Dark Matter and It's Indirect Detection

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The WE-Heraeus and NARIT Cosmology School 2025

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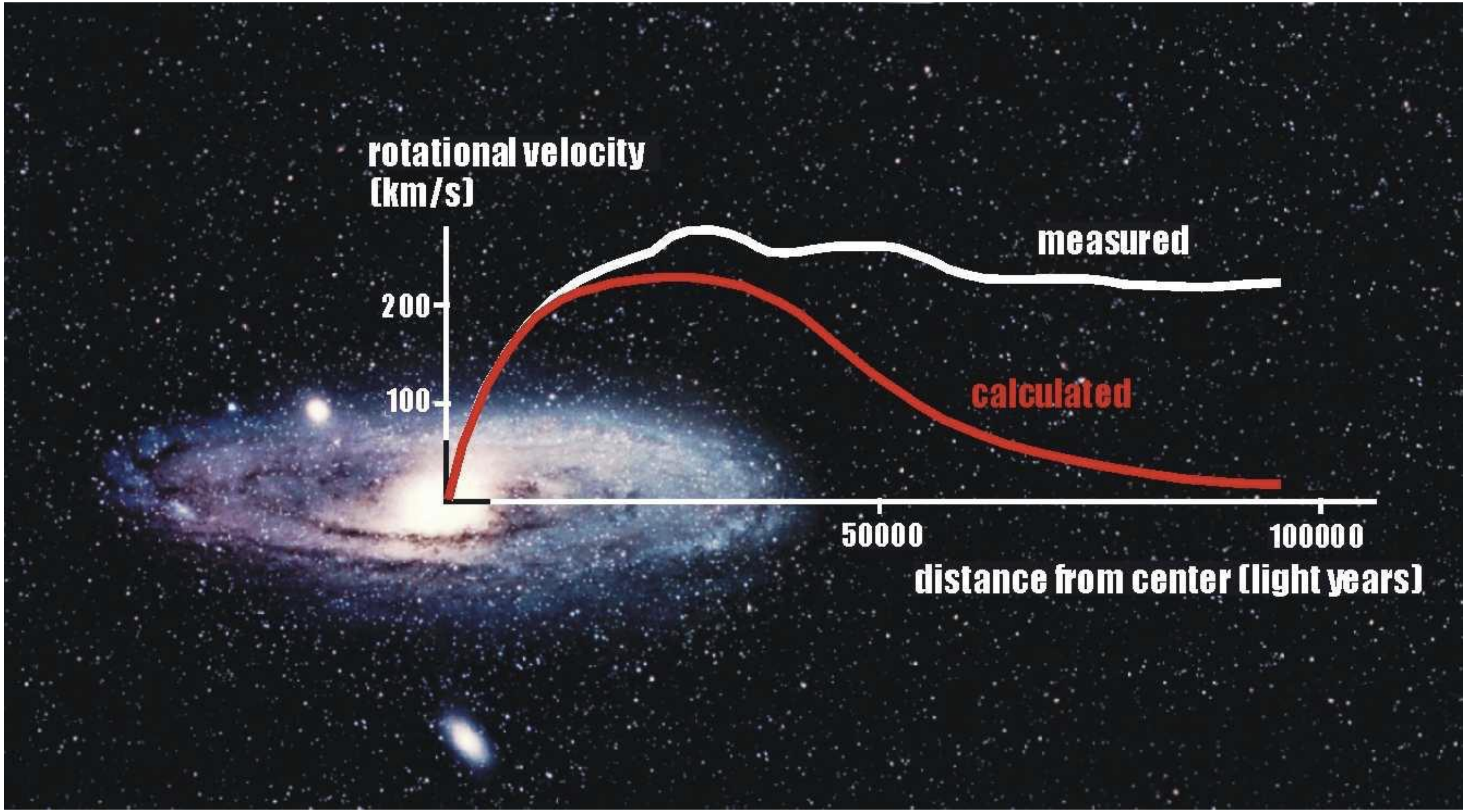
Image Credit: Ralf Kaehler/SLAC National Accelerator Laboratory, American Museum of Natural History

Why do we need dark matter?

Rotation Curve of Galaxies

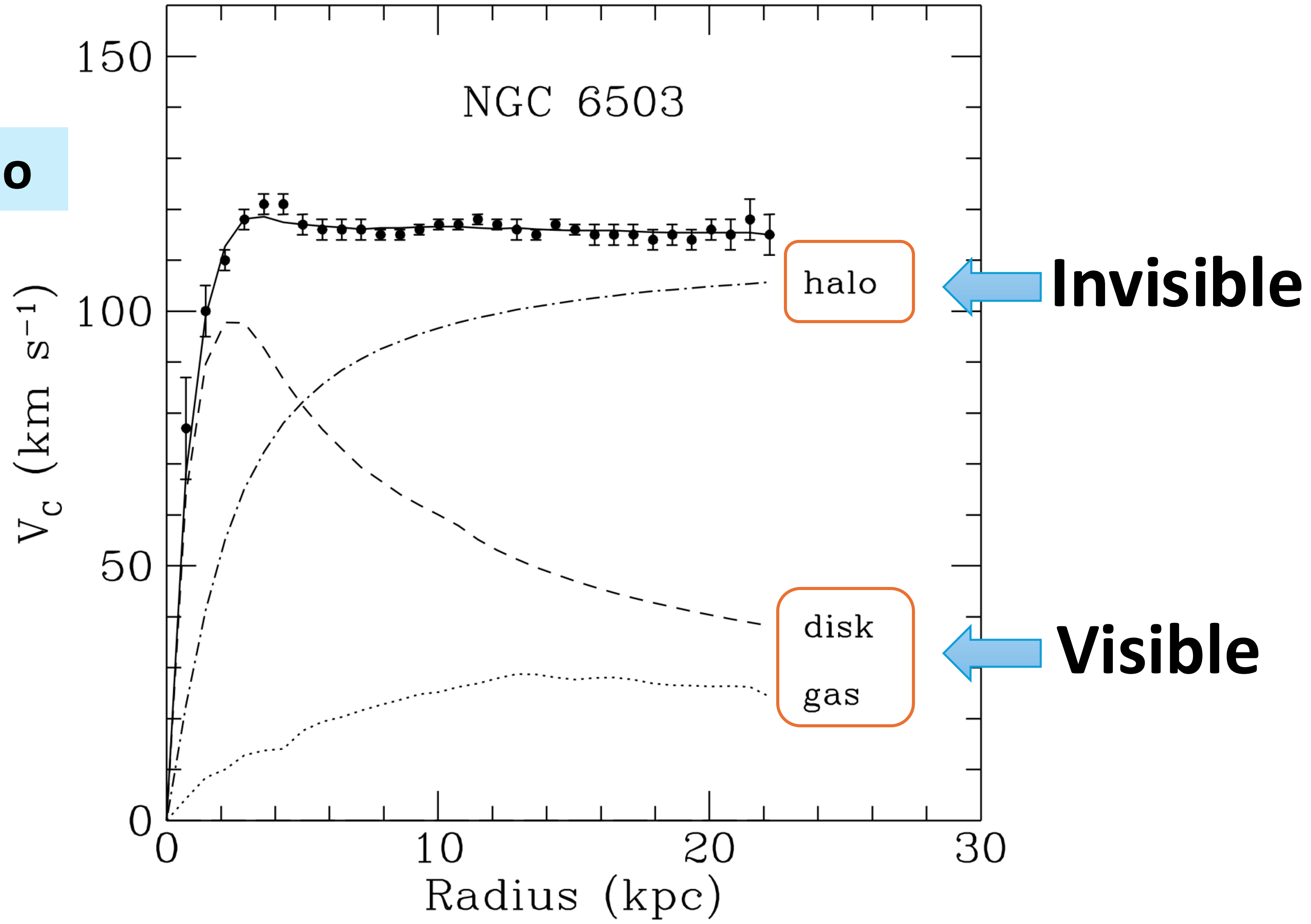


Vera Rubin et. al. 1978: Measured velocity curves

Image credit: http://cdms.phy.queensu.ca/Public_Docs/DM_Intro.html

Mass to Light Ratio

$$\frac{M}{L} \gg 1$$



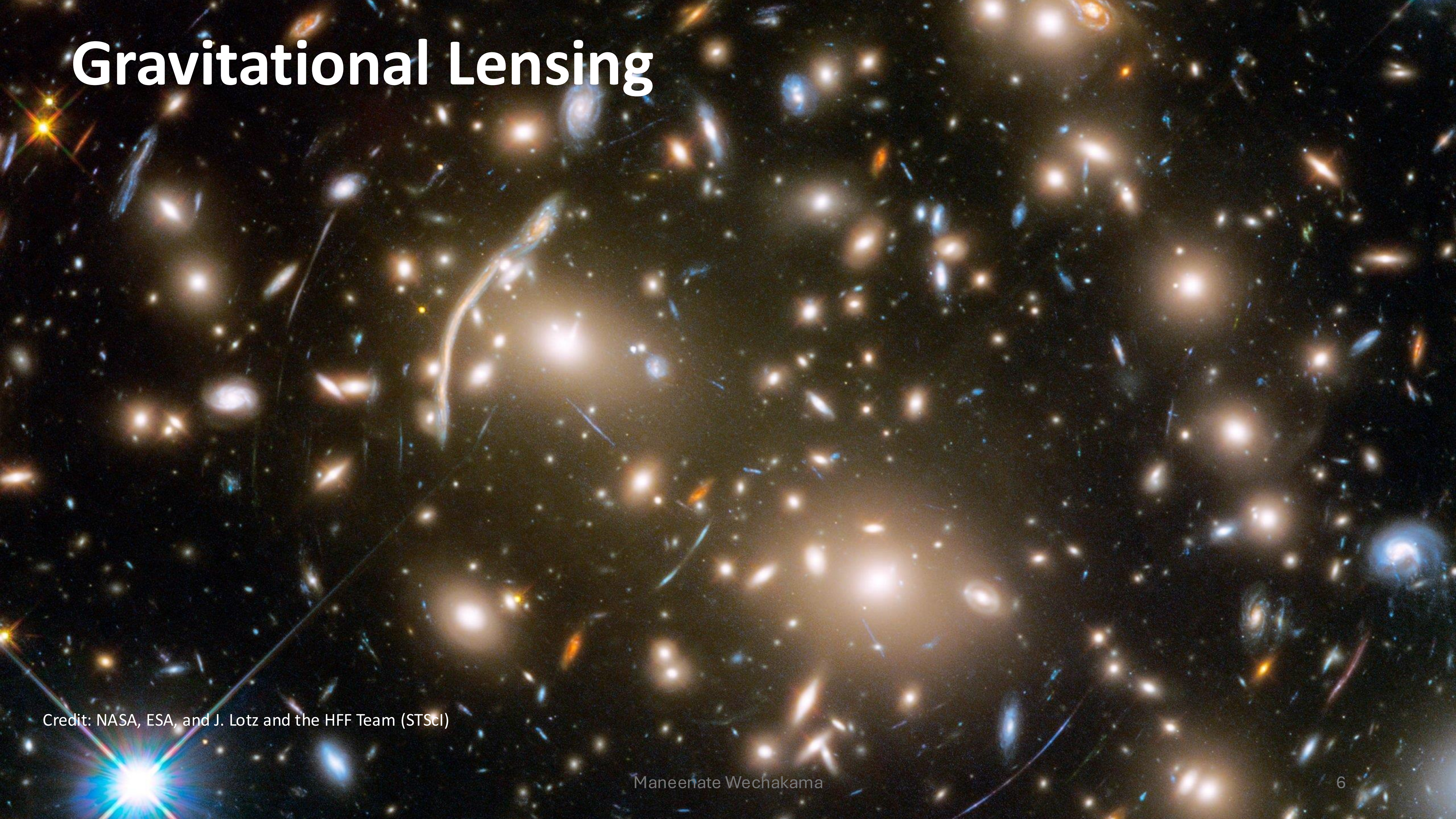
Begeman et al. 1991

Orbital Velocities of Galaxy Clusters

Invisible mass is required!

