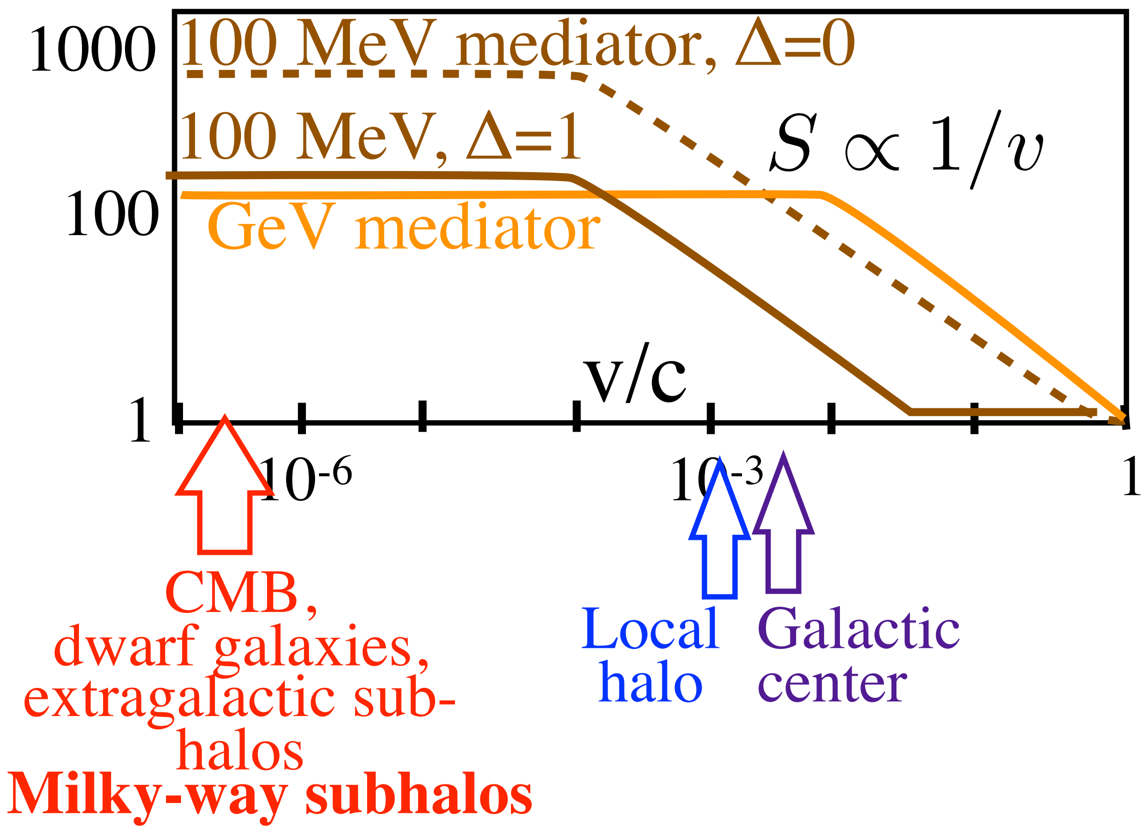

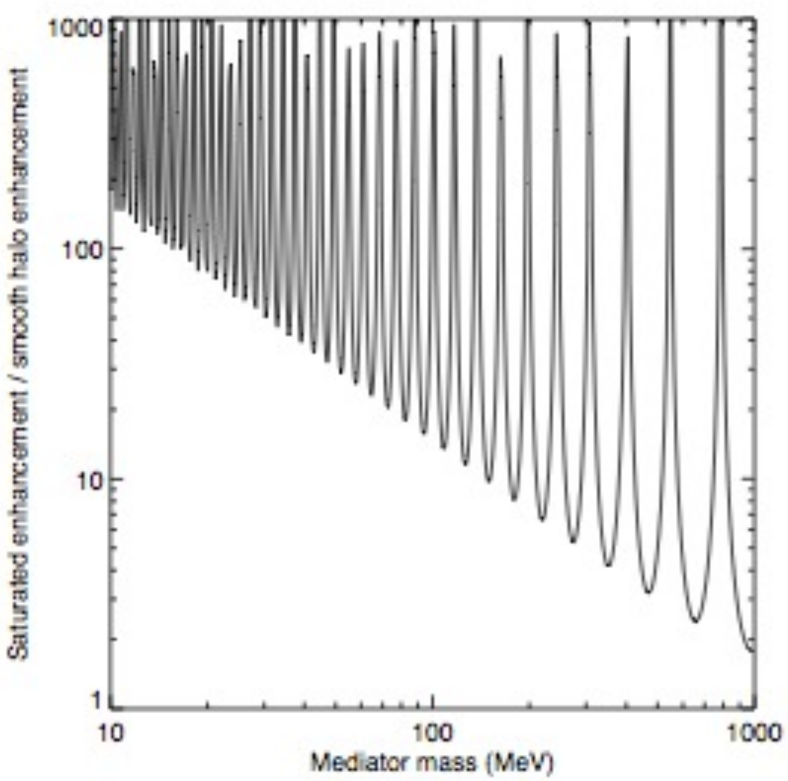

