

Charting the Dark Sector Theoretical Perspectives on Dark Matter

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UNIVERSITÀ
DI TORINO



Ministero
dell'Università
e della Ricerca



Fundamental Facts and Questions

- **Overwhelming evidence** that majority of pressurless, clustered matter in the Universe is non-baryonic
- **Gravitational** inference clear, **fundamental** nature still a mystery

Fundamental Facts and Questions

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- **Gravitational** inference clear, **fundamental** nature still a mystery
- **What** is Dark Matter?
 - A **particle** or a manifestation that we do not understand **gravity**?
 - If a particle, what are **key parameters**: mass, spin, interaction types and strengths
 - If not a particle, what **modification of gravity** or spacetime dynamics could reproduce what we call DM **across all scales** (galaxies, clusters, gravitational lensing, cosmology) ?

What is known

Relevant for the particle
cosmological behaviour,
production mechanism, mass
and interactions

- Cosmic density about 23% of the Universe total budget
CMB anisotropies, LSS

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- Local density: $0.3-0.4 \text{ GeV cm}^{-3} = 10^5$ average density
Local stellar motions
- Local velocity dispersion: $(200-300) \text{ km s}^{-1}$
Local stellar motions

Relevant for direct detection,
Earth/Sun neutrino flux

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Local stellar motions
- No preferred length scale
Galaxy clustering and evolution
- Behaves as non-relativistic and pressurless (cold or cold-enough)
Structure formation
Excludes lightest neutrinos, implications for light scalars
- Early appearance: gravitational influence way before CMB release
Galaxy clustering
For light bosons, this sets the latest epoch of particle creation/start of CDM behaviour
- No significant interaction with ordinary matter (or self-interaction)
Darkness, Bullet cluster

Relevant for the particle cosmological behaviour, production mechanism, mass, interactions, direct and indirect detection

Charting the unknown – Production

Thermal freeze-out	DM was initially in thermal equilibrium and later decoupled when annihilations became inefficient	WIMPs, secluded WIMPs, some SIMPs
Freeze-in	DM was never in equilibrium; produced gradually from rare interactions	FIMPs, sterile neutrinos, some axions
Misalignment mechanism	A classical field stores energy in the early Universe and later oscillates as cold DM	QCD axions, axion-like particles, ultralight scalars
Gravitational production	Produced purely by the expansion of spacetime or inflationary dynamics	Superheavy DM, some primordial relics
Asymmetric production	DM abundance generated by a particle–antiparticle asymmetry analogous to baryogenesis	Asymmetric DM
Dark-sector freeze-out	Freeze-out occurs within a hidden sector, not directly interacting with the Standard Model	Secluded DM, dark photons, hidden-sector DM
SIMP mechanisms	Number-changing self-interactions determine abundance	SIMPs, ELDERS
Non-thermal decay production	Produced from decays of heavier particles after decoupling	Moduli decay, inflaton decay, gravitino decay
Primordial relics	Produced through gravitational collapse or phase transitions	Primordial black holes

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Charting the unknown– Mass scale

10^{-19} eV	μeV	0.1 eV	keV	MeV	GeV	10^2 TeV	$10^{-16} M_\odot$	$10 M_\odot$	$10^3 M_\odot$
<u>Fuzzy DM</u>	<u>QCD axion/ALPs</u>		<u>Sterile ν</u>	<u>WIMPs & WIMPzillas</u>			<u>PBH</u>		
Bosonic	Boson		Boson Fermion	Boson Fermion			Non particle		
Quantum fluid	Thermal Non-thermal		Non-thermal	Thermal Non-thermal			Primordial		
Cold	Cold		Warm-ish	Cold			Cold		

Charting the unknown – Interaction

Gravitational only	No detectable non-gravitational coupling	Primordial black holes, compact dark objects
Feeble SM coupling	Never thermalizes with SM; tiny portal couplings	FIMPs / freeze-in DM, sterile-neutrino DM, very weak hidden sectors
Axion-like / Anomaly couplings	Very light bosons with suppressed couplings to photons, gluons, fermions	QCD axion, ALPs, wave-like DM
Portal-mediated hidden sector	DM couples to SM through a mediator	Dark photon / vector portal, Higgs portal, neutrino portal, scalar portal, pseudoscalar portal
Weak-scale interactions	Relic abundance may arise from freeze-out; sizeable annihilation/scattering	WIMPs, SUSY neutralino-like DM, electroweak multiplets, some Higgs-portal or Z' models
Self-interacting dark sector	DM-DM scattering is important, SM coupling may be tiny	SIDM, light dark mediators, atomic DM, mirror/dark plasma models
Strong/composite dark sector	Confined or composite dark states	Dark baryons, dark mesons, SIMP-like models, asymmetric composite DM

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Connection to particle physics models

- Axion-like, wave (scalar, pseudo-scalar)
 - String theory
 - Inflationary models
 - Ad hoc
- QCD axion (pseudo-scalar)
 - Strong CP-problem
- Sterile neutrinos
 - Very light, KeV, Heavy
 - Neutrino mass models, leptogenesis models
- Dark photons
 - Gauge group extensions: $U(1)'$, $SU(2)'$
- Heavy (pseudo) scalars
 - Scalar sector extensions: singlets, 2HDM, triplets
- WIMPs
 - Supersymmetry
 - Extra dimensions
 - Minimal DM models
 - Leptogenesis models
- Very heavy particles
 - GUT
 - Leptogenesis

All of them require that DM “cosmological stability” is ensured
(accidentally | through a symmetry | ad hoc | just live enough)

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String theory models often have many scalar field, which could either induce inflation or give a motivation for ALPs

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In principle, well motivated
ALP extension worth to be explored

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Well motivated extension (neutrinos need a mass) although different realizations possible and link to DM might or might not be present (would be a great economical option, especially if leptogenesis is part of the solution)

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Might be the DM or be part of a hidden sector which contains a DM particle (in which case it works as new force mediators and might be mixed with ordinary photons)

Introduce long-range forces if very light

Not too different from WIMPs if heavier (but require “millicharge”)

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Scalar field sector of the SM might be larger
Many NP extensions require/predict more scalars

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Very strong and predictive symmetry, but needs to be broken

SUSY breaking not understood: induces many frameworks, very large # of free parameters, losing somehow predictability (not always)

Accelerator bounds progressively increase, pushing SUSY scale at higher energies: naturalness in jeopardy, but technically not a short-stopper (SUSY is needed e.g. for string theory or preferred for gauge-coupling unification)

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Contrary to SUSY, it's possible to contain the # of free parameters (e.g. the compactification scale)

Accelerator bounds progressively increase the scale at higher energies

Extra-dim are needed for string theory, but the scale can be close to Planck scale (no need to be accelerator reachable, in principle)

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Ad hoc, but very predictive: e.g. MDM has just one free parameter (DM mass) and SM gauge couplings, successful MDM requires $M_{\text{DM}} = \text{several TeV}$, predicts a bunch of associated (almost degenerate in mass with DM) charged fermions

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In principle, well motivated since matter/antimatter asymmetry has to be generated

Often, this is achieved by providing also mass to neutrinos

It would be an excellent solution: hit 3 birds with a stone (disclaimer: no bird has been harmed in building these models)

Connection to particle physics models

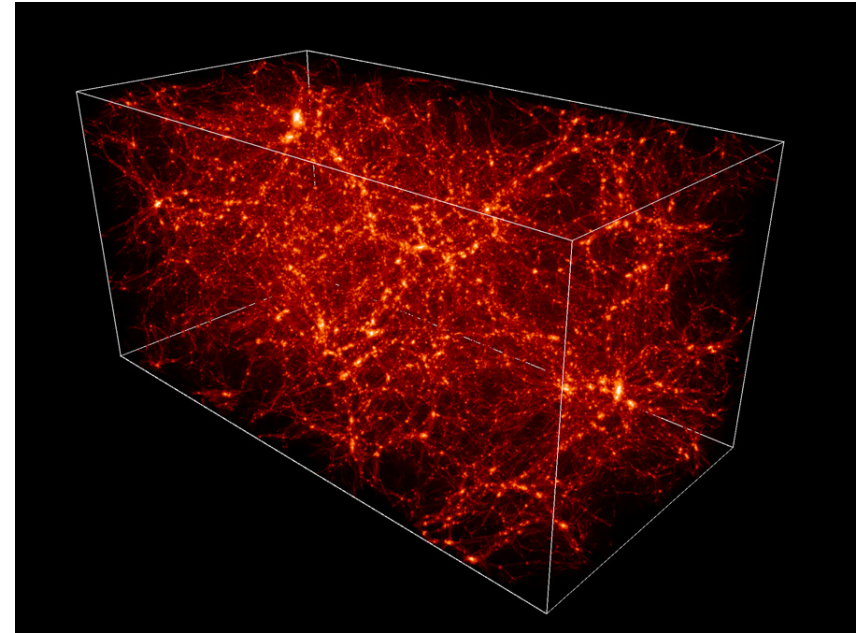
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Compelling or not? Theoretically intriguing, although protons are so stubborn not to have shown to decay (yet)

Tools at hand

Cosmic surveys

- CMB probes
- Galaxy surveys
- Galaxy clusters surveys
- Weak lensing surveys
- Ly-alpha
- Neutral Hydrogen intensity mapping surveys
- Voids surveys
- Filaments

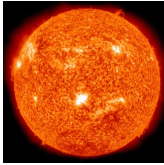


These probes are connected to the fundamental particle physics properties of the DM particle: mass, interaction, production mechanism, cosmological behaviour

- Allow to test DM on different scales and at different times
- Probe coldness, collisionless and pressurless hypotheses, interactions with visible sector, possibly single vs multi-component
- Probe DM clustering (non-linear scales) and growth of structures
- Probe of early DM injected energy: CMB distortion, ionization

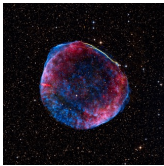
Tools at hand

Cosmic laboratories



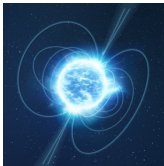
- Sun, other stars

- Can capture WIMPy DM and produce neutrino fluxes – possible for DM masses above the GeV scale
- DM can alter their inner structure and energy transport (both for WIMP and axions), thus affecting stellar properties and evolution
- DM rich environment can affect stellar formation rates and stellar evolution



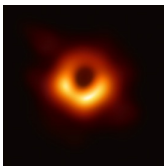
- Supernovae

- MeV DM production can affect cooling



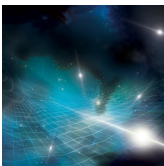
- Neutron stars

- WIMPy DM capture can modify NS temperature (kinetic heating) – very effective for sub-sub-GeV DM
- DM accreted around NS or inside the NS core can affect BH inspirals
- ALP conversion in magnetosphere



- Black Holes

- DM accreted around BH can affect BH physics
 - Formation of DM mini-spikes
 - Superradiance for light bosonic DM (ALPs) [effective also for NS]
 - Local DM environment affecting the inspiral signal of compact objects (backreaction on the metric, dynamical friction): extreme mass-ratio inspirals more affected
- Gravitational waves from PBH merging

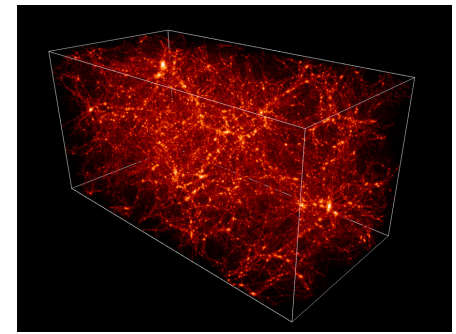


- DM compact objects

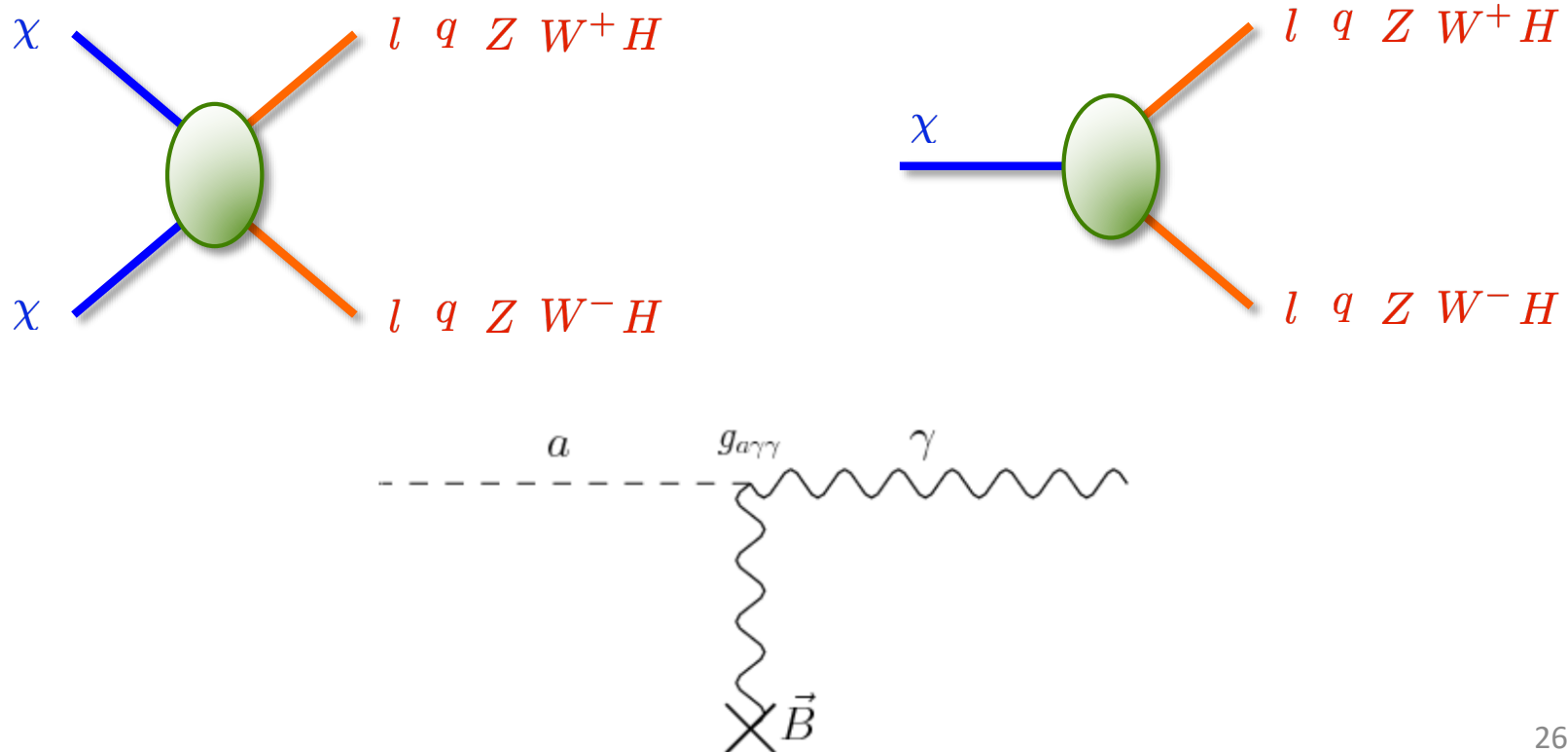


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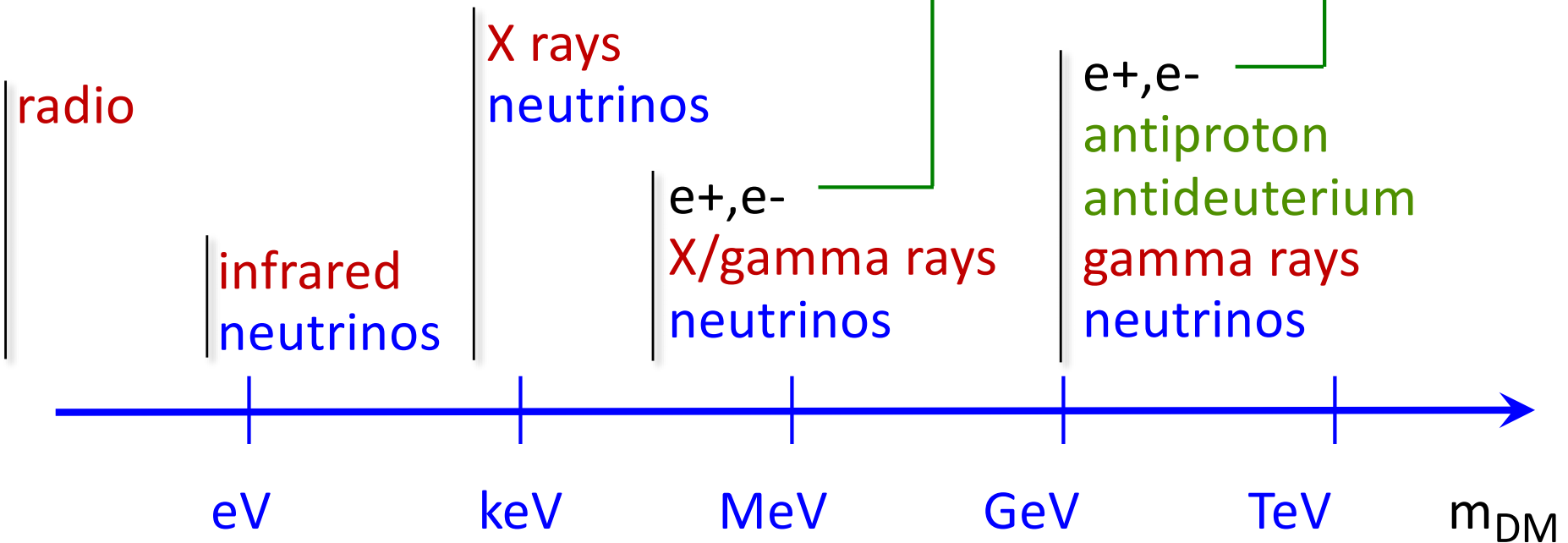
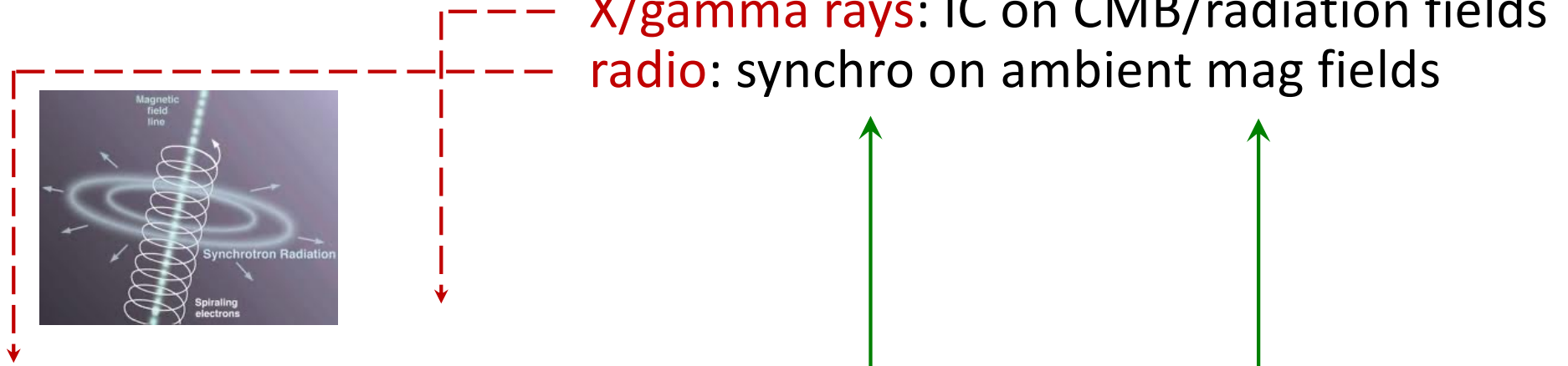
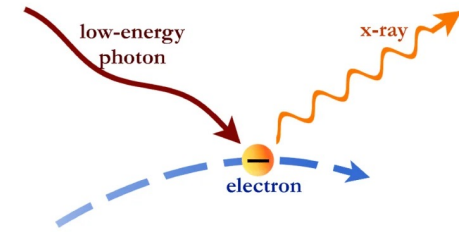
Cosmic messengers



