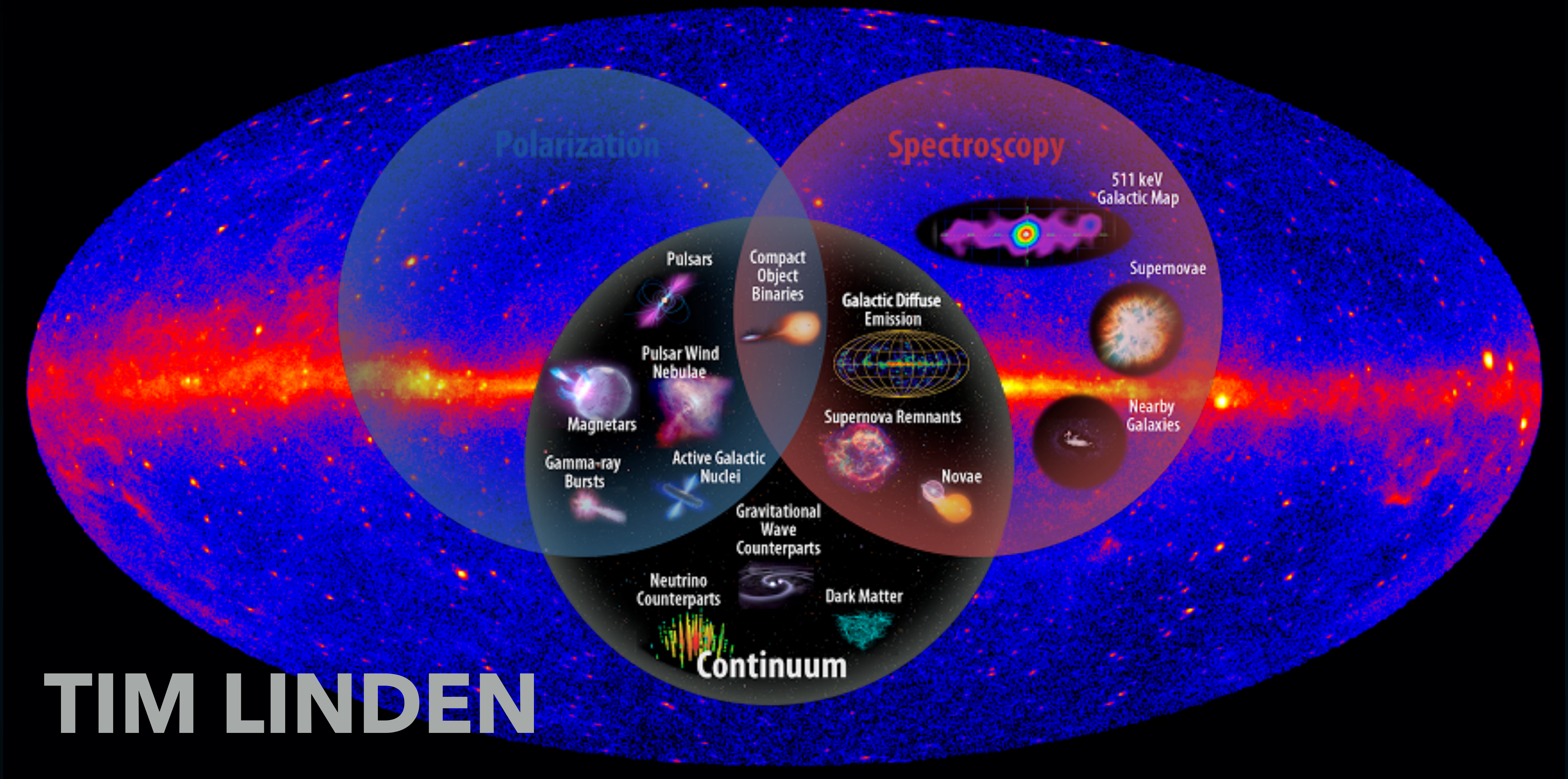


TIM LINDEN

SEARCHING FOR DARK MATTER IN THE MEV SKY

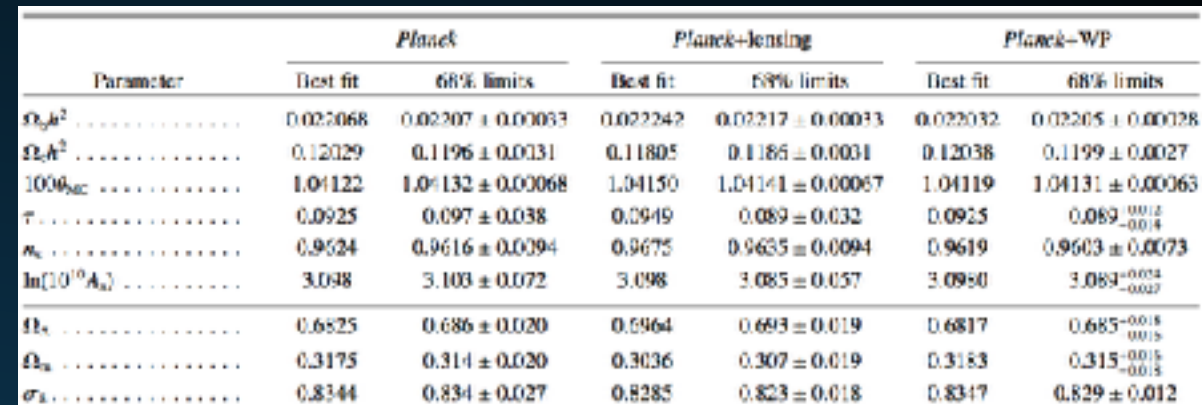
231st American Astronomical Society Meeting

January 10, 2018

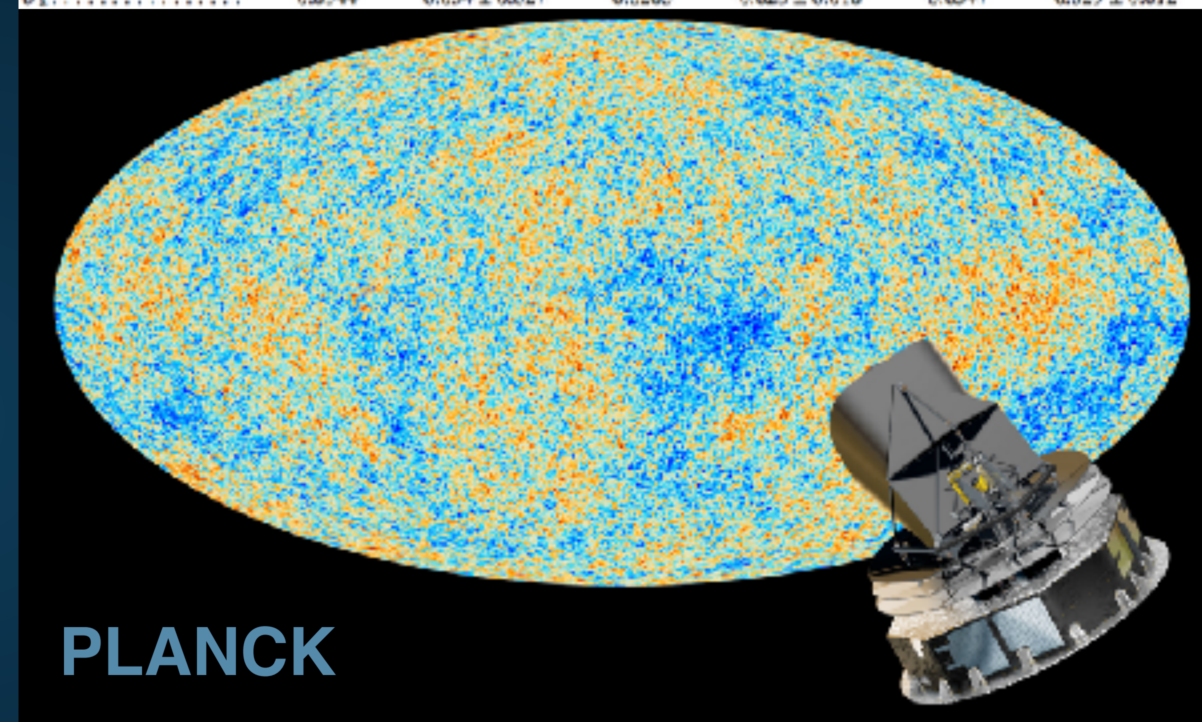
THE OHIO STATE UNIVERSITY
CENTER FOR COSMOLOGY AND ASTROPARTICLE PHYSICS

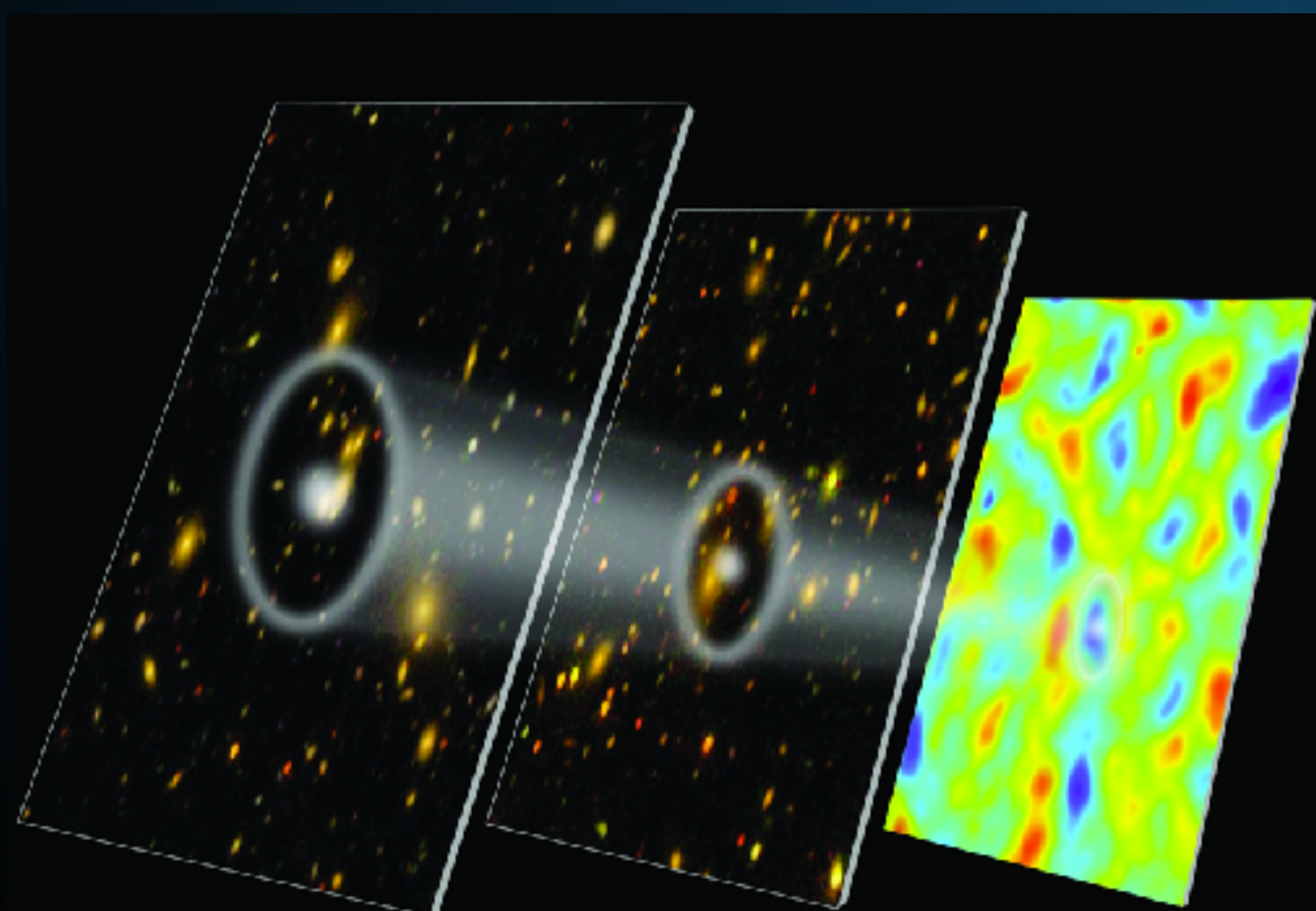
EVERYTHING WE KNOW ABOUT DARK MATTER

- CMB
- Galactic Rotation Curves
- Gravitational Lensing
- Baryonic Acoustic Oscillations



Parameter	*Planck* Best fit	*Planck* 68% limits	*Planck*+lensing Best fit	*Planck*+lensing 68% limits	*Planck*+WP Best fit	*Planck*+WP 68% limits
$\Omega_b h^2$	0.022068	0.02207 ± 0.00033	0.022242	0.02217 ± 0.00033	0.022032	0.02205 ± 0.00028
$\Omega_c h^2$	0.12029	0.1196 ± 0.0031	0.11805	0.1186 ± 0.0031	0.12038	0.1199 ± 0.0027
$100\theta_{MC}$	1.04122	1.04132 ± 0.00068	1.04150	1.04141 ± 0.00067	1.04119	1.04131 ± 0.00063
τ	0.0925	0.097 ± 0.038	0.0949	0.089 ± 0.032	0.0925	$0.089^{+0.012}_{-0.014}$
n_s	0.9624	0.9616 ± 0.0094	0.9675	0.9635 ± 0.0094	0.9619	0.9603 ± 0.0073
$\ln(10^{10} A_s)$	3.098	3.103 ± 0.072	3.098	3.085 ± 0.057	3.0980	$3.089^{+0.024}_{-0.027}$
Ω_Λ	0.6825	0.686 ± 0.020	0.6964	0.693 ± 0.019	0.6817	$0.685^{+0.018}_{-0.016}$
Ω_m	0.3175	0.314 ± 0.020	0.3036	0.307 ± 0.019	0.3183	$0.315^{+0.016}_{-0.018}$
σ_8	0.8344	0.834 ± 0.027	0.8285	0.823 ± 0.018	0.8347	0.829 ± 0.012





Galaxy map 3.8 billion years ago

Galaxy map 5.5 billion years ago

CMB 13.7 billion years ago

EVERYTHING WE KNOW ABOUT DARK MATTER

- CMB
- Galactic Rotation Curves
- Gravitational Lensing
- Baryonic Acoustic Oscillations

10^{-25} GeV — 10^{62} GeV

$\sigma_X > R_{UFD}$ — $m_X > M_{UFD}$

slide concept courtesy of Asher Berlin

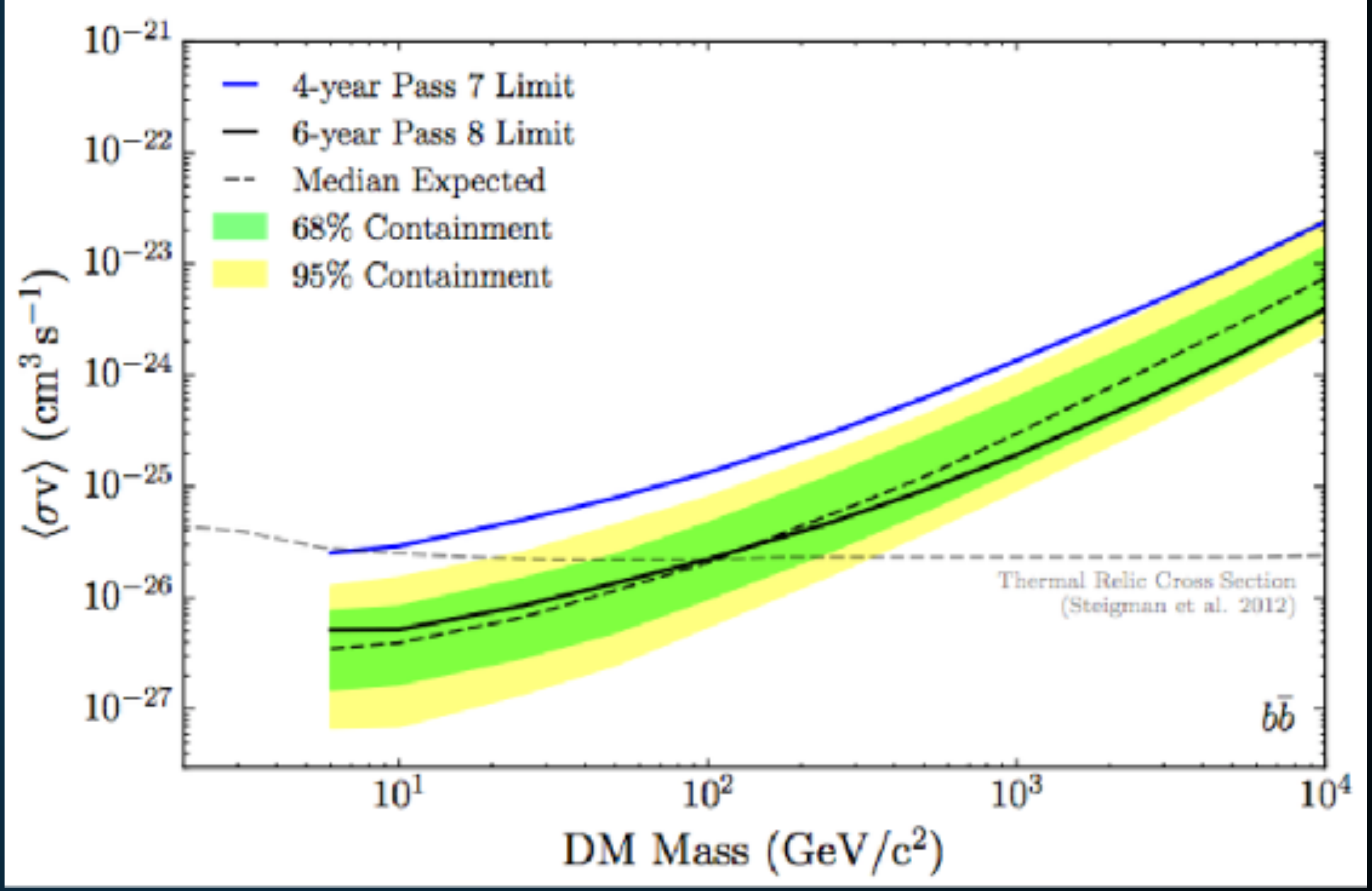
So, why look for dark matter in the MeV range?

Because we can.

THE MEV SCALE - A (CURRENT) LACK OF SENSITIVITY

- Many studies have been sensitive to GeV-scale dark matter, but most observations run out of steam in the MeV range.

