



# Experiment Summary

Jocelyn Monroe,  
University of Oxford

*IDM 2024*

July 11, 2024  
L'Aquila, Italy



*10 years ago...*

# ASTROPARTICLE PHYSICS 2014

A joint TeVPA/IDM conference



Jocelyn Monroe

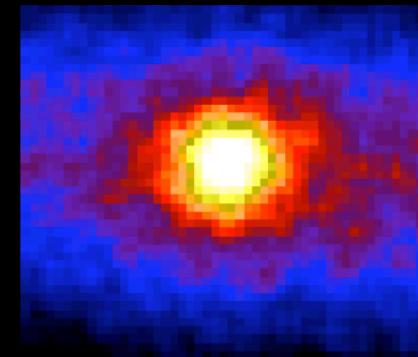
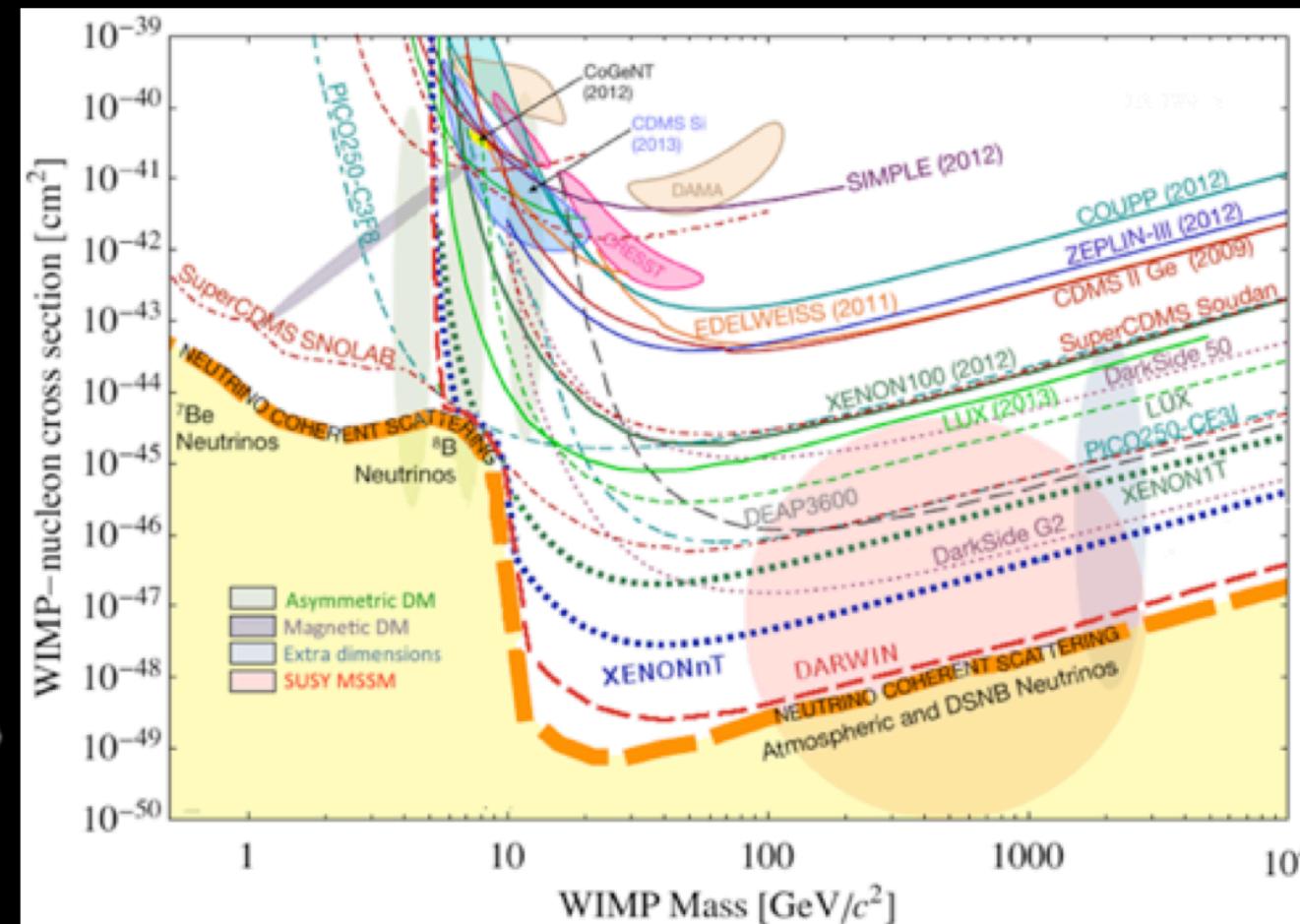
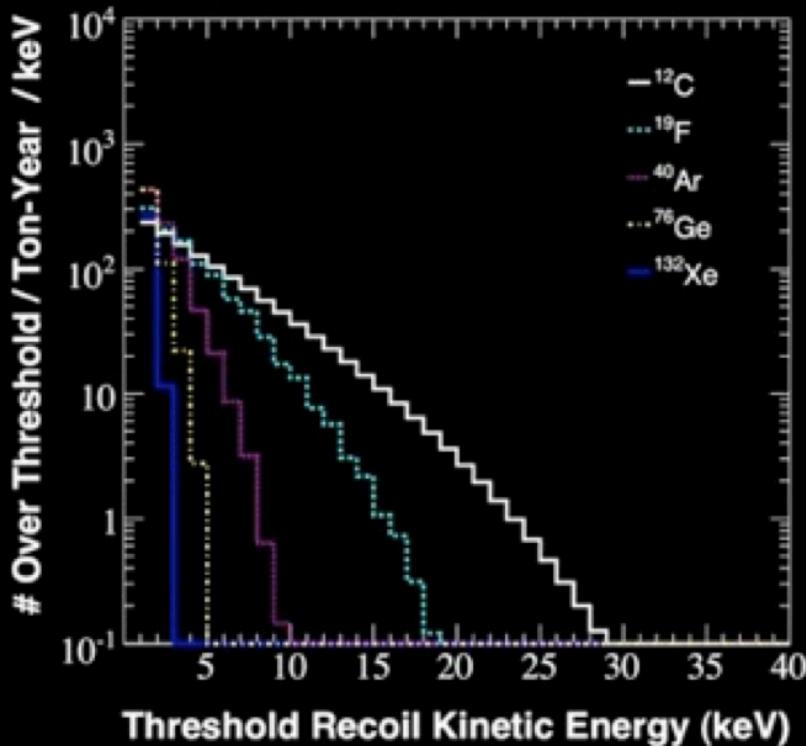
# Reminder: The Neutrino Bound

impossible to shield a detector from coherent neutrino scattering!

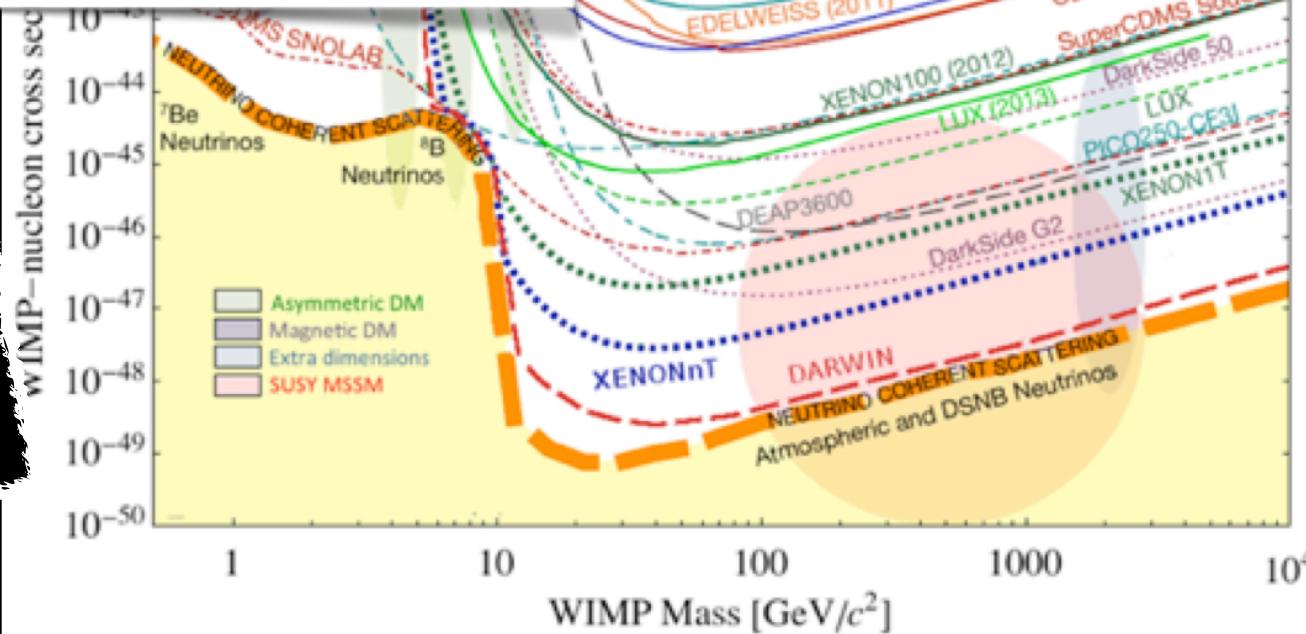
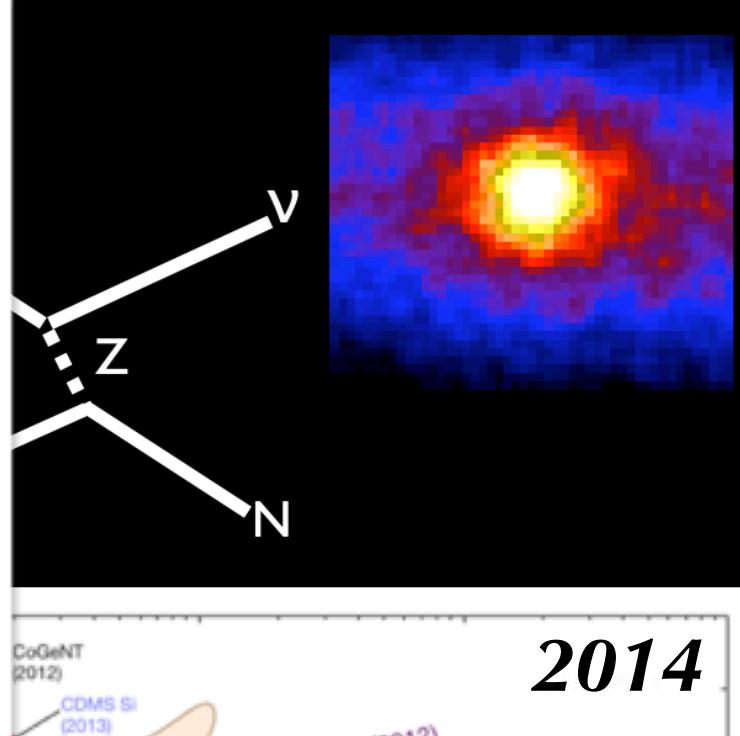
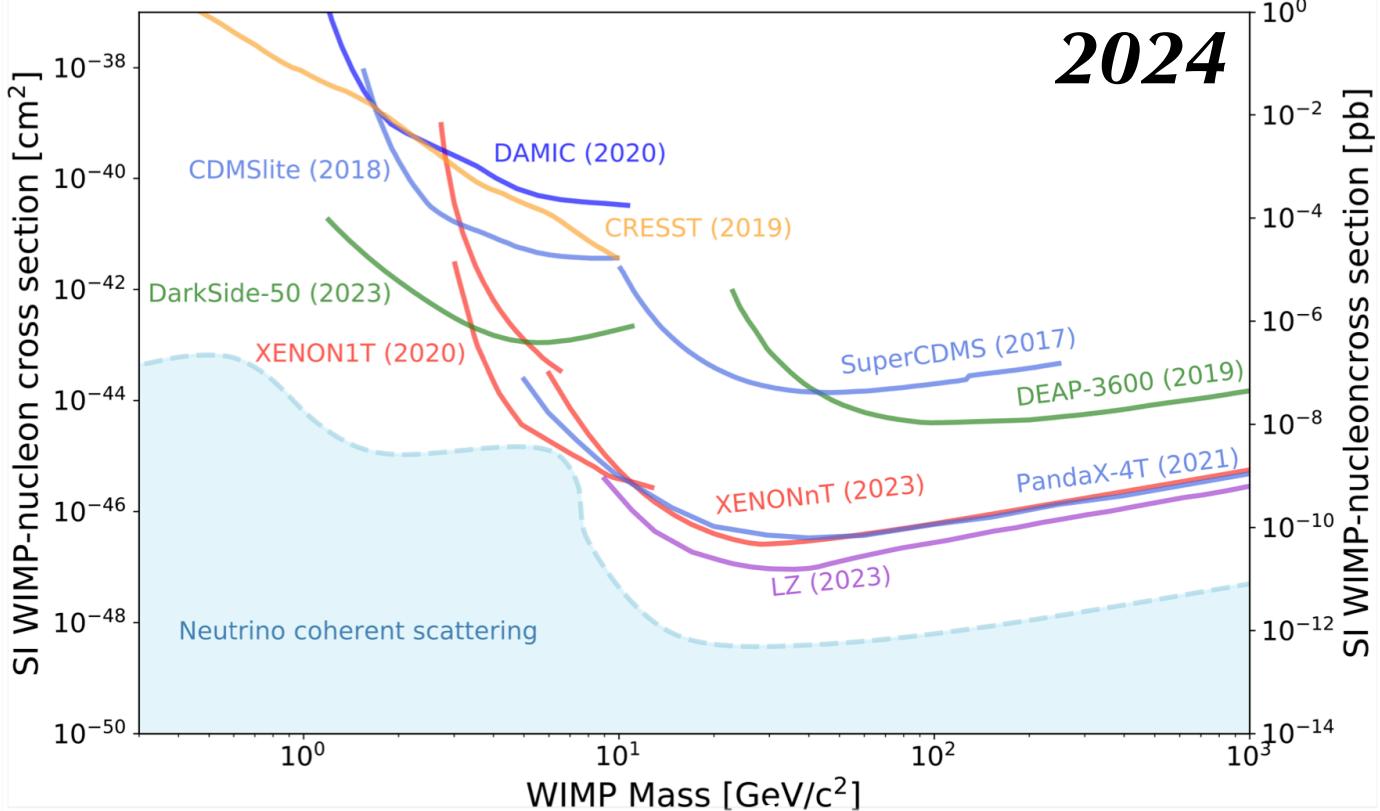
nuclear recoil final state

1 event/ton-year =  $10^{-46}$ - $10^{-48}$  cm $^2$  limit

JM, P. Fisher, PRD76:033007 (2007)



*irreducible background, unless you measure the direction!*



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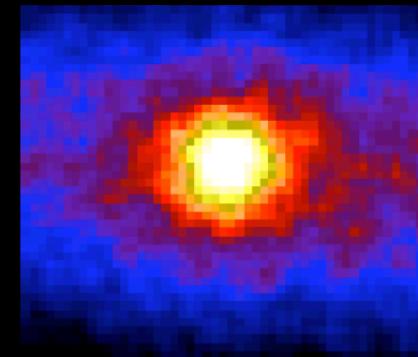
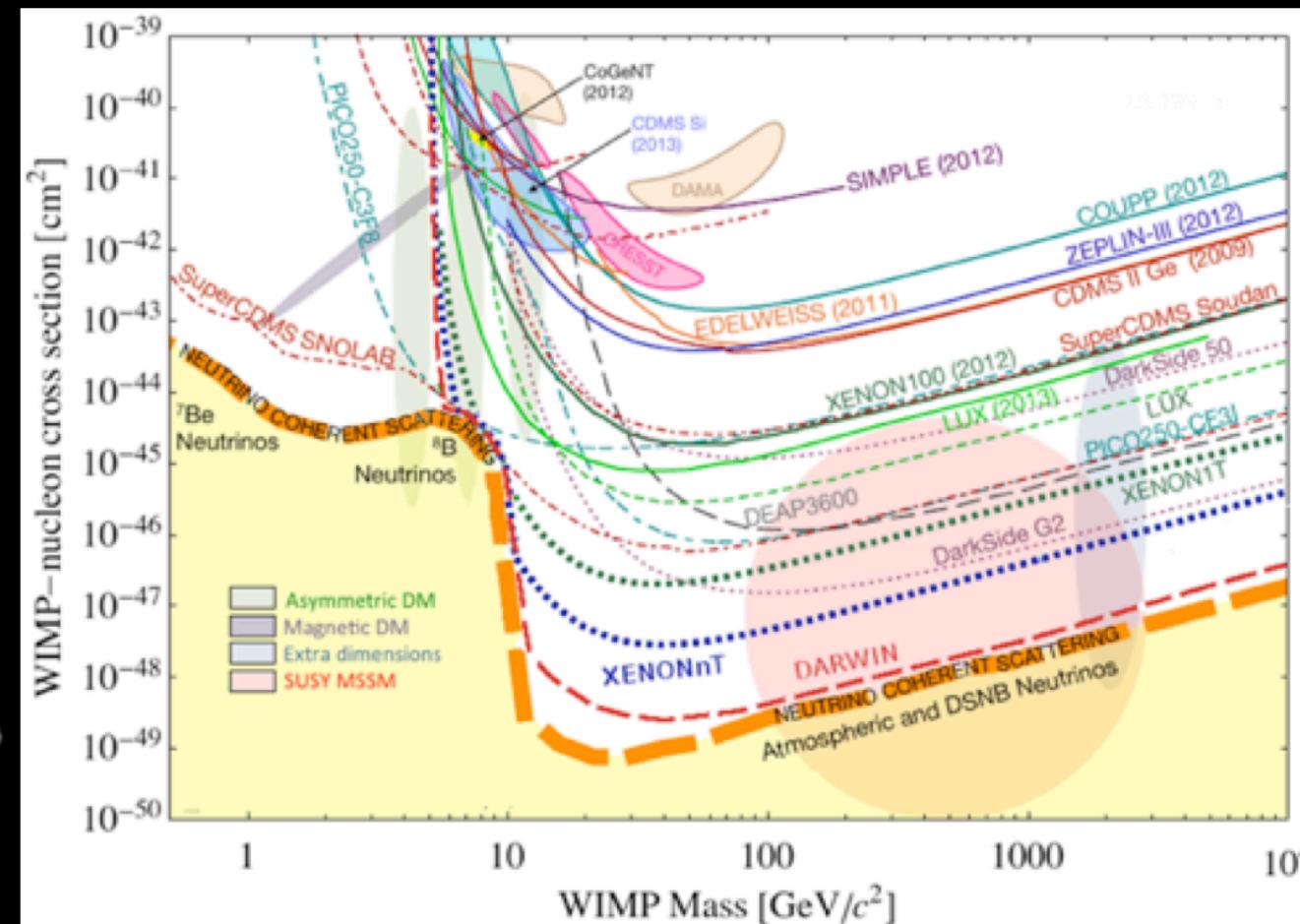
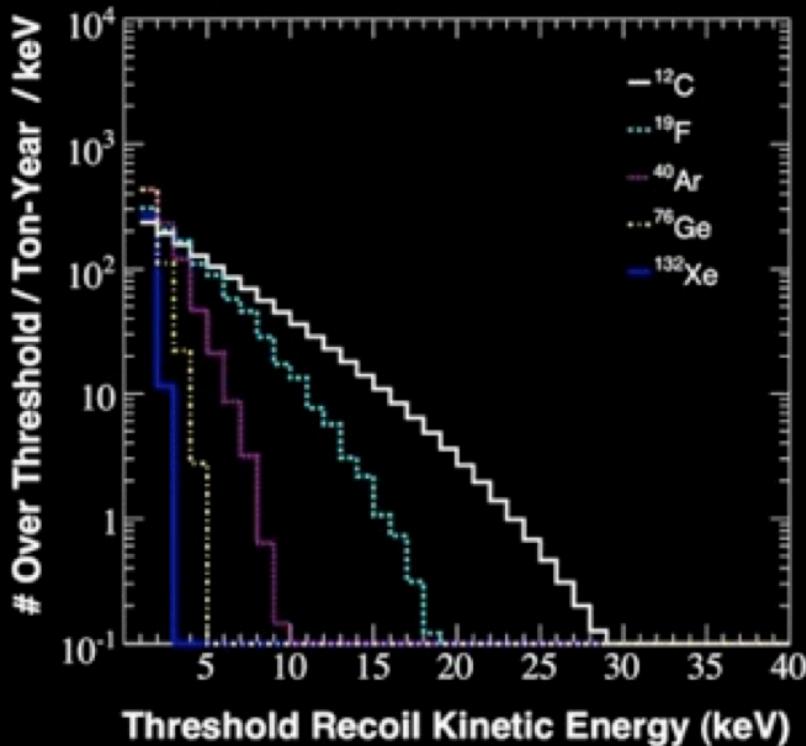
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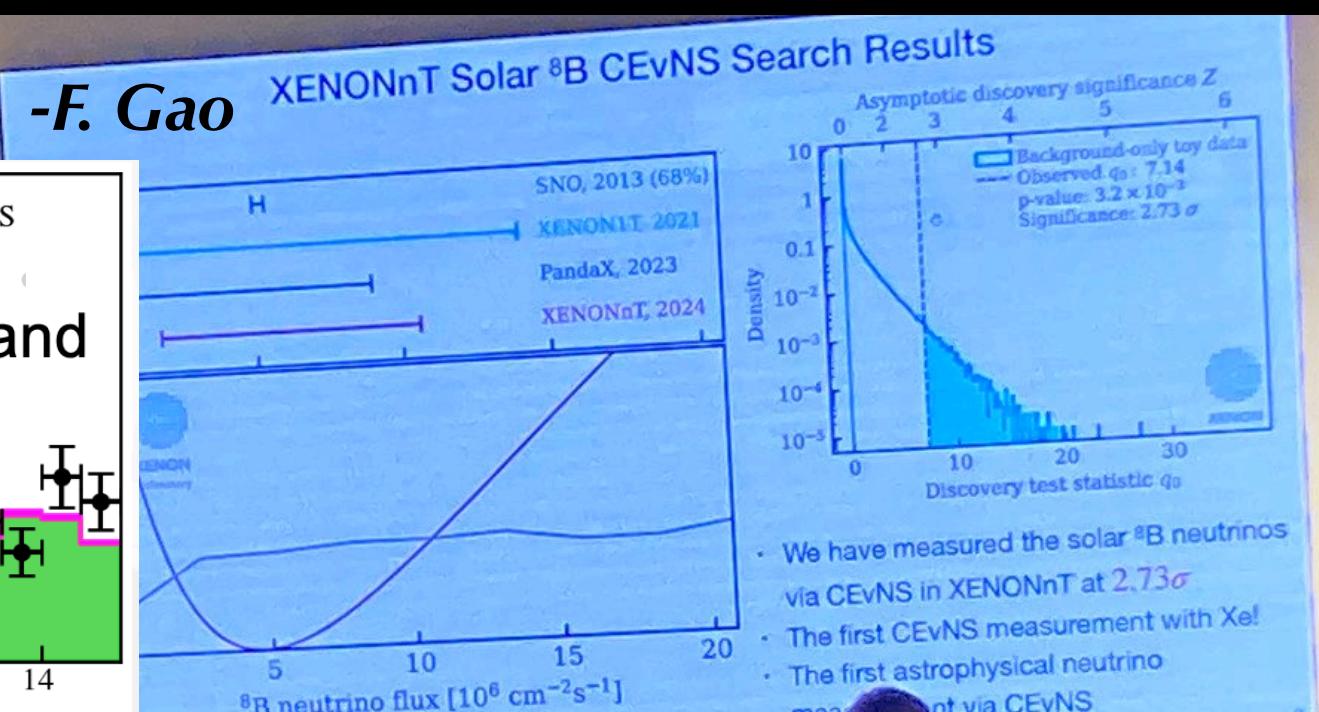
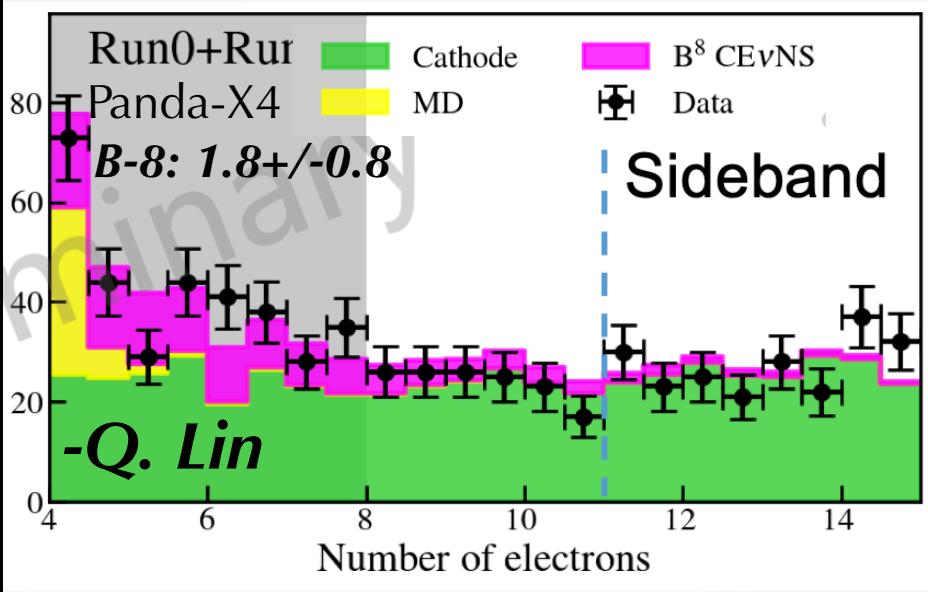
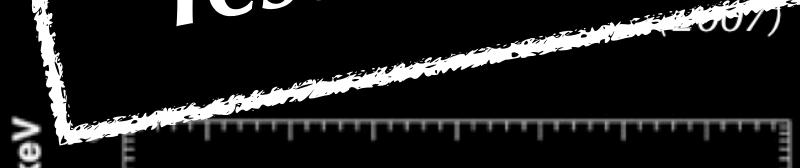


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Yesterday's background



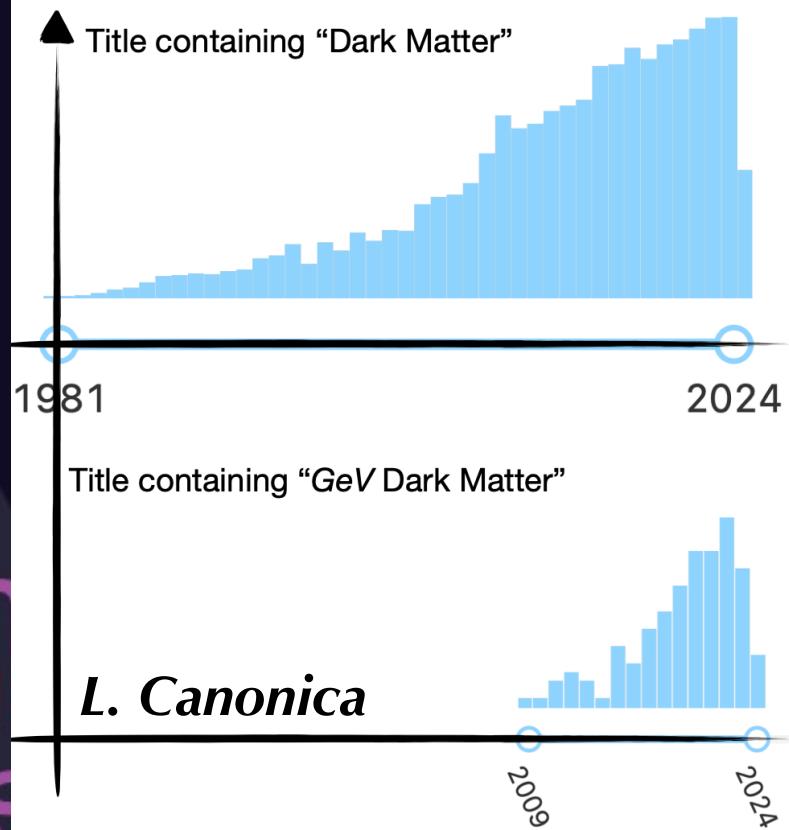
Threshold Recoil Kinetic Energy (keV)



irreducible background

# IDM2024 by numbers

154 talks,  $O(50)$  posters,  
256 participants, 41 organizers ...



L. Canonica

*Still searching...  
and in lots of  
new ways*

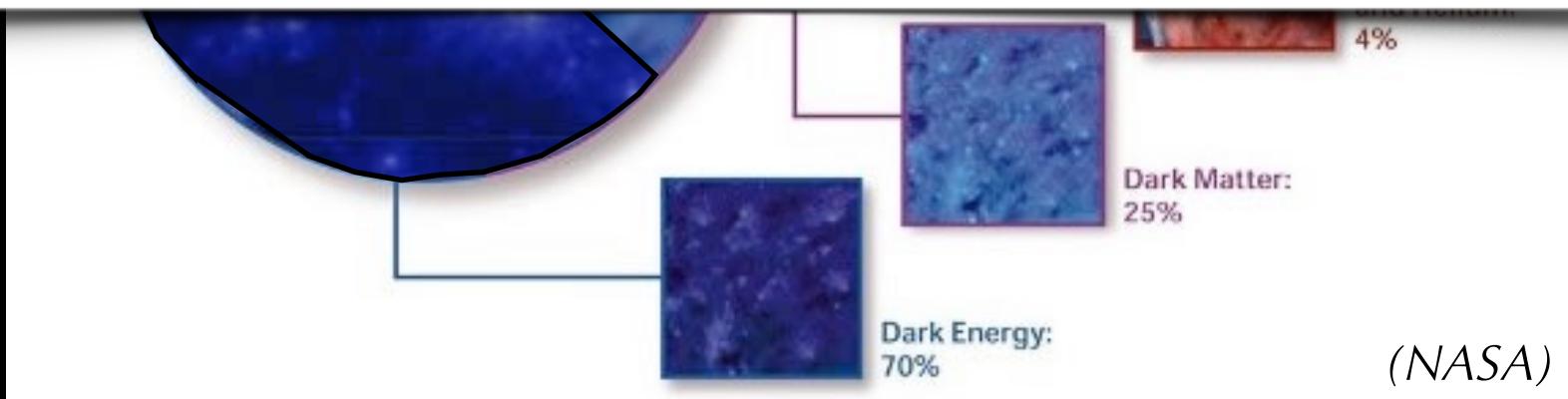


# Concordance Model of Cosmology

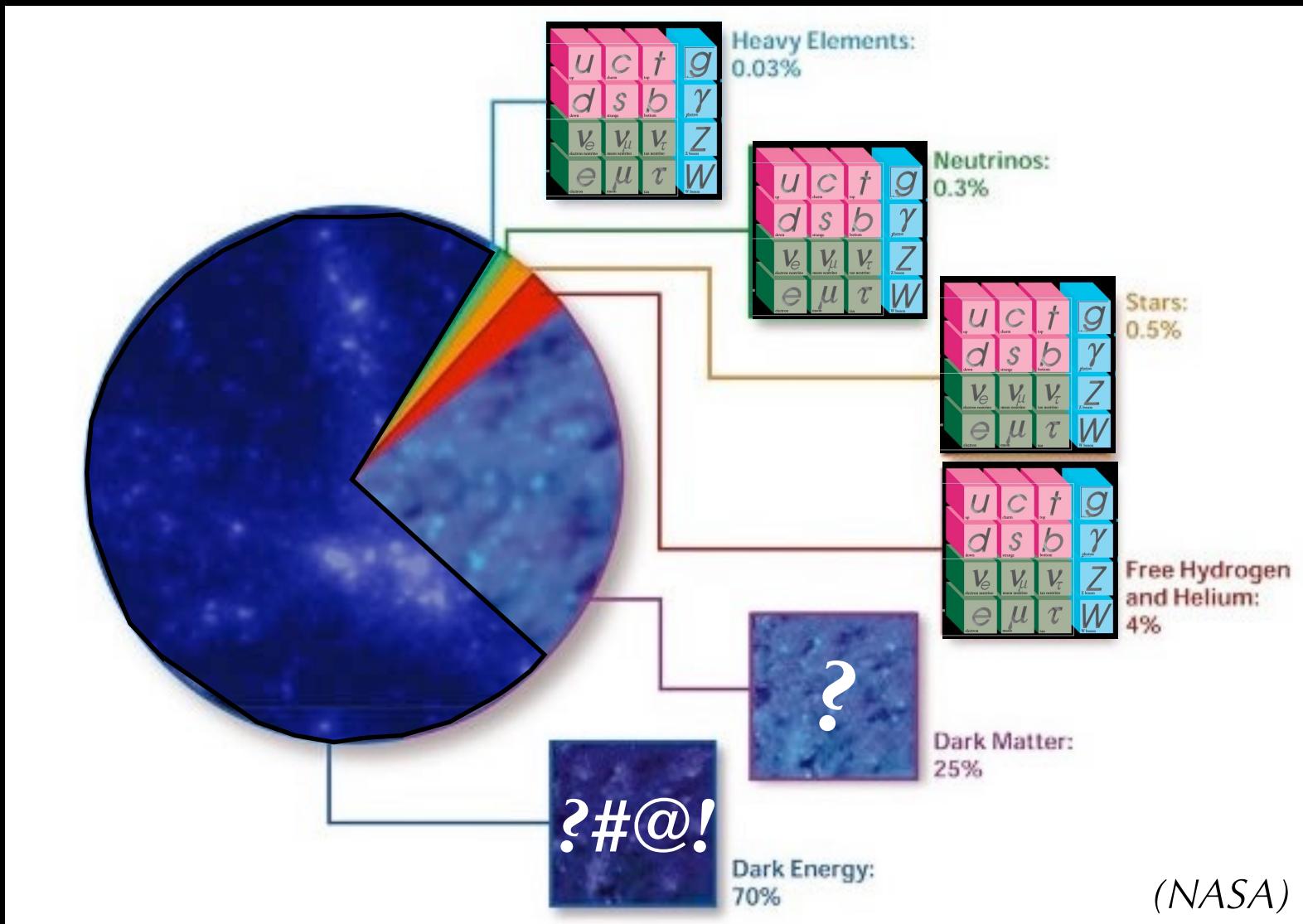


Steadily moving towards a scenario in which, rather than the SM + a DM particle, you have SM + a multicomponent dark sector in which address the dark matter problem and much more (e.g. the  $H_0$  tension with some early dark energy component???).

—Piero Ullio



# Concordance Model of Cosmology



*The Standard Model of Particle Physics  
describes <5% of the universe!*



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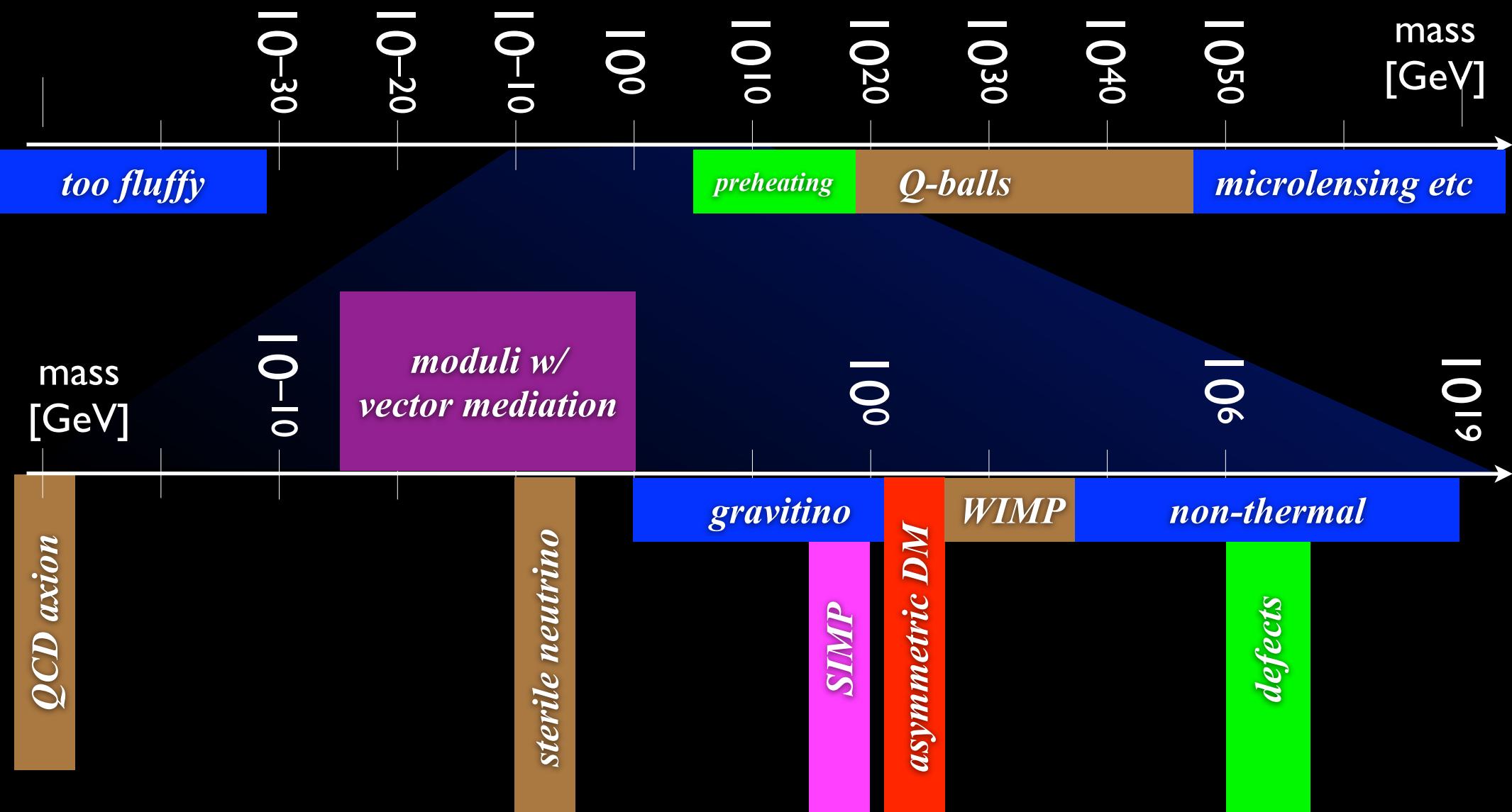


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# Theorist's View

(thanks to H. Murayama)



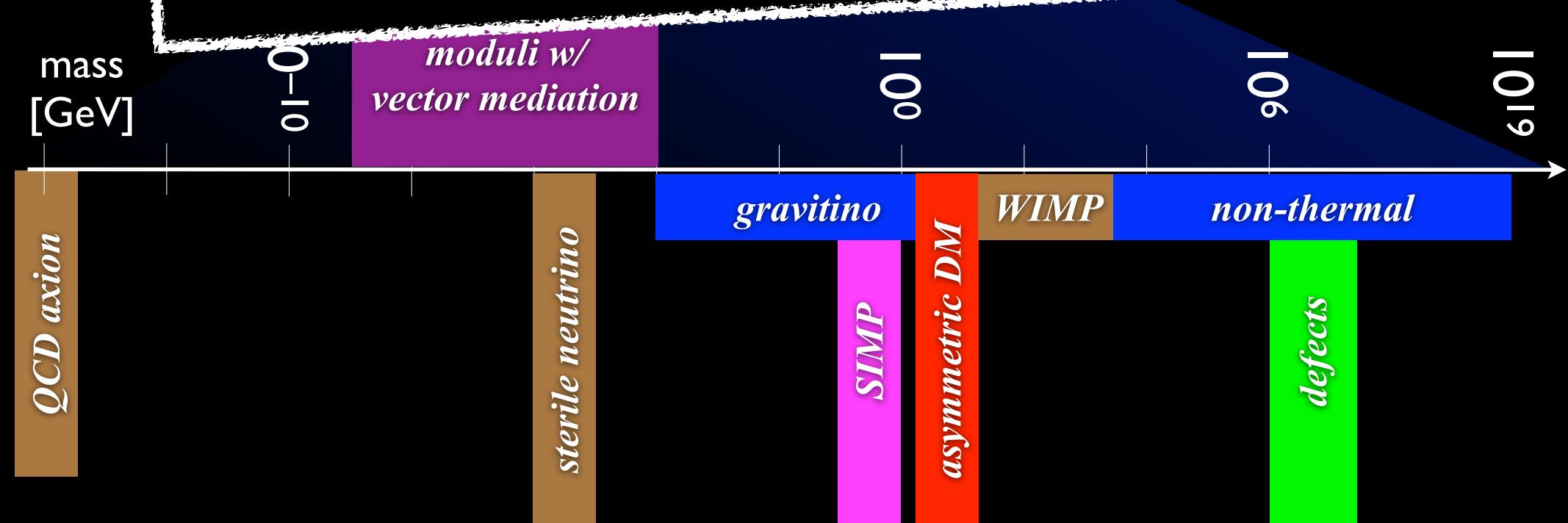
New sociology: dark matter definitely exists, naturalness problem may be optional? Need to explain dark matter on its own.