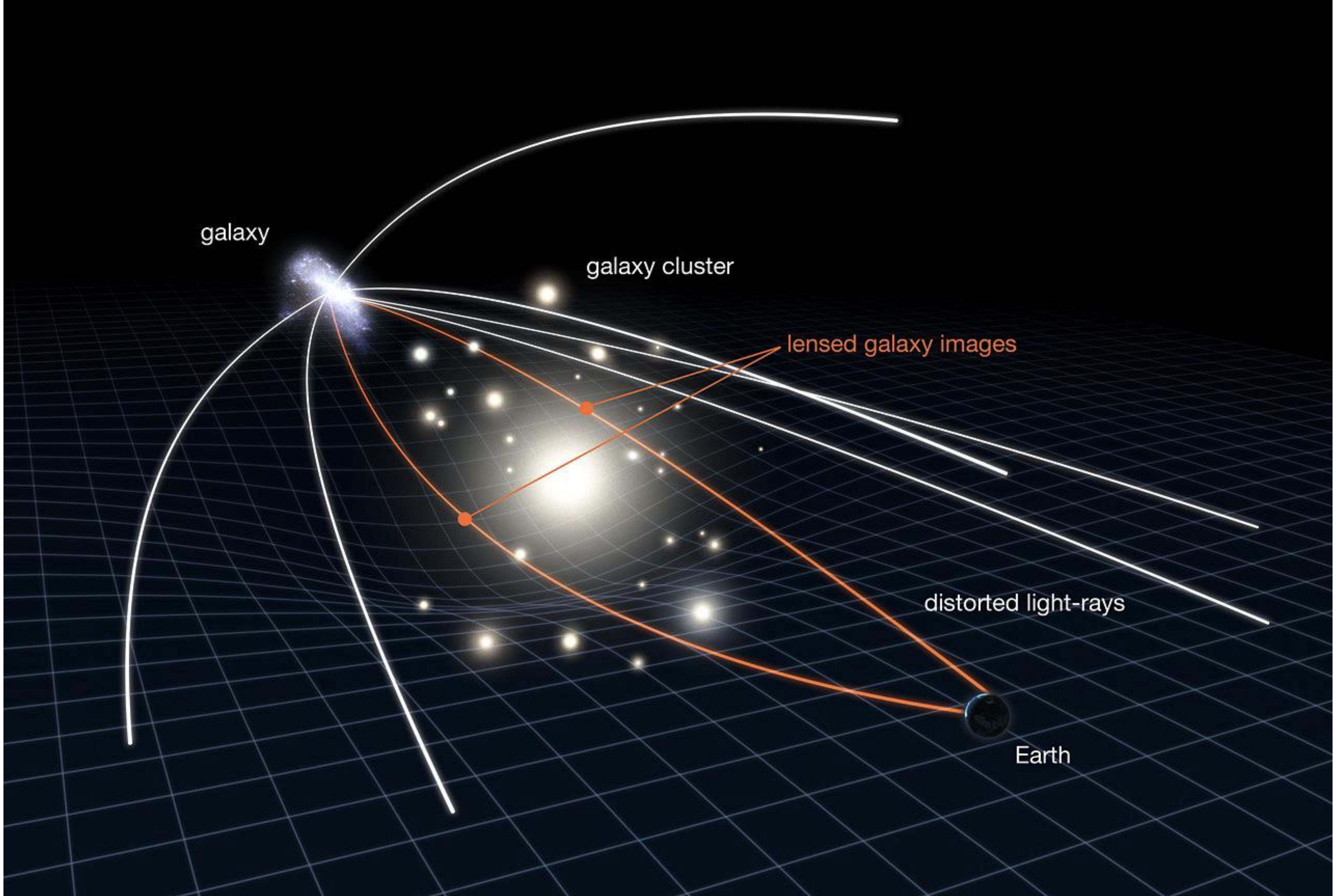
Image credit: Jim Misti

Gravitational Lensing



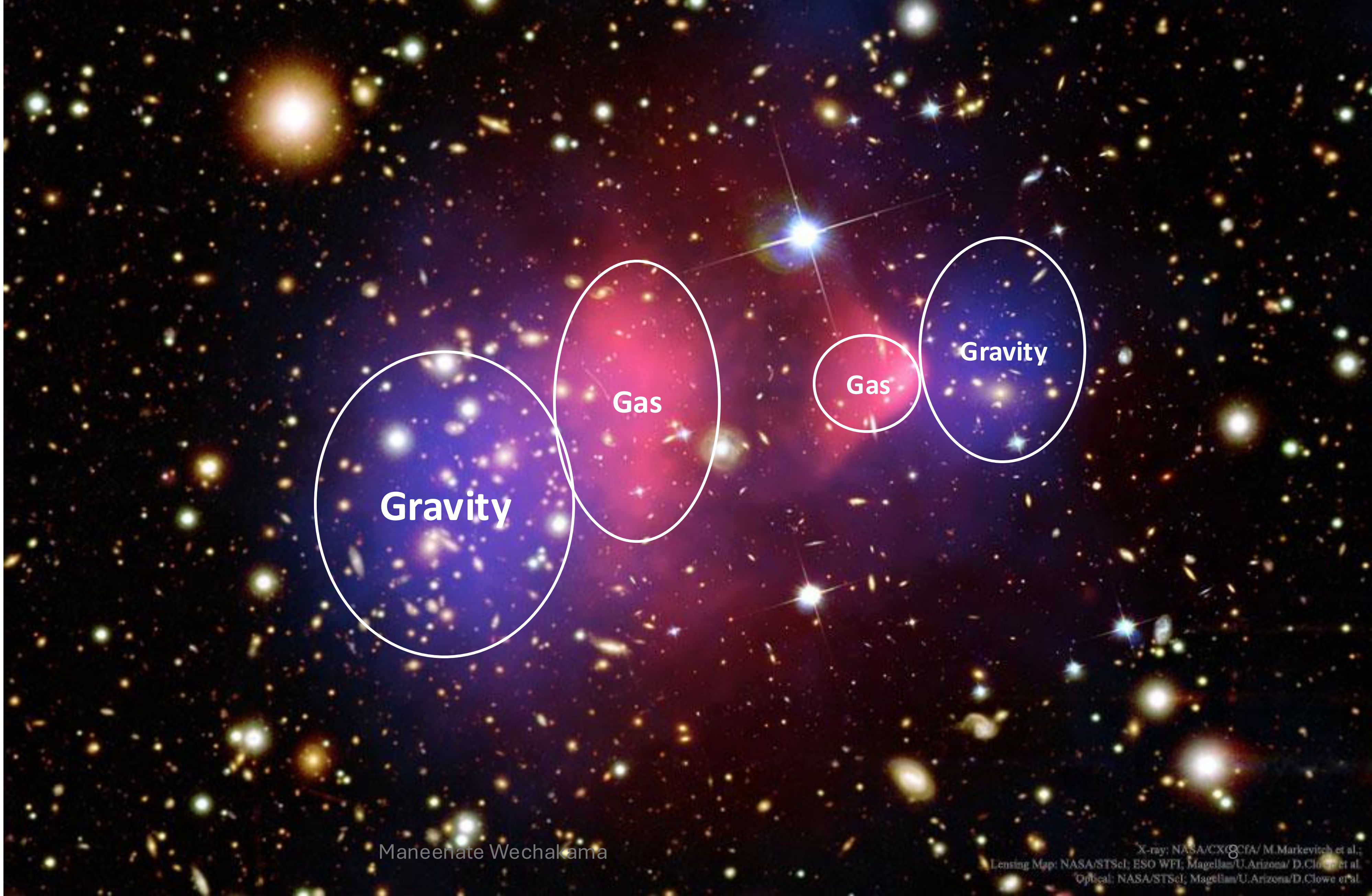
Credit: NASA, ESA, and J. Lotz and the HFF Team (STScI)

Lensing reveals invisible mass!



Credit: NASA, ESA & L. Calçada

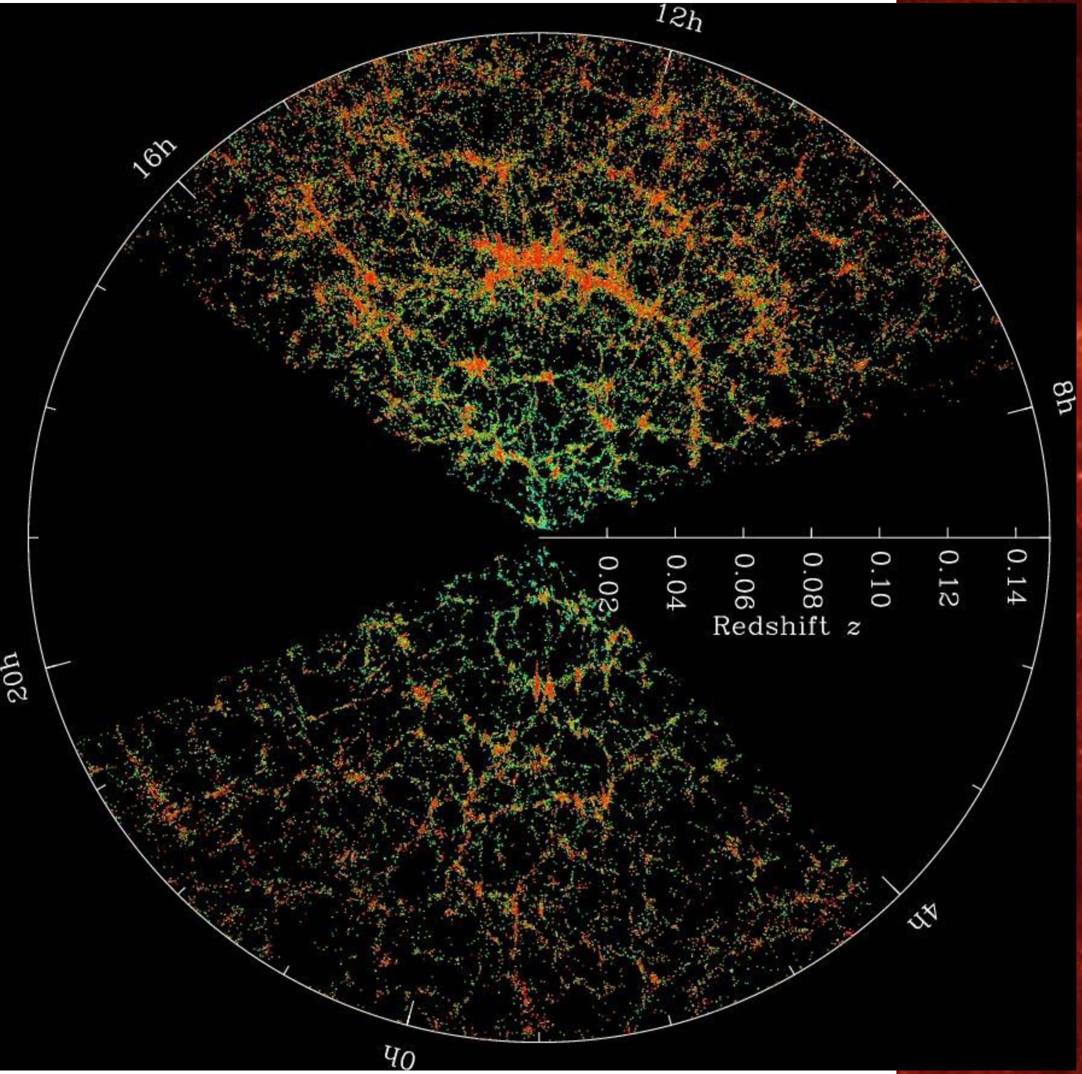
Bullet Cluster



Gravity doesn't follow the visible matter!

Structure Formation

Dark matter create gravitational “seeds”



