PPC 2023, IBS, June 12-16 2023

Indirect dark matter: searching for dark matter in the sky

Shunsaku Horiuchi

VIRGINIA TECH

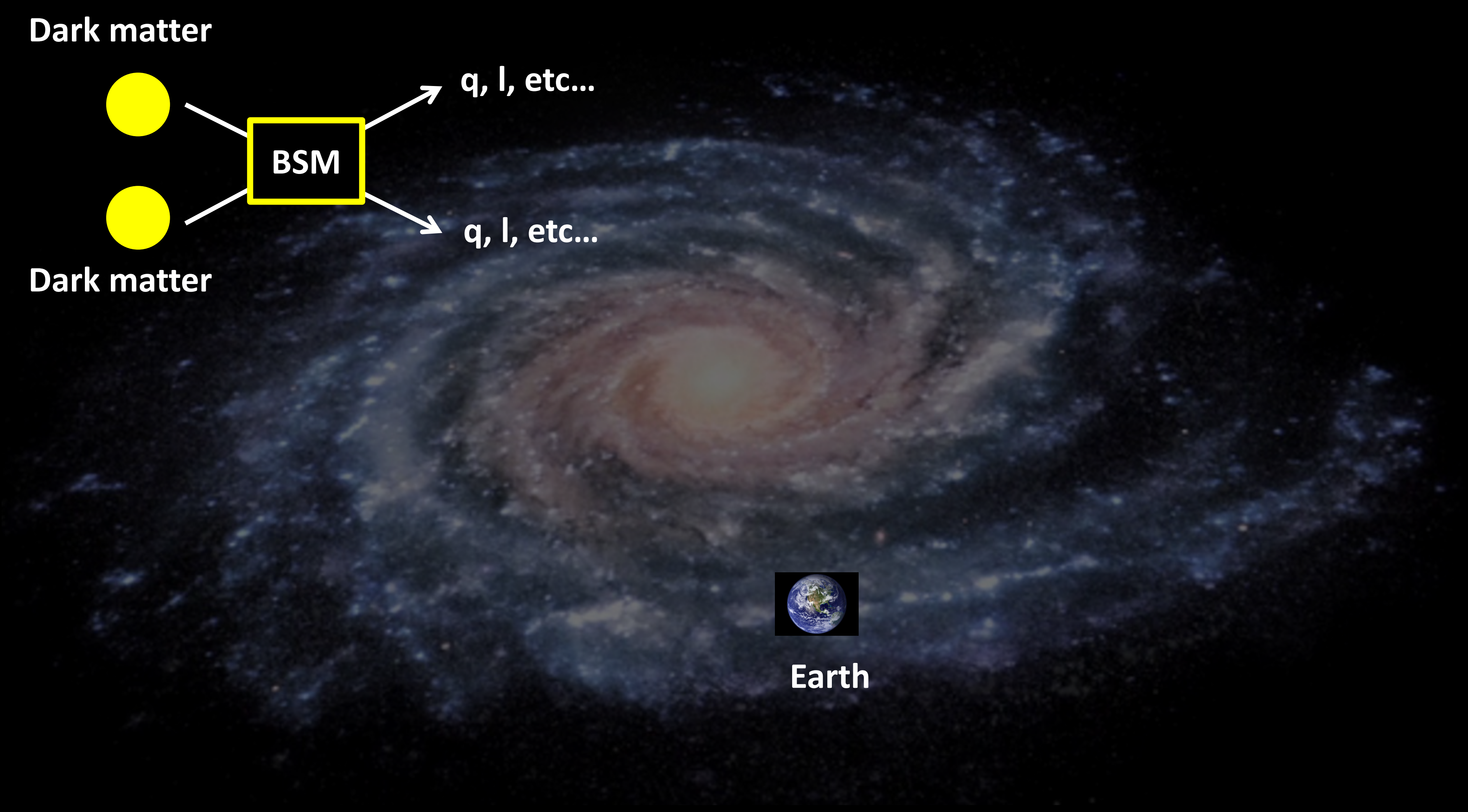
The Center for Neutrino Physics

KAVLI IPMU

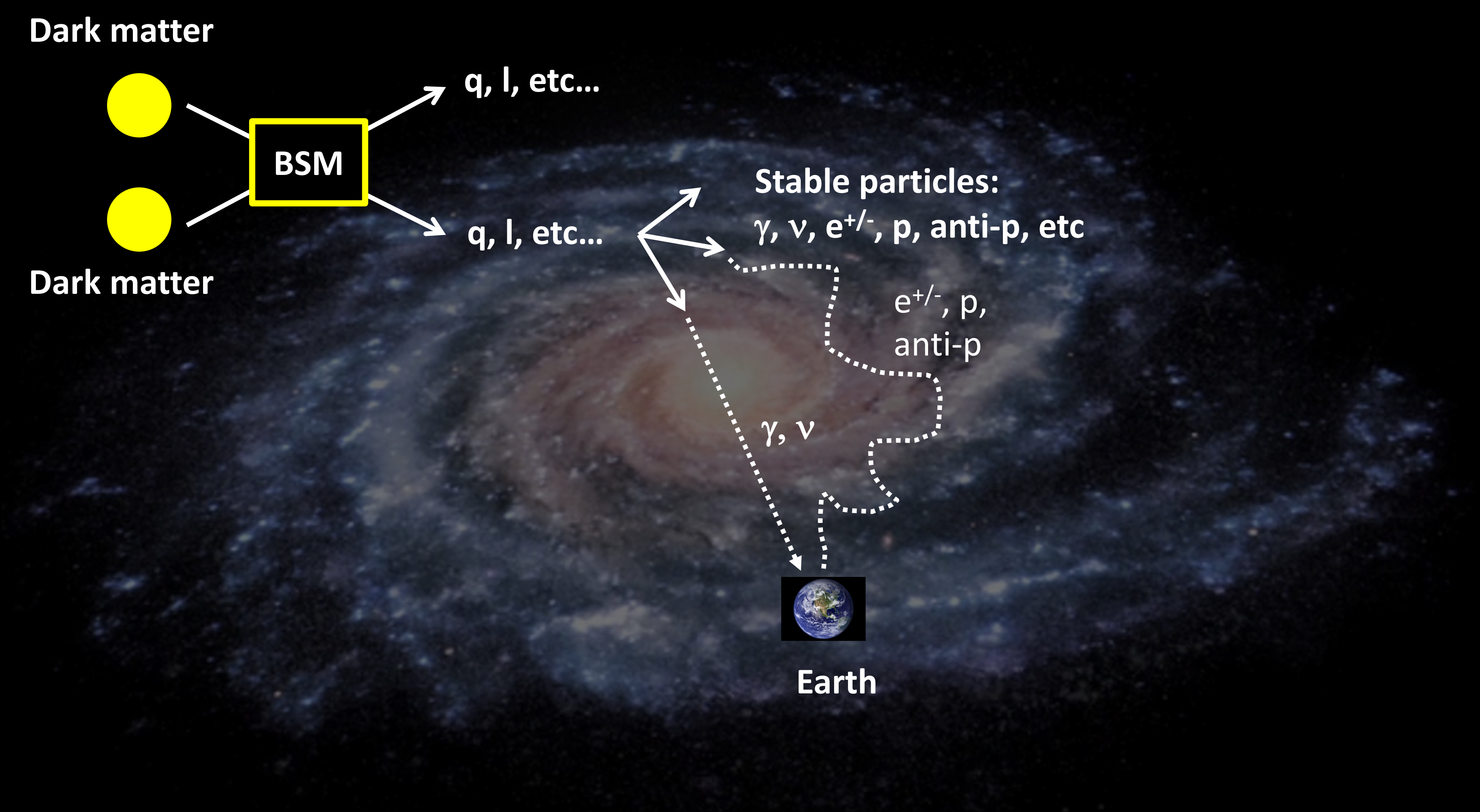
wpi

Overview of indirect searches

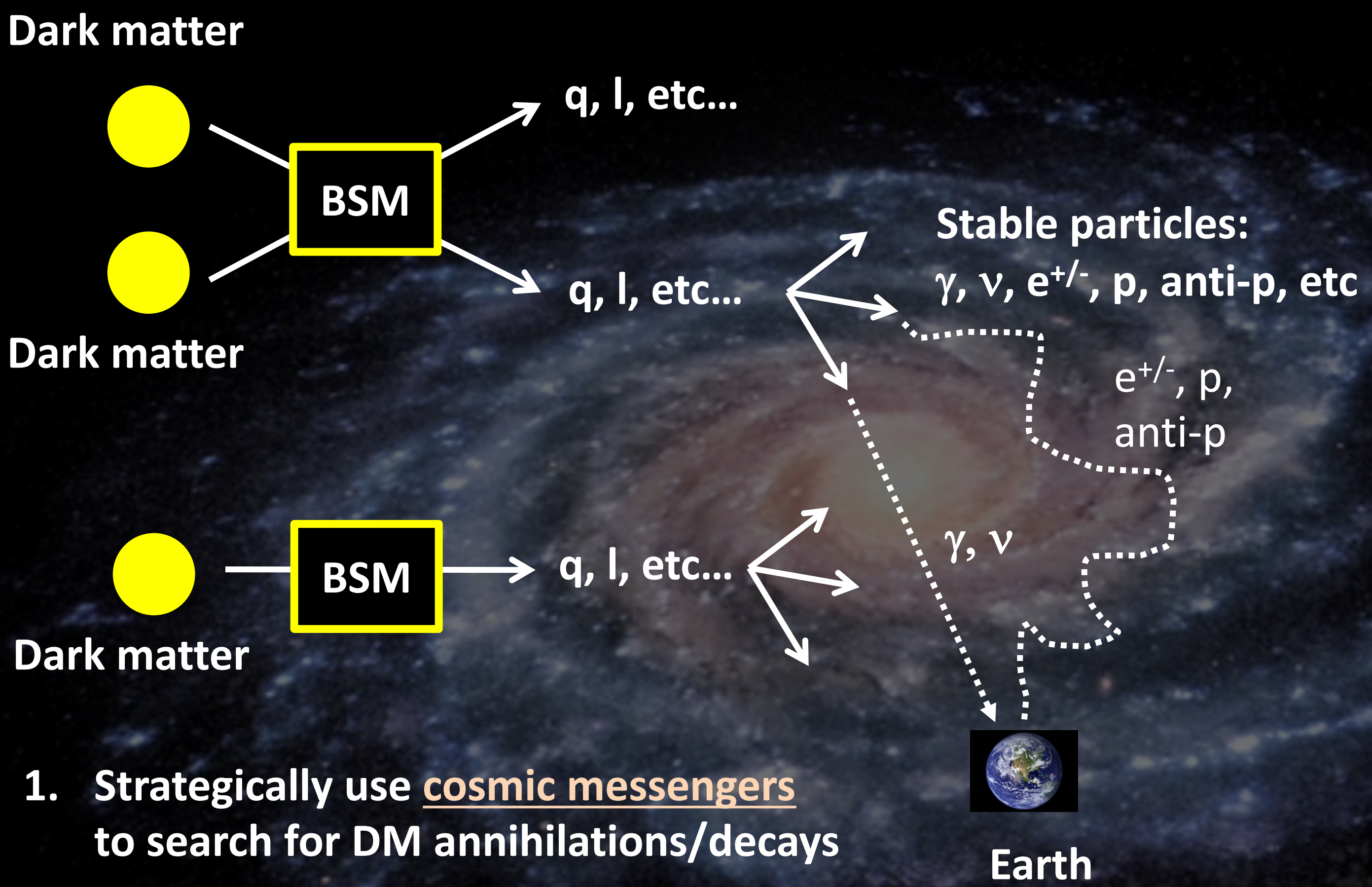
Overview of indirect searches



Overview of indirect searches



Overview of indirect searches



1. Strategically use cosmic messengers to search for DM annihilations/decays

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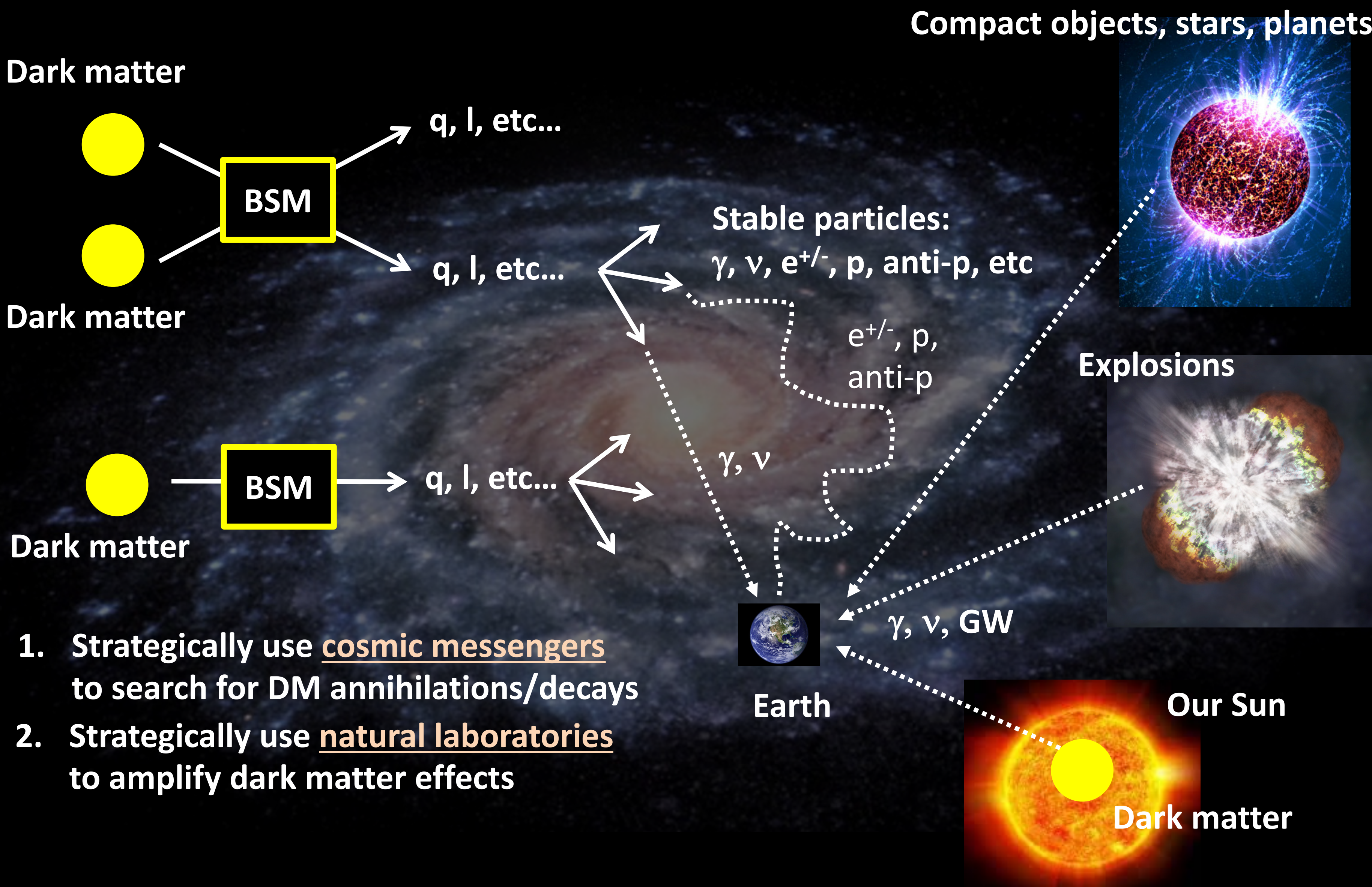
Overview of indirect searches



1. Strategically use cosmic messengers to search for DM annihilations/decays
2. Strategically use natural laboratories to amplify dark matter effects

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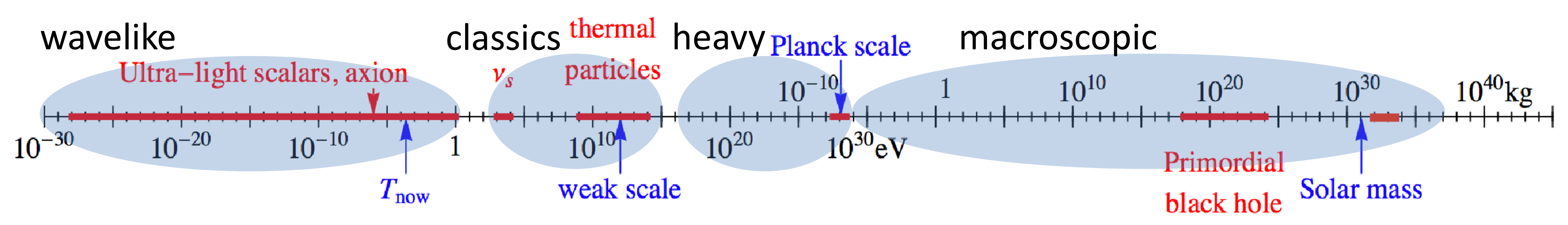
Synergies with multi-messenger

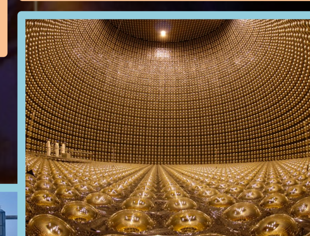
Exploit rise of multi-messenger astrophysics:

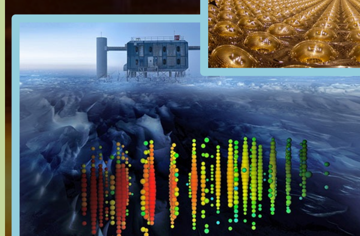
- **Probes broadest range of DM models**
  - **Ideas for dark matter span wide range of energies**
  - **Reduces blind spots: don't know which (if any) SM particle(s) would be produced**

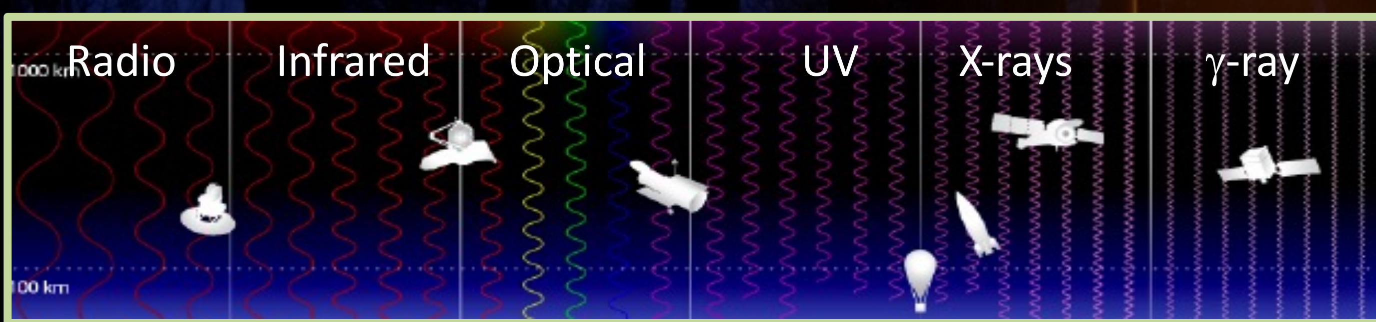


- **Helps understand extreme natural laboratories better**
- **Scrutinizes hints**

→ Meng-Ru, Ishihara-san, Tjonnie Li, Myungshin Im, A. Gopakumar talks



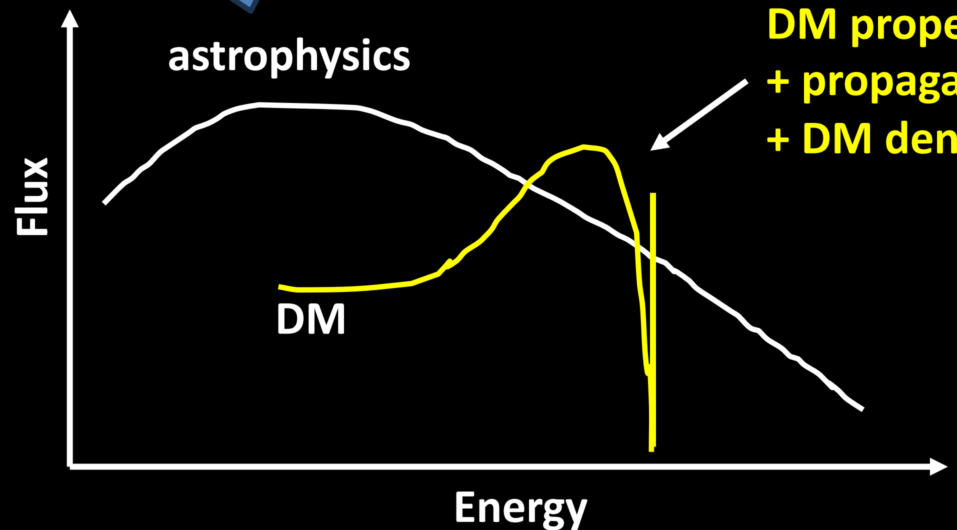




Common challenges

Astrophysics is complex, systematics is surely large

Propagation and/or modeling astrophysical environments are complex



DM properties
+ propagation/environmental modeling
+ DM density profile

The distribution of dark matter must be known well

Various strategies, but generally:

1. **Exploit region/messenger/etc with high DM signal**
2. **Exploit low or well-known backgrounds**
3. **Exploit well-known astrophysical objects/phenomena**

COSMIC MESSENGERS

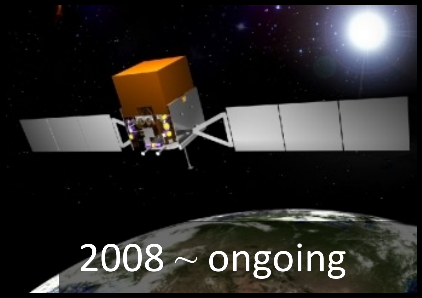
γ-ray non-detection → limits

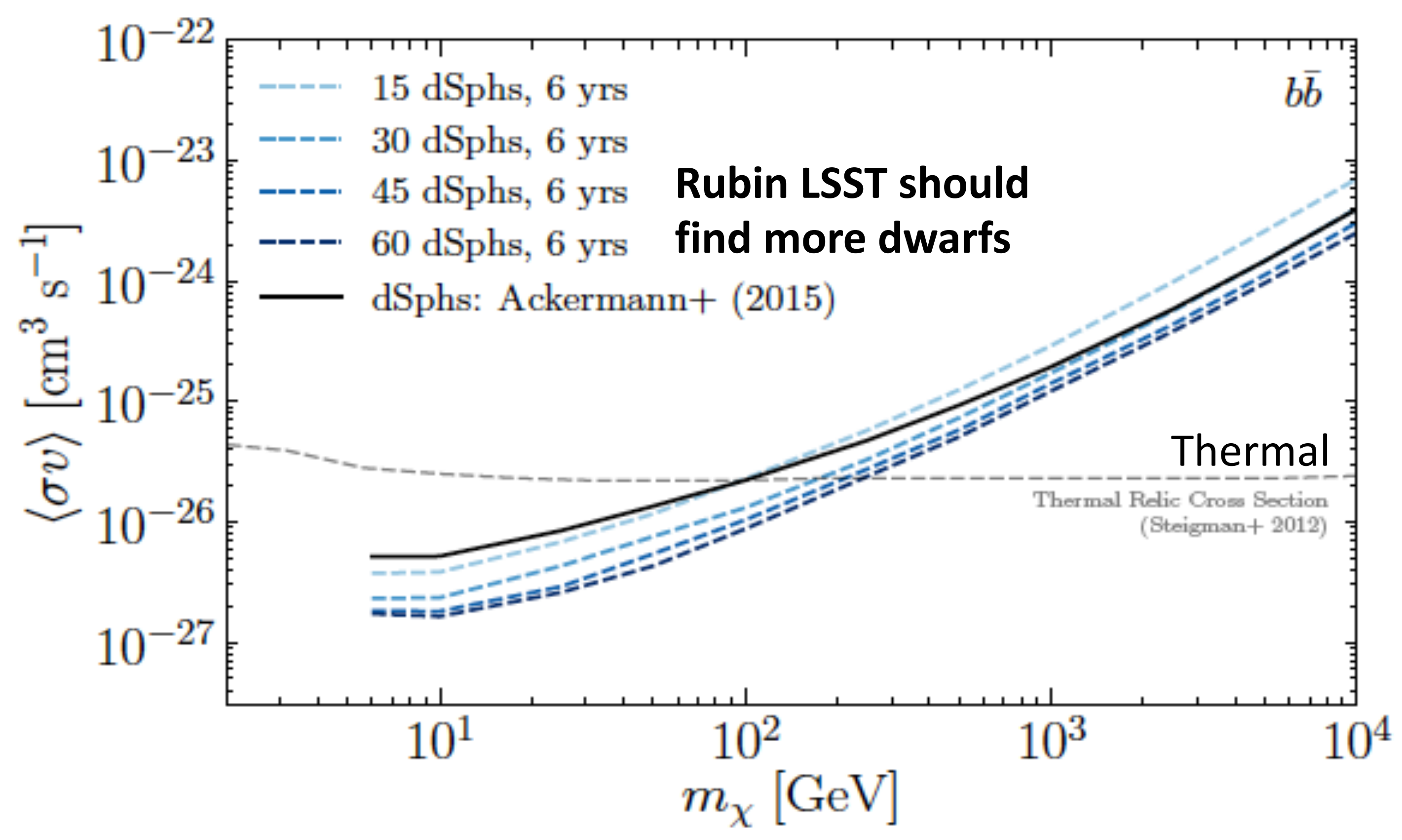
Dwarf galaxies:

- ✓ Low astrophysical backgrounds
- ✓ Dark matter dominated
- ✓ Spectrum: prompt (easy)
- ✓ Morphology: point-like (easy)

Status:

- A few dozen dwarfs
- No signal found → limits thermal DM from ~10 to ~100 GeV mass (depending on channel)



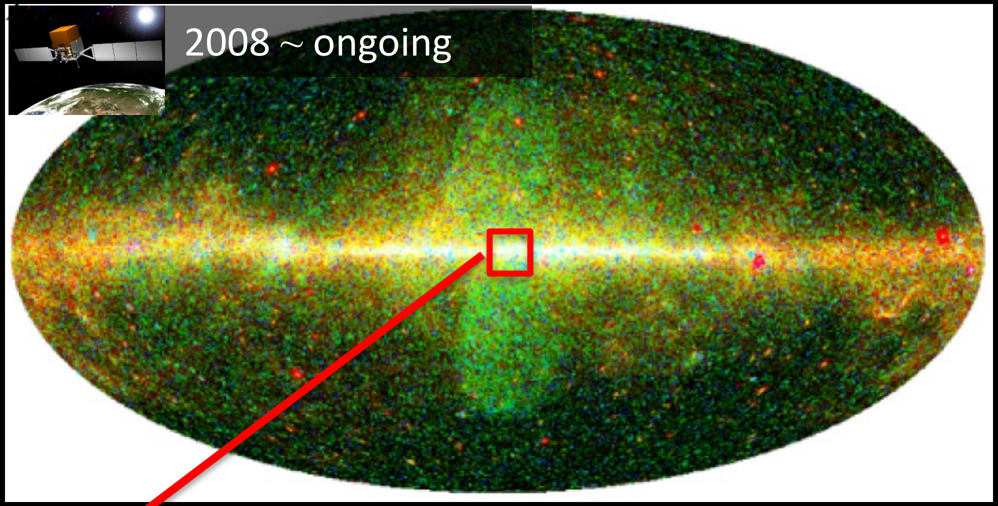


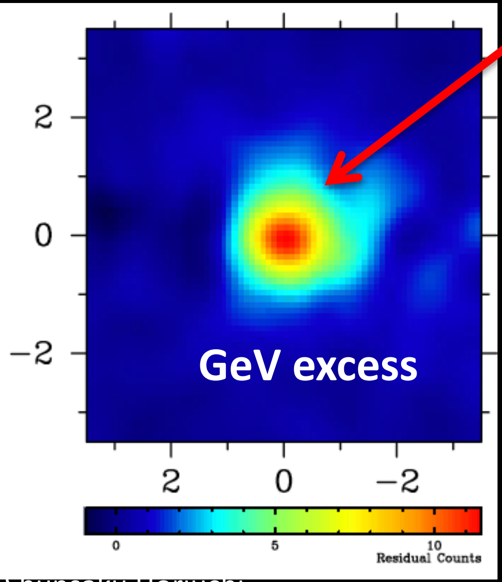
Fermi collab. (2012), Charles et al (2016), Albert et al (2017), Hoof et al (2020), Ando et al (2020)

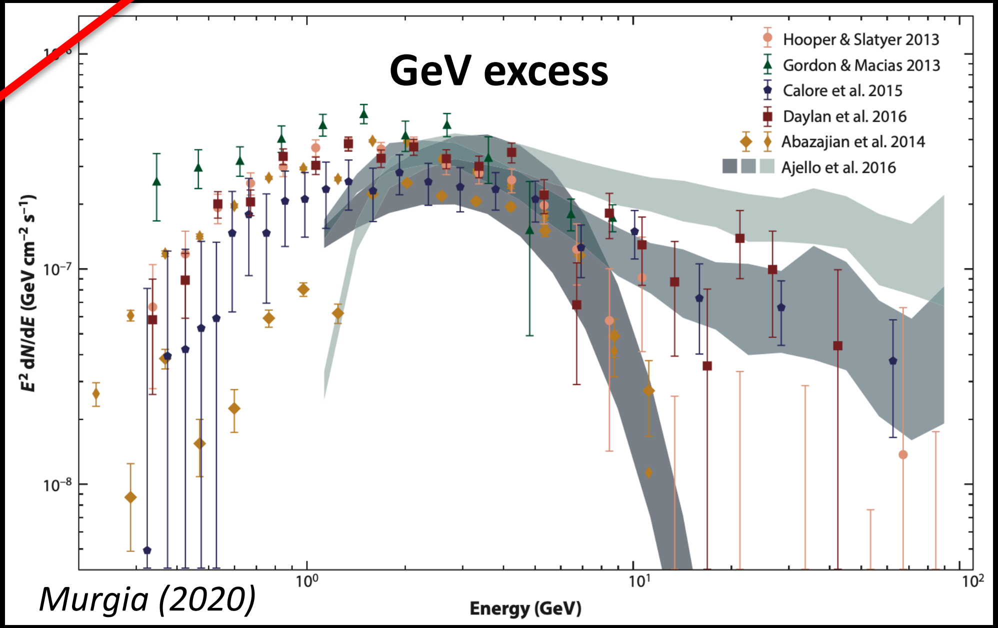
γ-ray detection → DM?

GeV excess:

- **High signal & high background**
- **Spectra: peaked**
- **Morphology: mostly spherical**
- **Significance 20–60σ**
- **Many systematics checks been done**
- **<u>Origins debated</u>**







Goodenough & Hooper (2009)
Vitale & Morselli (2009)
Hooper & Goodenough (2011)
Hooper & Linden (2011)
Boyarsky et al (2011)
Abazajian & Kaplinghat (2012)
Gordon & Macias (2013)
Macias & Gordon (2014)
Abazajian et al (2014, 2015)
Calore et al (2014)
Daylan et al (2014)
Hooper & Slatyer (2013)
Huang et al (2013)
Zhou et al (2014)
Daylan et al (2014)
Calore et al (2014)
Selig et al (2015)
Huang et al (2015)
Gaggero et al (2015)
Carlson et al (2015, 2016)
de Boer et al (2016)
Yang & Aharonian (2016)
Fermi Coll. (2016)
Abazajian et al (2018, 2020)
Horiuchi et al (2016)
Linden et al (2016)
Ackermann et al (2017)
Horiuchi et al (2016)
Linden et al (2016)
Ackermann et al (2017)
Macias et al (2019)
Bartels et al (2018)
Balaji et al (2018)
Zhong et al (2019)
Chang et al (2020)
Buschmann et al (2020)
Leane & Slatyer (2020)
List et L (2020)
Murgia (2020)
Di Mauro (2020)
Burns et al (2020)
Di Mauro (2021)
Calore et al (2021)
Cholis et al (2022)
Mishra-Sharma et al (2022,
McDermott et al (2023)
...

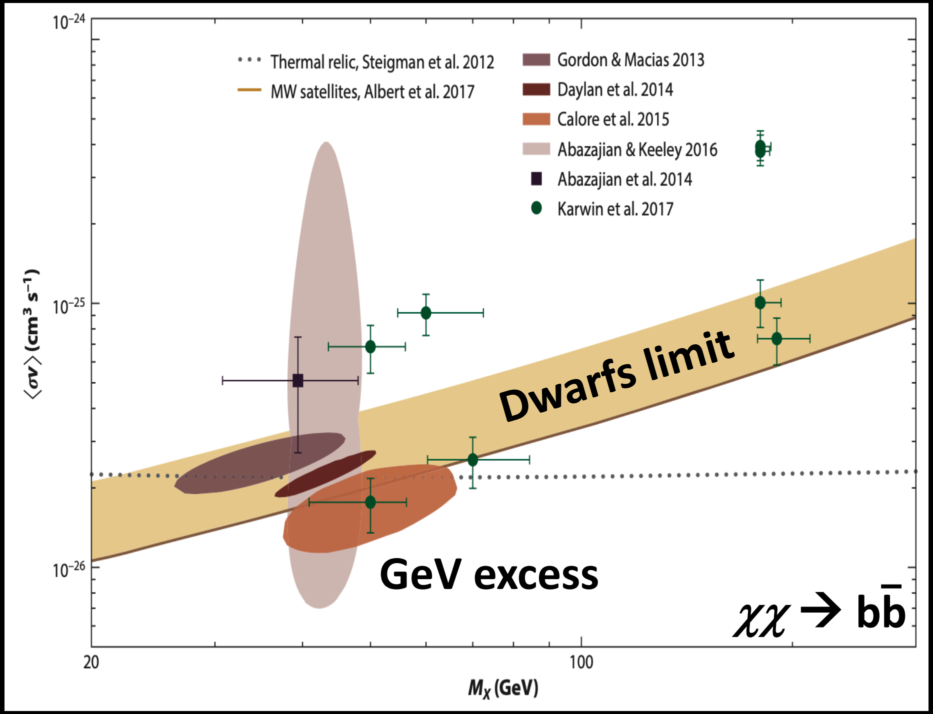
Origins: DM or pulsars?