*our experimental programme is much broader (and more interesting!) than just WIMPs*

*too far*

mass [GeV]  
ansing etc



New sociology: dark matter definitely exists, naturalness problem may be optional? Need to explain dark matter on its own.

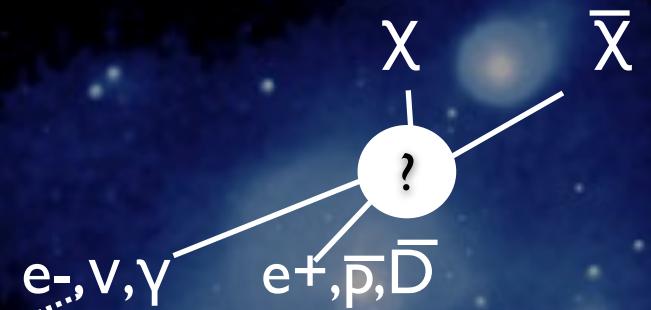


# Experimentalist's View

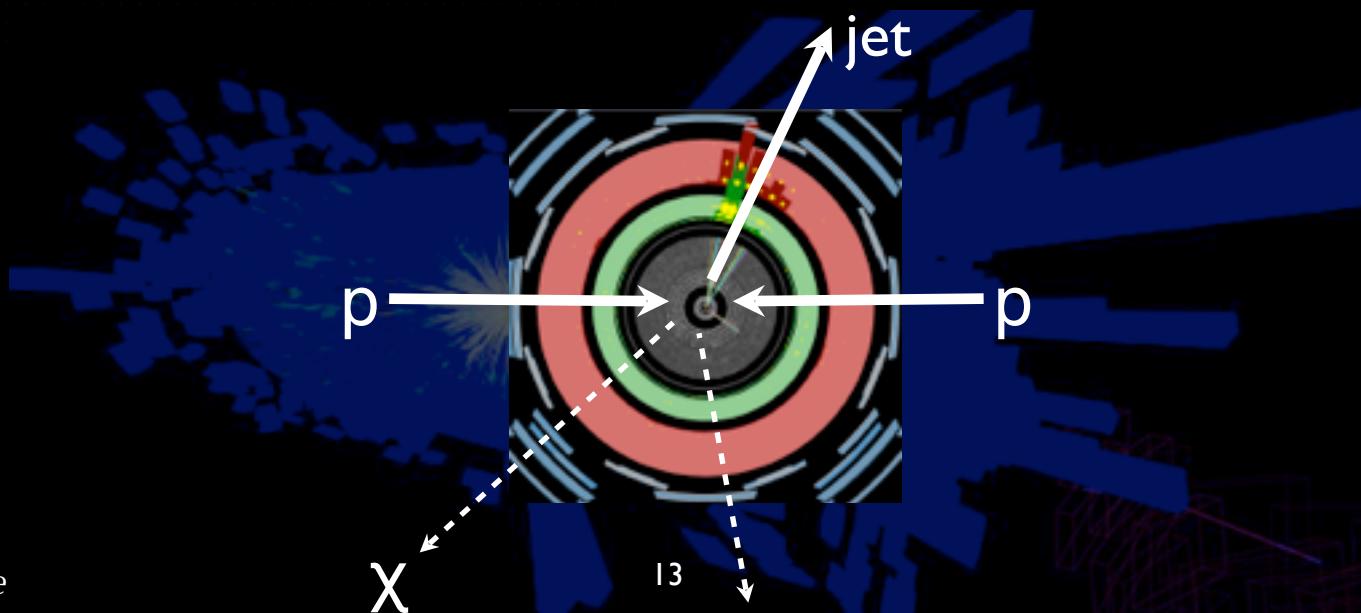


Direct Detection

Indirect Detection

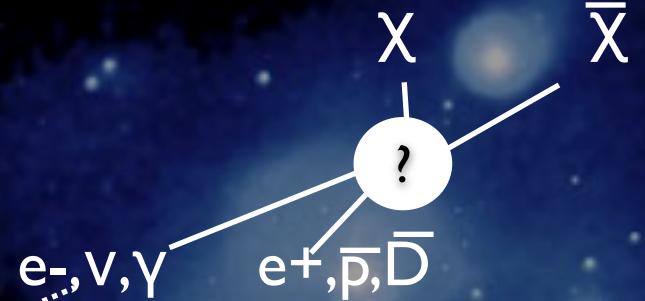


Accelerator Production

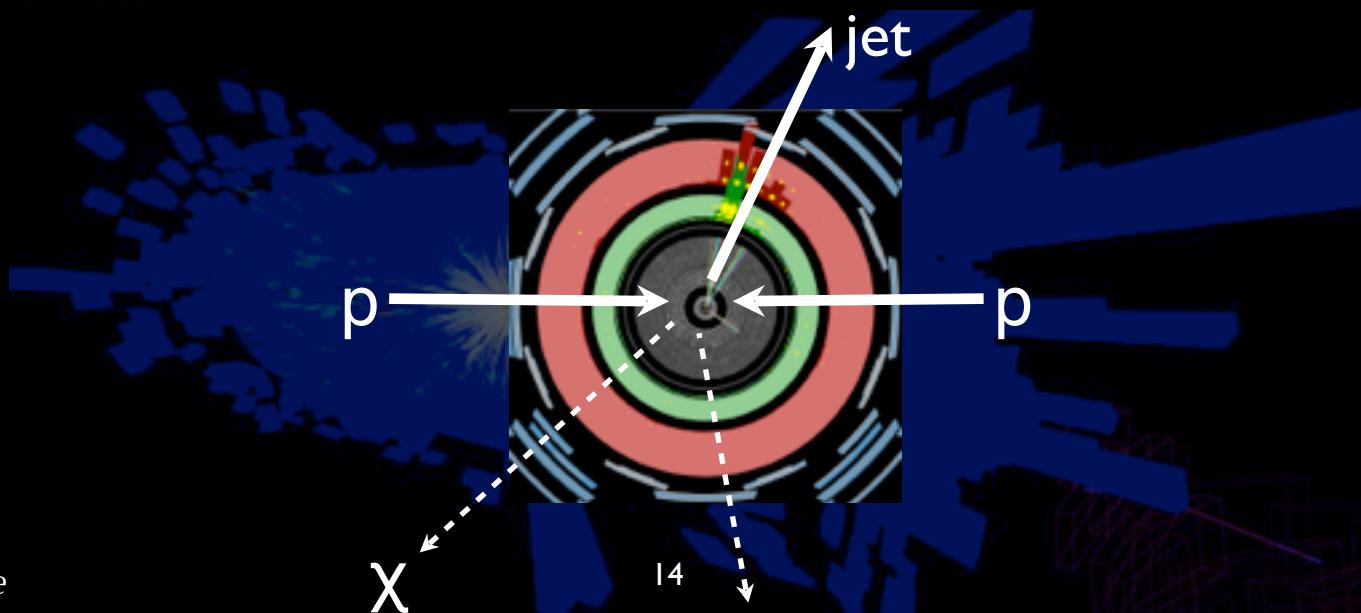


# Experimentalist's View

Indirect Detection

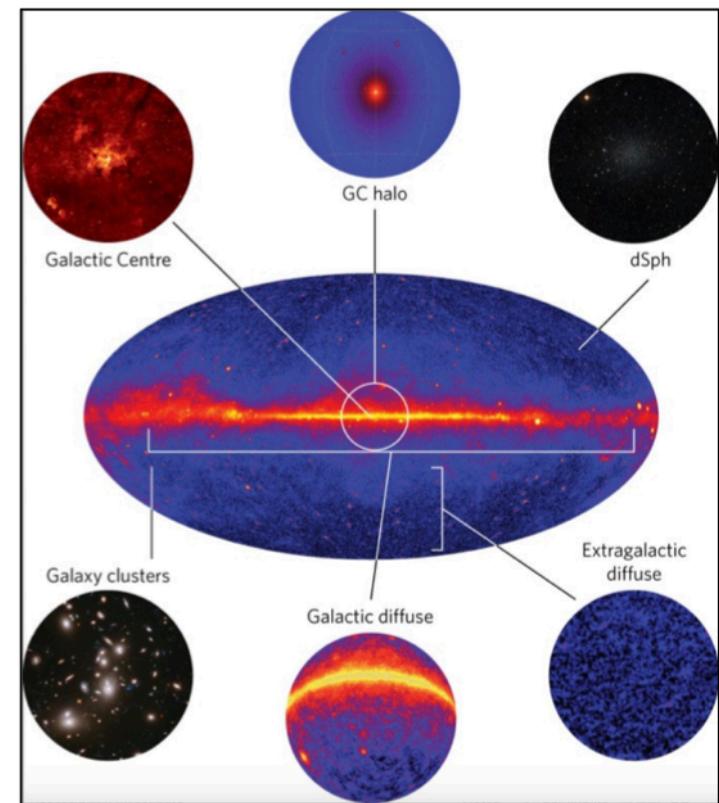
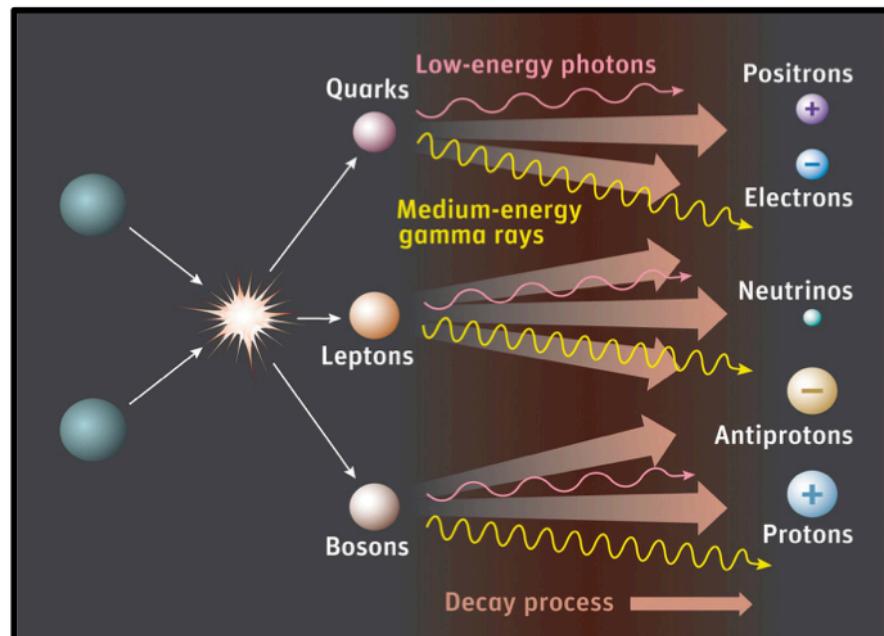


*~all of particle physics is looking for dark matter now!*



# The Many Paths Toward Indirect Detection

- Dark matter could produce a variety of different potentially observable annihilation/decay products, each of which feature various advantages and disadvantages; there is a great deal of complementary between these different indirect detection signals
- Searches with gamma rays and neutrinos employ many different search strategies, targeting different parts of the sky; again, bringing a great deal of complementary to the problem



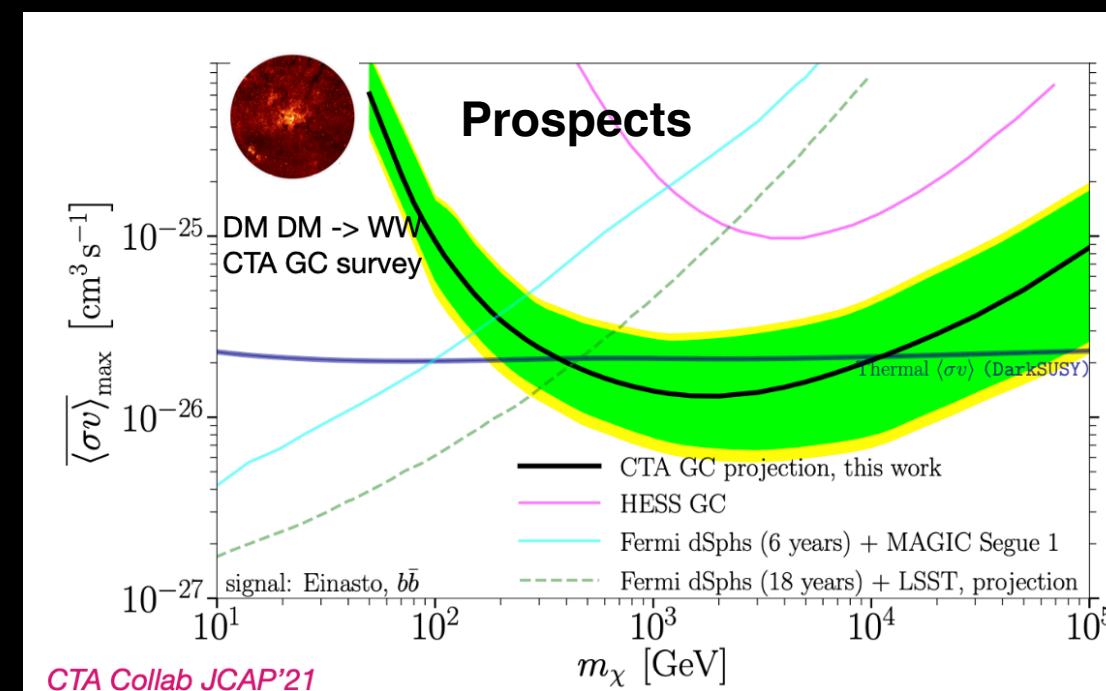
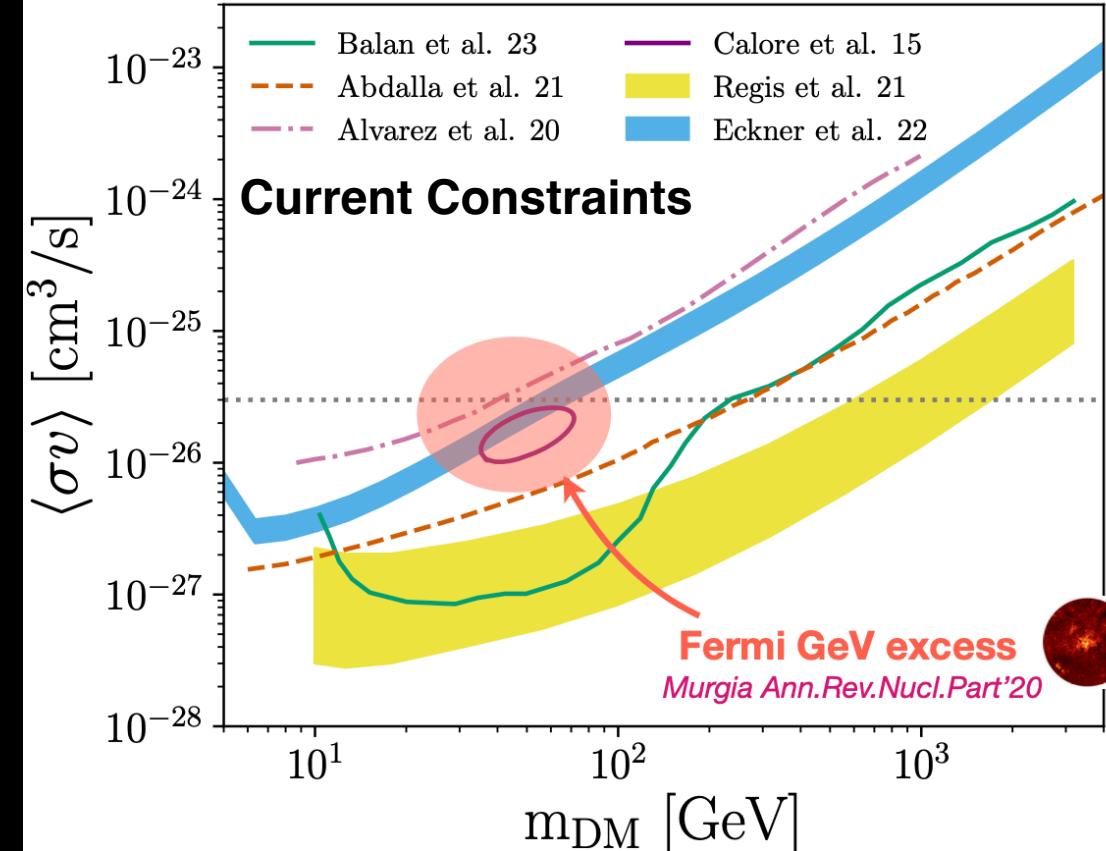
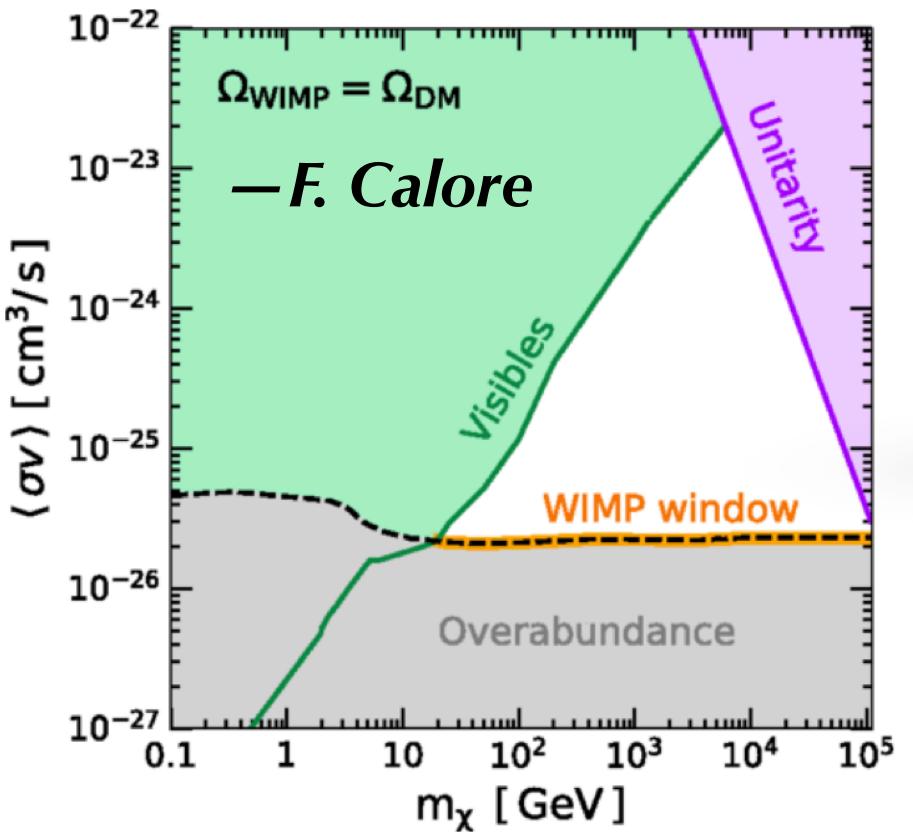
– D. Hooper



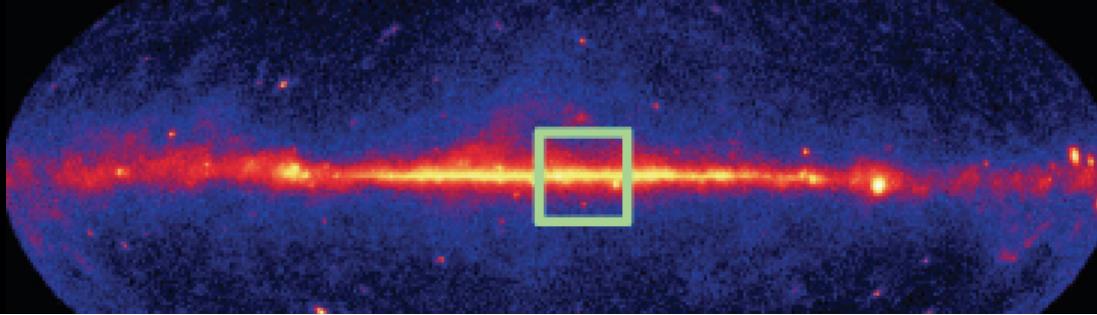
Jocelyn Monroe

# Self-Annihilation Searches

## Annihilation to “visible” SM states

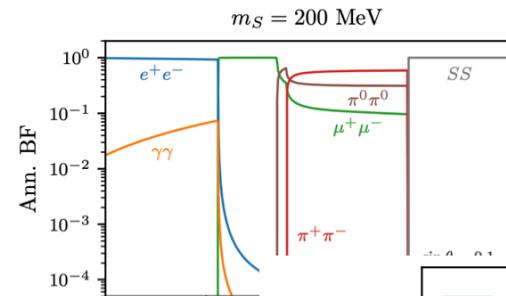


# Visible Final States Beyond WIMPs



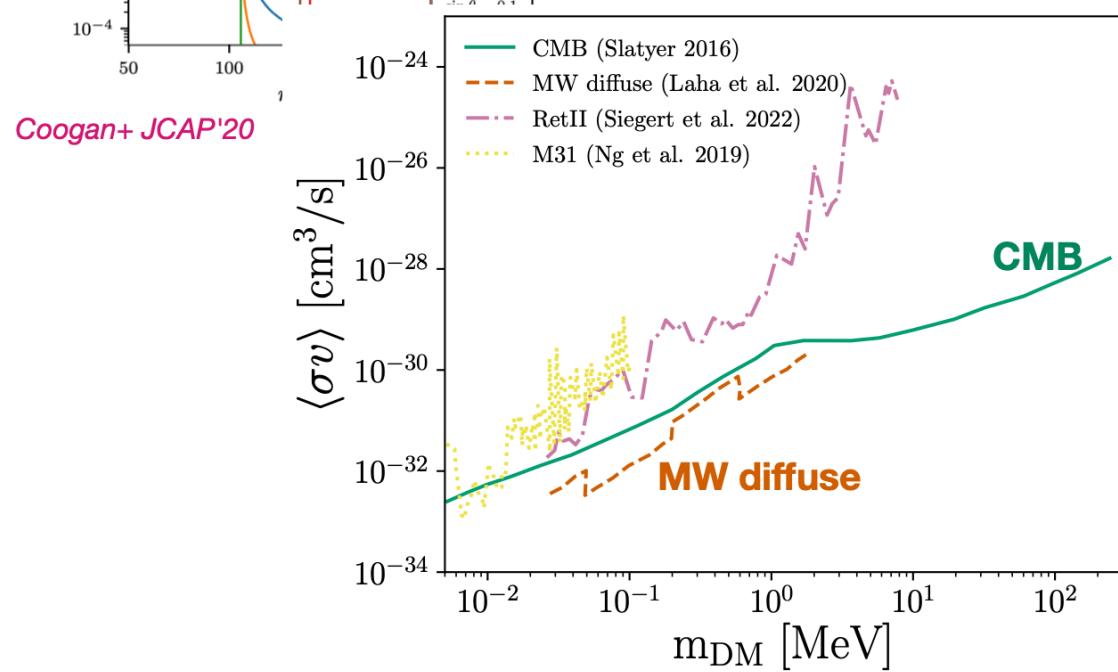
—F. Calore

## Sub-GeV dark matter limits



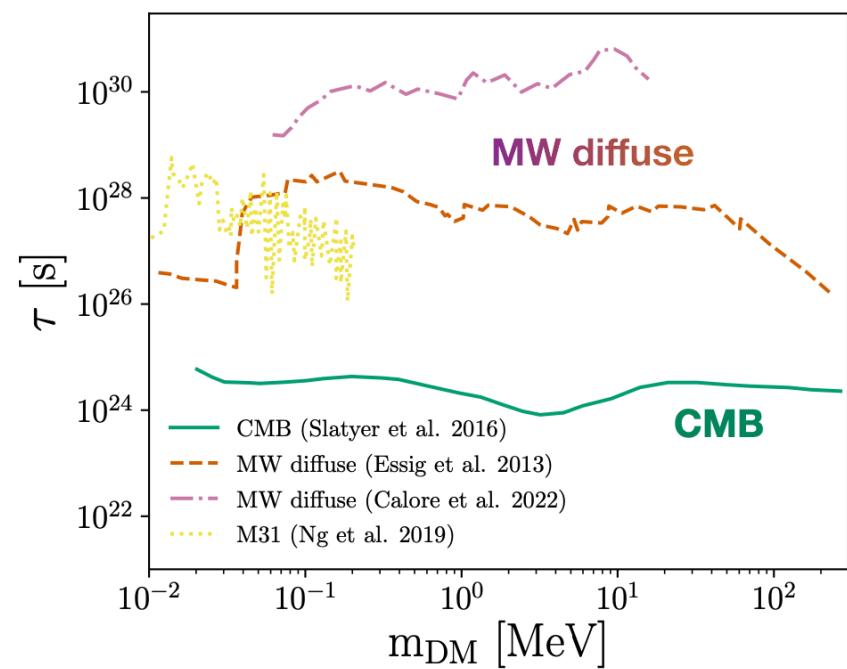
- Simple thermal freeze-out scenario for s-wave annihilation generically ruled out
- But p-wave models (many of the portals) still viable

FC FIPs2022 Proceedings



Two-photons annihilation

Siegert, FC+ MNRAS'24



Two-photons decay

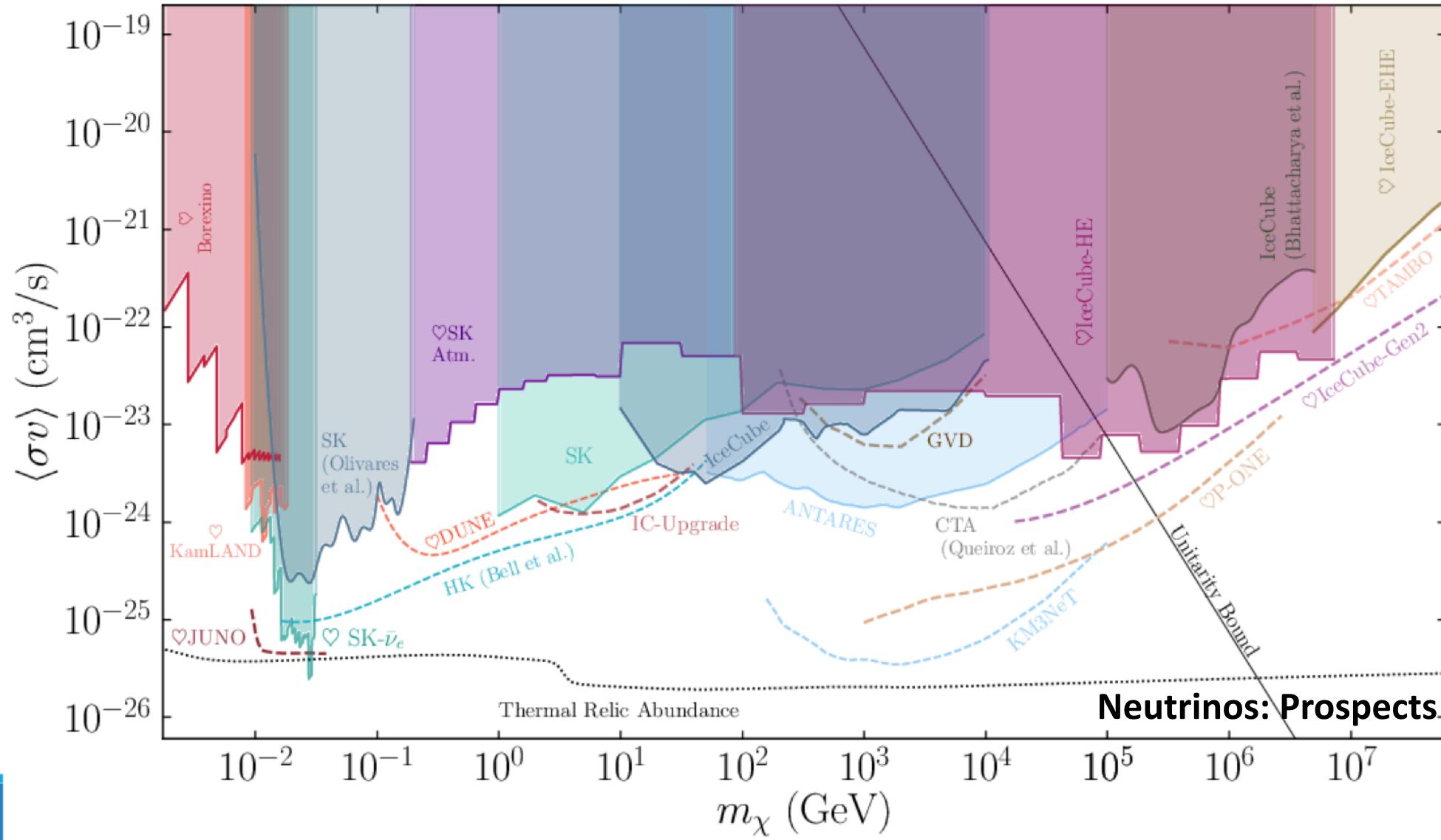
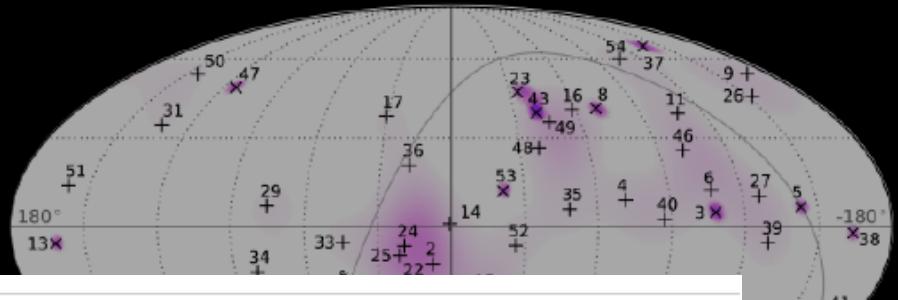
FC+ MNRAS'23

<https://zenodo.org/record/7984451>



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# Invisible Final States Beyond WIMPs



# Indirect Detection ... any Signals?

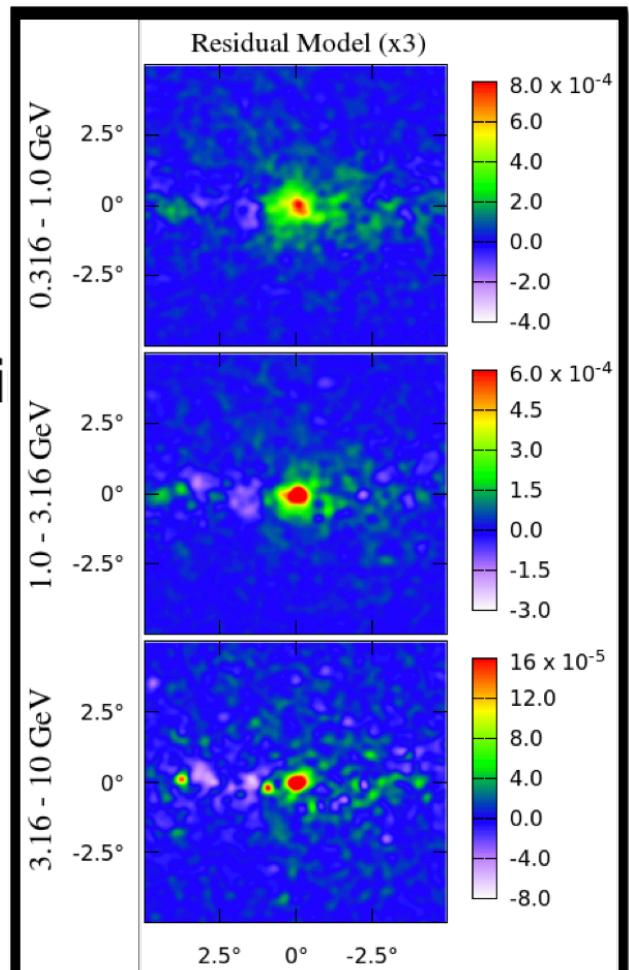
## Anomalies and Excesses – *D. Hooper*

- Cosmic-Ray Positron Excess
  - Very likely produced by pulsars
- Cosmic-Ray Antiproton Excess
  - Subject to significant hadronic uncertainties
- Anti-Deuterons, Anti-Helium at AMS?!?
  - Utterly perplexing if true
- 3.5 keV Line
  - There is no line.
- Galactic Center Gamma-Ray Excess
  - Consistent with arising from annihilating dark matter or from a large population of exotic pulsars

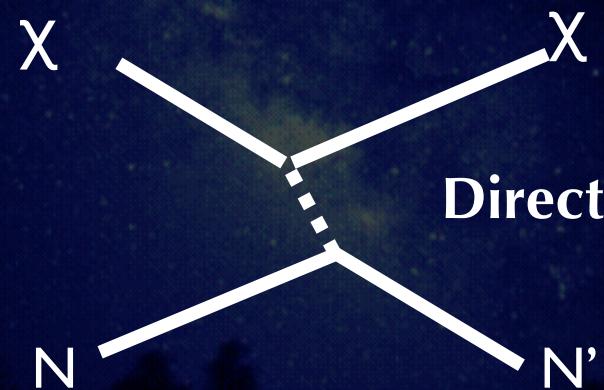


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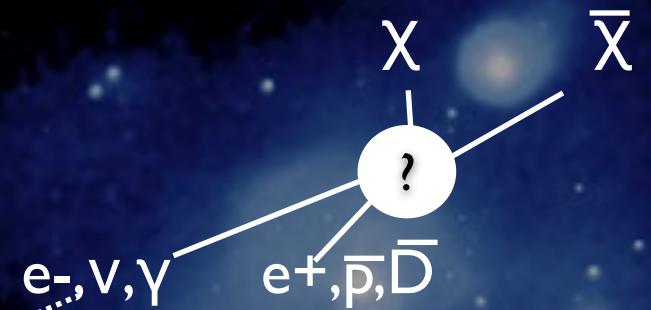


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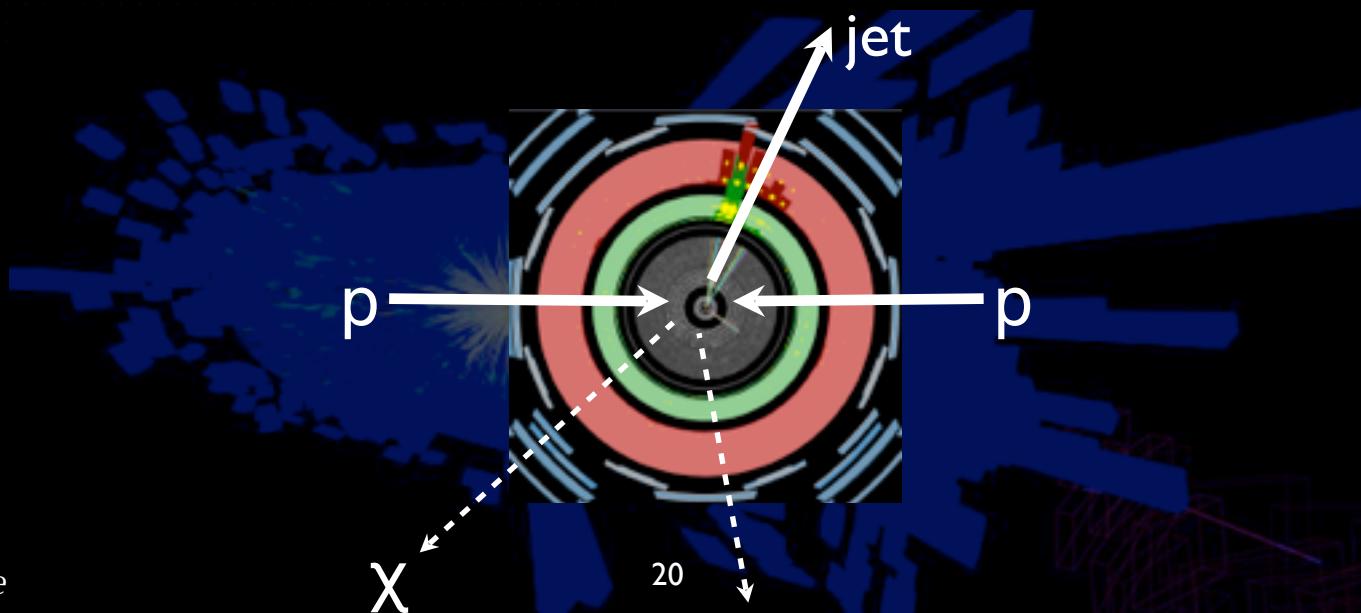
Direct Detection

Indirect Detection



Indirect Detection

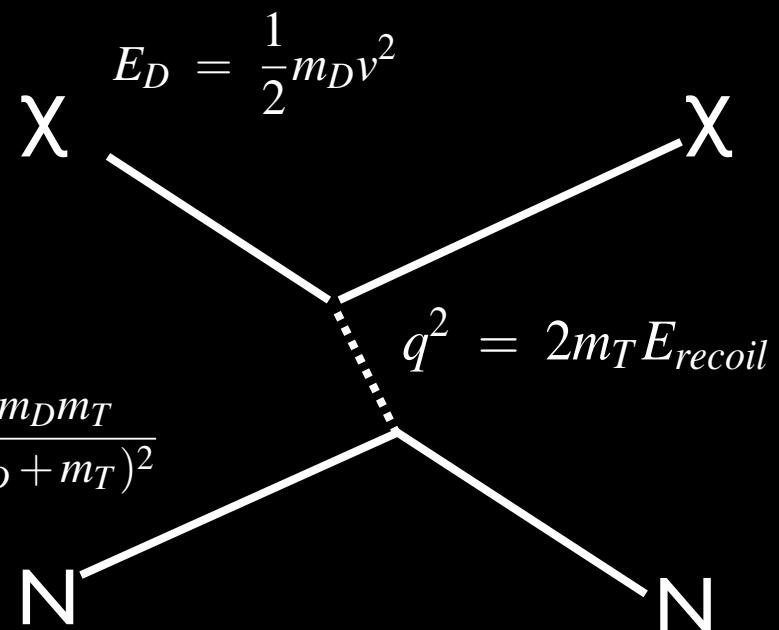
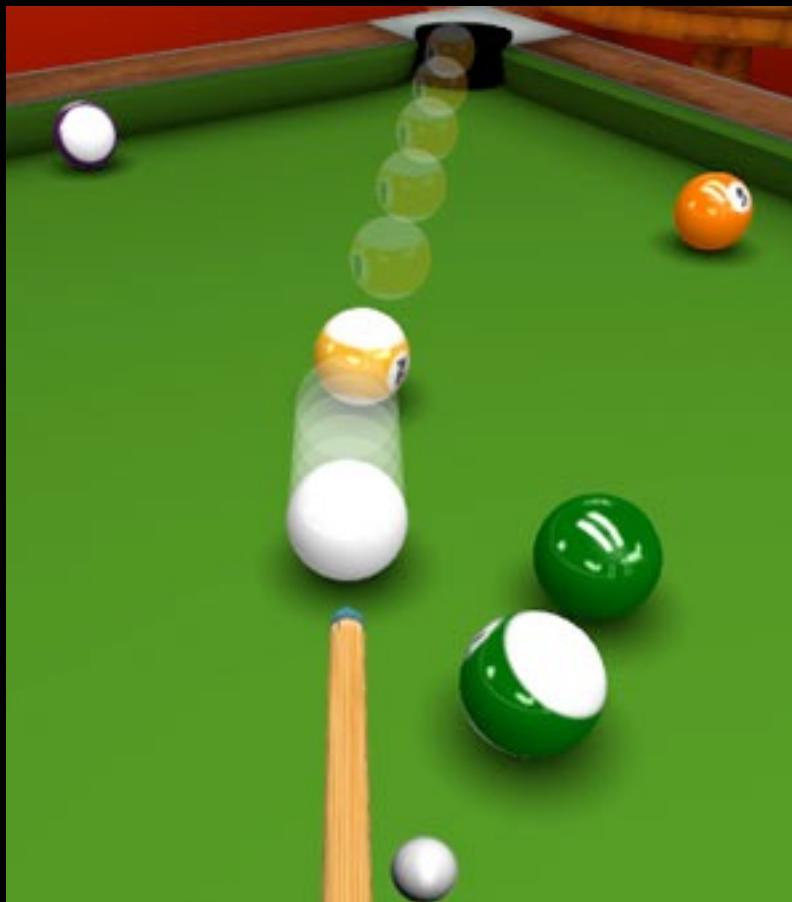
Accelerator Production



# Direct Detection Strategies

scattering kinematics:  $v/c \sim 8E-4!$

recoil angle strongly correlated  
with incoming WIMP direction



## Spin Independent:

$\chi$  scatters coherently off of  
the entire nucleus A:  $\sigma \sim A^2$   
*D. Z. Freedman, PRD 9, 1389 (1974)*

## Spin Dependent:

mainly unpaired nucleons contribute  
to scattering amplitude:  $\sigma \sim J(J+1)$

# Direct Detection Strategies

$$E_D = \frac{1}{2}m_D v^2$$

X

X

## Coherent effects of a weak neutral current

Daniel Z. Freedman<sup>†</sup>

National Accelerator Laboratory, Batavia, Illinois 60510

and Institute for Theoretical Physics, State University of New York, Stony Brook, New York 11790

(Received 15 October 1973; revised manuscript received 19 November 1973)

If there is a weak neutral current, then the elastic scattering process  $\nu + A \rightarrow \nu + A$  should have a sharp coherent forward peak just as  $e + A \rightarrow e + A$  does. Experiments to observe this peak can give important information on the isospin structure of the neutral current. The experiments are very difficult, although the estimated cross sections (about  $10^{-38}$  cm<sup>2</sup> on carbon) are favorable. The coherent cross sections (in contrast to incoherent) are almost energy-independent. Therefore, energies as low as 100 MeV may be suitable. Quasi-coherent nuclear excitation processes  $\nu + A \rightarrow \nu + A^*$  provide possible tests of the conservation of the weak neutral current. Because of strong coherent effects at very low energies, the nuclear elastic scattering process may be important in inhibiting cooling by neutrino emission in stellar collapse and neutron stars.

