



National
Astronomical
Research
Institute of
Thailand

Multi-messenger Dark Matter Indirect Detection

Utane Sawangwit



Why do we need dark matter?

Rotation Curve of Galaxies

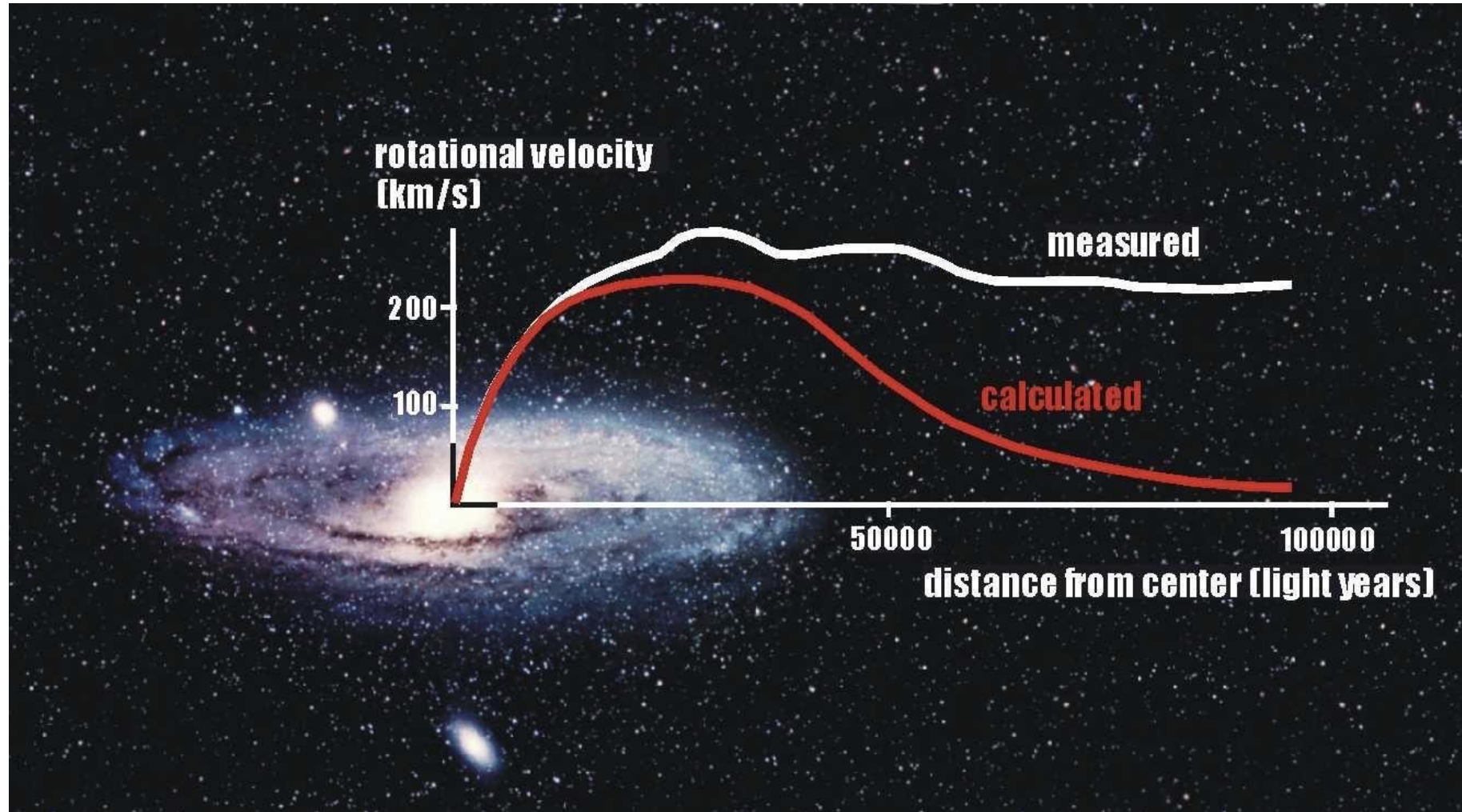
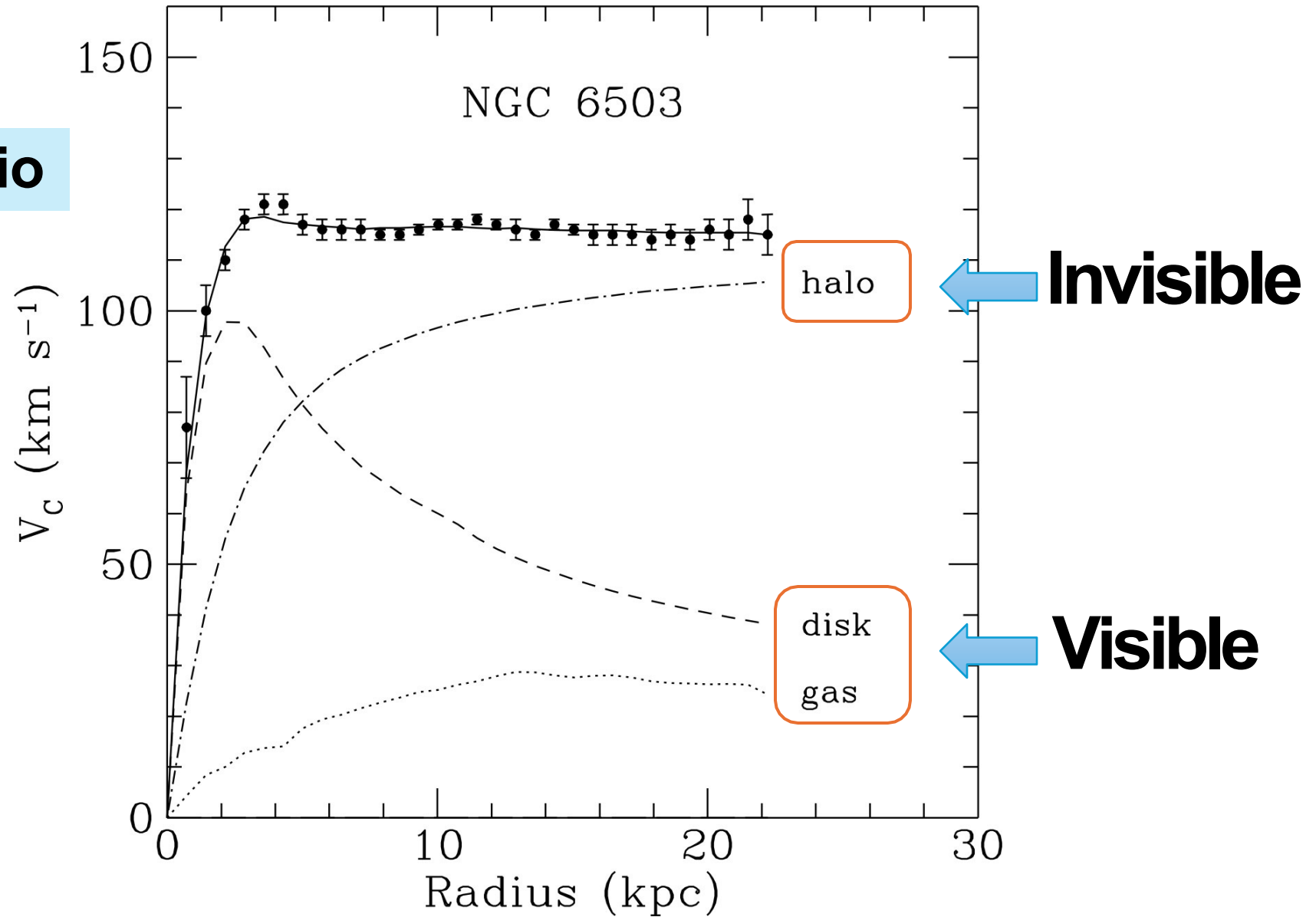


Image credit: http://cdms.phy.queensu.ca/Public_Docs/DM_Intro.html

Vera Rubin et. al. 1978: Measured velocity curves

Mass to Light Ratio

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



Begeman et al. 1991

Orbital Velocities of Galaxy Clusters

**Invisible
mass is
required!**

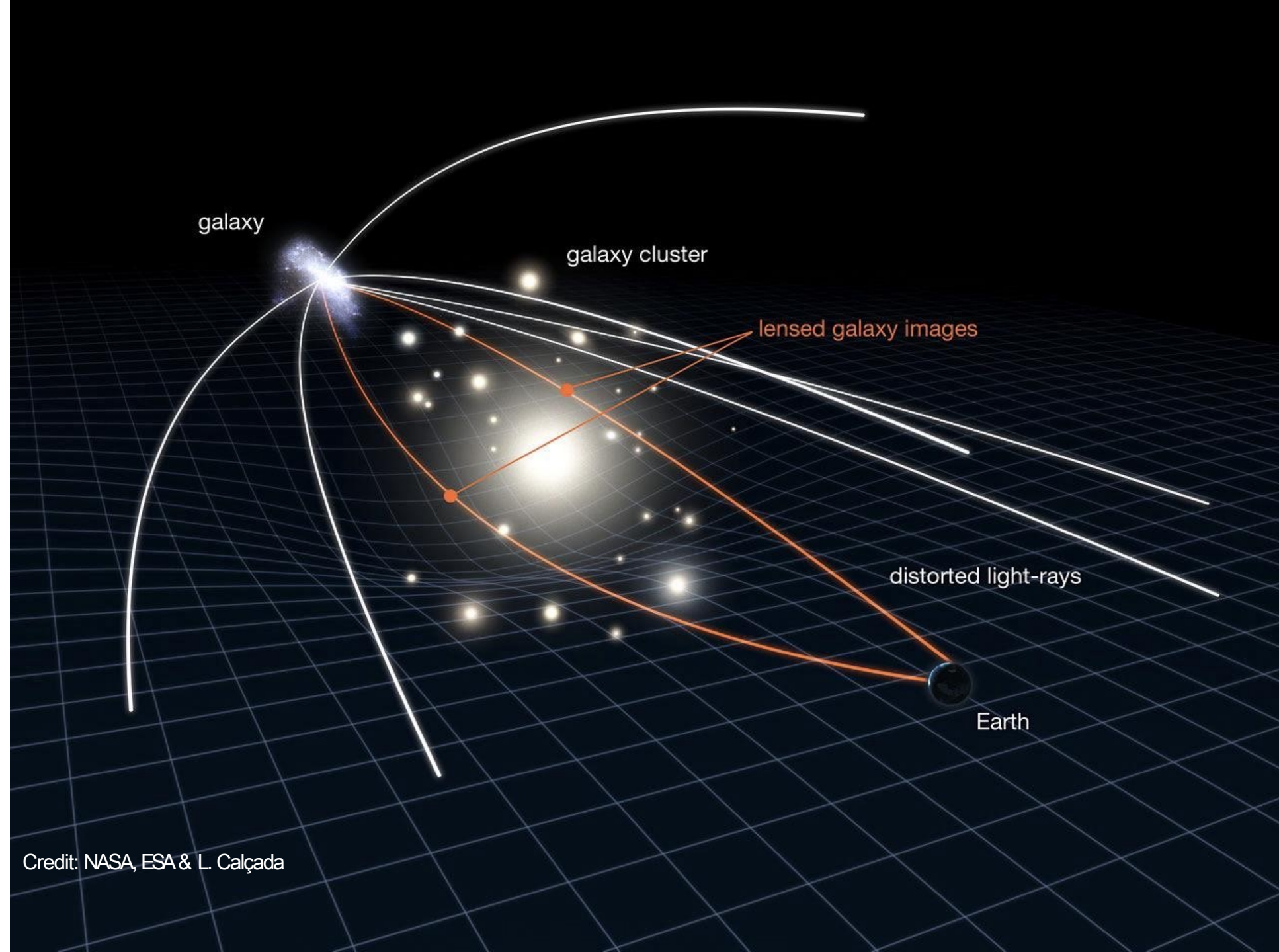


Gravitational Lensing



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

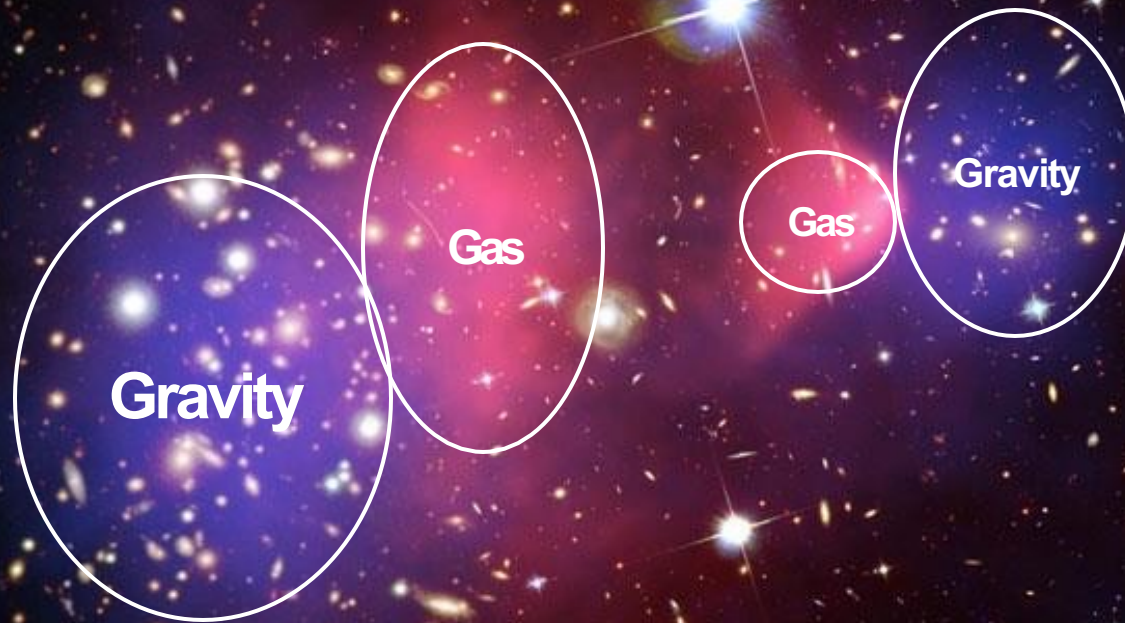
Lensing
reveals
invisible
mass!



Credit: NASA, ESA & L. Calçada

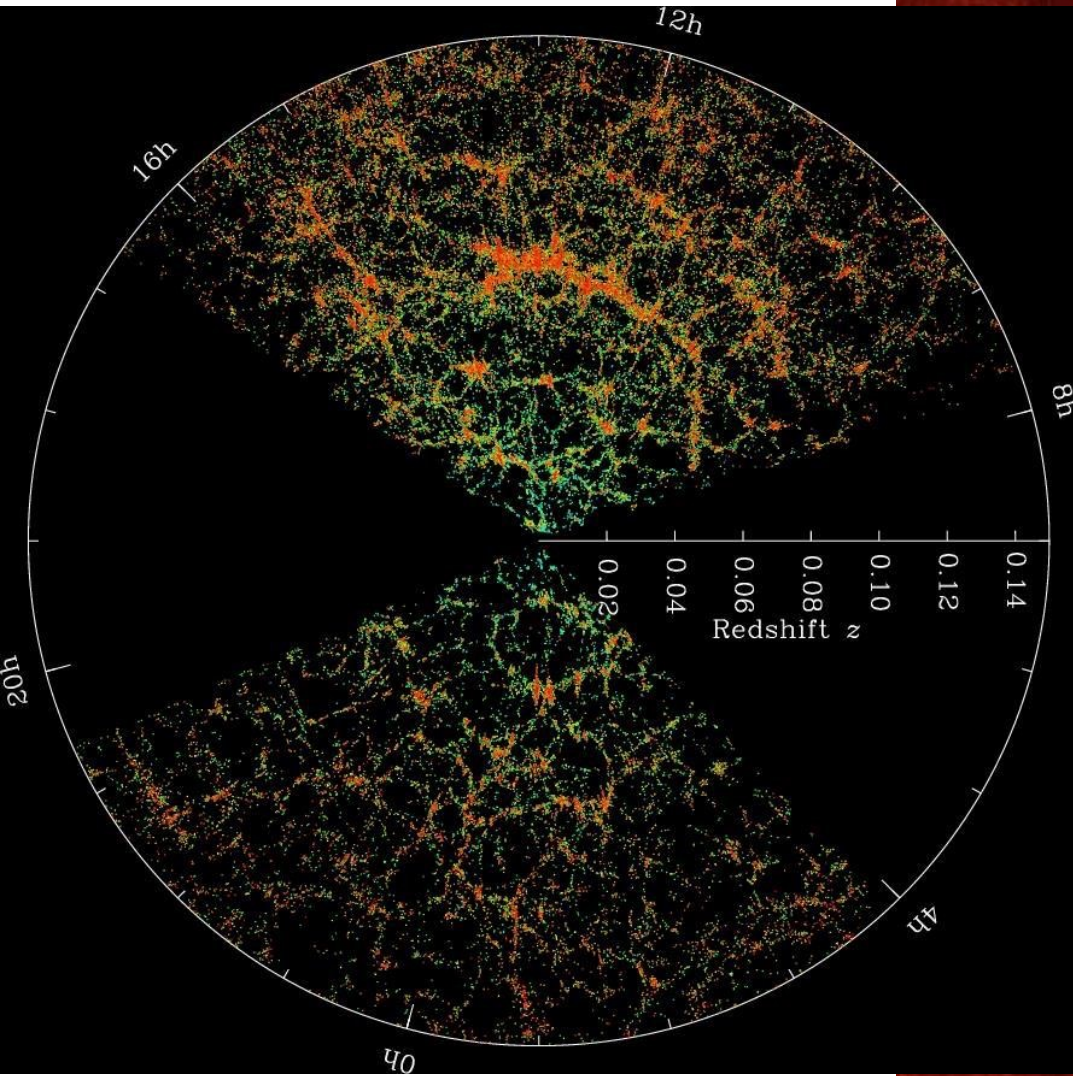
Bullet Cluster

**Gravity doesn't
follow the
visible matter!**



Dark matter create gravitational “seeds”

Structure Formation



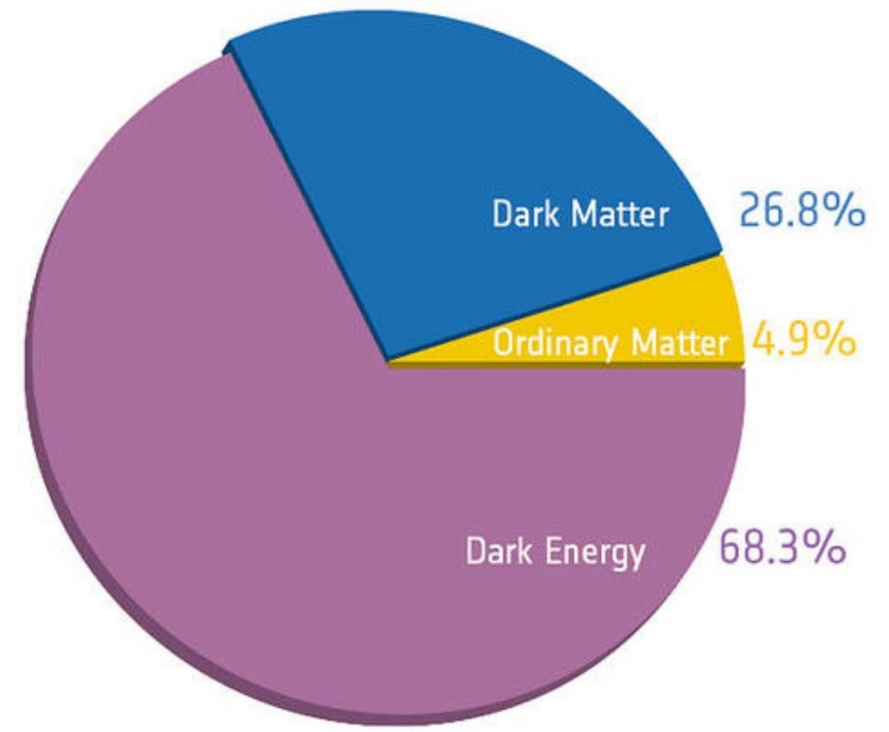
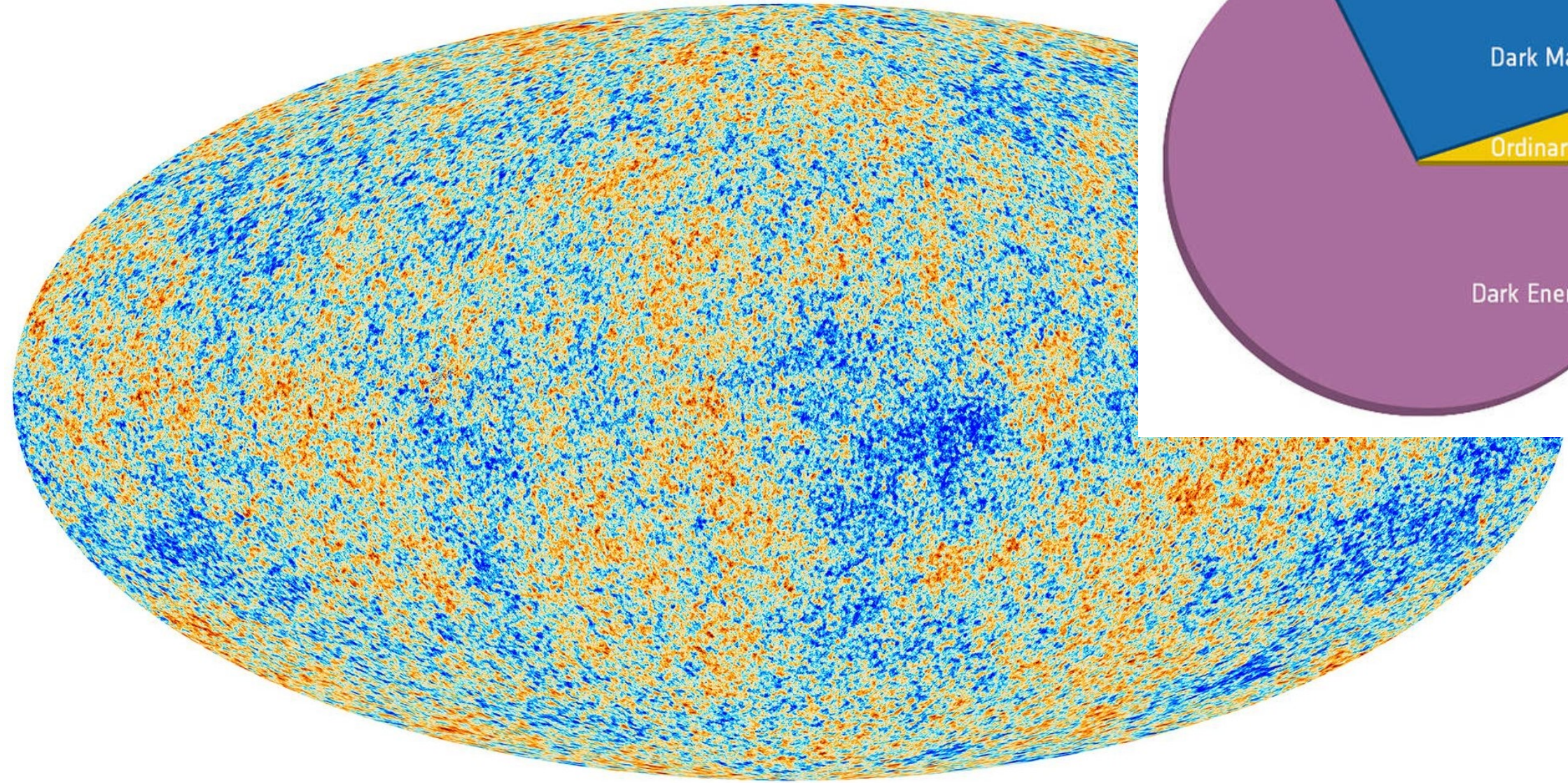
Sloan Digital Sky Survey

Virgo Cluster

Local Group

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

Cosmic Microwave Background



The evidence for dark matter is overwhelming!

