Physics Highlights and Challenges: Astroparticle Physics

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Royal Holloway, University of London

1st Joint ECFA-NuPECC-ApPEC Seminar
Fundamental Laws of the Universe in Orsay
October 14, 2019

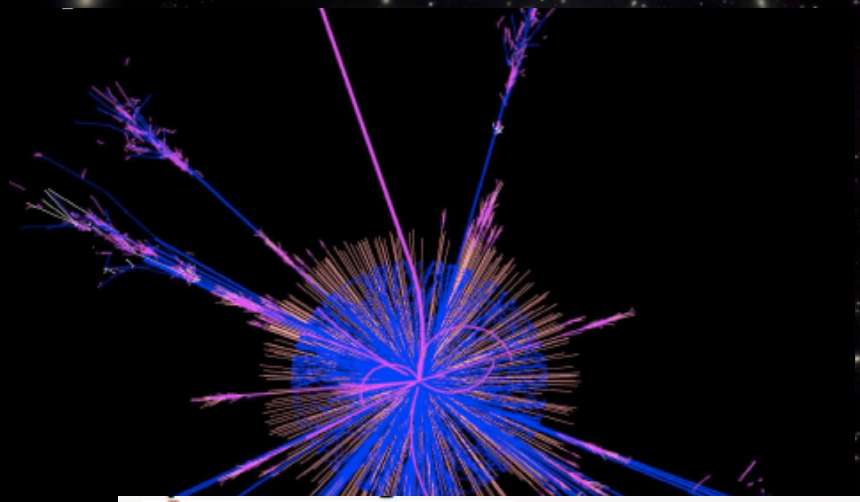
Science AAAS

#1: What is the universe made of?

FUTURE OF PHYSICS - THE 25 QUESTIONS

KAVLI ITP

1. How did the universe begin?
2. What is the nature of the dark matter that permeates the universe?



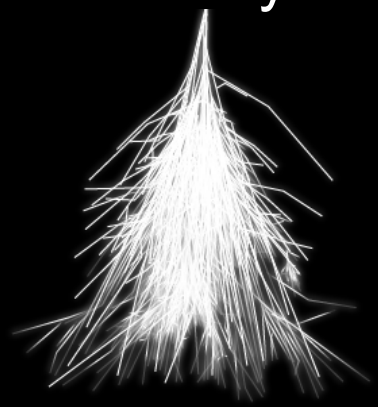
Associated Press
updated 5:15 p.m. ET, Sun., Aug. 12, 2007

Whoever discovers the nature of dark matter would solve one of modern science's greatest mysteries and be a shoo-in for the Nobel Prize.

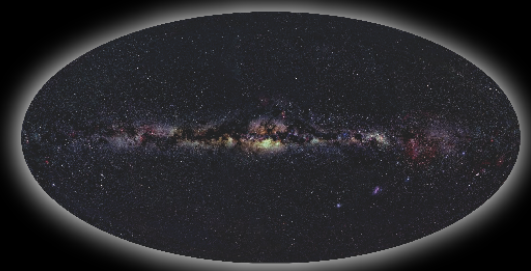
UK Particle Physics Roadmap

this talk:
*highlights, challengies, synergies in the context of dark matter**

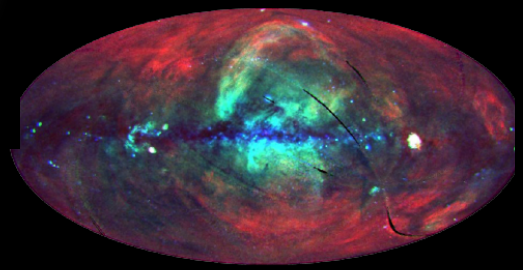
cosmic rays



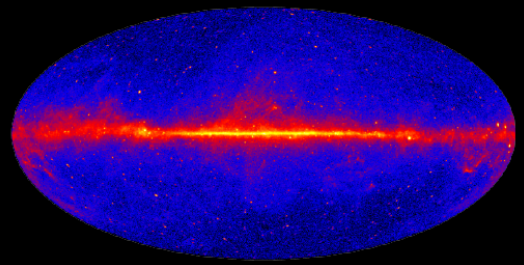
infrared/optical



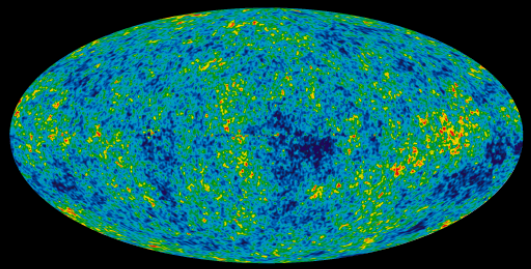
X-rays



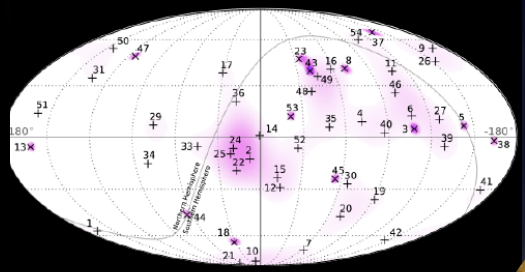
gamma-rays



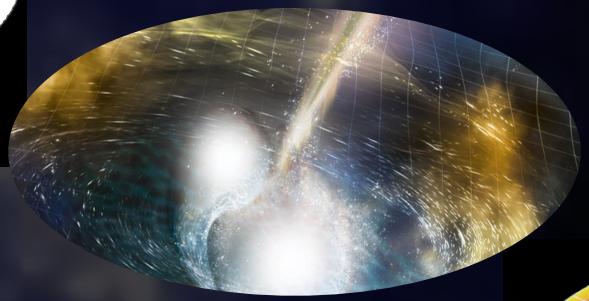
radio/microwave



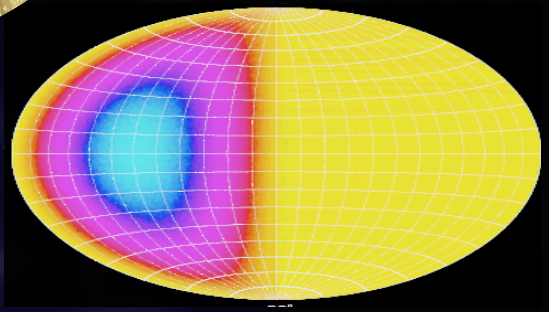
neutrinos



gravitational waves

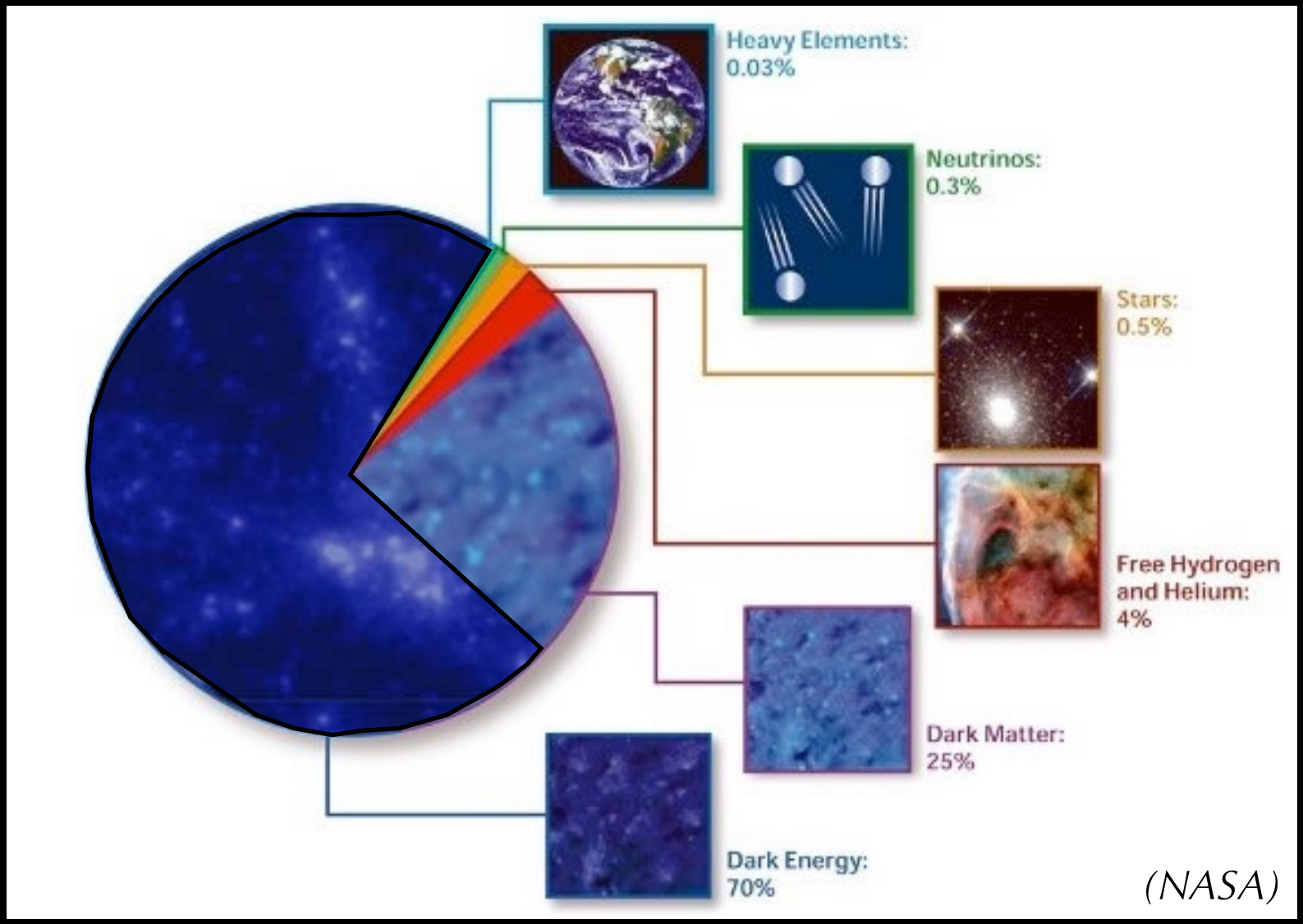


dark matter?



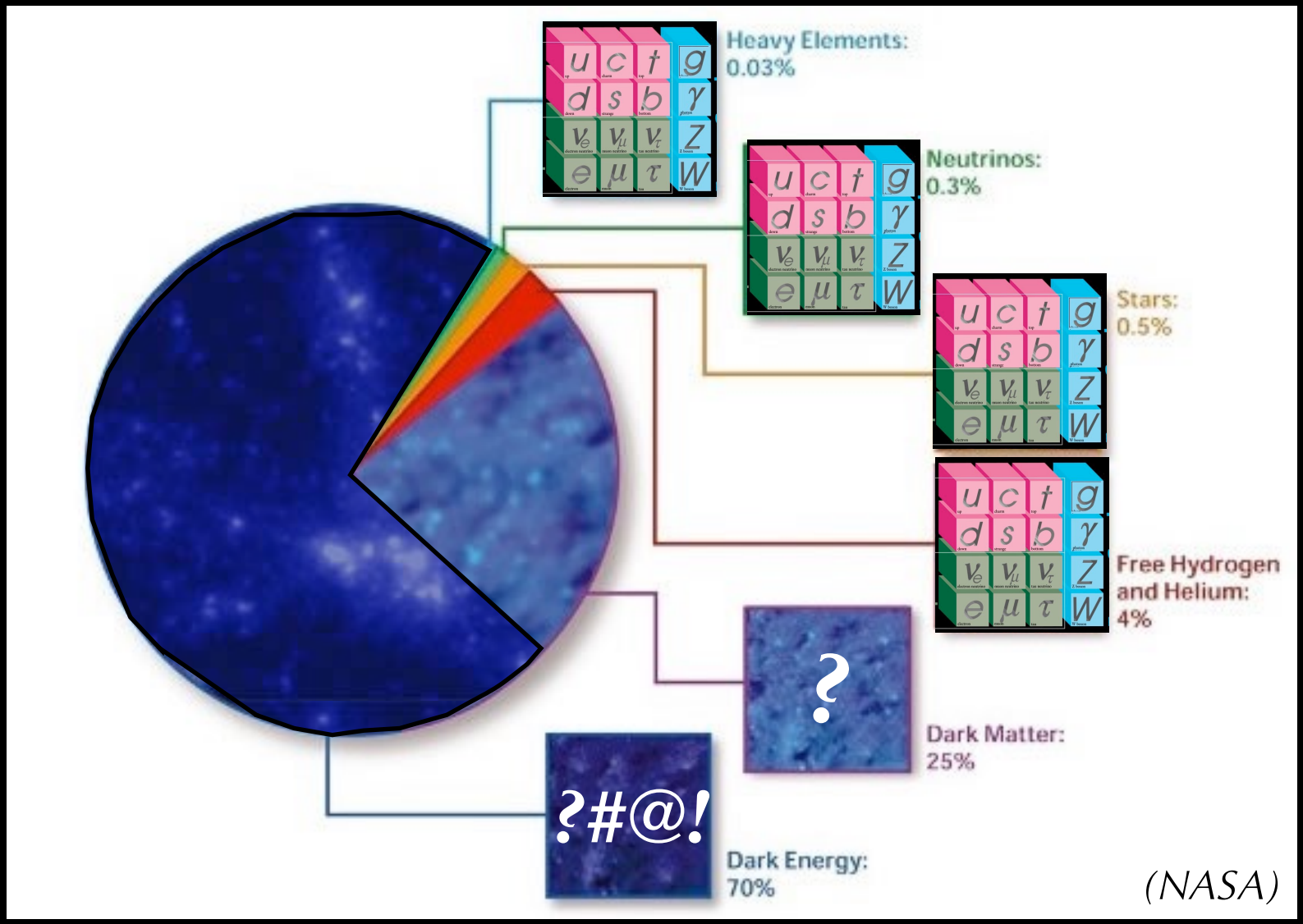
The tools of astroparticle physics probe the largest and smallest distance scales in the universe…

The Standard Model of Cosmology



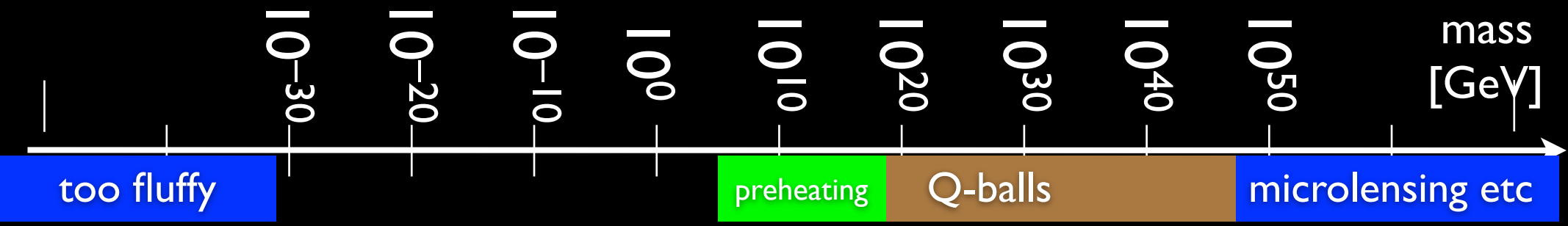
(NASA)

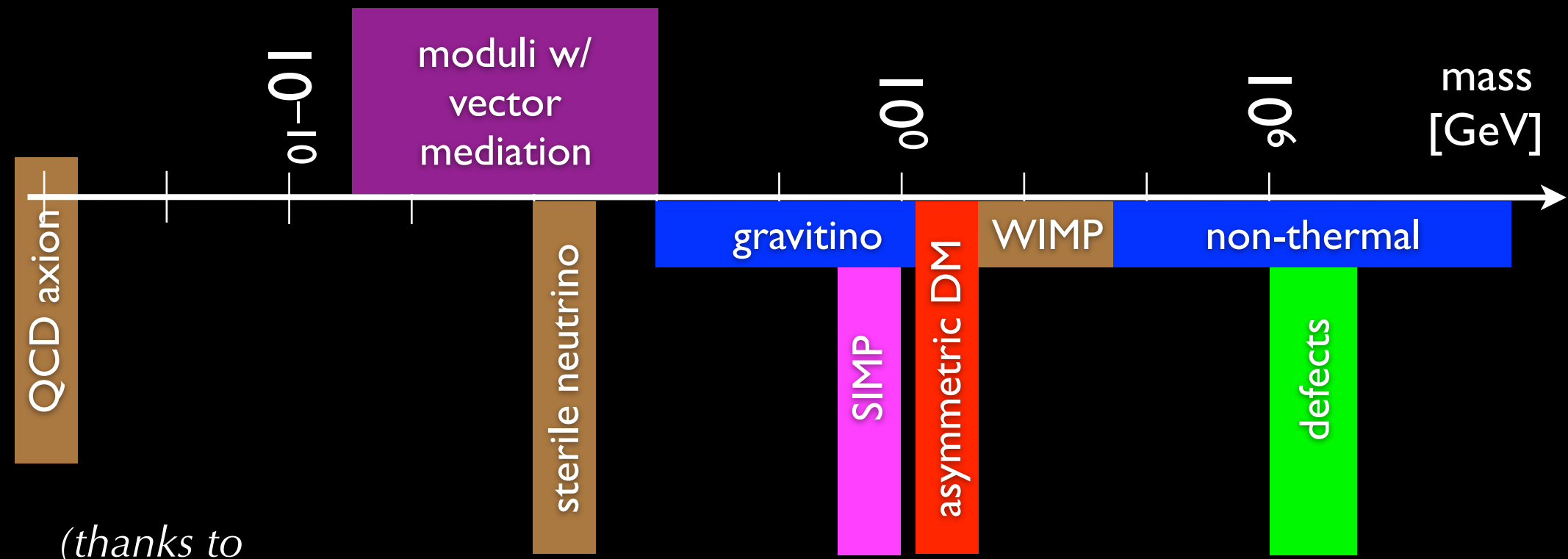
The Standard Model of Cosmology



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

Dark Matter Model Space: Theorist's View





(thanks to H. Murayama)

Big Questions for the Dark Sector

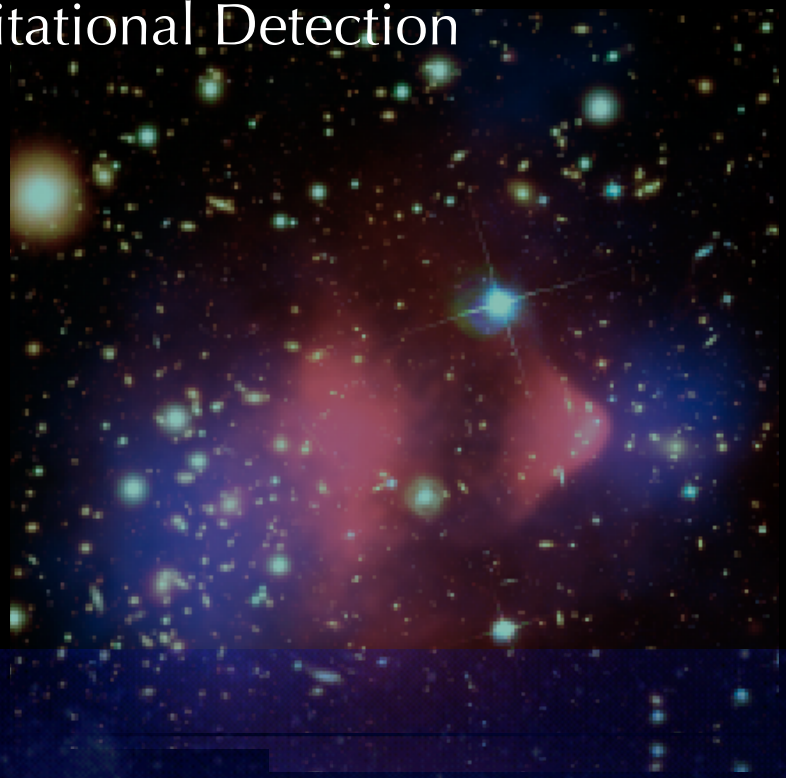
(a la European Strategy for Particle Physics Update 2019)

1) How do we search for dark matter, depending on its properties?

