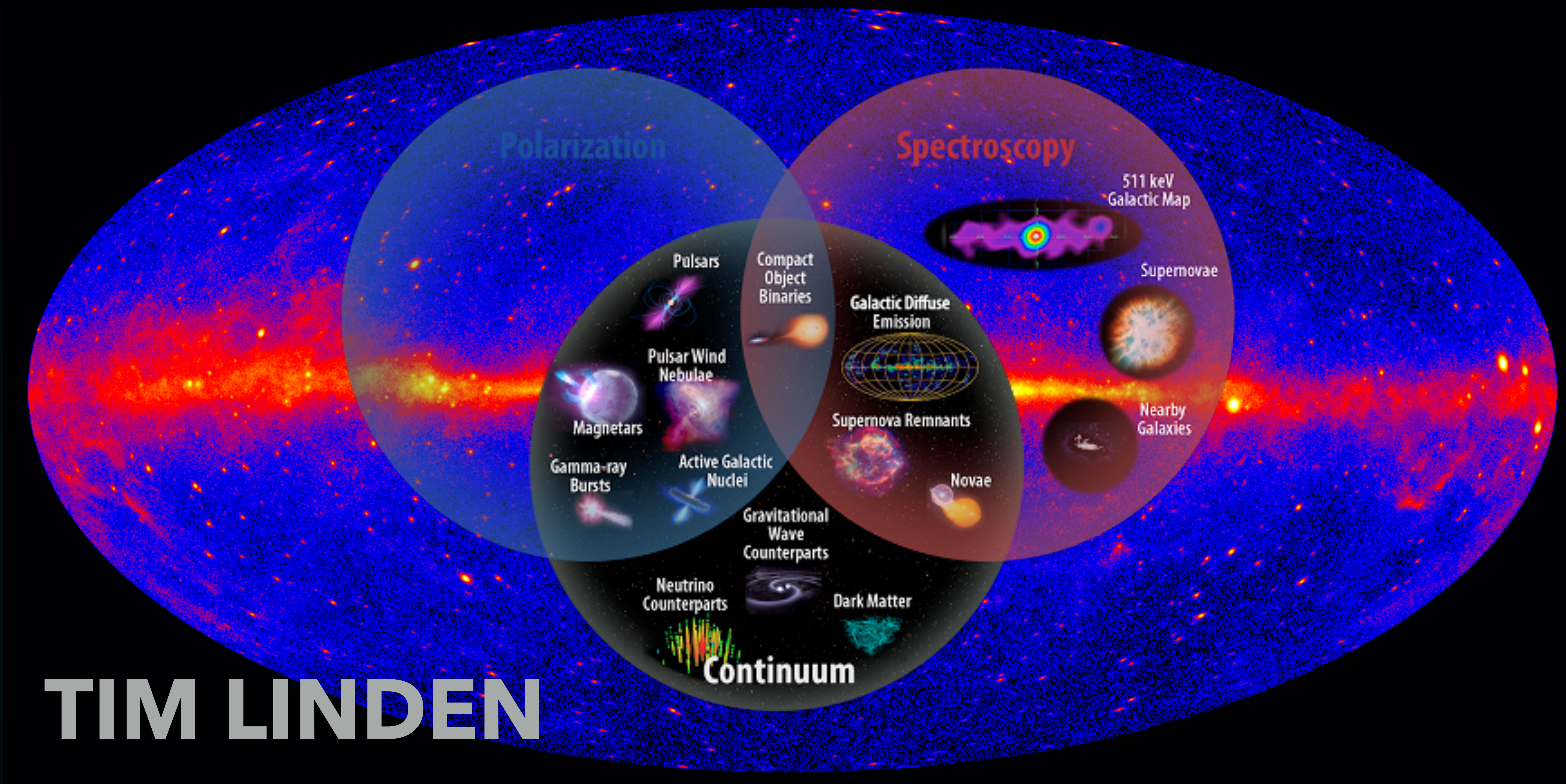




TIM LINDEN


# SEARCHING FOR DARK MATTER IN THE MEV SKY

American Physical Society April Meeting

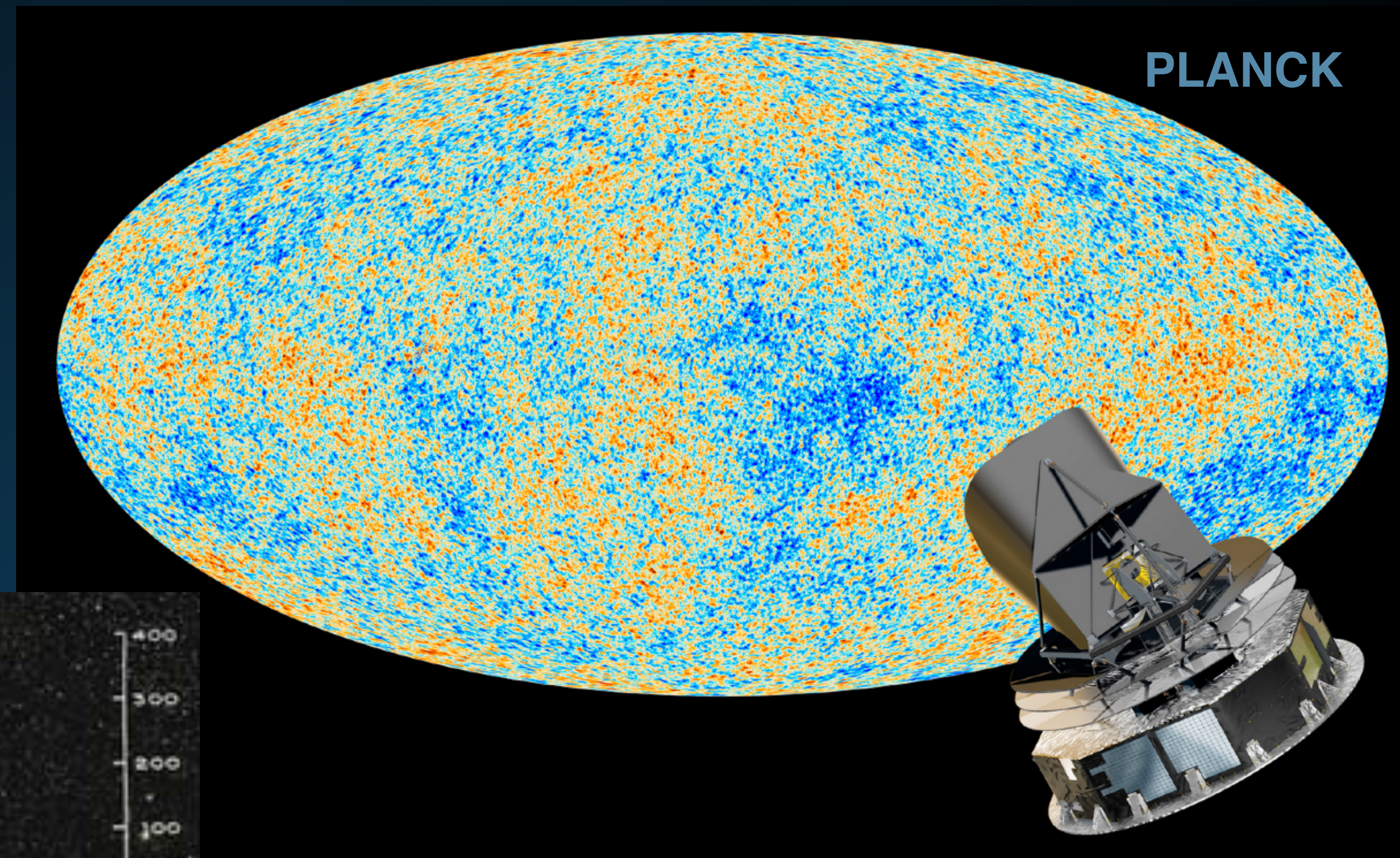
April 15, 2018


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





$10^{-25}$ GeV

$\sigma_X > R_{UFD}$

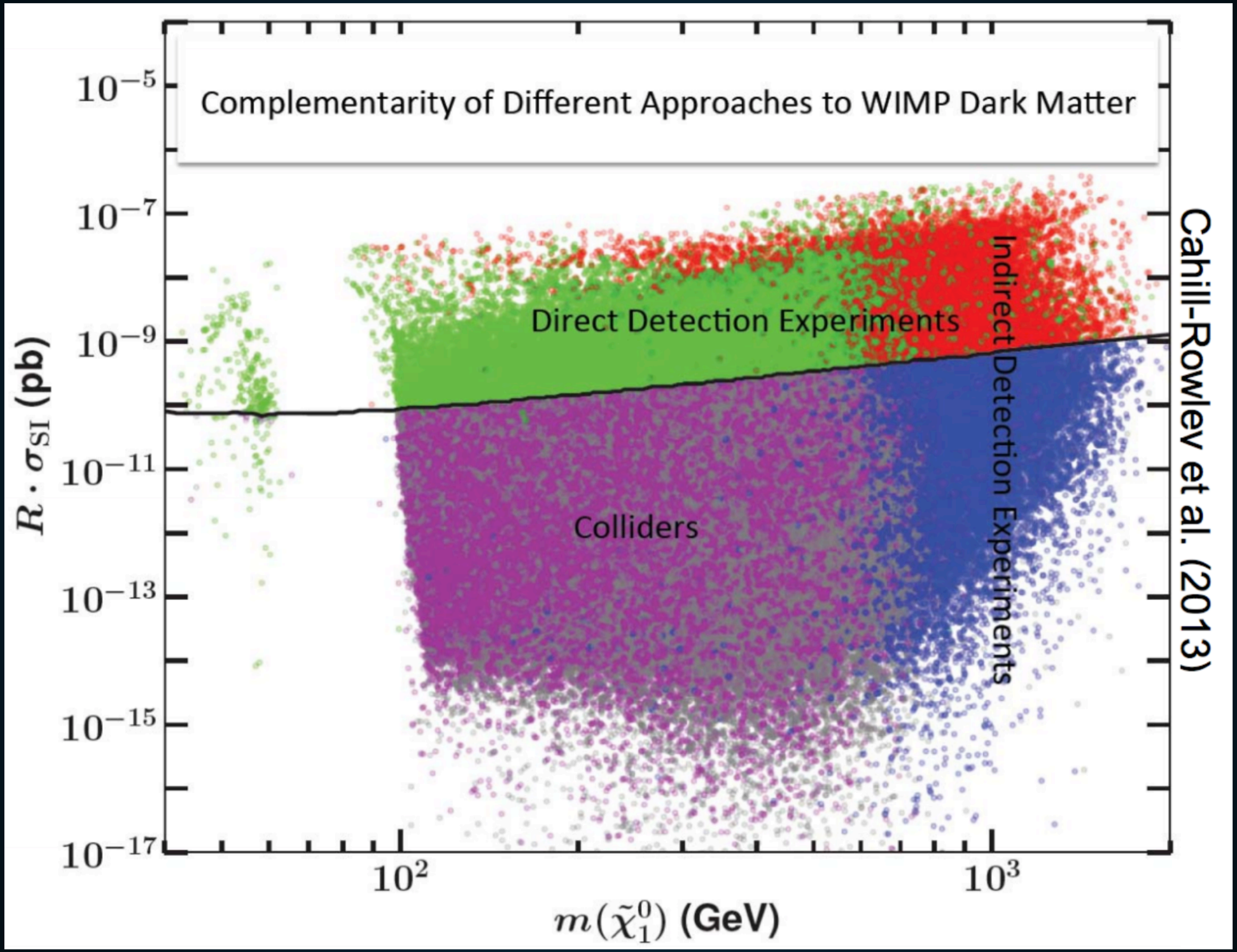
**MeV Dark Matter**

$10^{62}$ GeV

$m_X > M_{UFD}$

slide concept courtesy of Asher Berlin

# A MULTI-TIERED STRATEGY FOR GEV-SCALE DARK MATTER SEARCHES




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

**What is the landscape of MeV dark matter?**

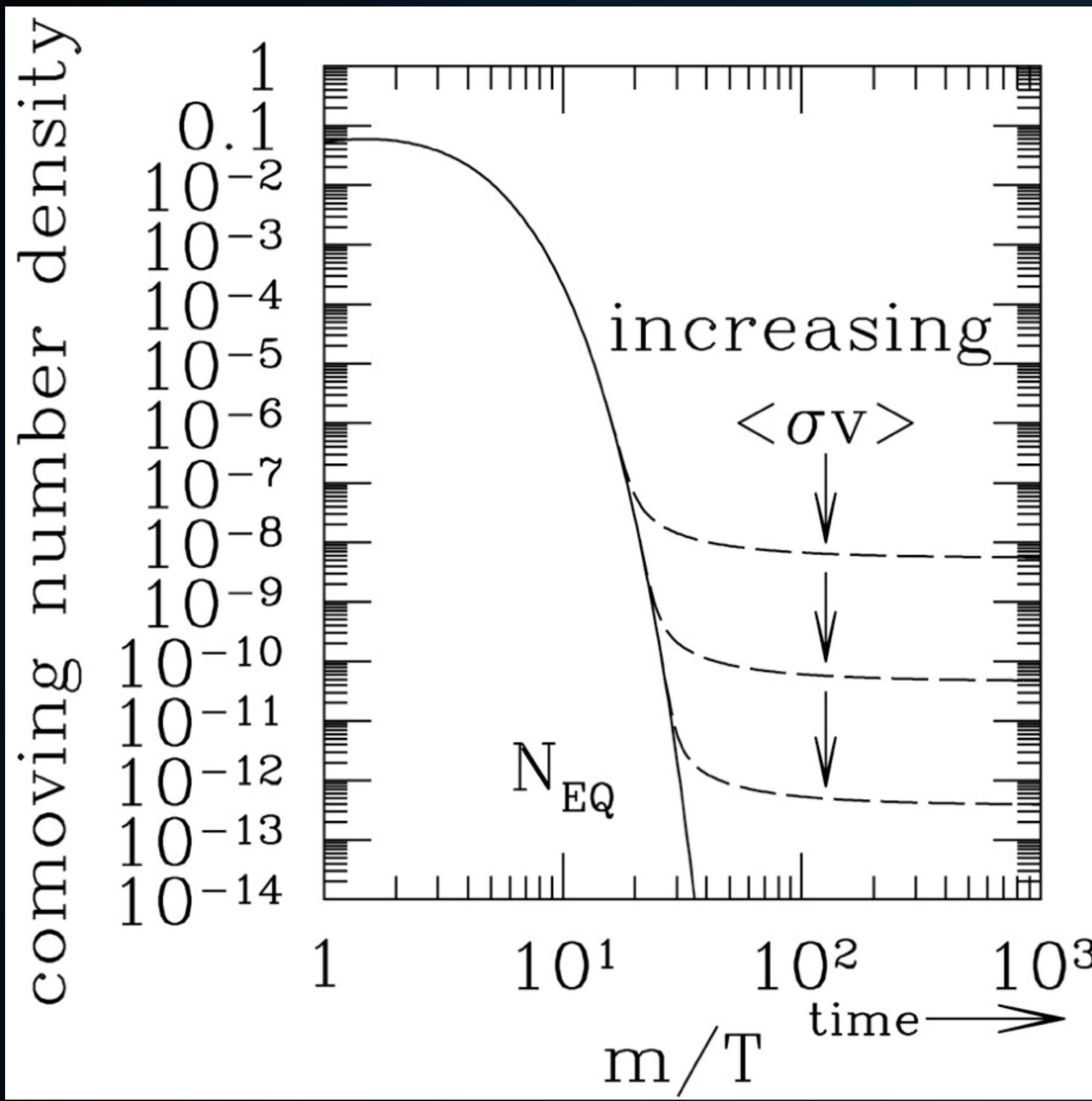
## MEV DARK MATTER - LESSONS FROM WIMPS

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


**Informative to use lessons from WIMP paradigm.**

slide concept courtesy of Asher Berlin

# MEV DARK MATTER - LESSONS FROM WIMPS




**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.**

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

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

- At high-masses we have the unitarity bound:

- What about the lower-limit?


slide concept courtesy of Asher Berlin

# MEV DARK MATTER - LESSONS FROM WIMPS

- **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 $2\times10^{-29}$ 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.**

- **$N_{eff}$ bound:**

**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

- **Under the assumption that the dark matter is thermal, the mass must be above 3-10 MeV to not contribute to the number of relativistic degrees of freedom.**

- What about the lower-limit?


slide concept courtesy of Asher Berlin

## A NEW PICTURE - NONSTANDARD WIMP MODELS

- Thinking outside the standard thermal-WIMP paradigm:
  - Asymmetric Dark Matter (e.g. Lin et al. 1111.0293)
  - Secluded Dark Matter (e.g. Pospelov et al. 0711.4866)
  - MeV Sterile neutrinos (e.g. 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.

- **Note: Annihilation signatures not guaranteed!**

# ANNIHILATION SIGNALS FROM MEV DARK MATTER

- **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.