- DM can inject high/low-energy particles (messengers) into cosmological environments (our Galaxy, external galaxies, clusters, filaments, voids):
 - Annihilation | decay | conversion if a particle
 - Evaporation or accretion if a PBH



The Multimessenger Landscape



Axions

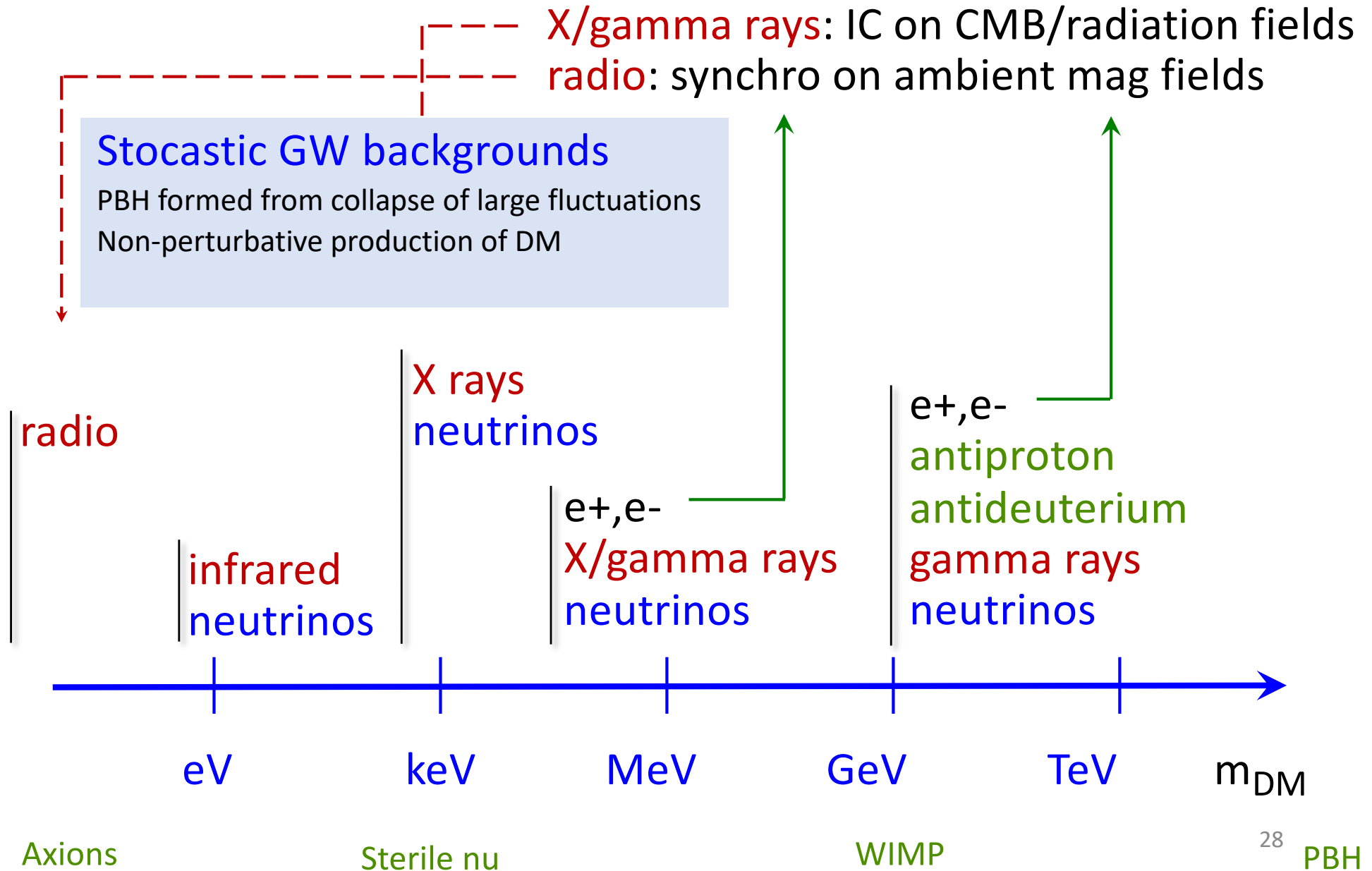
Sterile nu

WIMP

27

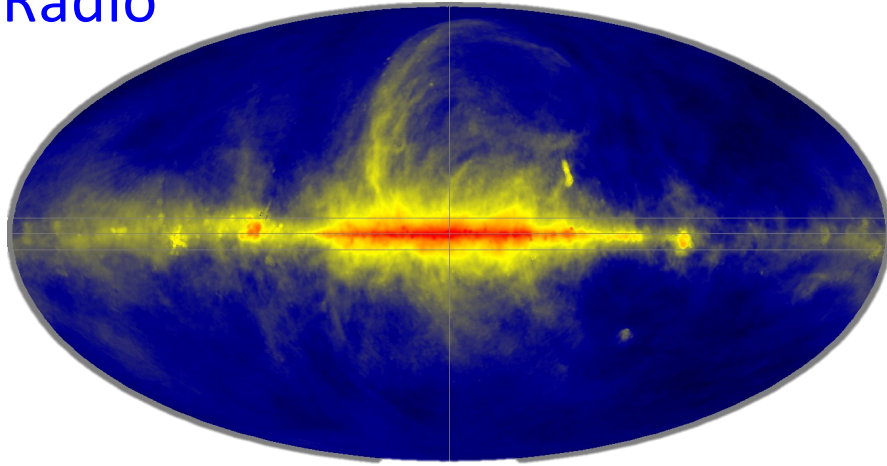
PBH

The Complete Multimessenger Landscape

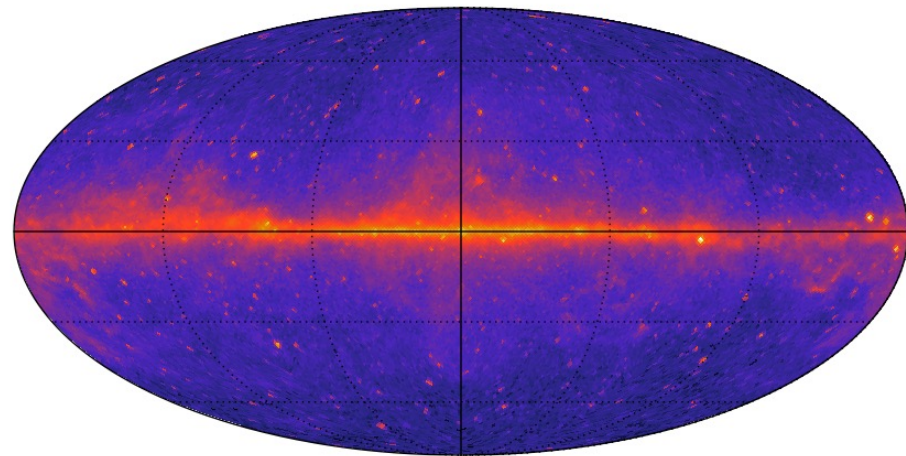
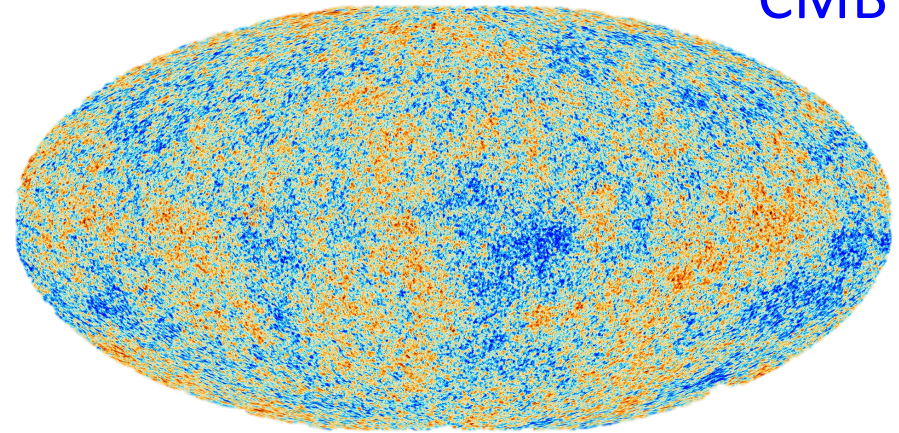