Candidate: WIMPs

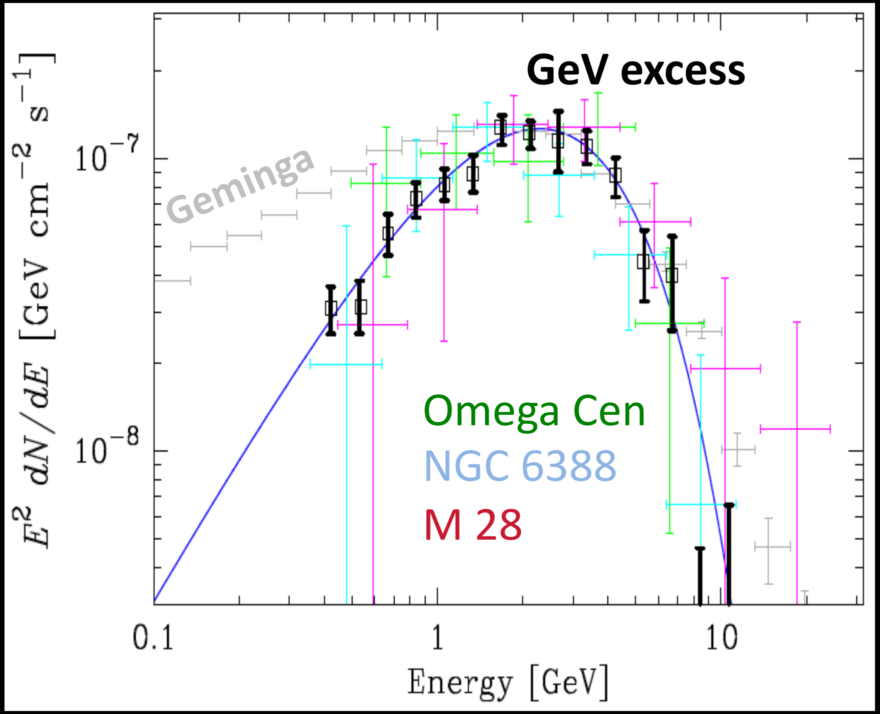
- **Spectra: well-matched by O(100) GeV mass and thermal cross sections; consistent with a wide range of annihilation channels**
- **<u>Consistent with dwarf constraints</u>**

Candidate: millisecond pulsars

- **Spectra: similar to the GeV excess. *O*(10^4) needed in the Galactic Center region, which is not unreasonable given the amount of stars present (~10^{10} Msun)**



Murgia (2020)



Abazajian (2014)

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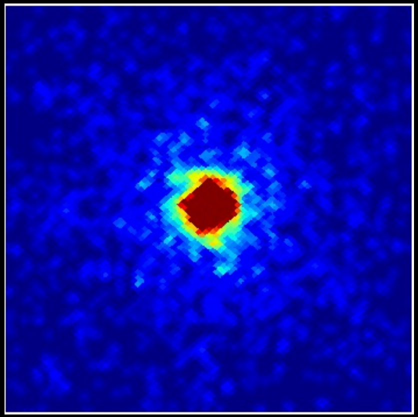
Ongoing debate: sub-threshold sources

Dark matter annihilation



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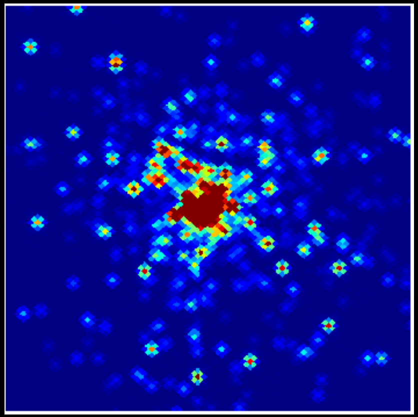
Lee et al (2016)
Bartels et al (2016)

Astrophysics (pulsar)



Ongoing debate: sub-threshold sources

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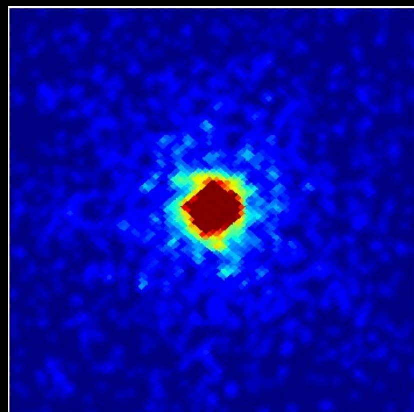

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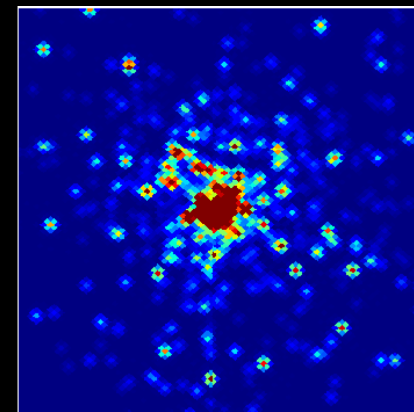

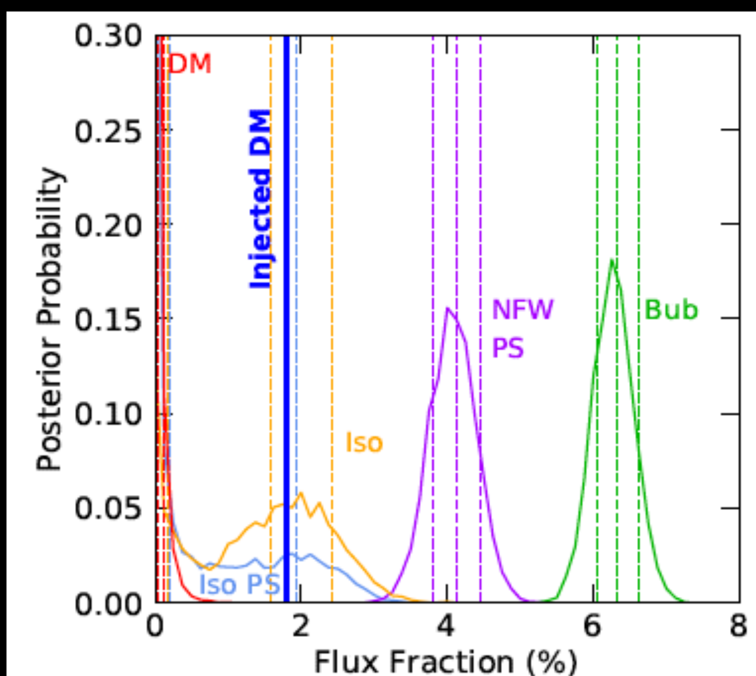

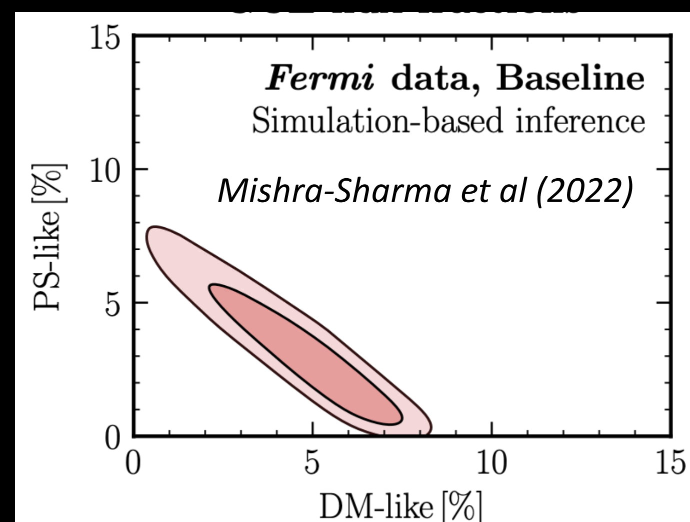

➔ **Cannot confidently detect smooth DM yet**
➔ **Updated analyses show either is plausible**

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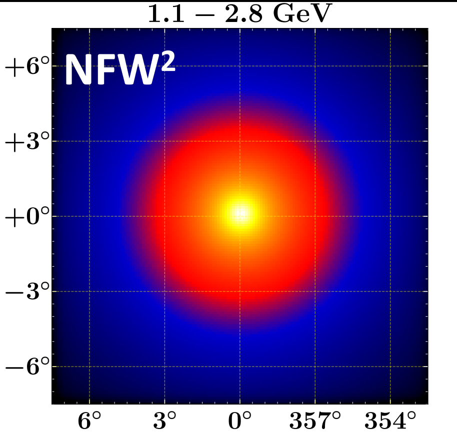
Leane & Slatyer (2019, 2020), Chang et al (2019), Zhong et al (2019), Buschmann et al (2020),

Ongoing debate: spatial morphology

Dark matter annihilation



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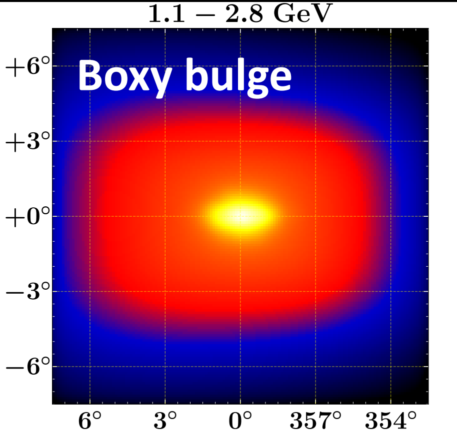
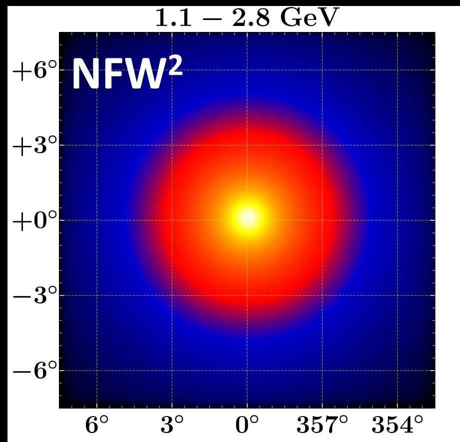
Macias et al (2018)
Bartels et al (2018)

Astrophysics (pulsar)



Ongoing debate: spatial morphology

Dark matter annihilation



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Macias et al (2018)
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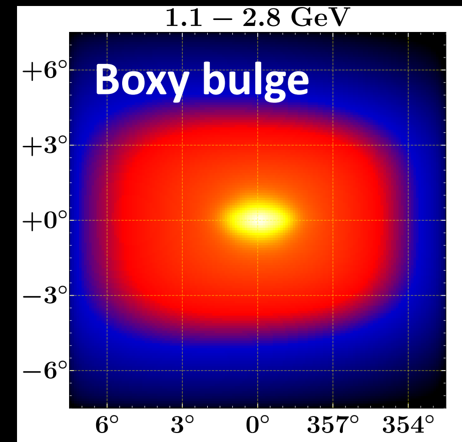
Astrophysics (pulsar)



(+ve is better)

Additional source	ΔTS	Significance
Cored ellips.	0.1	0.0 σ
Cored	0.7	0.0 σ
NFW ellips.	1.0	0.0 σ
NFW	3.4	0.2 σ
Boxy bulge	261.0	14.7 σ

Pohl et al (2022)

(-ve is better)

Excess Model	Bgd. Templates	$-2\Delta\ln\mathcal{L}$
No Excess	ring-based [23]	0
X-Shaped Bulge	ring-based [23]	+30
Dark Matter	ring-based [23]	−237
Boxy & X-Shaped Bulges	ring-based [23]	−634
Boxy Bulge	ring-based [23]	−724
Boxy Bulge "plus"	ring-based [23]	−765
No Excess	astrophysical [15]	−4539
Boxy Bulge	astrophysical [15]	−6398
Dark Matter	astrophysical [15]	−7288

Mc Dermott et al (2022)

➔ Different analysis setups arrive at competing results

➔ Ongoing studies: results soon!

See also, Macias et al (2019), Abazajian et al (2020), di Mauro (2021), Calore et al (2021)

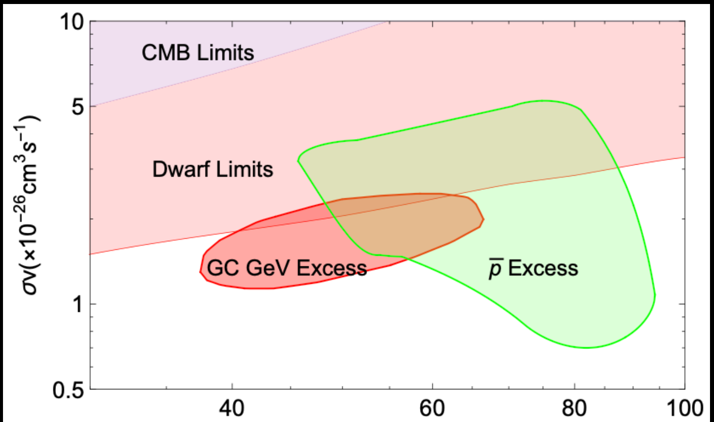
Anti-particle searches

Low-background strategy

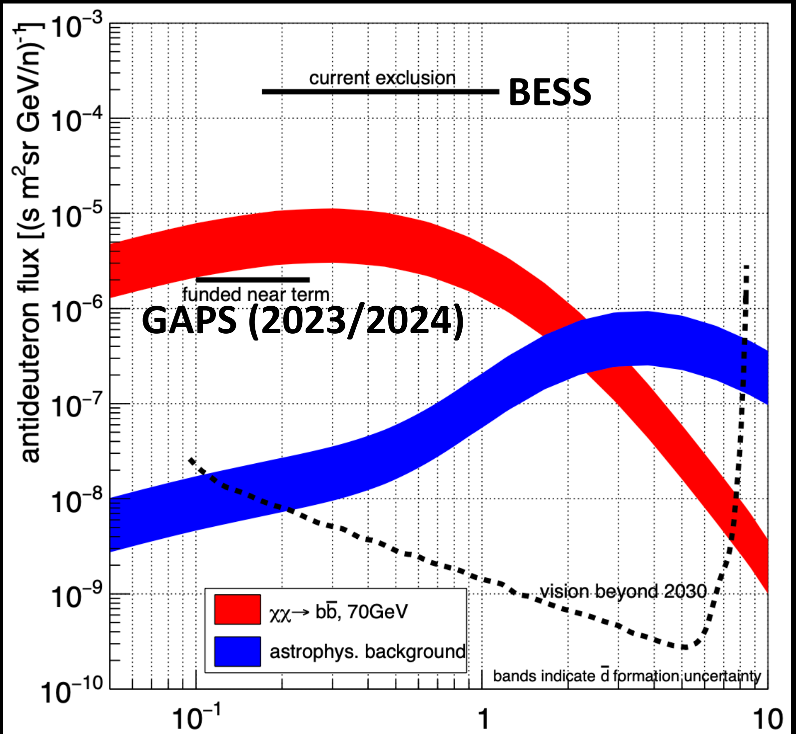
- Low backgrounds from CR secondaries
- Antiproton excess reported at ~5-20 GeV, consistent with GeV excess

Cuoco et al (2017), Cui et al (2018), Cholis et al (2019)

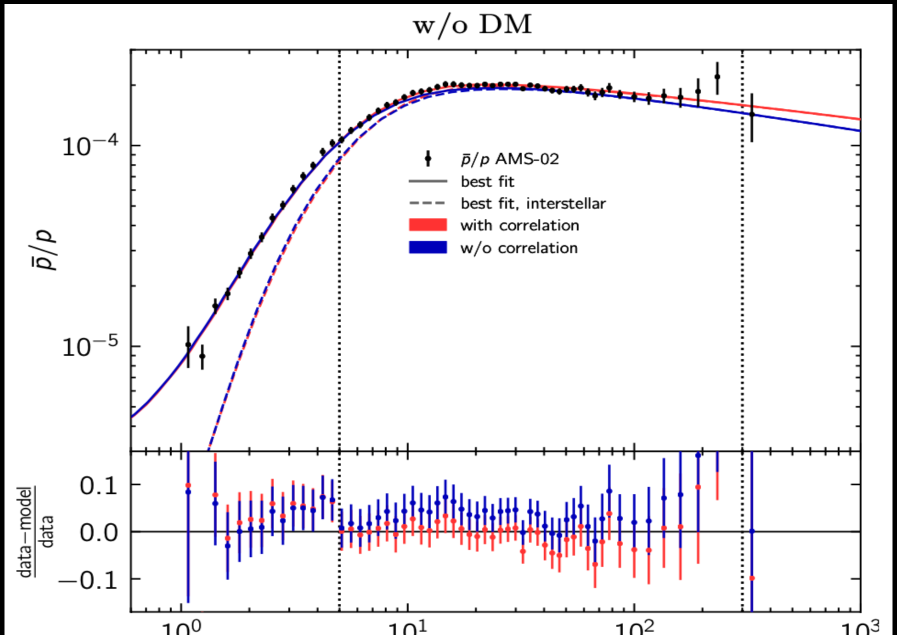
- But systematics are a concern → even removes the excess & constrains DM
- Promising near future antideuteron reach



Cholis et al (2019)



Cooley et al (2022)