Dark matter is essential for the Universe

What is Dark Matter?

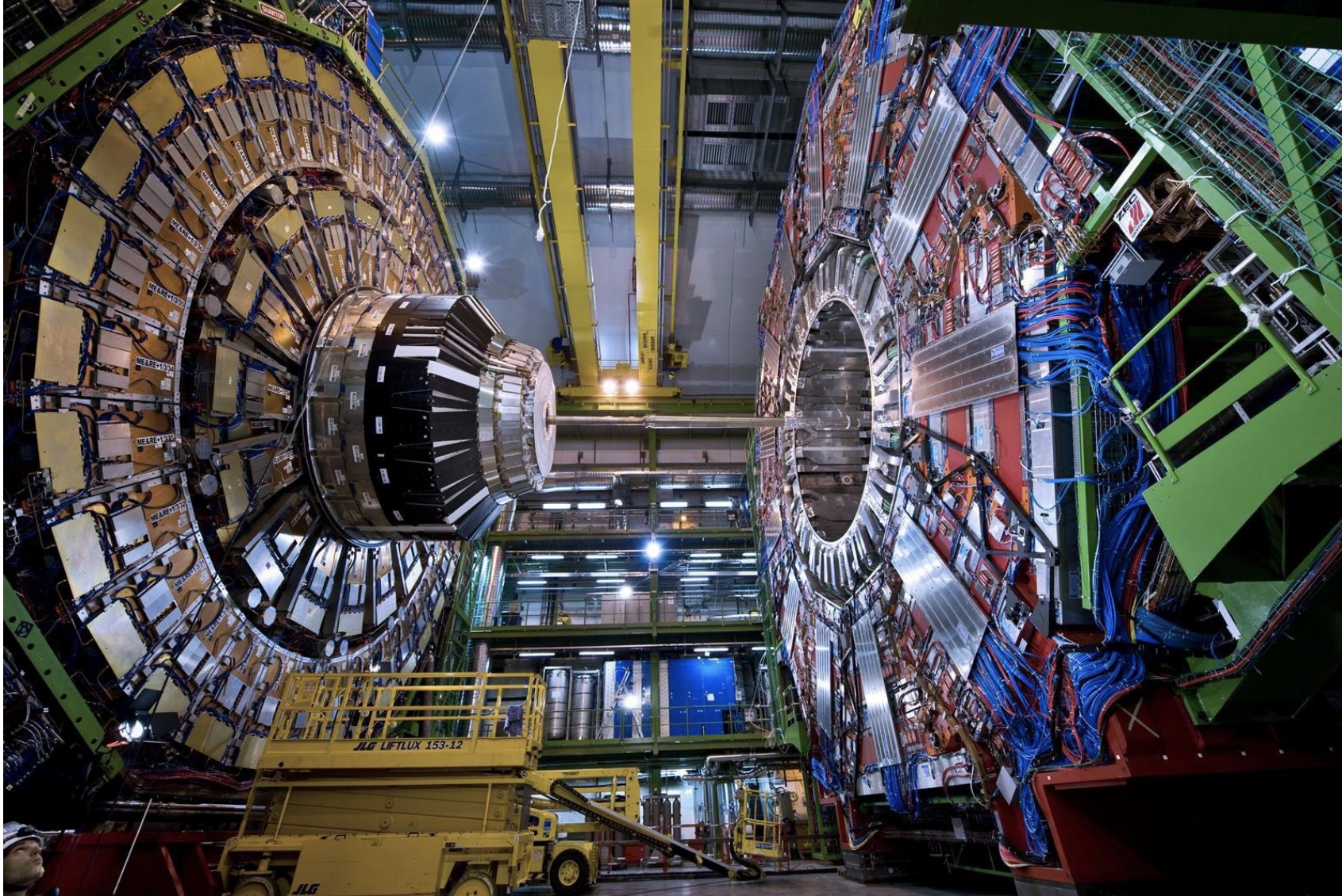
Dark Matter Properties

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



How can we detect dark matter?

Collider Searches

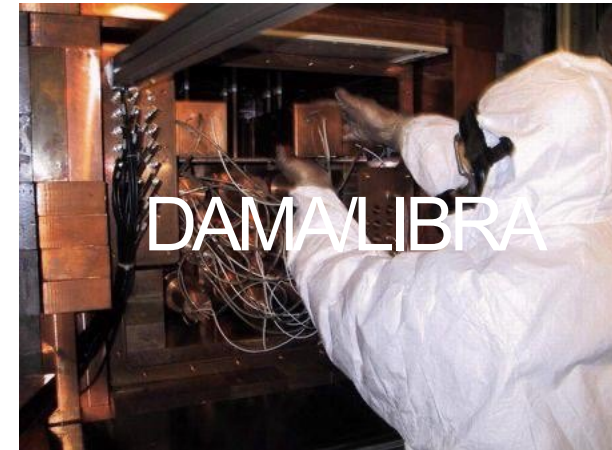
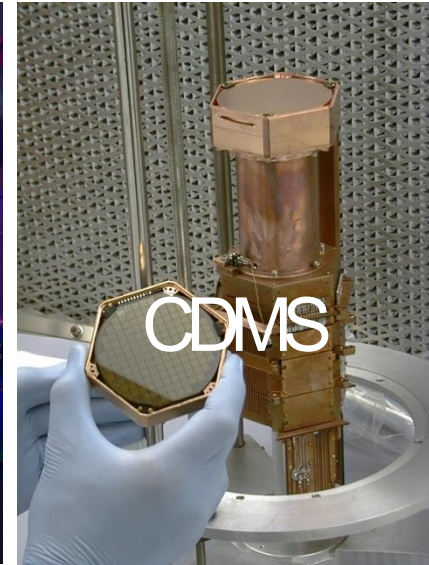
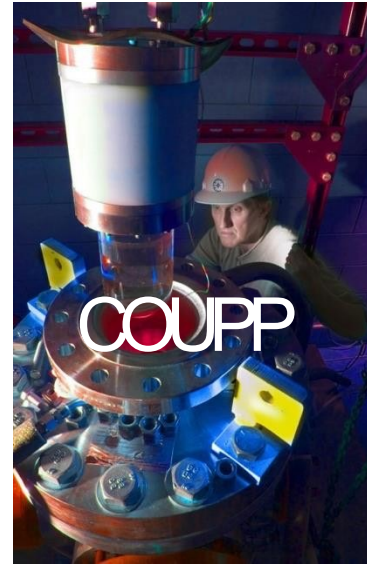
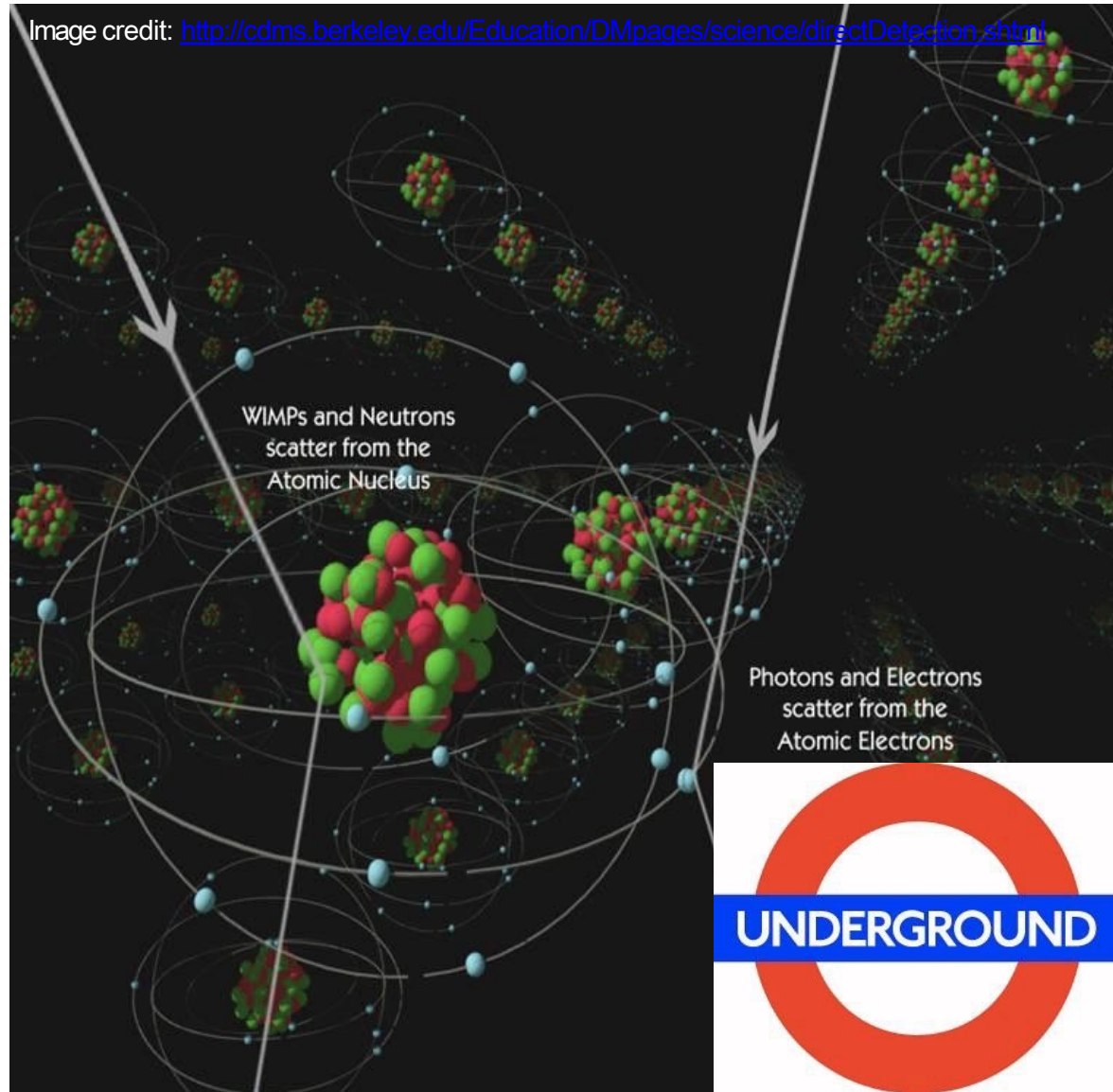


Production
at LHC

CERN | LHC

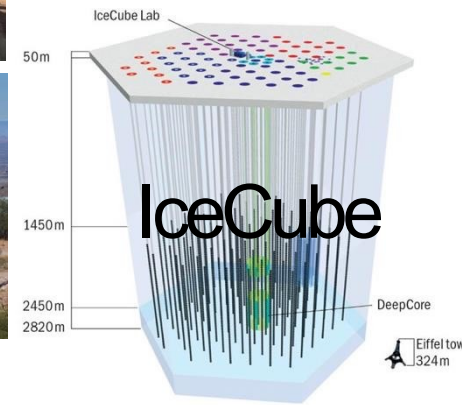
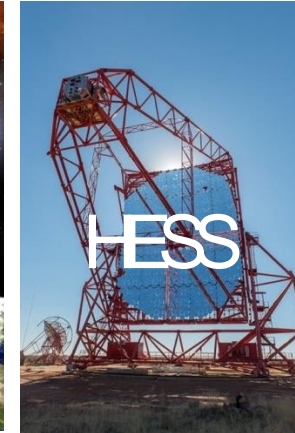
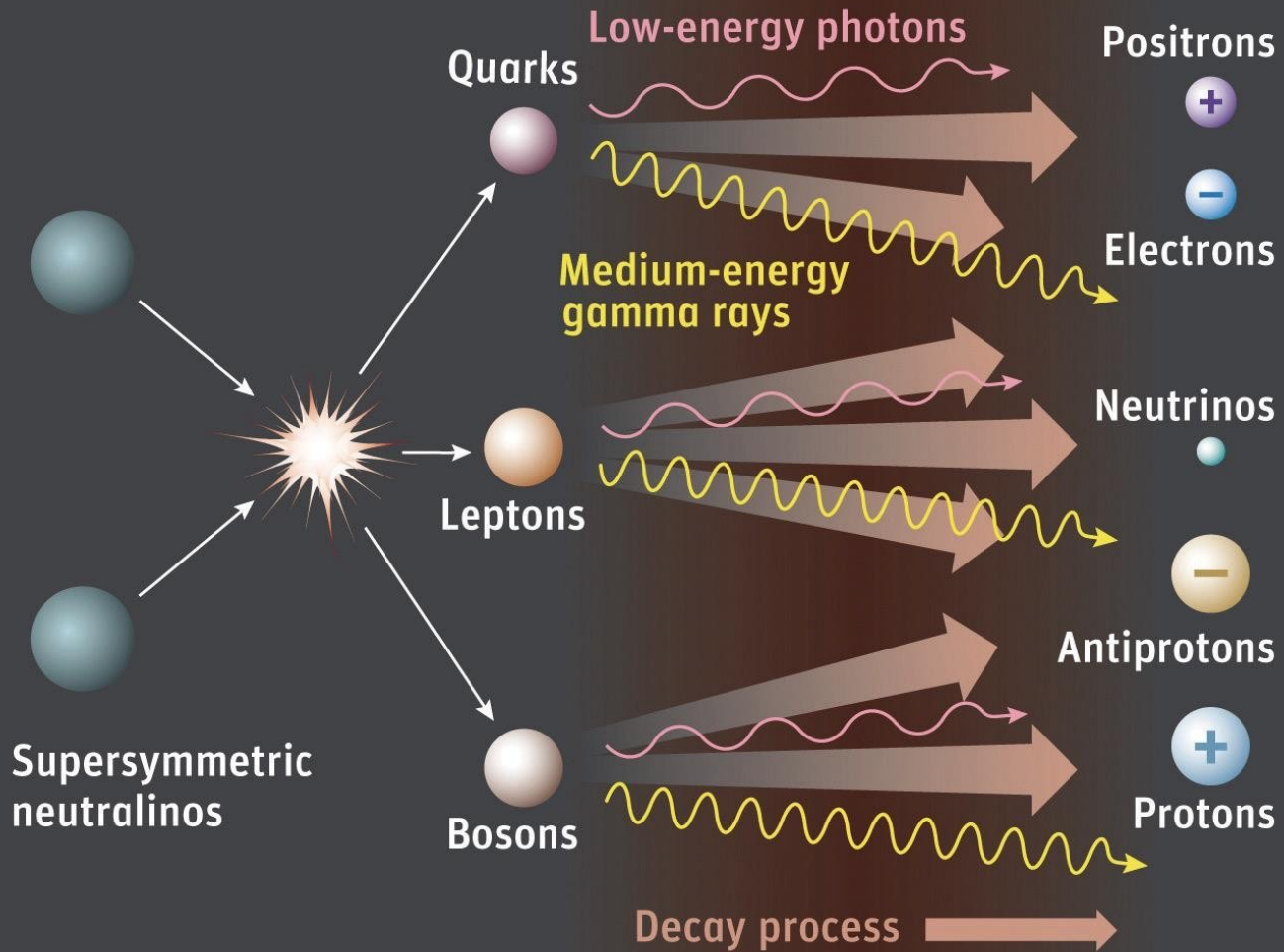
Direct Detection

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

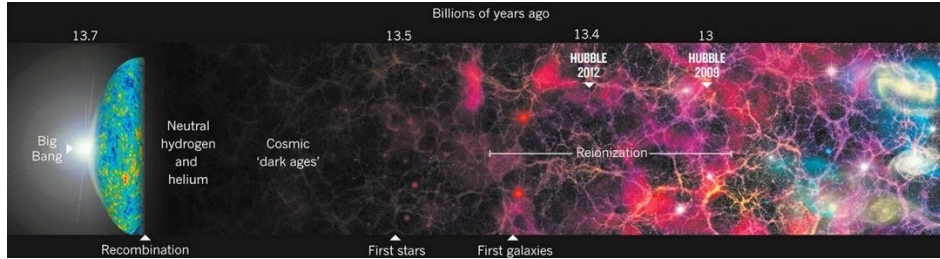


Indirect Detection

Image credit: Sky & Telescope / Gregg Dinderman



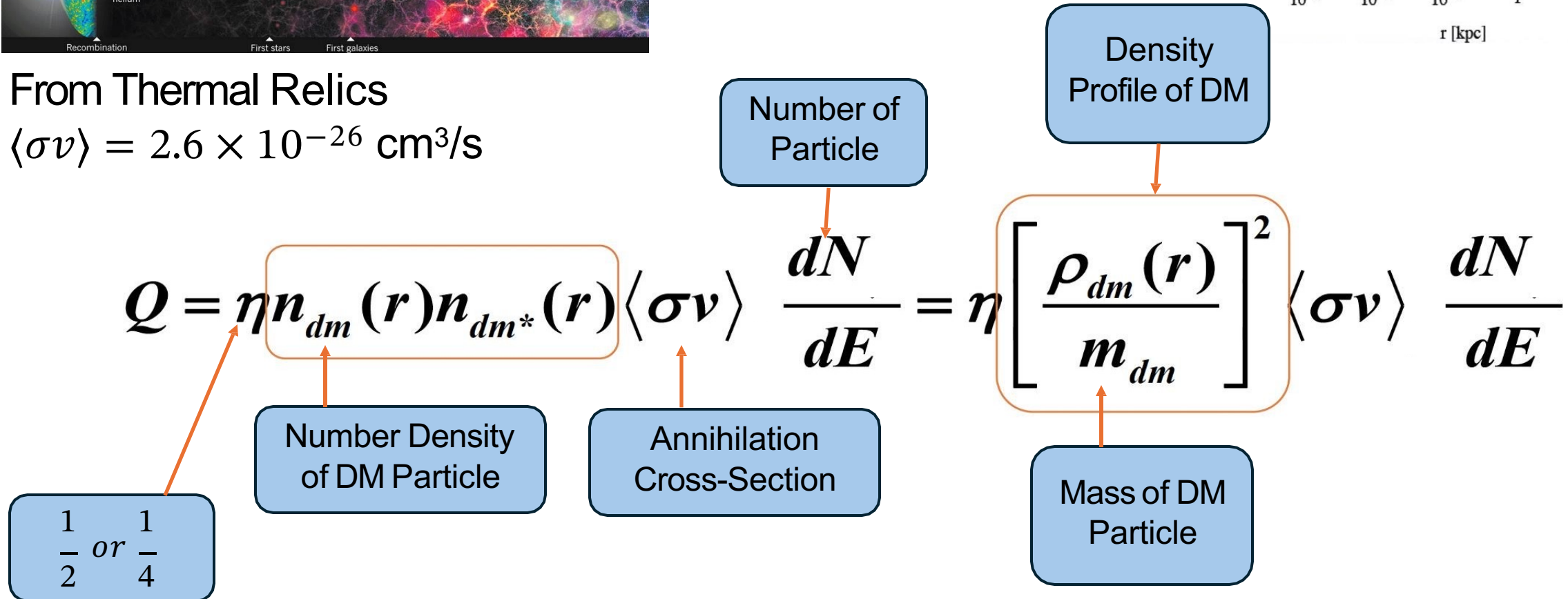
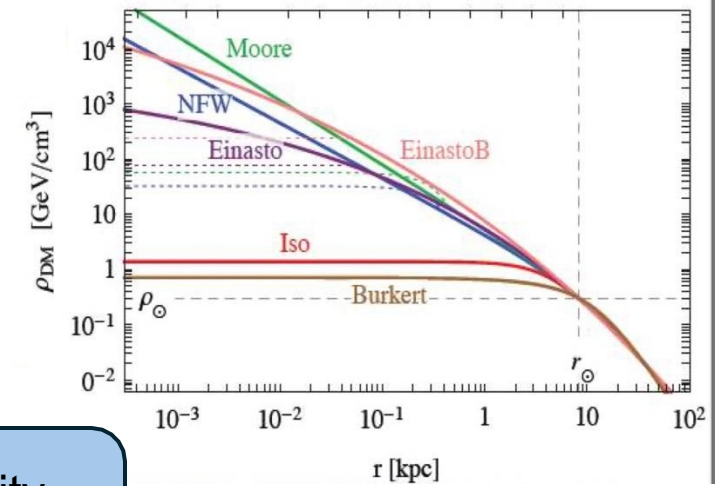
Dark Matter Annihilation