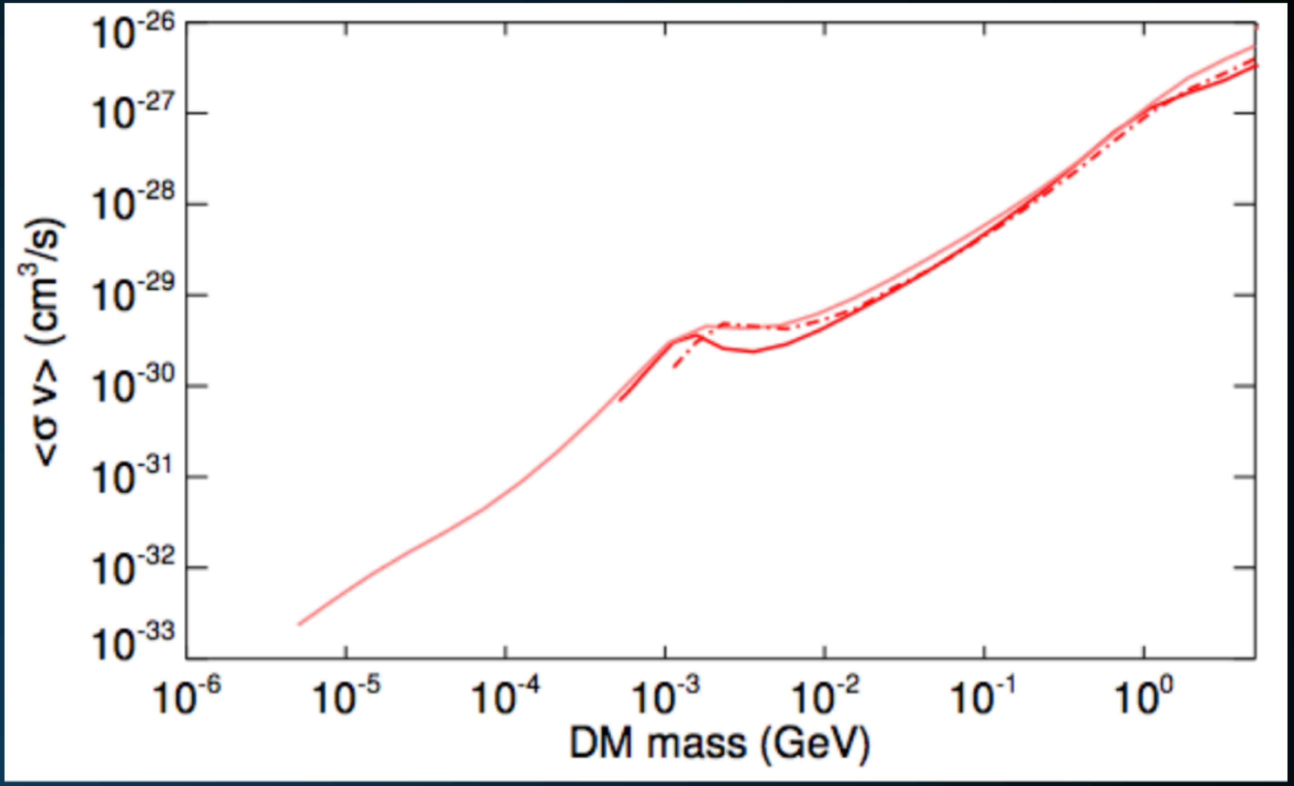
(iv) $\pi^+\pi^-$: Accessible for $\sqrt{s} \geq 2m_{\pi^\pm}$. The final state is $C$-even or $C$-odd.

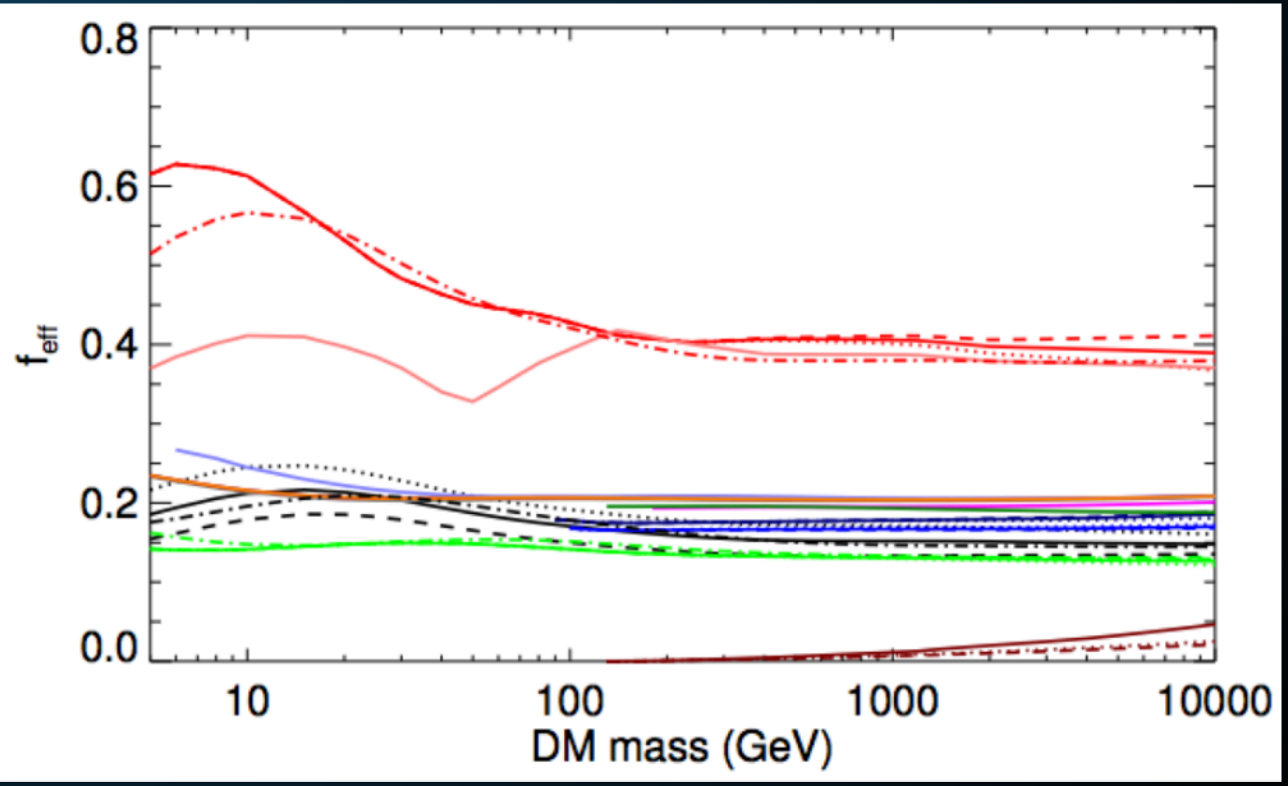
(v) $\bar{\ell}\ell$ ($\ell = e, \mu, \nu$): Accessible for $\sqrt{s} \geq 2m_\ell$. The final state is either $C$-odd or is weak suppressed.

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

Slatyer (1506.03811)

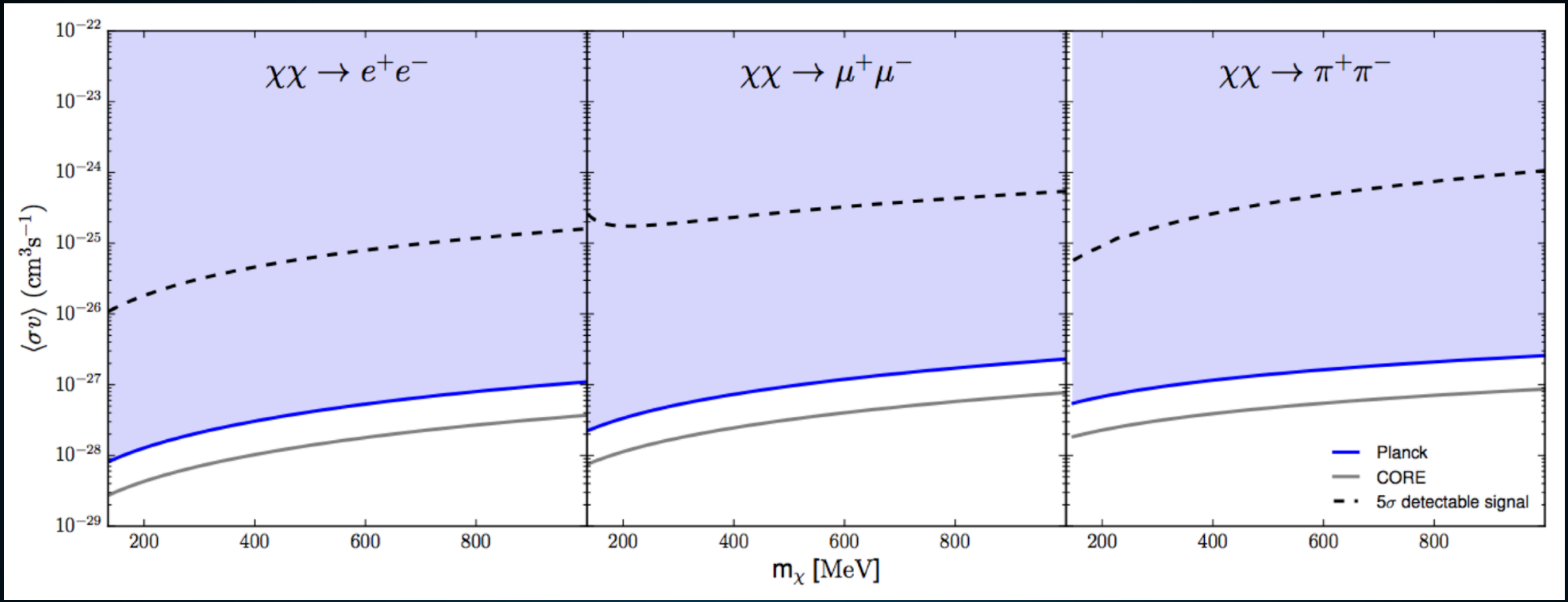
- **CMB Bounds:**
  - Energy injection during recombination affects the CMB anisotropy.
  - The constraint trends as <σv> ~ 1/m, and extends to small masses.
  - Only moderate variation with final state.



# COMPARISON OF CMB AND DWARF GAMMA-RAY CONSTRAINTS

Gonzalez-Morales et al. (1705.00777)




- CMB constraints fall between $1\text{x}10^{-28}$ and $1\text{x}10^{-27}$ in the 0.1-1 GeV range.
- These constraints are likely to outperform future MeV gamma-ray experiments for annihilation to charged final states.