There is recent experimental evidence<sup>1</sup> from CERN and NAL which suggests the presence of a neutral current in neutrino-induced interactions.

important to interpret experimental results in a very broad theoretical framework.<sup>4</sup> We assume a general current-current effective Lagrangian

<sup>1</sup>F. J. Hasert *et al.*, Phys. Lett. **46B**, 138 (1973);

A. Benvenuti *et al.*, Phys. Rev. Lett. (to be published).

scattering amplitude.  $\sigma \sim J(J+1)$



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If there is a weak neutral current, it will have a sharp cut-off at low energy.

CEvNS: ~50 years from prediction to discovery

The conservation of lepton number at very low energies, the effect of a weak neutral current in inhibiting cooling by neutrino emission from neutron stars.

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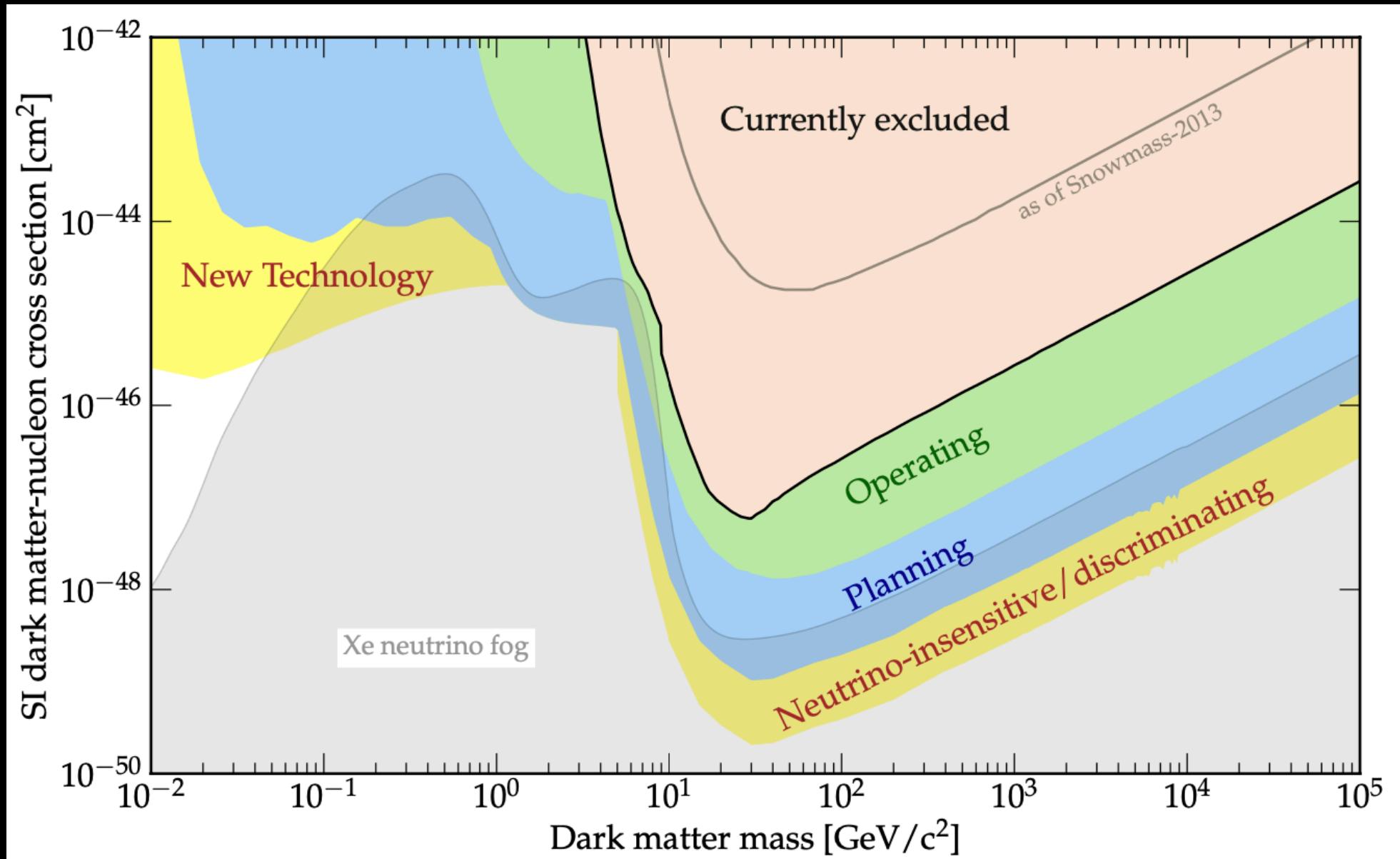
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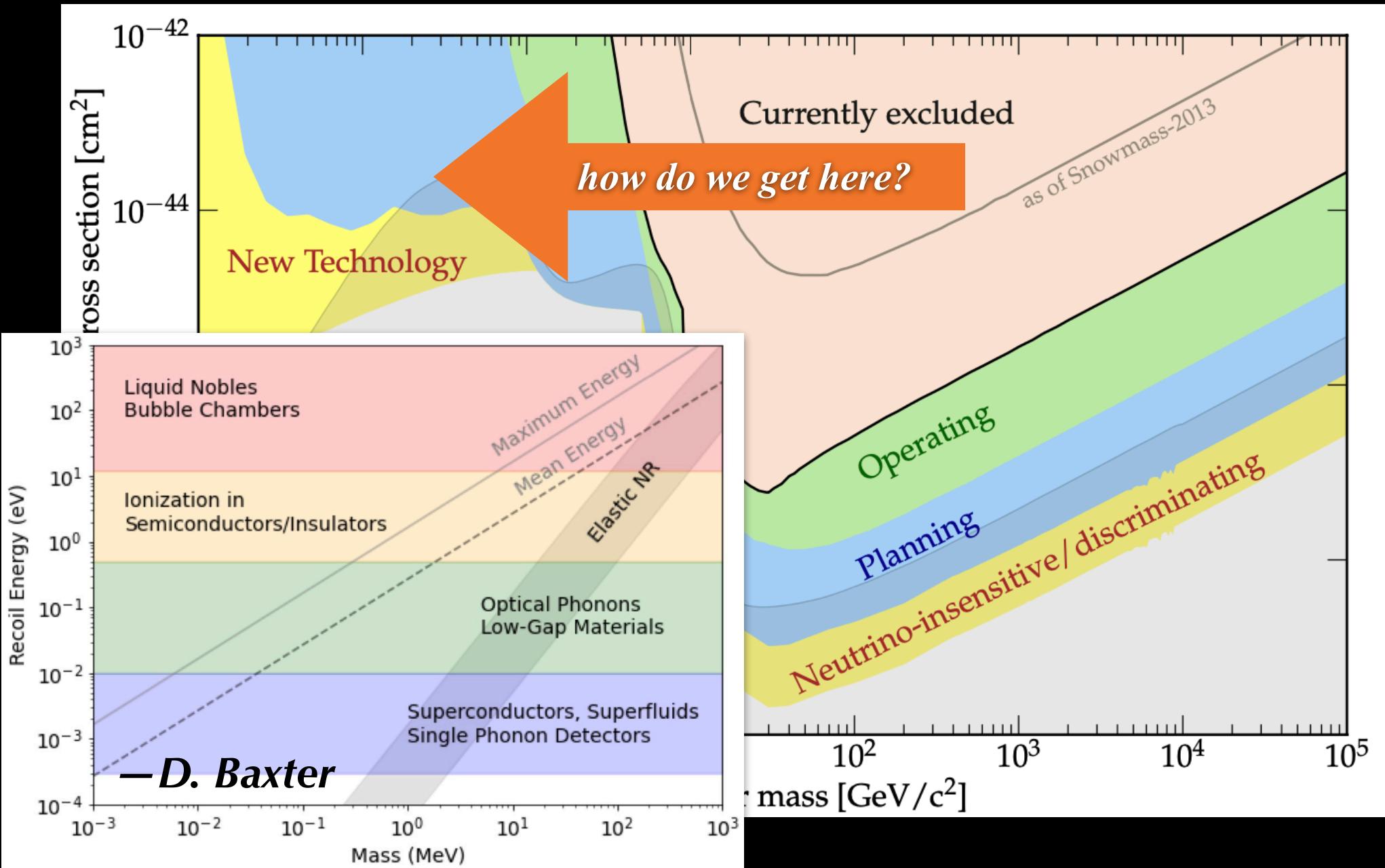
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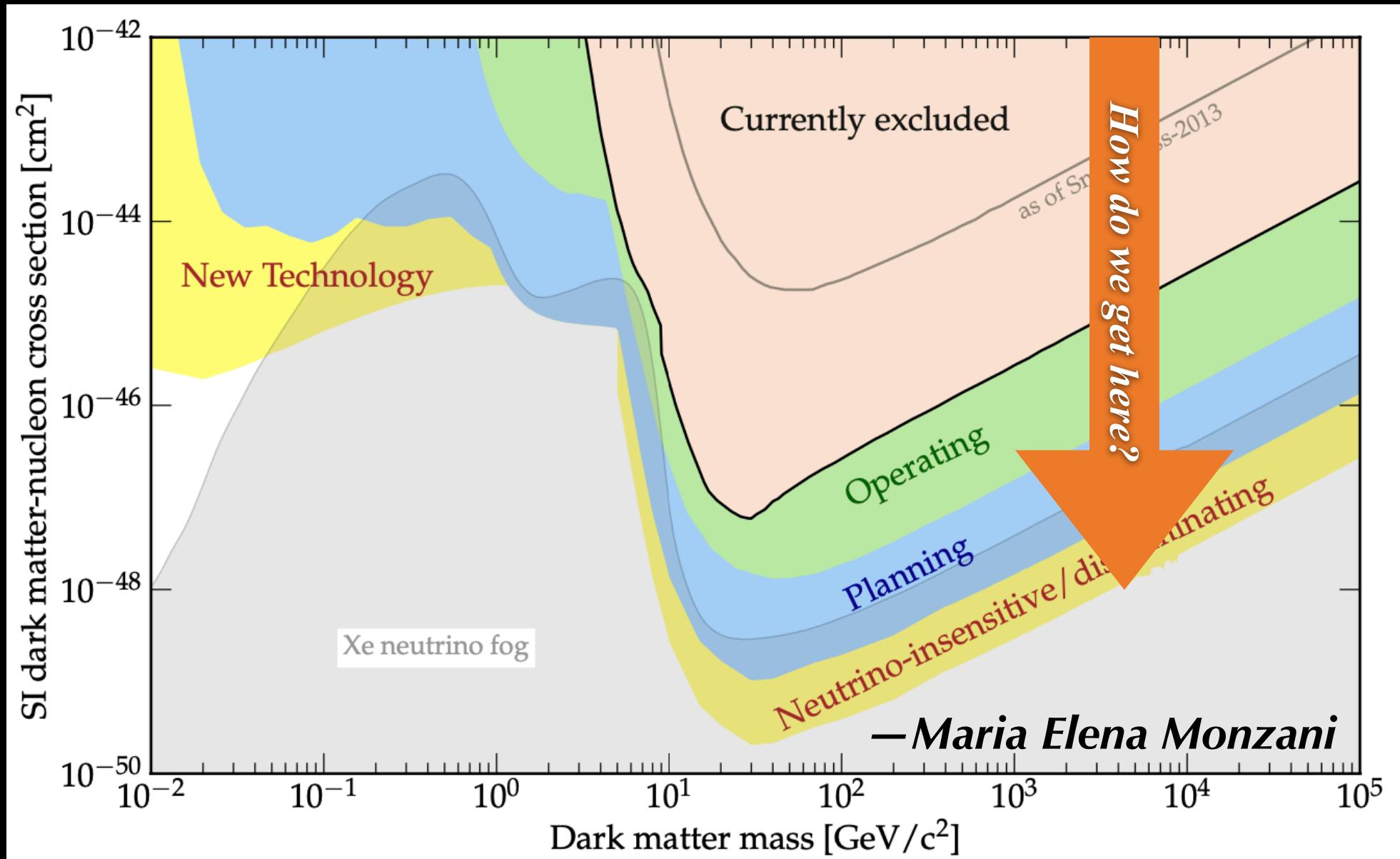
# Direct Detection WIMP Searches



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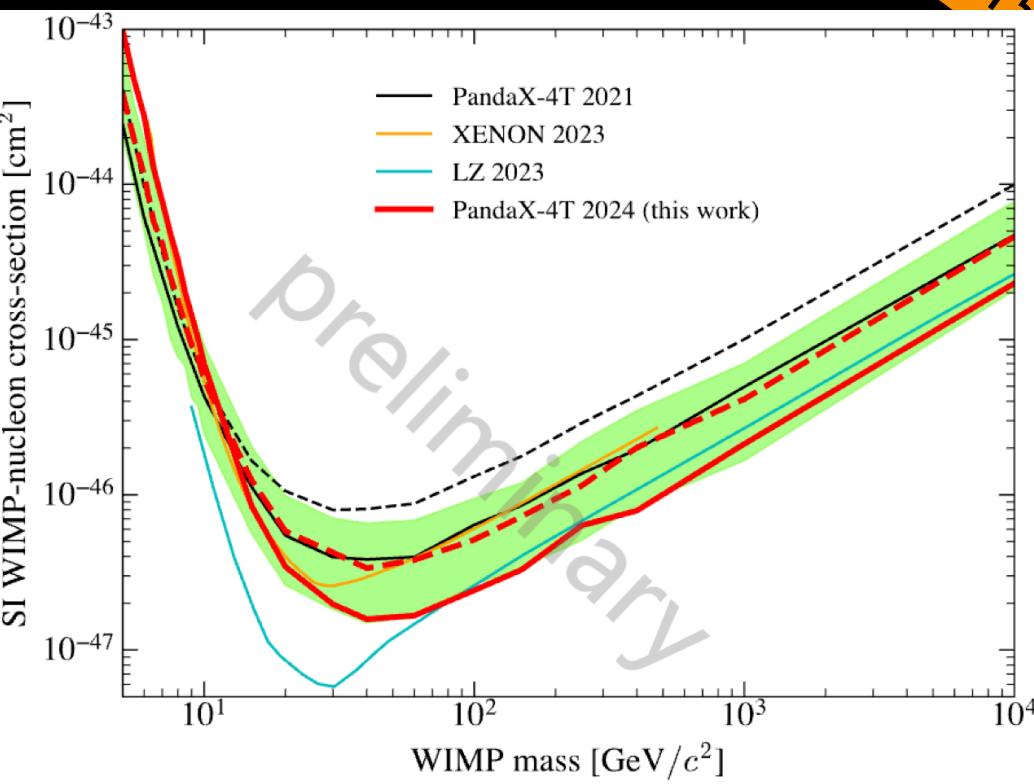


# Direct Detection WIMP Searches



# Xenon Detectors

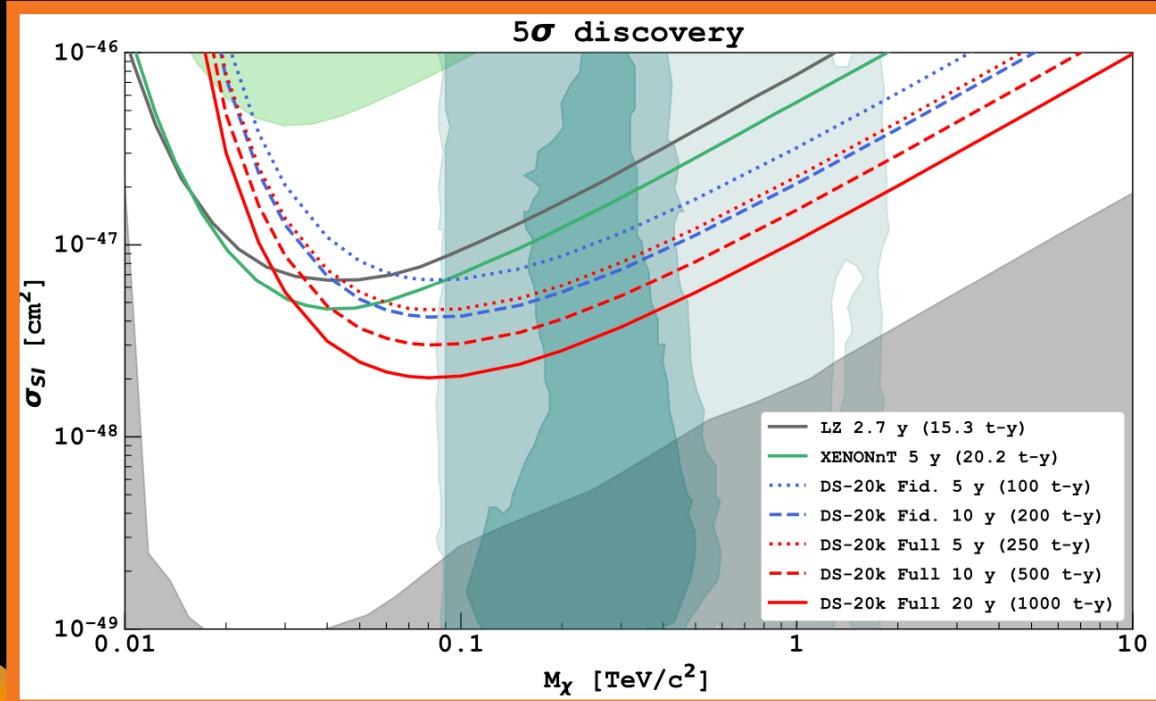
Aprile E., et al. SPIE, Vol. No. 4140 (2000) **LXeGRIT**



# Argon Detectors



DarkSide-20k: observatory for dark matter and  $\nu$ .



*Global Argon Dark Matter  
Collaboration formed*

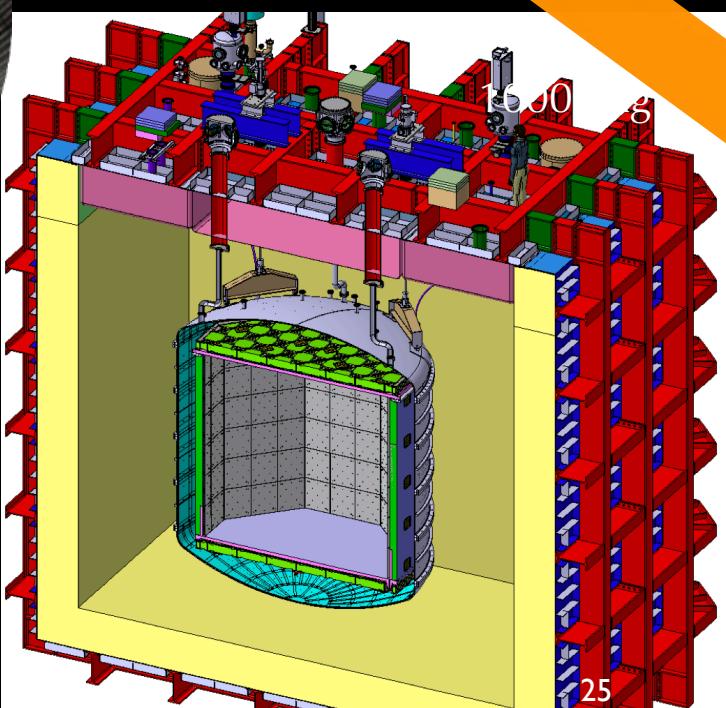


2020  
10,000 kg

100,000 kg

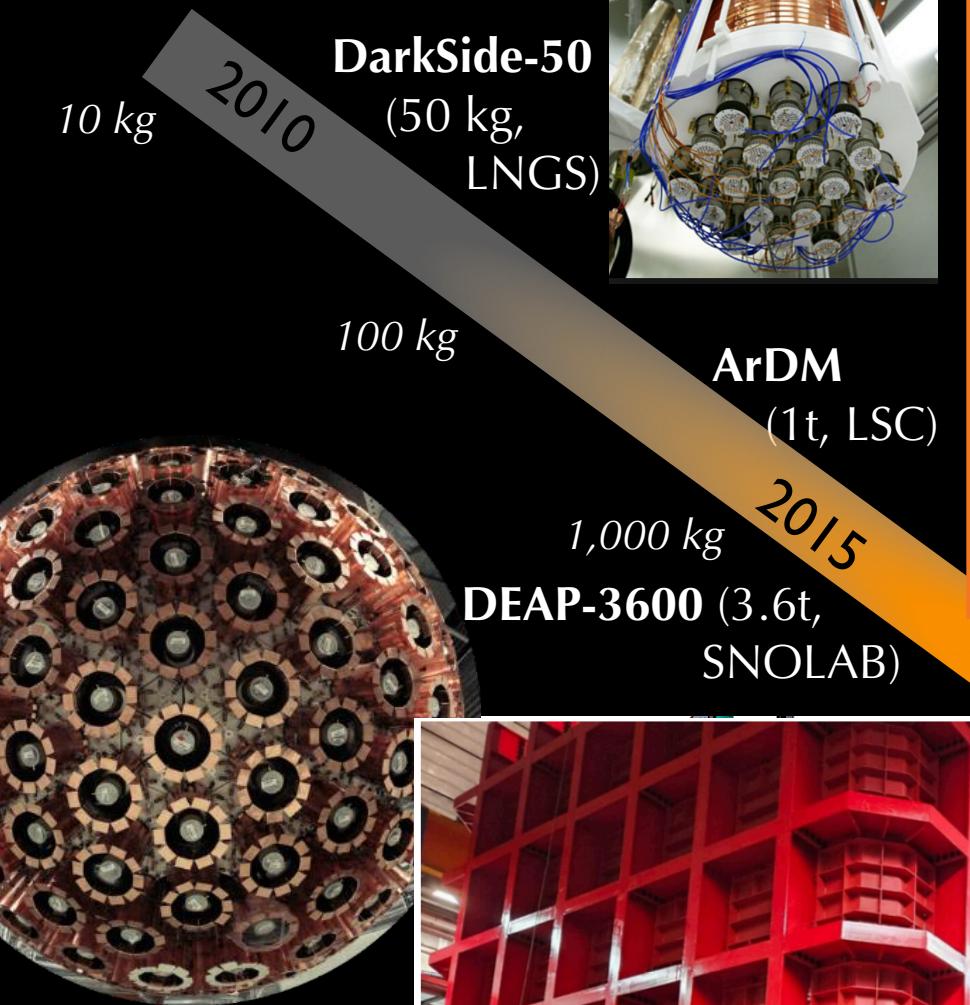
**DarkSide-20k**  
(50t, LNGS)

*Future:  
ARGO  
kt-scale*

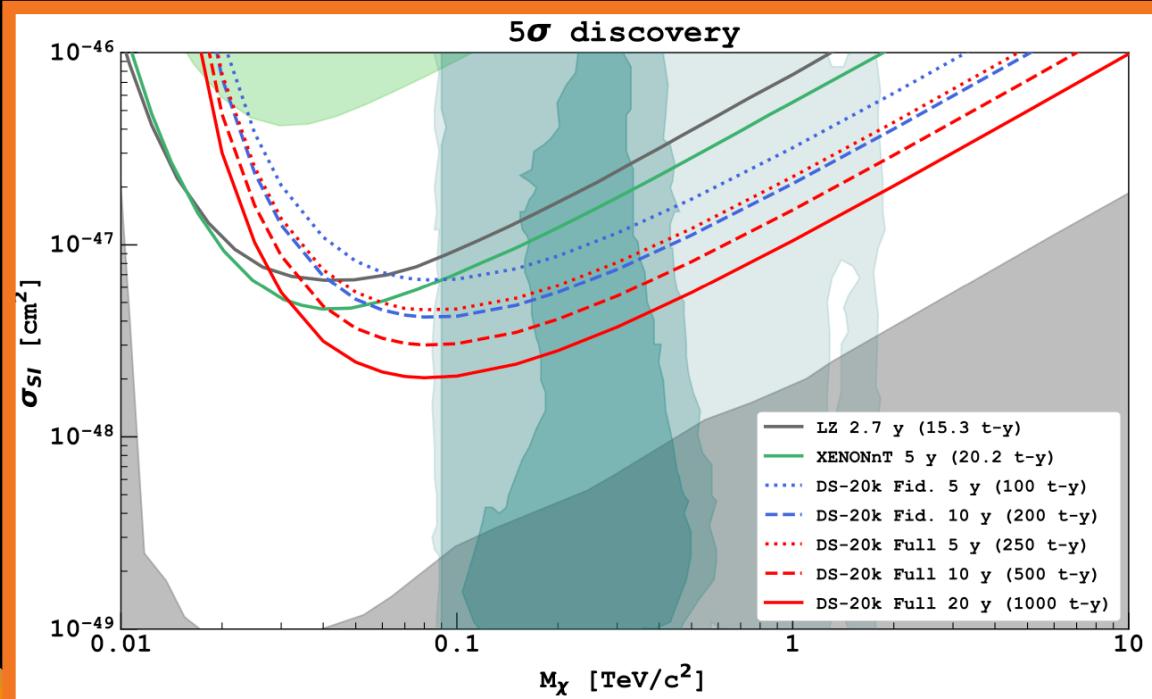


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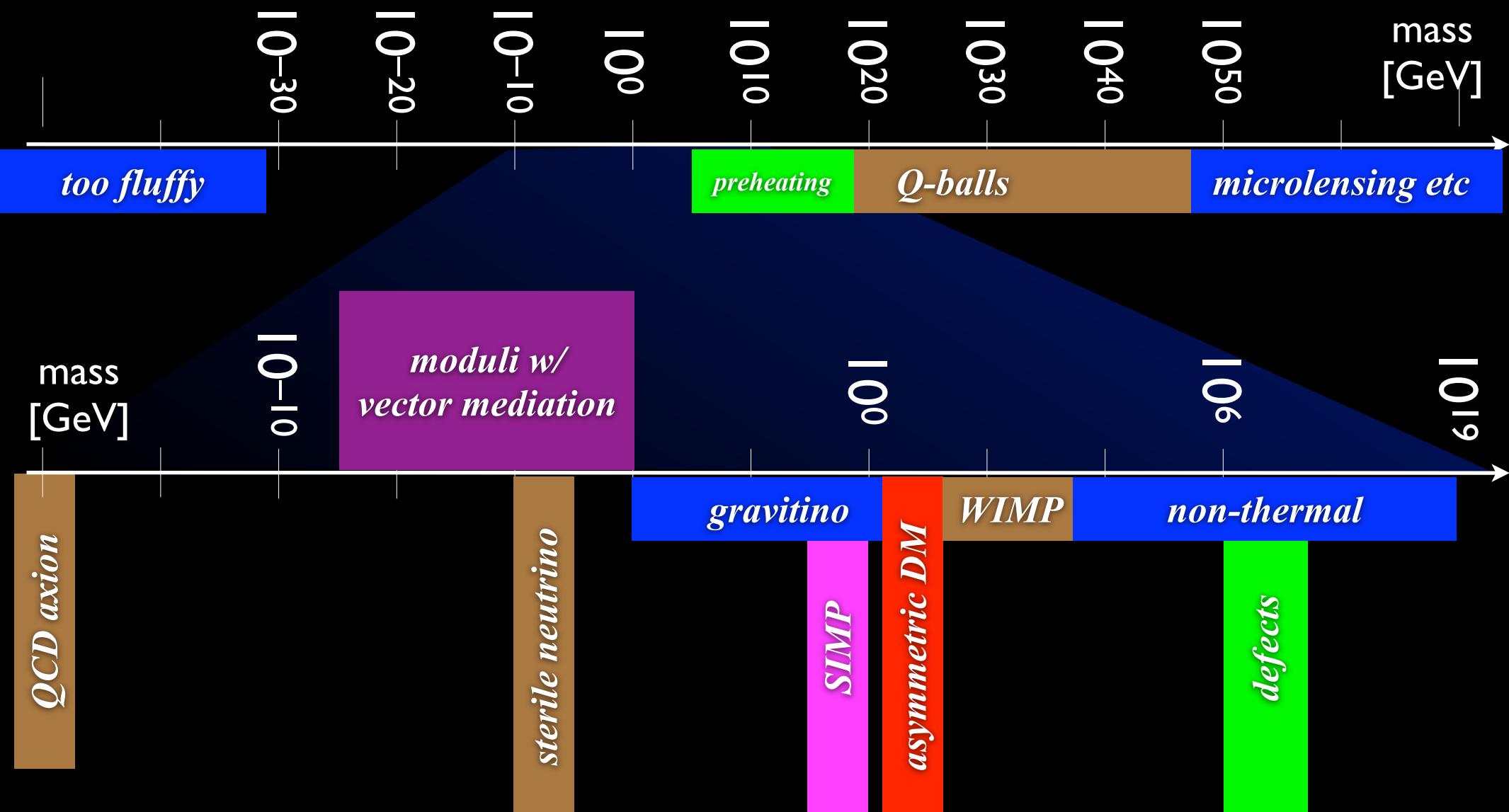
*Future:  
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(thanks to H. Murayama)

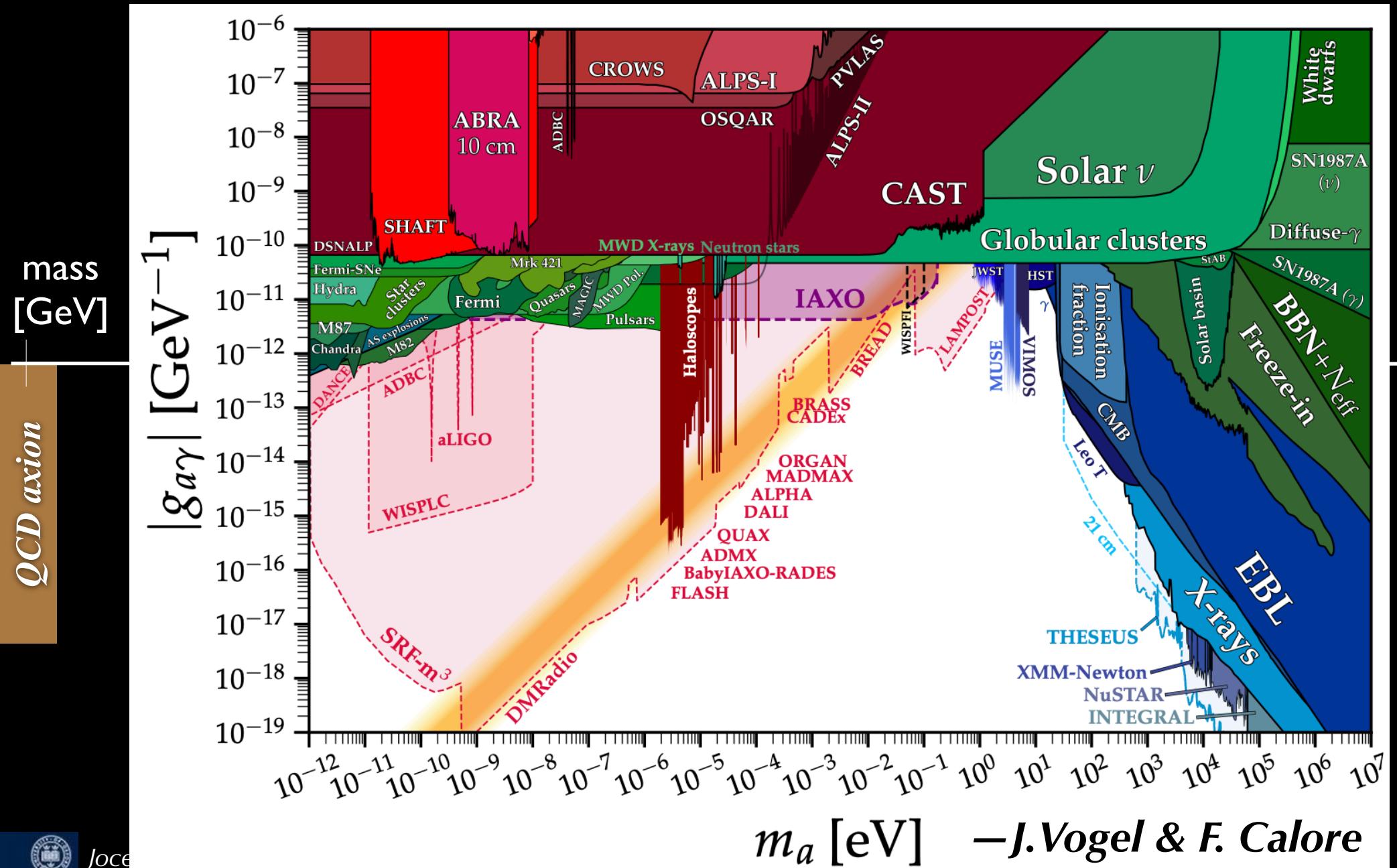


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# Axions

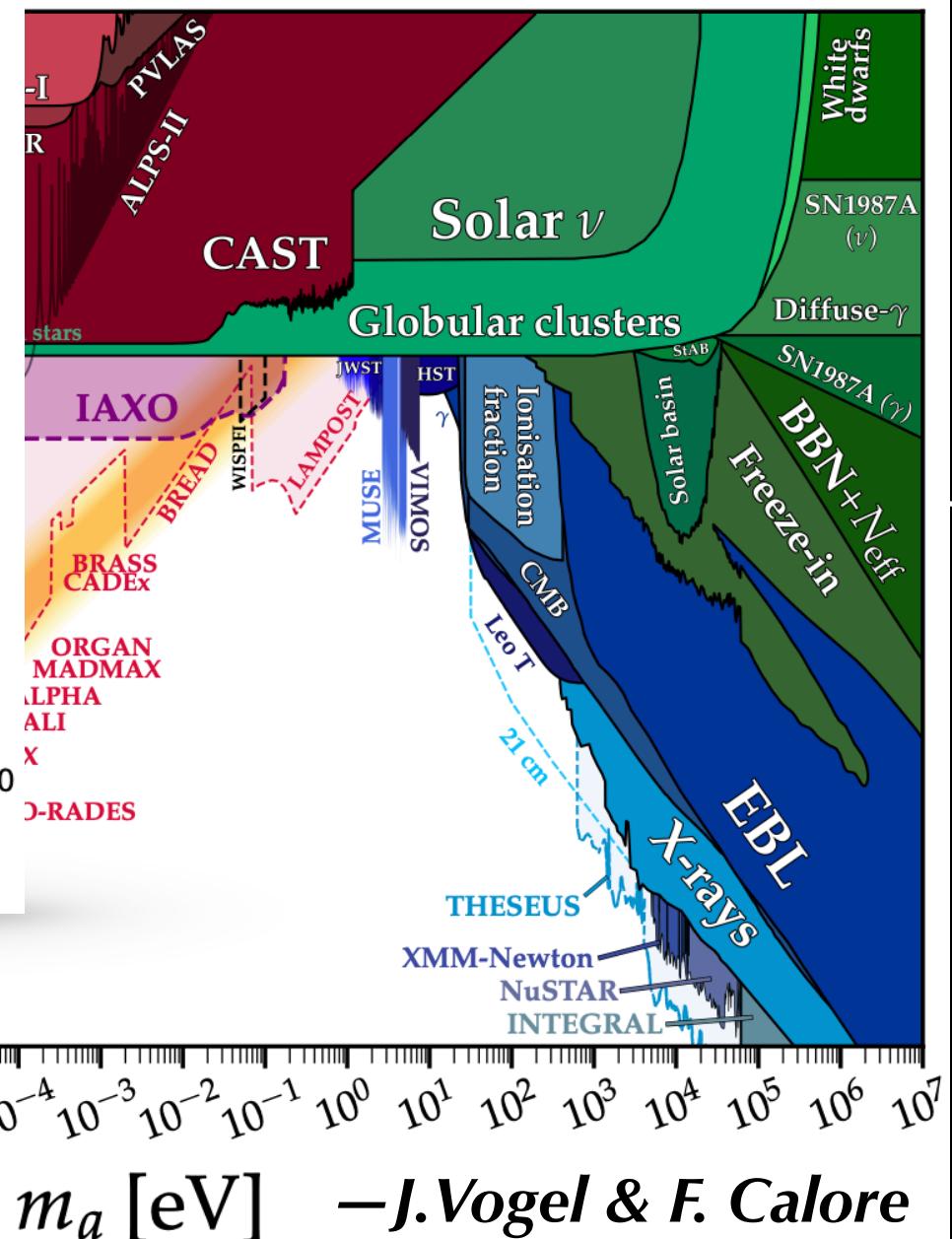
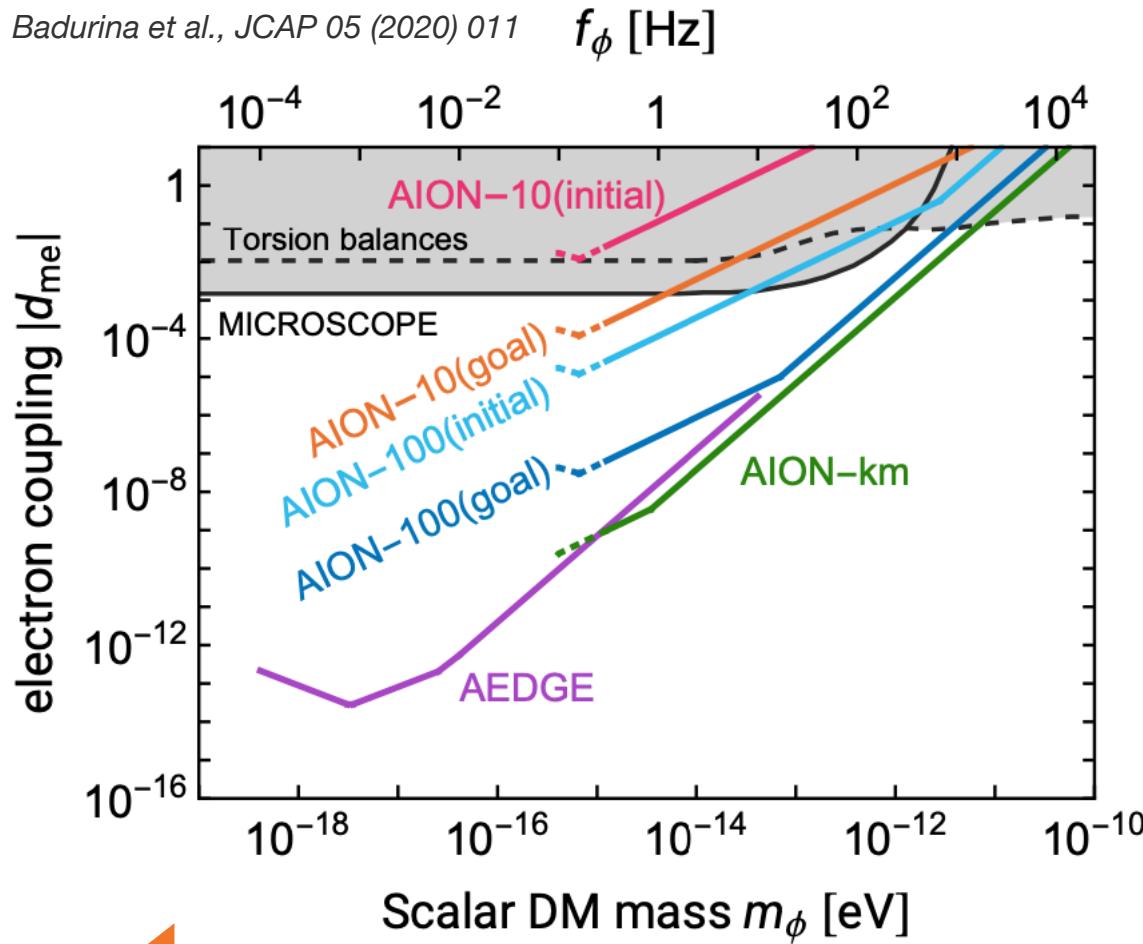
Huge range of techniques to detect axion-photon coupling: halo/helioscopes, "light through a wall," axion-induced RF motivating quantum sensors: QSHS, AION++



