A Multimessenger Window into

The Dark Matters of the Universe

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May 28, 2026

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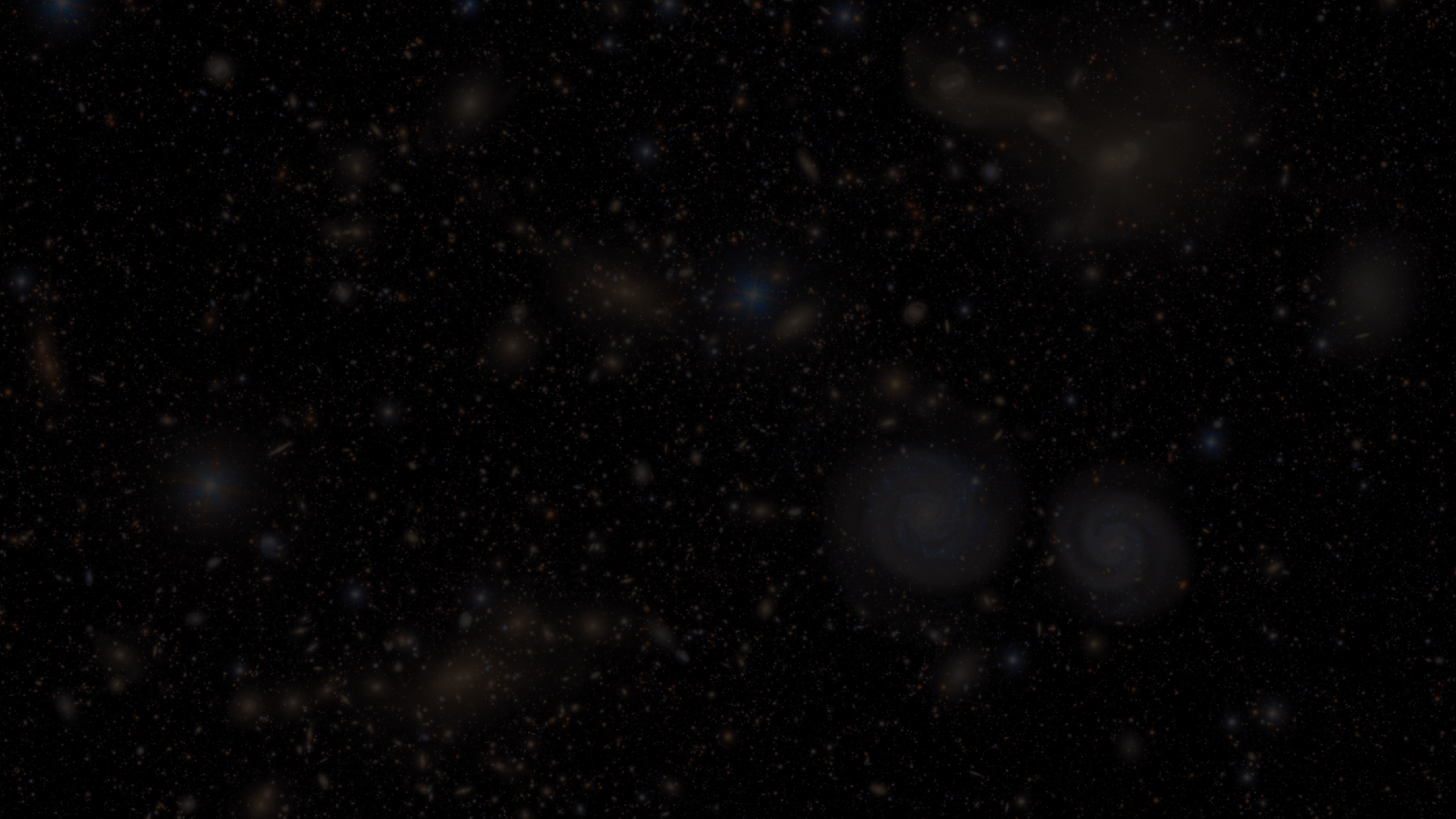
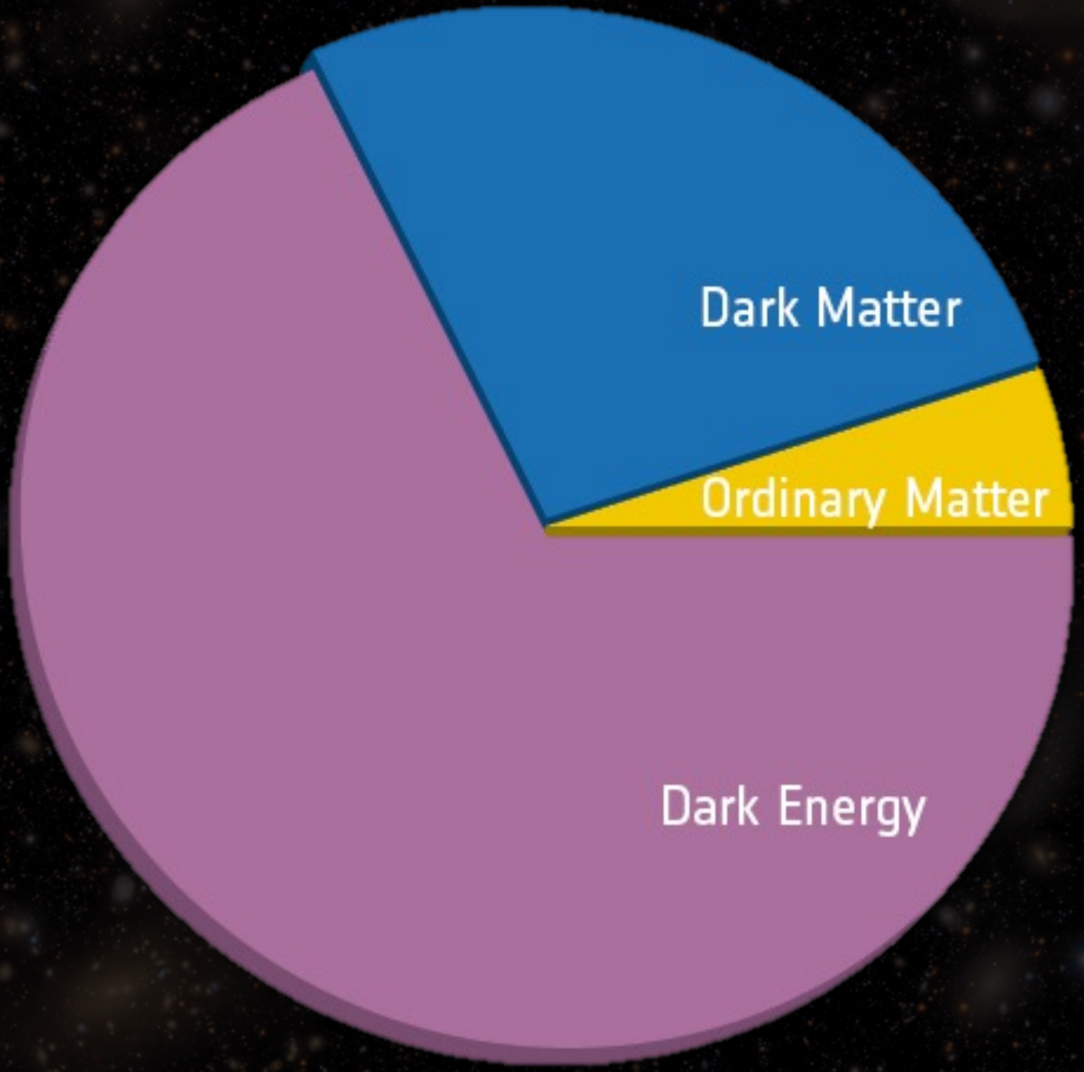
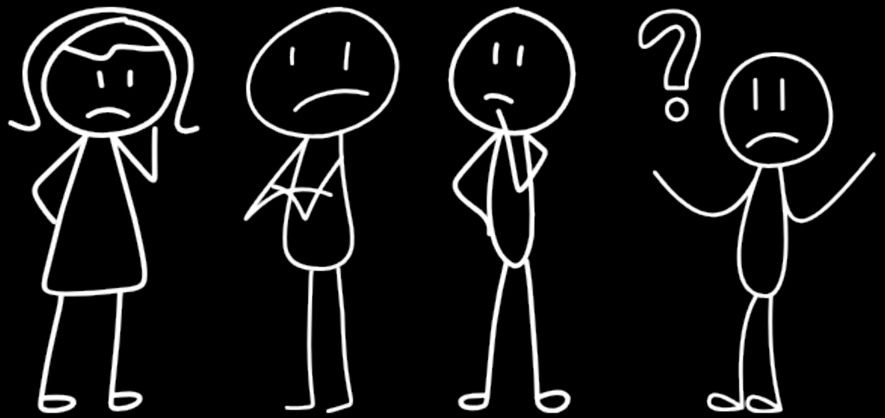
[Vera Rubin Observatory/LSST]




Dark Matter
Ordinary Matter
Dark Energy

How do we know* dark matter is there?



With a decent level of certainty…

Which photo was taken on a windy day?

[Images taken from Adobe Stock]

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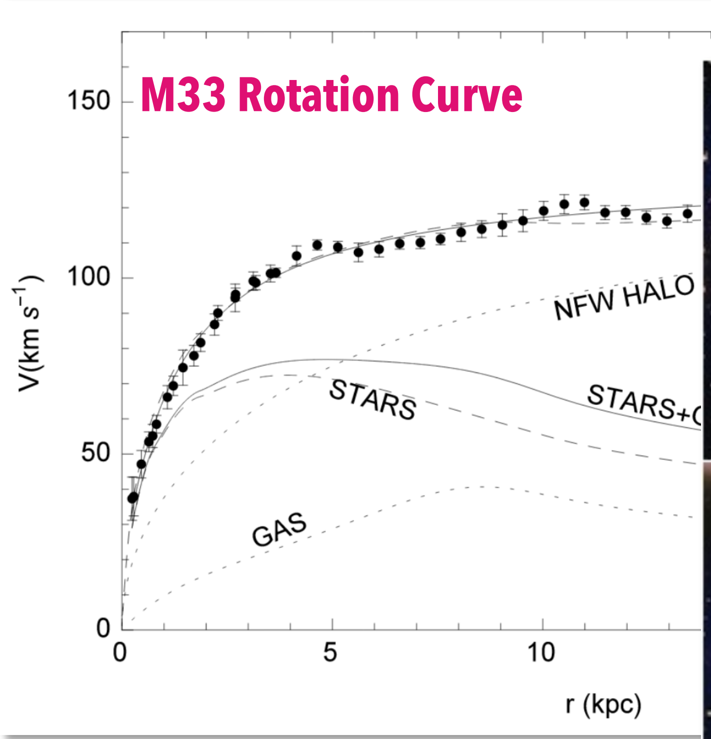
[Images taken from Adobe Stock]

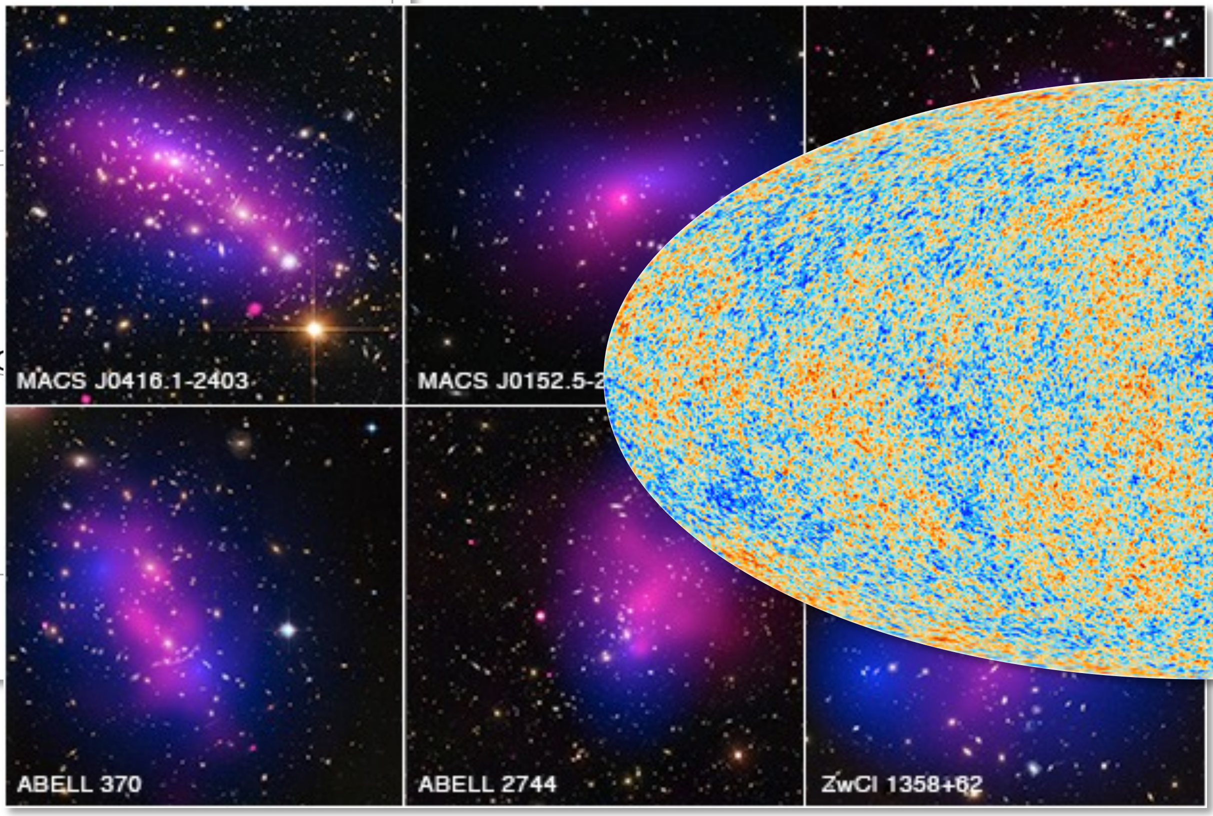
Overwhelming evidence for the existence of dark matter on all scales

local universe

cosmological distances

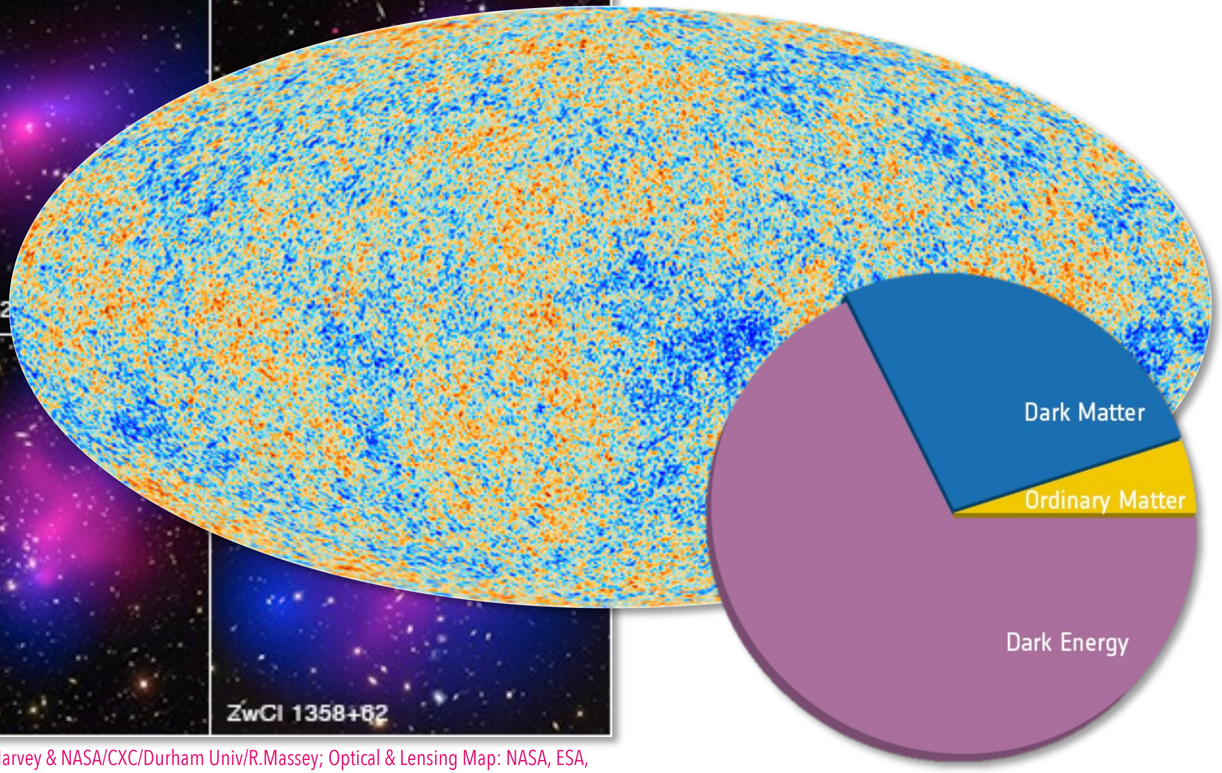


Galaxy Clusters



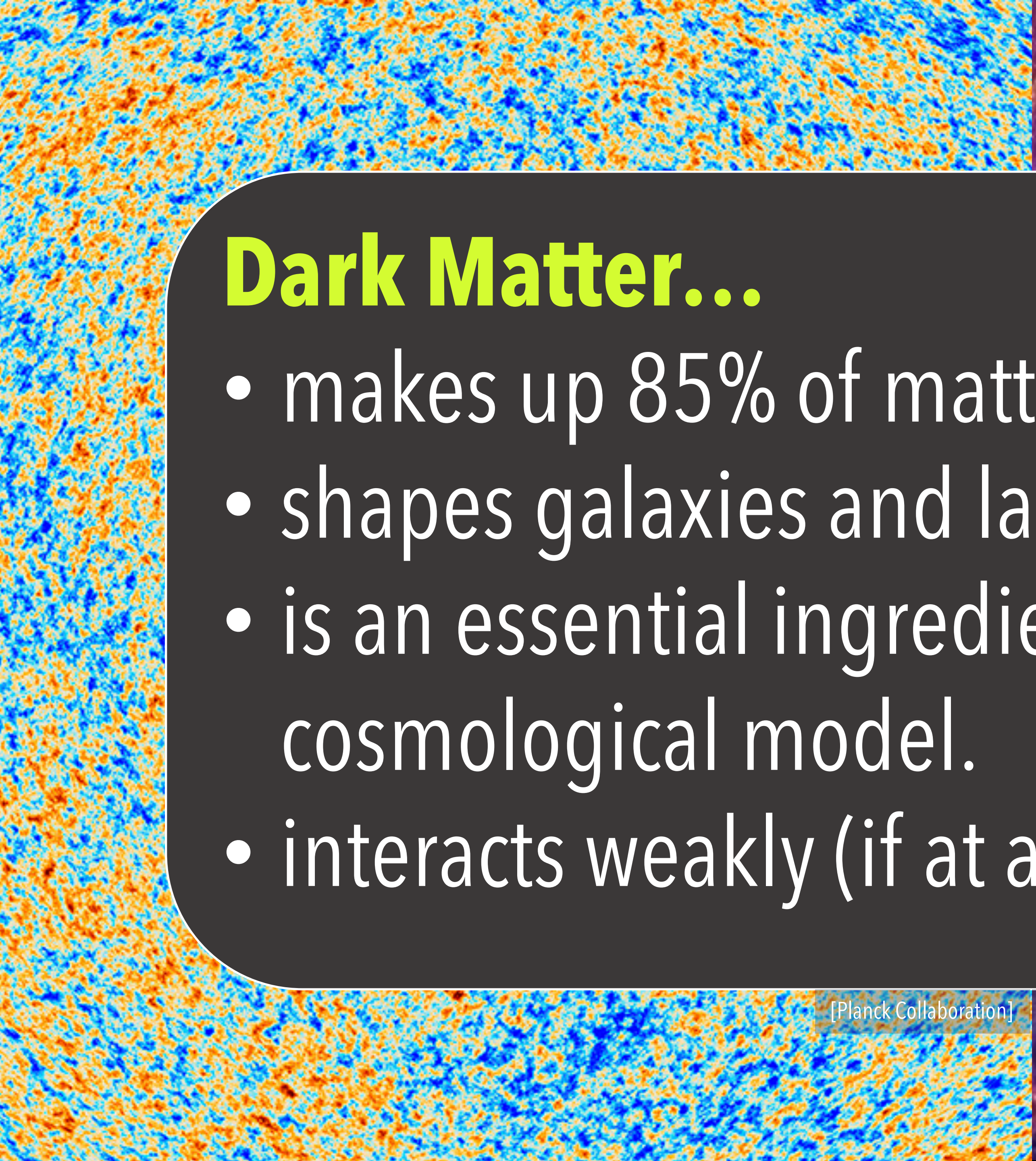
X-ray: NASA/CXC/Ecole Polytechnique Federale de Lausanne, Switzerland/D.Harvey & NASA/CXC/Durham Univ/R.Massey; Optical & Lensing Map: NASA, ESA, D. Harvey (Ecole Polytechnique Federale de Lausanne, Switzerland) and R. Massey (Durham University, UK)

CMB

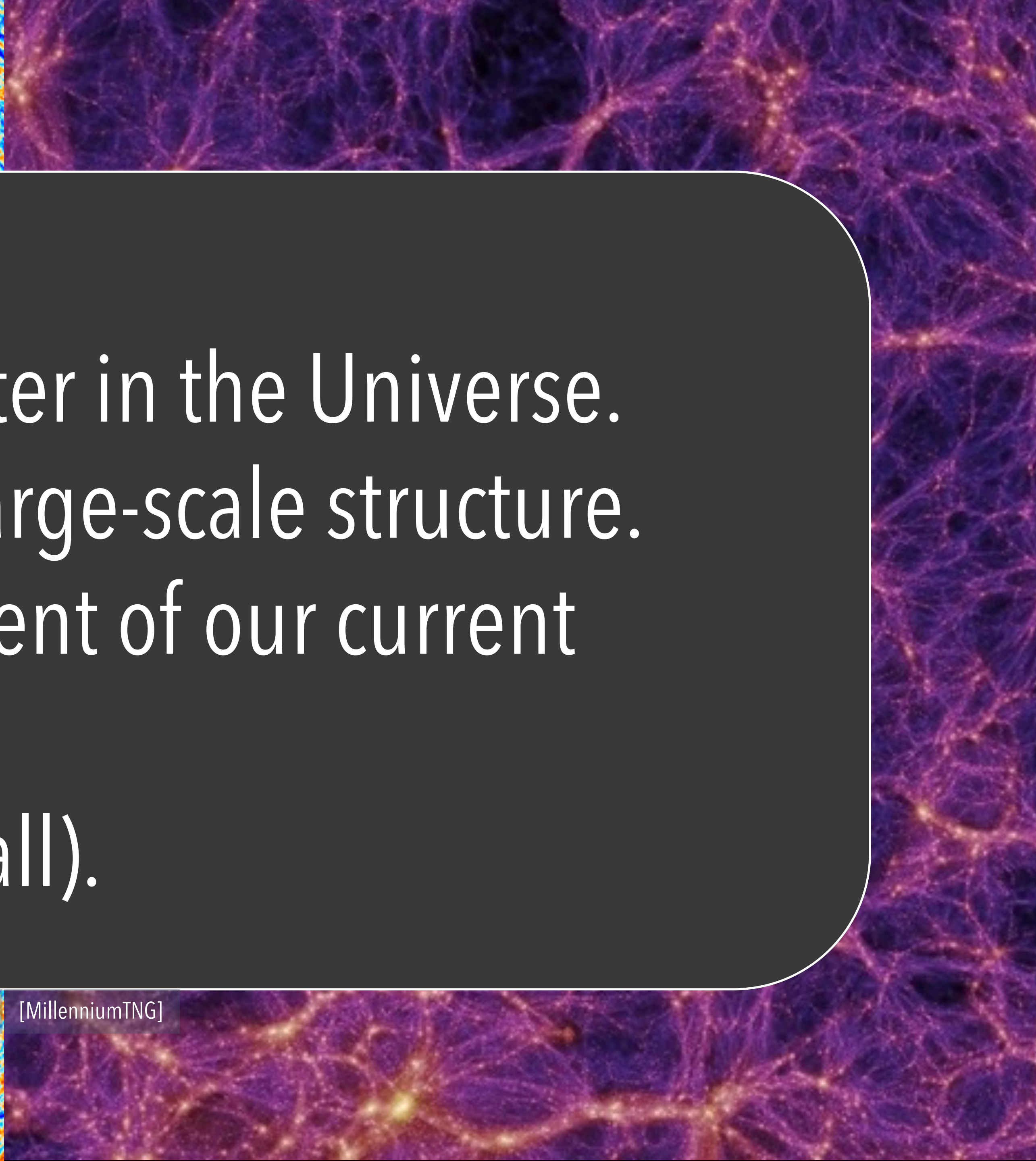


Dark Matter…

- makes up 85% of matter in the Universe.
- shapes galaxies and large-scale structure.
- is an essential ingredient of our current cosmological model.
- interacts weakly (if at all).



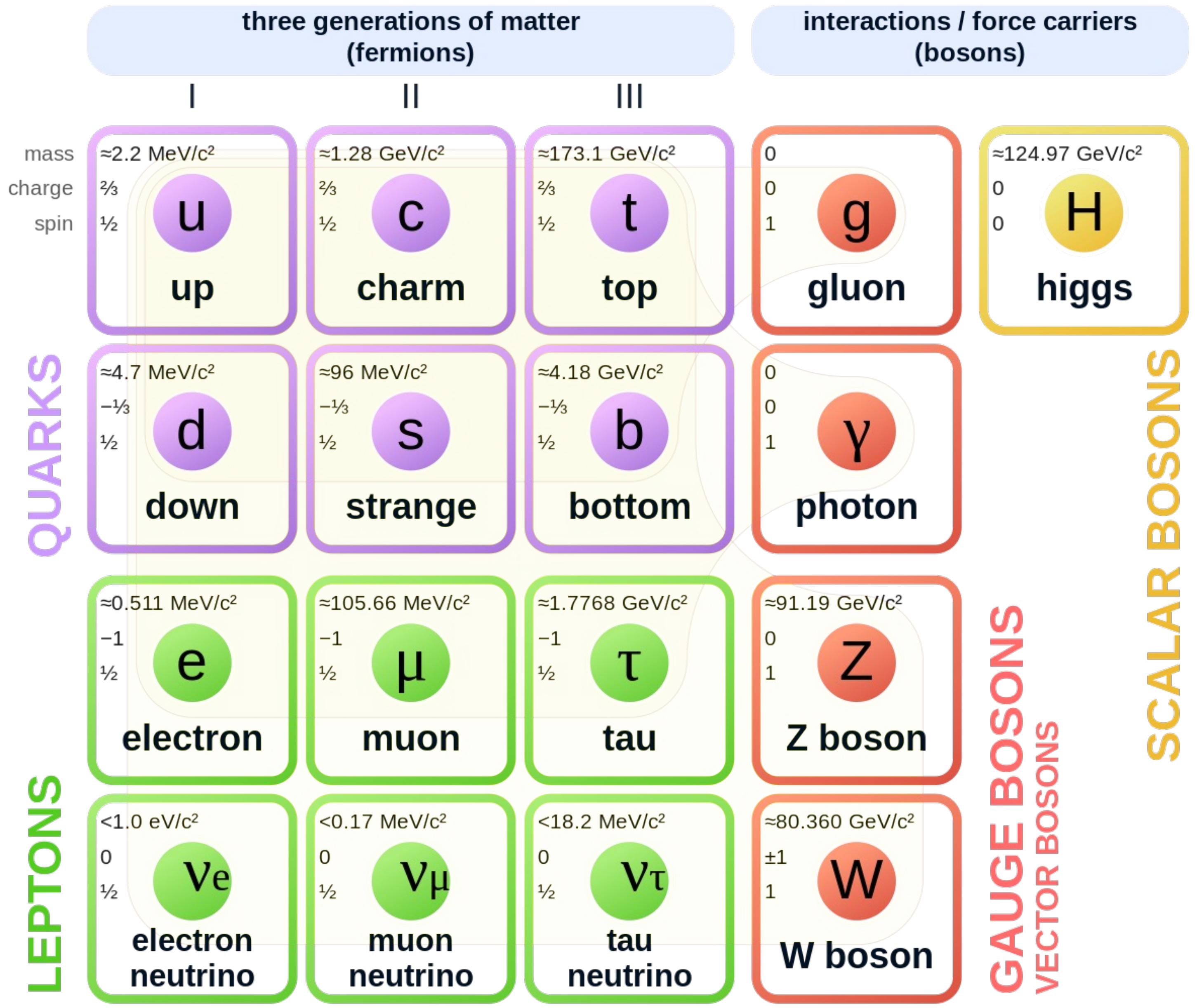
[Planck Collaboration]



[MillenniumTNG]

What is dark matter made of?