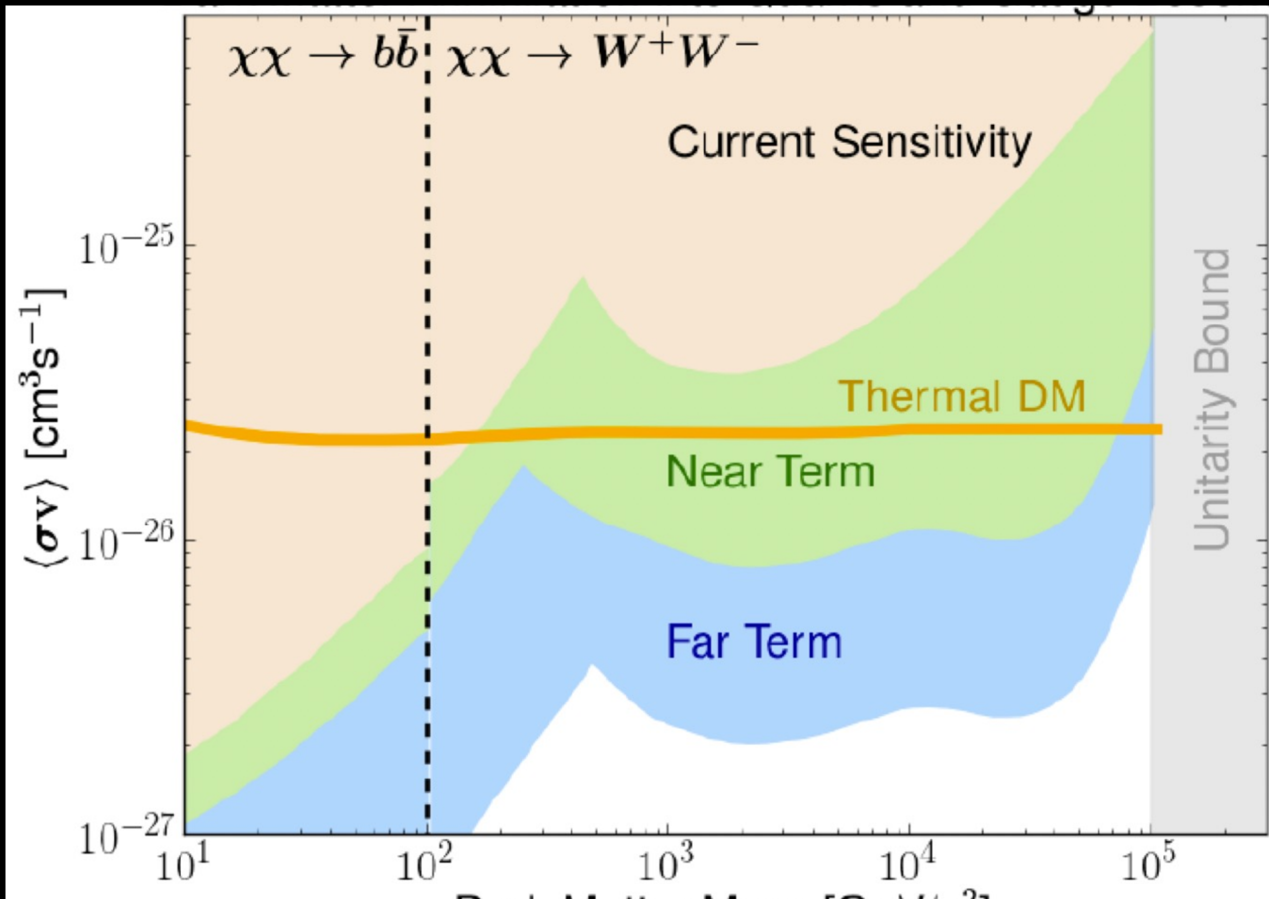
Heisig et al (2020)

To higher masses

New telescopes on the horizon:

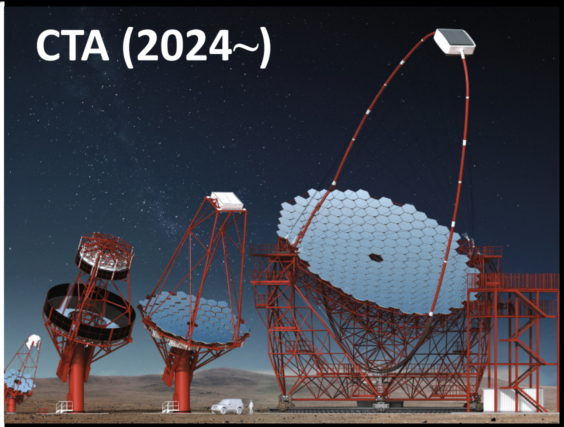
- **CTA: air Cherenkov telescope, 20 GeV – 300 TeV, construction 2022-2027**
- **SWGO: water Cherenkov telescope, 100 GeV – PeV, currently R&D**

Can observe the Galactic Center and reach most of the thermal cross section

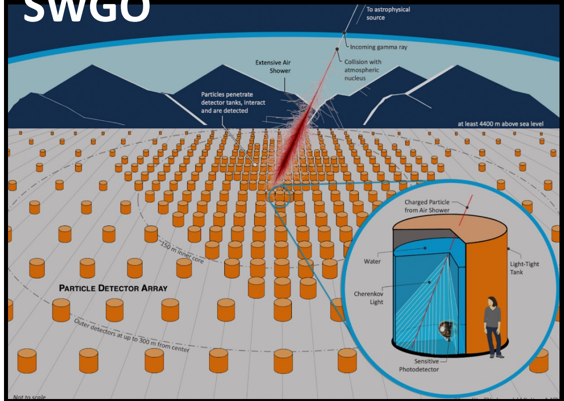


Cooley et al (2022)

CTA (2024~)



SWGO



Shuns

To lower masses

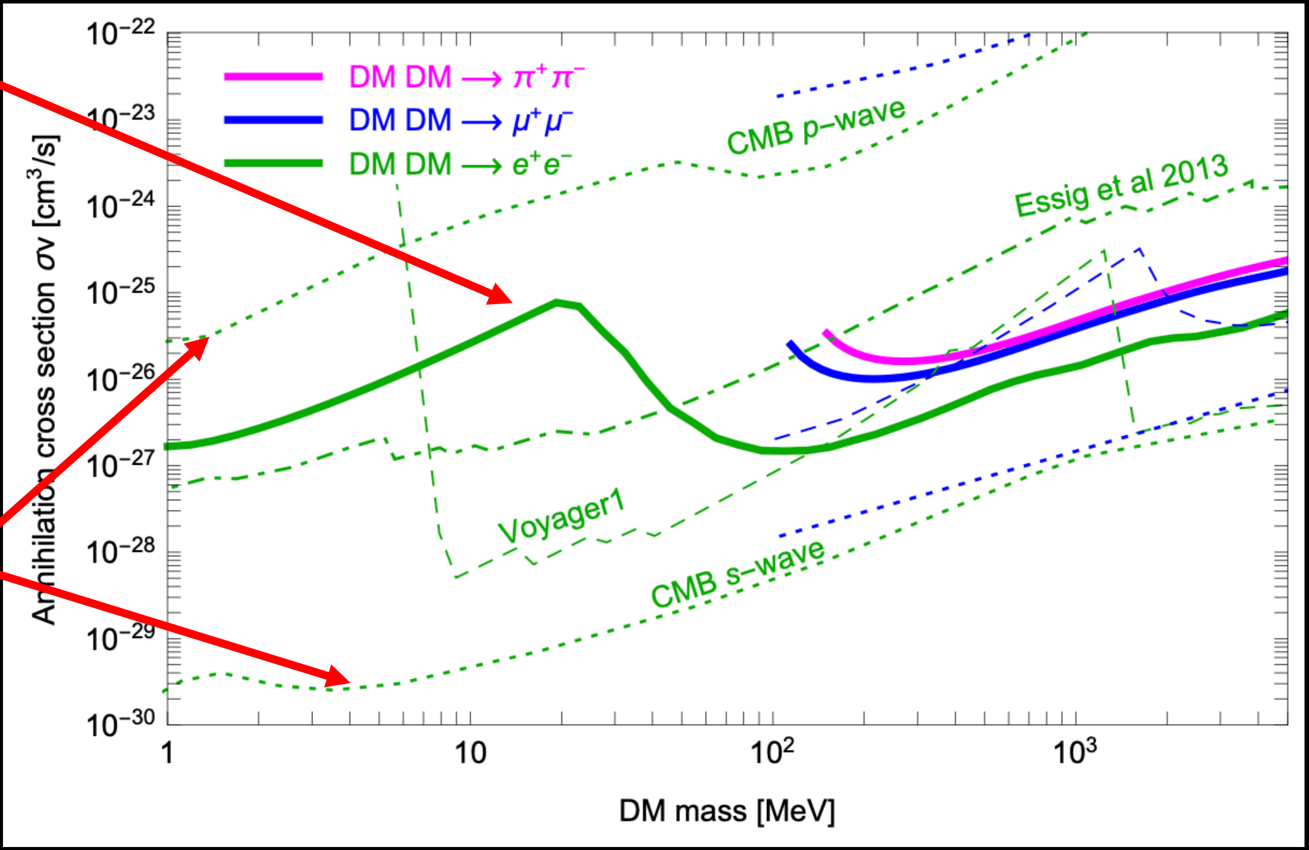
- Going below $O(10)$ GeV difficult due to "MeV gap" in current sensitivity
- Secondaries become useful (though harder):
  - Radio from synchrotron — *Eg Regis et al (2021)*
  - X-ray from inverse-Compton — *Eg Cirelli et al (2021, 2023)*

Search for DM-derived inverse-Compton X-rays in diffuse X-ray observations.

<u>But</u>: astro uncertainty is factor ~10 changes to limits

CMB anisotropies sensitive to ionizing radiation after recombination and into cosmic dark ages; s-wave, p-wave dependence

Eg Slatyer (2016)



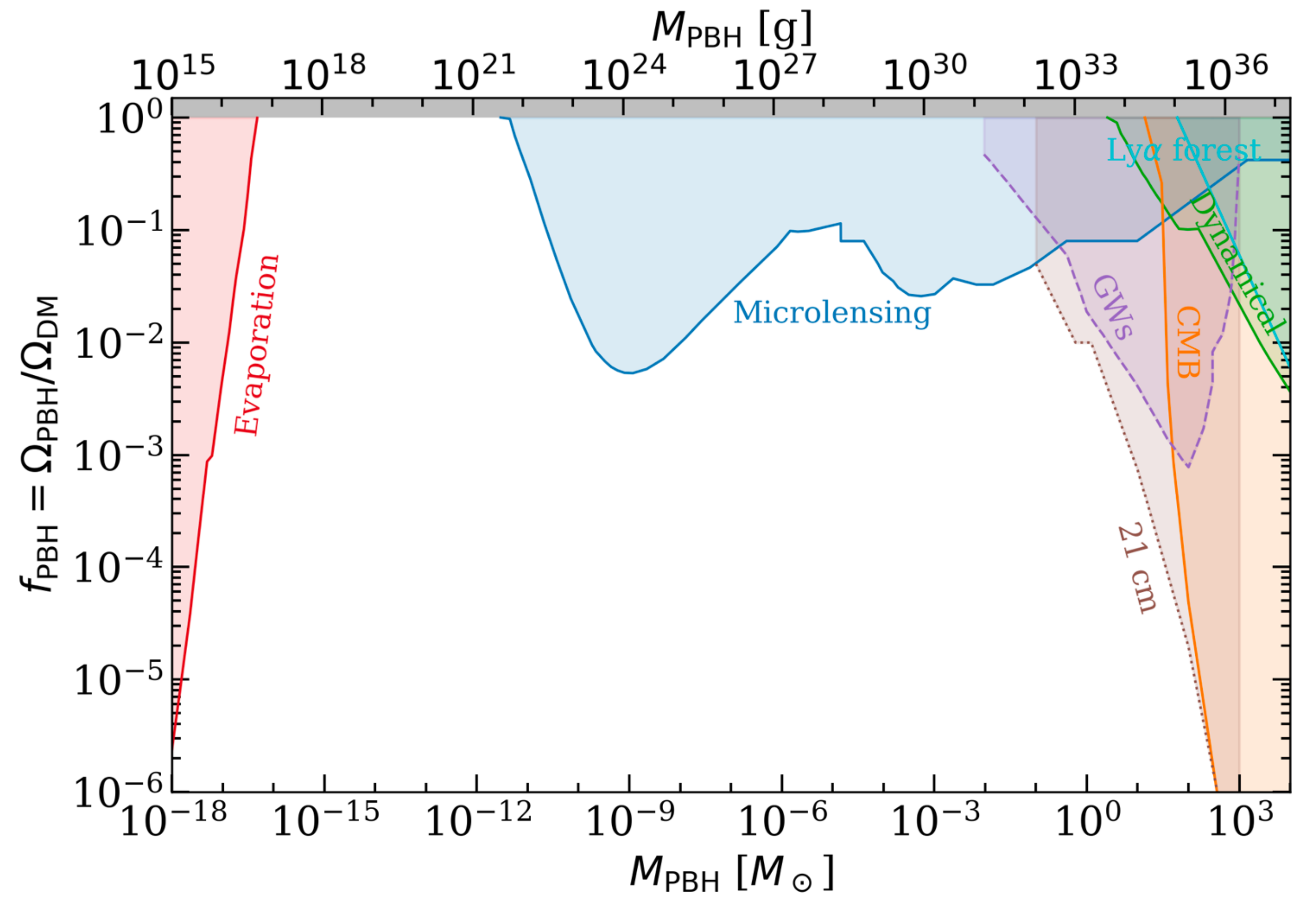
Cirelli et al (2023)

Future directions: MeV

Primordial black hole

- **Black holes exist; formed pre-BBN, can be DM**
- **Can only be probed via astronomy**
- **Like decaying DM due to Hawking radiation → MeV sensitivity**

→ Kohri-san's talk



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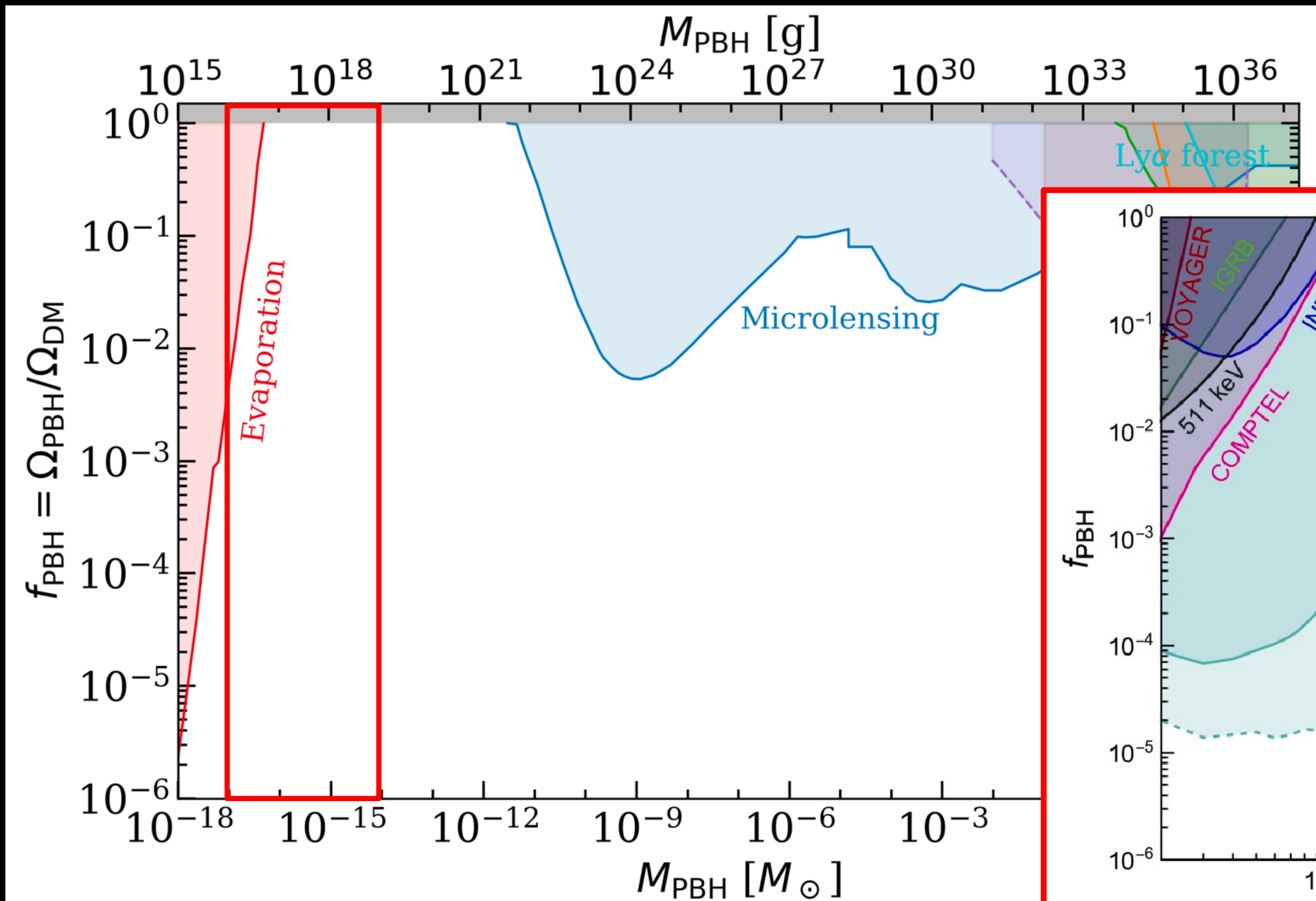
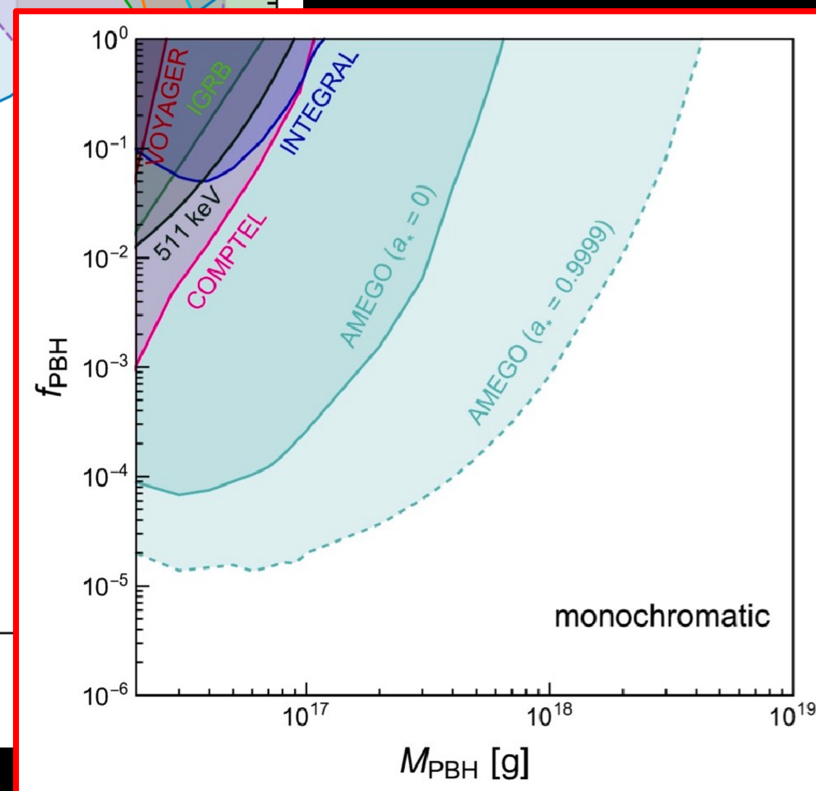
AMEGO: late 2020/2030
Also COSI, others