From Thermal Relics

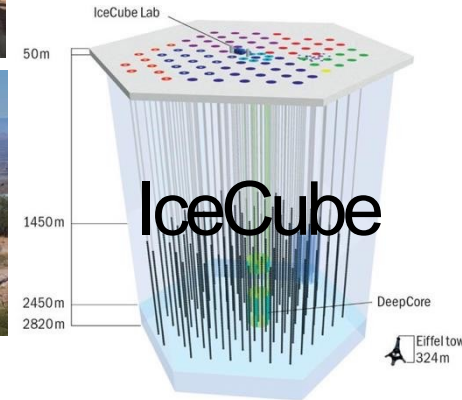
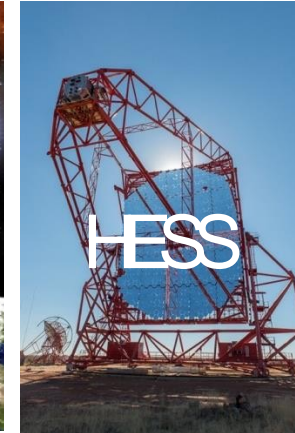
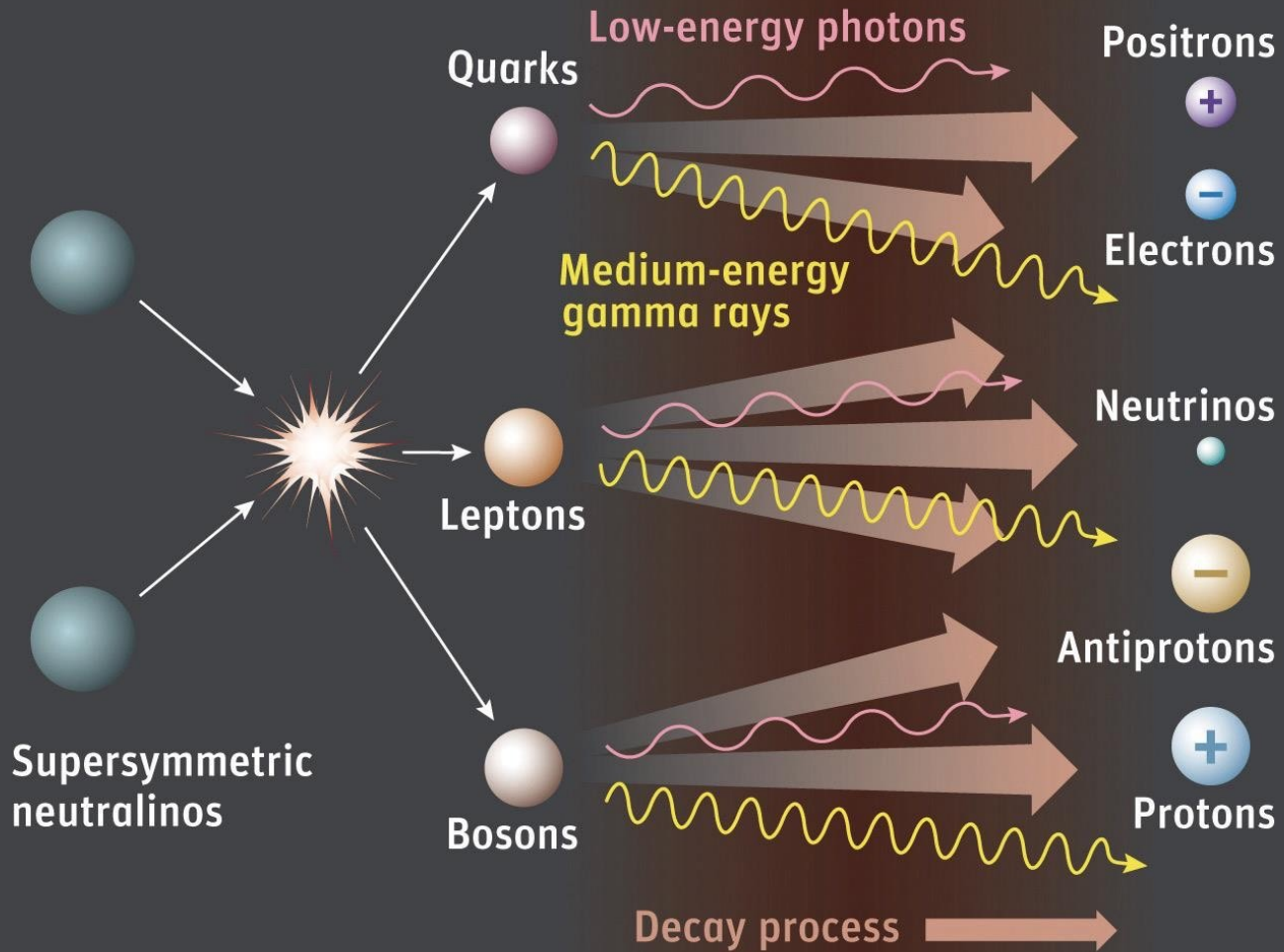
$$\langle \sigma v \rangle = 2.6 \times 10^{-26} \text{ cm}^3/\text{s}$$

$$\rho_{\text{dm}}(r) = \frac{\rho_s}{\left(\frac{r}{r_s}\right)^\alpha \left(1 + \frac{r}{r_s}\right)^{3-\alpha}}$$



Indirect Detection

Image credit: Sky & Telescope / Gregg Dinderman



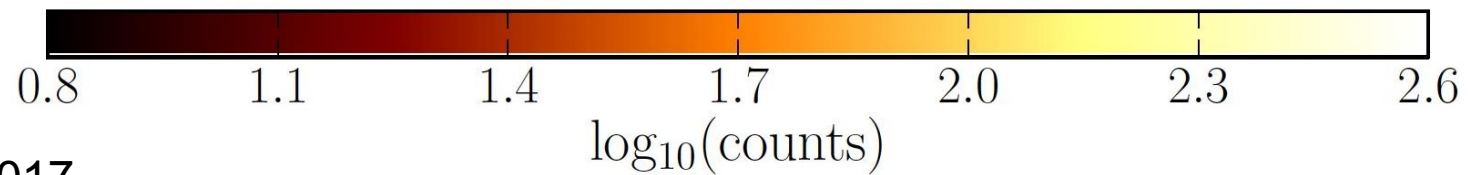
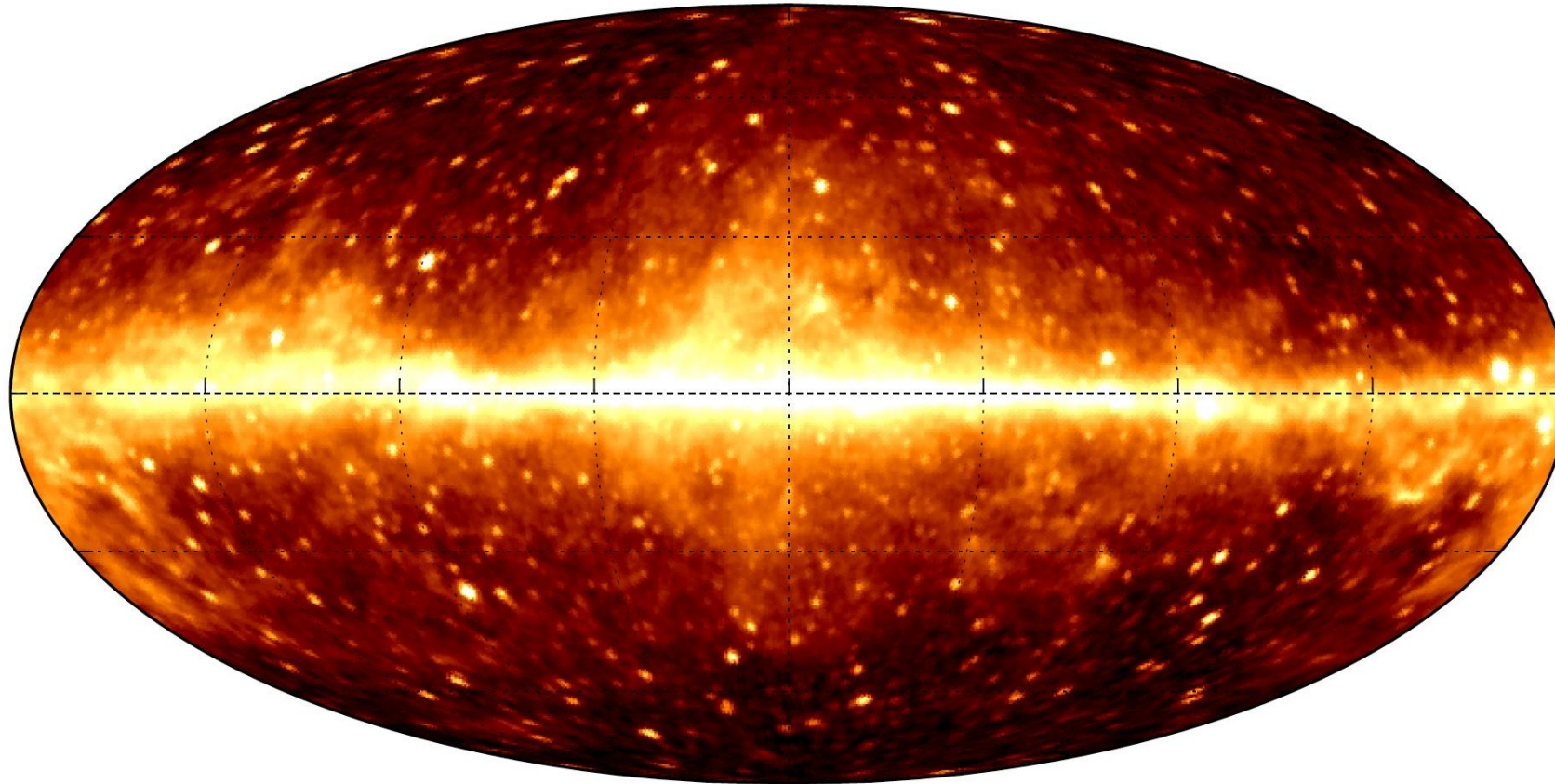
Multi-Messenger of Dark Matter Annihilation

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

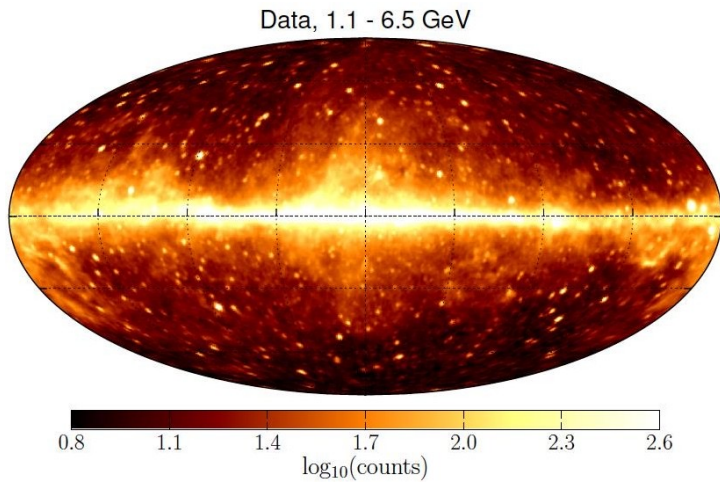
Galactic Centre Excess

Fermi-LAT all Sky Map

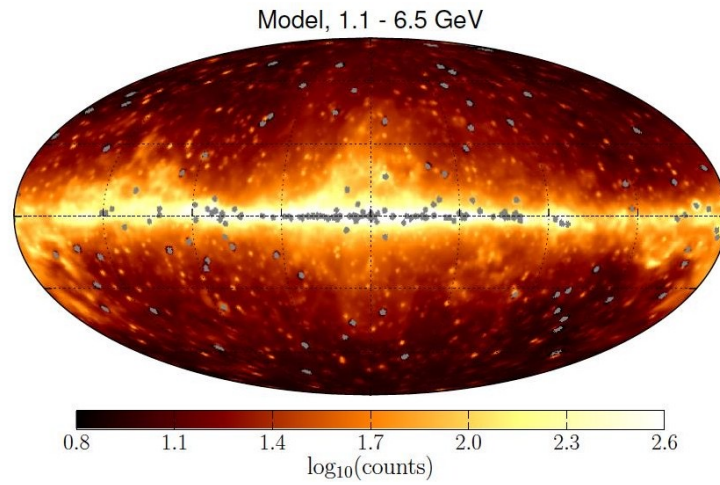
Data, 1.1 - 6.5 GeV



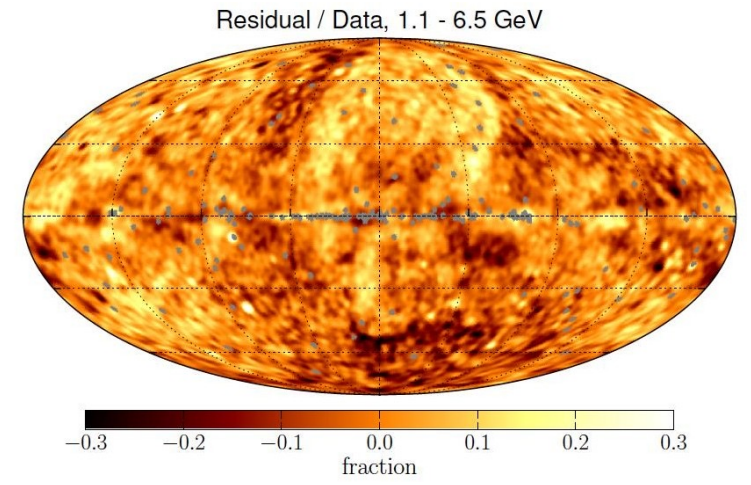
Ackermann et al. 2017



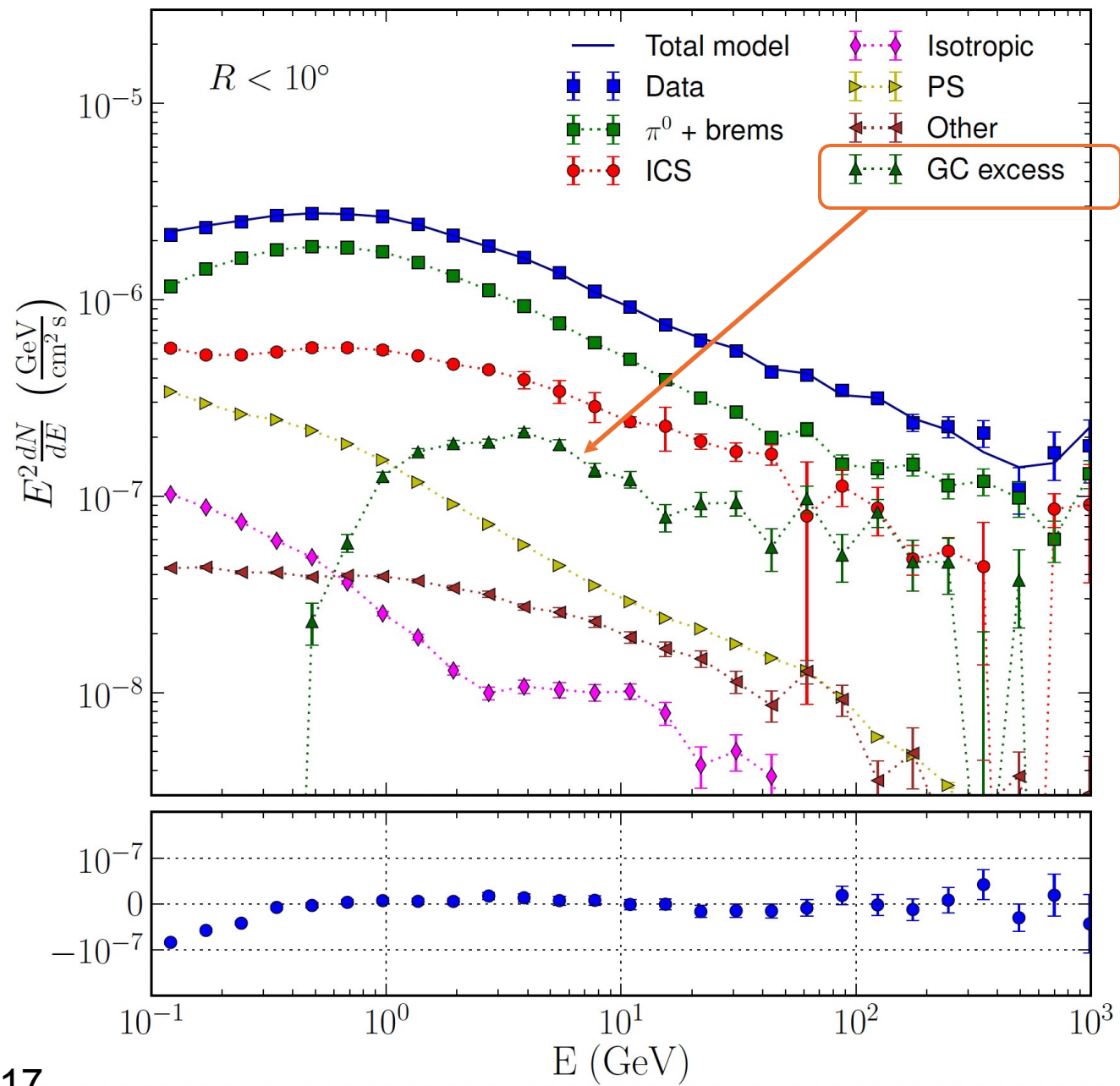
Data



Model



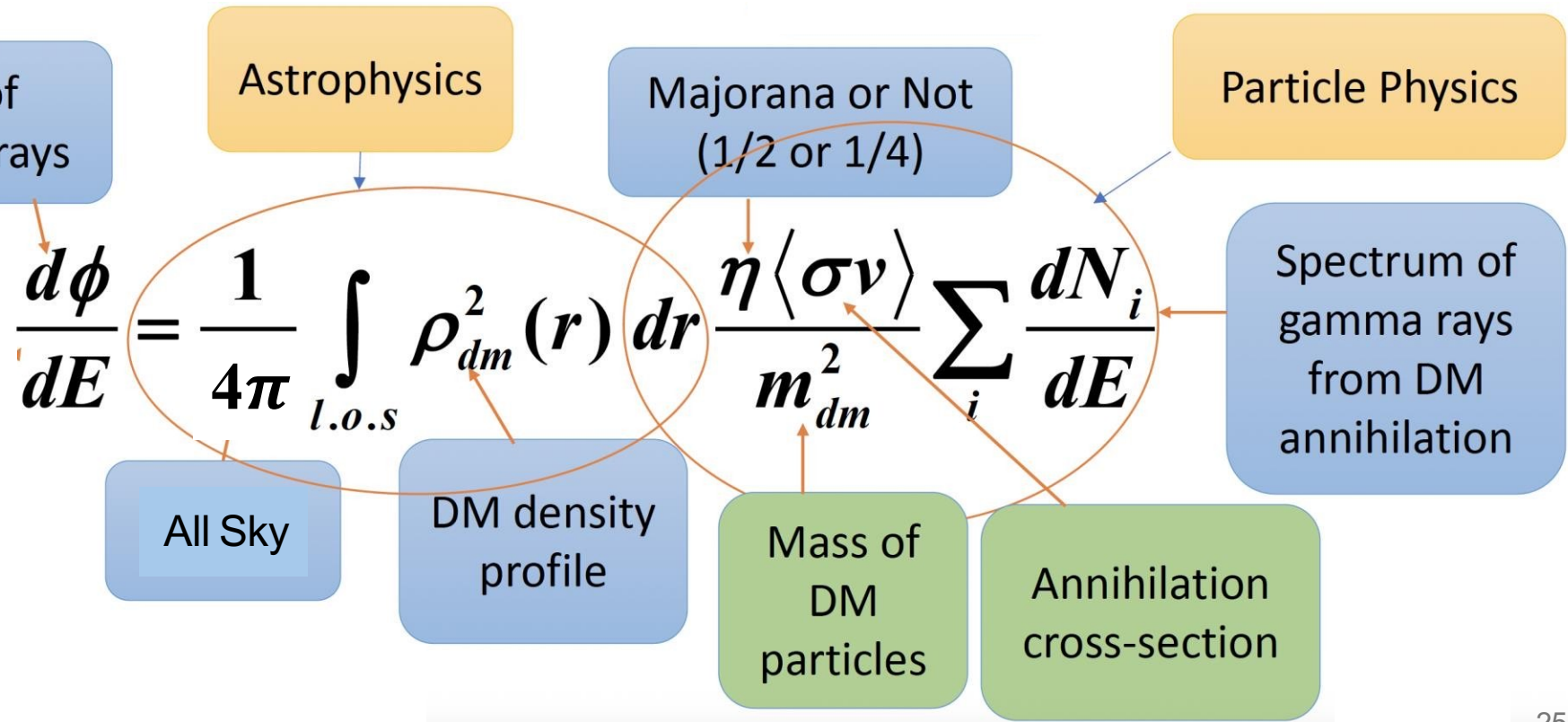
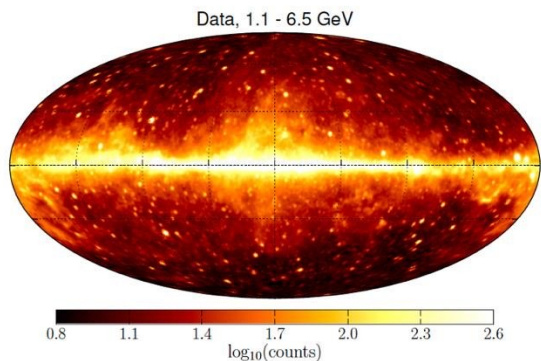
Residual