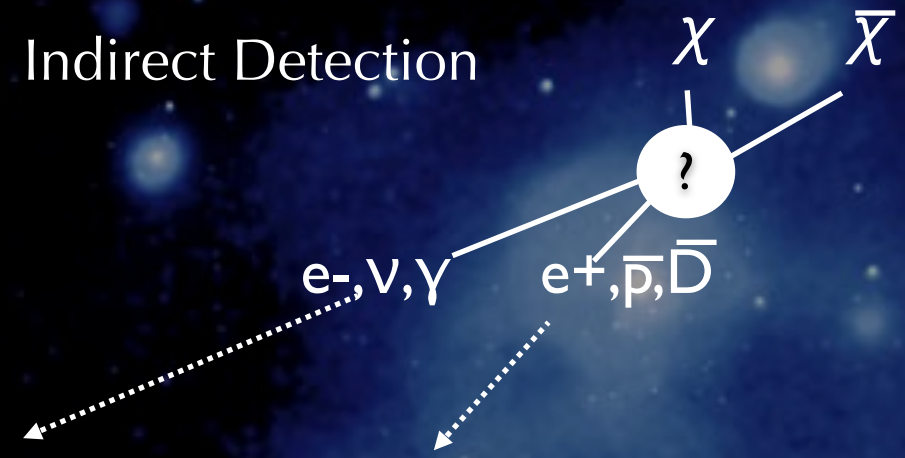
2) What are the highlights and challenges of the experimental programs, current or near-future, that address different regions of parameter space?

3) How can dark matter detection experiments inform/guide energy and intensity frontier experiments, and vice versa?

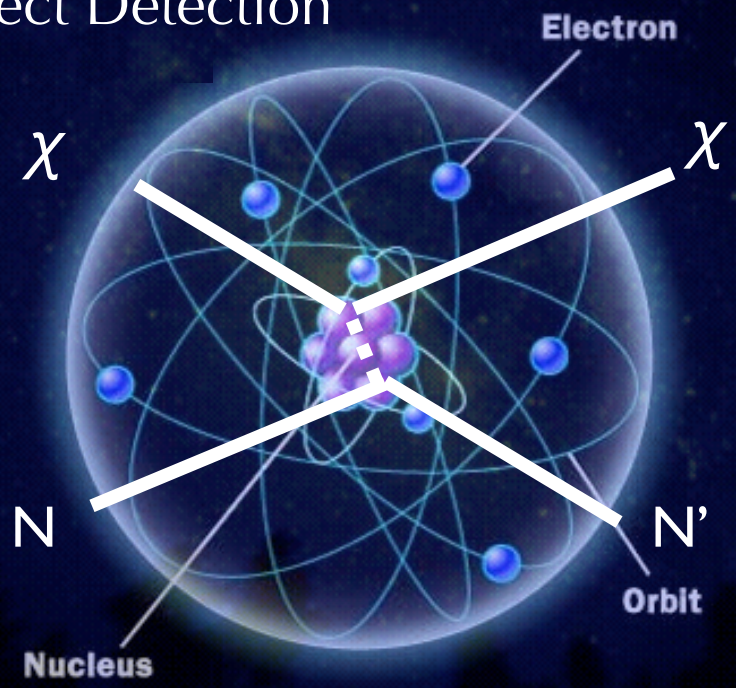
Gravitational Detection



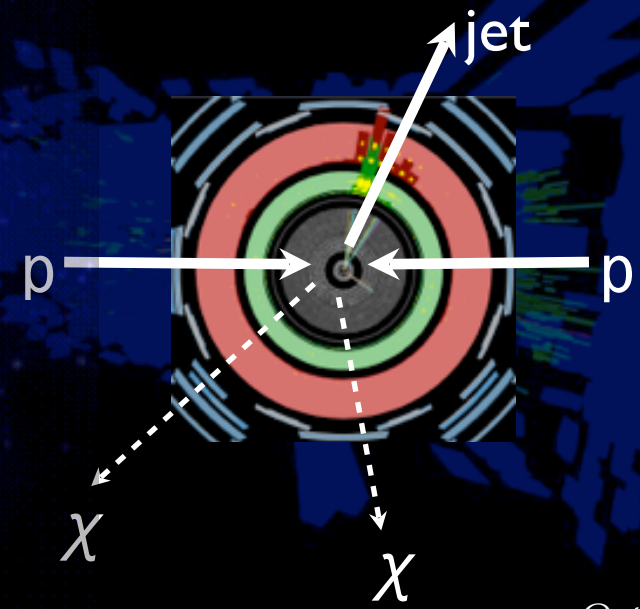
Indirect Detection



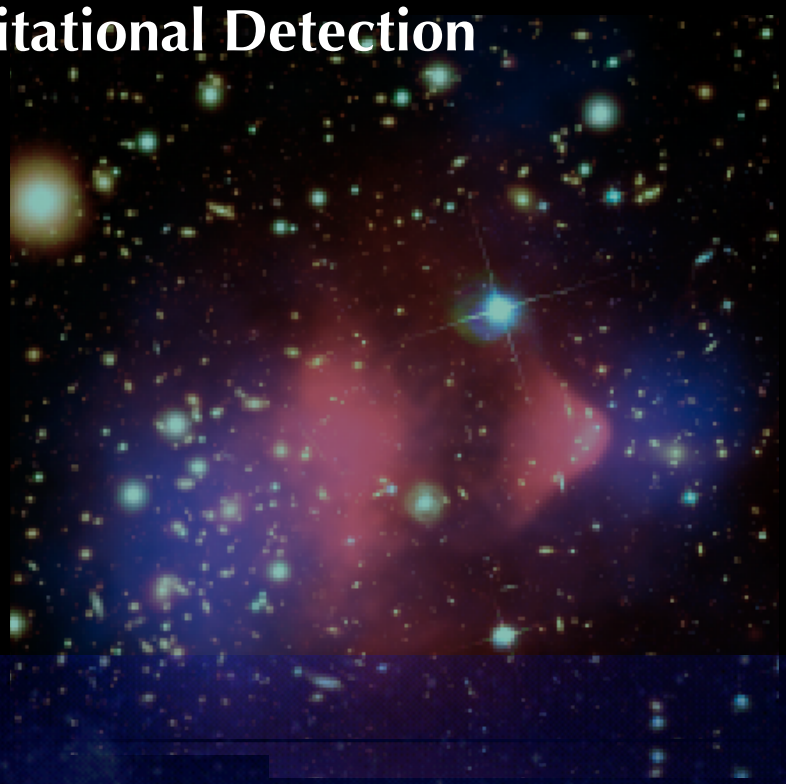
Direct Detection



Accelerator Production



Gravitational Detection



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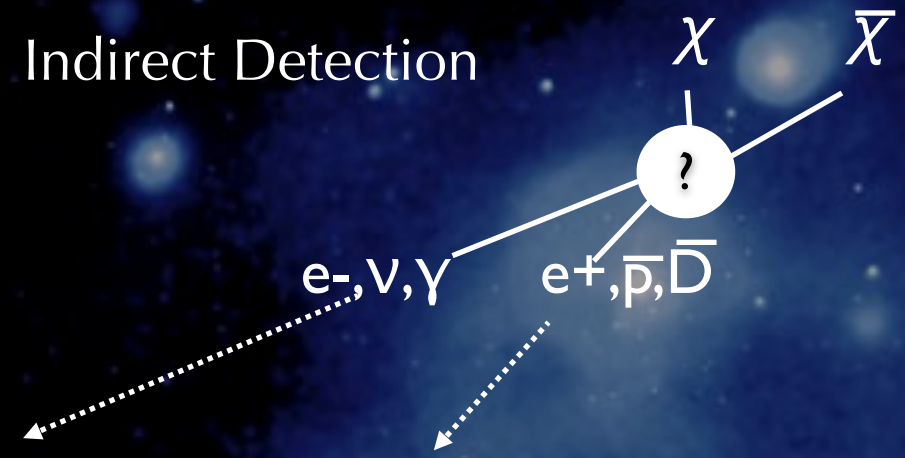
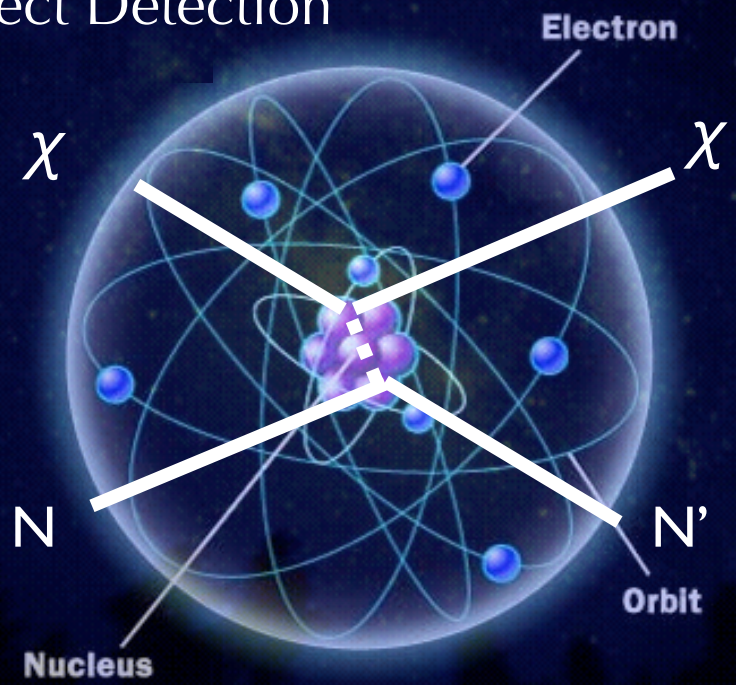
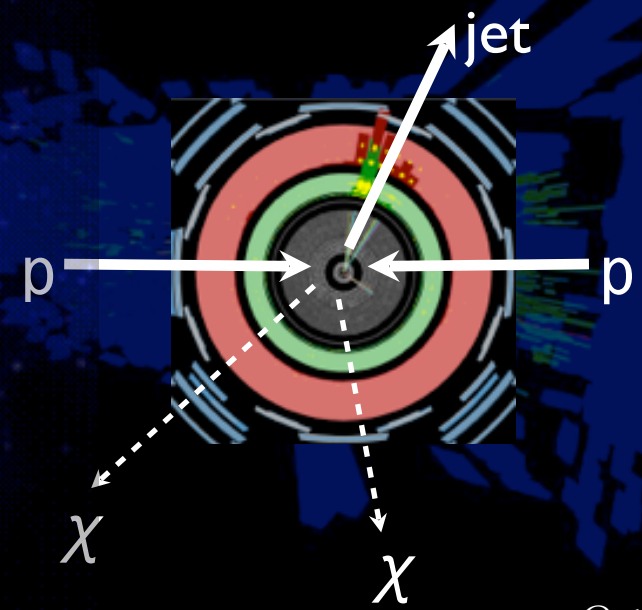


Direct Detection



Accelerator Production

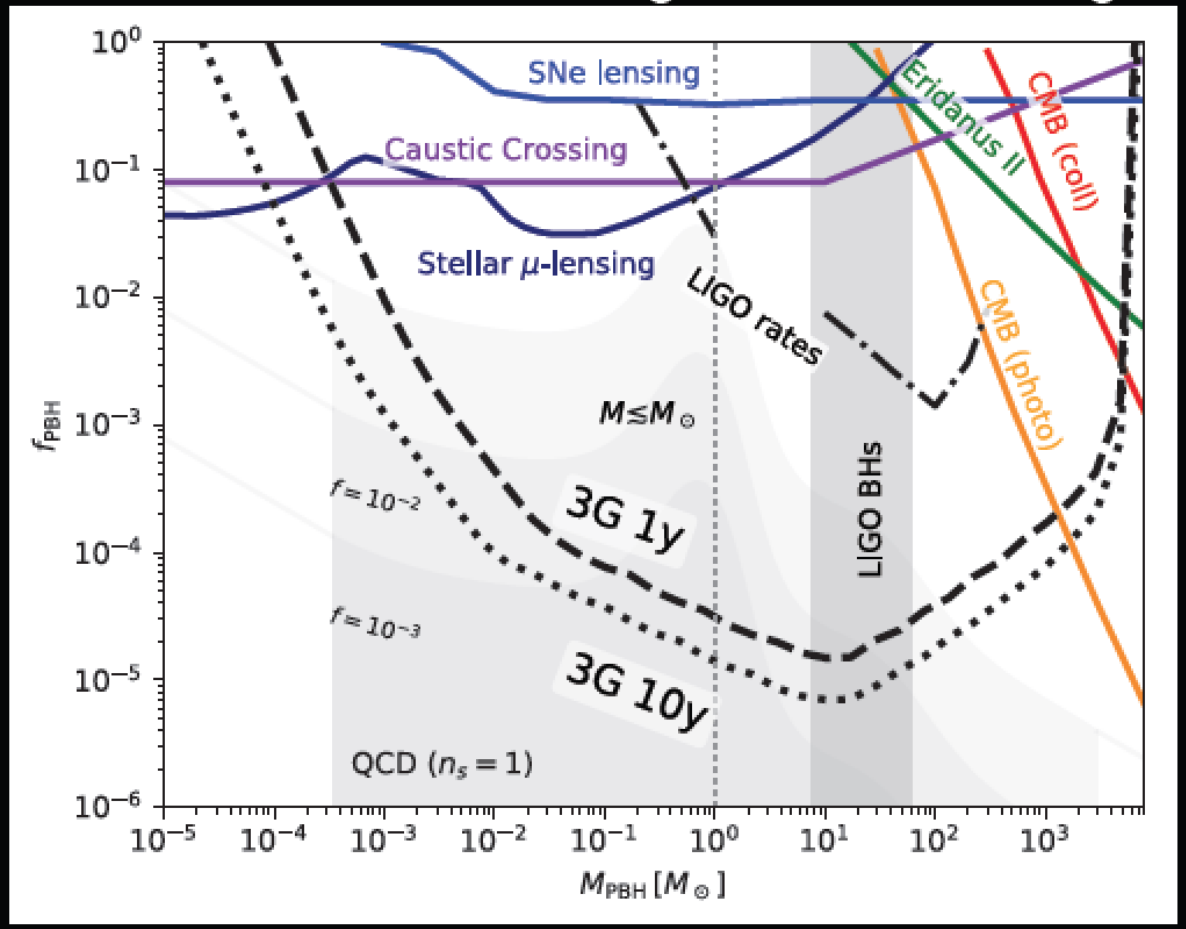


Detection of Gravitational Waves: PBH?

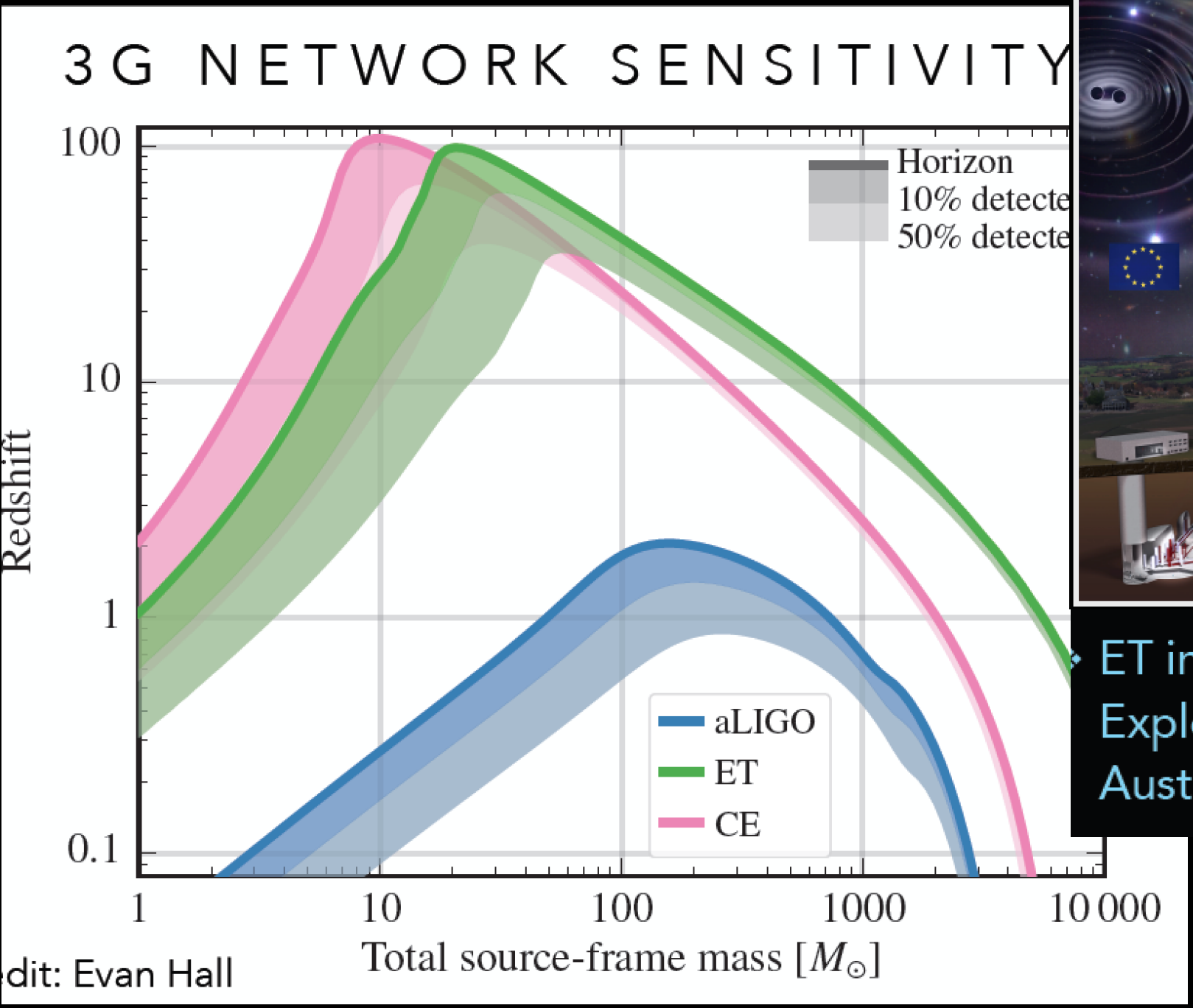
PRIMORDIAL BLACK HOLES AS DARK MATTER

- sub-solar black holes cannot form by stellar evolution
- must be primordial in origin
- 3G detectors can probe existence of light black holes