Sloan Digital Sky Survey

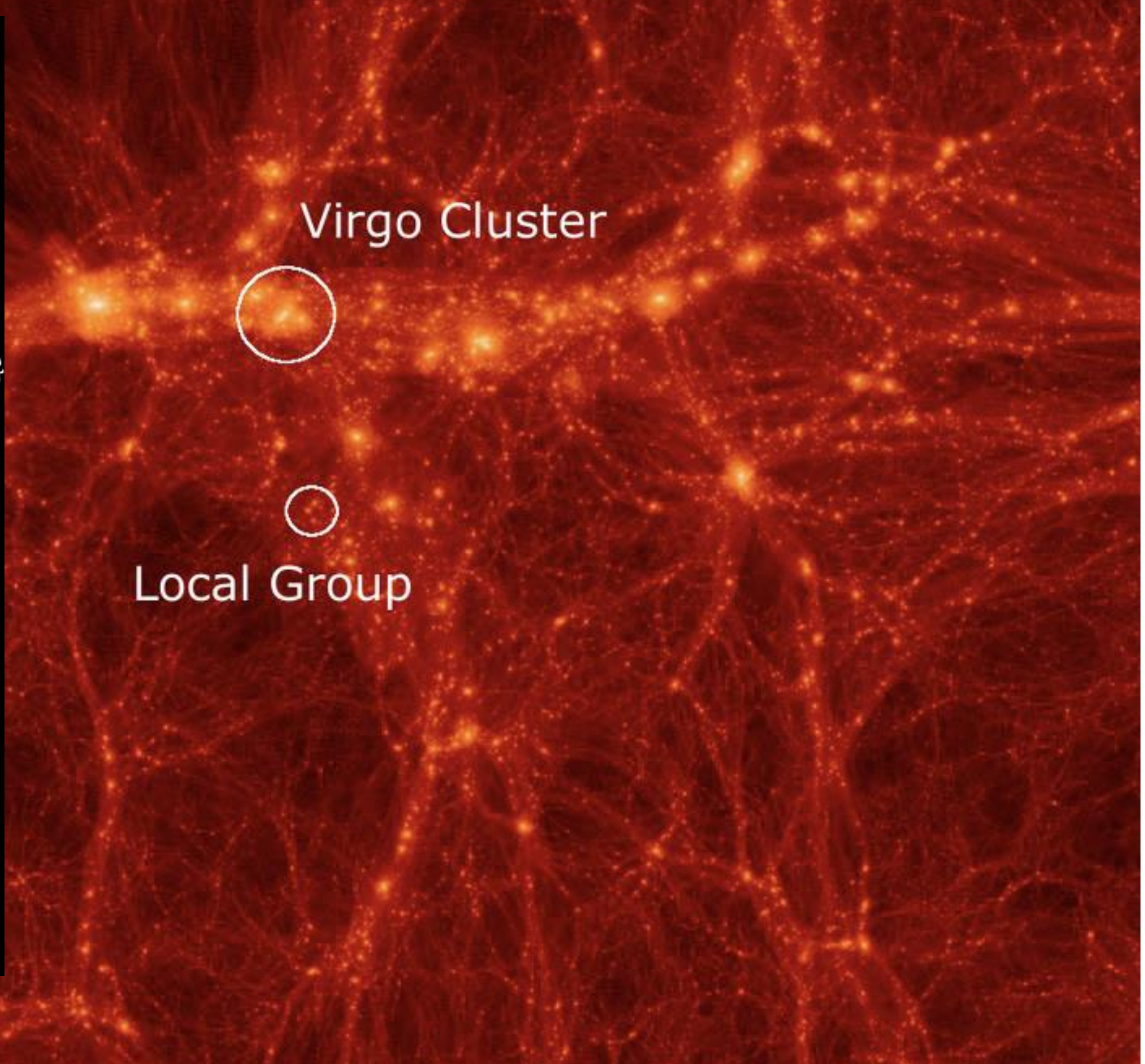
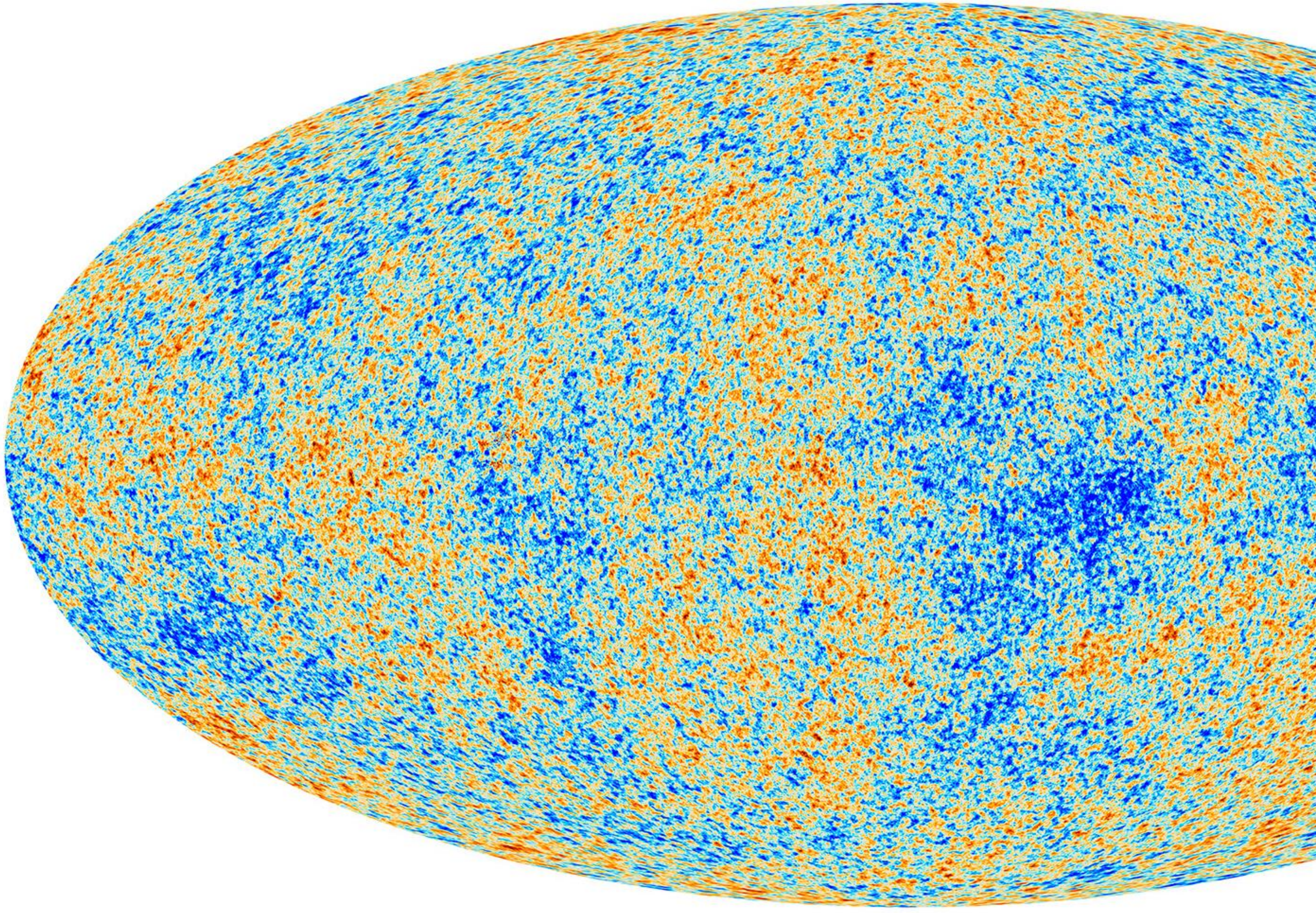


Image credit: S. Gottlöber, G. Yepes, A. Klypin, A. Khalatyan

Cosmic Microwave Background



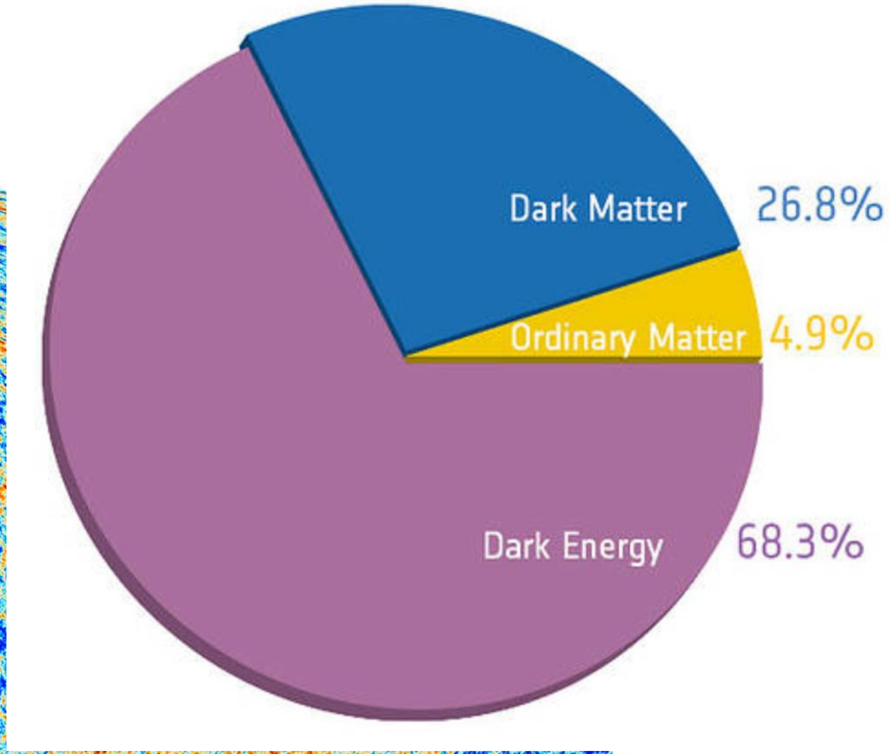


Image credit: ESA and the Planck Collaboration

The evidence for dark matter is overwhelming!

Dark matter is essential for the Universe

Image credit: ESA and the Planck Collaboration

What is Dark Matter?

Image credit: ESA and the Planck Collaboration

Dark Matter Properties

- Massive
- No charge
- Collisionless
- Stable
- Cold
- Abundant

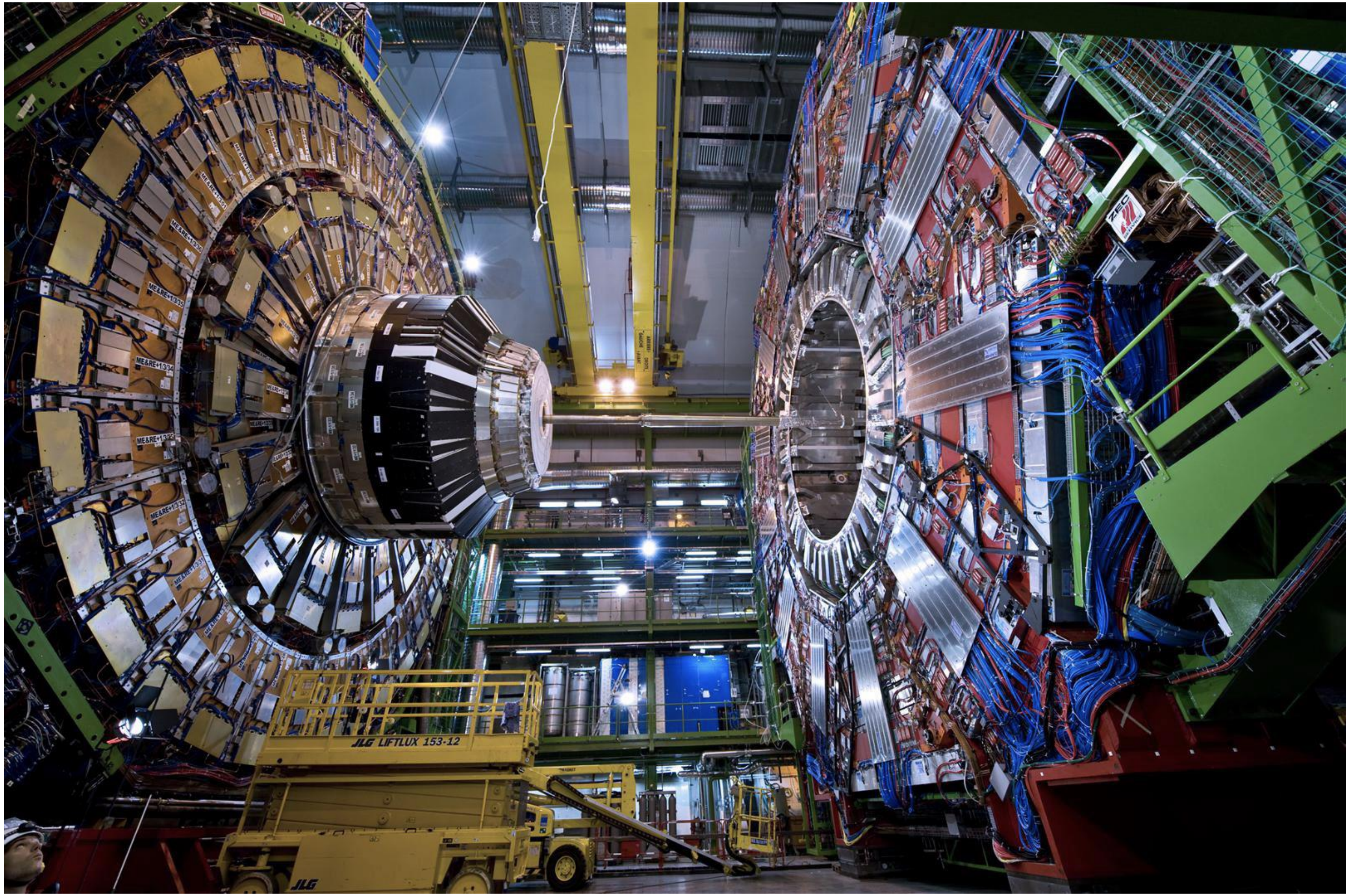
?

Image credit: ESA and the Planck Collaboration

How can we detect dark matter?