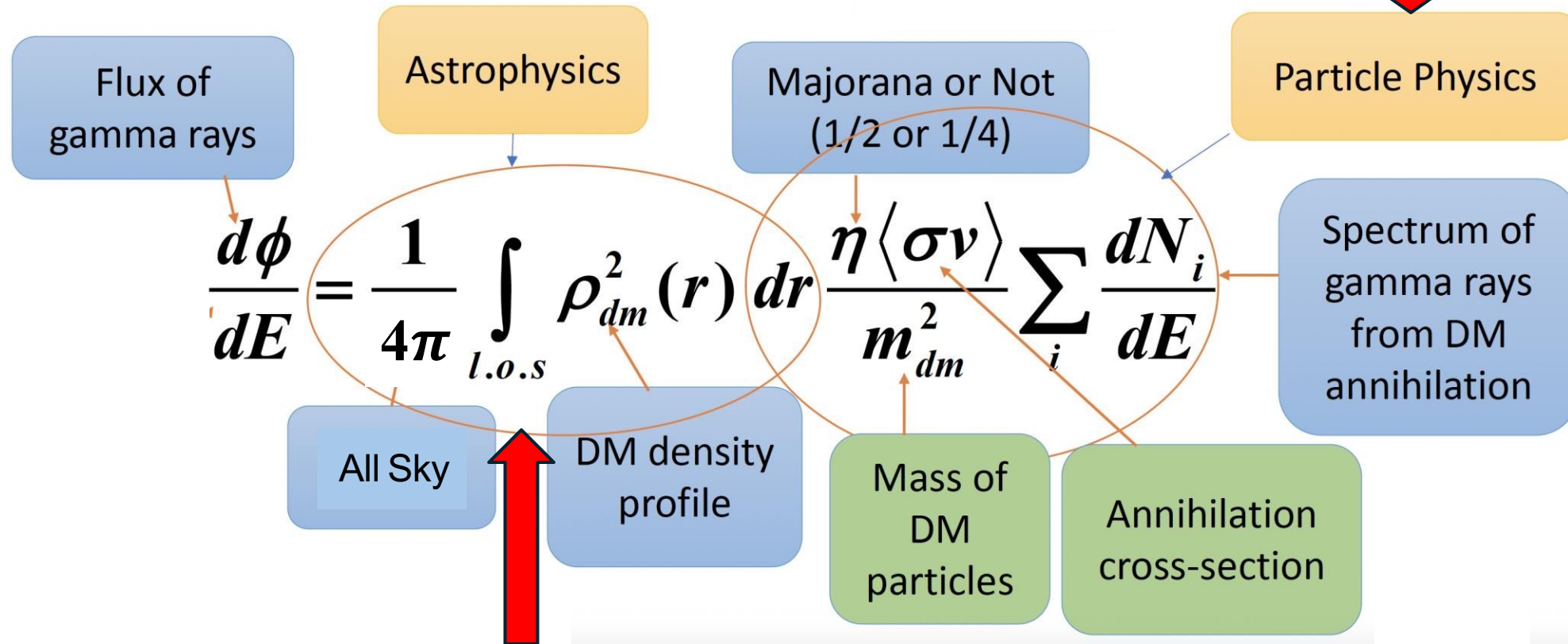
Explain the Galactic Centre Excess by Dark Matter Annihilation

Production of Gamma Rays from Dark matter

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

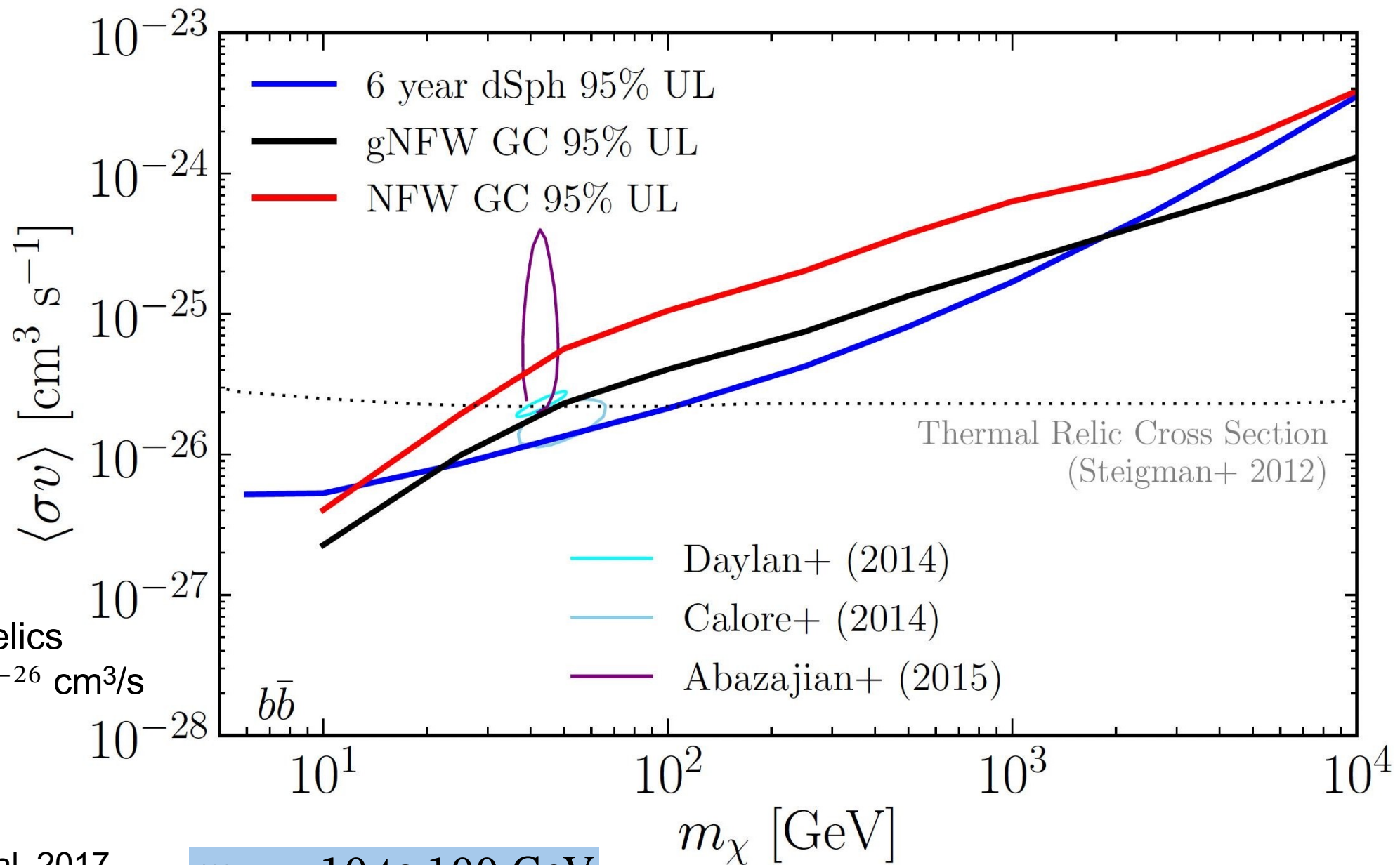


Define flux of gamma-ray



J-Factor
 Define the shape profile
 of gamma-ray

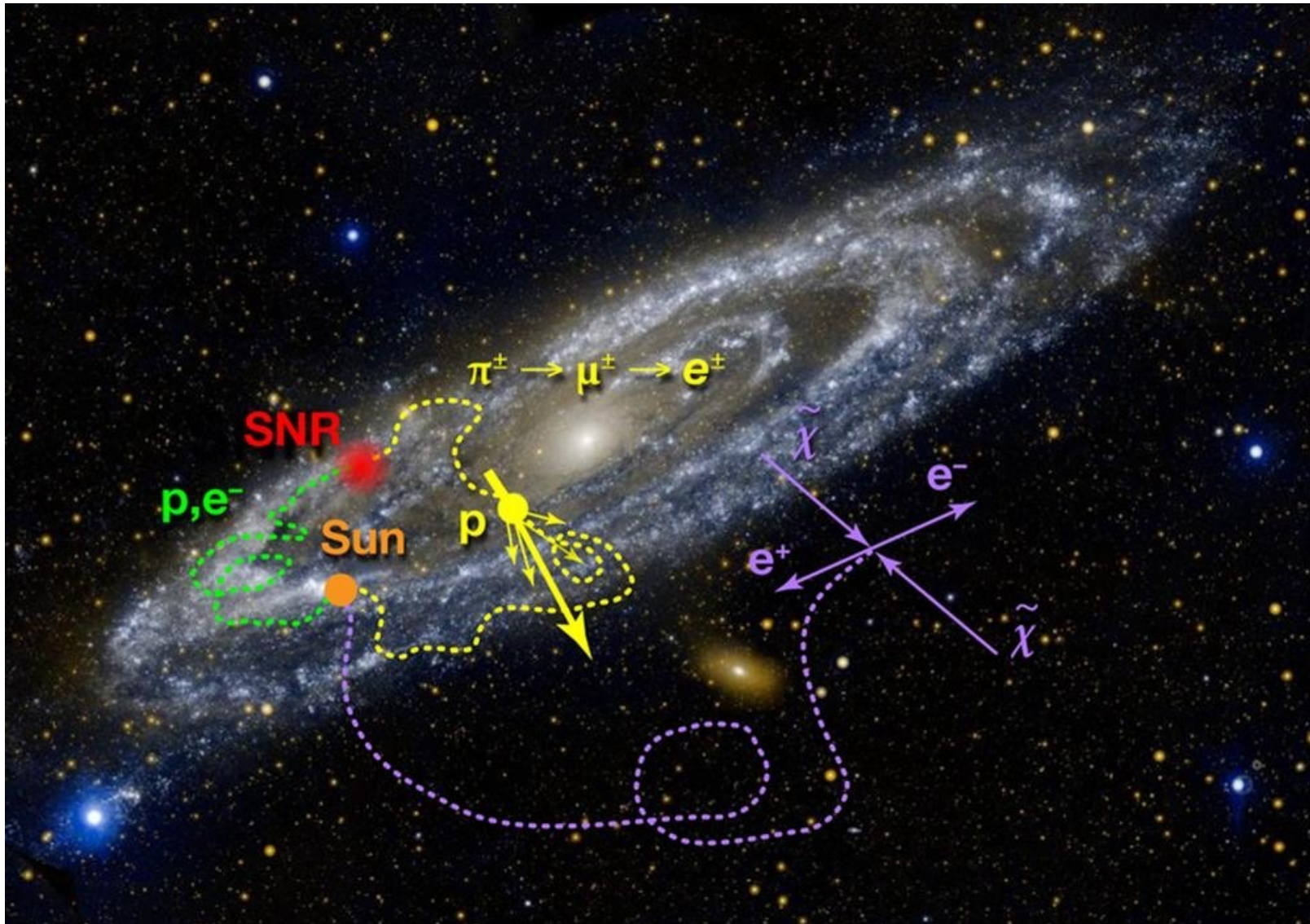
From Thermal Relics
 $\langle\sigma v\rangle = 2.6 \times 10^{-26} \text{ cm}^3/\text{s}$



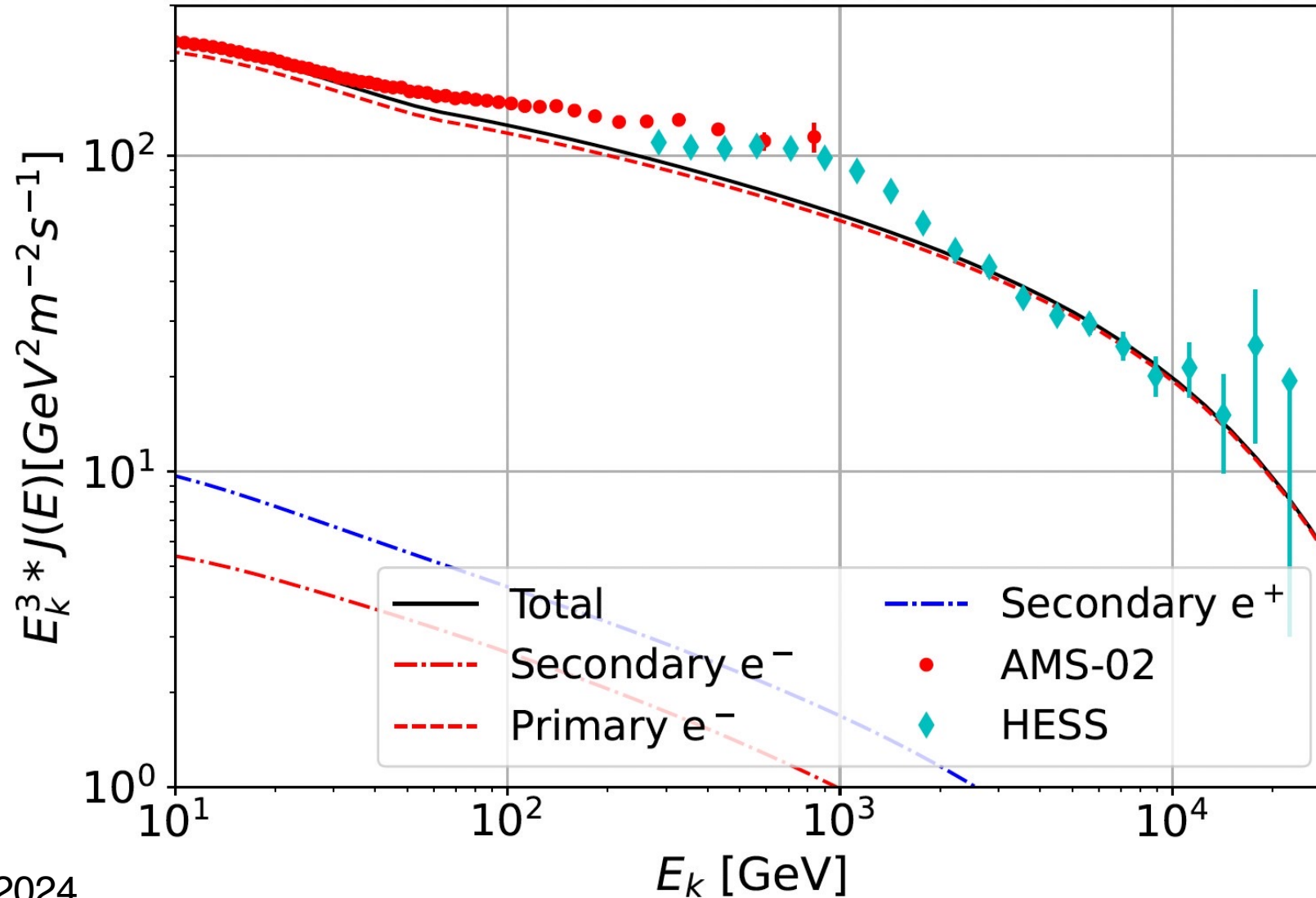
Ackermann et al. 2017

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

Electron and Positron Excess



Electron and Positron Excess



Electron and Positron Propagation

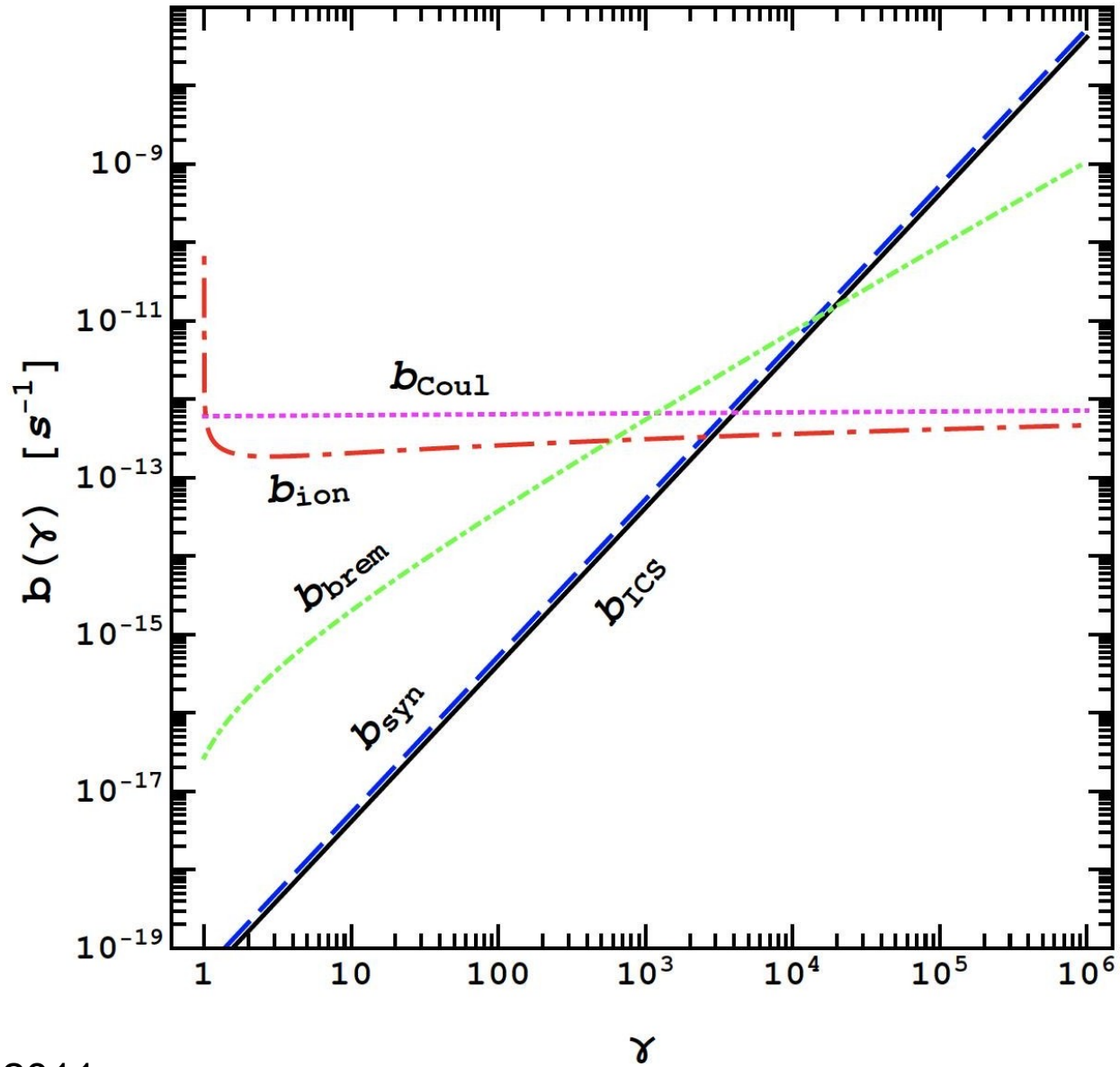
Diffusion-Loss Equation

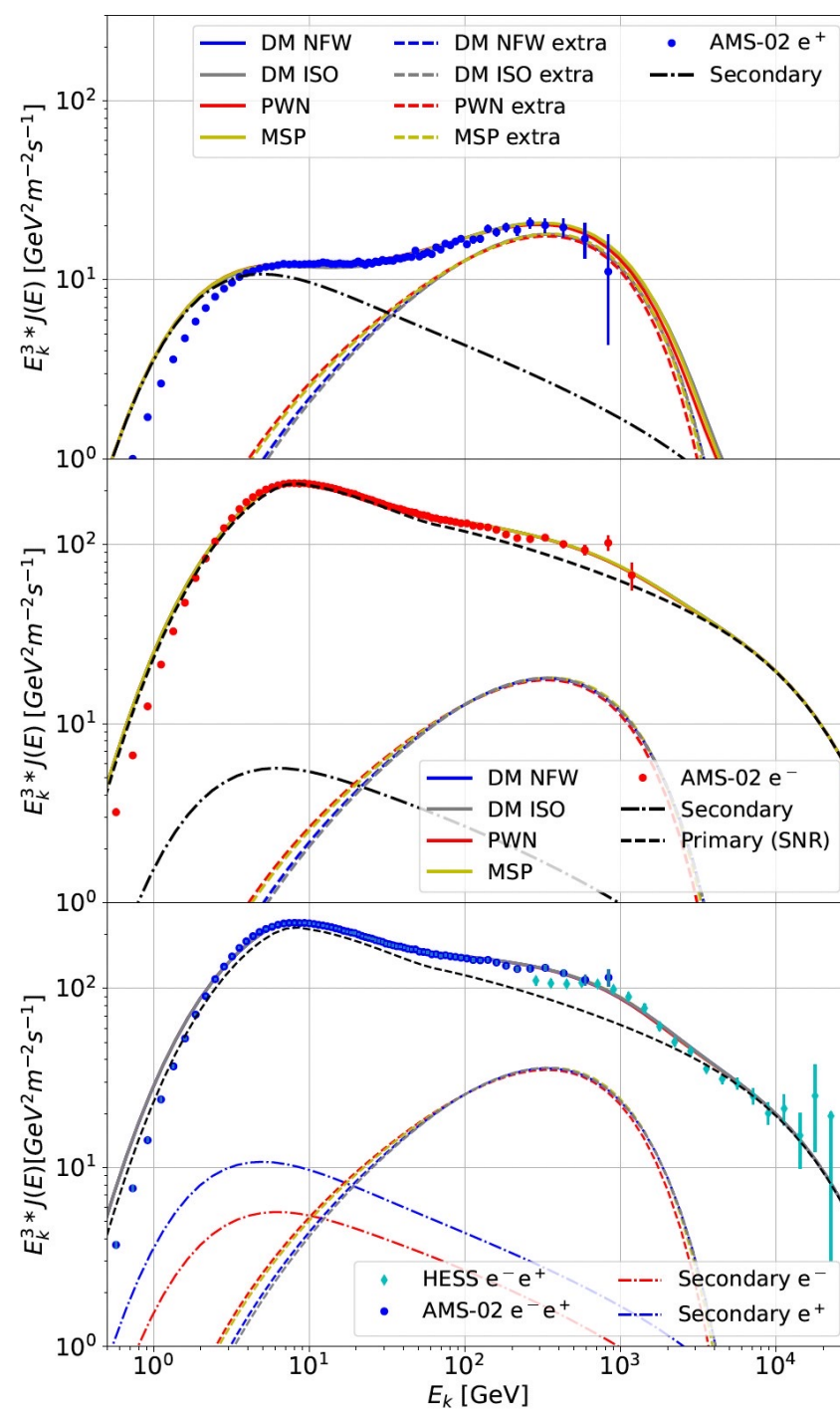
$$\frac{\partial}{\partial t} \frac{dn}{d\gamma}(\mathbf{x}, \gamma) = \nabla \left[K(\mathbf{x}, \gamma) \nabla \frac{dn}{d\gamma}(\mathbf{x}, \gamma) \right] + \frac{\partial}{\partial \gamma} \left[b(\mathbf{x}, \gamma) \frac{dn}{d\gamma}(\mathbf{x}, \gamma) \right] + Q(\mathbf{x}, \gamma).$$