Credit:Miguel Zumalacarregui

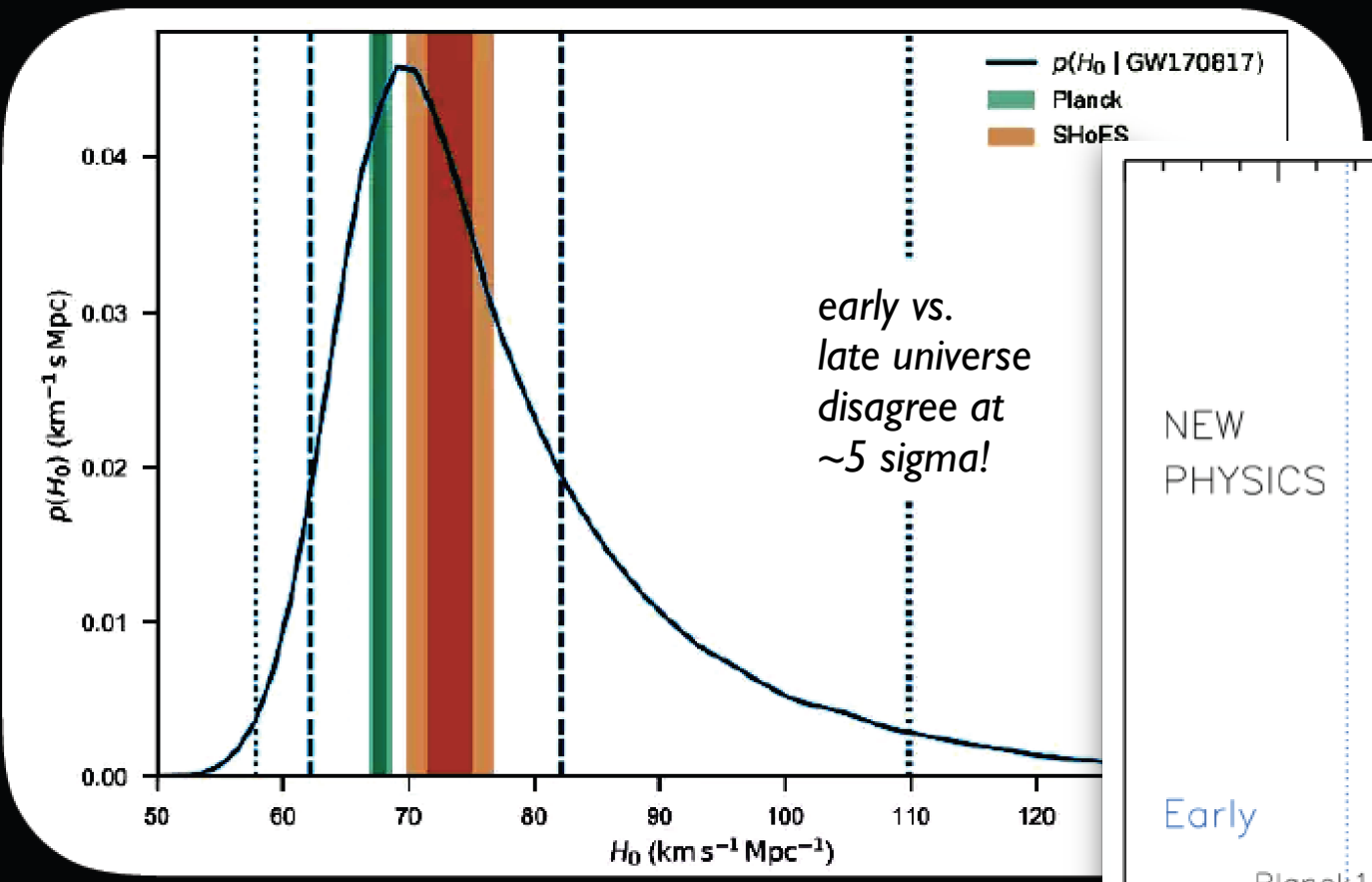


Future Prospects



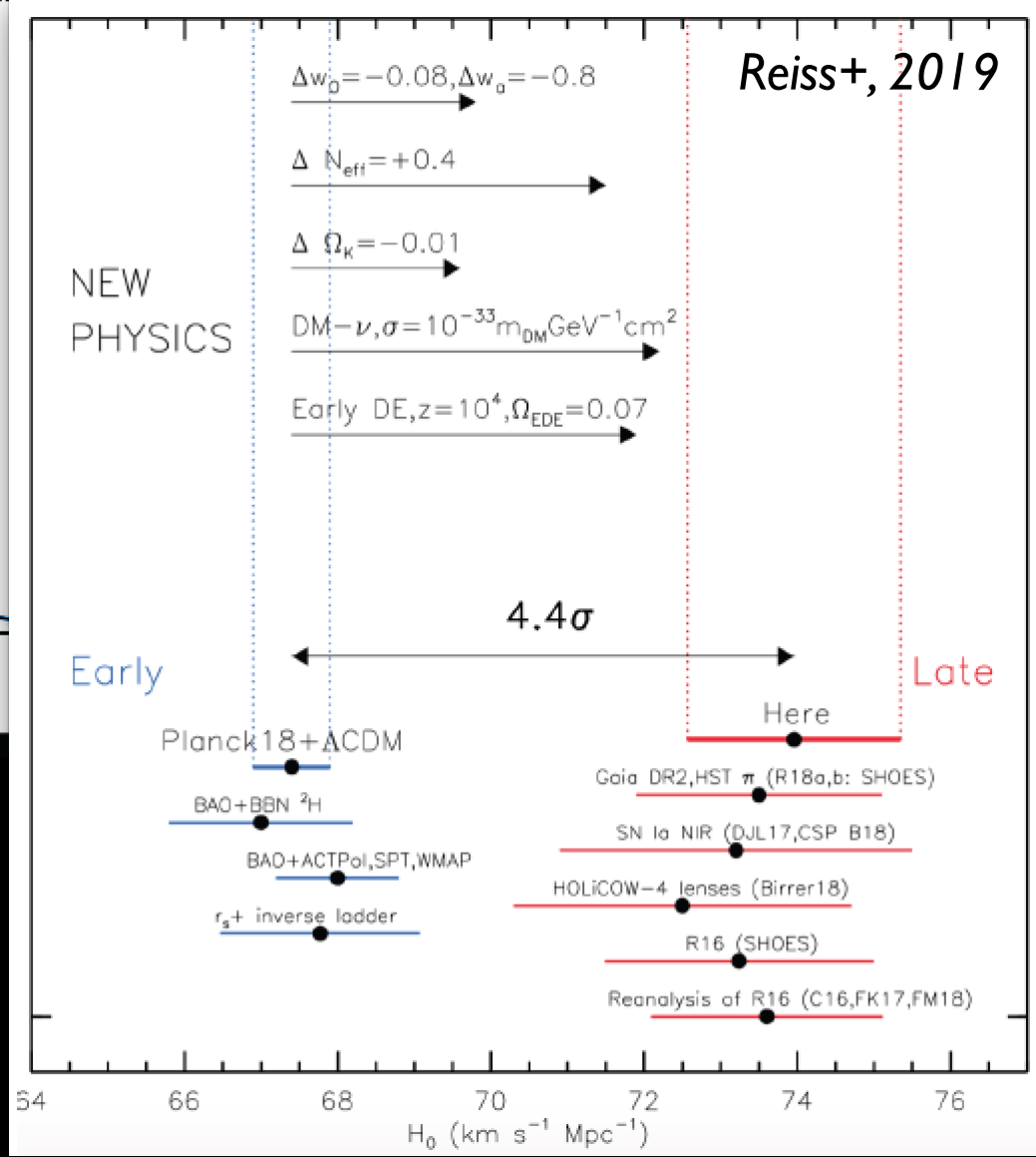
- ET in Europe, Cosmic Explorer in the US and Australia

Tension in H_0 Measurement from Standard Rulers (CMB) vs. Standard Candles (SH_0ES): DM Signal?



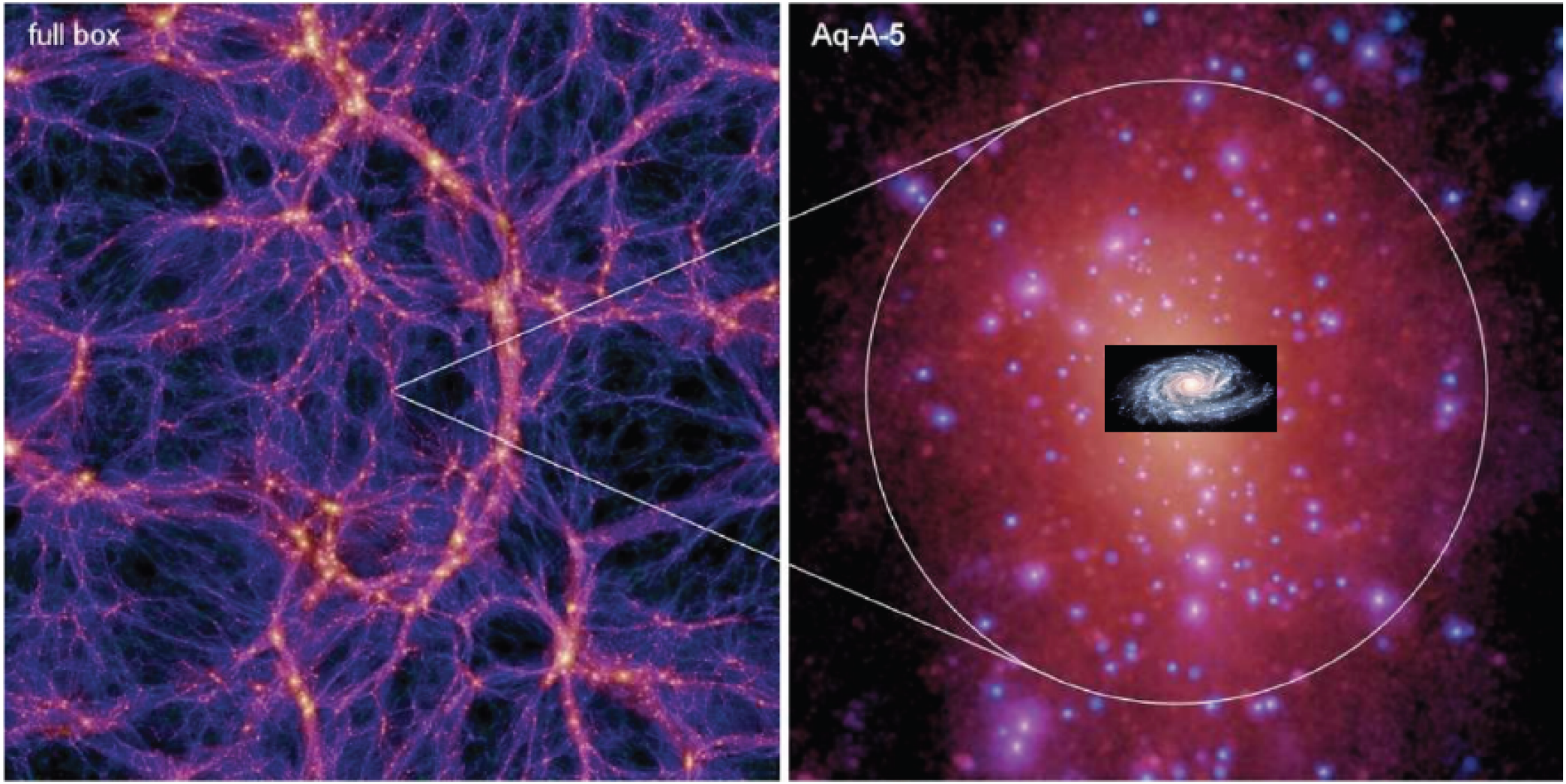
early vs. late universe disagree at ~5 sigma!

new/missing physics?



Near-future CMB polarization measurements will test new relativistic degrees of freedom + BSM neutrinos hypotheses…

Large Scale Structure Simulations

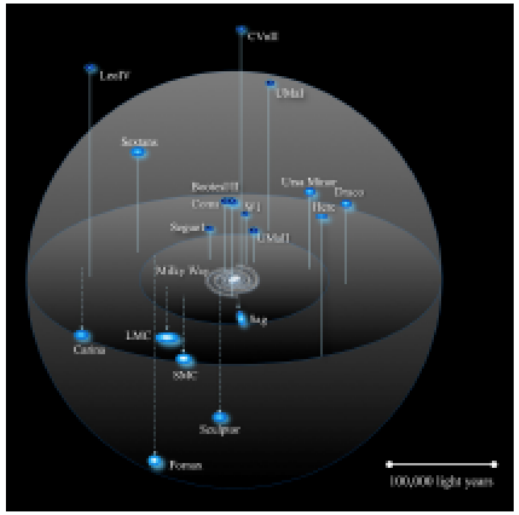


Aquarius Project, Springel+(2008)

Dark matter is the key for understanding structure formation of the universe

Detection Strategies: Dark Matter "Colliders"

Dwarf galaxies

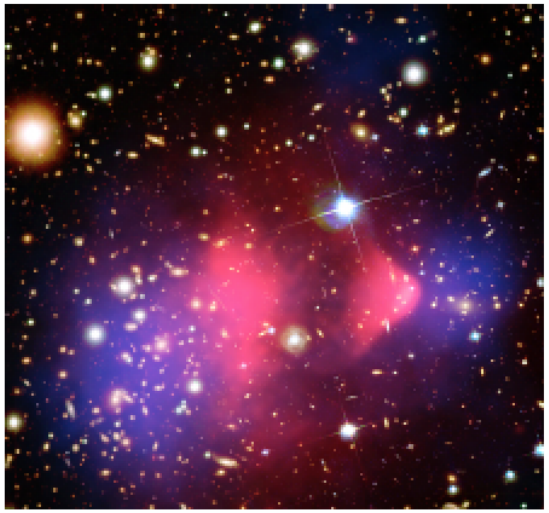


"B-factory" (v~30 km/s)

MW-like galaxies

"LEP" (v~200 km/s)

Clusters



"LHC" (v~1000 km/s)

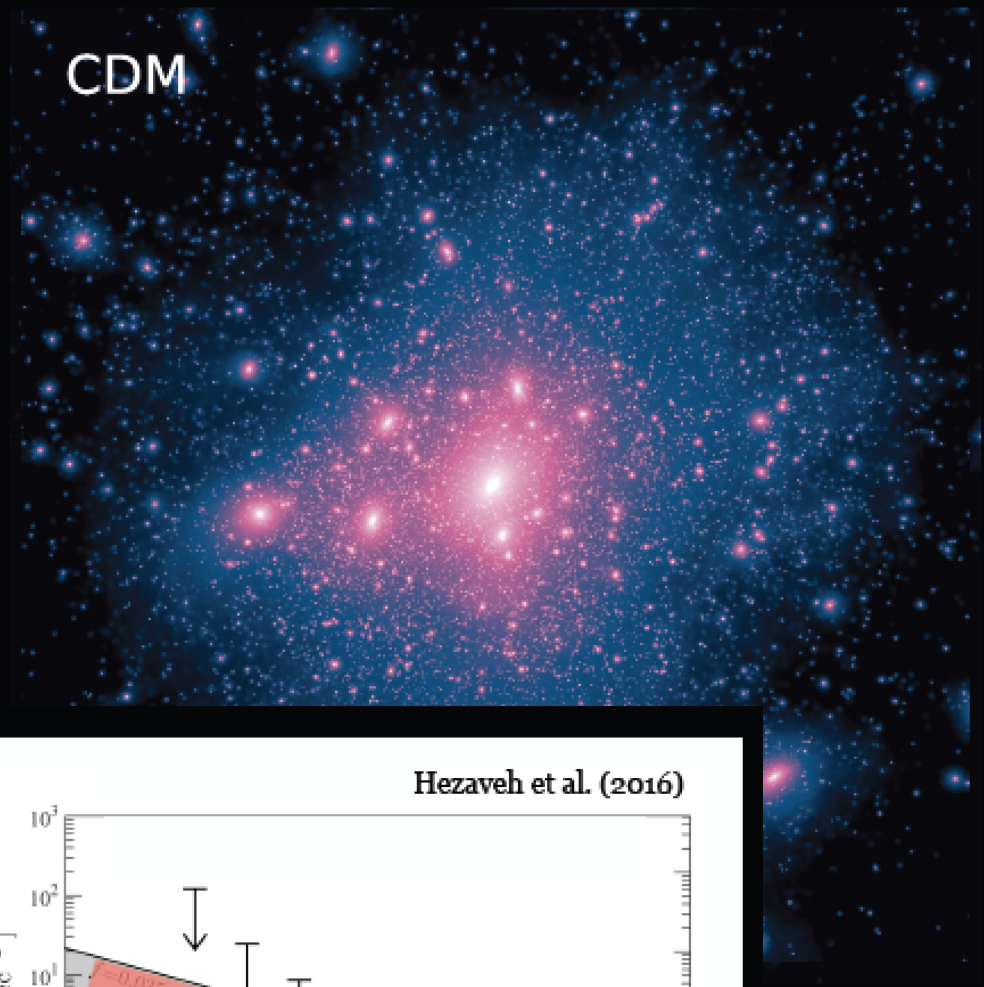
Self-scattering kinematics

Observations on all scales

Measure particle physics parameters σ_X, m_X, m_ϕ

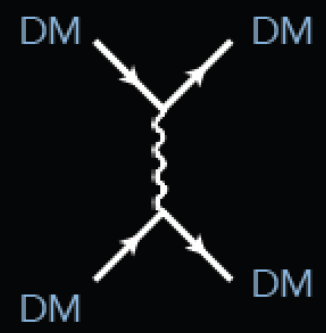
Small-Scale Structure Measurements

Lisanti, ESPPU 2019

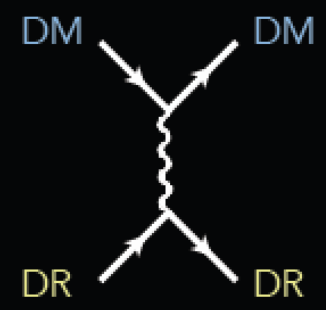


SIDM example that suppresses formation of low-mass subhalos:

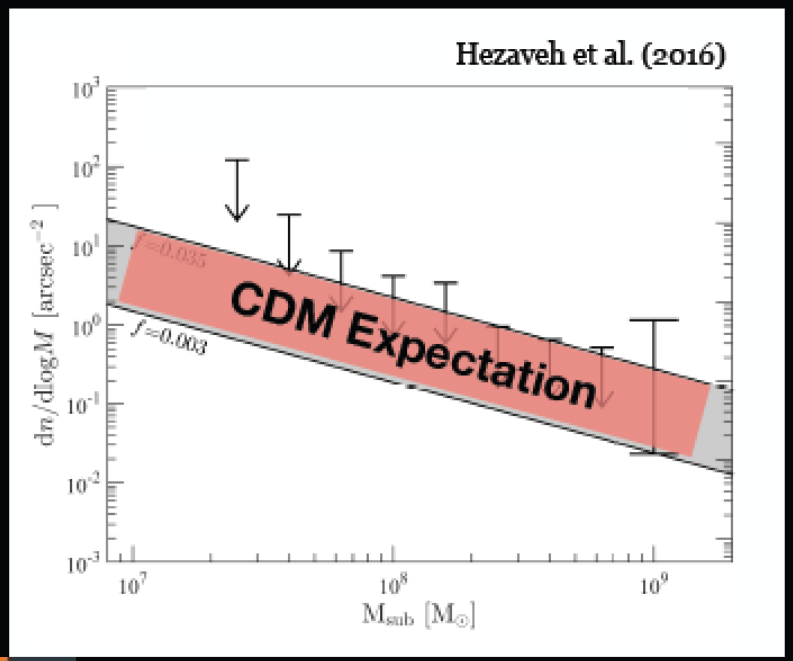
Dark Matter Self Interacting



Scattering off Dark Radiation

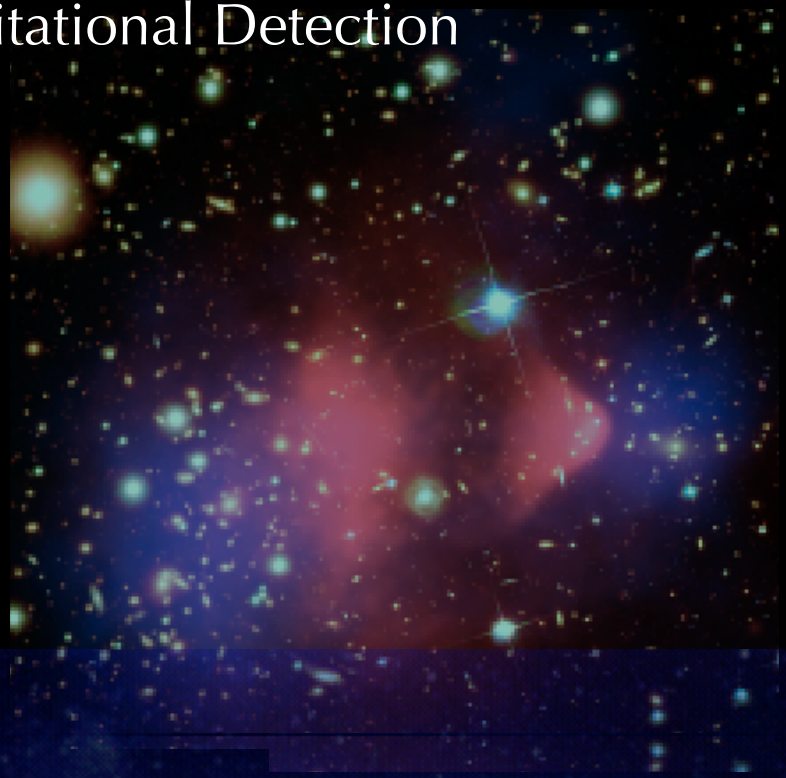


Dissipative dark sectors can also affect small-scale structure

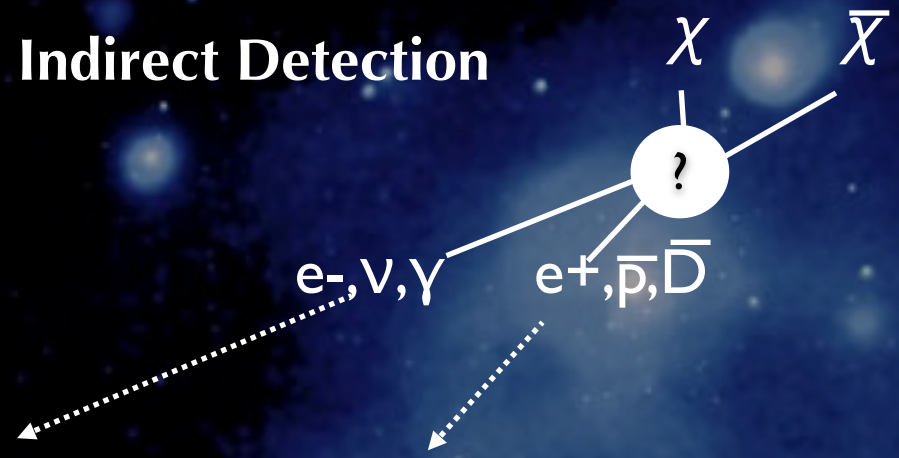


Observational constraints on subhalo masses are a powerful test of dark sectors, new data from e.g. GAIA, LSST will probe the CDM-predicted range