Standard Model of Elementary Particles



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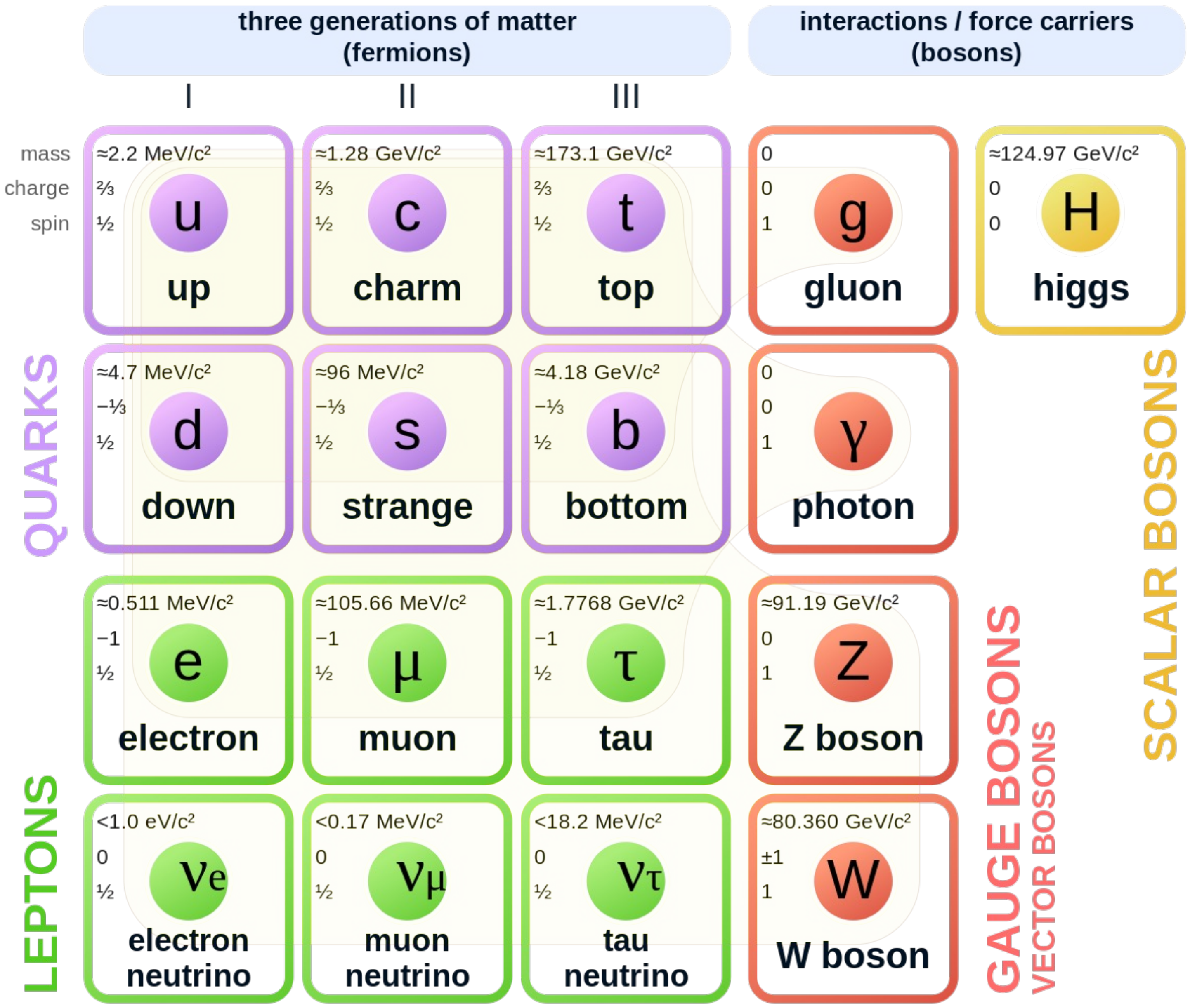
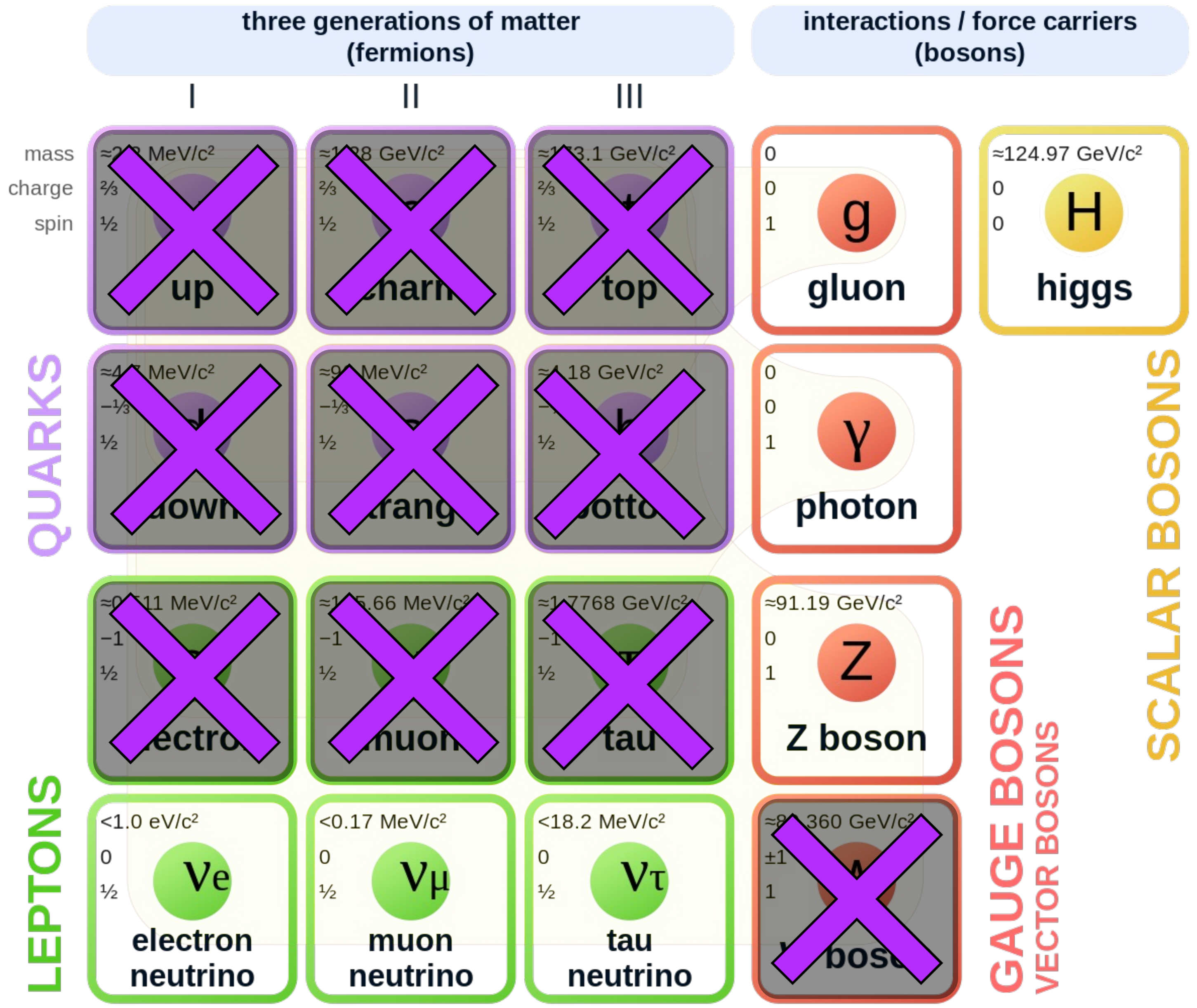


Dark matter should be:

1. Neutral
2. Stable
3. Cold

Standard Model of Elementary Particles



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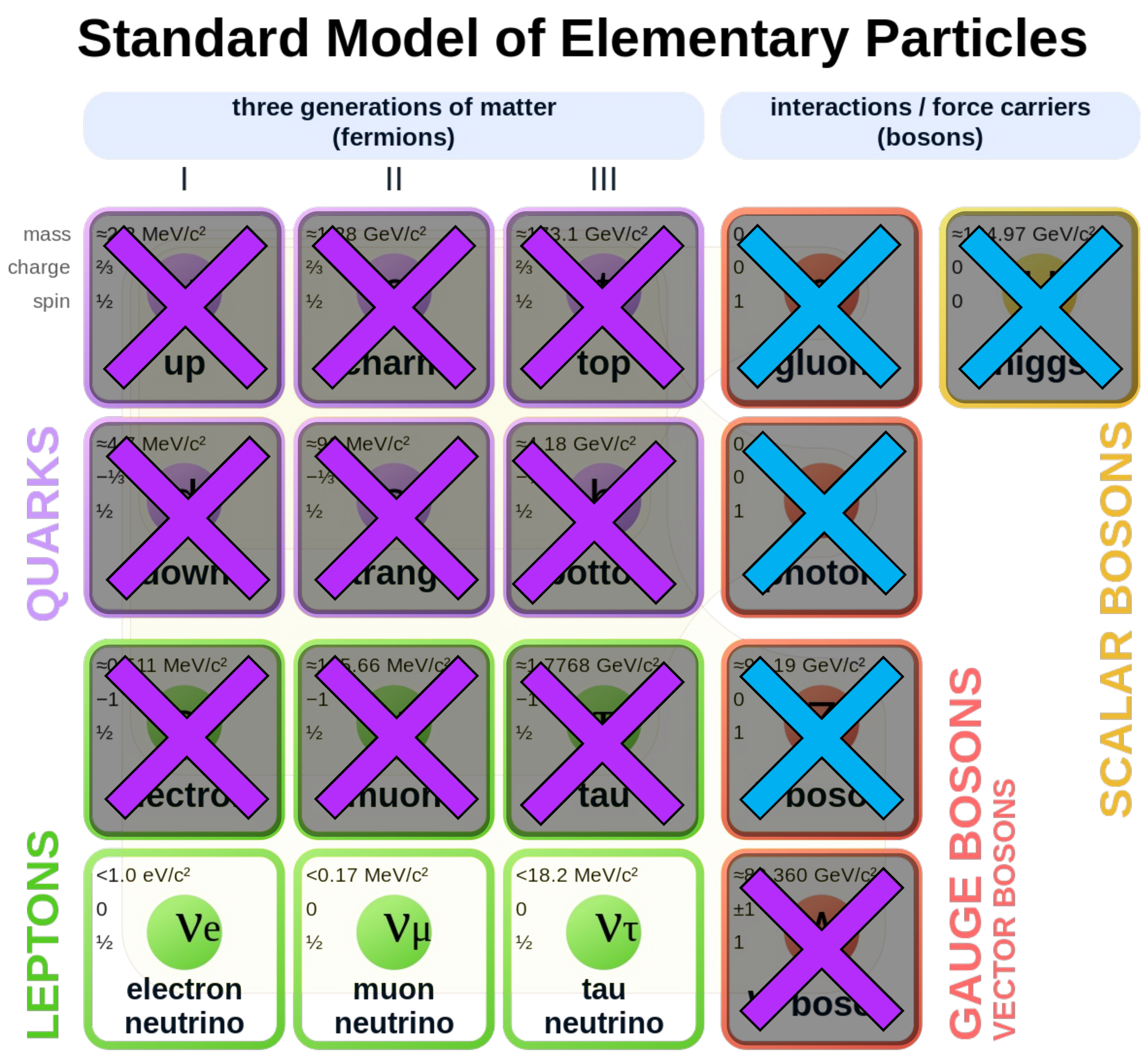

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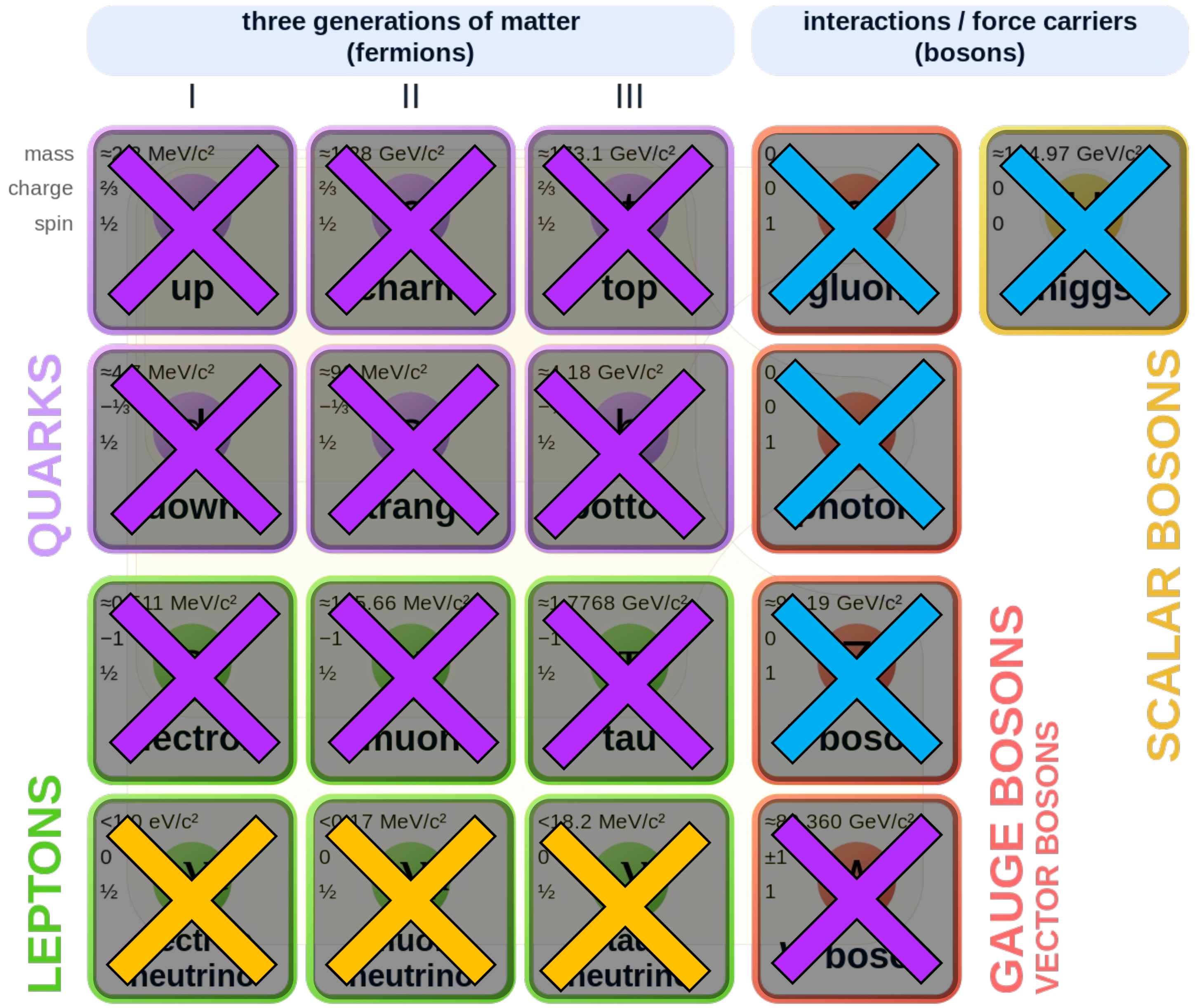

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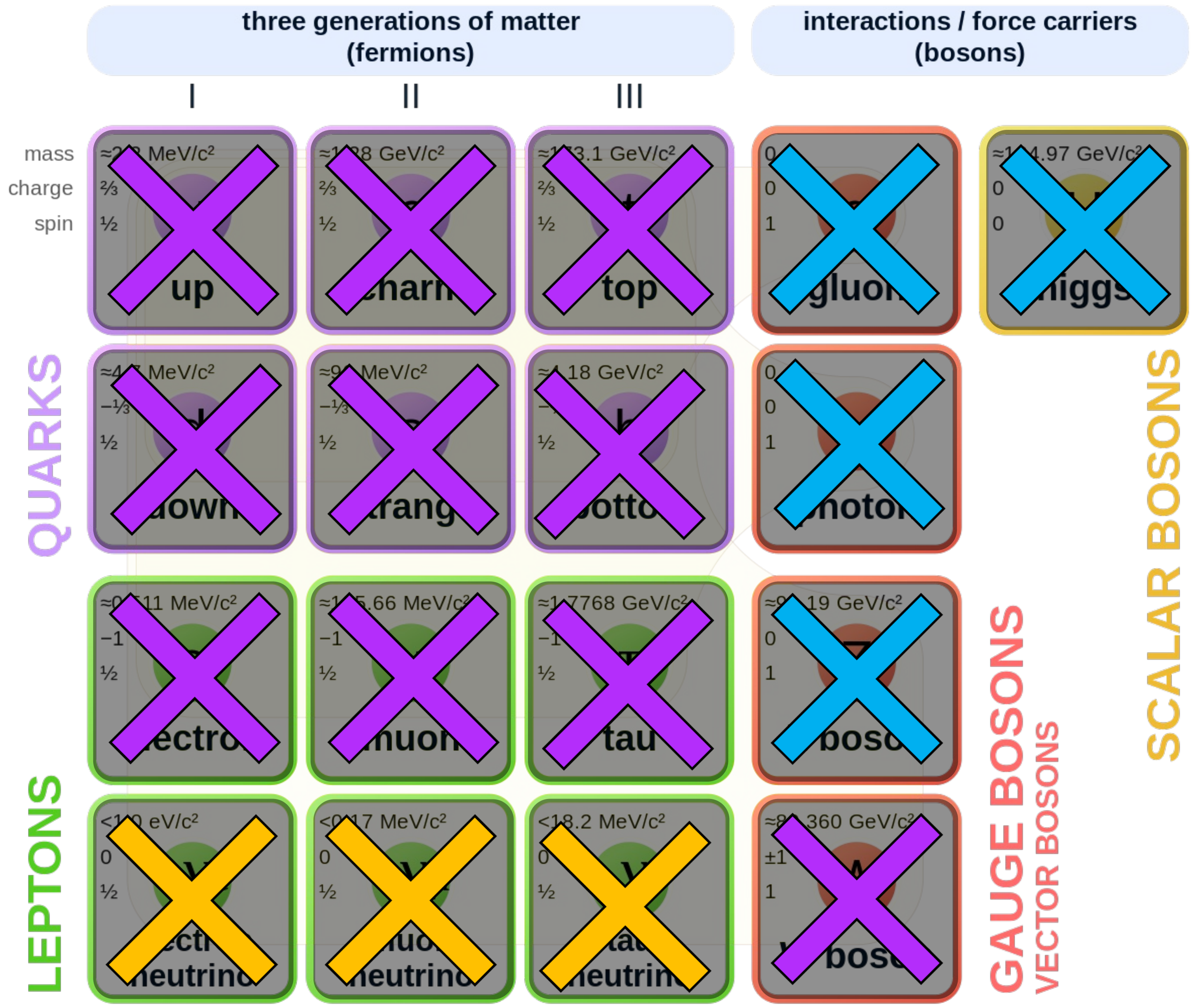


Houston, we have a problem!

Dark Matter Landscape: A Theorist's View

28 May 2026

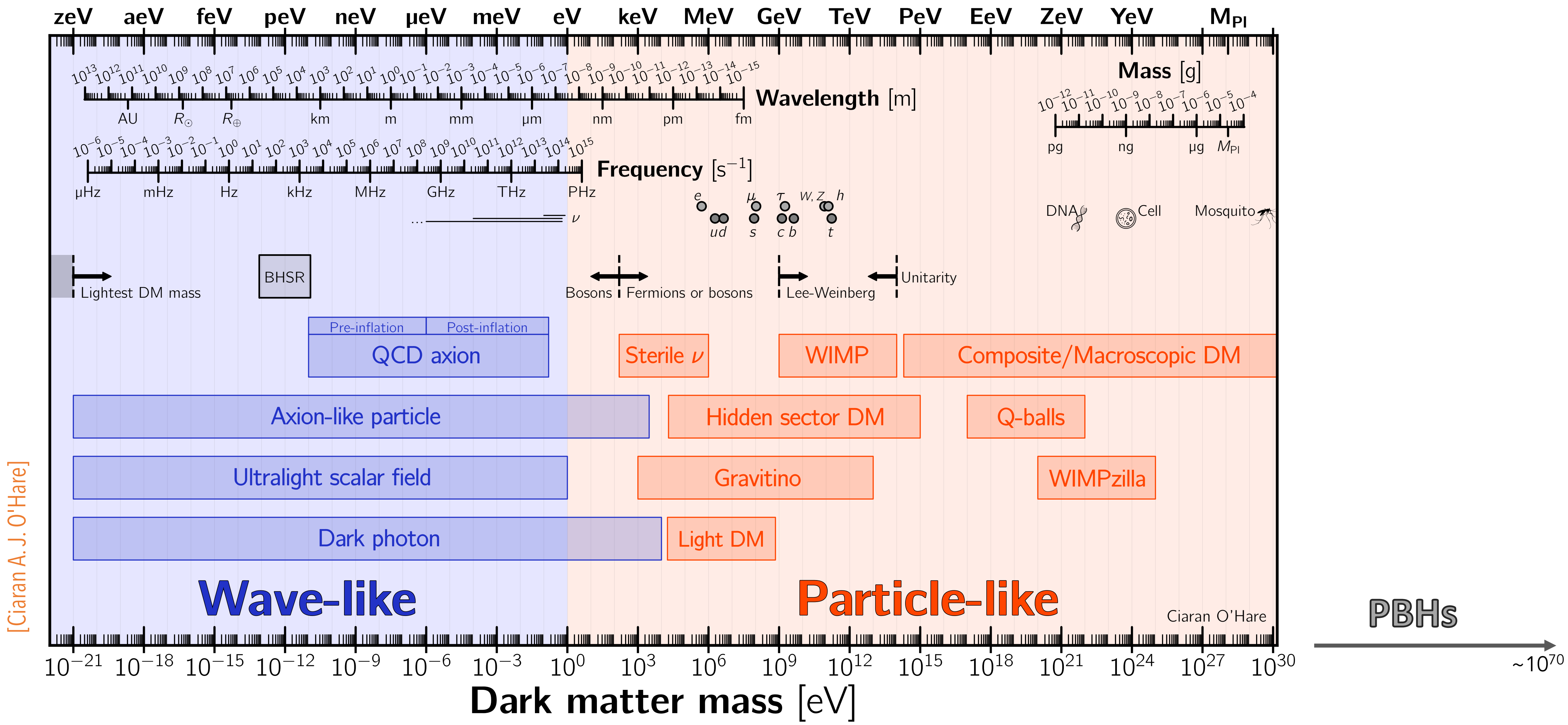
10:00 - 10:35

Dark matter and cosmology under the lens, Djuna Lize Croon

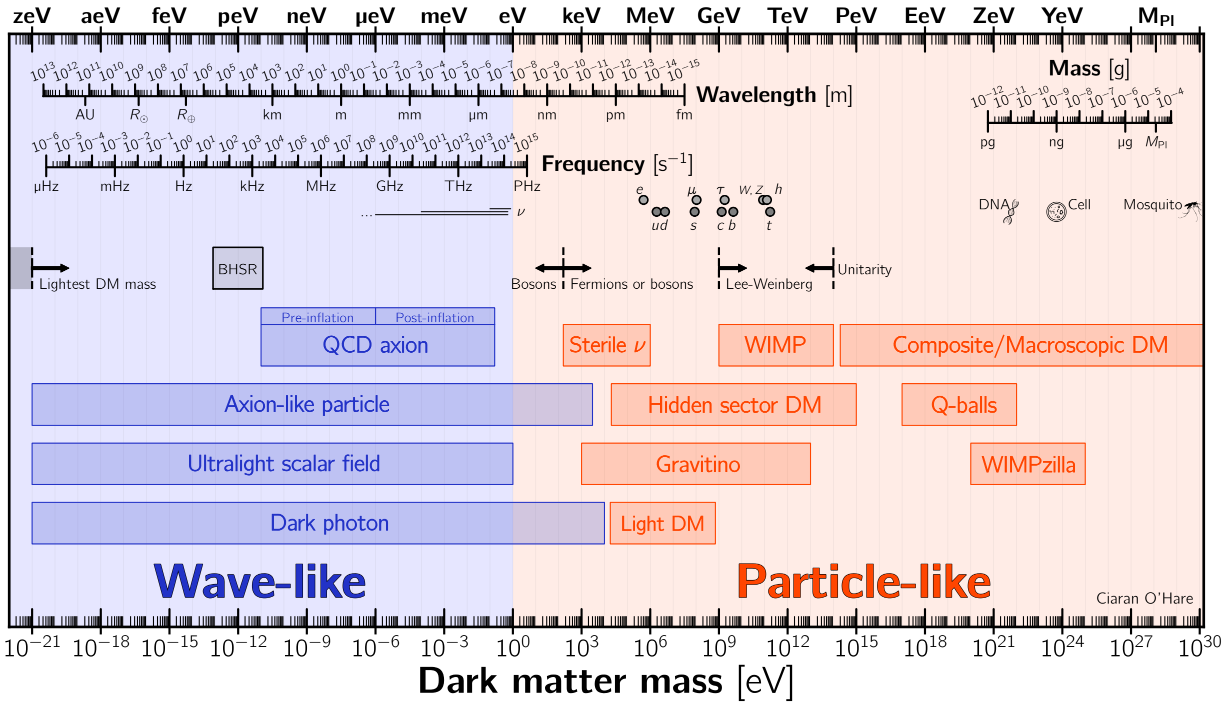
@FlipPhysics

26-29 mayo 2026
Jardín Botánico de la Universitat de València

Dark Matter Landscape: A Theorist's View



Dark Matter Landscape: A Theorist's View



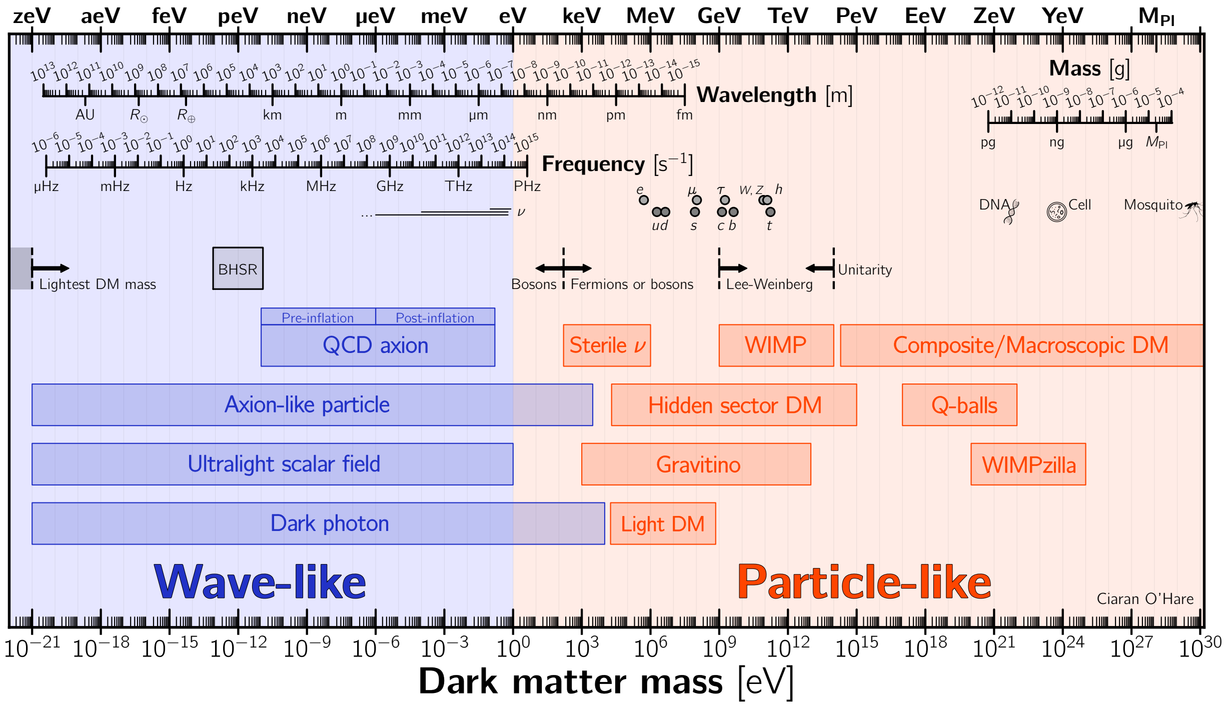
[Ciaran A. J. O'Hare]

Dark matter spans over **80 orders** of magnitude in mass (+ interaction strength)

proton
m~10^{-27} kg

(c) Pablo Carlos Budassi

Dark Matter Landscape: A Theorist's View

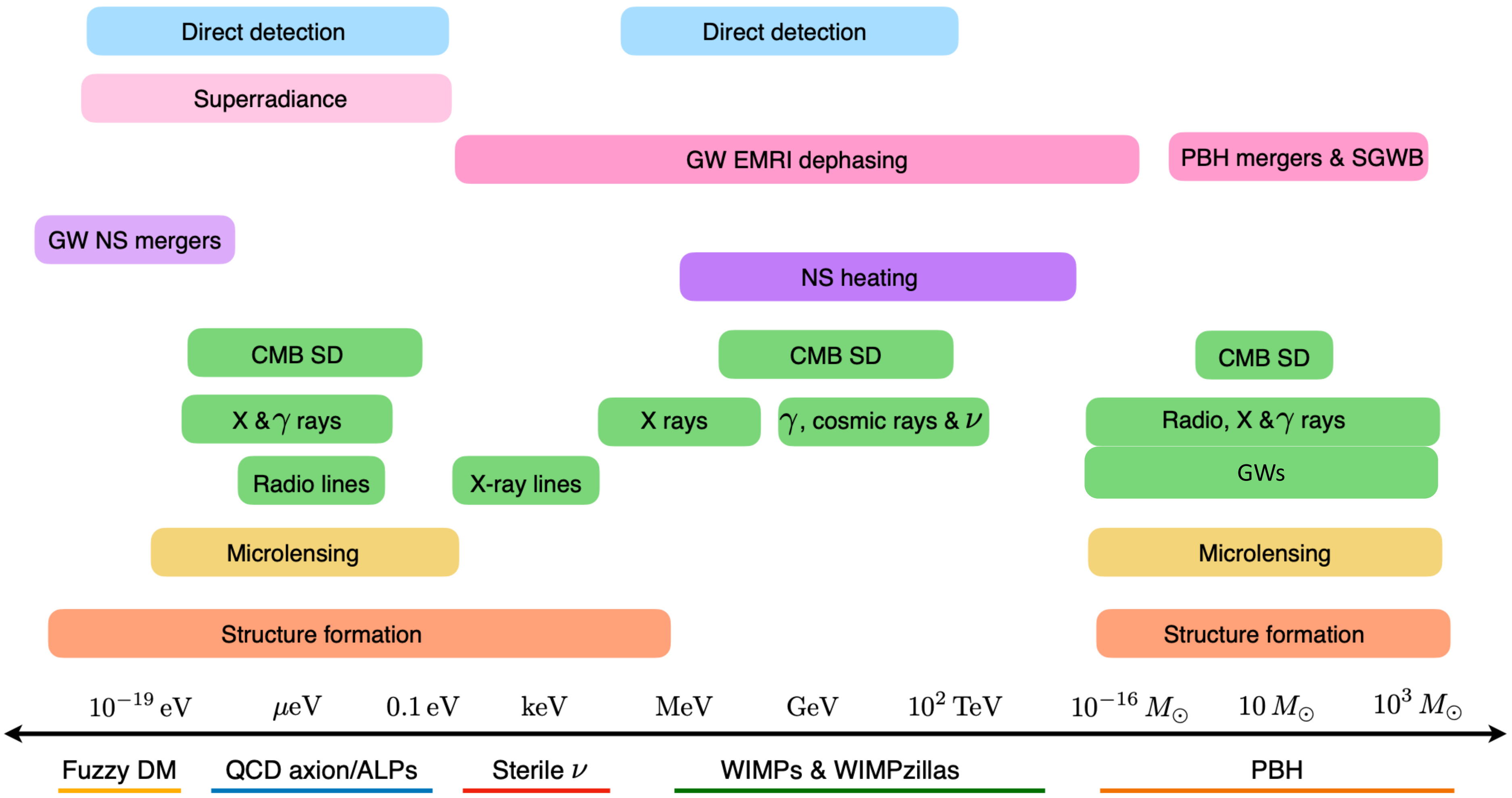


[Ciaran A. J. O'Hare]