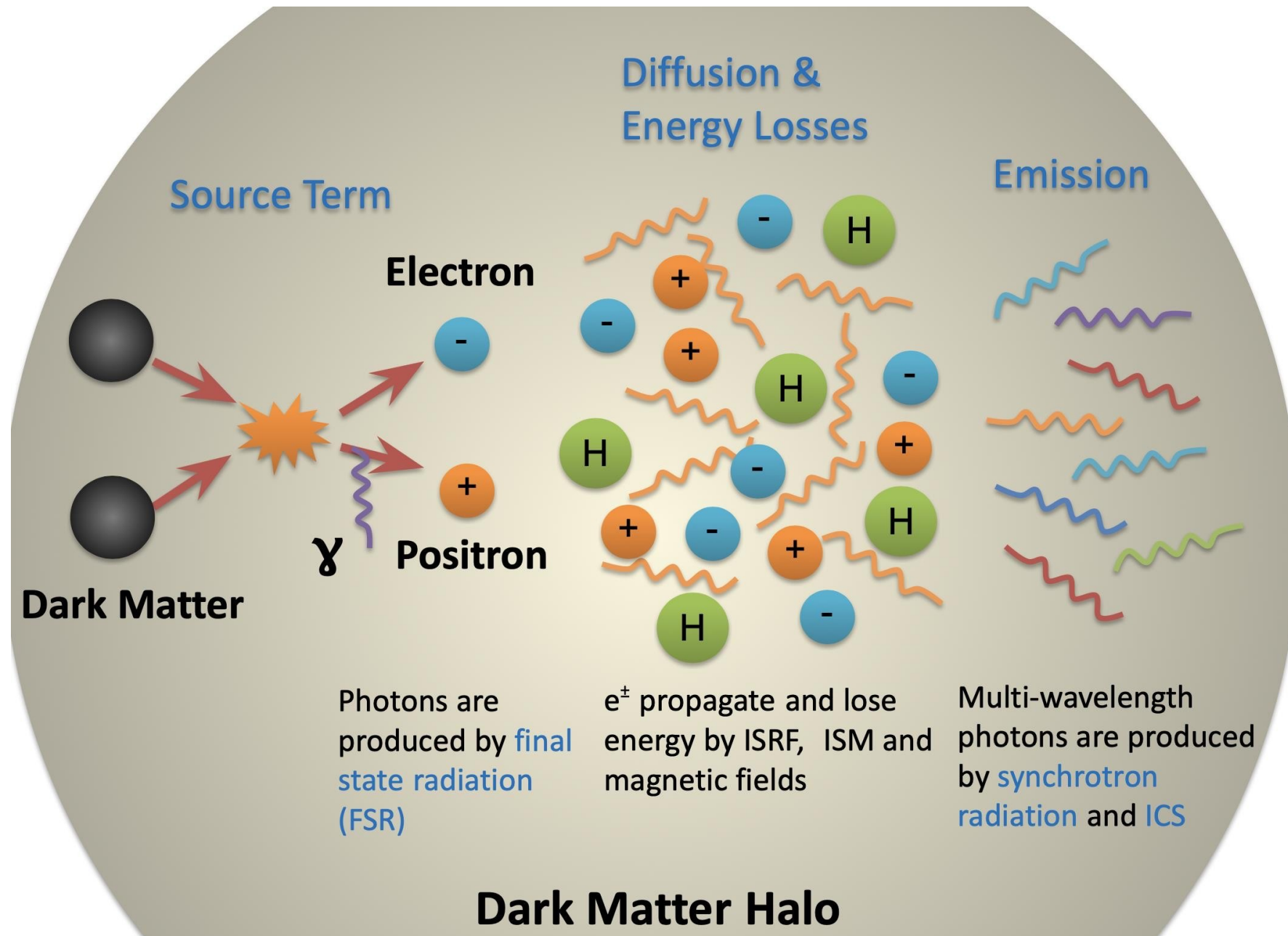
Diffusion

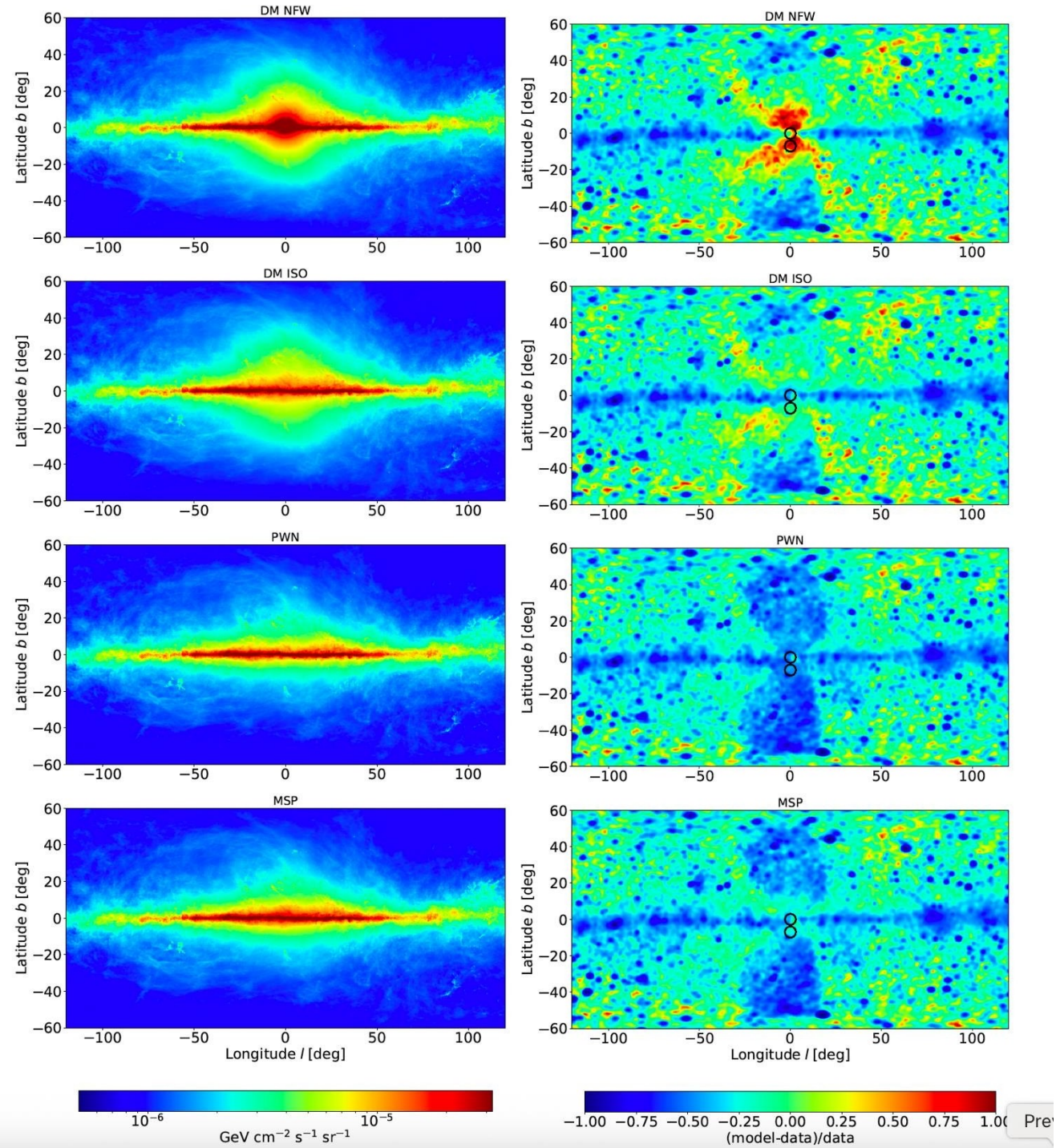
Loss Rate

Source Term,
DM, Pulsar

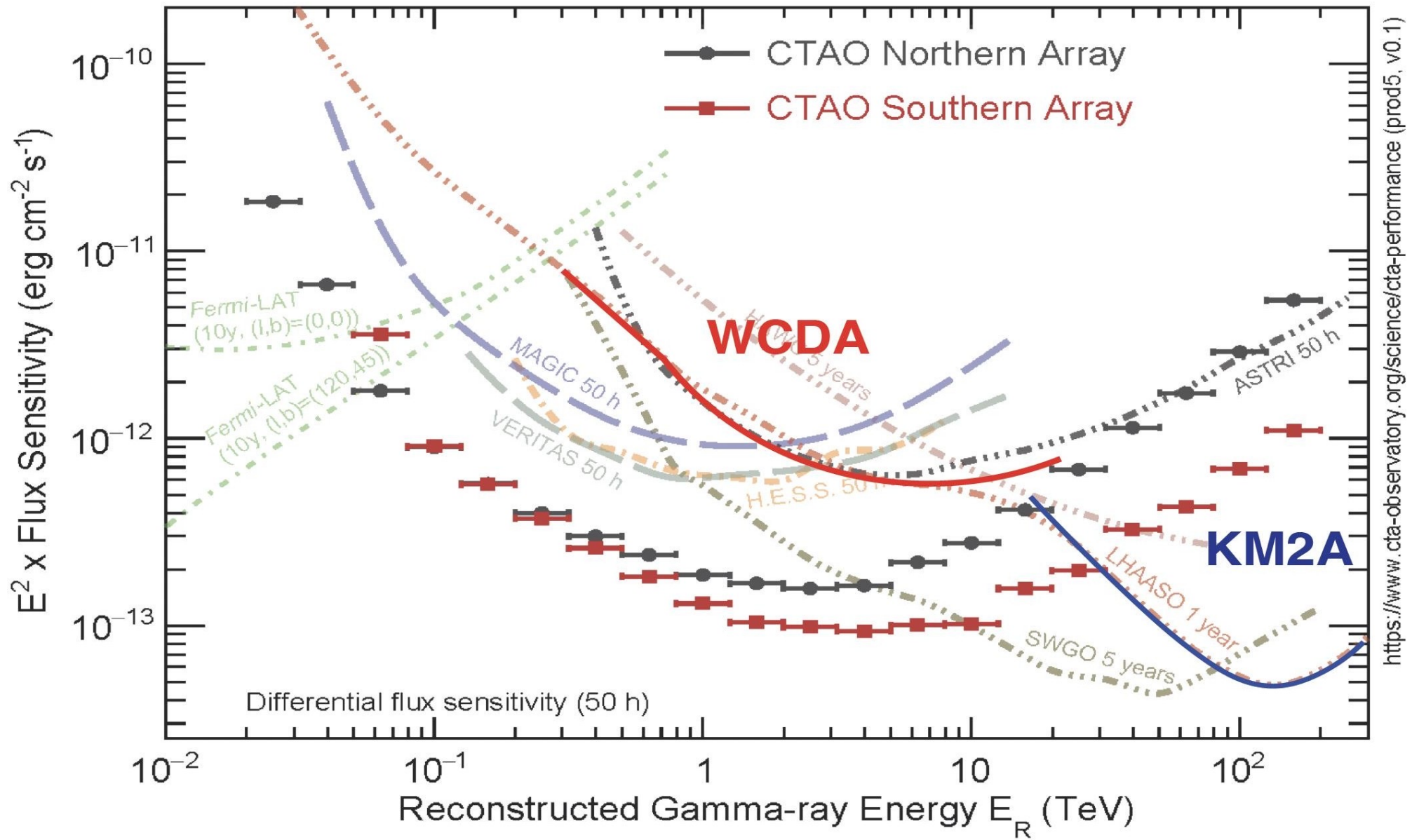








Rocamora et al. 2024



Jiangmen Underground Neutrino Observatory

JUNO

- Approved in Feb. 2013
- Ground-breaking in 2015
- Construction completed in 2024
- Data taking starting in Aug. 2025

A multiple-purpose neutrino experiment with rich physics

- Reactor neutrino for **Mass Hierarchy** and precision measurement of **oscillation parameters**
- Supernova neutrino
- Geo-neutrino
- Solar neutrino
- Atmospheric neutrino
- Proton decay
- Exotic searches; Dark Matter etc.

JUNO Physics and Detector,

arXiv:2104.02565



Acrylic Sphere:

ID: 35.4m

Thickness: 12cm

SS Lattice:

ID: 40.1m OD:

41.1m

17612 20-in PMTs

25600 3-in PMTs

Water pool:

ID: 43.5m

Height: 44m

Depth: 43.5m

2400 20-in PMTs



JUNO Collaboration

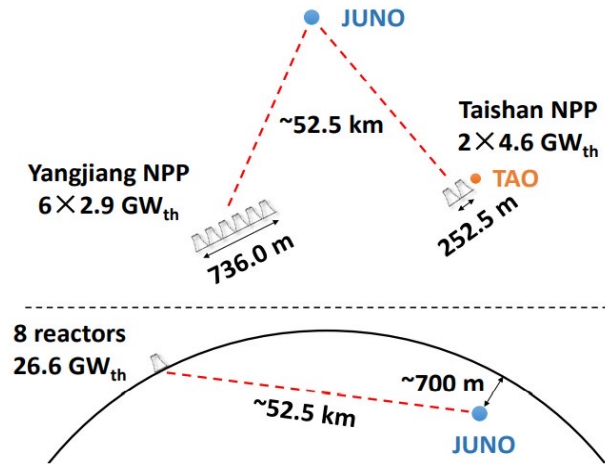


Country	Institute	Country	Institute	Country	Institute
Armenia	Yerevan Physics Institute	China	Tsinghua U.	Germany	U. Tuebingen
Belgium	Universite libre de Bruxelles	China	UCAS	Italy	INFN Catania
Brazil	PUC	China	USTC	Italy	INFN di Frascati
Brazil	UEL	China	U. of South China	Italy	INFN-Ferrara
Chile	SAPHIR	China	Wu Yi U.	Italy	INFN-Milano
Chile	UNAB	China	Wuhan U.	Italy	INFN-Milano Bicocca
China	BISEE	China	Xi'an JT U.	Italy	INFN-Padova
China	Beijing Normal U.	China	Xiamen University	Italy	INFN-Perugia
China	CAGS	China	Zhengzhou U.	Italy	INFN-Roma 3
China	ChongQing University	China	NUDT	Pakistan	PINSTECH (PAEC)
China	CIAE	China	CUG-Beijing	Russia	INR Moscow
China	DGUT	China	ECUT-Nanchang City	Russia	JINR
China	Guangxi U.	China	CDUT-Chengdu	Russia	MSU
China	Harbin Institute of Technology	Czech	Charles U.	Slovakia	FMPICU
China	IHEP	Finland	University of Jyvaskyla	Taiwan-China	National Chiao-Tung U.
China	Jilin U.	France	IJCLab Orsay	Taiwan-China	National Taiwan U.
China	Jinan U.	France	LP2i Bordeaux	Taiwan-China	National United U.
China	Nanjing U.	France	CPPM Marseille	Thailand	NARIT
China	Nankai U.	France	IPHC Strasbourg	Thailand	PPRLCU
China	NCEPU	France	Subatech Nantes	Thailand	SUT
China	Pekin U.	Germany	RWTH Aachen U.	U.K.	U. Liverpool
China	Shandong U.	Germany	TUM	U.K.	U. Warwick
China	Shanghai JT U.	Germany	U. Hamburg	USA	UMD-G
China	IGG-Beijing	Germany	GSI	USA	UC Irvine
China	SYSU	Germany	U. Mainz		

74 institutes

**> 700
collaborators**

JUNO Location



JUNO detector



A multi-purpose observatory



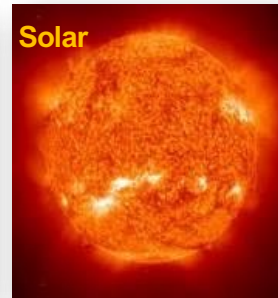
Mass Ordering



~60 IBDs per day



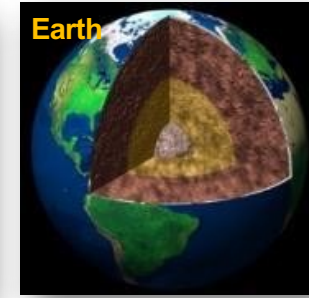
Several per day



Hundreds per day



~5000 IBDs for
CCSN @10 kpc



Several IBDs per
day

+
New
physics

Neutrino oscillation & properties

Neutrinos as a probe

IBD: inverse beta decay $\bar{\nu}_e + p \rightarrow e^+ + n$

CCSN: core-collapse supernova

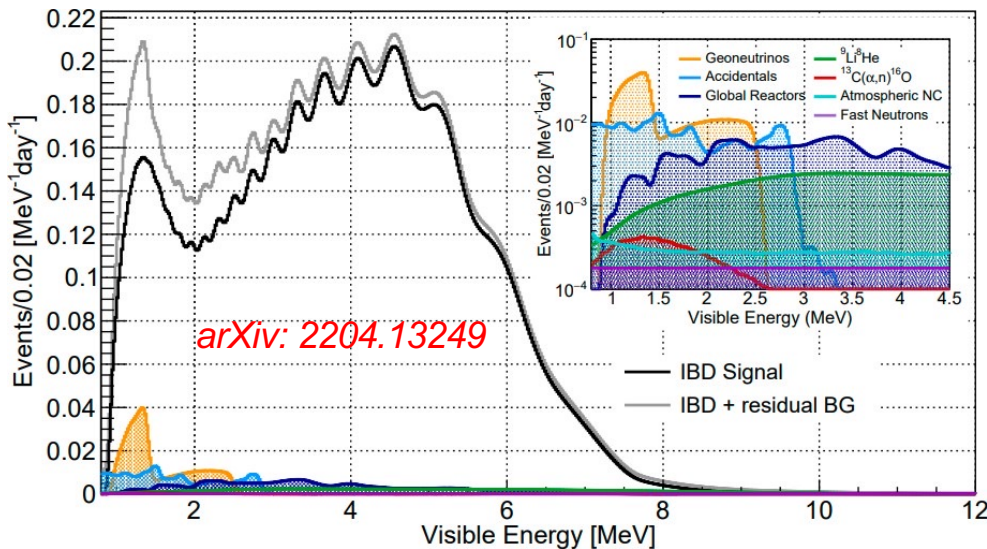
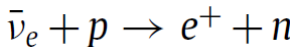
Reactor Antineutrino Oscillation & Detection



$$P_{\bar{\nu}_e \rightarrow \bar{\nu}_e} = 1 - \sin^2 2\theta_{13}(\cos^2 \theta_{12} \sin^2 \Delta_{31} + \sin^2 \theta_{12} \sin^2 \Delta_{32}) - \cos^4 \theta_{13} \sin^2 2\theta_{12} \sin^2 \Delta_{21},$$

(matter effect contributes maximal ~4% correction at around 3 MeV, [arXiv:1605.00900](#), [arXiv:1910.12900](#))

Inverse beta decay reaction



Event type	Rate [/day]	Relative rate uncertainty	Shape uncertainty
Reactor IBD signal	60 → 47	-	-
Geo-ν's	1.1 → 1.2	30%	5%
Accidental signals	0.9 → 0.8	1%	negligible
Fast-n	0.1	100%	20%
⁹ Li/ ⁸ He	1.6 → 0.8	20%	10%
¹³ C(α ,n) ¹⁶ O	0.05	50%	50%
Global reactors	0 → 1.0	2%	5%
Atmospheric ν's	0 → 0.16	50%	50%