# Axions

Huge range of techniques to detect axion-photon coupling: halo/helioscopes, "light through a wall," axion-induced RF motivating quantum sensors: QSHS, AION++

Badurina et al., JCAP 05 (2020) 011

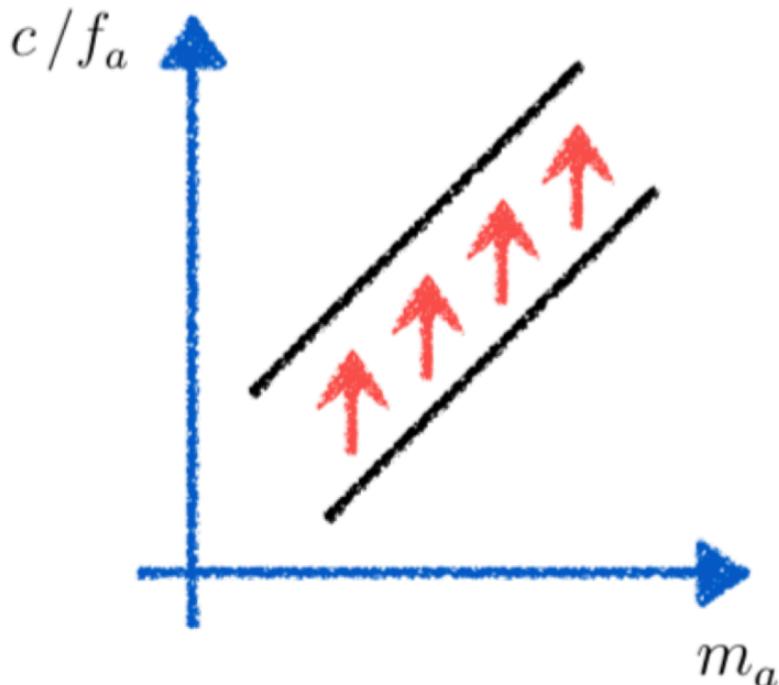


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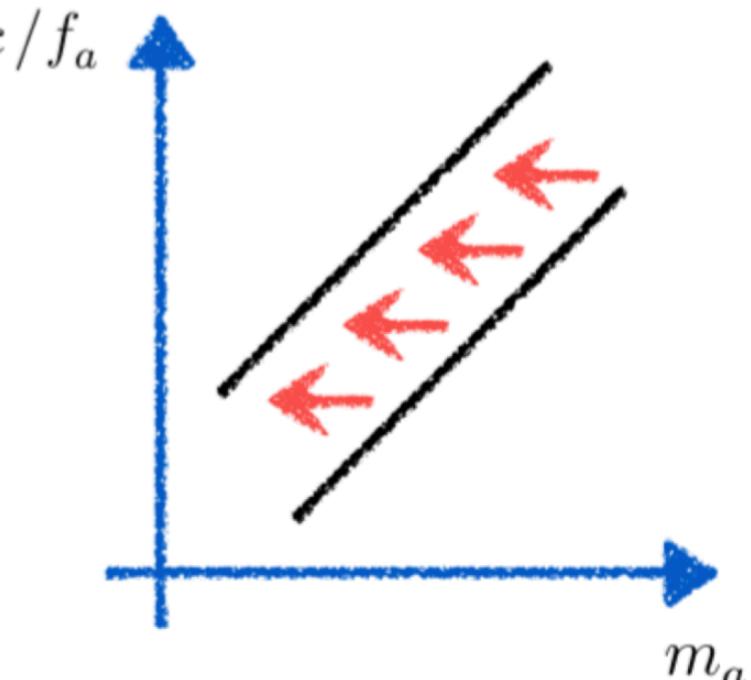
## Axions beyond benchmarks

—De Luzio



enhance Wilson coefficient for fixed  $m_a$

[LDL, Mescia, Nardi 1610.07593 + 1705.05370  
Carina, Pappadopulo, Rompineve, Tesi 1611.09855  
Cavalcaval, Fan, Reece, Wang 1709.06085  
Dobrescu, LDL, Giannotti, Nardi 2010.15846  
Ringwald, Slepakov 2104.02574, ...]



suppress axion mass for fixed  $f_a$

[Hook 1802.10093,  
LDL, Gavela, Quilez, Ringwald 2102.00012  
+ 2102.01082]

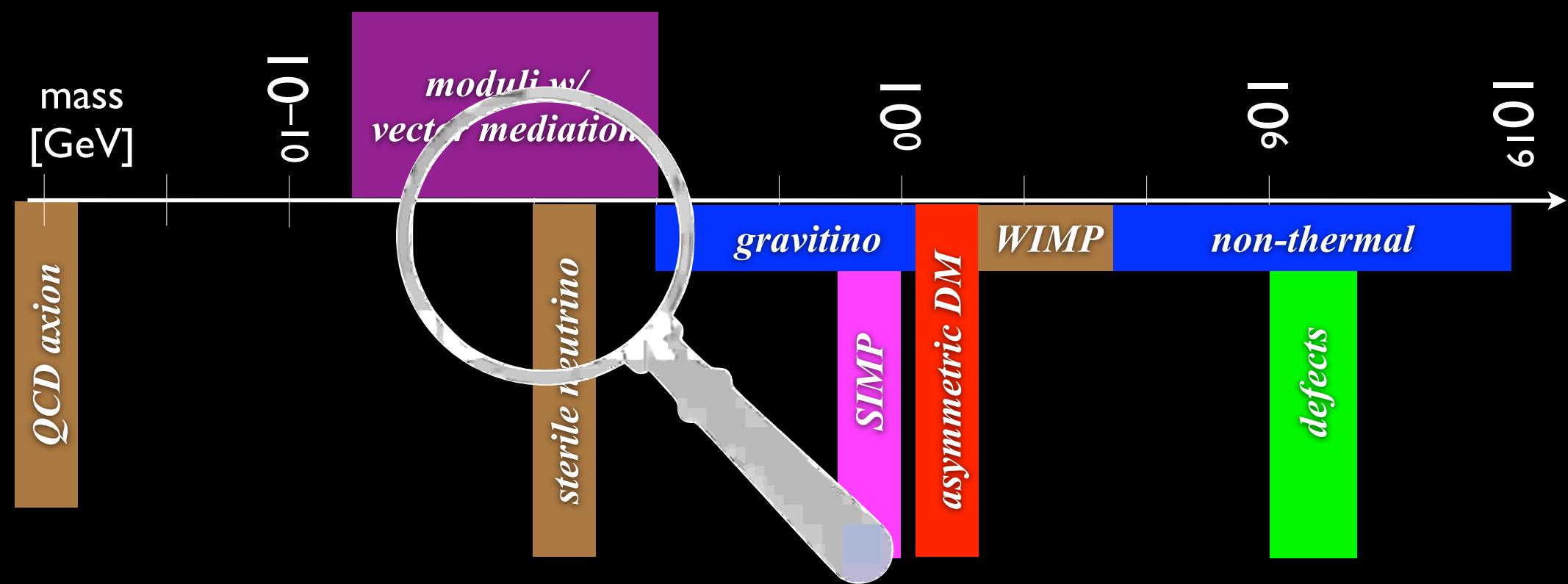
QCD axion parameter space much larger than what traditionally thought



Joc

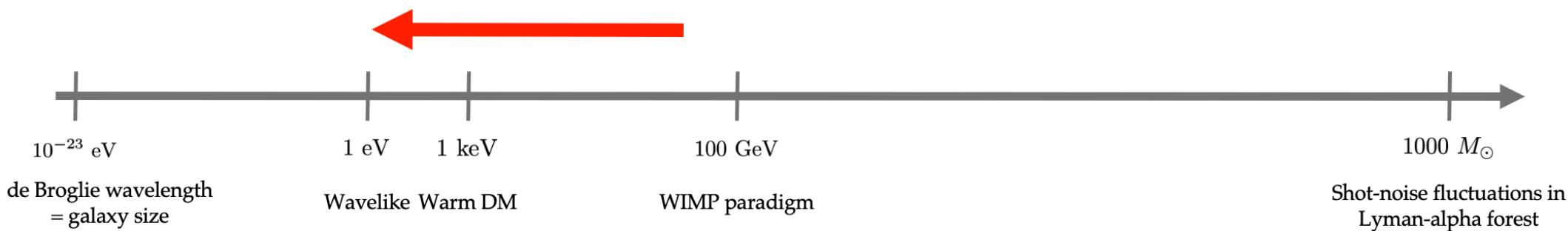


# Theorist's View



## Dark Matter of a Very Low Mass

### ***Dark Matter with Mass Below the Weak Scale***



- We will focus on an intermediate range where observation via particle interactions with SM is still highly motivated though not detectable with traditional experiments
- These are **hidden sector/valley** DM models, which arise generically in top-down constructions, and give rise to qualitatively different observational signatures

***—K. Zurek***

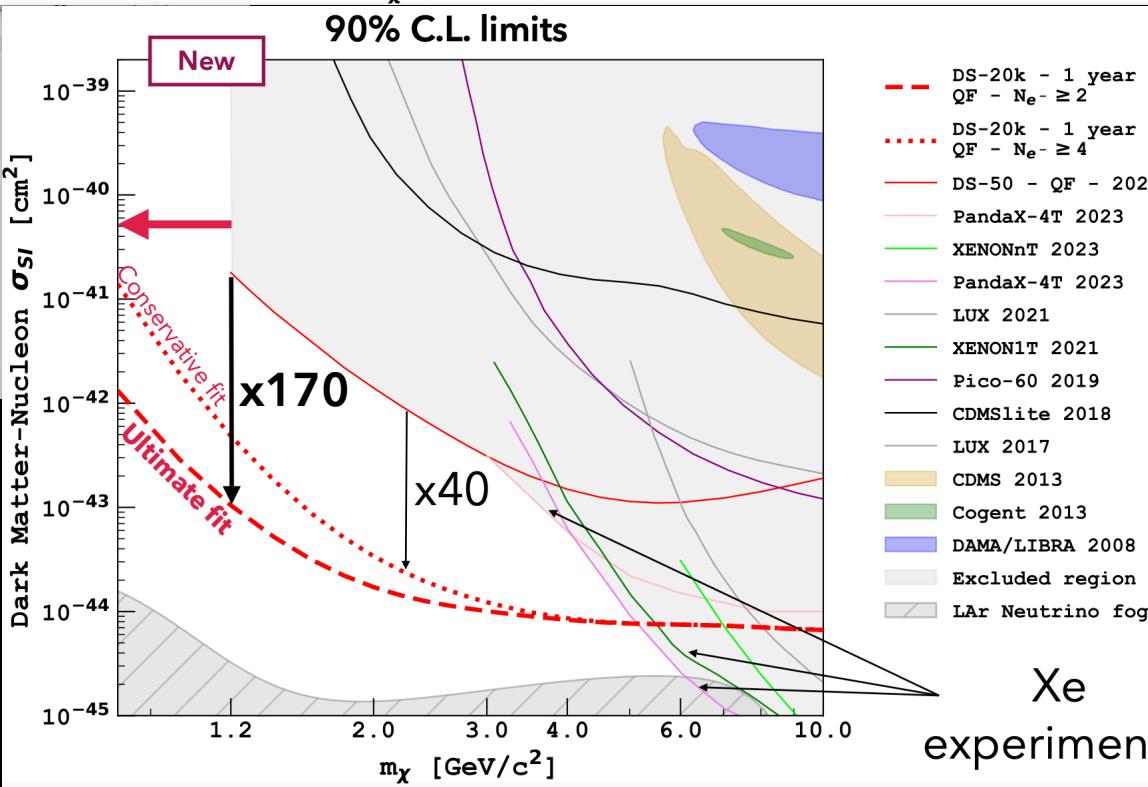
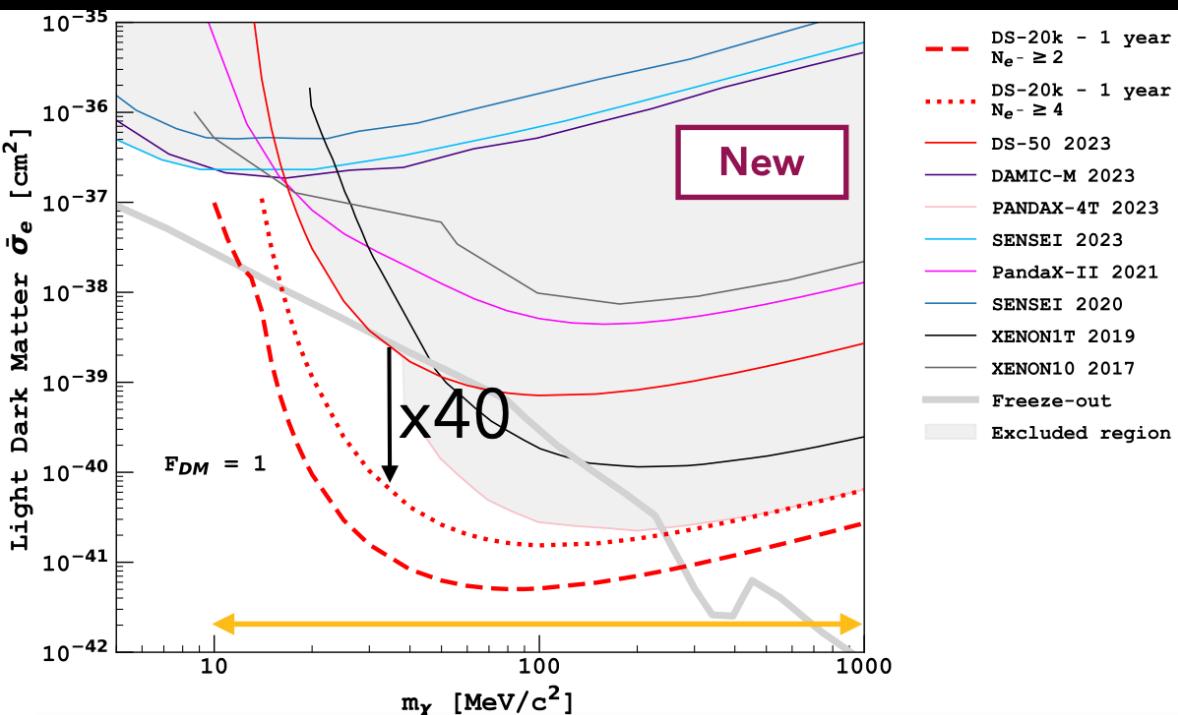
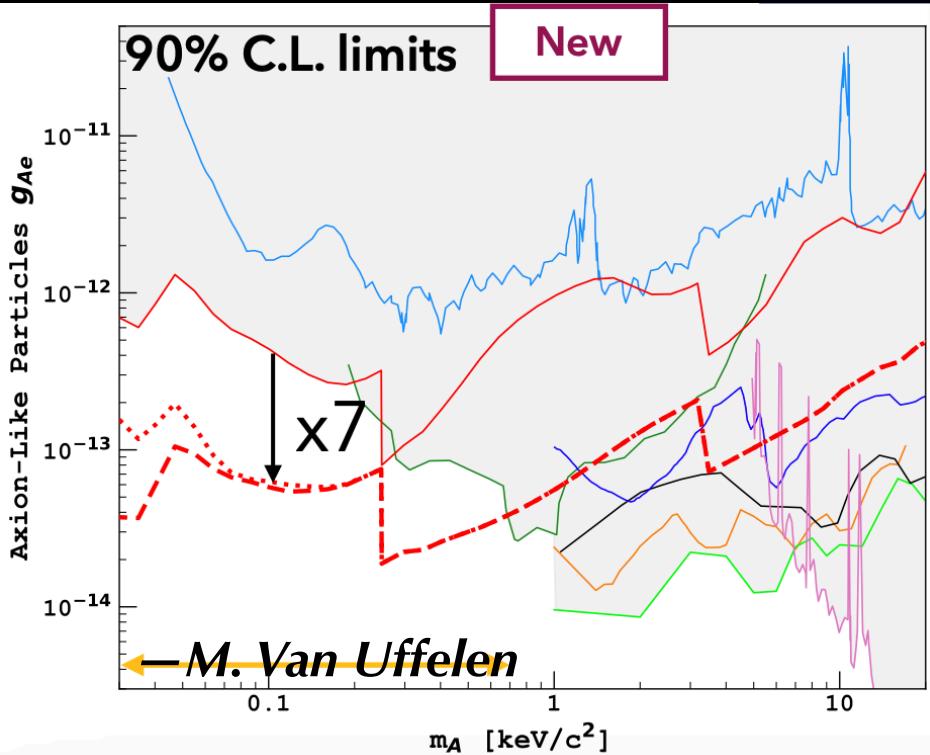
Review KZ 2401.03025



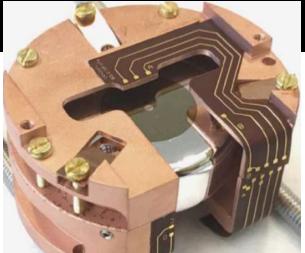
# Direct Detection Beyond WIMPs

MeV-scale dark matter: search for scattering

keV-scale dark matter: search for absorption:

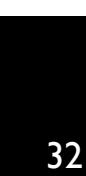
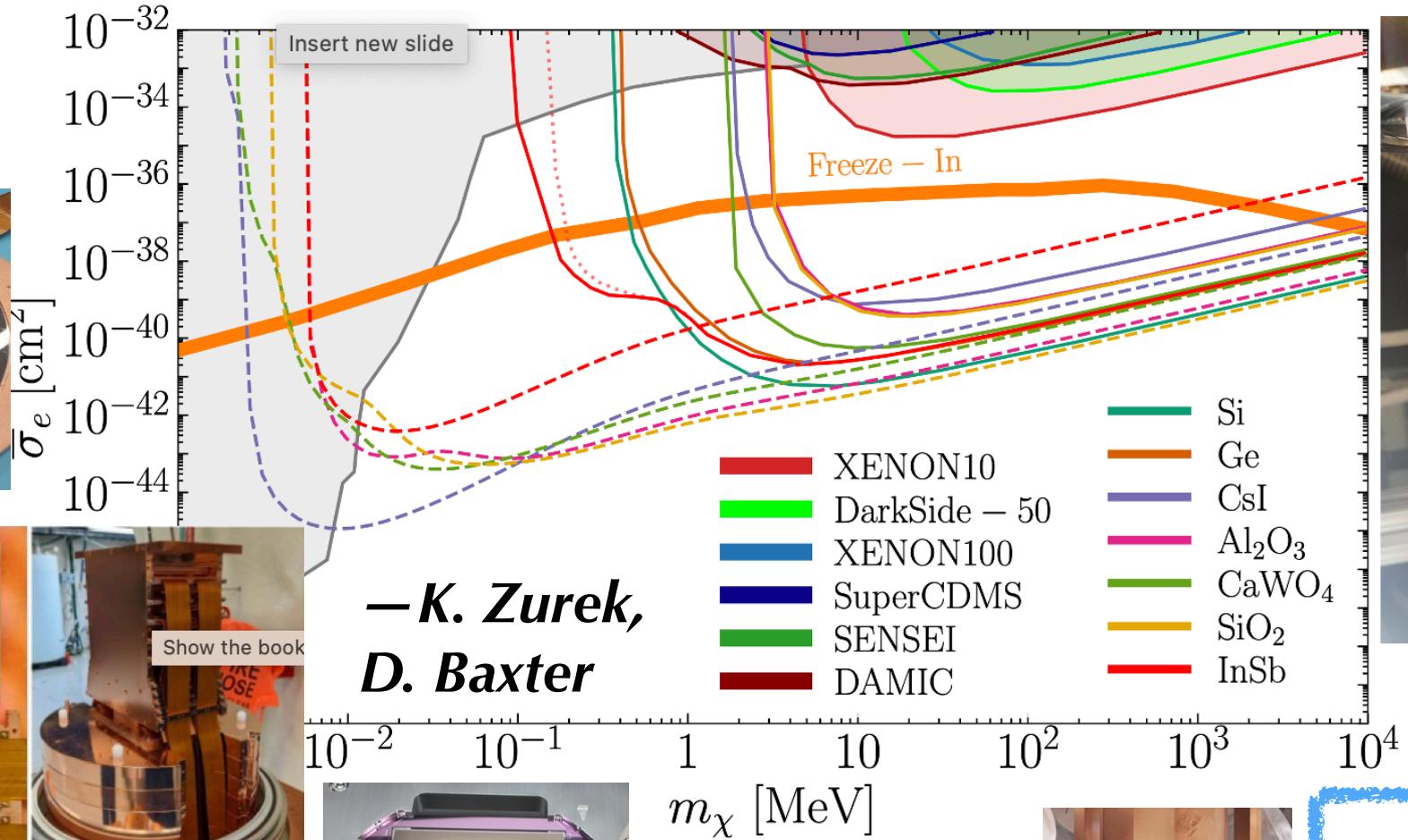
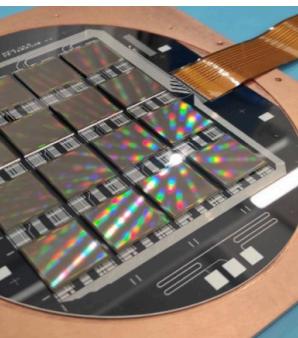
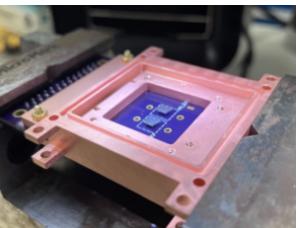


# Explosion of Creativity in Detector Technology



## Low-Mass DM Sensitivity

**Models Best-Motivated by Relic Abundance Can be Reached with  $1 \text{ kg}\cdot\text{yr}$  exposure**



Your  
detector  
here!

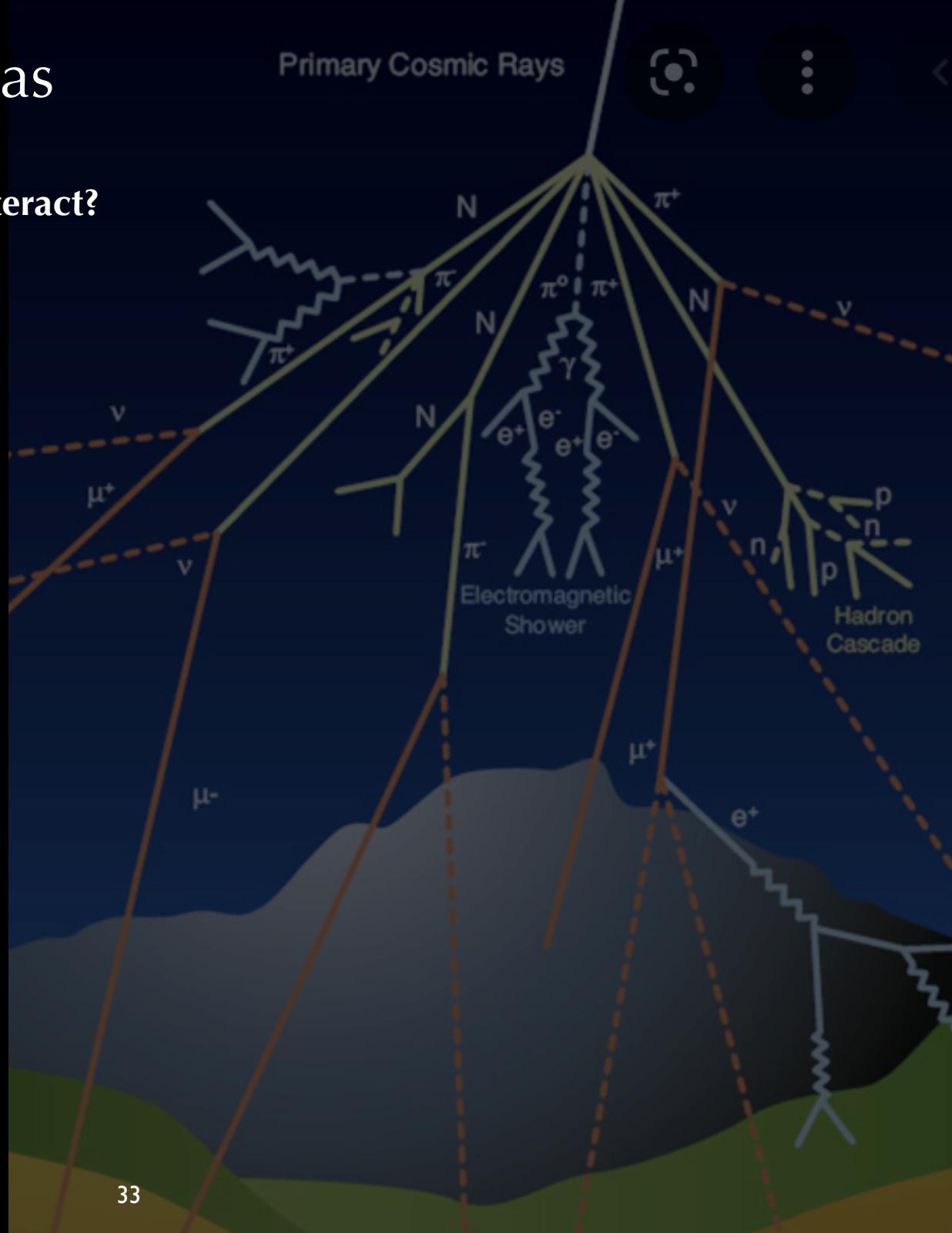


Jocelyn Monroe

# Explosion of Creative Ideas

Primary Cosmic Rays

What if dark matter and cosmic rays interact?

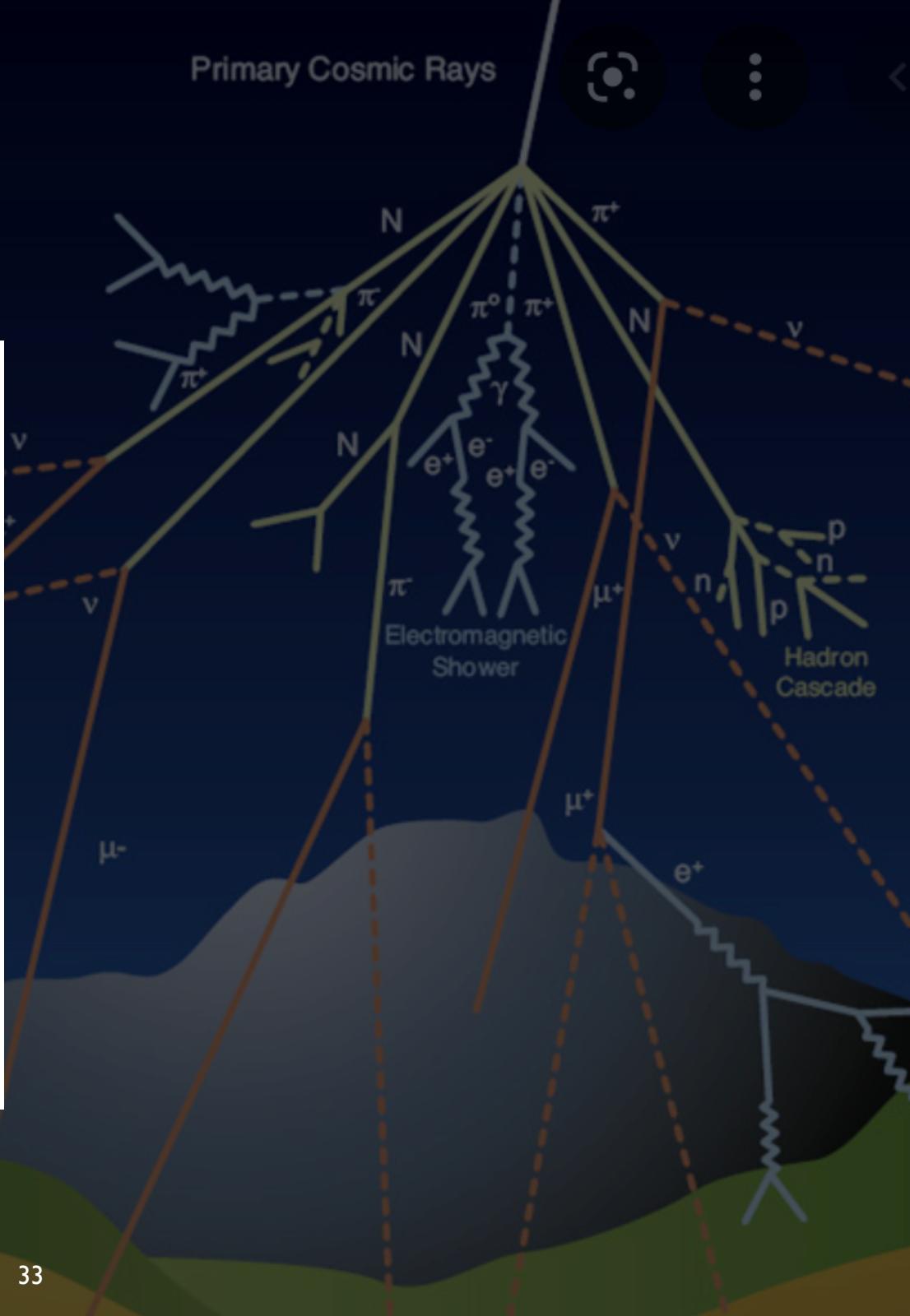
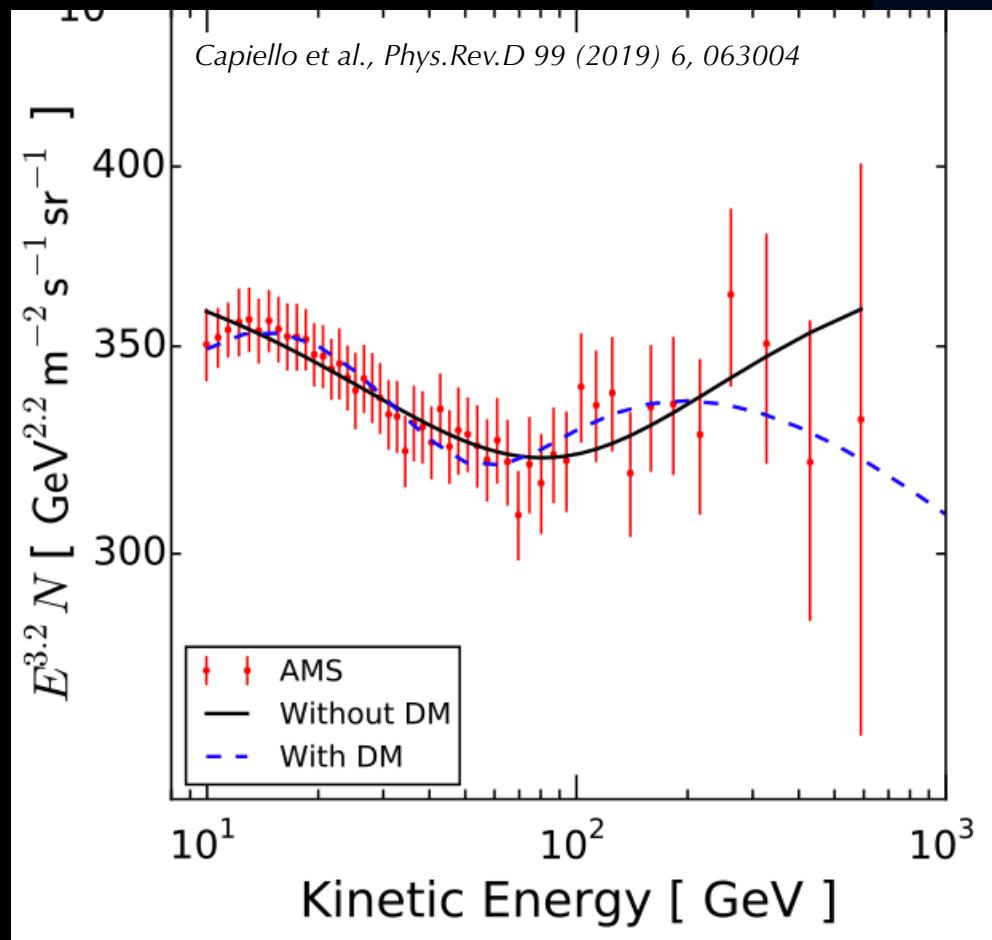


# Explosion of Creative Ideas

Primary Cosmic Rays

What if dark matter and cosmic rays interact?