Fermi Collab. (1503.02641)

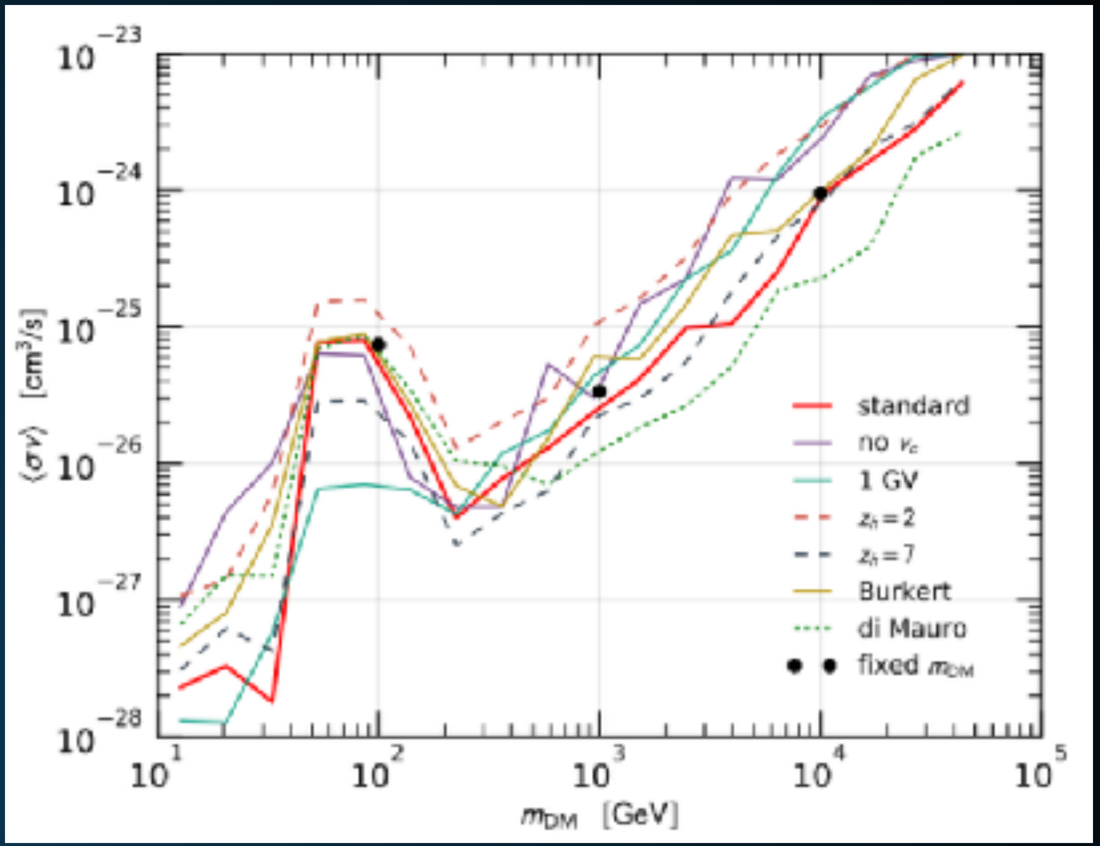


- Fermi-LAT gamma-ray observations are sensitive to DM heavier than ~5 GeV

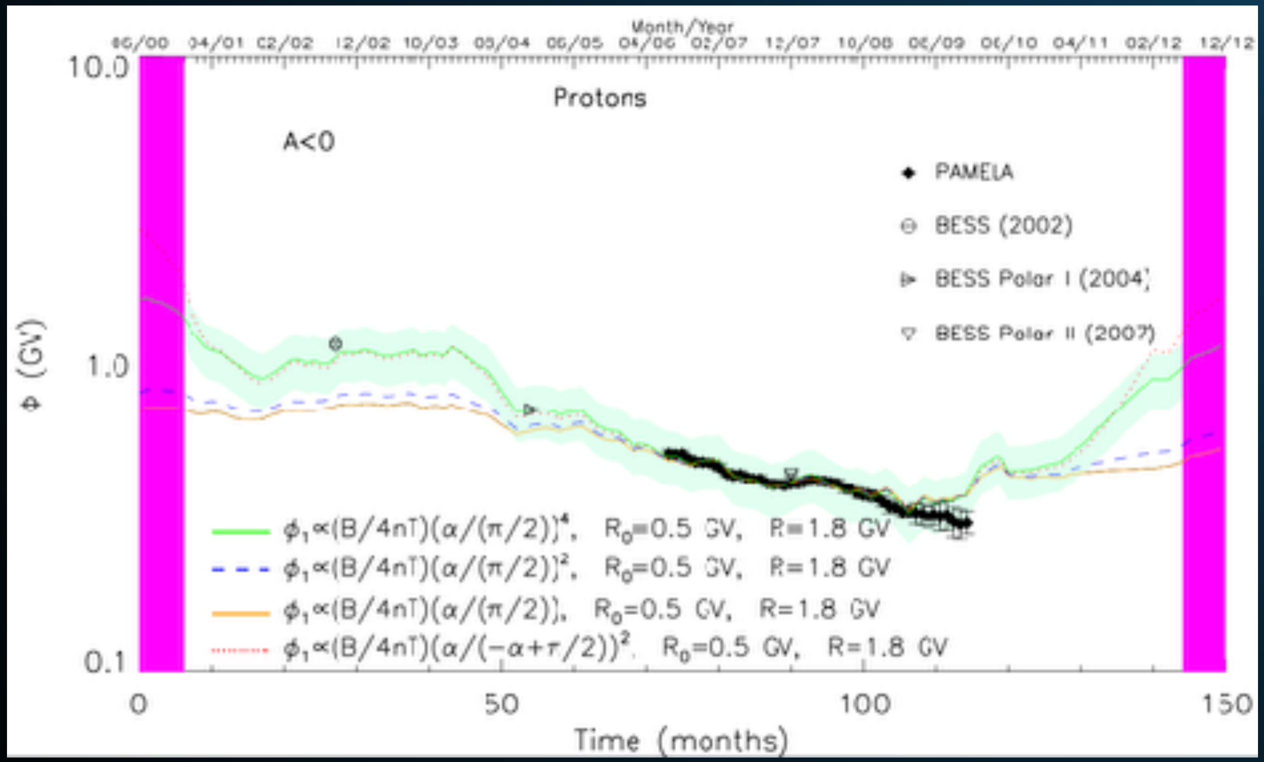
- A low energy mission could significantly improve this sensitivity.

THE MEV SCALE - A (CURRENT) LACK OF SENSITIVITY

Cuoco et al. (1610.03071)



- Space-based cosmic-ray instruments are sensitive to signals from MeV dark matter.

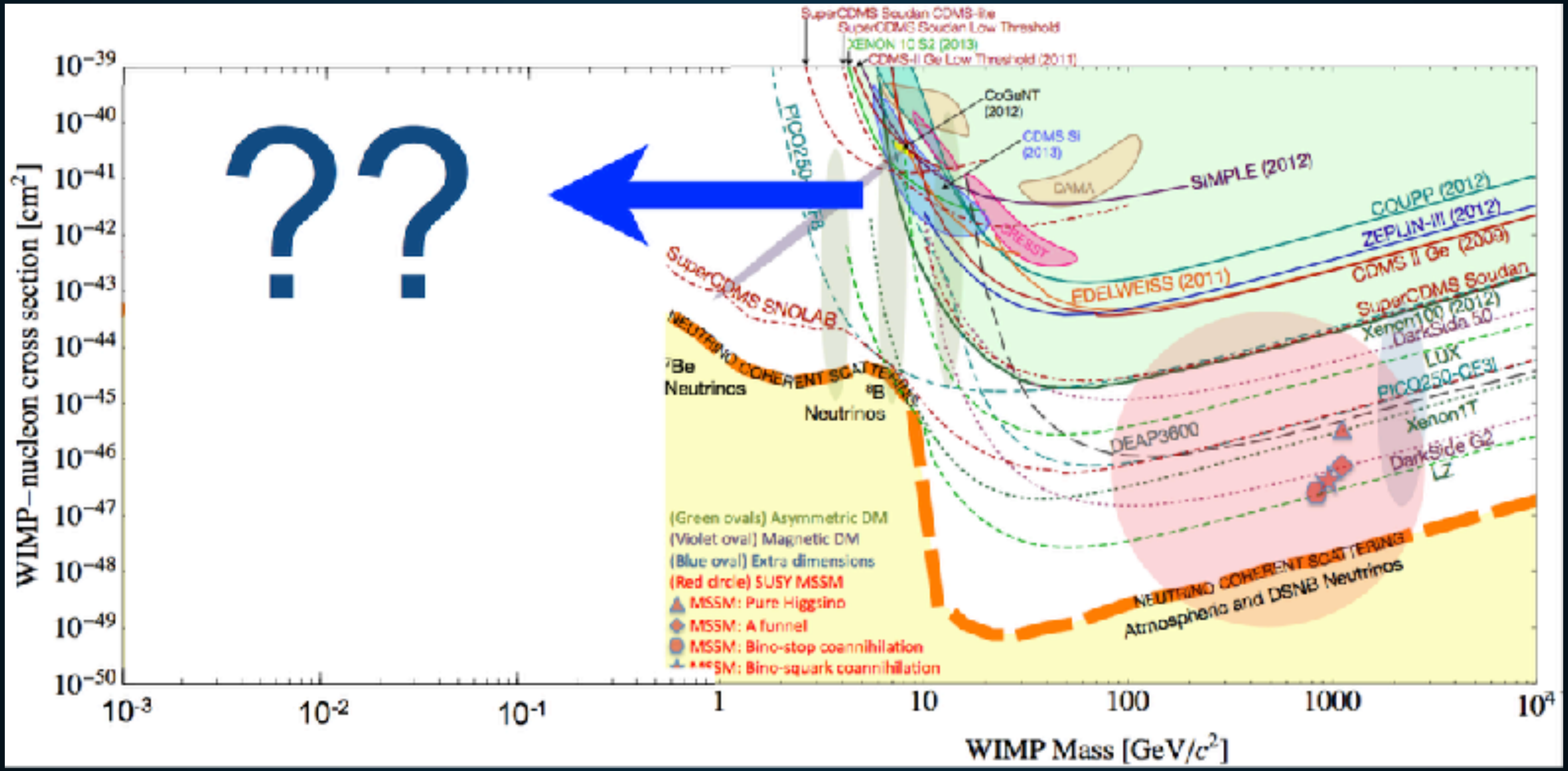


Cholis et al. (1511.01507)

- However, the heliospheric potential is ~1 GV.
- Significantly uncertain, prevents DM/background differentiation at low energies.

THE MEV SCALE - A (CURRENT) LACK OF SENSITIVITY

- Direct detection studies are not currently sensitive to dark matter masses below the proton mass.



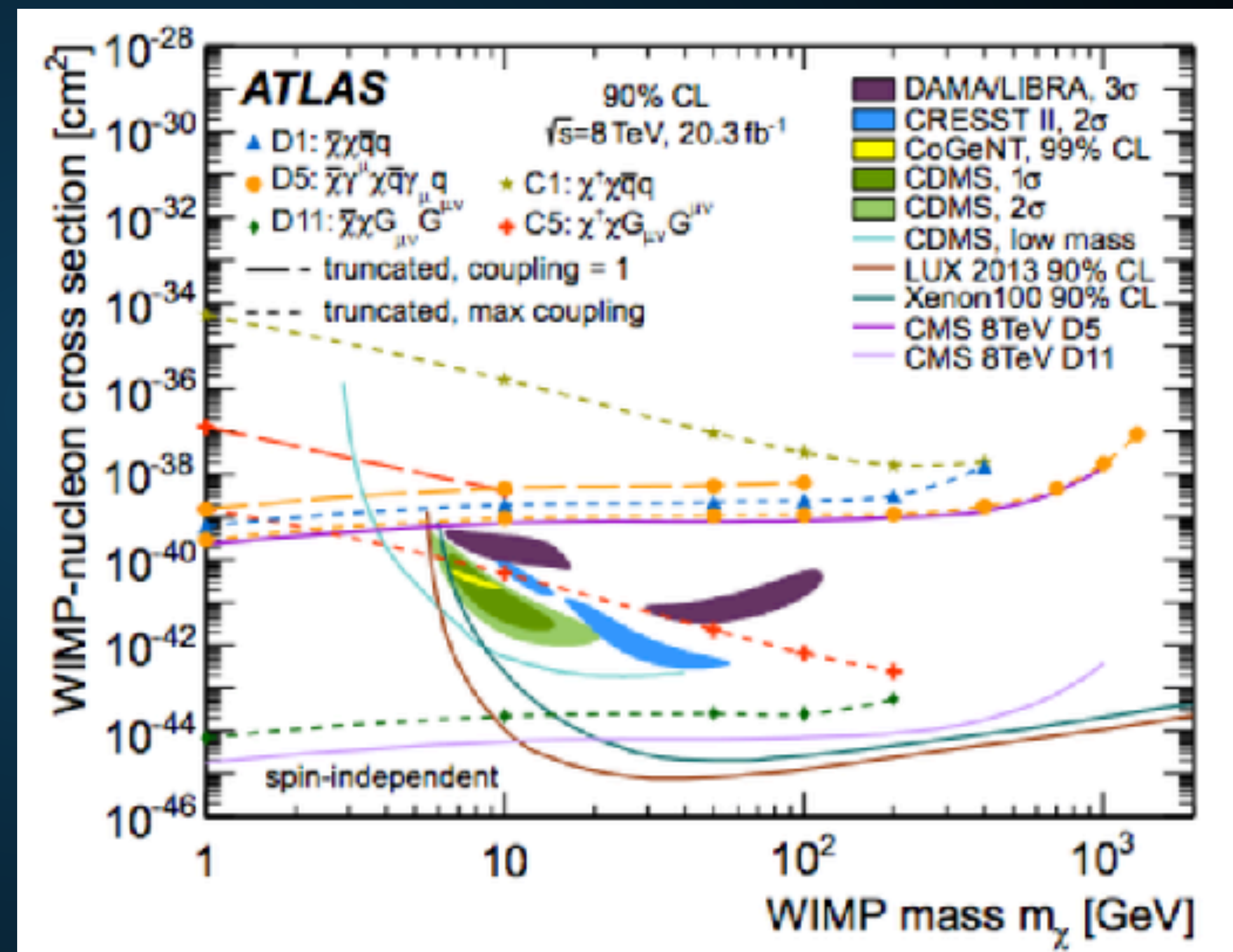
- May be improved someday with alternative technologies.

slide concept courtesy of Kathryn Zurek

THE MEV SCALE - A (CURRENT) LACK OF SENSITIVITY

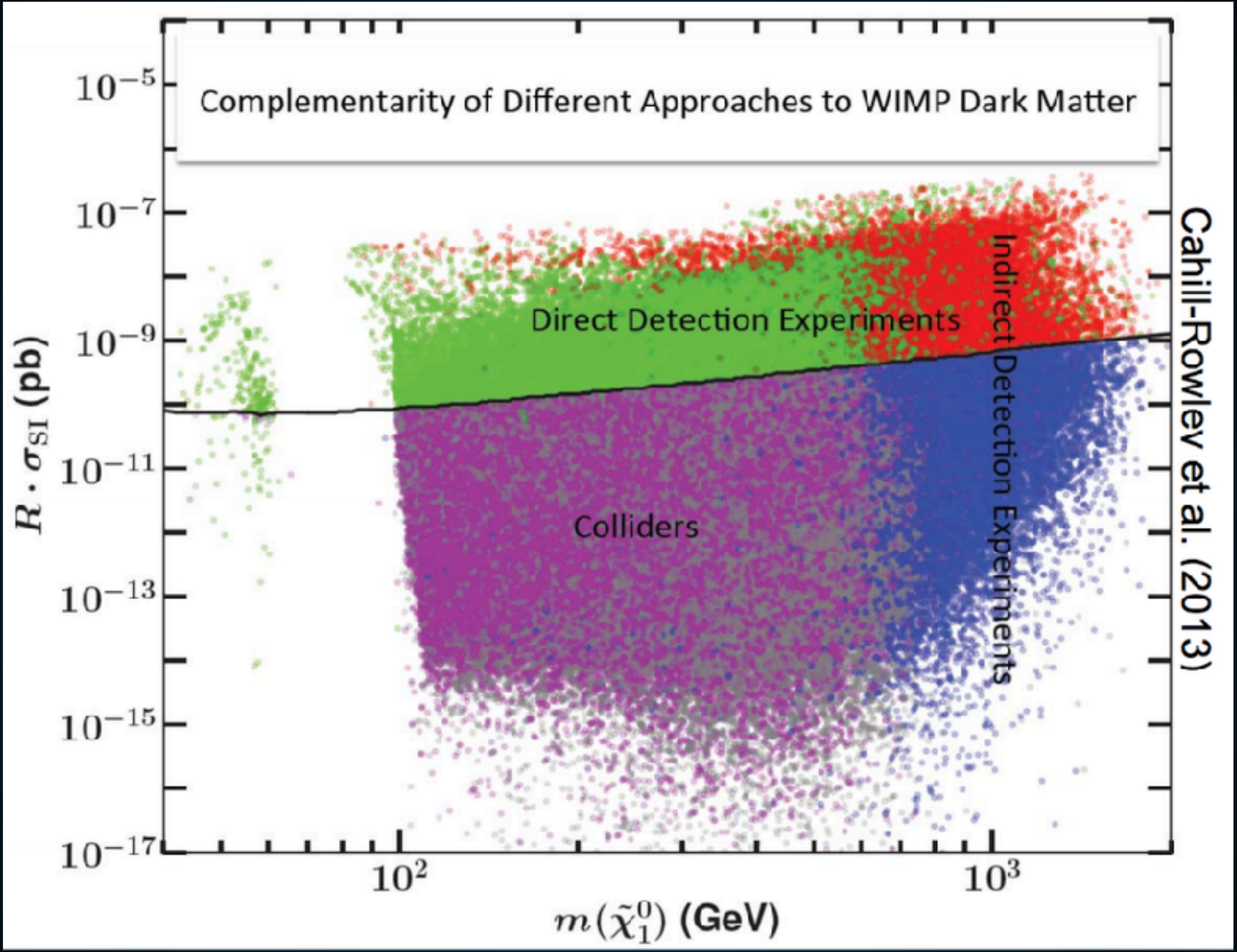
- **Many studies have been sensitive to GeV-scale dark matter, but most observations run out of steam in the MeV range.**

- **Colliders can potentially constrain very light dark matter, but their sensitivity is highly model dependent.**



- **Beam dump experiments may soon significantly increase the sensitivity of collider experiments in the MeV range.**

THE MEV SCALE - A WORLD OF POSSIBILITIES!



- **We need to transfer this picture of complementarity into the MeV regime.**

THE IMPETUS FOR MEV DARK MATTER - LESSONS FROM WIMPS

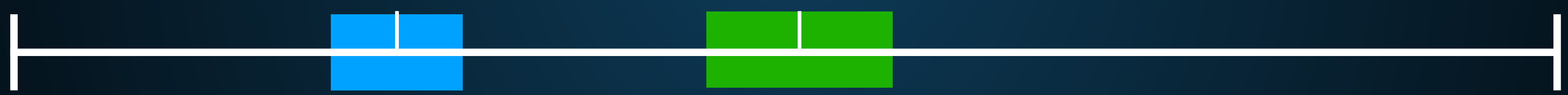
So, why look for dark matter in the MeV range?

What is the landscape of MeV dark matter?

THE IMPETUS FOR MEV DARK MATTER - LESSONS FROM WIMPS

- CMB
- Galactic Rotation Curves
- Gravitational Lensing
- Baryonic Acoustic Oscillations

10^{-13} GeV 10^{2} GeV



10^{-25} GeV
$\sigma_X > R_{UFD}$

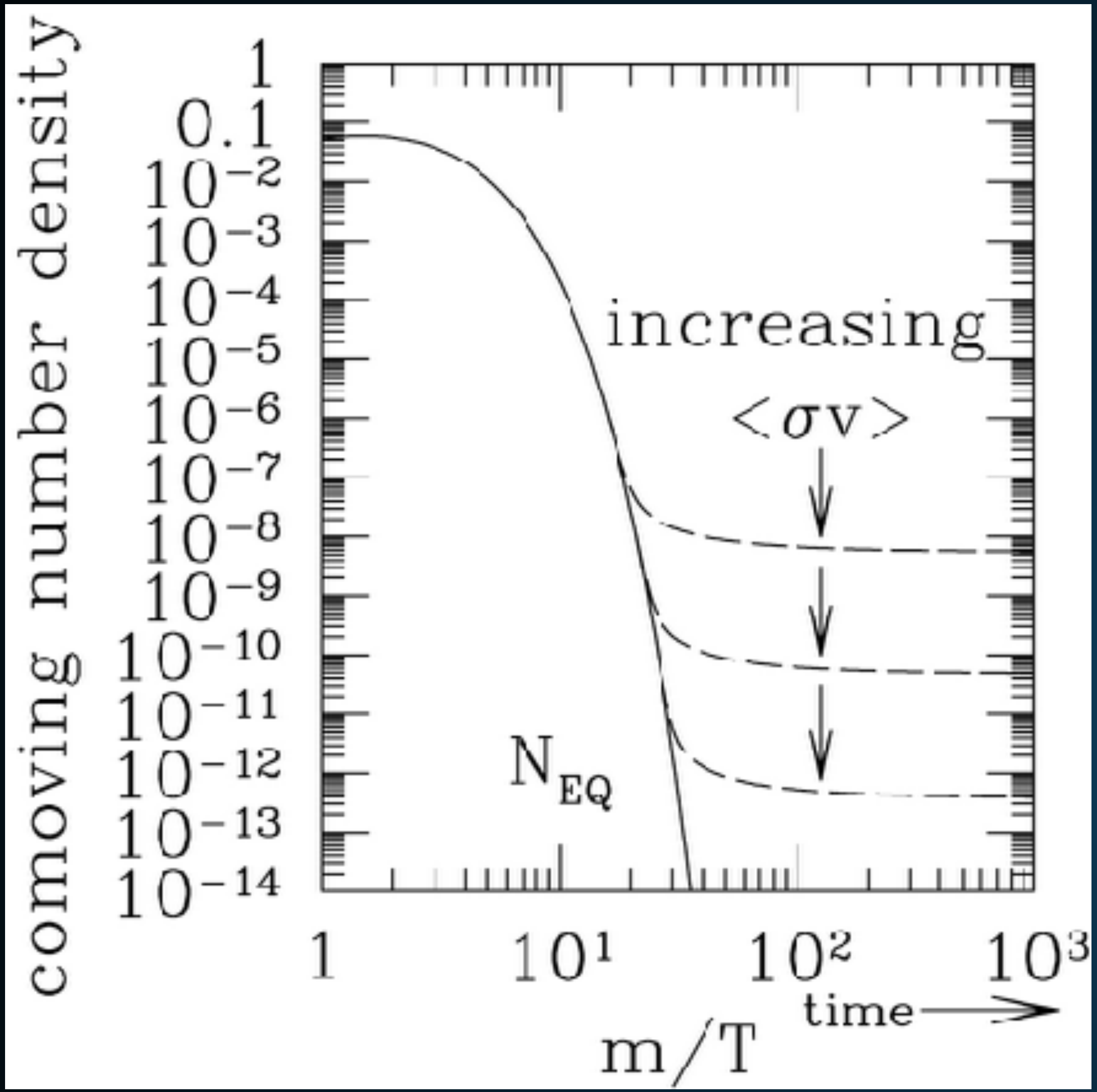
QCD
Axion

WIMP
Miracle!