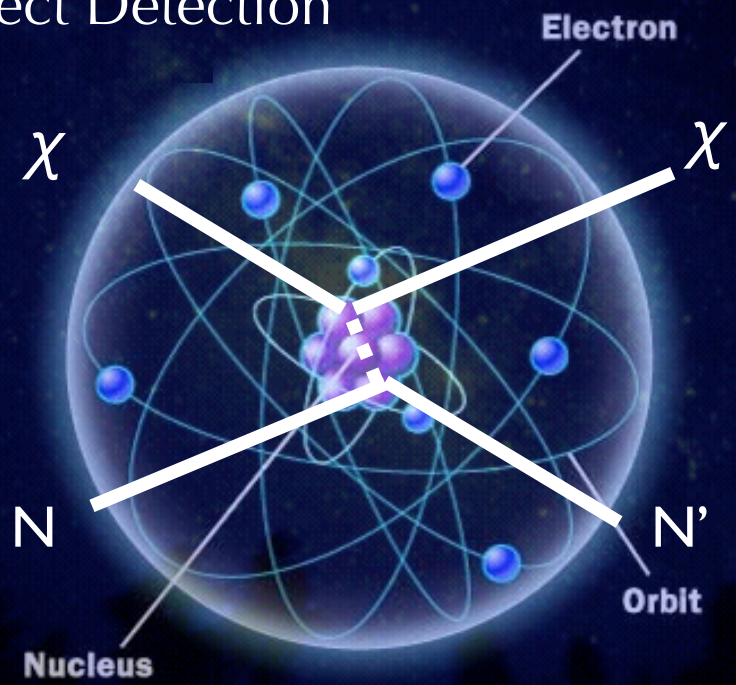
Gravitational Detection



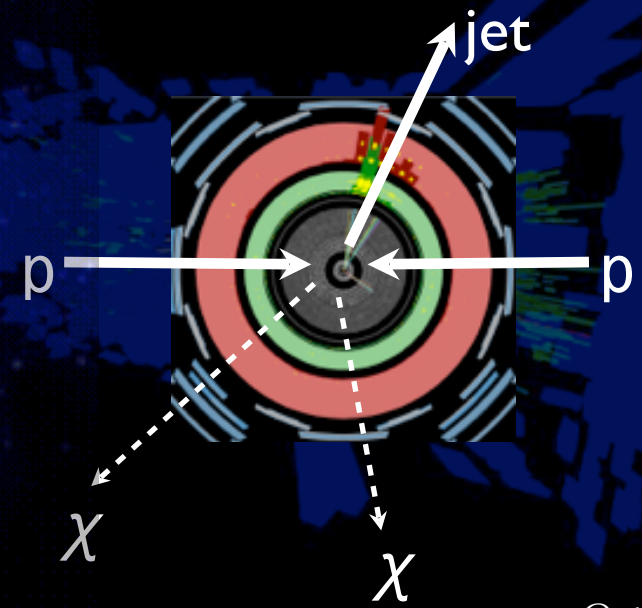
Indirect Detection



Direct Detection



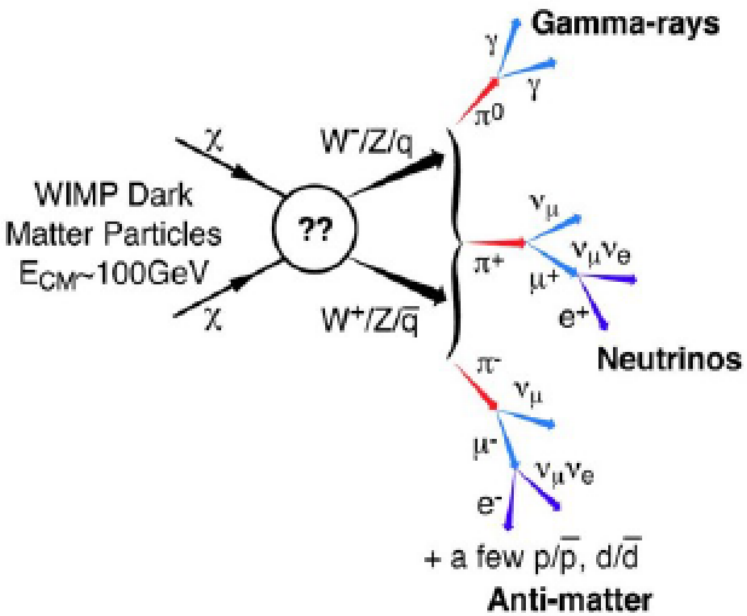
Accelerator Production



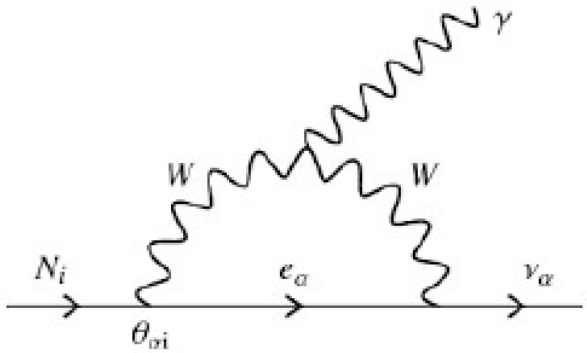
Indirect Detection Strategies

Weniger, ESPPU 2019

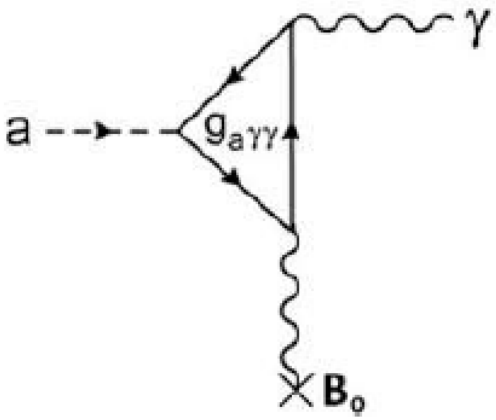
1) Self-annihilation
(e.g. WIMPs)



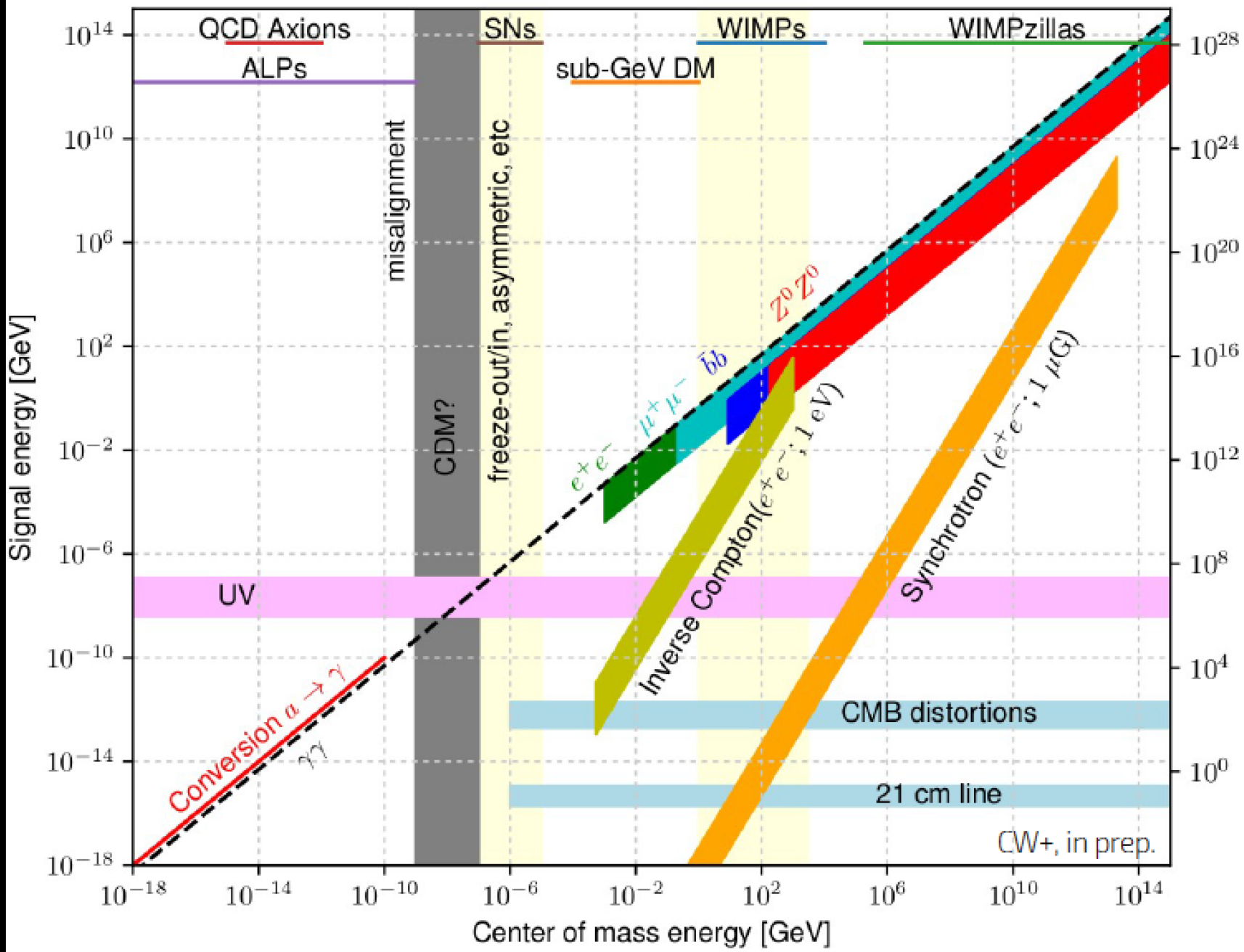
2) Decay
(e.g. sterile neutrinos)



3) Conversion
(e.g. axions)

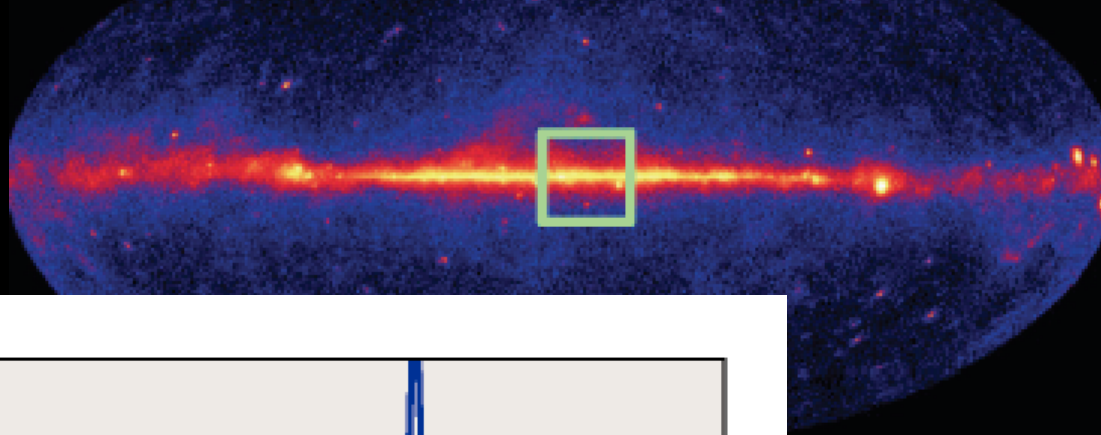


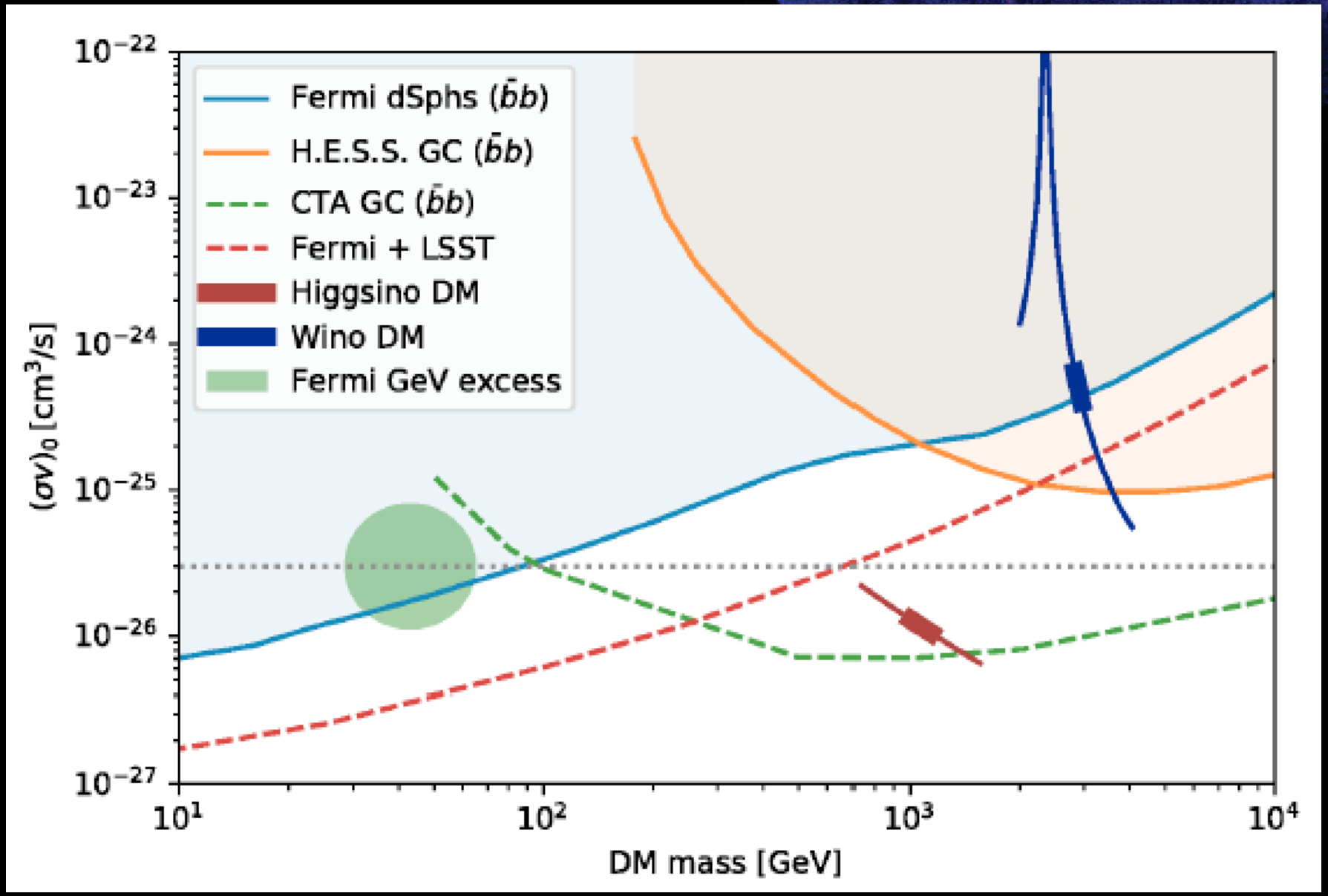
Emission energy vs. DM mass



LHAASO (~2021)
CTA (~2025)
KM3NeT-ORCA (construction)
GAPS (~2021)
AMEGO (proposed)
XRISM (~2022)
SKA (~2025)