Cosmic ray “downscattering:”

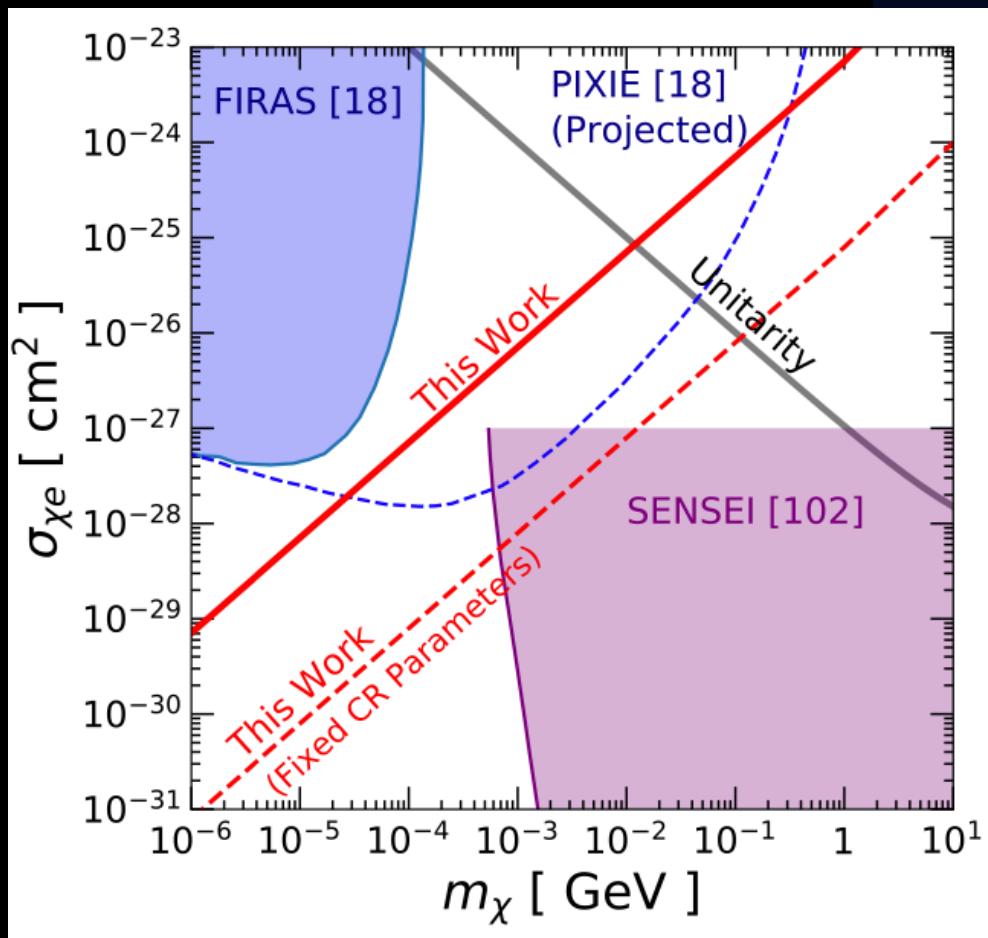


# Explosion of Creative Ideas

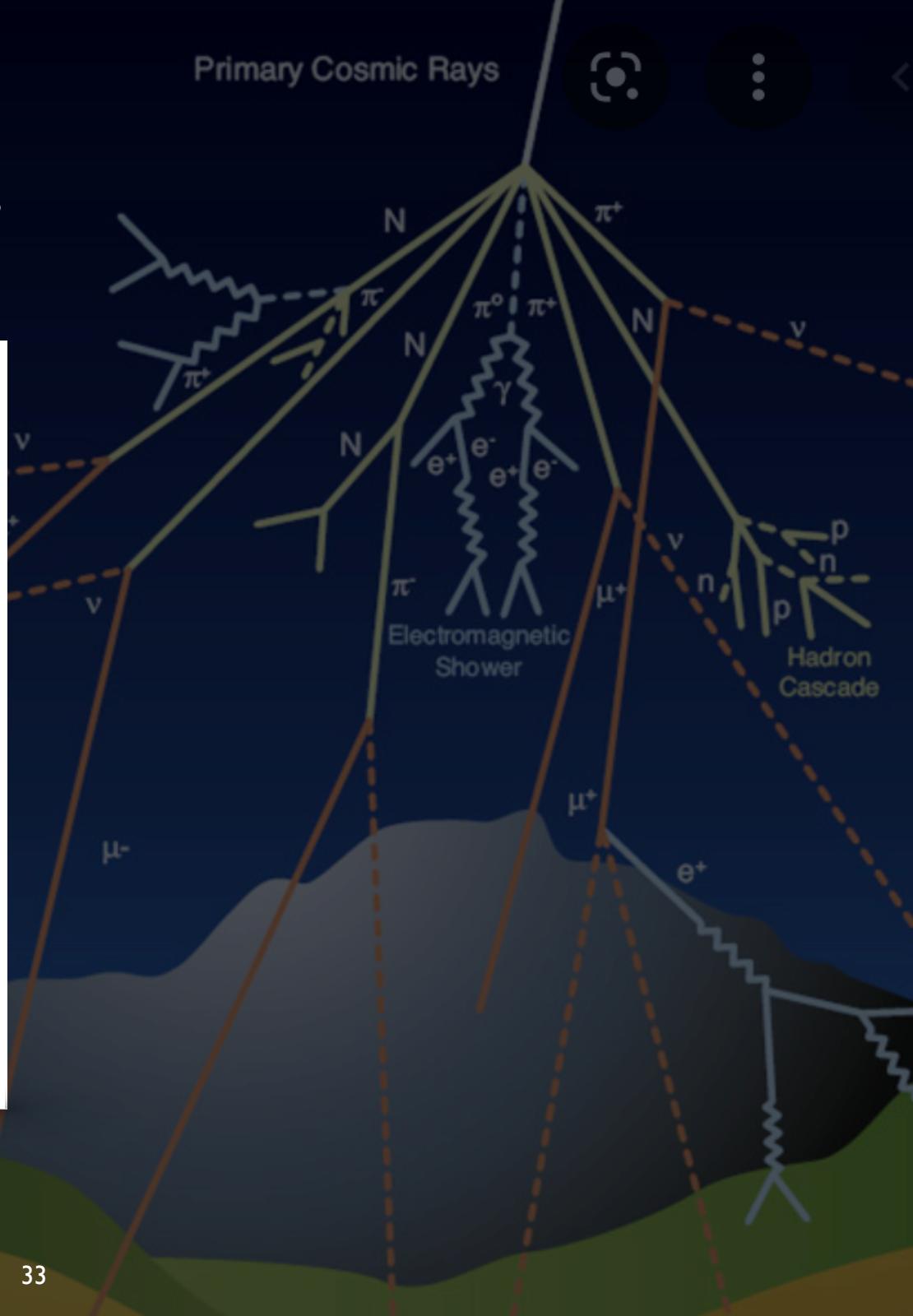
Primary Cosmic Rays

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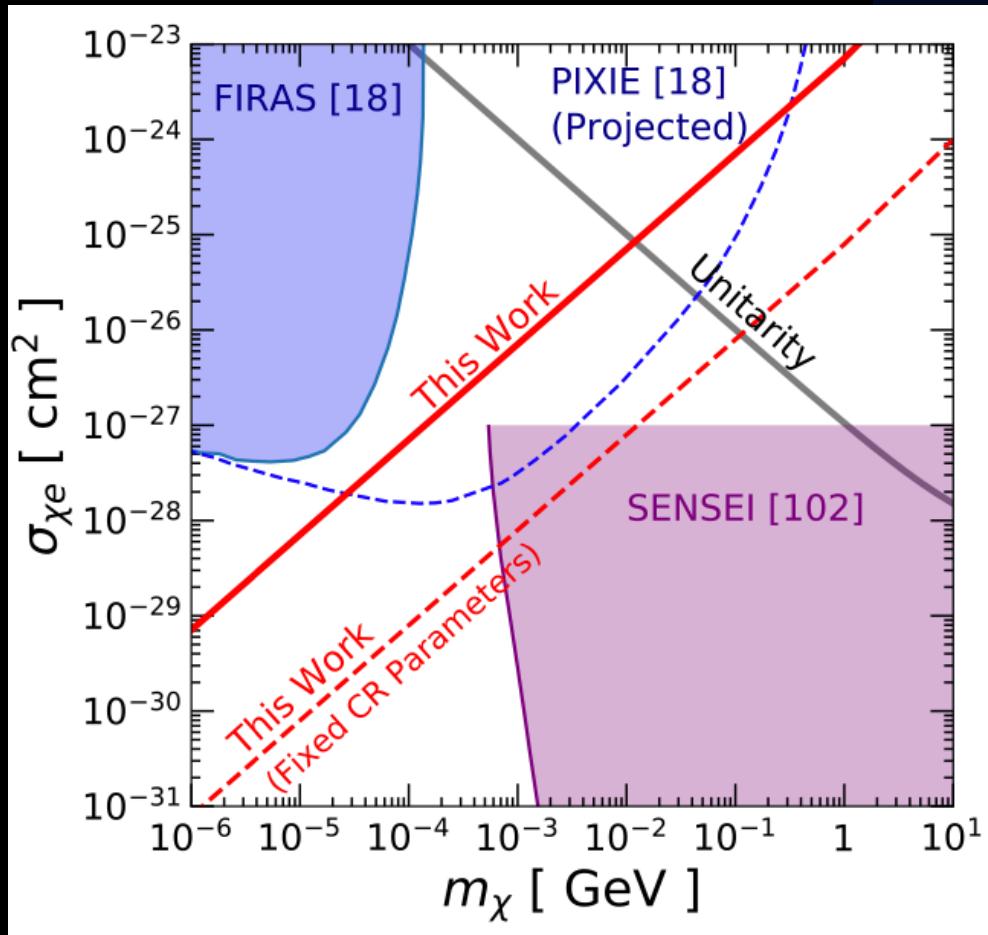
“Reverse Direct Detection”



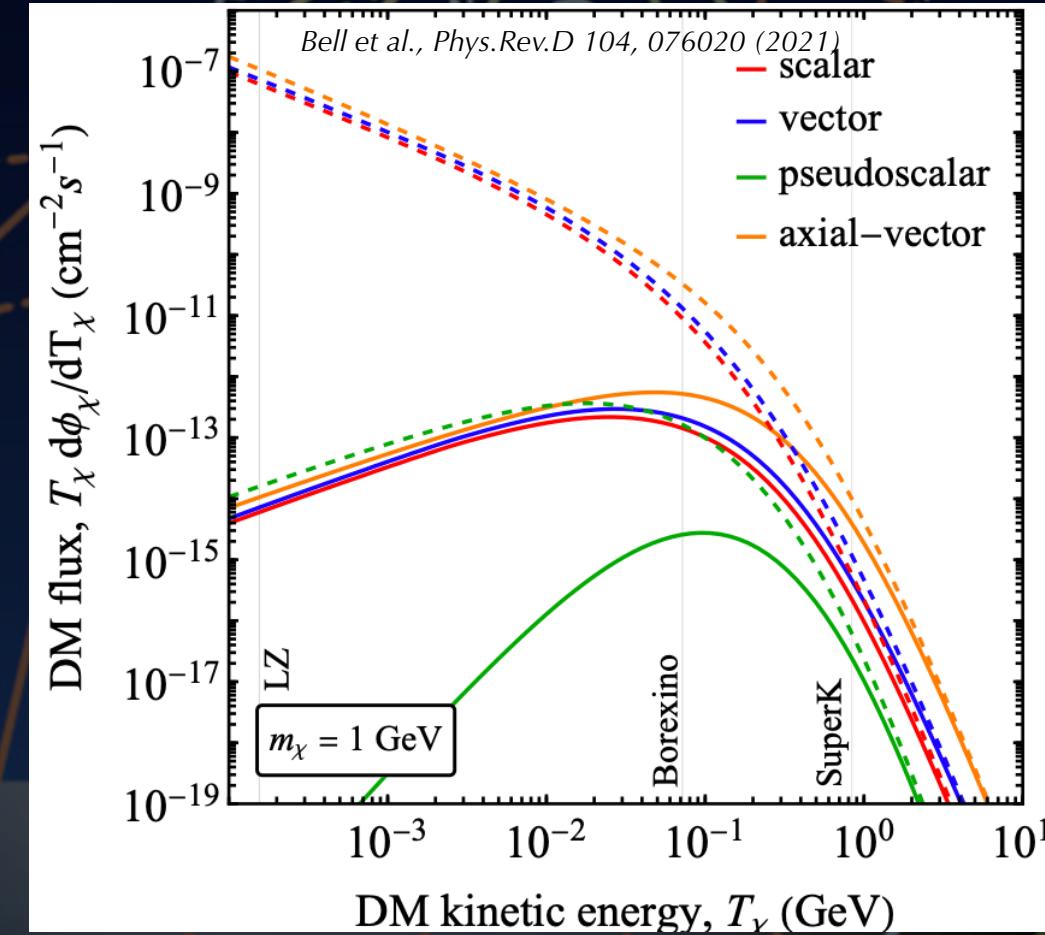
# Explosion of Creative Ideas

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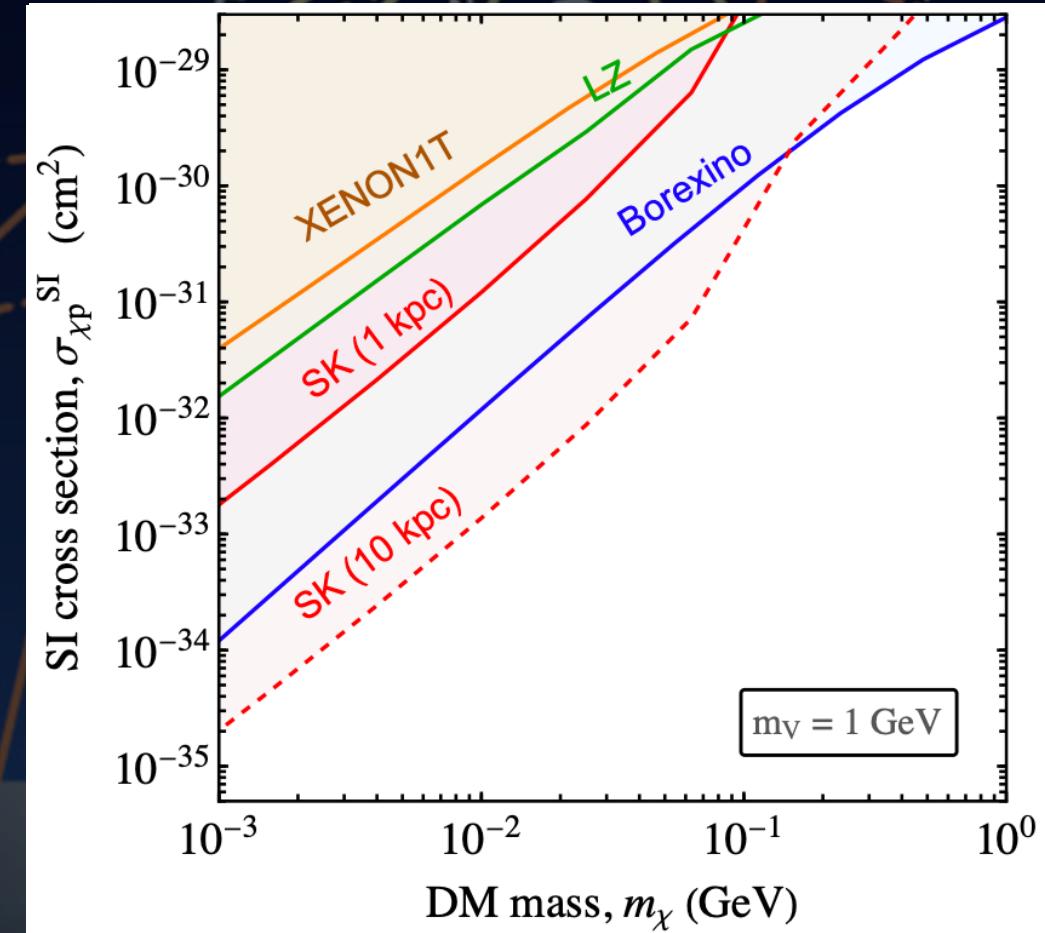
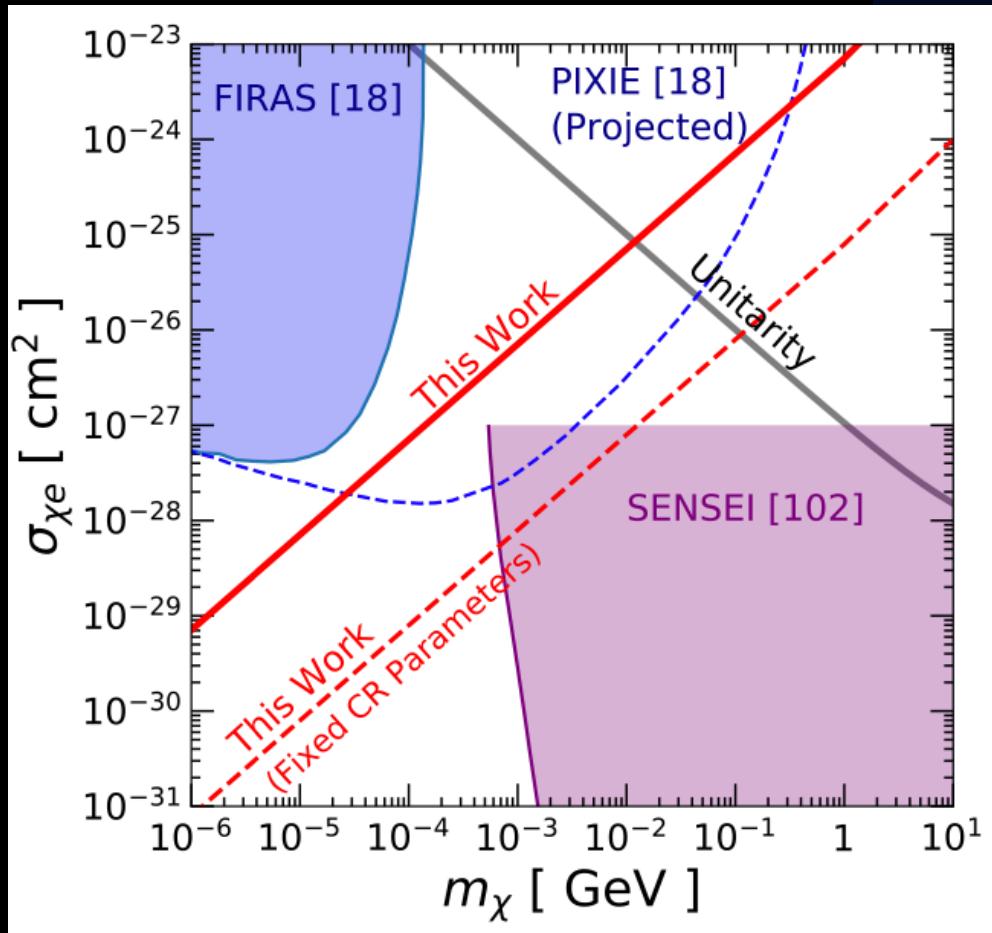
“Reverse Direct Detection”



# Explosion of Creative Ideas

What if dark matter and cosmic rays interact?

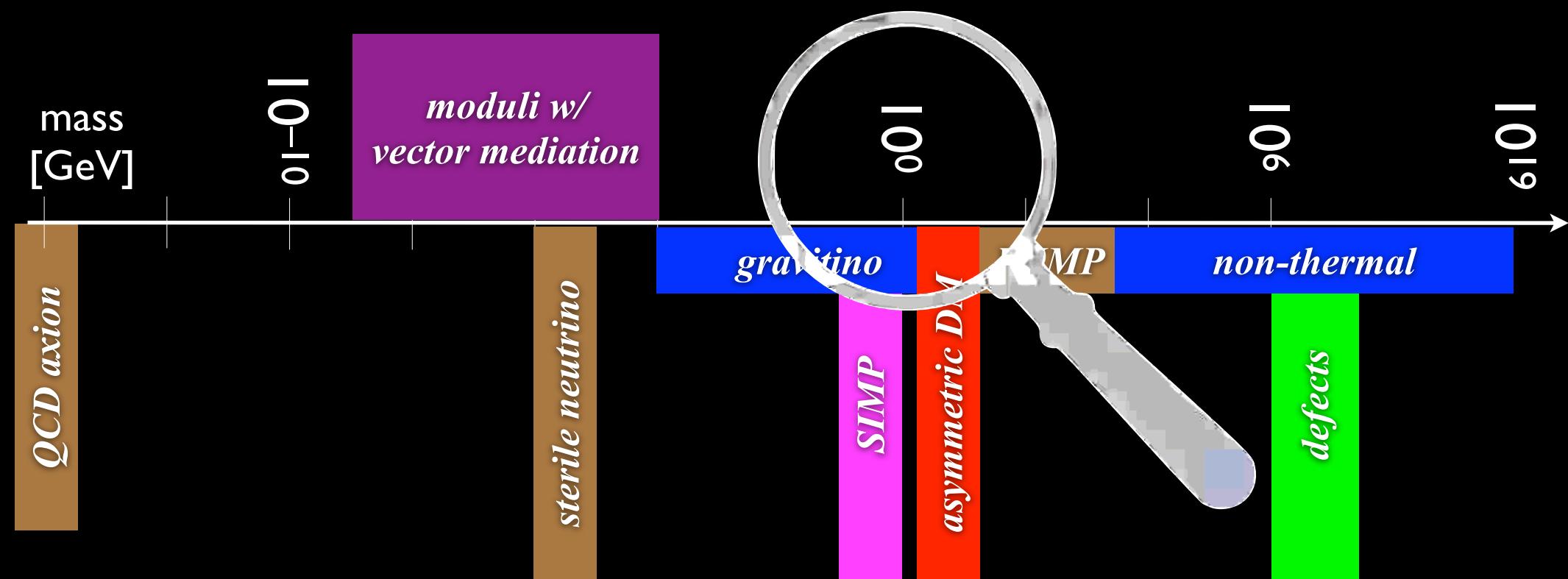
Cosmic ray “downscattering:”



“Reverse Direct Detection”

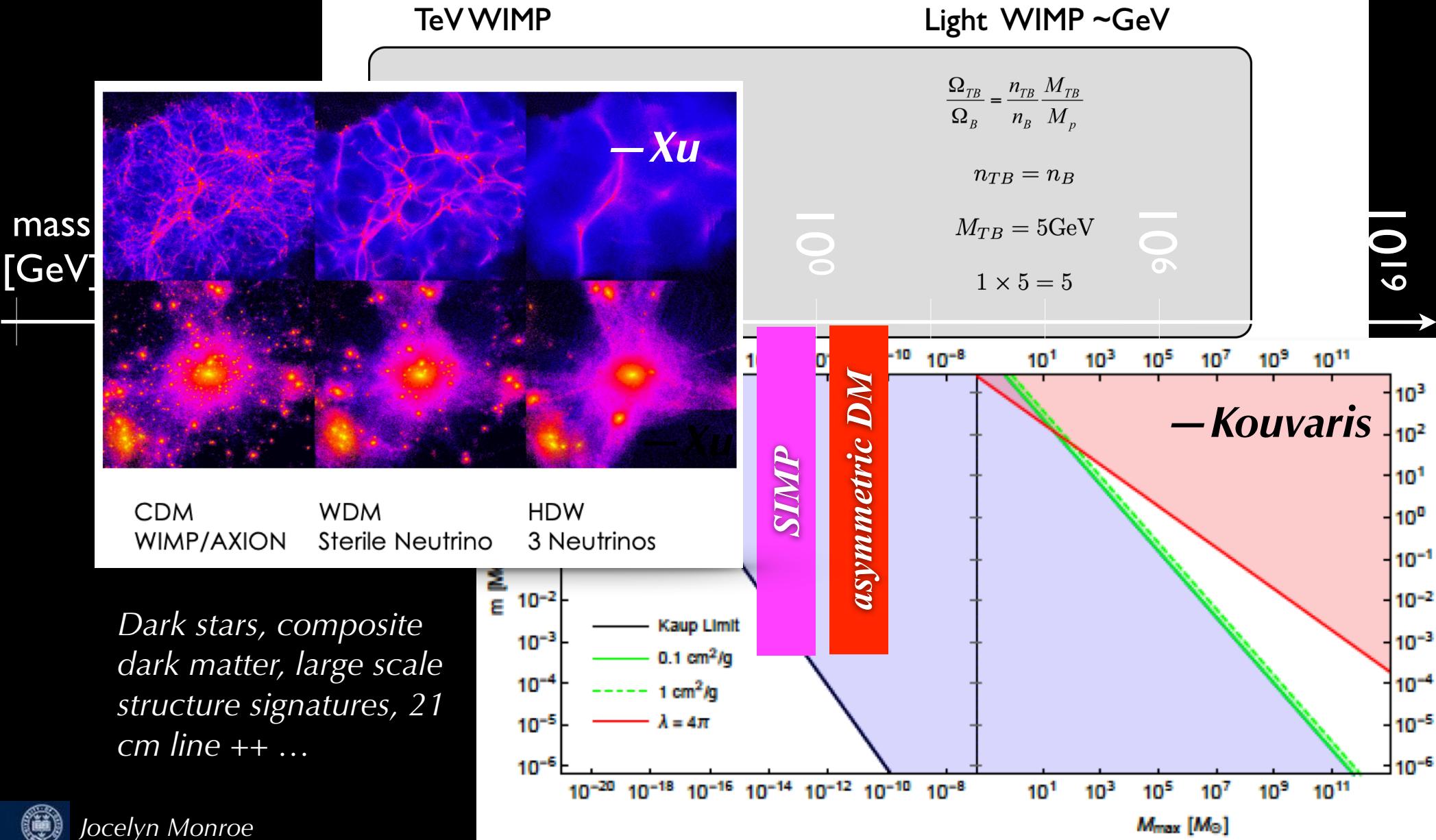


# Theorist's View



# Beyond WIMPs

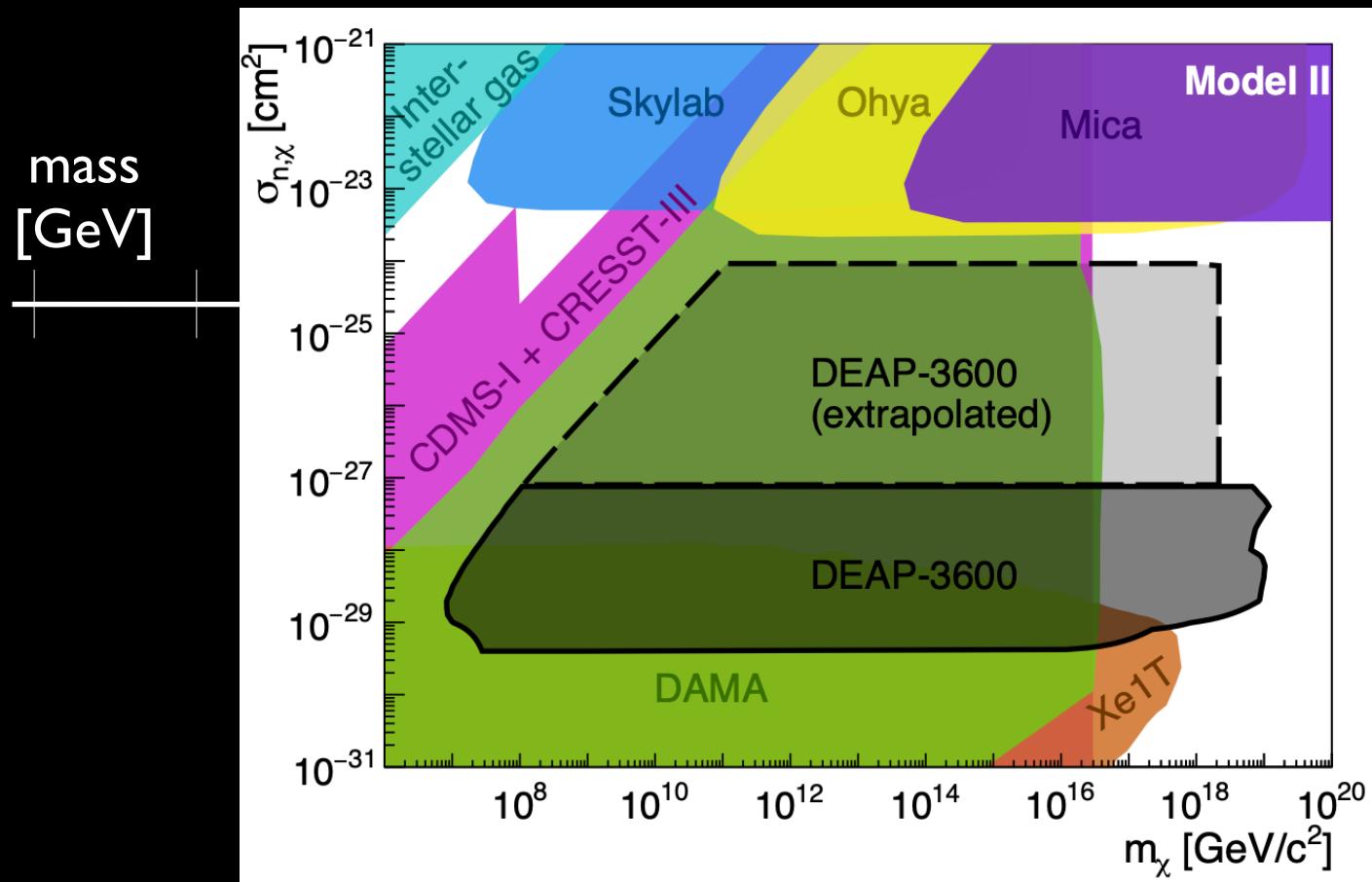
- Asymmetric DM can emerge naturally in theories beyond the SM
- Alternative to thermal production
- Possible link between baryogenesis and DM relic density



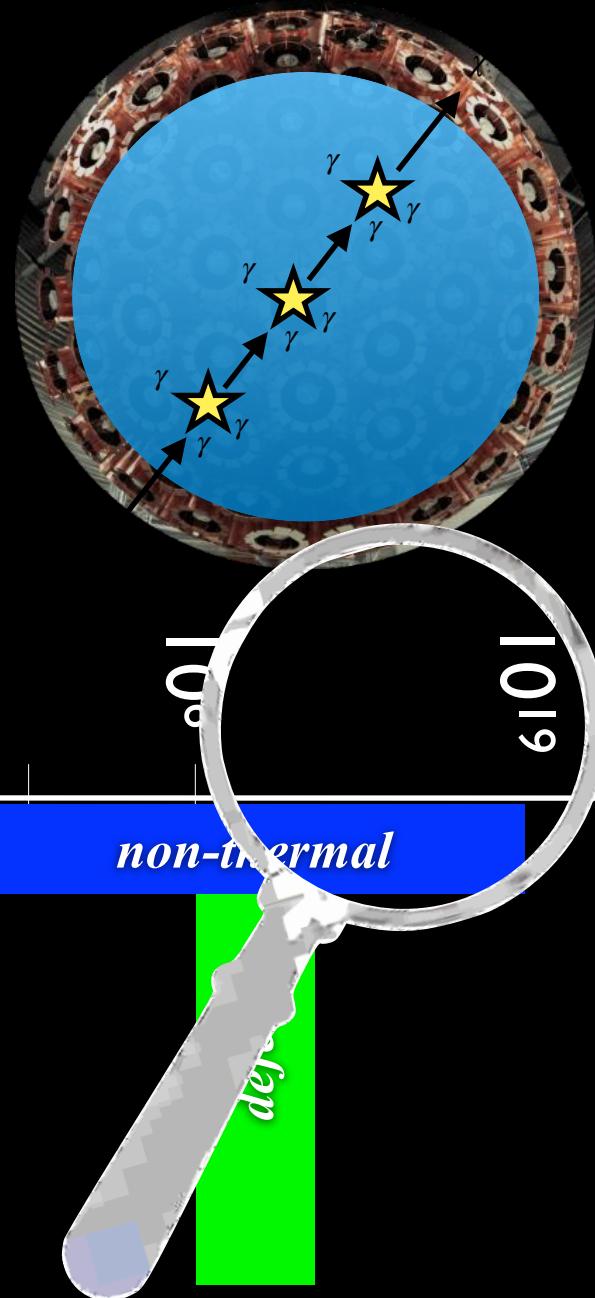
# Very Heavy Dark Matter

**Planck-scale dark matter** may be produced non-thermally in GUTs, primordial black hole radiation or extended thermal production in a dark sector

Unlike WIMPs, super heavy dark matter may scatter multiple it traverses a detector... signal: multiple nuclear recoils



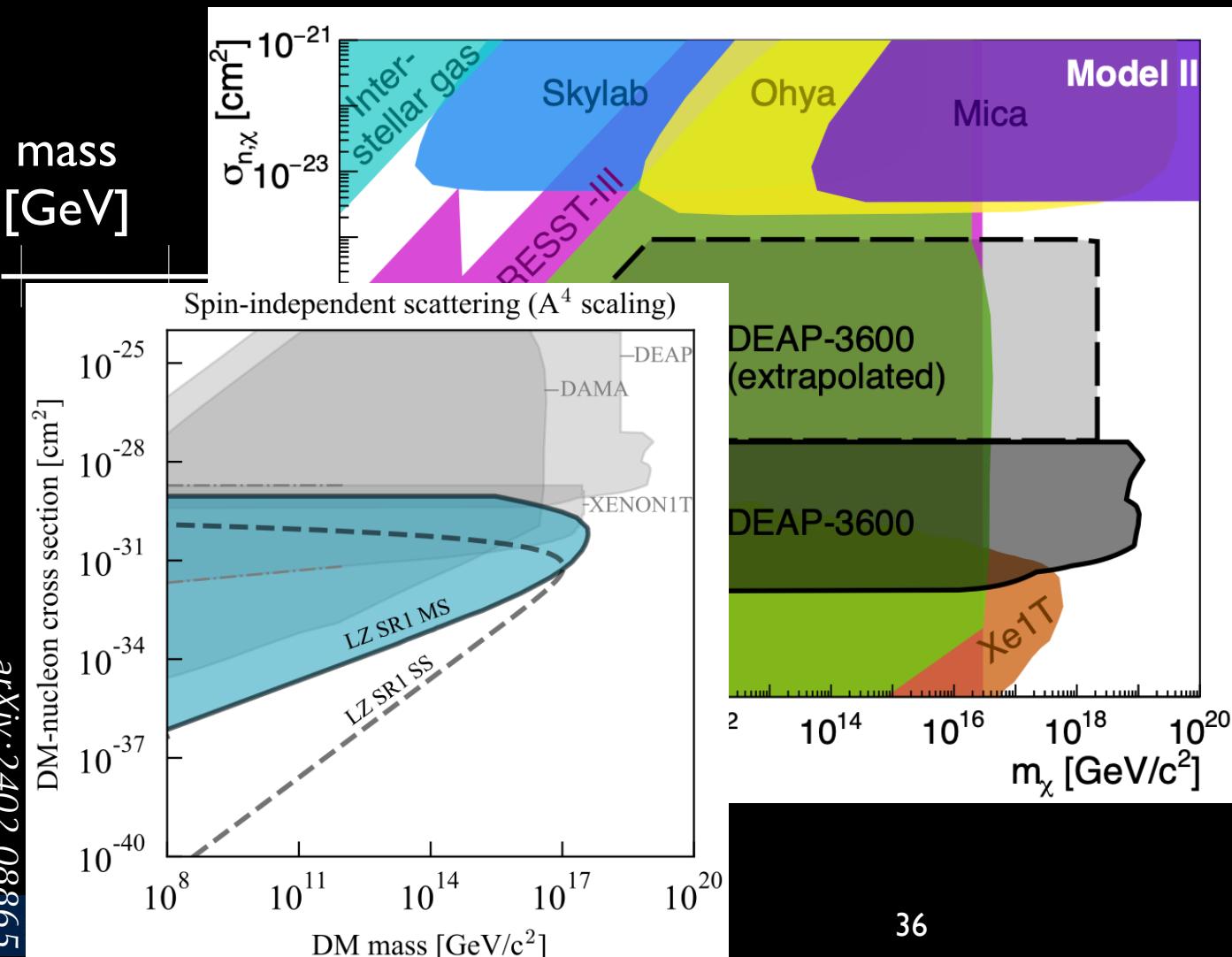
PRL 128 (2022) 1, 011801



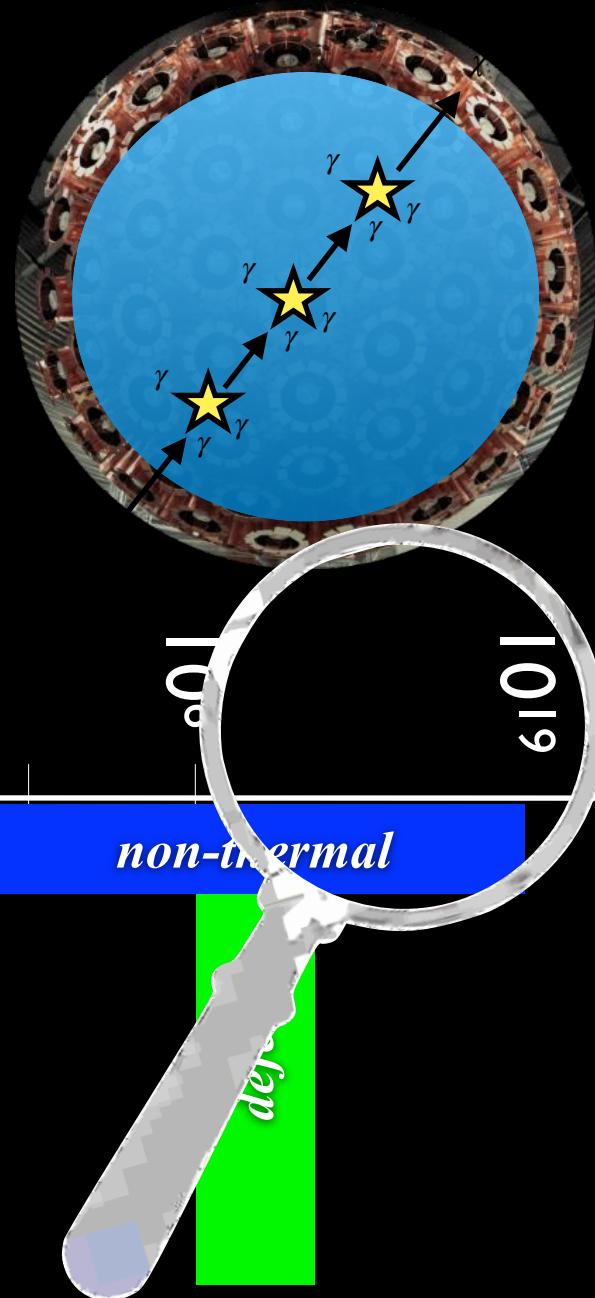
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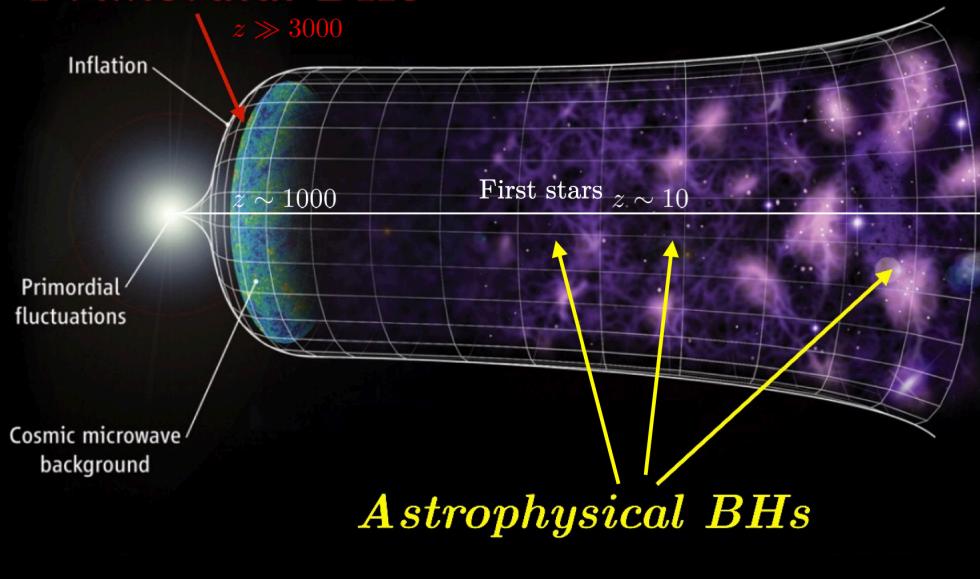
PRL 128 (2022) 1, 011801



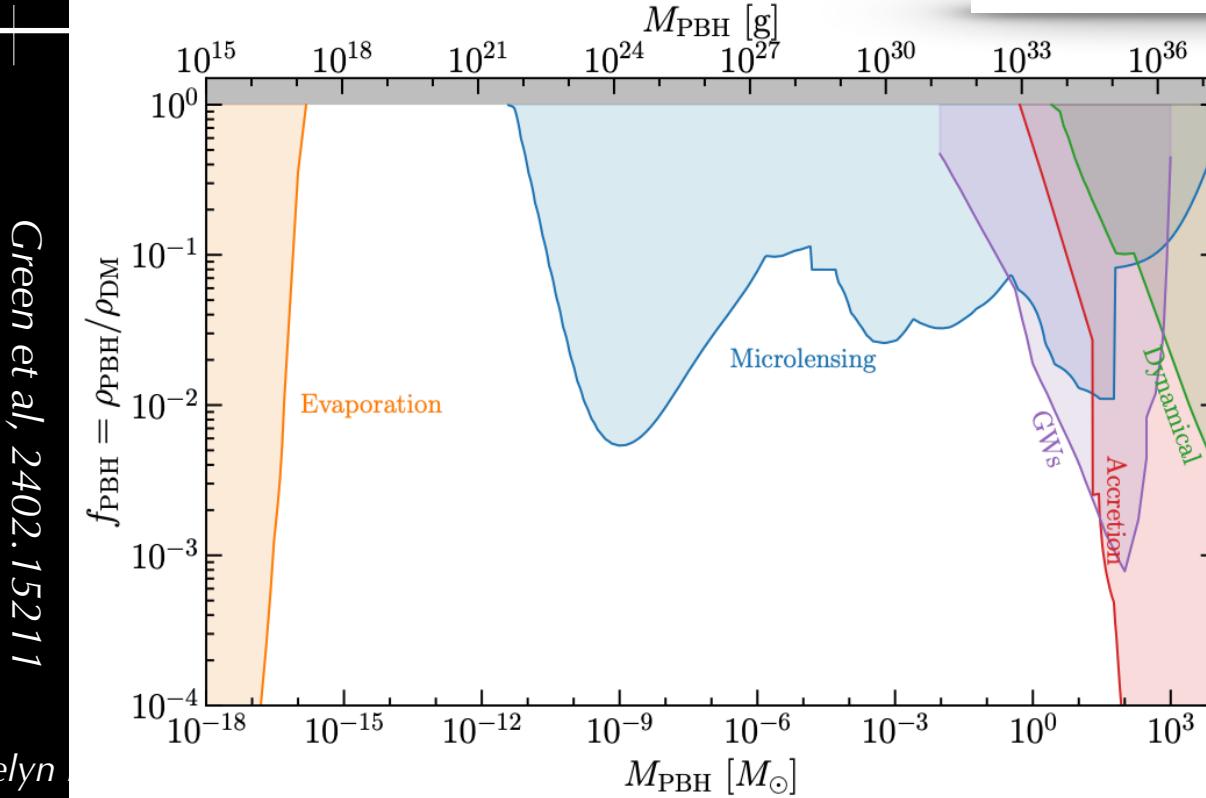
# Very, Very Heavy Dark Matter

*—P. Pani*

*Primordial BHs*

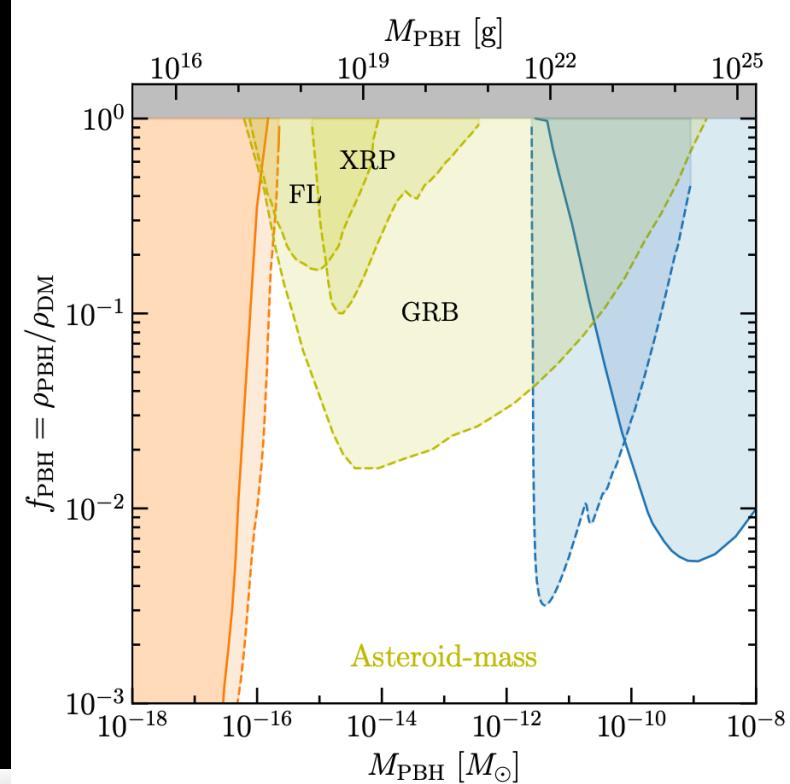


mass  
[GeV]