Astrophysical and cosmological radiation fields

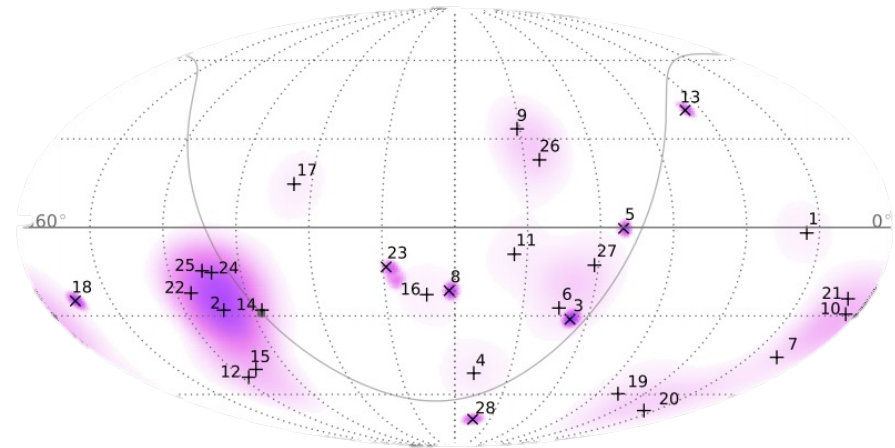
Radio



CMB



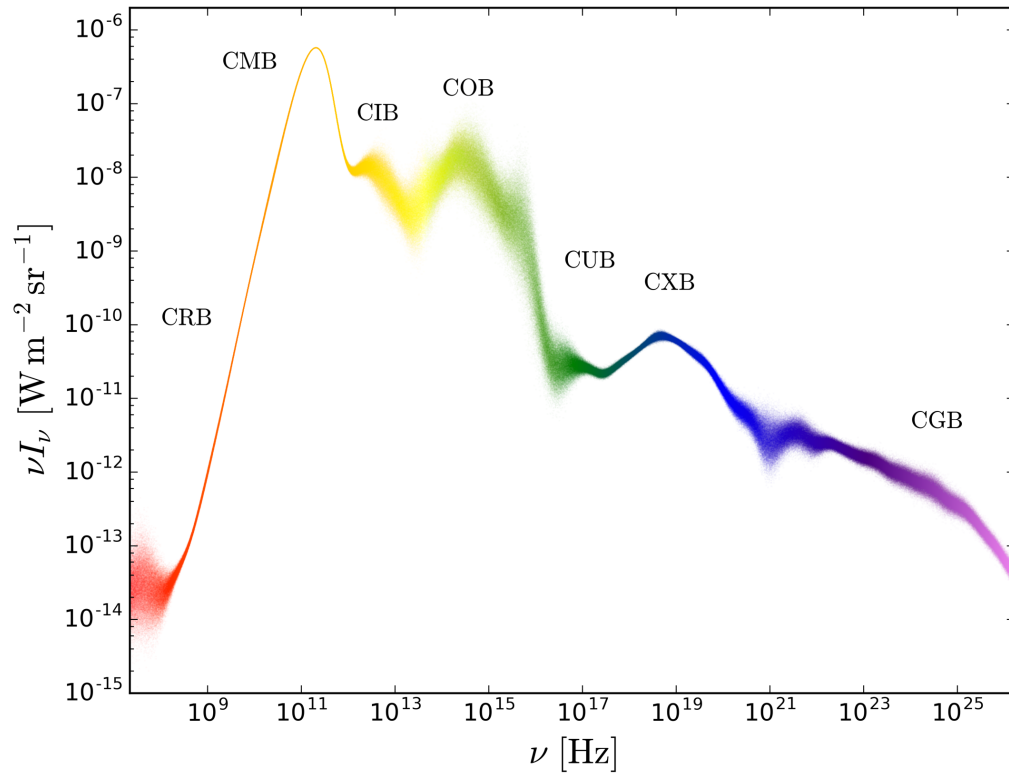
Gamma rays



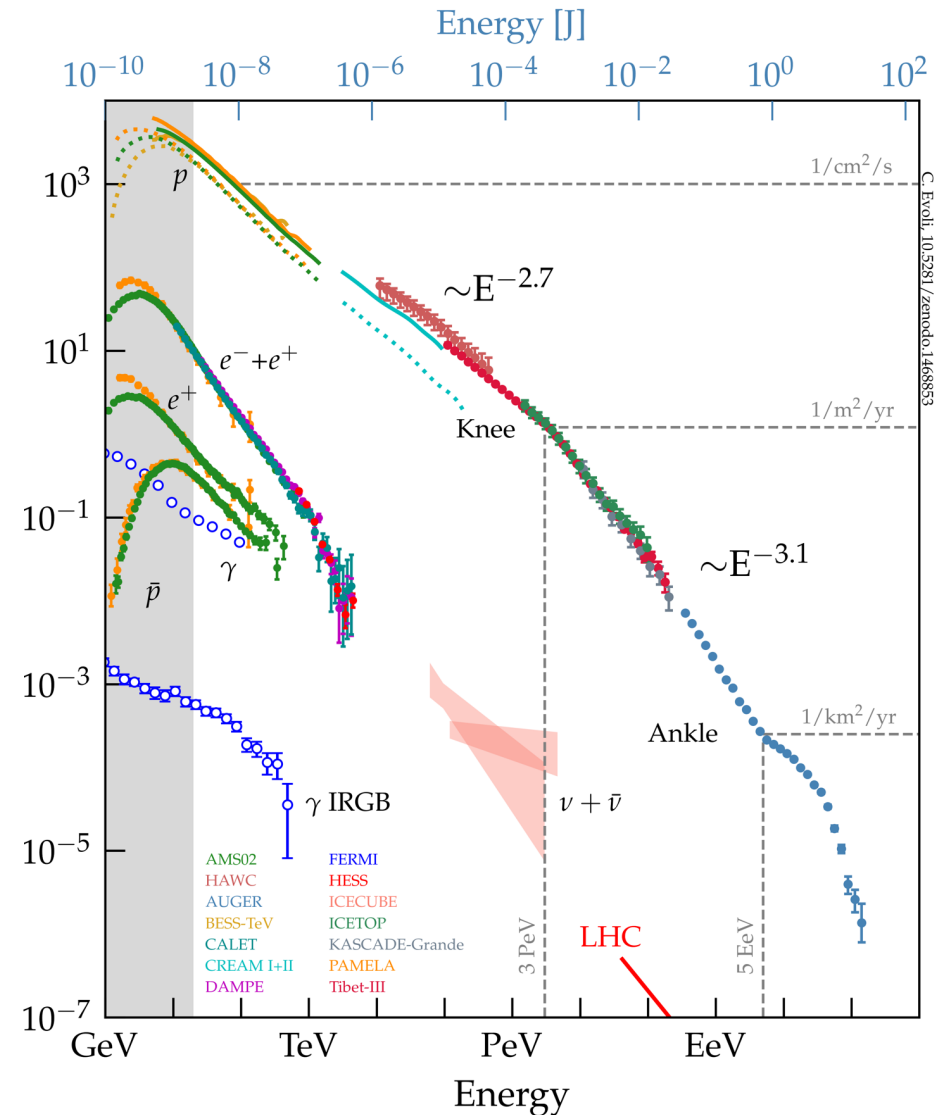
High-energy neutrinos

Astrophysical and cosmological radiation fields

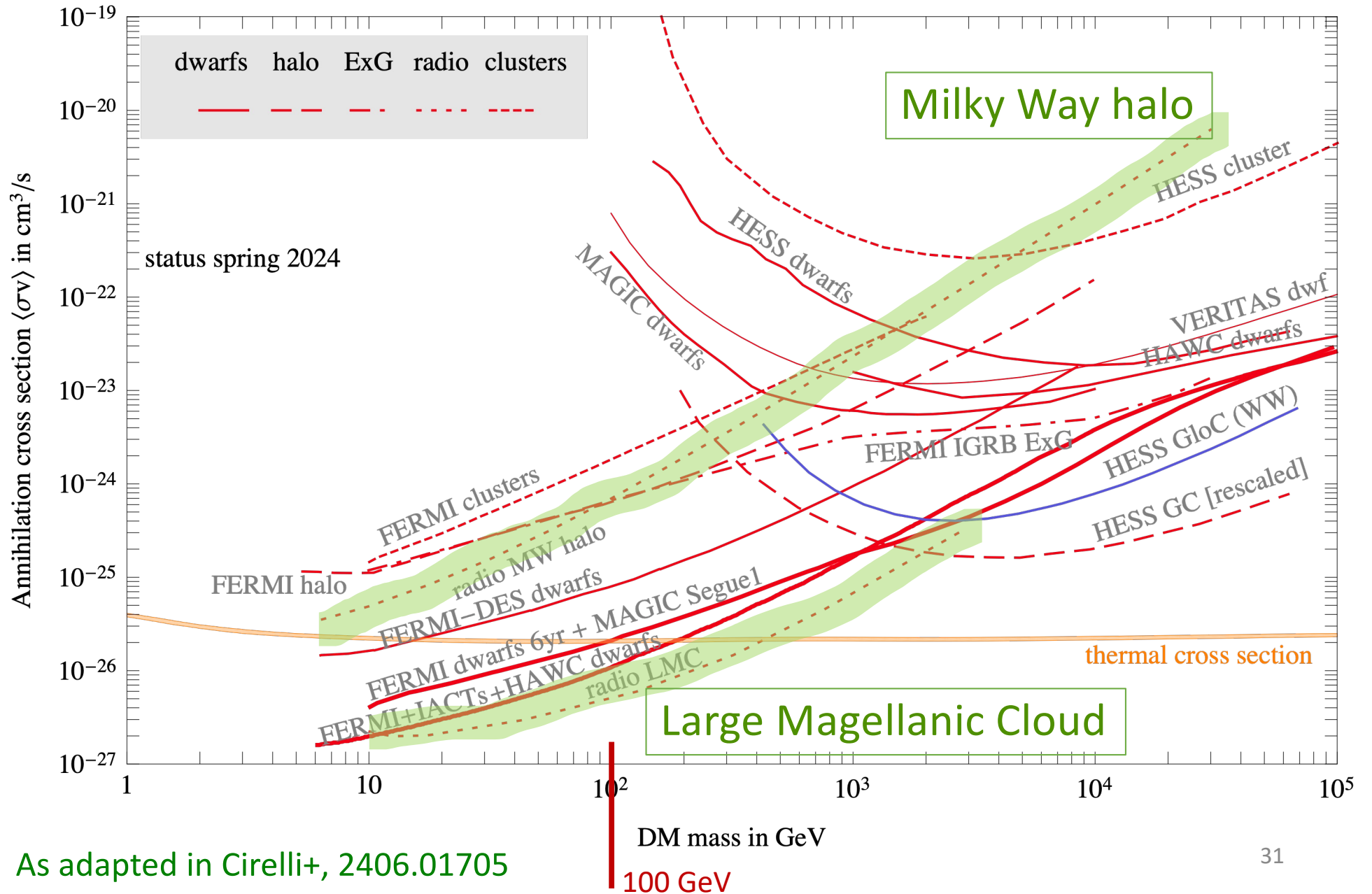
EM radiation



Charged cosmic rays

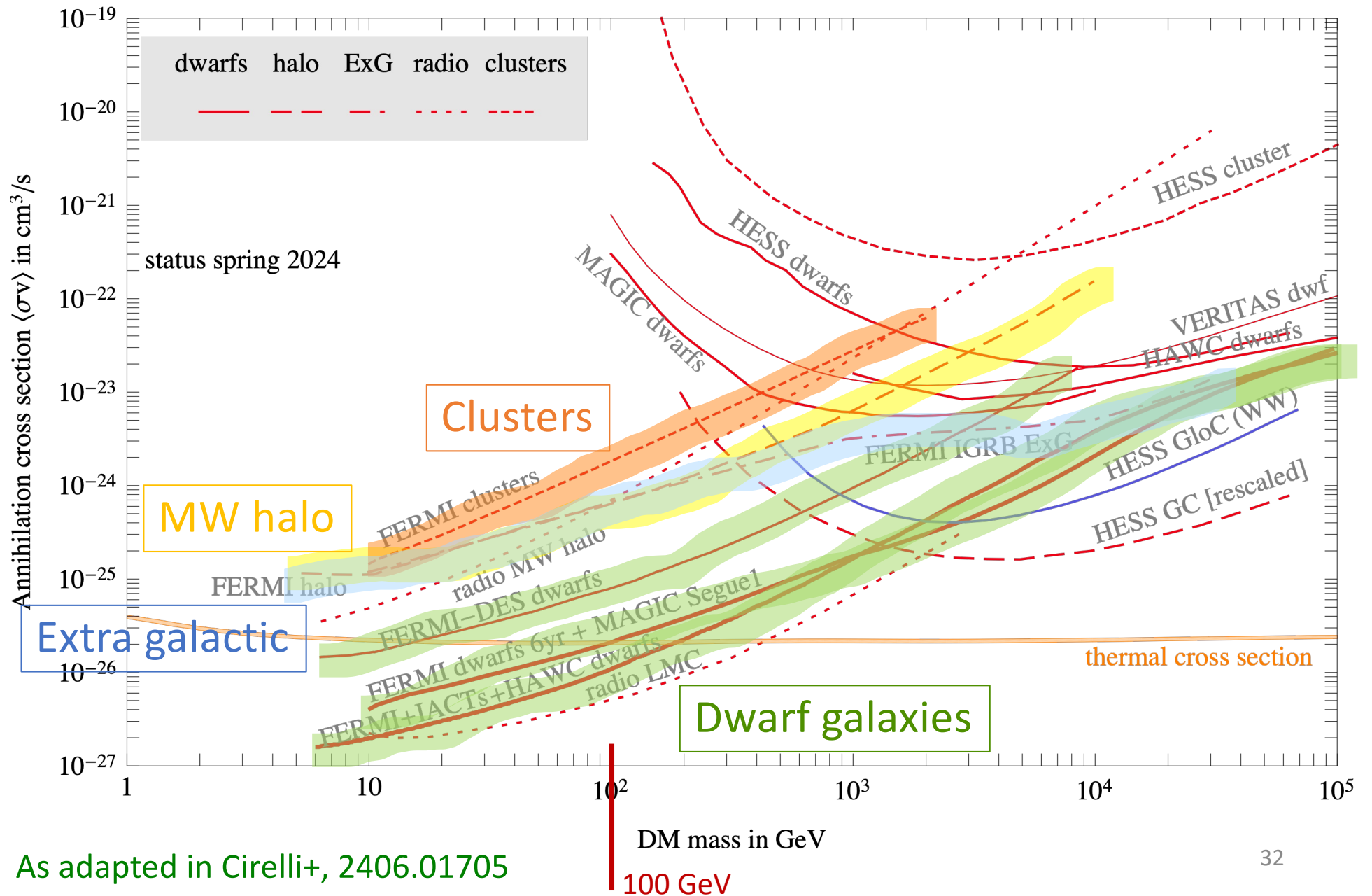


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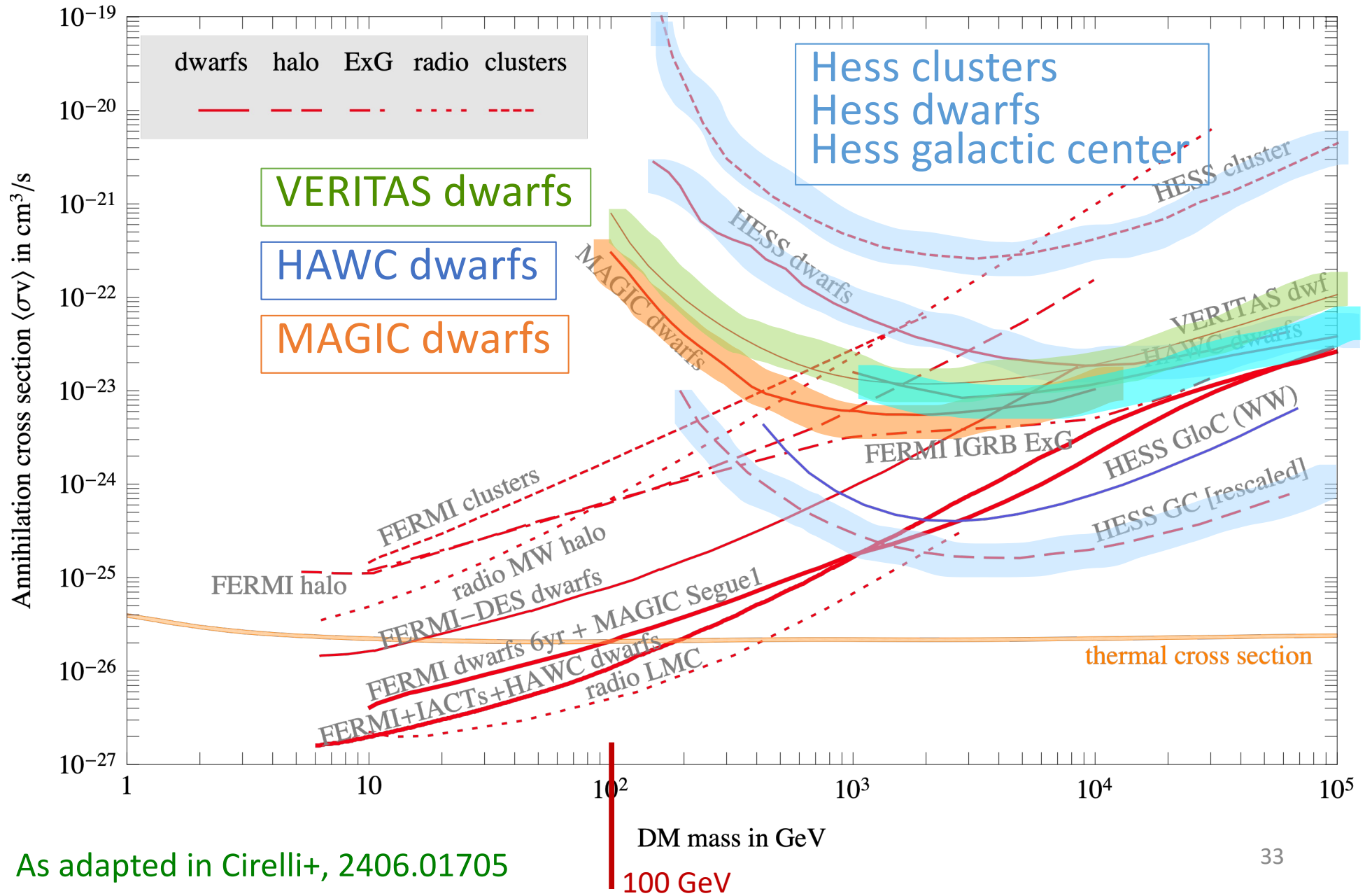
As adapted in Cirelli+, 2406.01705

Gamma rays: Fermi-LAT



As adapted in Cirelli+, 2406.01705

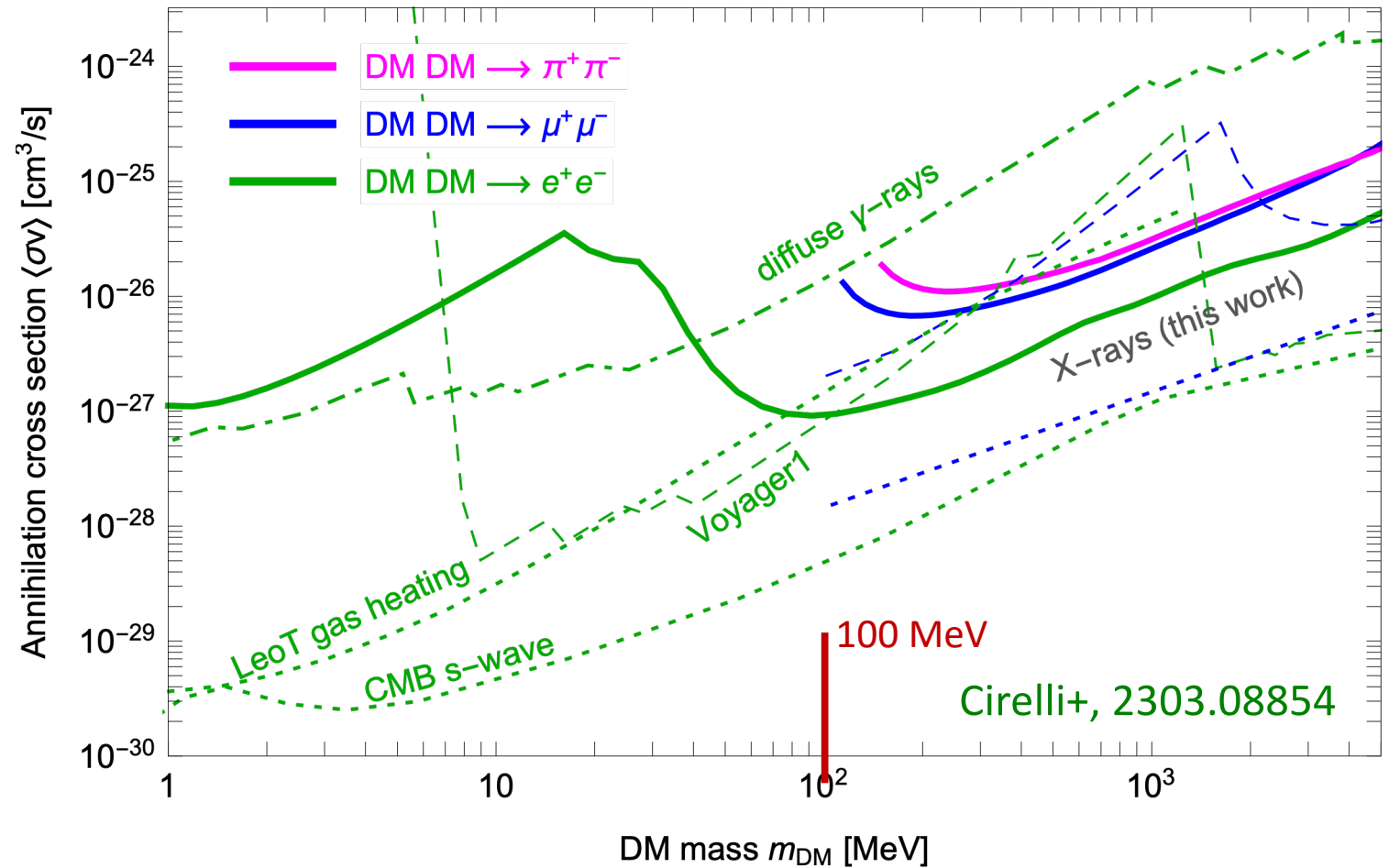
Gamma rays: Air Cerenkov Telescopes



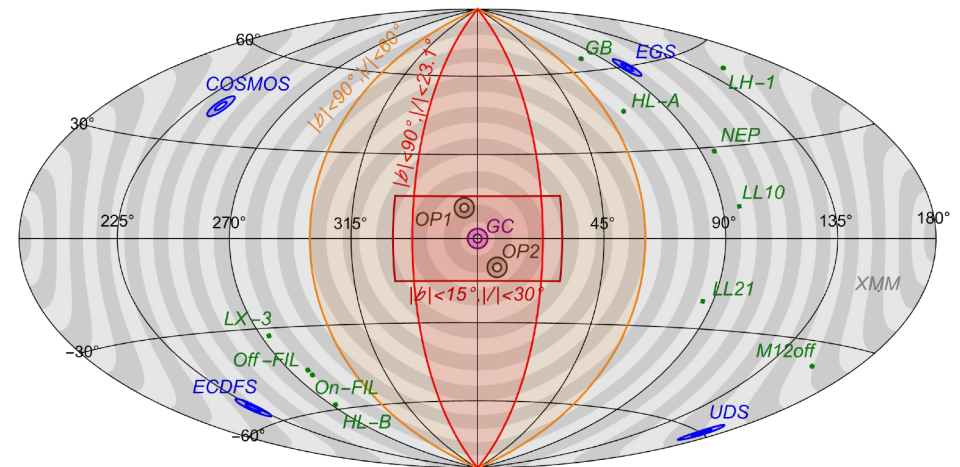
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X rays

IC is quite relevant

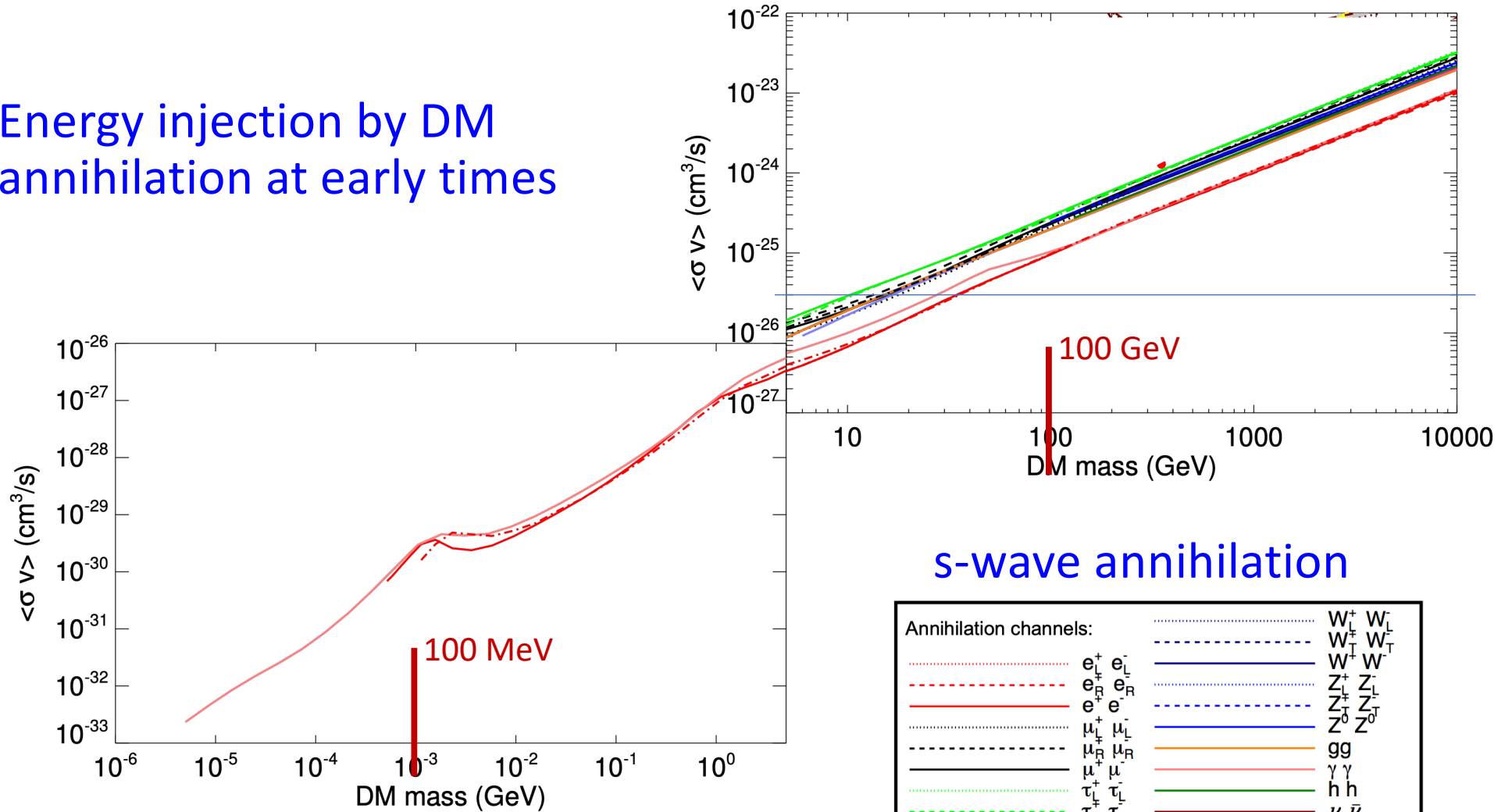


- Integral – orange and red
- NuStar Blank-Sky fields – blue
- NuStar Galactic Center – purple
- NuStar Off -Plane (OP1 & OP2) – dark brown
- Xmm-Newton rings – shades of grey
- Suzaku fields – green



CMB

Energy injection by DM annihilation at early times

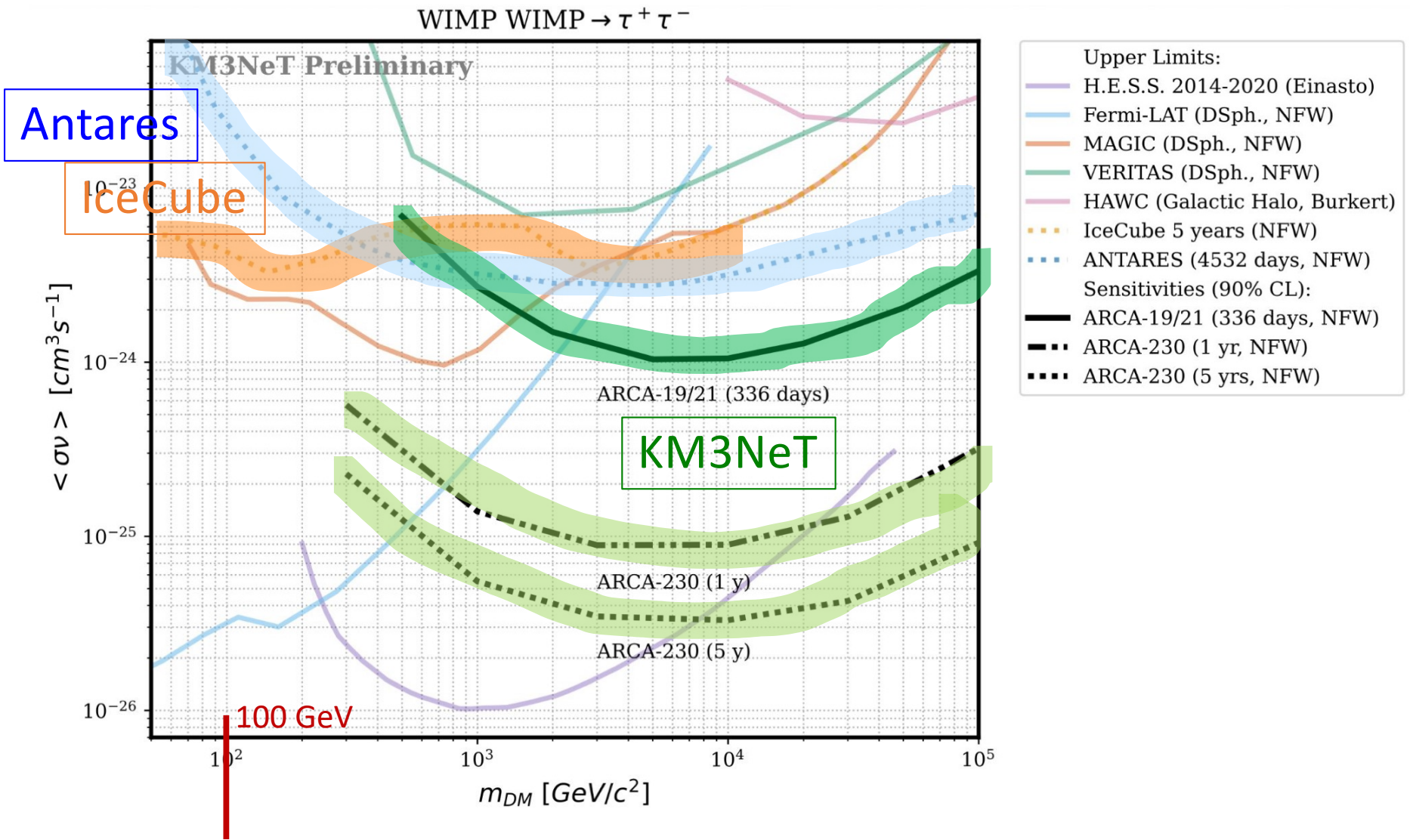


s-wave annihilation

Annihilation channels:	
.....	$W_L^+ W_L^-$
-----	$W_T^+ W_T^-$
————	$W^+ W^-$
.....	$Z_L^+ Z_L^-$
-----	$Z_T^+ Z_T^-$
————	$Z^0 Z^0$
.....	gg
————	$\gamma \gamma$
.....	$h h$
-----	$\nu_e \bar{\nu}_e$
————	$\nu_\mu \bar{\nu}_\mu$
.....	$\nu_\tau \bar{\nu}_\tau$
-----	$VV \rightarrow 4e$
————	$VV \rightarrow 4\mu$
.....	$VV \rightarrow 4\tau$
.....	$e^+ e^-$
-----	$e^+ e^-$
————	$e^+ e^-$
.....	$\mu^+ \mu^-$
-----	$\mu^+ \mu^-$
————	$\mu^+ \mu^-$
.....	$\tau^+ \tau^-$
-----	$\tau^+ \tau^-$
————	$\tau^+ \tau^-$
.....	$q\bar{q}$
-----	$c\bar{c}$
————	$b\bar{b}$
.....	$t\bar{t}$