Self-Annihilation Status and Prospects for WIMPs

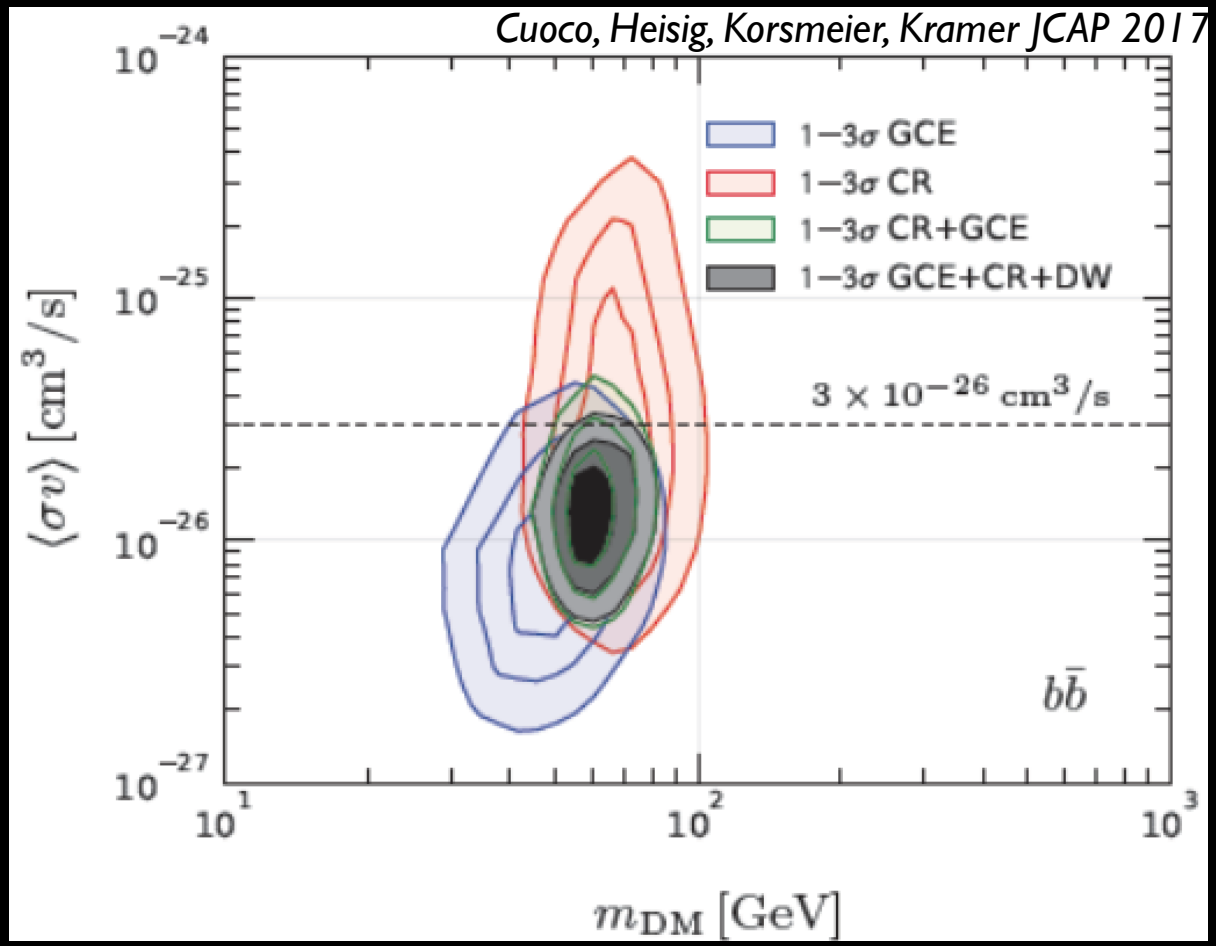




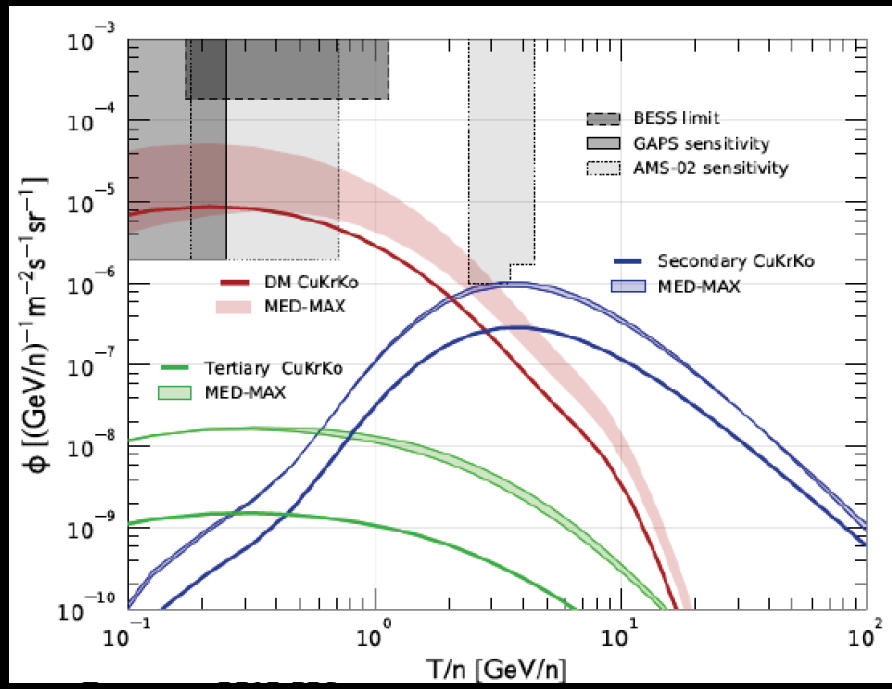
Weniger, ESPPU Briefing Book

Indirect Detection Candidate Signals: Combined Fits

Cuoco, TAUP2019



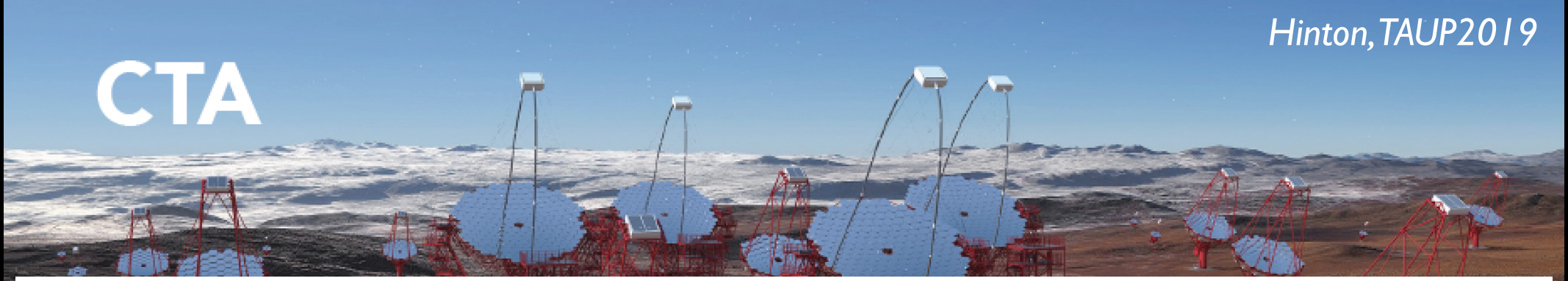
Testable prediction: expect anti-deuterons in AMS-02, GAPS



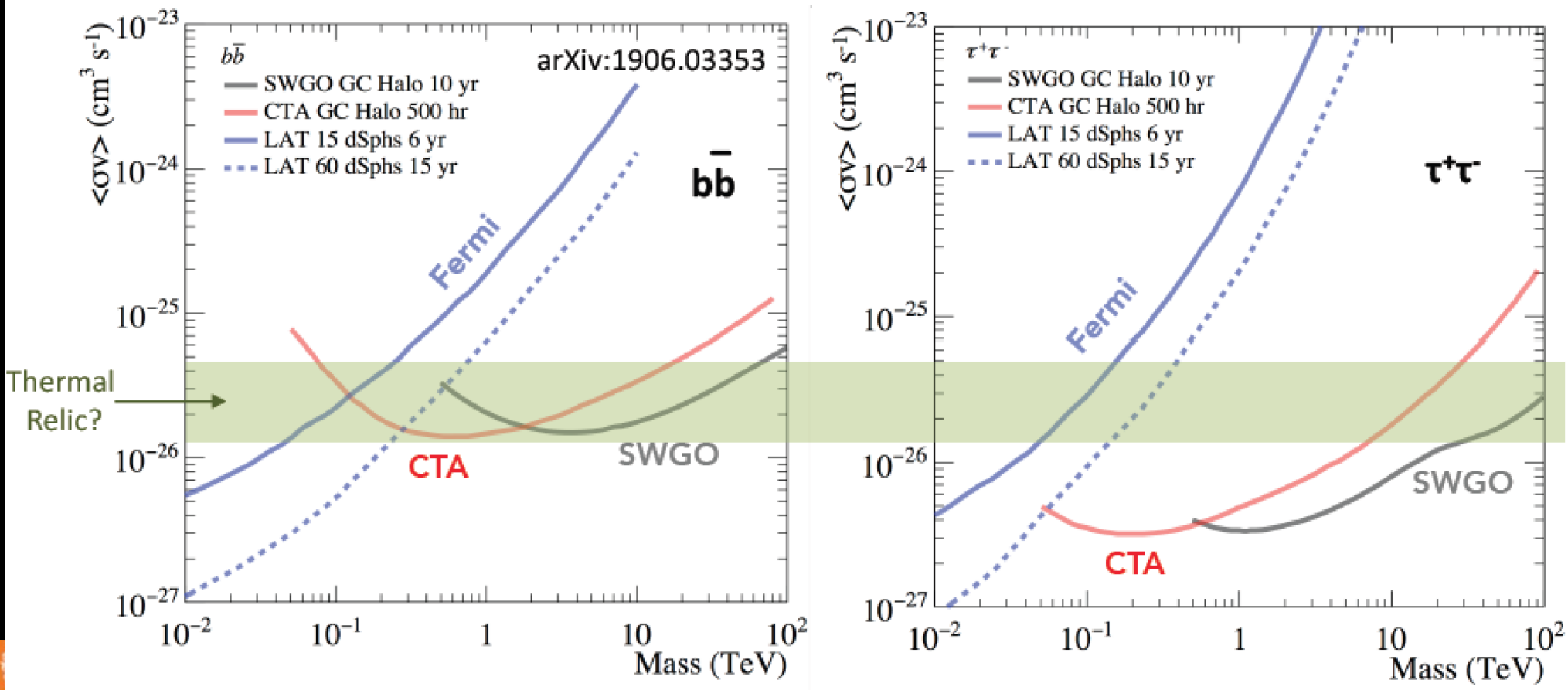
Korsmeier, Donato, Fornengo 2018
Leane, Slatyer 1904.08430

- We made a joint fit of the GC gamma-ray excess and of the CR excess, taking into account uncertainties in the DM distribution in the Milky Way.
- Depending on the channel there is good overlap of the two signals
- The joint-fit region is also compatible with the most recent dwarf galaxies constraints

CTA

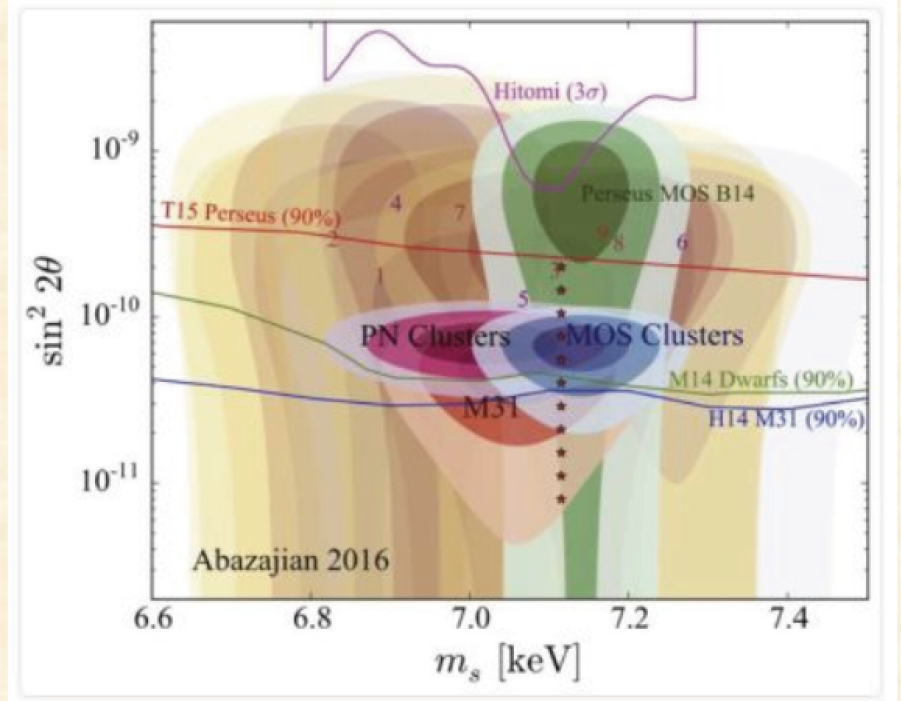


- New generation of instruments reaches the critical sensitivity
- Thermal relic WIMP accessible over a very wide mass range (Galactic Centre/Halo observations @ VHE)

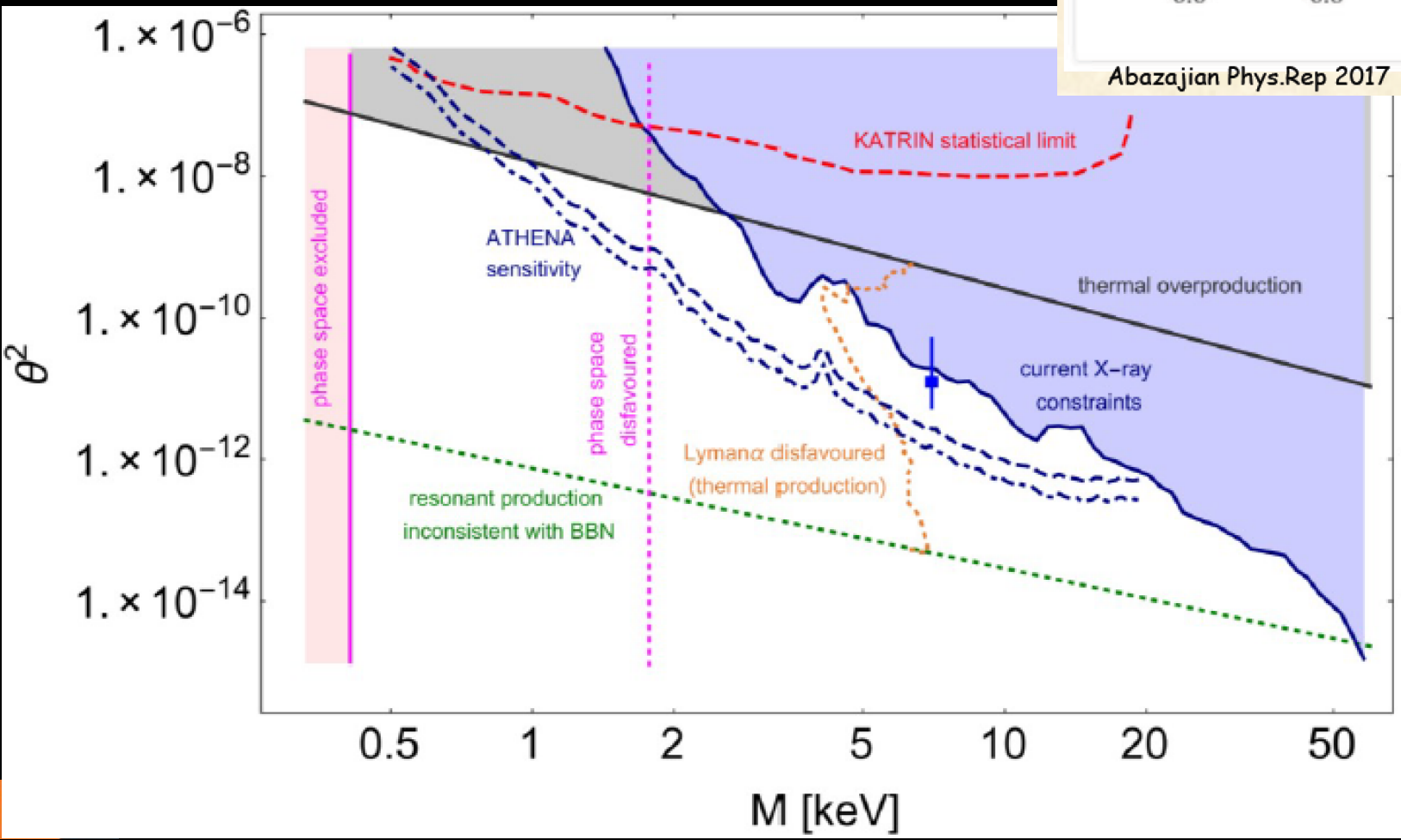


Decay: Sterile Neutrino Dark Matter Status, Prospects

Excess x-ray flux at 3.5 keV observed by XMM-MOS/PN, Chandra, Suzaku, NuStar in some targets but not others.

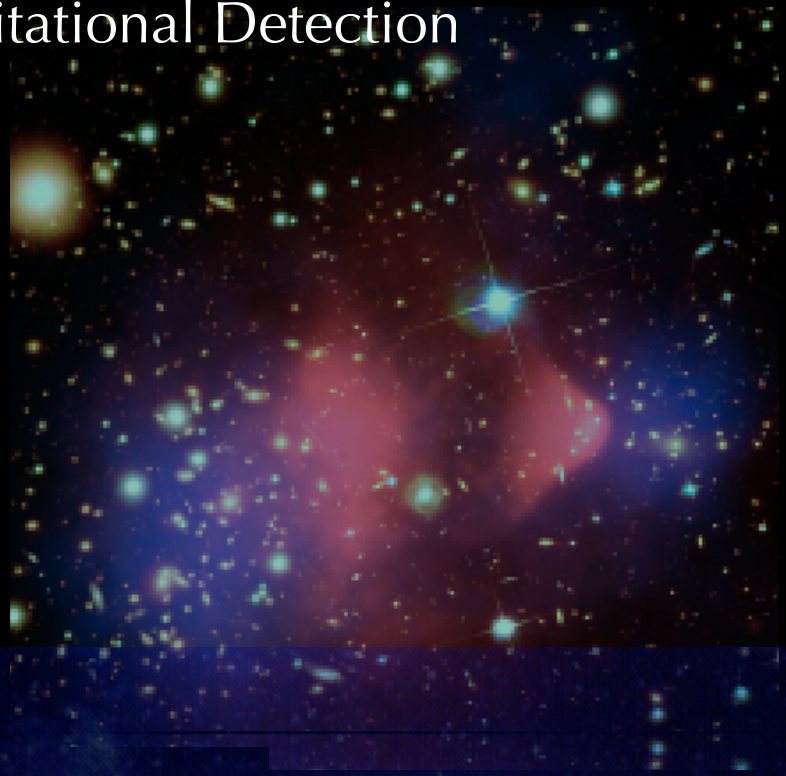


Abazajian Phys.Rep 2017

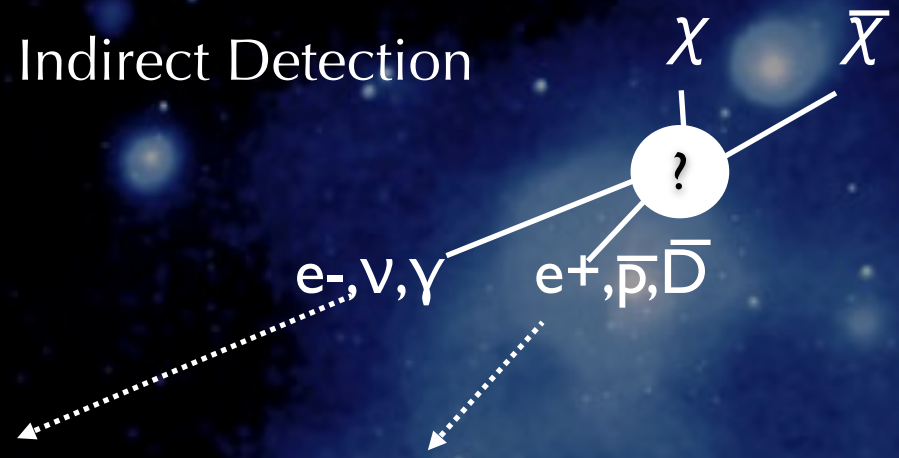


Prospect to test atomic line background hypotheses in near-future experiments (XRISM ++)