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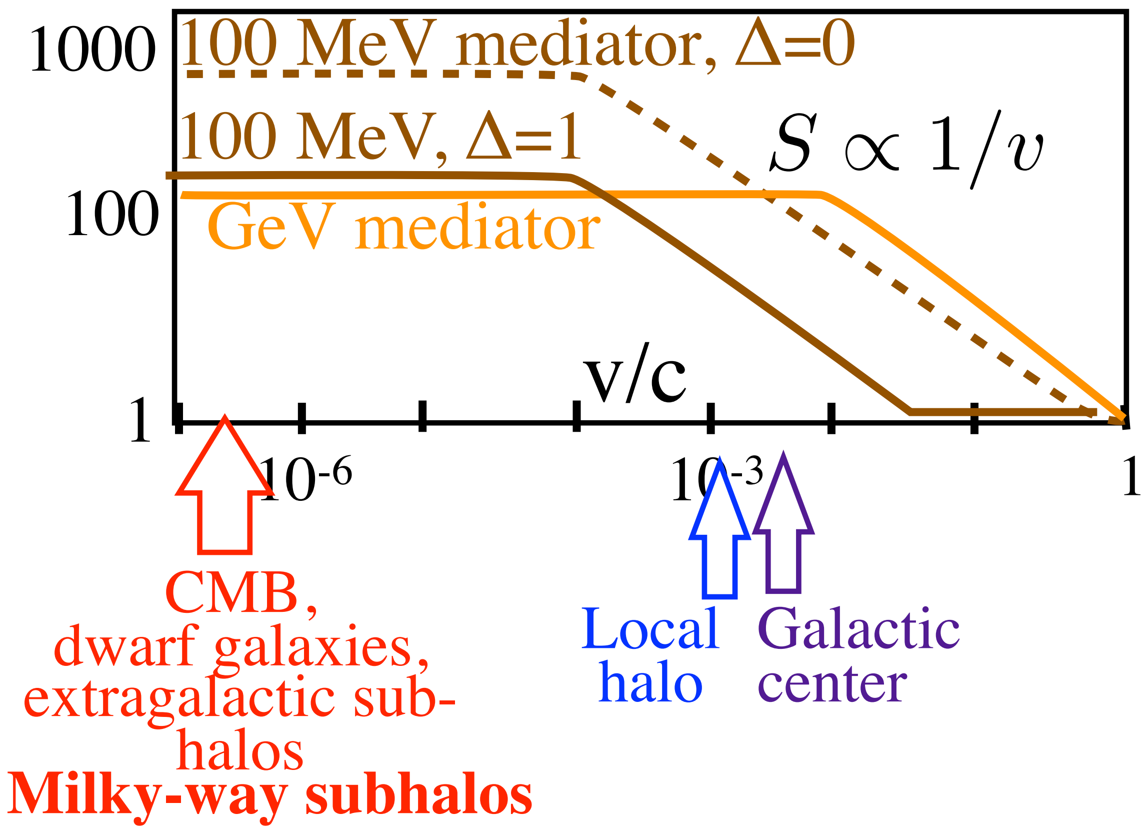