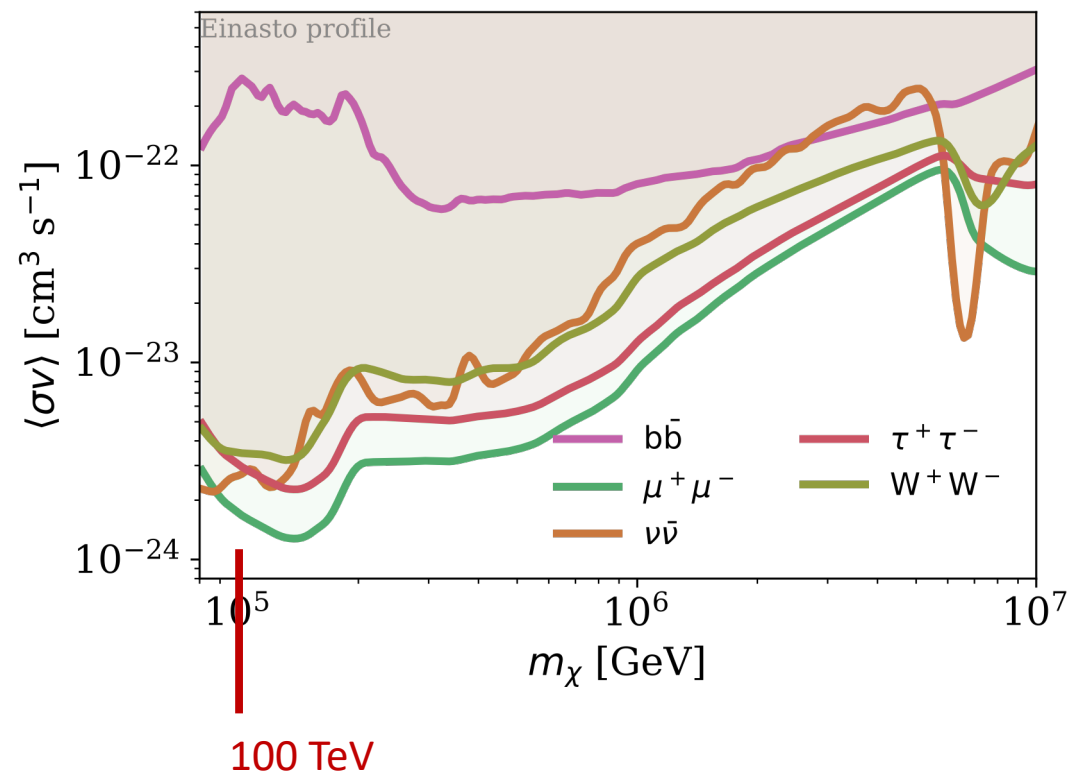
Slatyer, 1506.03811

Neutrinos: Galactic center



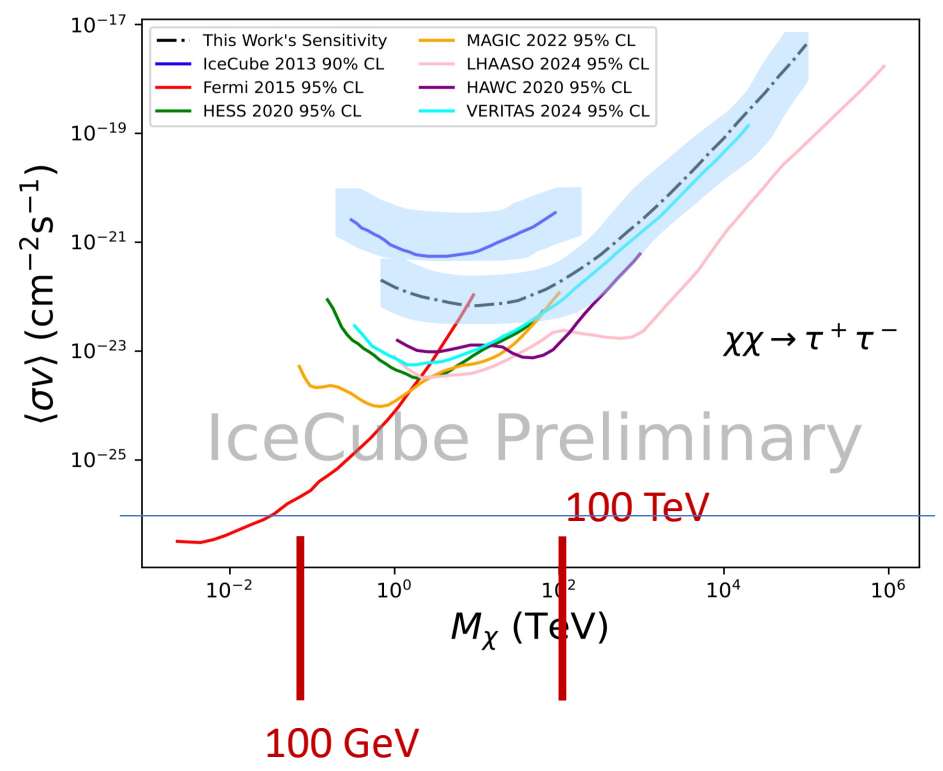
Neutrinos: high DM masses

Galactic halo



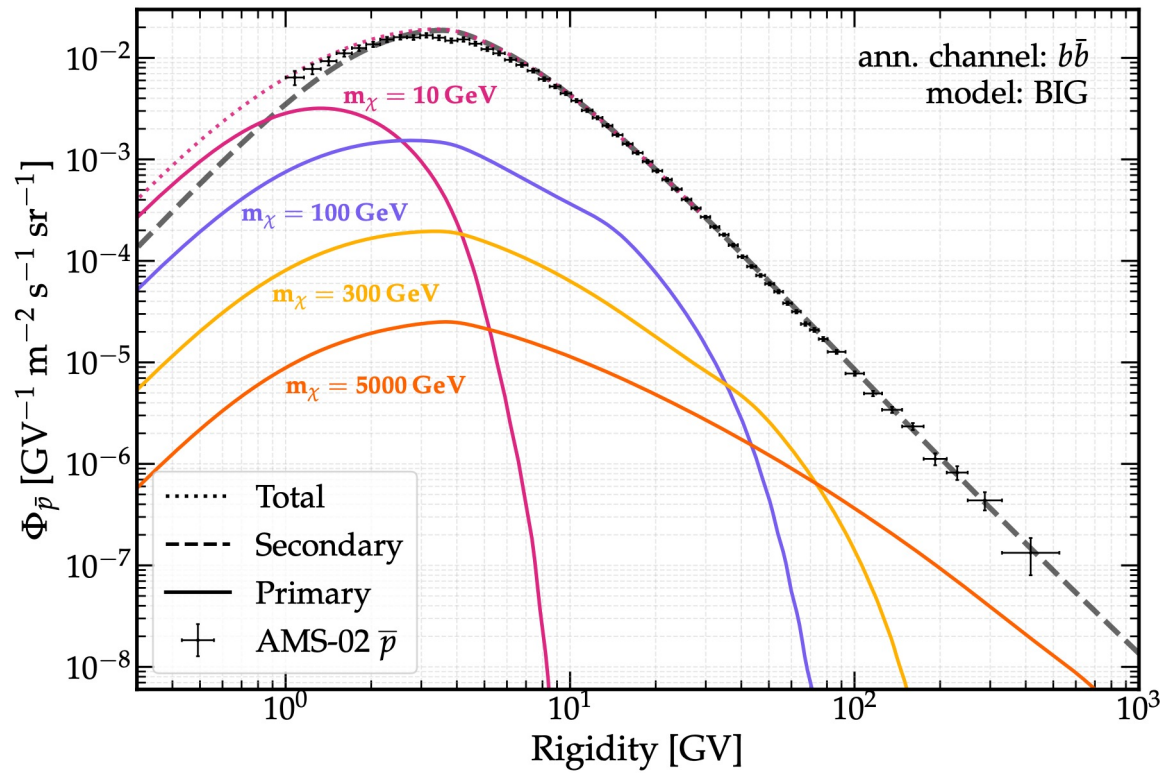
Abbasi+, 2205.12950

Dwarf galaxies

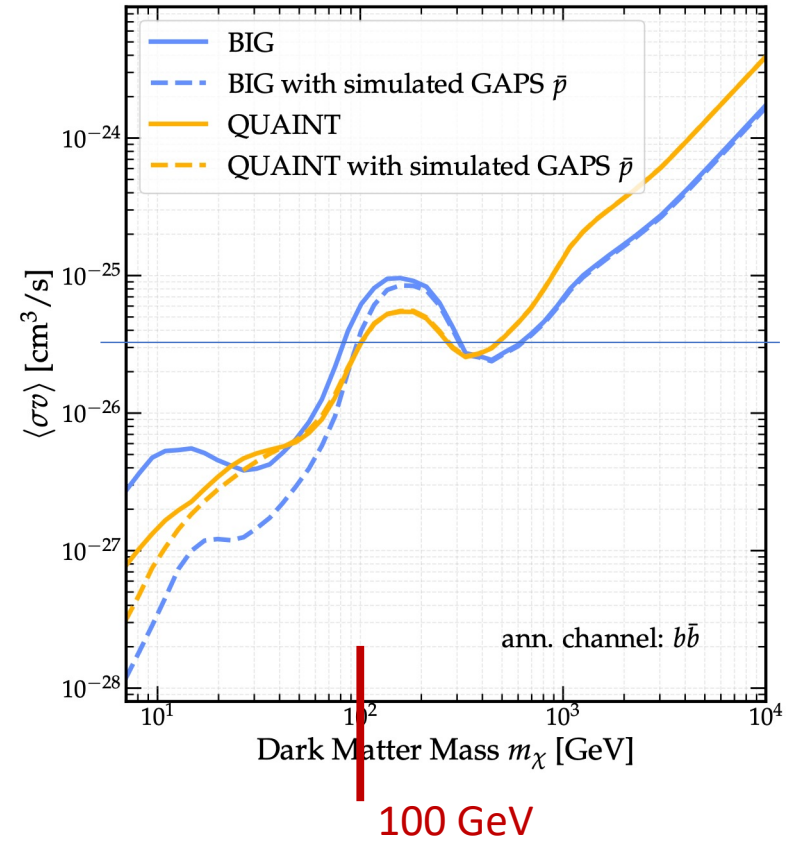


Abbasi+, PoS (ICRC2025) 523

Antiprotons

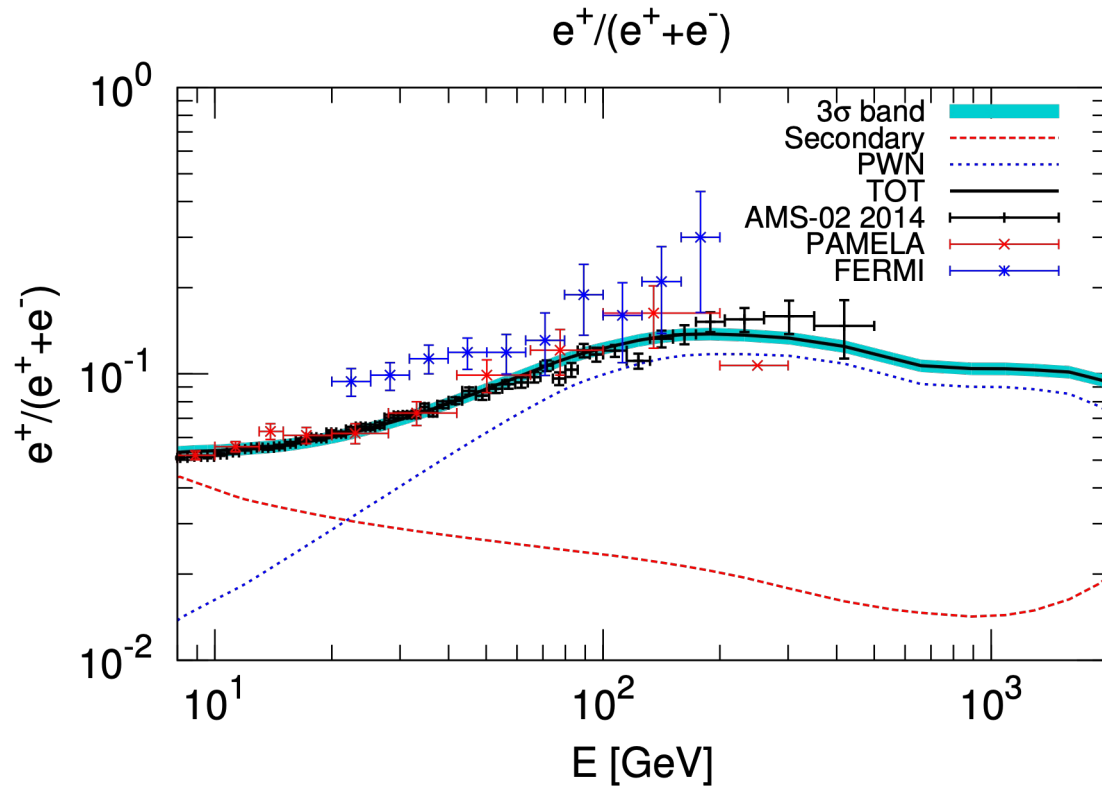


Antiproton flux at Earth

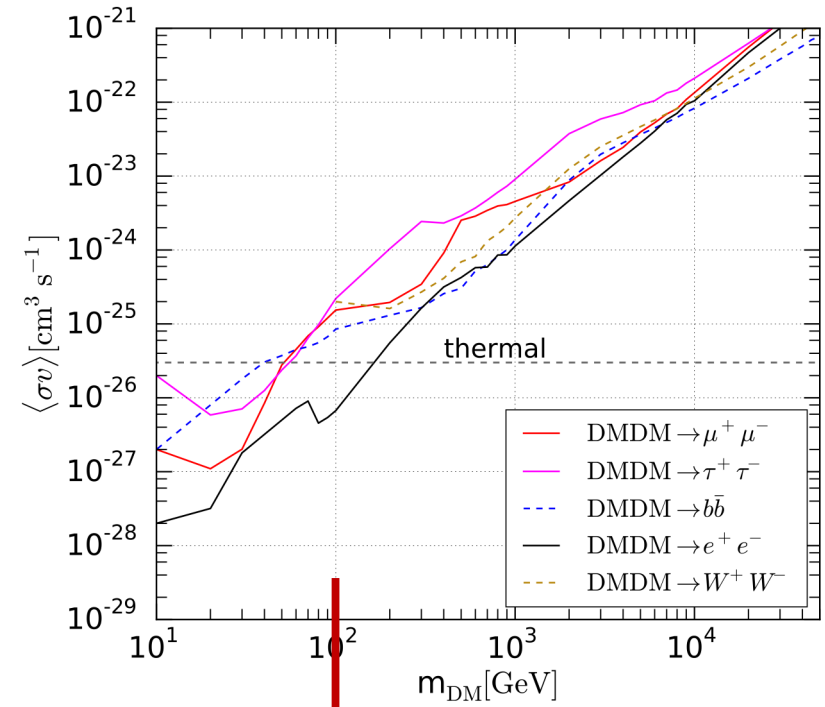


DM bounds

Positrons



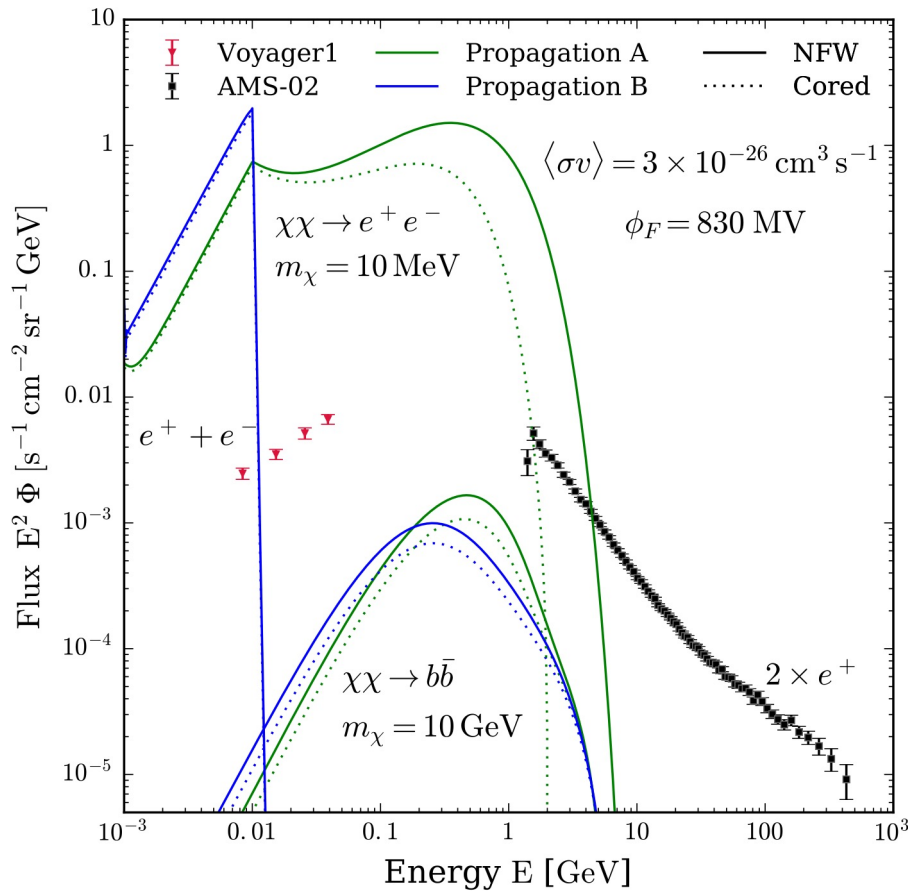
Positron fraction at Earth



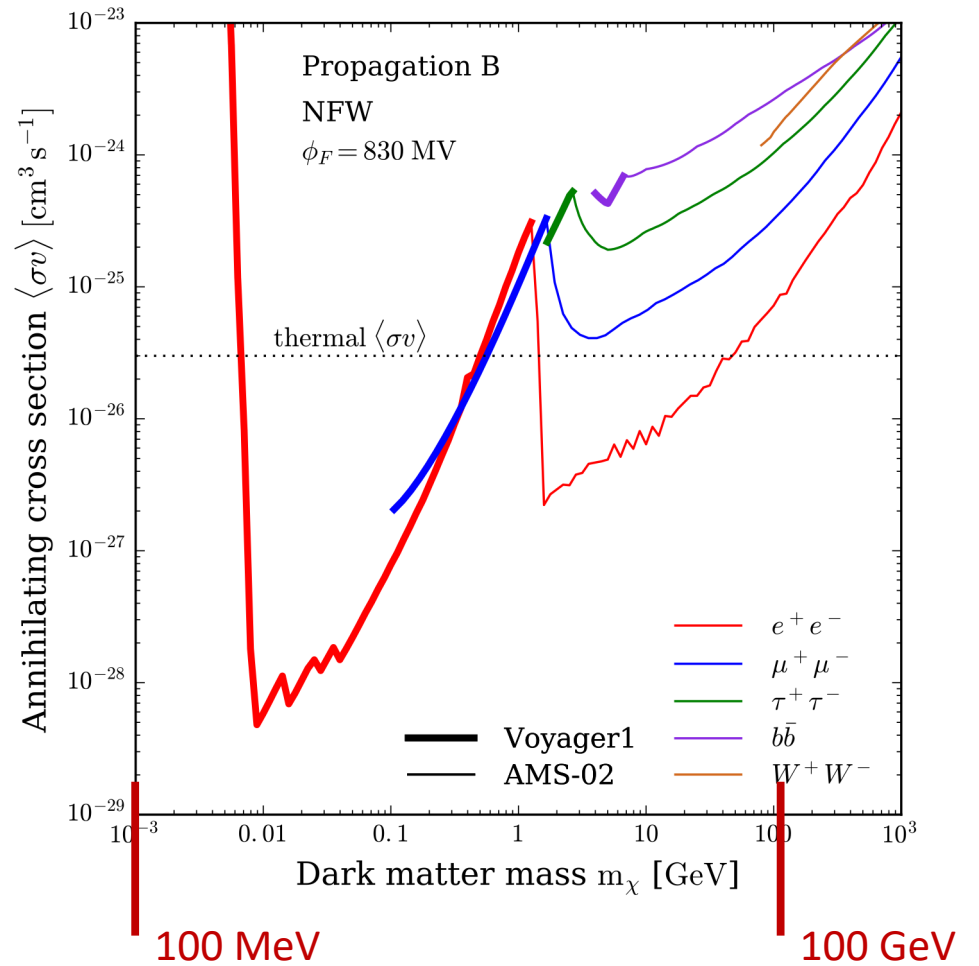
100 GeV

DM bounds

Positrons – Voyager data



Positron flux



DM bounds

Tools at hand

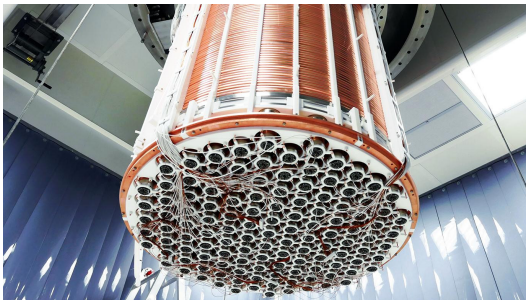
Cosmic messengers

- DM can inject high/low-energy particles (messengers) into cosmological environments (our Galaxy, external galaxies, clusters, filaments, voids):
 - Decay | annihilation | conversion if a particle
 - Evaporation or accretion if a PBH
- Messengers might be **reprocessed** during their travel to us