Green et al., 2402.15211

Jocelyn

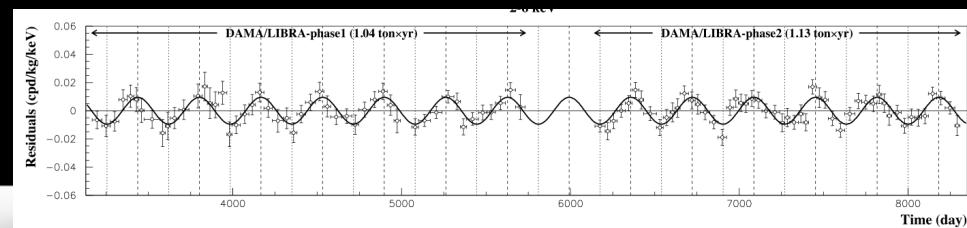


*non-thermal*

*defects*



# Direct Detection ... any Signals?

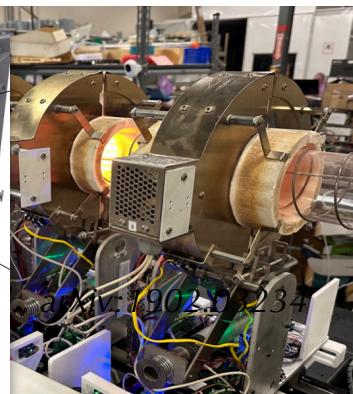
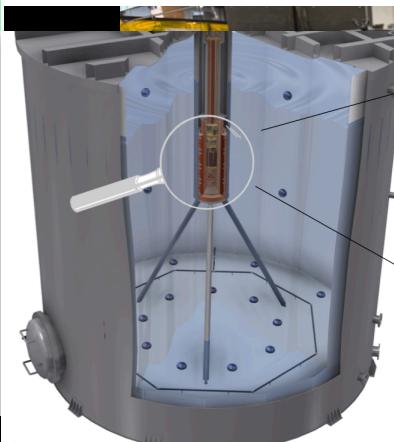
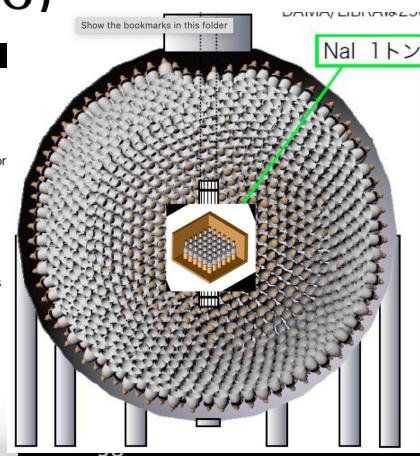
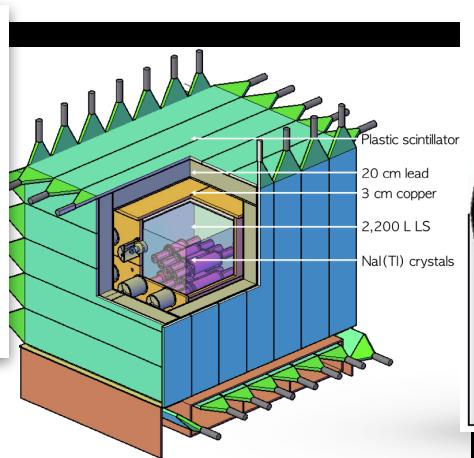
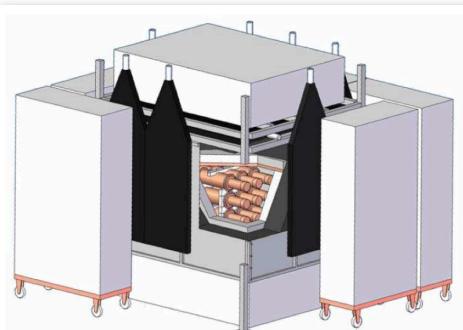


—A. Ianni

- **DAMA/LIBRA:** end of data taking by 2024
  - ✓ Outstanding crystal development achieved, still unmatched
  - ✓ A **crucial anomaly** in DM direct detection standing still
  - ✓ Currently taking data with new PMT dividers since 2021
  - ✓ Since 2021 in data taking without interruptions till Feb 2024 (Phase 2 empowered, ~0.5 ton x yr)
  - ✓ Crucial comprehensive analysis of background time dependence ongoing

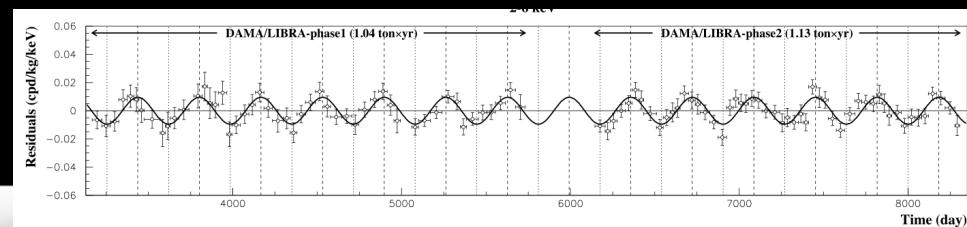
## • ANAIS-112 and COSINE-100

- ✓ Achieved outstanding noise events rejection in the ROI
- ✓ Time-dependent background MC simulations: [more details on systematics](#)
- ✓ Stronger **tests of DAMA/LIBRA accessible** from preliminary analysis reported at this meeting (goal: towards  $5\sigma$ )



Jocelyn Monroe

# Direct Detection ... any Signals?



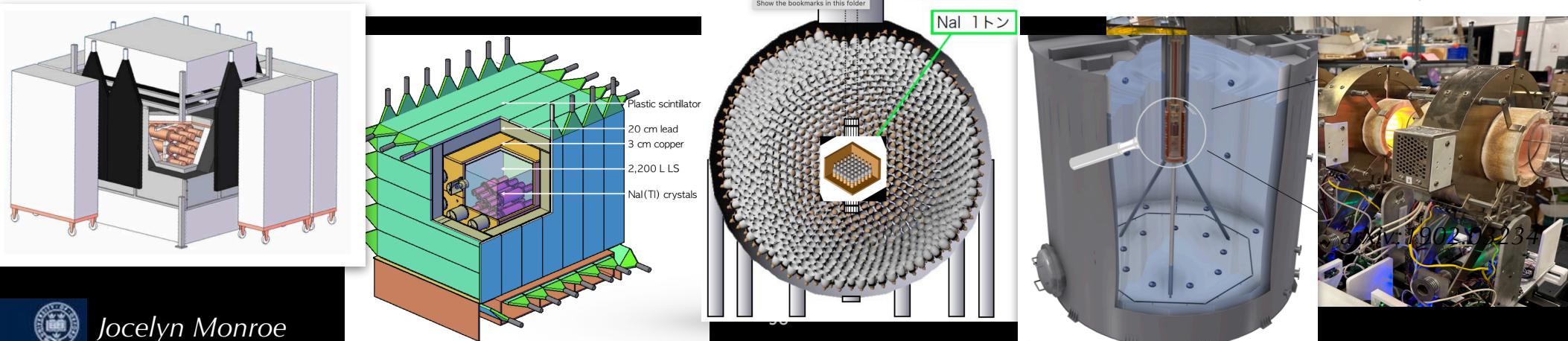
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- ✓ Time-dependent background MC simulations: [more details on sys](#)
- ✓ Stronger **tests of DAMA/LIBRA accessible** from preliminary analysis reported at this meeting (goal: towards  $5\sigma$ )

Excluded at  $>3$  sigma



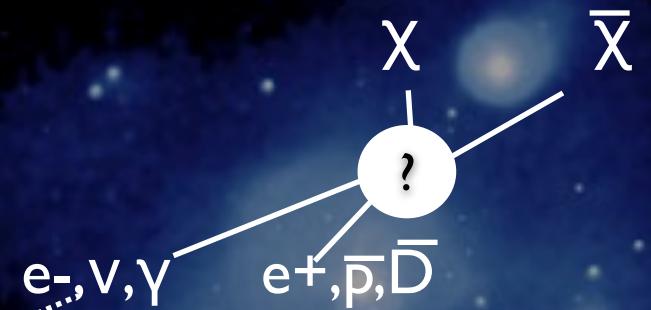
Jocelyn Monroe

# Experimentalist's View

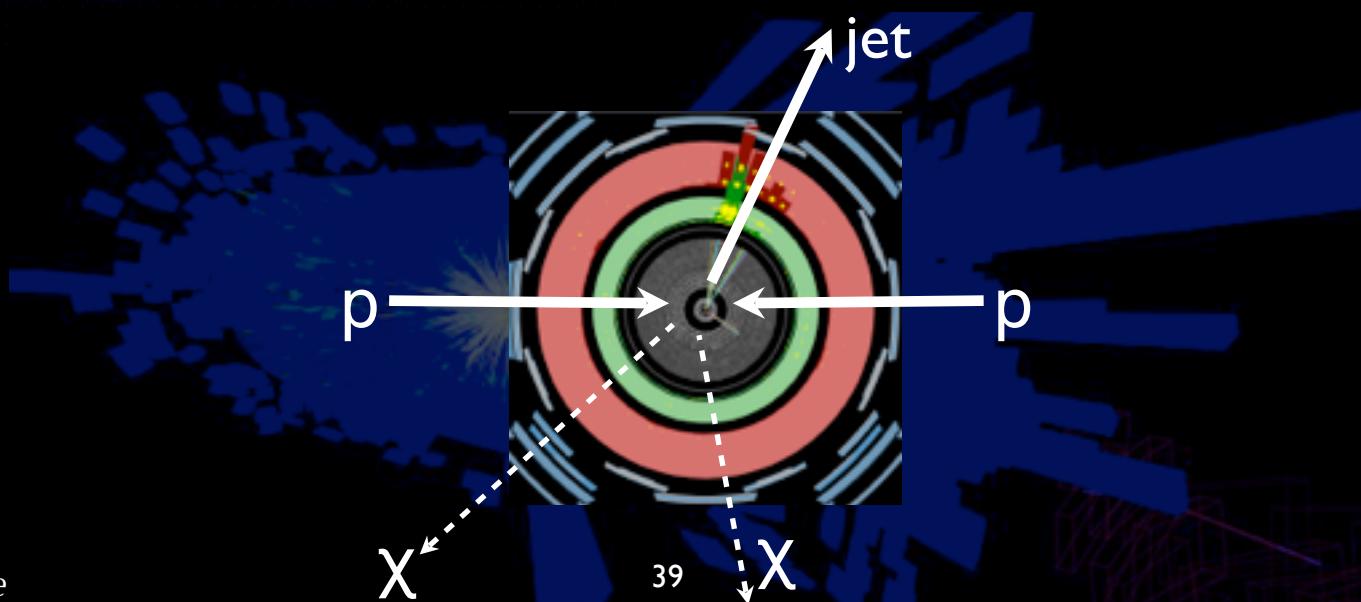


Direct Detection

Indirect Detection

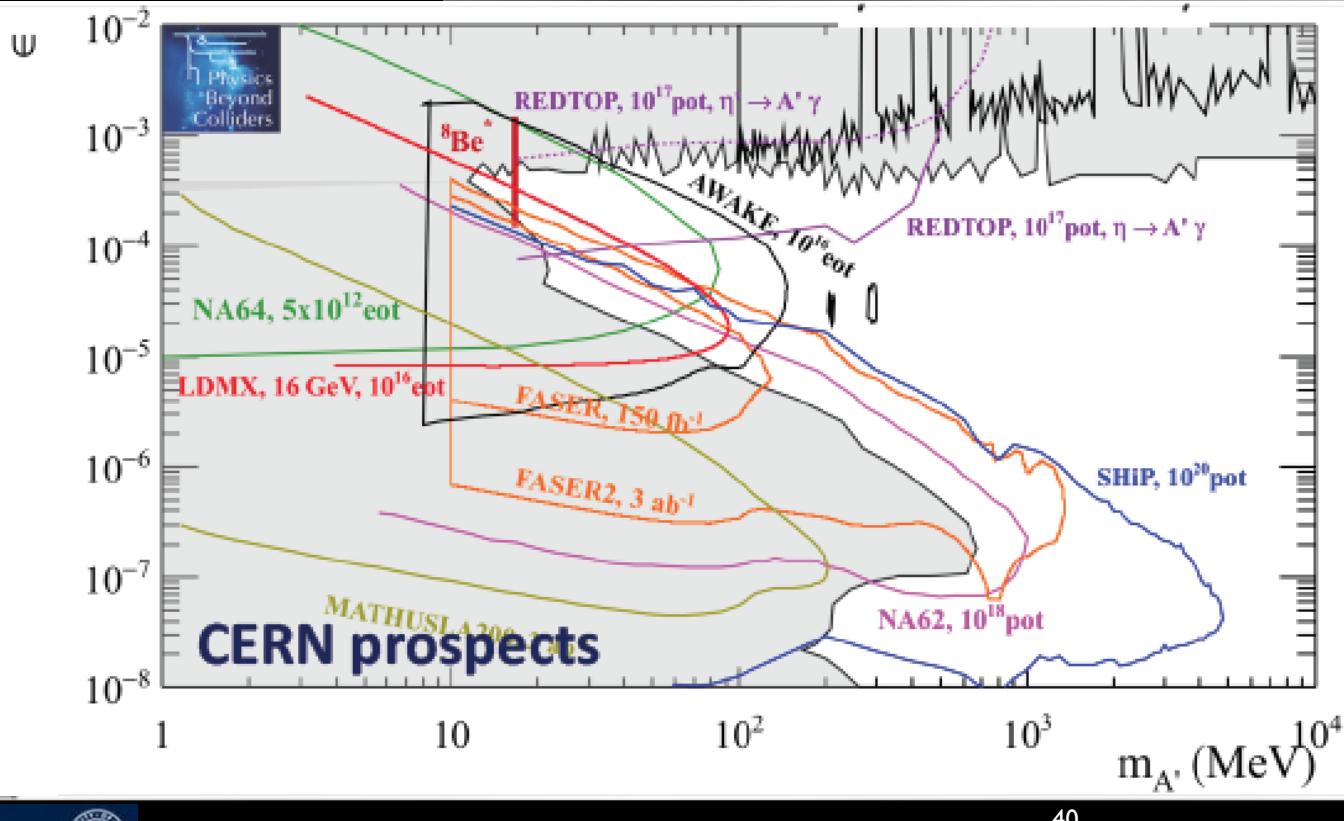
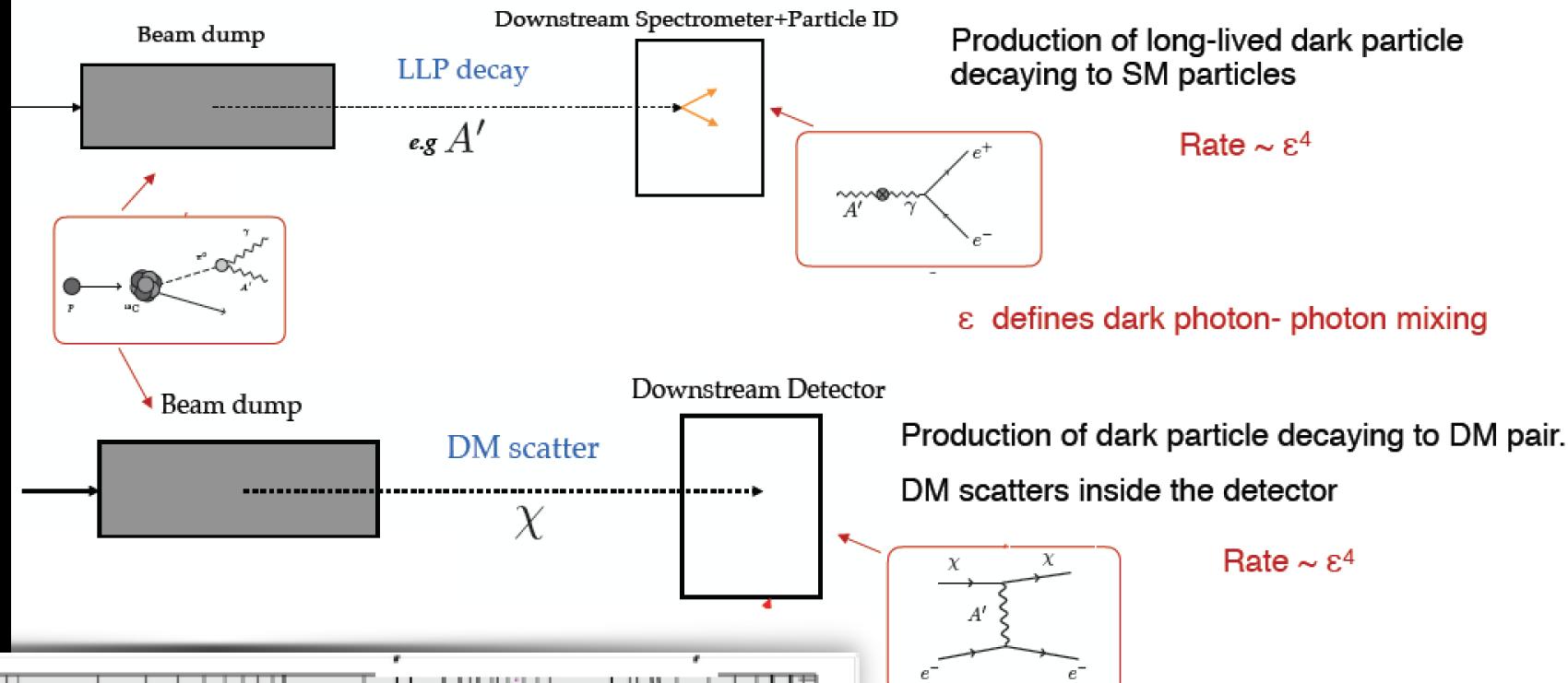


Accelerator Production



# Fixed- Target Strategies

*Renaissance of  
the fixed-target!*



Production of long-lived dark particle decaying to SM particles

Rate  $\sim \varepsilon^4$

$\varepsilon$  defines dark photon-photon mixing

Downstream Detector

Production of dark particle decaying to DM pair.  
DM scatters inside the detector

Rate  $\sim \varepsilon^4$

*Many new experiments planned or proposed for hidden sector searches.*

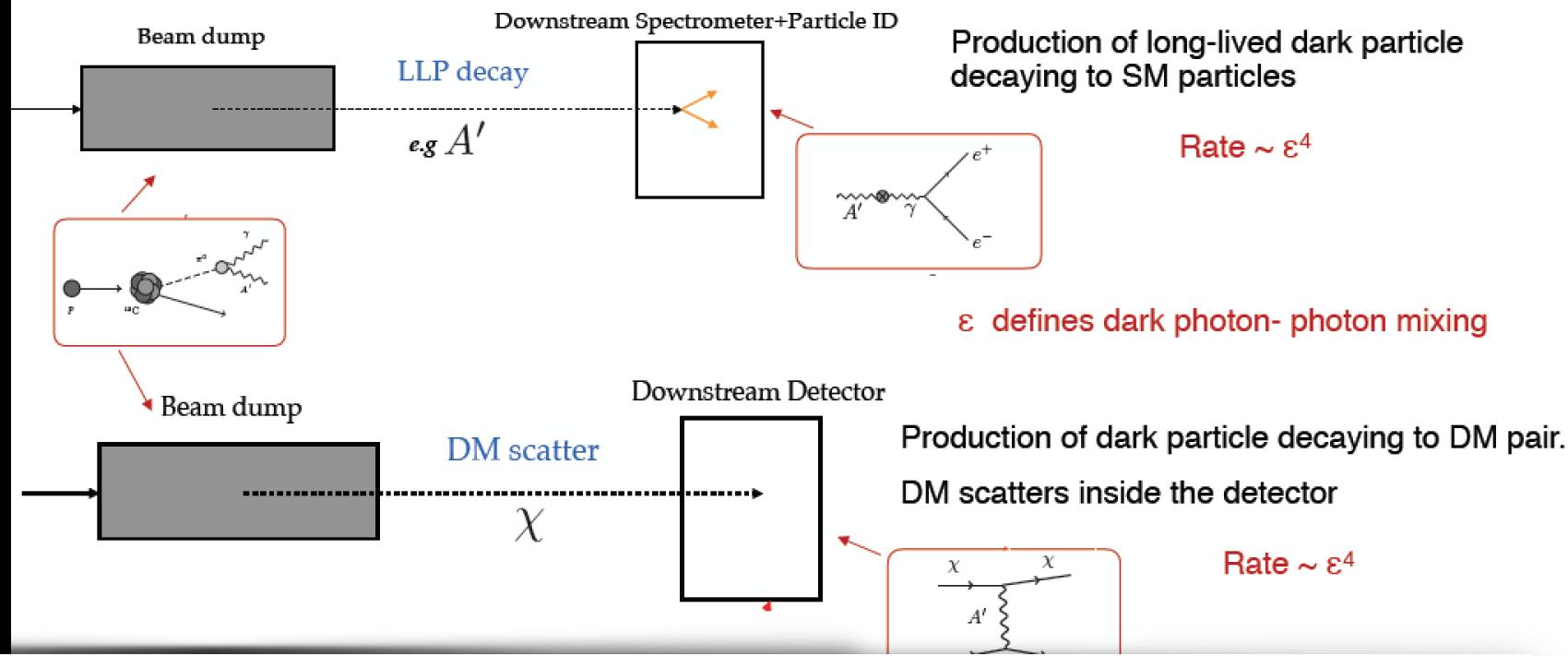
Major synergistic topic of Dark Sectors work at CERN.

*Ellis et al., ESPPU Physics Briefing Book, CERN-ESU-004 (2019)*



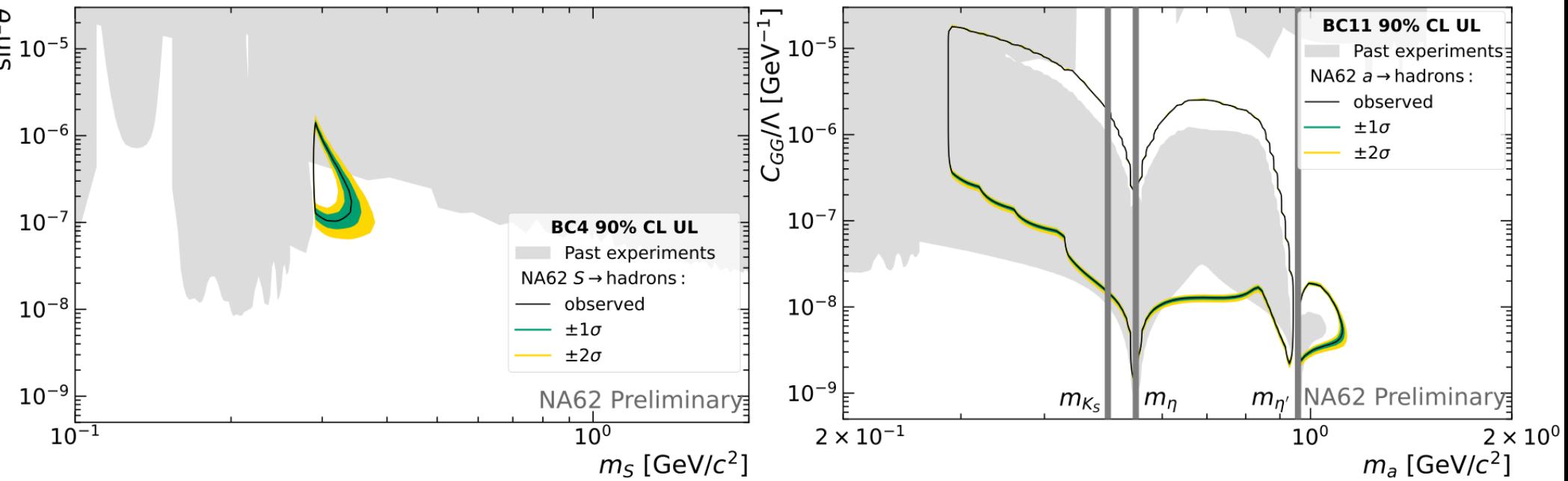
# Fixed- Target Strategies

*Renaissance of  
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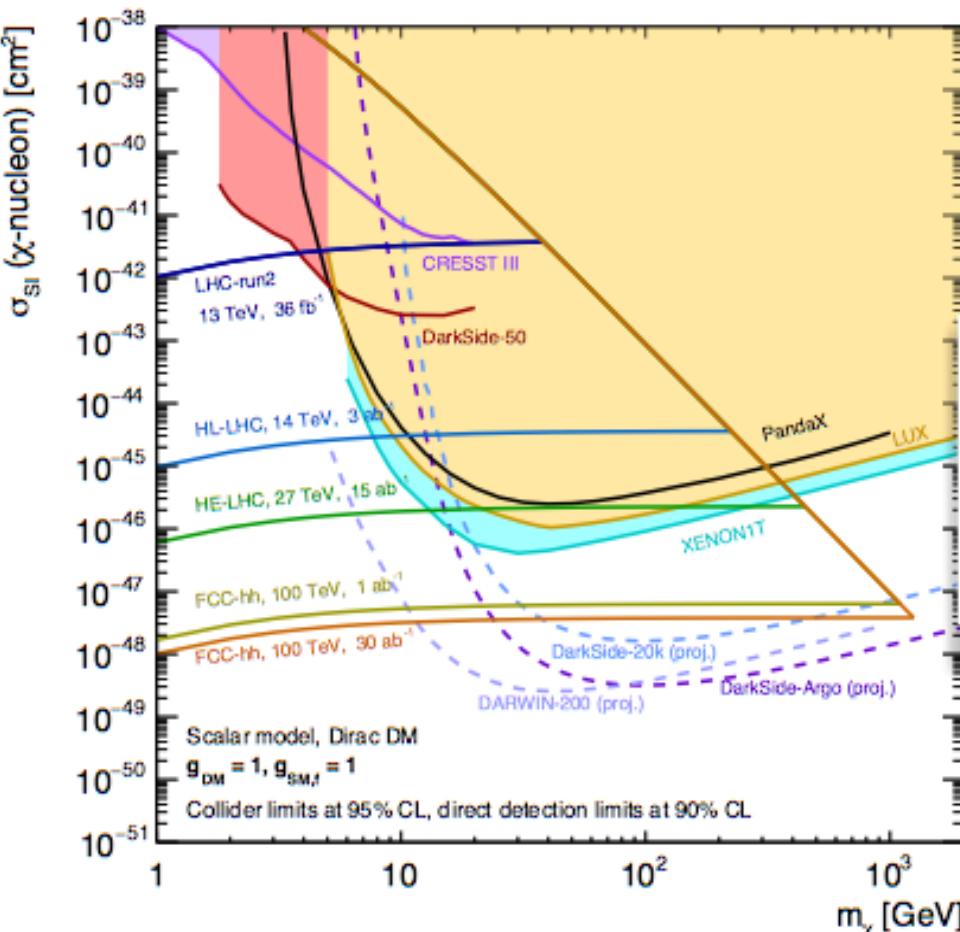
**Upon opening 0 events were found in all Control and Signal Regions**

**-J. Schubert**

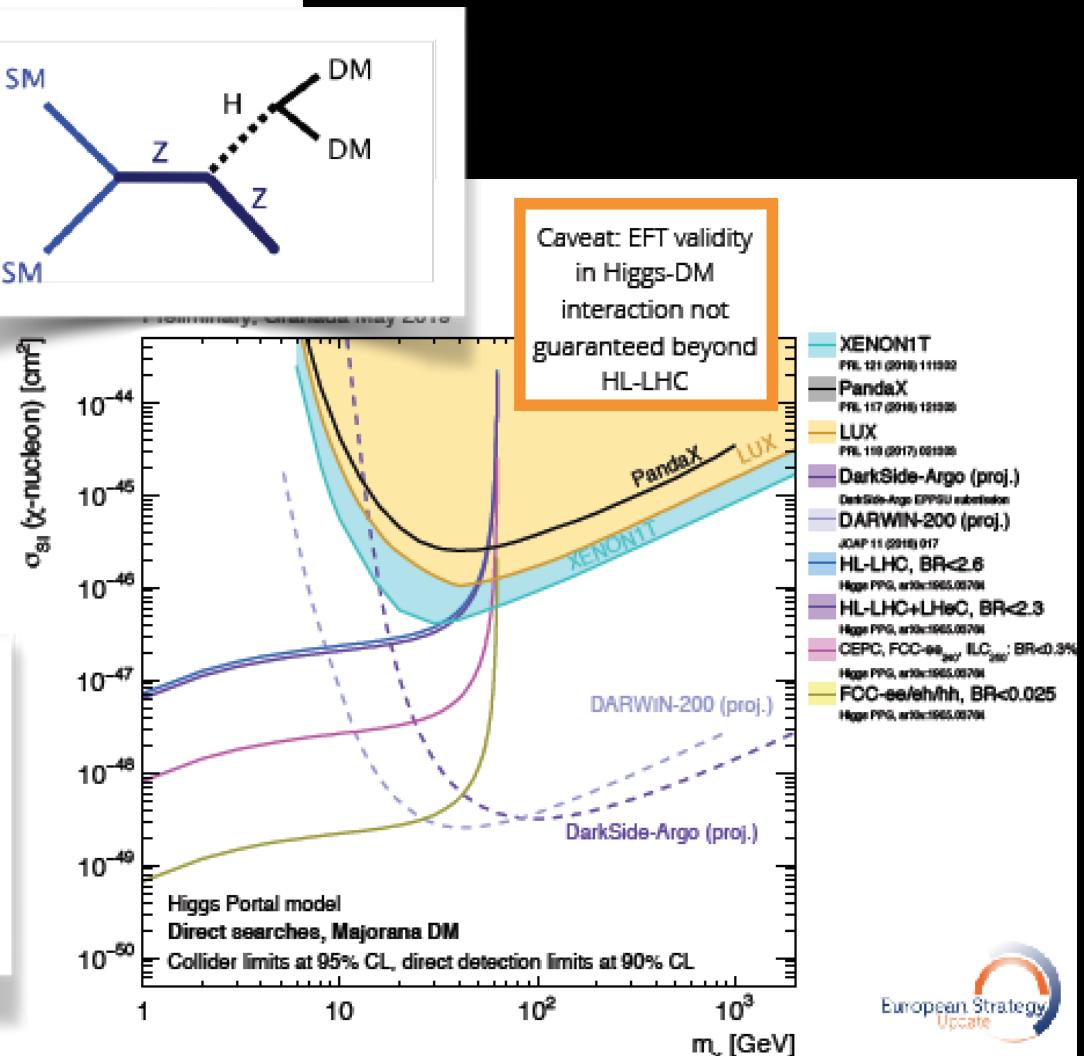


**Stand alone parameter exclusions on Dark Scalar (BC4) and gluon coupled Axion Like Particle (BC11)**

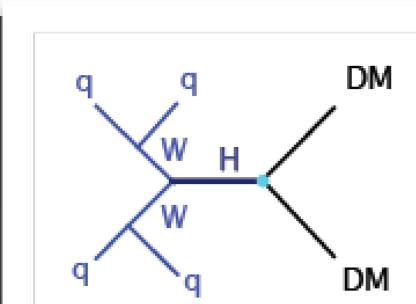
# Collider Complementarity with Direct Detection



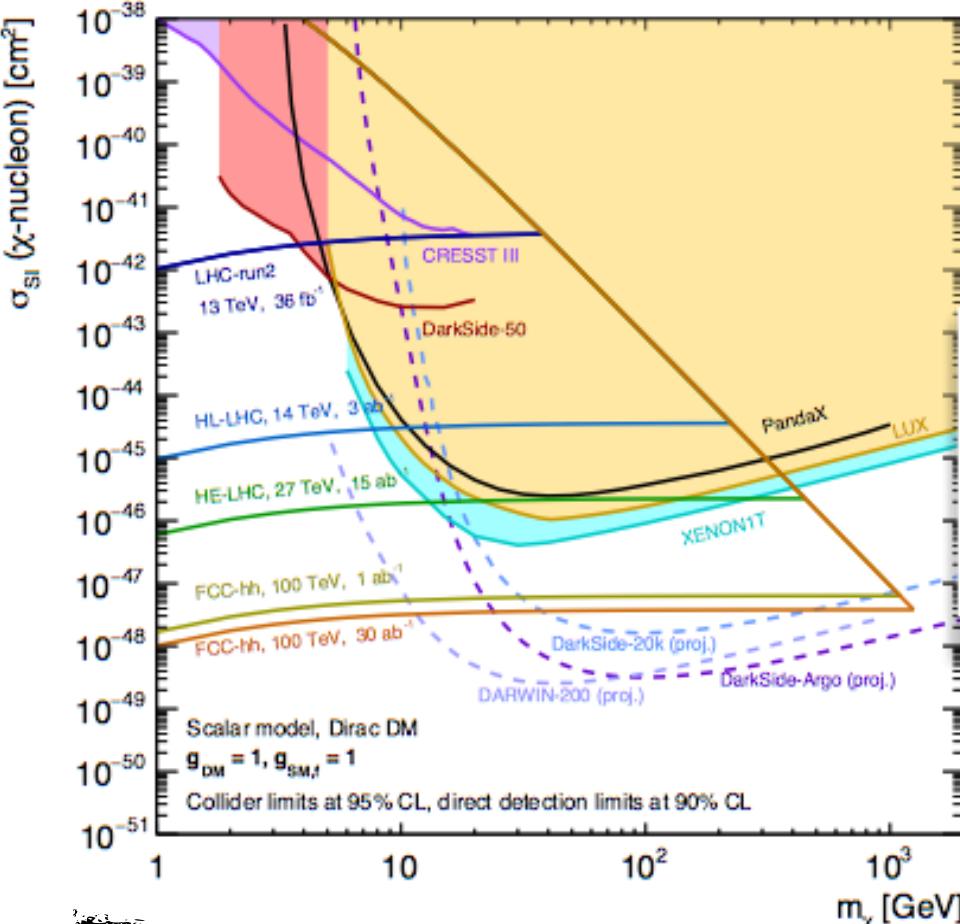
limits on branching ratio translated to limits on cross section vs. mass



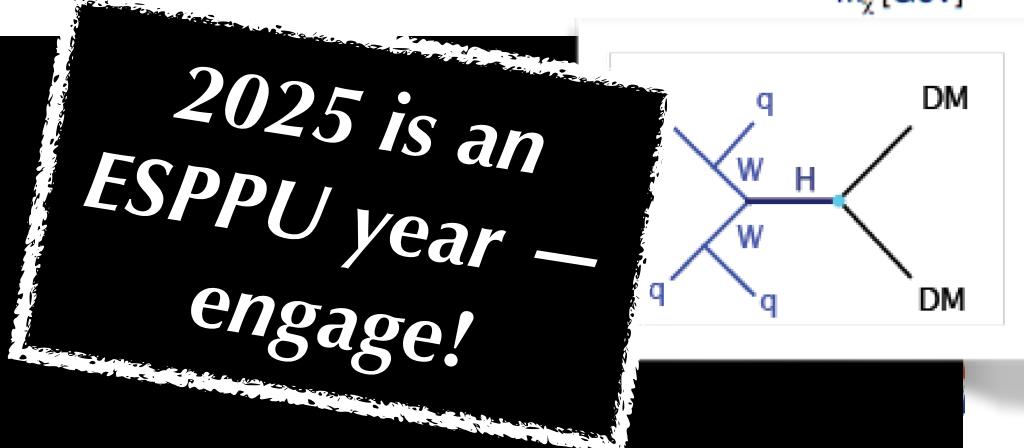
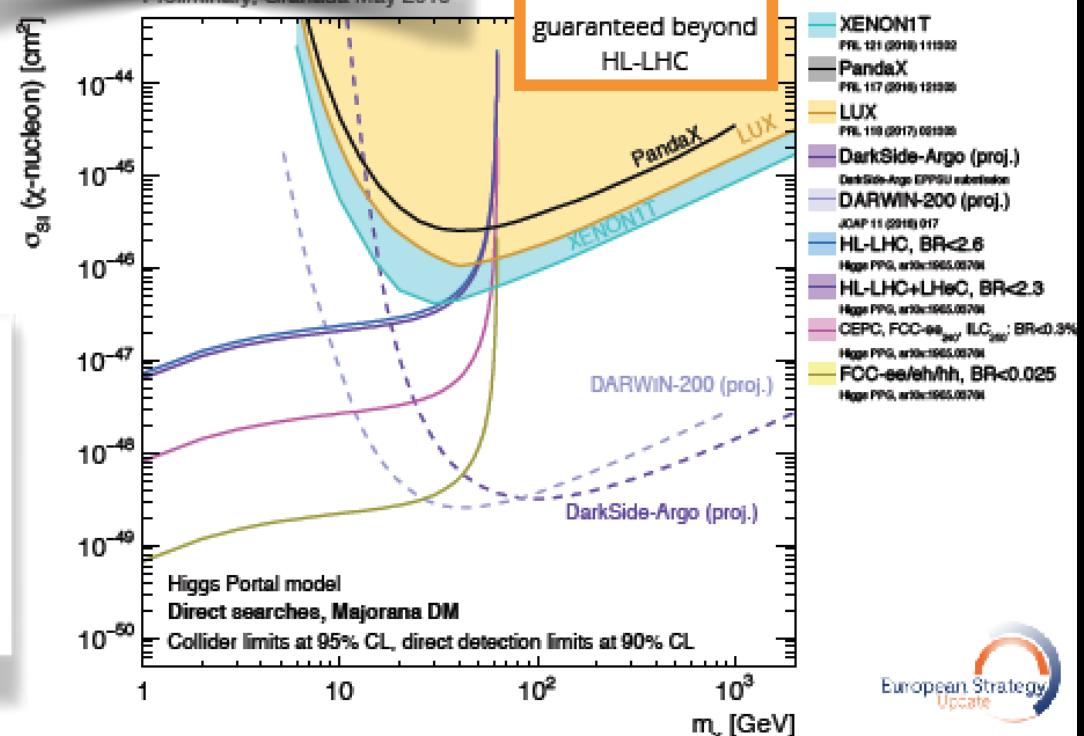
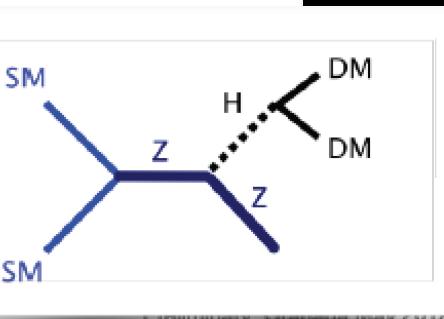
ESPPU Physics Briefing Book,  
CERN-ESU-004 (2019)



# Collider Complementarity with Direct Detection



limits on branching ratio translated to limits on cross section vs. mass



# Final Thought 1

***This conference shows a phenomenally productive field***

New Results at this conference:

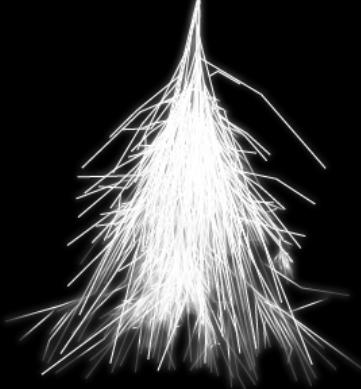
- PANDA-X4 new WIMP search result, best >100 GeV
- 2.73 sigma significance solar B-8 CEnNS measurement
- new MeV DM search results from CRESST-III for SI and SD on lithium
- SENSEI@SNOLAB 2nd science run results on DM-electron final states
- NEWS-G@SNOLAB SD-p search preliminary results
- NA62 dark scalar and ALPs constraints
- ANALIS-112 0.6 t-y modulation search test of DAMA/LIBRA
- COSINE-100 new results — >3 sigma away from DAMA/LIBRA signal
- ... + your new result here! (apologies if I missed it!)

