'Cosmic Rays / Dark Matter'

Professor Jocelyn Monroe
Professor of Particle Physics
University of Oxford

jocelyn.monroe@physics.ox.ac.uk

OXFORD MASTER SERIES IN PARTICLE PHYSICS, ASTROPHYSICS, AND COSMOLOGY

SECOND EDITION

Particle Astrophysics

Donald Perkins

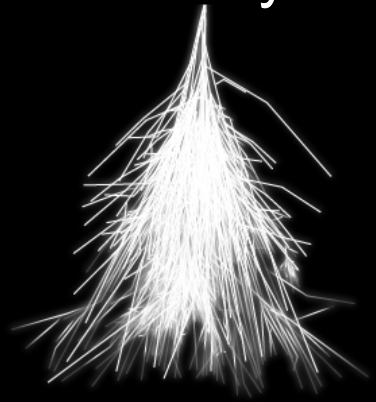
Preface, 2nd ed. (2009)

One could say that particle physics at accelerators in Part 1 is an extremely well-understood subject, with agreement between theory and experiment better than one part per million in the case of quantum electrodynamics. Whatever the form might be of an ultimate 'theory of everything'—-if there ever is one—-the Standard Model of particle physics will surely be part of it, even if it only accounts for a paltry 4% of the energy density of the universe at large.

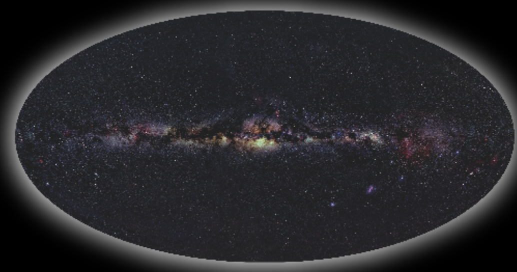
[The second] part also underlines the great questions and mysteries in cosmology: the nature of dark matter; the nature of dark energy and the magnitude of the cosmological constant; the matter–antimatter asymmetry of the universe; the precise mechanism of inflation; and, just as is the case for the 20 or so parameters describing the Standard Model of particles, the arbitrary nature of the parameters in the Concordance Model.

Part 3 (Chapters 9 and 10) is concerned with the study of the particles and radiation which bombard us from outer space, and to the stellar phenomena, such as pulsars, active galactic nuclei, black holes, and supernovae which appear to be responsible for this 'cosmic rain'. We encounter here some of the most energetic and bizarre processes in the universe, with new experimental discoveries being made on an almost daily basis.

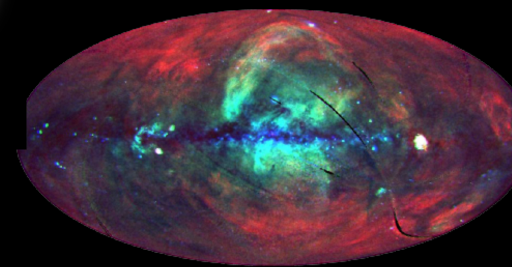
cosmic rays



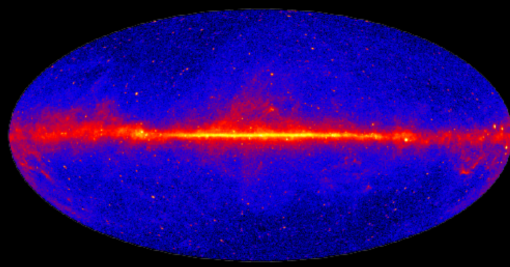
infrared/optical



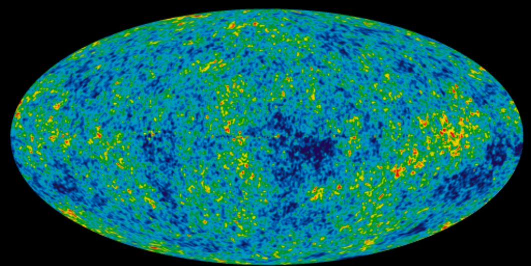
X-rays



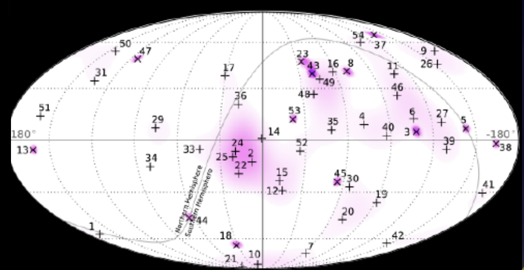
gamma-rays



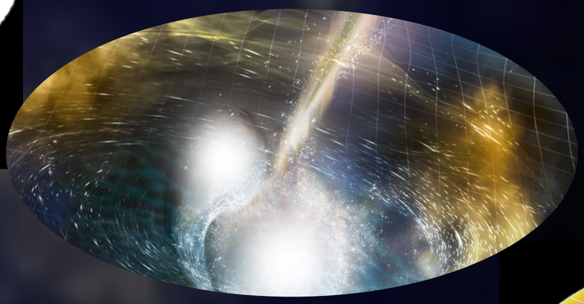
radio/microwave



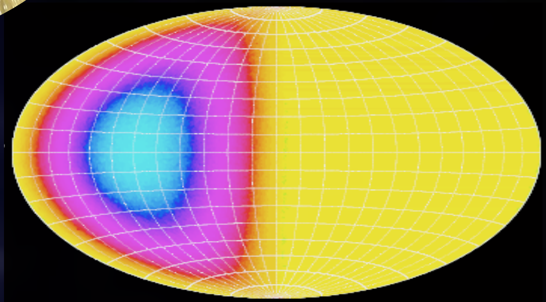
neutrinos



gravitational waves

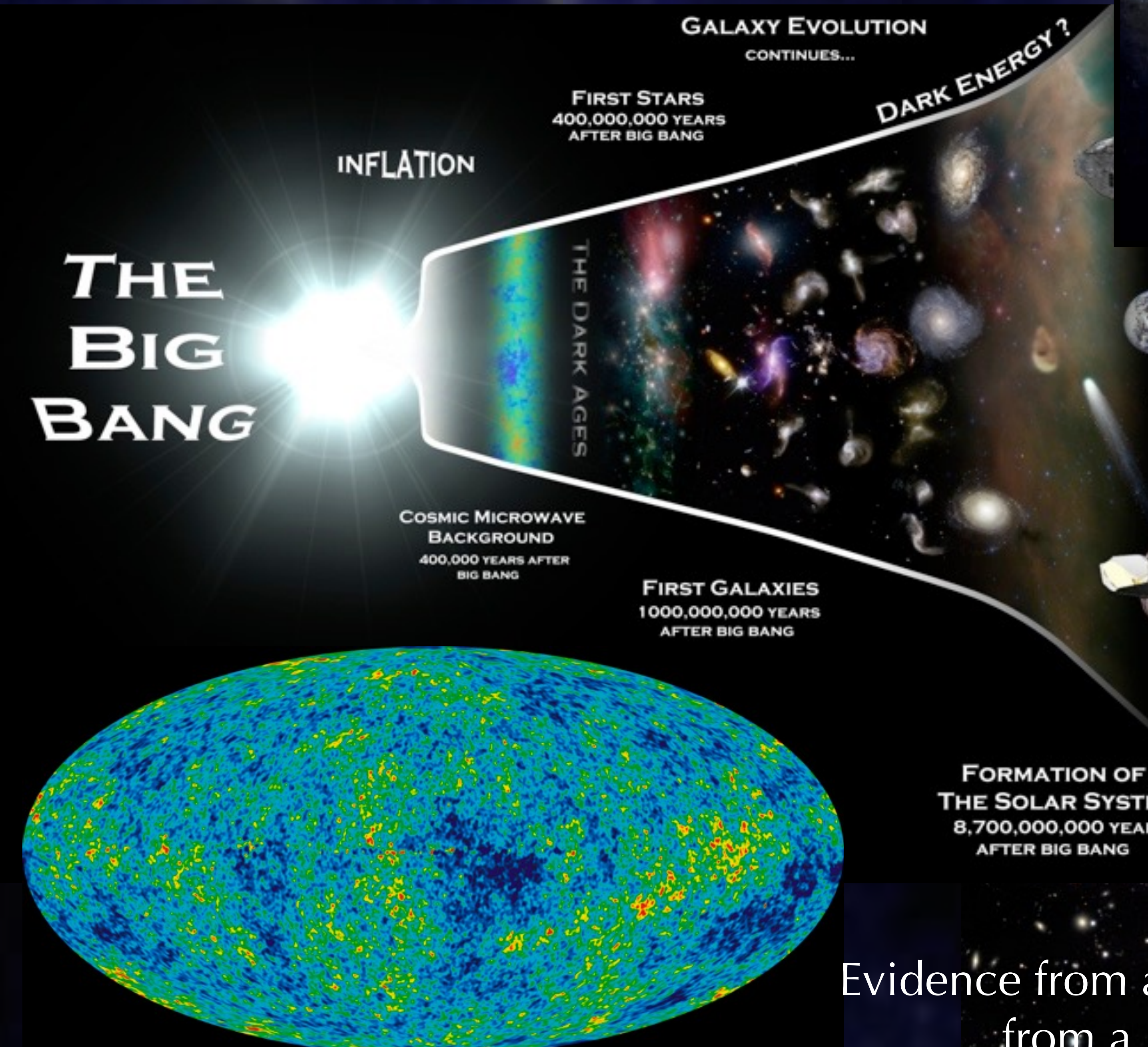


dark matter



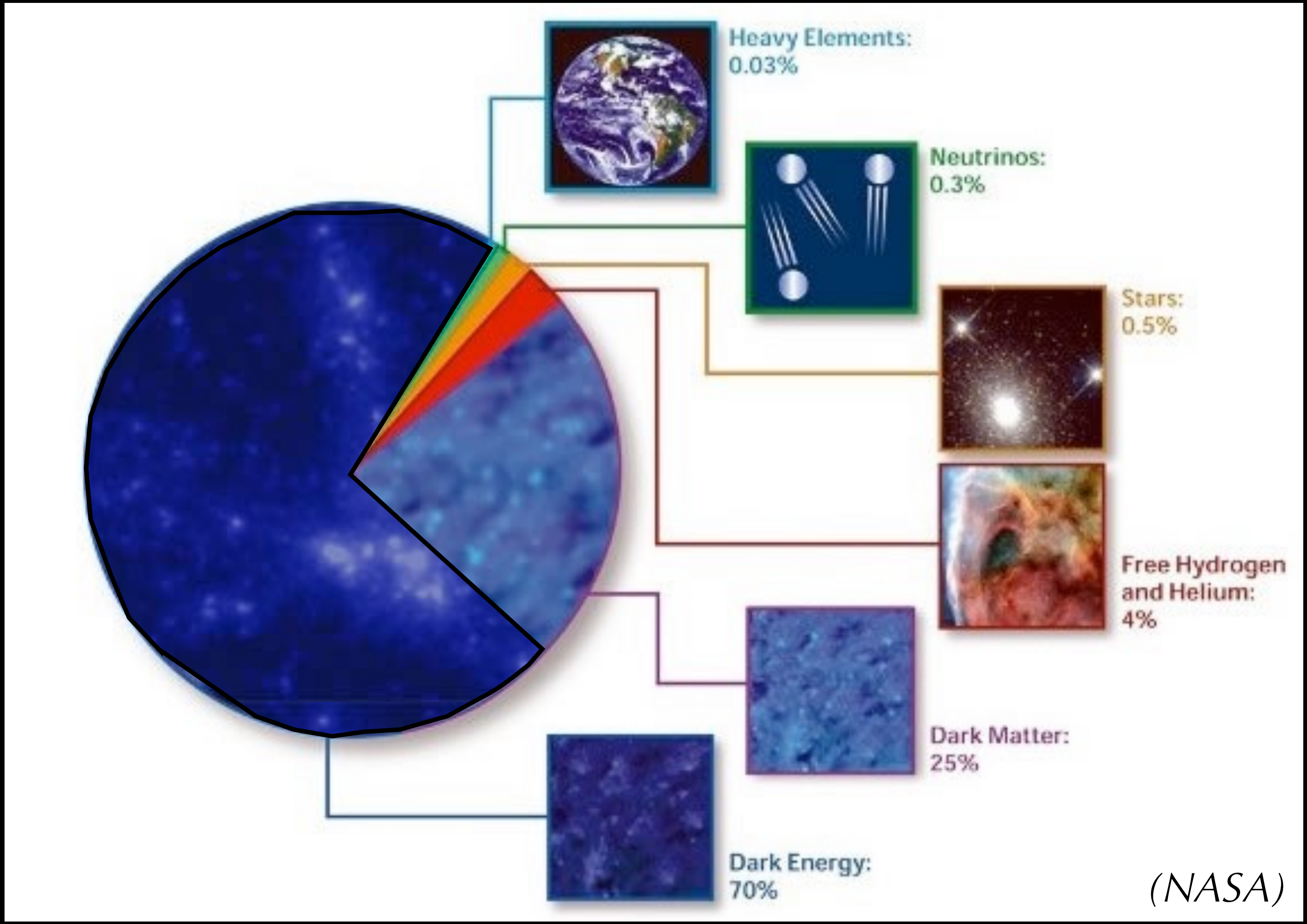
The tools of particle astrophysics probe the largest and smallest distance scales in the universe…

Evidence for Dark Matter

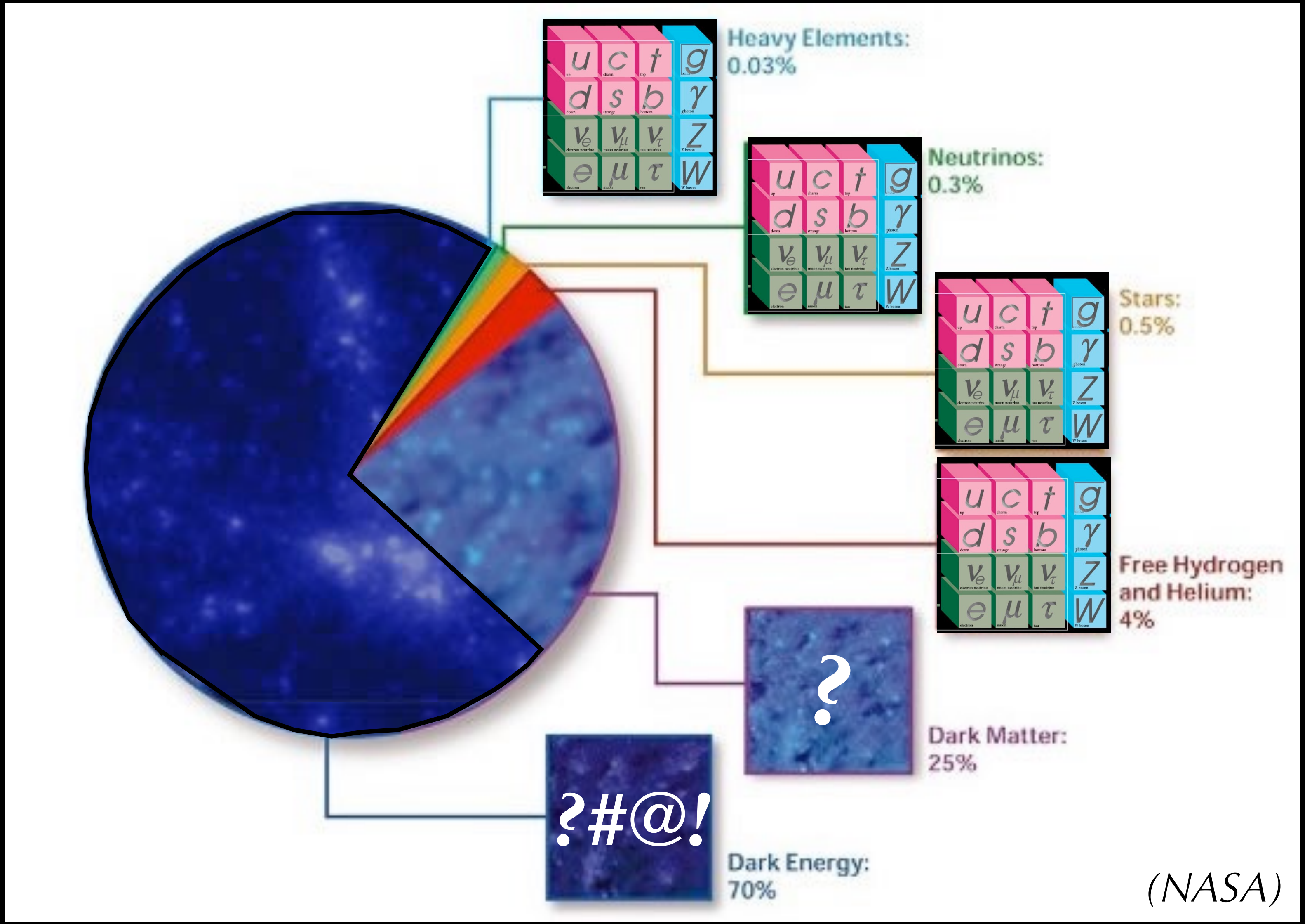


Evidence from a range of scales,
from a range of times

The Standard Model of Cosmology



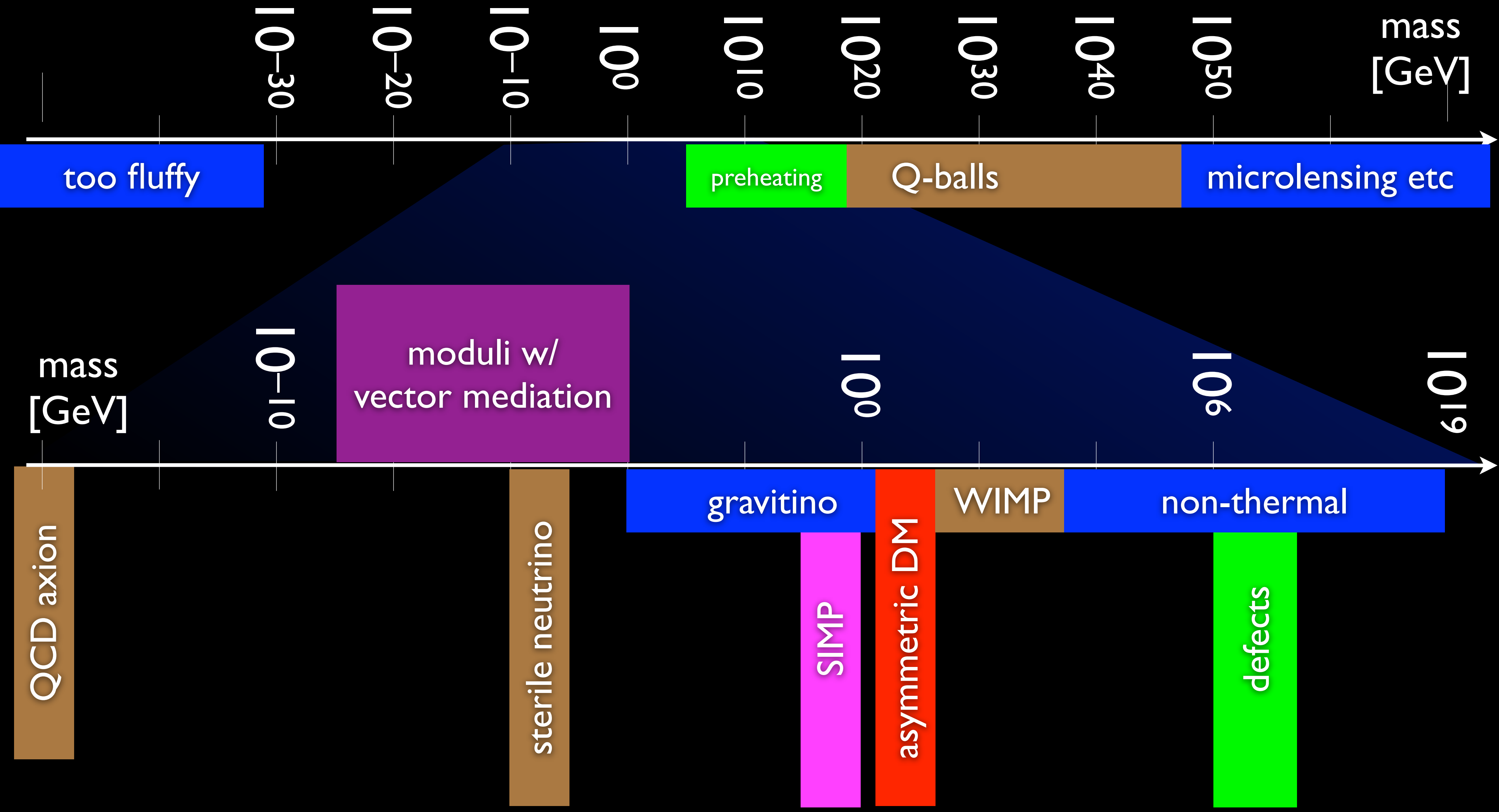
The Standard Model of Cosmology



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

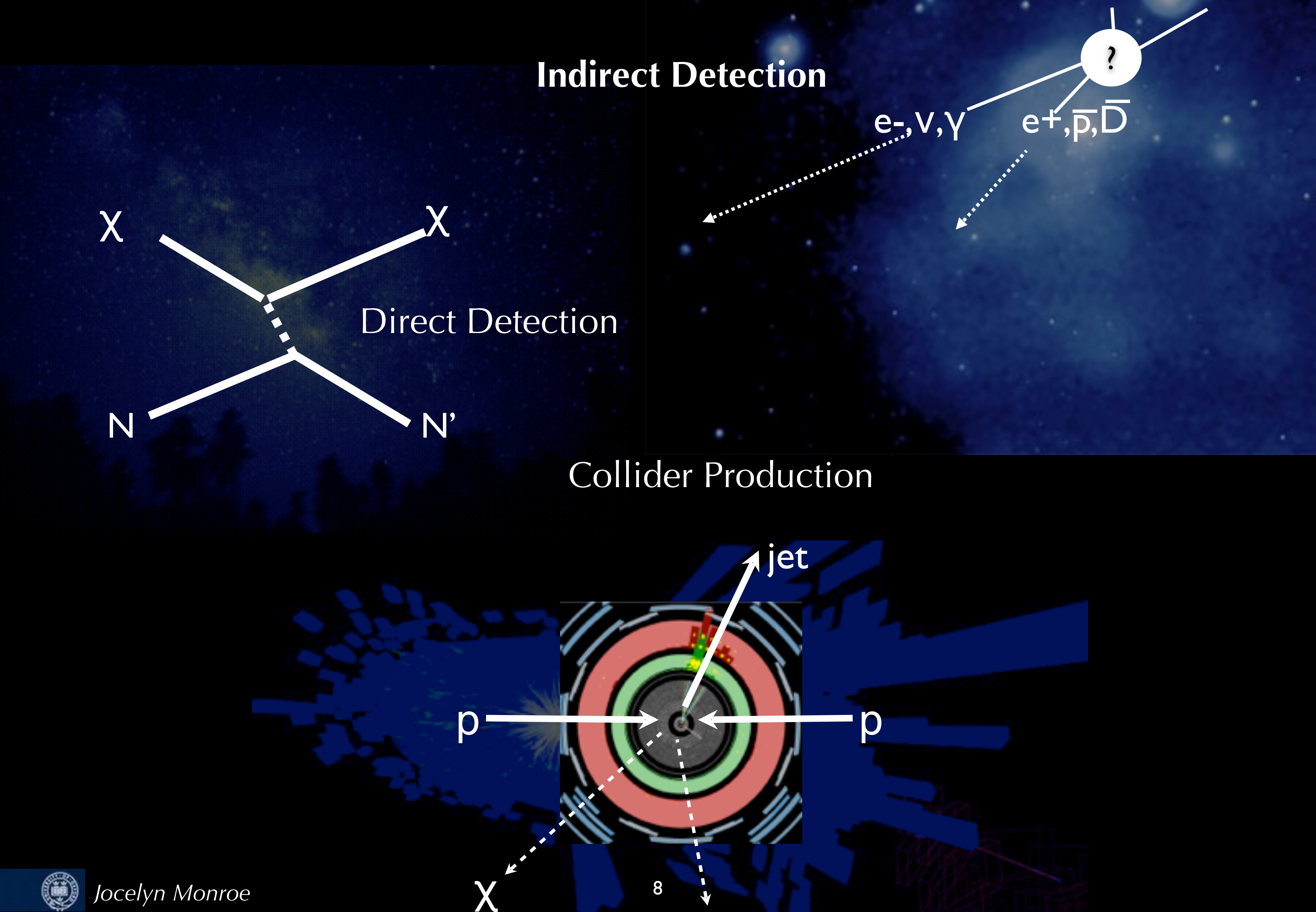
Theorist's View

(thanks to H. Murayama)



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

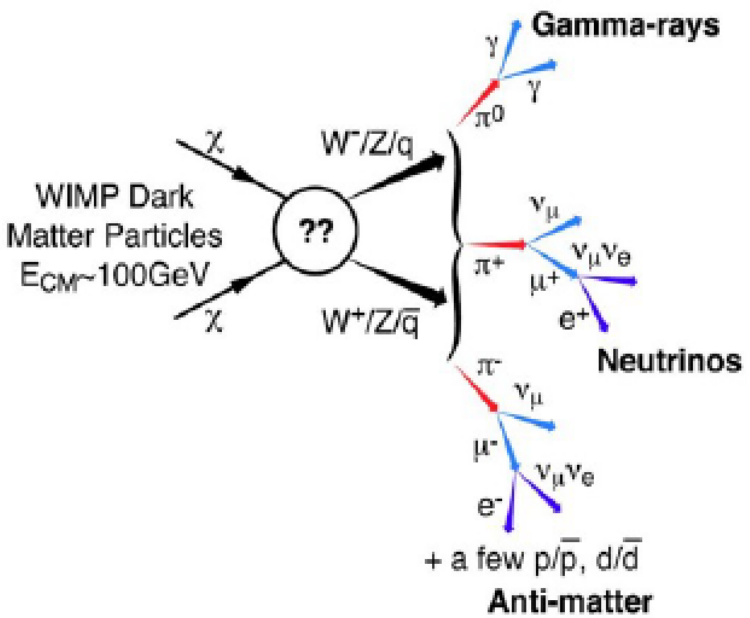
Experimentalist's View



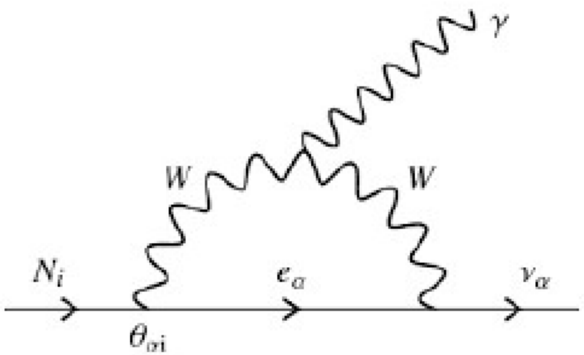
Indirect Detection Strategies

concerned with the study of the particles and radiation which bombard us from outer space, *… to look for dark matter*

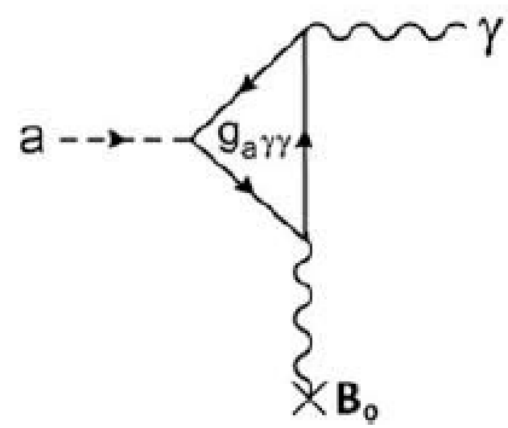
1) Self-annihilation
(e.g. WIMPs)



2) Decay
(e.g. sterile neutrinos)



3) Conversion
(e.g. axions)



Self-Annihilation Signal

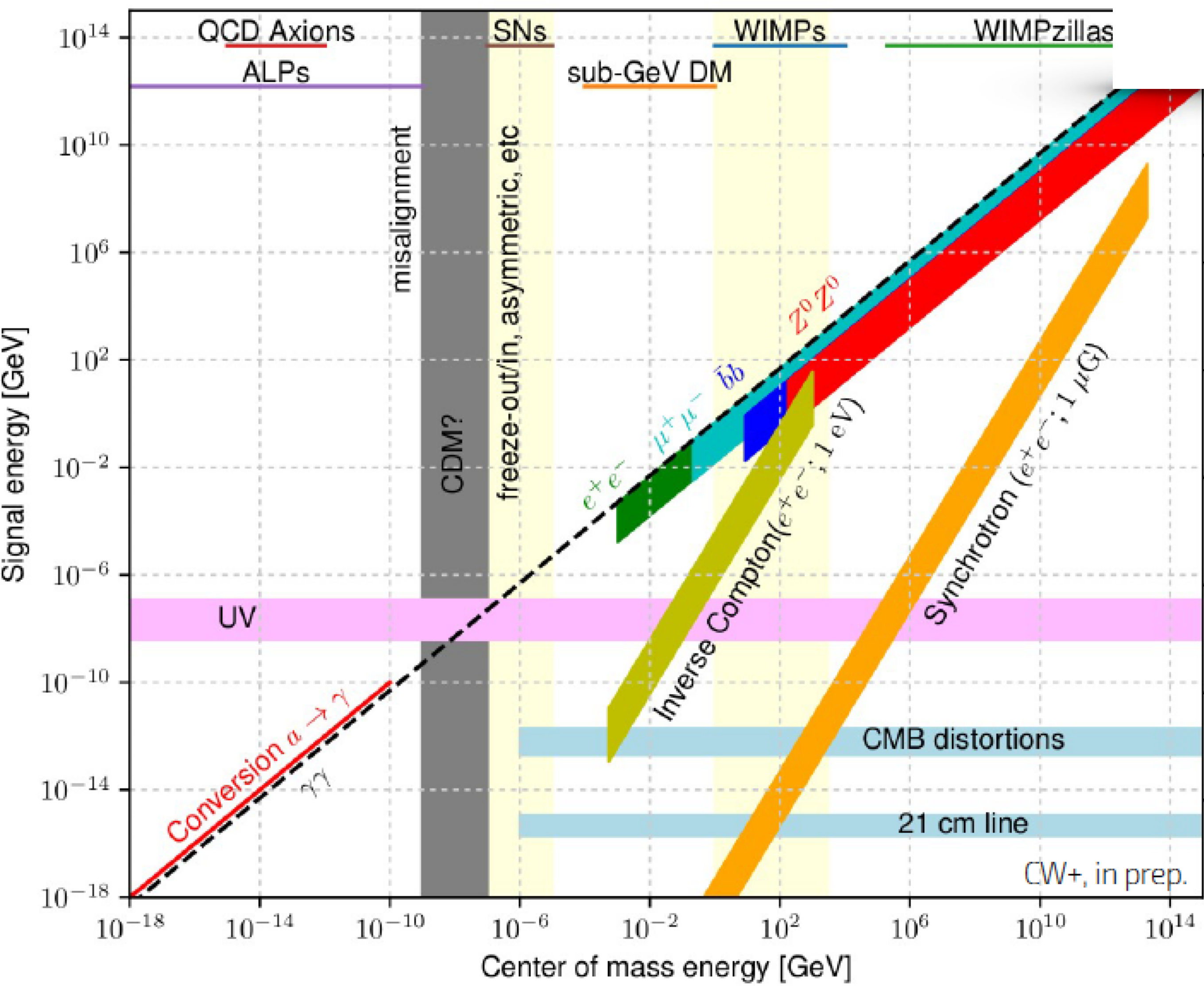
$$\frac{d\Phi_{\Delta\Omega}}{dE} = \langle\sigma v\rangle \frac{J_{\Delta\Omega}}{8\pi m_{DM}^2} \frac{dN}{dE}$$