Our search strategies are inherently *biased*

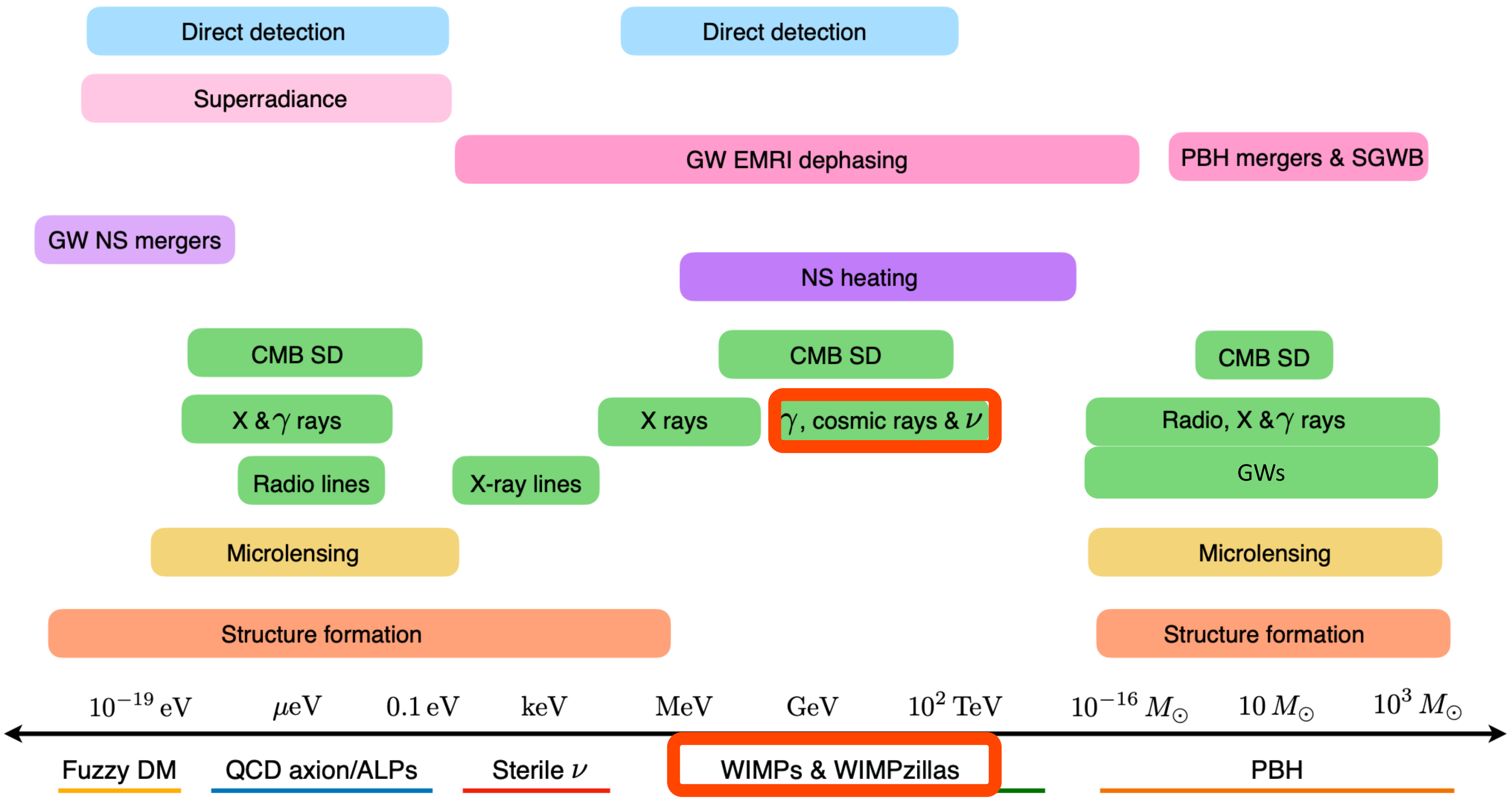
1. **model dependency bias:** theory guides our search strategies
2. **observational bias:** disparity between the data we have and the data we need
3. **identifiable signature bias:** required for observation

Dark Matter Landscape: An Observer's View



[EuCAPT WhitePaper, 2021]

Dark Matter Landscape: An Observer's View



[EuCAPT WhitePaper, 2021]

WIMPs

Indirect observables

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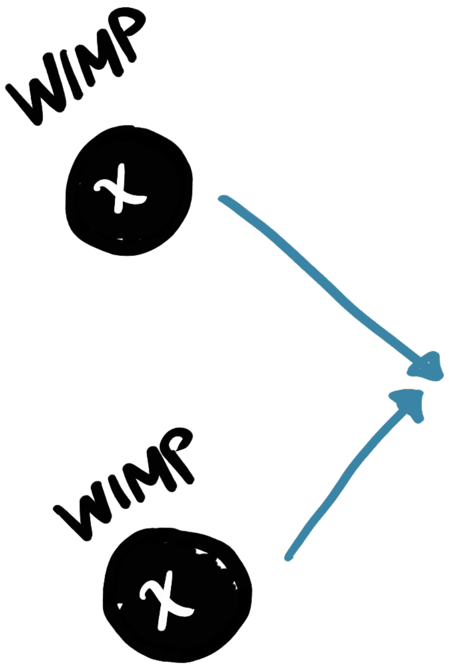
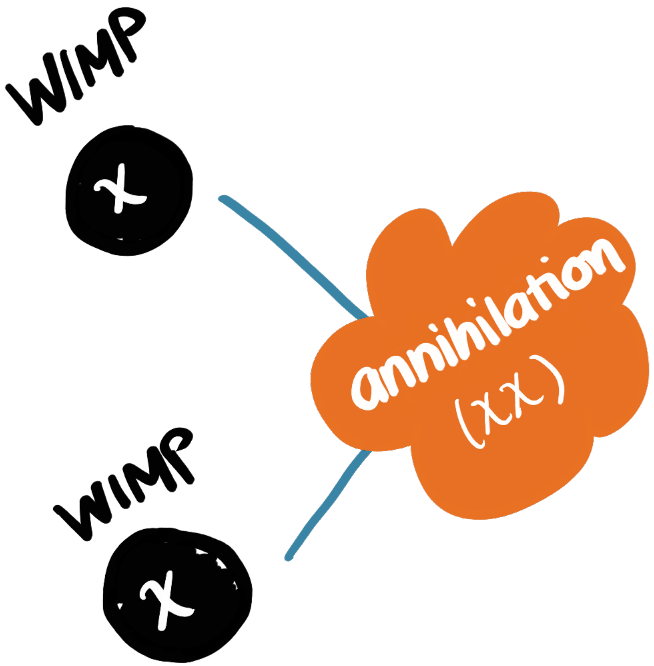
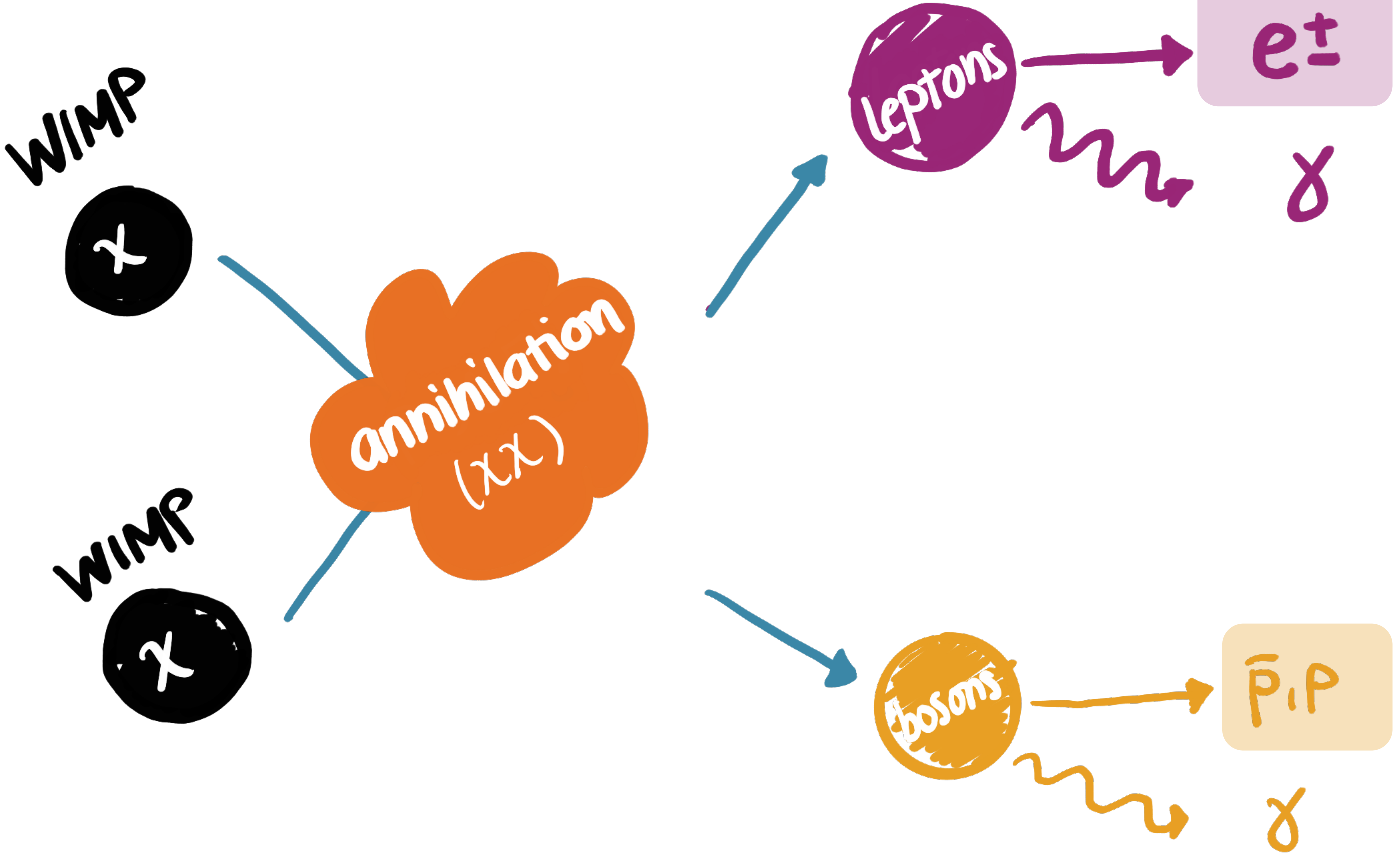
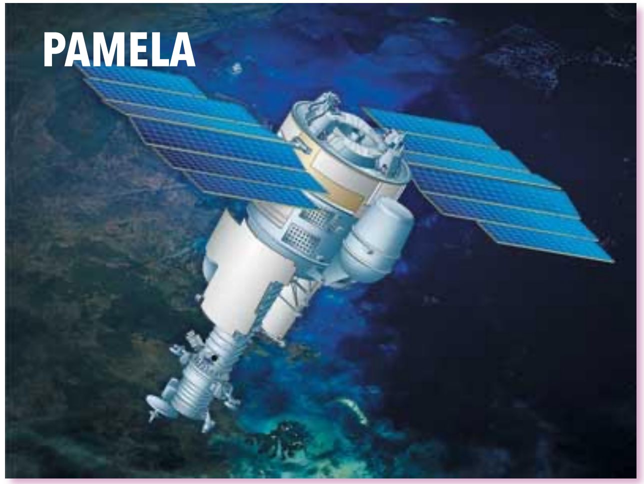


Indirect observables



Indirect observables





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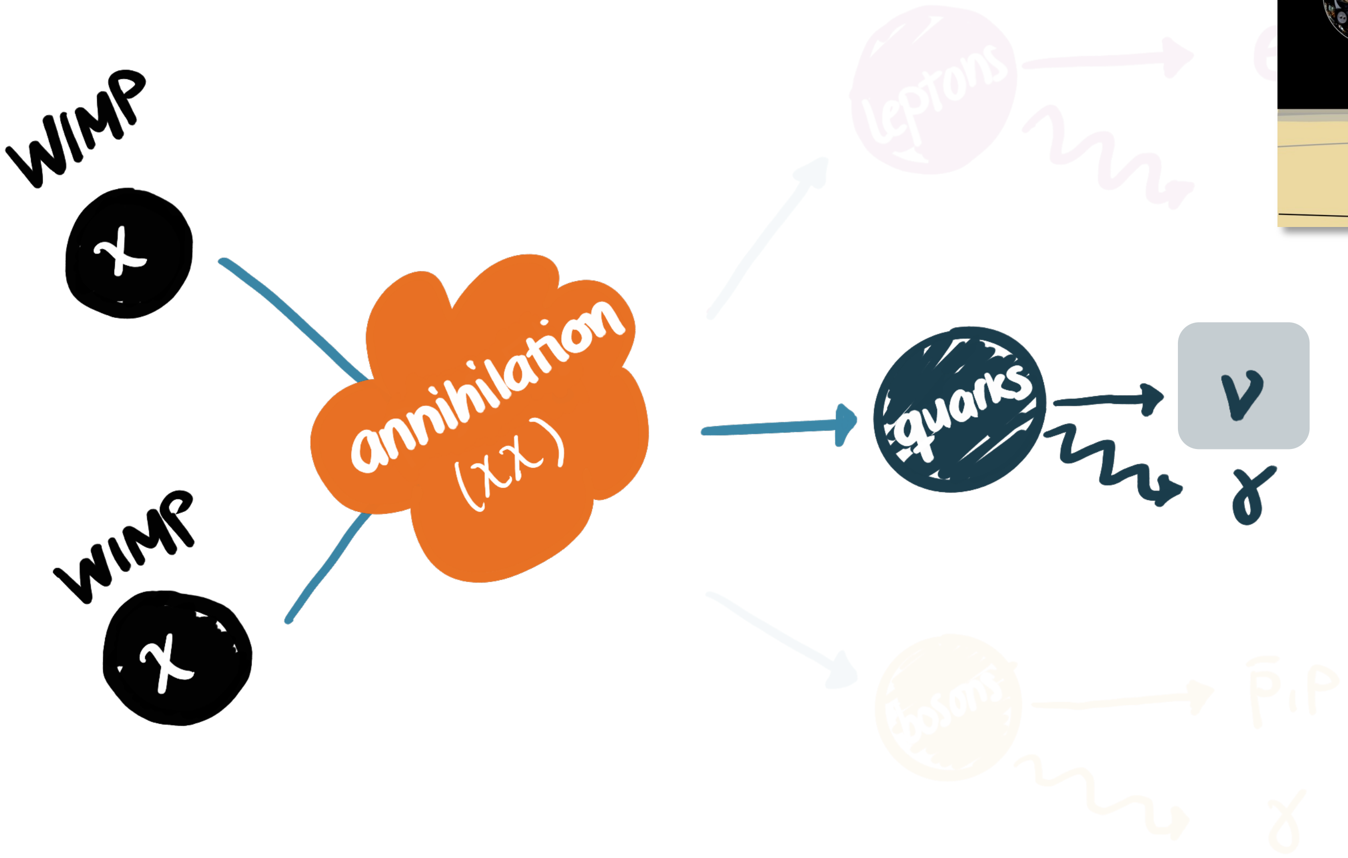
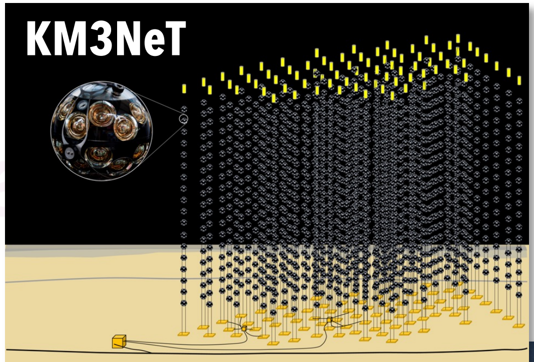
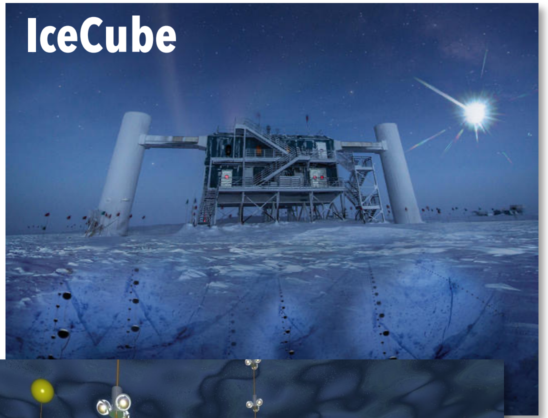
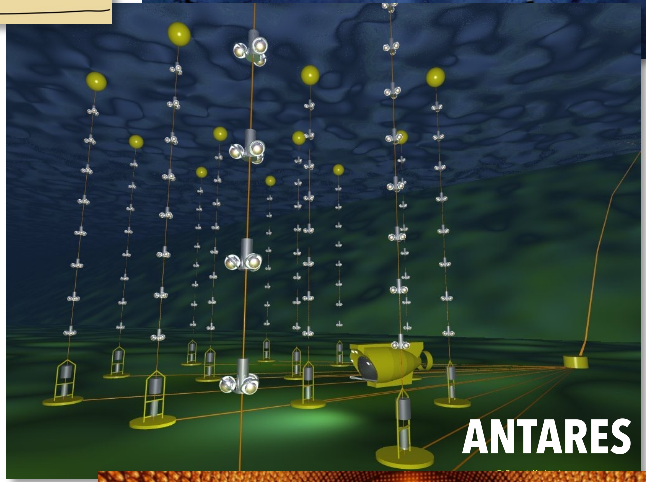
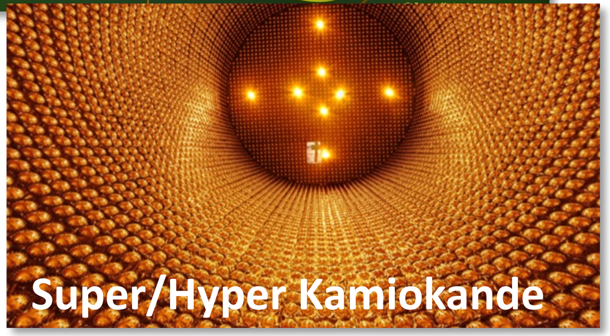


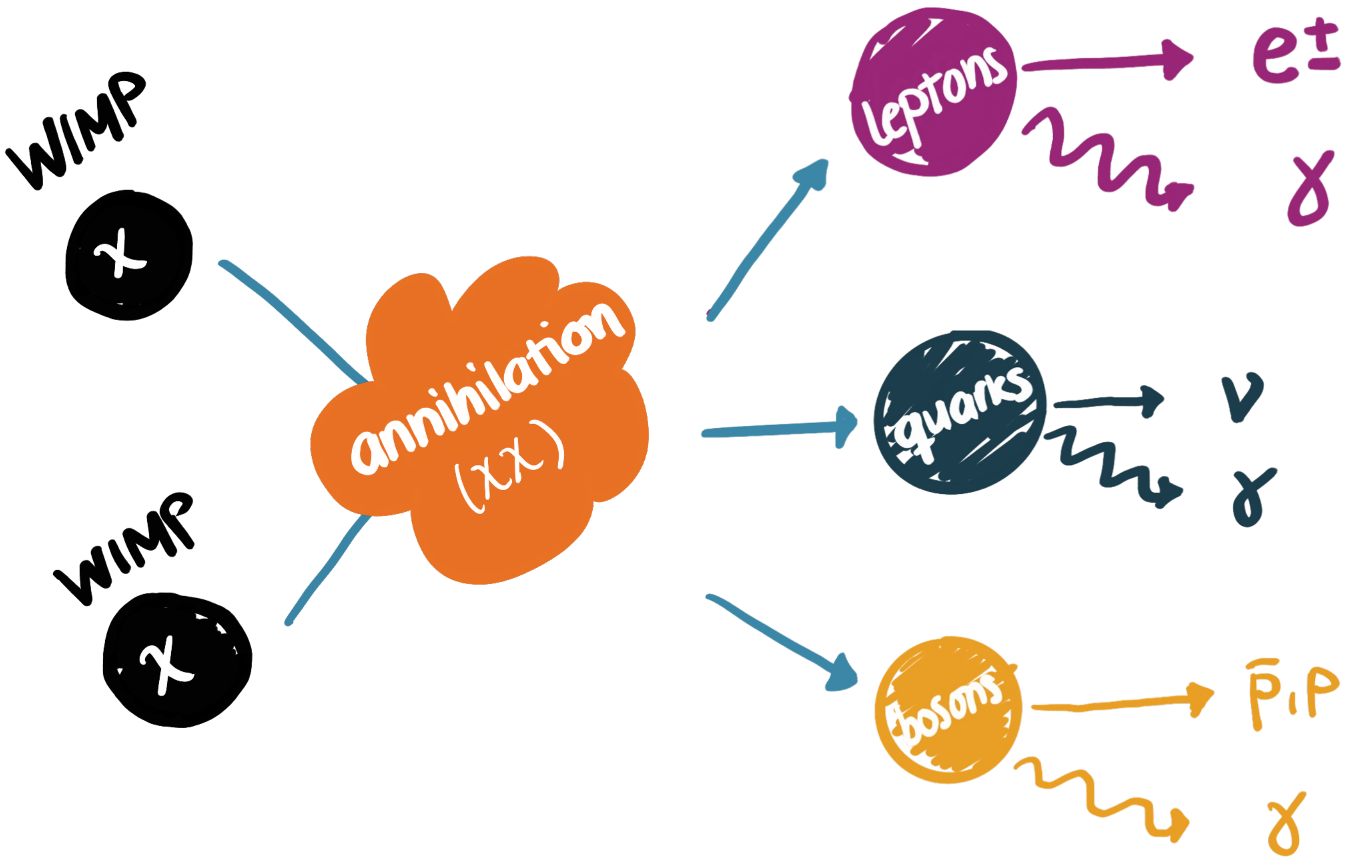








Indirect observables



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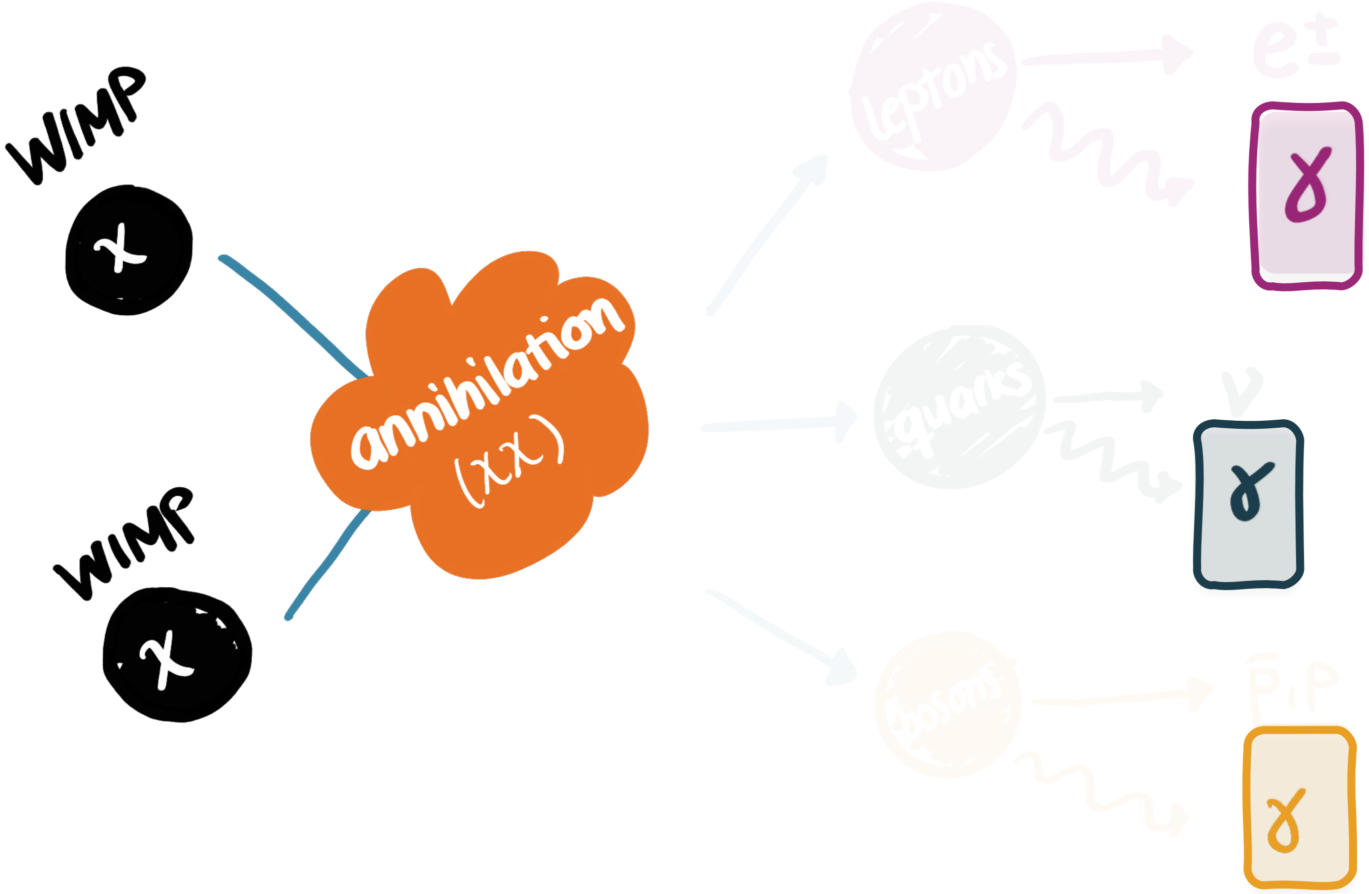

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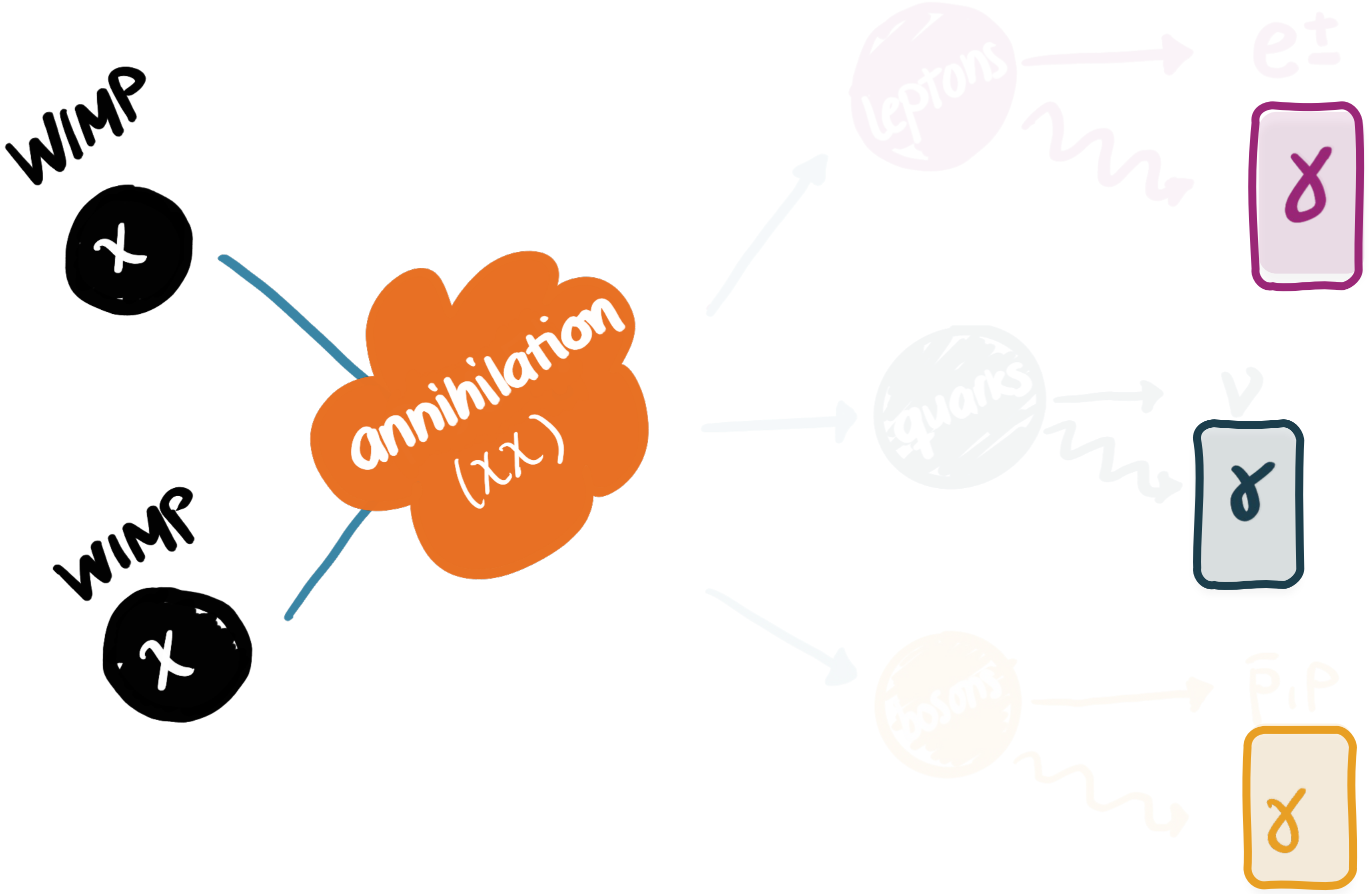