- Dark matter itself can be the origin of “cosmic messengers reprocessing” (e.g.: ALP birefringence, gamma-ray hardening through ALPs)
- **Complex system** of signals
- Typically dominant **astrophysical backgrounds**
- Probe **DM interactions** with itself and visible sector
- Multi-messenger and multi-wavelength **correlations**
- **Correlations** with cosmological surveys

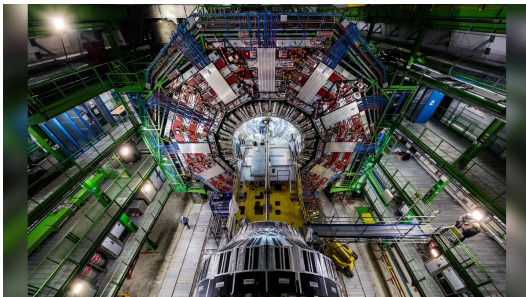
Tools at hand

Experiments in the Lab

- **Passive but directly probe DM:** direct detection, haloscopes, helioscopes



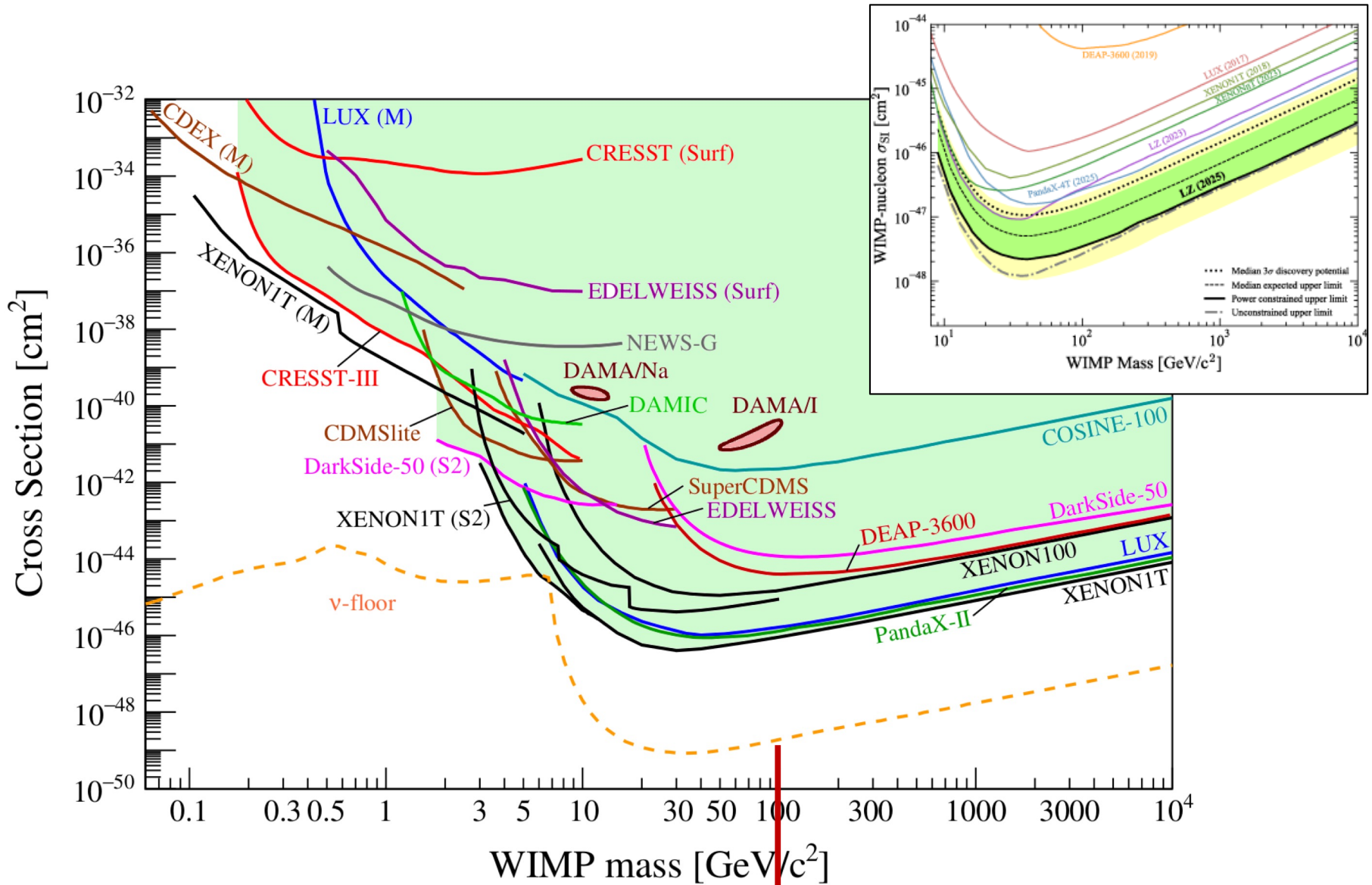
- **Active but indirect:** production at high energy accelerators | high intensity beams | axion lab experiments



Direct detection: bounds

Aalbers+
PRL 153 (2025) 011802

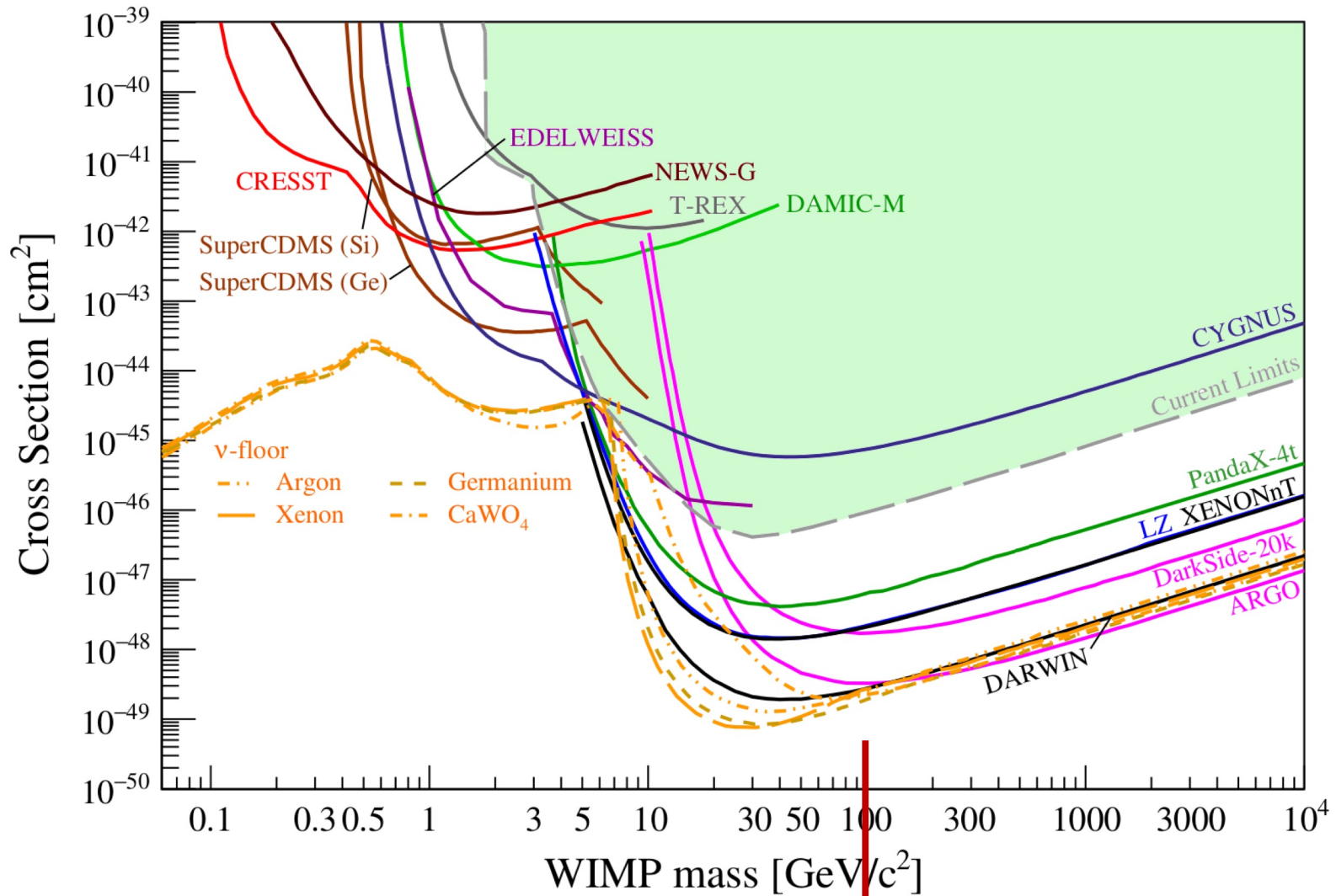
Scattering cross section with matter



100 GeV

Billard+, 2104.07634

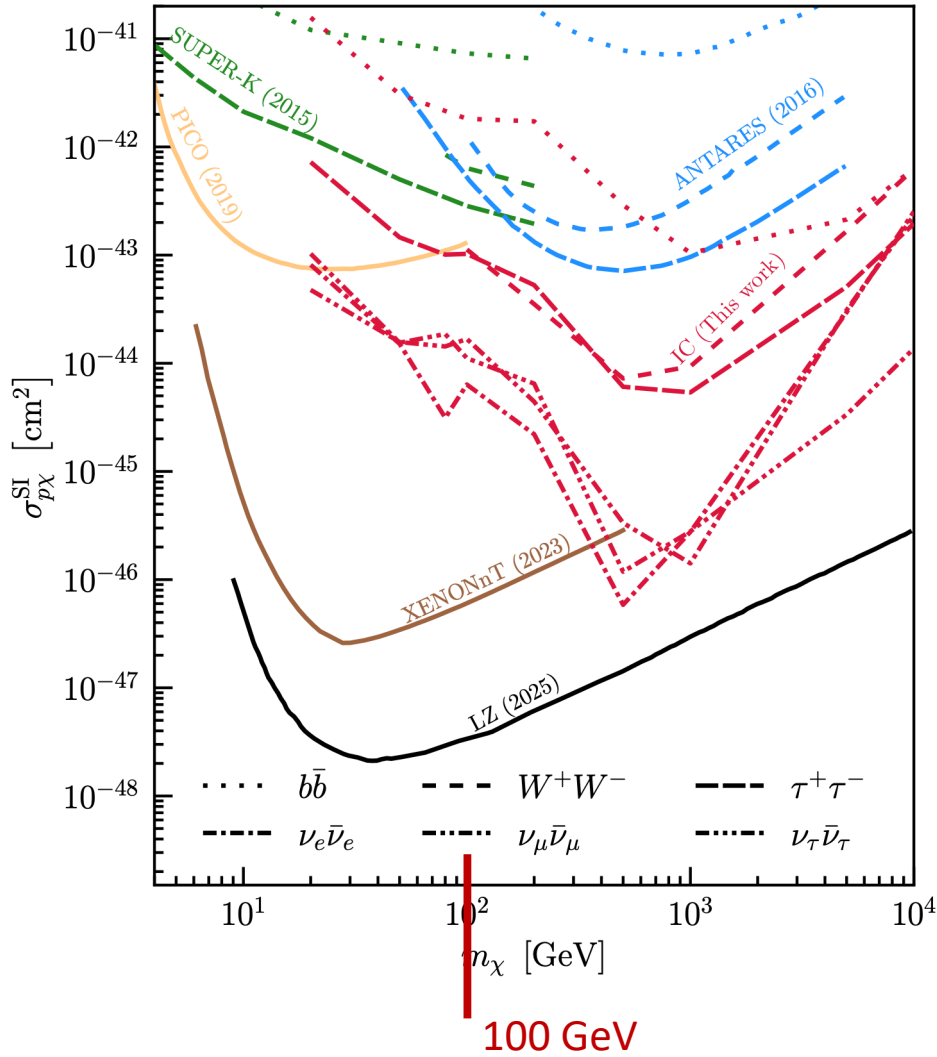
Direct detection: prospects



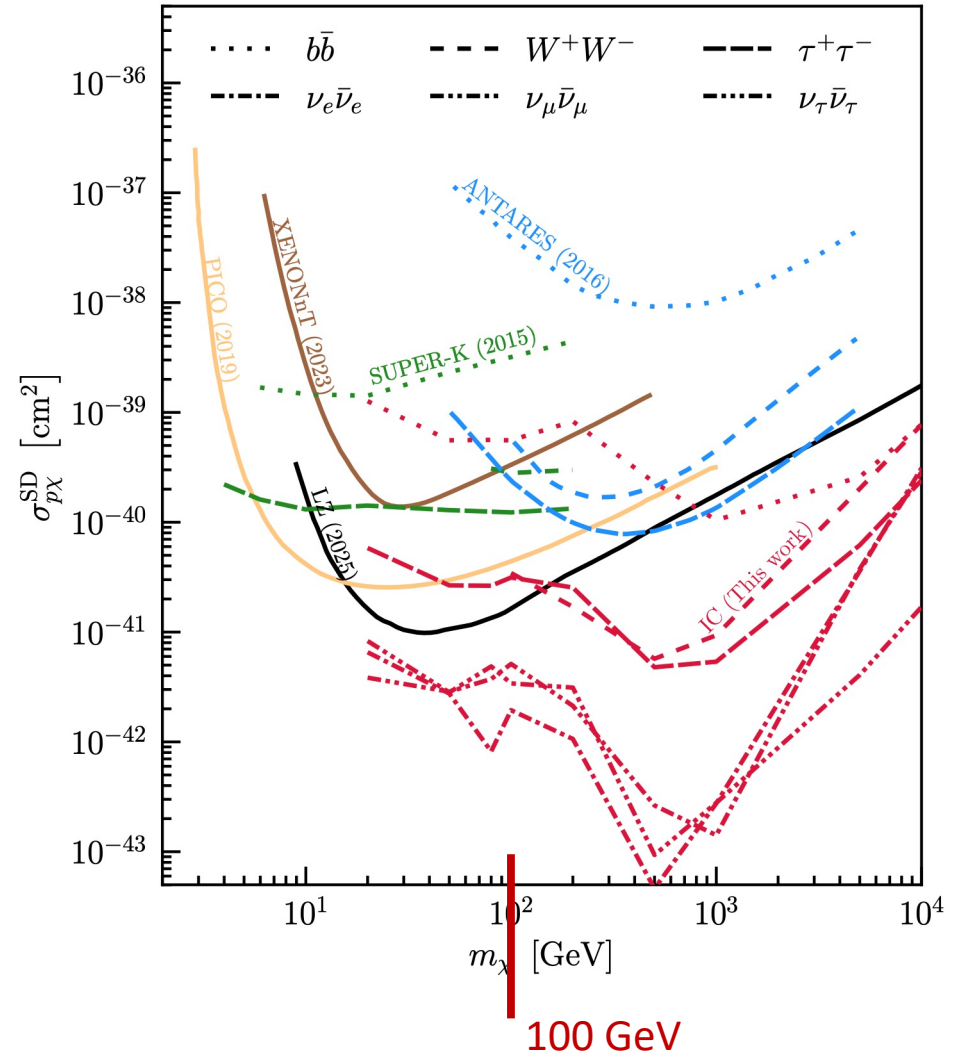
100 GeV

Neutrinos: Sun

Scattering cross section with matter (not annihilation)