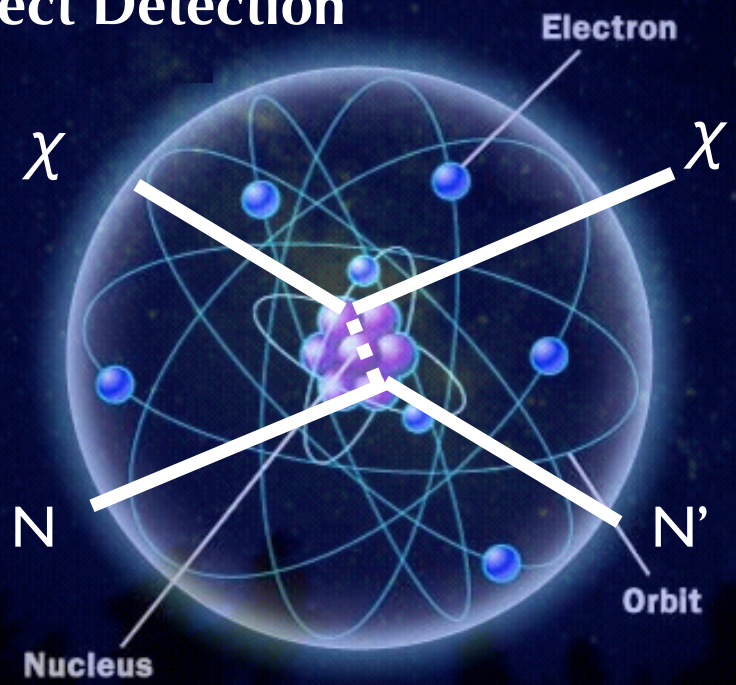
Gravitational Detection



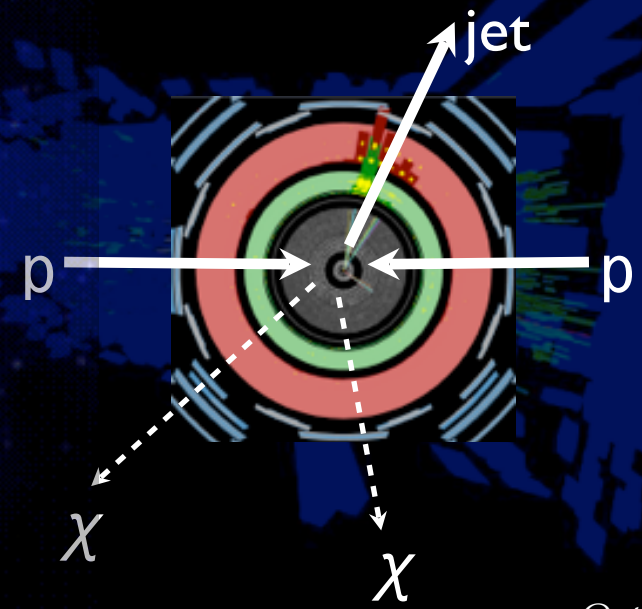
Indirect Detection



Direct Detection



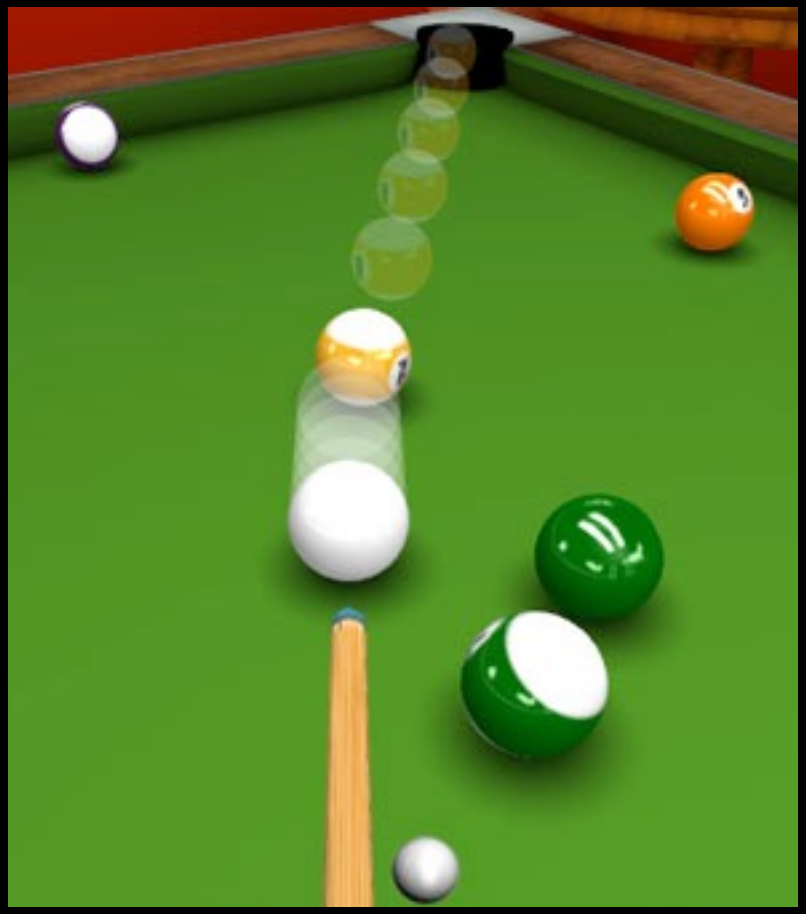
Accelerator Production

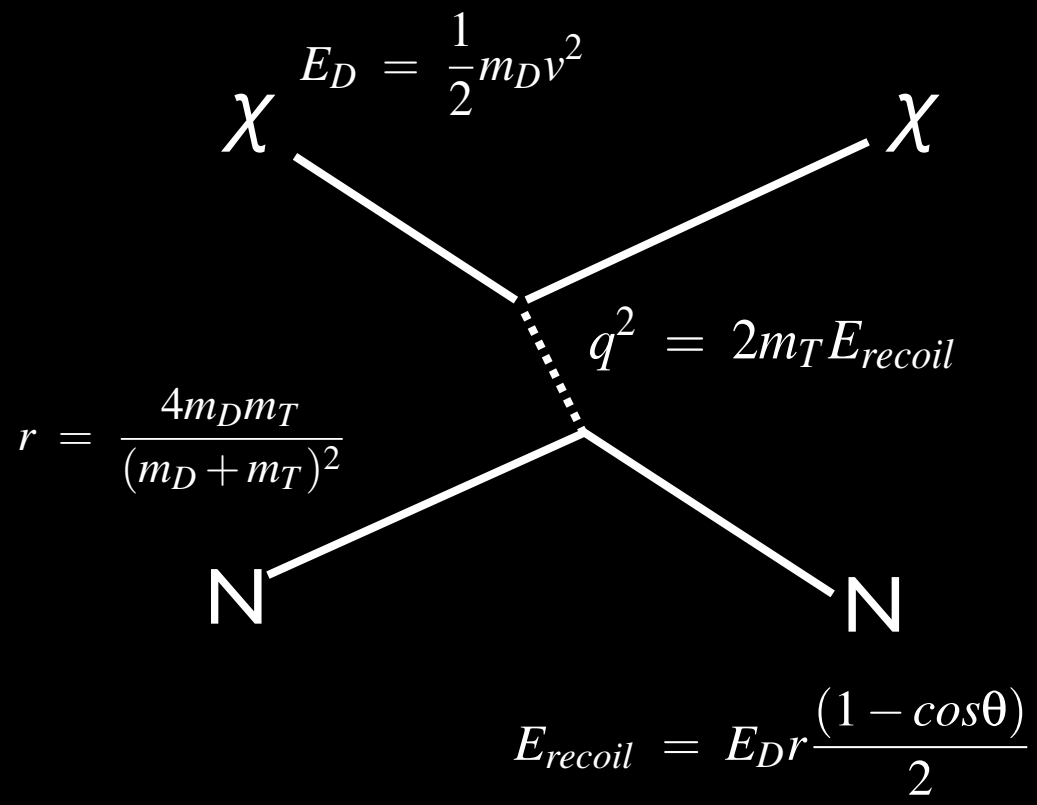


Direct Detection Strategies

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

recoil angle strongly correlated with incoming WIMP direction

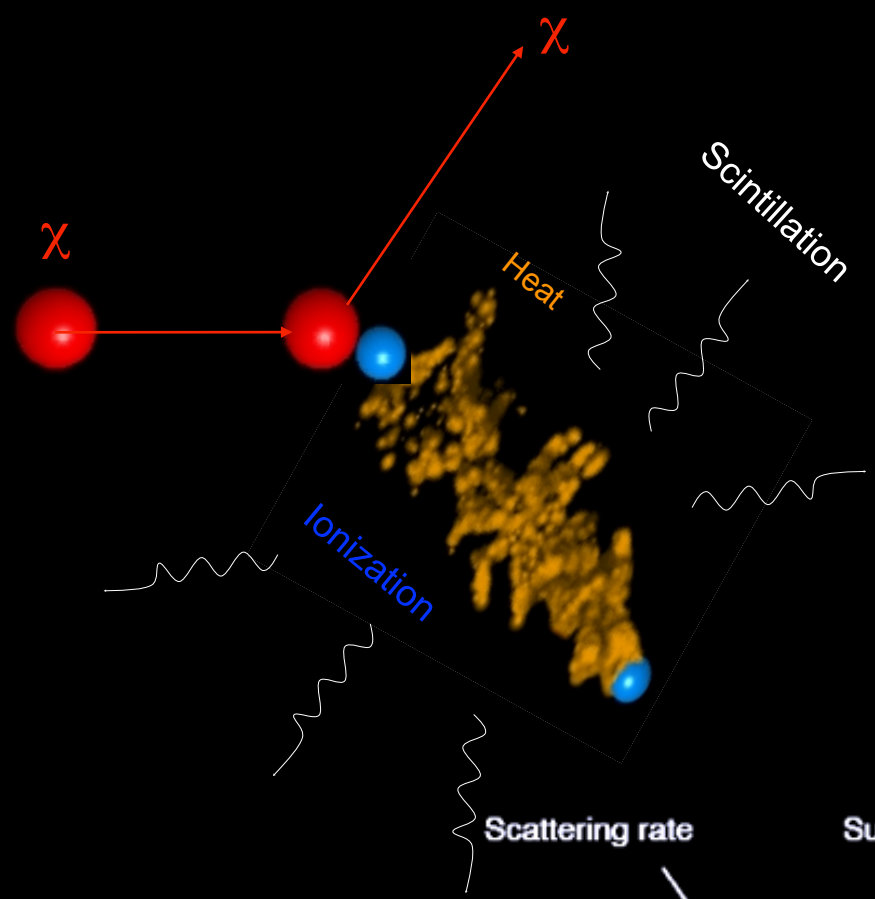


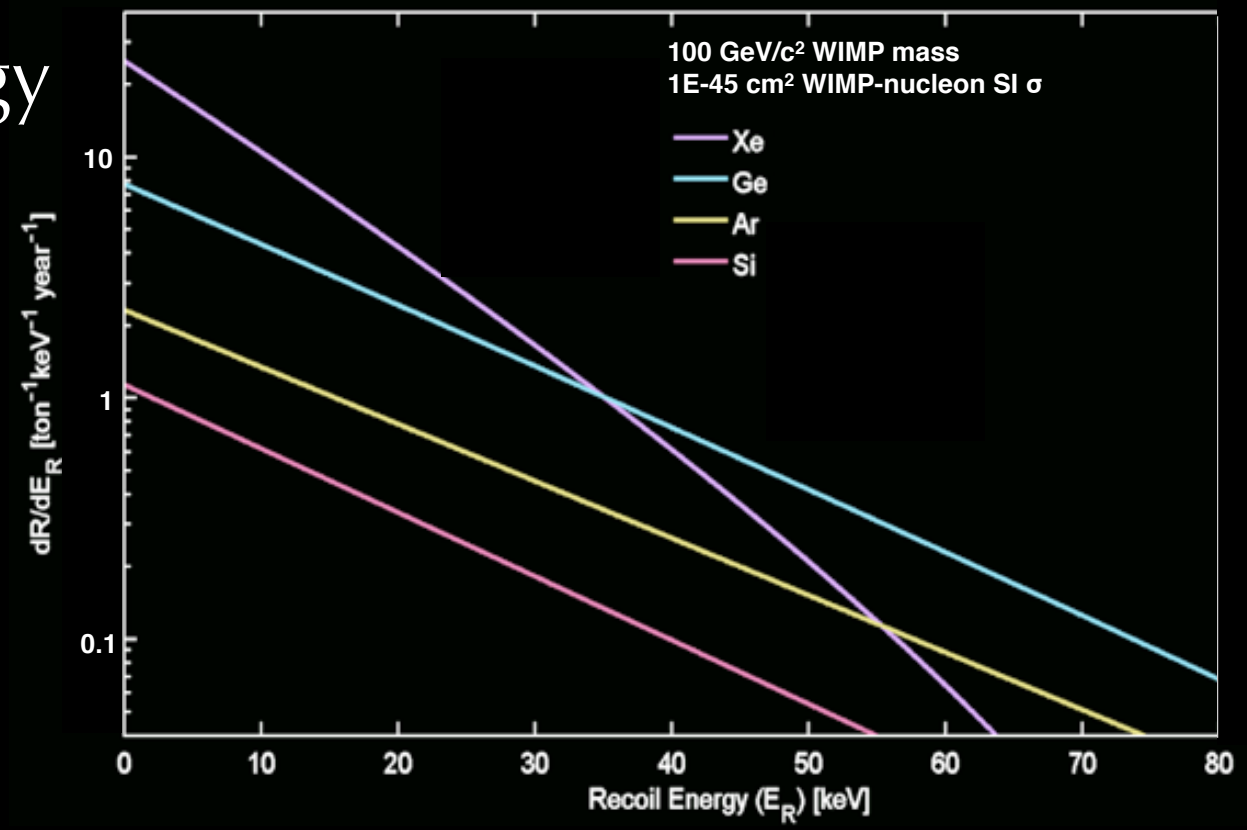


<u>Spin Independent:</u>
χ scatters coherently off of the entire nucleus A: $\sigma \sim A^2$
D. Z. Freedman, PRD 9, 1389 (1974)

<u>Spin Dependent:</u>
mainly unpaired nucleons contribute to scattering amplitude: $\sigma \sim J(J+1)$

Observable: Recoil Energy





Scattering rate

Sun's velocity around the galaxy

WIMP velocity distribution

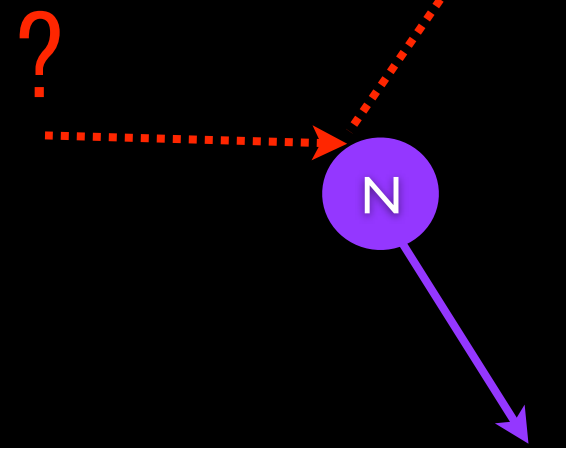
$$dR/dQ \sim (\sigma_0 \rho_0 / \sqrt{\pi}\, v_0 m_\chi m_r^2)\, F^2(Q)\, T(Q)$$

WIMP energy density, 0.3 GeV/cm³

Form factor

experimental requirements: ~1-10s of keV energy threshold, very low backgrounds

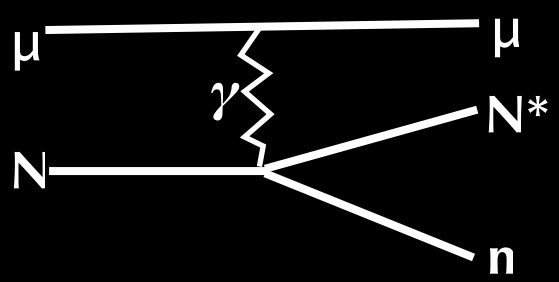
Reducible Backgrounds

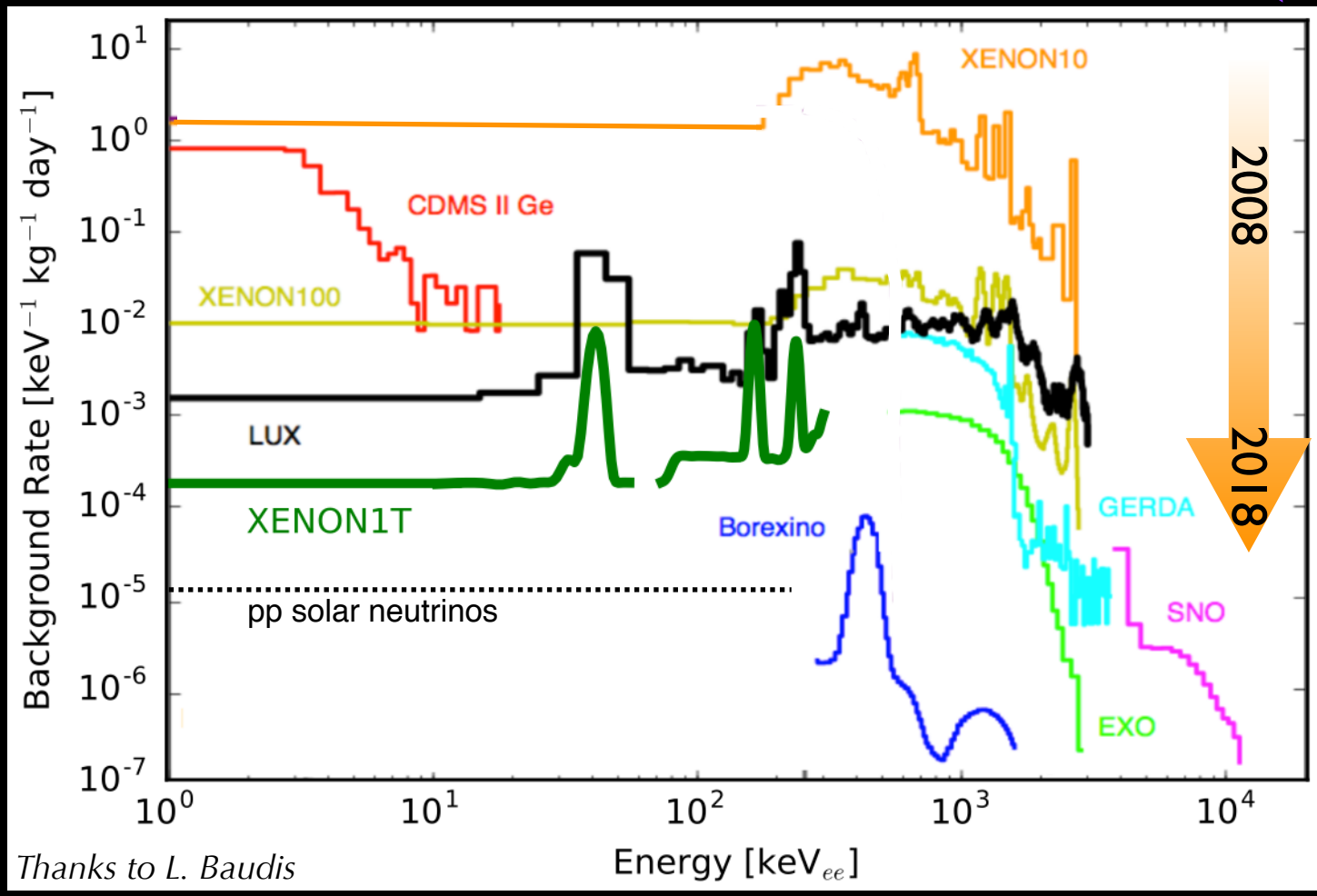


Gamma ray interactions: electron recoil final states
rate ~ N_e x (gamma flux), O(1E7) events/(kg day)
mis-identified electrons mimic nuclear recoils

Contamination:
^{238}U and ^{232}Th decays, recoiling progeny and mis-identified alphas, betas mimic nuclear recoils

Neutrons:
Nuclear recoil final state. (alpha,n), U, Th fission, cosmogenic spallation





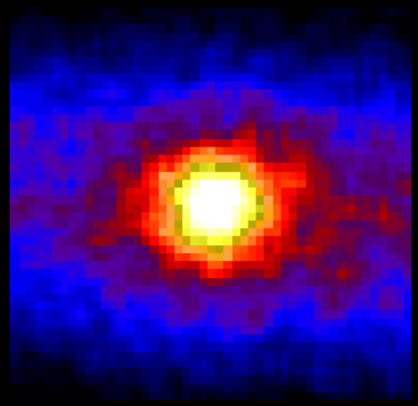
Thanks to L. Baudis

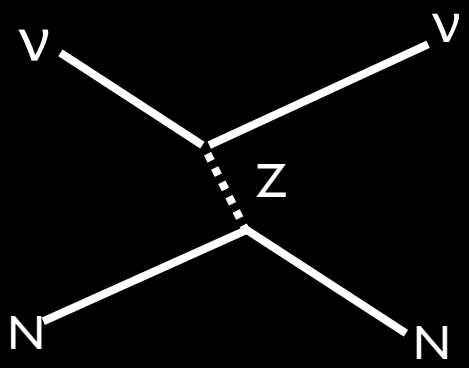
Motivates underground laboratories, ultra-low radioactivity developments.