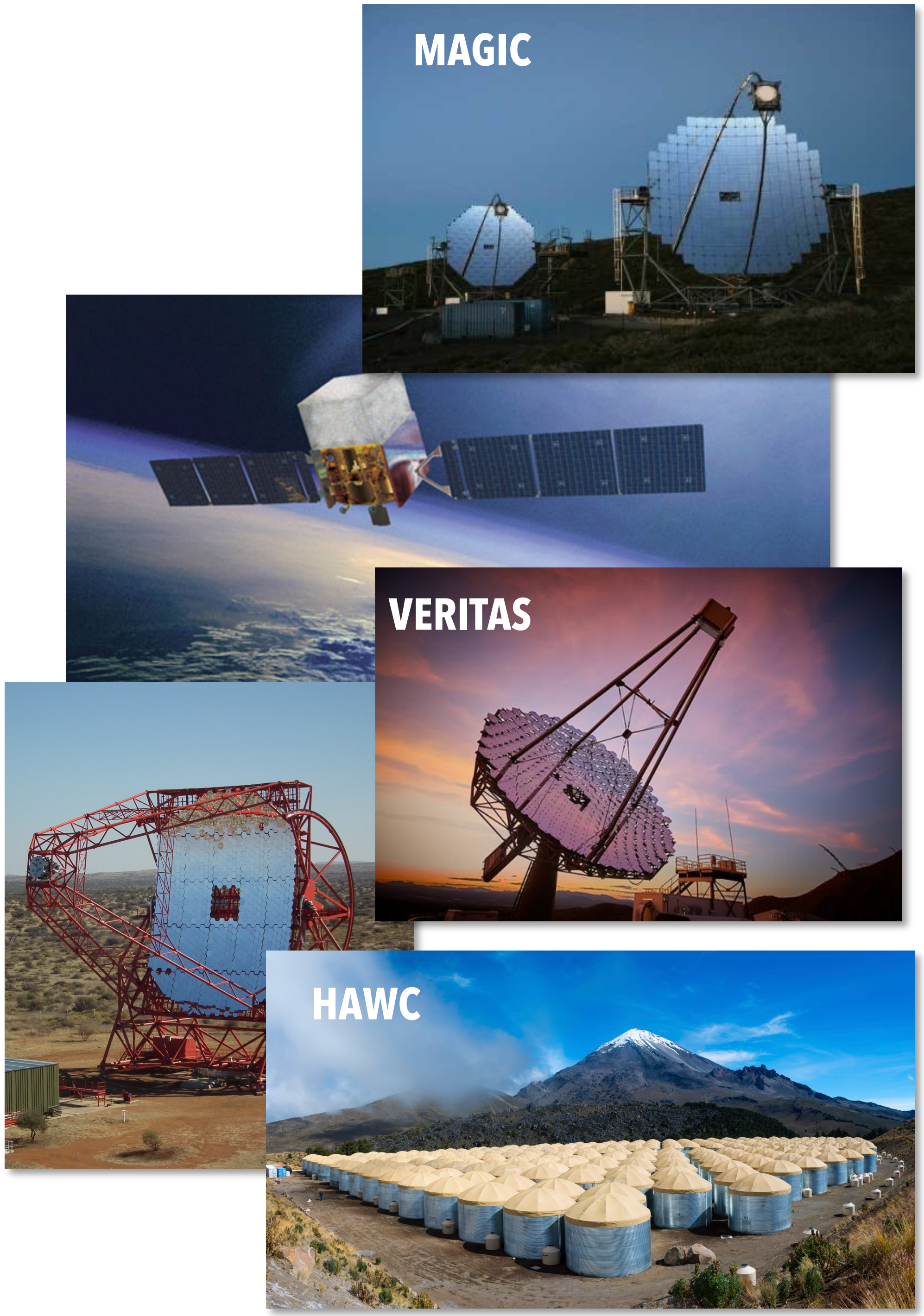

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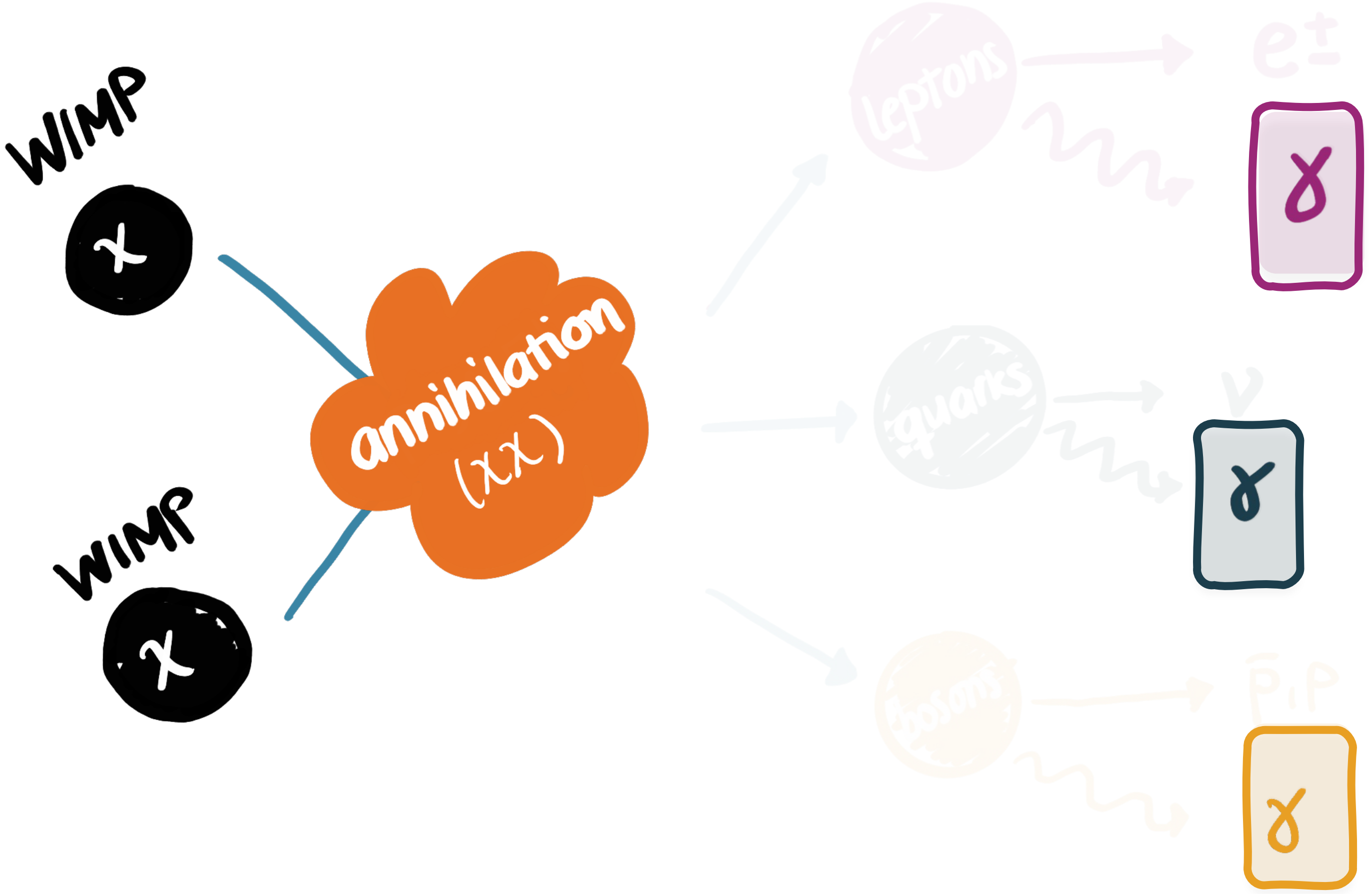
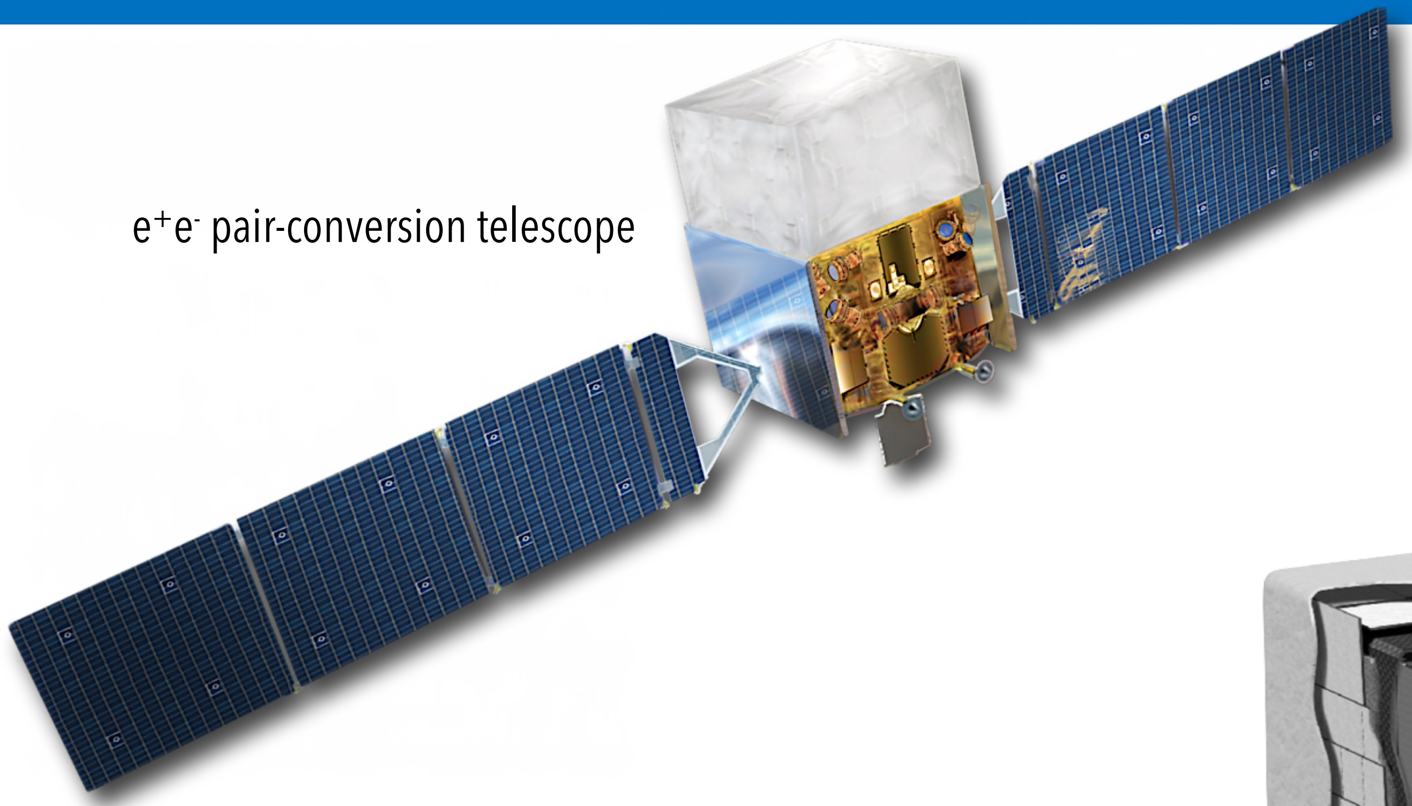


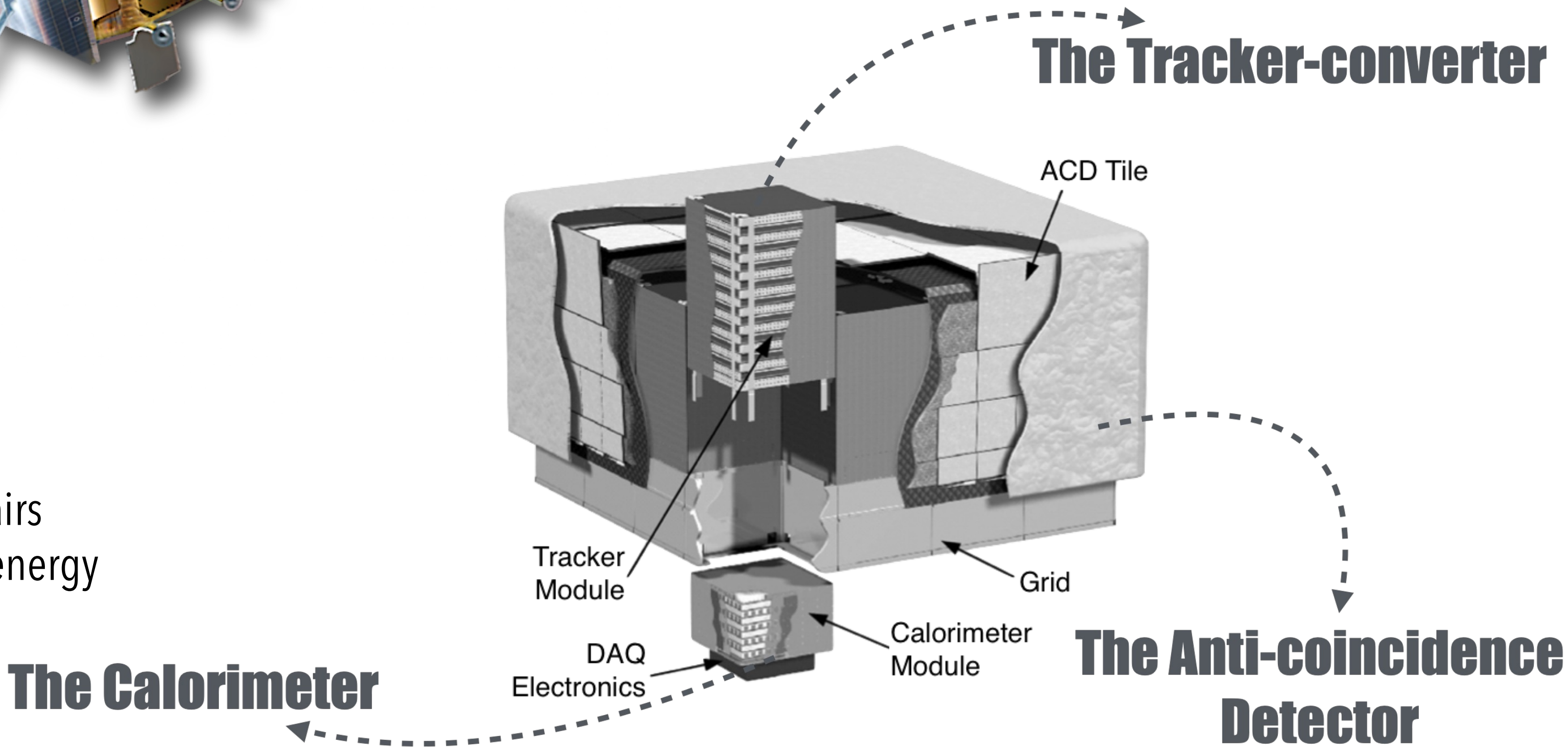
The *Fermi*-LAT



e^+e^- pair-conversion telescope

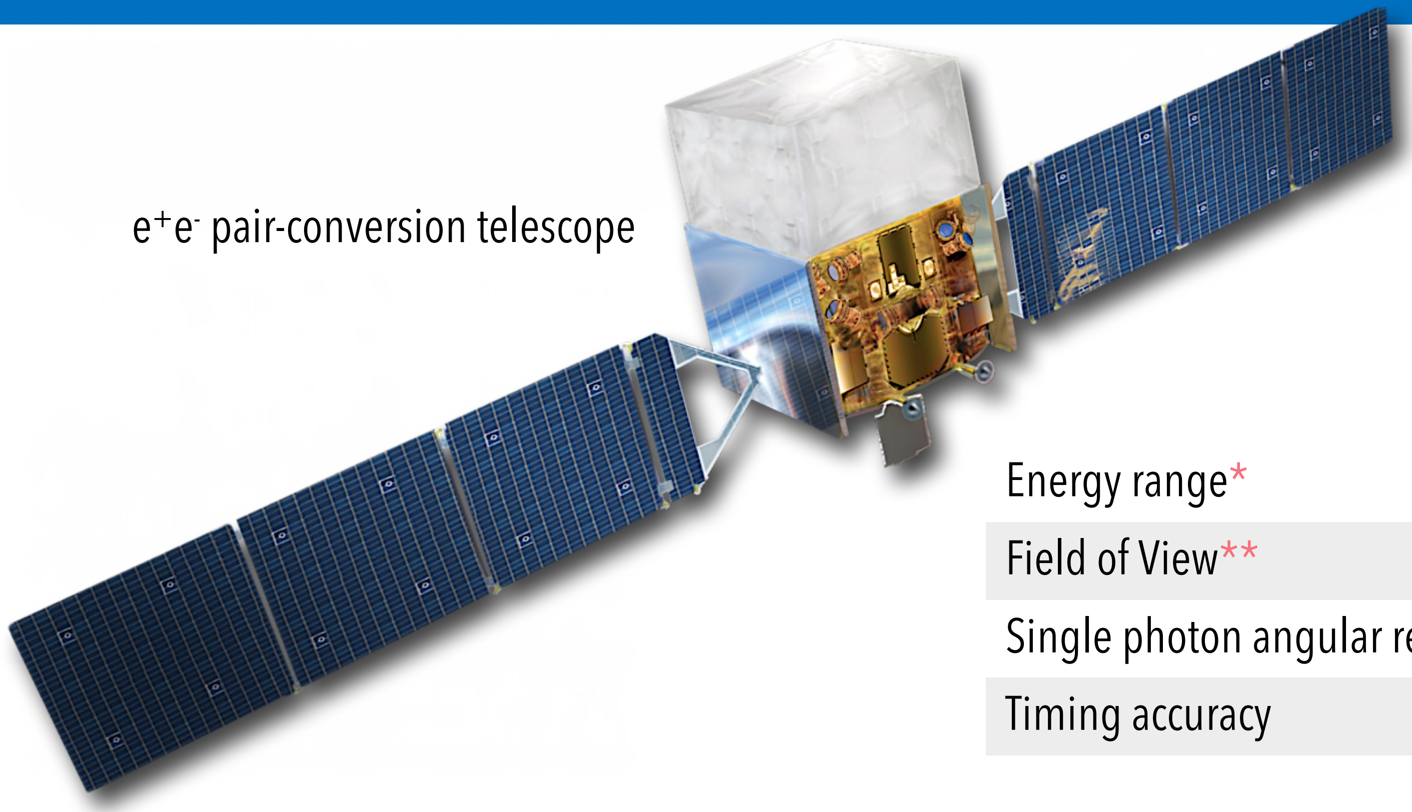
individual γ rays convert into e^+e^- pairs
→ tracks (localization) & deposited energy

…it also detects electrons.



The *Fermi* -LAT

e^+e^- pair-conversion telescope



Energy range*	20 MeV to > 300 GeV
Field of View**	2.4 sr (~1/5 of the whole sky)
Single photon angular resolution***	< 1 deg at 1 GeV
Timing accuracy	1 microsecond

*ideally suited for WIMP searches
**whole sky every ~3 hours
***point-source localization <0.5 arcmin

individual γ rays convert into e^+e^- pairs
→ tracks (localization) & deposited energy

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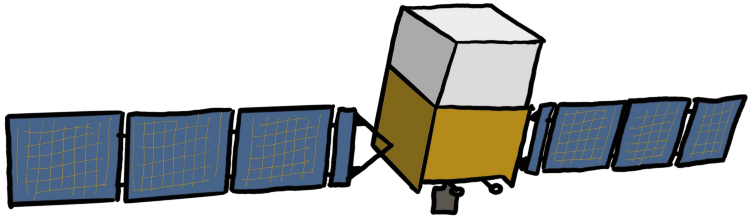


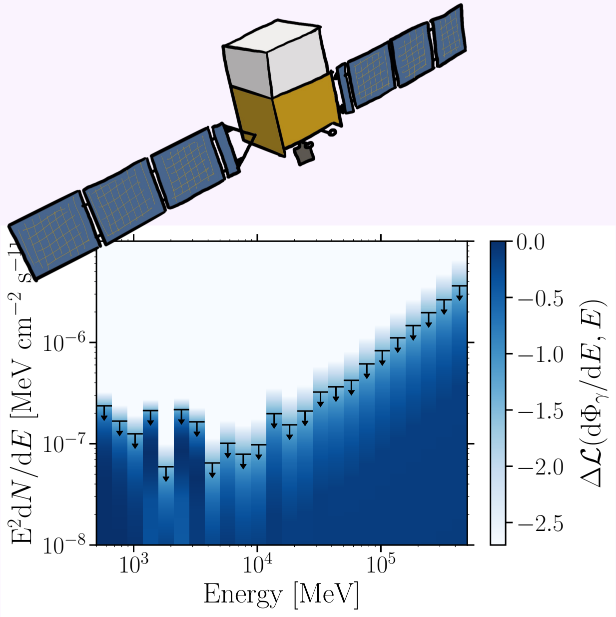
What do we see?

…but not understand (gamma rays edition).

Dark Matter Signal

DM flux

$$\frac{d\Phi}{dE}$$



Dark Matter Signal

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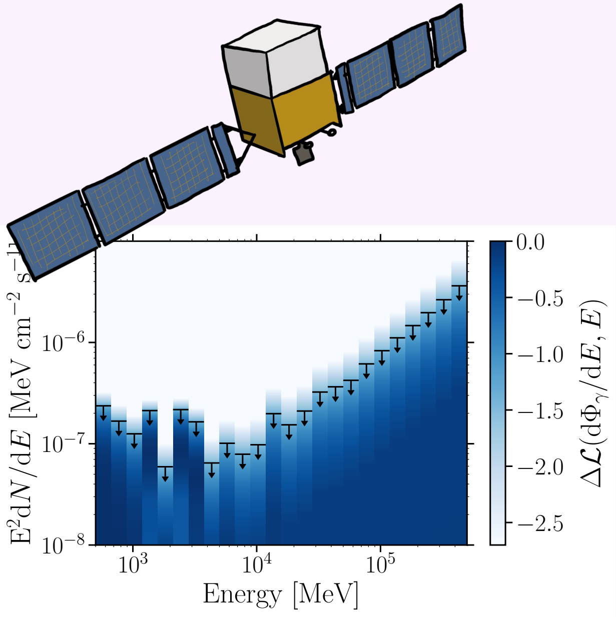
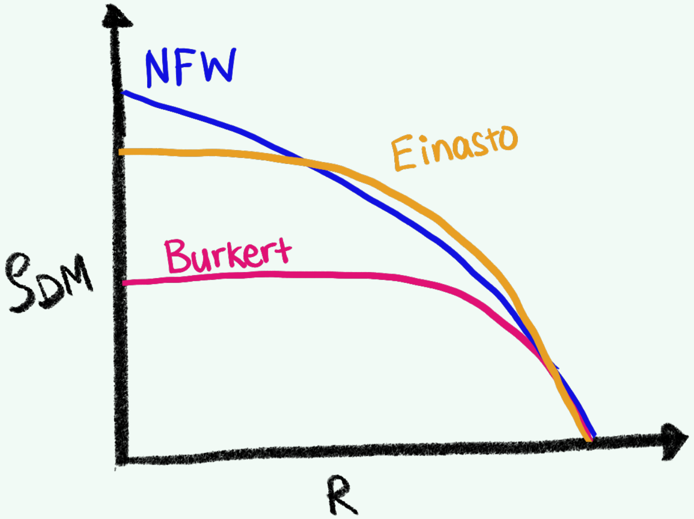


=

astrophysics J-factor

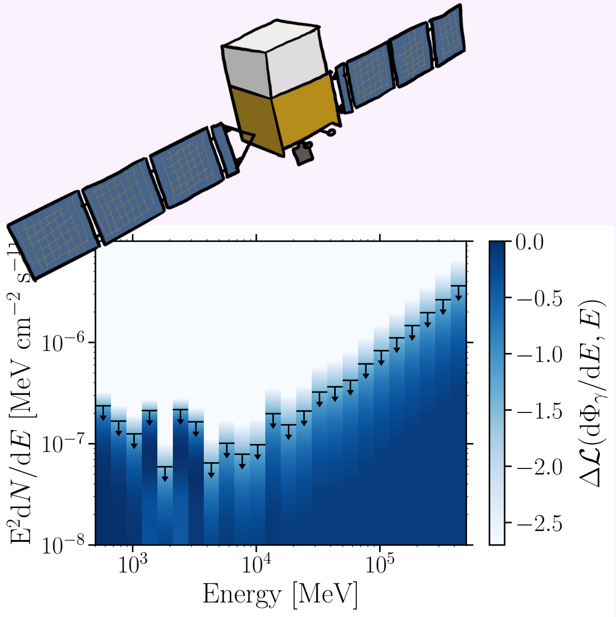
$$\int_{\Delta\Omega,\mathrm{los}} \rho_{DM}^2$$

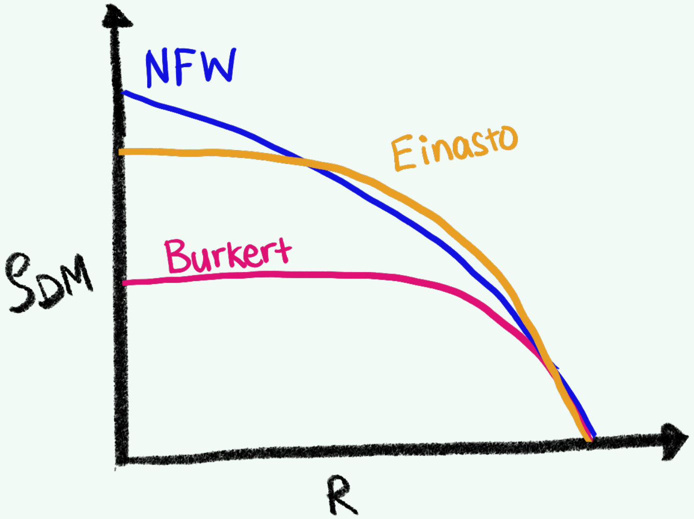


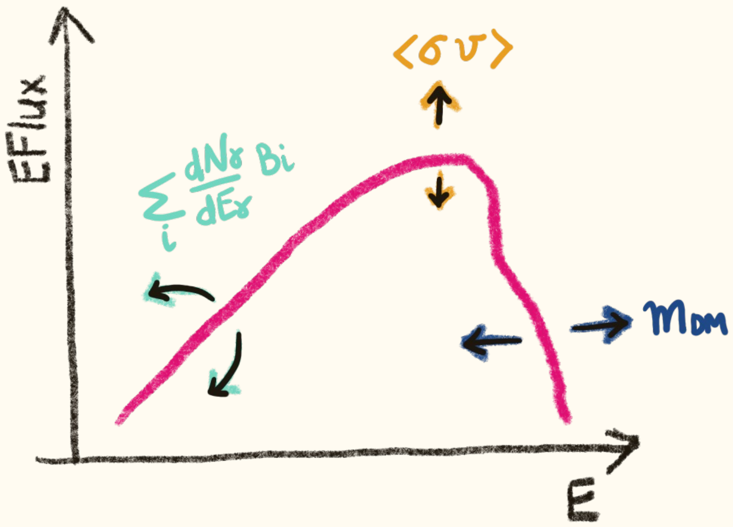
Dark Matter Signal

DM flux = **astrophysics J-factor** × **particle physics**

$$\frac{d\Phi}{dE} = \int_{\Delta\Omega,\mathrm{los}} \rho_{DM}^2 \; \frac{\langle \sigma v \rangle}{2M_{DM}^2} \sum B_i \frac{dN_\gamma}{dE}$$







FERMILAB-PUB-09-494-A

Possible Evidence For Dark Matter Annihilation In The Inner Milky Way From The Fermi Gamma Ray Space Telescope

Lisa Goodenough[1] and Dan Hooper[2,3]

[1] *Center for Cosmology and Particle Physics, Department of Physics, New York University, New York, NY 10003*
[2] *Center for Particle Astrophysics, Fermi National Accelerator Laboratory, Batavia, IL 60510*
[3] *Department of Astronomy and Astrophysics, University of Chicago, Chicago, IL 60637*

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Draft version March 1, 2017

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CrossM

Fermi-LAT Observations of γ-Ray Emission toward the Outer Halo of M31

Christopher M. Karwin[1], Simona Murgia[1], Sheldon Campbell[1], and Igor V. Moskalenko[2]
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FERMILAB-15-093-A
On The Gamma-Ray Emission From Reticulum II and Other Dwarf Galaxies
Dan Hooper[1,2] and Tim Linden[3]
[1] Fermi National Accelerator Laboratory, Center for Particle Astrophysics, Batavia, IL
[2] University of Chicago, Department of Astronomy and Astrophysics Chicago, IL
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Simone[11]
Zaharijas[59,60], D. F. Torres[44,56]
M. Zhou[34,36,37]
CrossM
Fermi-LAT Observations of γ-Ray Emission toward the Outer Halo of M31
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Received 2019 March 19; revised 2019 June 7; accepted 2019 June 8; published 2019 July 30


FERMILAB-15-093-A
ma-Ray Emission From Reticulum II and Other Dwarf Galaxies
Tim Linden[3]
Possible Evidence For Dark Matter A
Fermi Gamm
OBSERVATIONS OF M31 A
A GALACTIC
Legacy Analysis of Dark Matter Annihilation from the Milky Way Dwarf Spheroidal Galaxies with 14 Years of Fermi-LAT Data
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Miguel Sànchez-Conde
Instituto de Física Teórica, IFT UAM-CSIC, Departamento de Física Teórica,
Universidad Autónoma de Madrid, ES-28049 Madrid, Spain
(Dated: November 10, 2023)
Fermi-LAT Observations of
Christopher M. Karwin[1], Simo
[1] Department of Physics and Astronomy, Un
[2] Hansen Experimental Physics Laboratory and Kavli In
Received 2019 March 19;

Possibl... ...vidence For Dark Matter ...
Fermi Gamm...