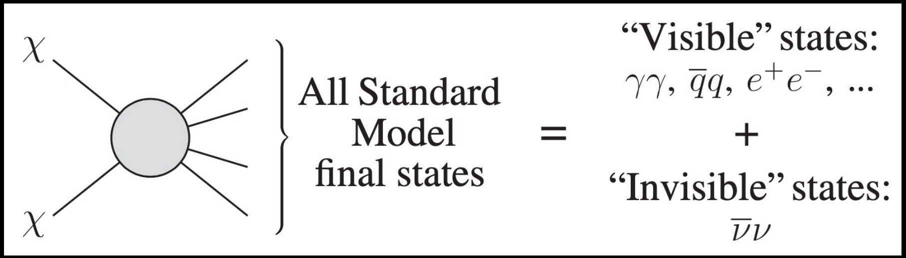


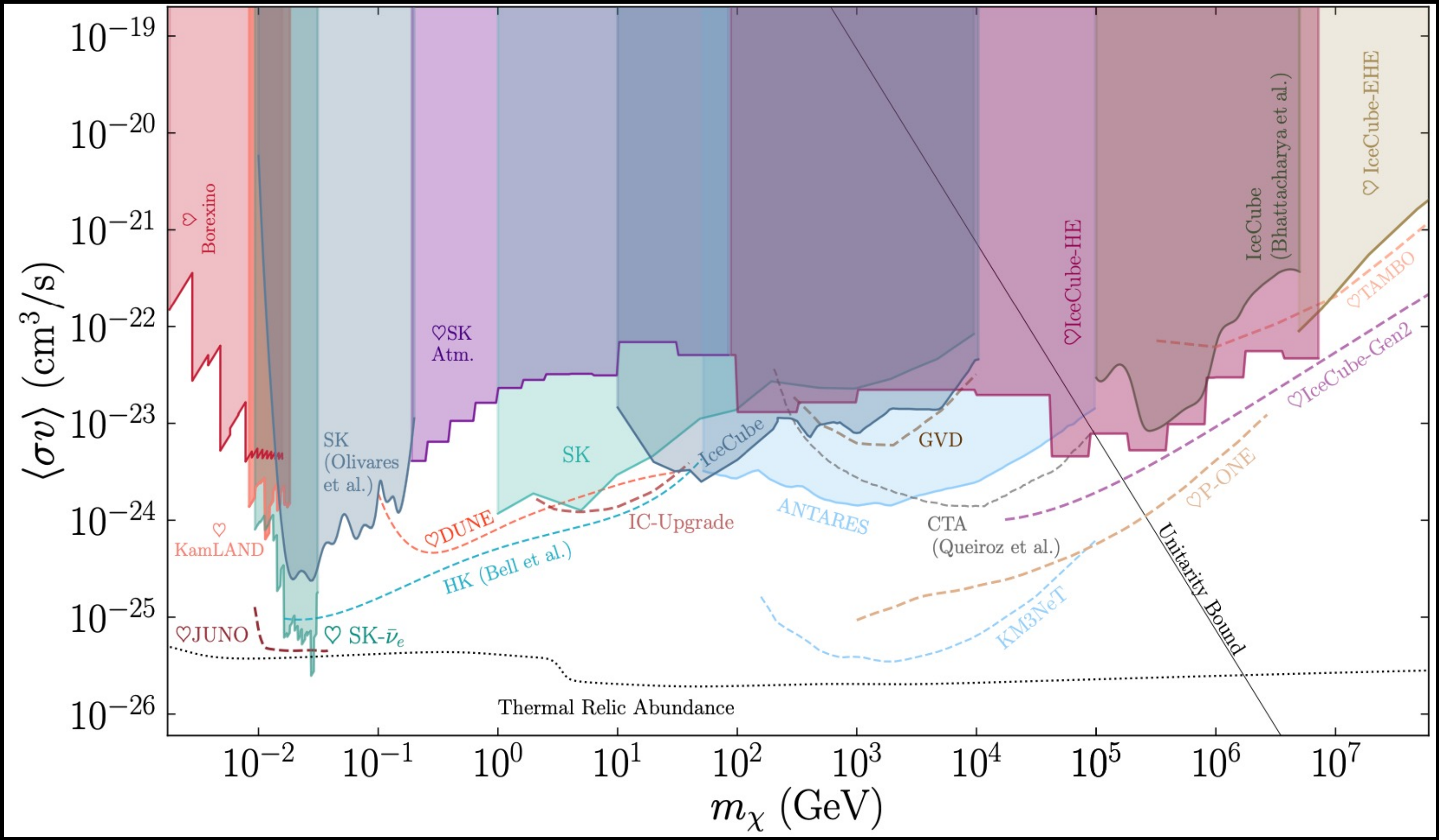
Ray et al (2021)

Neutrino non-detection → Limits

Must reduce blind spots: full coverage of cosmic messengers corners dark matter more completely

Beacom et al (2007)





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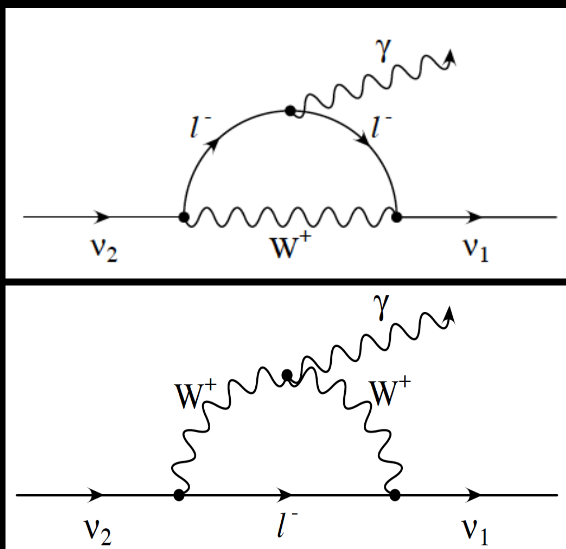
Argüelles et al (2021); for decays see Argüelles et al (2022)

Sterile neutrino DM

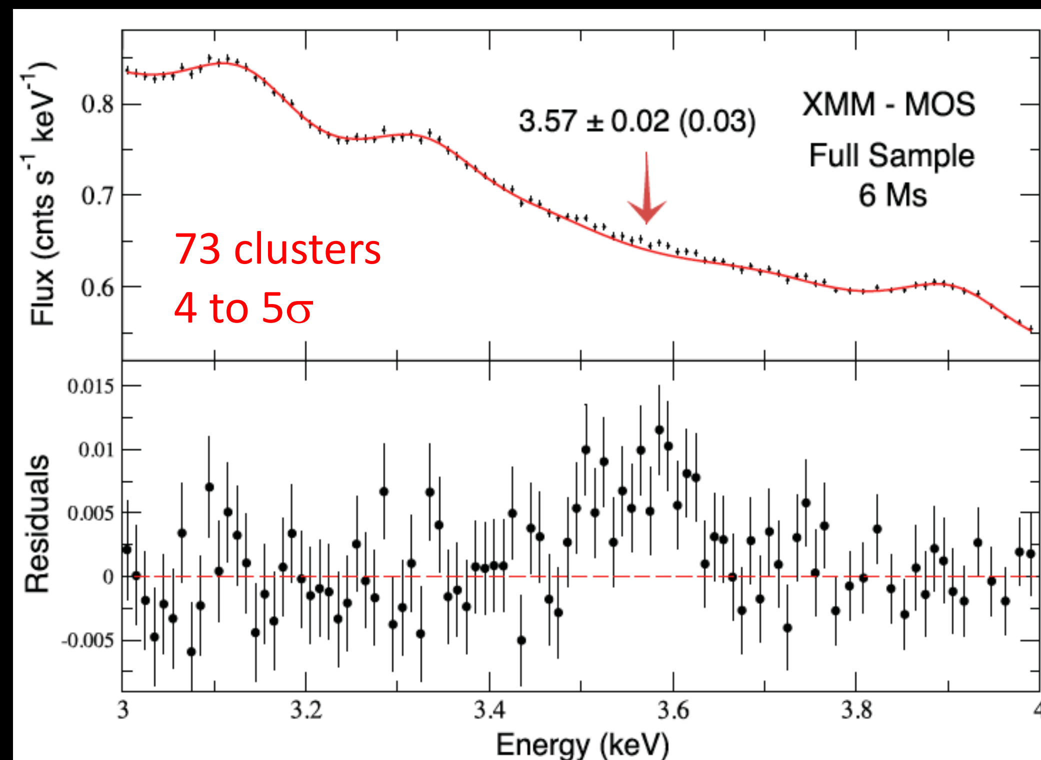
- **keV sterile neutrinos can be produced via oscillations in Early Universe**
- **Small mixing with active neutrino ensures long lifetime**
- **But rare 2-body decay can be detectable**



$$E_\gamma = m_s/2$$

Chandra, XMM-Newton, Suzaku, Hitomi, Swift, Fermi-GBM, NuSTAR….and in future Athena

~7 keV sterile neutrino?

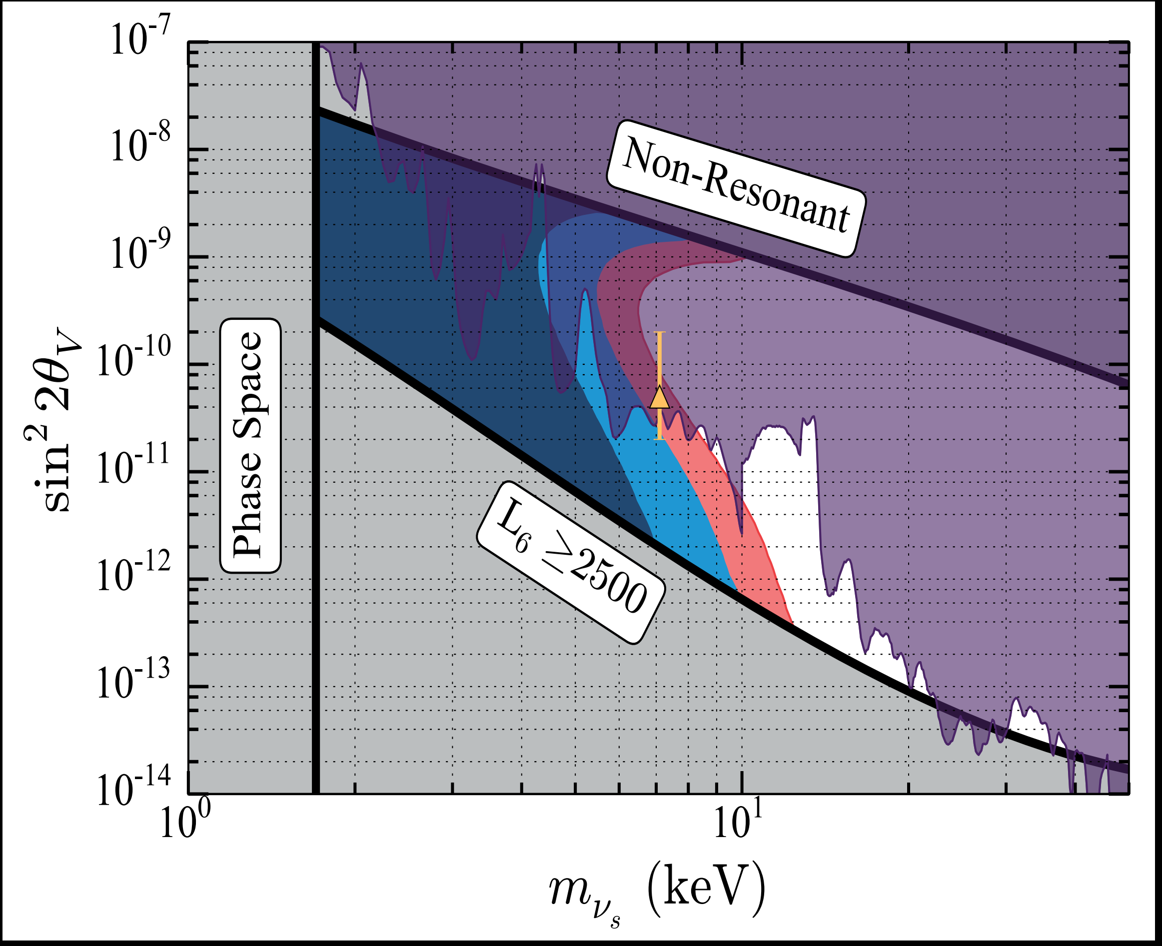


Bulbul et al (2014), Boyarsky et al (2014); many follow-up studies

Constraints from all sides

Many searches & constraints

Oscillation-based model space is being cornered from all sides



Cherry & Horiuchi (2017)

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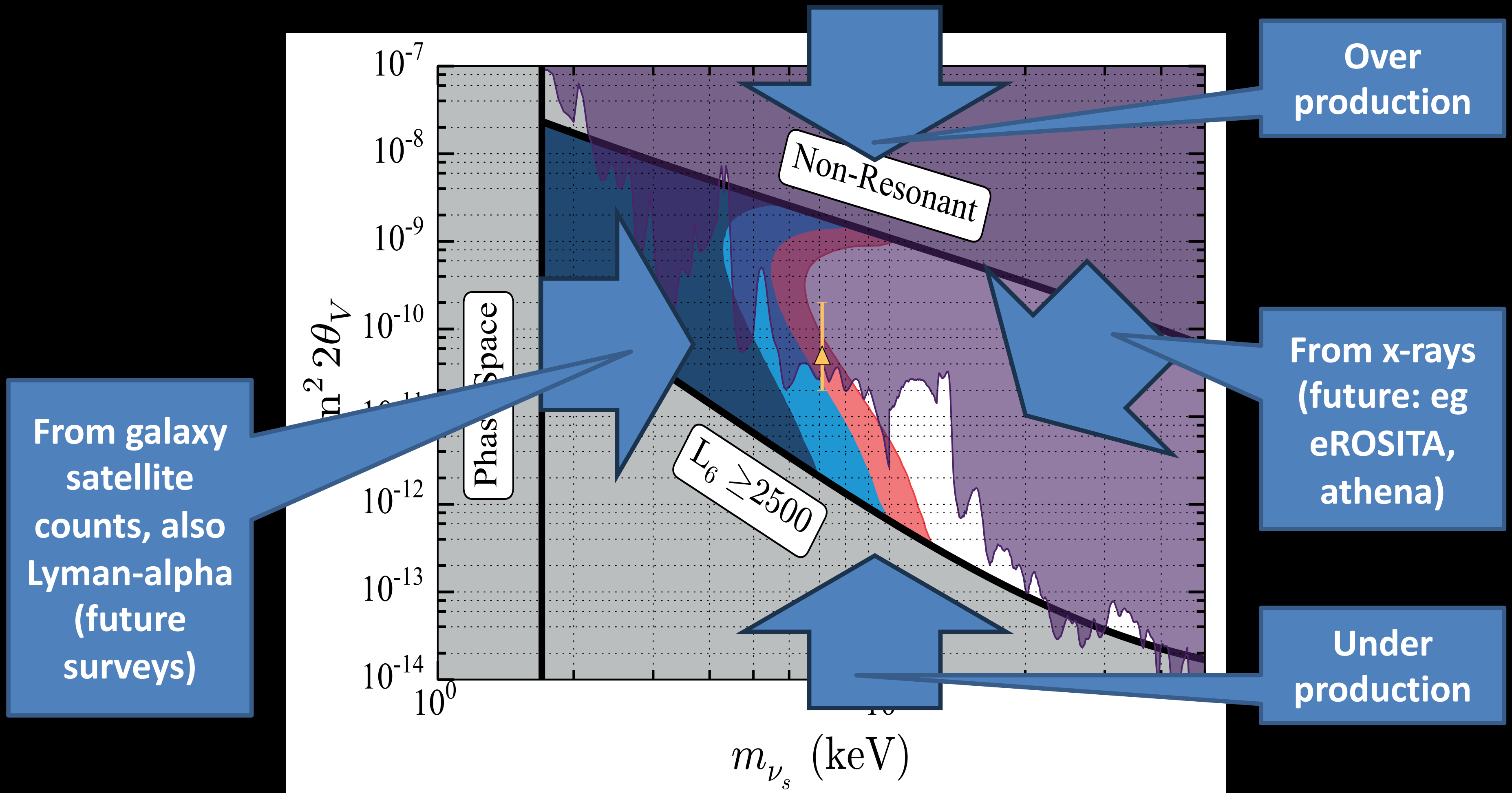