- ☹️ **2 fewer reactor cores in Taishan**
- ☺️ **Better muon veto strategy**
- ☺️ **Improved energy resolution:**
3.0% @1MeV → 2.9% @1MeV

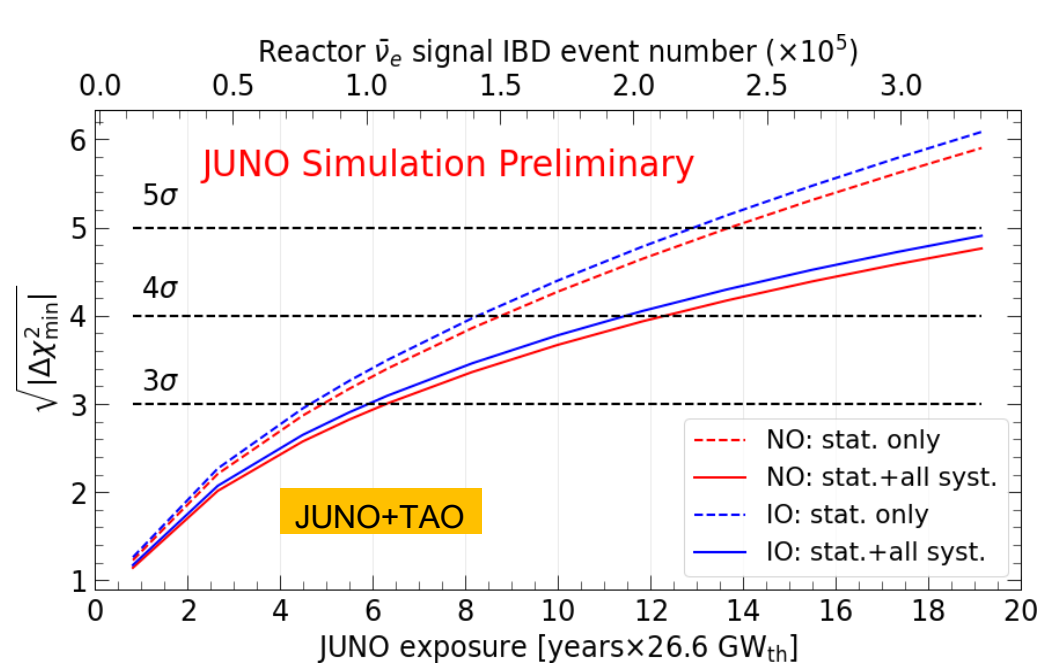
JUNO physics book (*J. Phys. G*43:030401(2016)) → **updated values**

Signal and backgrounds now assessed with full JUNO simulation

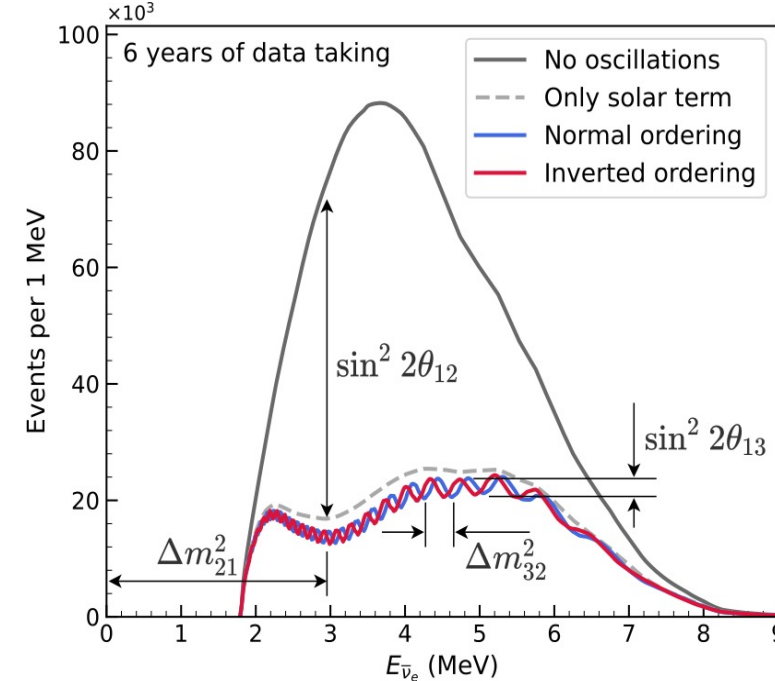
Slight less overburden

Lower radioactivity background based on latest measurements on material radiopurities

Neutrino Mass Ordering



[arXiv: 2405.18008](https://arxiv.org/abs/2405.18008)



JUNO sensitivity on NMO: 3 σ (reactors only) @ ~6 yrs * 26.6 GW_{th} exposure

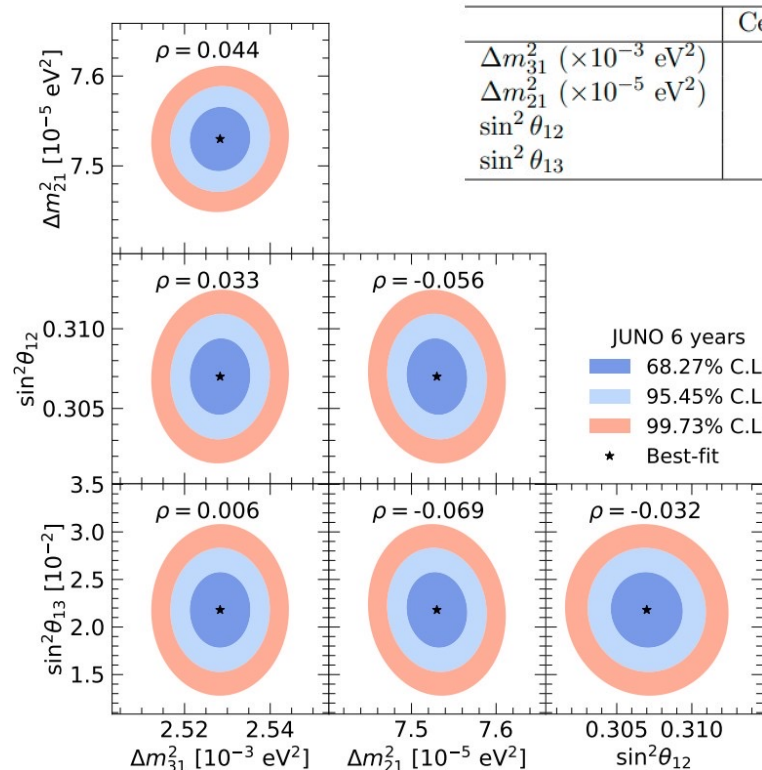
Combined reactor + atmospheric neutrino analysis is in progress → further improve the NMO sensitivity

Neutrino oscillation parameters

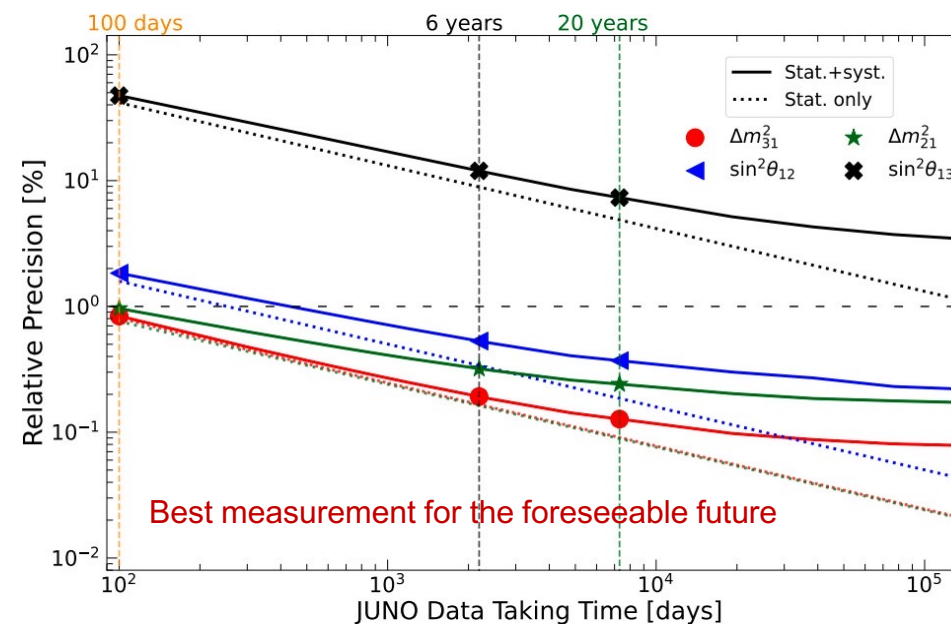


arXiv:2204.13249, Chin. Phys. C 46 (2022) 123001

Precision of $\sin^2\theta_{12}$, Δm_{21}^2 , $|\Delta m_{32}^2| < 0.5\%$ in 6 yrs



	Central Value	PDG2020	100 days	6 years	20 years
$\Delta m_{31}^2 (\times 10^{-3} \text{ eV}^2)$	2.5283	± 0.034 (1.3%)	± 0.021 (0.8%)	± 0.0047 (0.2%)	± 0.0029 (0.1%)
$\Delta m_{21}^2 (\times 10^{-5} \text{ eV}^2)$	7.53	± 0.18 (2.4%)	± 0.074 (1.0%)	± 0.024 (0.3%)	± 0.017 (0.2%)
$\sin^2\theta_{12}$	0.307	± 0.013 (4.2%)	± 0.0058 (1.9%)	± 0.0016 (0.5%)	± 0.0010 (0.3%)
$\sin^2\theta_{13}$	0.0218	± 0.0007 (3.2%)	± 0.010 (47.9%)	± 0.0026 (12.1%)	± 0.0016 (7.3%)



The improvement in precision over existing constraints will be about one order of magnitude

Indirect-Detection of Dark Matter

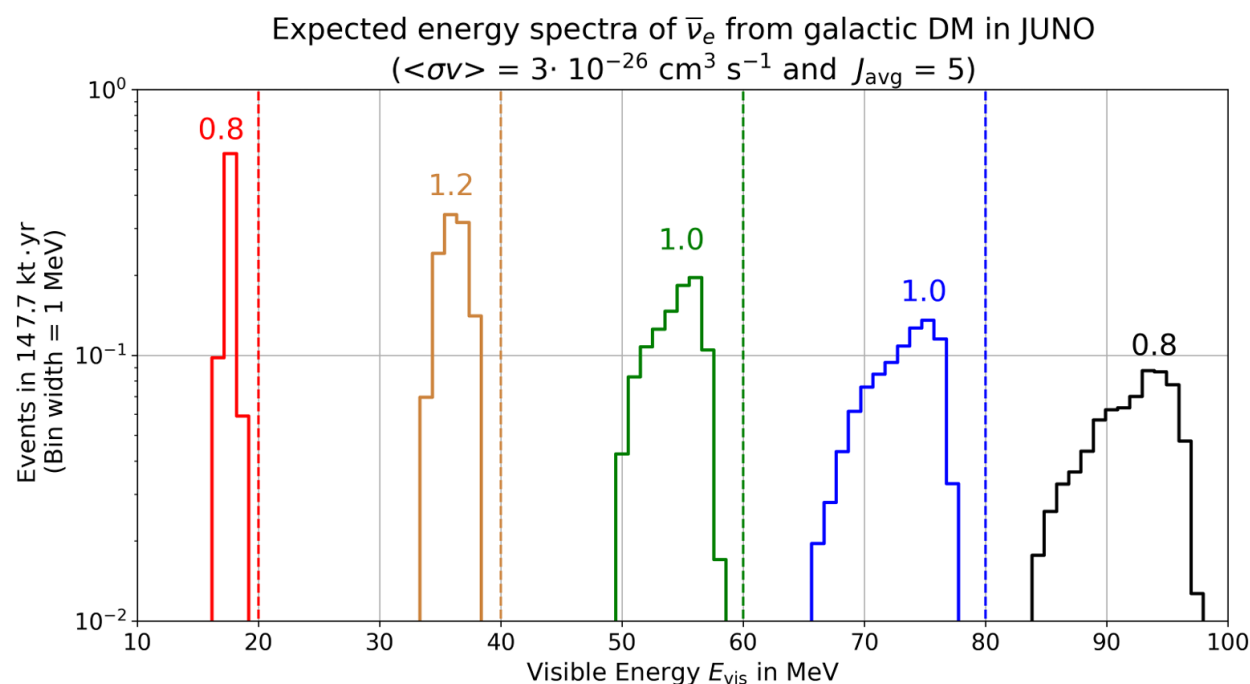


JUNO sensitivity to the annihilation of MeV dark matter in the galactic halo
(arXiv: 2306.09567)

-produced directly from DM annihilation $\chi\chi \rightarrow \nu\bar{\nu}$

$$\frac{d\phi_{\bar{\nu}_e}^{\text{DM}}}{dE_{\bar{\nu}_e}} = \frac{1}{2} \langle \sigma v \rangle J_{\text{avg}} \frac{R_{\text{sc}} \rho_0^2}{m_\chi^2} \frac{1}{3} \delta(E_\nu - m_\chi).$$

$$\frac{dN_S(E_{\bar{\nu}_e})}{dE_{\bar{\nu}_e}} = \sigma_{\text{IBD}}(E_{\bar{\nu}_e}) \cdot \frac{d\phi_{\bar{\nu}_e}^{\text{DM}}(E_{\bar{\nu}_e})}{dE_{\bar{\nu}_e}} \cdot N_{\text{target}} \cdot t \cdot \epsilon$$



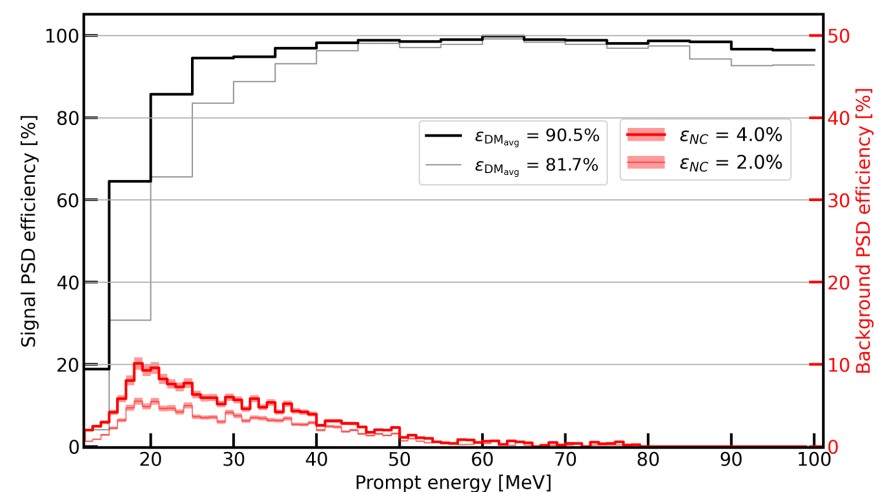
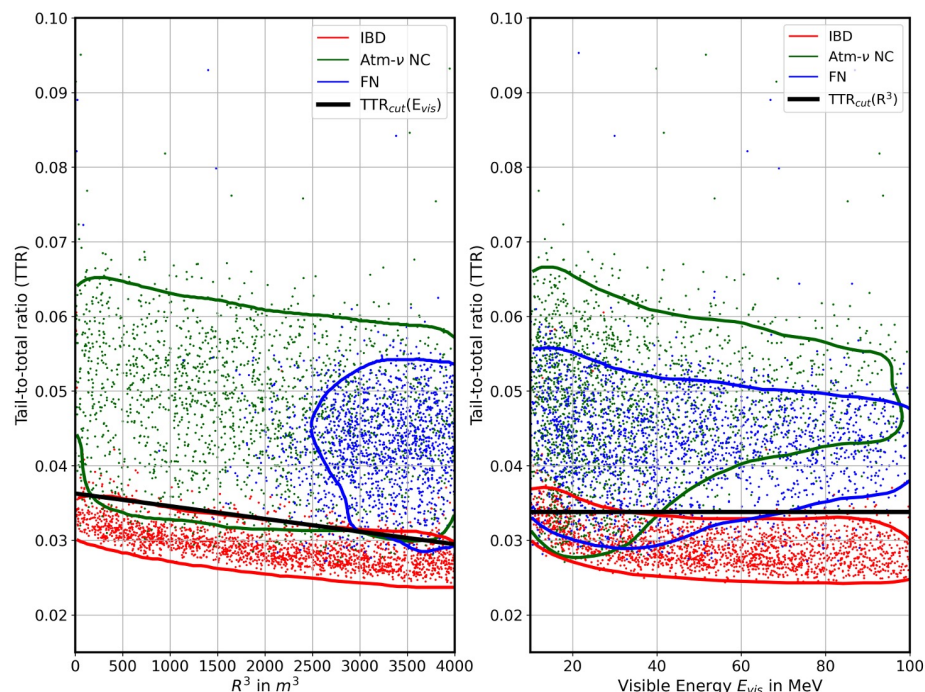
**Visible energy
spectra in the
JUNO detector with
10 years of
exposure time**

Background neutrino

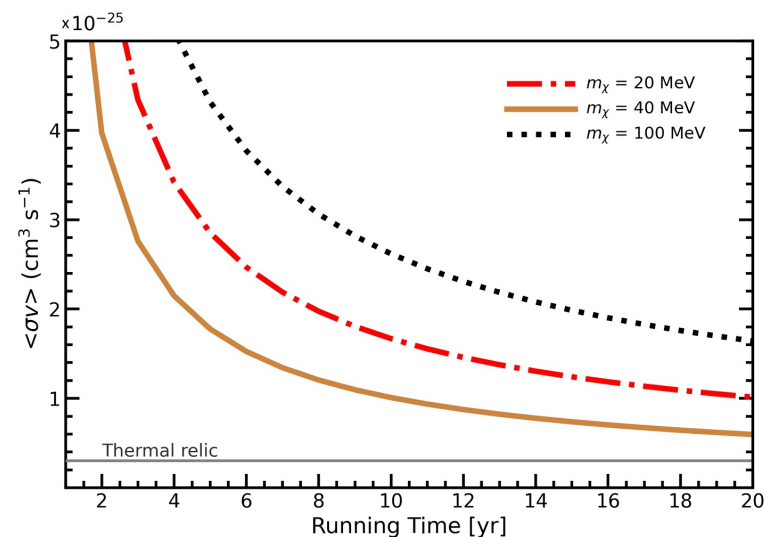
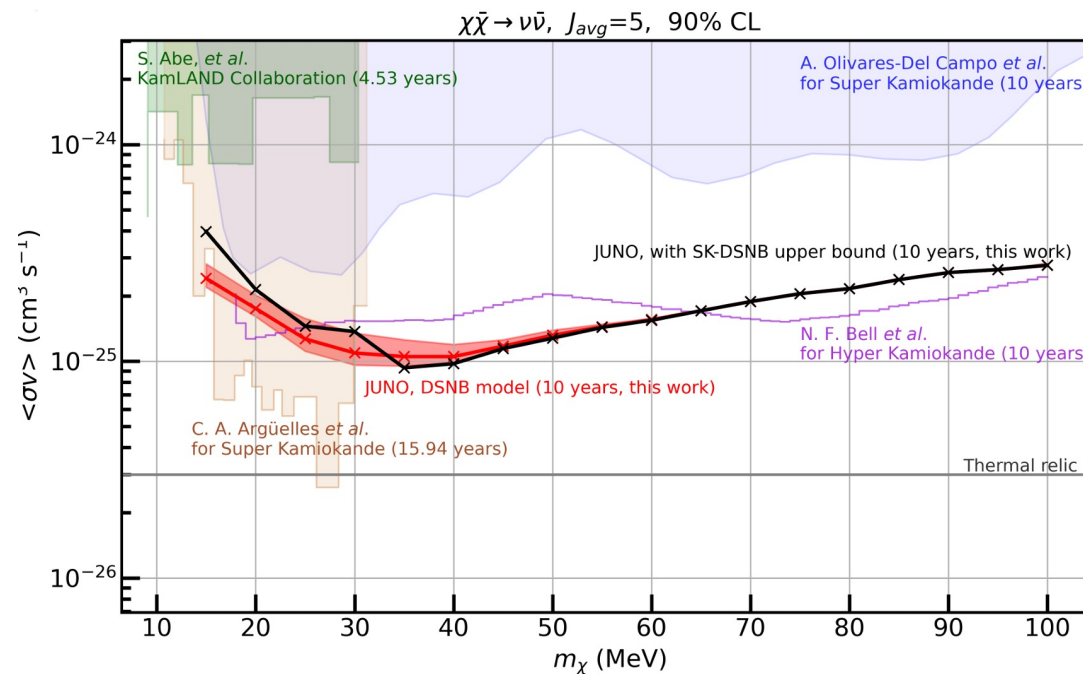
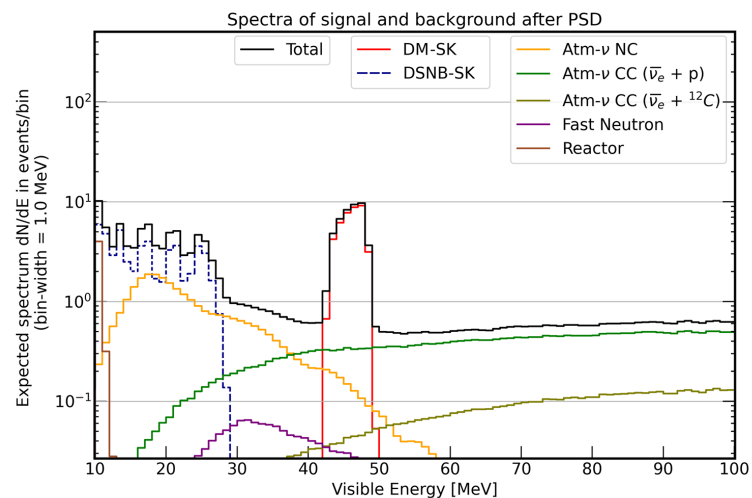
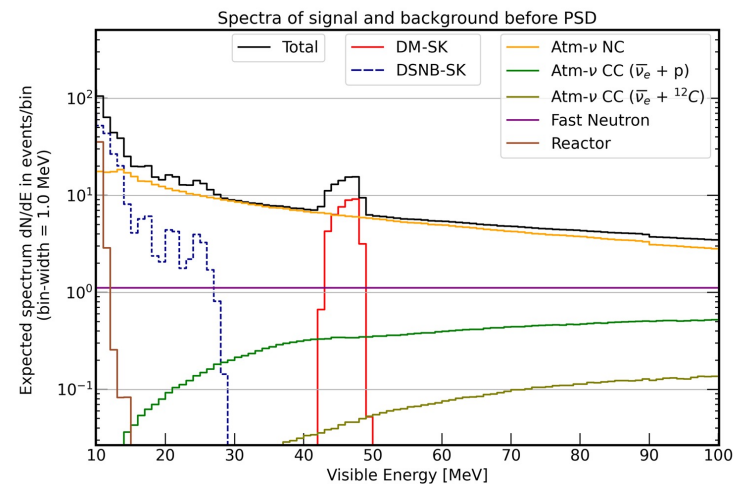