...isa Goode...

FERMILAB-15-093-A

...ma-Ray Emission From Reticulum II and Other Dwarf Galaxies

...Tim Linden[3]

...Batavia, IL

OBSERVATIONS OF M31 ...
A GALACTI...

M. Ackermann[1], M. Ajello[2], A. Albert[3], L...
E. Bissaldi[11], E. D. Bloom[12], R. Bonin...
R. Buehler[1], R. A. Cameron[12], R. Caputo...
E. Charles[12], A. Chekhtman[24,61], G. Chia...
F. de Palma[11,27], R. Desiante[13,28], S. W. Dig...
S. Funk[29], P. Fusco[11,19], F. Gargano[11], N...
D. Green[15,30], I. A. Grenier[5], L. Guillemot...
T. Kamae[39], J. Knödlseder[40,41], A. K. ...
F. Longo[6,7], F. Loparco[11,19], ...
M. N. Mazziotta[11], ...
A. Mors...

Fermi-LAT Observations of ...

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Legacy Analysis of Dark Matter Annihilation from the Milky Way Dwarf Spheroidal Galaxies with 14 Years of *Fermi*-LAT Data

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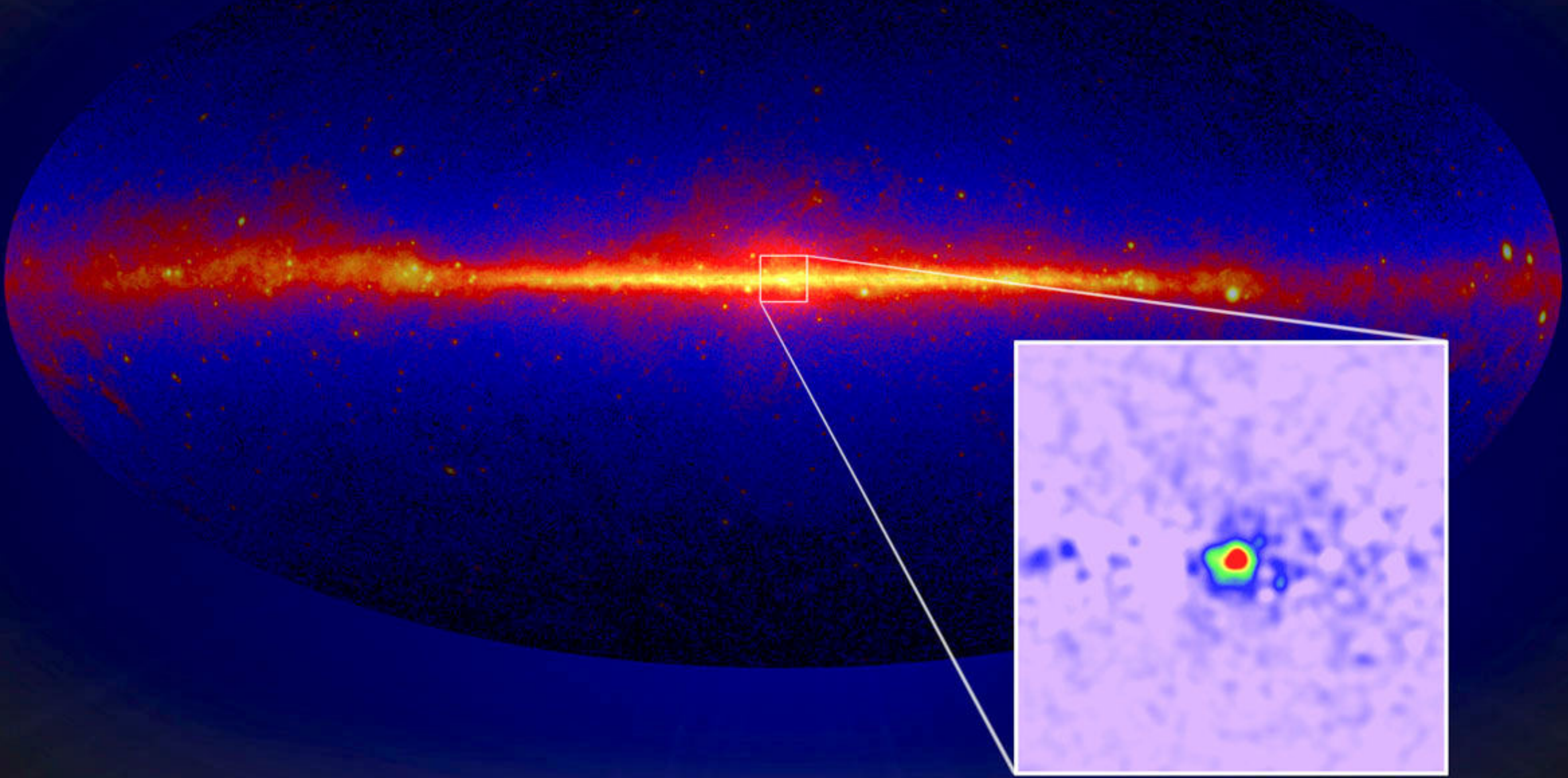
Universidad Autónoma de Madrid, ES-28049 Madrid, Spain

(Dated: November 10, 2023)

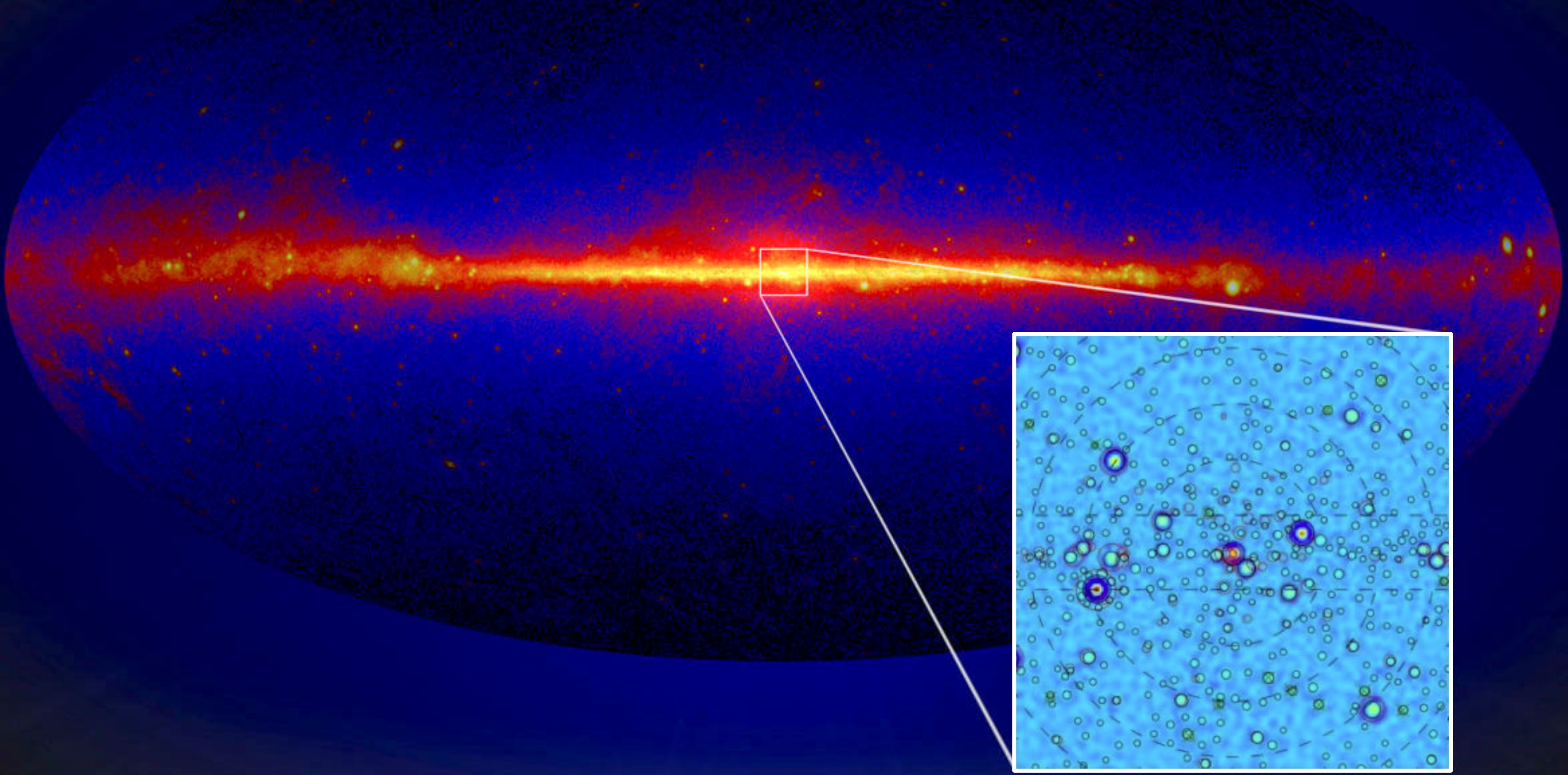
some reports of excesses in the MW halo
and galaxy clusters (line and extended…)

The Galactic Center Excess



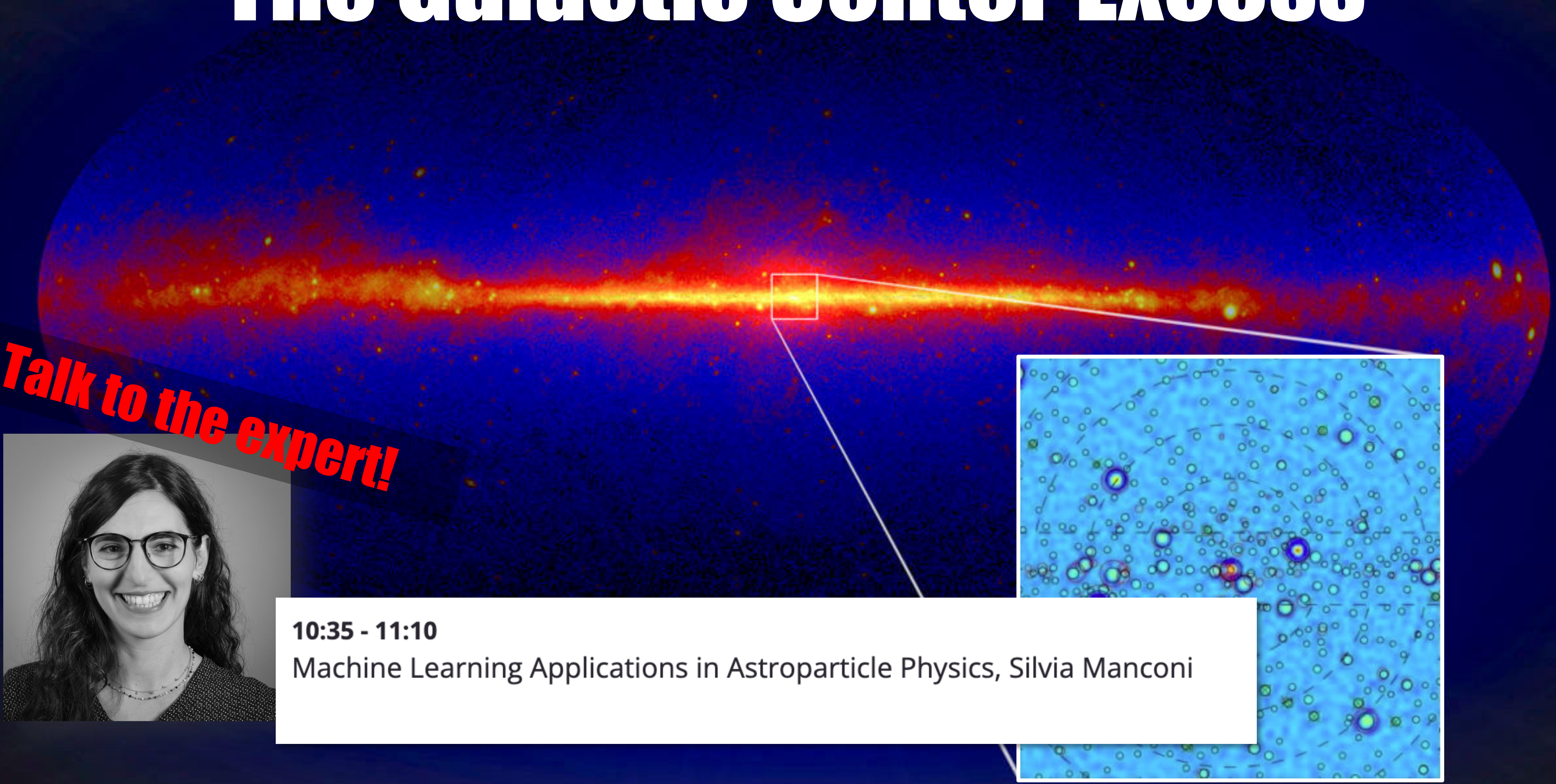
Credit: NASA/DOE/FERMI LAT COLLABORATION; T. LINDEN

The Galactic Center Excess



Credit: NASA/DOE/FERMI LAT COLLABORATION; T. LINDEN

The Galactic Center Excess



Talk to the expert!

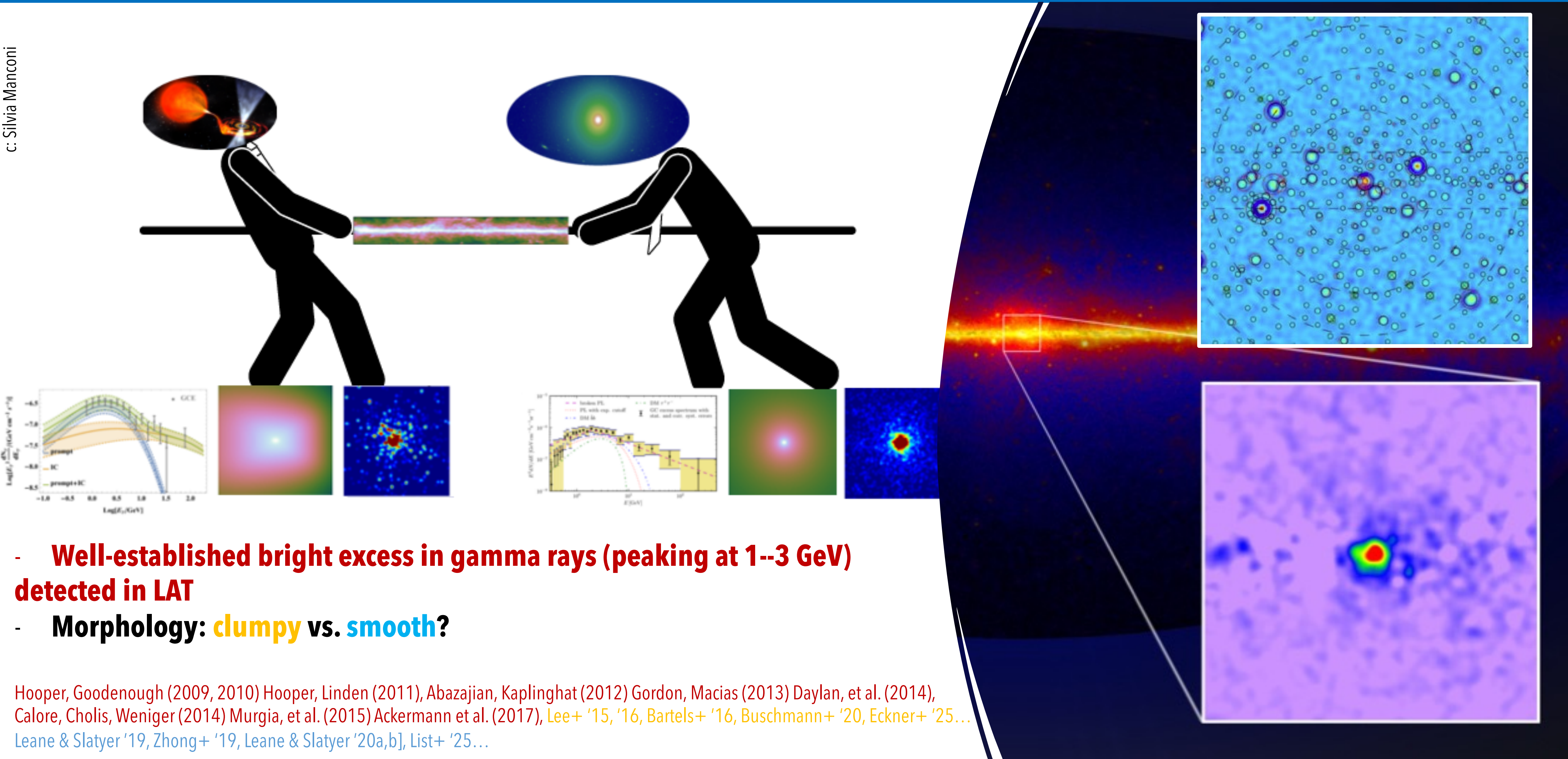
10:35 - 11:10

Machine Learning Applications in Astroparticle Physics, Silvia Manconi

Credit: NASA/DOE/FERMI LAT COLLABORATION; T. LINDEN

Gamma rays from the Galactic Center

c: Silvia Manconi

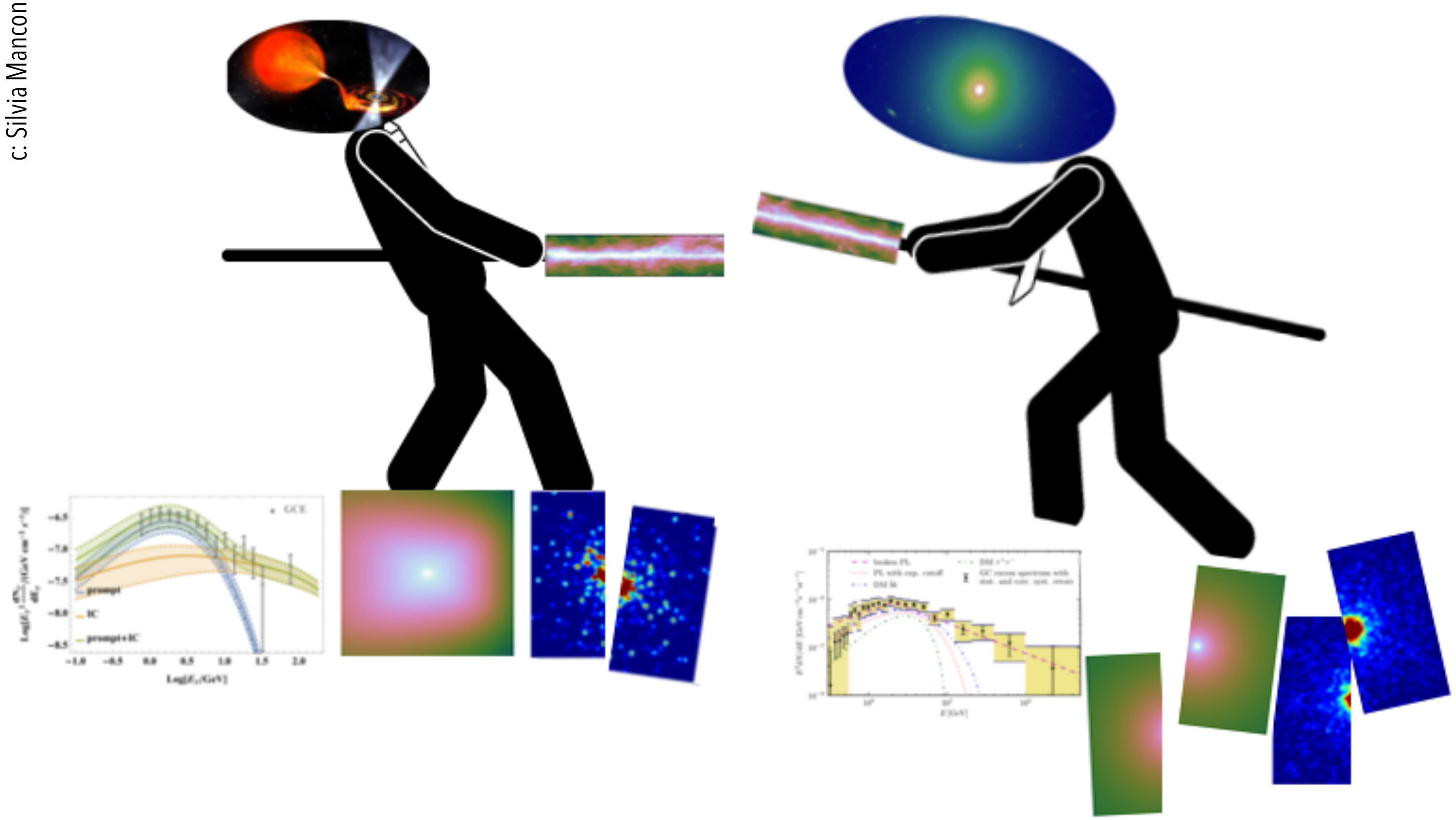


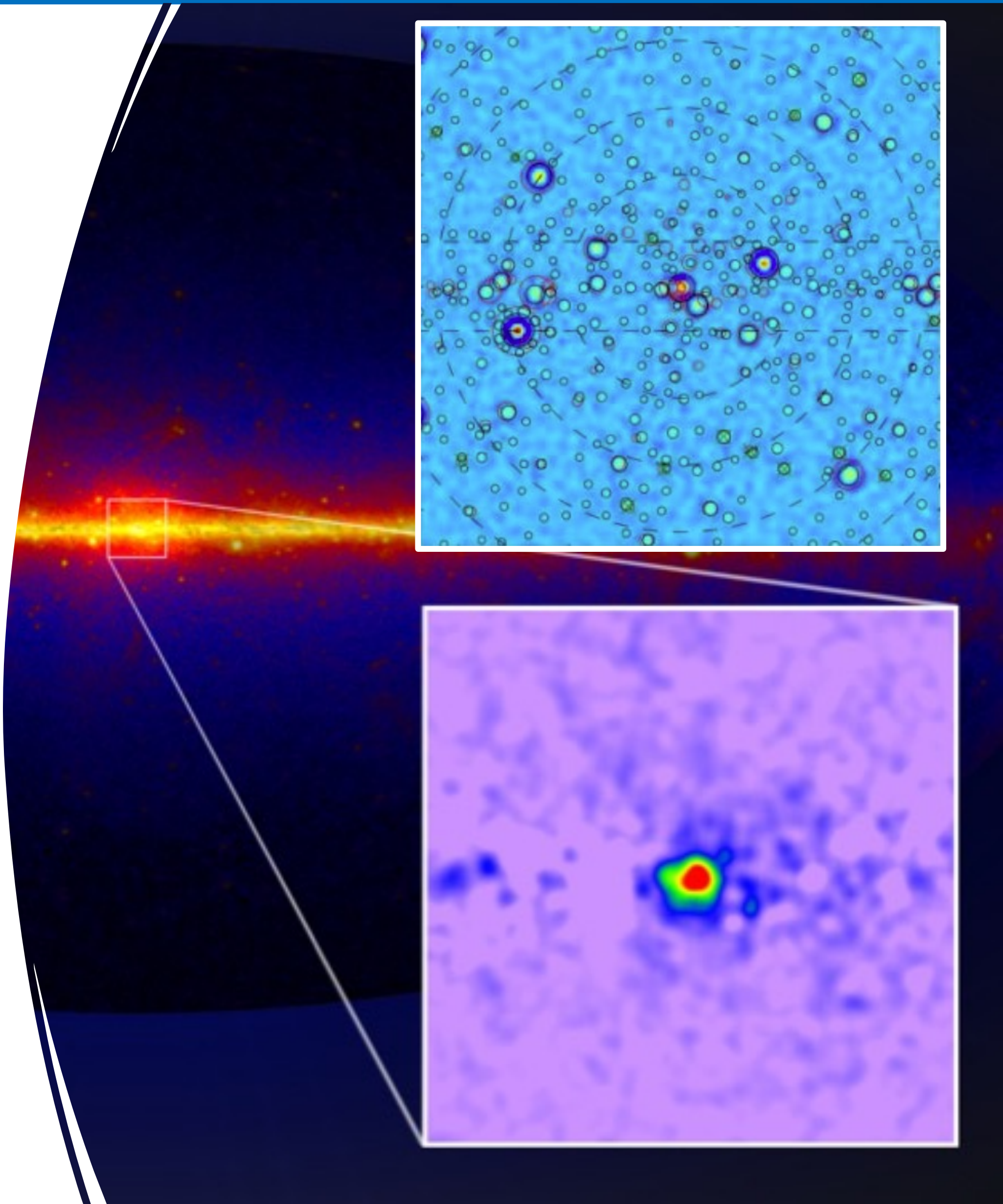
- **Well-established bright excess in gamma rays (peaking at 1--3 GeV) detected in LAT**
- **Morphology: clumpy vs. smooth?**

Hooper, Goodenough (2009, 2010) Hooper, Linden (2011), Abazajian, Kaplinghat (2012) Gordon, Macias (2013) Daylan, et al. (2014), Calore, Cholis, Weniger (2014) Murgia, et al. (2015) Ackermann et al. (2017), Lee+ '15, '16, Bartels+ '16, Buschmann+ '20, Eckner+ '25…
Leane & Slatyer '19, Zhong+ '19, Leane & Slatyer '20a,b], List+ '25…

Gamma rays from the Galactic Center

c: Silvia Manconi





-Did we reach the instrumental limits? What about theoretical models?

Diffuse models are not representative of the data
Confirming pulsars: future detections of radio emission by MeerKat and SKA
Confirming dark matter: check for signals elsewhere (or build a better instrument?)