Image credit: ESA and the Planck Collaboration

Collider Searches



Production at LHC

CERN|LHC

Direct Detection

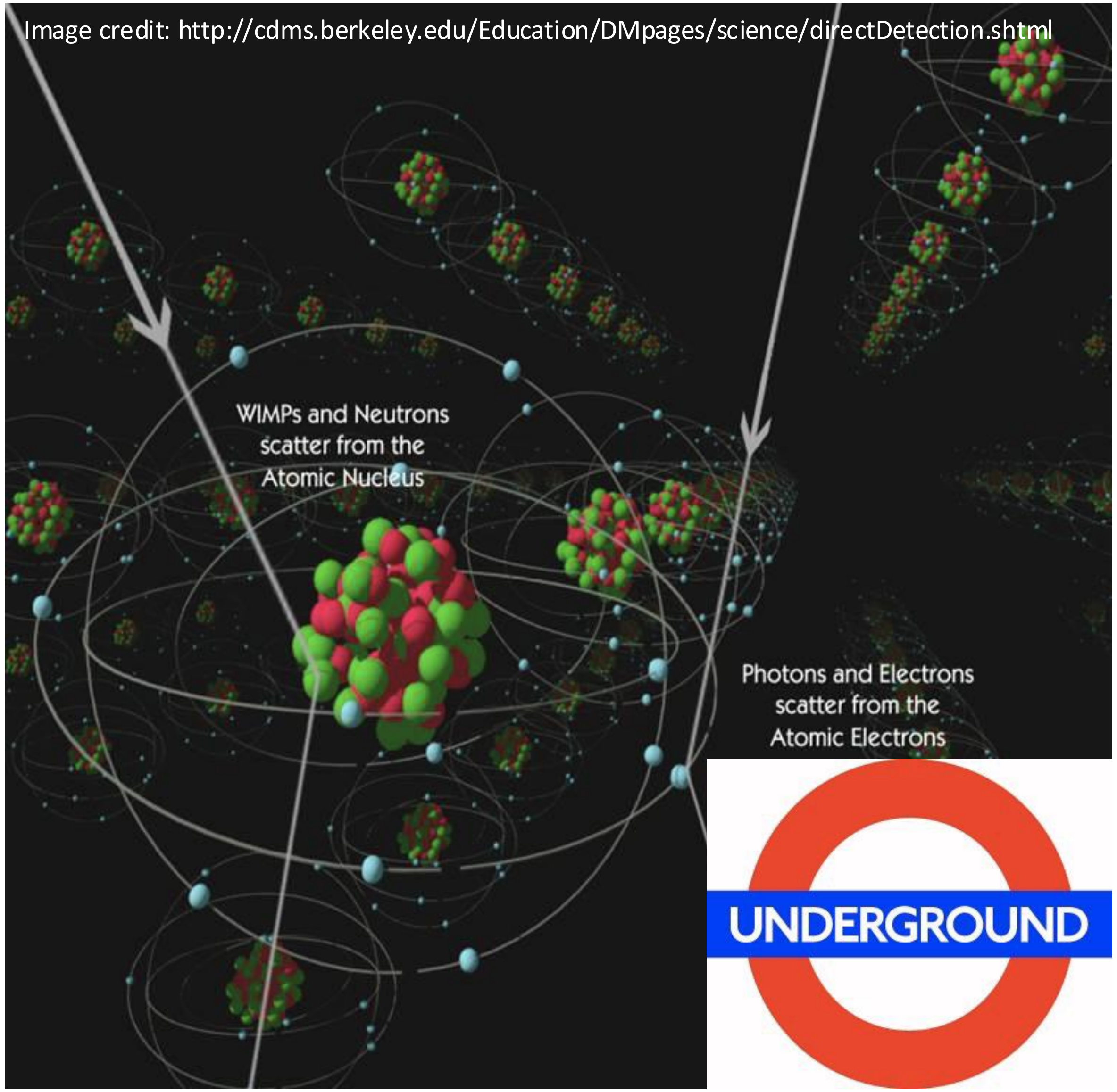
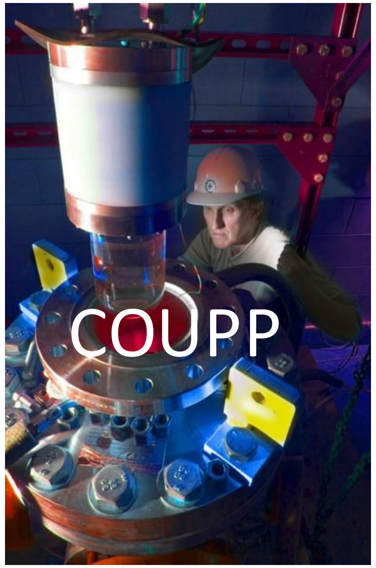
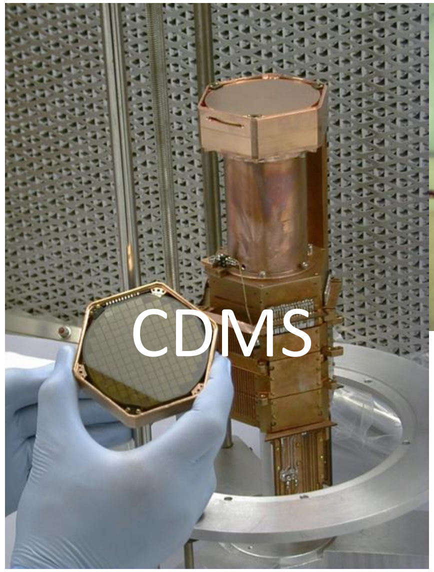
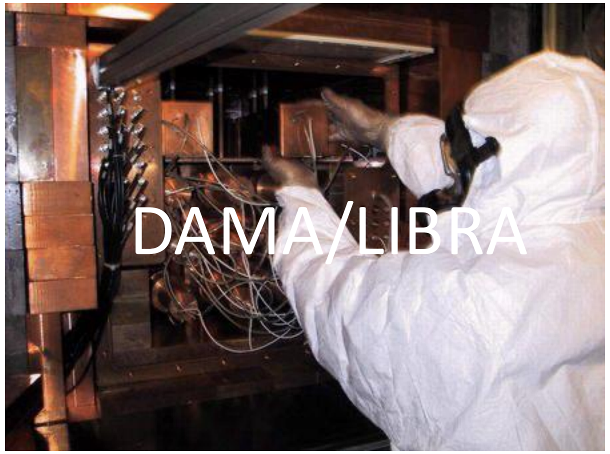


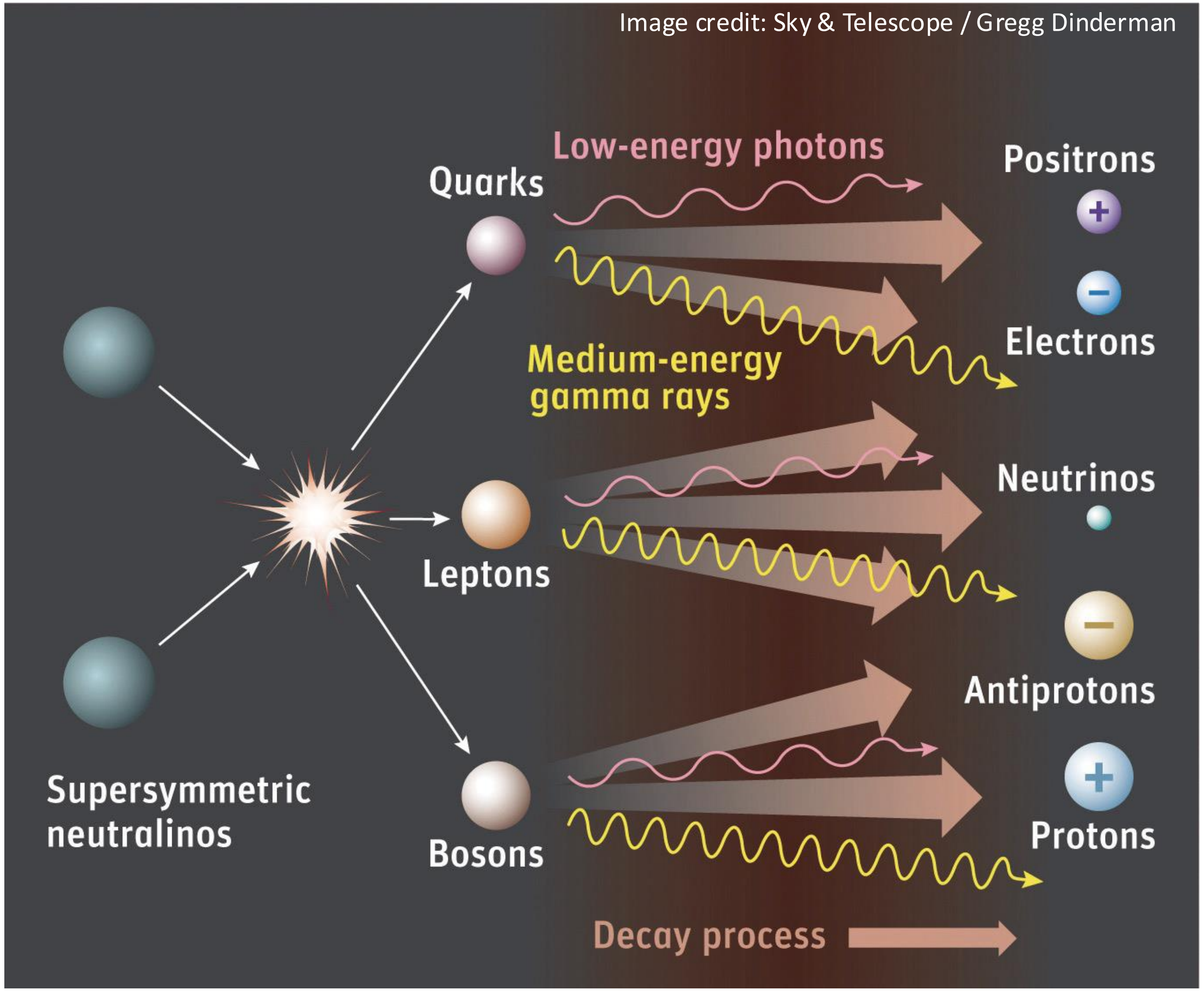
Image credit: http://cdms.berkeley.edu/Education/DMpages/science/directDetection.shtml

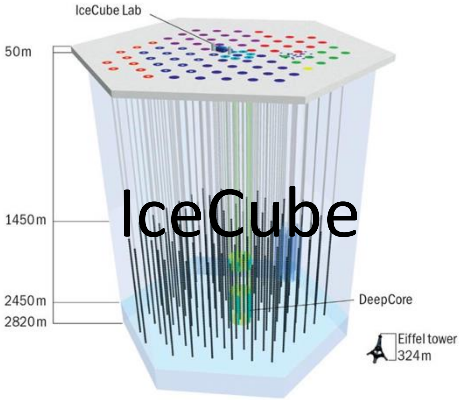




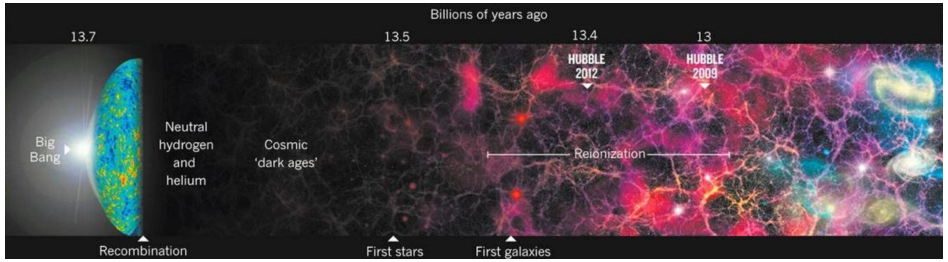


Indirect Detection

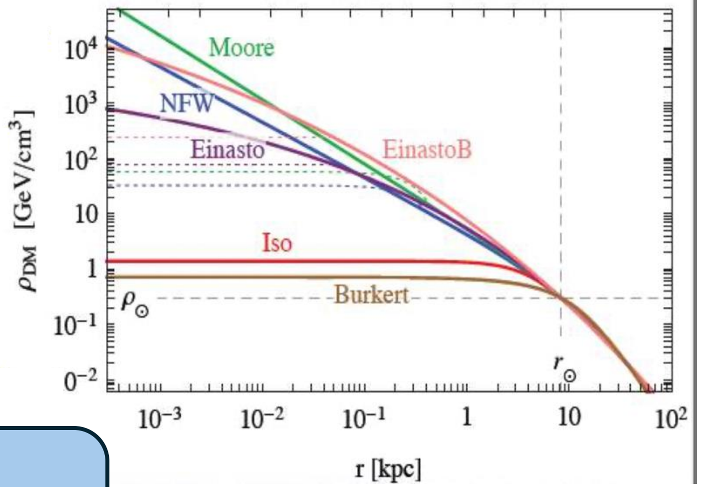




Dark Matter Annihilation



$$\rho_{\rm dm}(r) = \frac{\rho_{\rm s}}{\left(\frac{r}{r_{\rm s}}\right)^{\alpha}\left(1+\frac{r}{r_{\rm s}}\right)^{3-\alpha}}$$



From Thermal Relics

$\langle\sigma v\rangle = 2.6 \times 10^{-26}$ cm³/s

Number of Particle

Density Profile of DM

$$Q = \eta\, \boxed{n_{dm}(r)\, n_{dm*}(r)}\, \langle\sigma v\rangle \frac{dN}{dE} = \eta \boxed{\left[\frac{\rho_{dm}(r)}{m_{dm}}\right]^2} \langle\sigma v\rangle \frac{dN}{dE}$$