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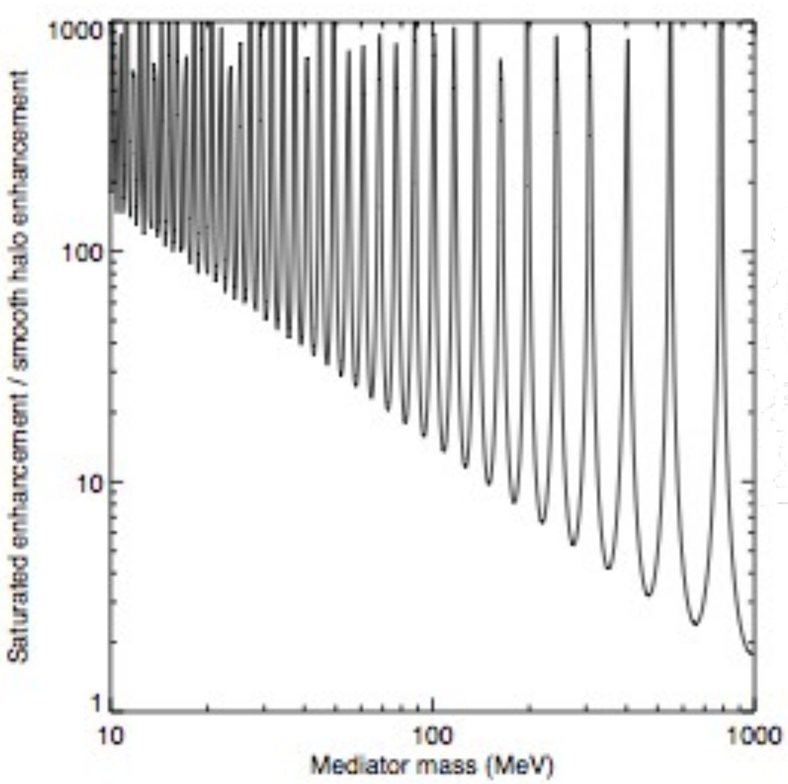


$$\frac{S_{\rm now}}{S_{\rm sat}} \sim \frac{m_\phi}{\rm GeV} + \Delta$$

For low m_ϕ , CMB is a limit on Δ

$$\frac{S_{\rm now}}{S_{\rm GC}} \sim \frac{m_\phi/GeV + \Delta}{m_\phi/GeV}$$

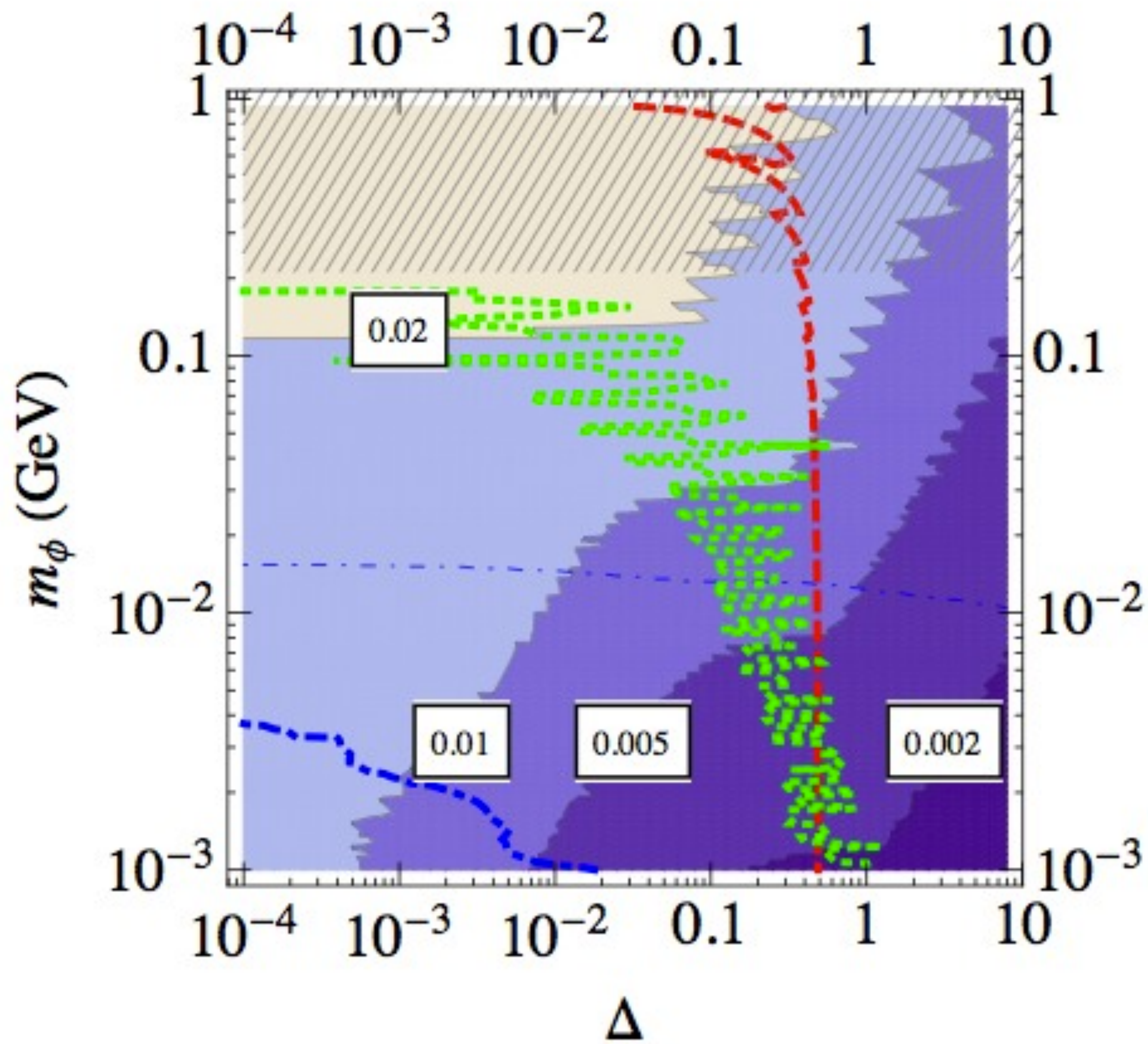
For low m_ϕ & O(1) Δ, GC constraints suppressed by m_ϕ/GeV $\Rightarrow$ cuspy halos ok.