Let's look elsewhere…


Fornax Dwarf Galaxy, ESO/Sky Survey 2

Dwarf spheroidal galaxies (dSphs)

Dwarf spheroidal galaxies (dSphs)

→ most dark-matter dominated systems known in the Universe

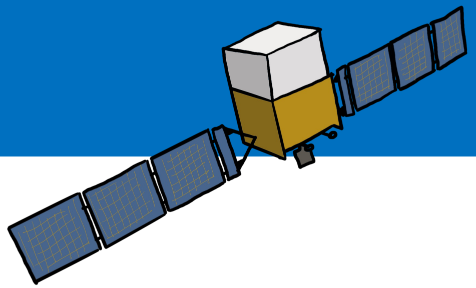
→ 61 dwarf satellites identified so far in the Milky Way, more on the horizon

→ nearby (furthest 460 kpc), some within single-digit kpc

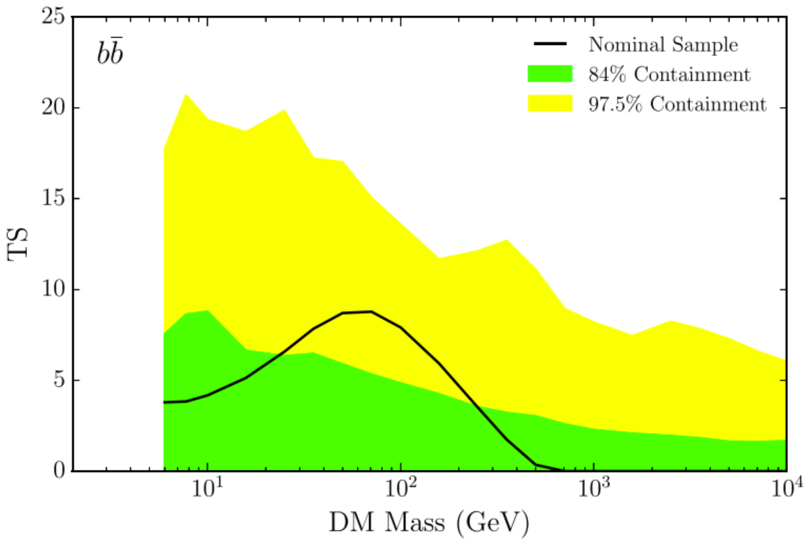
→ not much astrophysical background, inactive

Fornax Dwarf Galaxy, ESO/Sky Survey 2

Combined dSph Analyses



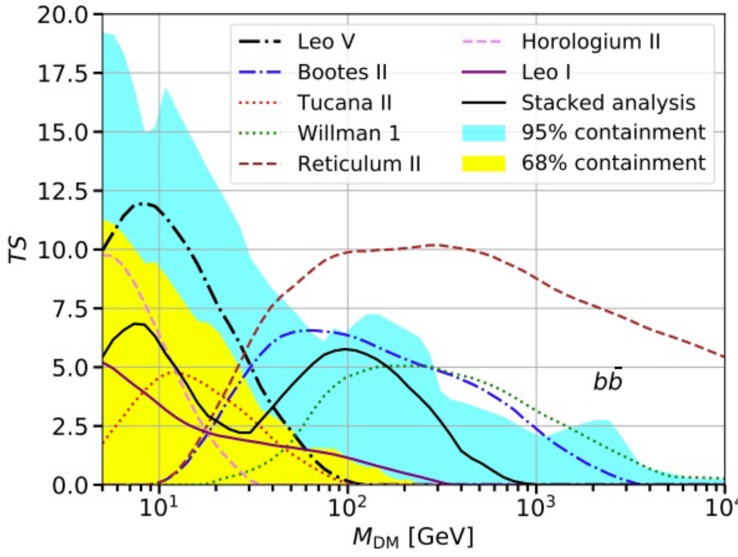
6 years



$< 2\,\sigma$

[Fermi-LAT Collaboration '17]

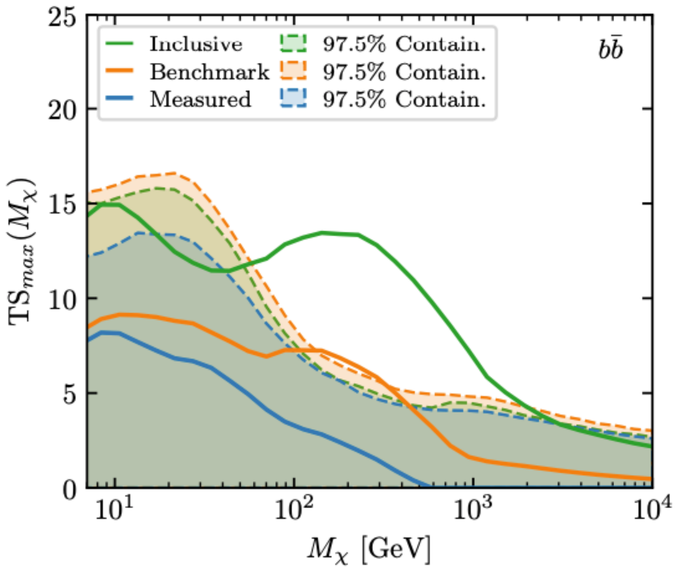
11 years



$\lesssim 2\,\sigma$

[Fermi-LAT Collaboration '21]

14 years



$\gtrsim 2\,\sigma$

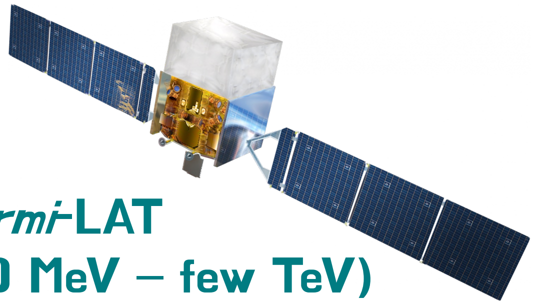
[Fermi-LAT Collaboration+ '24]

Shaded regions: blank-field analysis

Think: $\sqrt{TS} \sim \sigma$

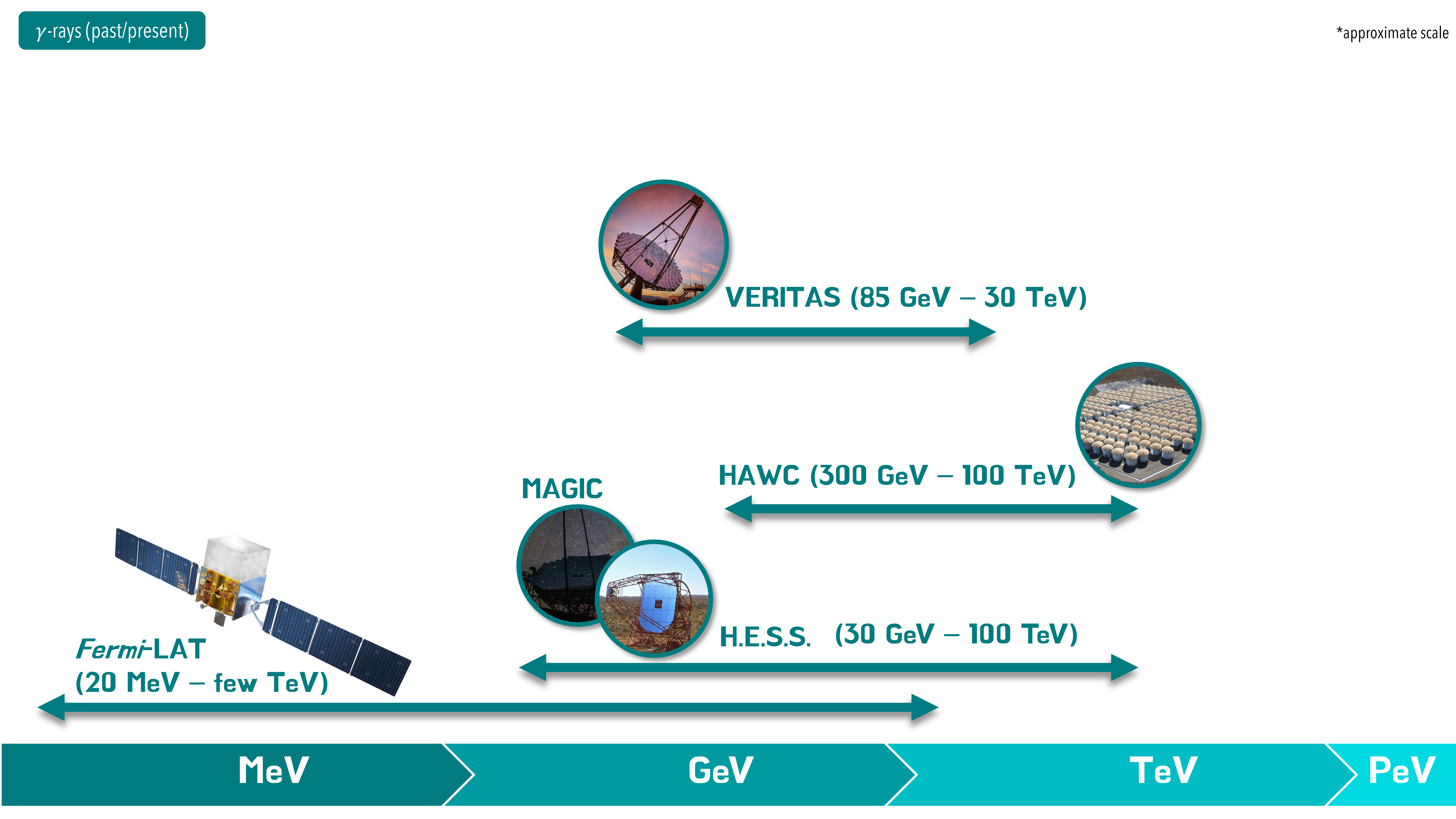
γ-rays (past/present)

*approximate scale



Fermi-LAT
(20 MeV – few TeV)

MeV | GeV | TeV | PeV

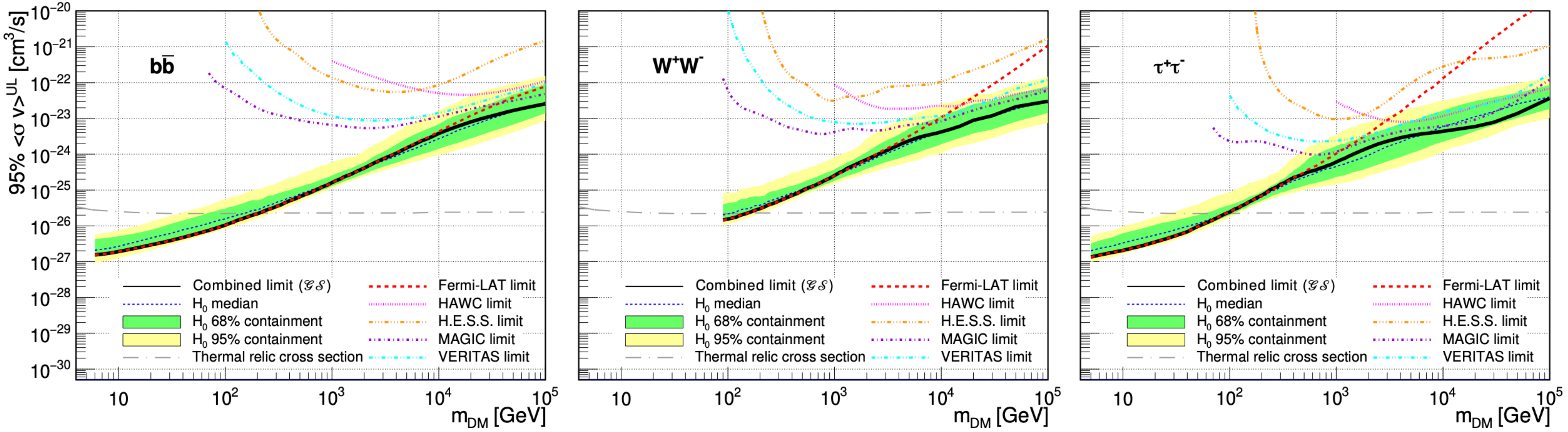

γ-rays (past/present)
*approximate scale
VERITAS (85 GeV – 30 TeV)
HAWC (300 GeV – 100 TeV)
MAGIC
H.E.S.S. (30 GeV – 100 TeV)
Fermi-LAT
(20 MeV – few TeV)
MeV
GeV
TeV
PeV

GloryDuck (LAT, HAWC, HESS, MAGIC, VERITAS)

- Perform multi-instrument and multi-target analysis to obtain the most sensitive and robust results
- Joining likelihoods across instruments is challenging
- Focus: dSphs
- Limits driven by LAT sensitivity
- Legacy analysis of the current-generation gamma-ray instruments

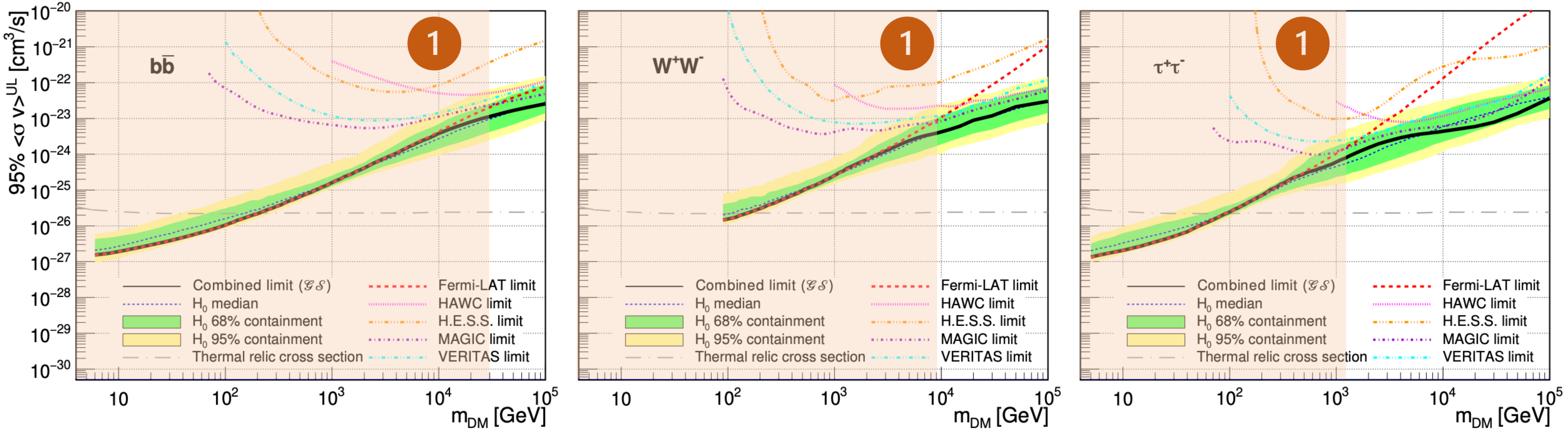
GLORY DUCK

GloryDuck (LAT, HAWC, HESS, MAGIC, VERITAS)



*[LAT, HAWC, H.E.S.S., MAGIC, & VERITAS, incl. **MC,** JCAP03(2026)035]

GloryDuck (LAT, HAWC, HESS, MAGIC, VERITAS)

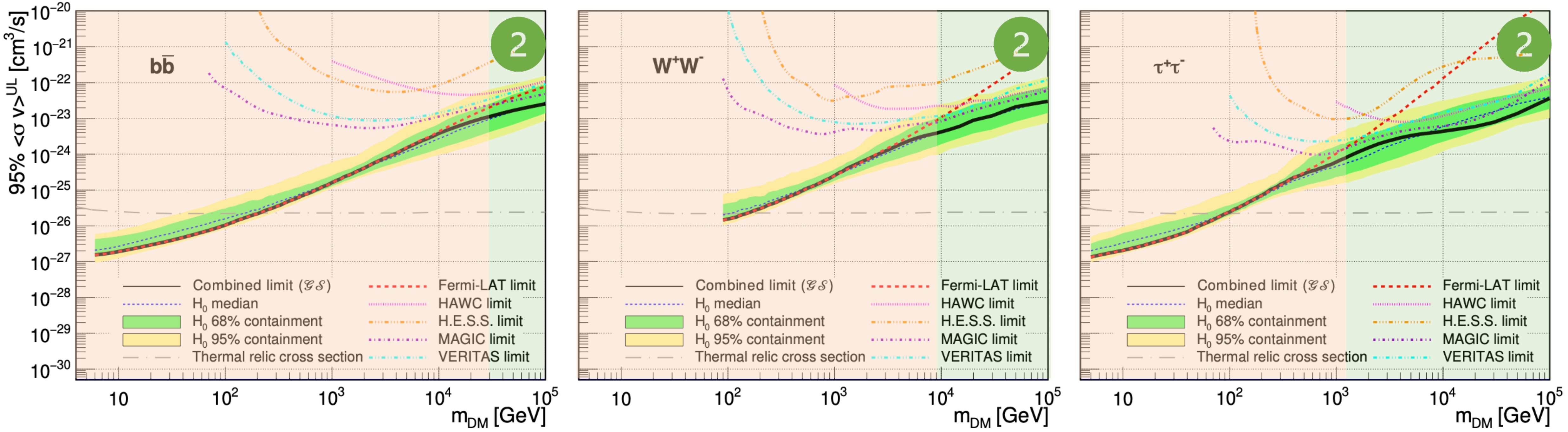


Dominated by *Fermi* LAT 1

*[LAT, HAWC, H.E.S.S., MAGIC, & VERITAS, incl. **MC,** JCAP03(2026)035]

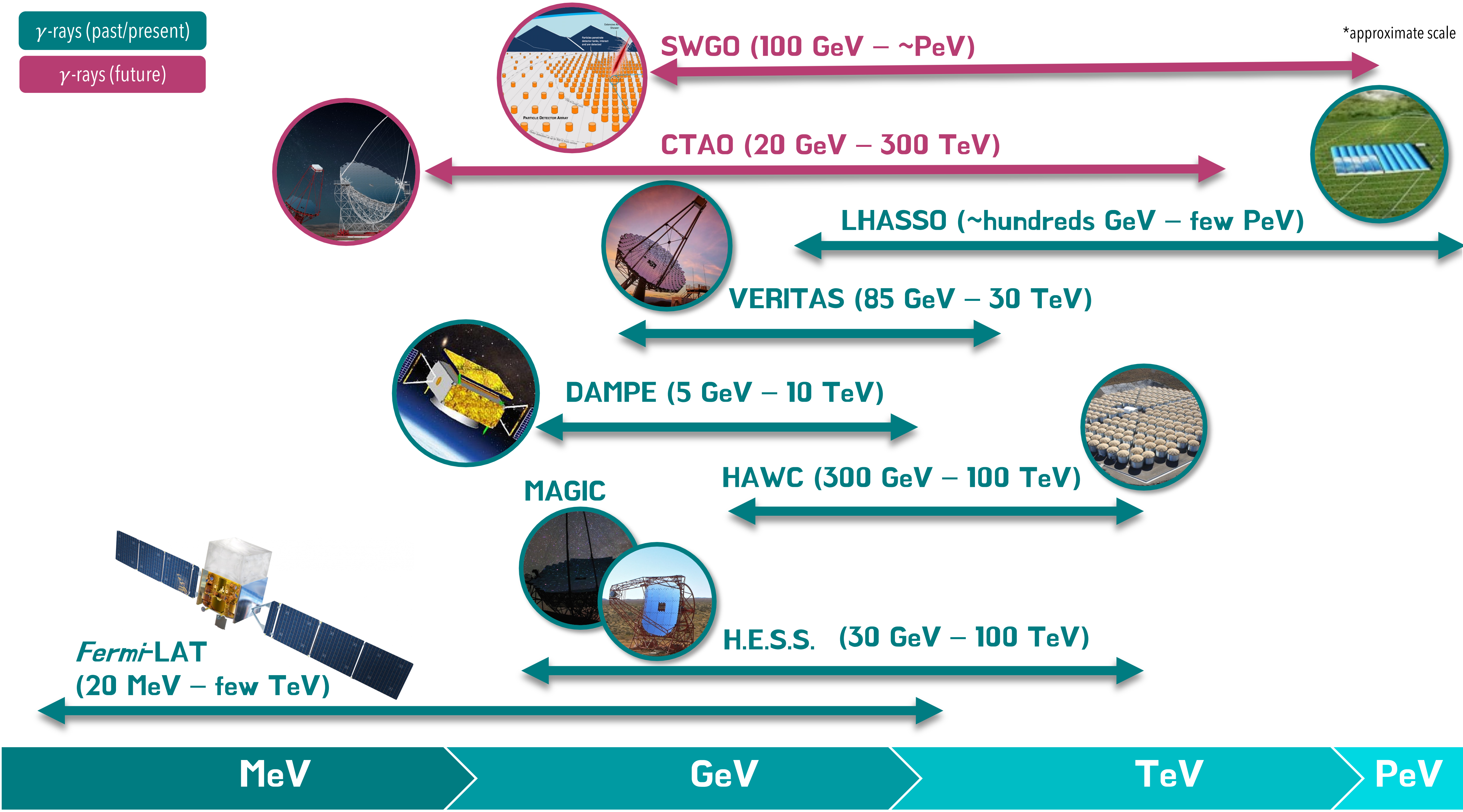
GloryDuck (LAT, HAWC, HESS, MAGIC, VERITAS)

GLORY DUCK



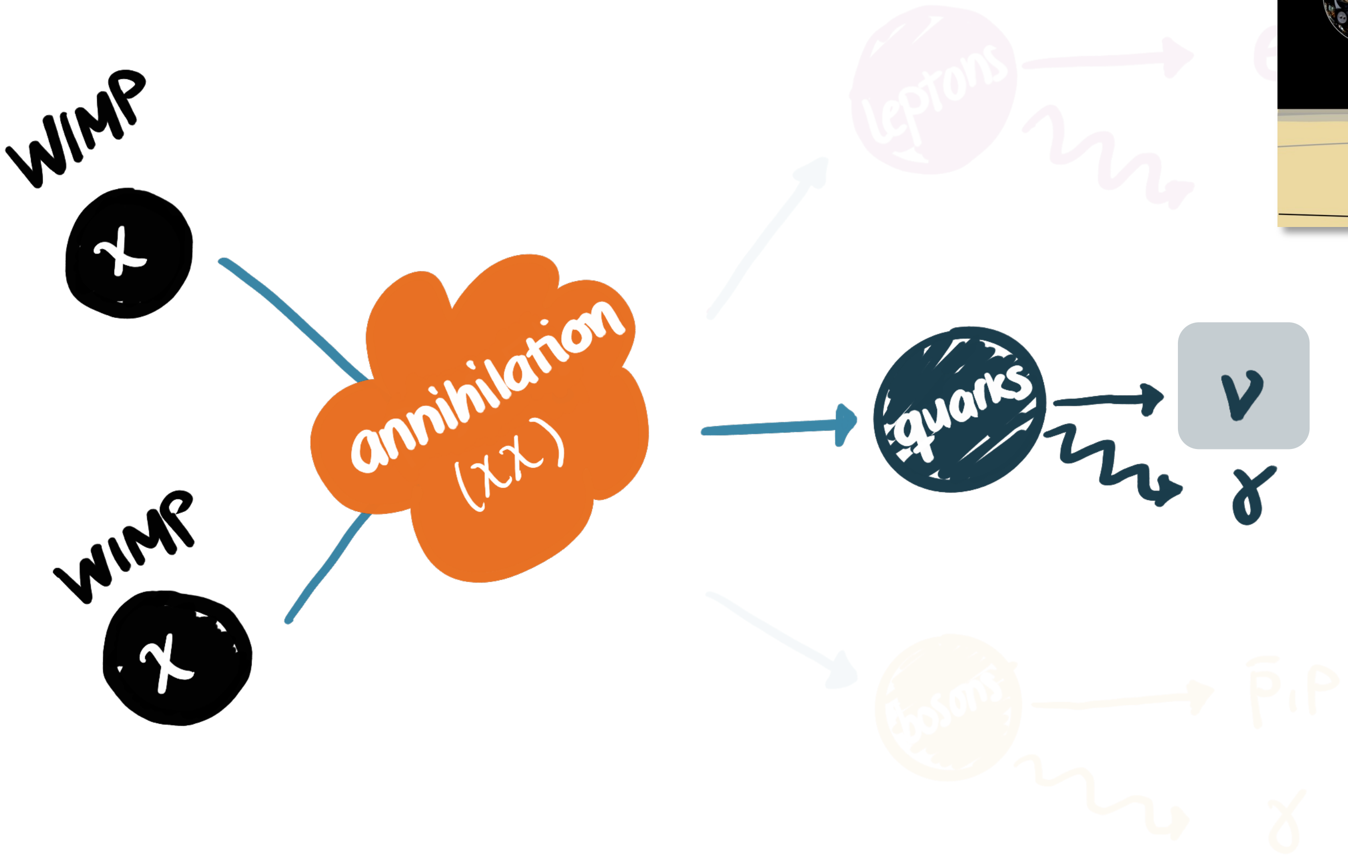
HAWC, HESS, MAGIC, VERITAS take over 2

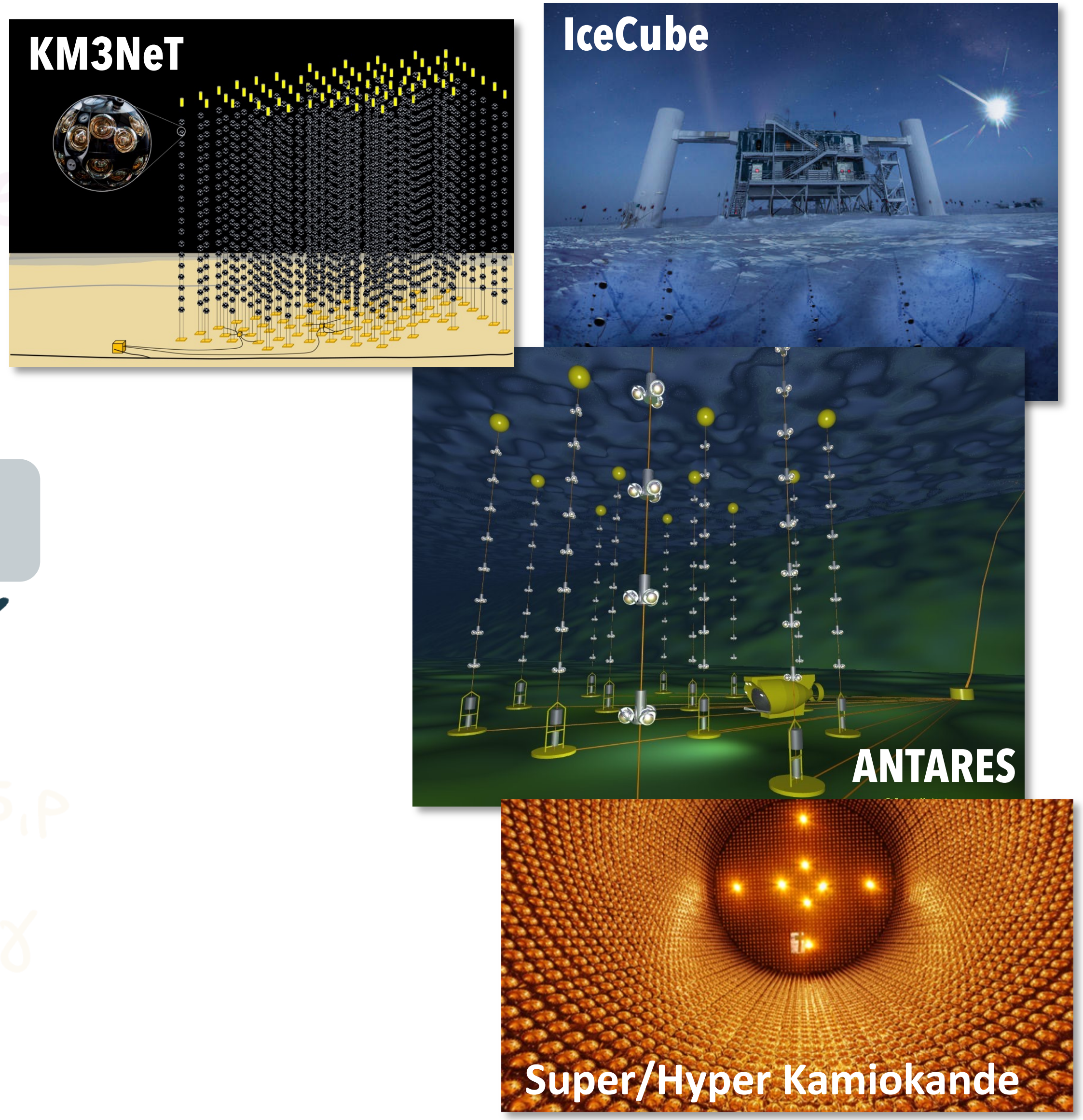
*[LAT, HAWC, H.E.S.S., MAGIC, & VERITAS, incl. **MC,** JCAP03(2026)035]

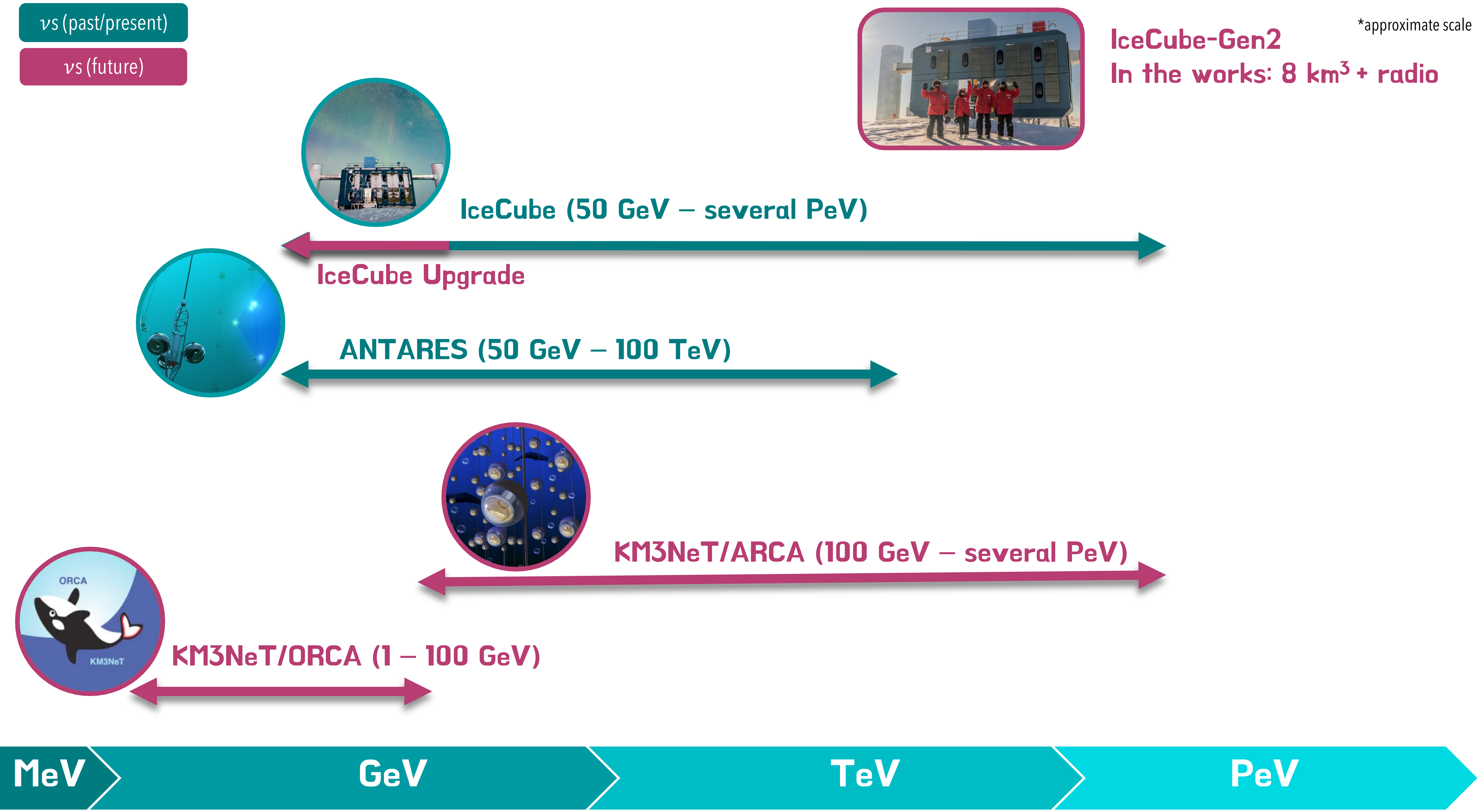


γ-rays (past/present)
γ-rays (future)
*approximate scale
SWGO (100 GeV – ~PeV)
CTAO (20 GeV – 300 TeV)
LHASSO (~hundreds GeV – few PeV)
VERITAS (85 GeV – 30 TeV)
DAMPE (5 GeV – 10 TeV)
HAWC (300 GeV – 100 TeV)
MAGIC
H.E.S.S. (30 GeV – 100 TeV)
Fermi-LAT
(20 MeV – few TeV)
MeV
GeV
TeV
PeV