***...and, since 2014, huge creativity –  
both in experiment and theory***

(NASA)



cosmic rays

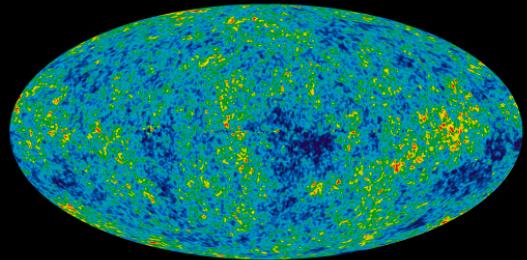


infrared/optical

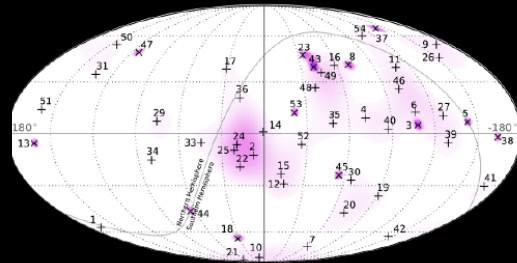


Final Thought 2

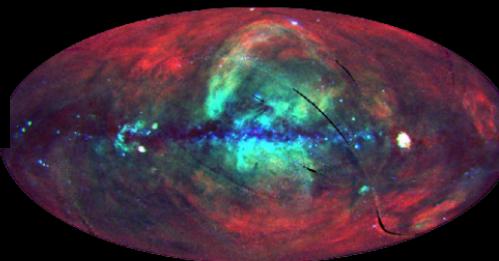
radio/microwave



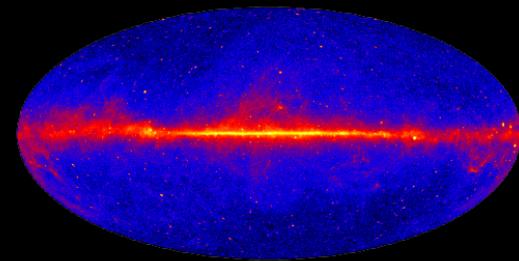
neutrinos



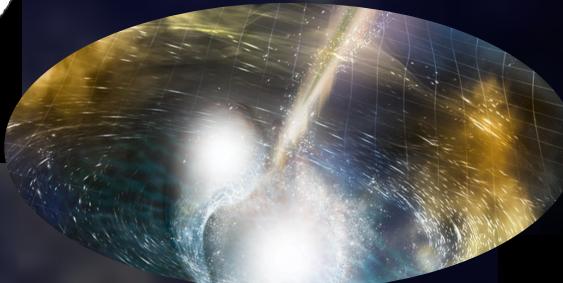
X-rays



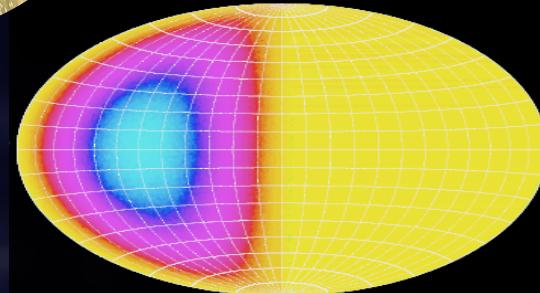
gamma-rays



gravitational waves



dark matter



To do list for IDM2034:

Today: find dark matter. **Where is it??**

Next: dark matter observatories (**-Baudis++**)

Ultimately: dark matter telescopes (**-O'Hare++**)



# Thank you





# Extra Slides

## Dark Matter

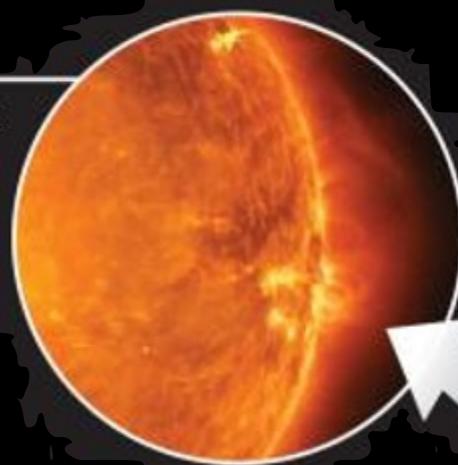
- Dark photons
- Axion-like particles
- Planck mass

## WIMPs

- Spin-independent
- Spin-dependent
- Sub-GeV

## Sun

- Solar pp neutrinos
- Solar Boron-8 neutrinos



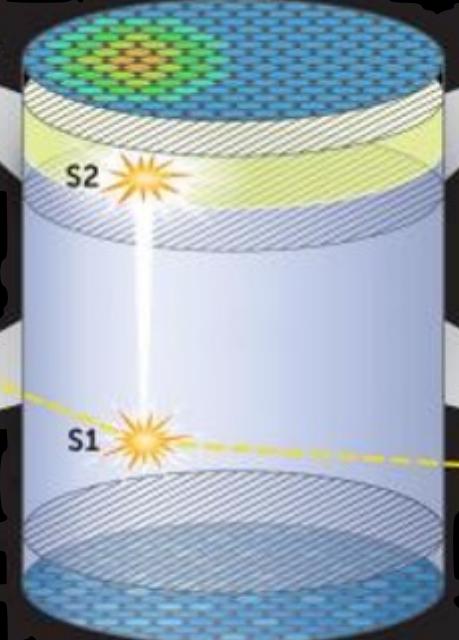
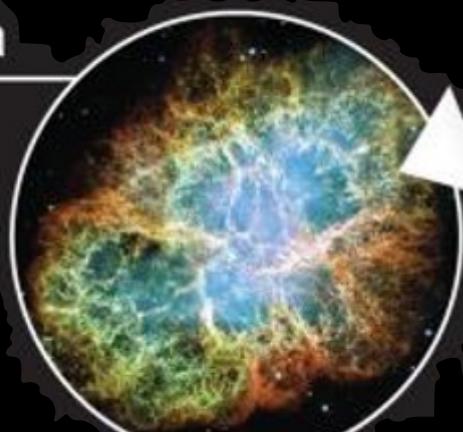
## Big Bang

- Neutrinoless double beta decay
- Double electron capture



## Supernova

- Supernova neutrinos
- Multi-messenger



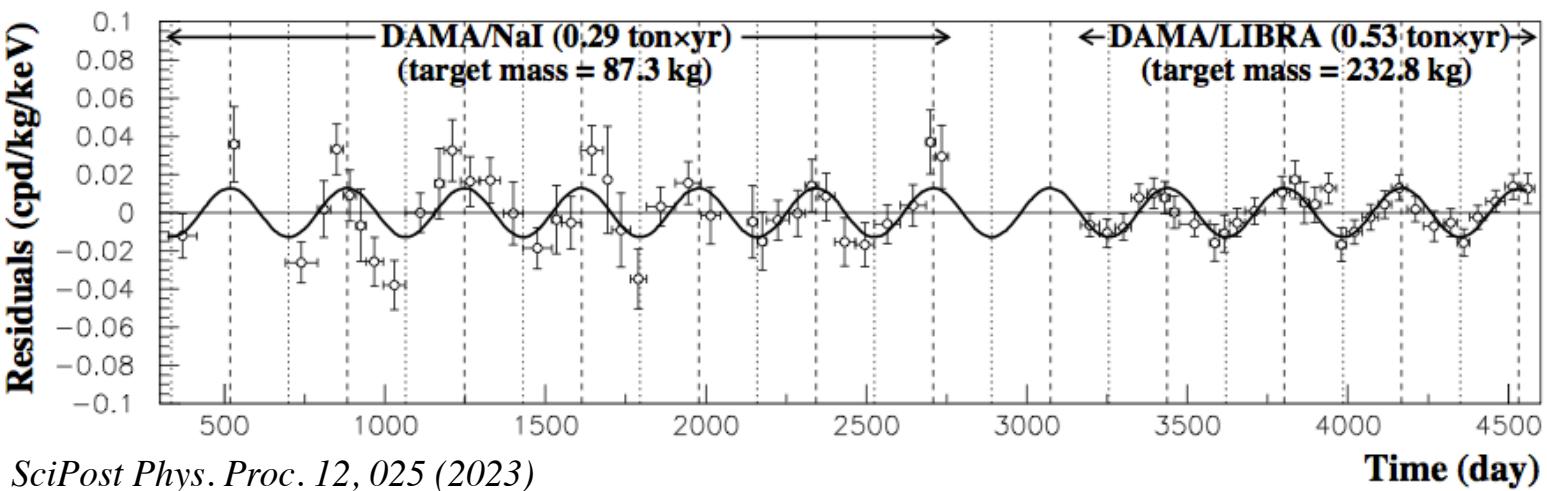
## Cosmic Rays

- Atmospheric neutrinos



# Annual Modulation Tests

predicted modulation  $A \sim 0.02\text{--}0.1$ ,  $t_0 = 152.5$  days



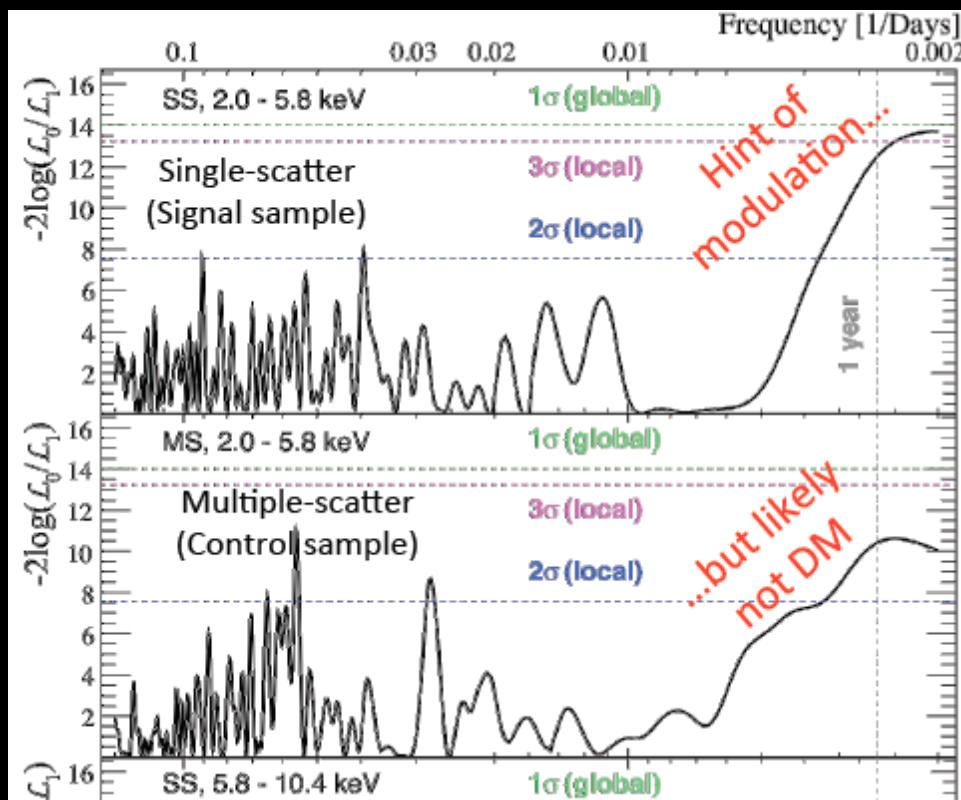
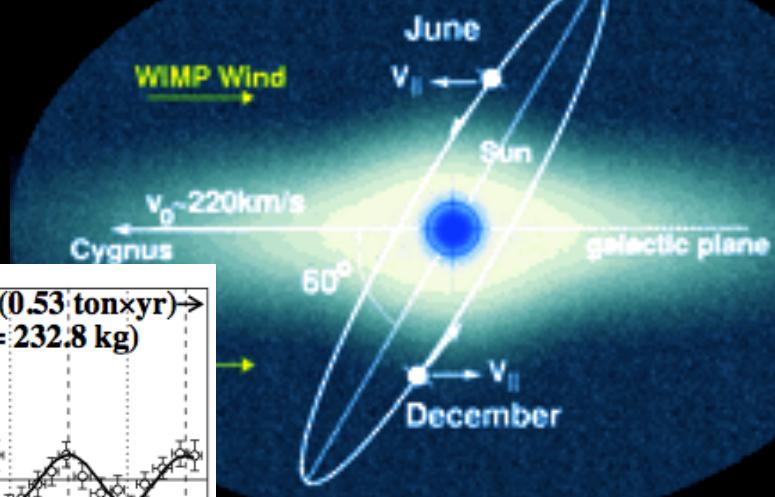
SciPost Phys. Proc. 12, 025 (2023)

**DAMA/LIBRA:** measure  $(0.0112 \pm 0.0012)$  cpd/kg/keV,  
 $t_0 = (144 \pm 7)$  d in 1.33 T-yr.

many other searches, on Ge, CsI, Xe, etc.  
observe no evidence of modulation.

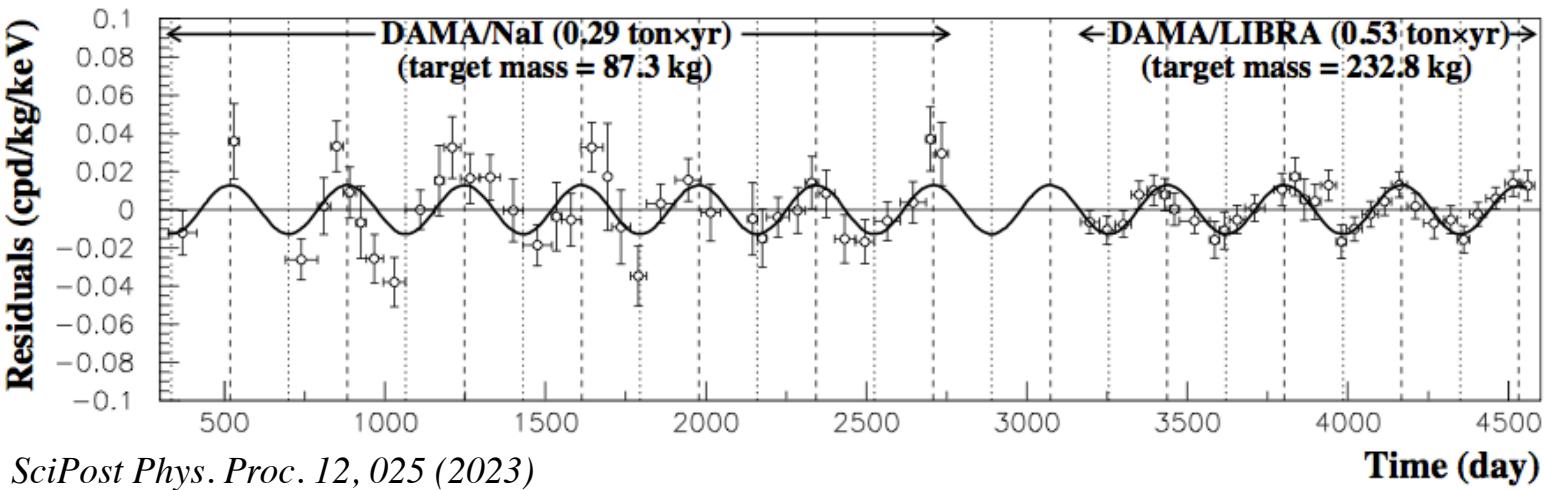
*In the same underground laboratory:*

**XENON100:** Xe,  $4.8\sigma$  exclusion of DAMA,  
test of leptophilic dark matter arXiv:1507.07748

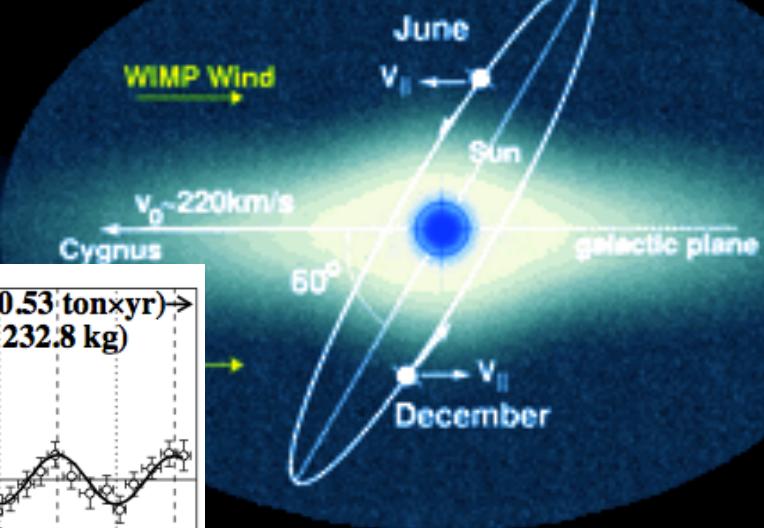


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SciPost Phys. Proc. 12, 025 (2023)



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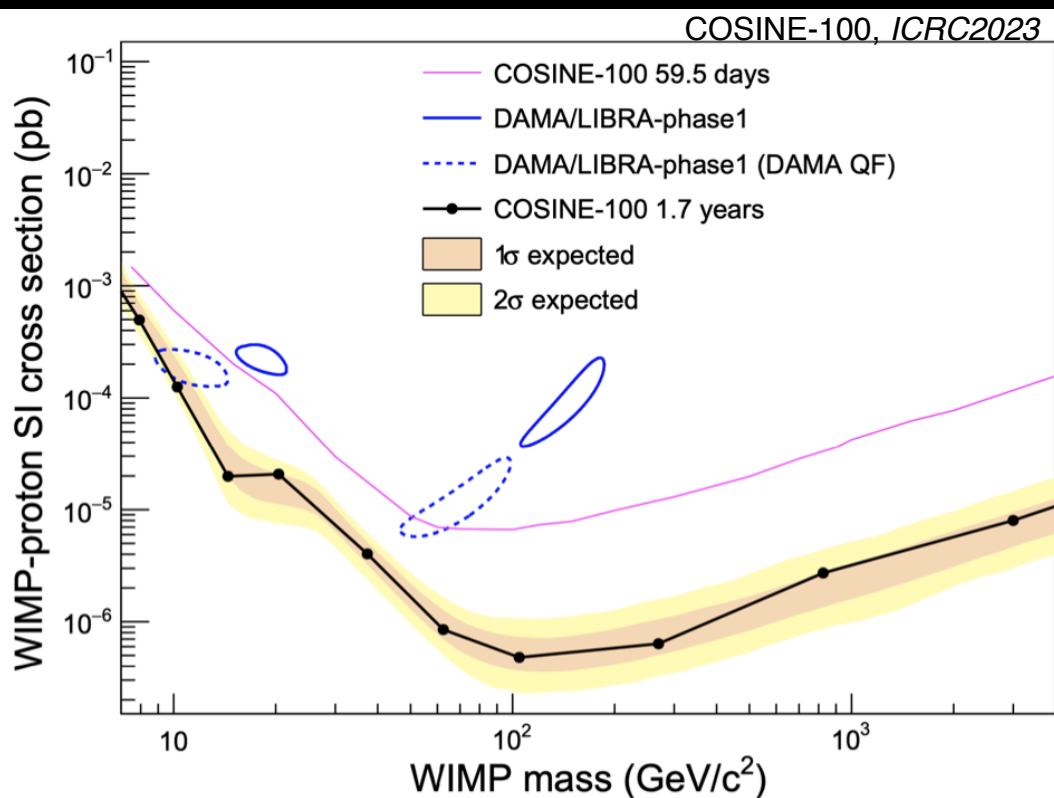
*In the same underground laboratory:*

**XENON100:** Xe,  $4.8\sigma$  exclusion of DAMA,  
test of leptophilic dark matter [arXiv:1507.07748](https://arxiv.org/abs/1507.07748)

*With the same target (different laboratories):*

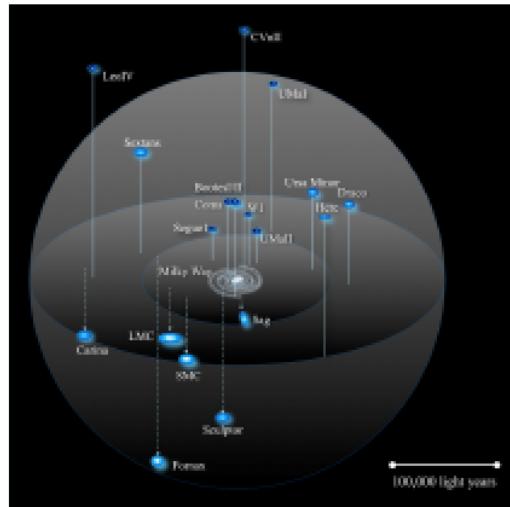
**COSINE-100:** no evidence of modulation

**ANALIS:** PRD 103, 102005 (2021)



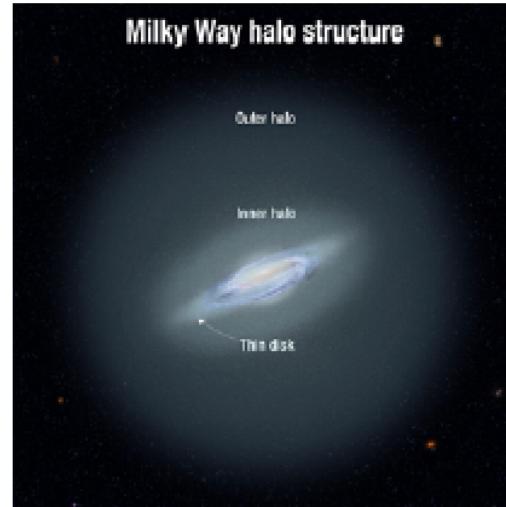
# Gravitational Detection Strategies

## Dwarf galaxies



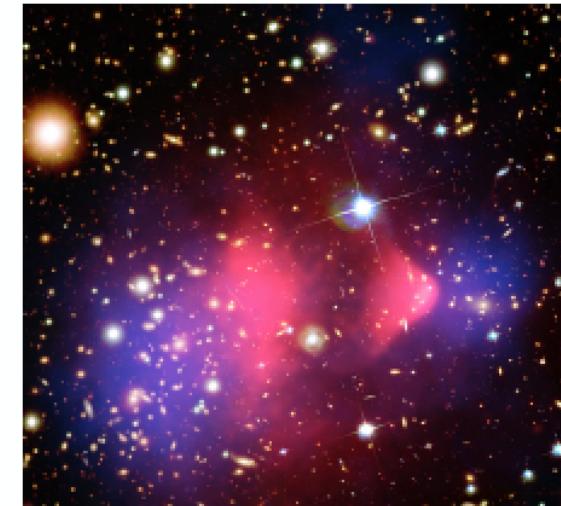
“B-factory” ( $v \sim 30$  km/s)

## MW-like galaxies



“LEP” ( $v \sim 200$  km/s)

## Clusters



“LHC” ( $v \sim 1000$  km/s)

Self-scattering  
kinematics



Observations  
on all scales

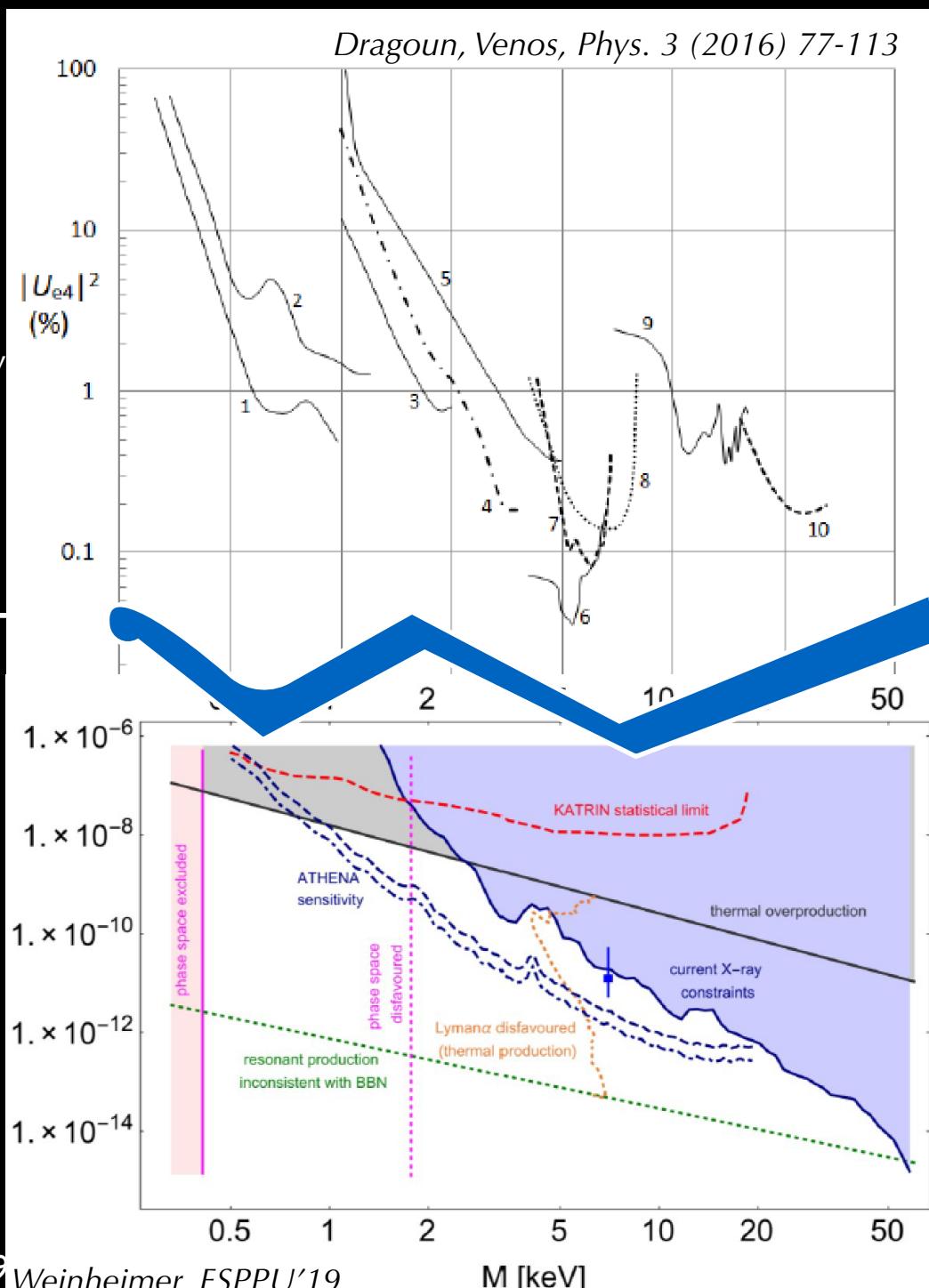
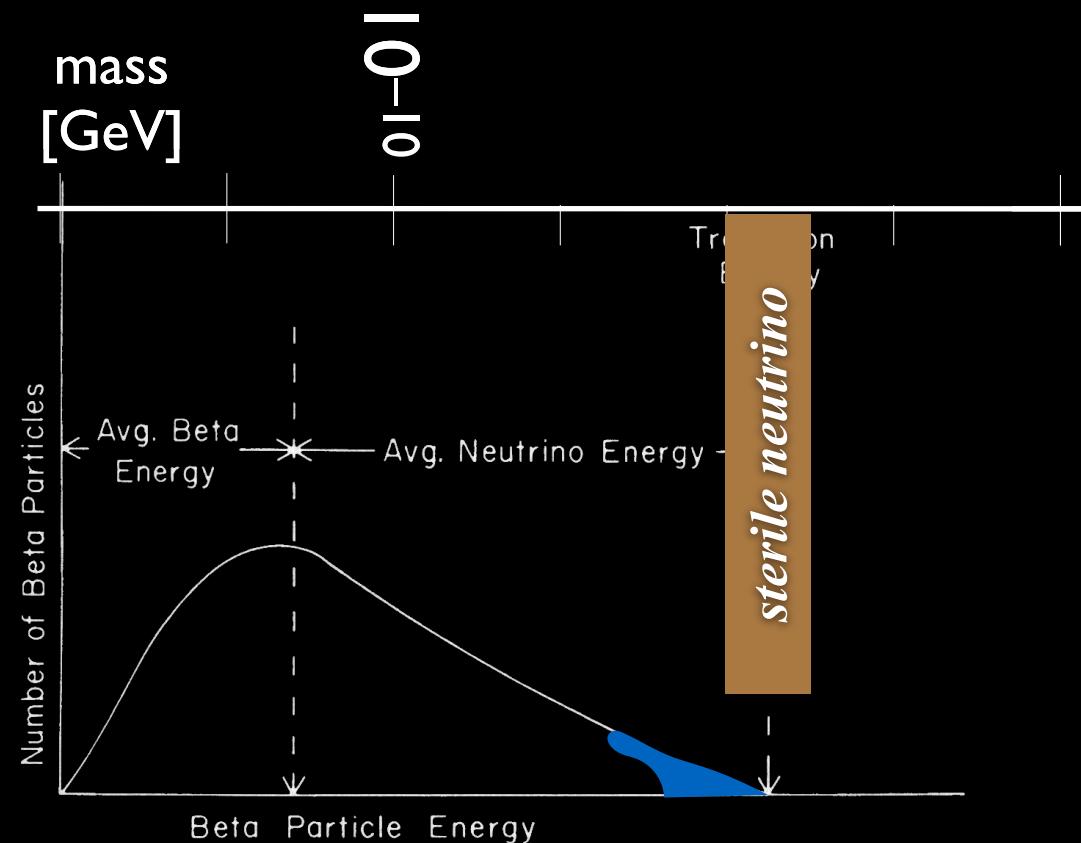
Measure particle  
physics parameters  
 $\sigma_x, m_x, m_\phi$

# Warm Dark Matter

**Sterile neutrino dark matter** can scatter with electrons  $N_S e^- \rightarrow \nu_e e^-$

Constraints on  $|U_{e4}|^2$  from beta decay: energy spectrum modified by sterile neutrino mixing.

Constraints from indirect detection: x-ray energy spectrum strongly limits  $|U_{e4}|^2 + 3.5$  keV anomaly

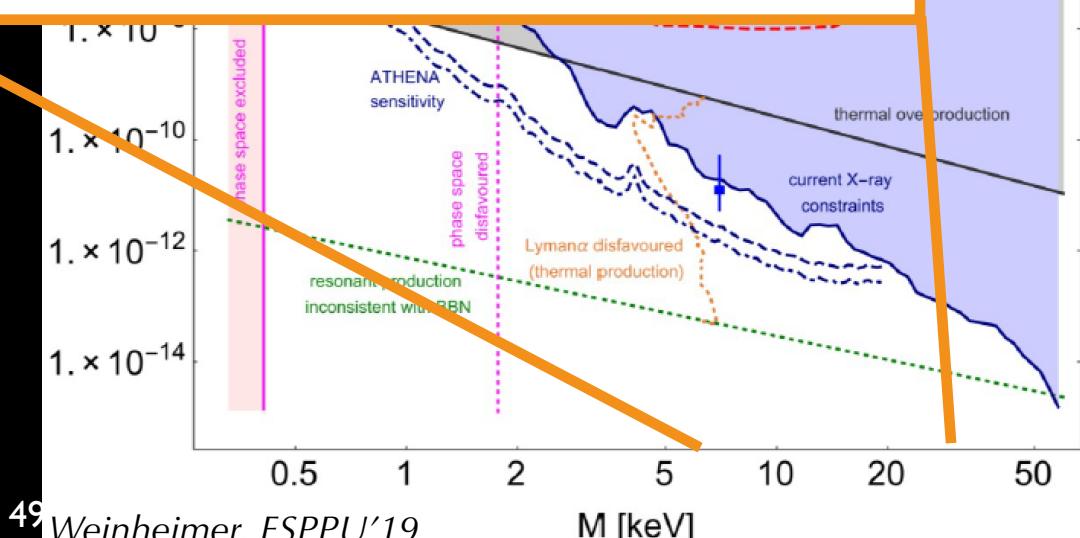
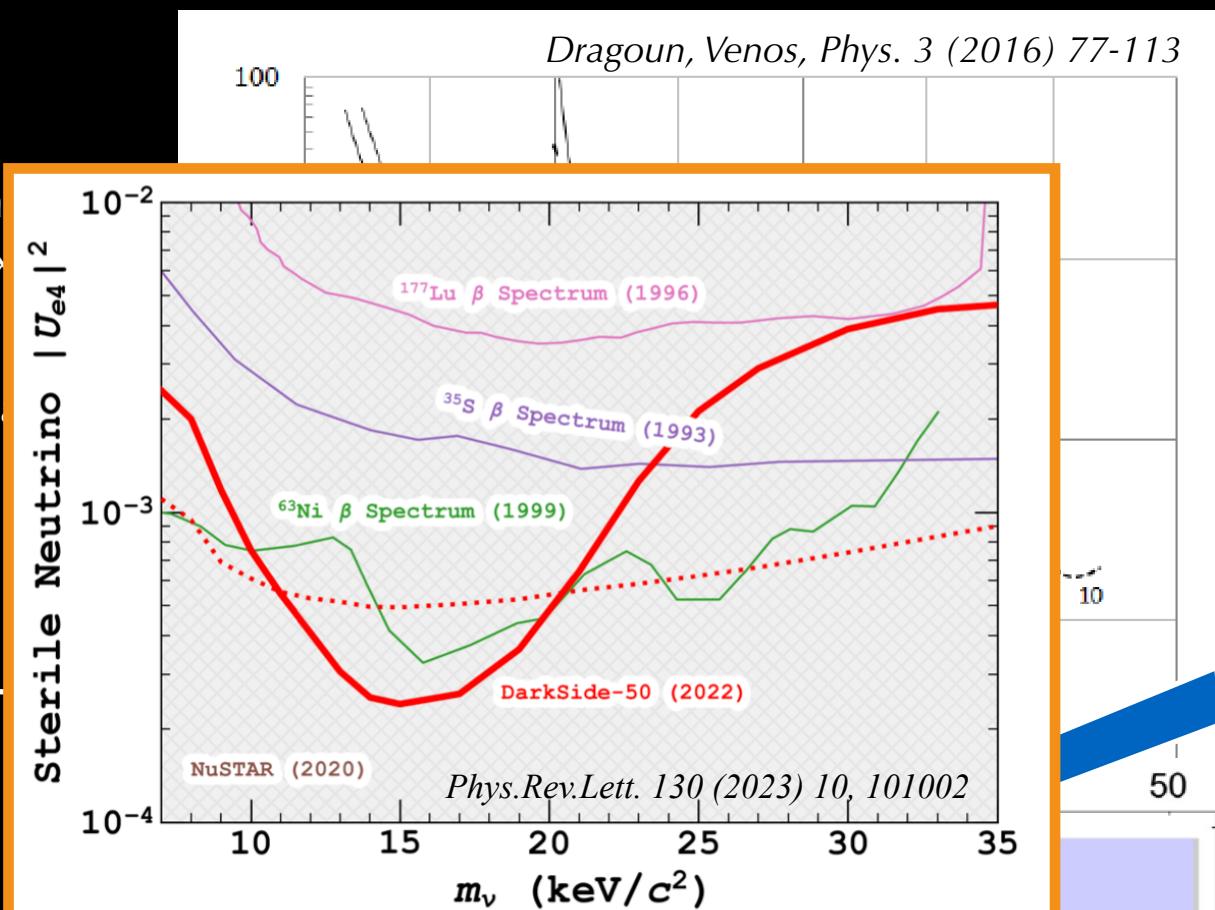
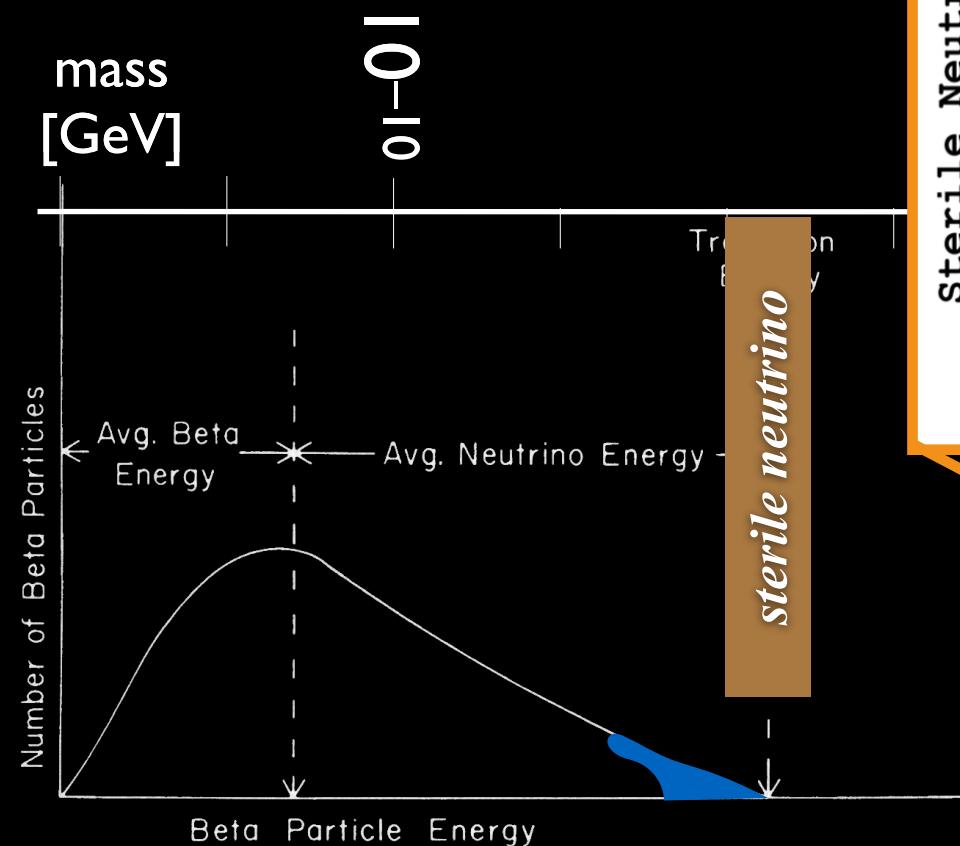