10^{62} GeV
$m_X > M_{UFD}$

slide concept courtesy of Asher Berlin

THE WIMP MIRACLE



A particle with a weak interaction cross-section and a mass on the weak scale is expected to naturally obtain the correct relic abundance through thermal freeze-out in the Earth universe.

$$\left(\frac{\Omega_\chi}{0.2}\right) \simeq \frac{x_{\mathrm{f.o.}}}{20}\left(\frac{10^{-8}\ \mathrm{GeV}^{-2}}{\sigma}\right)$$

$$\langle\sigma v\rangle \sim 10^{-8}\ \mathrm{GeV}^{-2}\left(3\times10^{-28}\ \mathrm{GeV}^2\ \mathrm{cm}^2\right)\ 10^{10}\ \frac{\mathrm{cm}}{\mathrm{s}} = 3\times10^{-26}\ \frac{\mathrm{cm}^3}{\mathrm{s}}$$

THE WIMP MIRACLE

- At high-masses we have the unitarity bound:
  - Electroweak coupling constant is proportional to m_χ^2.
  - Coupling constant must be 1, or loop contributions diverge.

$$\left(\frac{\Omega_\chi}{0.2}\right) \simeq \frac{x_{\mathrm{f.o.}}}{20}\left(\frac{10^{-8}\ \mathrm{GeV}^{-2}}{\sigma}\right)$$

$$\sigma \sim \frac{g^4}{m_\chi^2},$$

$$g^2 \sim \frac{m_\chi}{10\ \mathrm{TeV}}$$

slide concept courtesy of Asher Berlin

THE WIMP MIRACLE

- What about the lower-limit?

slide concept courtesy of Asher Berlin

THE WIMP MIRACLE

- **Lee-Weinberg bound:**

$$\Omega_\chi h^2 \sim 0.1 \frac{10^{-8}}{\mathrm{GeV}^{-2}} \cdot \frac{1}{G_F^2\, m_\chi^2} \sim 0.1 \left(\frac{10\ \mathrm{GeV}}{m_\chi}\right)^2$$

PHYSICAL REVIEW LETTERS

VOLUME 39 | 25 JULY 1977 | NUMBER 4

Cosmological Lower Bound on Heavy-Neutrino Masses

Benjamin W. Lee[a]
Fermi National Accelerator Laboratory,[b] *Batavia, Illinois 60510*

and

Steven Weinberg[c]
Stanford University, Physics Department, Stanford, California 94305
(Received 13 May 1977)

The present cosmic mass density of possible stable neutral heavy leptons is calculated in a standard cosmological model. In order for this density not to exceed the upper limit of 2×10^{-29} g/cm^3, the lepton mass would have to be *greater* than a lower bound of the order of 2 GeV.

- **Under the assumption that the interaction is electroweak (G_F^2), the dark matter mass must be larger than 10 GeV.**
- **Two caveats:**
  - **Dark matter may still be thermal, if the interaction that thermalizes DM is not electroweak.**
  - **Electroweak models may still be reasonable, but only if a light scalar exists to boost the annihilation rate.**

- **N_{eff} bounds:**
  - **If dark matter falls out of thermal equilibrium during or after neutrino decoupling, then dark matter contributes to the effective number of degrees of freedom.**
  - **Bounds dark matter to be >~ 3-10 MeV**

Limits on MeV Dark Matter from the Effective Number of Neutrinos

Chiu Man Ho and Robert J. Scherrer
Department of Physics and Astronomy, Vanderbilt University, Nashville, TN 37235

Thermal dark matter that couples more strongly to electrons and photons than to neutrinos will heat the electron-photon plasma relative to the neutrino background if it becomes nonrelativistic after the neutrinos decouple from the thermal background. This results in a reduction in N_{eff} below the standard-model value, a result strongly disfavored by current CMB observations. Taking conservative lower bounds on N_{eff} and on the decoupling temperature of the neutrinos, we derive a bound on the dark matter particle mass of $m_\chi > 3 - 9$ MeV, depending on the spin and statistics of the particle. For p-wave annihilation, our limit on the dark matter particle mass is stronger than the limit derived from distortions to the CMB fluctuation spectrum produced by annihilations near the epoch of recombination.

2012

THE WIMP MIRACLE

- What about the lower-limit?

slide concept courtesy of Asher Berlin

A NEW PICTURE - NONSTANDARD WIMP MODELS

- Thinking outside the standard thermal weakly interacting particle box:
  - Asymmetric Dark Matter (e.g. Lin et al. 1111.0293)
  - Secluded Dark Matter (e.g. Pospelov et al. 0711.4866)
  - MeV Sterile neutrinos (Huang & Nelson, 1306.6079)
  - Strongly Interacting Massive Particles (e.g. Hochberg et al. 1402.5143)
  - Hidden Dark Sectors (e.g. Hufnagel et al. 1712.03972)
  - Late Decay to DM (e.g. Choquette et al. 1604.01039)
  - Also: Mirror Dark Matter, Atomic Dark Matter, Magnetic Dark Matter, WIMPless dark matter, etc.

INVISIBLE DARK MATTER MODELS

- Need to be careful - many of these models produce no dark matter annihilation signal.

- Our dark matter models need to produce <u>a little bit of light.</u>

- **What can light dark matter annihilate into?**

(i) $\gamma\gamma$: Accessible at all energies. The final state is C-even.

(ii) $\gamma\pi^0$: Accessible for $\sqrt{s} > m_{\pi^0}$. The final state is C-odd.

(iii) $\pi^0\pi^0$: Accessible for $\sqrt{s} \geq 2m_{\pi^0}$. The final state is C-even.

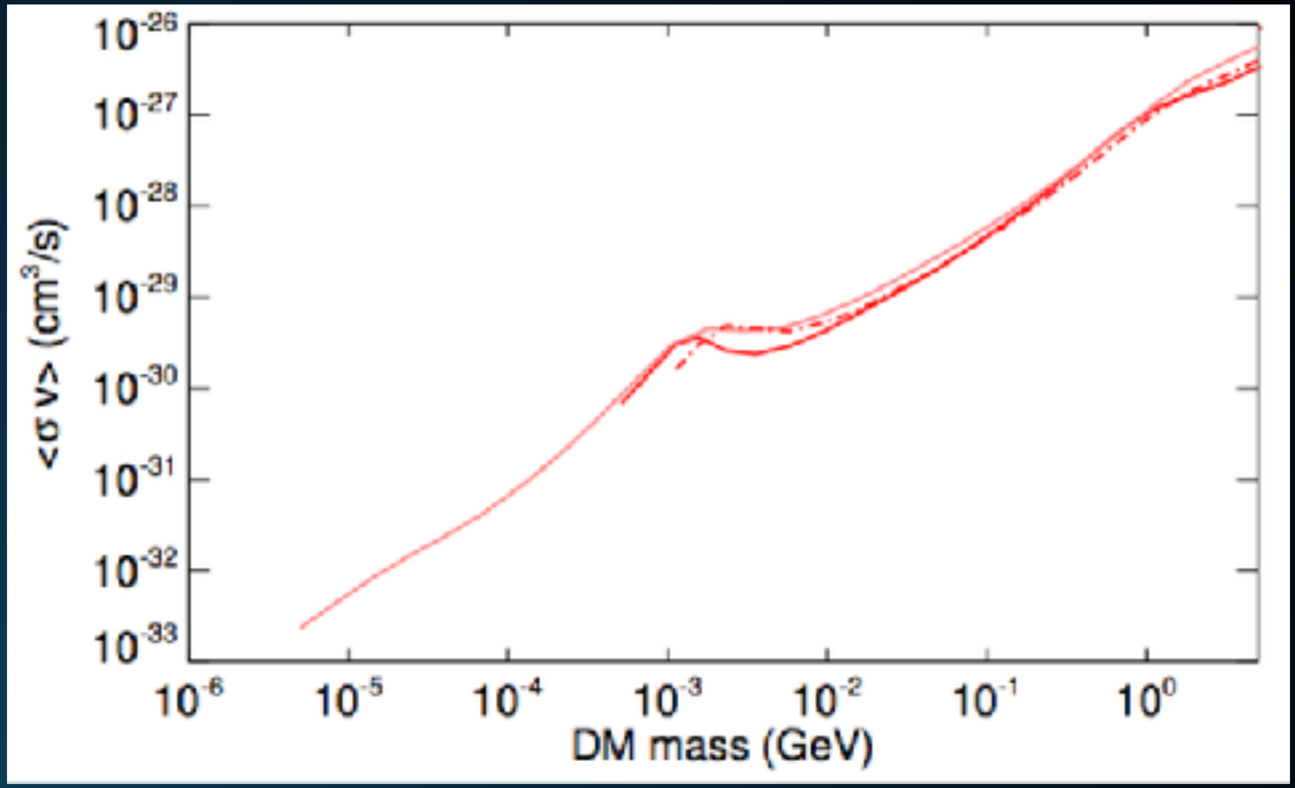
(iv) $\pi^+\pi^-$: Accessible for $\sqrt{s} \geq 2m_{\pi^\pm}$. The final state is C-even or C-odd.

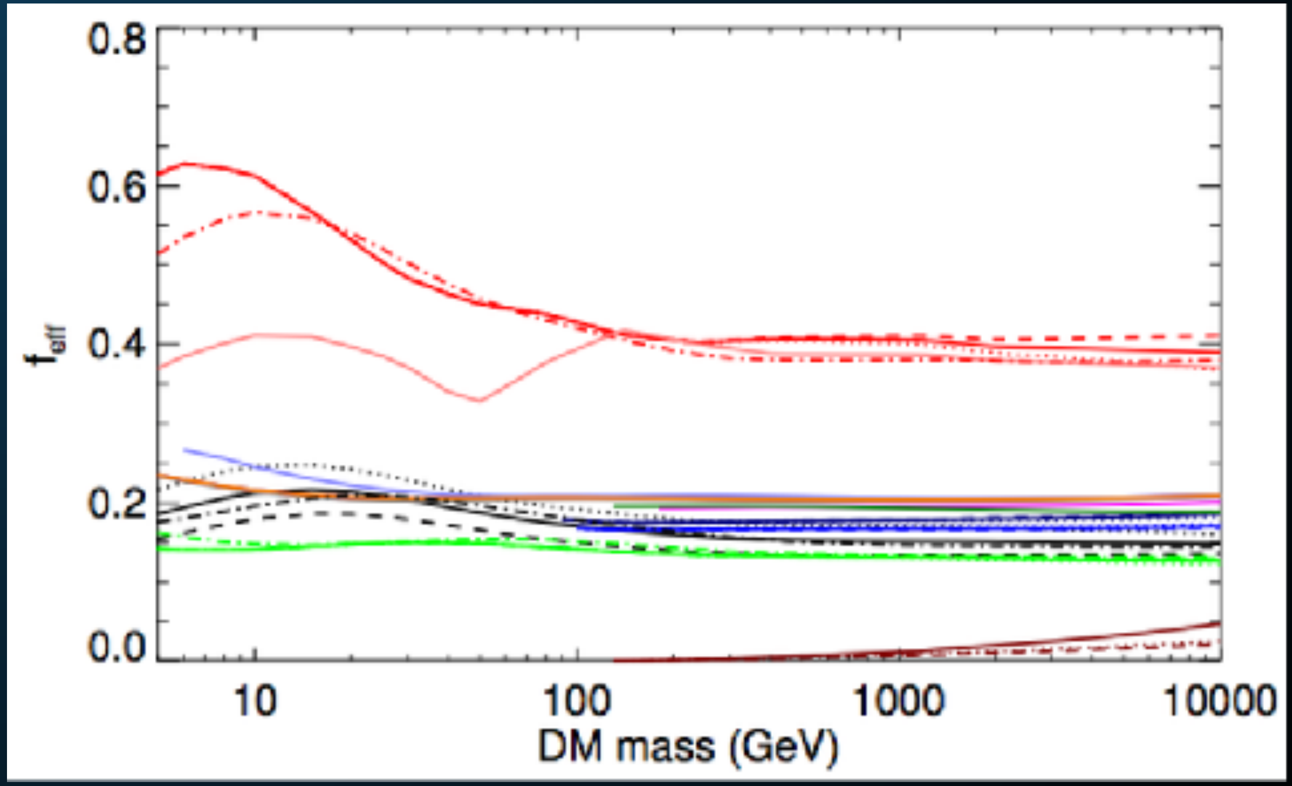
(v) $\bar{\ell}\ell$ ($\ell = e, \mu, \nu$): Accessible for $\sqrt{s} \geq 2m_\ell$. The final state is either C-odd or is weak suppressed.

- **This significantly limits the possible annihilation channels, especially for masses below 135 MeV.**

Slatyer (1506.03811)

- CMB Bounds:
  - Any energy deposition during recombination affects the CMB anisotropy
  - The constraint trends as <σv> ~ 1/m
  - Small changes due to the fraction of total power which is transferred to electrons.

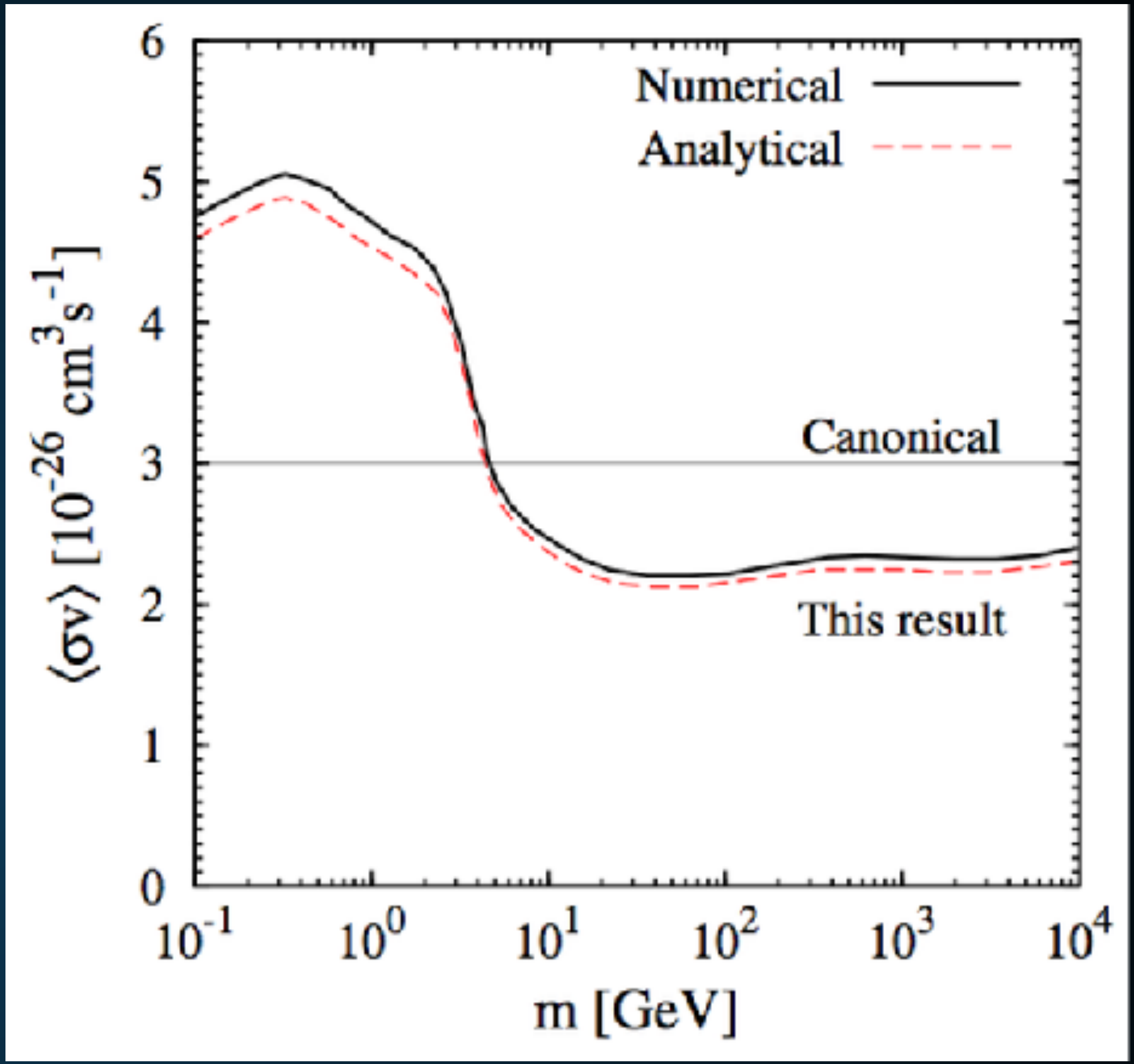




THE CMB DOUBLE-BIND

Steigman et al. (1204.3622)

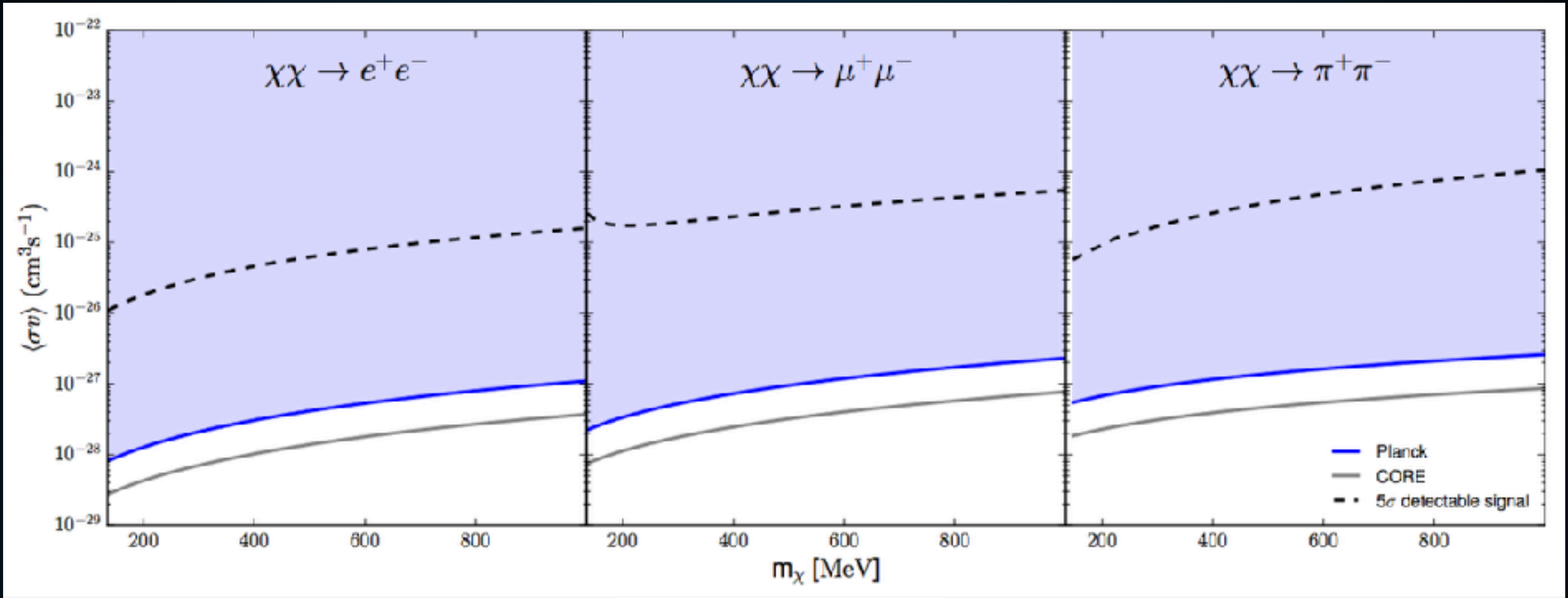
- Moreover - the annihilation rate at low masses should exceed $3 \times 10^{-26}\ cm^3\ s^{-1}$.
- CMB bounds appear to remove most of the parameter space for thermal DM.



- We can try to model build around this, for example invoking p-wave suppressed annihilations:
  - But these typically suppress gamma-ray emission today even more than the CMB!