Annihilation cross section

Integral of (density)^2 along line of sight

Spectrum f… annihilatio…

Emission energy vs. DM



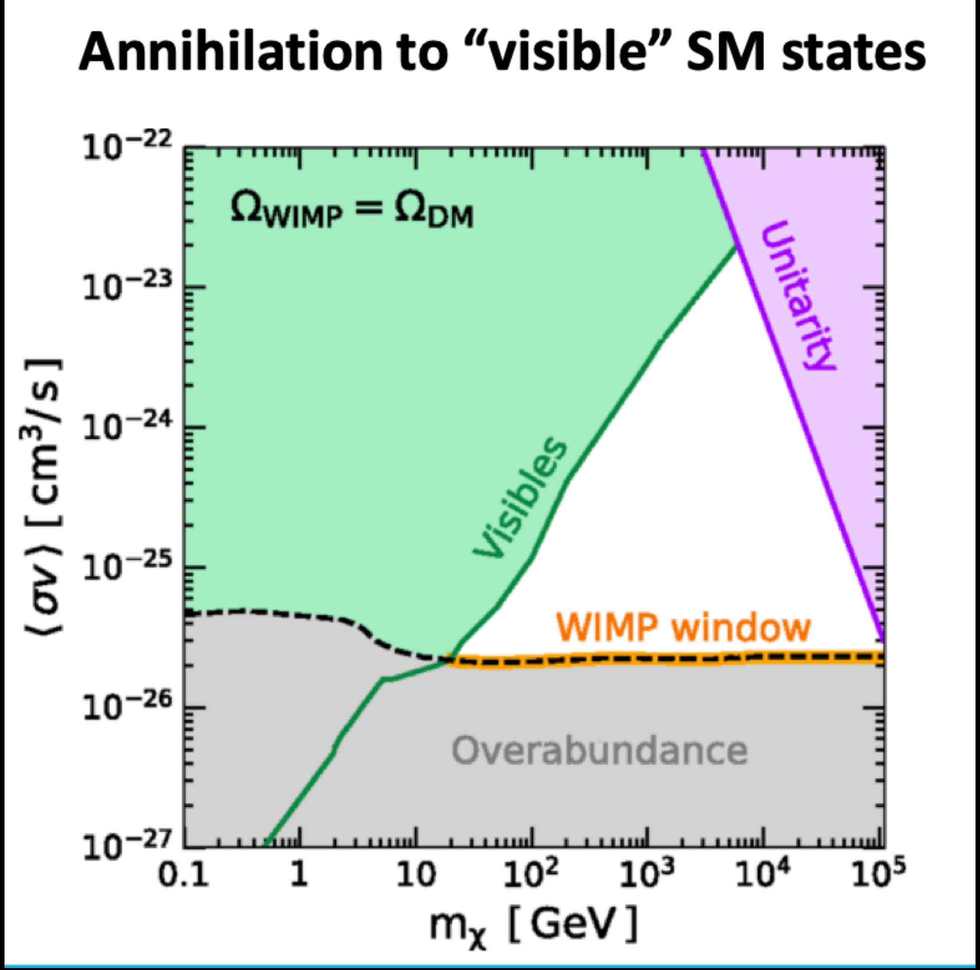
LHAASO (~2021)
CTA (~2025)
KM3NeT-ORCA (construction)
GAPS (~2021)
AMEGO (proposed)

XRISM (~2022)

SKA (~2025)

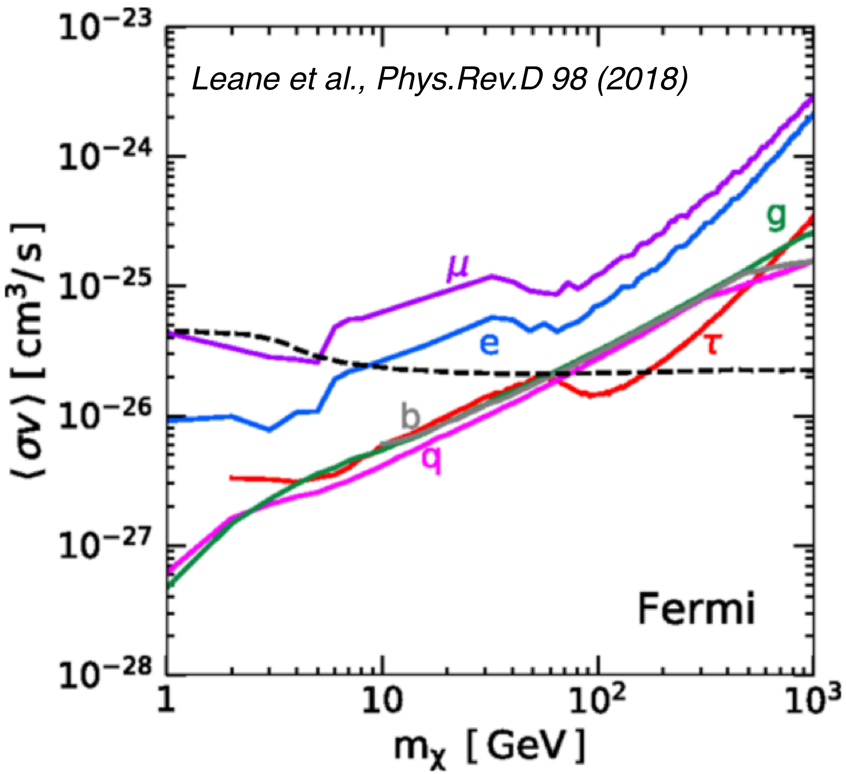
Weniger, ESPPU 2019

Self-Annihilation Searches

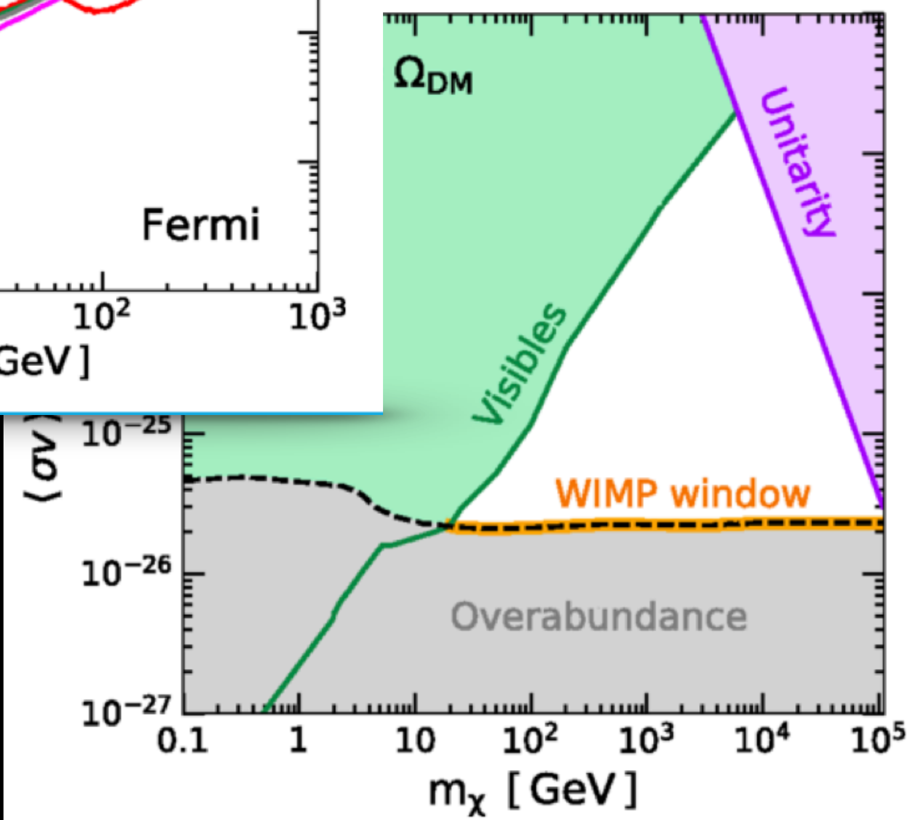


Bell, TAUP 2023

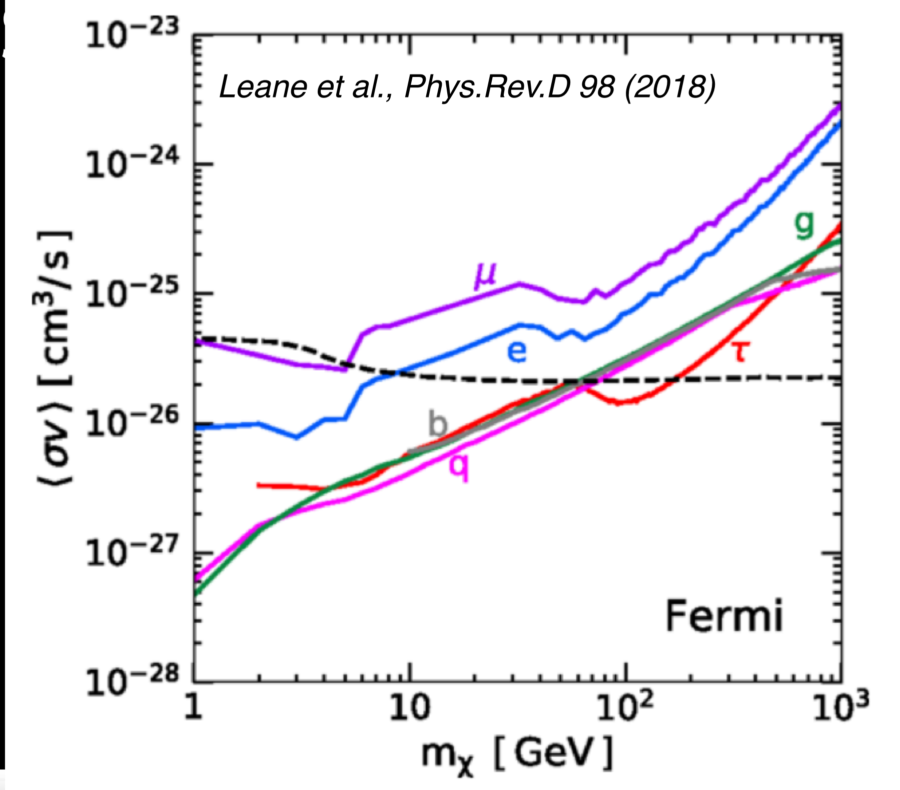
Fermi dSph limits



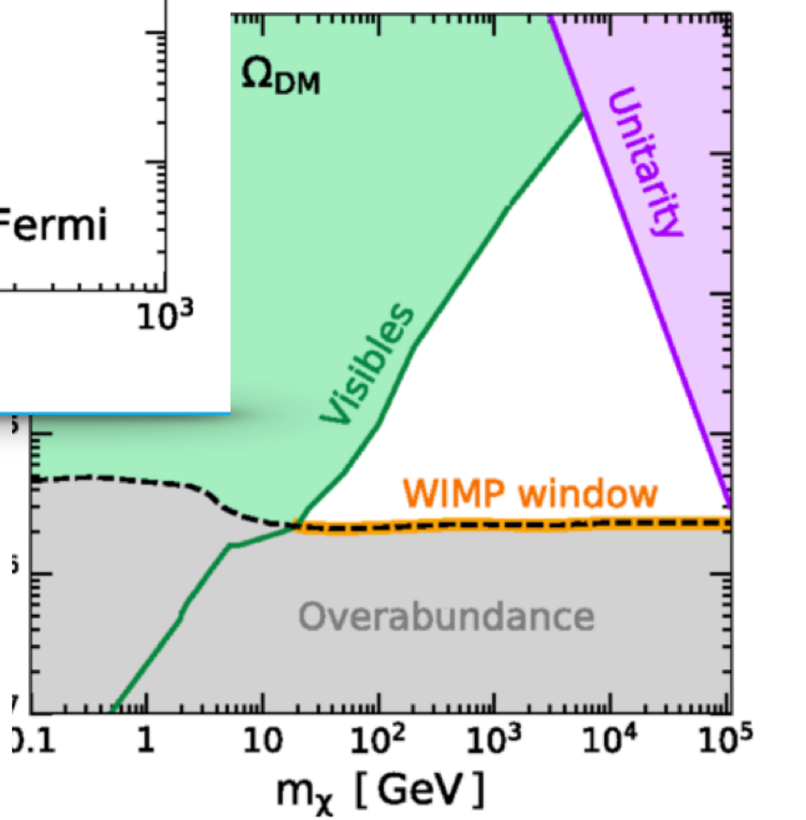
to “visible” SM states

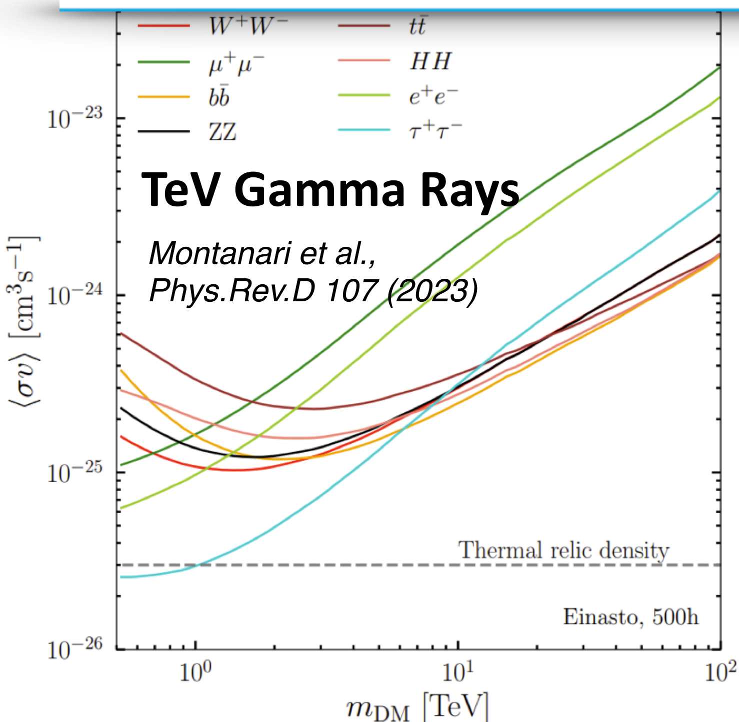


Fermi dSph limits



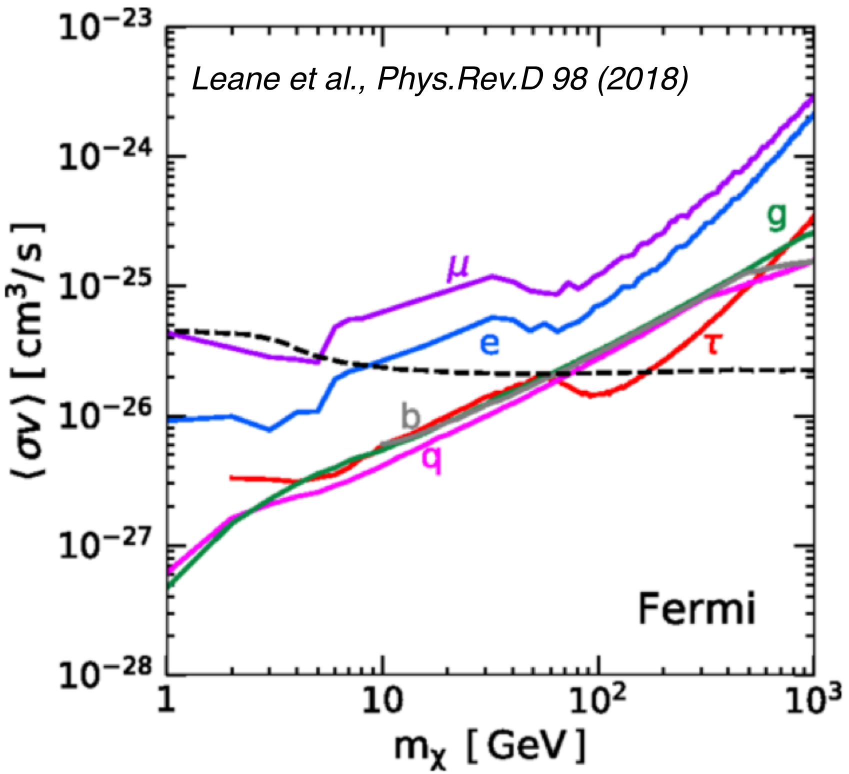
to "visible" SM states





Bell, TAUP 2023

Fermi dSph limits



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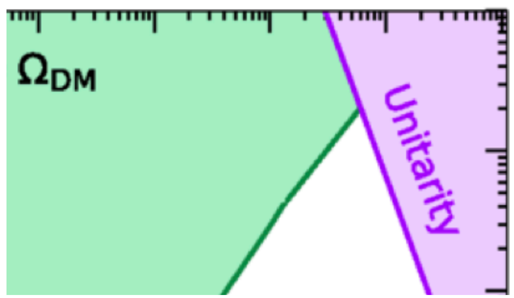
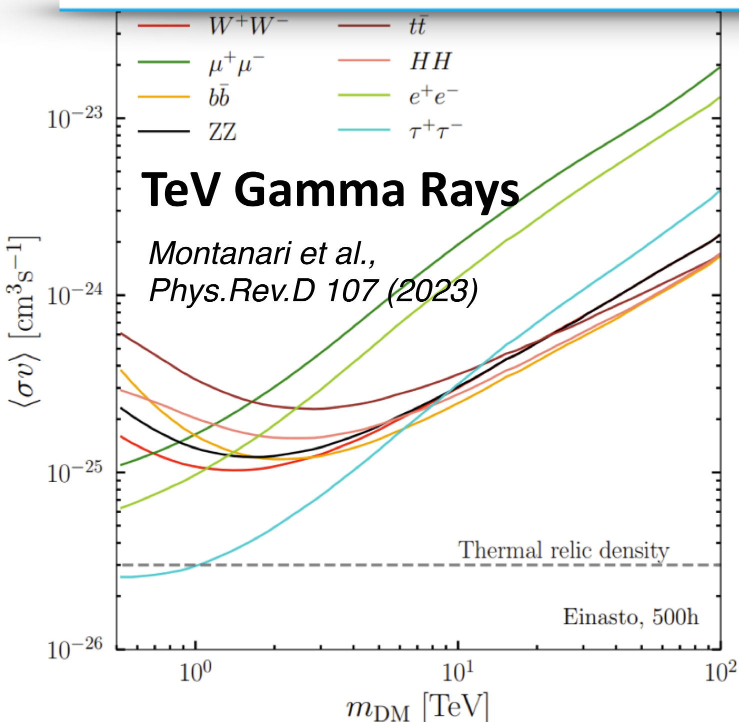
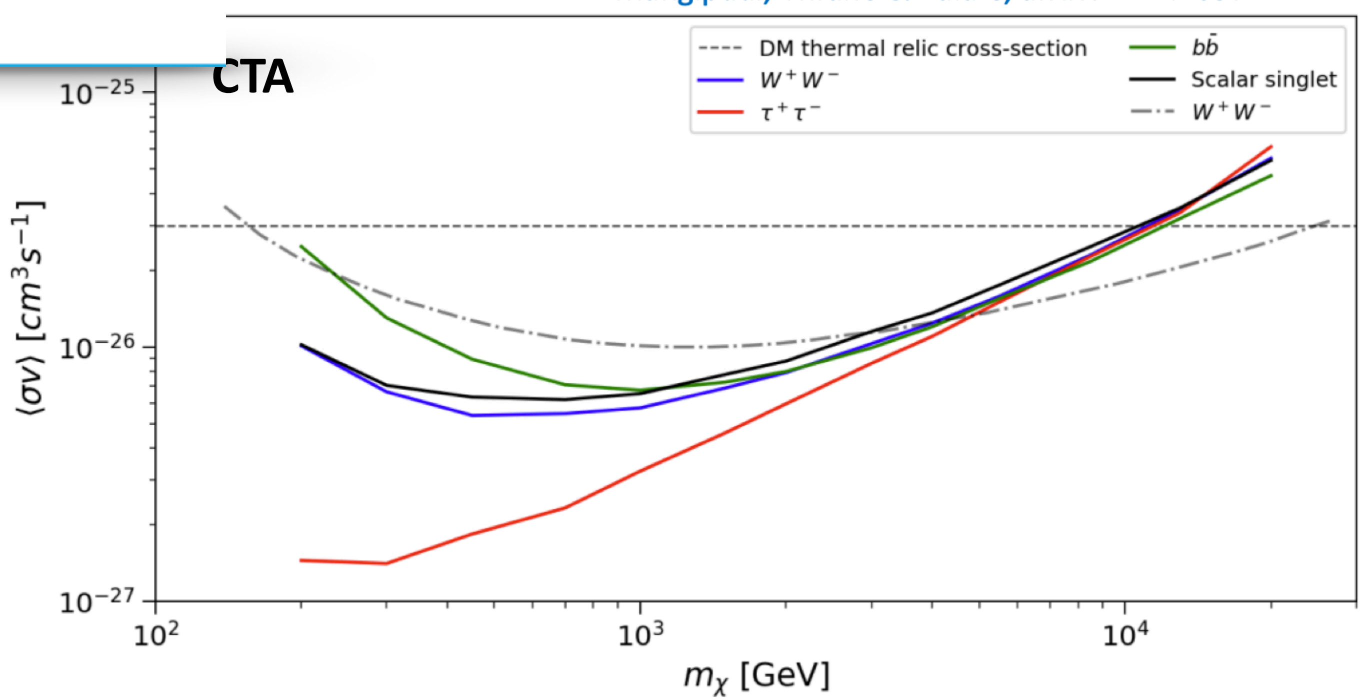
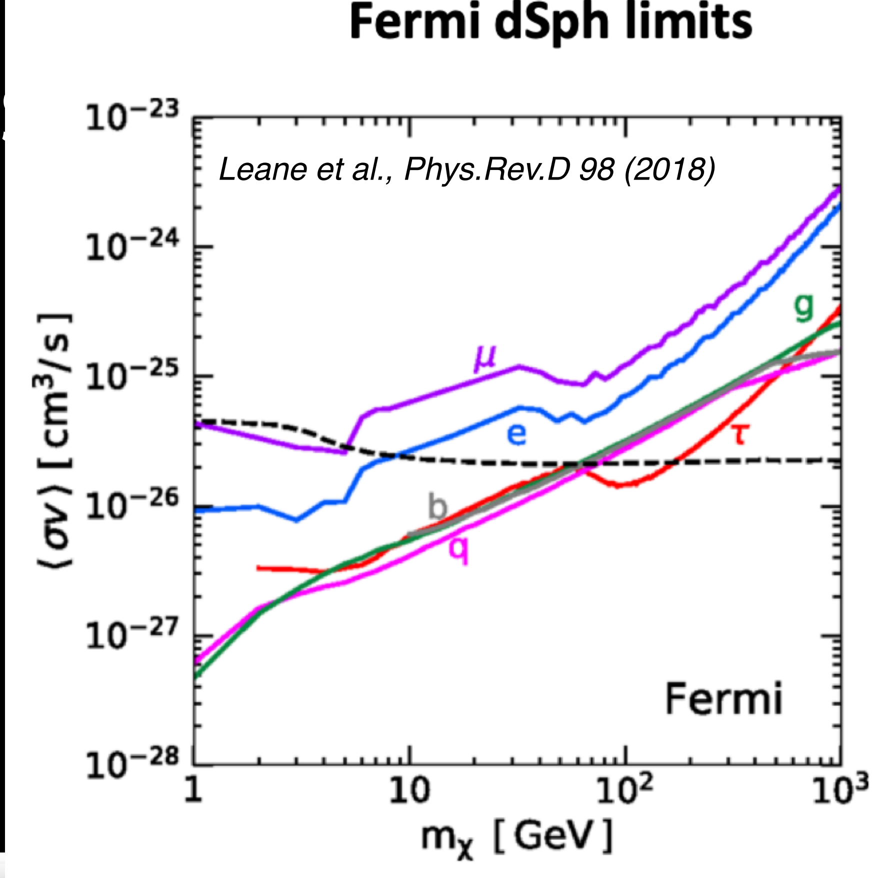


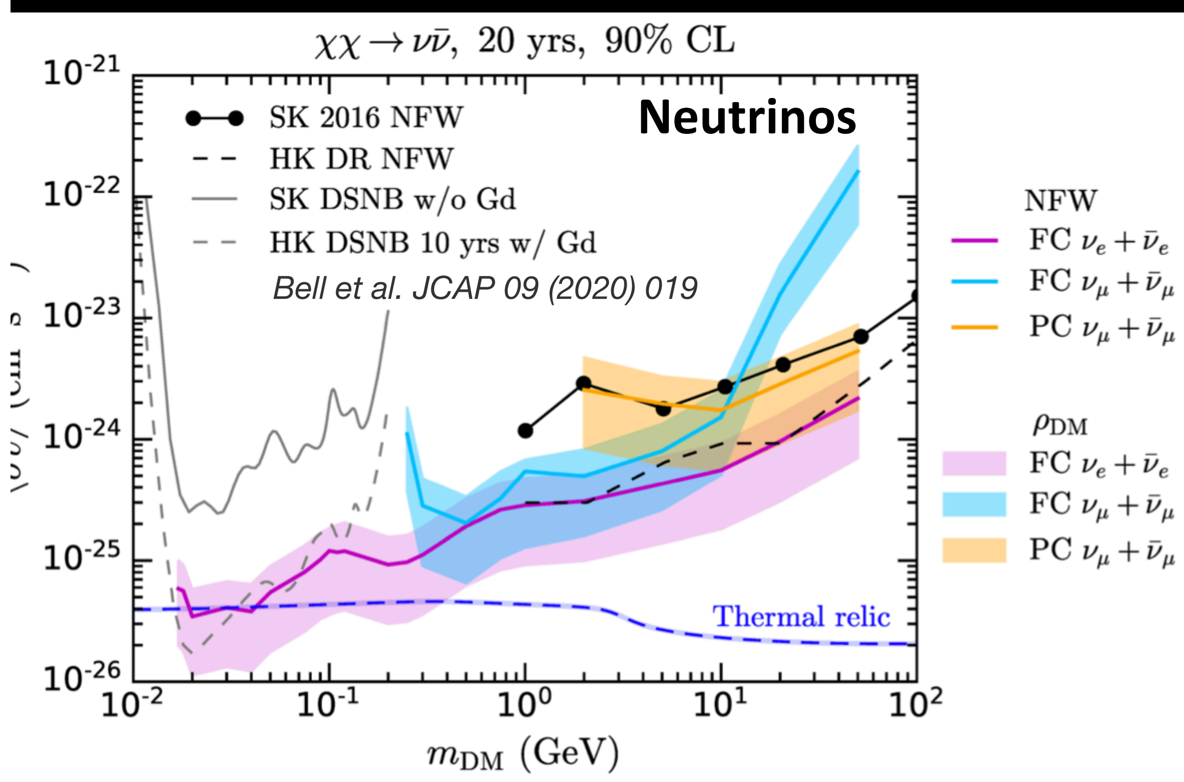


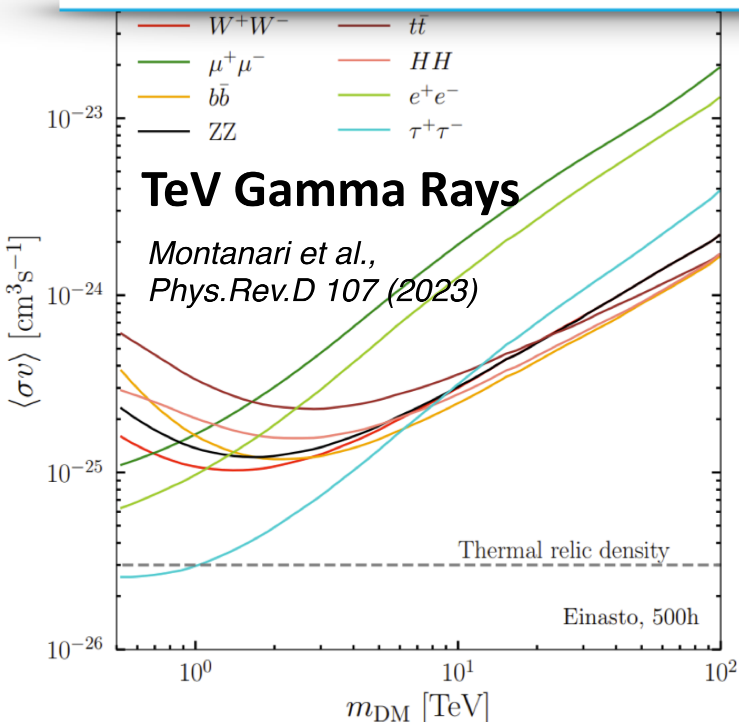
Mangipudi, Thrane & Balazs, arXiv:2112.10371