Parameter Space

Contours: dark-sector self-coupling required for PAMELA/Fermi (target boost factor of 100)

Assume additional processes **at freeze-out BUT NOT today** to get correct relic abundance.

Arrows: regions excluded by
DM self-interaction
CMB re-ionization by DM
(green line is not a constraint)



(from 1107.3546 – T. Slatyer, NT, N. Weiner)

PAMELA consistent with WMAP-5 for *any* mediator mass, if $\Delta > 0.4$
No significant constraints from self-interaction
(but PLANCK will be sensitive to 10x smaller signals…)

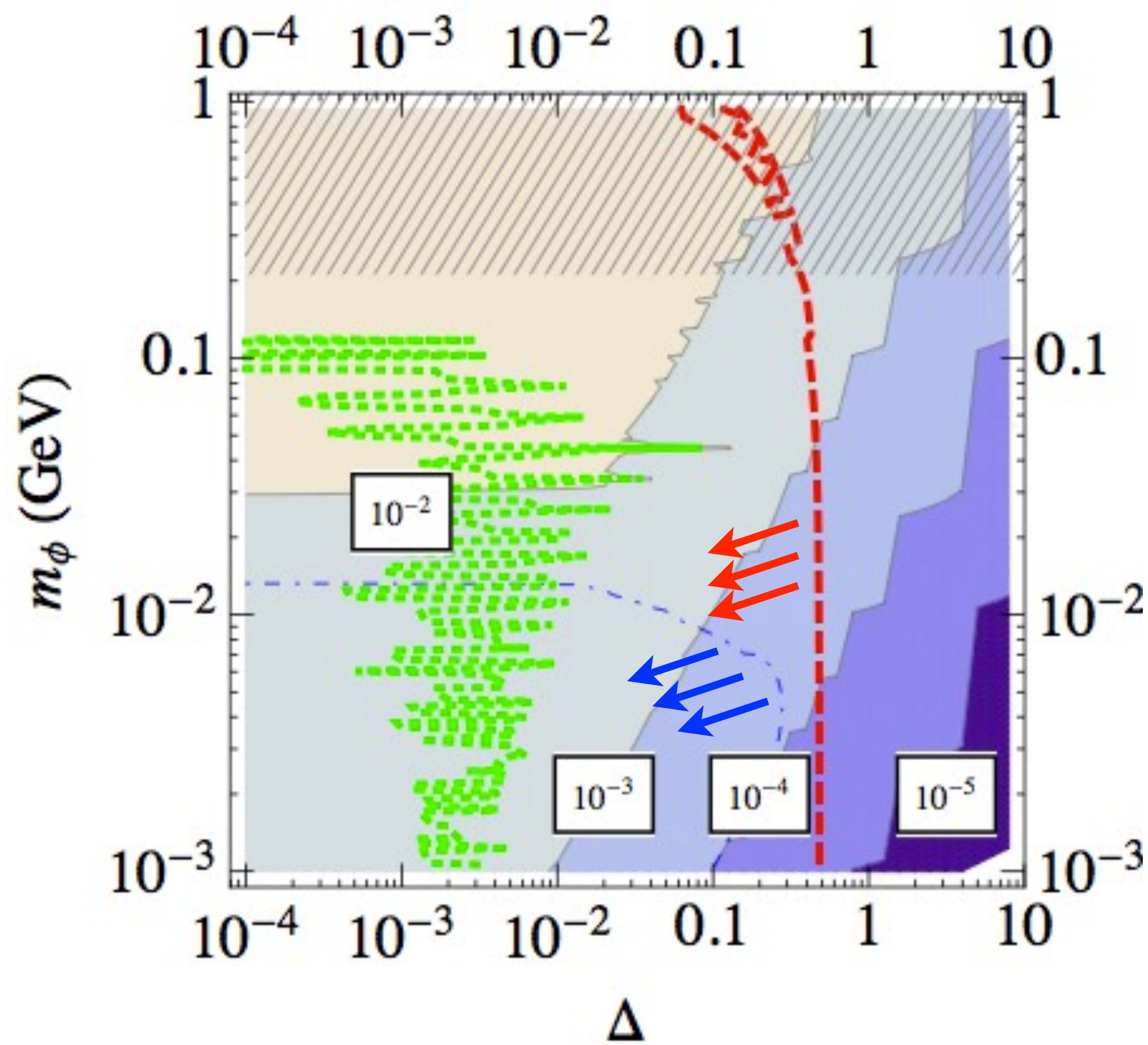
Parameter Space

Contours: dark-sector self-coupling required for PAMELA/Fermi (target boost factor of 100)

Assume additional processes **at freeze-out and today** to get correct relic abundance ⇒ smaller favored coupling.

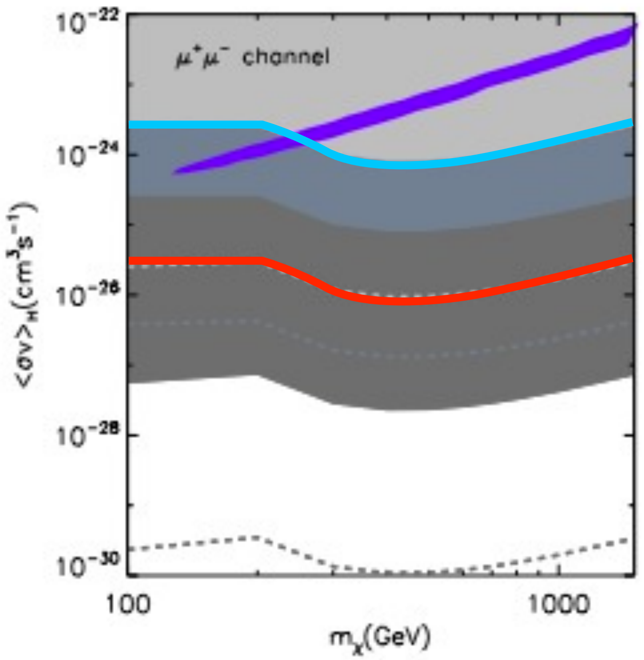
Arrows: regions excluded by
 DM self-interaction
 CMB re-ionization by DM

(green region – not a constraint, but region where WIMPonium matters)



(from 1107.3546 – T. Slatyer, NT, N. Weiner)

Substructure & Extragalactic Limits



Limit (low-substructure)

Limit (high-substructure)

- EG and local fluxes depend on different parameters and no one simulation has enough dynamic range to estimate both

  e.g. local signal depends on **radial** profile of subhalo density, EG signal depends on the distribution of main-halo sizes