Pulse Shape Discrimination (PSD): Background separation

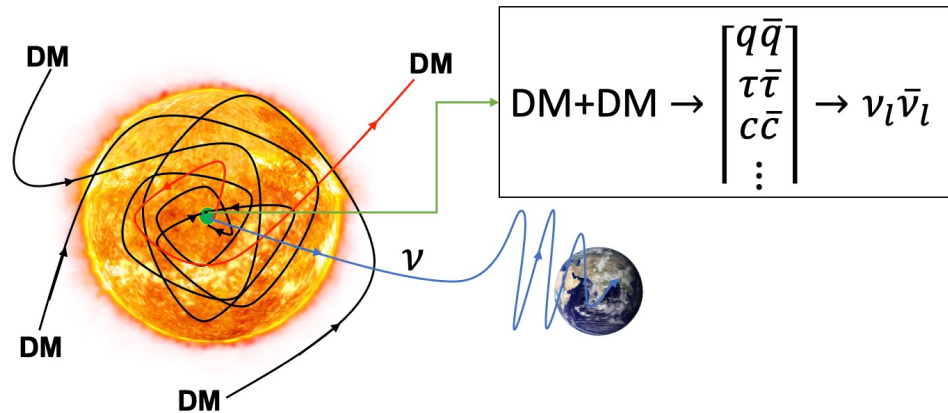
$\epsilon_{\text{PSD,NC}}$	$\epsilon_{\text{PSD,IBD}}$	$\epsilon_{\text{PSD,FN}}$	Tail window (ns)	mean $N_S/\sqrt{N_S + N_B}$
2.0%	81.7%	0.5%	[200,600]	4.092
3.0%	87.5%	1.2%	[250,600]	4.140
4.0%	90.5%	2.0%	[200,600]	4.151
5.0%	92.3%	3.9%	[200,600]	4.120
6.0%	93.6%	7.0%	[150,600]	4.071
7.0%	95.5%	8.2%	[200,600]	4.054



Predicted Sensitivity



Solar Captured: GeV-Scale DM



- DM supposed to be captured by the gravitational force in the solar core

DM velocity $\lesssim$ solar escape velocity (~ 600 km/s)

- Number of DM in the sun at equilibrium

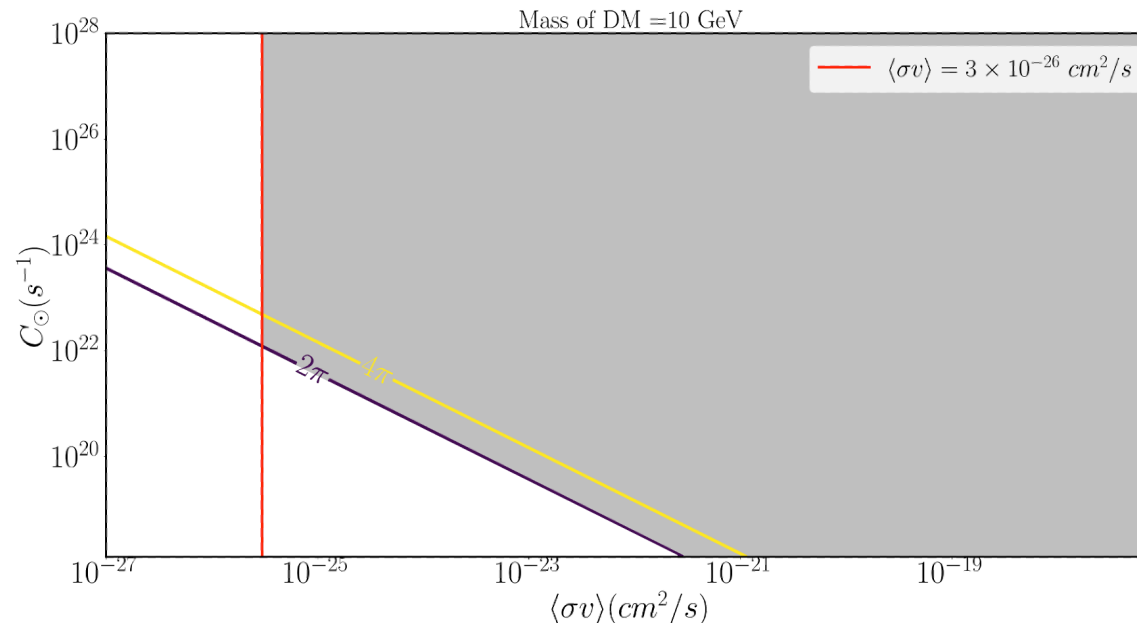
$$\frac{dN}{dt} = C_c - C_a N^2 - C_e N$$

$$C_a = \frac{C_c}{2}$$

$$C_c \propto \sigma_{\chi-n,p}^{SD}, \sigma_{\chi-n,p}^{SI}$$

$$C_a \propto \langle \sigma v \rangle_{\chi\chi}$$

For $M_{DM} > 4\text{GeV}$



arXiv: 9506380

Expected neutrino signal @ JUNO

- Flux ($f\bar{f}$):

$$\frac{d\phi}{dE} = P_{\nu_{\alpha} \rightarrow \nu_{\beta}} \frac{C_a}{4\pi R^2} \sum_f B_{DM\overline{DM}}^{f\bar{f}} \frac{dN}{dE}$$

- The expected number of events:

$$N \sim \Phi \cdot \sigma \cdot n_t \cdot \epsilon \cdot t$$

- DM parameter:

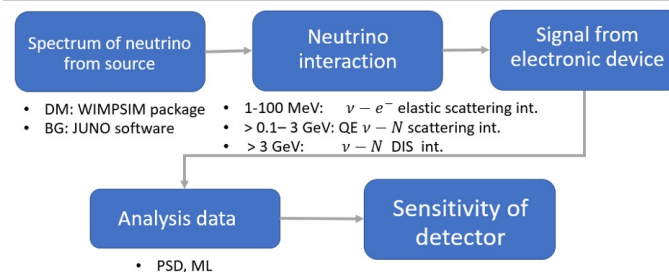
Ann. Channel: $\tau\bar{\tau}$

$$\sigma_{\chi p}^{SD} = 1 \times 10^{-40} \text{ cm}^2$$

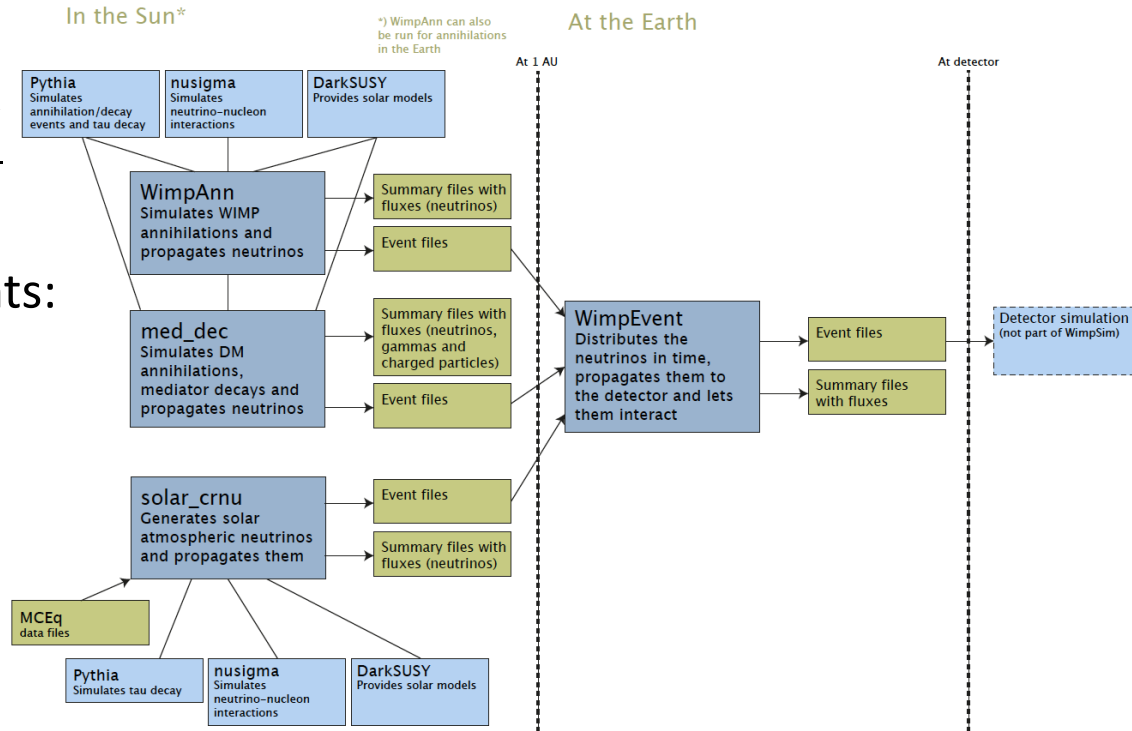
$$\rho_{NFW} = 0.3 \frac{\text{GeV}}{\text{cm}^3}$$

$$v_{NFW} = 270 \text{ km/s}$$

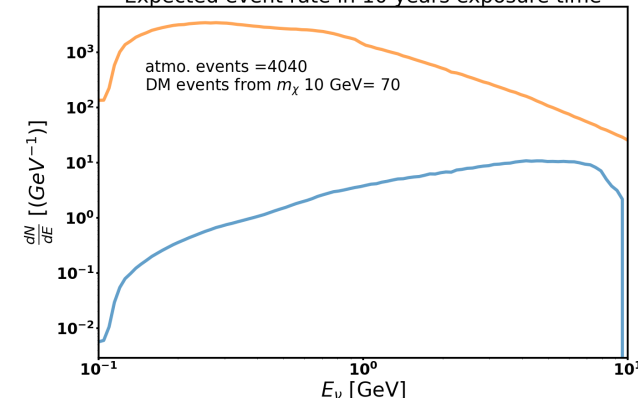
$$\epsilon_{det}, \epsilon_{veto} = 1$$



WimpSim code layout



Expected event rate in 10 years exposure time



Background Rejections

Energy: $20 \text{ MeV} - m_\chi$
Reconstruction radius
< 16 m.

PSD: ν_e from DM with
atmo NC and CC

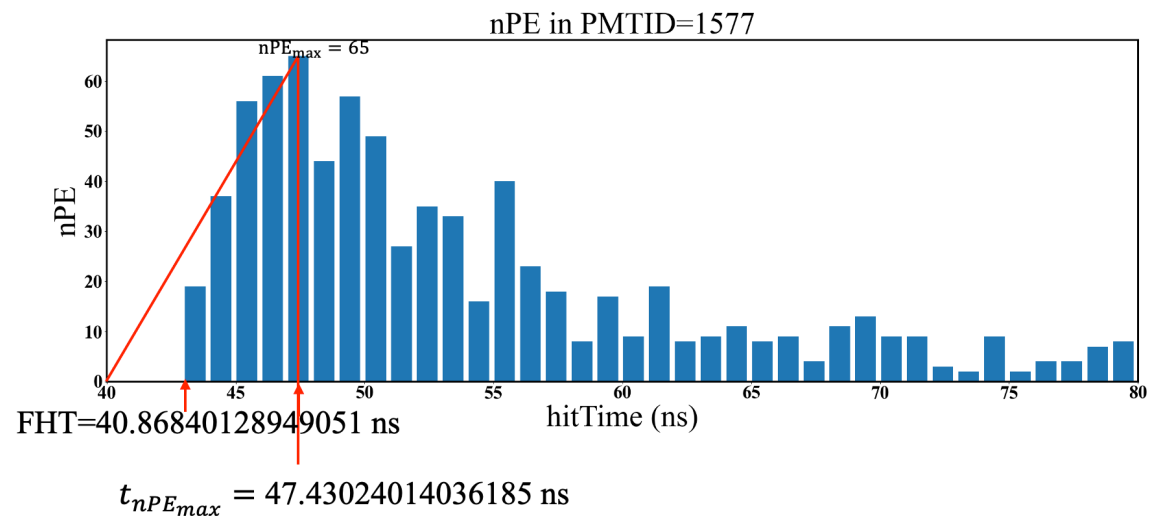
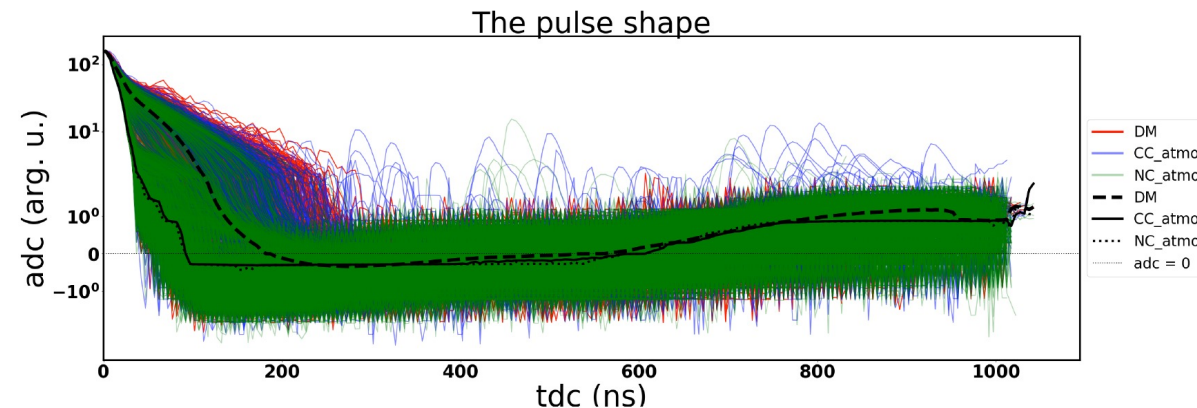
Directionality

Center of charge
method

Distribution:

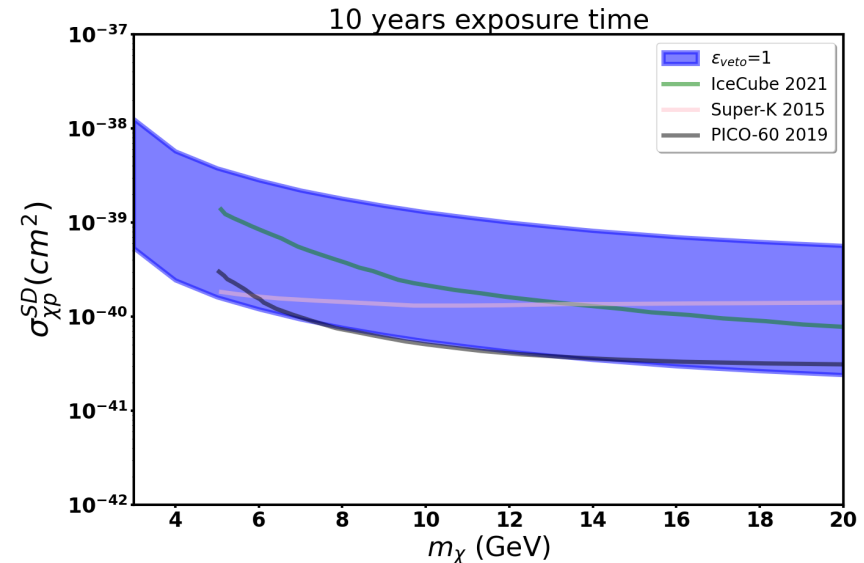
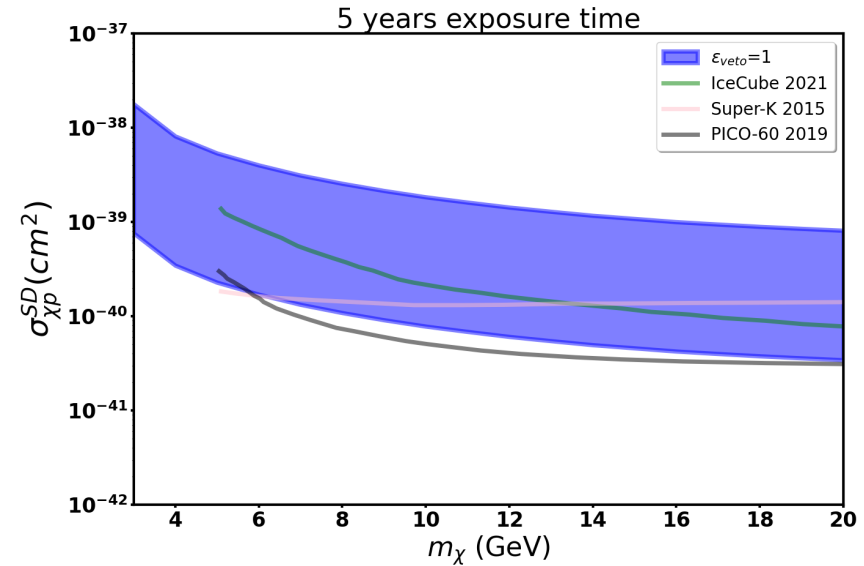
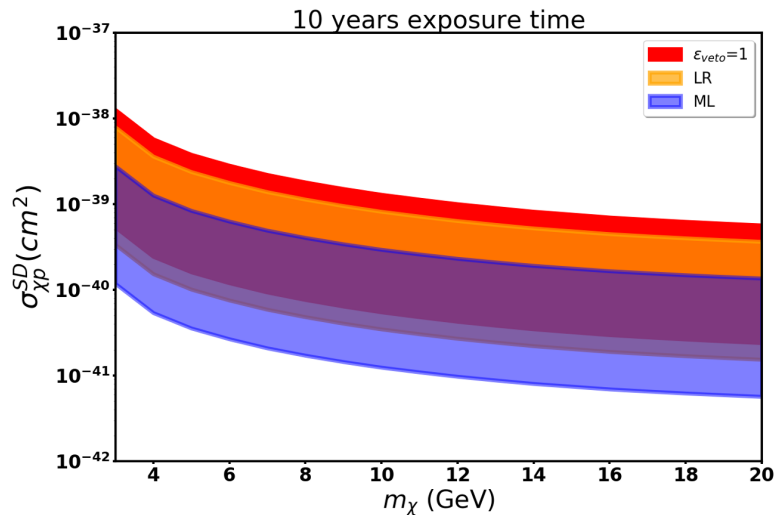
FHT
nPE
Slope
Charge

+ ML/DL



Sensitivity

- The preliminary result of 2σ .
(spin-dependent DM and proton cross-section)
 - Upper line for the worst case: $\epsilon_{det} = 0.6, B_{\chi\bar{\chi}}^{\tau\bar{\tau}} = 0.055^{[4]}$
 - lower line for the best



DeepSphere

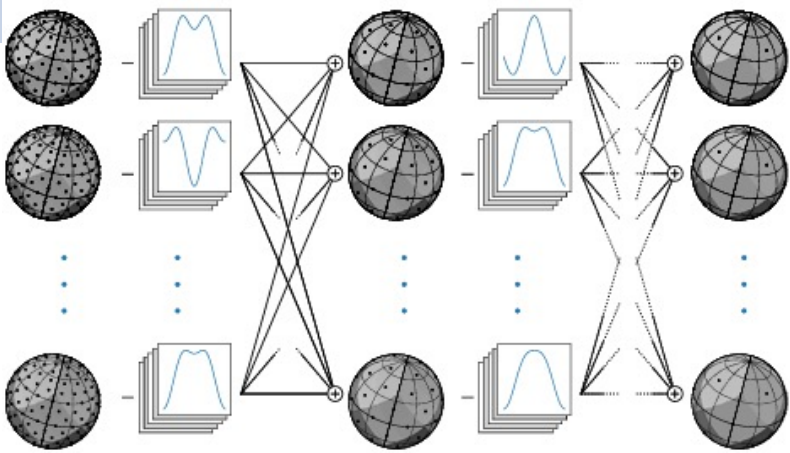
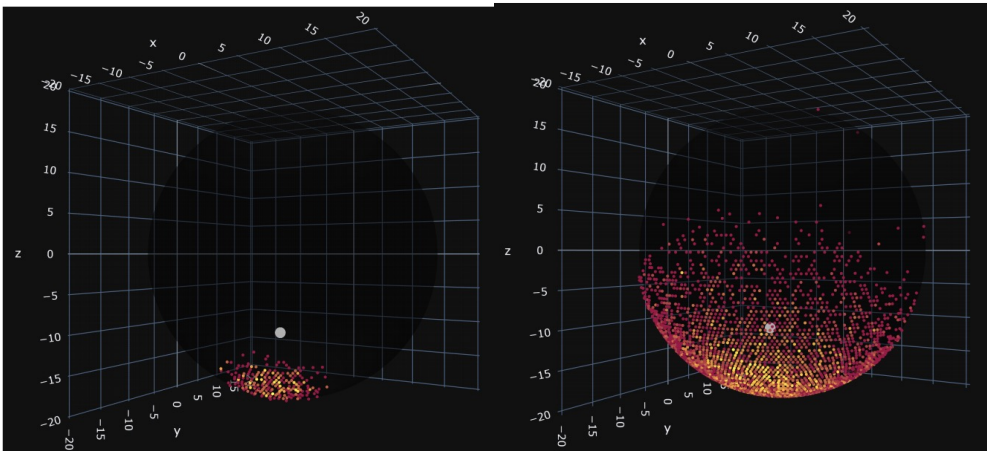