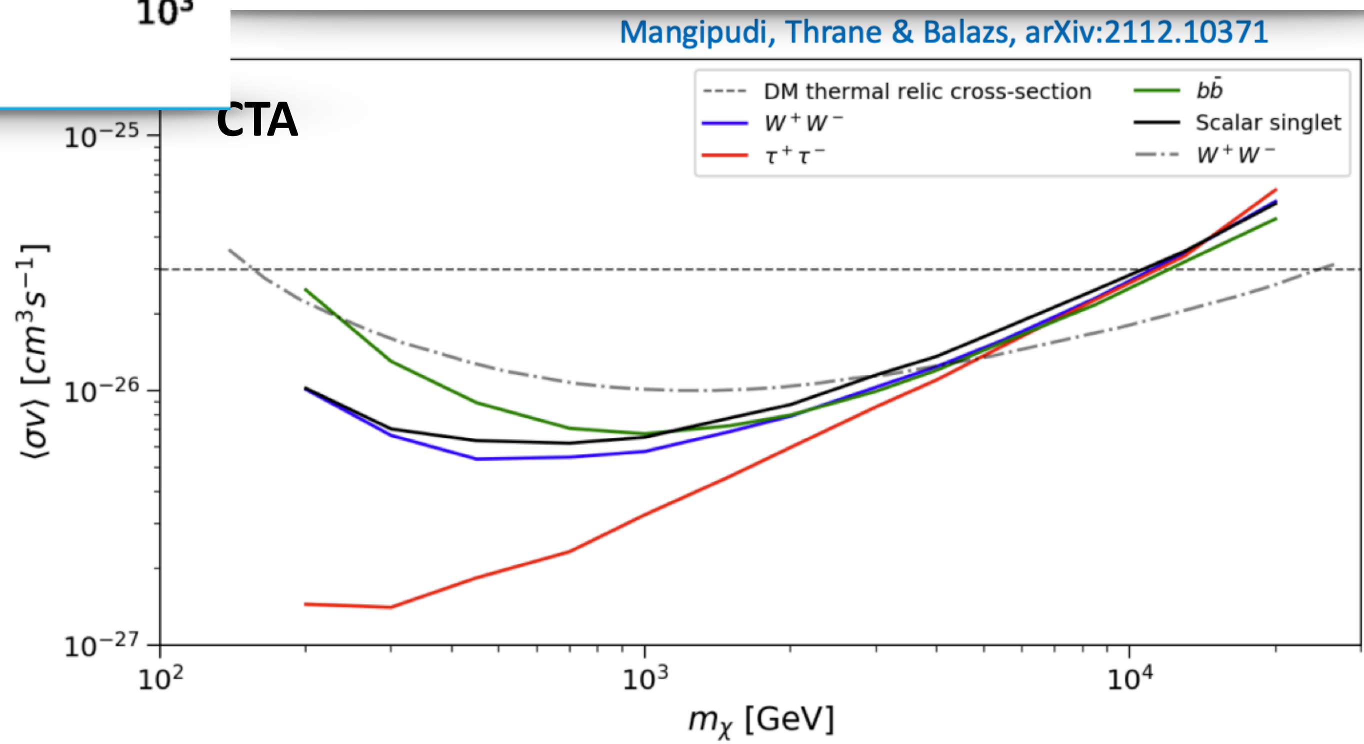


Bell, TAUP 2023



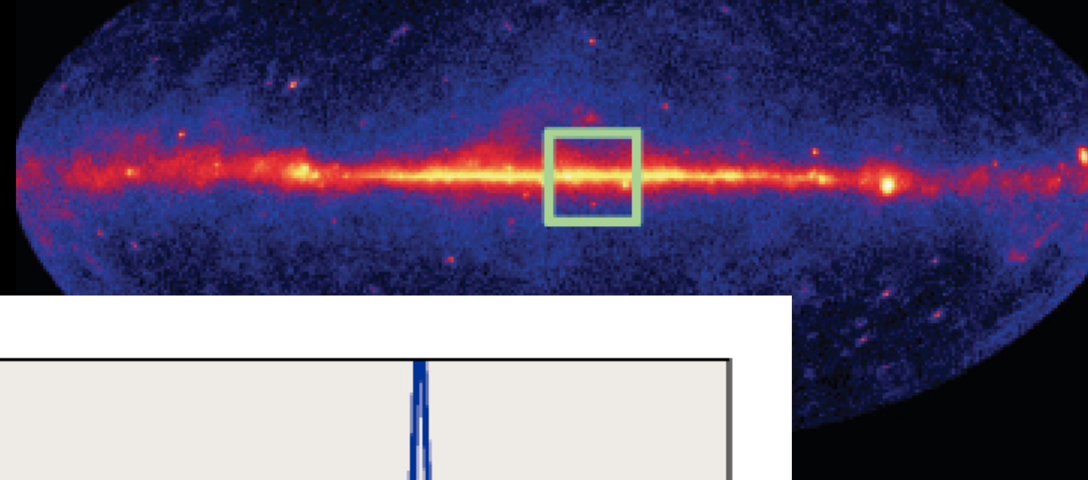


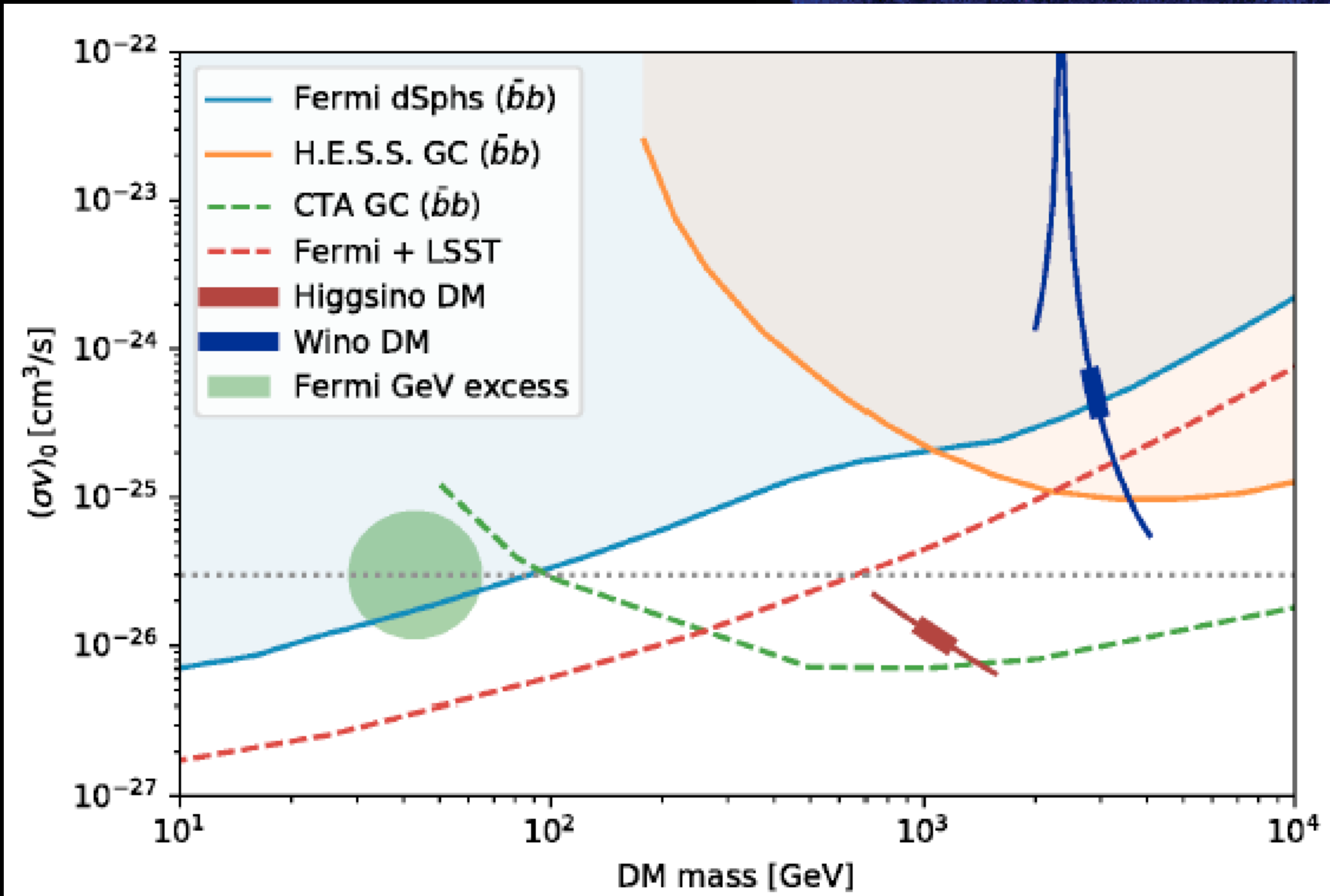




Bell, TAUP 2023

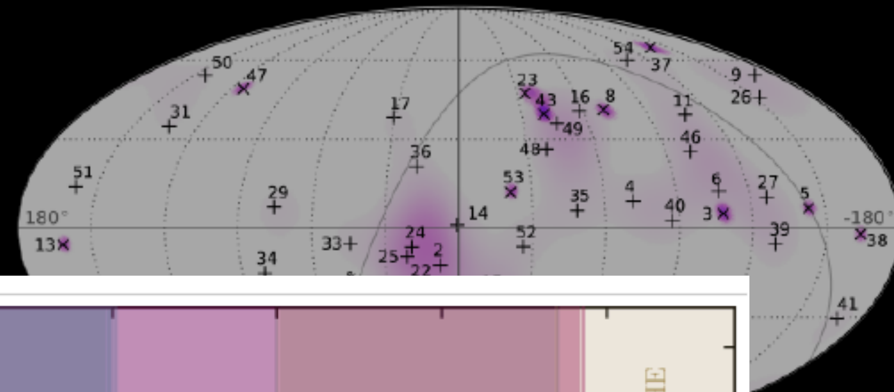
Visible Final States
Prospects for WIMPs

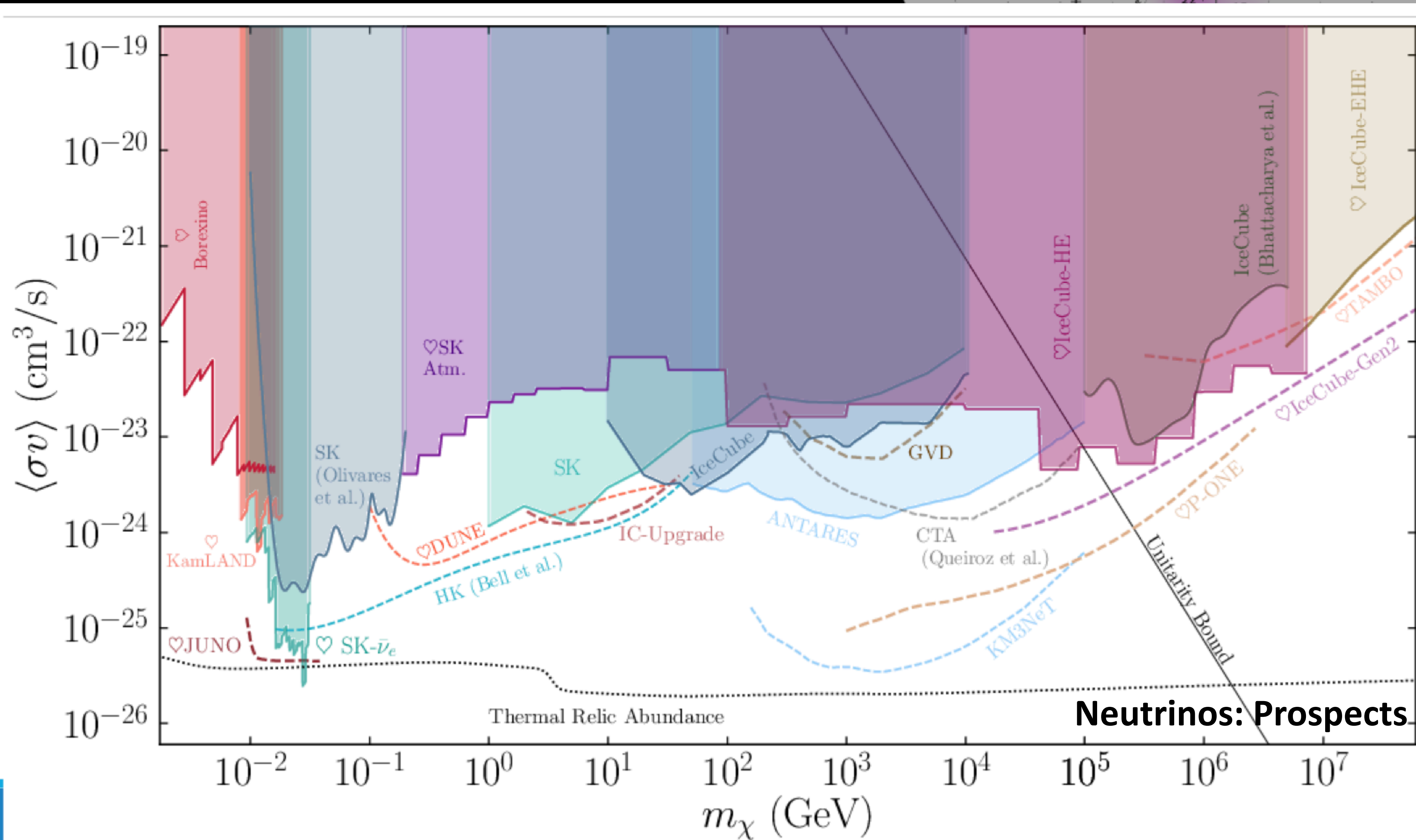




Weniger, ESPPU Briefing Book

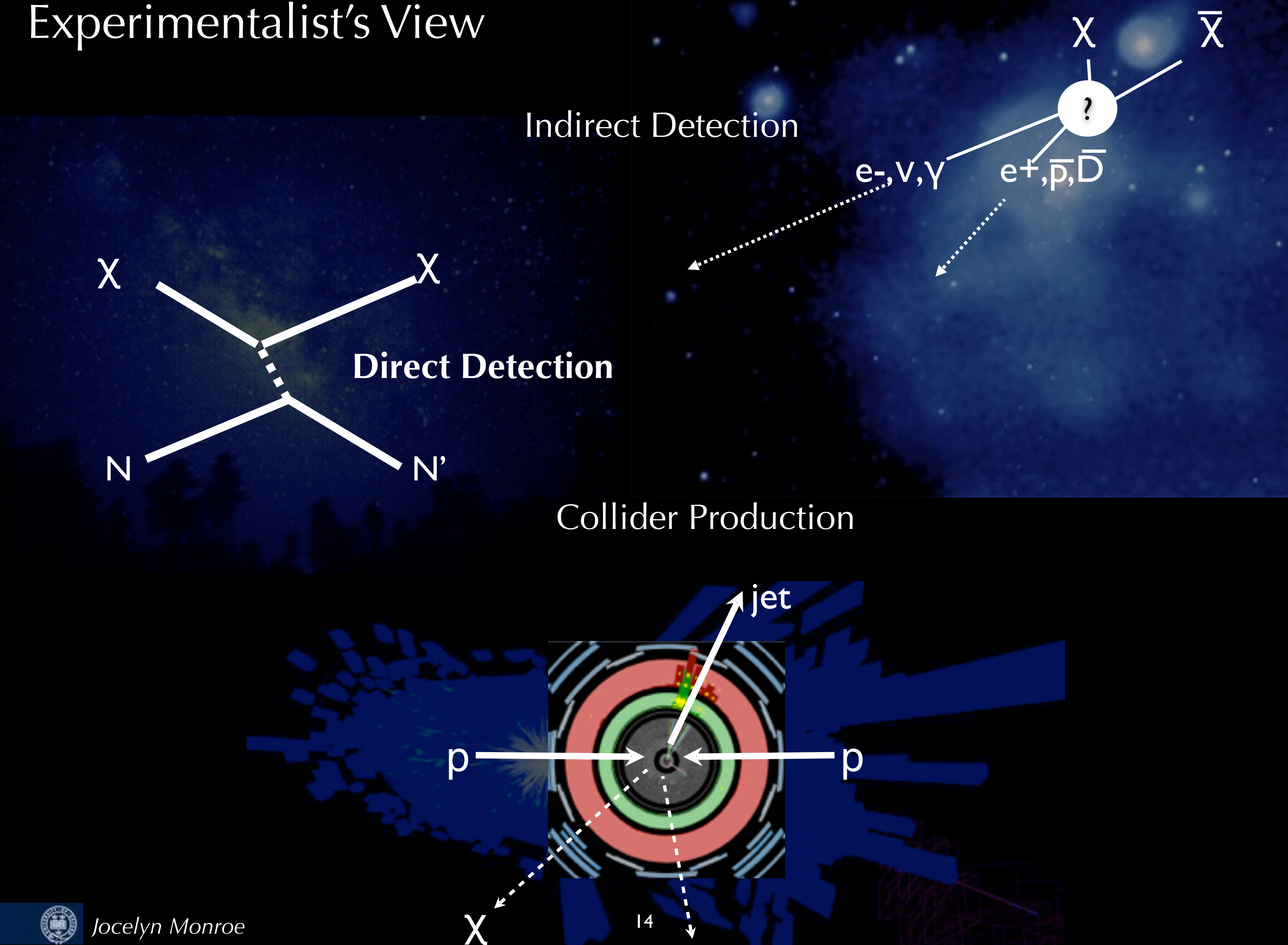
Invisible Final States
Prospects for WIMPs++





Arguelles et al. Rev. Mod. Phys. 93, 35007 (2021)

Experimentalist's View

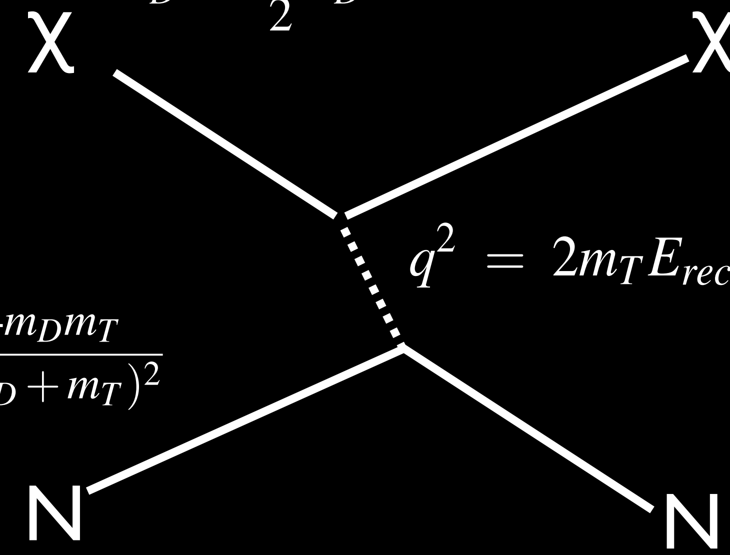


Direct Detection Strategies

scattering kinematics: *v/c ~ 8E-4!*

recoil angle strongly correlated with incoming WIMP direction

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



$$q^2 = 2 m_T E_{recoil}$$

$$r = \frac{4 m_D m_T}{(m_D + m_T)^2}$$

$$E_{recoil} = E_D r \frac{(1 - cos\theta)}{2}$$

<u>Spin Independent:</u>
χ scatters coherently off of the entire nucleus A: $\sigma \sim A^2$
D. Z. Freedman, PRD 9, 1389 (1974)

<u>Spin Dependent:</u>
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†
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^2 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[1] 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.[4] We assume a general current-current effective Lagrangian

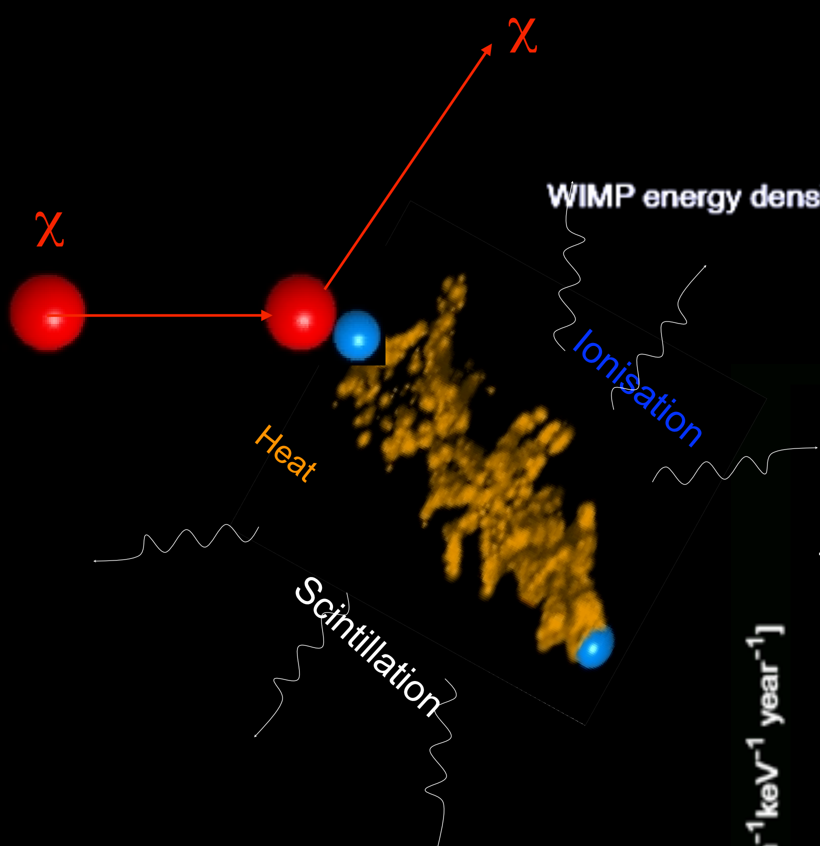
[1]F. J. Hasert *et al.*, Phys. Lett. 46B, 138 (1973); A. Benvenuti *et al.*, Phys. Rev. Lett. (to be published).

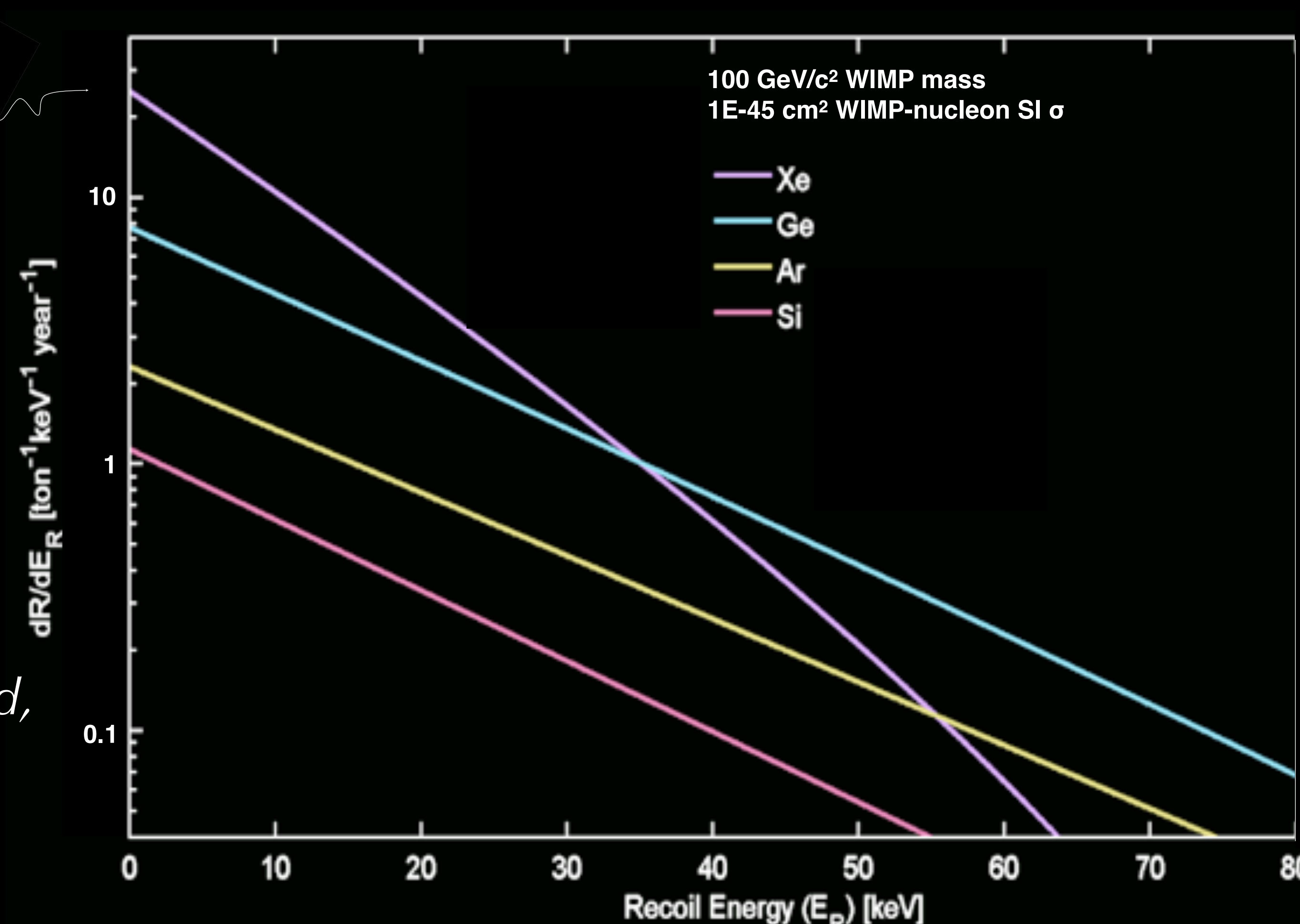
Scattering Signal

Scattering rate — Sun's velocity around the galaxy — WIMP velocity distribution

$$dR/dQ \sim (\sigma_0 \rho_0 / \sqrt{\pi}\, v_0 m_\chi m_r^2)\, F^2(Q)\, T(Q)$$

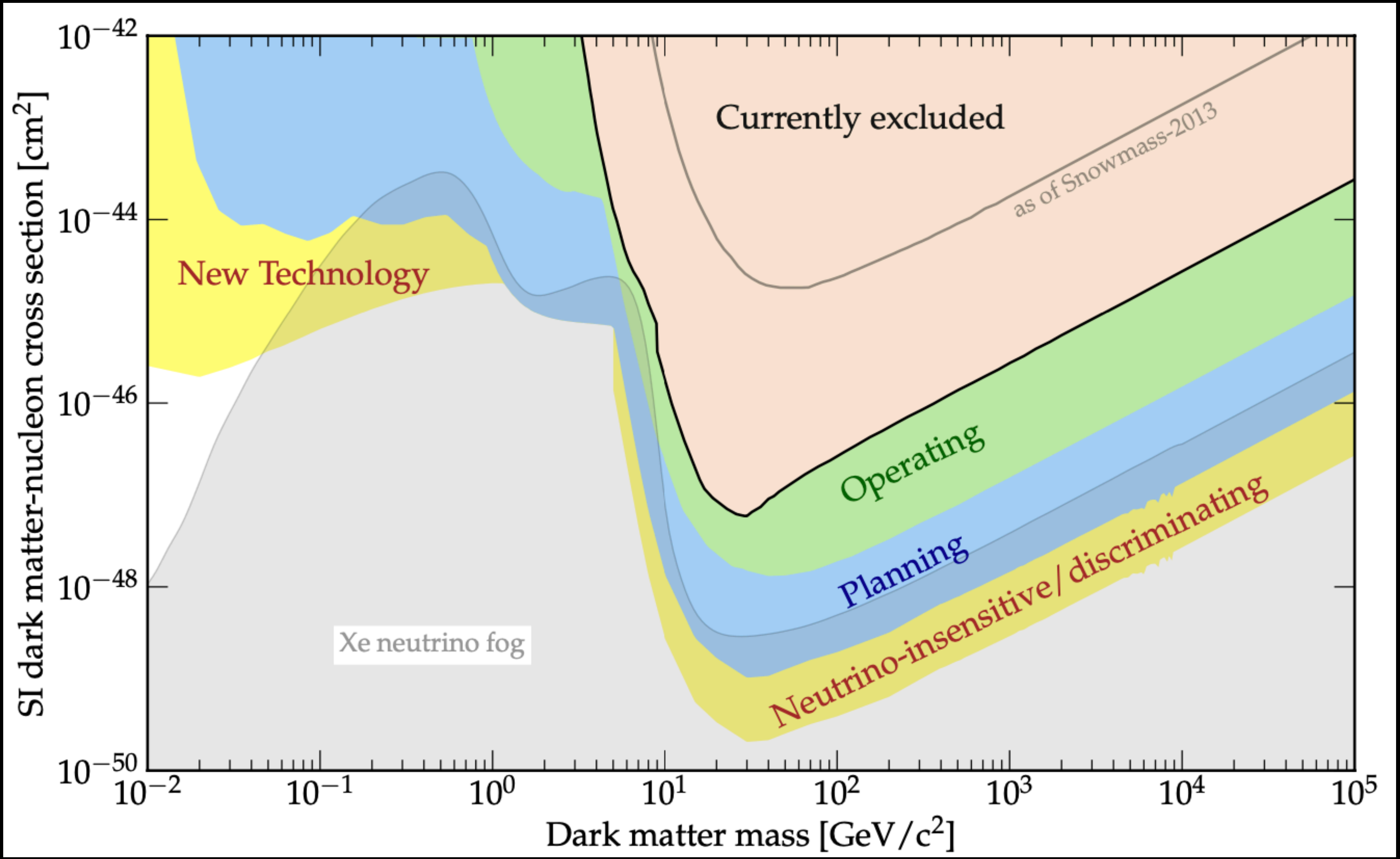
WIMP energy density, 0.3 GeV/cm³ — Form factor





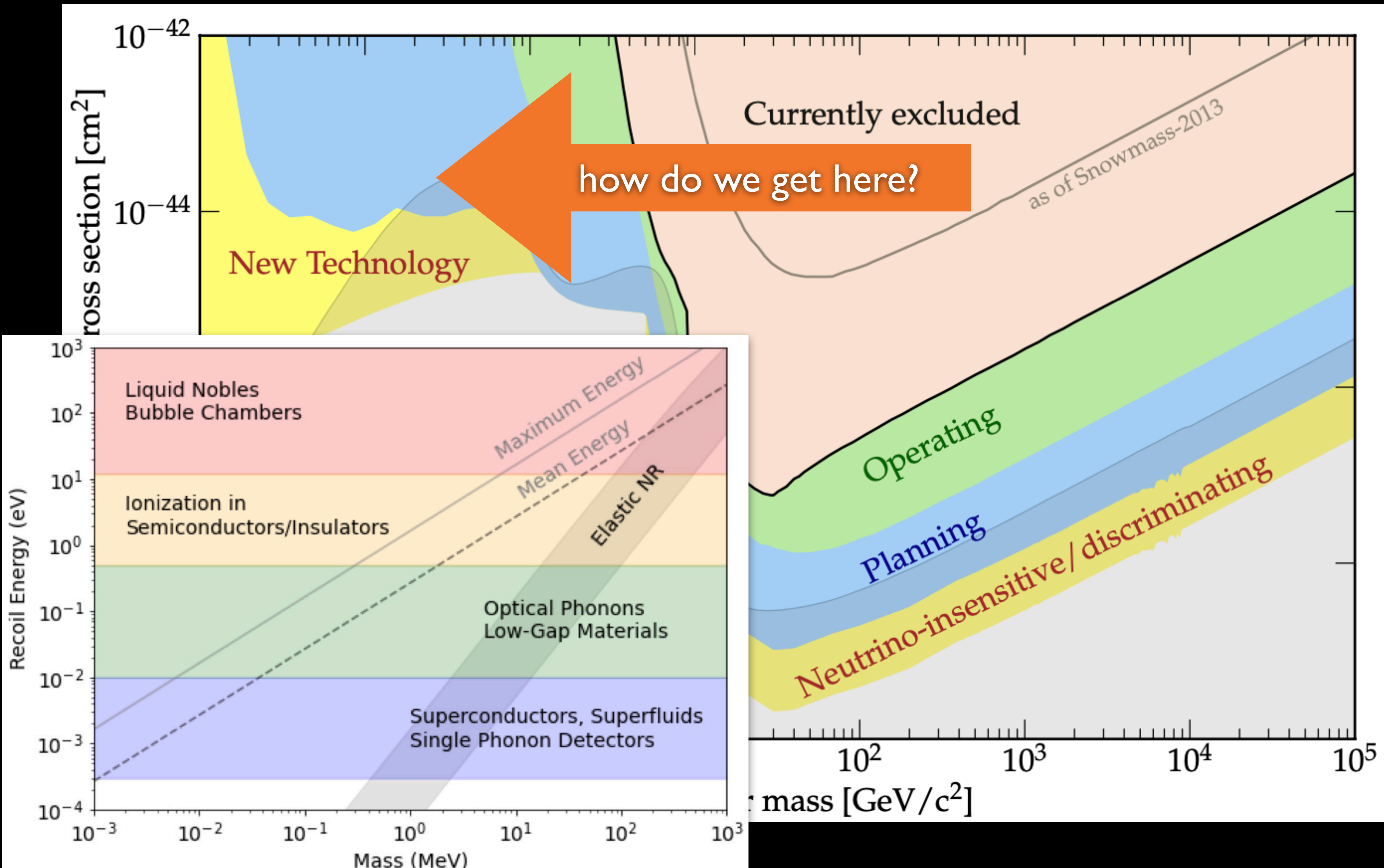
experimental challenges:
~1-10s of keV energy threshold,
low signal rate,
backgrounds!