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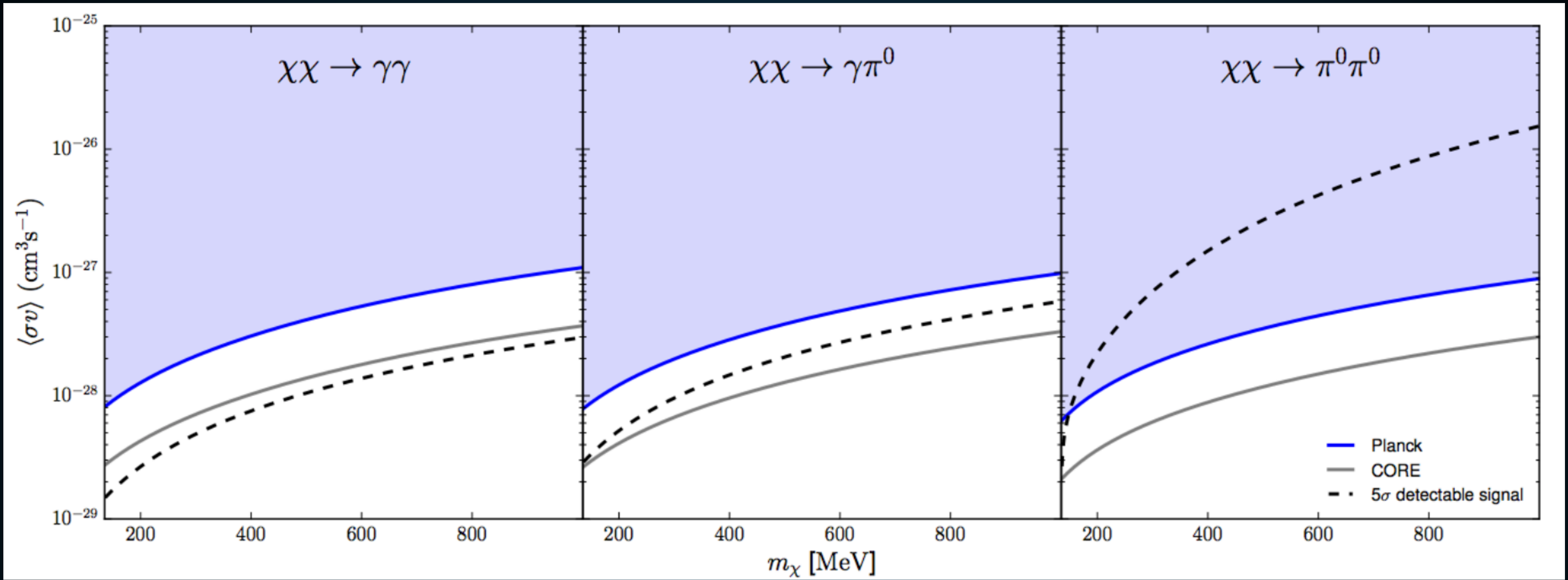
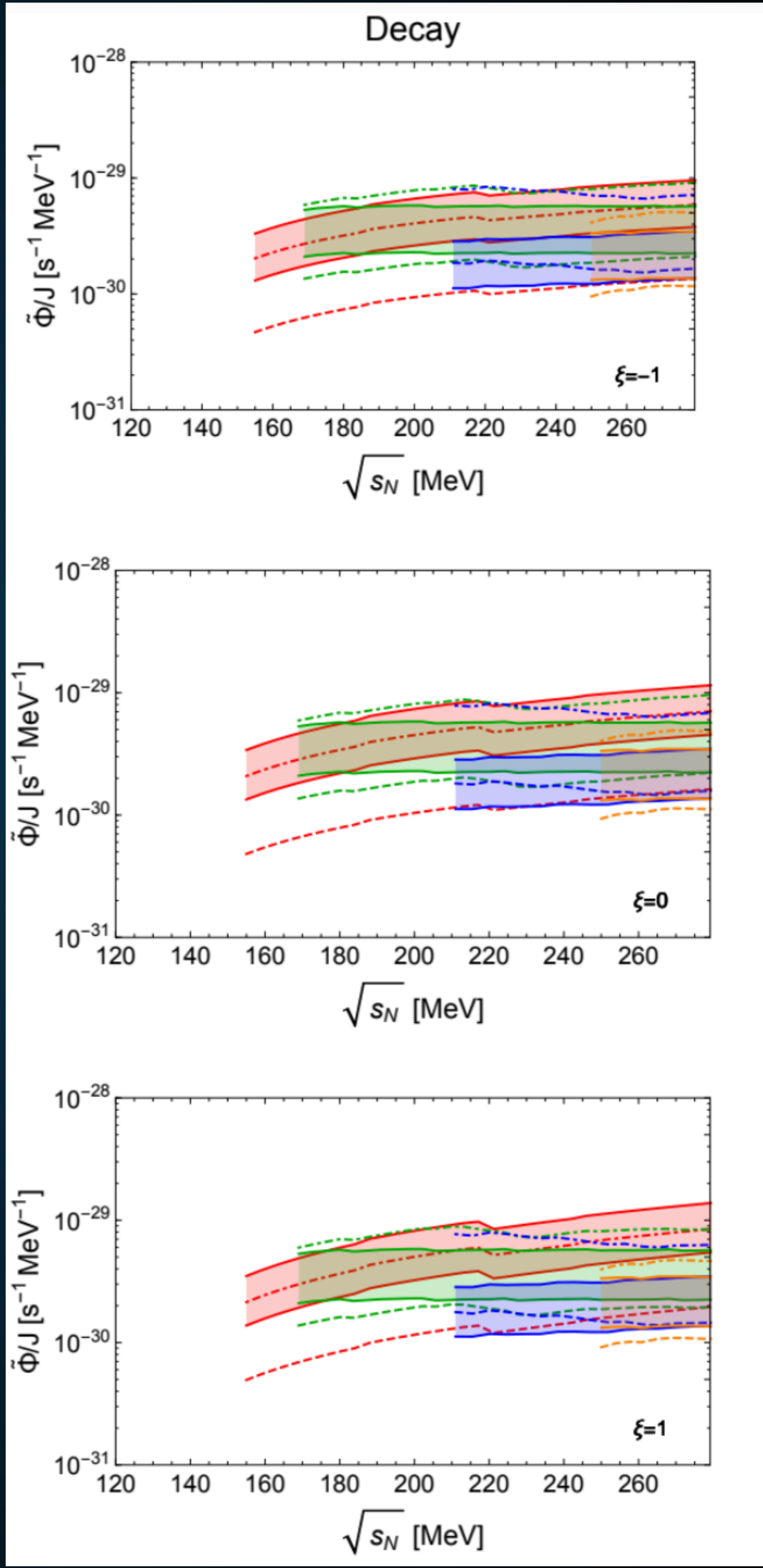



- In the case of annihilation to neutral particles:
  - The CMB constraints stay the same
  - The gamma-ray sensitivity improves drastically.

## 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)

## 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!

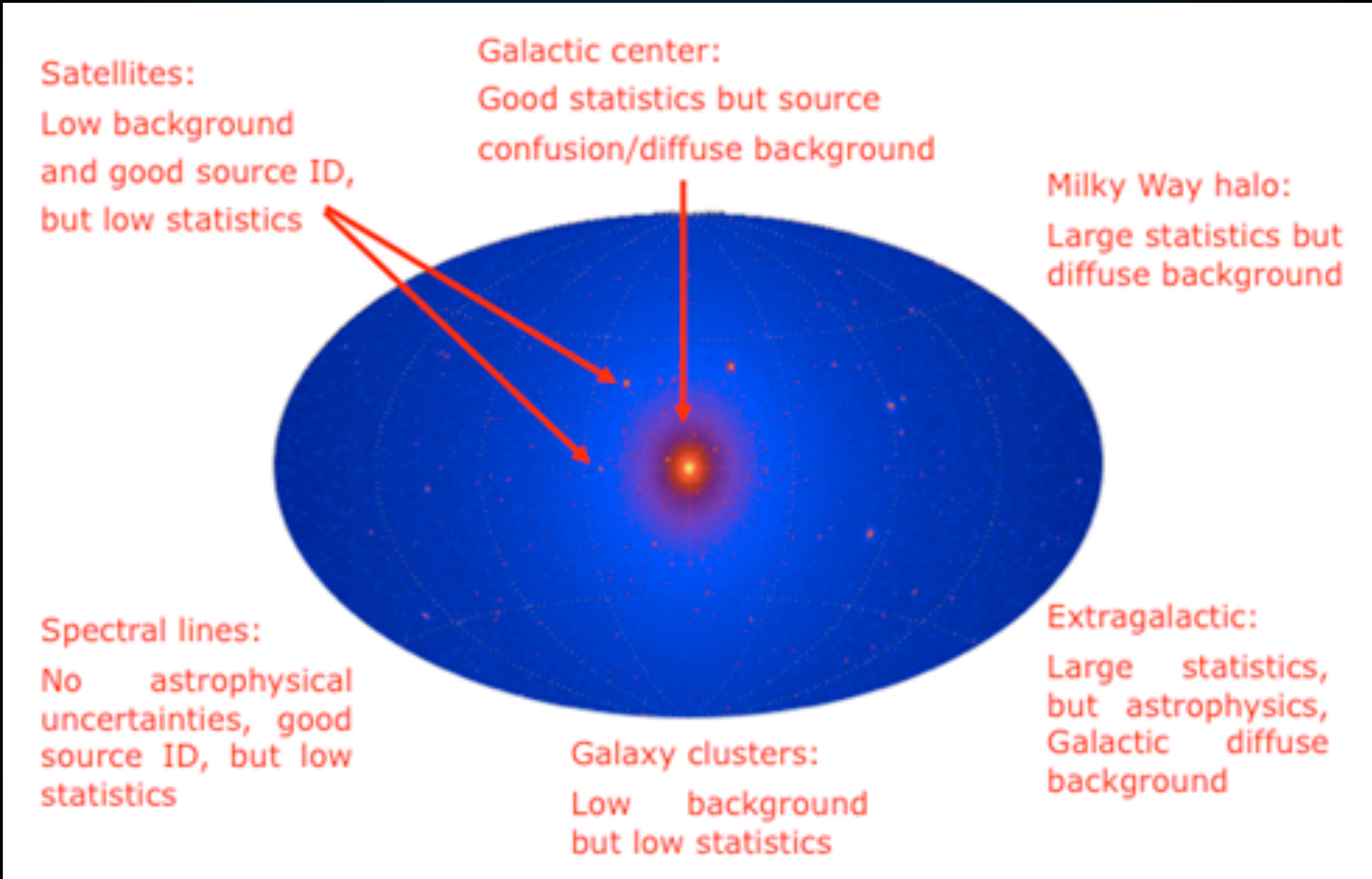
- There are many models for producing MeV dark matter!