COMPARISON OF CMB AND DWARF GAMMA-RAY CONSTRAINTS

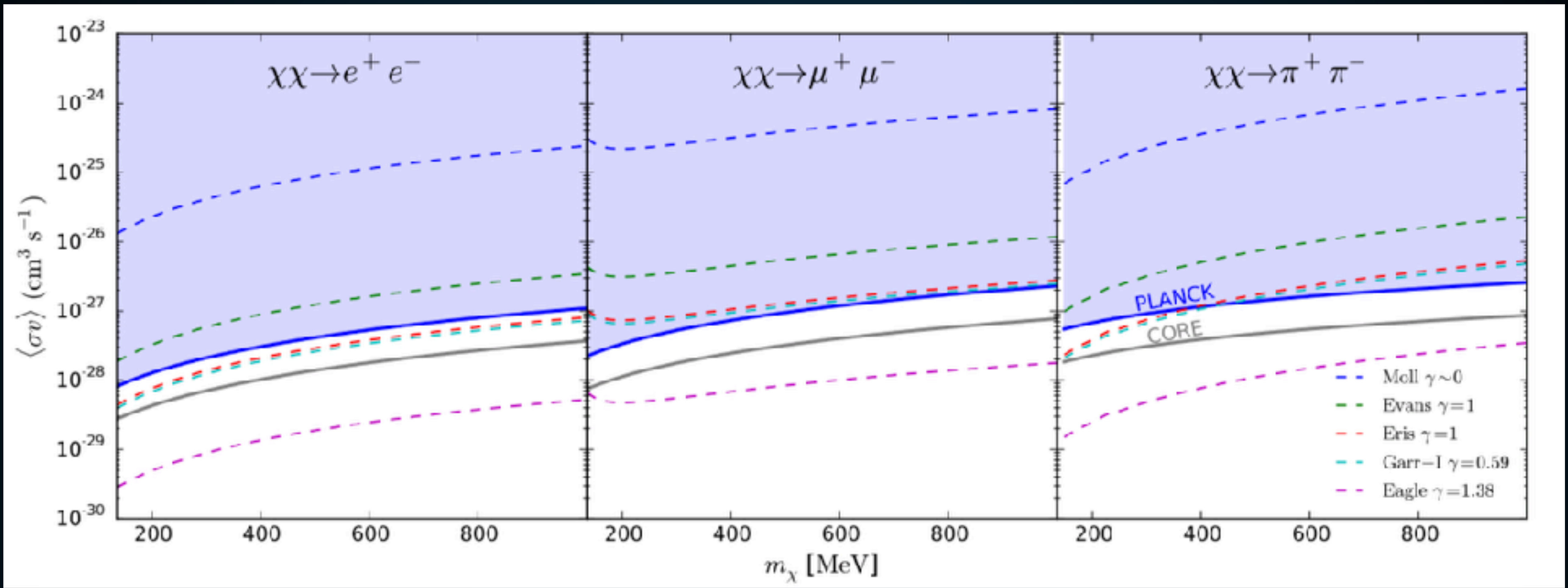
Gonzalez-Morales et al. (1705.00777)



- CMB constraints fall between 1x10^{-28} and 1x10^{-27} in the 0.1-1 GeV range.
- These constraints are likely to outperform future MeV gamma-ray experiments for annihilation to charged final states.

COMPARISON OF CMB AND GALACTIC CENTER GAMMA-RAY CONSTRAINTS

Gonzalez-Morales et al. (1705.00777)



- **CMB constraints are typically even more sensitive than annihilation in the Galactic center.**
- **There is allowable parameter space if the dark matter density near the galactic center is very peaked.**

A NEW PICTURE

Gonzalez-Morales et al. (1705.00777)

- So the combination of

(i) $\gamma\gamma$: Accessible at all energies. The final state is C-even.

(ii) $\gamma\pi^0$: Accessible for $\sqrt{s} > m_{\pi^0}$. The final state is C-odd.

(iii) $\pi^0\pi^0$: Accessible for $\sqrt{s} \geq 2m_{\pi^0}$. The final state is C-even.

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~~(v) $\bar{\ell}\ell$ ($\ell = e, \mu,$~~ ν): ~~Accessible for $\sqrt{s} \geq 2m_\ell$. The final state is either C-odd or is weak suppressed.~~

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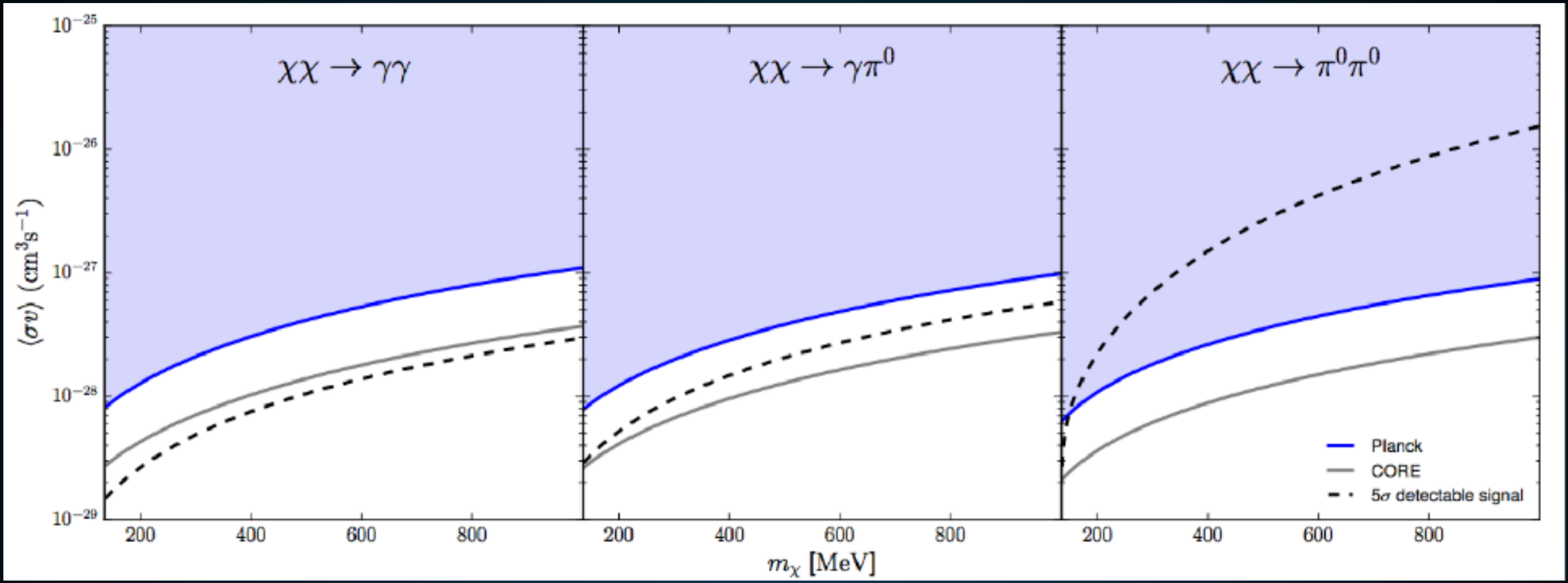
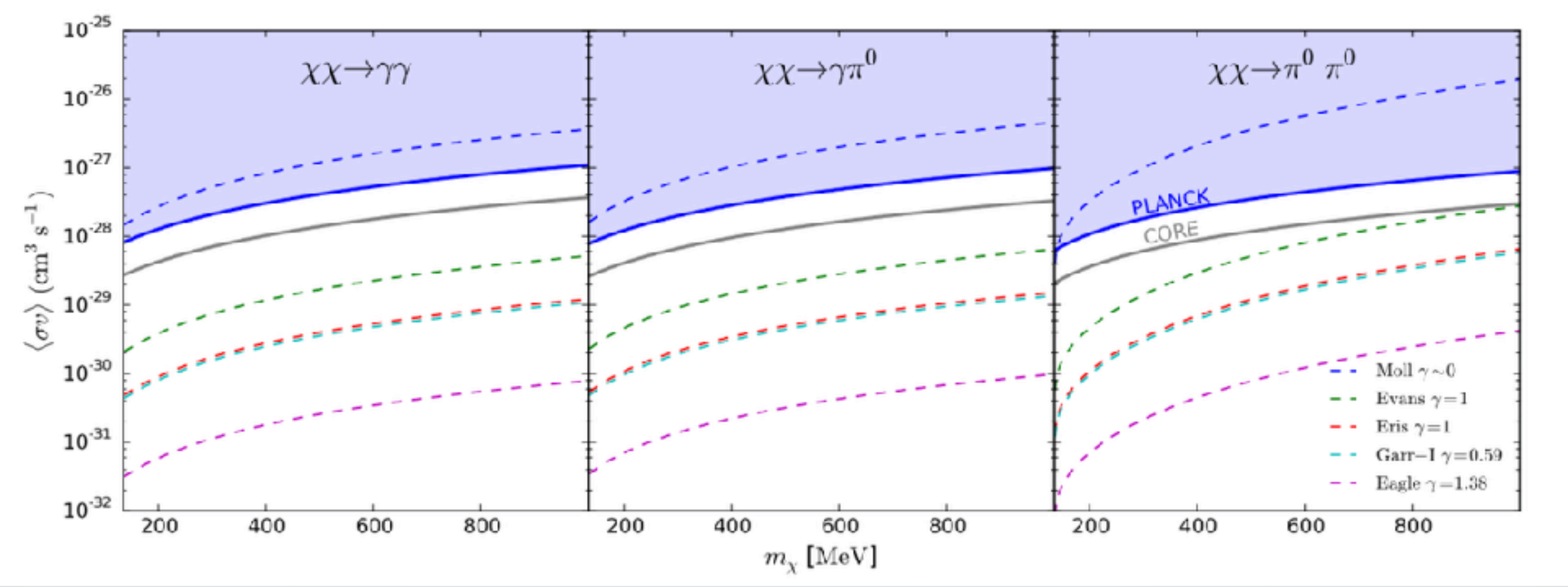


- In the case of annihilation to neutral particles:
  - The CMB constraints stay the same
  - The gamma-ray sensitivity improves drastically.
- Gamma-Rays are the most sensitive channel!

COMPARISON OF CMB AND GALACTIC CENTER GAMMA-RAY CONSTRAINTS

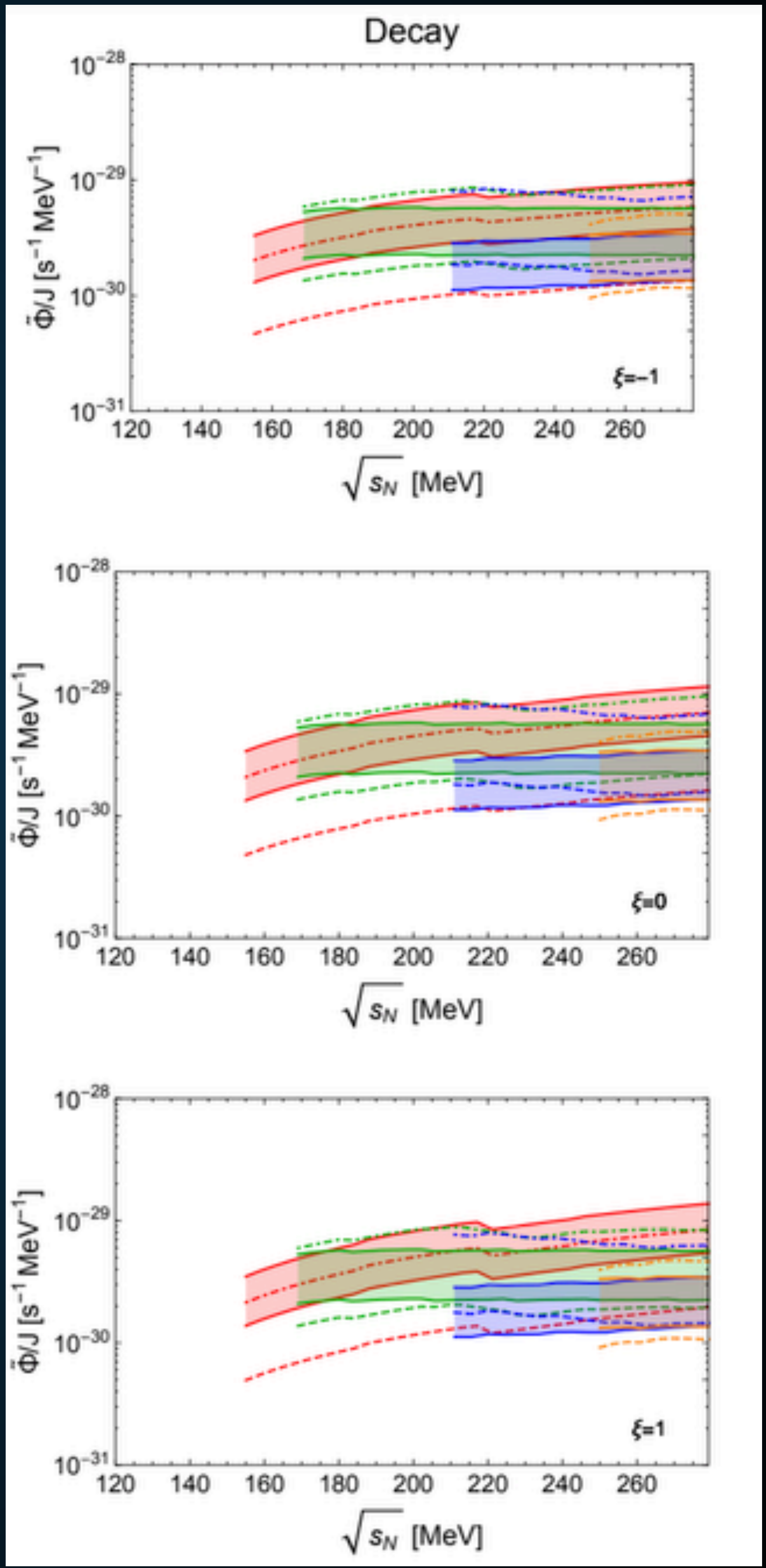
Gonzalez-Morales et al. (1705.00777)



- **In the Galactic center, nearly every density profile outperforms CMB constraints.**
- **Can potentially observe the same dark matter signal in two ROIs!**

DECAYING DARK MATTER IS, AS ALWAYS, REASONABLE

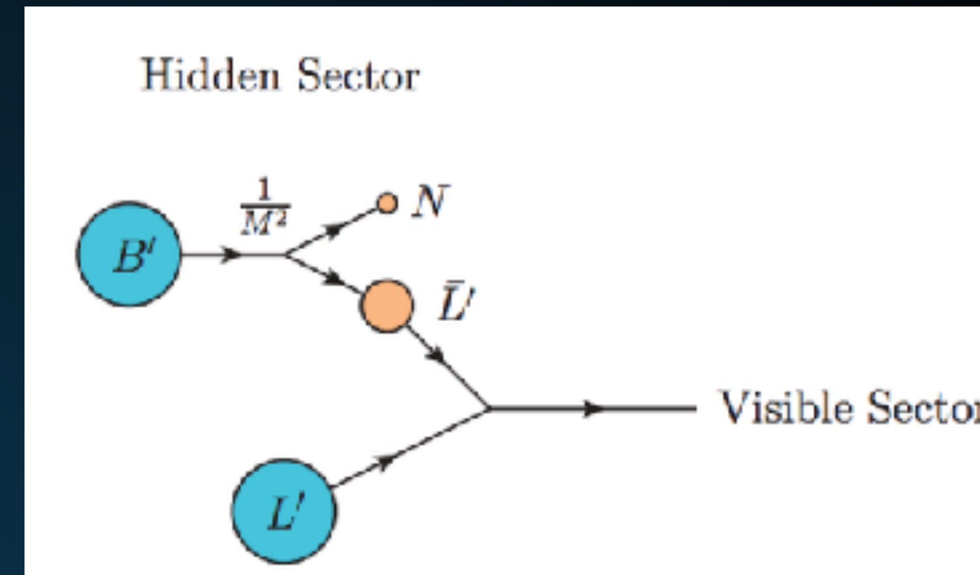
- **Dark Matter decay rate is not enhanced in the early universe.**
- **In general, the MeV scale of these models is not highly motivated (similar to GeV range).**
- **Analyzing these models will proceed similarly to GeV searches.**

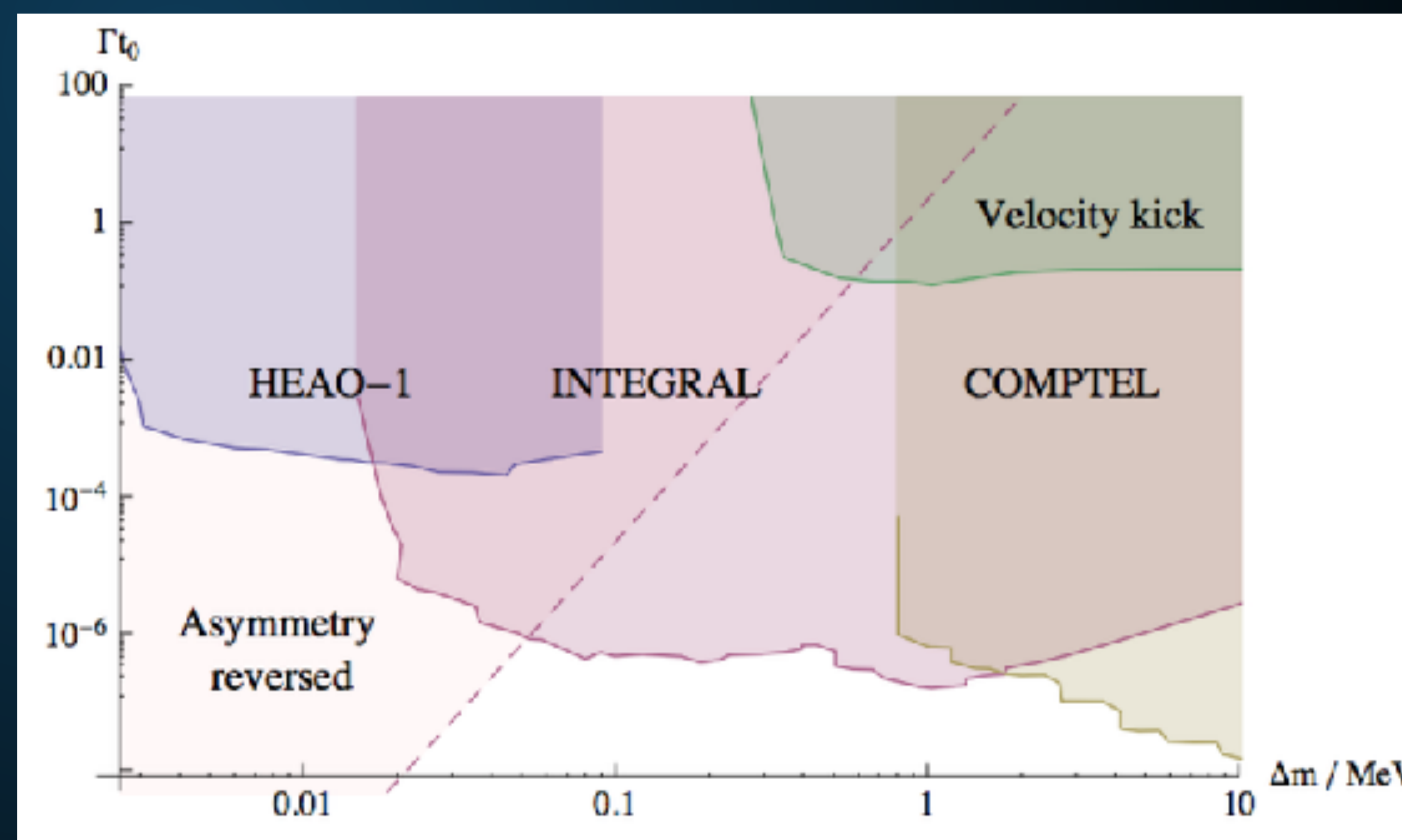


Boddy et al. (1606.07440)

MOREOVER, CAN DECAY AT LATE TIMES INTO ANNIHILATING COMPONENT

- Some well motivated models generate the dark matter asymmetrically, and then decay to the annihilating component.





- These models can naturally produce MeV emission.