Direct Detection WIMP Searches



Direct Detection WIMP Searches

Snowmass Cosmic Frontier Report, arXiv:2211.09978



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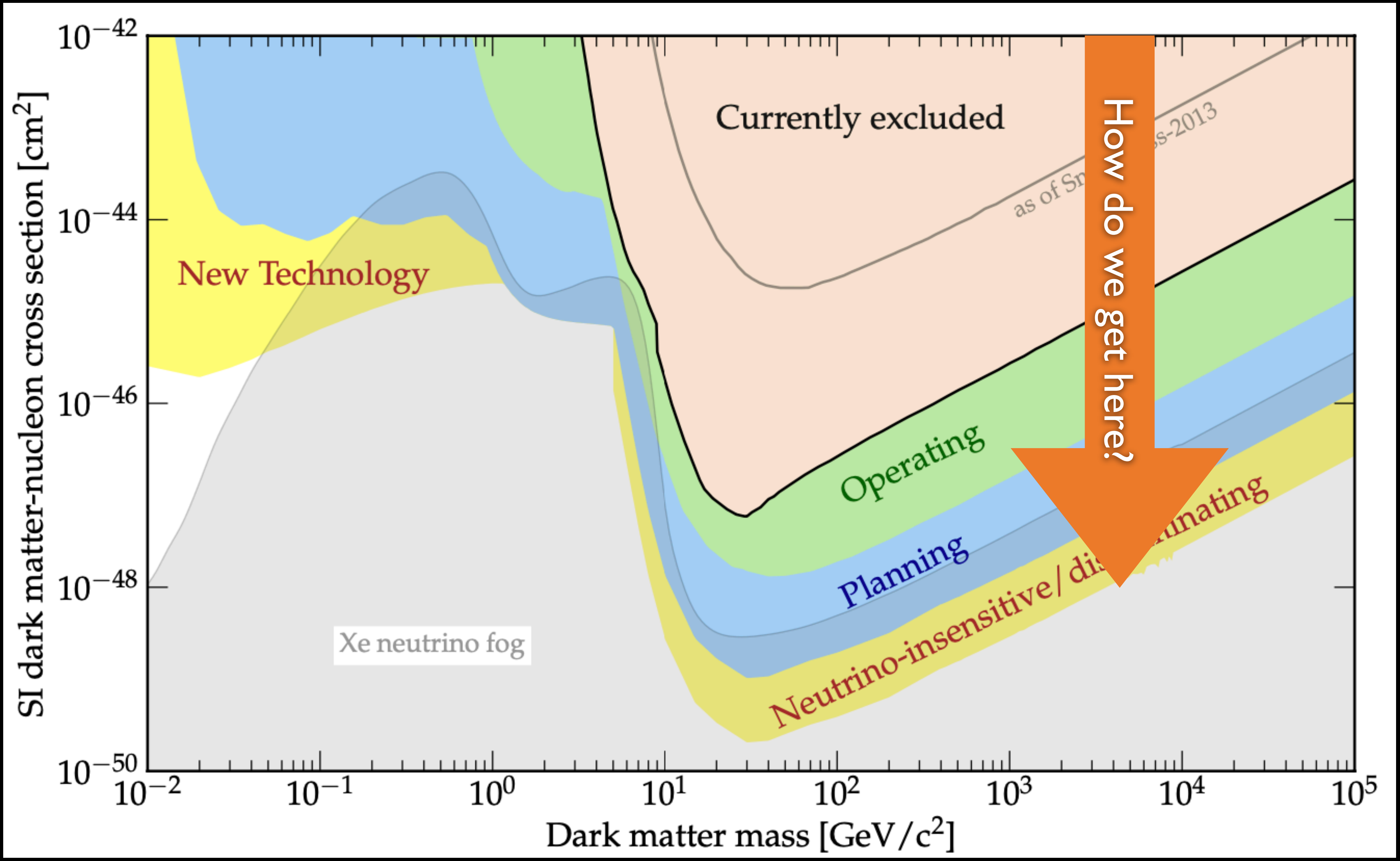


Xenon Detectors

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

10 kg

2010

XENON 10 (LNGS)

ZEPLIN I,II,III (Boulby)

XENON 100 (LNGS)

100 kg

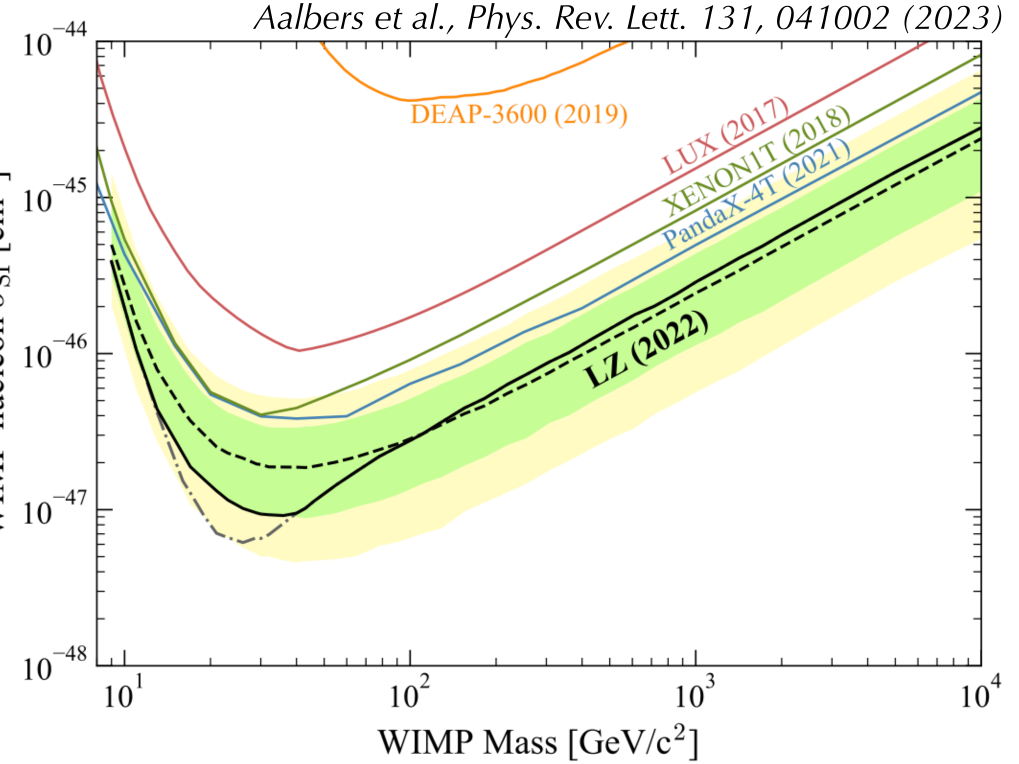
LUX (250 kg, SURF)

PANDA-X 500 kg, CJPL)

XMASS (800 kg, Kamioka)

2015

Aalbers et al., Phys. Rev. Lett. 131, 041002 (2023)



00 kg

ENON 1T (1t, LNGS)

PandaX-4:(4t, CJPL)

XENONnT: (6t, LNGS)

LZ: (7t, SURF)

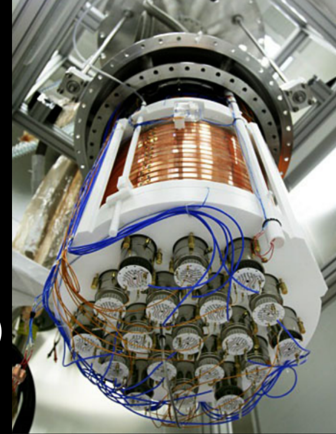
2020

10,000 kg

DARWIN/ XLZD

50 t

Argon Detectors



DarkSide-50 (50 kg, LNGS)

10 kg

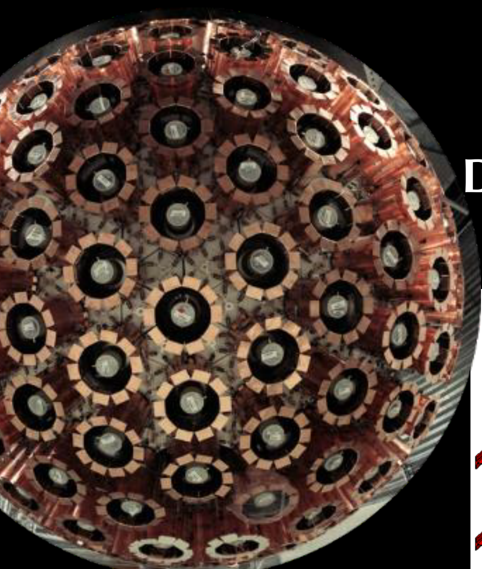
2010

100 kg

ArDM (1t, LSC)

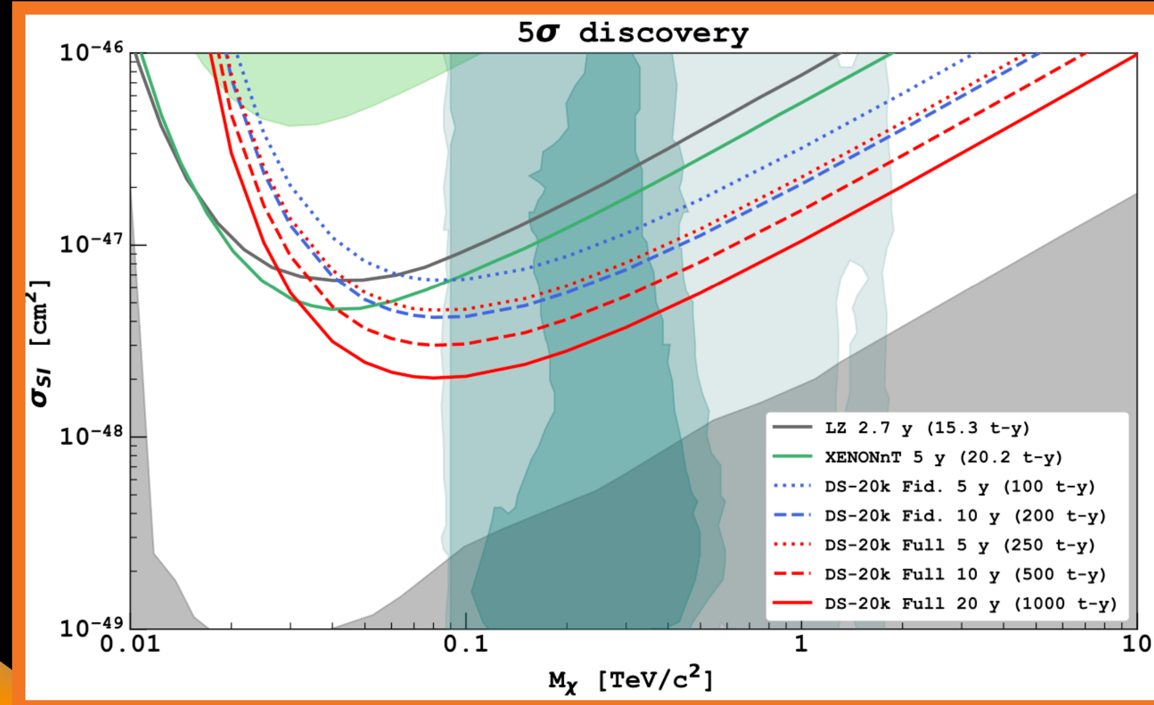
1,000 kg

2015



DEAP-3600 (3.6t, SNOLAB)

DarkSide-20k: observatory for dark matter and **ν.**

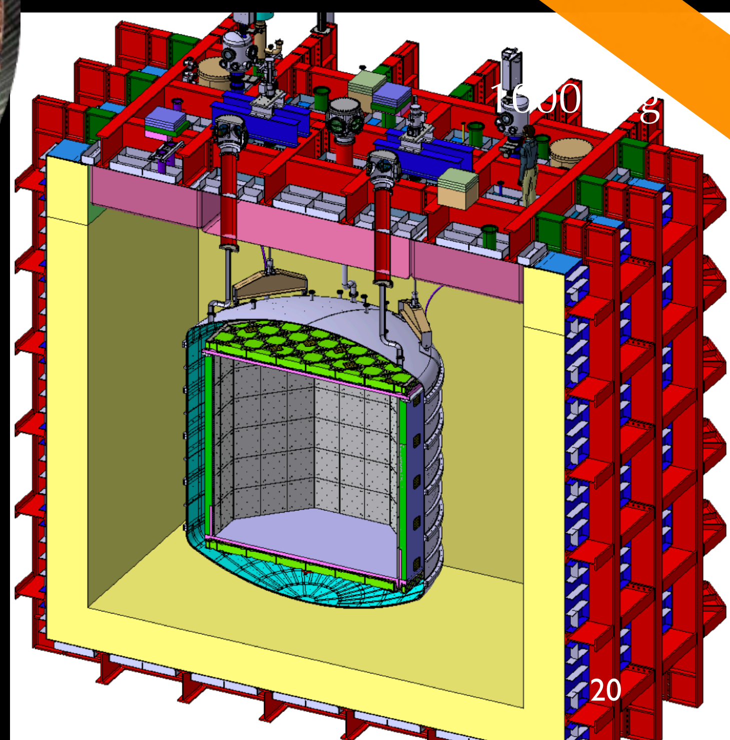


Global Argon Dark Matter Collaboration formed

APPEC

10,000 kg

2020

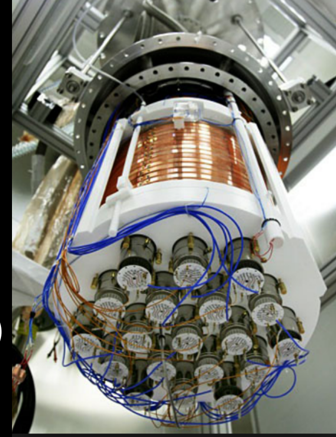


100,000 kg

DarkSide-20k (50t, LNGS)

Future: ARGO kt-scale

Argon Detectors



DarkSide-50 (50 kg, LNGS)

10 kg

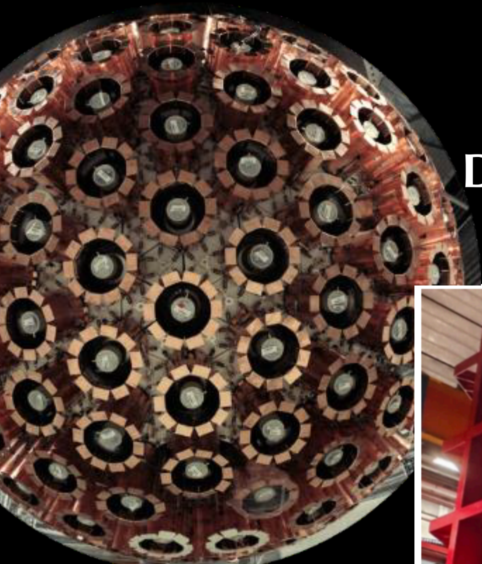
2010

100 kg

ArDM (1t, LSC)

2015

1,000 kg



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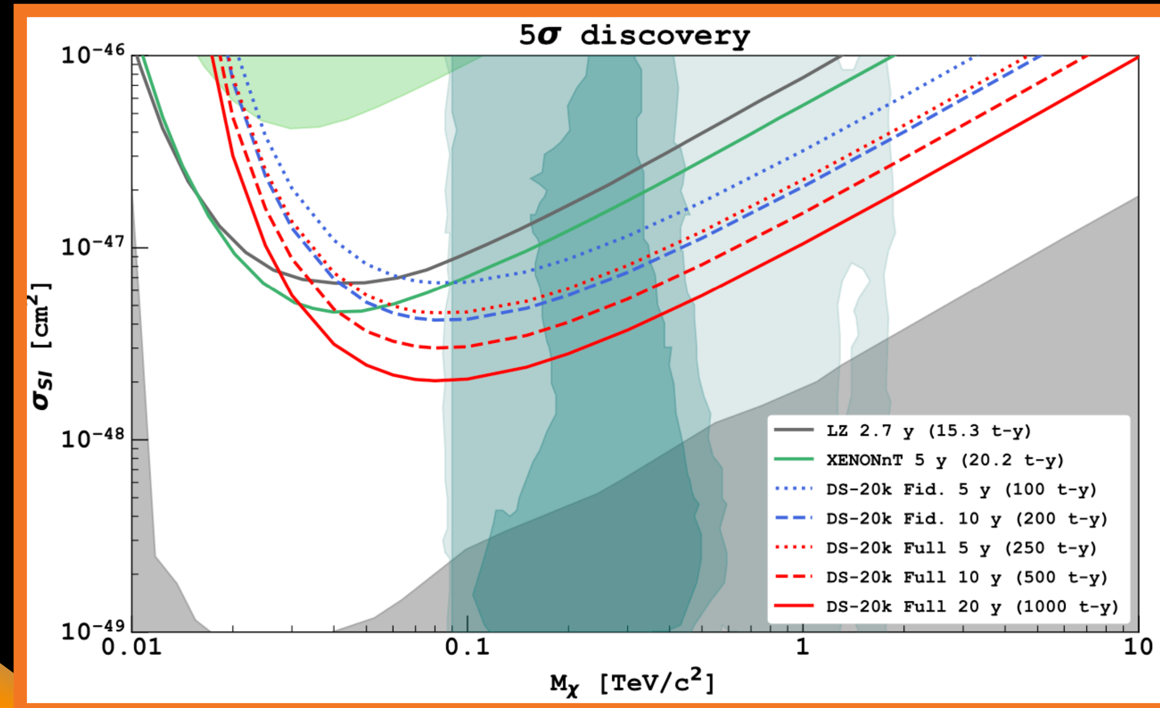

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10,000 kg

APPEC

2020

100,000 kg

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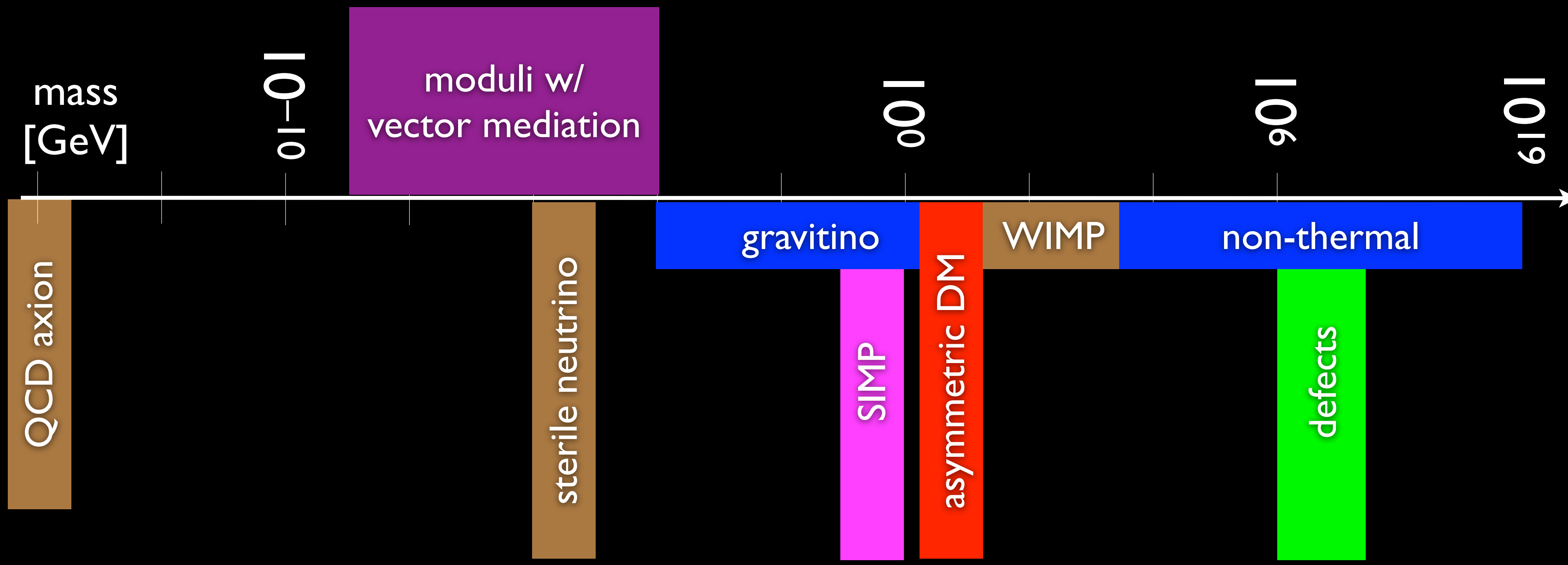
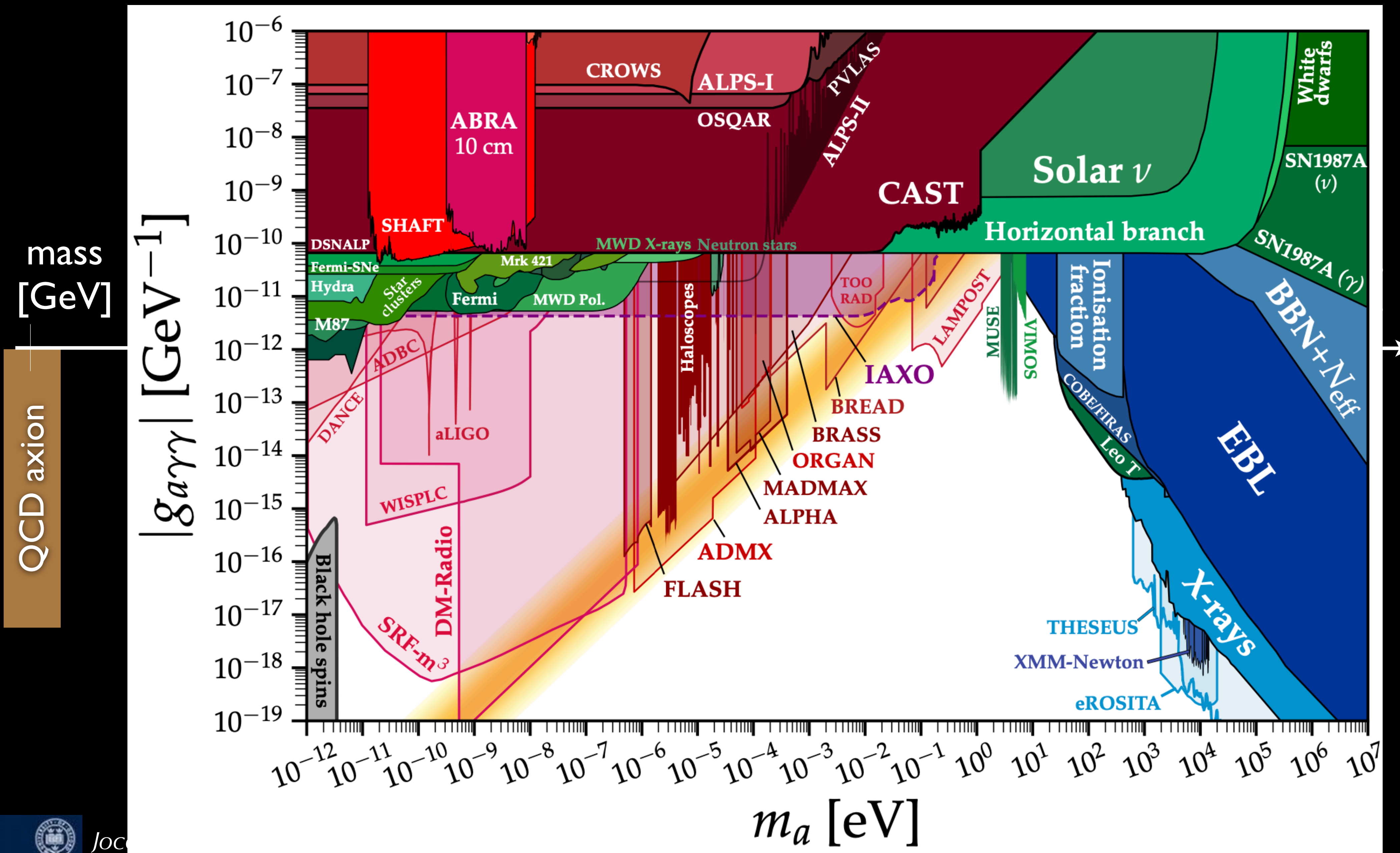
Direct Detection Beyond WIMPs