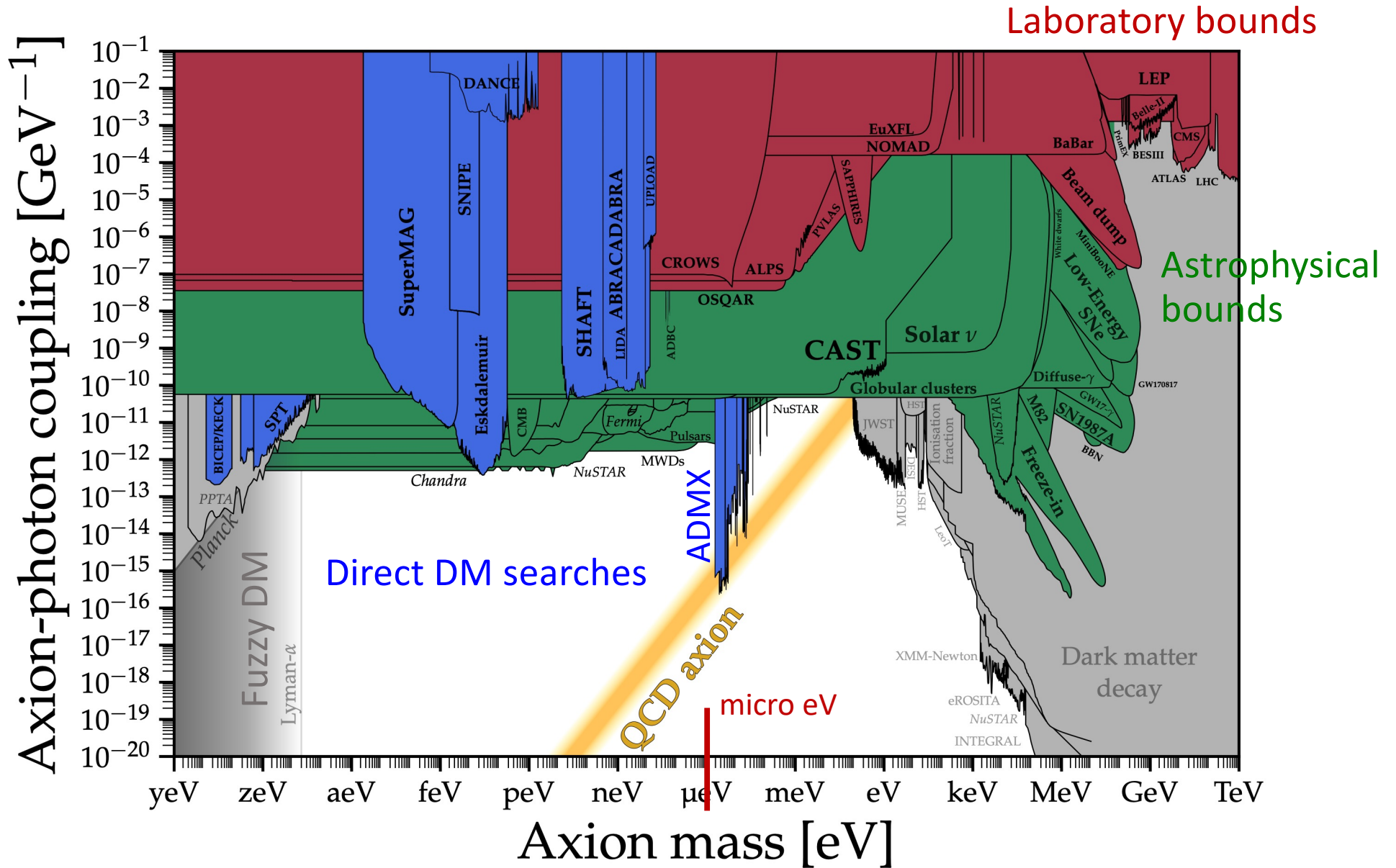


Spin in dependent (coherent)



Spin dependent

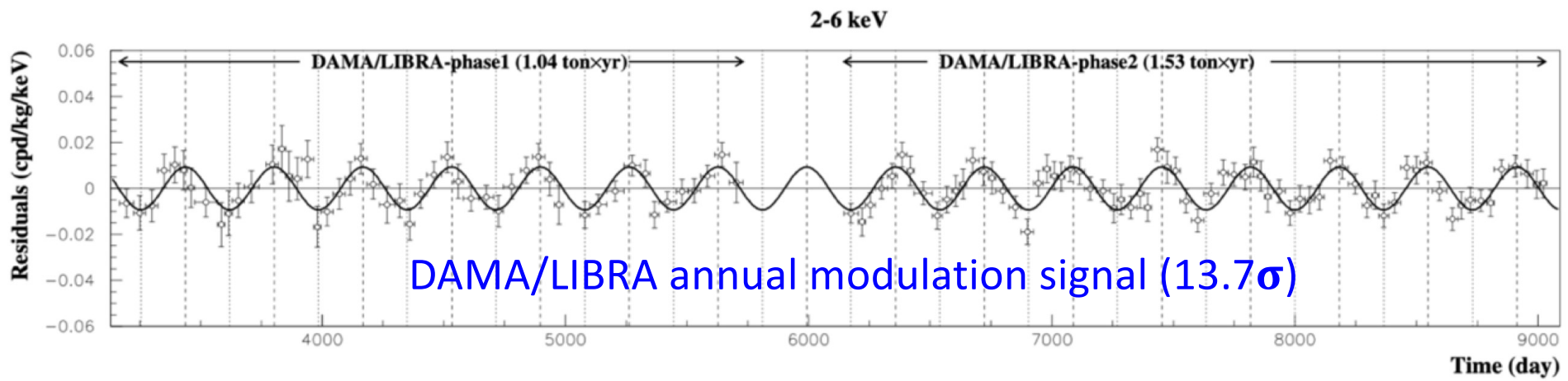
Axions and ALP searches



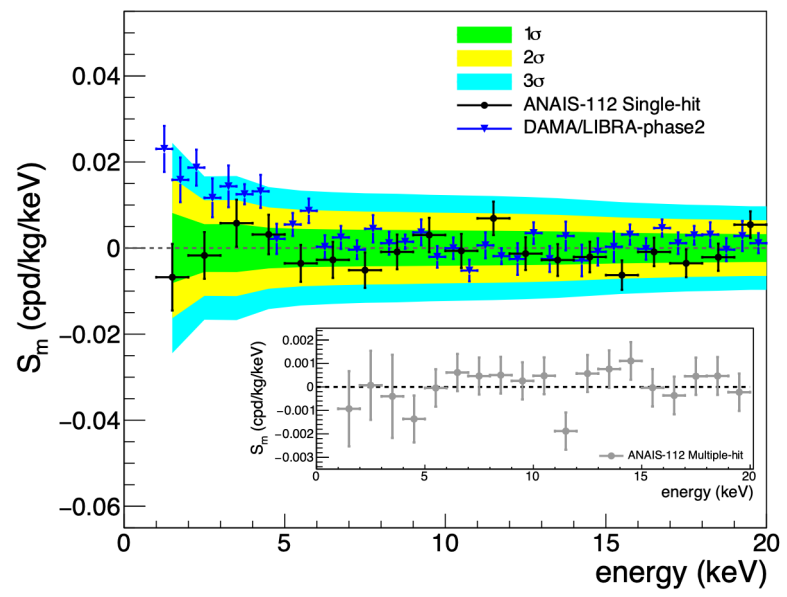
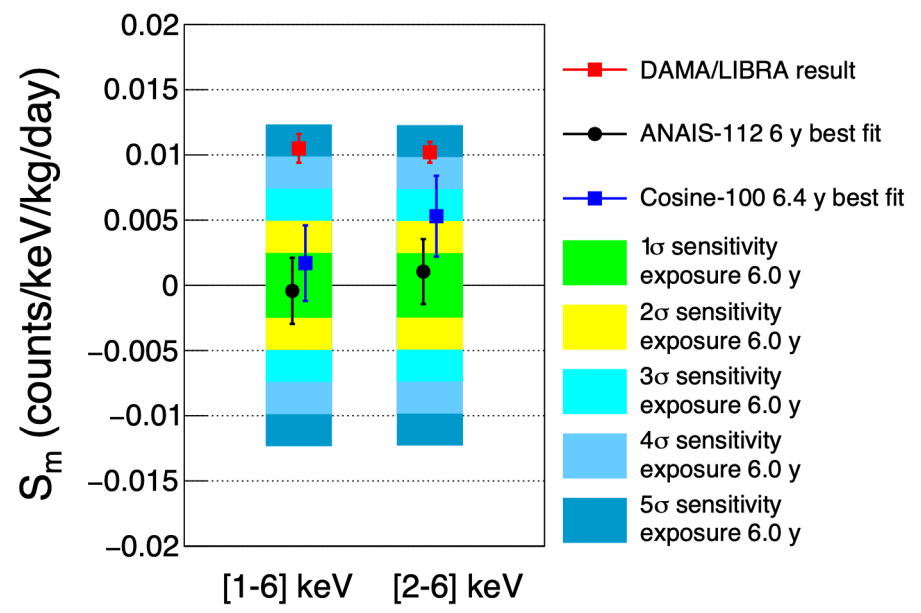
Opportunities

- Do we have clear **signatures** for astrophysical | lab signals? How **clear** are them?
 - **Direct detection**: annual/diurnal modulation | directionality

Direct detection: modulation

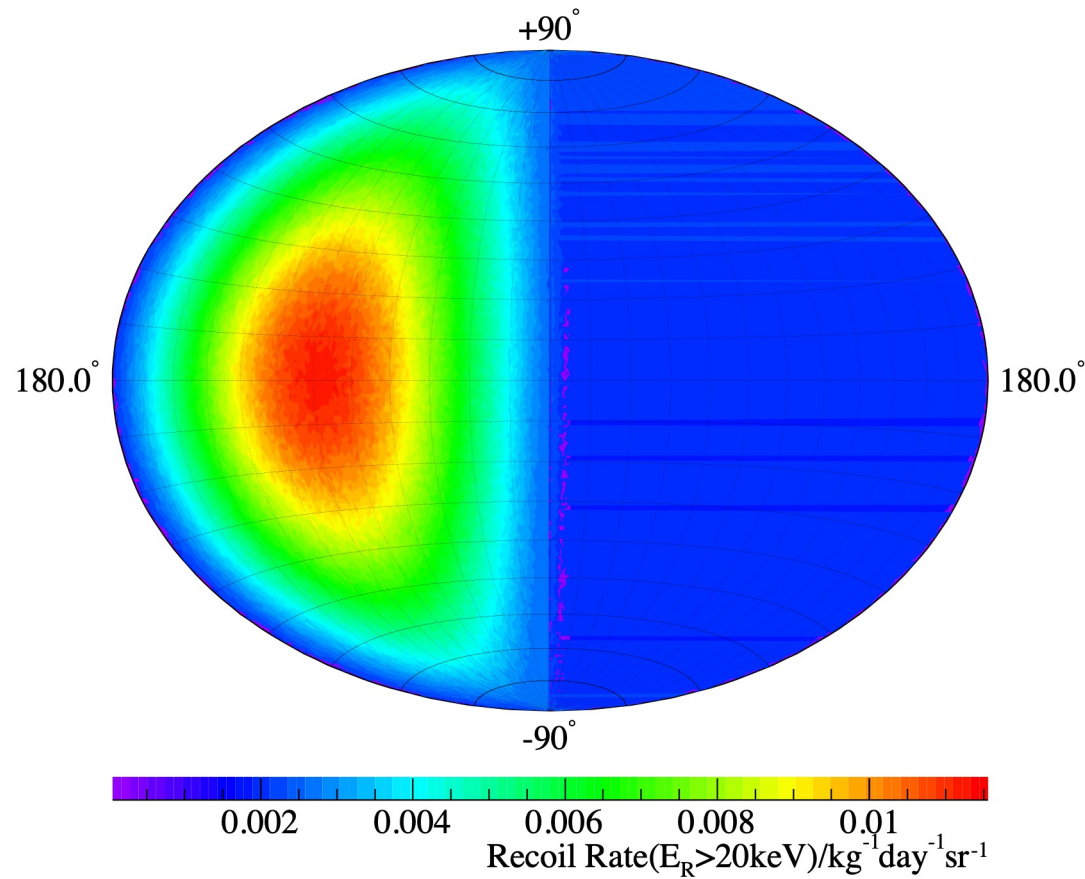


Bernabei+, Nucl. Phys. At. Energy 2021



Amaré+, 2502.01542

Direct detection: directionality



CYGNO
NEWAGE
MIMAC
NEWSdm

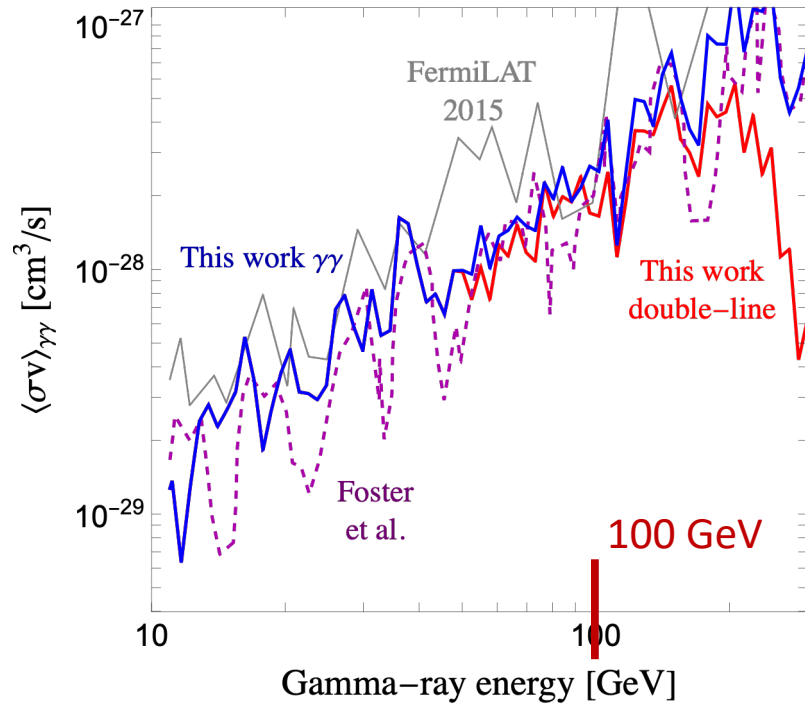
Green+, astro-ph/0609115

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 - **Direct detection**: annual/diurnal modulation | directionality
 - **Indirect searches**:
 - Photon **lines** (axion, WIMPs) in all bands (radio, IR, UV, X, gamma)
 - Low-energy **AntiD**, **antiHe**
 - Other?

Photon lines

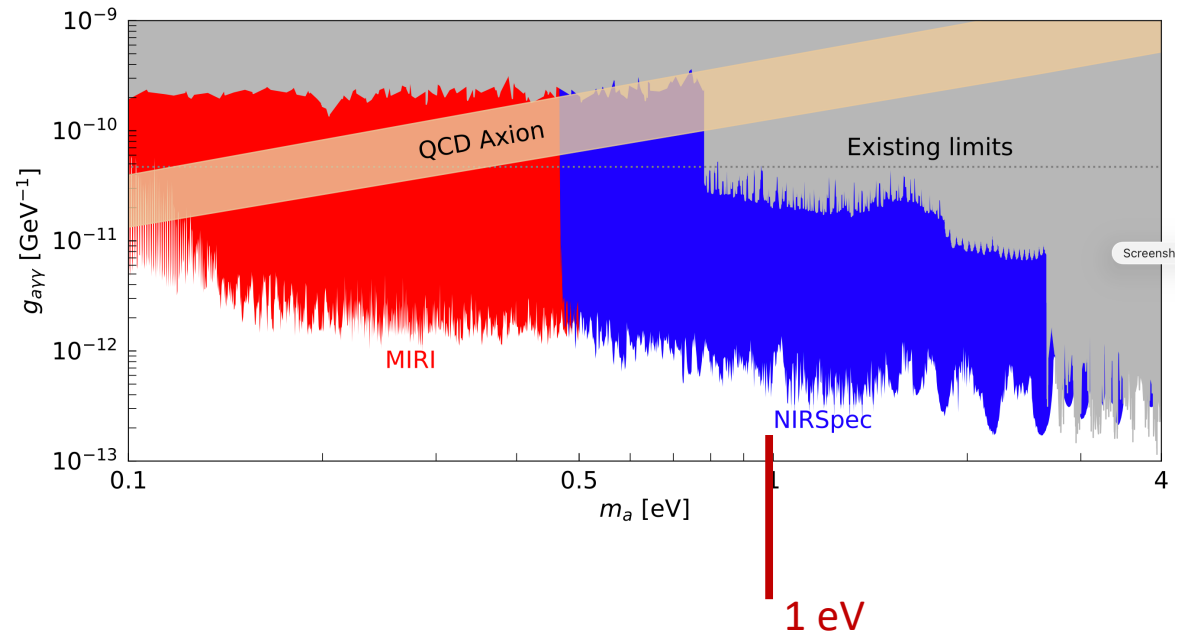
Gamma rays – Bounds on WIMPs



Fermi-LAT

De La Torre+, 2309.03281

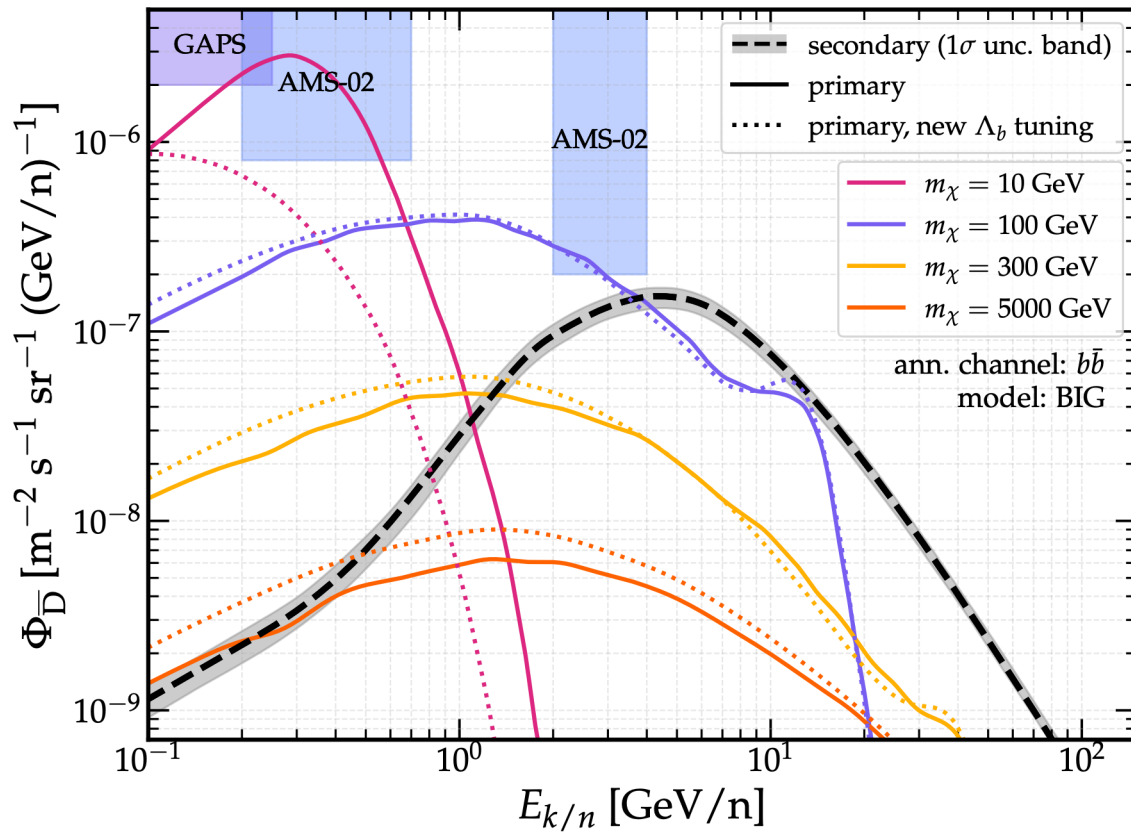
Infrared – Bounds on ALPs



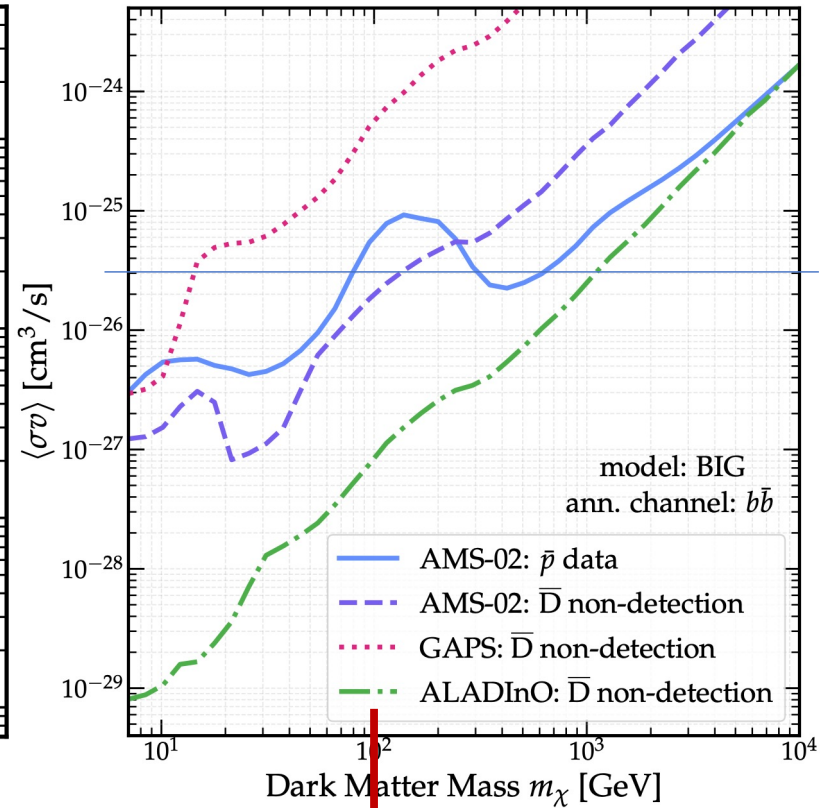
JWST MIRI and NIRISpec blank-sky observations