Hardy et al. (1402.4500)

A NEW PICTURE

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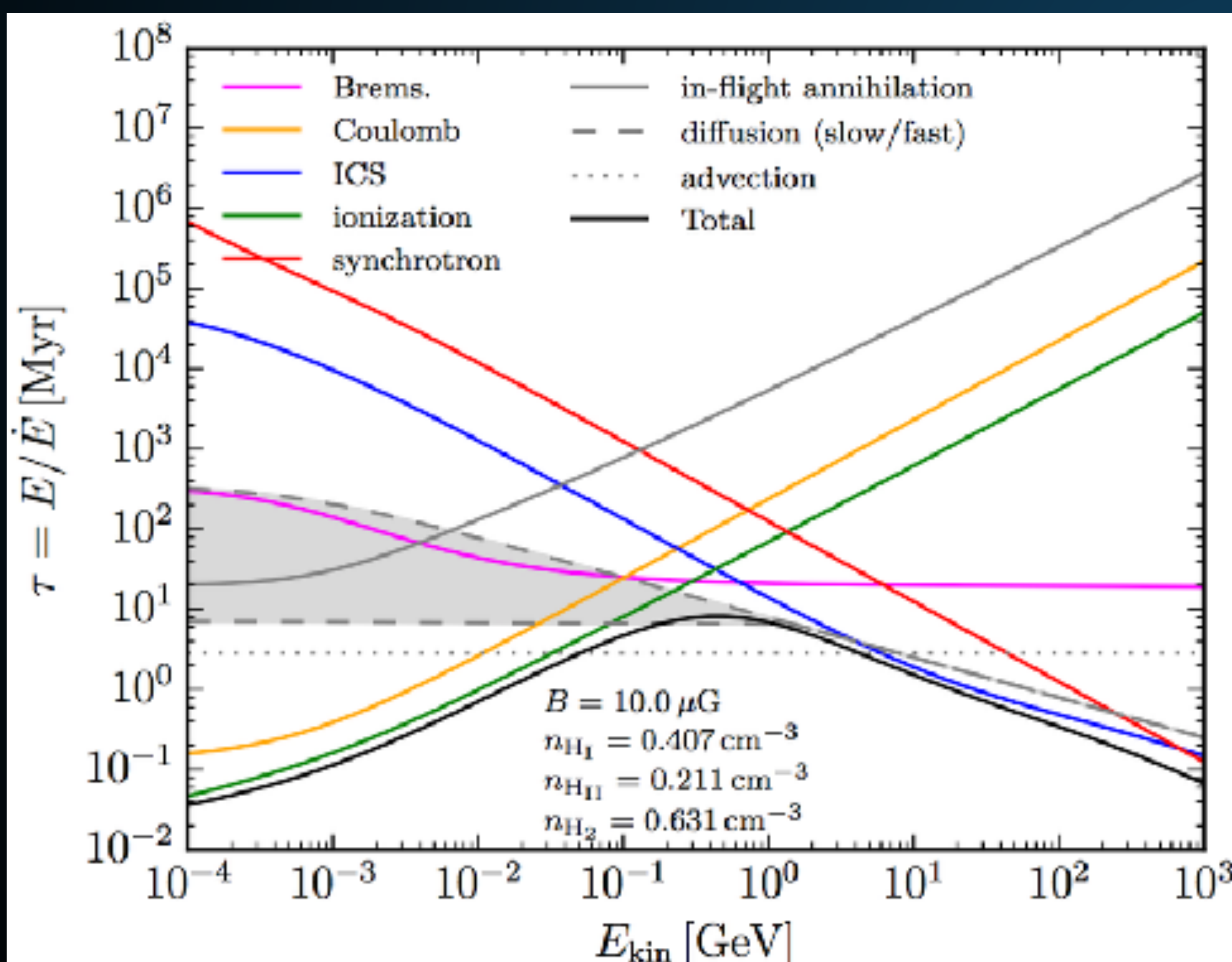
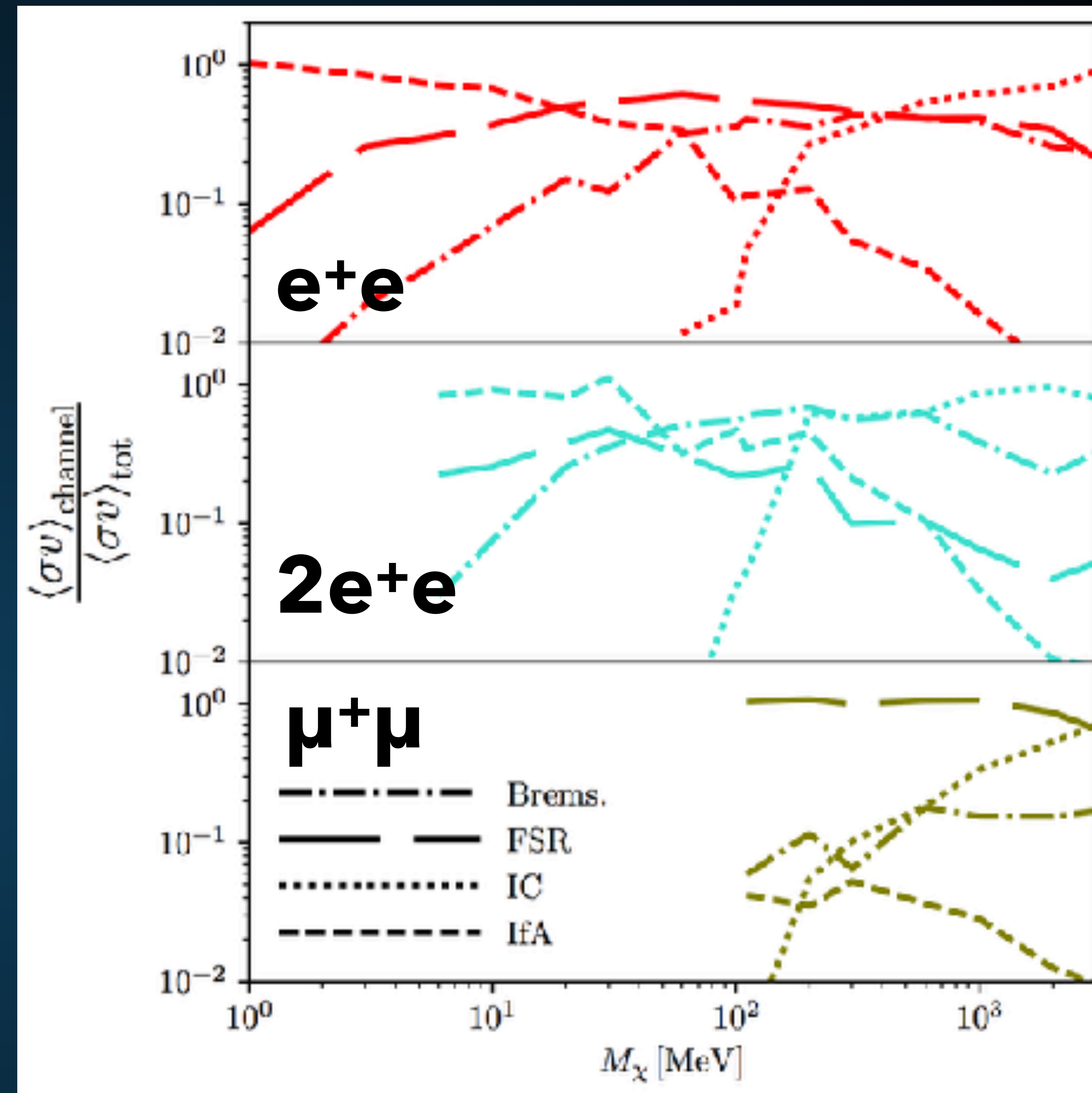
(v) $\bar{\ell}\ell$ ($\ell = e, \mu, \nu$): Accessible for $\sqrt{s} \geq 2m_\ell$. The final state is either C-odd or is weak suppressed.

- **In general - annihilation into uncharged states is better for gamma-ray observation.**

ANOTHER BENEFIT OF ANNIHILATION INTO UNCHARGED PARTICLES

- **If annihilation proceeds to charged particles, secondary emission becomes important.**





- **This signal will diffuse, complicating analyses.**
- **Must be taken into account.**

PARTICLE PHYSICS CONCLUSIONS

1.) Standard Thermal Electroweak WIMP largely excluded from gamma-ray detection in the MeV range

- Can still be thermal if interaction is not electroweak

- Some exceptions, like p-wave suppressed interactions which may be observable in the Galactic center.

2.) Never fear!

- There are many models for producing MeV dark matter!

- Many models will have unique signatures:

  * Harder to use a one-size fits all approach

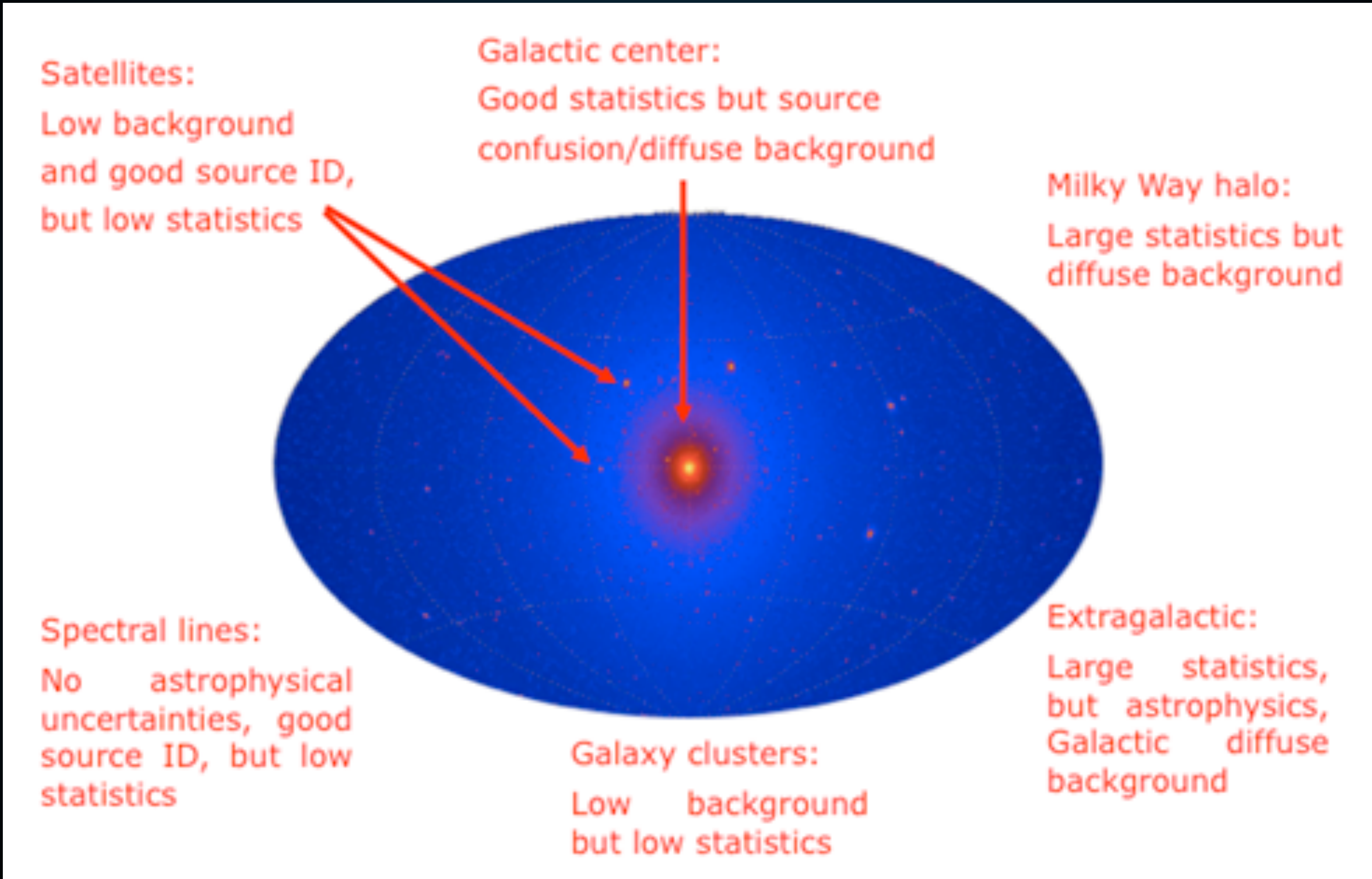
  * Easier to distinguish between models if you see something.

EVERYTHING WE KNOW ABOUT DARK MATTER

So, why look for dark matter in the MeV range?

New Techniques for looking at MeV dark matter!

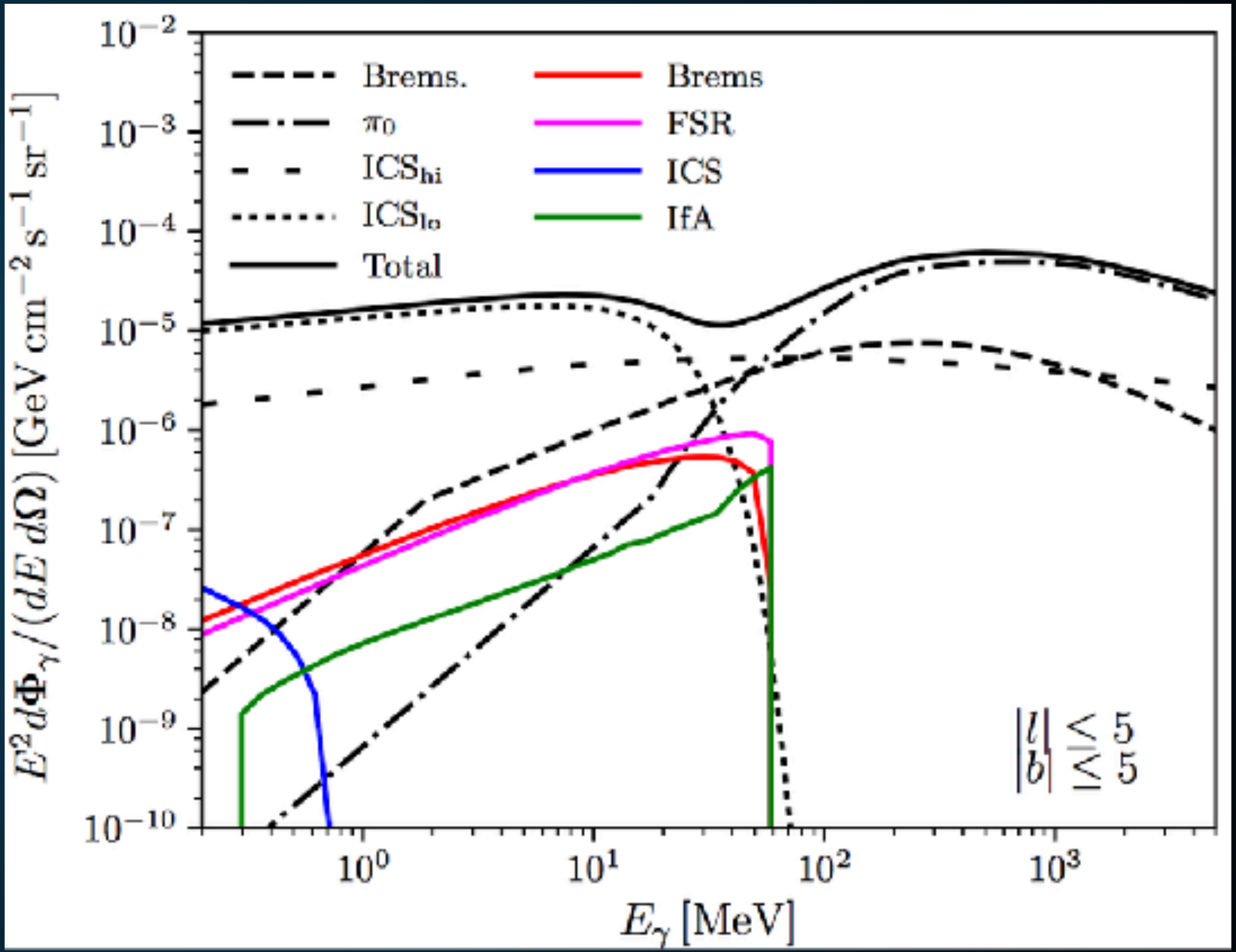
EVERYTHING WE KNOW ABOUT DARK MATTER



slide courtesy of KIPAC

THE ANNIHILATION SPECTRA WILL UNIVERSALLY BE HARD

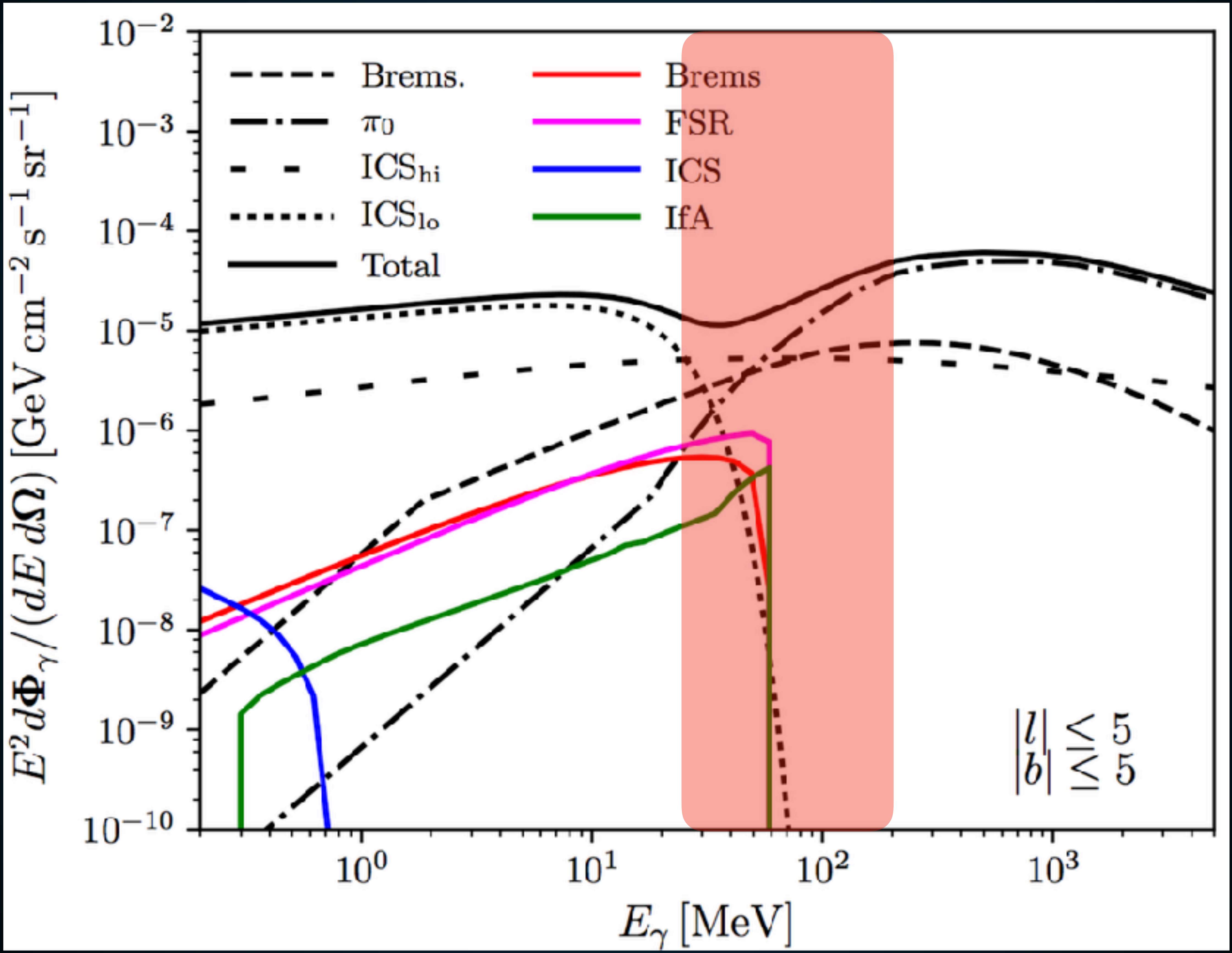
- Annihilation of 80 MeV DM -> e^+e^- produces gamma-rays primarily through final state radiation and bremsstrahlung.



- These spectra are brightest at the dark matter mass.

- Comparison of multiple targets becomes significantly easier at MeV energies - look for identical energy cuts!

WHAT ABOUT THE BACKGROUNDS?