- Many models will have unique signatures:

  * Harder to use a one-size fits all approach

  * Easier to distinguish between models if you see something.

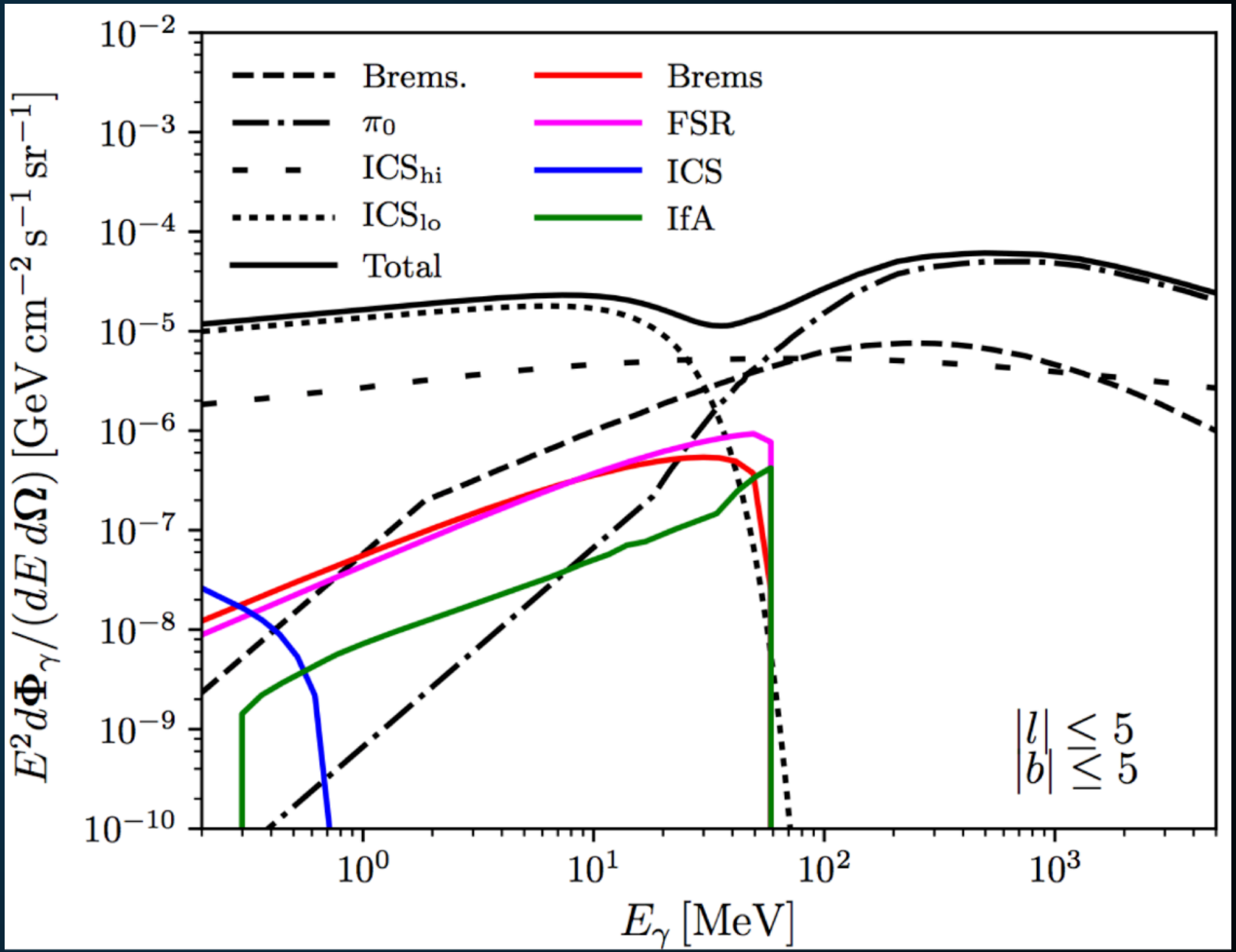
# EVERYTHING WE KNOW ABOUT DARK MATTER




slide courtesy of KIPAC

# THE ANNIHILATION SPECTRA WILL UNIVERSALLY BE HARD

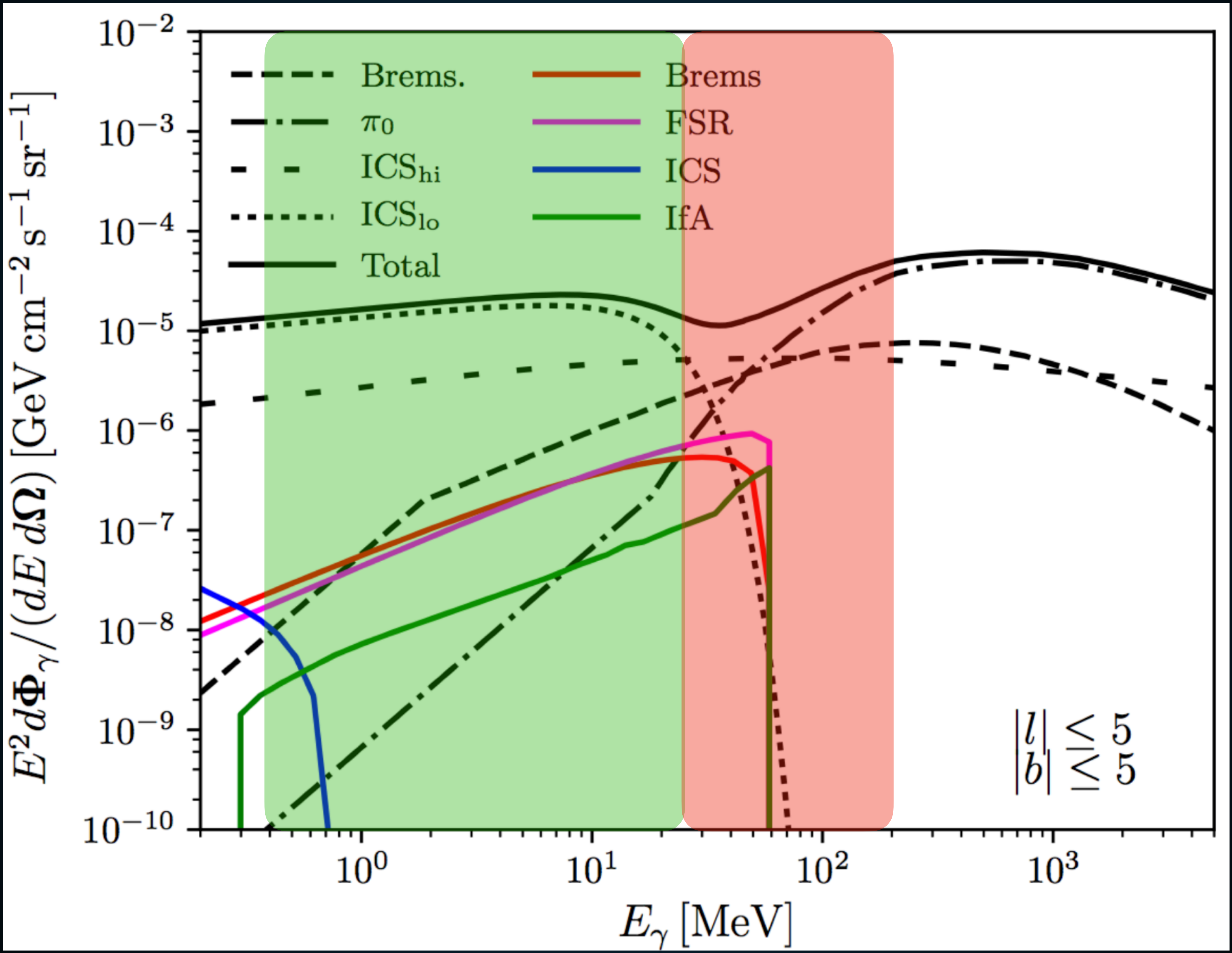
- Annihilation of 80 MeV DM -> $e^+e^-$ produces gamma-rays primarily through final state radiation and bremsstrahlung.