Direct Detection Beyond WIMPs

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



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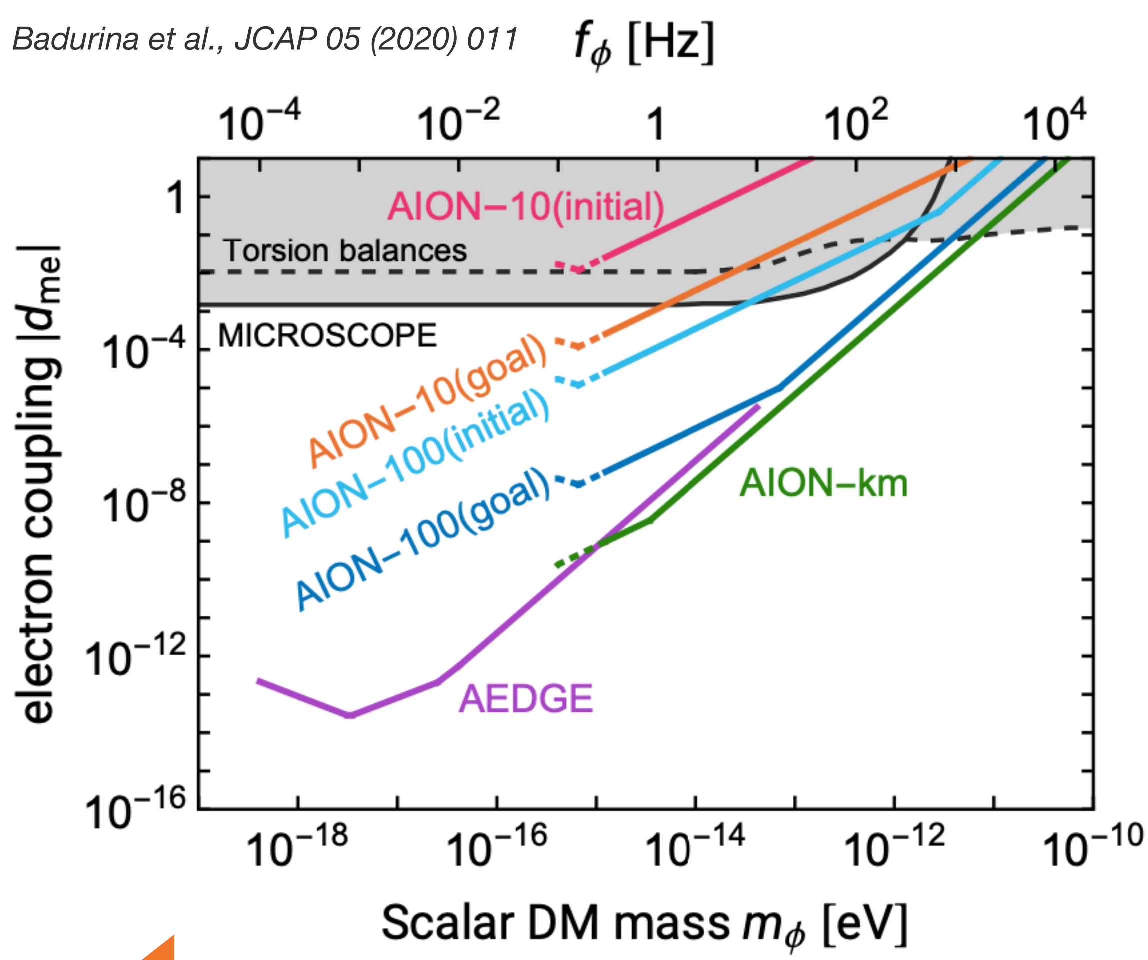
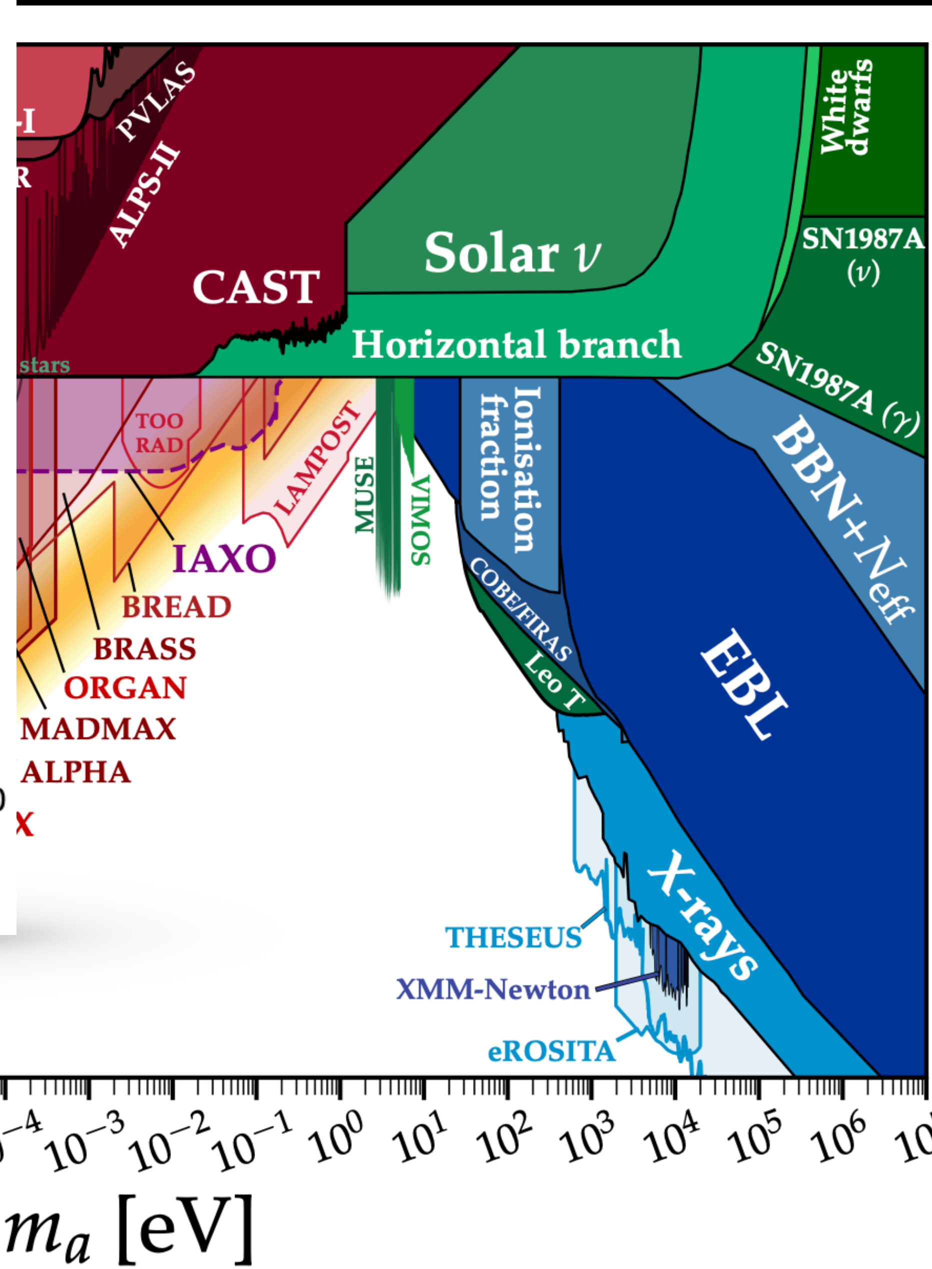
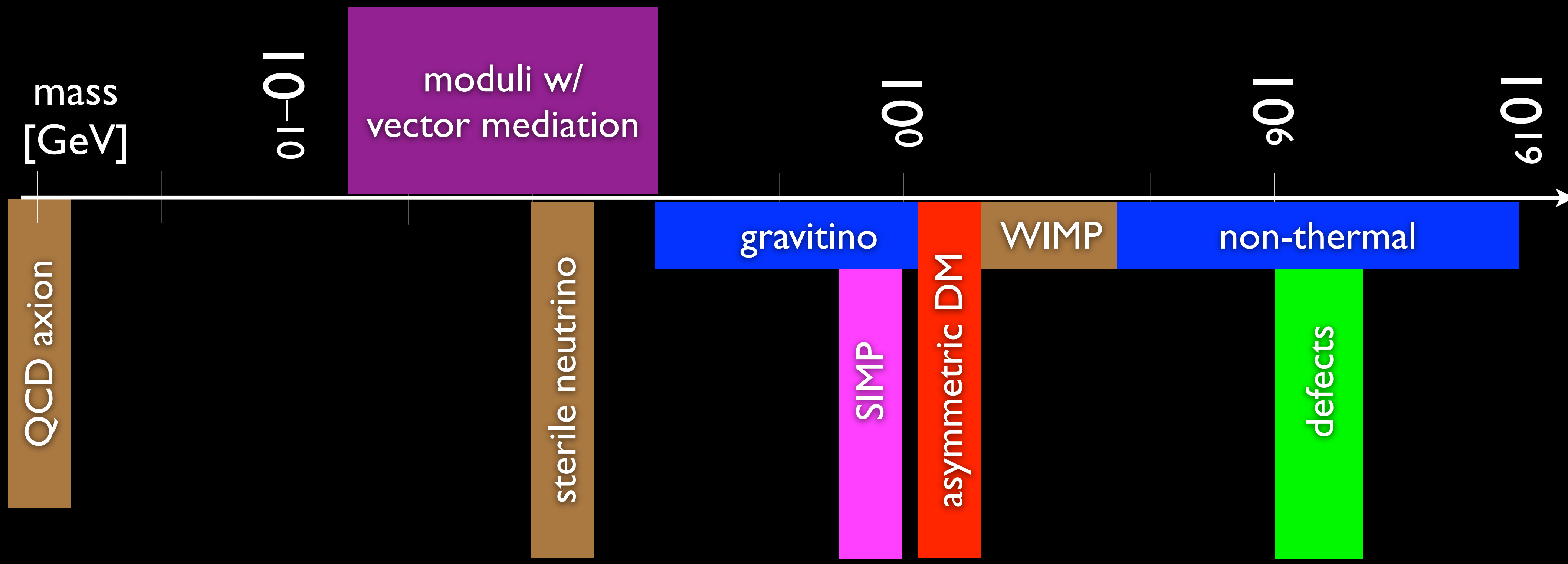




how do we get here?

Direct Detection Beyond WIMPs

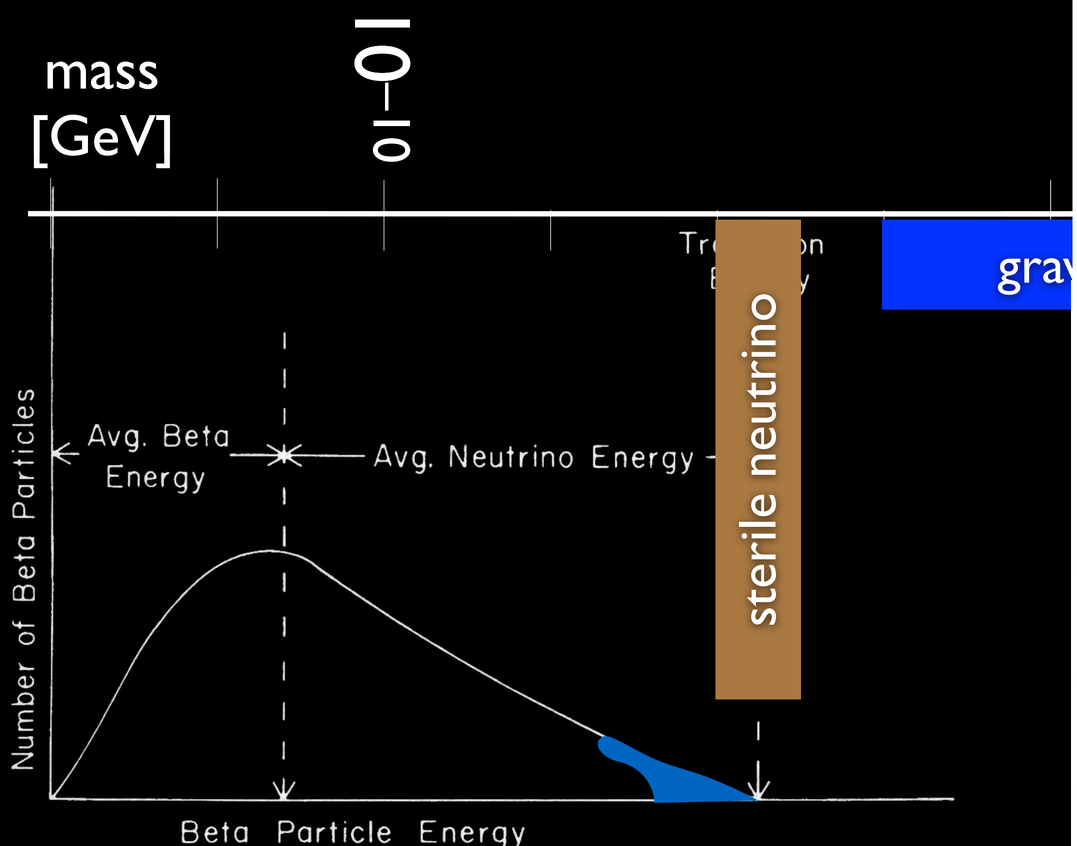


Direct Detection Beyond WIMPs

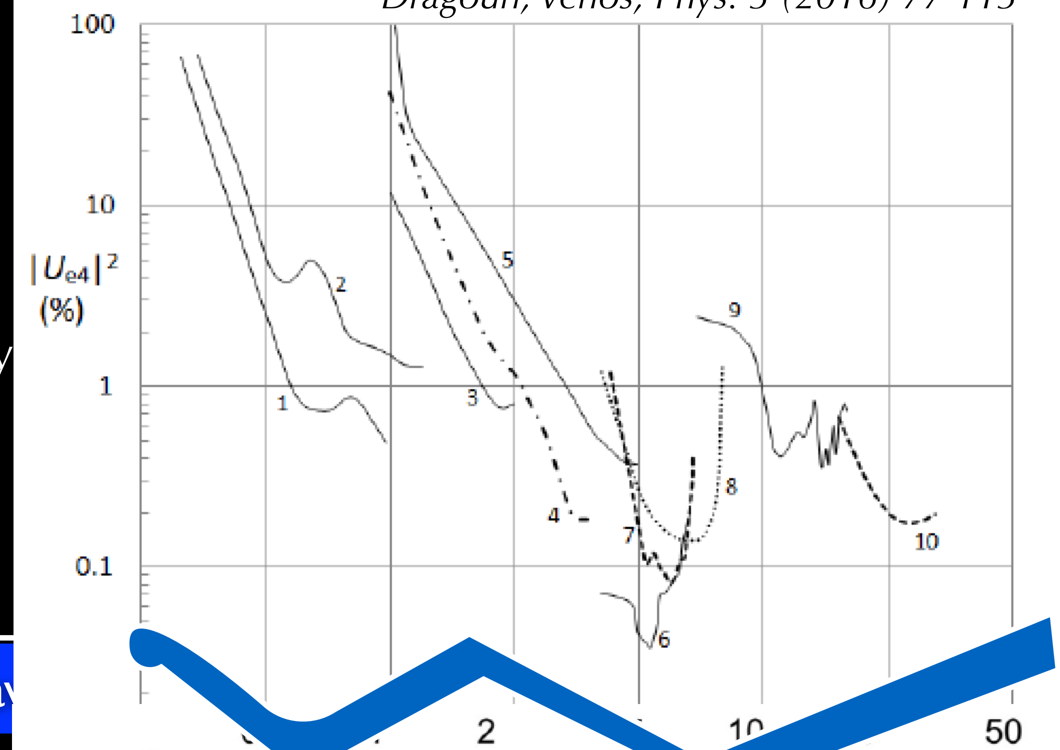
Sterile neutrino dark matter can scatter with electrons $N_S\, e^- \rightarrow \nu_e\, e^-$

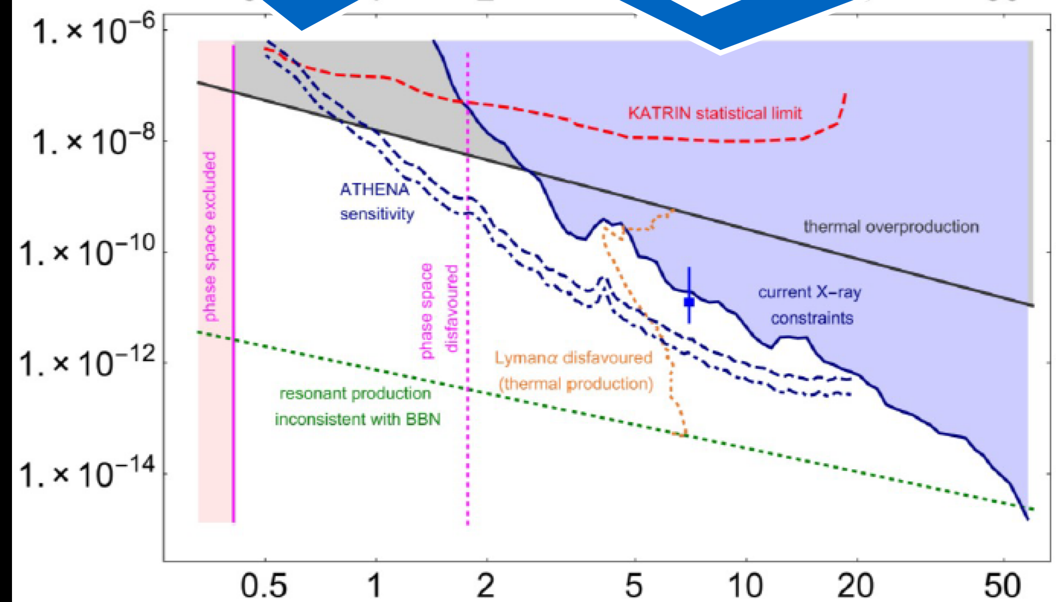
Constraints on $|U_{e4}|^2$ from beta decay: energy spectrum modified by sterile neutrino mixing.

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



Dragoun, Venos, Phys. 3 (2016) 77-113





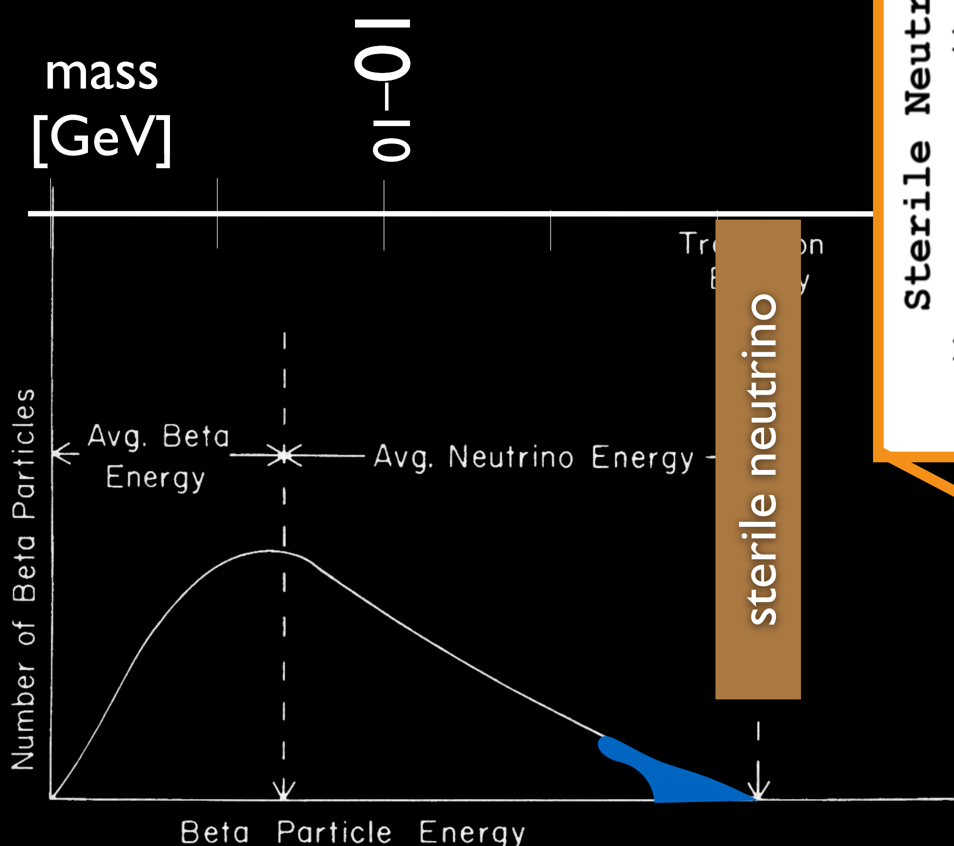
Weinheimer, ESPPU'19

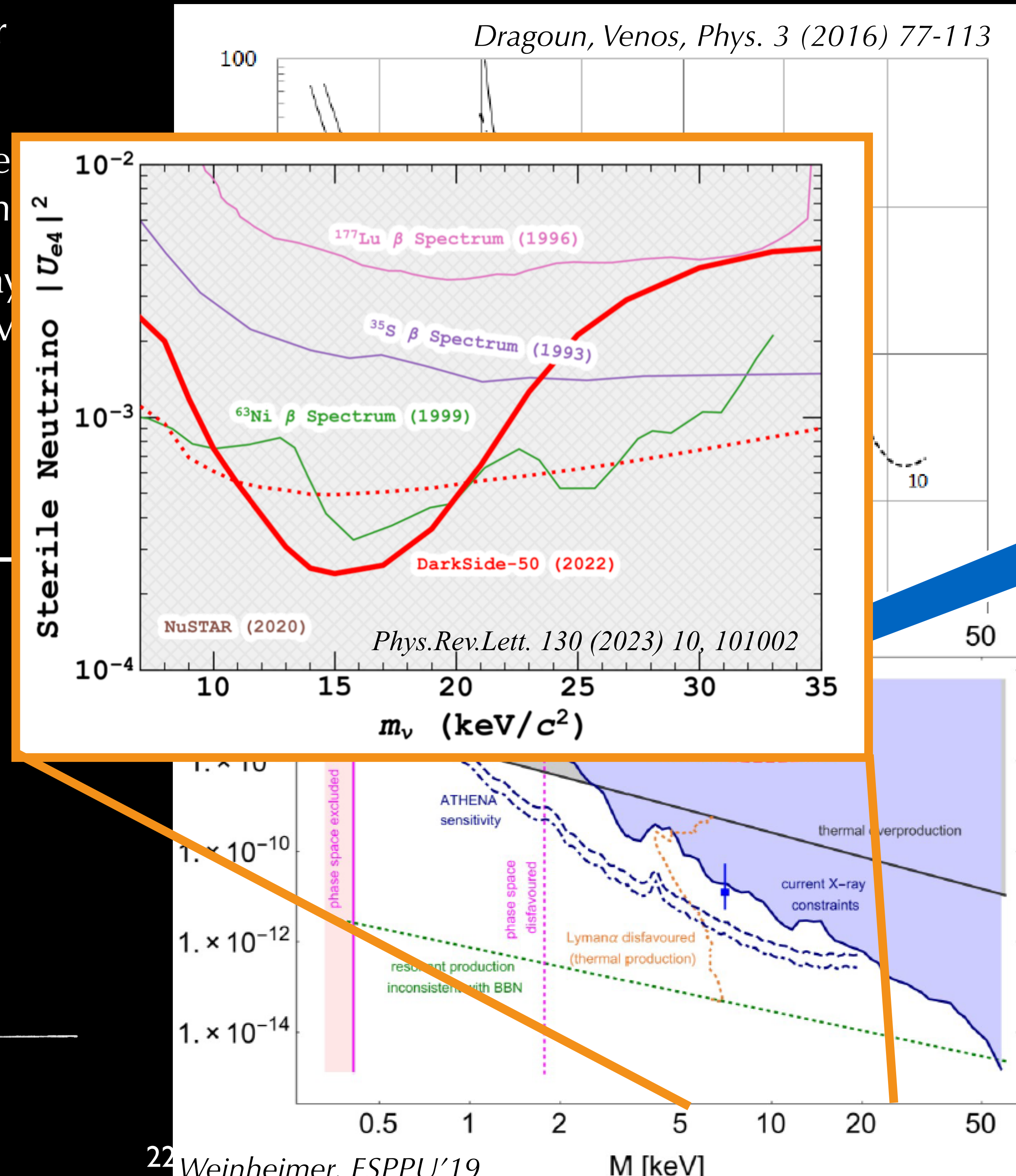
Direct Detection Beyond WIMPs

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

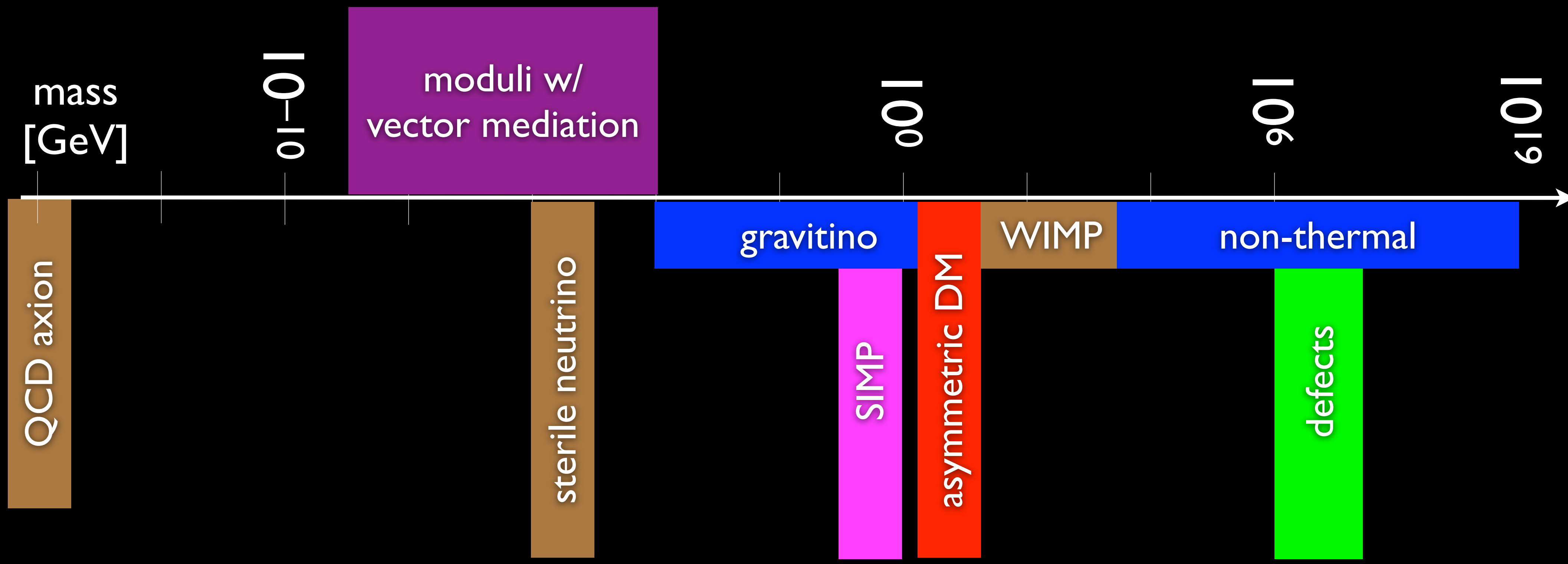
Constraints on $|U_{e4}|^2$ from beta decay: e spectrum modified by sterile neutrino m

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



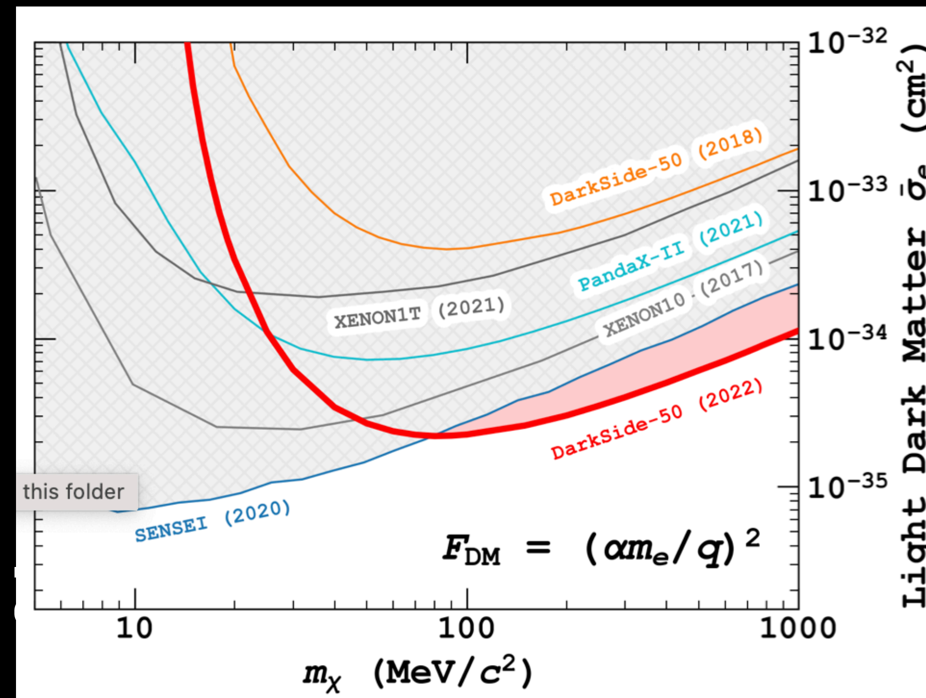


Direct Detection Beyond WIMPs

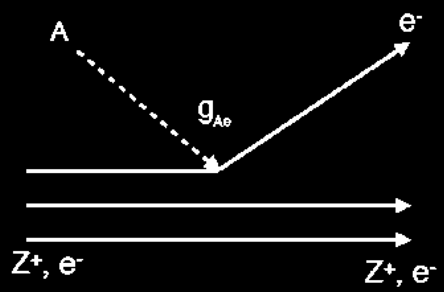


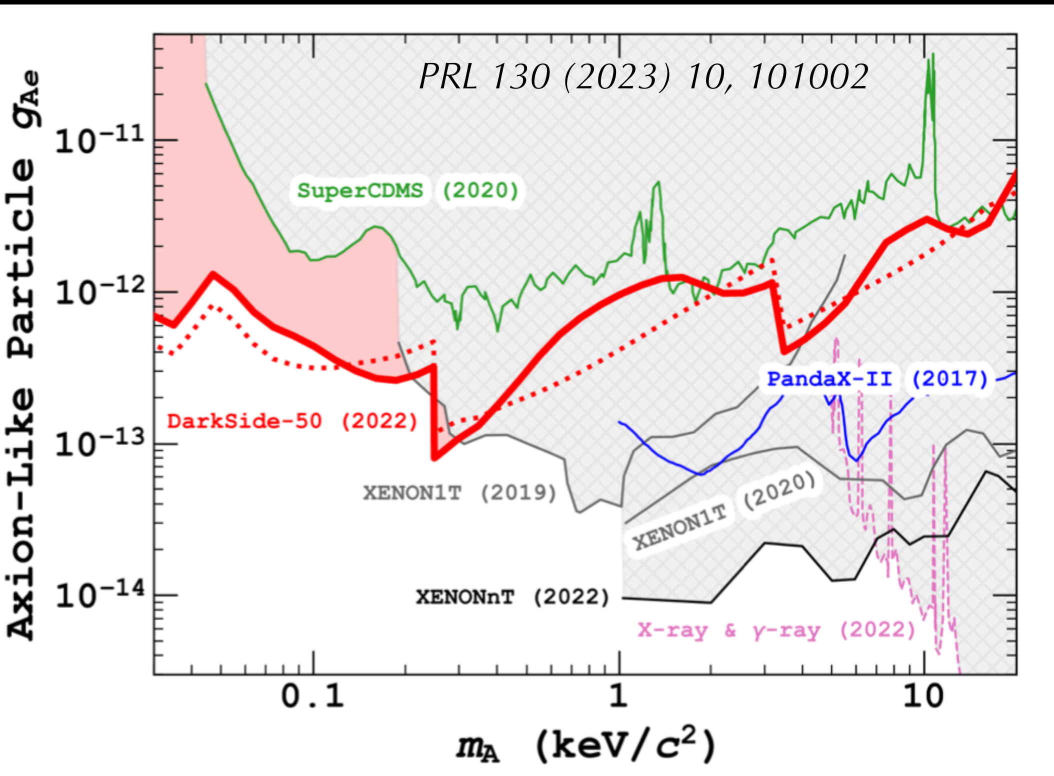
Direct Detection Beyond WIMPs

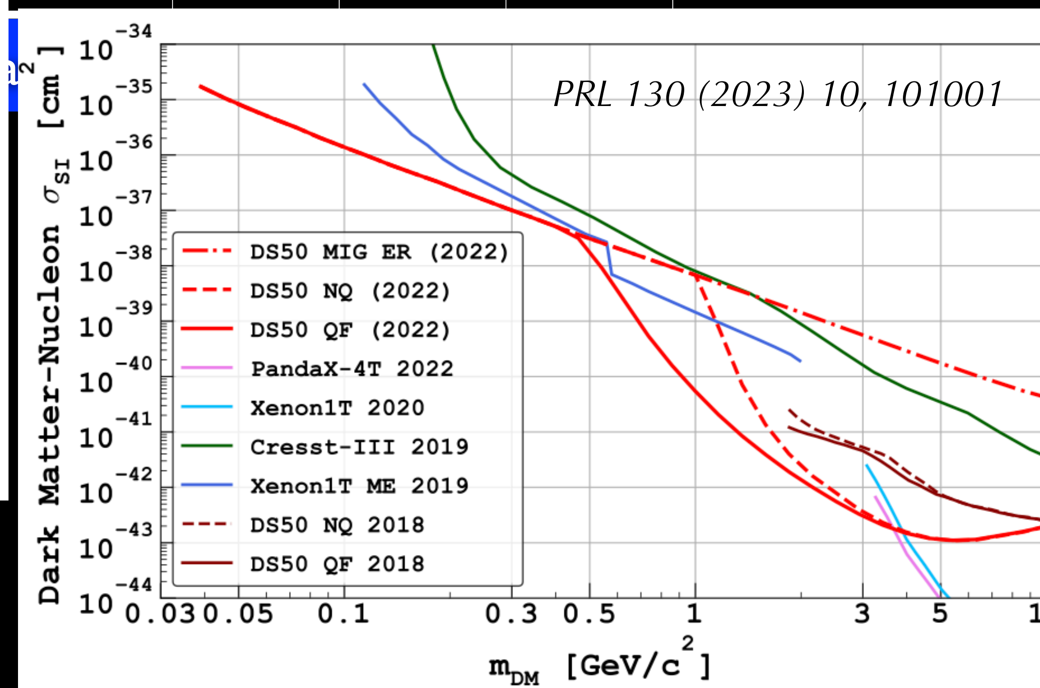
MeV-scale dark matter: search for scattering



keV-scale dark matter: search for absorption:



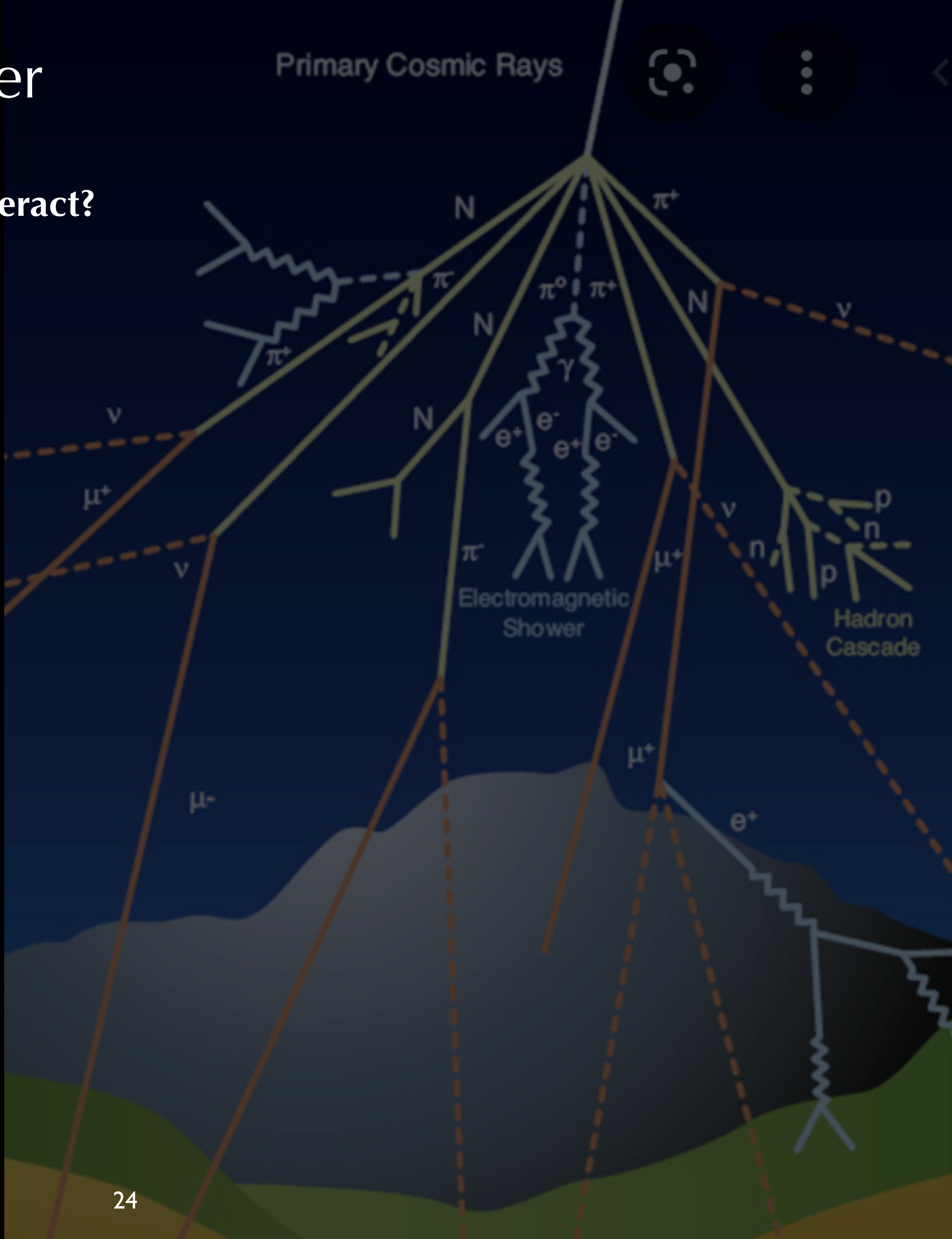




GeV-scale dark matter: search for scattering with nuclear + electronic recoil final states

Cosmic Rays / Dark Matter

What if dark matter and cosmic rays interact?



Cosmic Rays / Dark Matter

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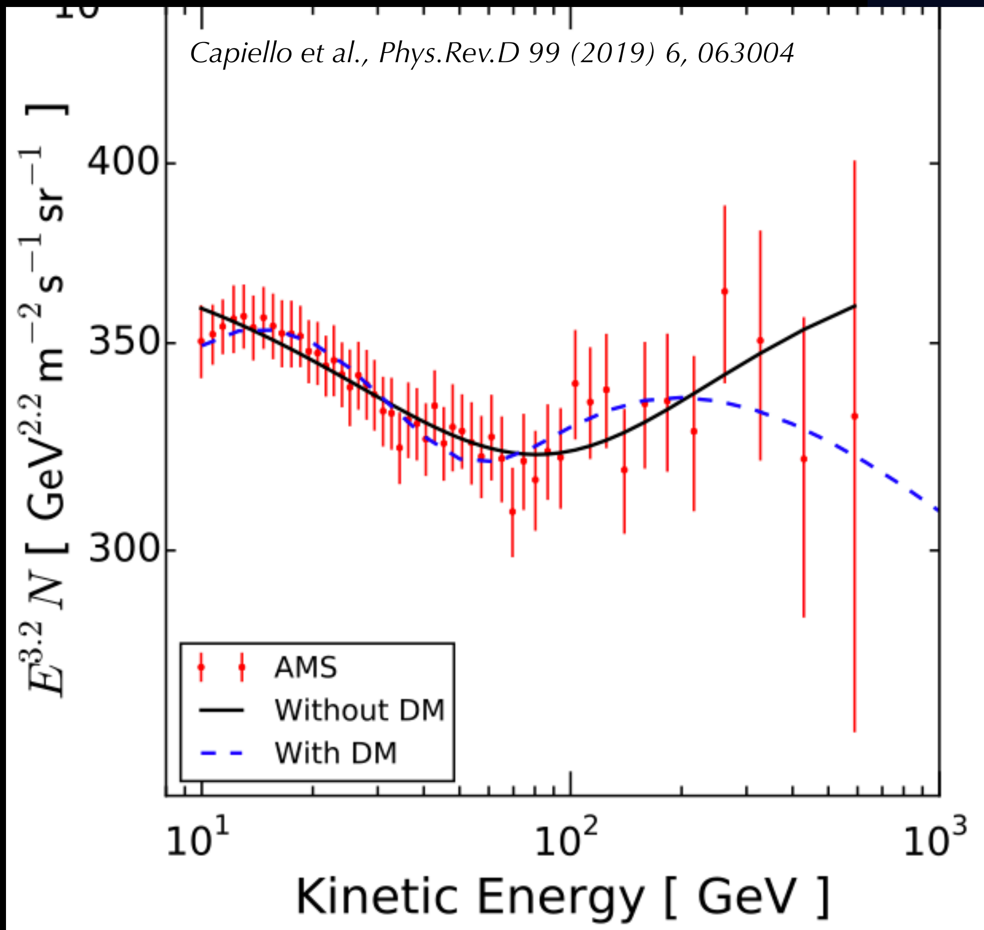
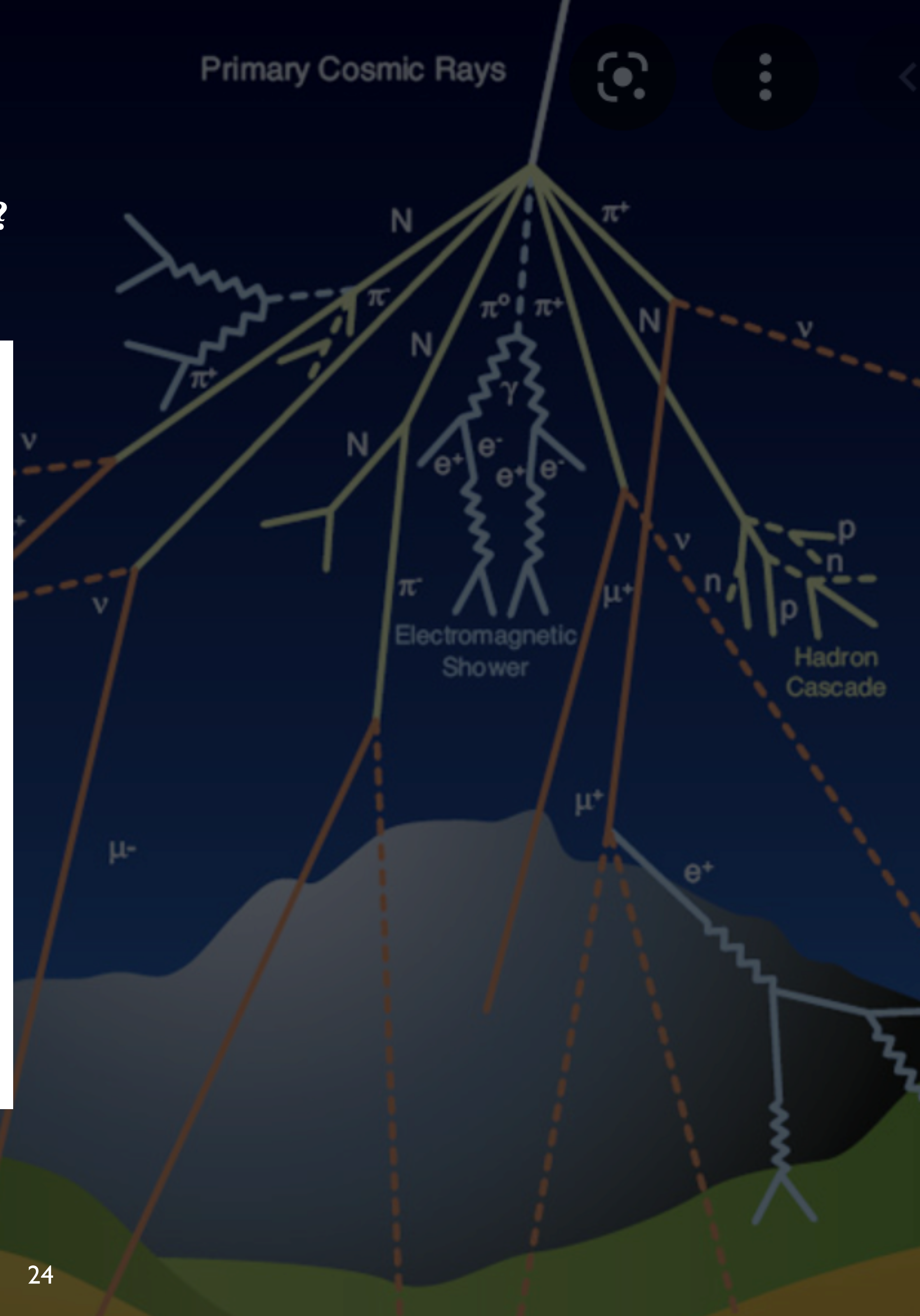
Cosmic ray "downscattering:"





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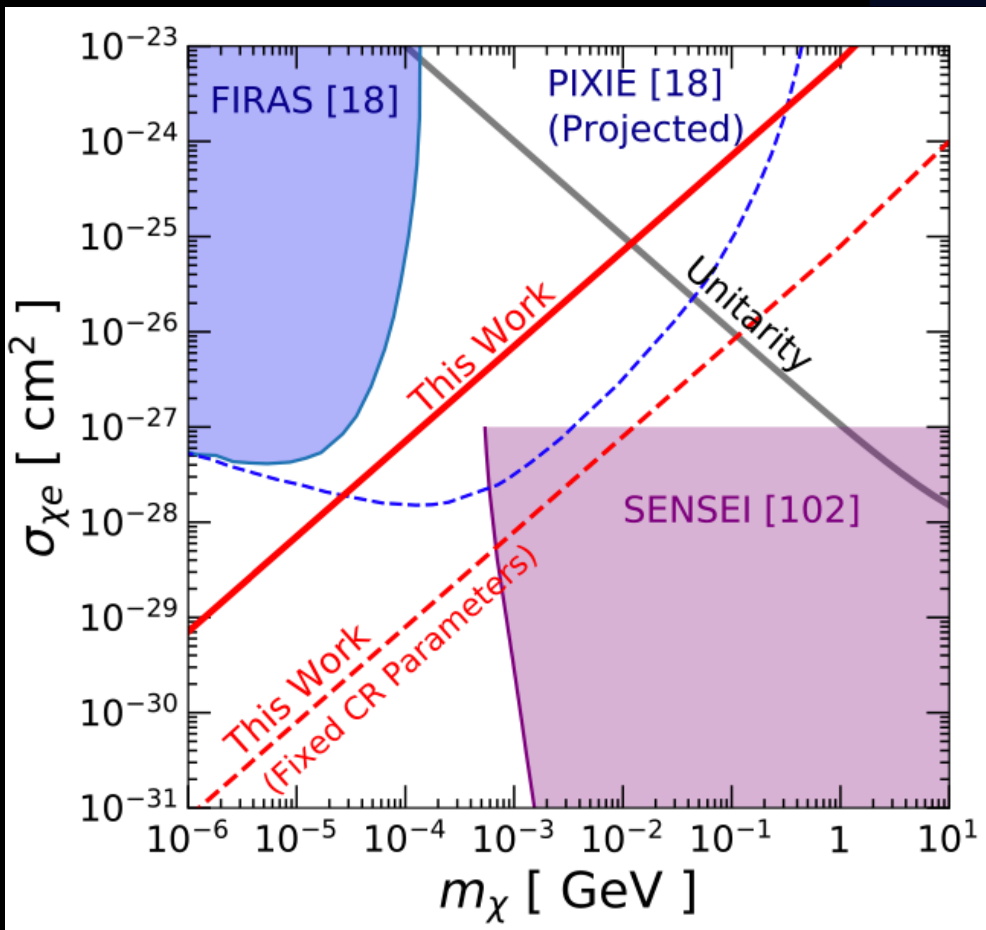
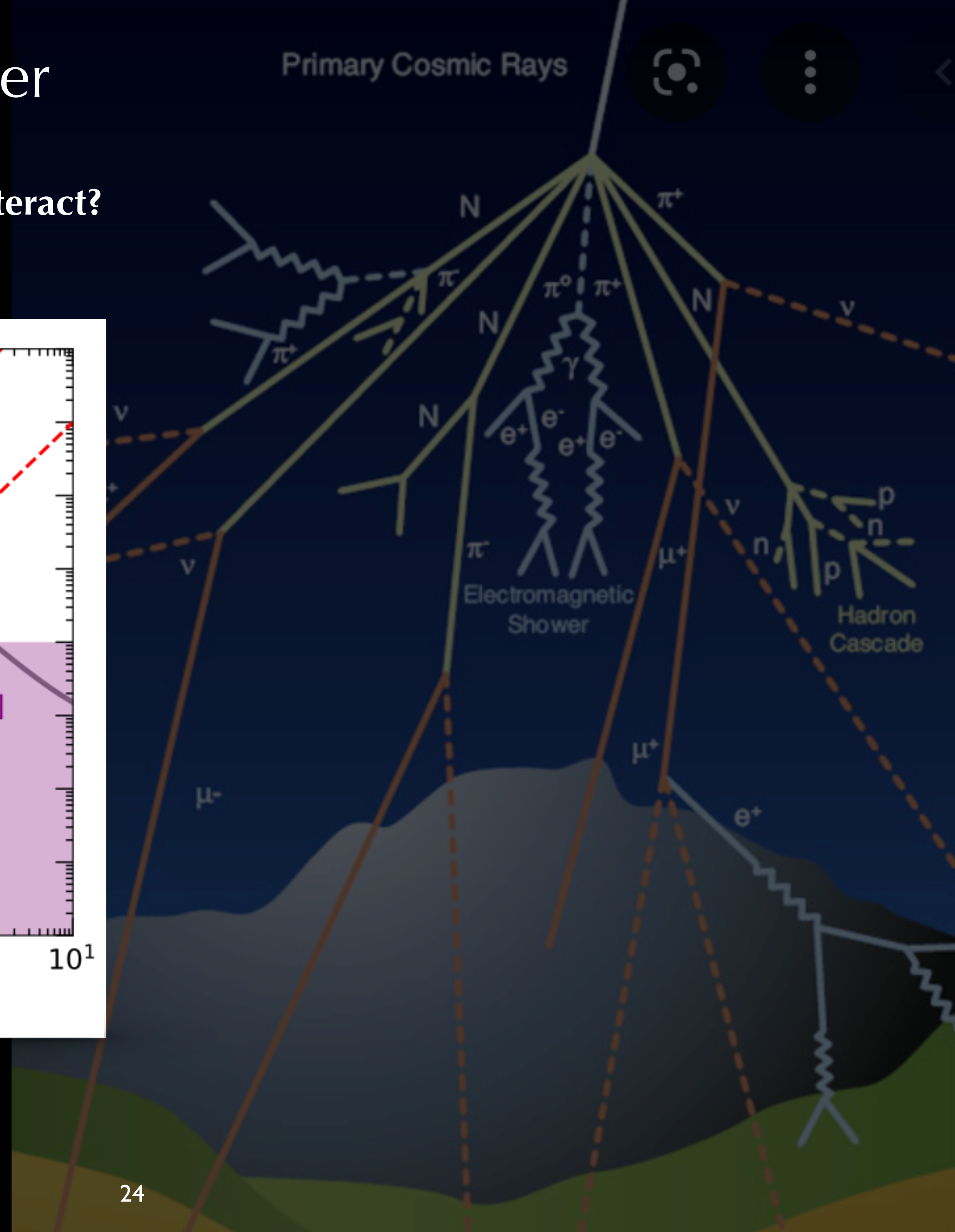


"Reverse Direct Detection"



Cosmic Rays / Dark Matter

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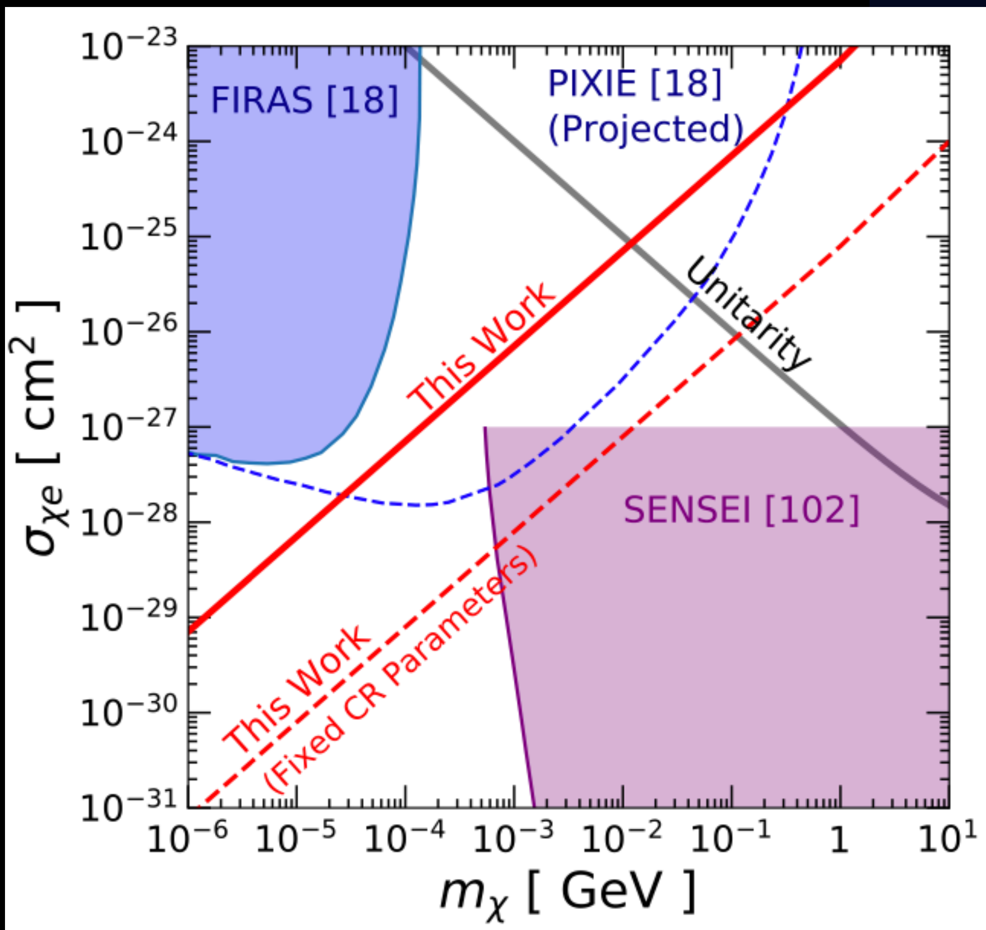
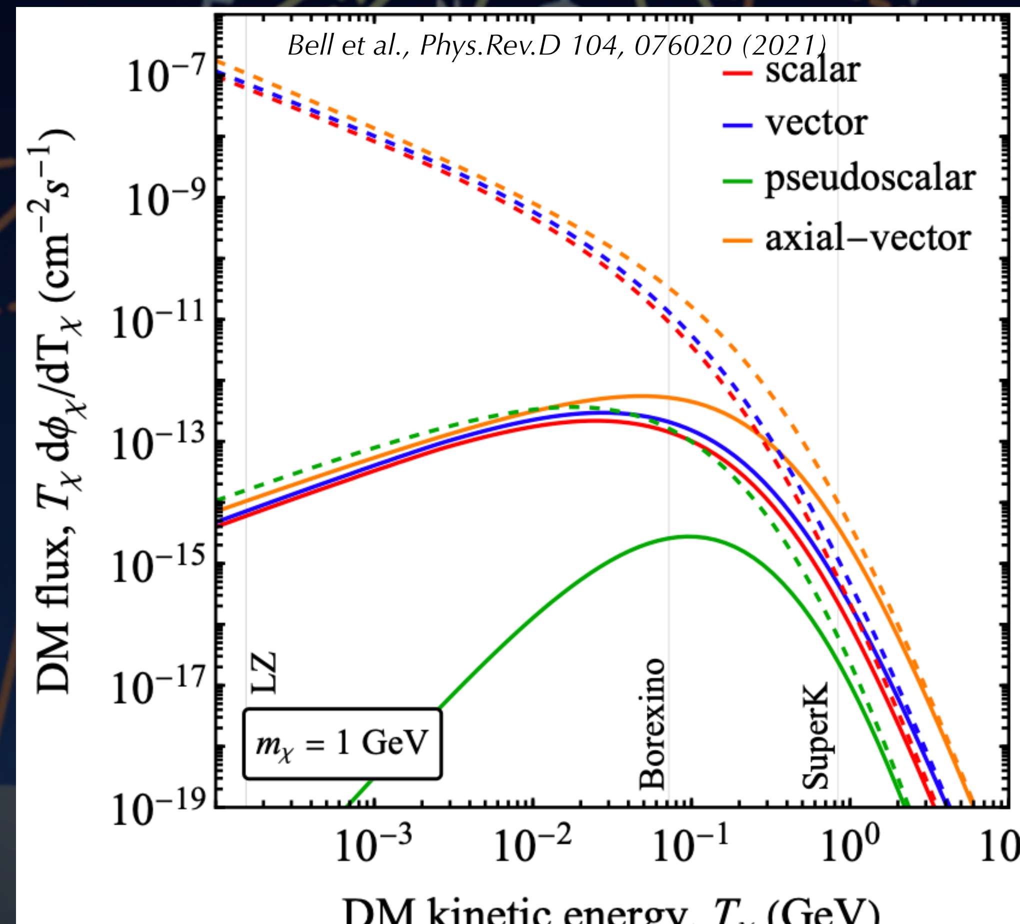


"Reverse Direct Detection"

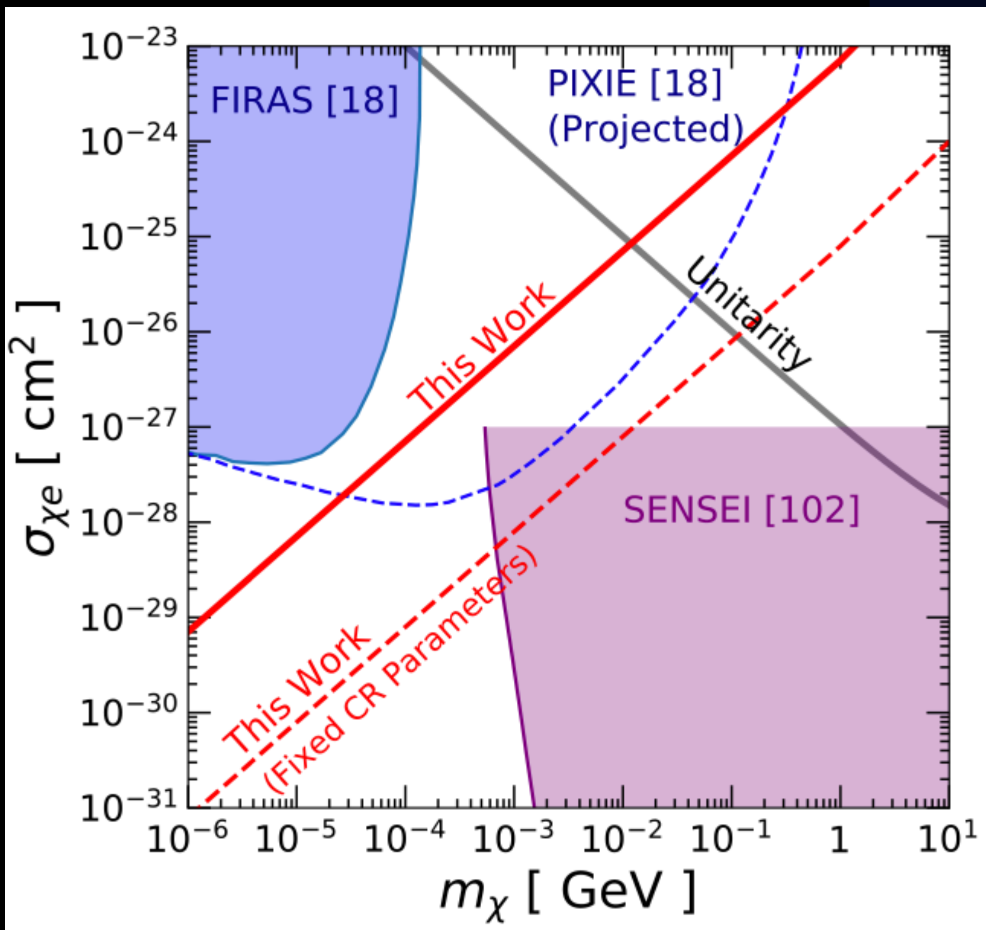
Dark matter "upscattering:"



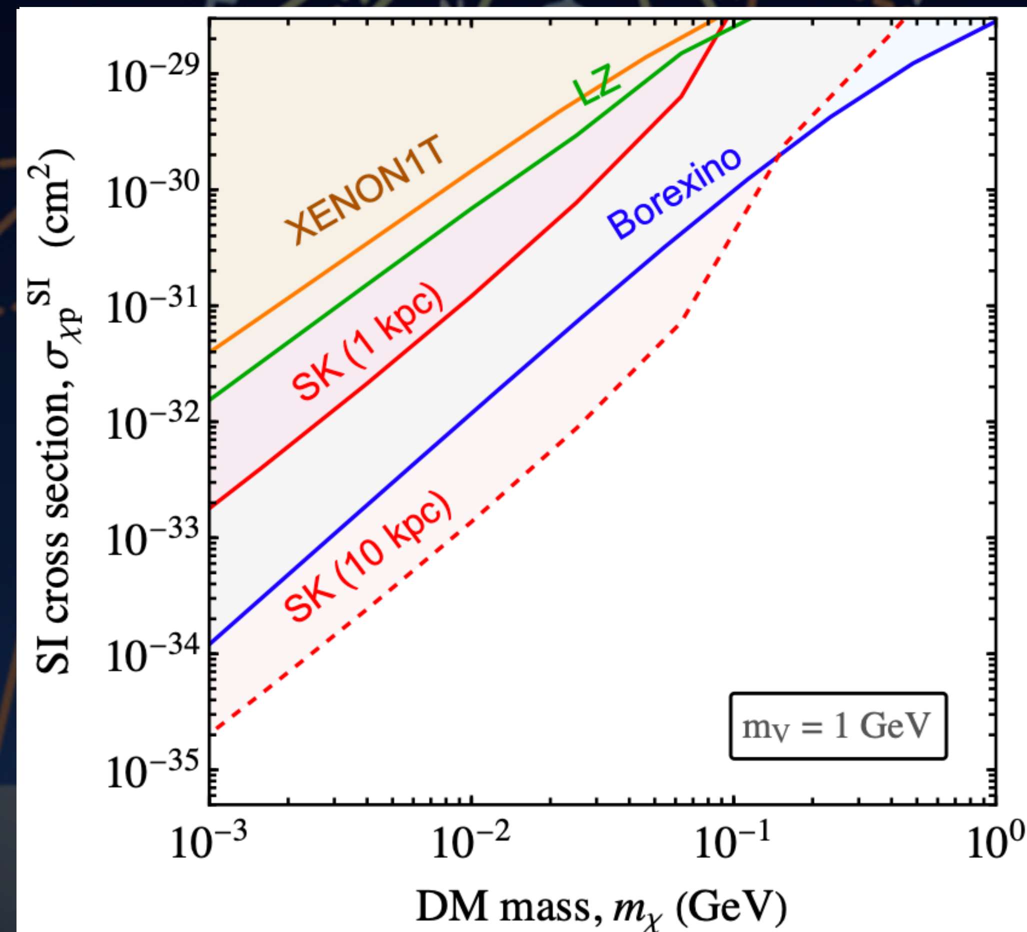
Cosmic Rays / Dark Matter

What if dark matter and cosmic rays interact?