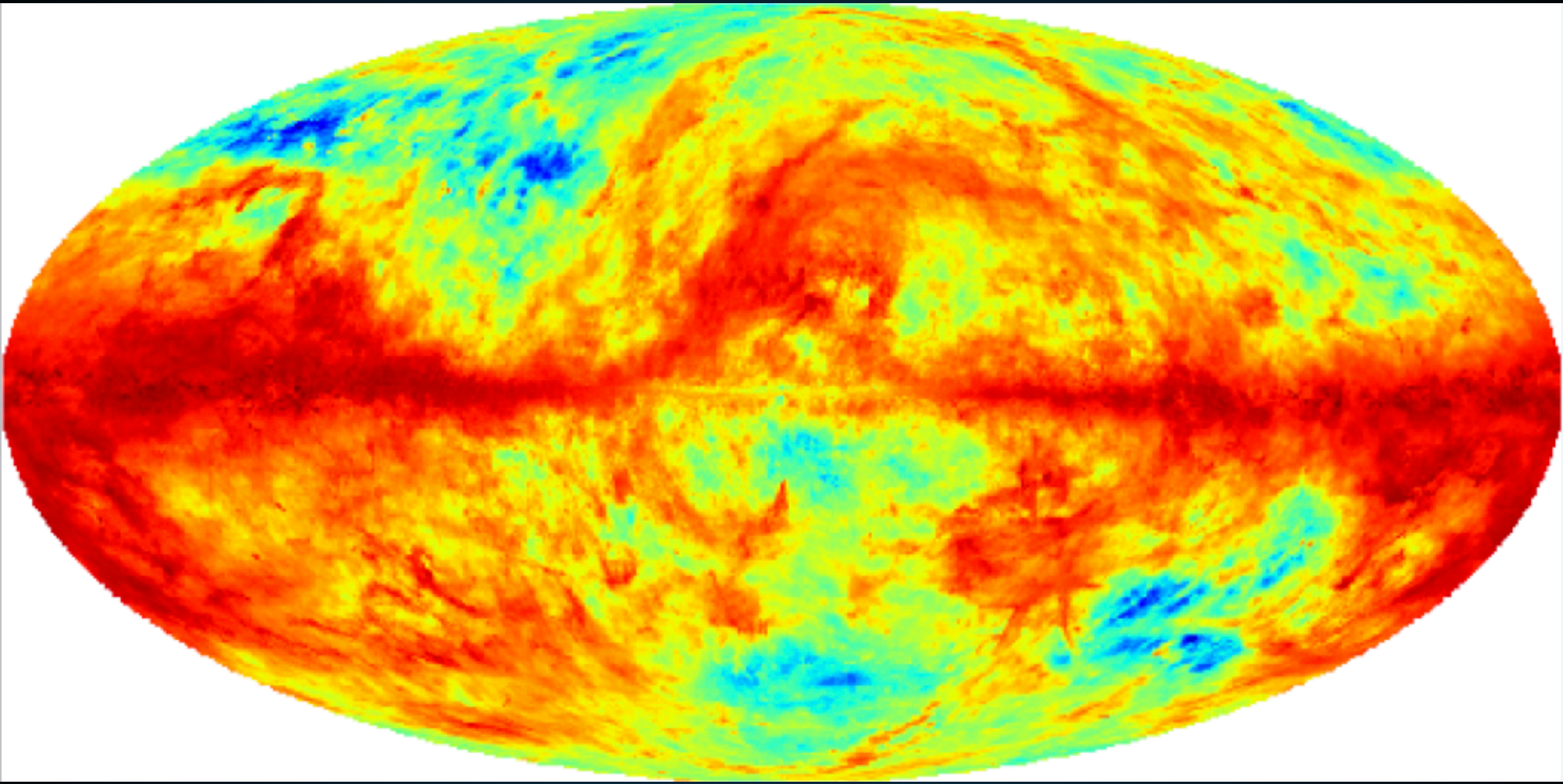
ADDITIONAL COMPLEXITIES IN BACKGROUND MODELING

$$D_{xx} = \beta D_0 \left(\frac{\rho}{4\,\mathrm{GV}} \right)^{\delta}$$

$$\begin{aligned} t^{p}_{\mathrm{pp}} &\simeq 3.1 \times 10^5\ \mathrm{yr} \left(\frac{n_H}{120\ \mathrm{cm}^{-3}} \right)^{-1}, \\ t^{e}_{\mathrm{inztn}} &\simeq 6.7 \times 10^5\ \mathrm{yr} \left(\frac{E}{\mathrm{GeV}} \right) \left(\frac{n_H}{120\ \mathrm{cm}^{-3}} \right)^{-1}, \\ t^{e}_{\mathrm{brems}} &\simeq 2.4 \times 10^5\ \mathrm{yr} \left(\frac{n_H}{120\ \mathrm{cm}^{-3}} \right)^{-1}, \end{aligned}$$

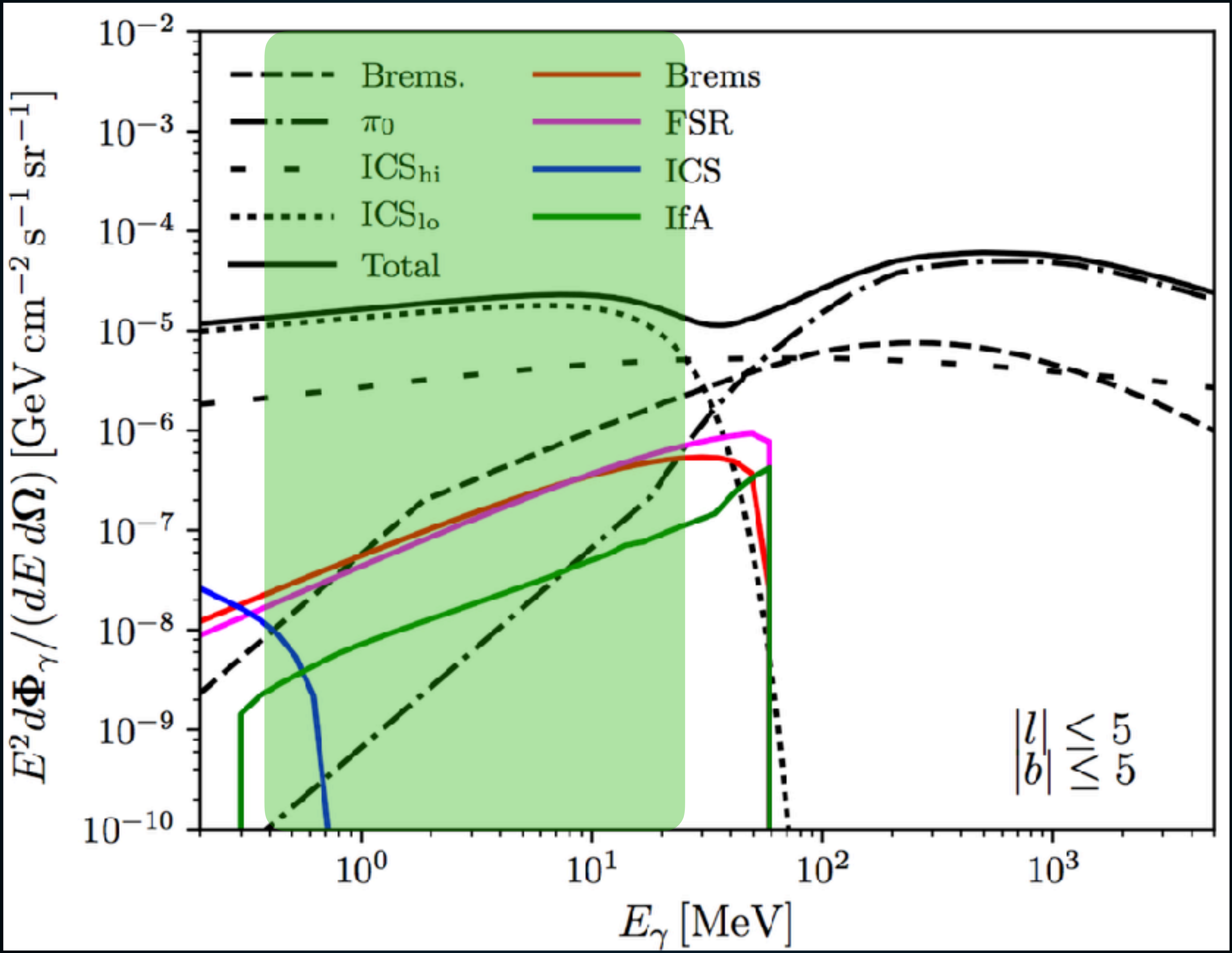
- **Assuming Kolmogorov Diffusion in the MeV regime:**
  - **A ~10 GeV proton which produces a 1 GeV gamma-ray travels approximately: 2.8 kpc.**
  - **A 100 MeV electron which produces a ~1-10 MeV gamma-ray travels approximately: 0.5 kpc.**
- **MeV diffuse emission will be more sensitive to local injection around 100 MeV.**

ADDITIONAL COMPLEXITIES IN BACKGROUND MODELING

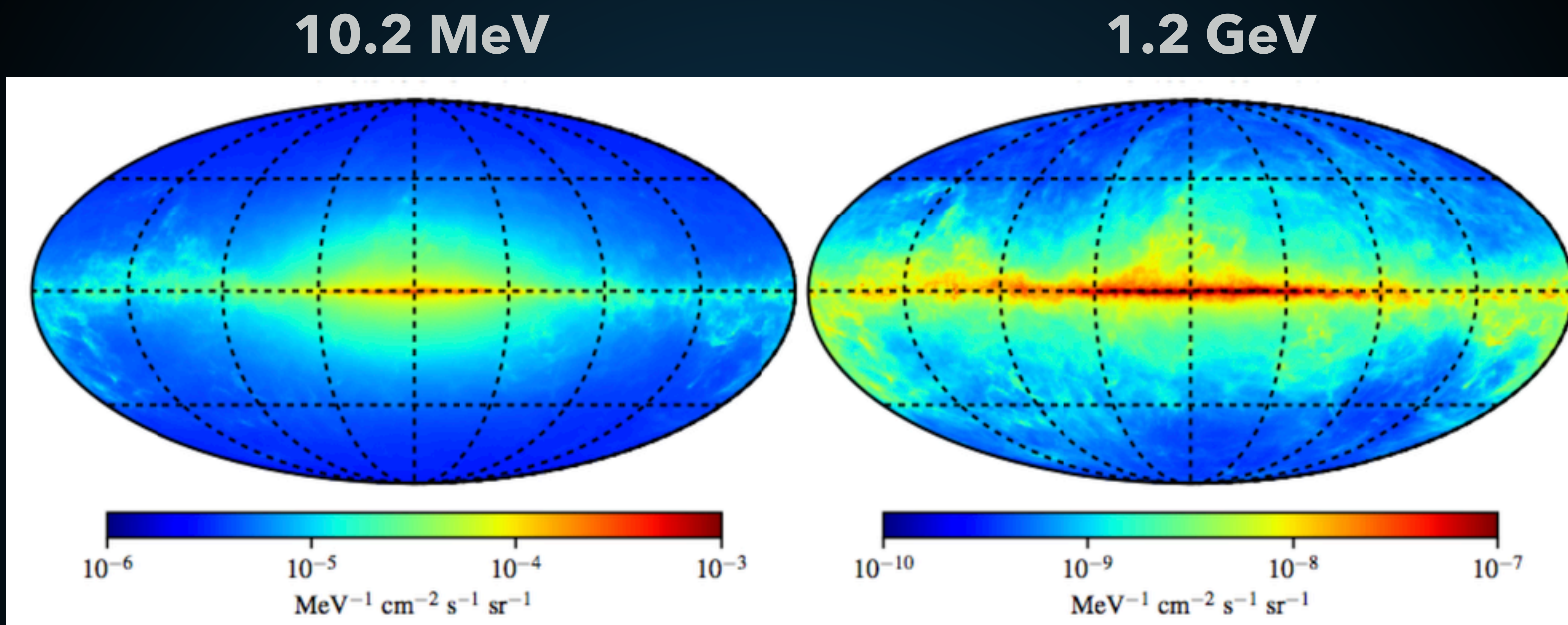


- In general models are not yet equipped for this detail.

WHAT ABOUT THE BACKGROUNDS?



WHAT ABOUT THE BACKGROUNDS?



Porter et al. (1708.00816)

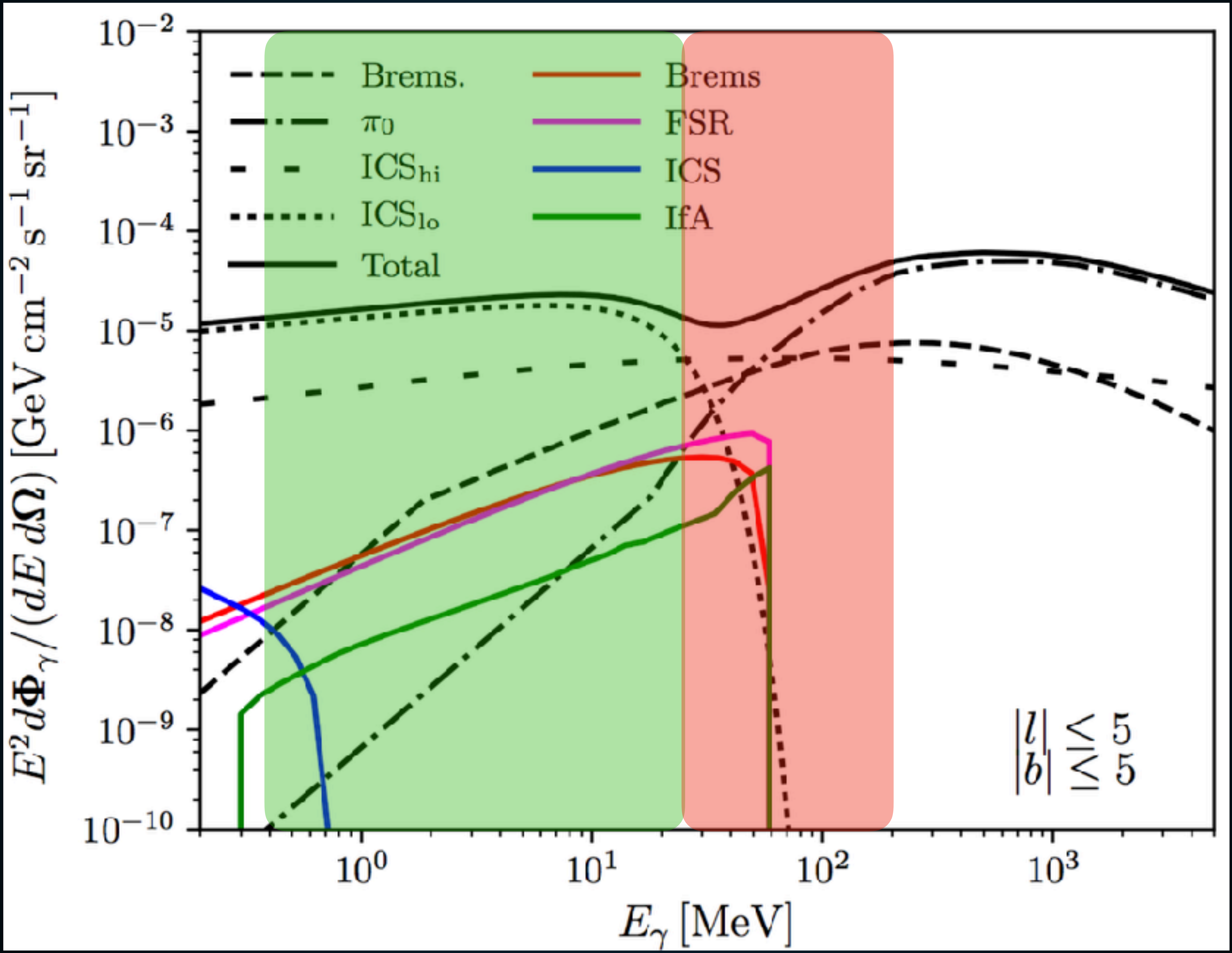
- The ISRF energy density is extremely smooth
  - Most of the substructure washes away, and you get very smooth background gamma-ray emission.

WHAT ABOUT THE BACKGROUNDS?

- Propagation in 10 Myr at 100 GeV:
  - Diffusion: ~2.1 kpc
  - Convection (20 km/s) - ~100 pc

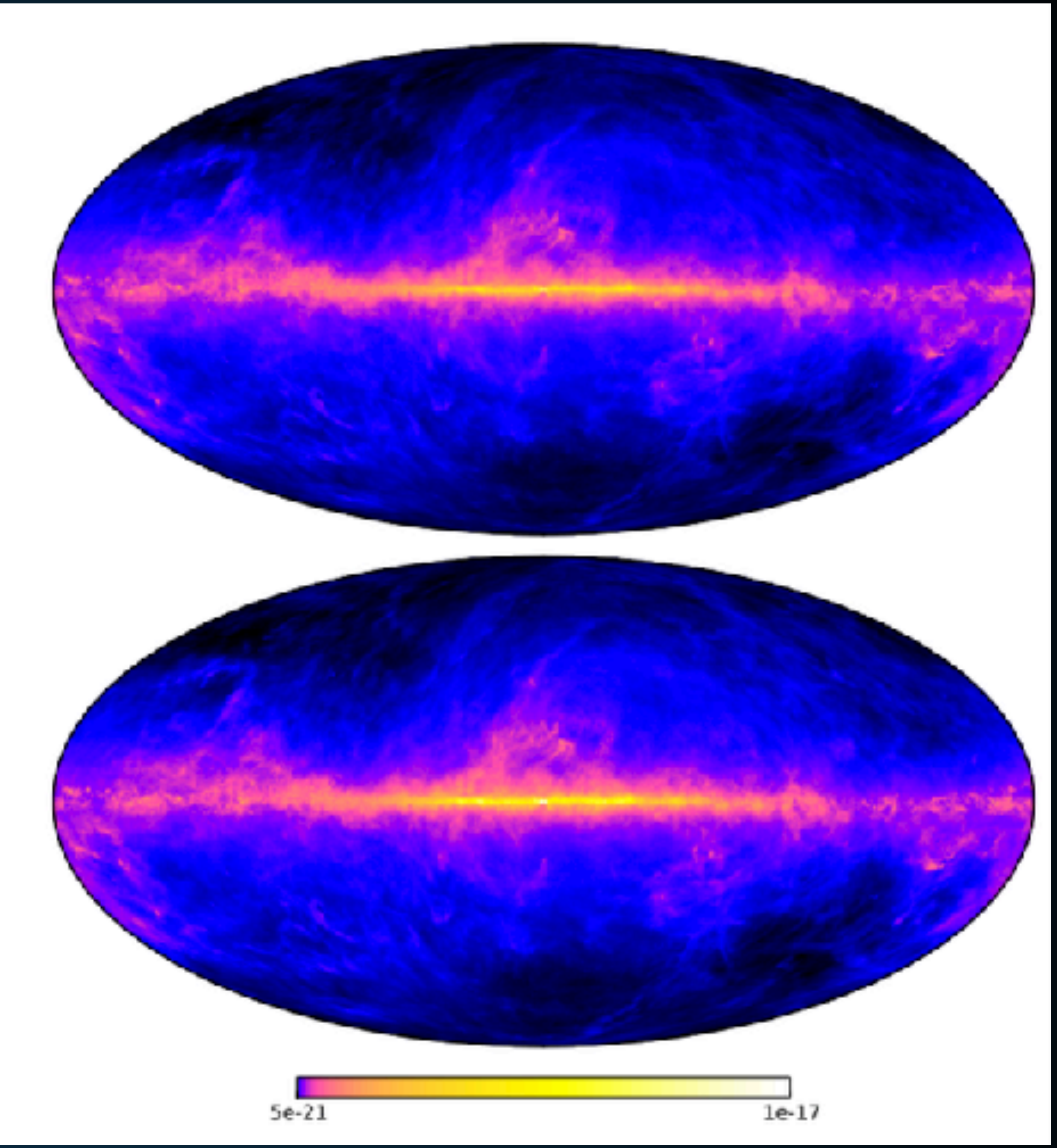
- Propagation in 10 Myr at 10 MeV:
  - Diffusion: ~466 pc
  - Convection (20 km/s) - ~200 pc

DIFFICULTIES IN DIFFUSE BACKGROUND MODELING



OPPORTUNITIES IN DIFFUSE BACKGROUND MODELING!

- The MeV sky might shed significant new light on galactic cosmic-ray diffusion!
- We will soon have a diffuse sky from ~1 MeV to ~100 TeV (HAWC). Exciting potential for significant advancement.



- Cosmic-Ray Propagation Codes are rising to the challenge (e.g. PICARD; 1701.07285).

LINKING THIS BACK TO DARK MATTER

- Direct gamma-rays from dark matter annihilation will have a profile that is relatively energy independent.
- In the GeV range, excesses at 10 GeV are also likely to be excesses at 500 MeV
    - same production Mechanism
- Multi-wavelength models may provide more systematic cross-checks in the MeV regime.