- These spectra are brightest at the dark matter mass.

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

# ADVANTAGES IN DIFFUSE BACKGROUNDS



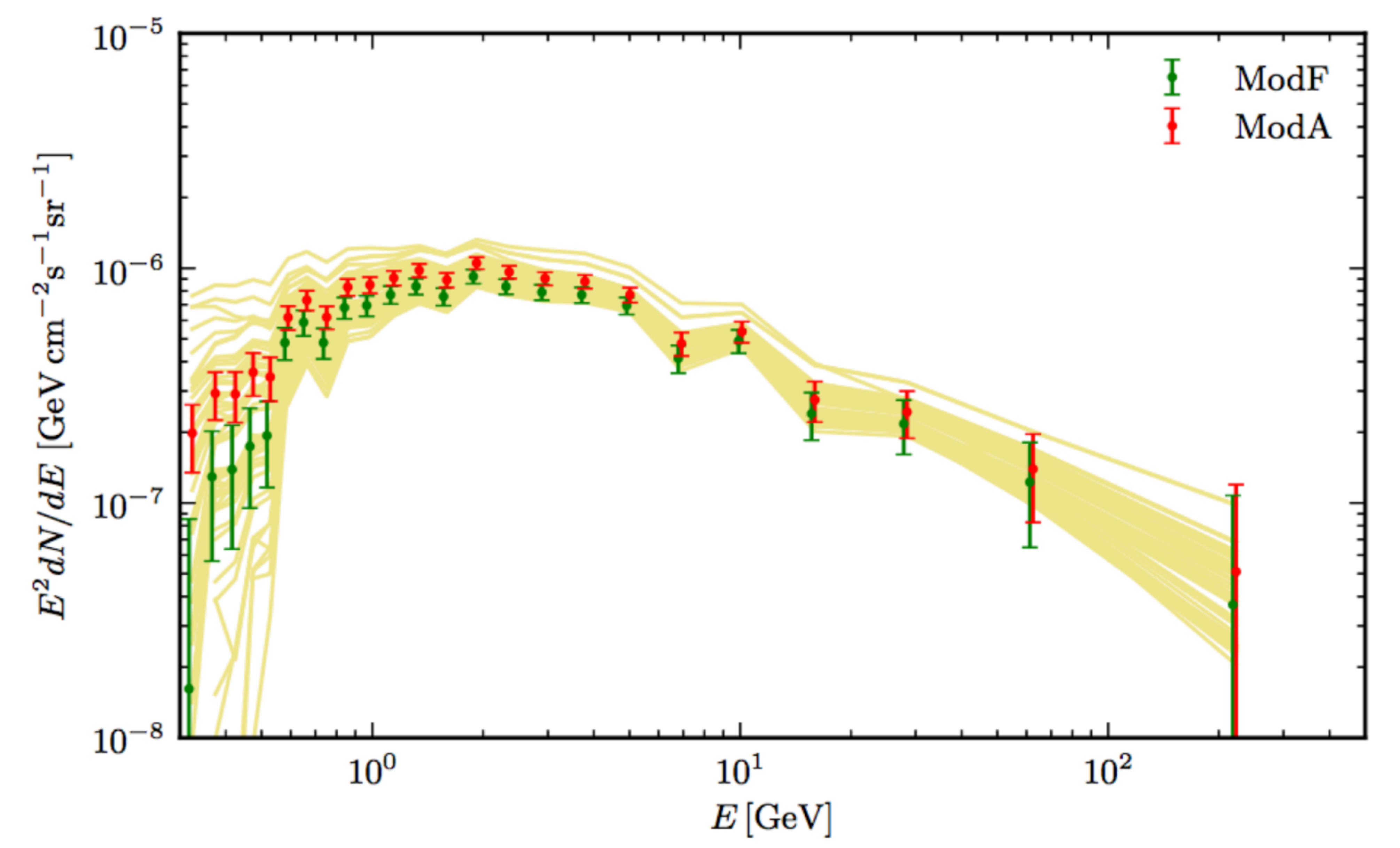
# EVERYTHING WE KNOW ABOUT DARK MATTER


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

**Does the MeV lamppost connect to the GeV range?**

# COMPLEMENTARITY BETWEEN AMEGO AND FERMI

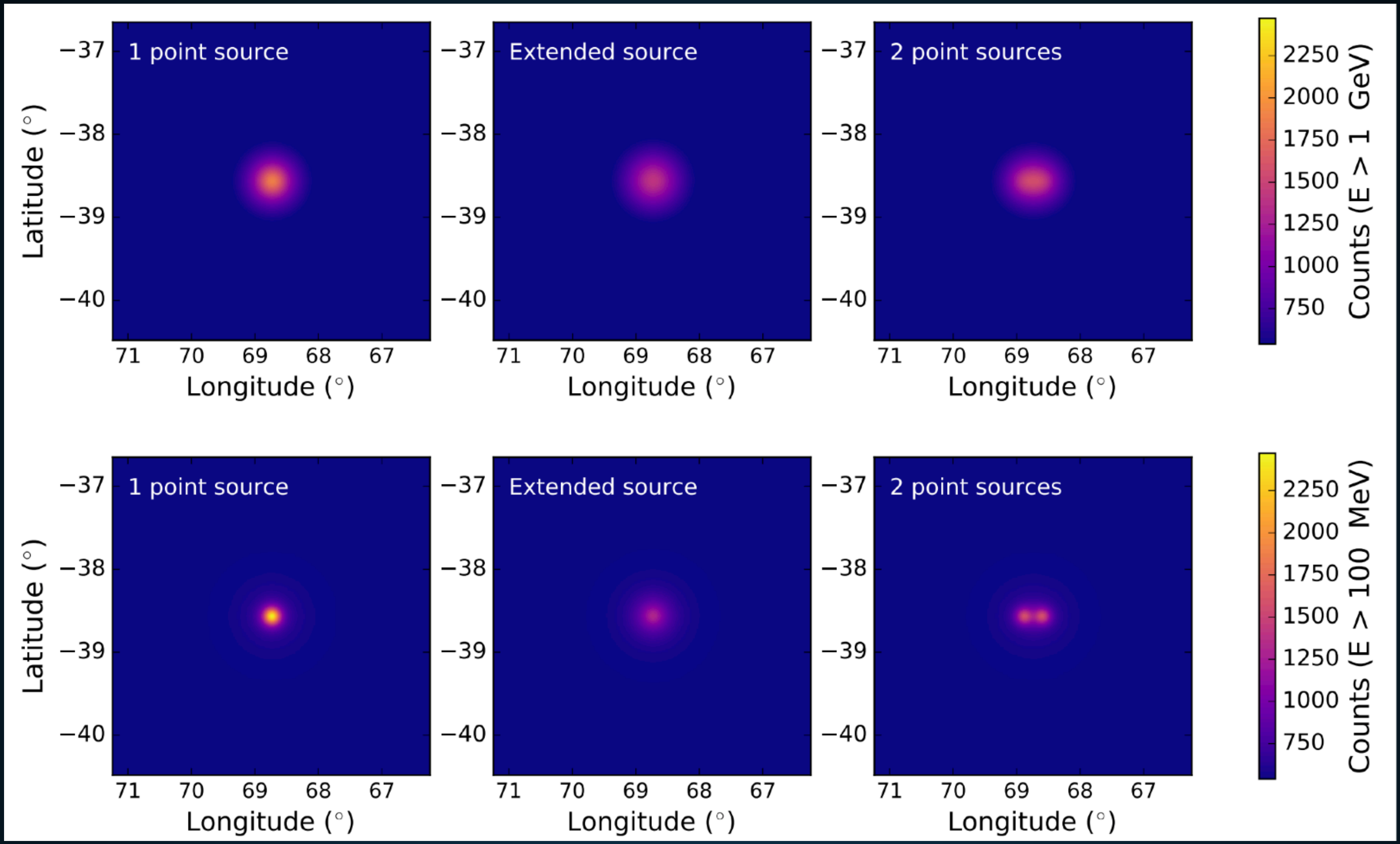
- The separation of ~10-100 GeV DM from background (including $\pi^0$-decay and blazars) depends sensitively on the strength of ~100 MeV gamma-ray limits.