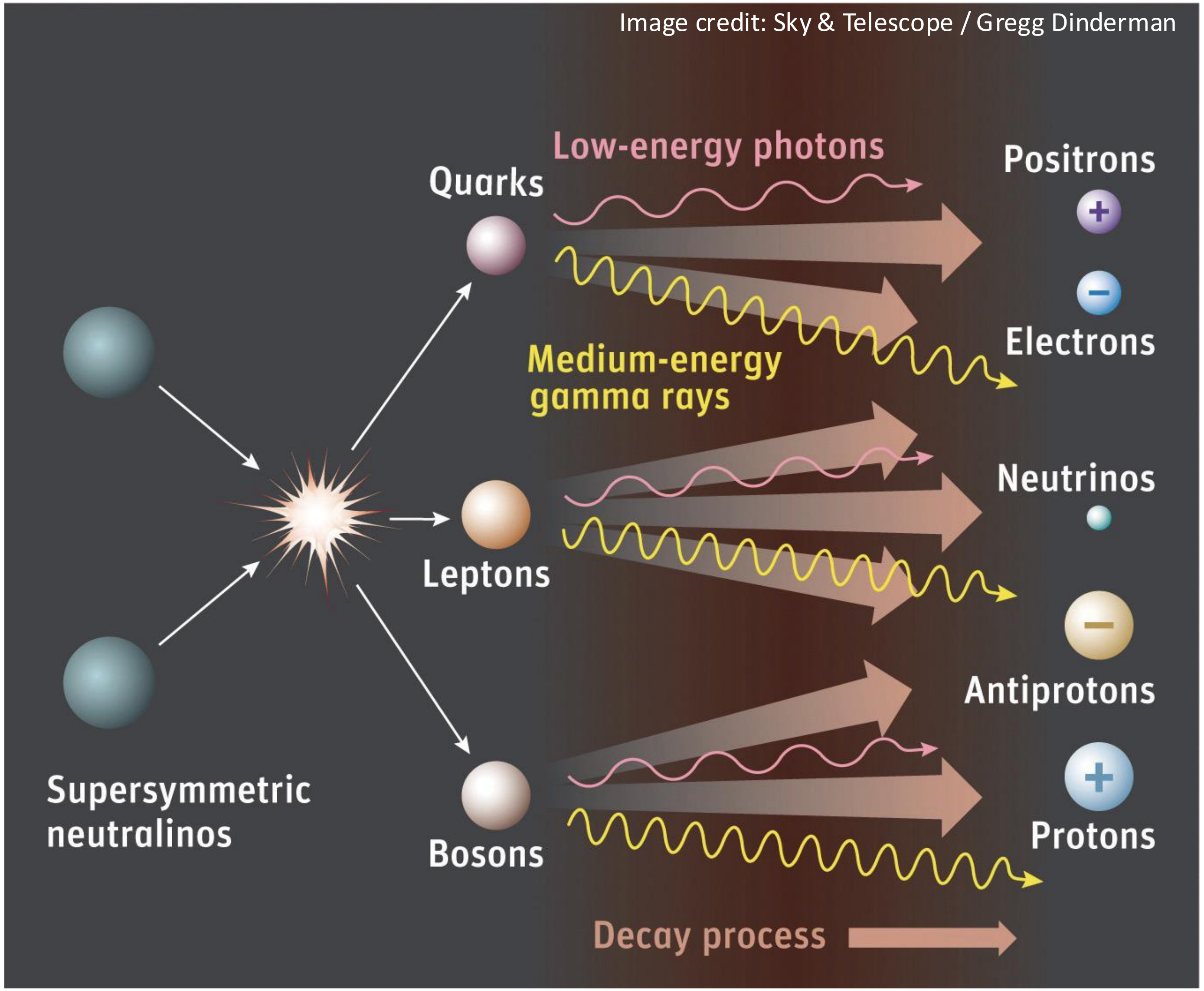
$\frac{1}{2}$ or $\frac{1}{4}$

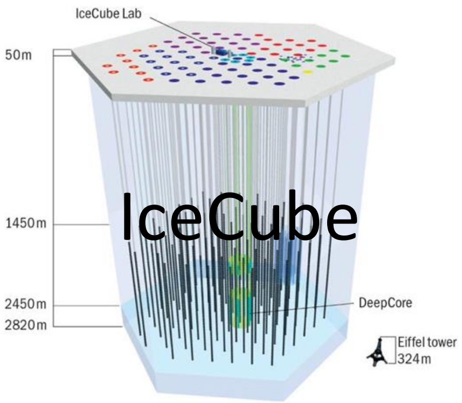
Number Density of DM Particle

Annihilation Cross-Section

Mass of DM Particle

Indirect Detection



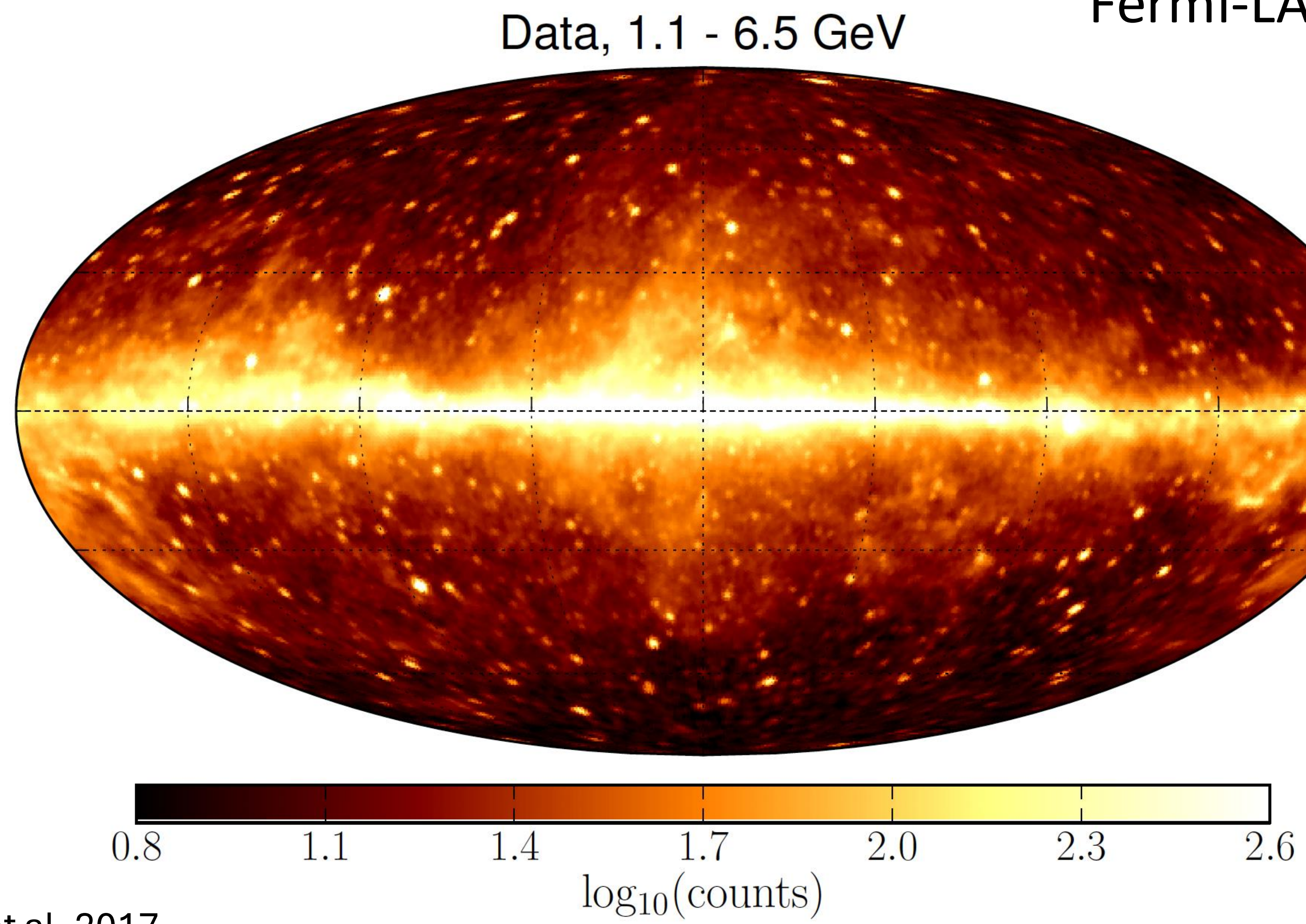


Multi-Messenger of Dark Matter Annihilation

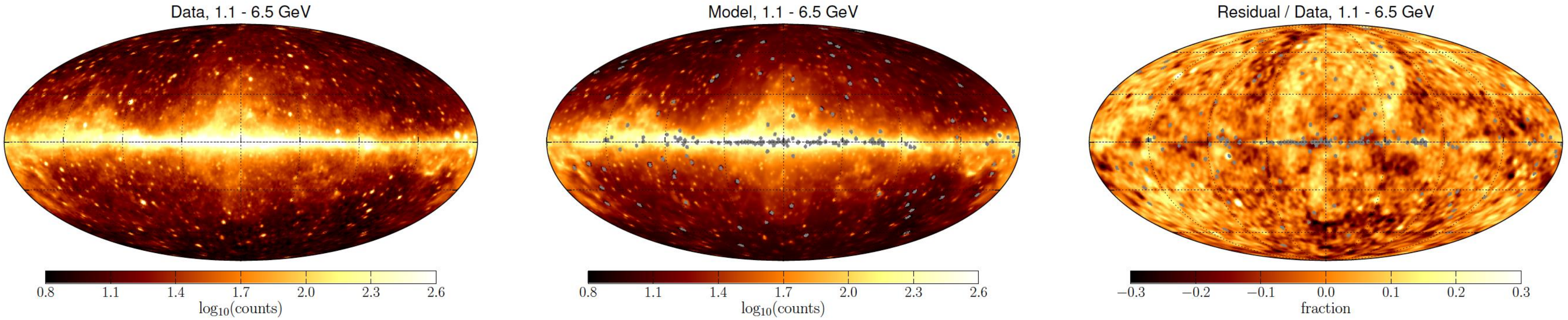
Messenger	Observable	Main Experiments
γ-rays	Continuum, lines	Fermi-LAT, H.E.S.S., MAGIC, CTA
Cosmic rays (e^+, $\bar{p}$)	Energy spectra	AMS-02, DAMPE, CALET
Neutrinos	Upgoing muons	IceCube, ANTARES, KM3NeT
Radio/X-rays	Synchrotron, IC	Planck, SKA, Chandra

Galactic Centre Excess

Fermi-LAT all Sky Map



Ackermann et al. 2017

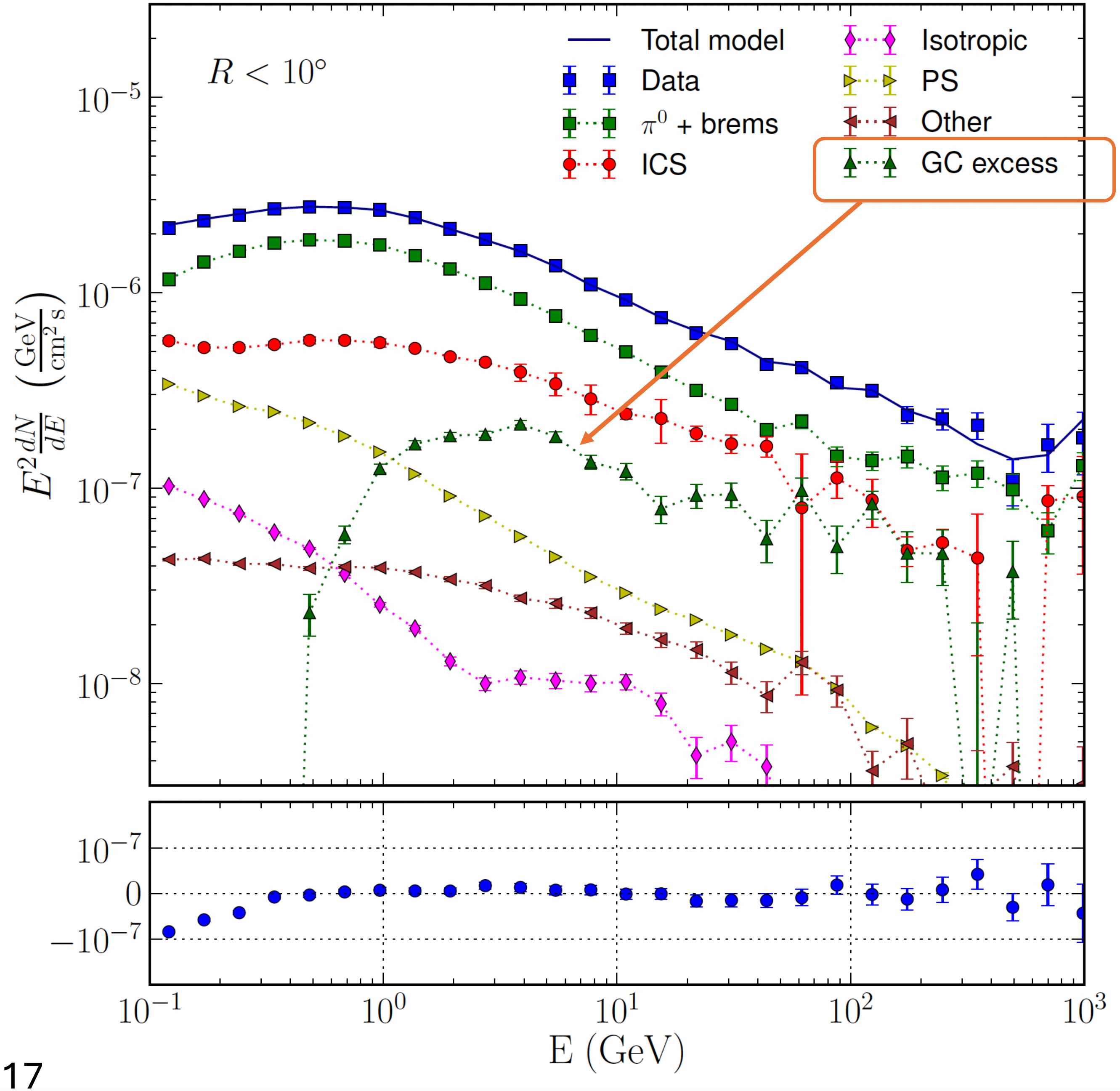


Data

Model

Residual

Ackermann et al. 2017



Ackermann et al. 2017

Explain the Galactic Centre Excess by Dark Matter Annihilation

Production of Gamma Rays from Dark matter

$$Q = \eta \boxed{n_{dm}(r) n_{dm*}(r)} \langle \sigma v \rangle_\gamma \frac{dN_\gamma}{dE} = \eta \boxed{\left[\frac{\rho_{dm}(r)}{m_{dm}} \right]^2} \langle \sigma v \rangle_\gamma \frac{dN_\gamma}{dE}$$