Illustration of DeepSphere working process [1]



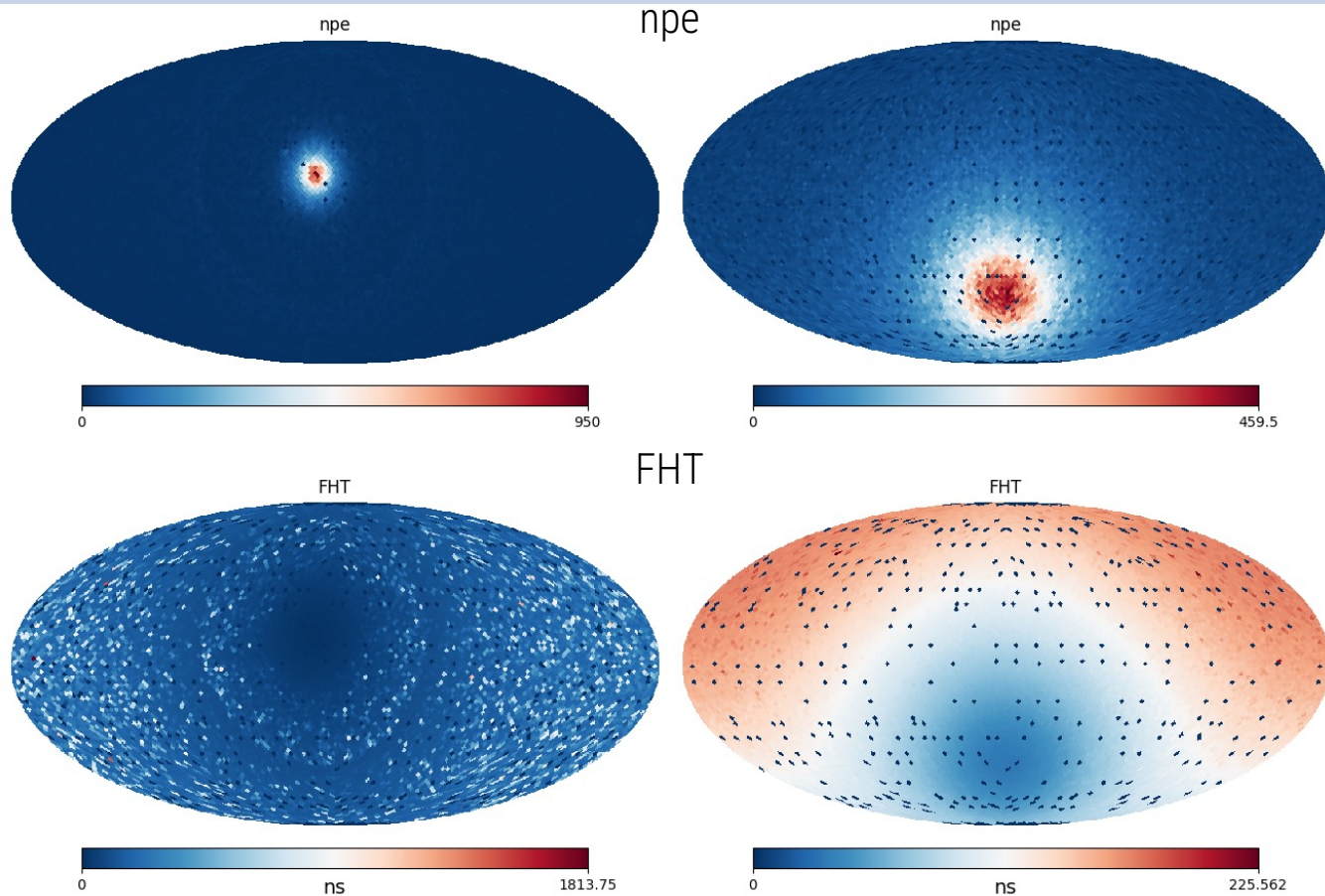
Example of data use in energy and vertex reconstruction [2]

- DeepSphere is DL model specifically created for spherical data
- JUNO data come in from of spherical maps
- Neural network is normally made for flat data
- Project spherical data into flat space cause distortion
- Using of DeepSphere on JUNO data in energy and vertex reconstruction give better result than ML

[1] (Perraudin et al., 2019)

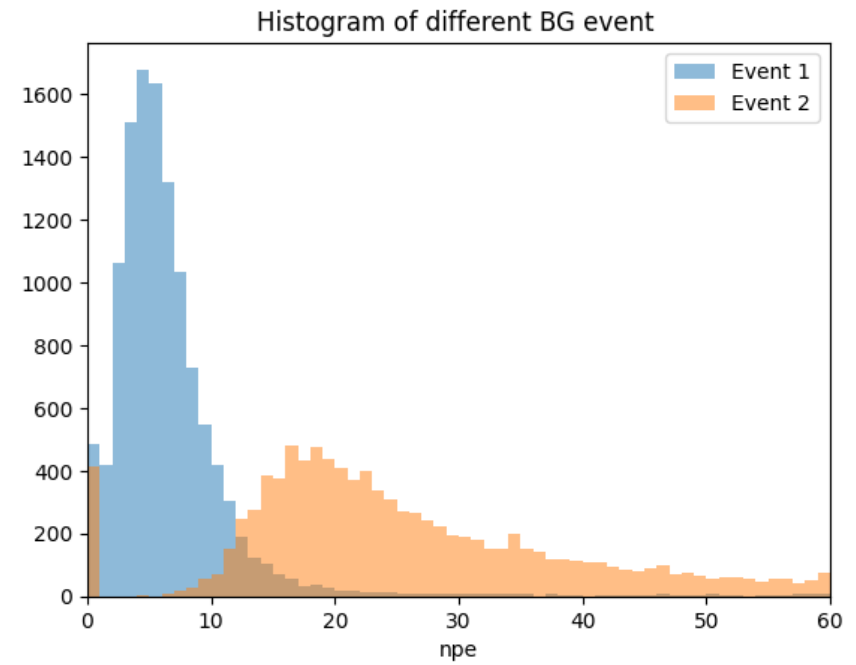
[2] (Qian Z., Belavin V., et al., 2021)

Example of atmospheric neutrino data



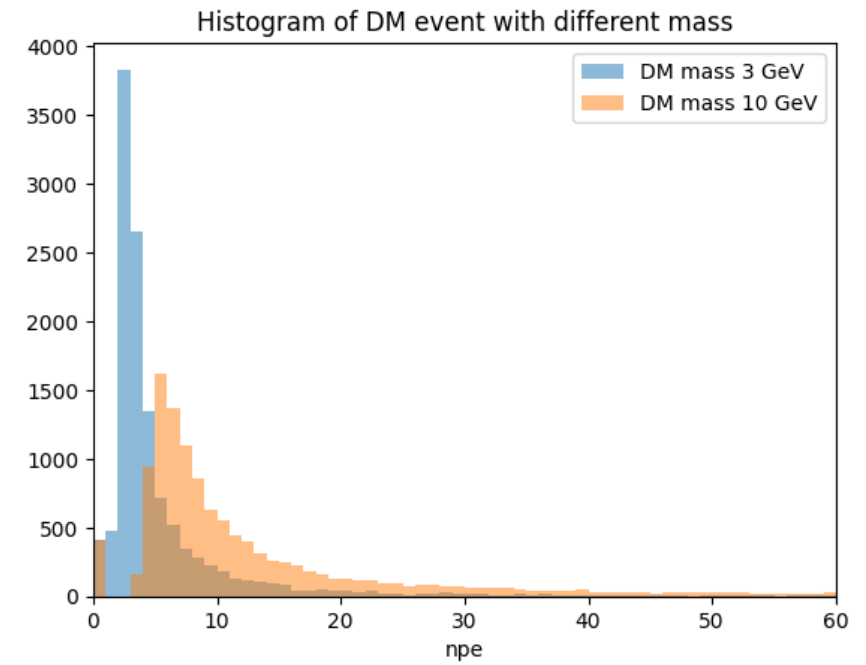
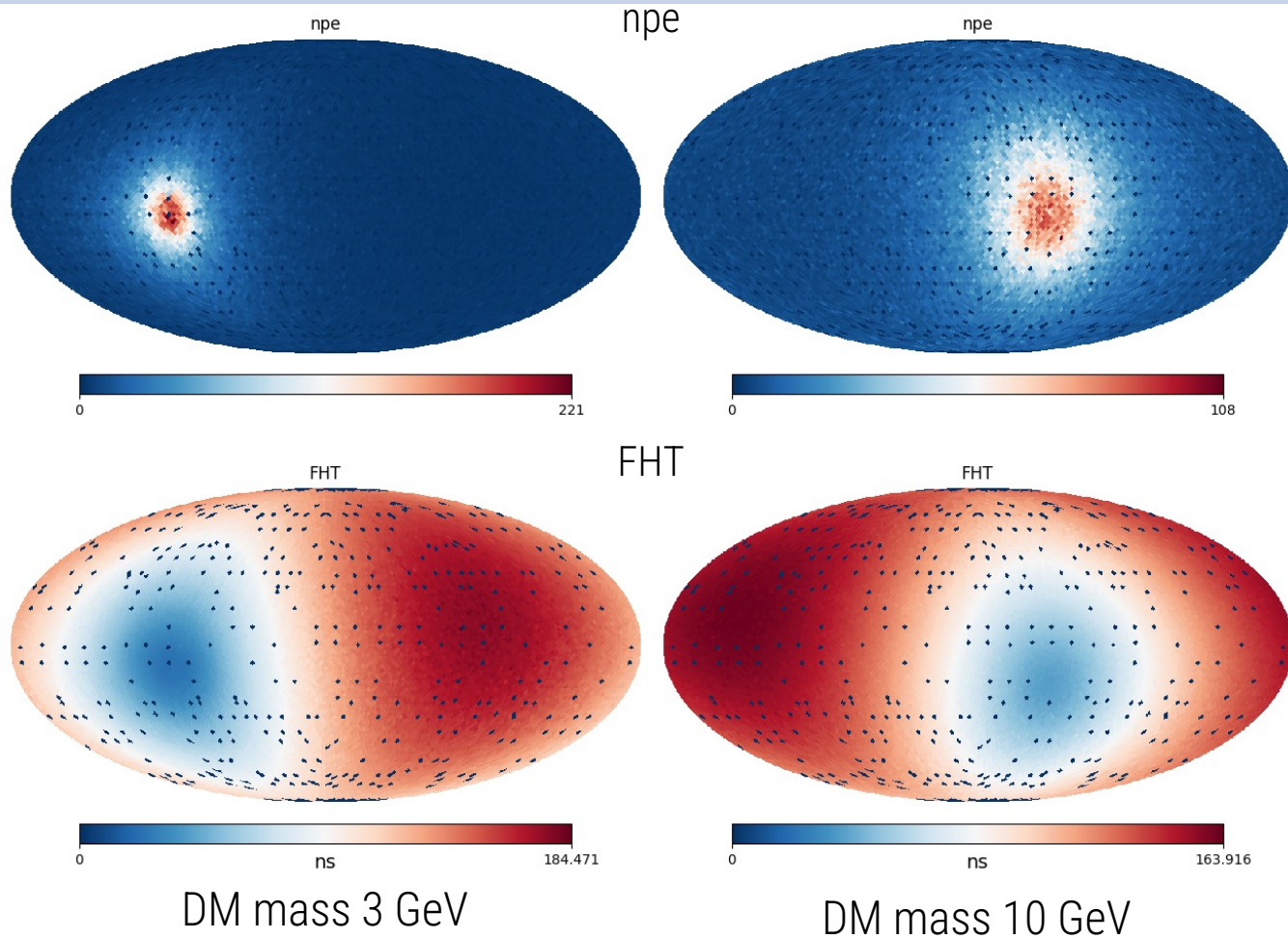
Sample Event 1

Sample Event 2



- Total npe
 - ▷ Event 1: 130861
 - ▷ Event 2: 592204

Example of dark matter neutrino data



Total npe

▷ 3 GeV: 73298

▷ 10 GeV: 168818

DL performance Default model

DM input	Performance (ratio)			
	Accuracy	Recall	Precision	F1 score
DM 3 GeV	0.940	1.000	0.935	0.967
DM 4 GeV	0.922	0.993	0.924	0.957
DM 5 GeV	0.979	1.000	0.972	0.986
DM 6 GeV	0.912	1.000	0.911	0.953
DM 7 GeV	0.862	0.859	0.968	0.910
DM 8 GeV	0.972	1.000	0.945	0.972
DM 9 GeV	0.908	1.000	0.899	0.947
DM 10 GeV	0.939	0.986	0.940	0.962
DM 11 GeV	0.961	0.993	0.959	0.976
DM 12 GeV	0.963	0.993	0.959	0.975
DM 13 GeV	0.913	1.000	0.911	0.954
DM 14 GeV	0.997	0.994	1.000	0.997
DM 15 GeV	0.993	1.000	0.986	0.993
DM 16 GeV	0.968	0.935	1.000	0.966
DM 17 GeV	0.987	1.000	0.975	0.987
DM 18 GeV	0.985	1.000	0.969	0.984
DM 19 GeV	0.984	0.981	0.987	0.984
DM 20 GeV	0.994	1.000	0.987	0.994

		True	
		DM	Atmo
Predicted	DM	120	12
	Atmo	4	144

Performance Matrices

Confusion matrix

- Accuracy = 0.934 $\left(= \frac{TP+TN}{TP+TN+FP+FN} \right)$
- Precision = 0.923 $\left(= \frac{TP}{TP+FP} \right)$
- Recall = 0.973 $\left(= \frac{TP}{TP+FN} \right)$
- F1-score = 0.947 $\left(= \frac{2 \times \text{precision} \times \text{recall}}{\text{precision} + \text{recall}} \right)$

Predicted Class

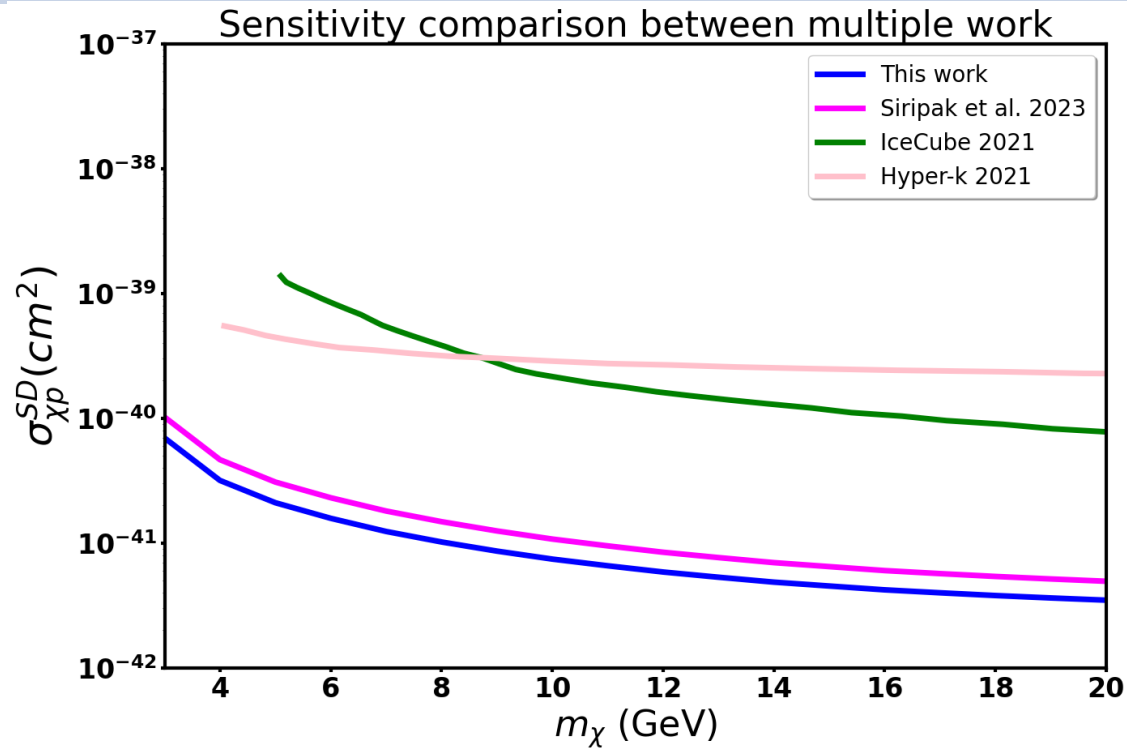
Positive
Negative

True Class

Positive Negative

	Positive	Negative
Positive	TP	FP
Negative	FN	TN

Comparison with other work

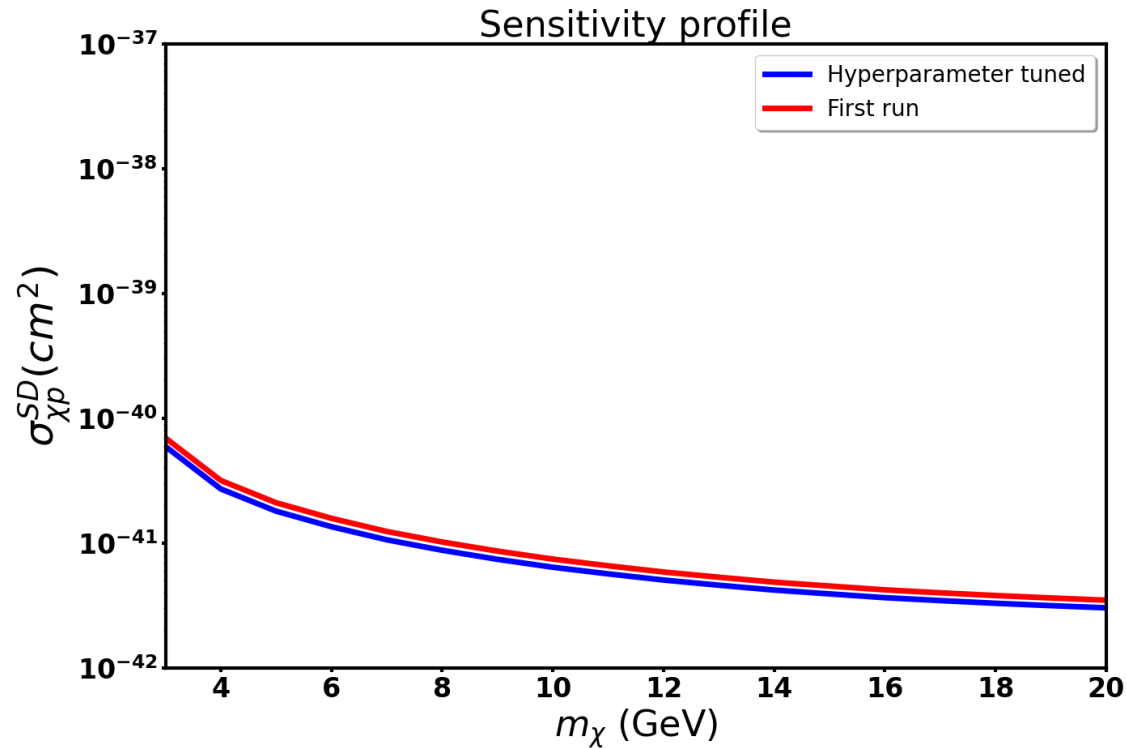


- At 10 GeV result is
 - ▷ Ice cube: $2.09 \times 10^{-40} cm^2$
 - ▷ Hyper-k: $2.874 \times 10^{-40} cm^2$
 - ▷ JUNO-ML: $1.077 \times 10^{-41} cm^2$
 - ▷ This work: $7.441 \times 10^{-42} cm^2$
- Compare to Ice cube and Hyper-k this work give better result at 28 and 38 times respectively
- Compare to similar work DL give better result than ML at 40%

Hyperparameter Tuning

- Change hyperparameter of model to improve result
 - Default model:
 - ▷ Activation function = “relu”
 - ▷ K-value = 10
 - ▷ Batch Size = 8
 - ▷ Epoch = 10
 - ▷ Bias = True
 - ▷ Batch Norm = True
- Do not show significant change in result

Cross section profile from optimal model



- At 10 GeV result is
 - ▷ First run: $7.441 \times 10^{-42} cm^2$
 - ▷ Tuned run: $6.402 \times 10^{-42} cm^2$
- Compare to the first run tuned run give better result at 16%

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 and JUNO) will improve sensitivity by 1–2 orders of magnitude.
- Combining multi-wavelength and multi-messenger data remains the best path forward.