Cosmic ray "downscattering:"

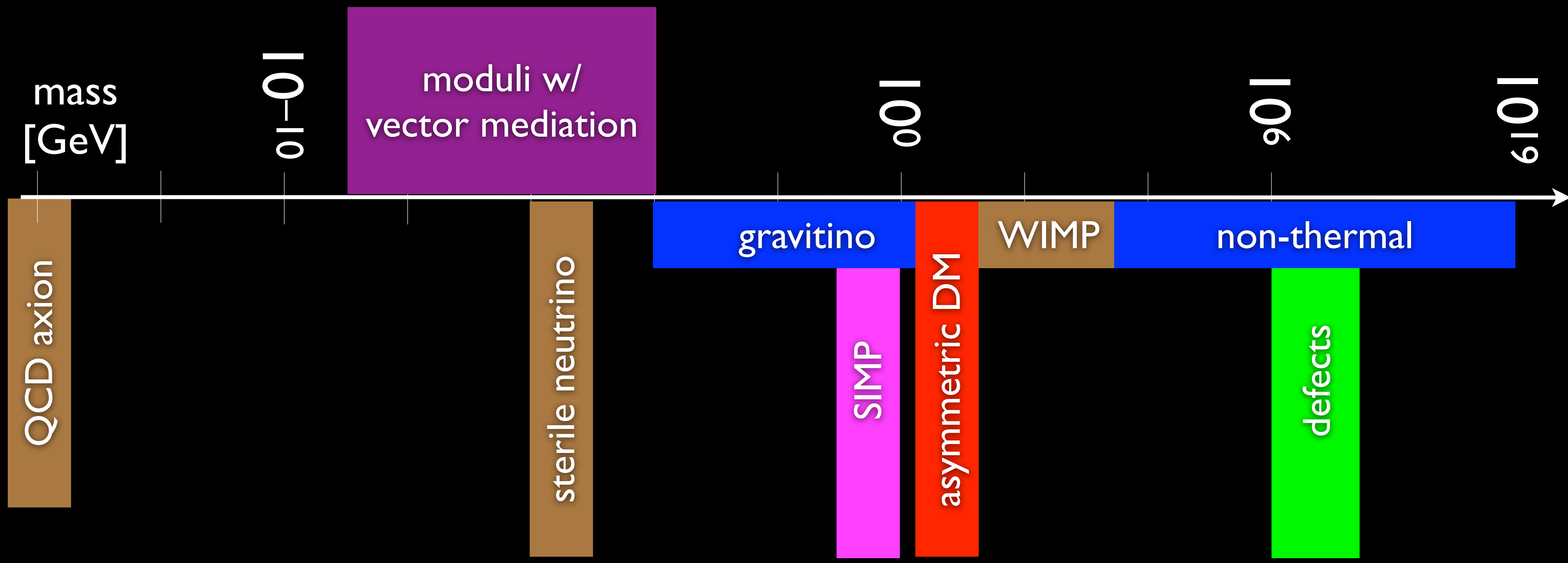


Dark matter "upscattering:"



"Reverse Direct Detection"

Direct Detection Beyond WIMPs



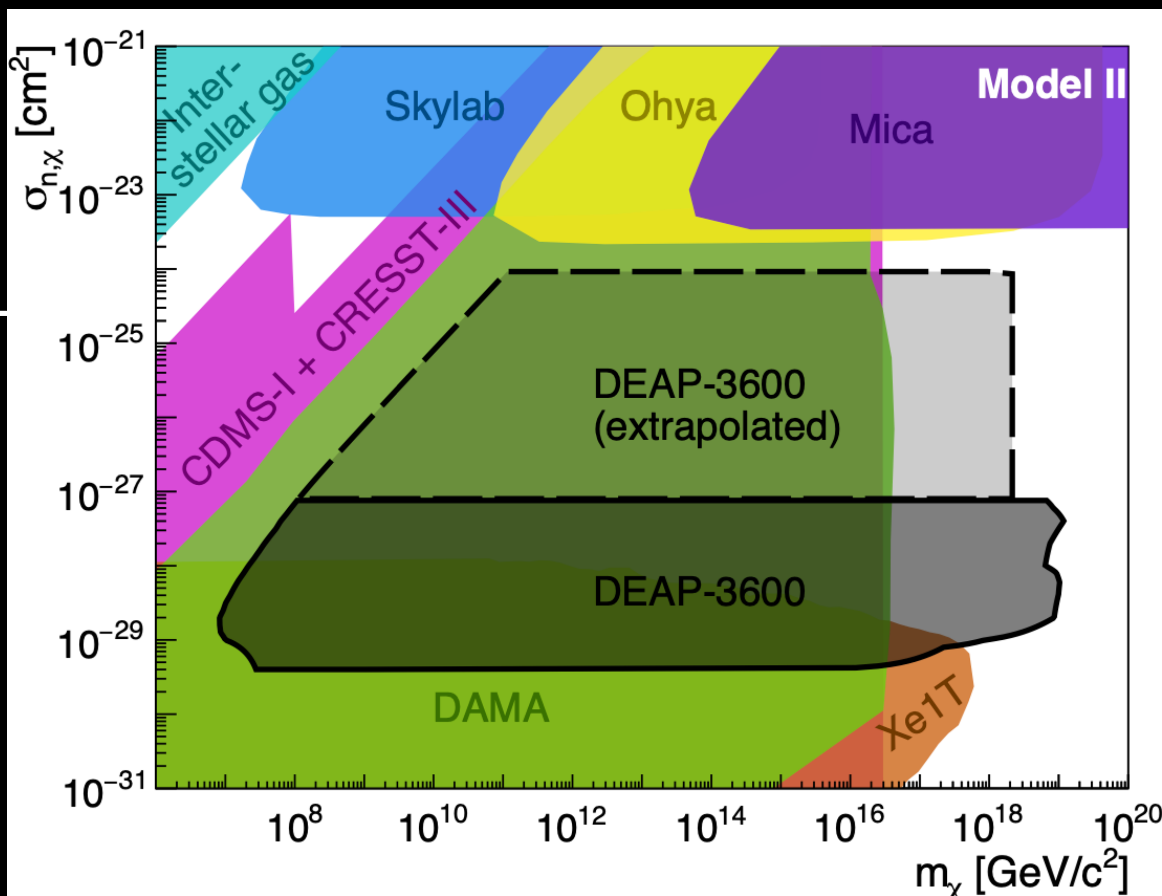
Direct Detection Beyond WIMPs

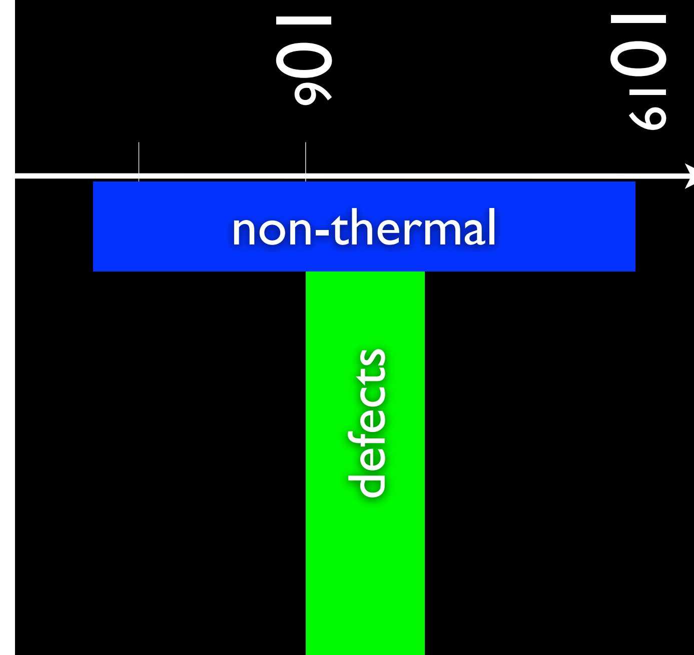
Planck-scale dark matter may be produced non-thermally in GUTs, primordial black hole radiation or extended thermal production in a dark sector

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

mass [GeV]

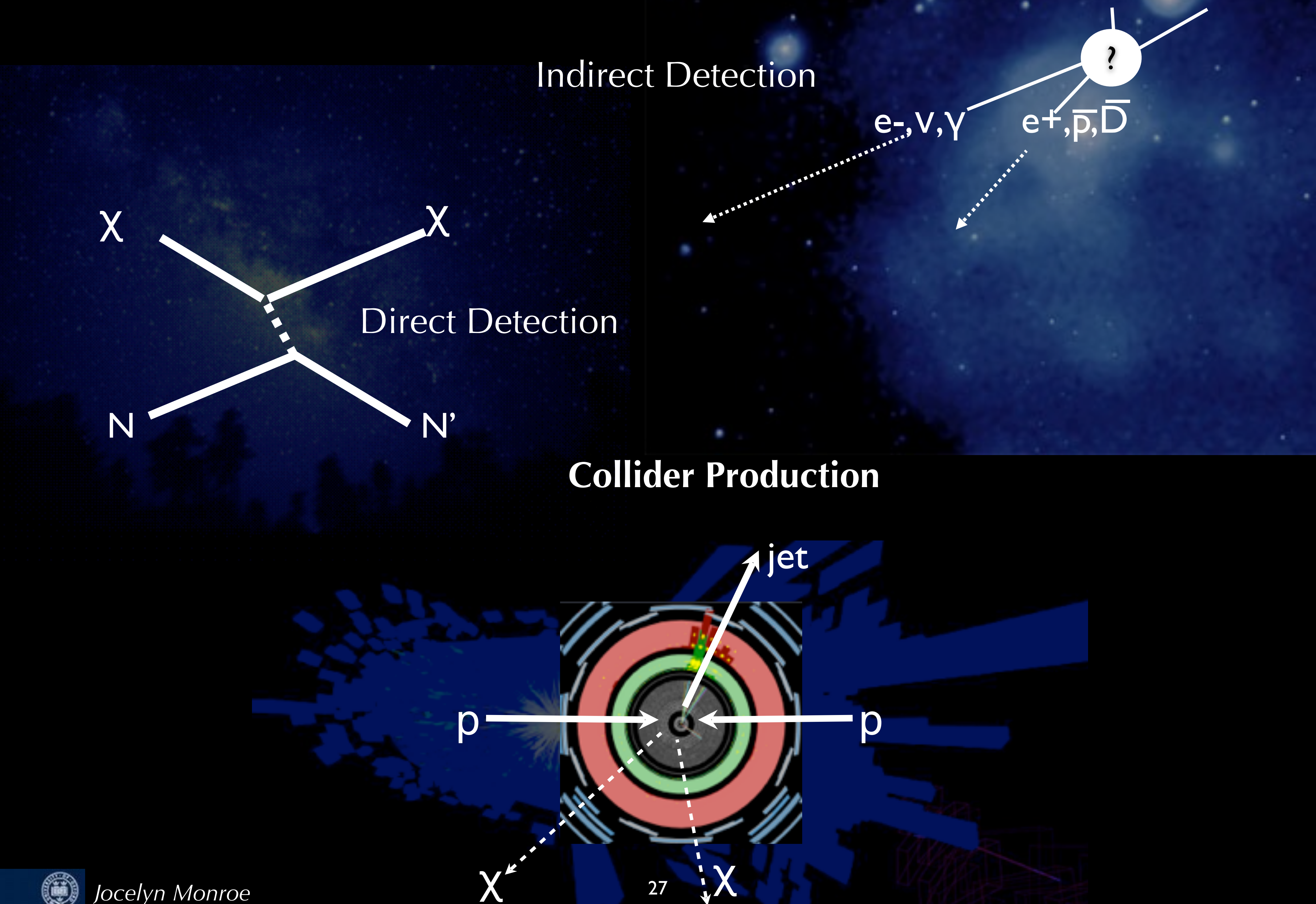
PRL 128 (2022) 1, 011801





Extrapolation: scales flux with n_χ and regions of m_χ consistent with null result

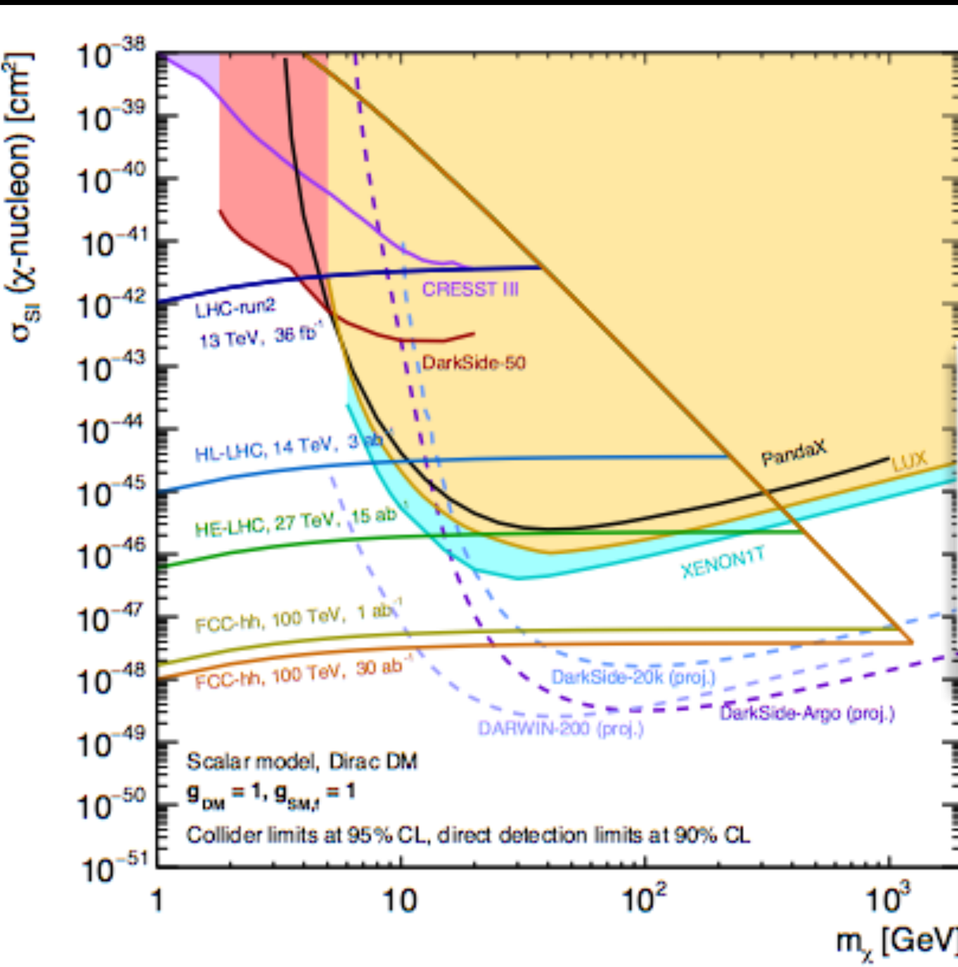
Experimentalist's View

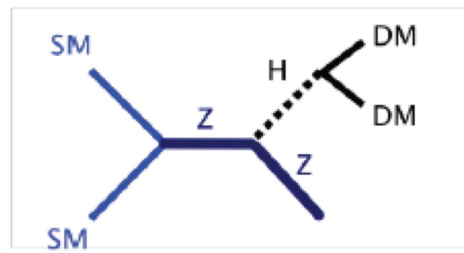


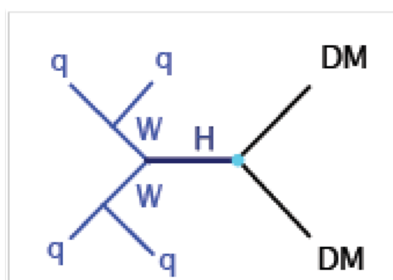
Complementarity with Direct Detection

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

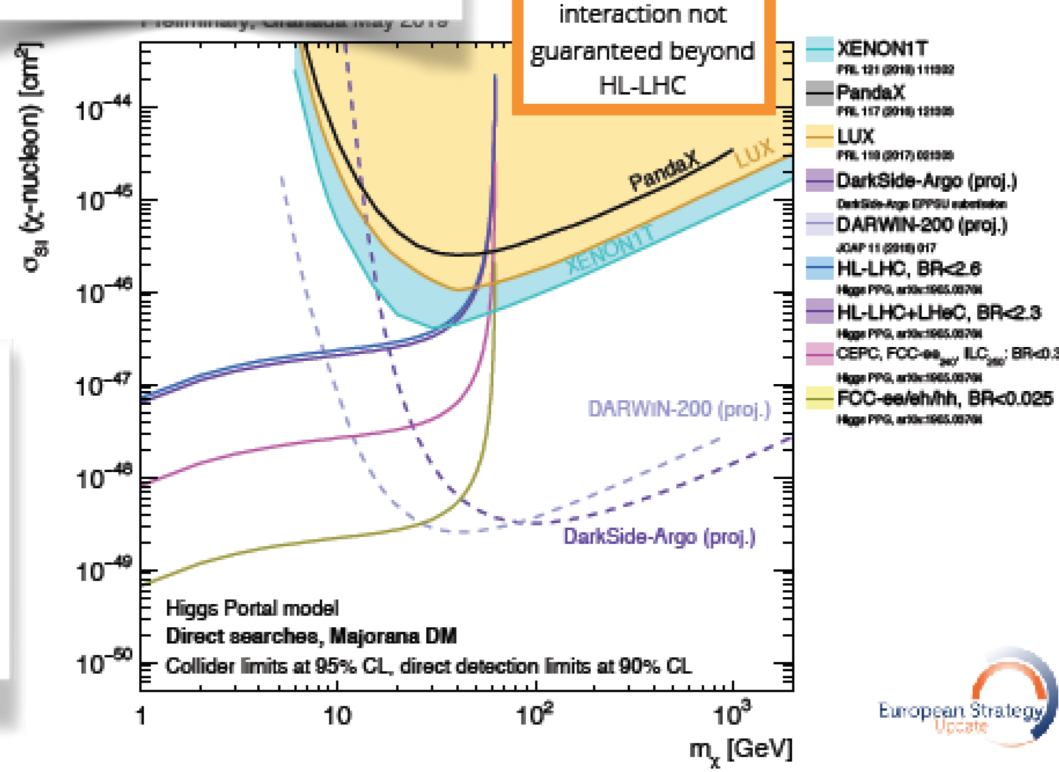
limits on branching ratio translated to limits on cross section vs. mass

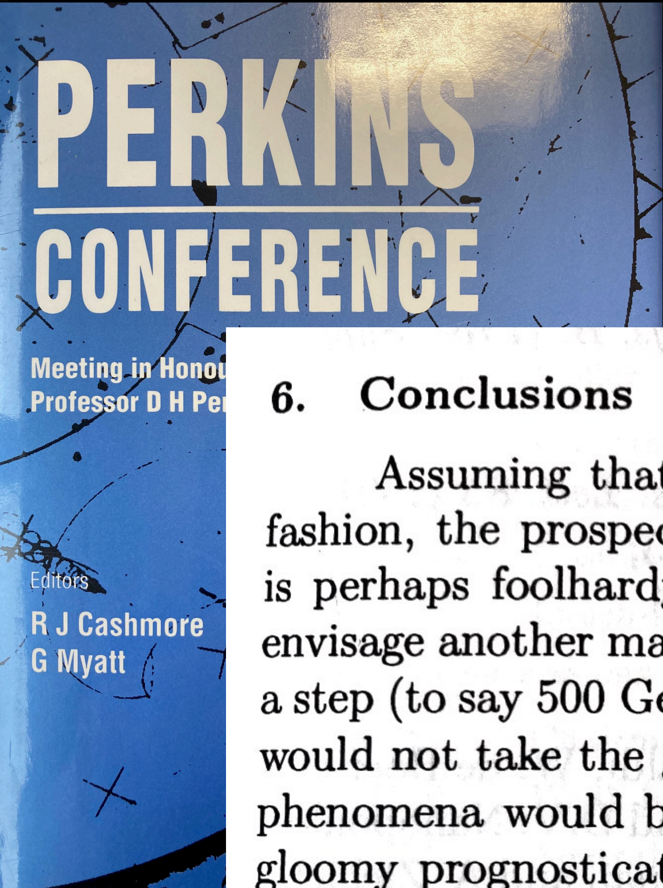






Caveat: EFT validity in Higgs-DM interaction not guaranteed beyond HL-LHC





Final Thought

"Particle Physics in the Future" C. Llewellyn Smith (1993)

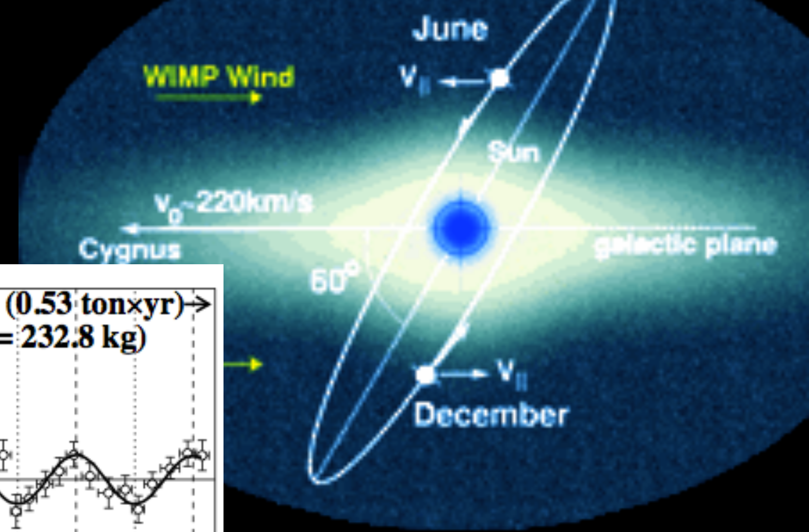
6. Conclusions

Assuming that the LHC is approved, and/or the SSC is completed in a timely fashion, the prospects for particle physics in the next twenty years are excellent. It is perhaps foolhardy to try to look further ahead, but it is currently very hard to envisage another major step with hadron colliders beyond LHC and SSC, or more than a step (to say 500 GeV) or two (to the TeV range) with electron–positron colliders (this would not take the gross reach beyond LHC and SSC, but the sensitivity to different phenomena would be complementary). It is of course very possible that these rather gloomy prognostications will suffer the same fate as similar predictions in the past, and be made to look absurd by future breakthroughs. If not, the long-term future of experimental particle physics may be with non-accelerator/cosmic-ray experiments, with which Don Perkins began his career. However, these experiments are likely to be focused more on problems in astrophysics and cosmology than on particle physics per se, a trend anticipated by Don who is currently working on just such an experiment.

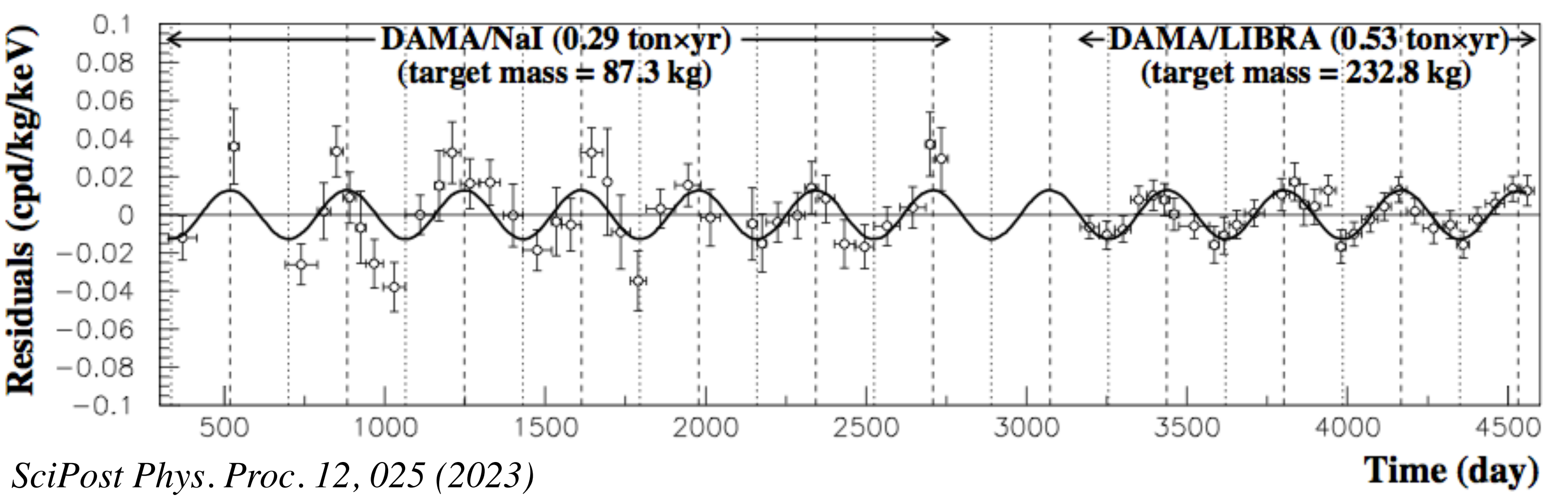
May Perkins' optimism for *"particles and radiations which bombard us from outer space … with new experimental discoveries being made on an almost daily basis"* continue to be justified!