Calore et al. (1409.0042)

# COMPLEMENTARITY BETWEEN AMEGO AND FERMI

Chou et al. (1709.08562)



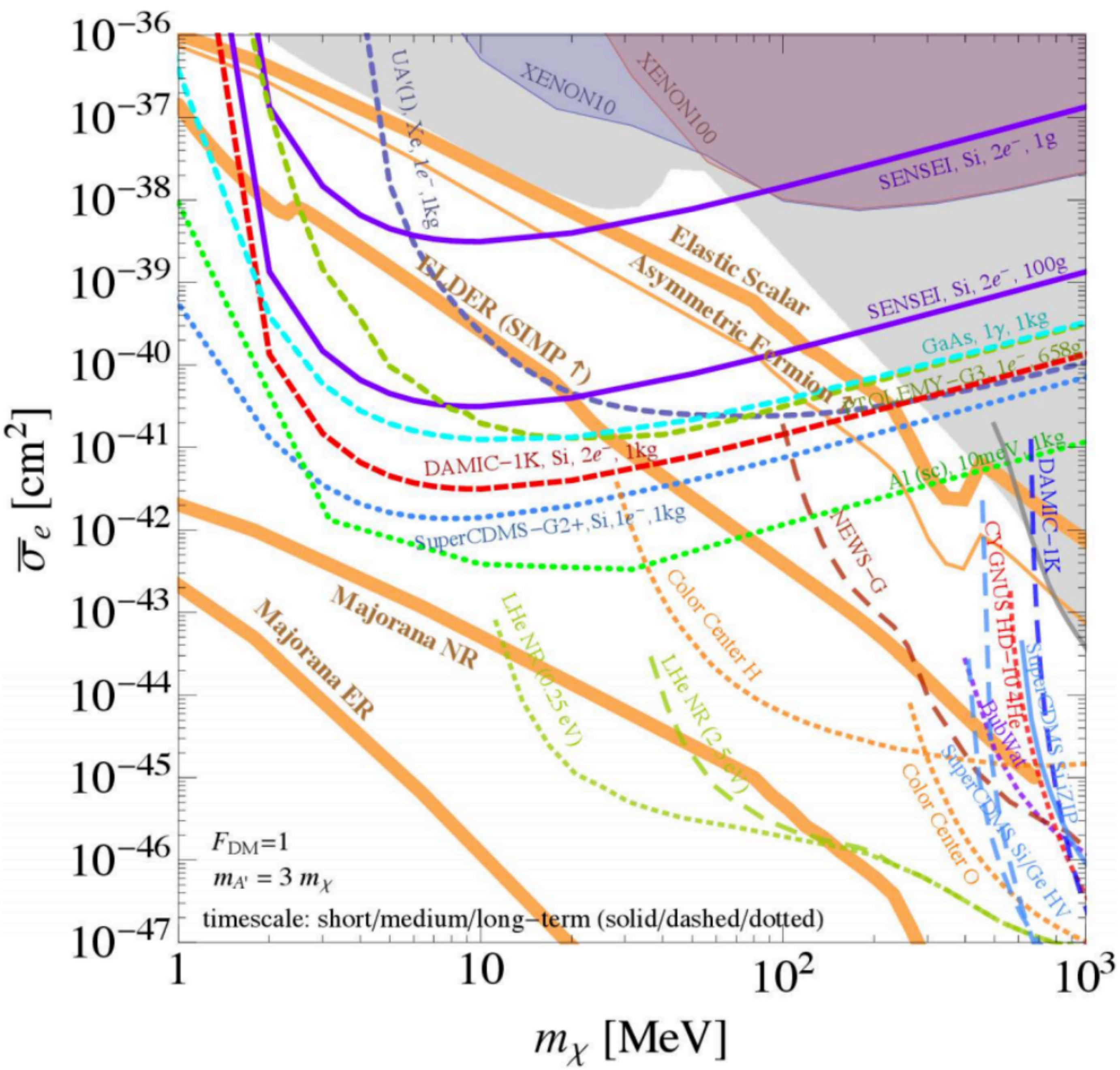

- Another example is the observation of spatial extension in unassociated Fermi-LAT sources
    - In this scenario, improved angular resolution at ~100 MeV is particularly important.

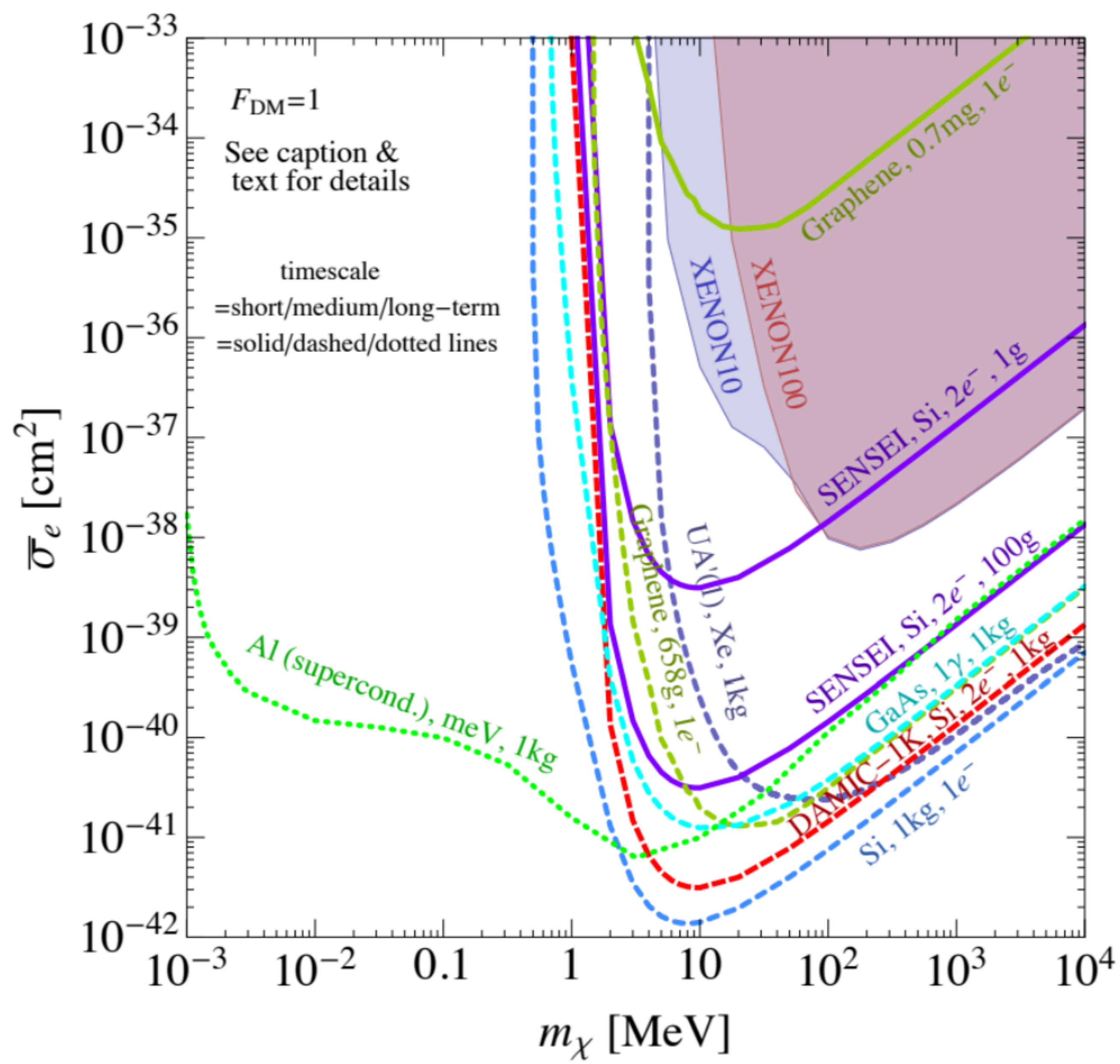
## THE MEV SCALE - A RANGE OF POSSIBILITIES!

- A vision for the next decade.