Flux of gamma rays

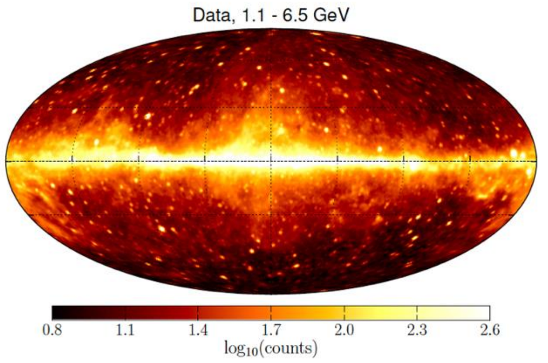
Astrophysics

Majorana or Not (1/2 or 1/4)

Particle Physics

$$\frac{d\phi}{dE} = \frac{1}{4\pi} \int_{l.o.s} \rho^2_{dm}(r)\, dr \frac{\eta \langle \sigma v \rangle}{m^2_{dm}} \sum_i \frac{dN_i}{dE}$$

Spectrum of gamma rays from DM annihilation



All Sky

DM density profile

Mass of DM particles

Annihilation cross-section

Define flux of gamma-ray

Flux of gamma rays

Astrophysics

Majorana or Not (1/2 or 1/4)

Particle Physics

$$\frac{d\phi}{dE} = \frac{1}{4\pi}\int_{l.o.s} \rho_{dm}^{2}(r)\, dr \; \frac{\eta\langle\sigma v\rangle}{m_{dm}^{2}} \sum_i \frac{dN_i}{dE}$$