Cherry & Horiuchi (2017)

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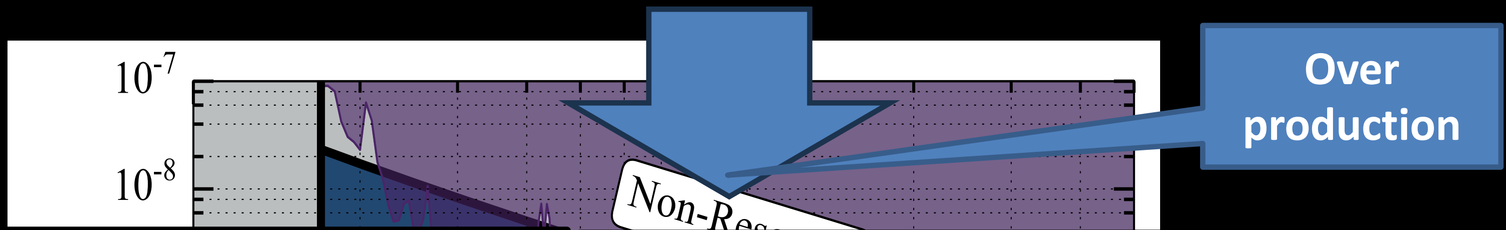
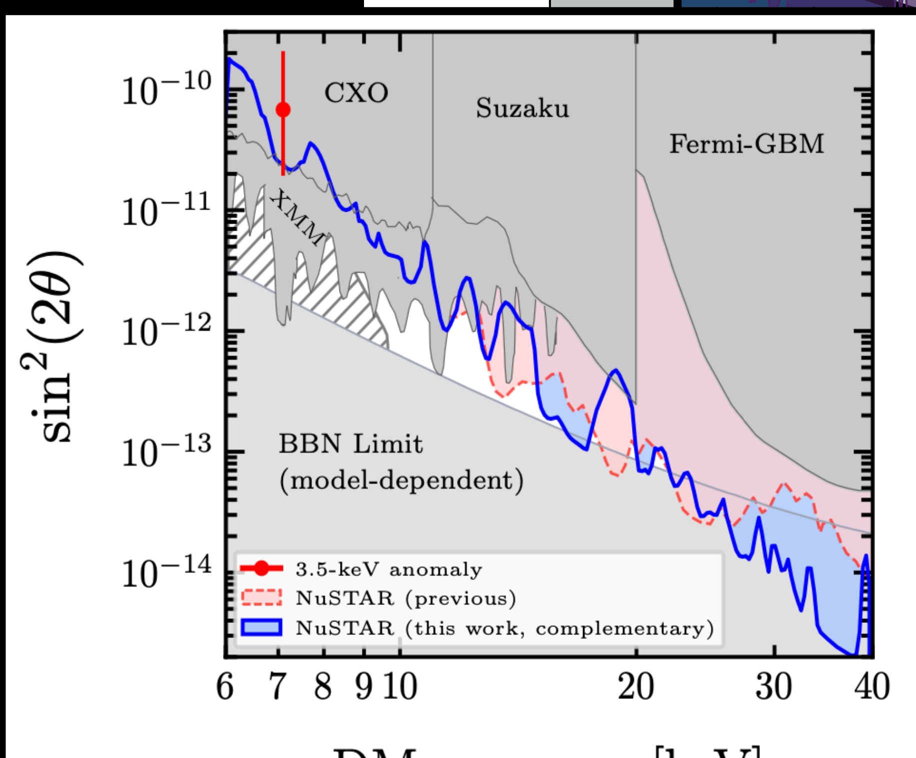
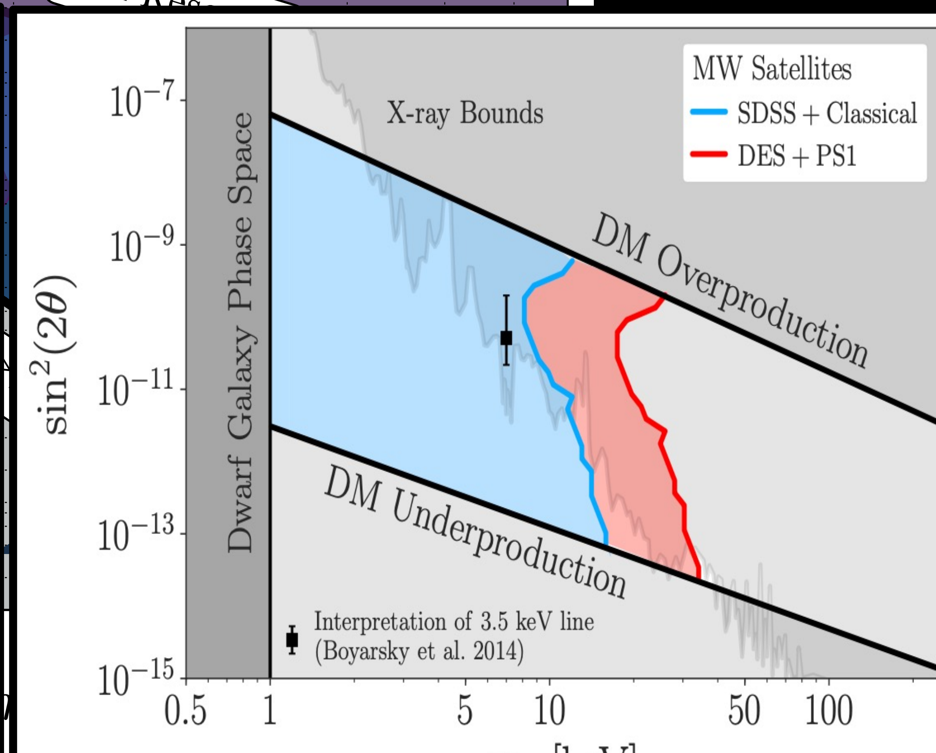




Roach et al (2022)



Nadler et al (2021)

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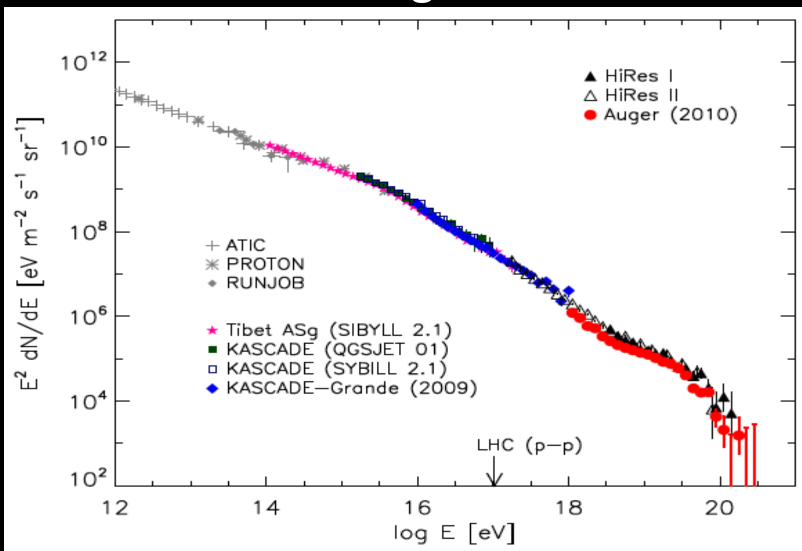
NATURAL LABORATORIES

Natural laboratories

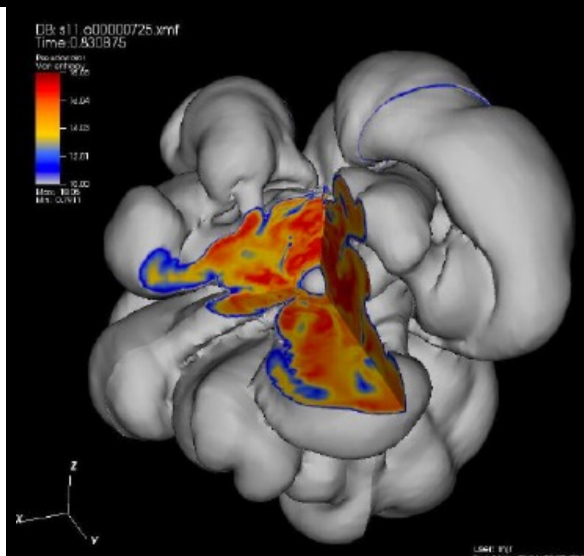
Astrophysics: natural laboratory often exceeding terrestrial environments

Energies



Cosmic rays reaching ~10^{20} eV

Intensity



Supernova neutrinos reaching ~10^{60} per collapse

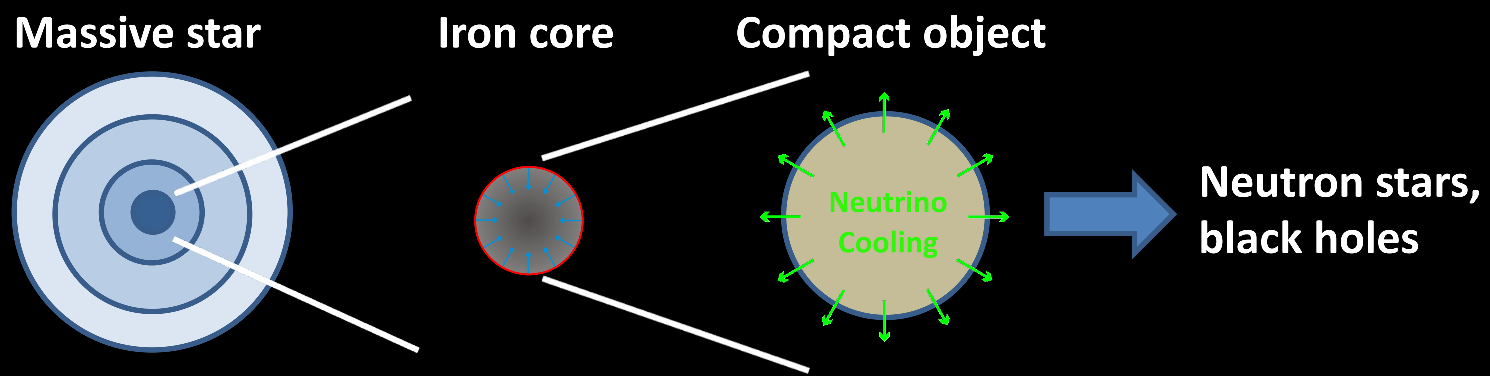
Density, etc.

Compact objects exceeding ~ 10^{14} g/cc, B-fields of ~ 10^{16} G, temperatures ~MeV

Complex, but rewards would be big

Core-collapse supernovae

Gravitational collapse of star's core:



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Core-collapse supernovae

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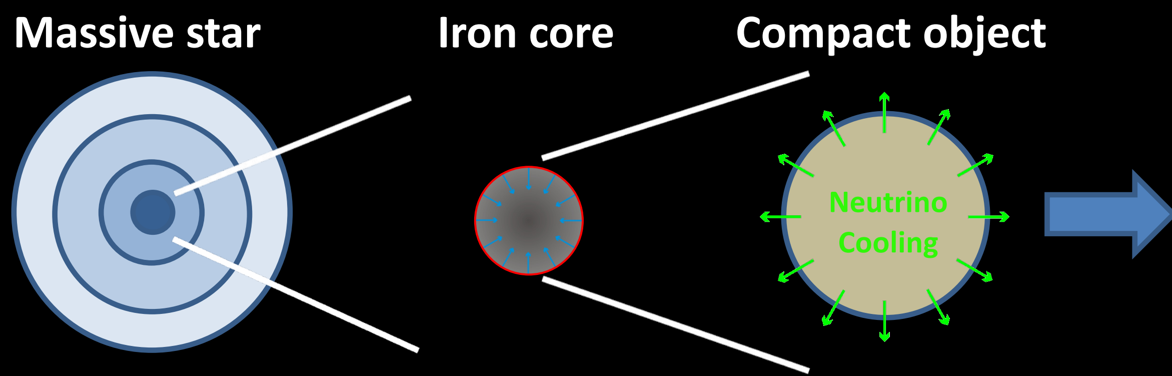

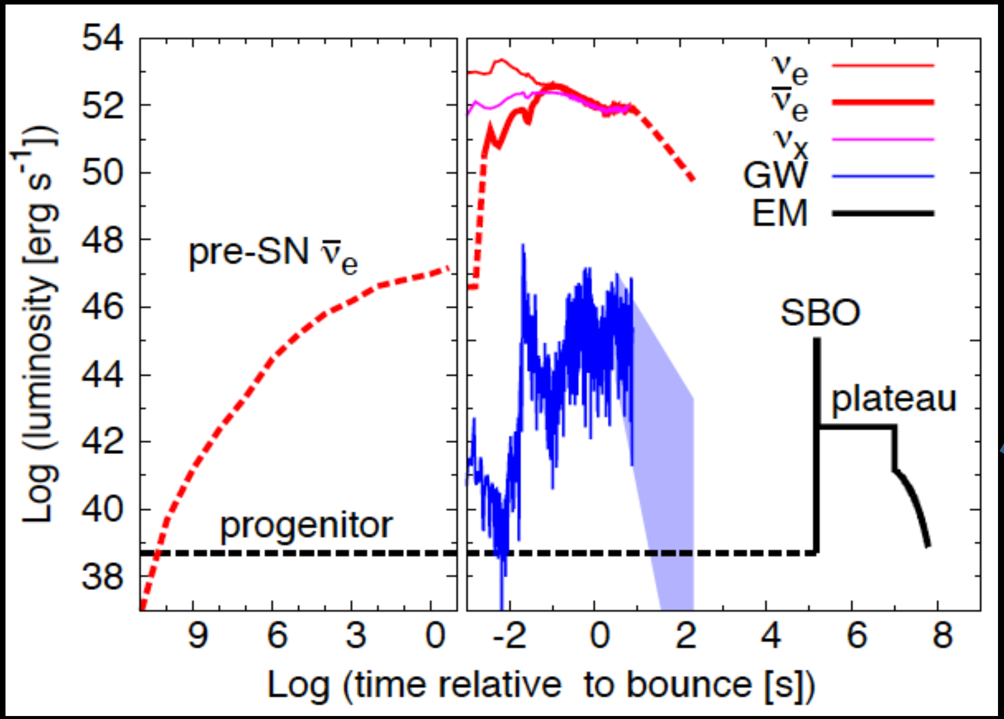

Nakamura, Horiuchi, et al (2016)

Astro

- Explosion mechanism
- Instabilities, turbulence
- Equation of state
- Black hole formation
- Surprises

HEP

- Neutrino mass, hierarchy, decays, magnetic moment, …
- New particles: axions, sterile neutrinos, …
- Surprises