Pinetti+, 2503.11753

Antideuterons



Antideuteron flux at Earth
up to 1-3 events in GAPS/AMS



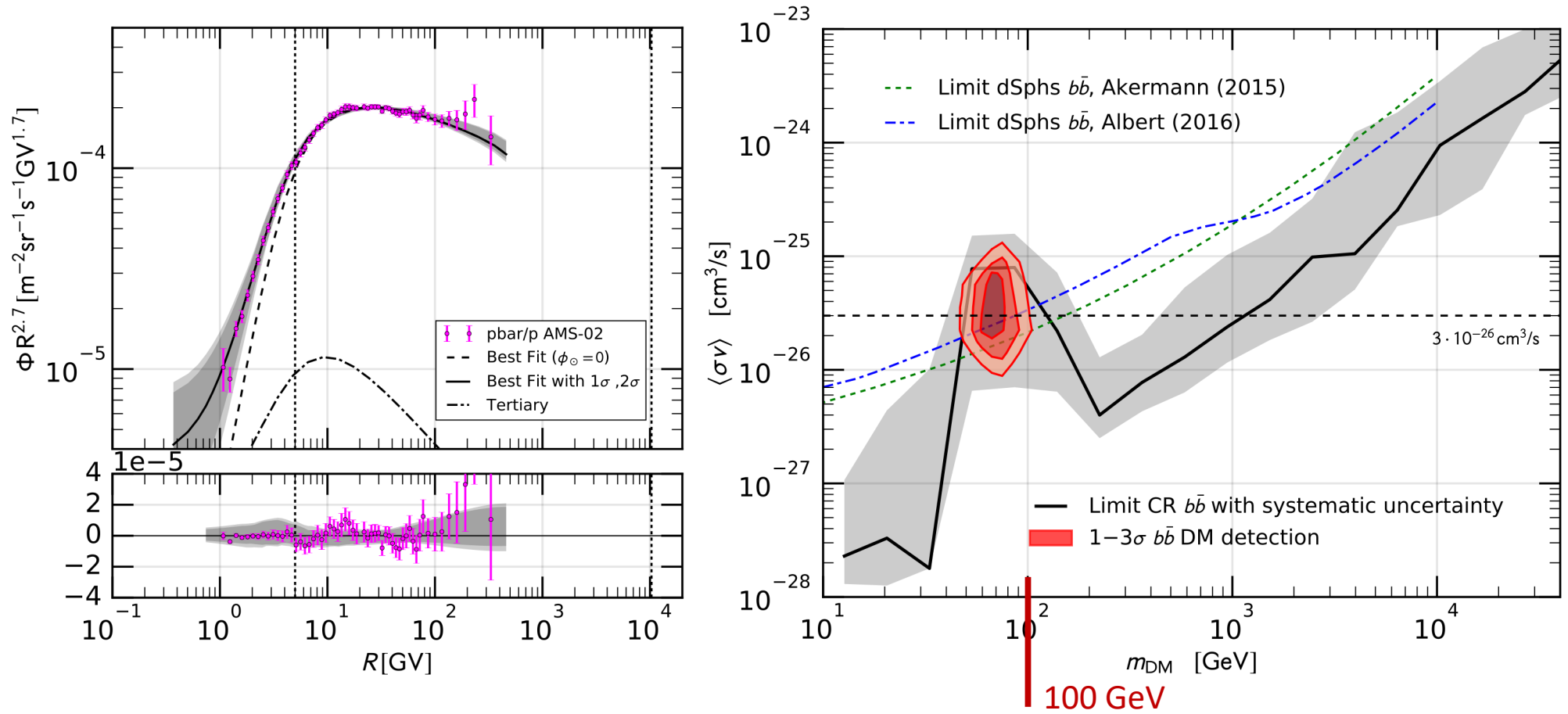
100 GeV

DM bounds

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- **Spectral | morphological distortions | excesses** are enough?
 - Antiproton** few GeV excess (spectral)
 - Gamma-ray galactic center** excess (morphological with spectral info)
 - ARCADE** radio excess (size)
 - Positron** “excess” (spectral – likely pulsars)
 - CMB, ionization** history

Antiproton “excess”

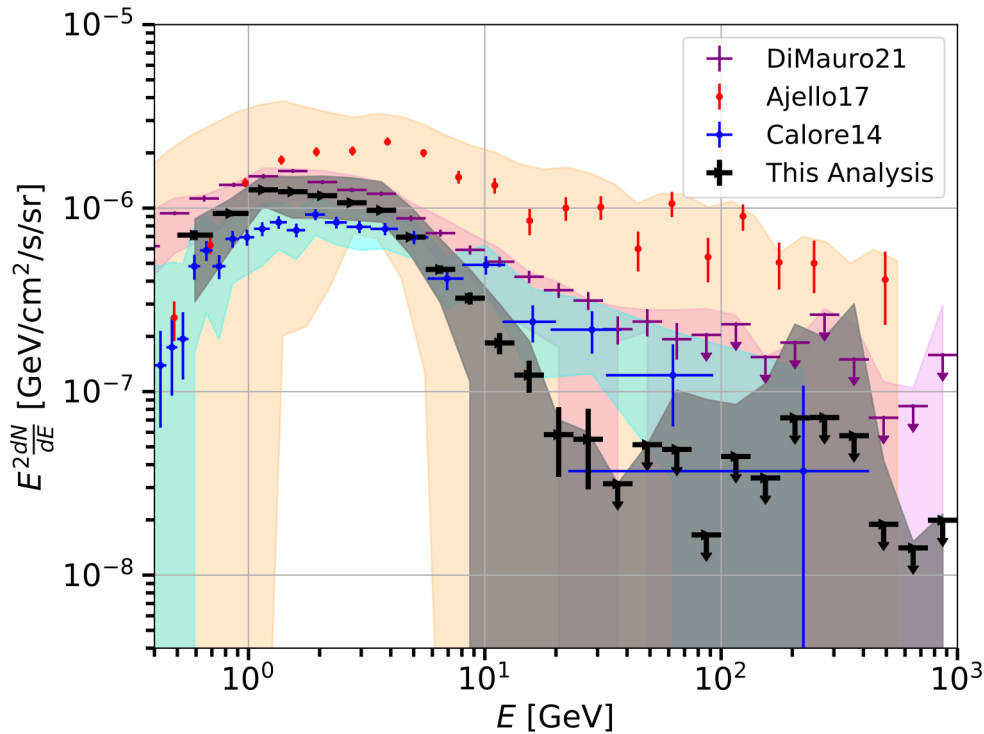


Cuoco+, 1610.03071

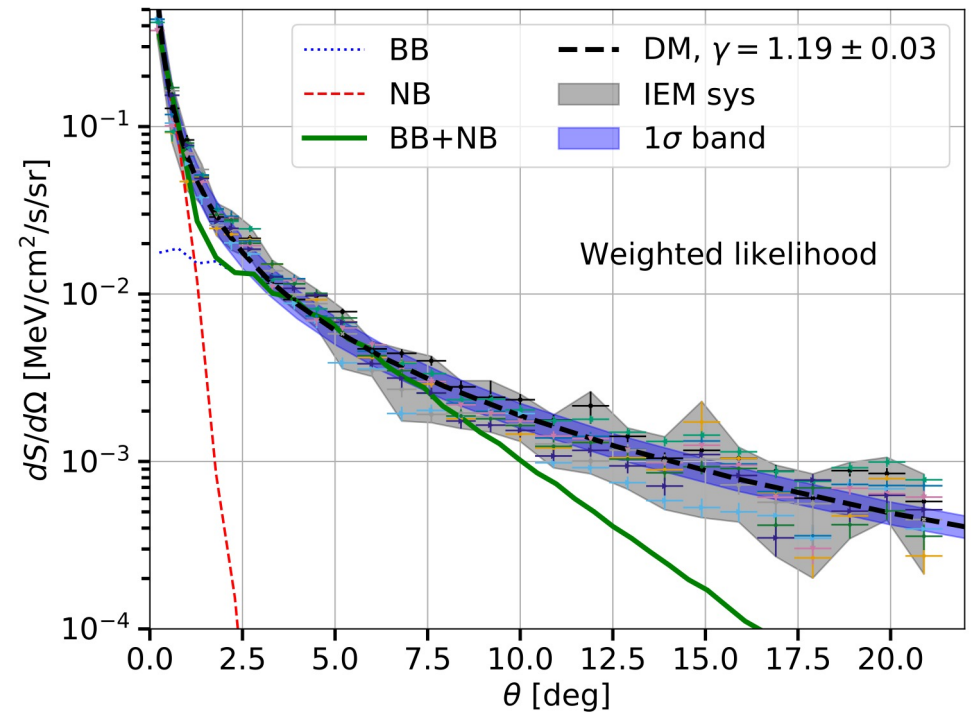
Recent analysis: max 2σ (global)

Calore+, 2202.03076

Galactic center gamma-ray “excess”

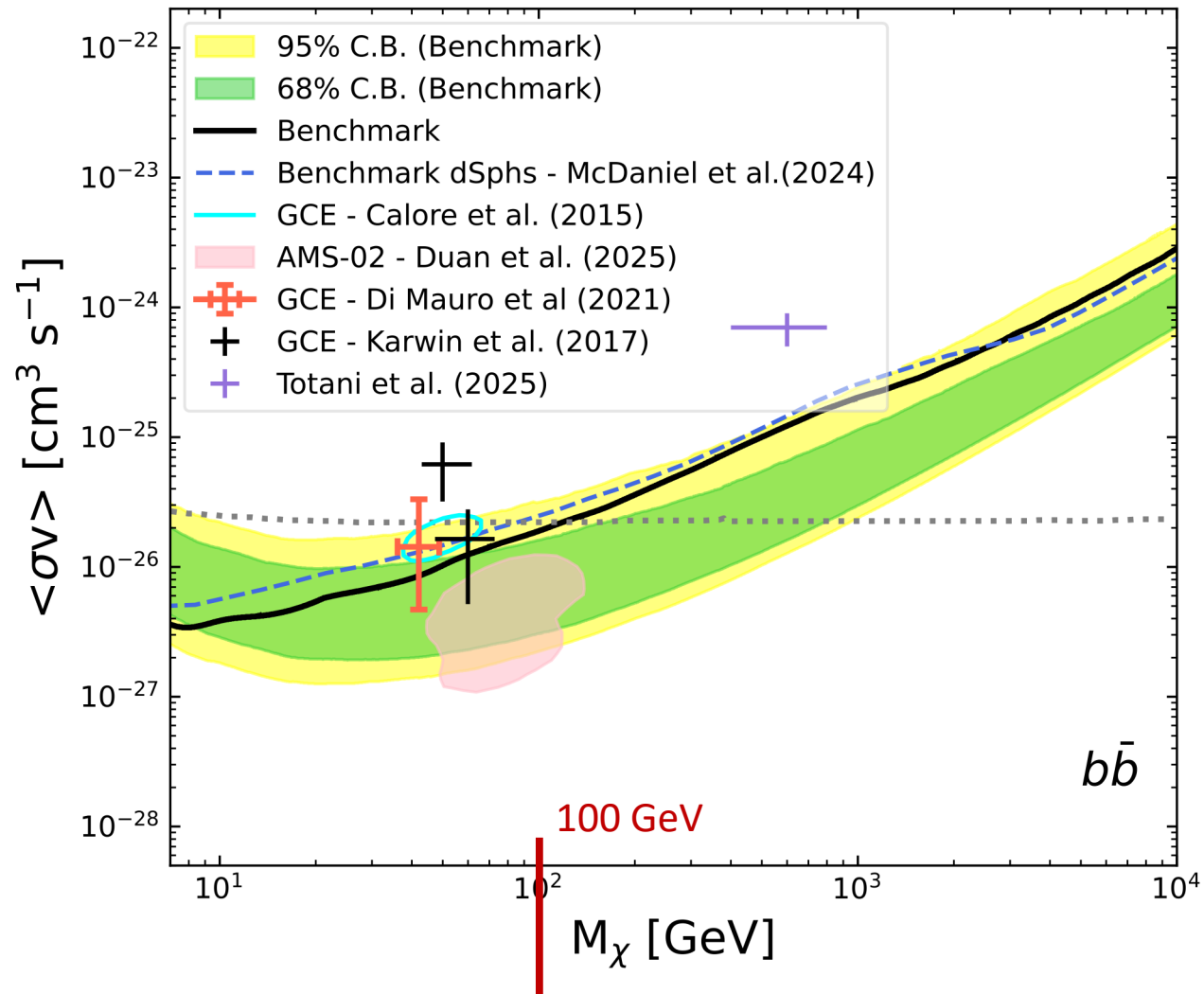


Energy spectrum

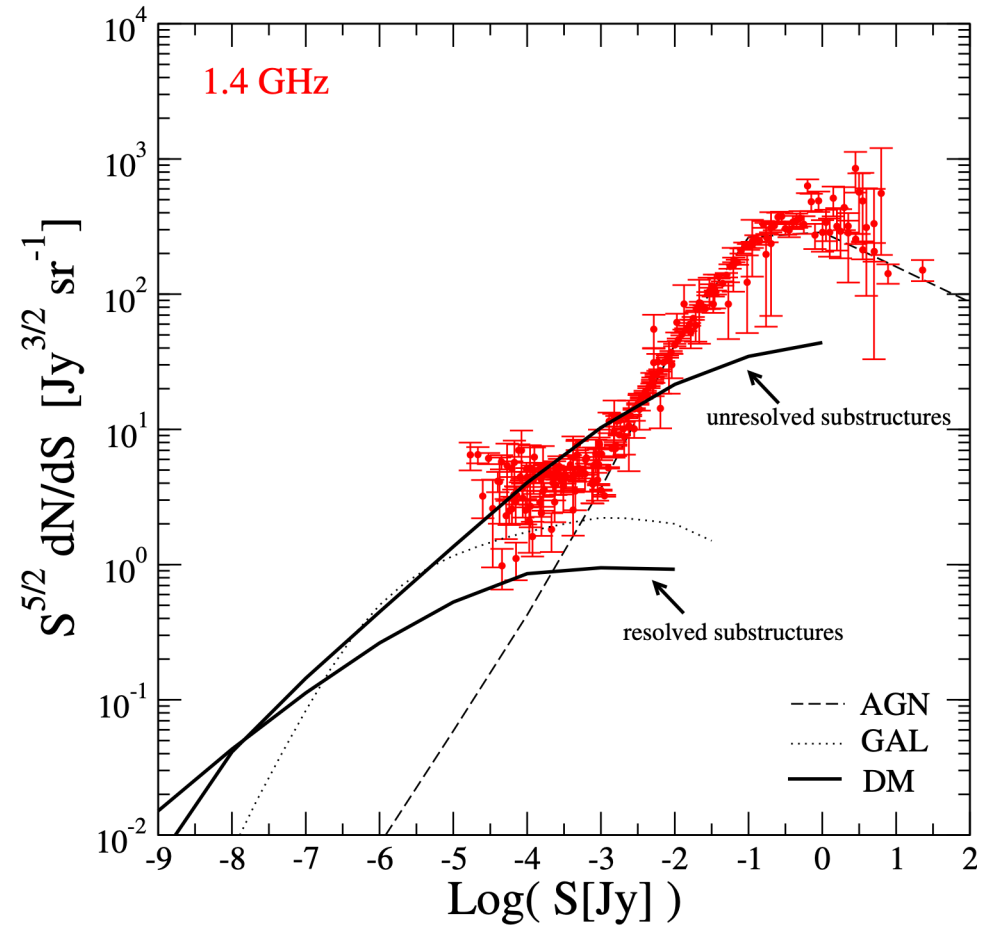
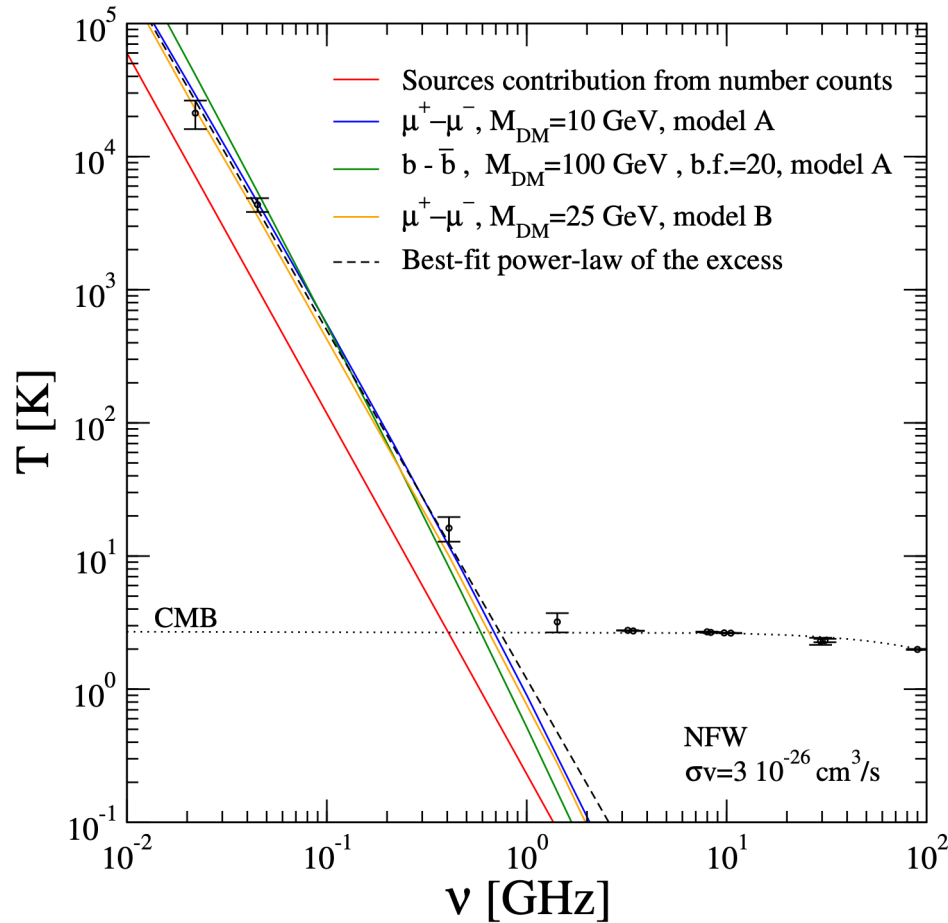


Angular profile

Galactic center gamma-ray “excess”



ARCADE radio "excess"



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- How to better control astrophysical **backgrounds | foregrounds**?