Spectrum of gamma rays from DM annihilation

All Sky

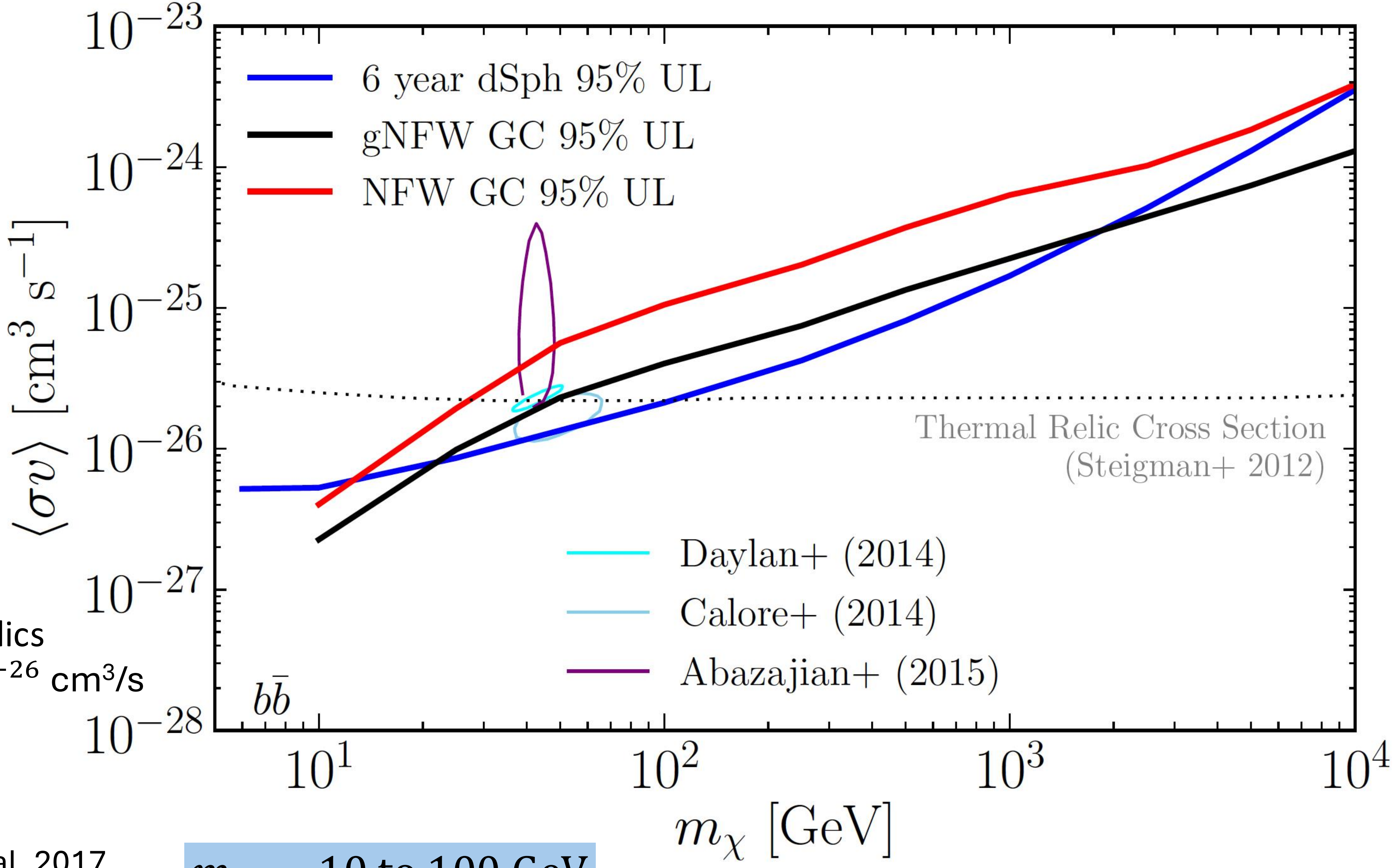
DM density profile

Mass of DM particles

Annihilation cross-section

J- Factor

Define the shape profile of gamma-ray

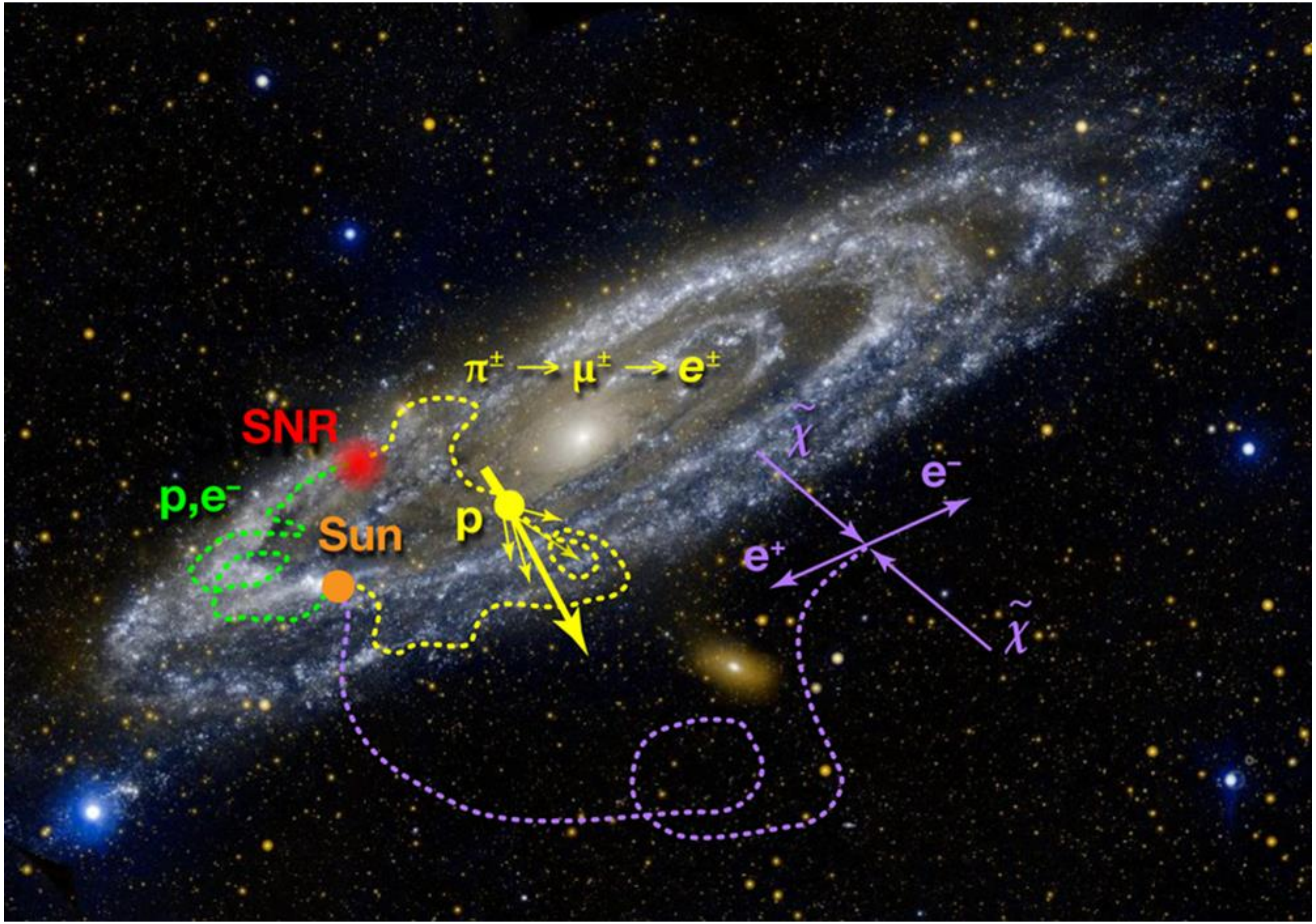


From Thermal Relics
$\langle \sigma v \rangle = 2.6 \times 10^{-26}$ cm^3/s

Ackermann et al. 2017

$m_{DM} \sim 10$ to 100 GeV

Electron and Positron Excess



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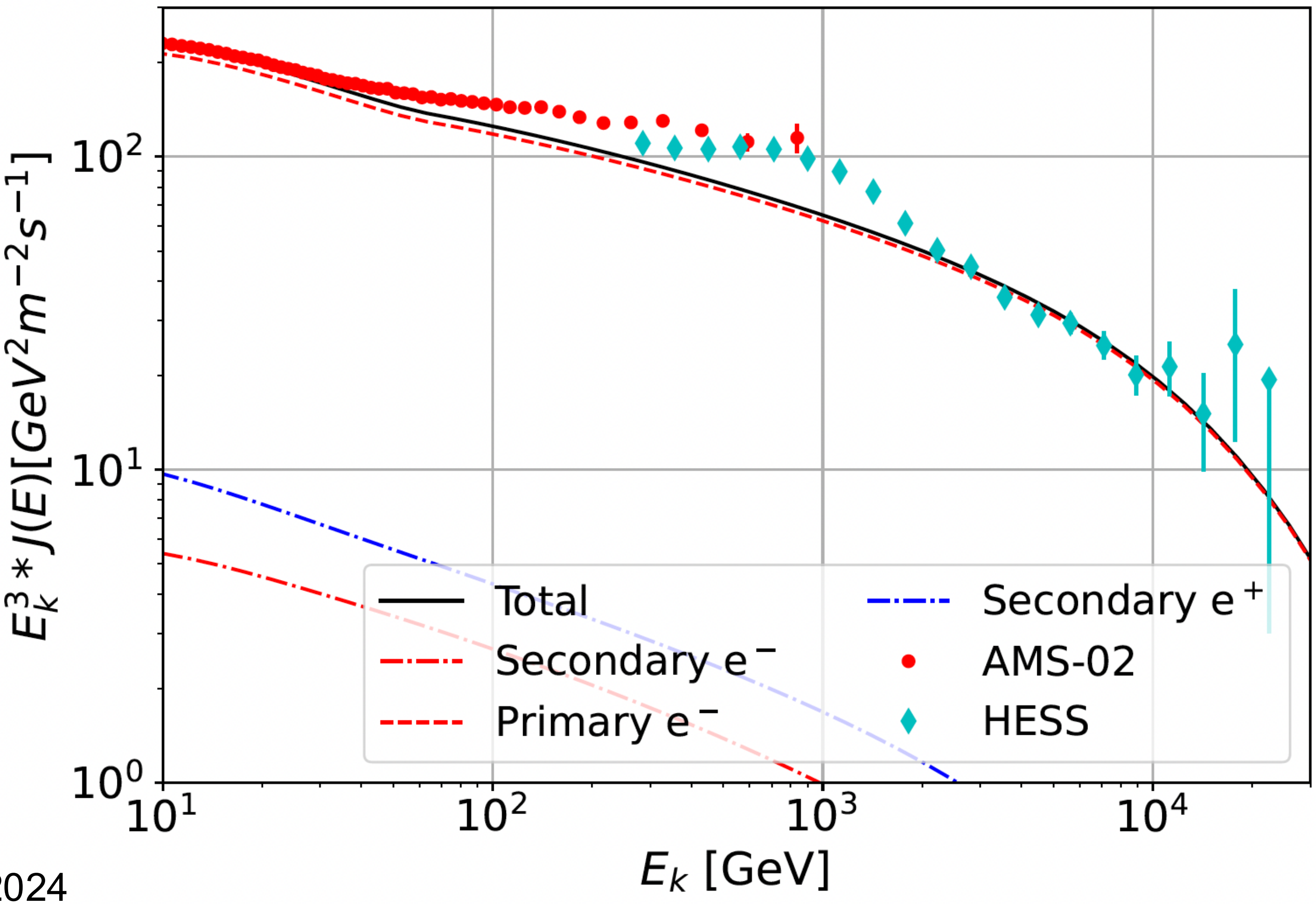
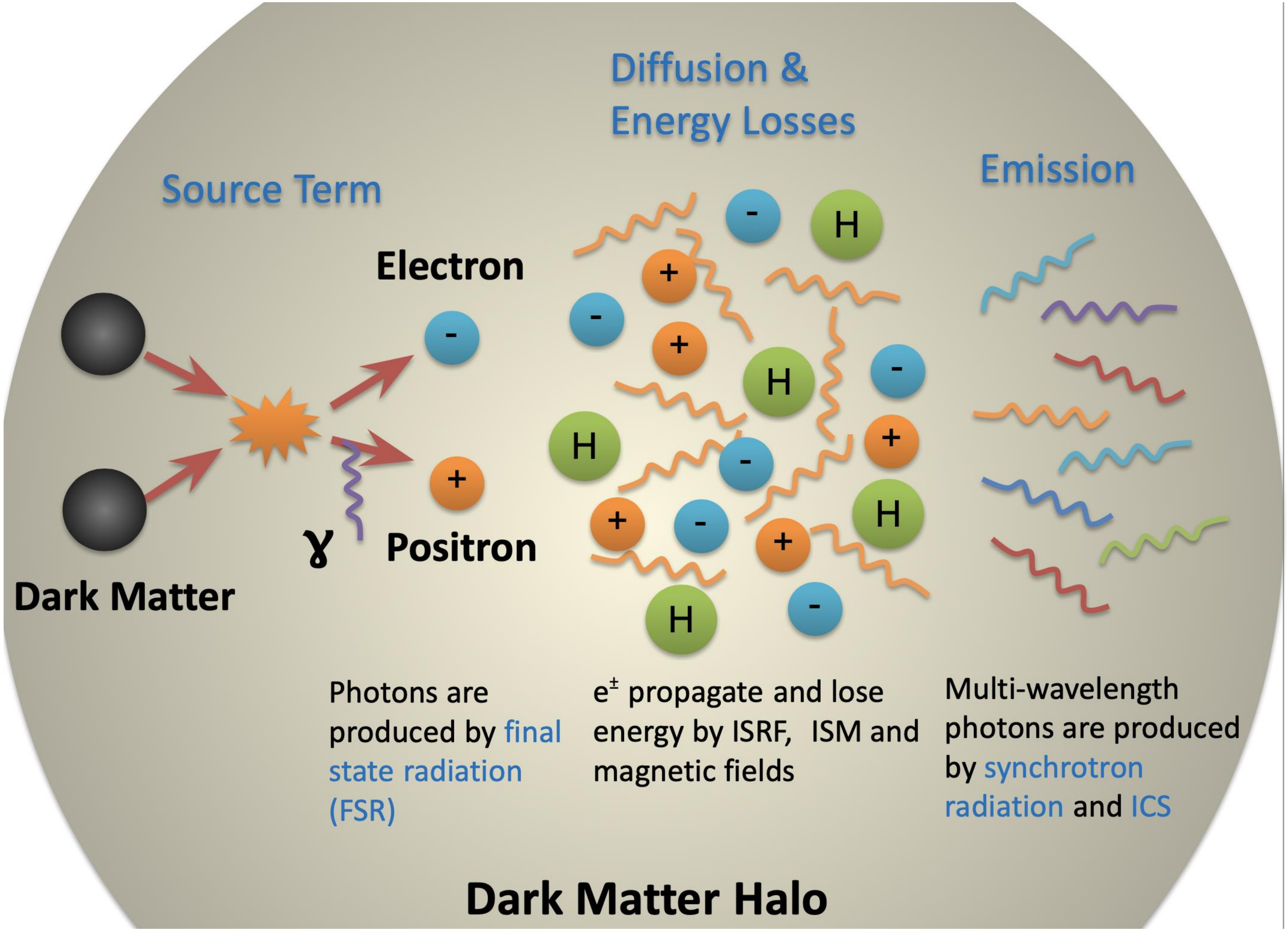


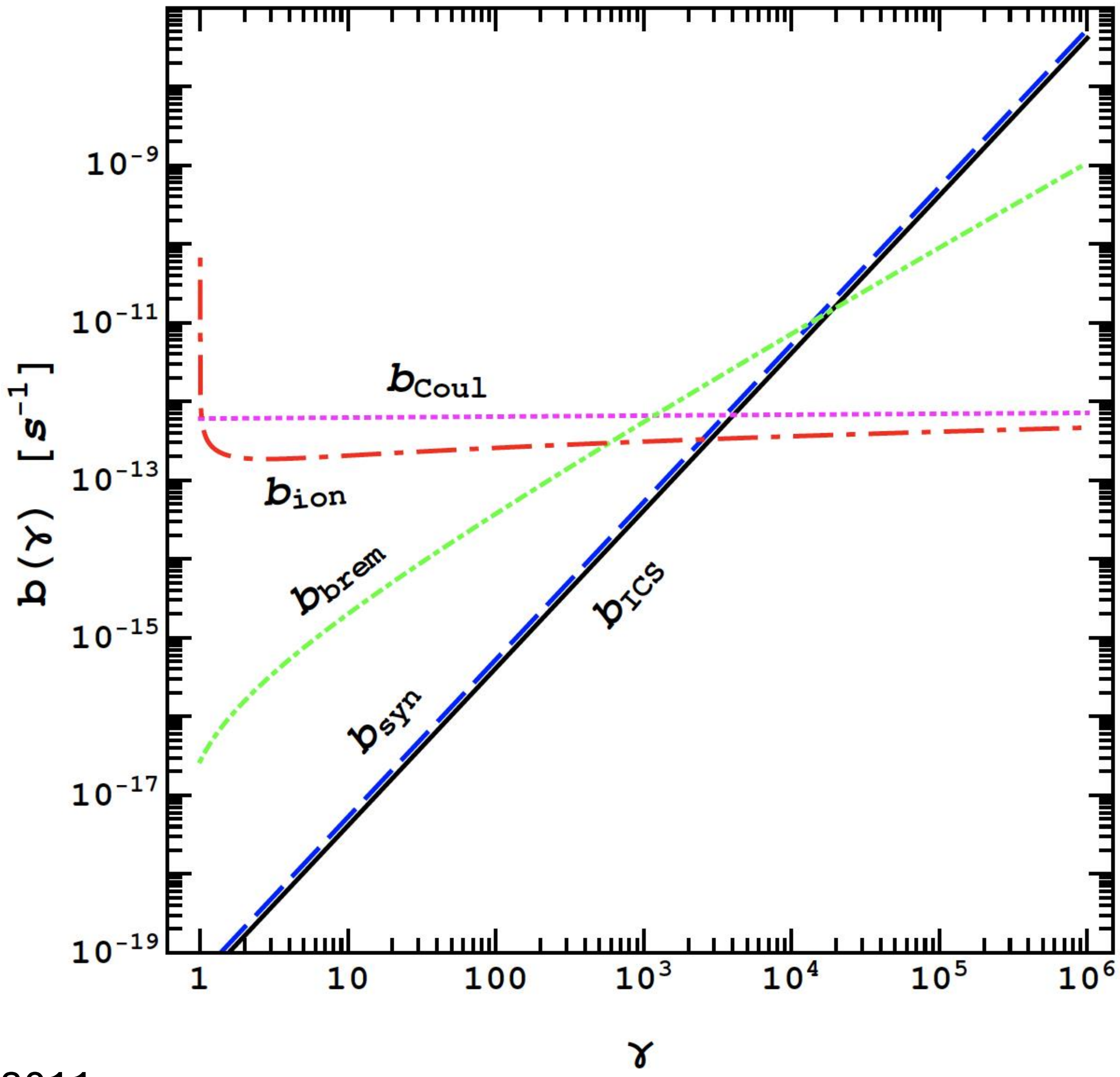
Rocamora et al. 2024


Diffusion &
Energy Losses
Source Term
Emission
Electron
Dark Matter
ɣ
Positron
Photons are produced by final state radiation (FSR)
e± propagate and lose energy by ISRF, ISM and magnetic fields
Multi-wavelength photons are produced by synchrotron radiation and ICS
Dark Matter Halo