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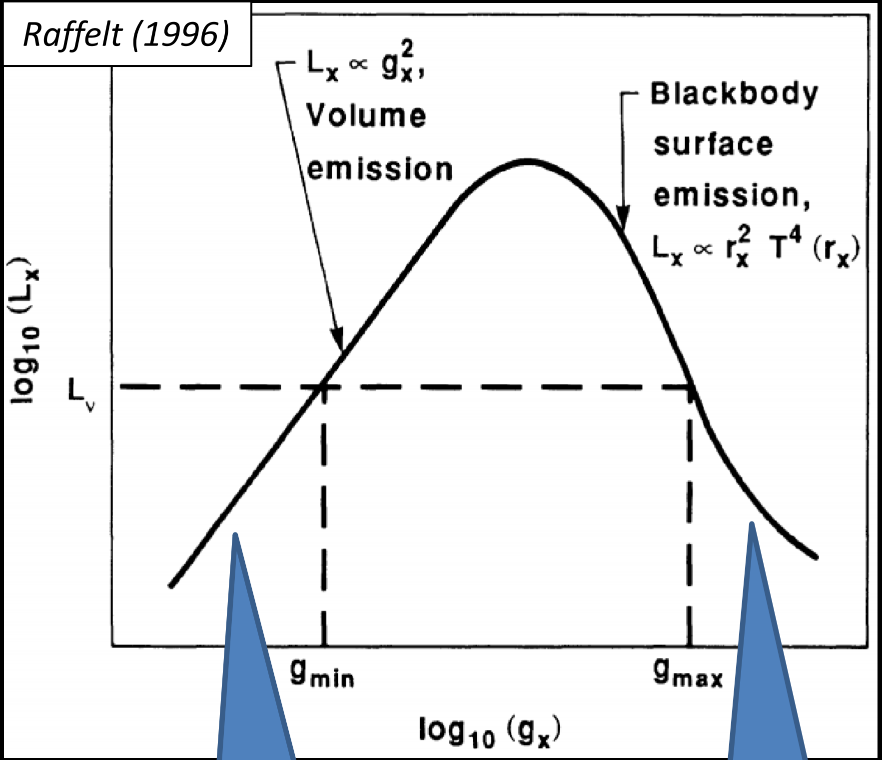
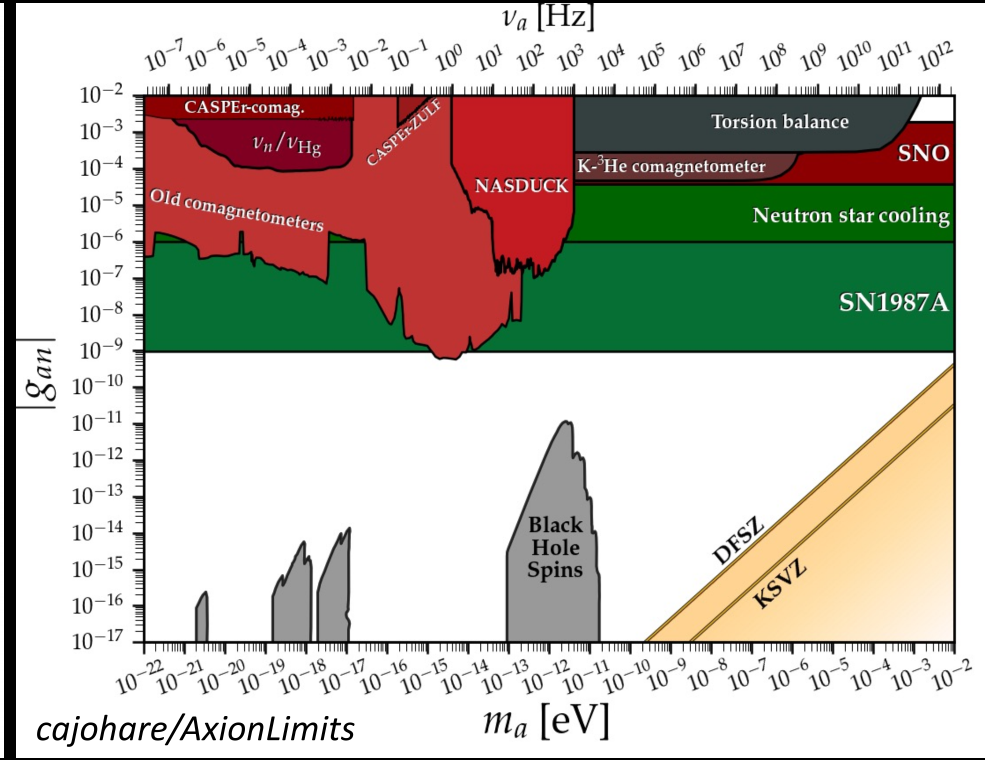
Light, weakly interacting particles

- **Light:** because thermal temperatures are *O*(10) MeV
- **Weakly coupled:** because occurring in nuclear densities
- e.g., axion, dark photon, sterile neutrinos



Not efficiently produced

Efficiently trapped & reabsorbed



SN1987A: require that L_a not excess $L\nu$
Also: neutron star cooling via axion emission

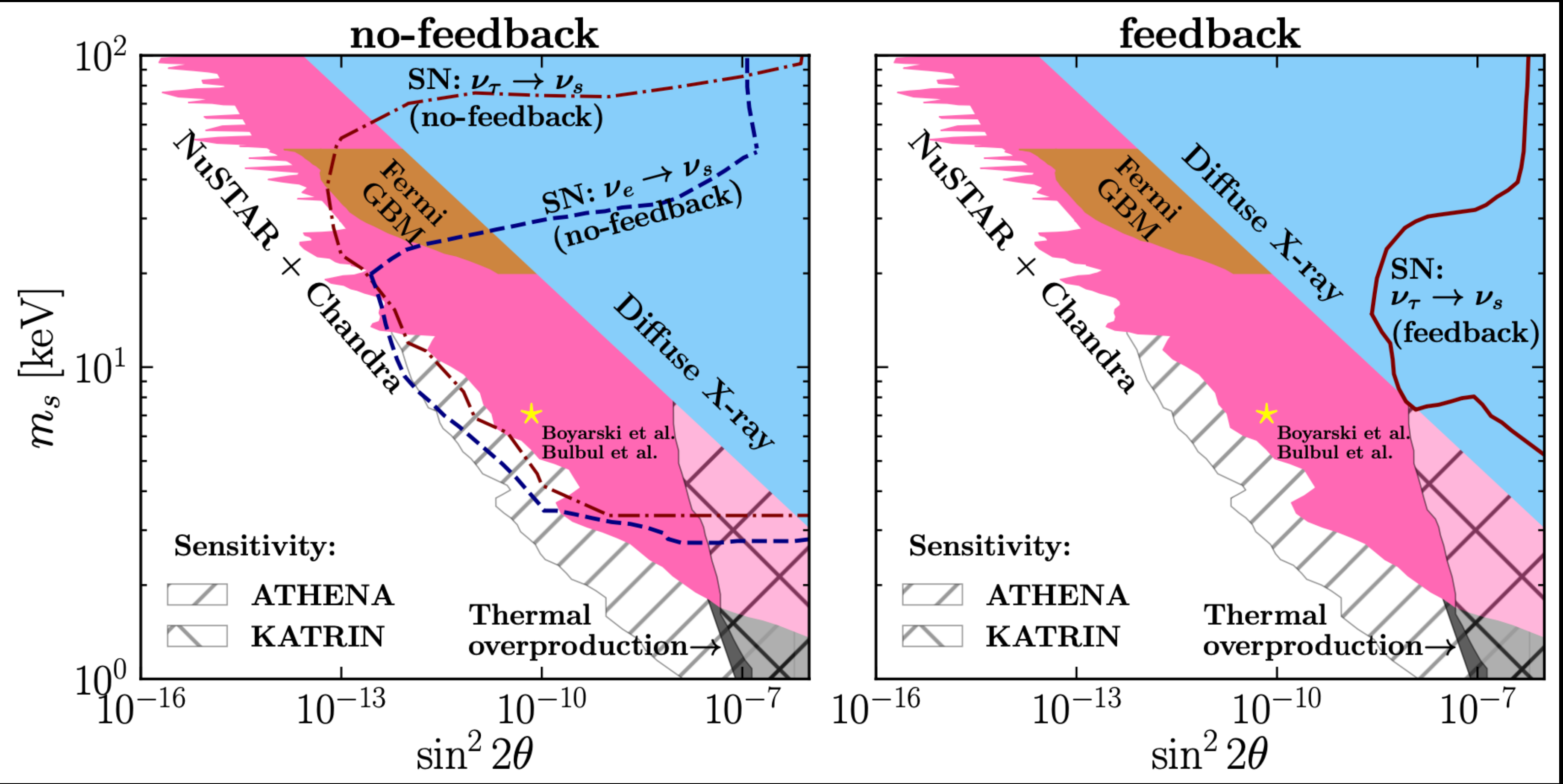
➔ Raymond Co talk

Carenza et al (2020), Buschmann et al (2022)

Importance of self-consistent treatment

Sterile neutrinos

- Sterile neutrinos are produced from active neutrinos (oscillation, collisional)
- Neglecting feedback over-estimates active neutrino lepton number
- Including feedback dramatically relaxes bounds from supernovae

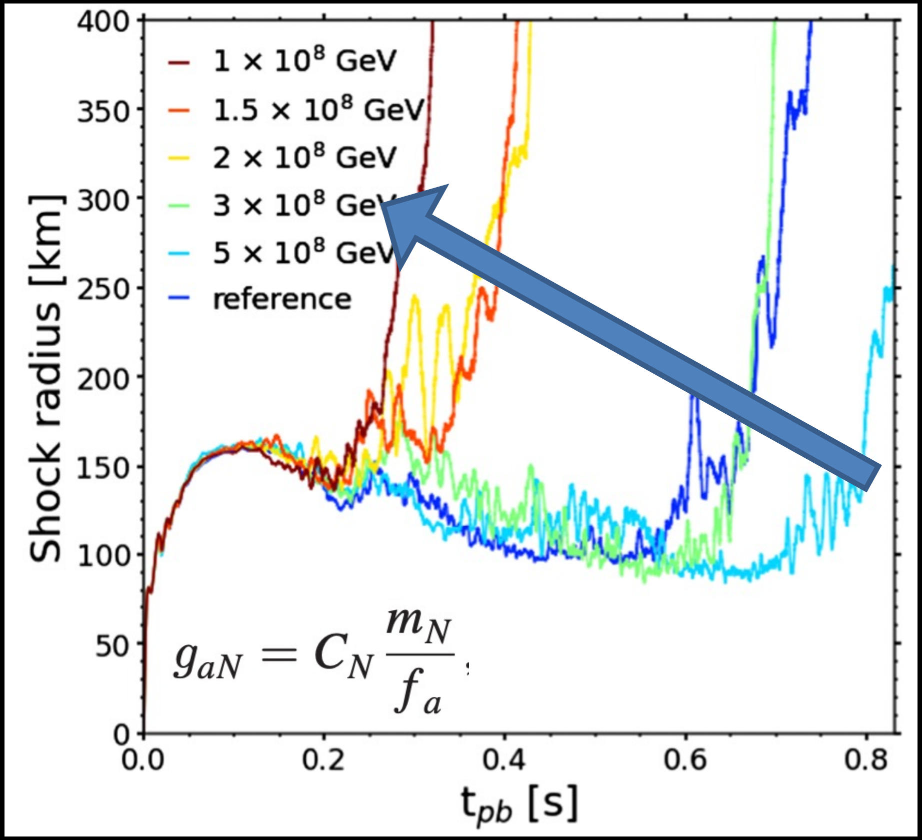


Suliga et al (2020)

Self-consistent treatments

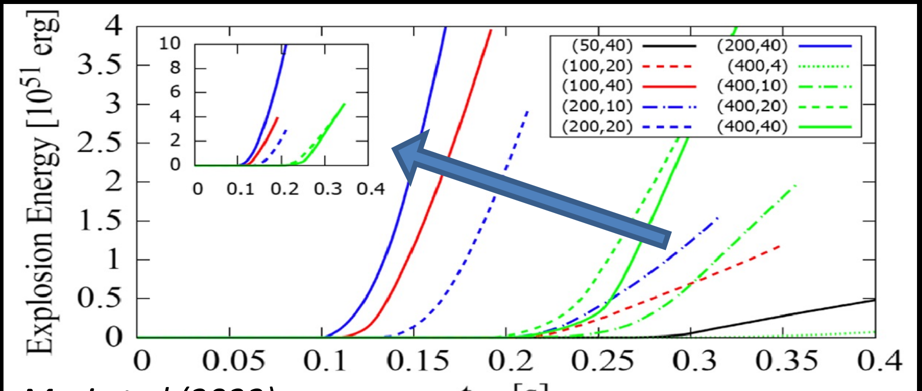
Numerical implementations of axions important due to non-linear evolution of supernovae

QCD axion: leads to faster core cooling, but unexpectedly neutrino heating improves & earlier explosions occur

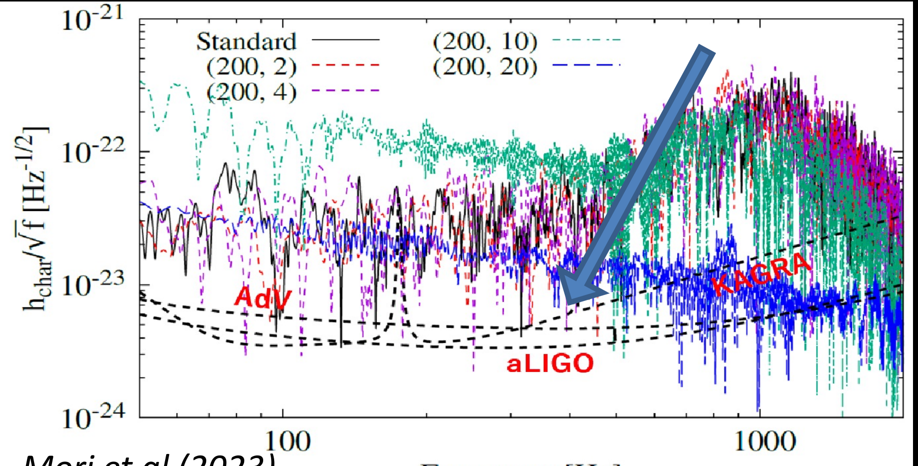


Betranhandy & O'Connoer (2022)

MeV ALP: decays before escape and increases explosion energy. Neutrinos and gravitational waves are suppressed due to ALP heating.



Mori et al (2022)



Mori et al (2023)

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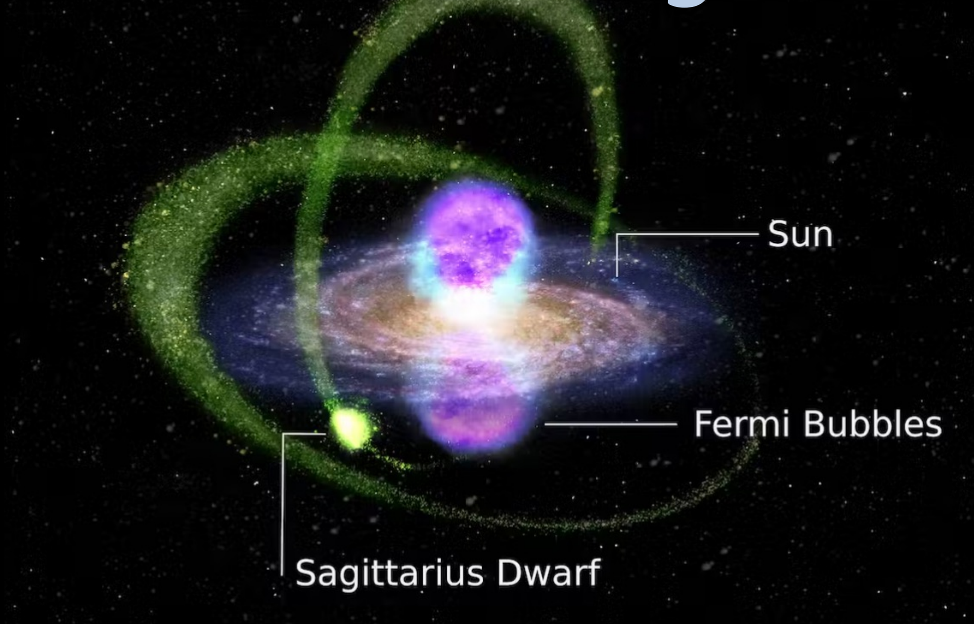
Concluding remarks

- **Indirect searches of DM probes DM in its natural habitat, making it essential for the ultimate DM solution**
- **Indirect DM search is multi-energy, multi-messenger, multi-target**
- **Cosmic messengers: can set some of the strongest constraints, e.g.:**
  - **Thermal cross sections up to ~100 GeV, reaching ~100 TeV in future**
  - **Corners the oscillation-based sterile neutrino DM scenario**
  - **Many anomalies could be hinting at a DM signal. However, they all have counter arguments in the form of astrophysical origins or backgrounds. Works ongoing to conclude the origins.**
- **Cosmic laboratories offer extreme conditions to further probe DM**
  - **Improved astrophysical modeling and future astronomical observations will further the reach into DM properties.**

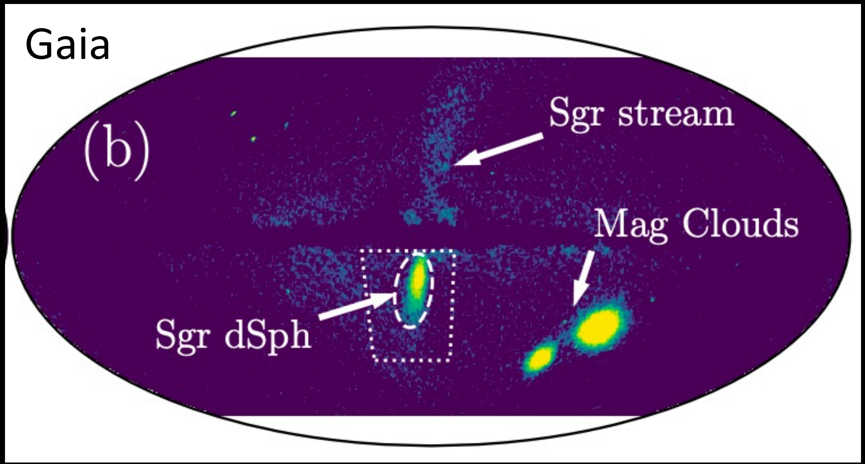
Thank you!