Indirect observables

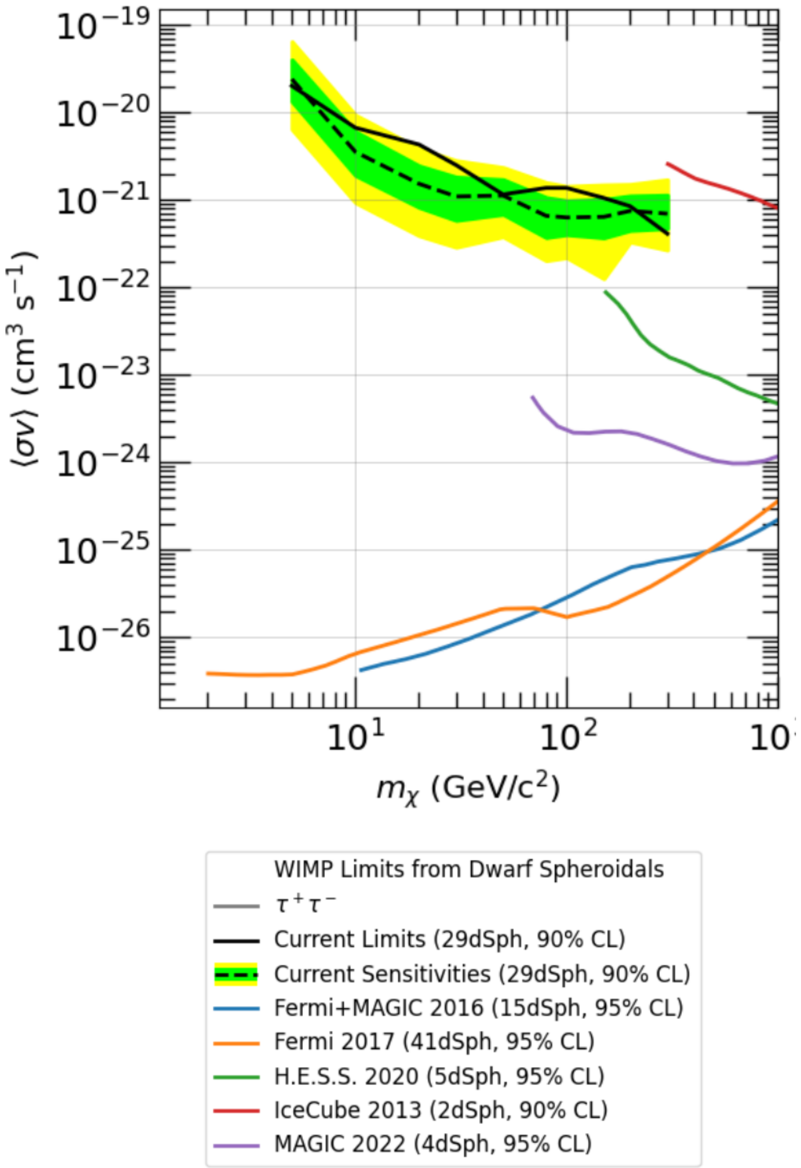


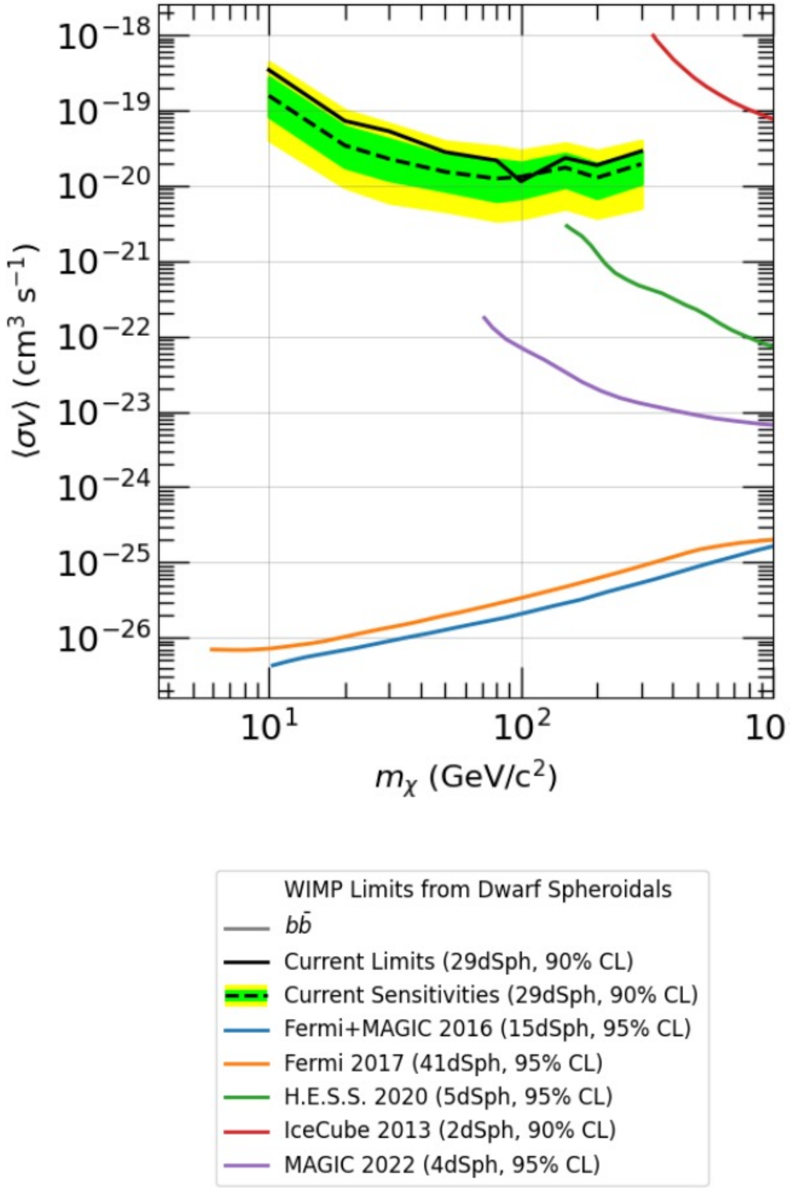




νs (past/present)
νs (future)
*approximate scale
IceCube-Gen2
In the works: 8 km³ + radio
IceCube (50 GeV – several PeV)
IceCube Upgrade
ANTARES (50 GeV – 100 TeV)
KM3NeT/ARCA (100 GeV – several PeV)
ORCA
KM3NeT
KM3NeT/ORCA (1 – 100 GeV)
MeV
GeV
TeV
PeV

What about neutrinos?





IceCube Collaboration.

How many dwarf galaxies do we *really* need?

How many dwarf galaxies do we *really* need?

Maybe just one, but a good one?

Ursa Major III

[Discovery: Smith+ 2023]

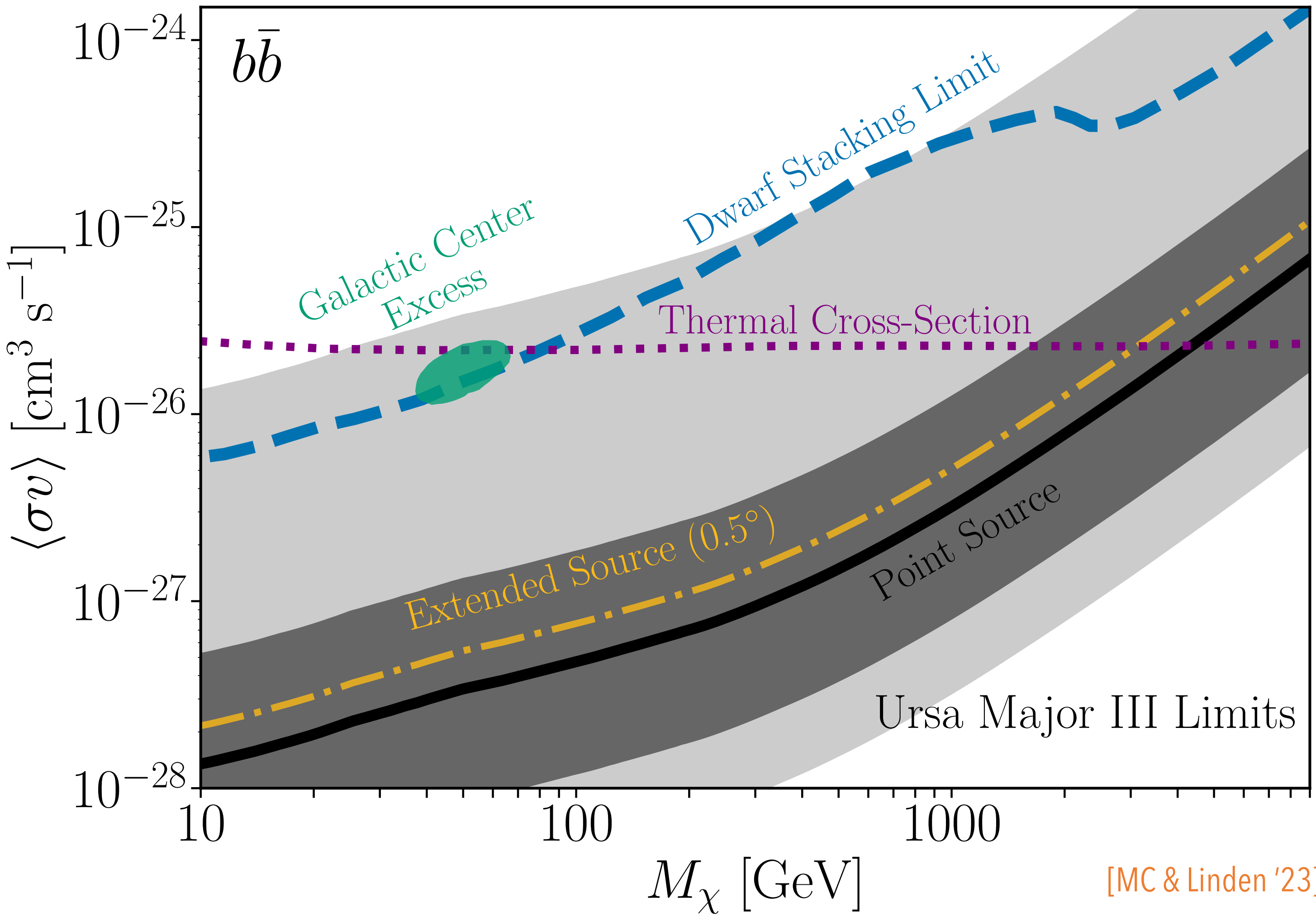
[J-factor: Errani+ 2023]

→ Unstable unless large DM content

→ Nearby (~10 kpc)

→ Strong constraints on DM annihilation

→ Confirming the dark matter density requires deeper optical surveys

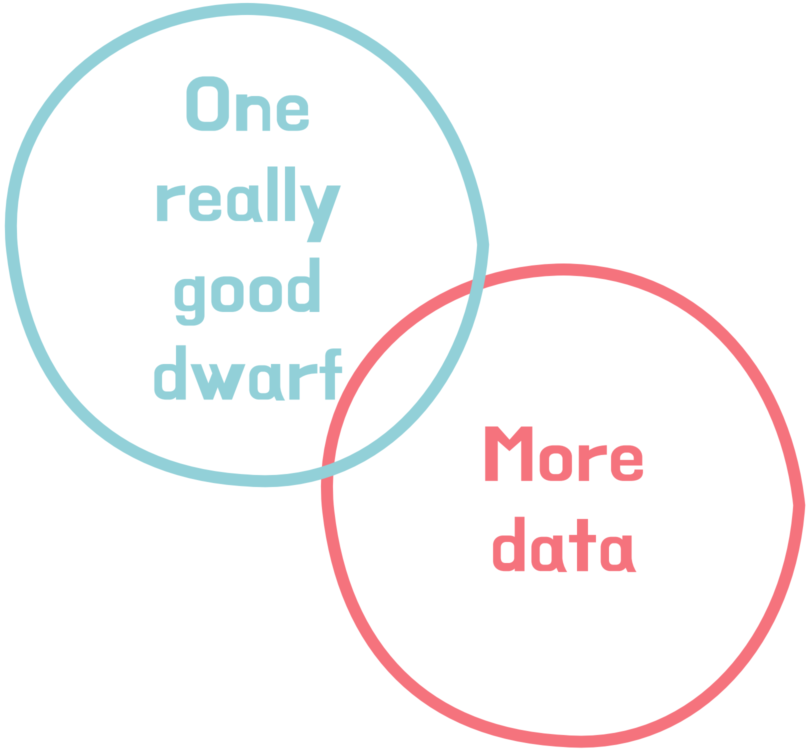


[MC & Linden '23]

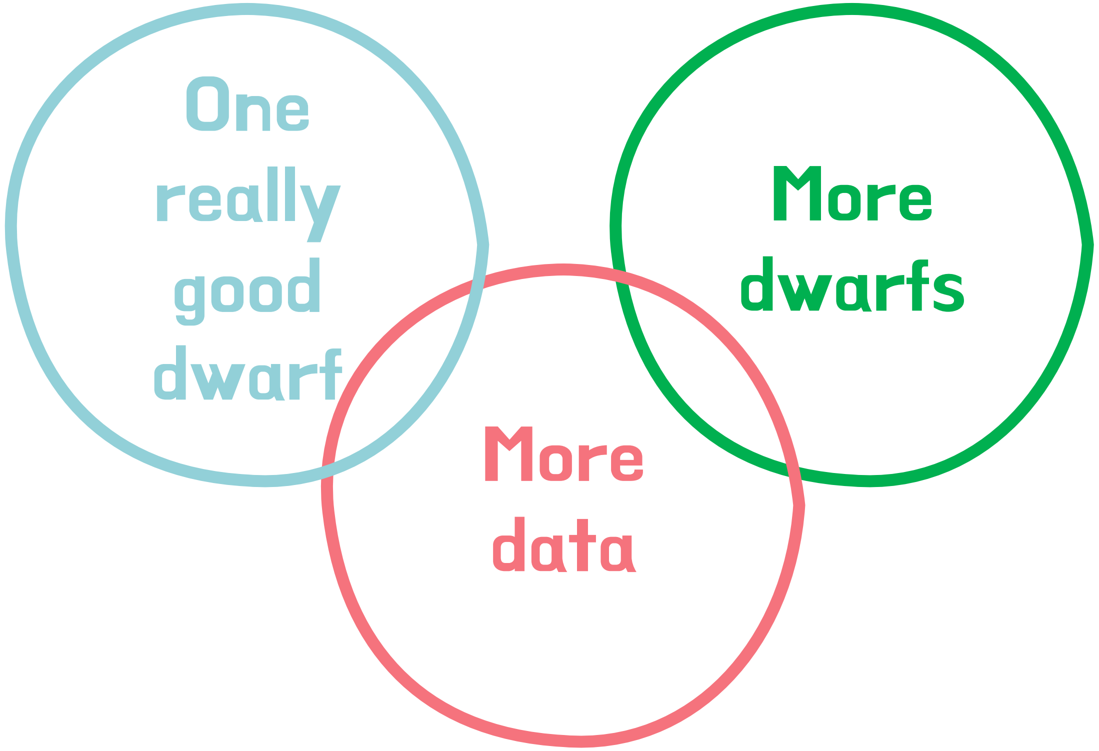
Future of dwarfs: observer's view

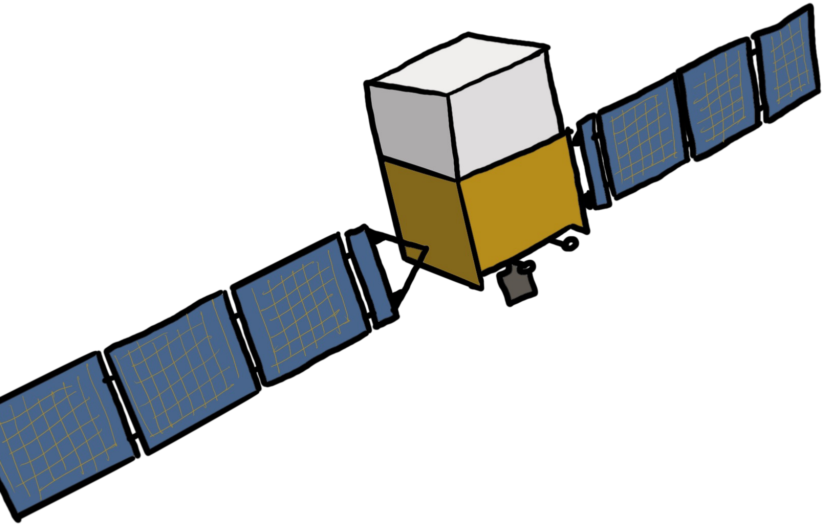
One
really
good
dwarf

Future of dwarfs: observer's view

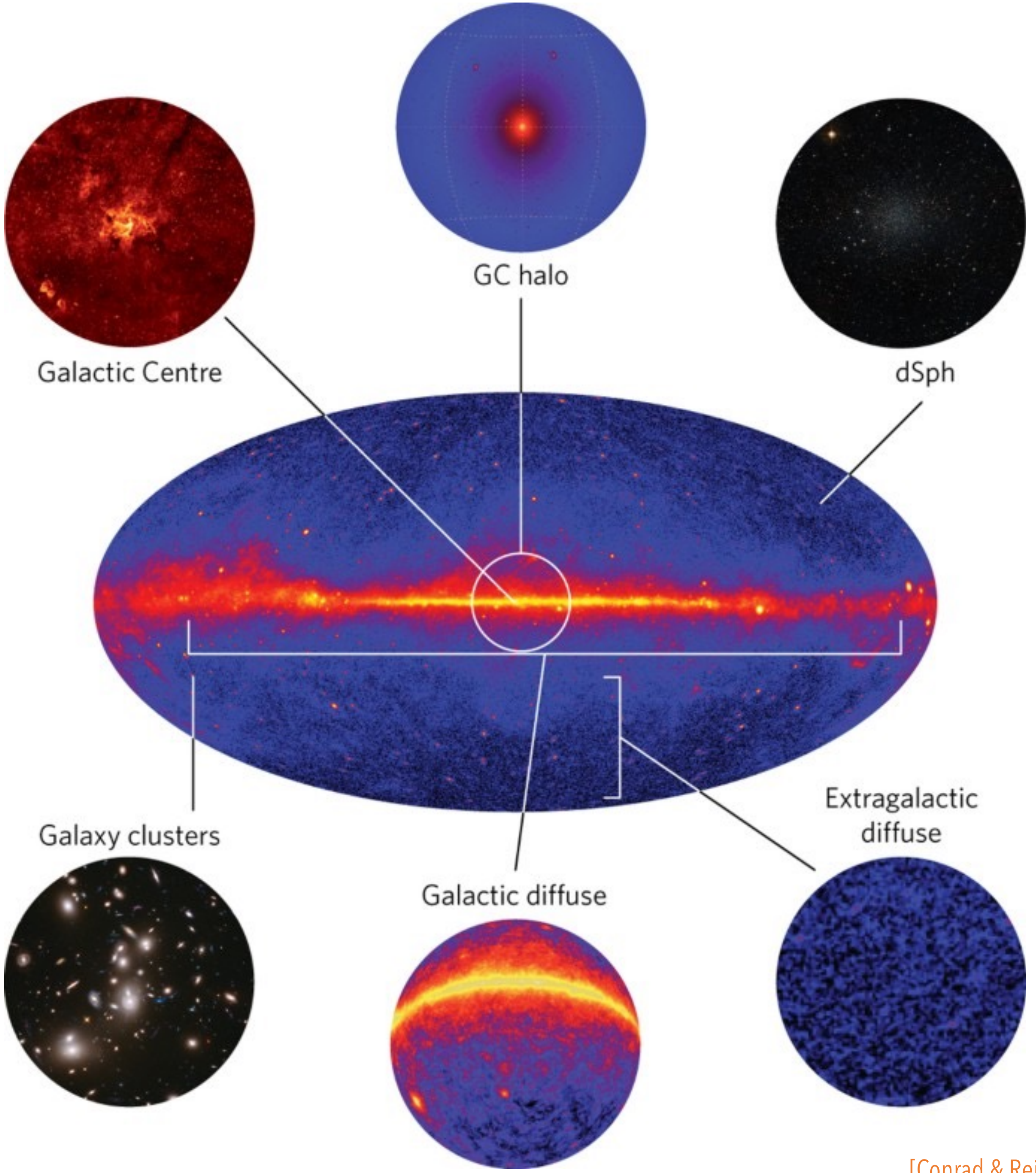


Future of dwarfs: observer's view



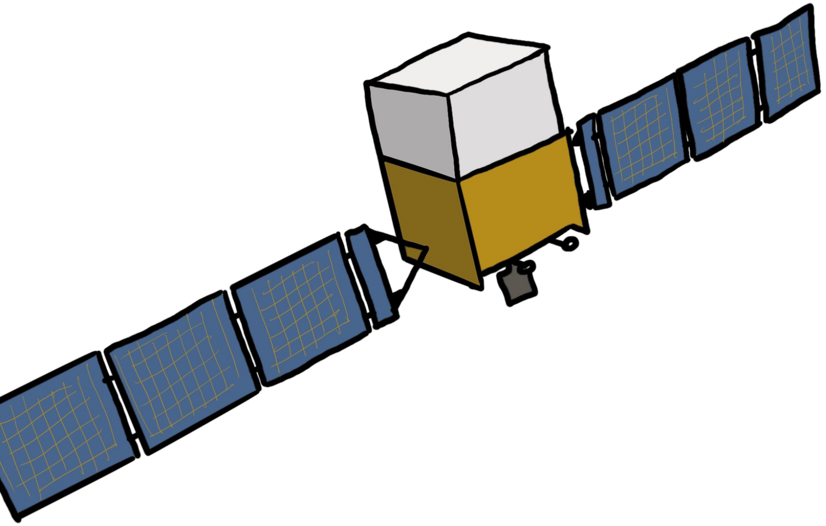


DM targets

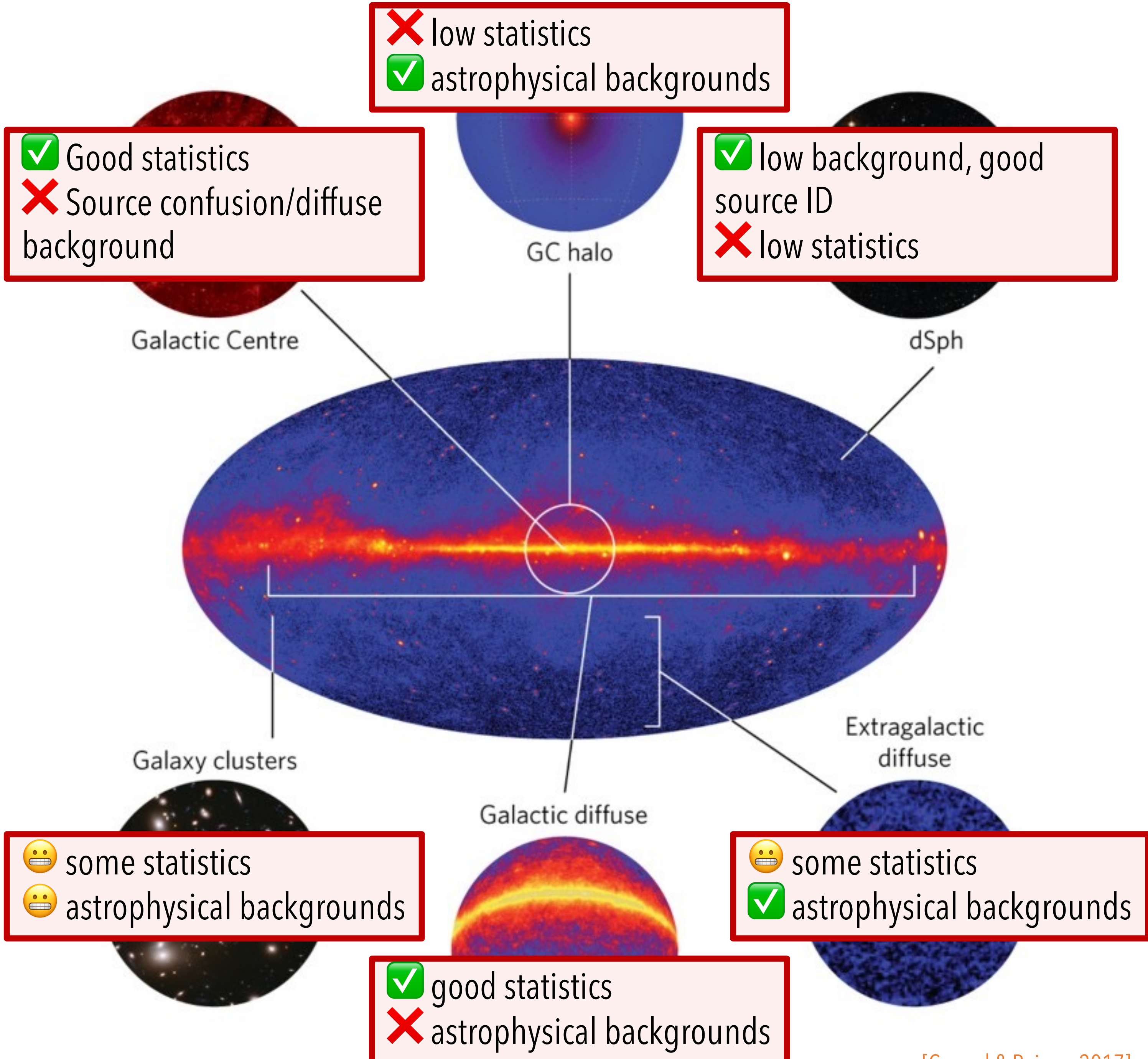


Also: Solar System (Sun, Jupiter), brown dwarfs, exoplanets, etc.
Nguyen+ 25, 26, Leane+ 23, Blanco+ 24, 25, etc.

[Conrad & Reimer 2017]



DM targets



[Conrad & Reimer 2017]

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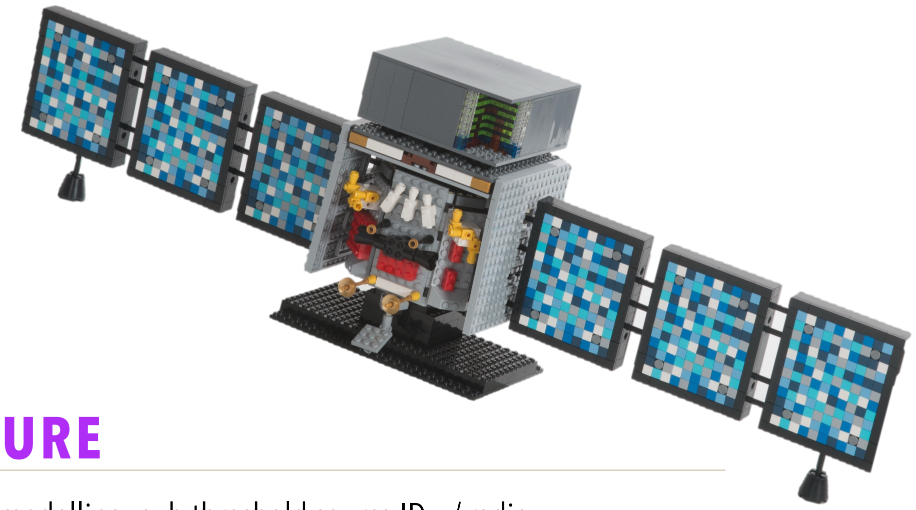
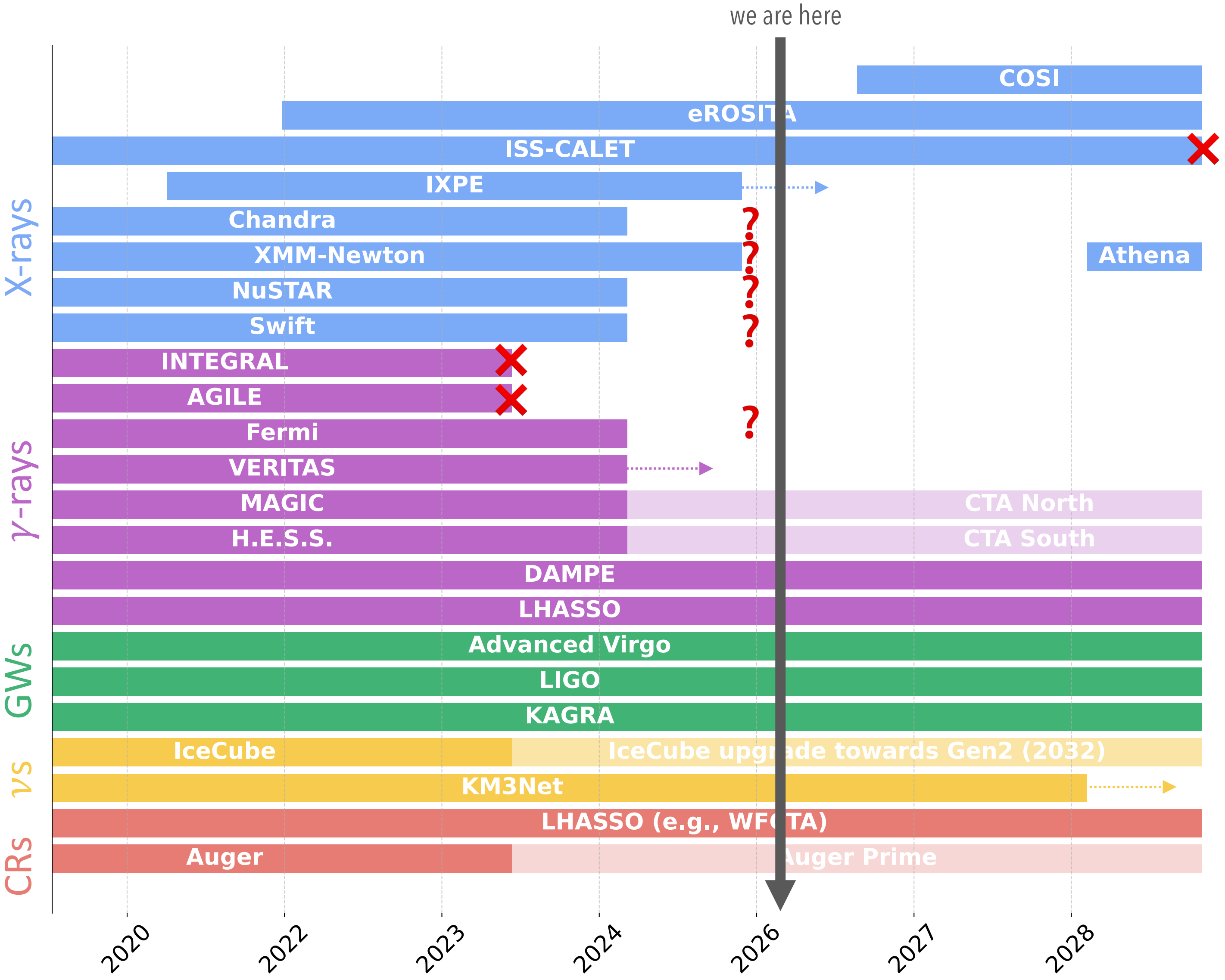
Nguyen+ 25, 26, Leane+ 23, Blanco+ 24, 25, etc.