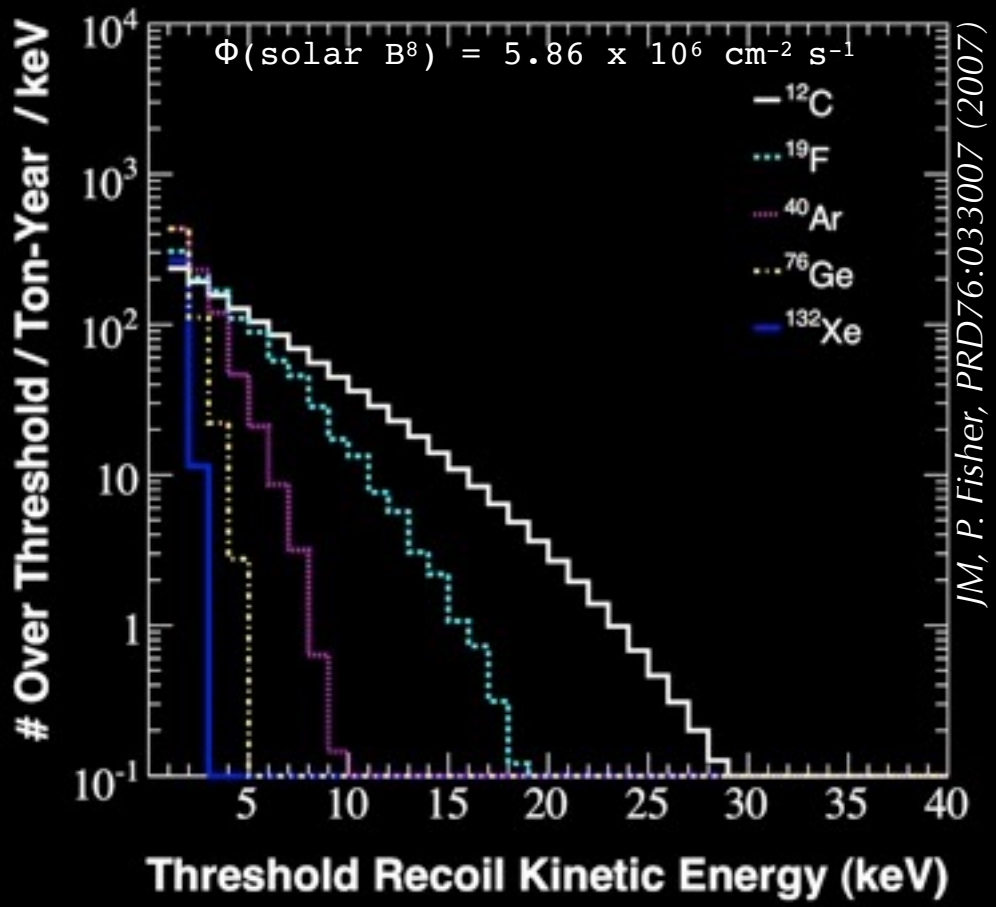
Irreducible Backgrounds

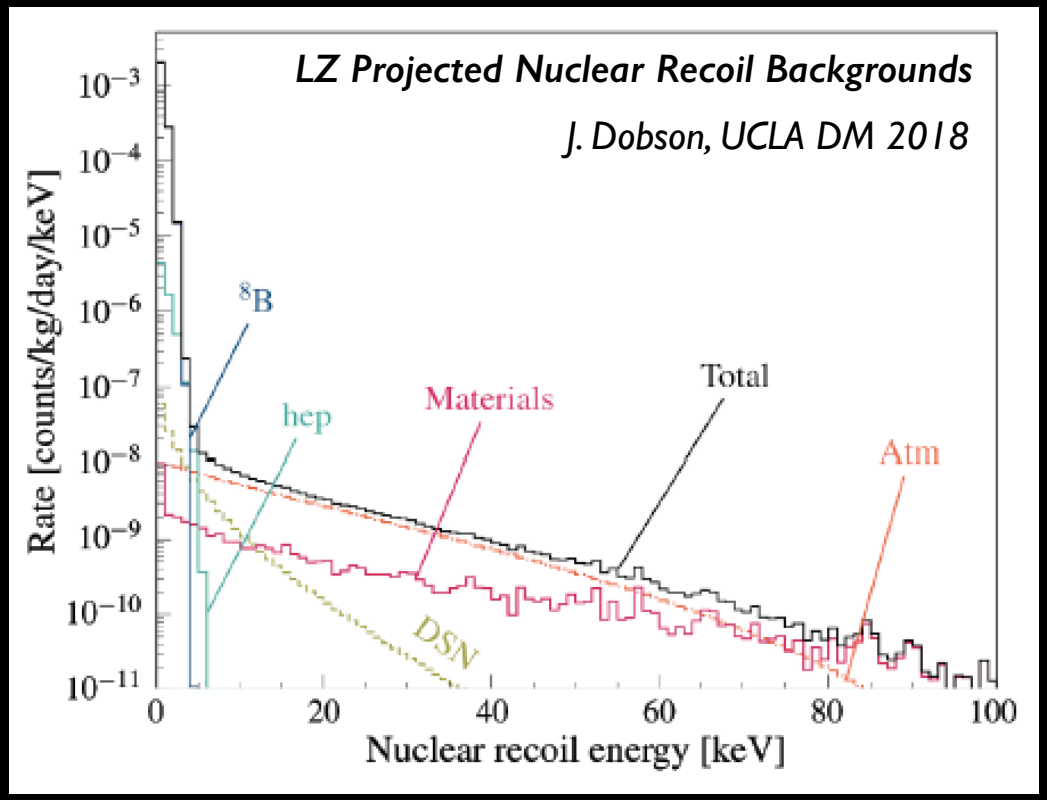
impossible to shield a detector from neutrino scattering!

- "neutrino floor:" both ν-N and ν-e contribute backgrounds





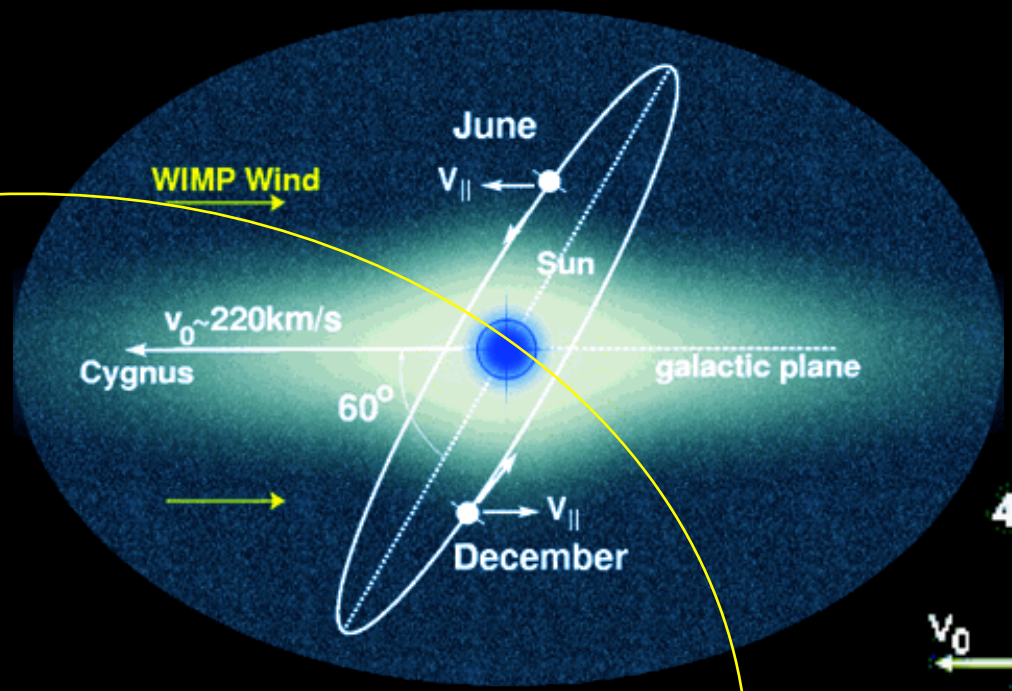


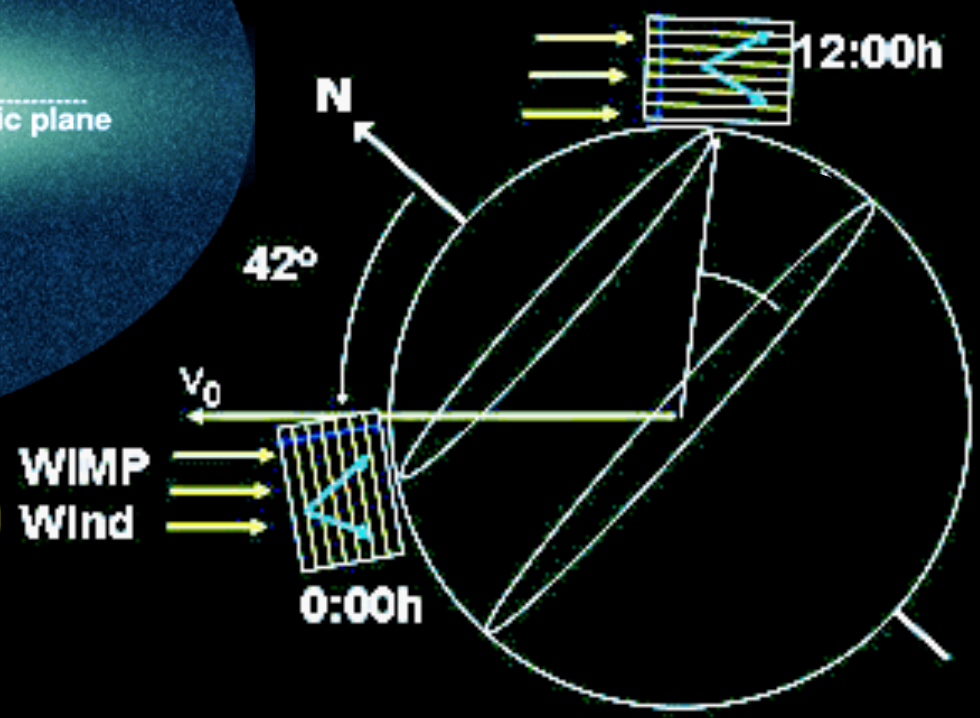


Modulation Signatures

Annual event rate modulation:
June-December asymmetry ~2-10%.

Drukier, Freese, Spergel, Phys. Rev. D33:3495 (1986)





Sidereal direction modulation:
asymmetry ~ 20-100% in
forward-backward event rate.

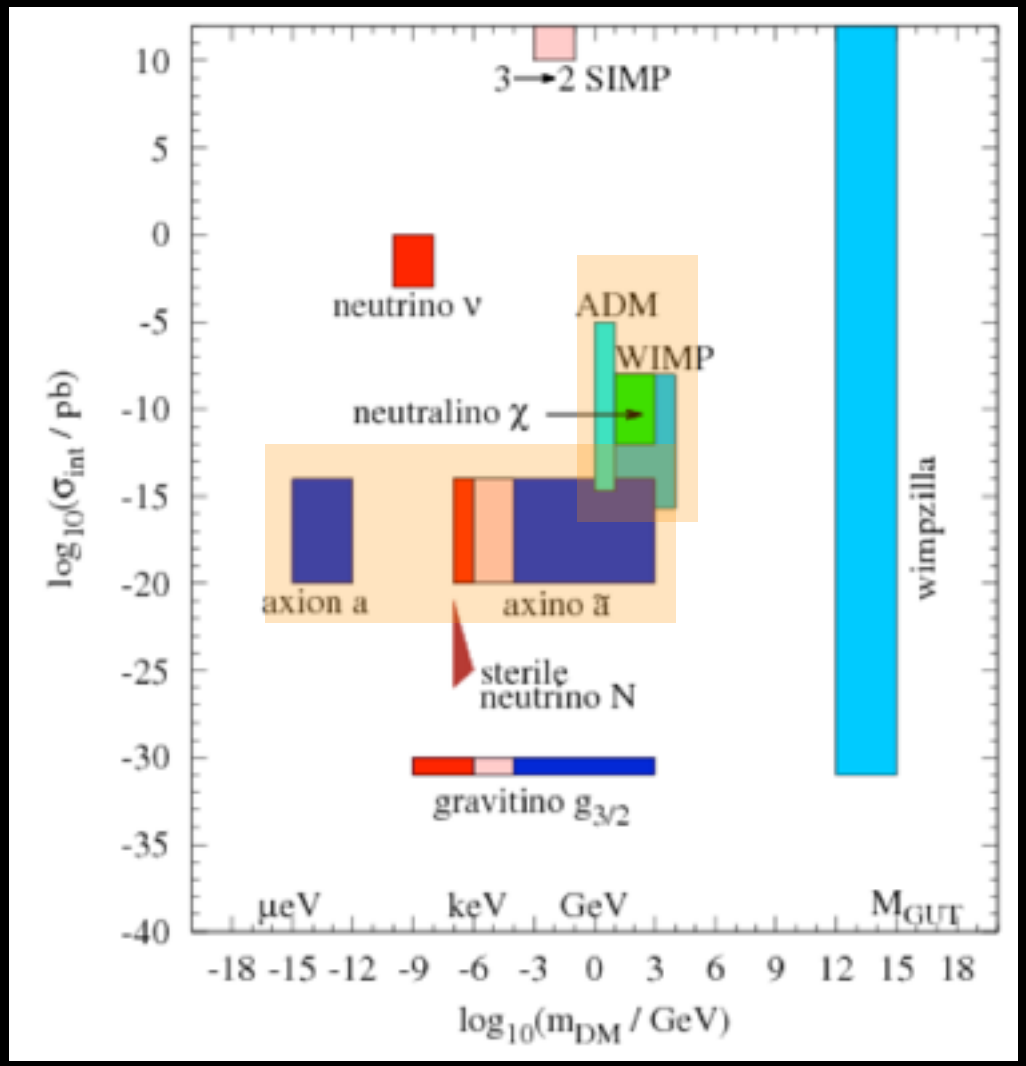
Spergel, Phys. Rev. D36:1353 (1988)

need readout capable of direction measurement

Direct Detection Status

Wide range of parameters!

Direct detection searches historically optimised for WIMP sensitivity...