BACKUP

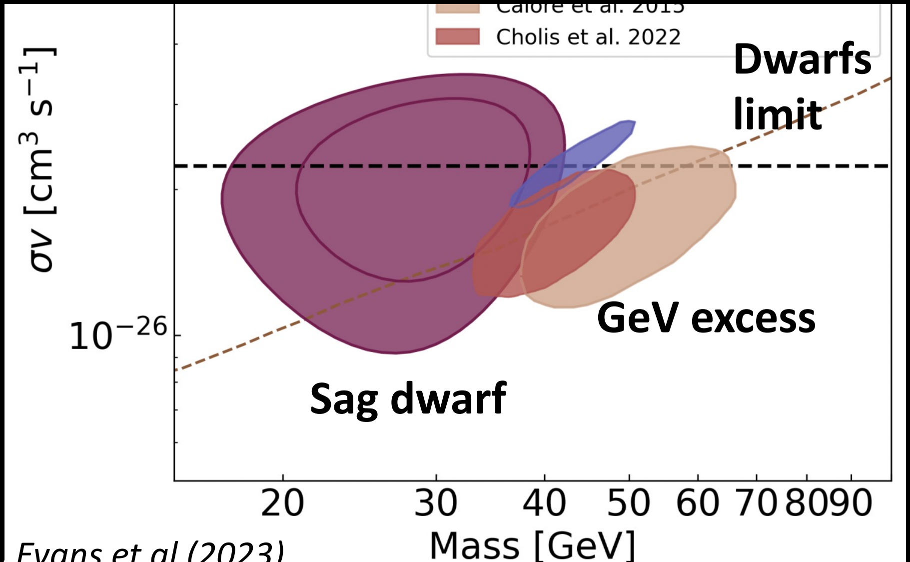
Sagittarius dwarf



Crocker et al (2022)

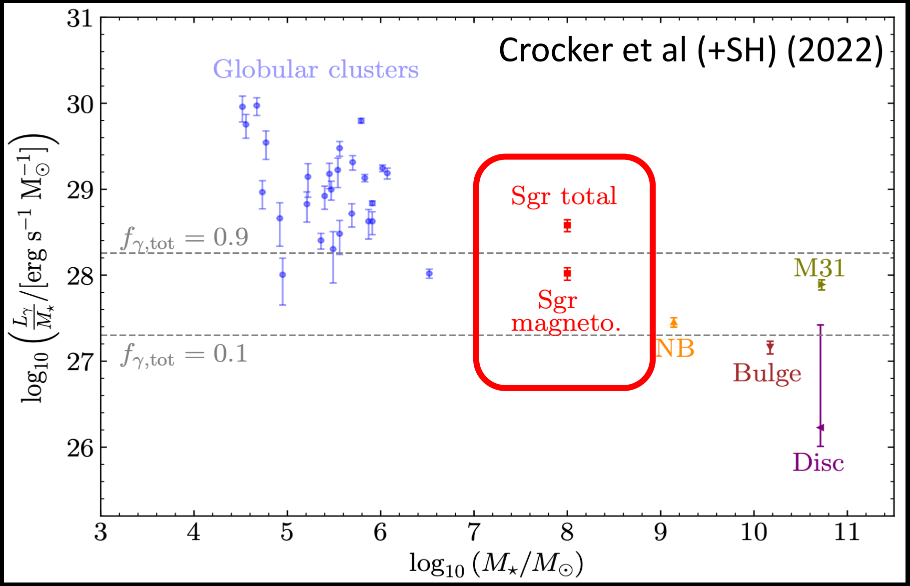


If dwarf core emission is DM, consistent:



Evans et al (2023)

Also extended emission: if pulsars:



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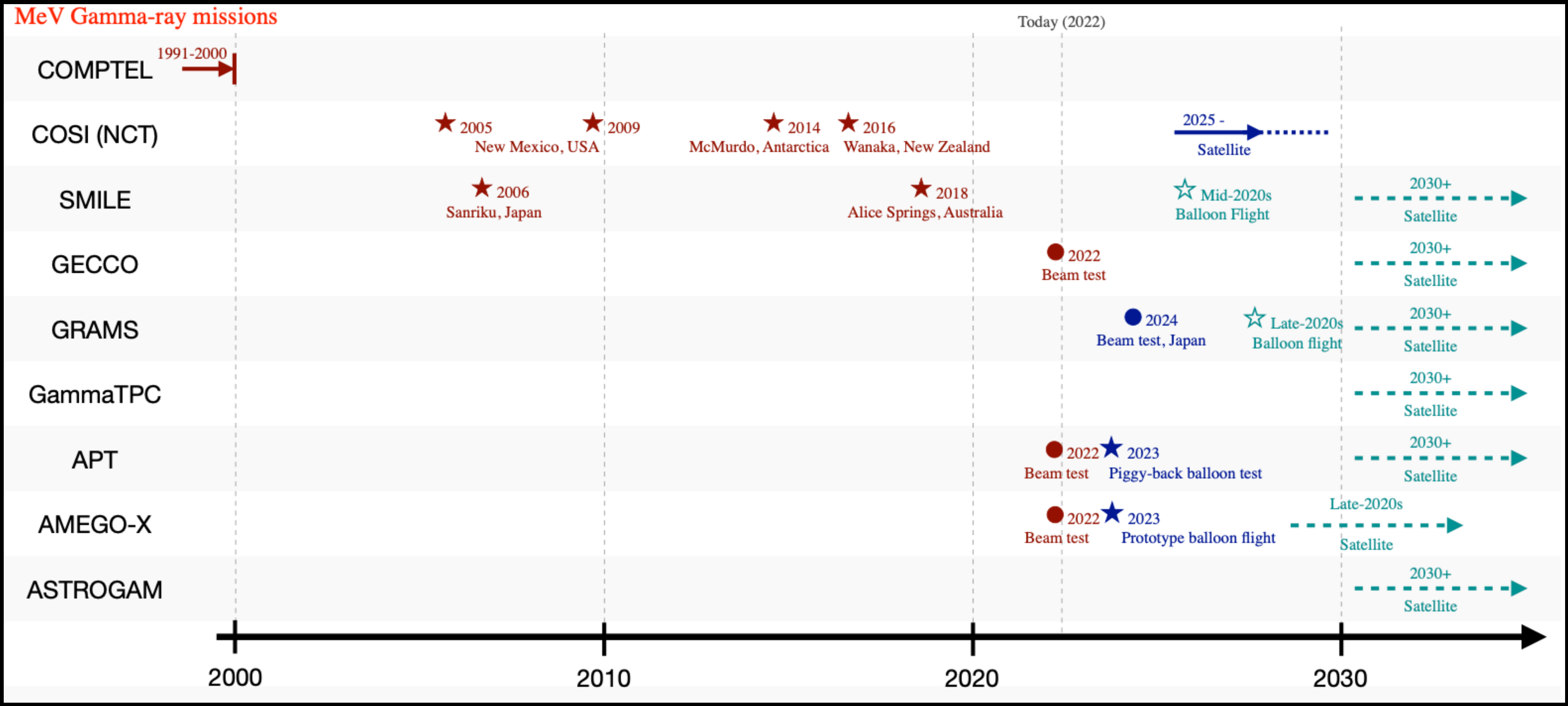

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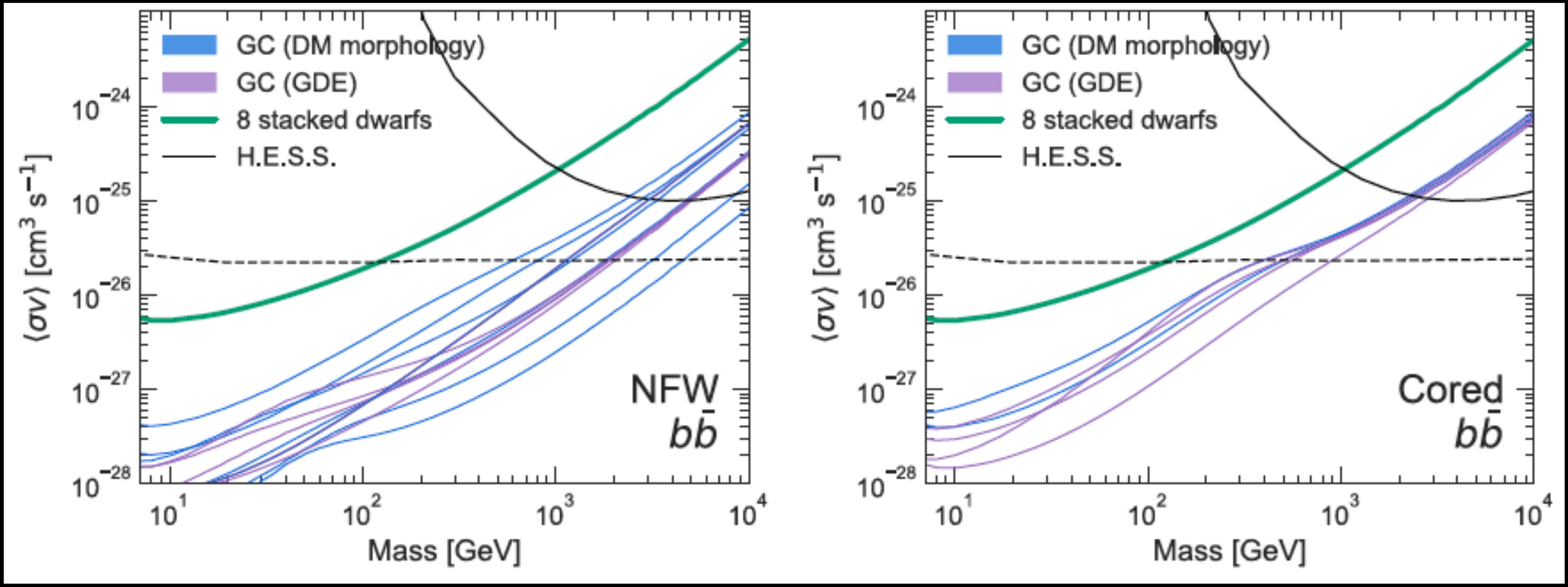
Dark matter limits

Perhaps we found a physically-motivated, *better astrophysical model* which provides a better explanation of the data than DM annhilation

➔ **Constrains thermal dark matter up to ~500 GeV**

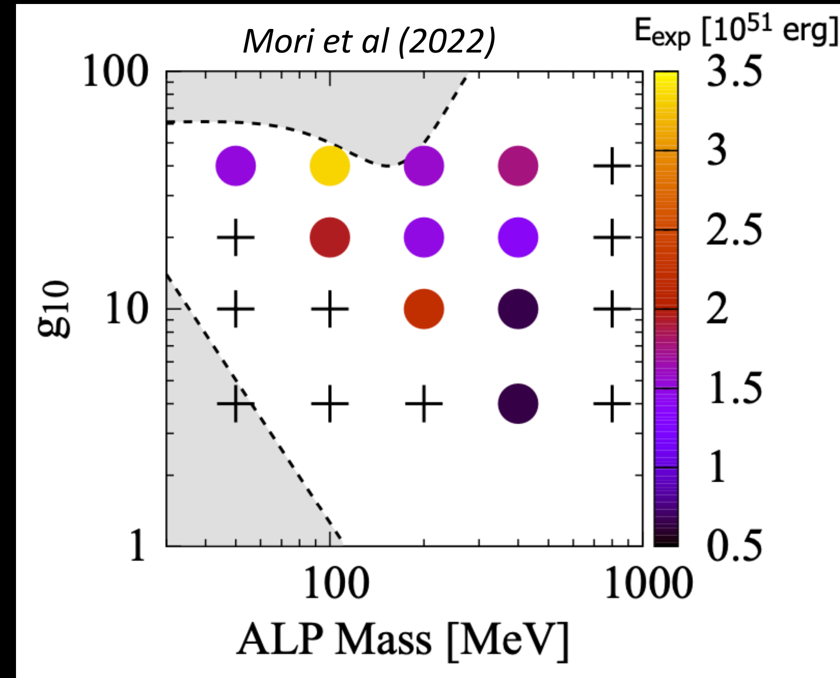
Abazajian et al (2020)



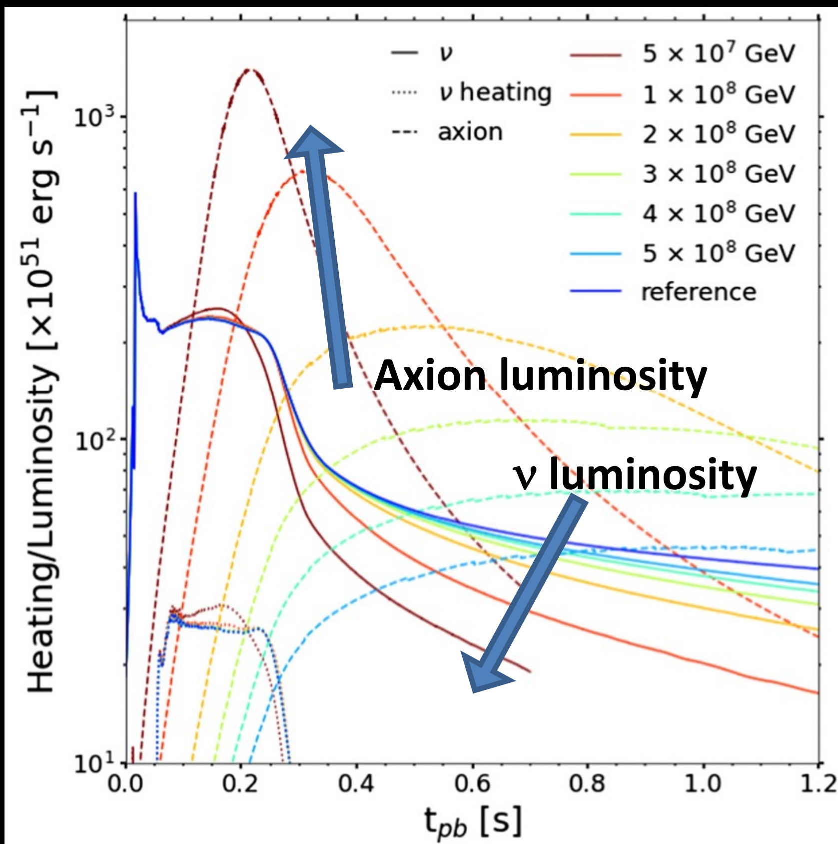
- Impacts of NFW slope [0.5,1.5] & sphericity
- Impacts of background modeling

- Impacts of core (1 kpc) & sphericity
- Impacts of background modeling

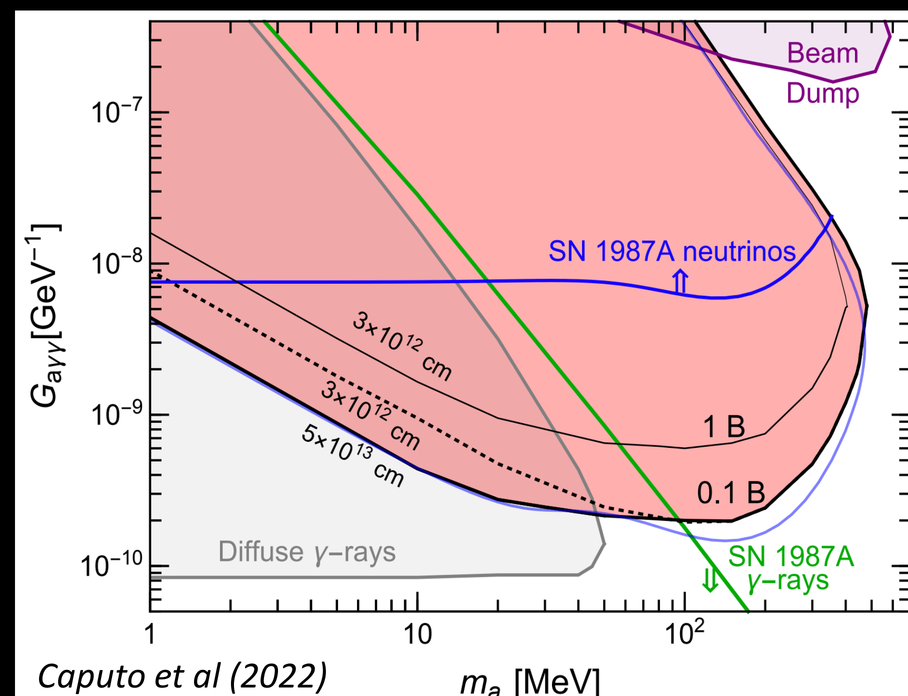
Heavy (MeV) axion: **decays before escape and increase explosion energy. Set constraints based on lowest energy supernovae**



QCD axion: **time-dependent neutrino and axion luminosity predictions**



Betranhandy & O'Connoer (2022)



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