Opportunities

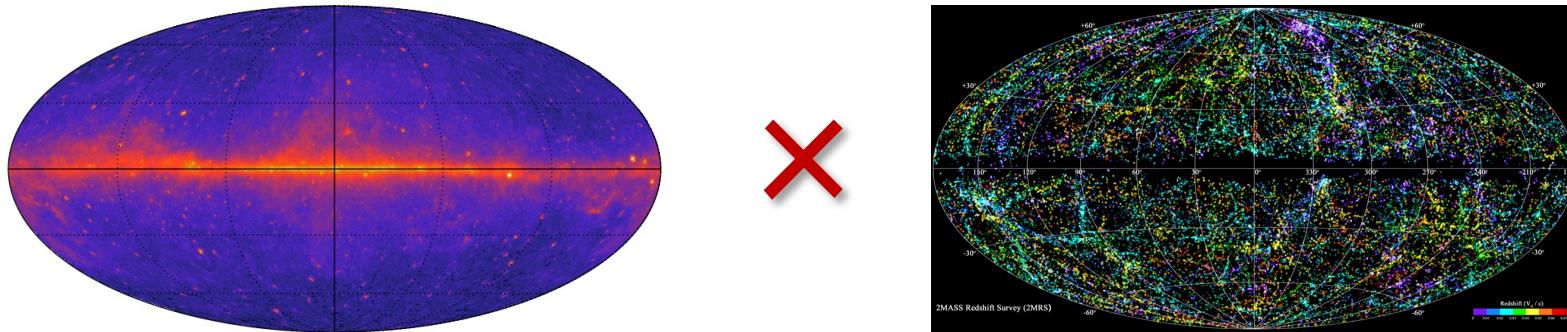
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- How to better control astrophysical **backgrounds | foregrounds**?
- Are there **windows** that are still not properly exploited (e.g. **MeV gap**)? **Gravitational waves** are a new window of opportunity for DM?
- How relevant is to exploit **statistical correlations** among signals? Not just redundancy, explicit correlations (**radiation fields**) x (**gravitational probes**)

(full multi-wavelength/messenger) x (LSS, voids, lensing)

Cross correlations



The fluctuations in the cosmic radiation fields need to be **statistically correlated** to the DM distribution in the universe

This **cross-correlation** is a statistical observable (it allows to infer **global information**, not identify individual sources) and exploits in a unified way two distinctive features of particle DM:

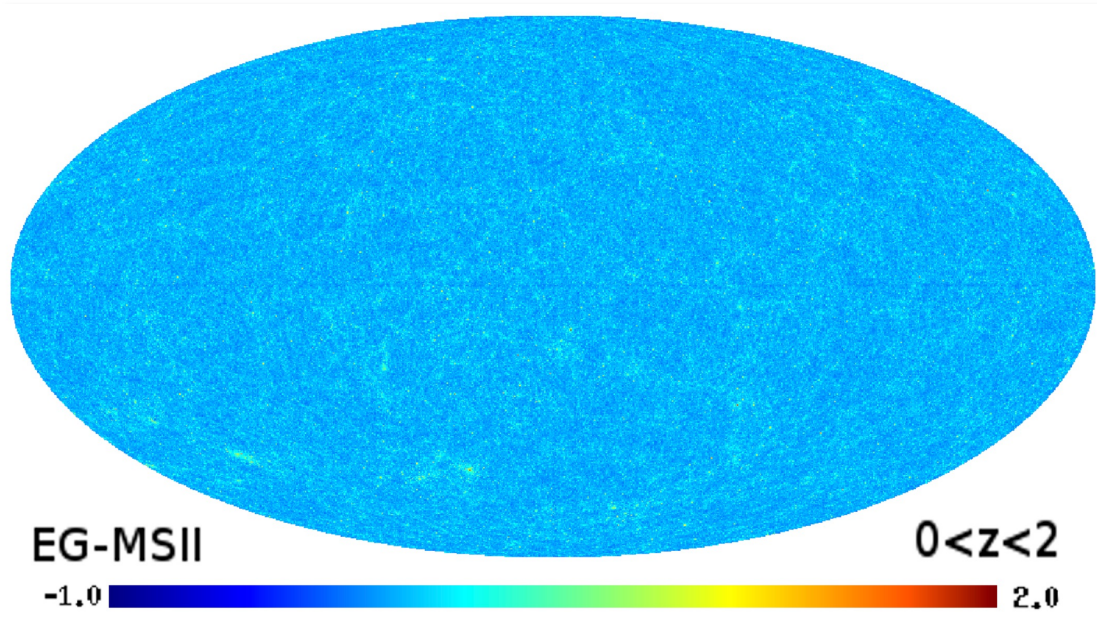
An electromagnetic signal, manifestation of the particle nature of DM

A gravitational probe of the existence of DM

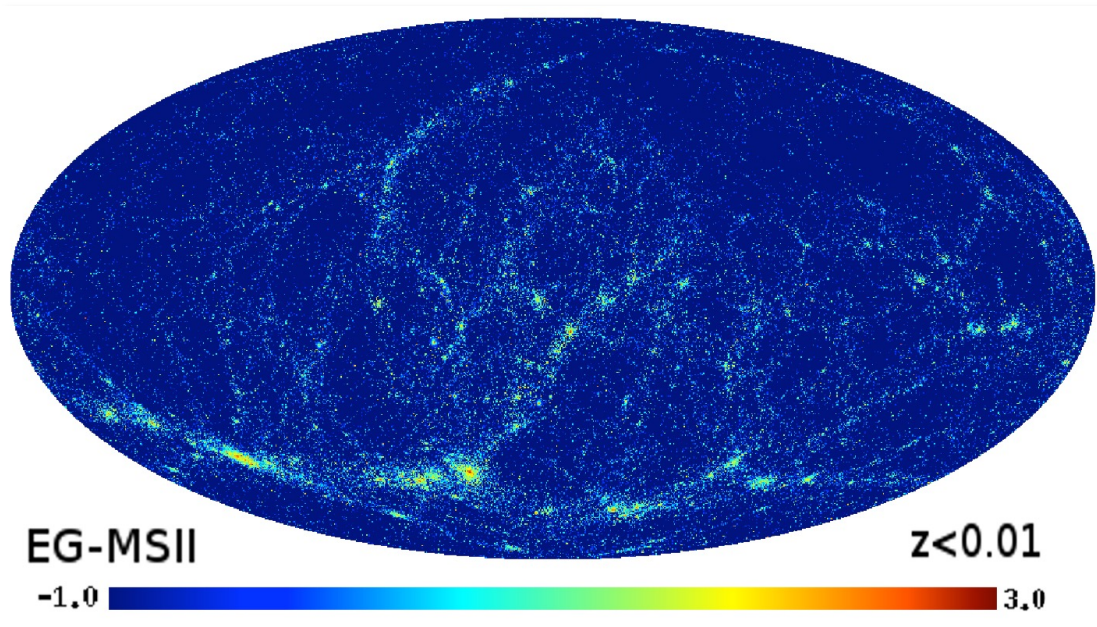
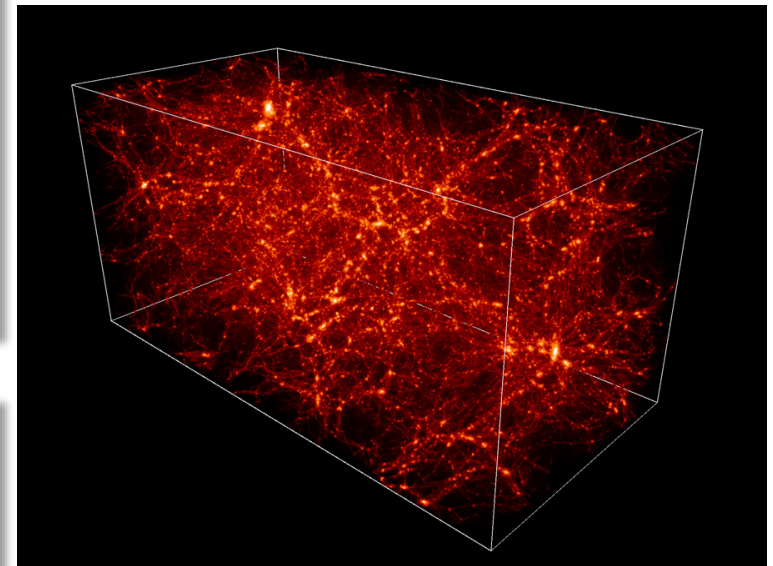
It allows to 'add' distance (redshift) information to a probe (like gamma-rays) that does not have it

Anisotropic DM gamma-ray emission

(simulated maps)



Extra galactic emission
Higher redshift



Extra galactic emission
Lower redshift

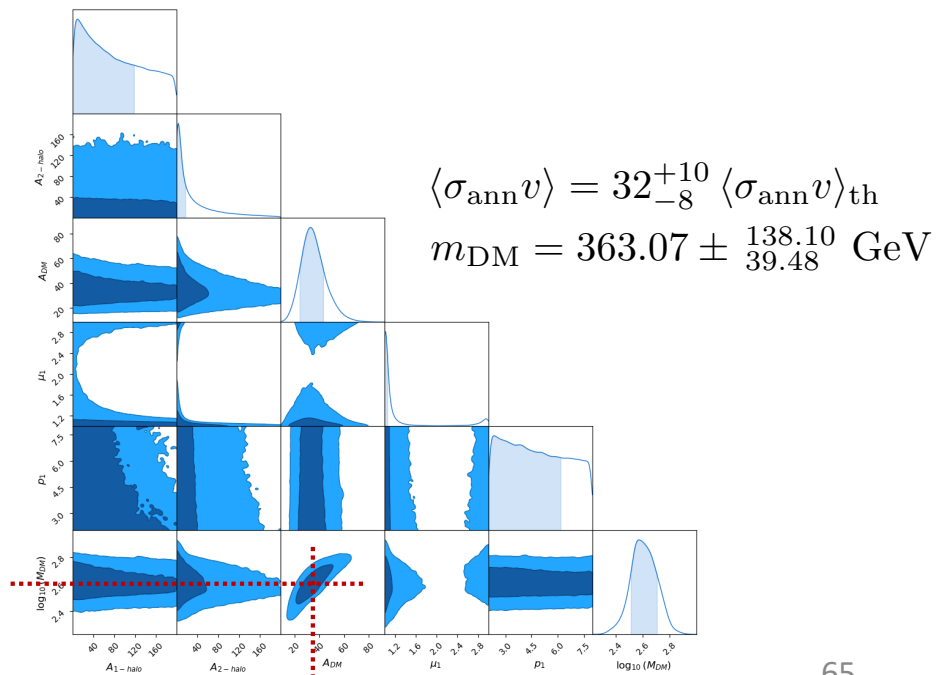
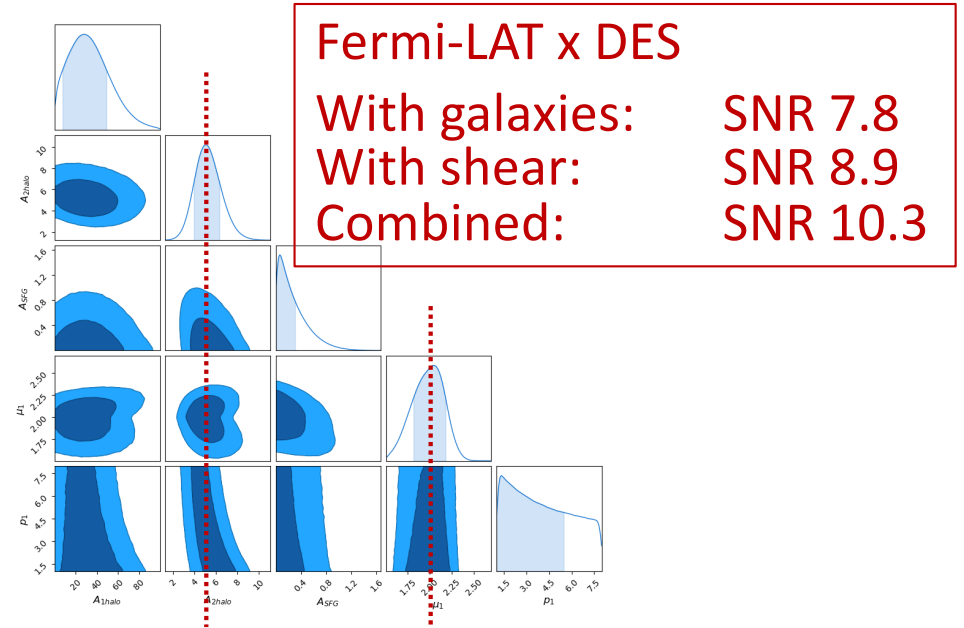
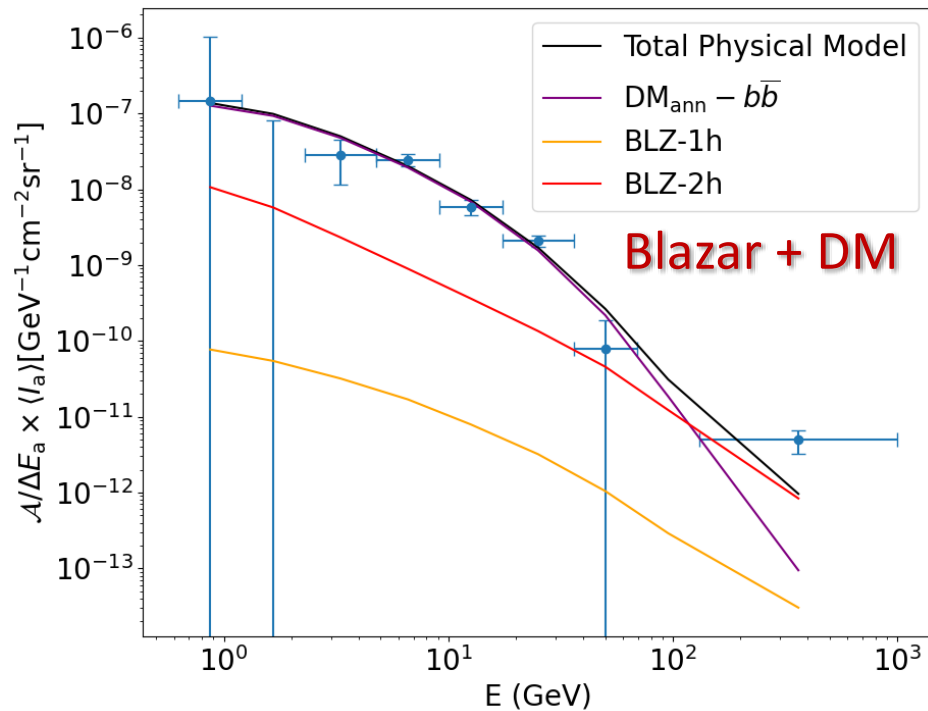
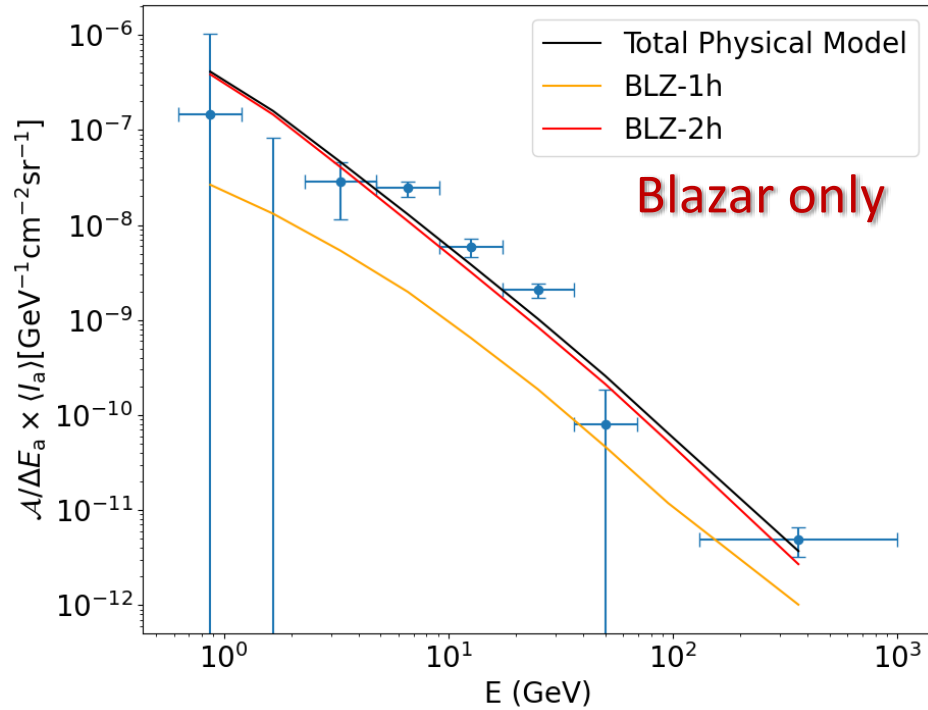
Cross-Correlations w/ Gamma Rays

Lensing observables

- **Cosmic shear**: directly traces the whole DM distribution
Camera, Fornasa, NF, Regis, ApJLett 771 (2013) L5
Camera, Fornasa, NF, Regis, JCAP 06 (2015) 029
- **CMB lensing**: traces DM imprints on CMB anisotropies
NF, Regis, Frontiers in Physics, 2 (2014) 6
NF, Perotto, Regis, Camera, Ap. J. Lett. 802 (2015) 1 L1

Large scale structure observables:

- **Galaxy catalogs**: trace DM by tracing light
Cuoco, Brandbyge, Hannestad, Haugbolle, Miele, PRD 77 (2008) 123518
Ando, Benoit-Levy, Komatsu, PRD 90 (2014) 023514
NF, Regis, Front. Physics 2 (2014) 6
Ando, JCAP 1410 (2014) 061
- **Cluster catalogs**
Branchini, Camera, Cuoco, NF, Regis, Viel, Xia, ApJS 228 (2017) 1
- **Neutral hydrogen (through HI intensity mapping)**
Pinetti, Camera, NF, Regis, JCAP 07 (2020) 044
- **Cosmic voids**
Arcari, NF, Pinetti, JCAP 11 (2022) 011



Conclusion

- DM evidence is overwhelming but fully gravitational
- Unfortunately, there is **no single and clear** theoretical direction to follow (although there are some guiding principles)
- “Aesthetic” motivations like naturalness for supersymmetry are declining (susy scale progressively pushed up by accelerators searches)
- Even if a new particle is found in a lab experiment, a key challenge will be to confirm that it is **the** DM particle (caveat: DM might **not** be a particle, see PBH or wavy DM – or even modified gravity)
- A **single technique** is currently **insufficient** to probe the vast landscape of viable DM candidates, and this will not change anytime soon – maybe it's not even desirable
- Looking for general features of **classes of dark sectors** (theoretically) and **classes of signals** (phenomenologically and observationally) might be particularly effective: once something is found, more specific model specifications will follow
- Many (although not all) DM scenarios have many **complementary signals** available: this is very captivating and need to be exploited