EVERYTHING WE KNOW ABOUT DARK MATTER

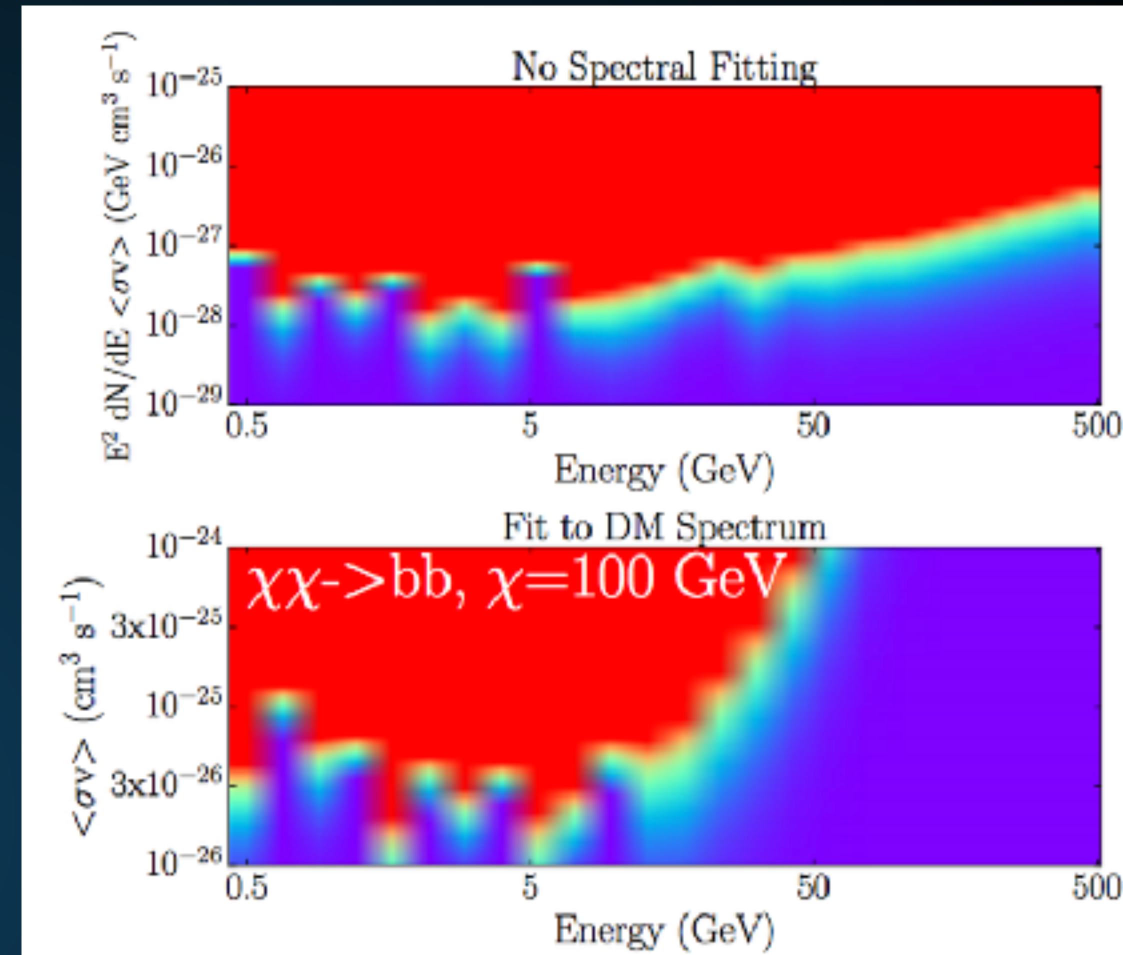
MeV **GeV** **TeV**

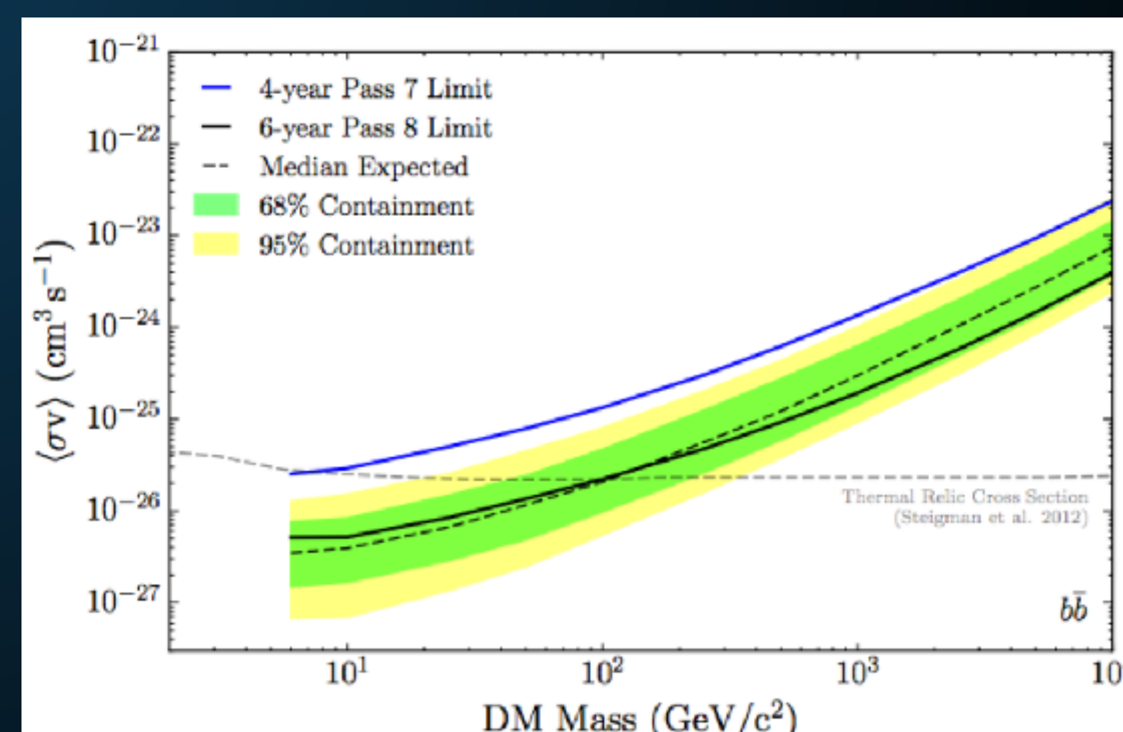
So, why look for dark matter in the MeV range?

Does the MeV lamppost connect to the GeV range?

COMPLEMENTARITY BETWEEN AMEGO AND FERMI

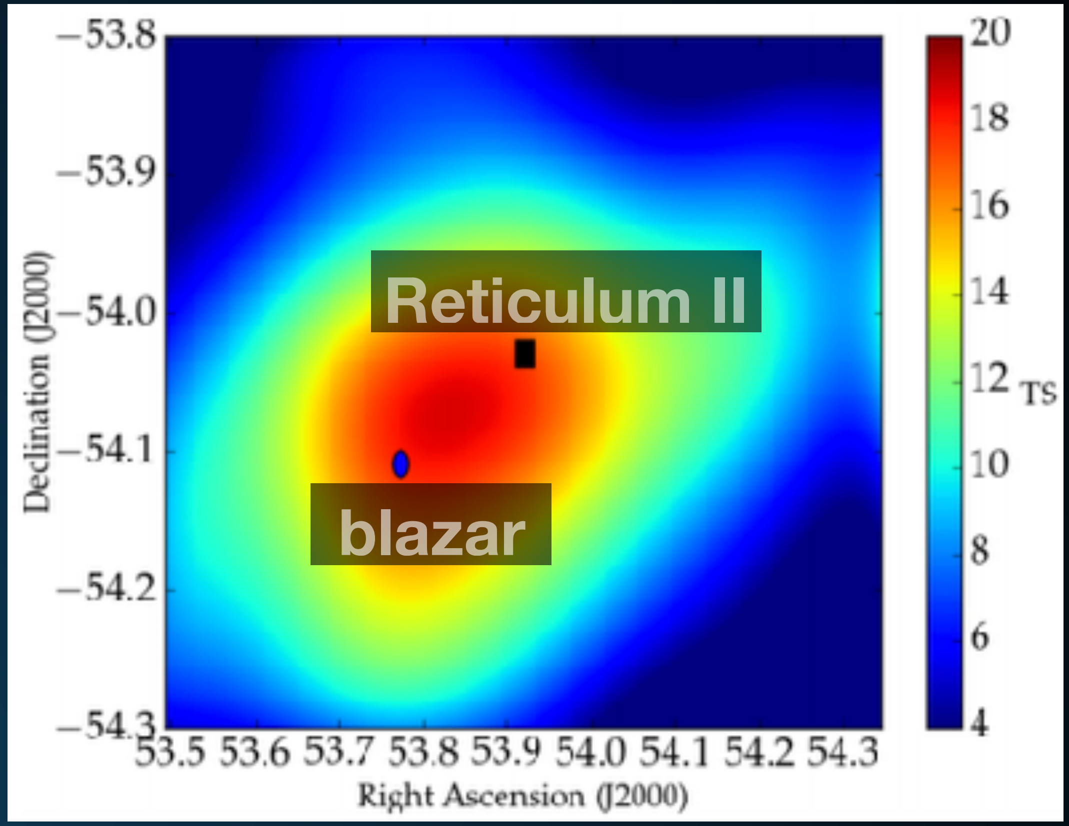
- Fermi-LAT Constraints on 100 GeV dark matter
    - 1-5 GeV most sensitive
- For 5-10 GeV dark matter?
    - Fermi already shows signs of lost sensitivity.
    - AMEGO can compete in this range of “standard” dark matter.
    - Interesting range due to asymmetries!



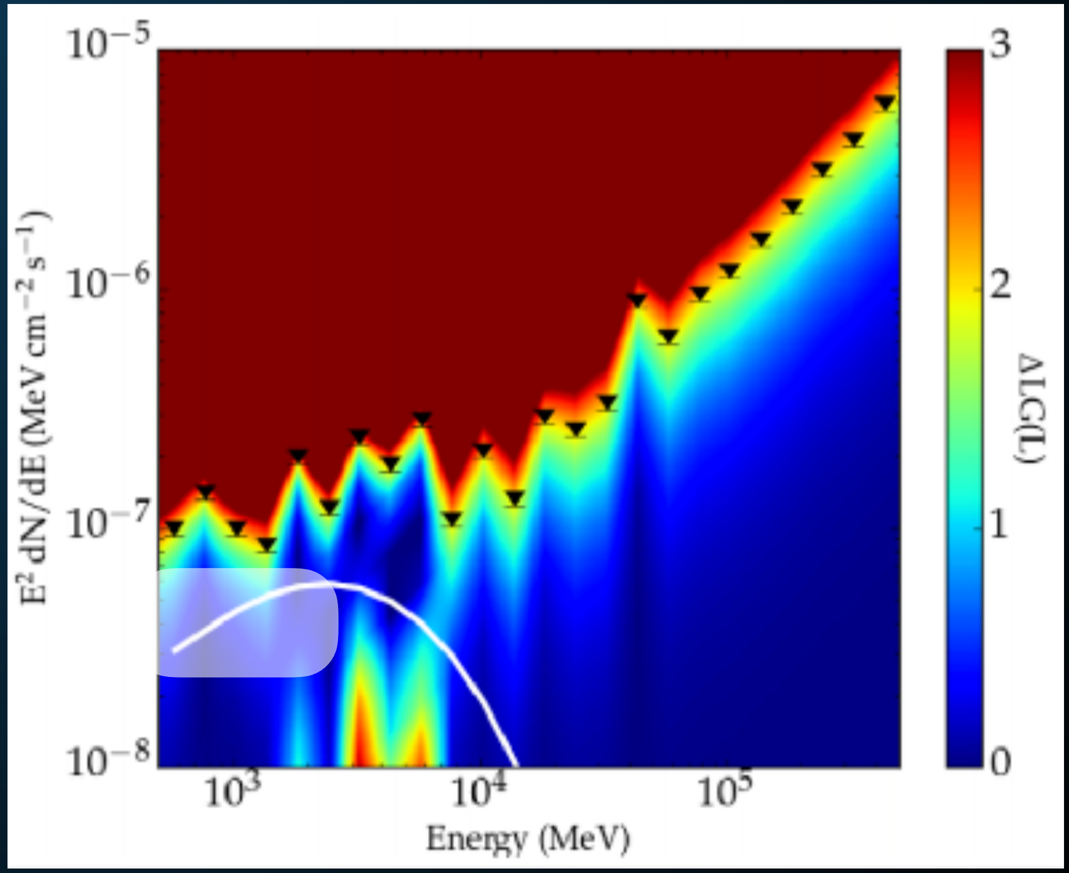


COMPLEMENTARITY BETWEEN AMEGO AND FERMI

- **Should not forget the capability of MeV instrumentation to solve current uncertainties from Fermi-LAT observations.**



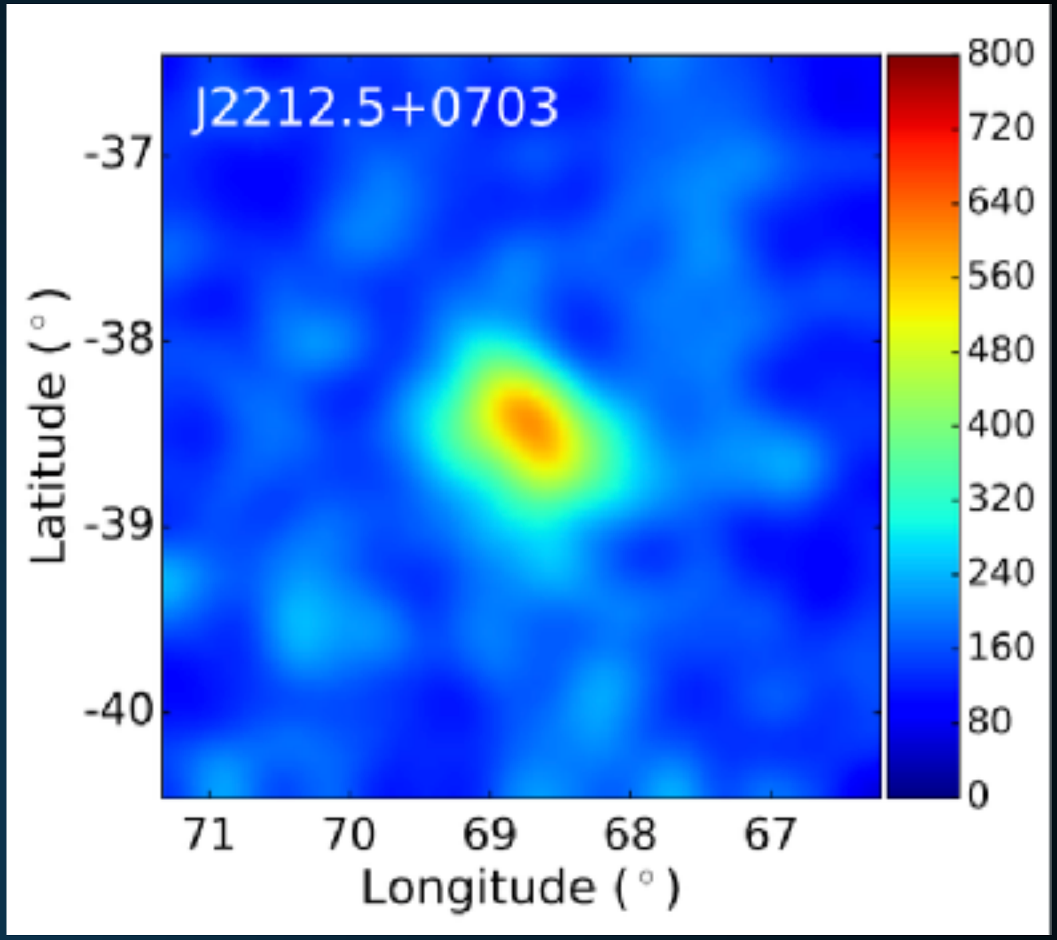
- **The separation of ~10-100 GeV DM from background (including π^0-decay and blazars) depends sensitively on the strength of ~100 MeV gamma-ray limits.**

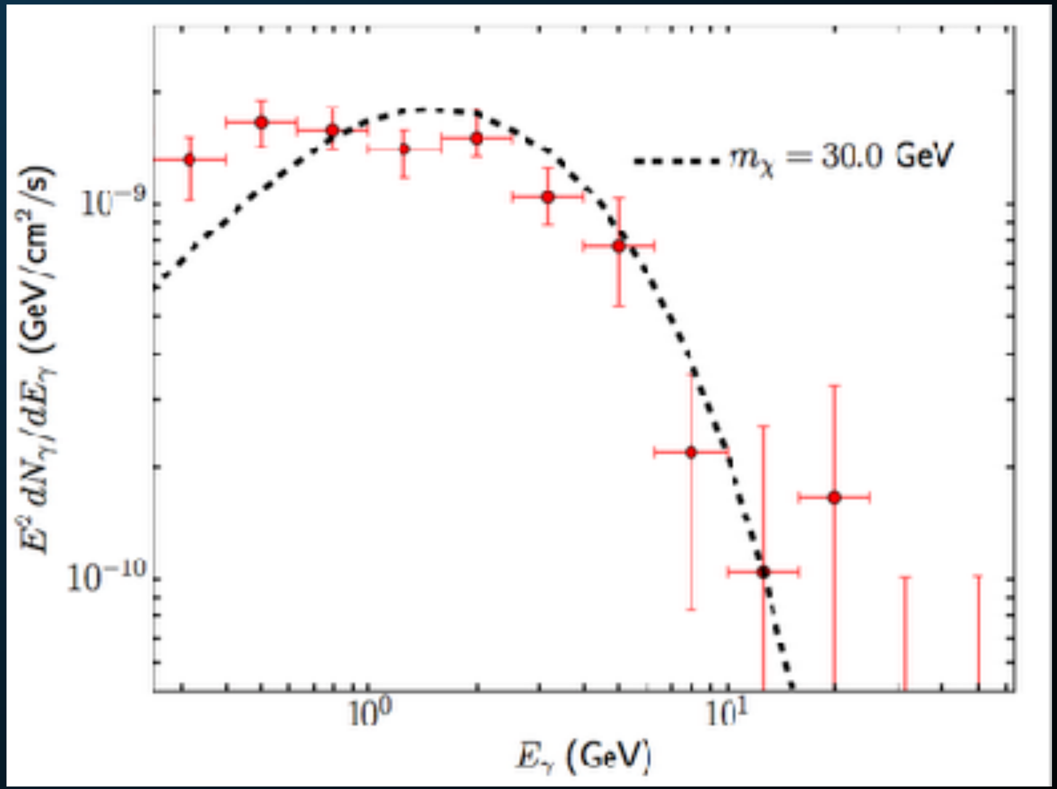


Hooper & TL (1503.06209)

COMPLEMENTARITY BETWEEN AMEGO AND FERMI

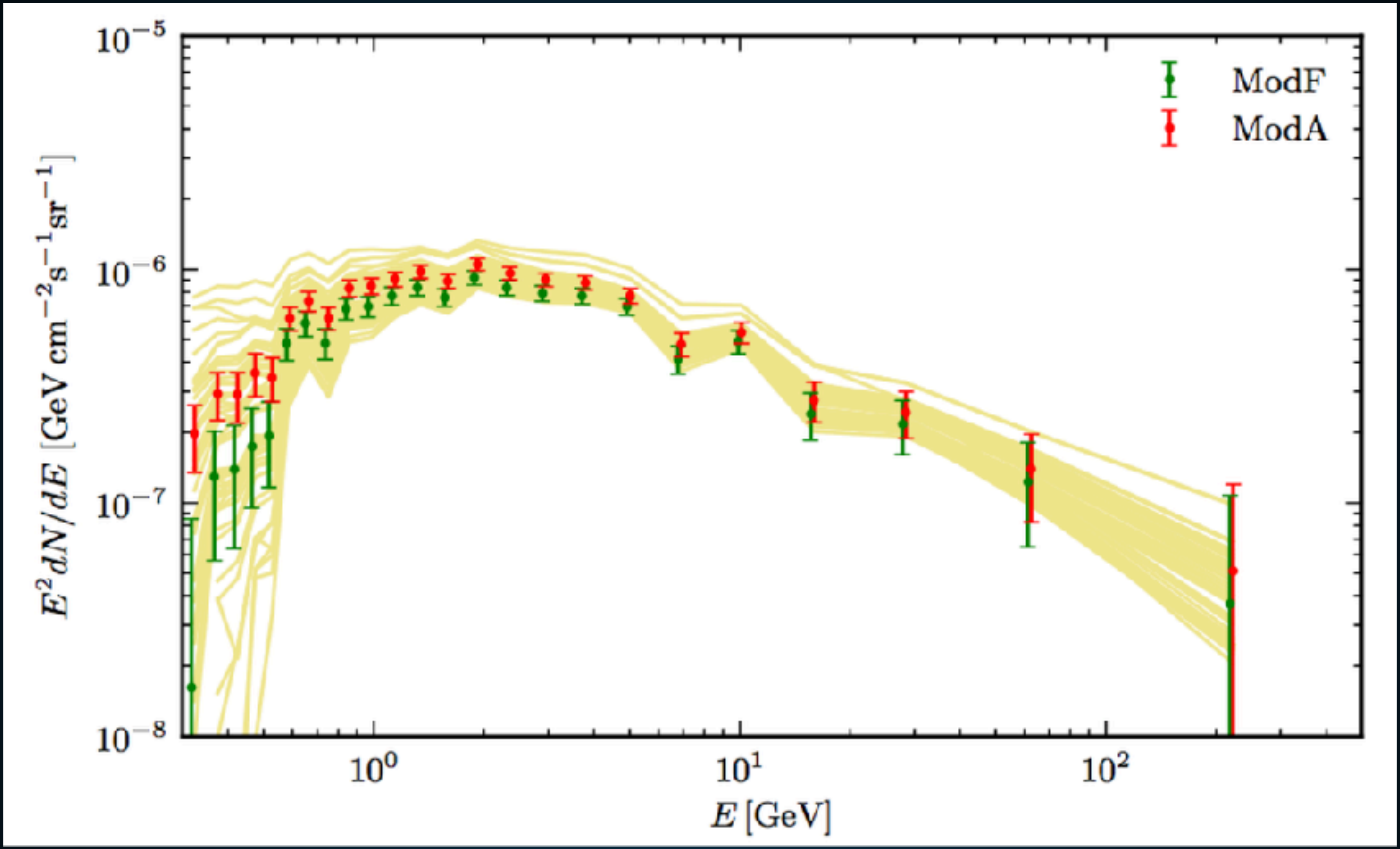
- Another example is the observation of spatial extension in unassociated Fermi-LAT sources
    - In this scenario, improved angular resolution at ~100 MeV is particularly important.
- Because many of these sources are bright, instruments like AMEGO should have plenty of sensitivity.