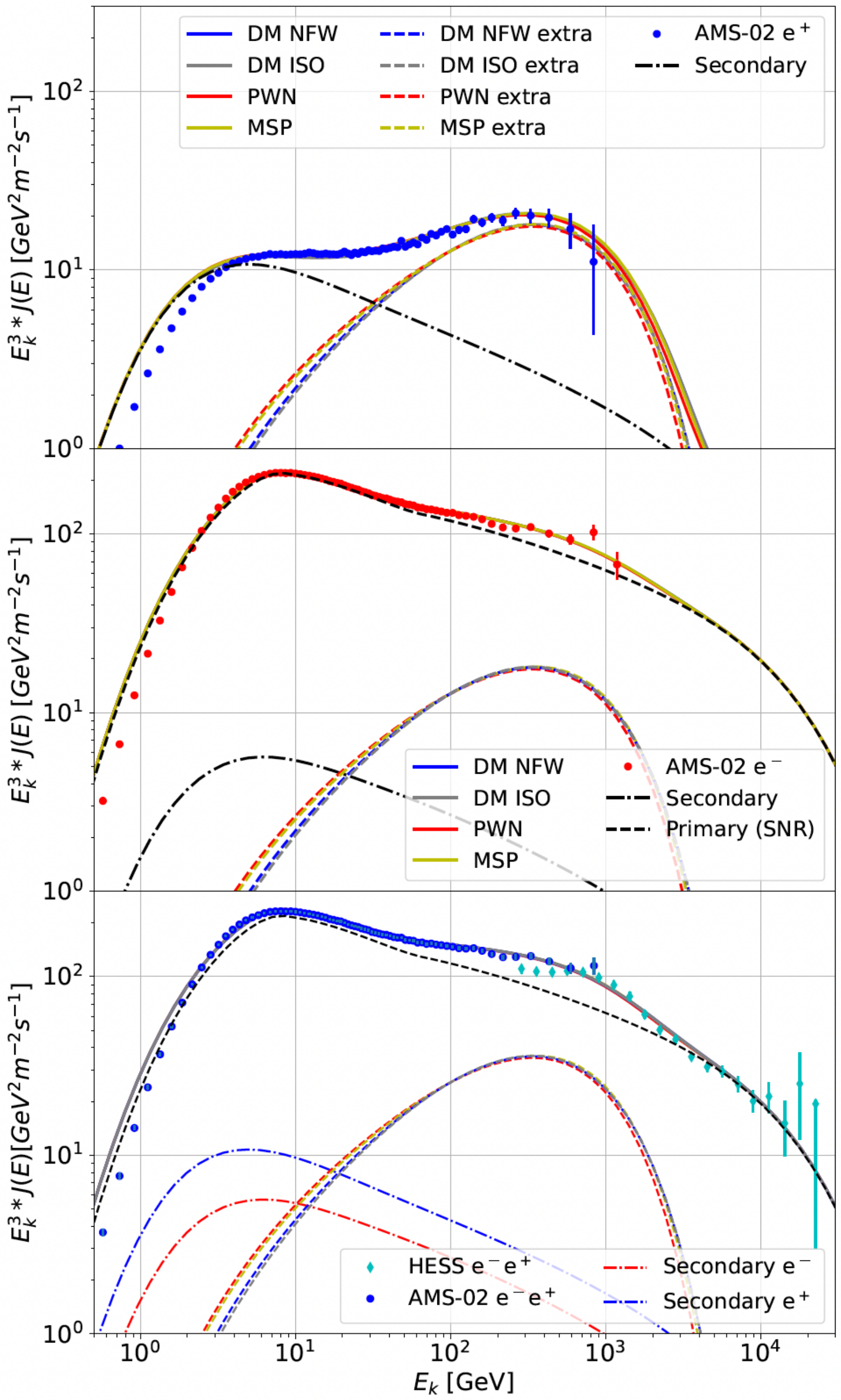
Electron and Positron Propagation

Diffusion-Loss Equation

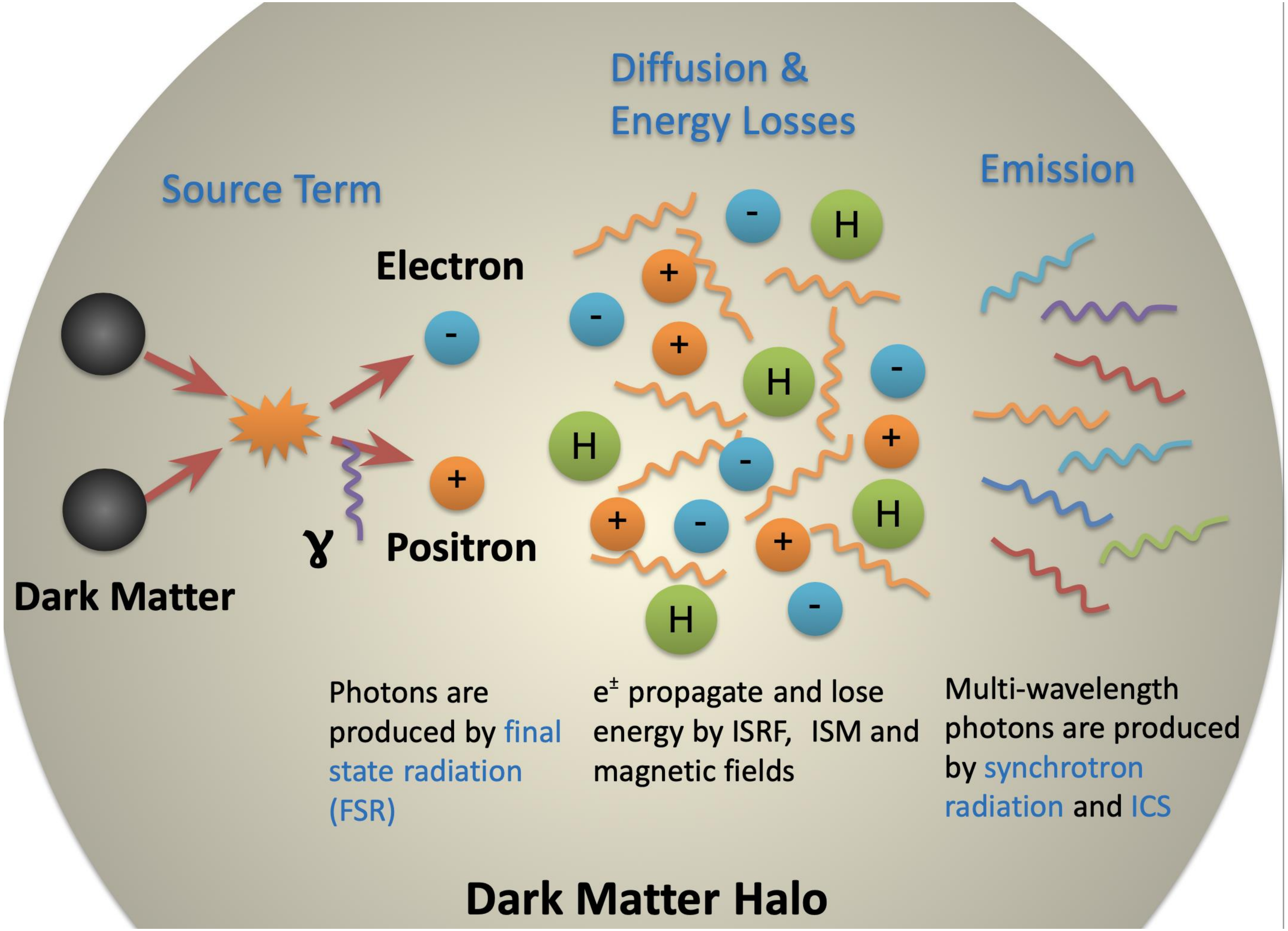
$$\frac{\partial}{\partial t}\frac{\mathrm{d}n}{\mathrm{d}\gamma}(\mathbf{x},\gamma) = \nabla\left[\underbrace{K(\mathbf{x},\gamma)}_{\text{Diffusion}}\nabla\frac{\mathrm{d}n}{\mathrm{d}\gamma}(\mathbf{x},\gamma)\right] + \frac{\partial}{\partial\gamma}\left[\underbrace{b(\mathbf{x},\gamma)}_{\text{Loss Rate}}\frac{\mathrm{d}n}{\mathrm{d}\gamma}(\mathbf{x},\gamma)\right] + \underbrace{Q(\mathbf{x},\gamma)}_{\text{Source Term, DM, Pulsar}}.$$



Wechakama & Ascasibar 2011



Rocamora et al. 2024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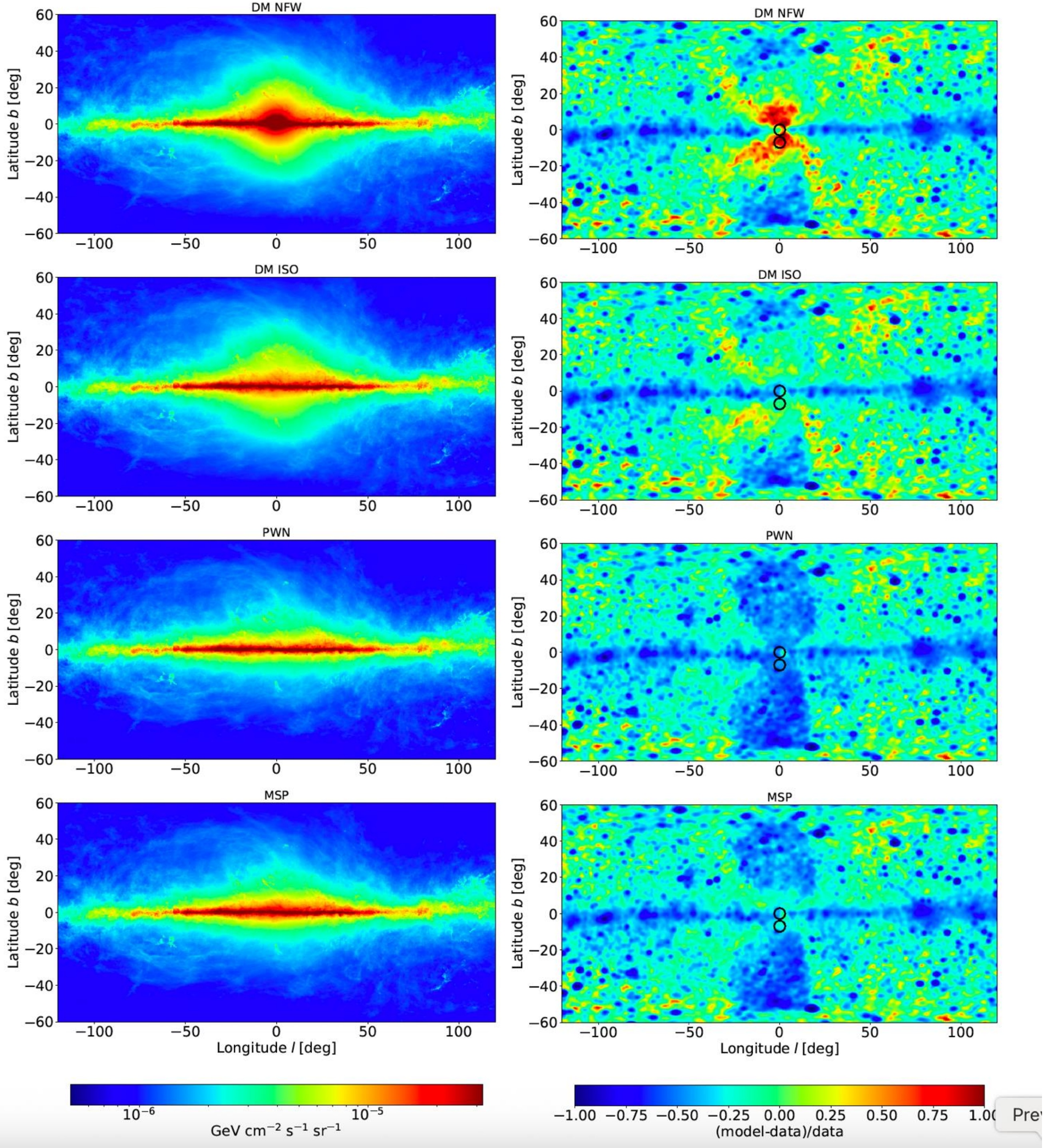
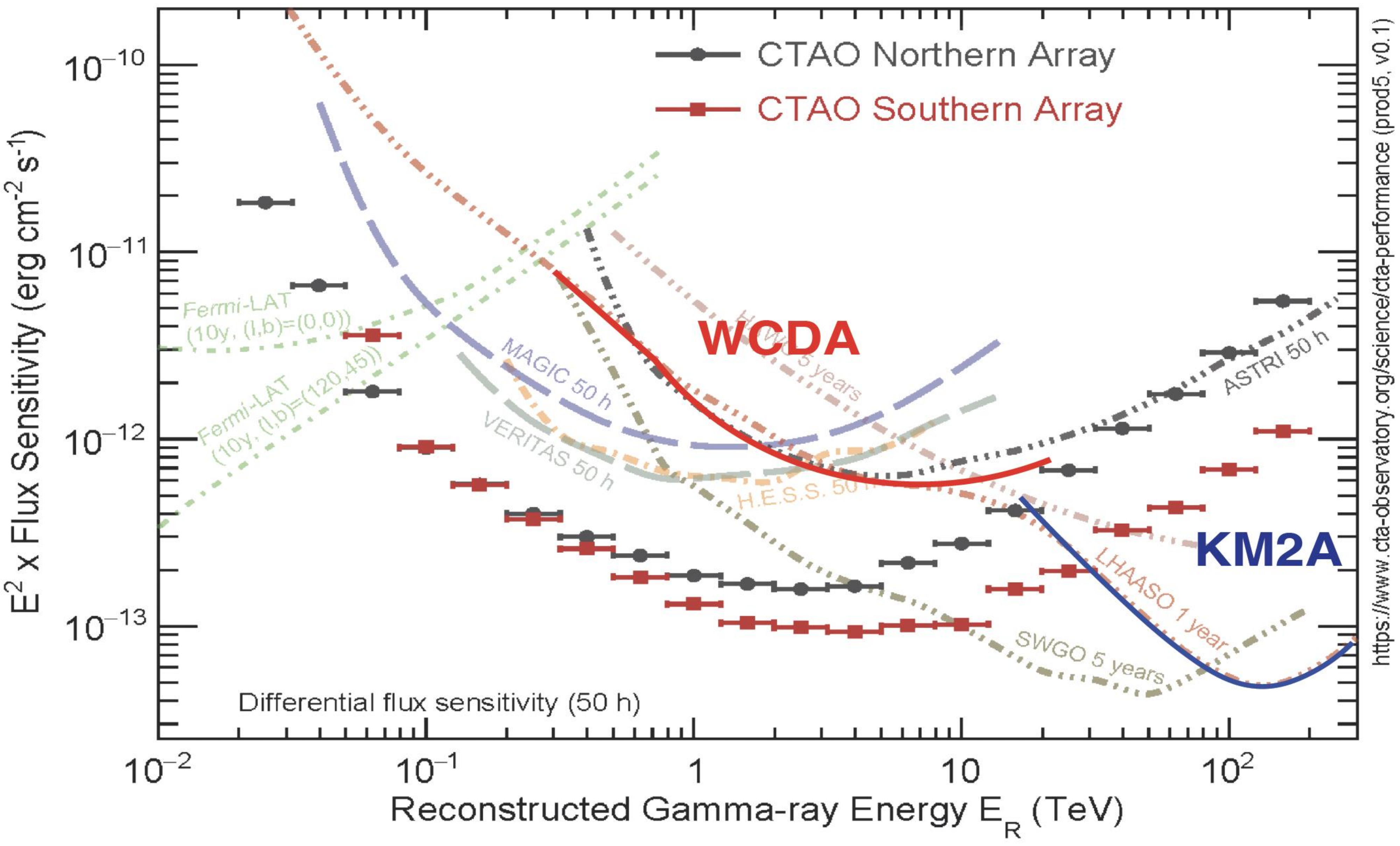


Rocamora et al. 2024

Conclusions

- Indirect detection searches for secondary particles (γ-rays, e^+/e^-, antiprotons, neutrinos) produced by dark matter annihilation or decay in astrophysical environments.
- Main Observational Hints:
  - Galactic Center GeV excess: possible DM signature, but pulsars remain a strong alternative.
  - Positron excess: shows an unexpected rise above 10 GeV; can be explain by pulsars and dark matter
- Future instruments (e.g., CTA, LHAASO, SWGO, SKA, IceCube-Gen2) will improve sensitivity by 1–2 orders of magnitude.
- Combining multi-wavelength and multi-messenger data remains the best path forward.



Domenico della Volpe$a$ and LHAASO Collaboration 2022