# Warm Dark Matter

**Sterile neutrino dark matter** can scatter with electrons  $N_S e^- \rightarrow \nu_e e^-$

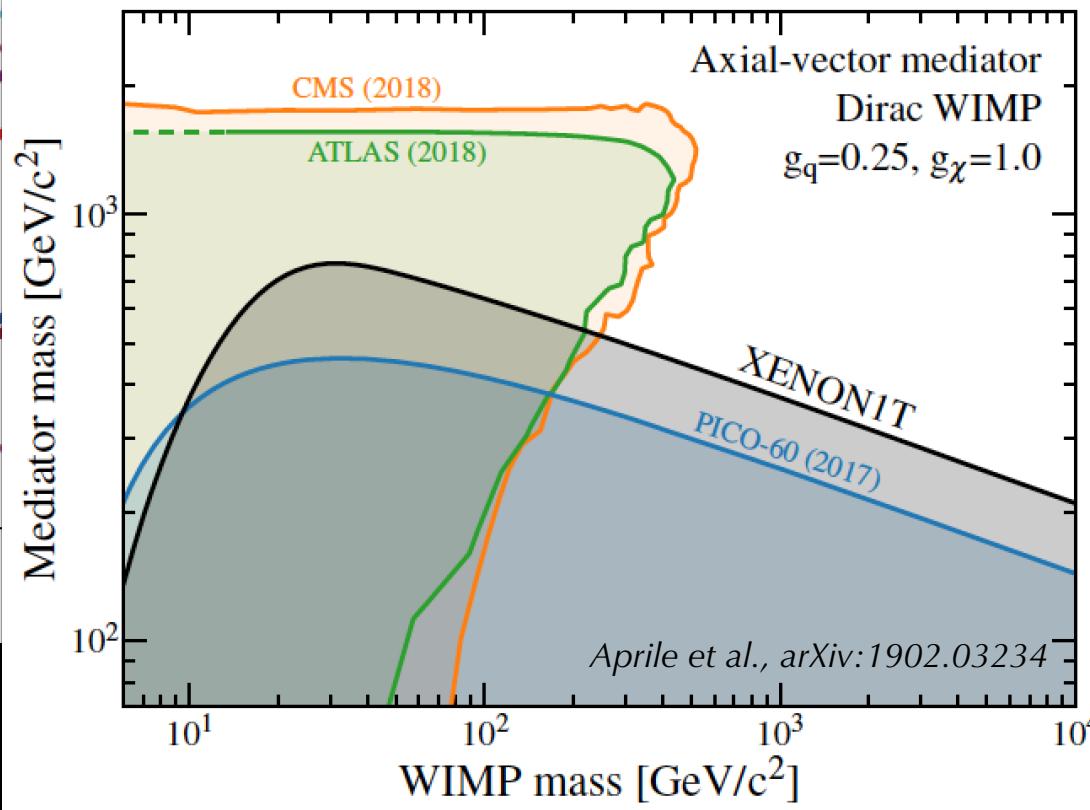
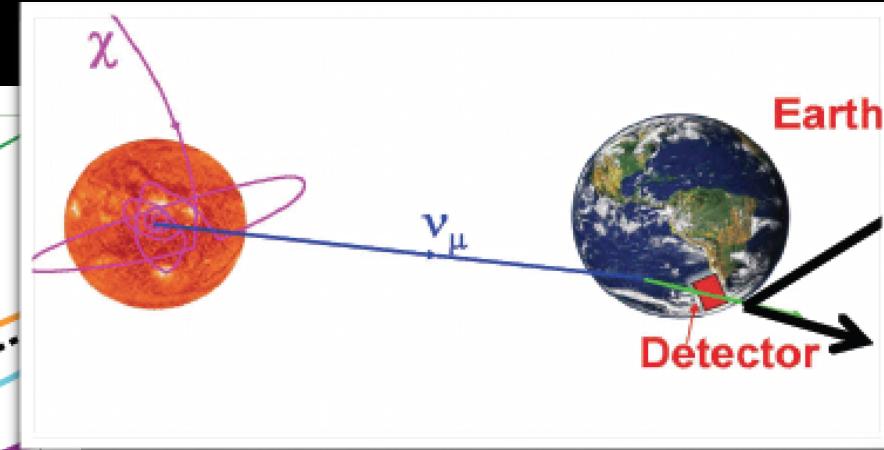
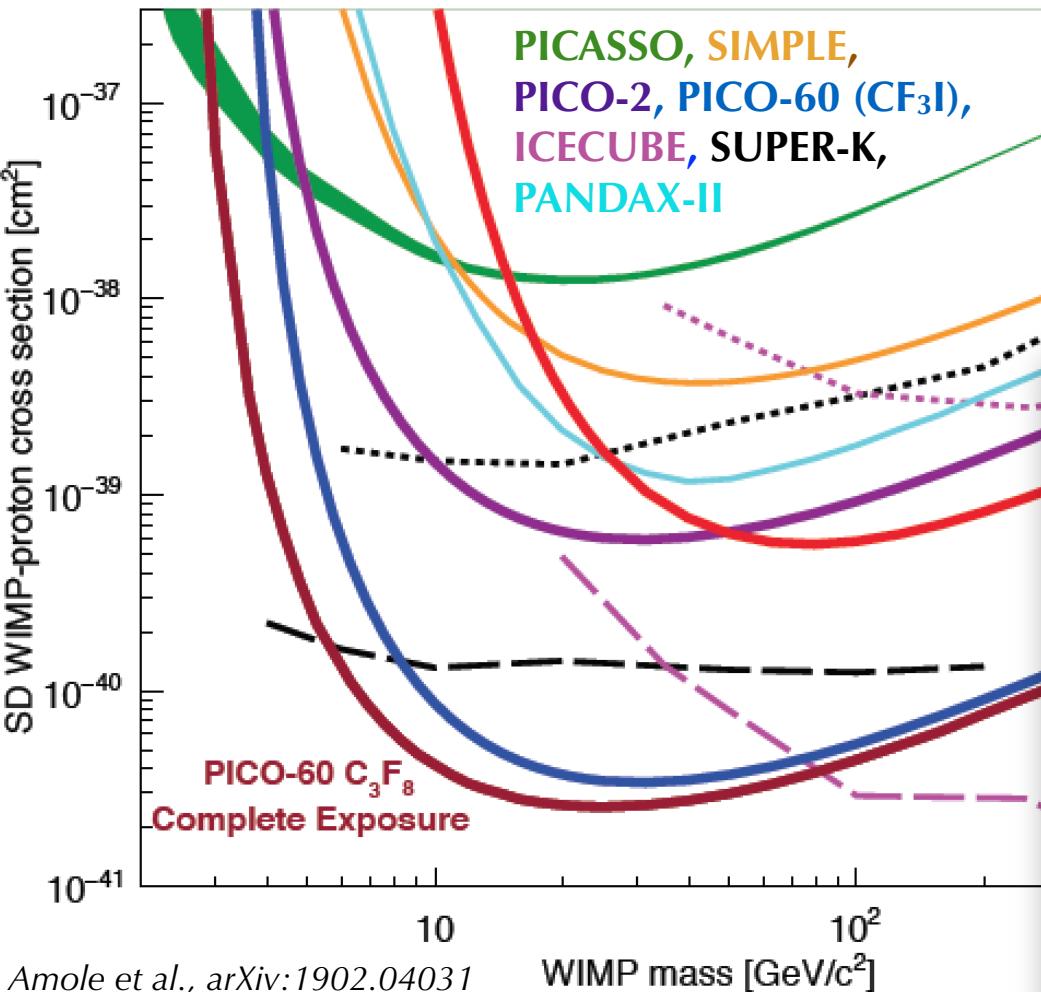
Constraints on  $|U_{e4}|^2$  from beta decay: energy spectrum modified by sterile neutrino mix

Constraints from indirect detection: x-ray spectrum strongly limits  $|U_{e4}|^2 + 3.5 \text{ keV}$



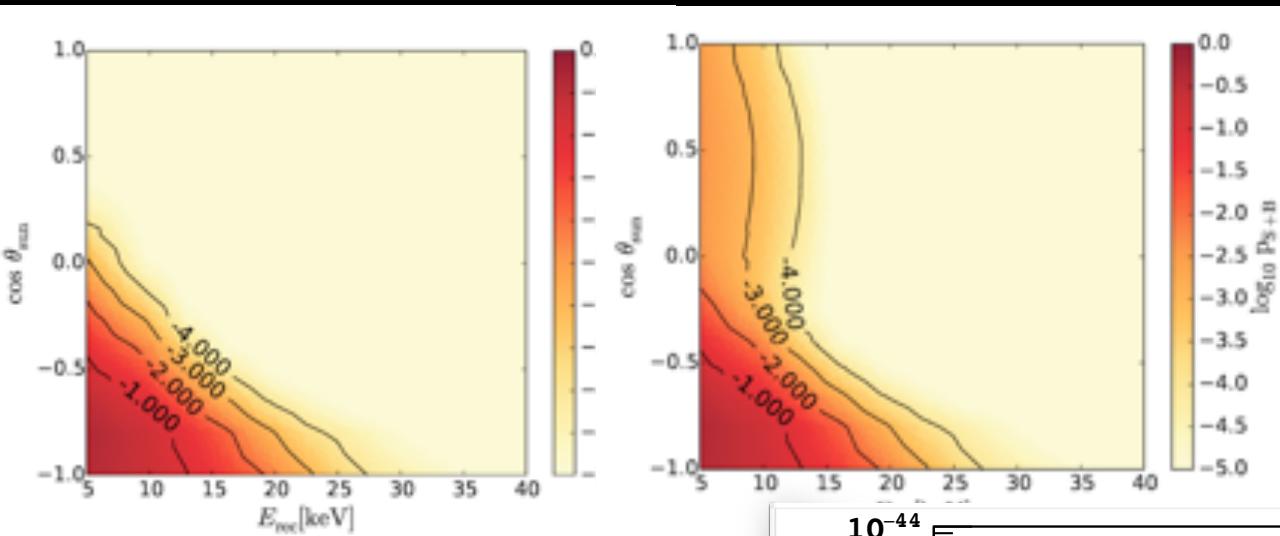
# Complementarity with Indirect Detection

Complementarity with **Indirect Detection**: leading constraints at high mass from WIMP-p scattering + capture in the sun, leading to annihilation signatures in neutrino telescopes.



# Direct Detection: Is the Neutrino Bound the End? No.

- sensitivity scales with  $\text{sqrt}(\text{time})$  instead of linearly in time (with zero background)

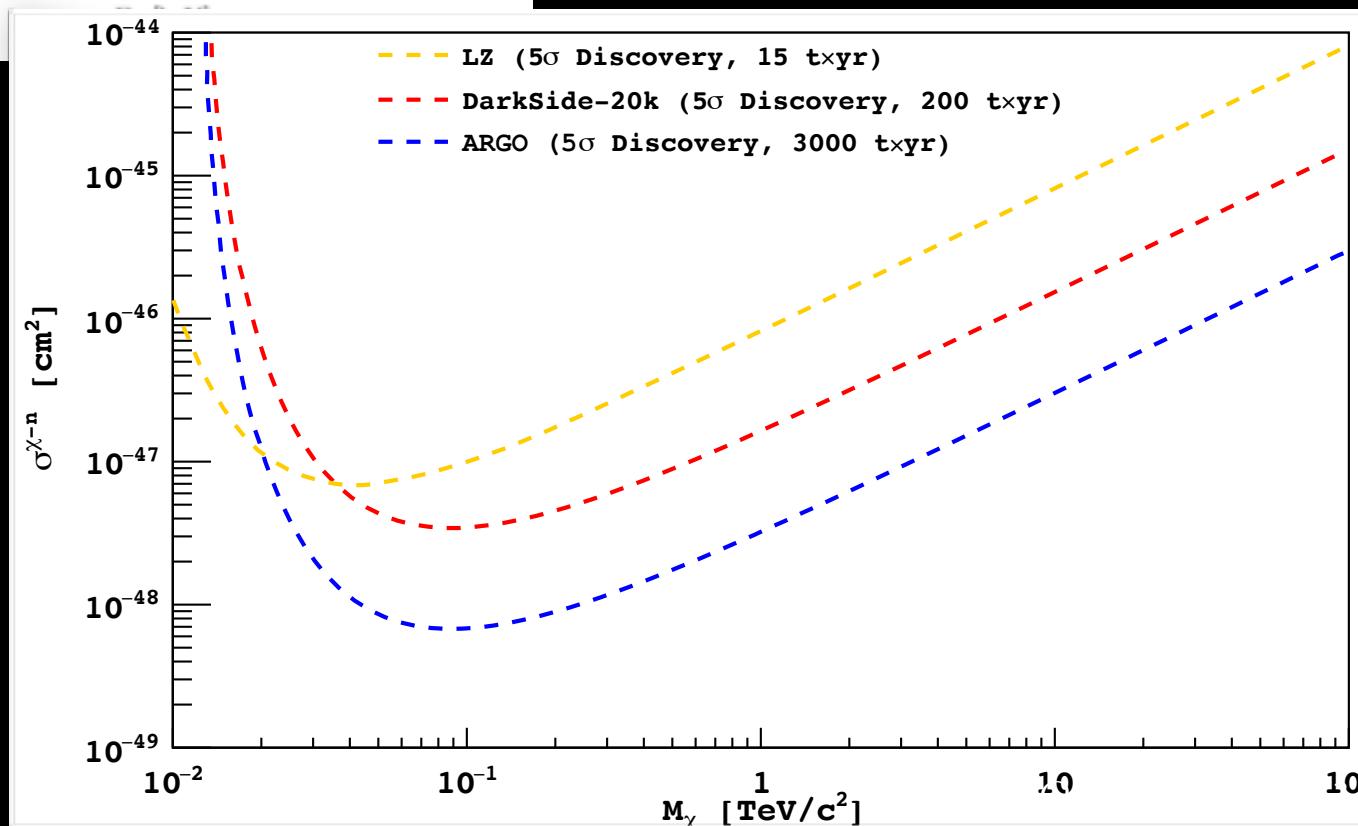


(energy, angle, time) of neutrino background vs. DM signal differ.

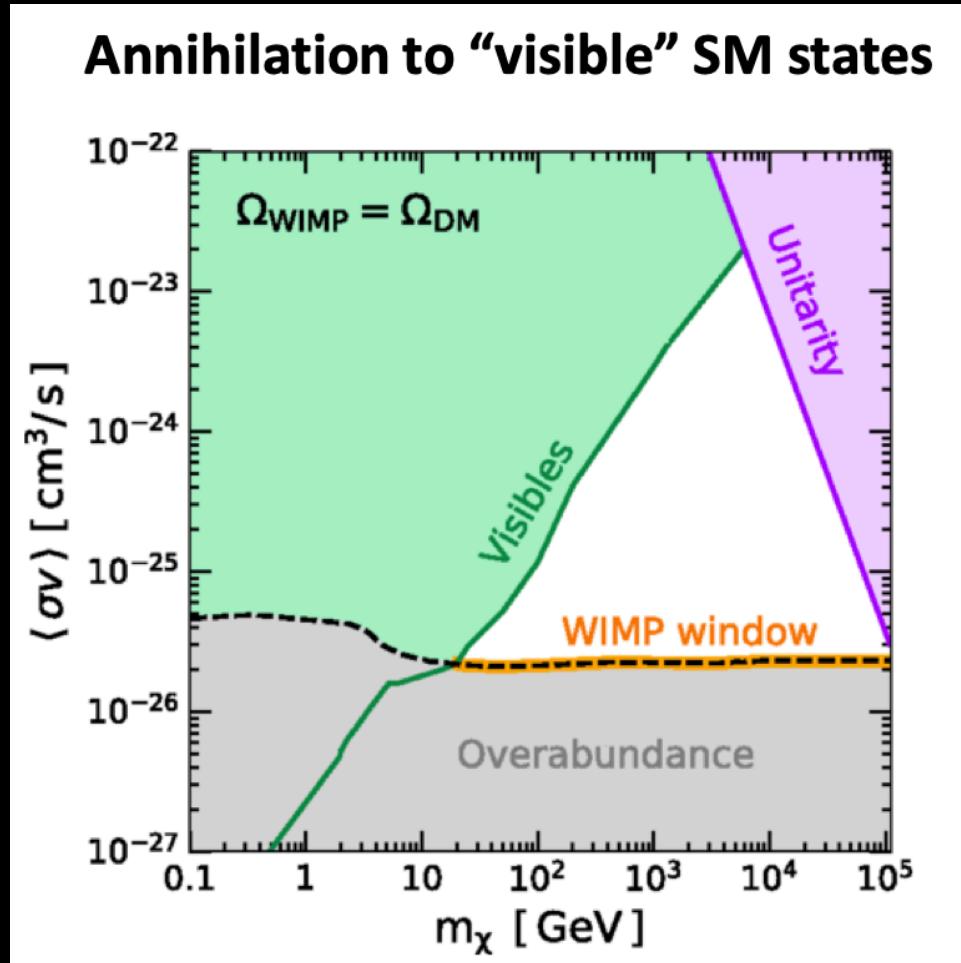
- no  $\nu$  bound for directional detectors  
*Grothaus, Fairbairn, JM, Phys.Rev.D90 (2014)*

A  $\nu$  background paradigm...  
for non-directional detectors

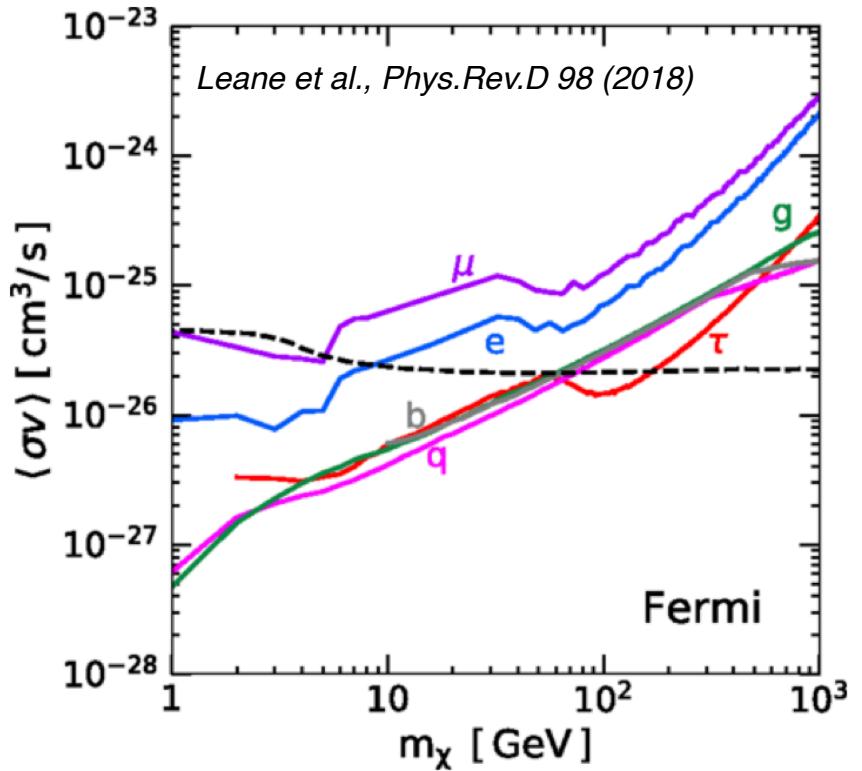
the discovery reach  
depends on  $\nu$  flux errors  
and on  $\nu$ -e discrimination.



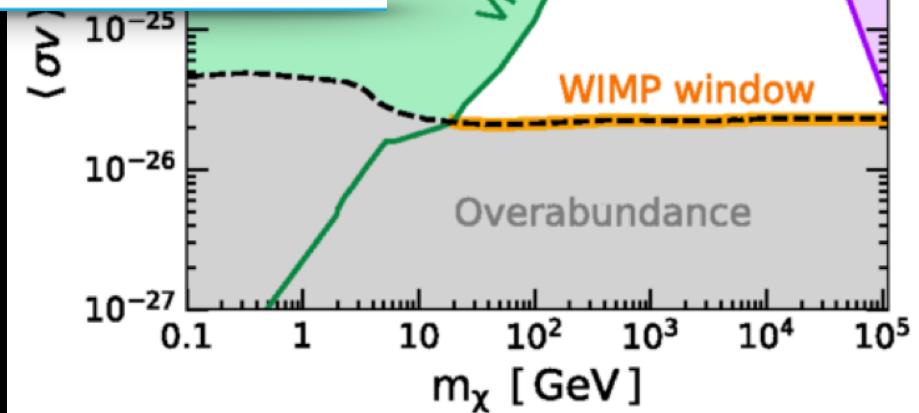
# Self-Annihilation Searches



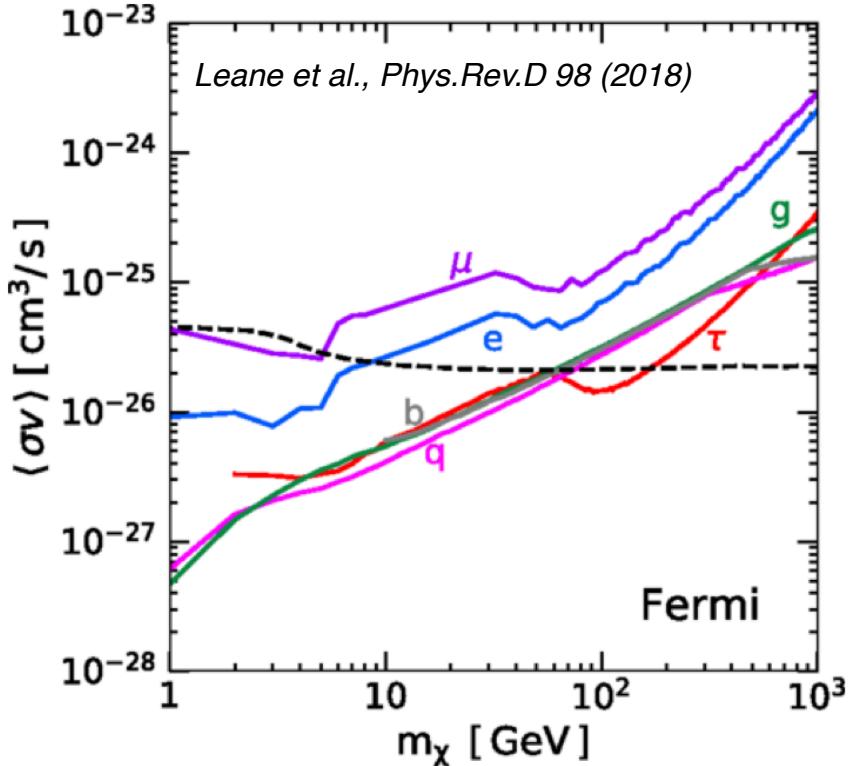
# Fermi dSph limits



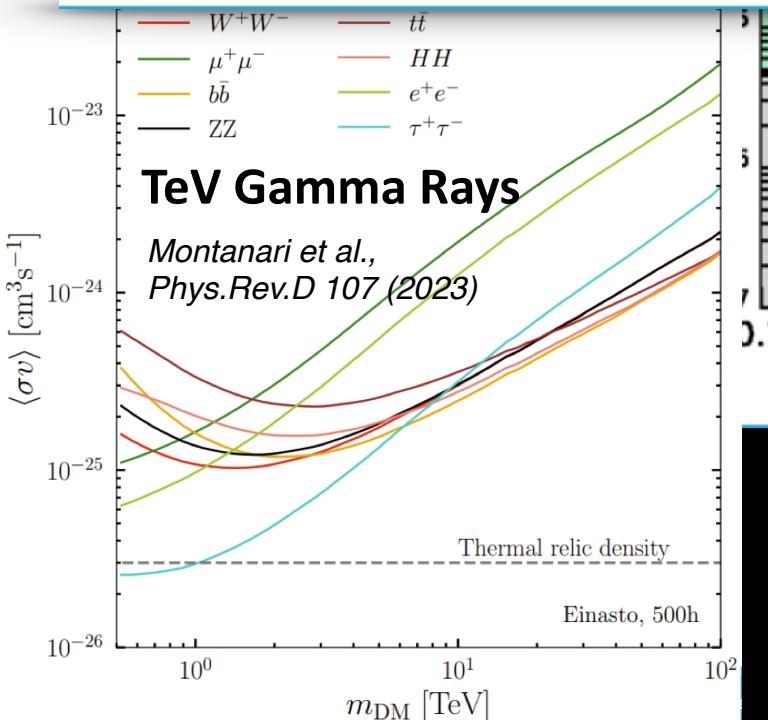
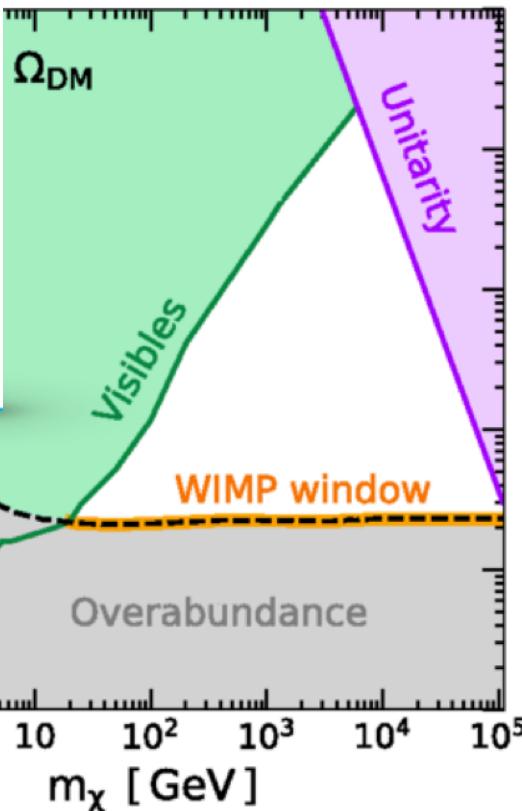
to “visible” SM states



# Fermi dSph limits

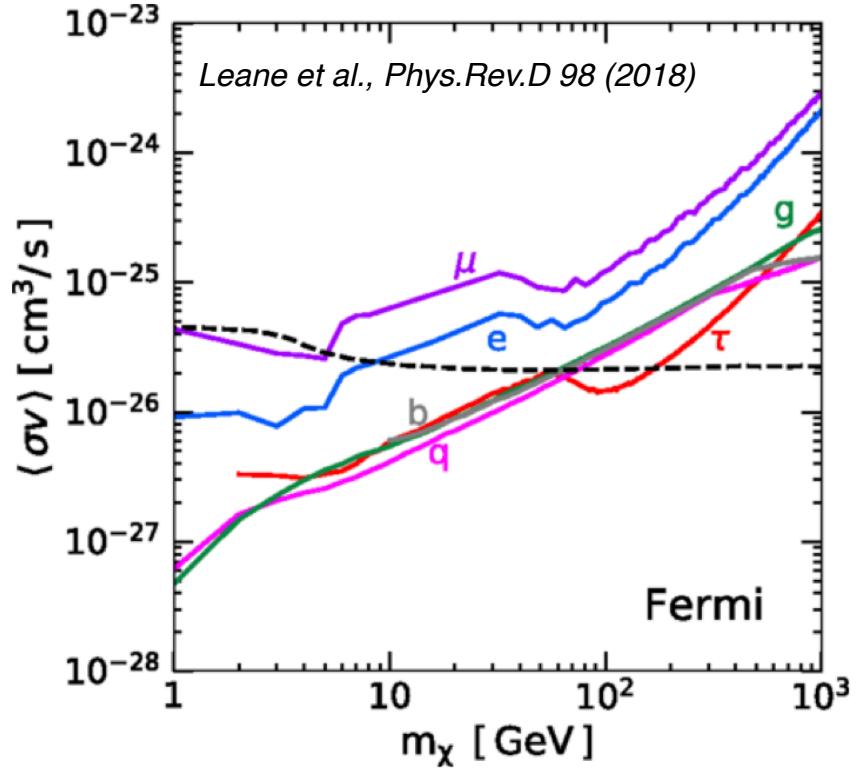


to “visible” SM states

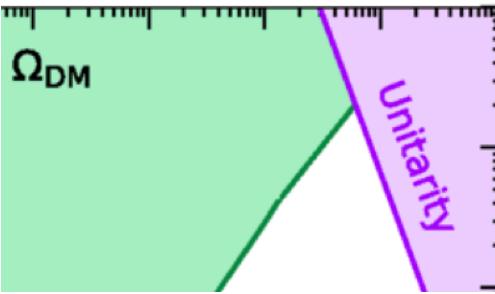


— Calore

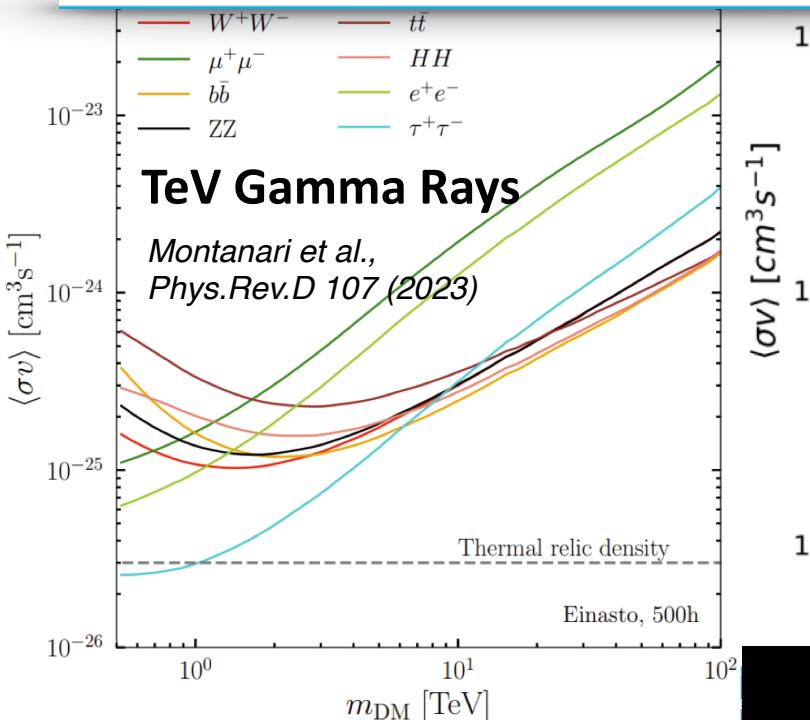
# Fermi dSph limits



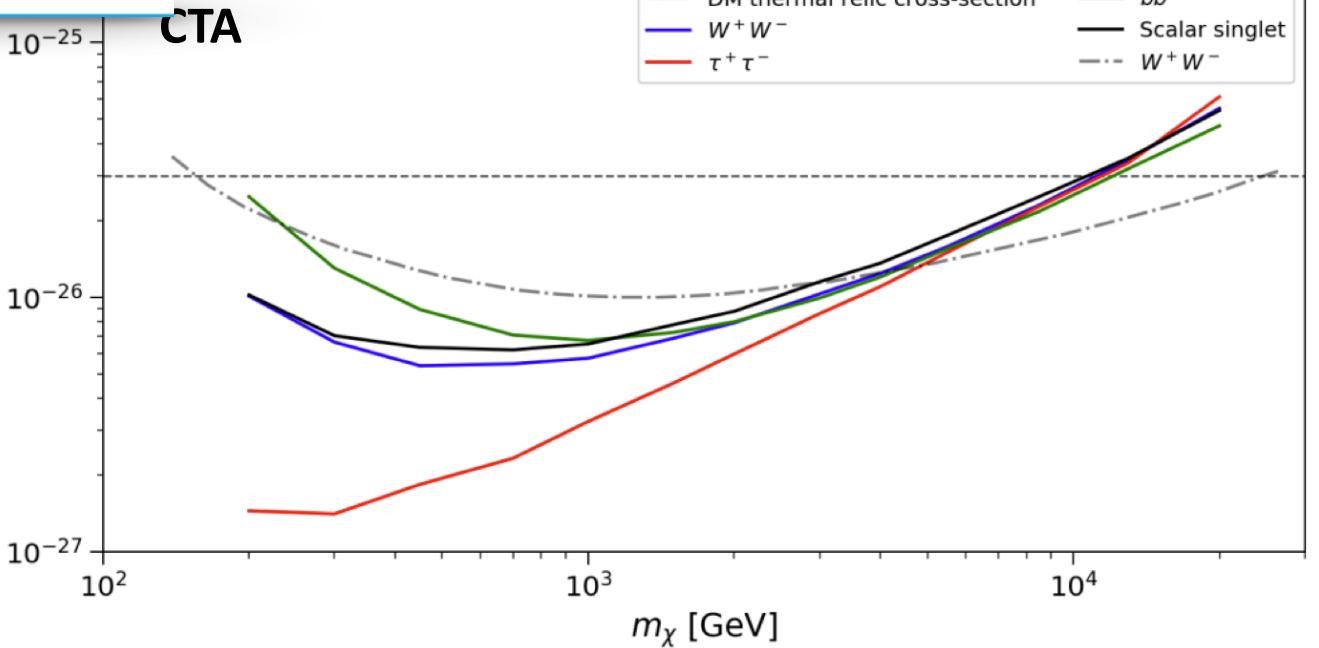
to “visible” SM states



Mangipudi, Thrane & Balazs, arXiv:2112.10371

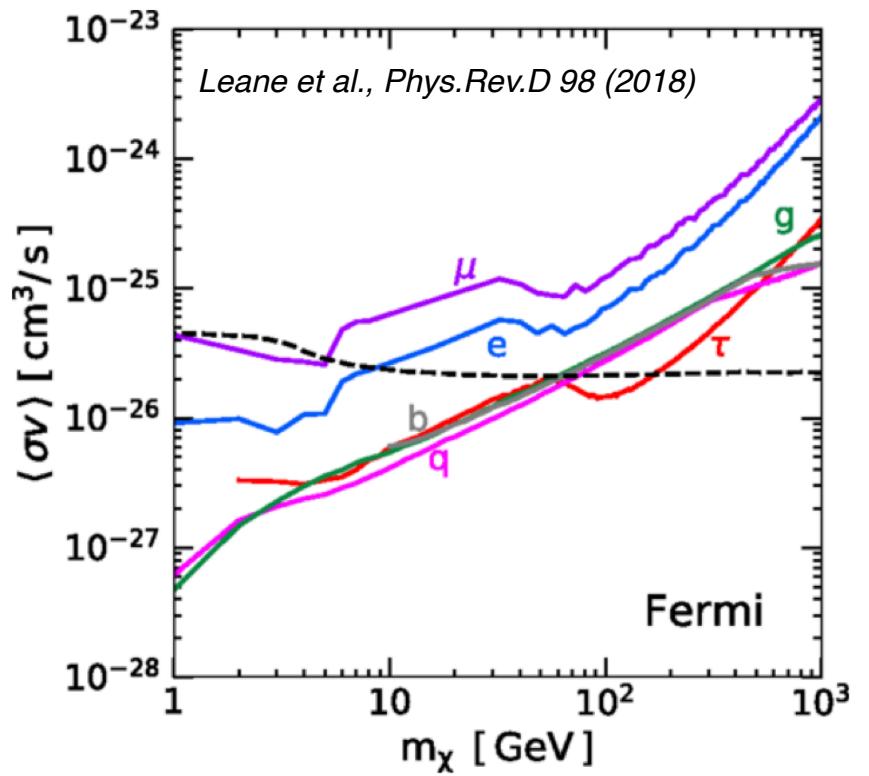


CTA

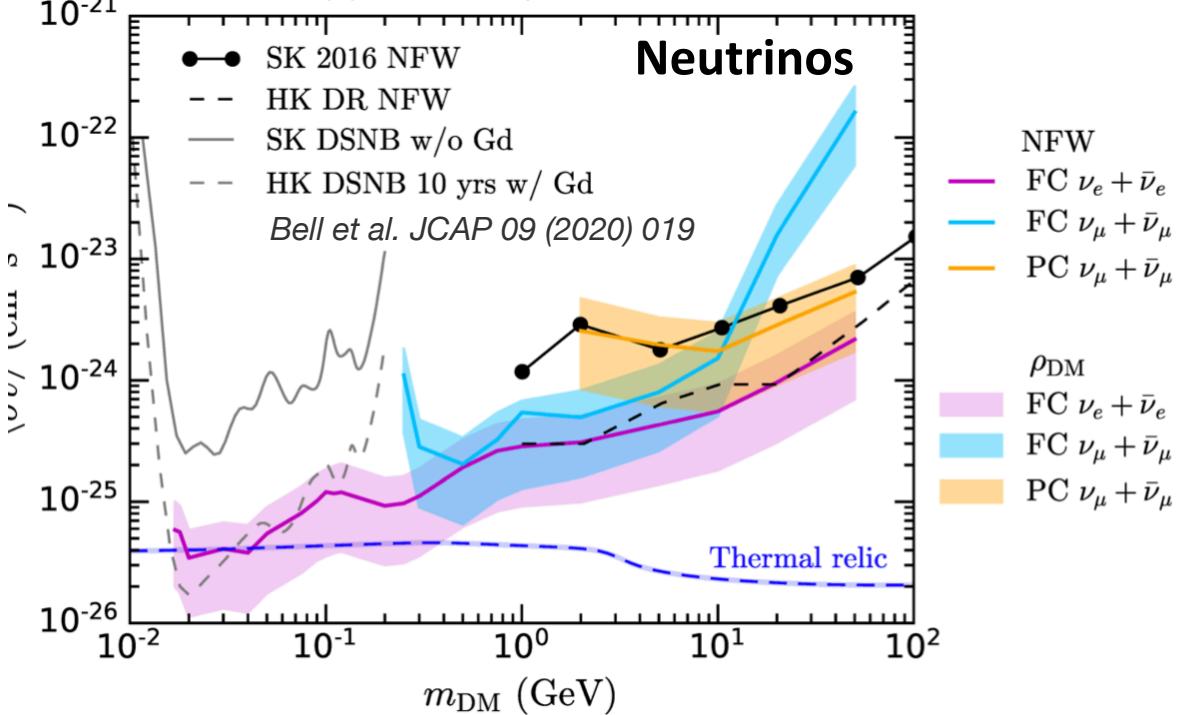


— Calore

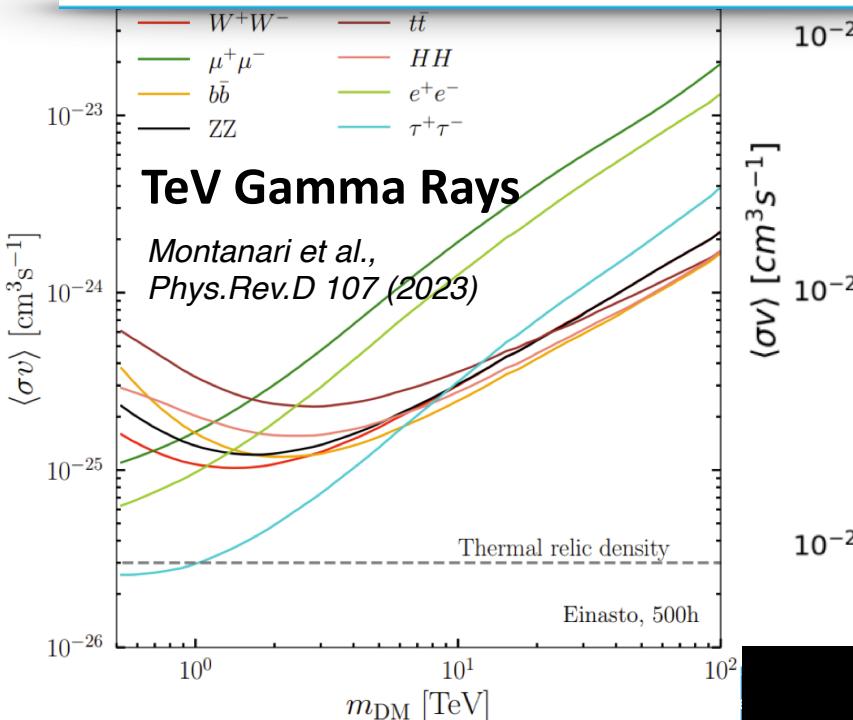
# Fermi dSph limits



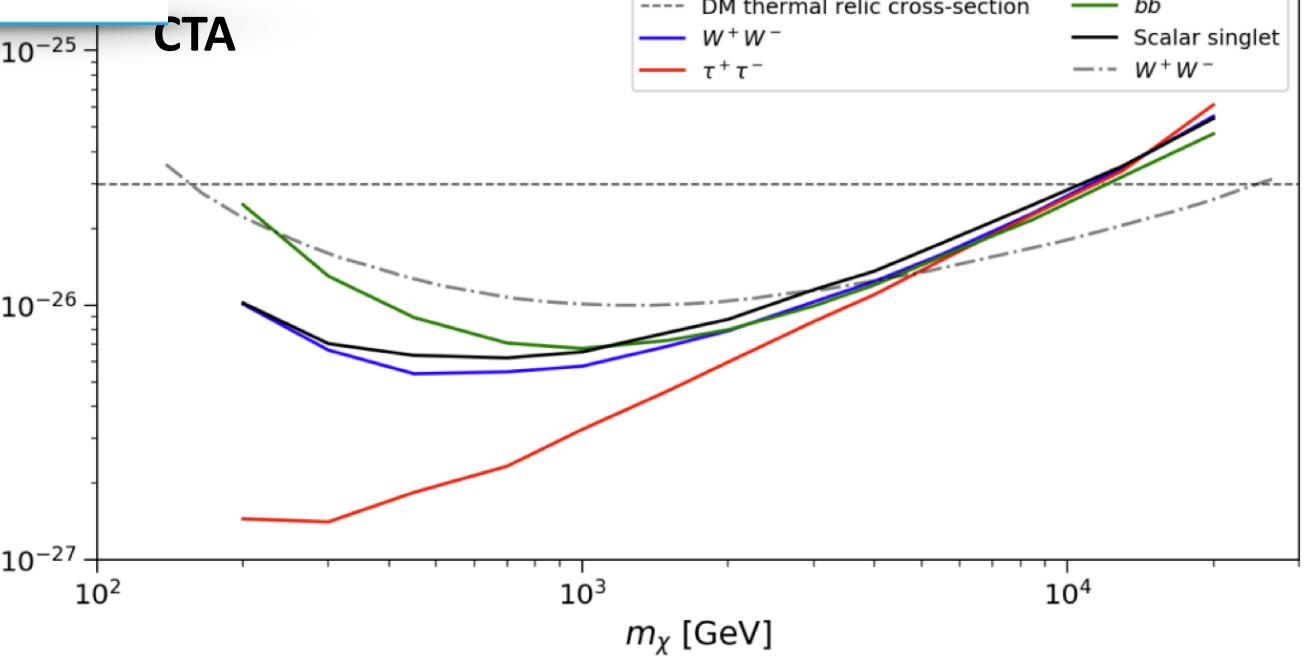
$\chi\chi \rightarrow \nu\bar{\nu}$ , 20 yrs, 90% CL



Mangipudi, Thrane & Balazs, arXiv:2112.10371



CTA



— Calore