TARGET	CURRENT STATUS	FUTURE
Galactic Center	Bright GeV excess; disputed origin	Diffuse modelling; sub-threshold source ID w/ radio
Dwarf spheroidals	Thermal ⟨σv⟩ excluded below 100 GeV	LSST/Rubin: hundreds of new dSphs/a few good ones/JLA
Galaxy clusters	Strong limits (high-latitude halo, groups)	J-factor + CR systematics
DM subhaloes	Candidates in LAT unassociated sources	ML identification + Gaia follow-up
Galactic halo	Most constraining at $E > 1$ TeV (HESS)	CTAO improves HESS by up to ×10
MeV / sub-GeV sky	Largely unexplored	AMEGO-X, e-ASTROGAM, VLAST

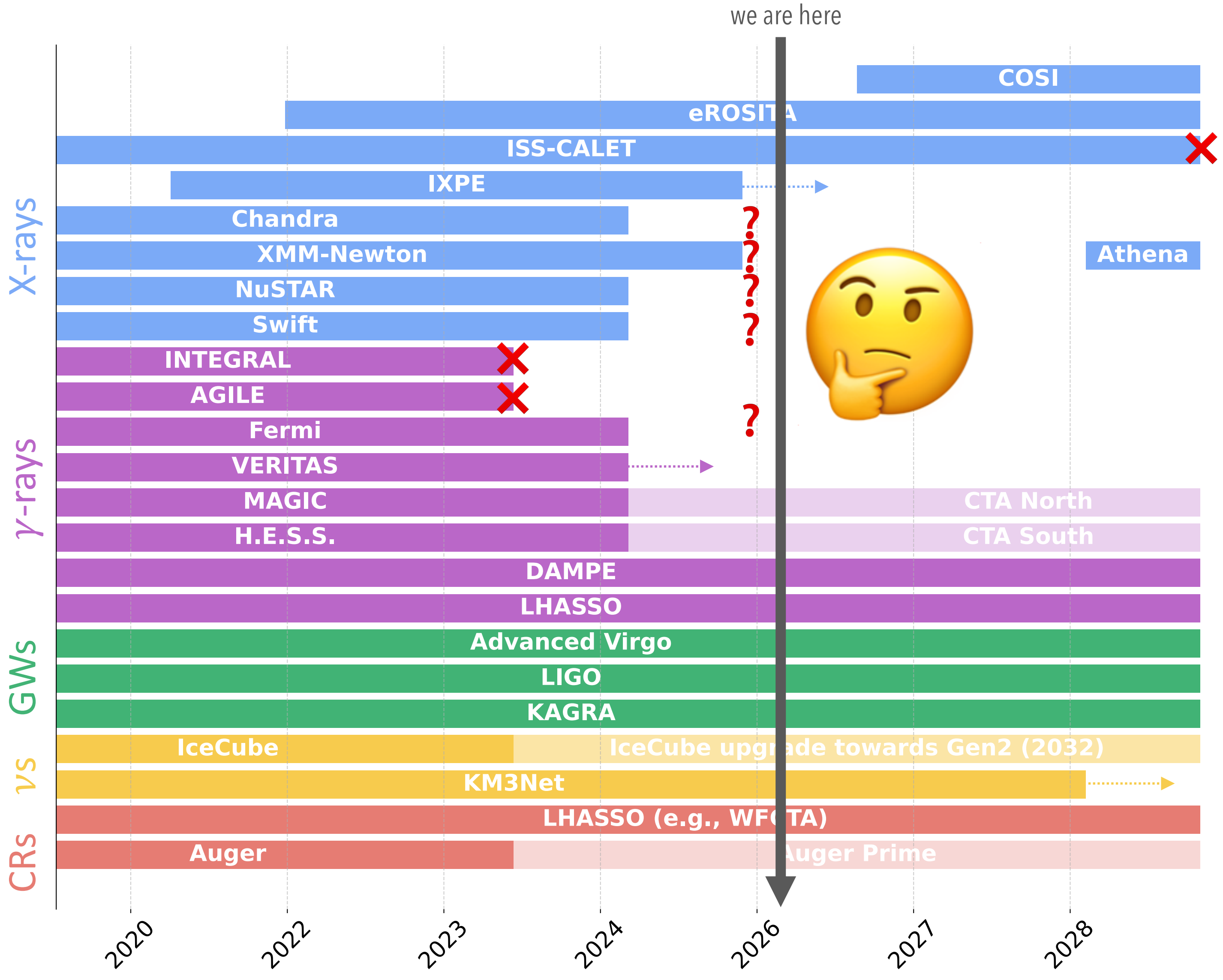
Dark Matter Landscape: An Instrumentationalist's View



e-ASTROGAM
AMEGO
AMEGO-X
…

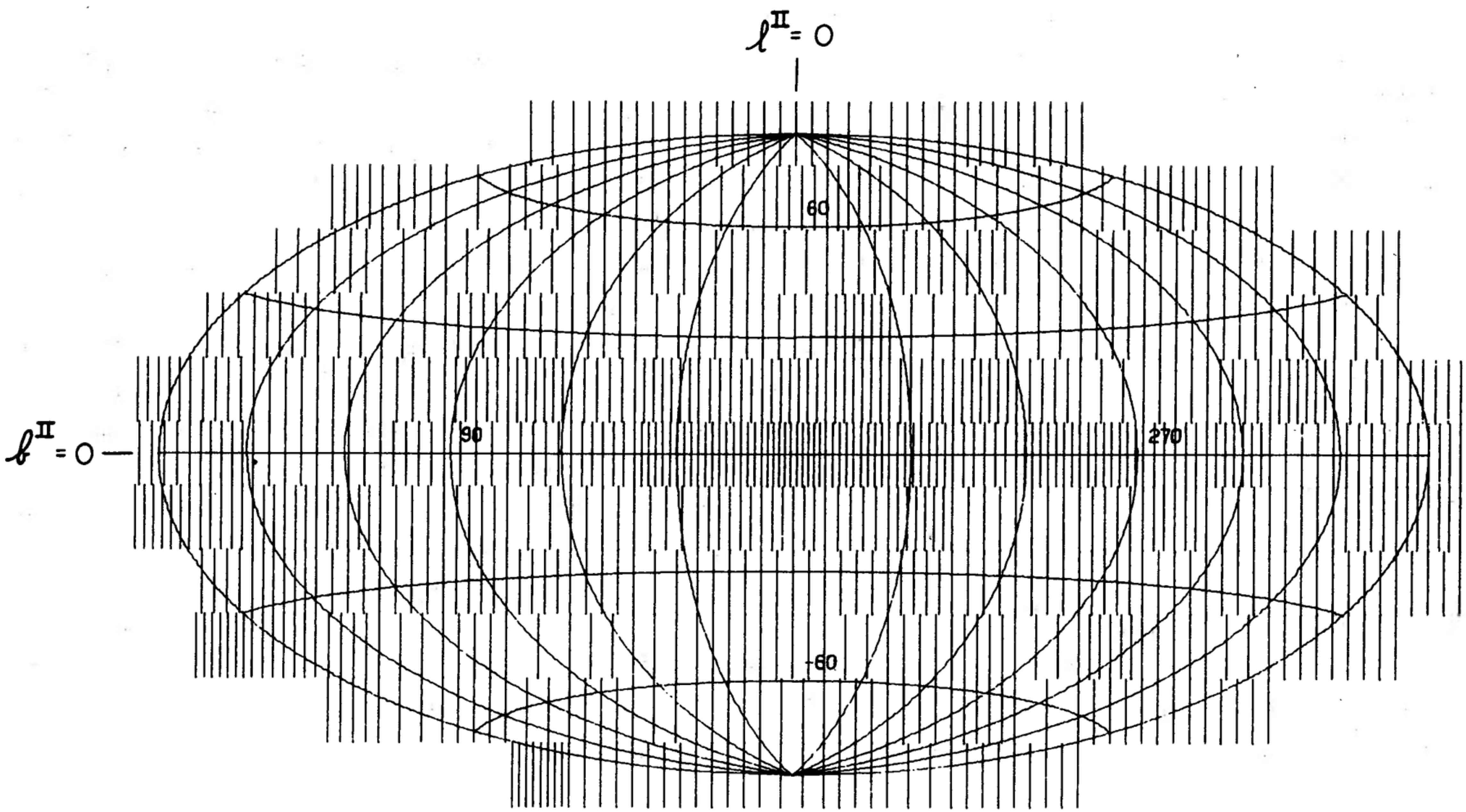
VLAST?

Dark Matter Landscape: An Instrumentationalist's View

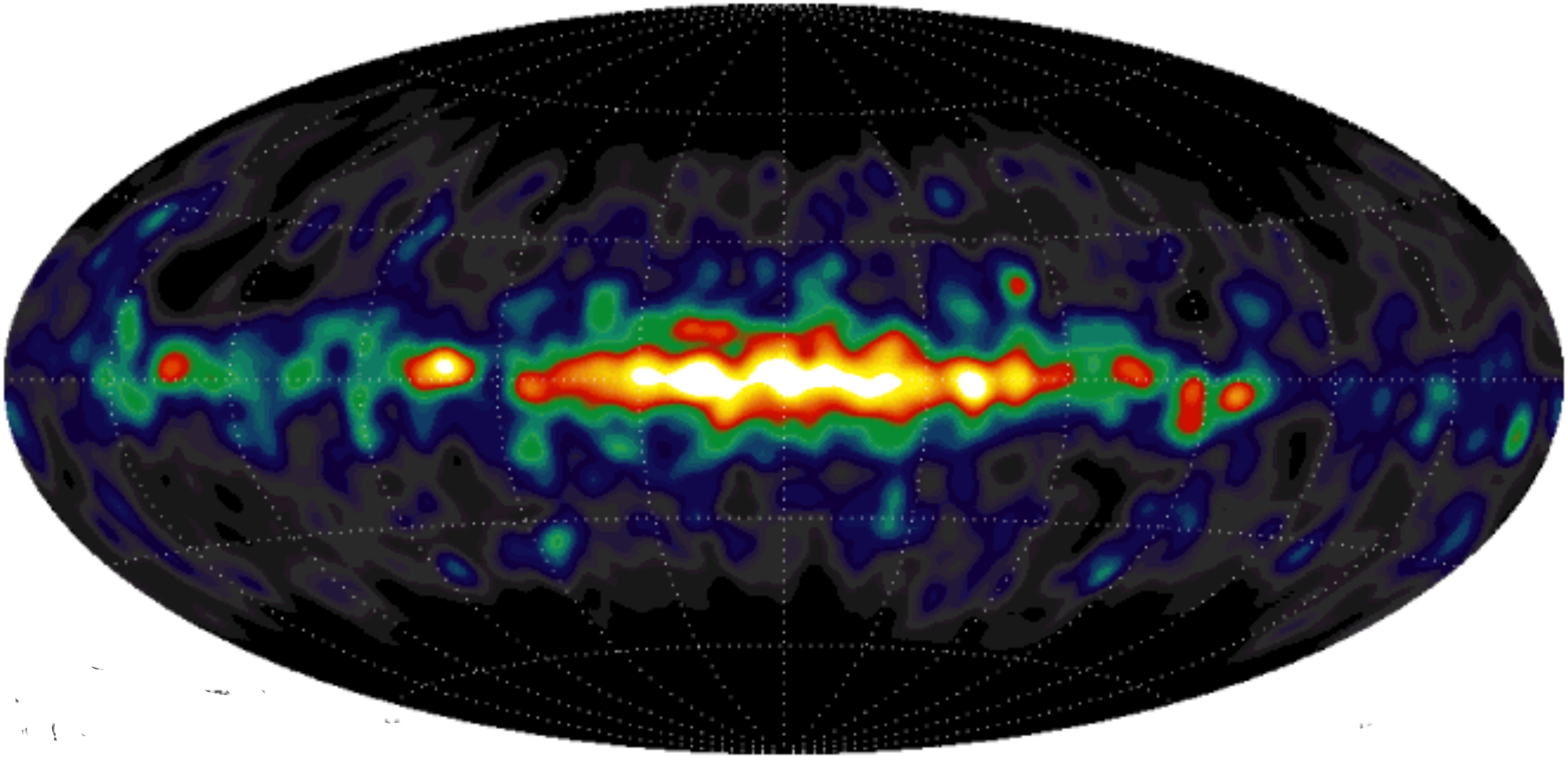


e-ASTROGAM
AMEGO
AMEGO-X
…

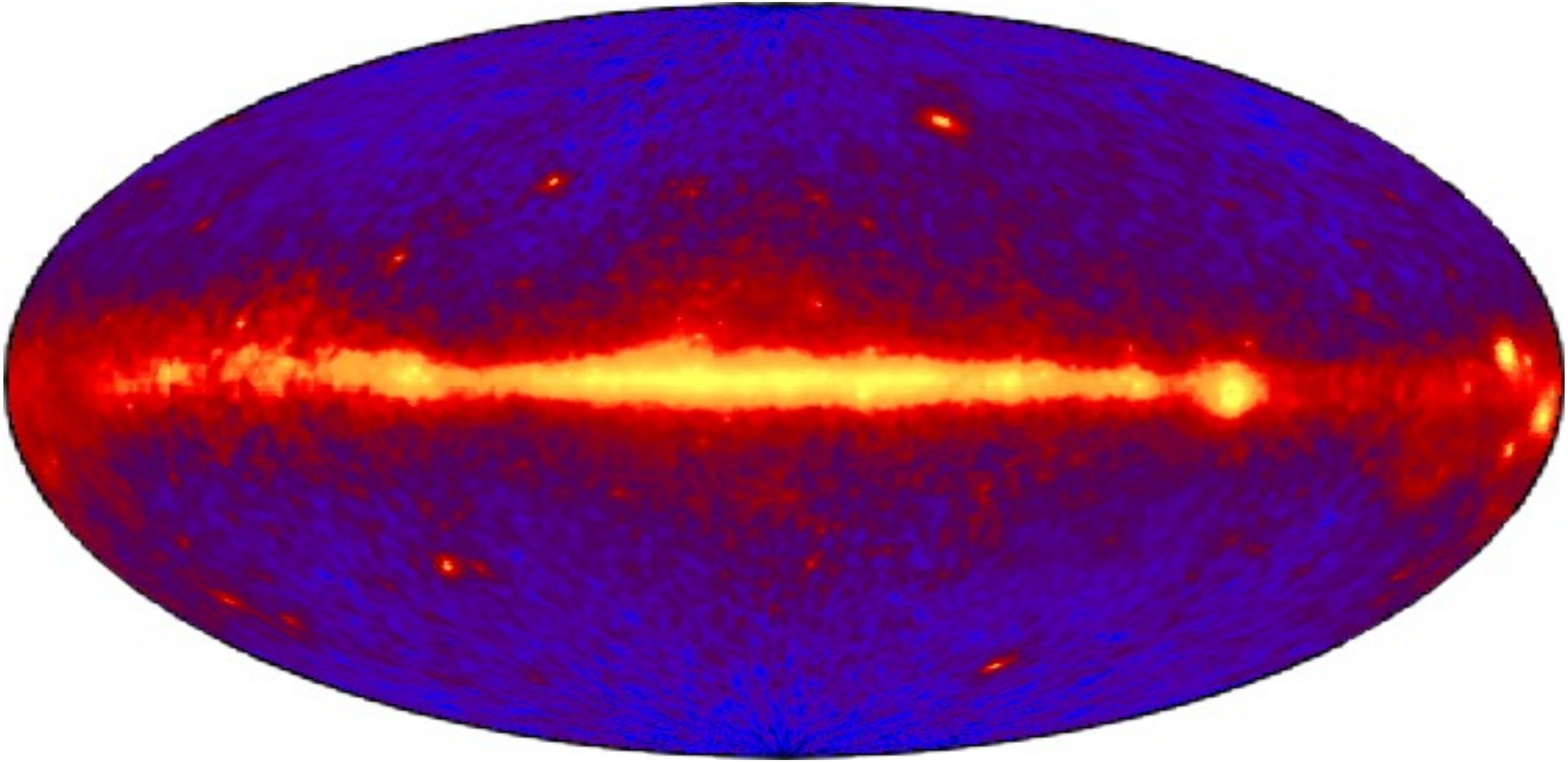
VLAST?



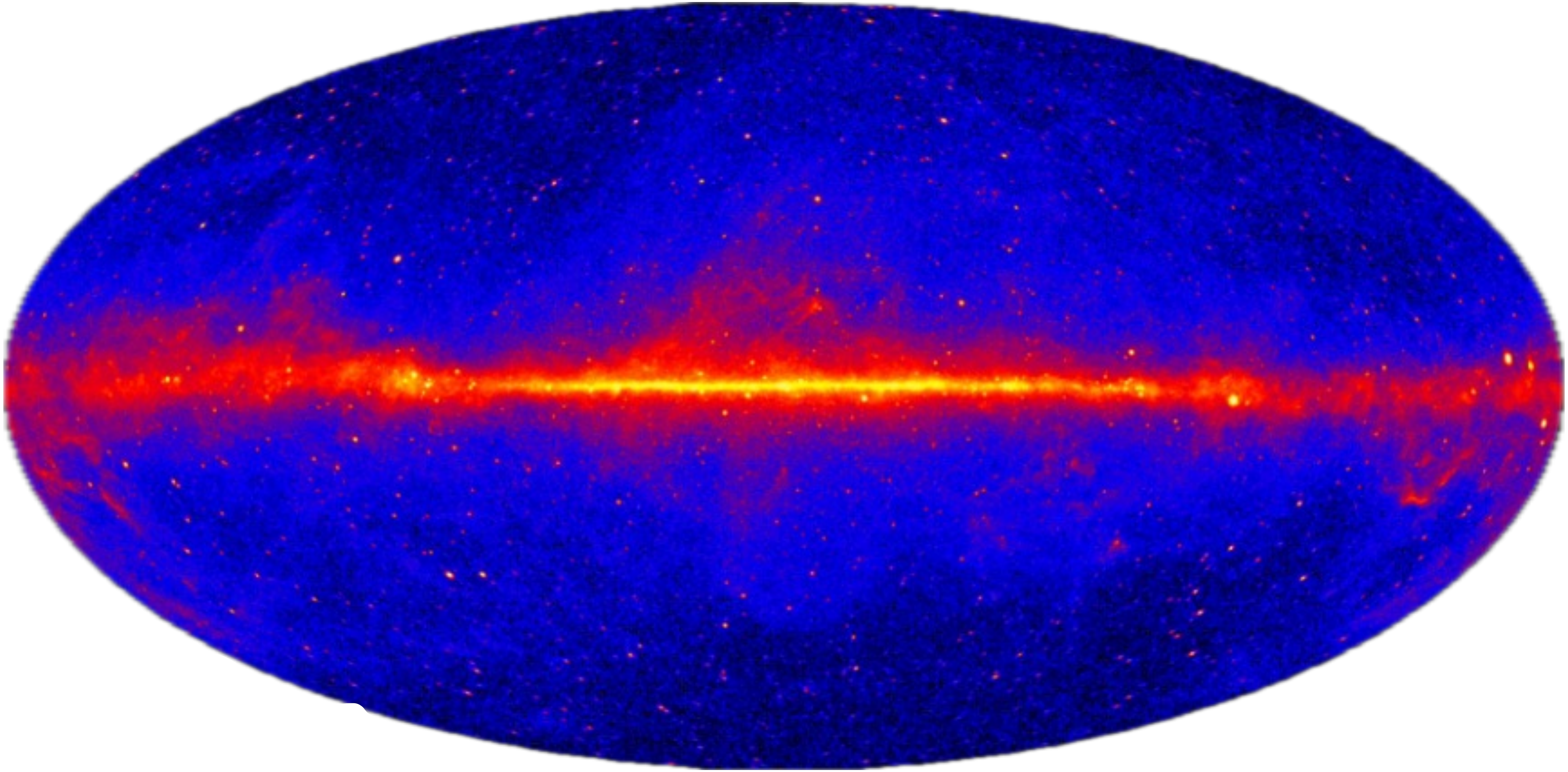
1968, Orbiting Solar Observatory, OSO-3 (~50 MeV)



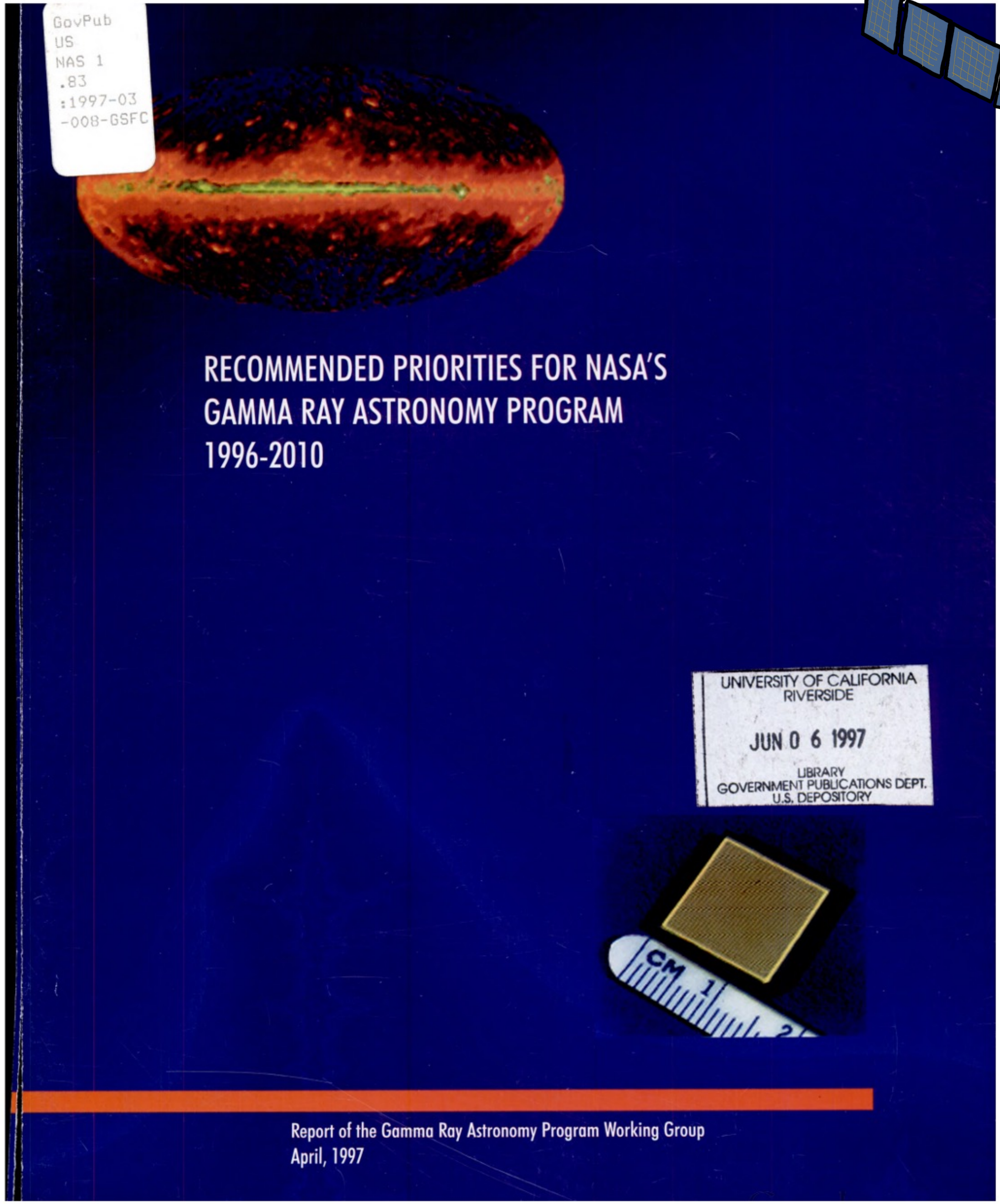
2000, COMPTEL (onboard CGRO), 1–30 MeV



2000, EGRET (onboard CGRO), above 100 MeV



2020, LAT (onboard *Fermi*), above 500 MeV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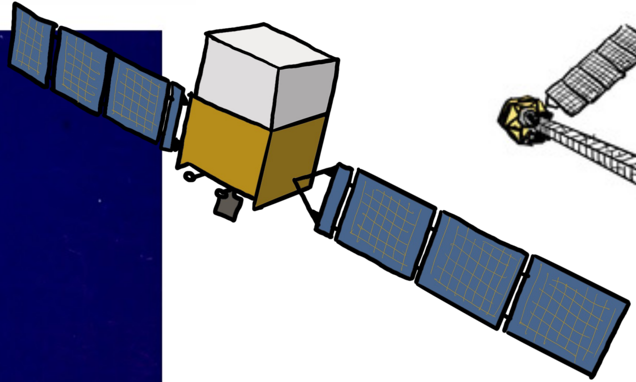
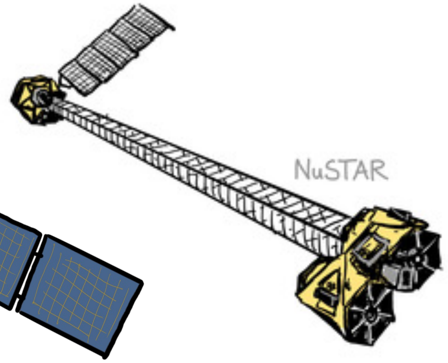
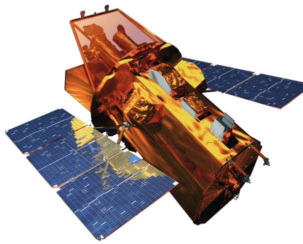
RECOMMENDED PRIORITIES FOR NASA'S
GAMMA RAY ASTRONOMY PROGRAM
1996-2010

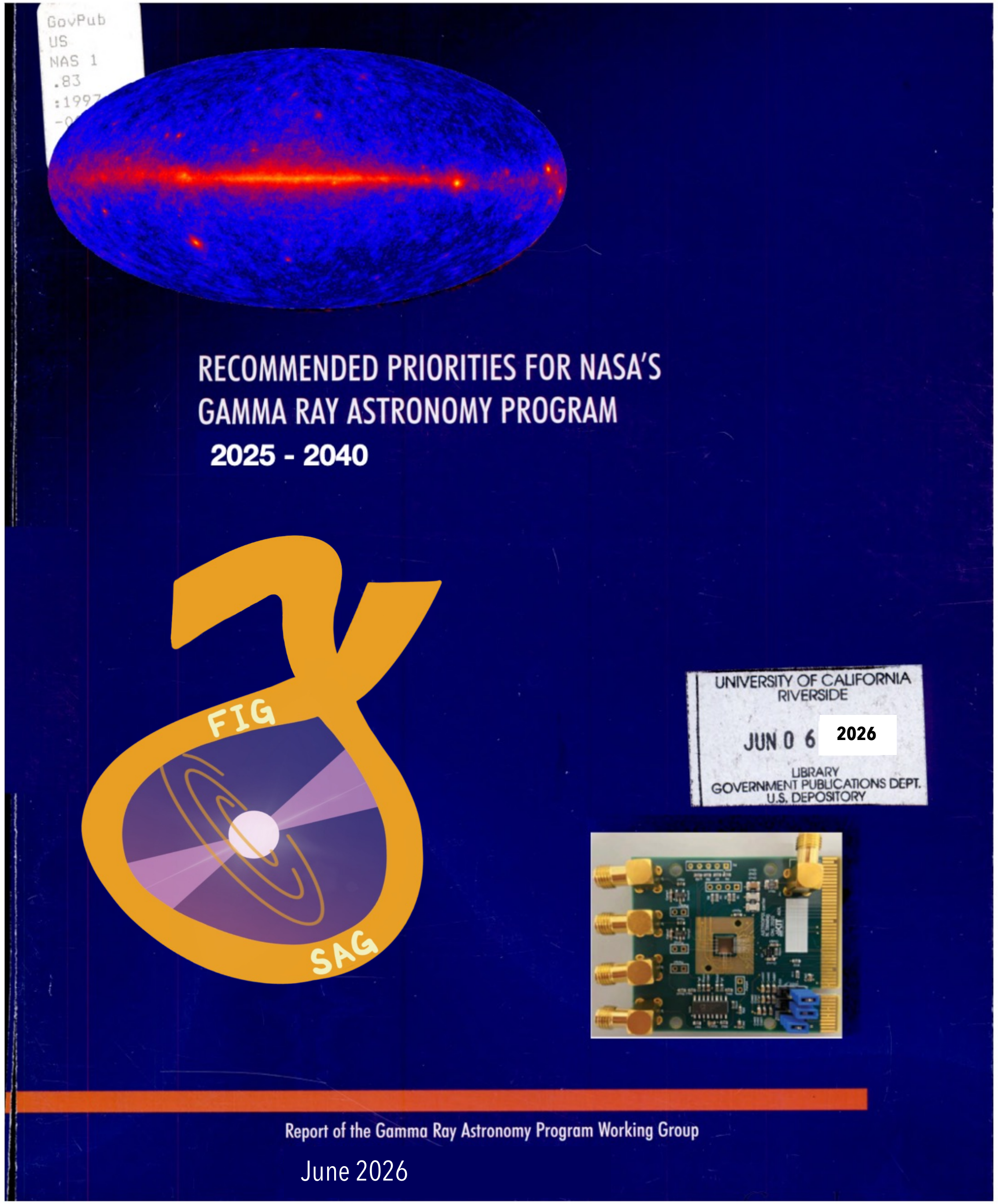
Report of the Gamma Ray Astronomy Program Working Group
April, 1997







- Intermediate Missions: Fermi, NuSTAR and now COSI
- MIDEX and SMEX: Swift and NICER
- Technology: a robust technology development program (SiPMs, new scintillators, upgraded silicon detectors, etc)
- Balloons (+ CubeSats!): long duration balloons enabled COSI, LEAP, etc.
- Data Analysis & Theory: mainly supported through GI programs
- TeV Astronomy: VERITAS, HESS, HAWC, and MAGIC.



Submitted to the NASA Astrophysics Advisory Committee by

The Future Innovations in Gamma Ray Science Analysis Group

Future Innovations in Gamma Rays SAG: A Report on Gamma-ray Science Objectives Beyond 2025

Chris Fryer[1], C. Michelle Hui[2], Paolo Coppi[3], Milena Crnogorcevic[4], Tiffany R. Lewis[5], Marcos Santander[6], and Zorawar Wadiasingh[7]

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[2]NASA Marshall Space Flight Center
[3]Yale University
[4]Stockholm University
[5]Michigan Technological University
[6]University of Alabama, Huntsville
[7]University of Maryland, College Park

Thank you!

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@FlipPhysics
May 28, 2026