# 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!

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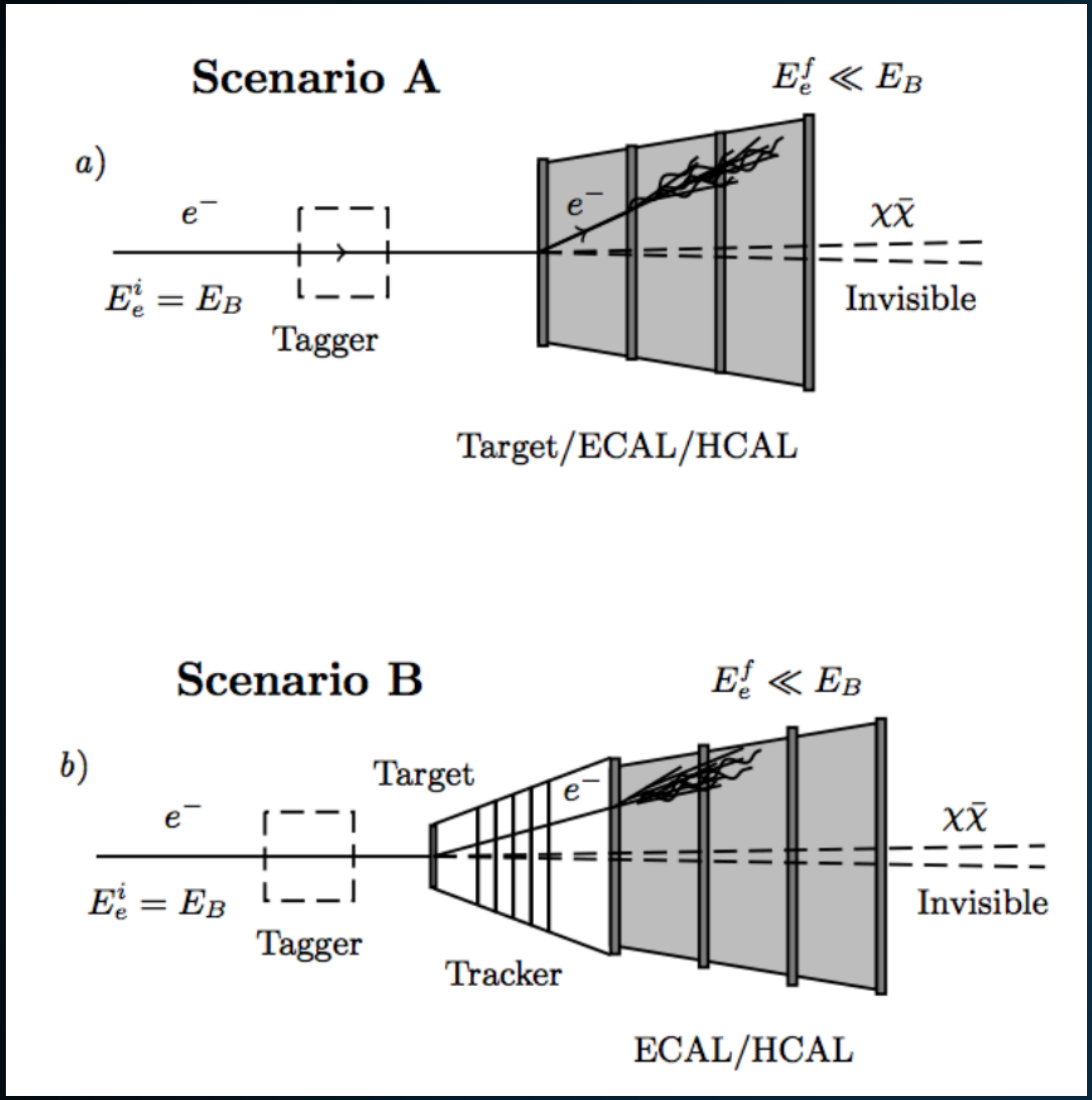
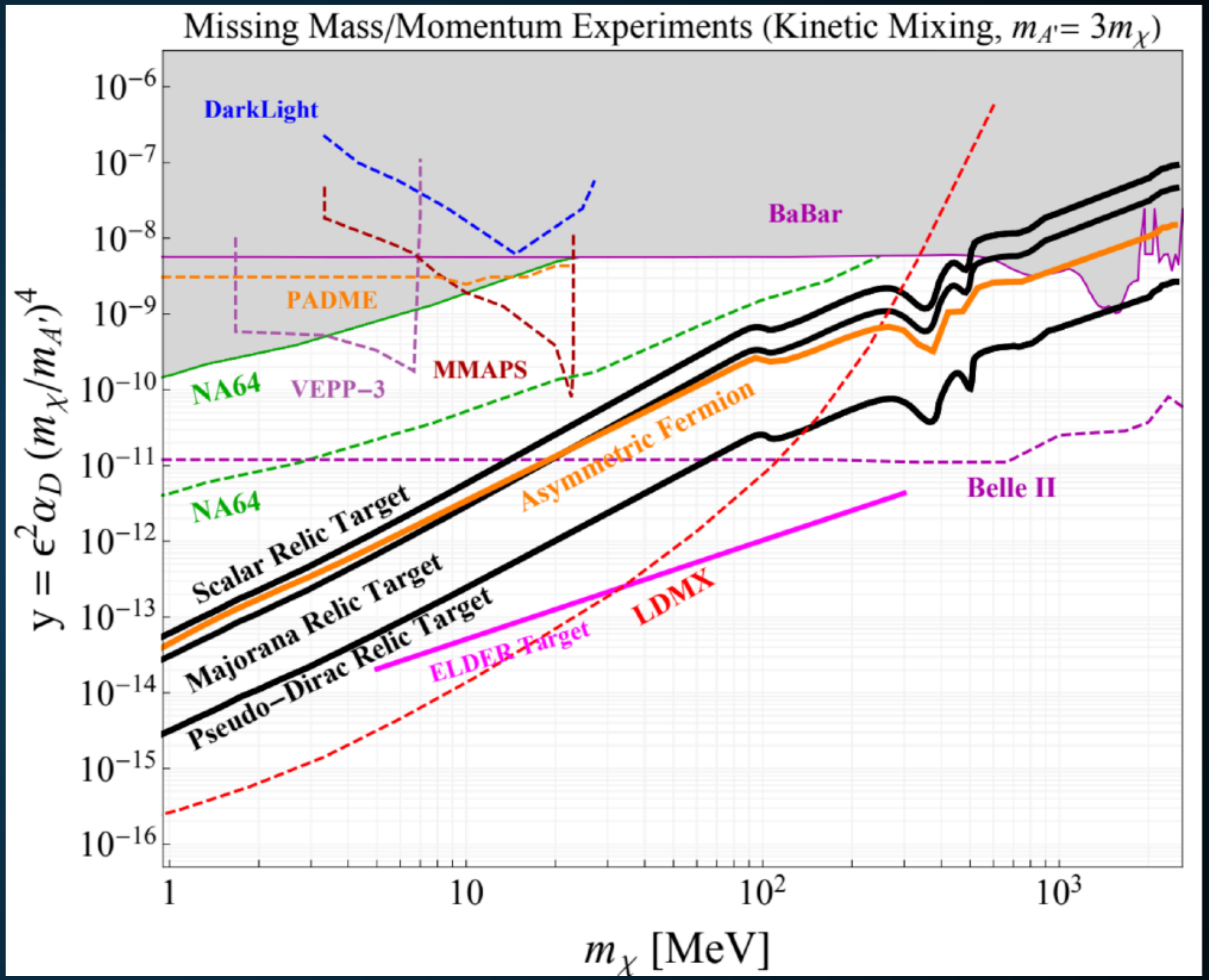


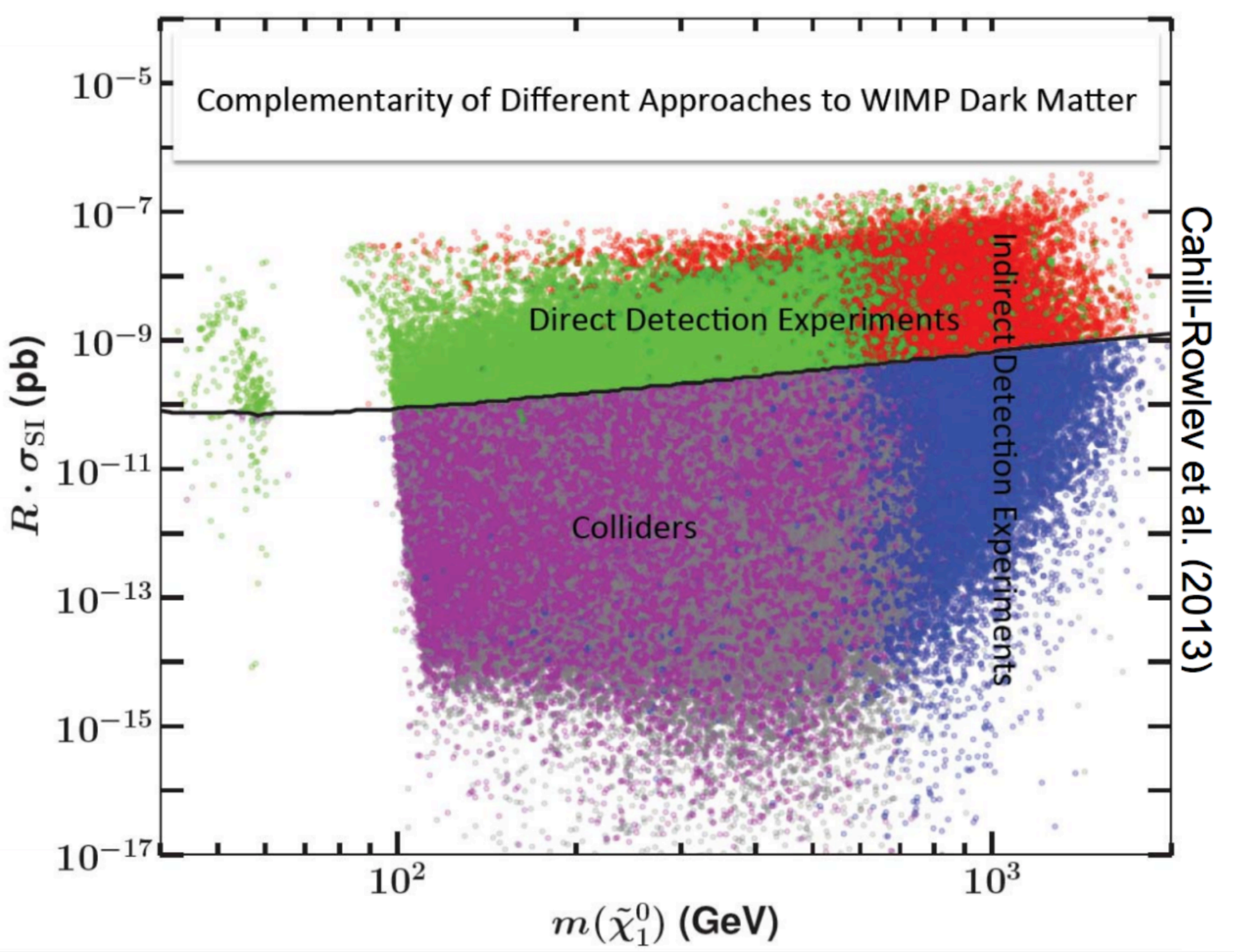




Izaguirre et al. (1411.1404)

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

# THE MEV SCALE - A RANGE OF POSSIBILITIES!

ALL-SKY MEDIUM ENERGY GAMMA-RAY OBSERVATORY




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