Extra Slides

Annual Modulation Tests



predicted modulation A~0.02-0.1, t_0=152.5 days

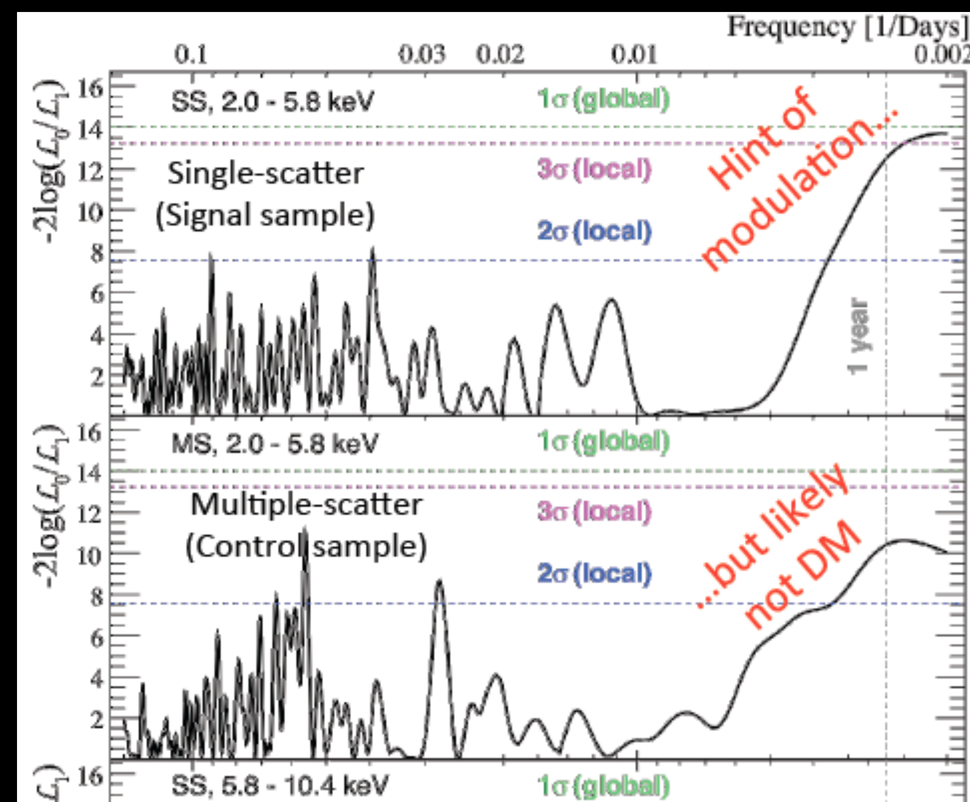


SciPost Phys. Proc. 12, 025 (2023)

DAMA/LIBRA: measure (0.0112±0.0012) cpd/kg/keV, t_0 = (144±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, 4.8σ exclusion of DAMA, test of leptophilic dark matter *arXiv:1507.07748*



Annual Modulation Tests

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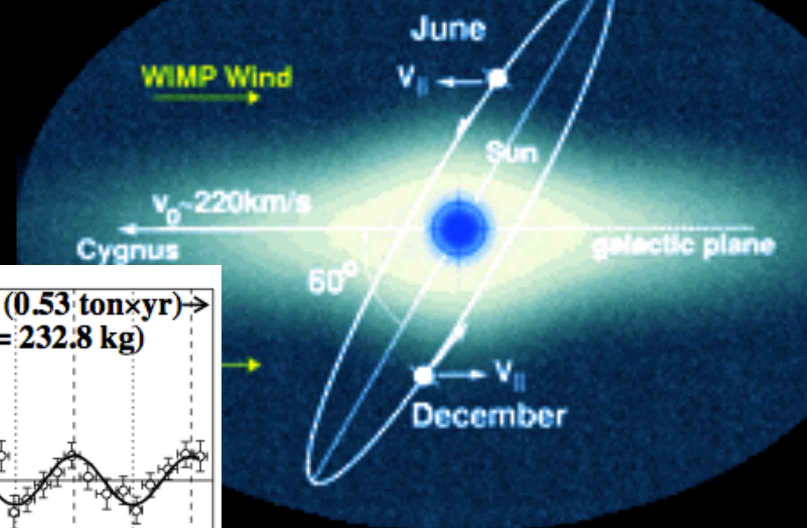

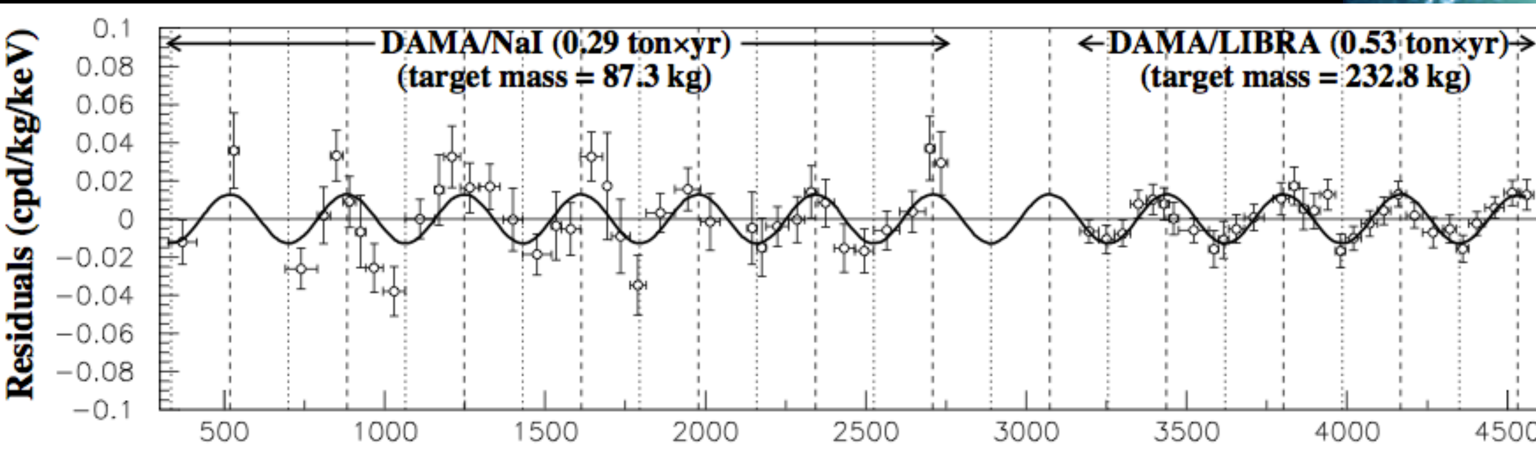

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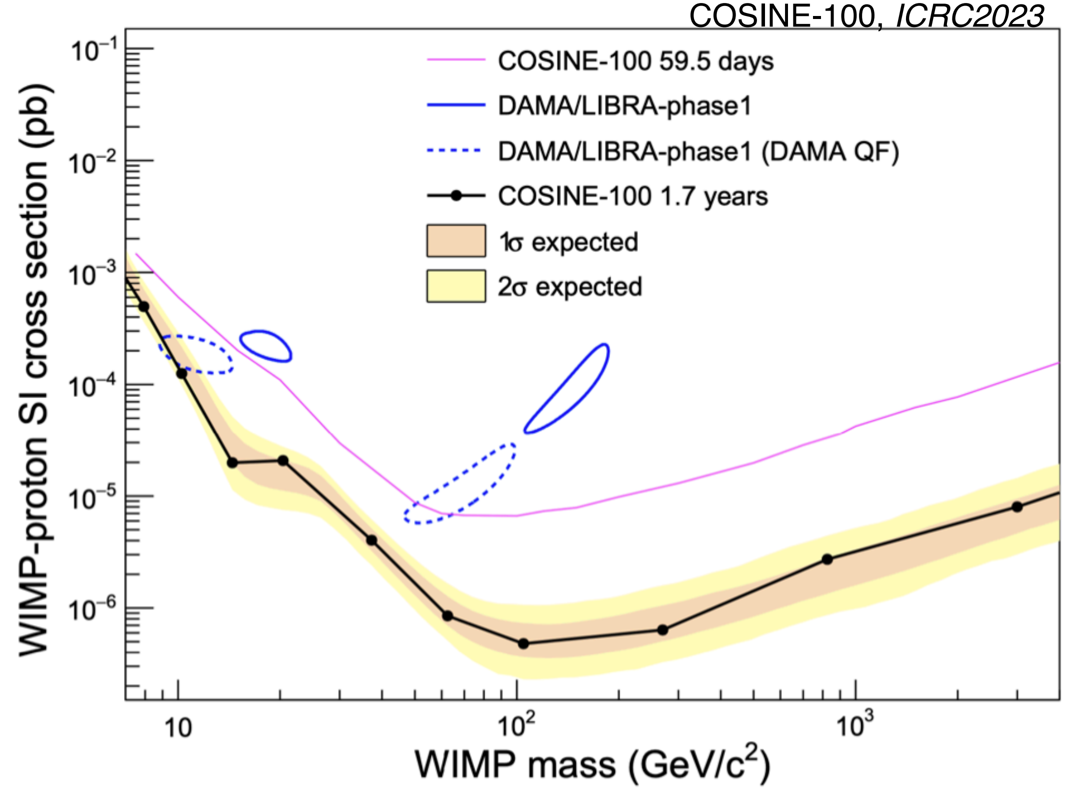
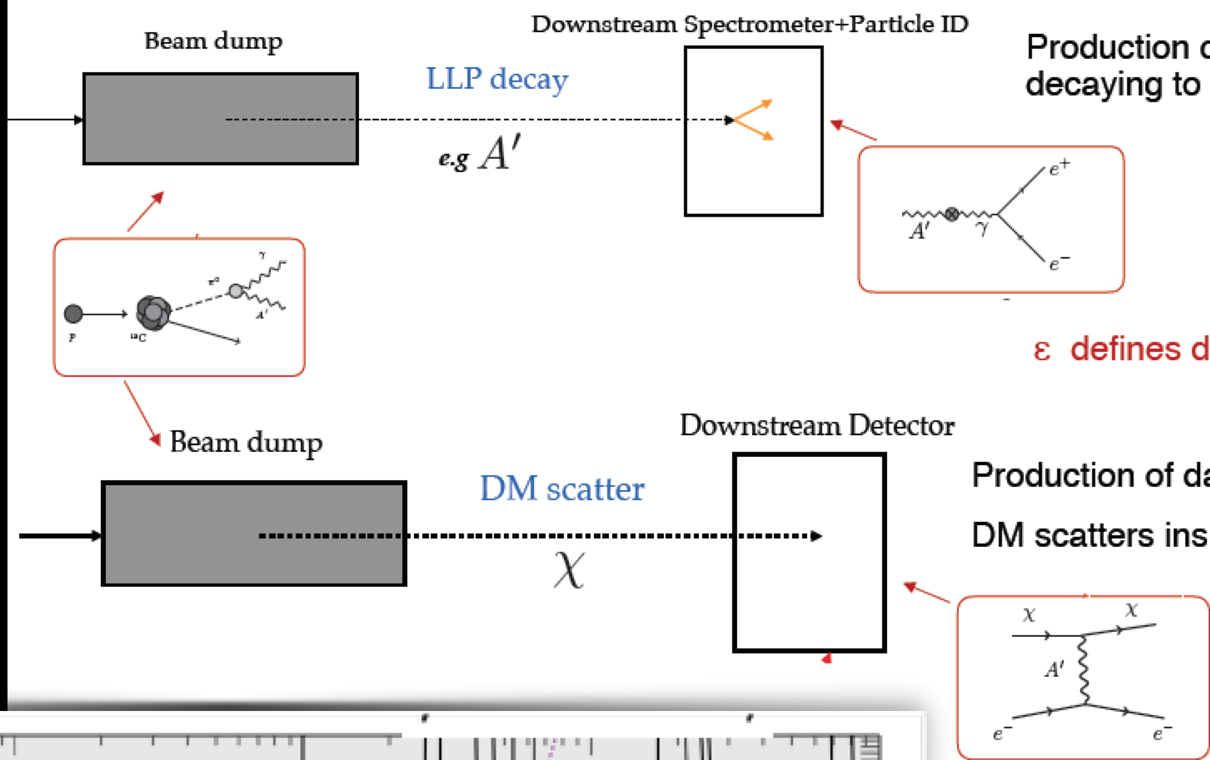
With the same target (different laboratories):
COSINE-100: no evidence of modulation
ANAIS: *PRD 103, 102005 (2021)*

COSINE-100, *ICRC2023*



Fixed-Target Strategies

Renaissance of the fixed-target!



Production of long-lived dark particle decaying to SM particles

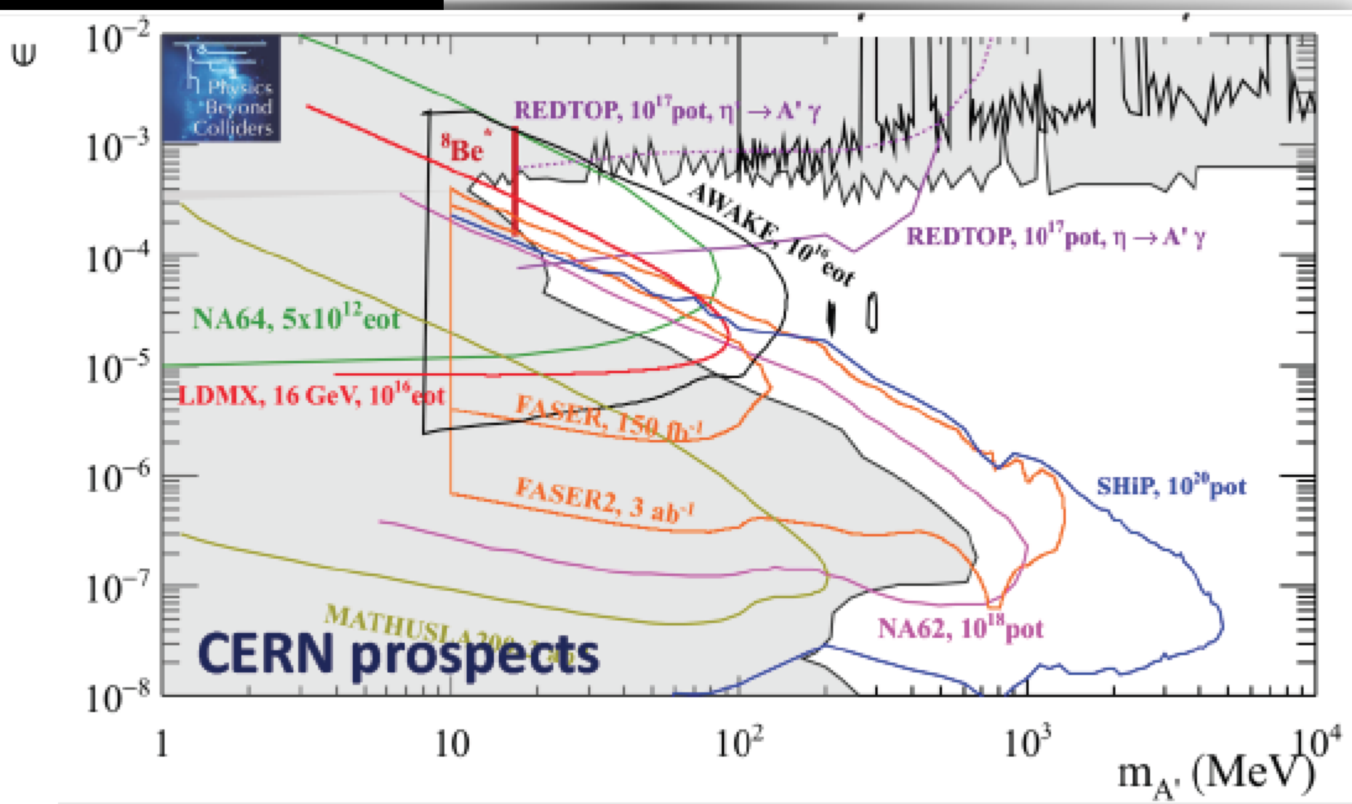
Rate ~ ε^4

ε defines dark photon- photon mixing

Production of dark particle decaying to DM pair.

DM scatters inside the detector

Rate ~ ε^4



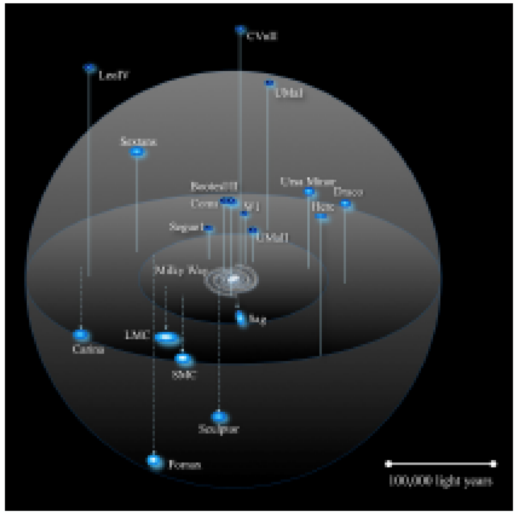
Many new experiments planned or proposed for hidden sector searches.

Major synergistic topic of Dark Sectors work at CERN.

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

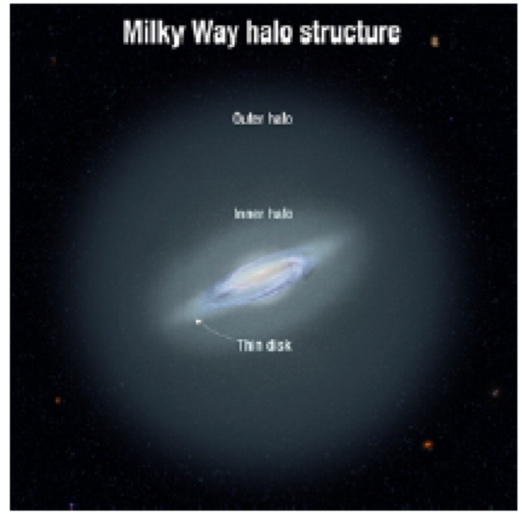
Gravitational Detection Strategies

Dwarf galaxies



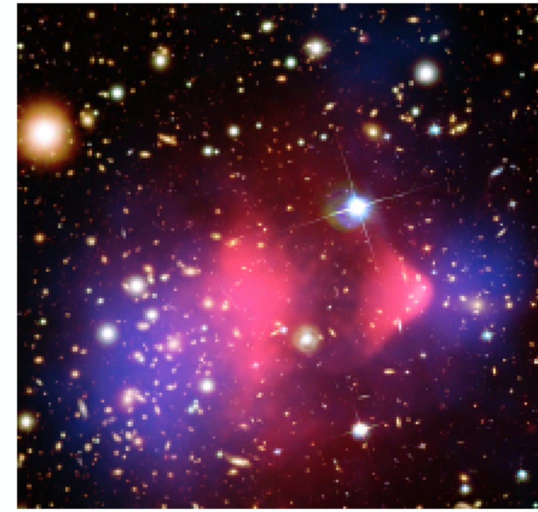
"B-factory" (v~30 km/s)

MW-like galaxies



"LEP" (v~200 km/s)

Clusters



"LHC" (v~1000 km/s)

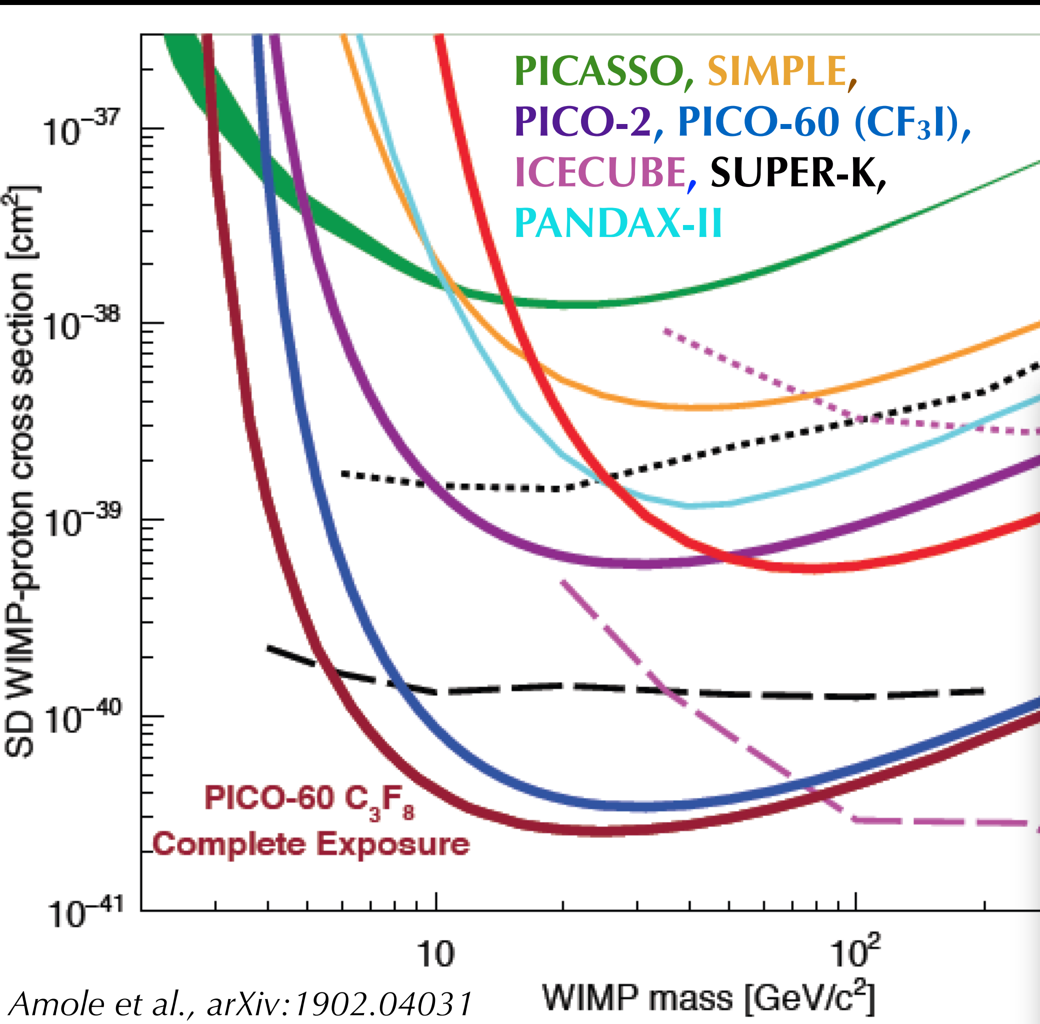
Observations on all scales

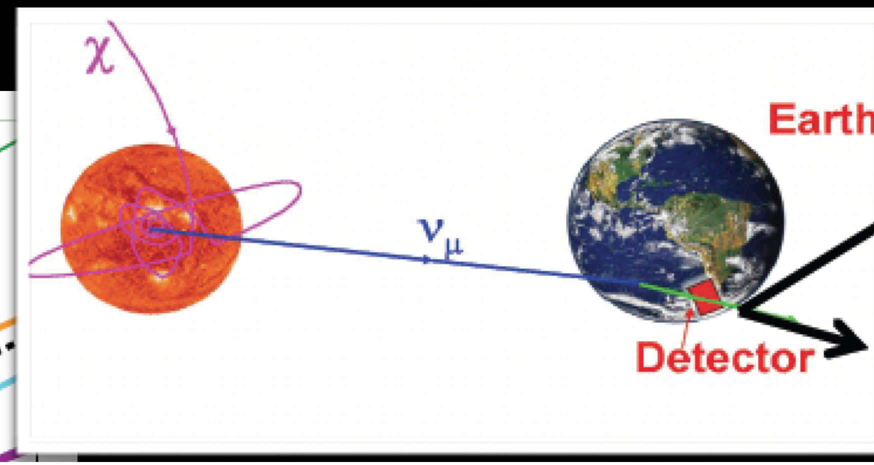
Self-scattering kinematics →

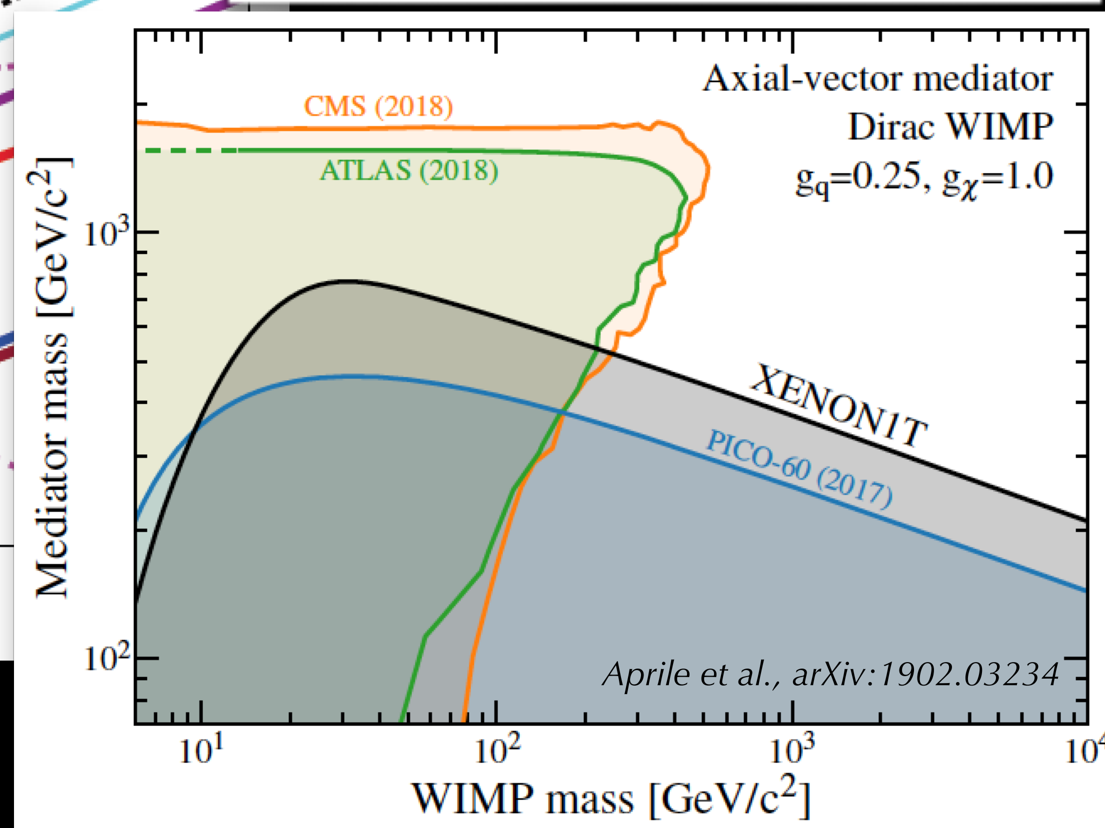
Measure particle physics parameters σ_χ, m_χ, m_ϕ

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.

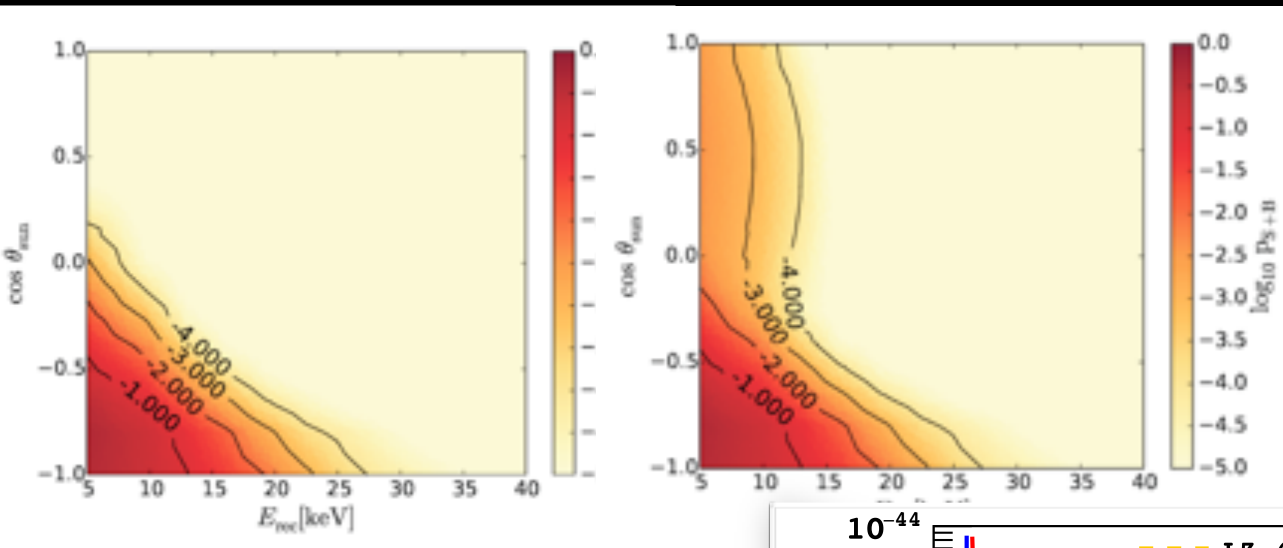






Direct Detection: Is the Neutrino Bound the End? No.

- sensitivity scales with sqrt(time) instead of linearly in time (with zero background)



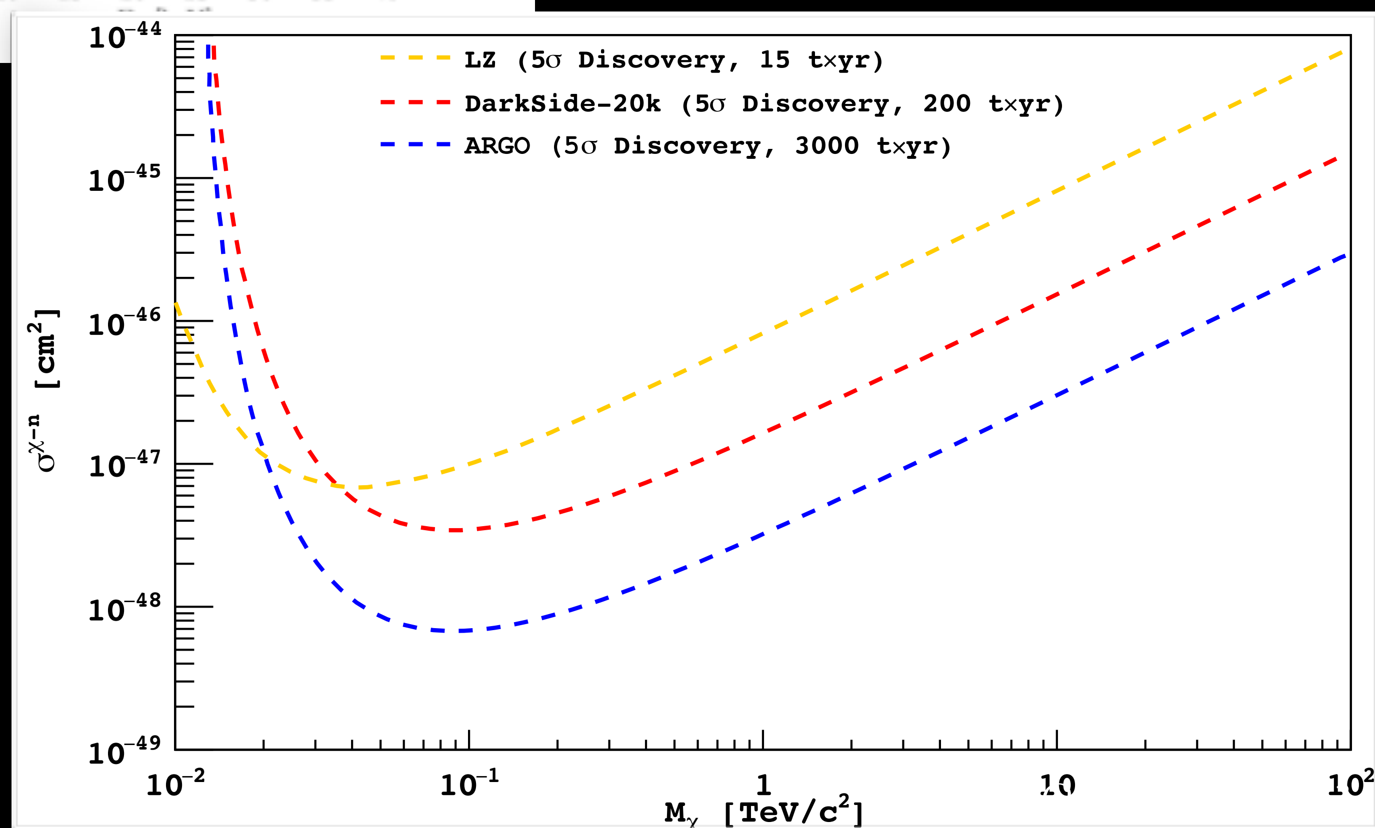
(energy, angle, time) of neutrino background vs. DM signal differ.

- no ν bound for directional detectors

Grothaus, Fairbairn, JM, Phys.Rev.D90 (2014)

A ν background paradigm…
for non-directional detectors

the discovery reach depends on ν flux errors *and* on ν-e discrimination.



Jocelyn Monroe