- Limit ⇒ (Local/MW) x (MW/extragalactic) ≥ 1/20

  ~1/6 – 1/18 (Pieri et al 2009, Kamionkowski, Koushiappas, Kuhlen 2010)

  ~1 – 1/**3** – 1/10 (Zavala, Springel, Boylan-Kolchin)

  – Expected signal is certainly same order-of-magnitude as bound
  – Fully consistent *if* star-forming galaxy BG is small, and substructure distribution is favorable

Conclusions

- If PAMELA and Fermi are signs of enhanced DM annihilation, the same physics should also leave imprints elsewhere
  - No evidence so far ⇒ strong constraints
- Present constraints are subject to considerable uncertainties
  - Most often talked about: uncertainties in the constraining signals
    - **gal. center:** halo profile, ICS, backgrounds
    - **distant galaxies, outer galaxy, dwarves:** substructure
  - **Velocity-dependence is important** for light ($\lesssim$200 MeV) mediator models, affects local signals as well as constraints
    - Local substructure ⇒ less annihilation in gal. center (fast DM), comparable in CMB and dwarfs, extragalactic signals (slow DM)
    - CMB is robust but not decisive, extragal. is strong but not robust…. **PLANCK in 2013: x5 improved sensitivity!**
  - **DM could have shown its face in many places, and didn't...but has wiggle-room left.**