Bertoni, Hooper & TL (1602.07303)

COMPLEMENTARITY BETWEEN AMEGO AND FERMI

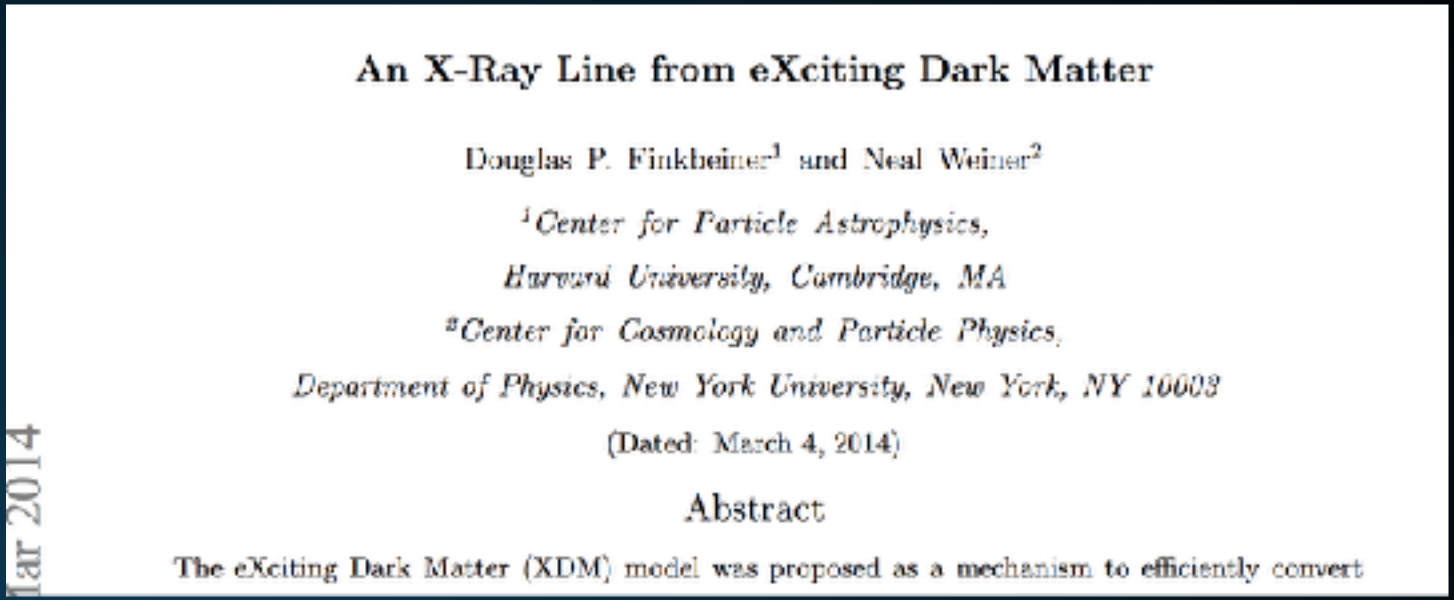


- synergy with radio telescopes, dependence on leptonic final states

Calore et al. (1409.0042)

COMPLEMENTARITY WITH TEV DARK MATTER

- **Exciting dark matter is another natural model for MeV instruments to investigate.**



An X-Ray Line from eXciting Dark Matter

Douglas P. Finkbeiner[1] and Neal Weiner[2]

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(Dated: March 4, 2014)

Abstract

The eXciting Dark Matter (XDM) model was proposed as a mechanism to efficiently convert

- **For many TeV -> PeV dark matter sectors, the momentum transfer in a dark matter scattering collision is in the keV to MeV range.**
  - **Gamma-Ray Morphology will track dark matter mass and rotation velocity.**
- **MeV sensitivity is complementary for known excesses (e.g. PAMELA).**

CONCLUSION - PART 1

1.) Current dark matter limits in the MeV range are significantly lacking.

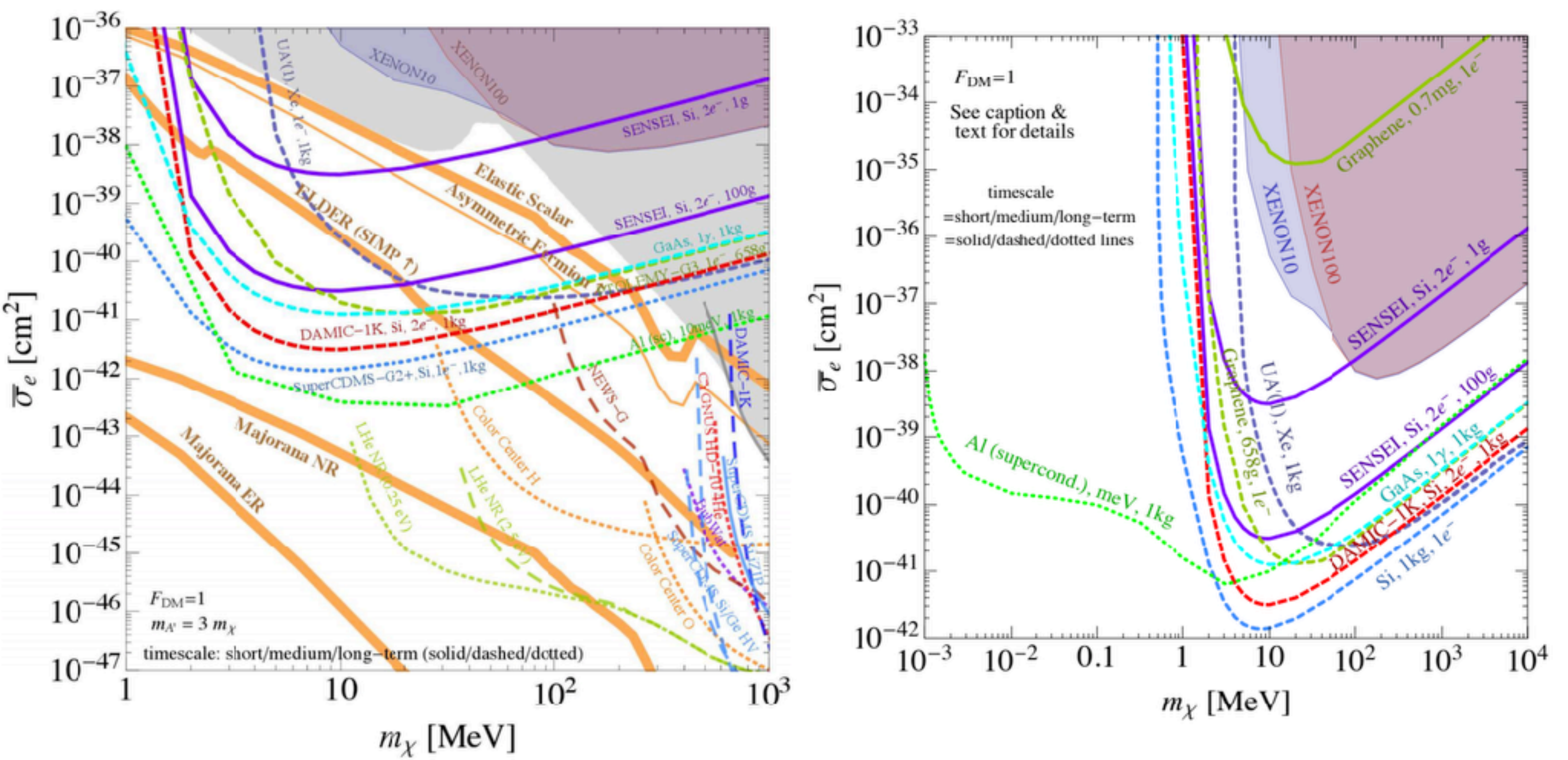
2.) Dark Matter model building is not as straightforward in the MeV range, compared to GeV energies.

- a.) More diversity in models -> more diversity in signals.
- b.) More diversity in models -> more diversity in techniques.

3.) MeV sensitivity is key to unlock the full power of Fermi in the GeV range.

THE MEV SCALE - A RANGE OF POSSIBILITIES!

- The next decade is likely to include a significant push to MeV energies.

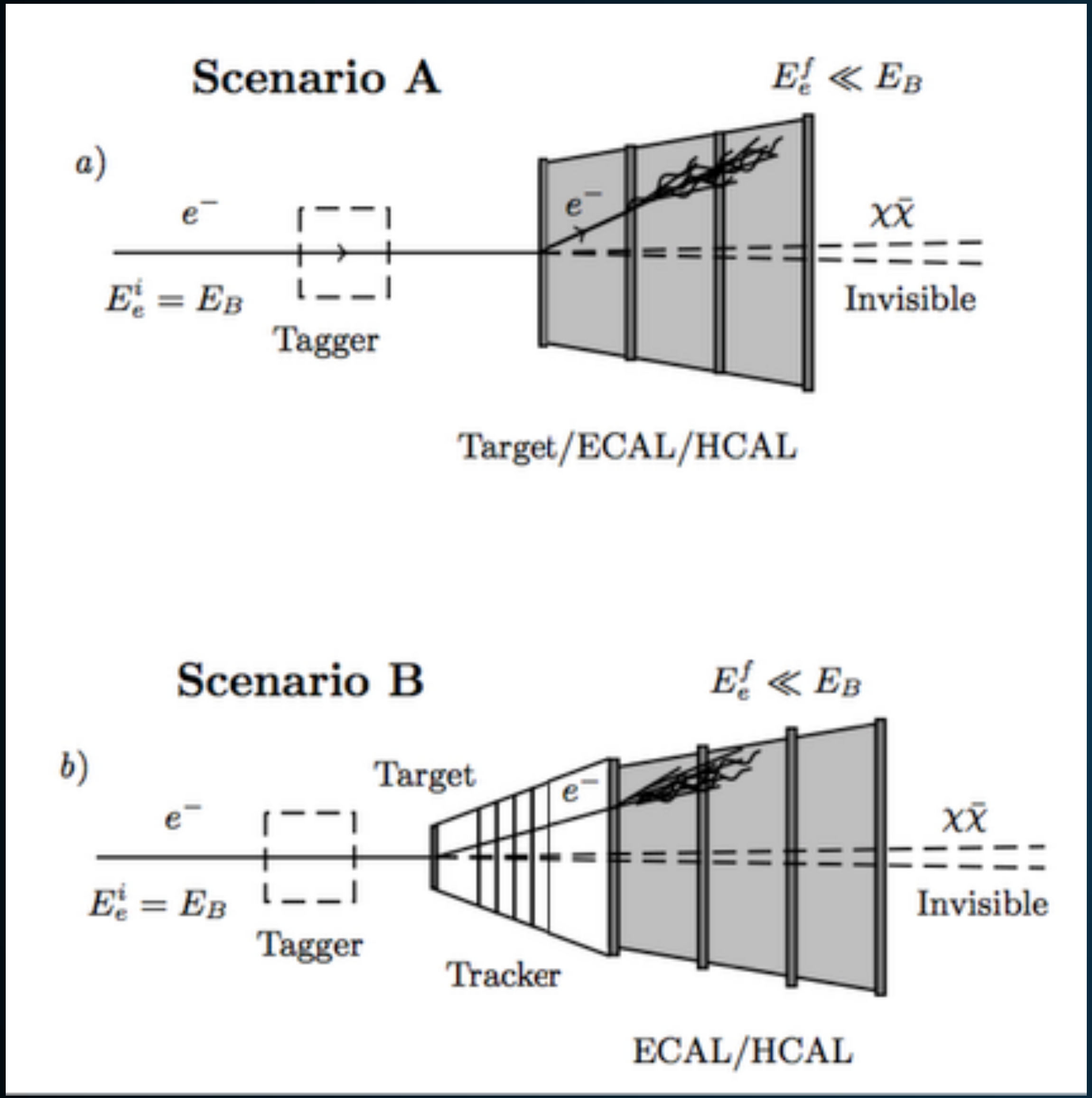


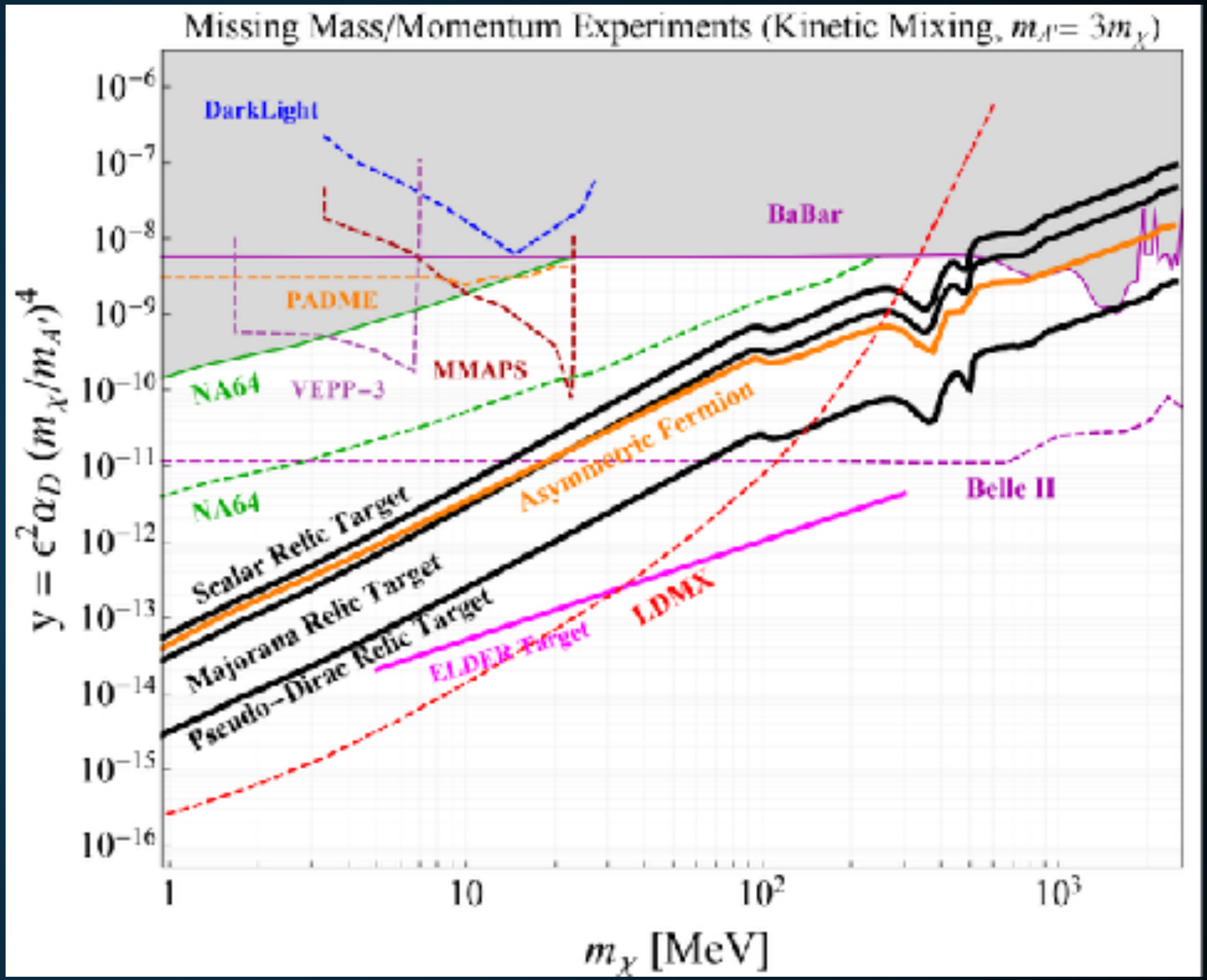
Cosmic Visions Whitepaper

Direct Detection will utilize electron recoils and superconductors.

THE MEV SCALE - A WORLD OF POSSIBILITIES!

- The next decade is likely to include a significant push to MeV energies.

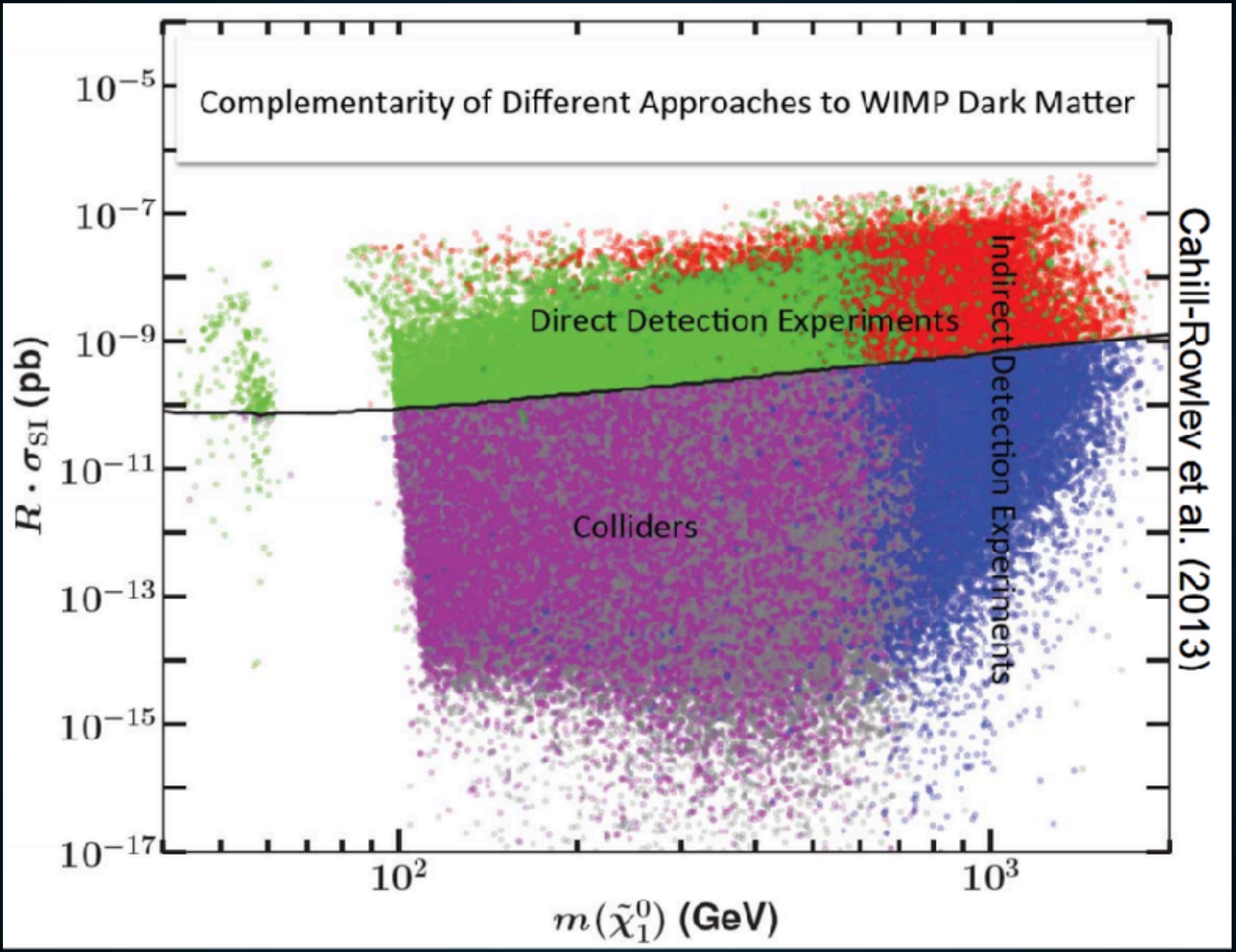




Izaguirre et al. (1411.1404)

Fixed-target experiments can make colliders significantly more sensitive to MeV-scale dark matter

THE MEV SCALE - A RANGE OF POSSIBILITIES!



- **This vision is obtainable at MeV energies!**