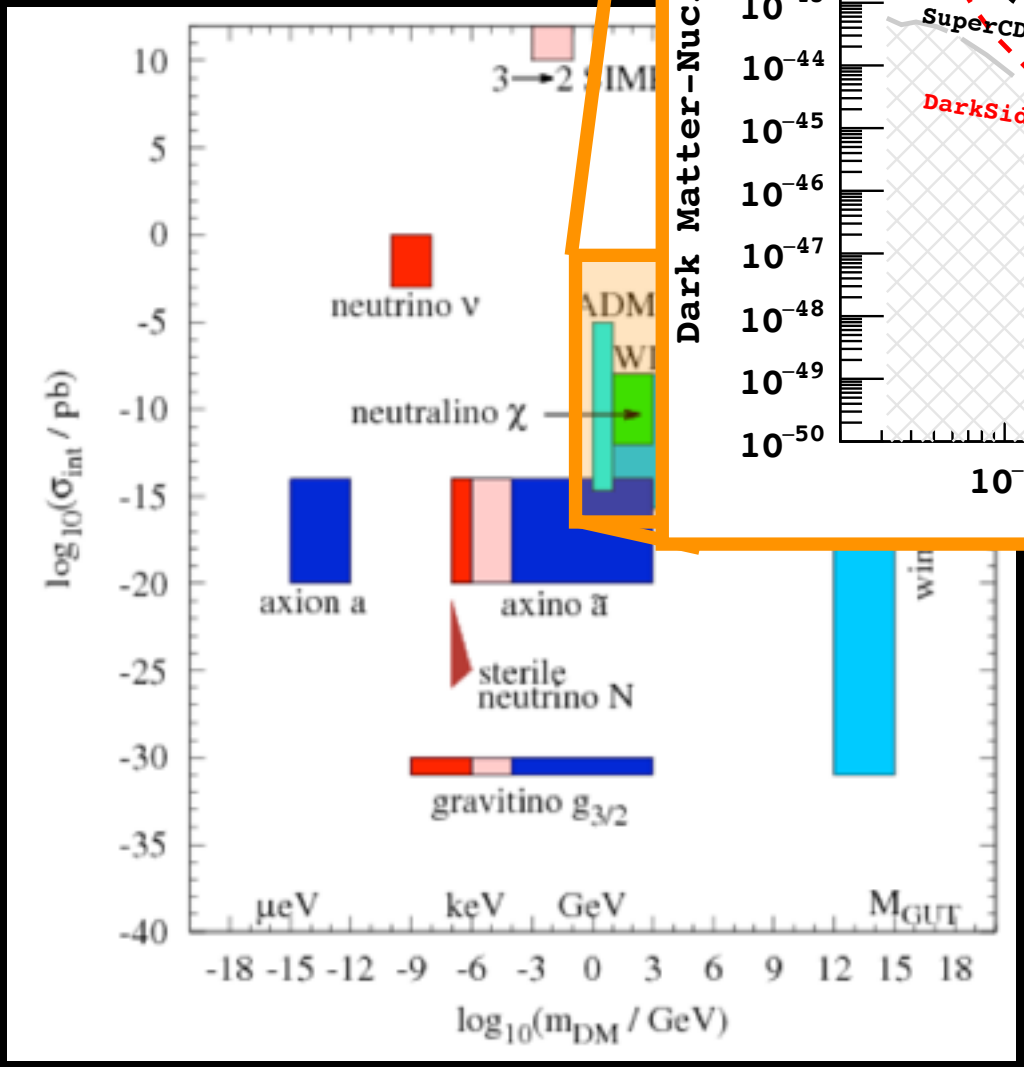


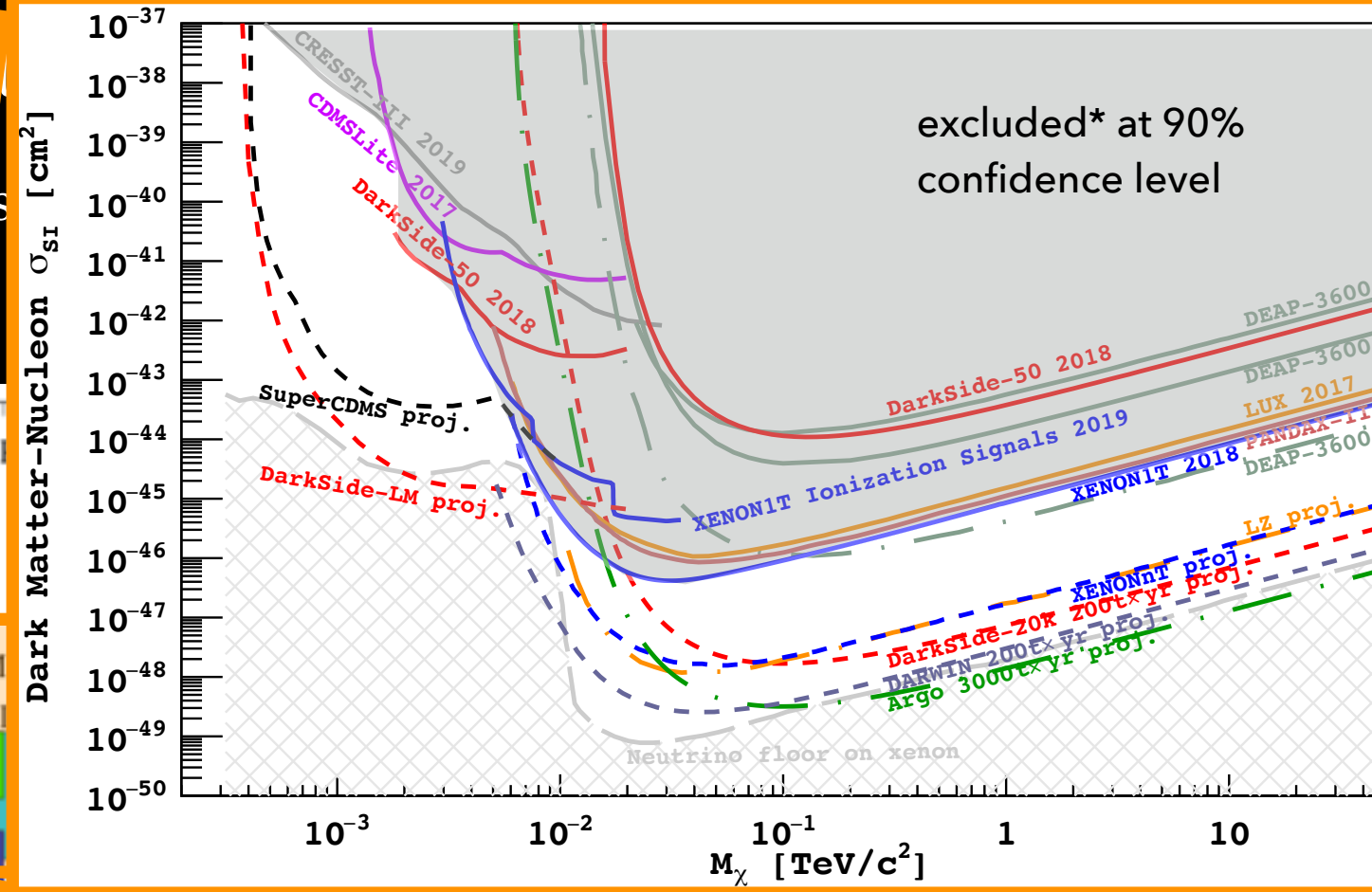
Baer et al., arXiv:1407.0017

Direct Detection S

Wide range of parameter s

Direct detection searches

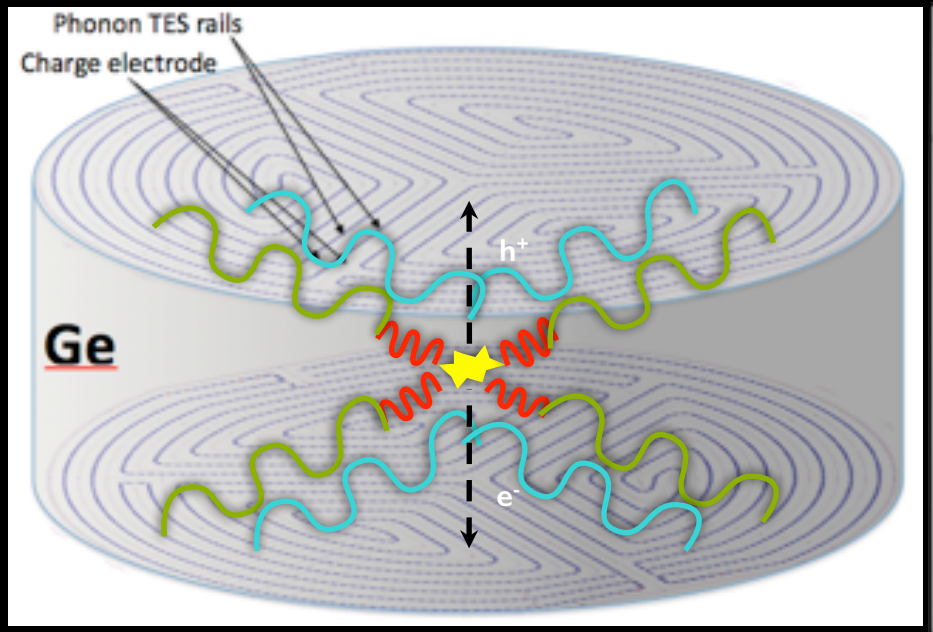




Baer et al., arXiv:1407.0017

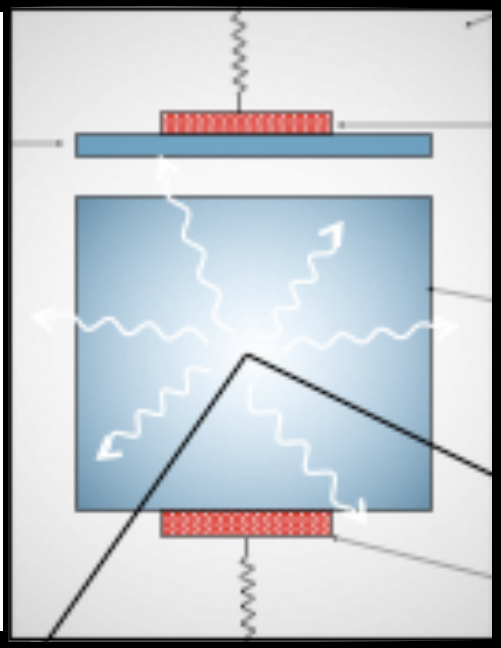
Low Mass Prospects: Solid State Detectors

Phonons: **SuperCDMS** and **EDELWEISS** (Ge), TES for E_{recoil} & R (timing)



Charge: biased at V, used to measure E_{recoil}, configured to reject surface events

Phonons: **CRESST** ($CaWO_4$) TES for E_{recoil}

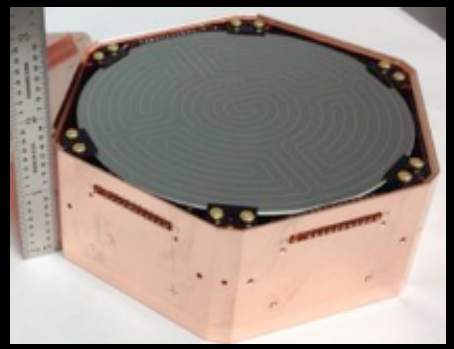


Scintillation: TES for particle ID

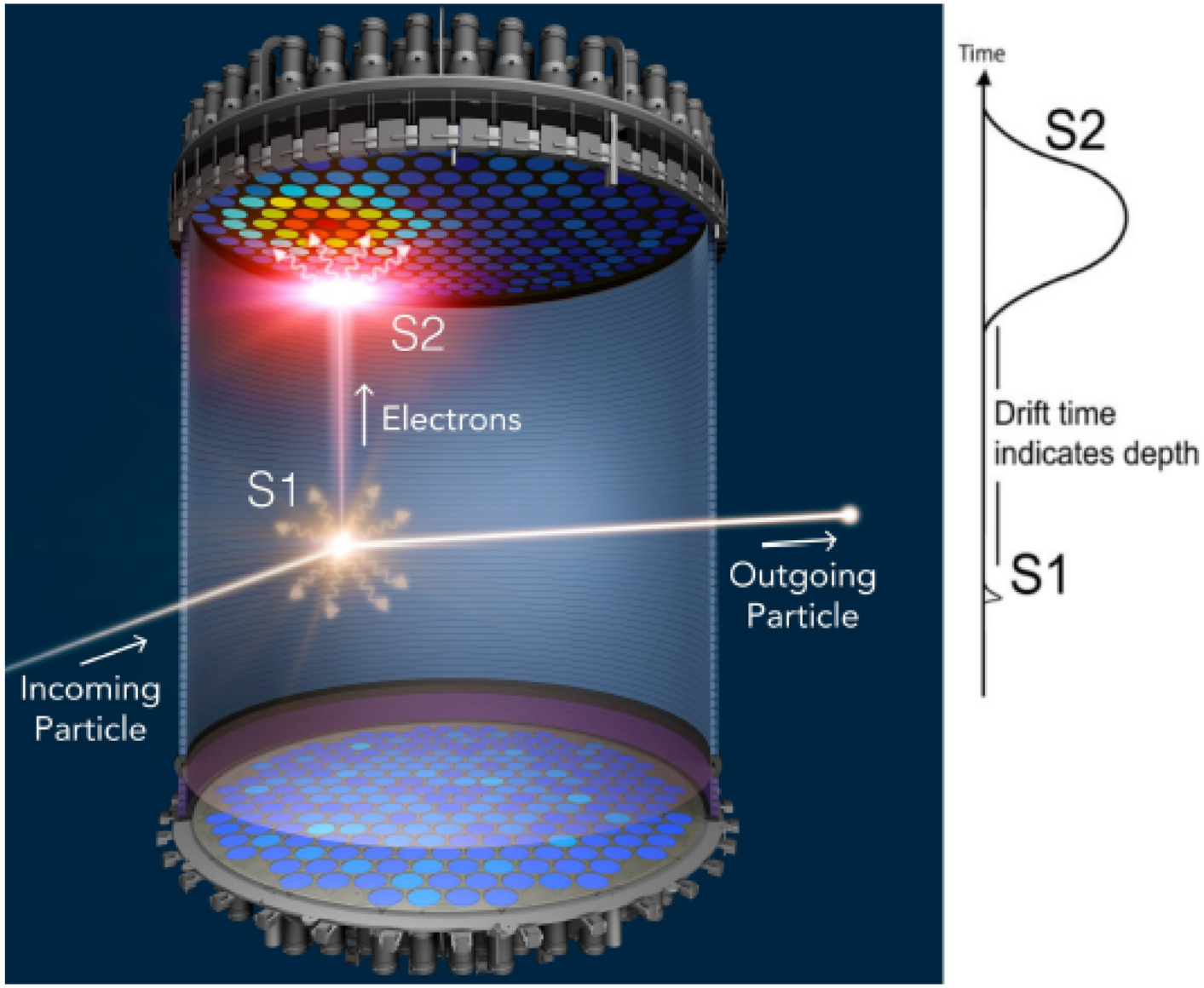
Detector Technology:
crystal bolometers with Transition Edge Sensor readout at O(10 mK) for phonon detection + scintillation/ionization

+ many new ideas (e.g. skipper CCDs, high pressure gas ….)

detectors reach energy thresholds of < 1 keV, with FWHM < 0.3 keV



Large Mass Prospects: Liquid Noble Detectors



https://lz.slac.stanford.edu/our-research/lz-research

Detector Technology:
dual-phase
Time Projection
Chambers
with multi-tonne
liquid Xe, Ar targets

read out primary
scintillation: "S1" +
proportional gas
scintillation from
drifted electrons: "S2"

Xenon Detectors

XENON 10 (LNGS)
ZEPLIN (Boulby)

10 kg

2010

100 kg

XENON 100 (LNGS)

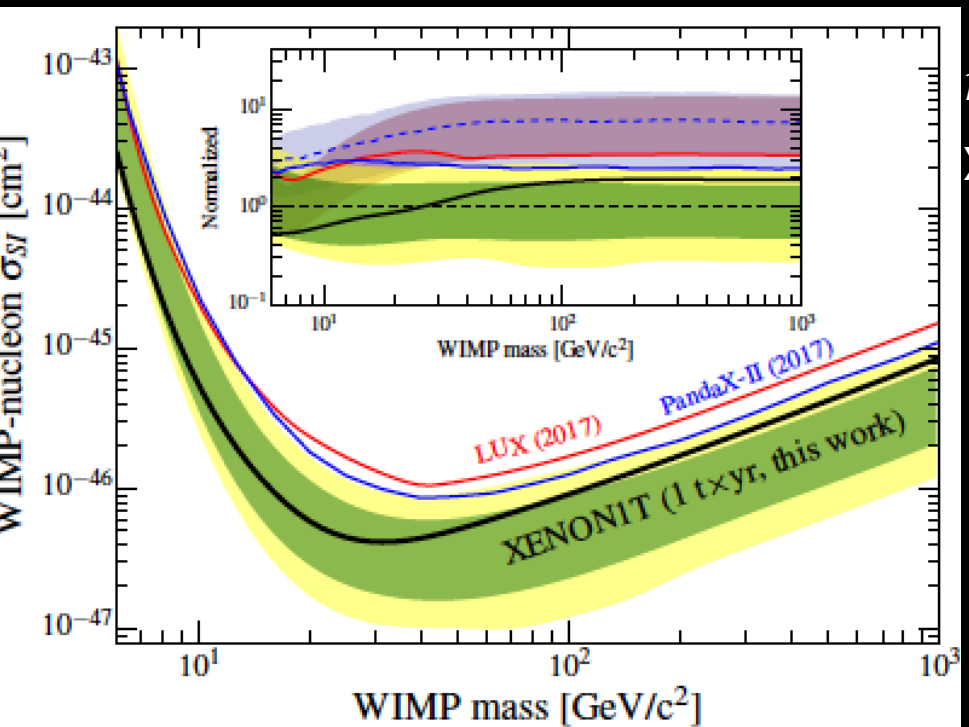
LUX (250 kg, SURF),

PANDA-X
(500 kg, CJPL)

XMASS
(0.8t, Kamioka)

2015

Aprile et al, arXiv:1805.12565



1,000 kg

XENON 1T
(1t, LNGS)

PandaX-4:(4t, CJPL)

XENONnT: (6t, LNGS)

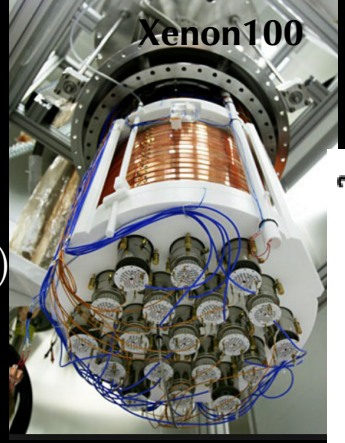
LZ: (7t, SURF)

2020

10,000 kg

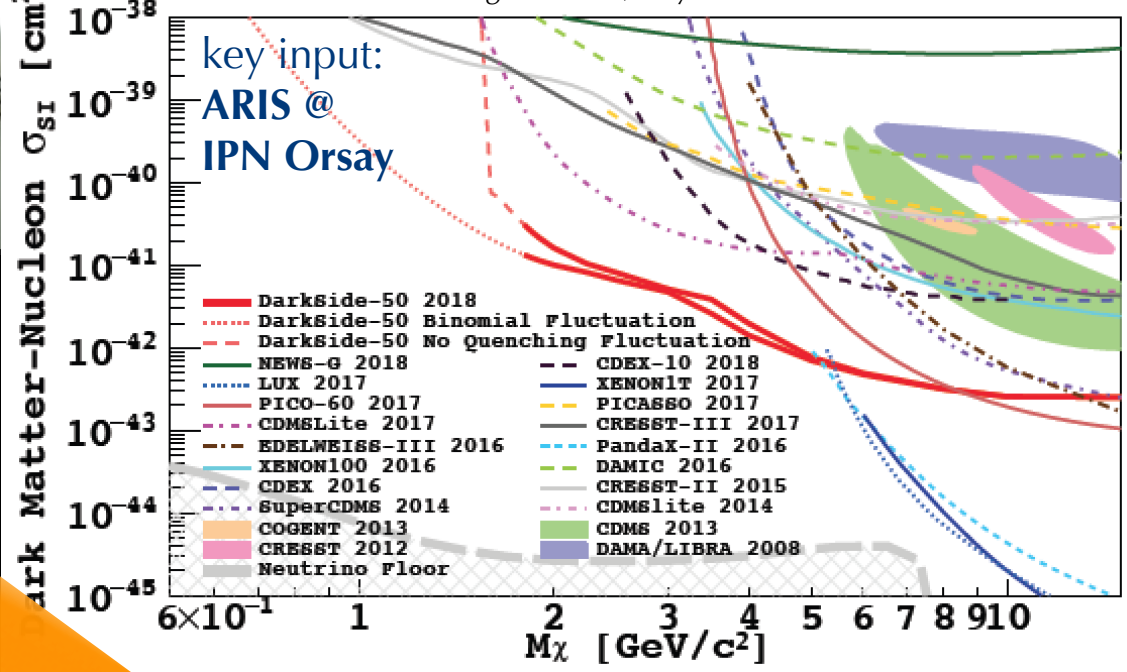
***Future: DARWIN**: 50 t*

Argon Detectors



DarkSide-50: leading SI limit at 1-5 GeV/c^2 for WIMP-nucleus and WIMP-e scattering

Agnes et al., Phys. Rev. Lett.121.081307 (2018)



DarkSide-50
(50 kg, LNGS)

10 kg

2010

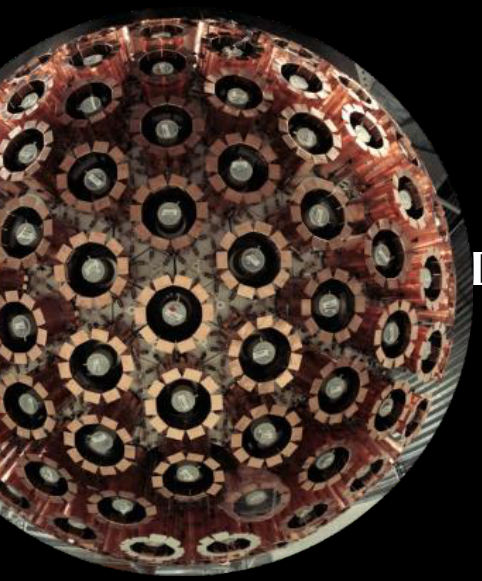
100 kg

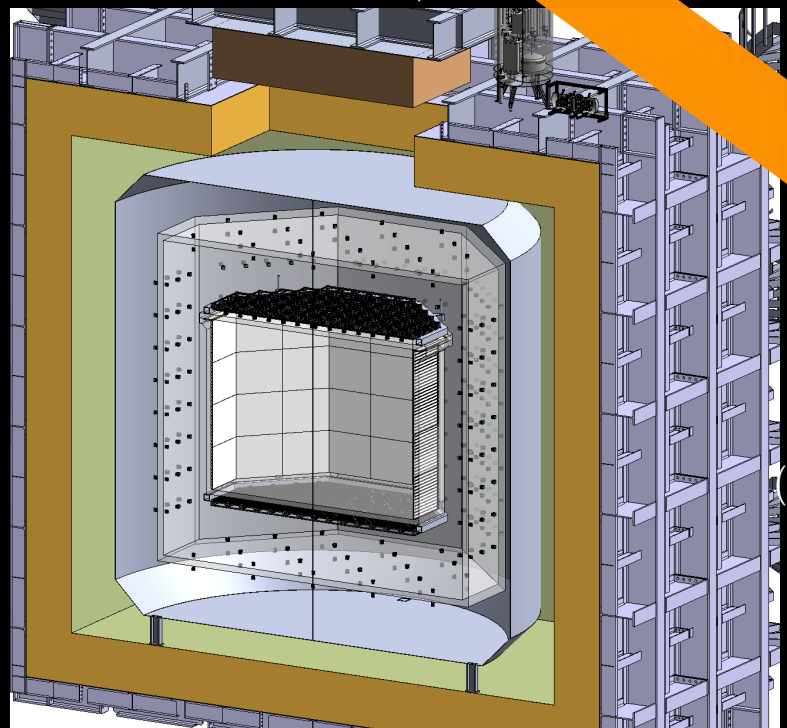
ArDM
(1t, LSC)

1,000 kg

2015

DEAP-3600 (3.6t, SNOLAB)





DEAP-3600:
parts-per-billion level
"S1" particle ID,
ultrapure acrylic cryostat

Ajaj et al,Phys. Rev. D (2019)

Global Argon Dark Matter Collaboration formed

APPEC

10,000 kg

2020

DarkSide-20k
(50t, LNGS)

100,000 kg

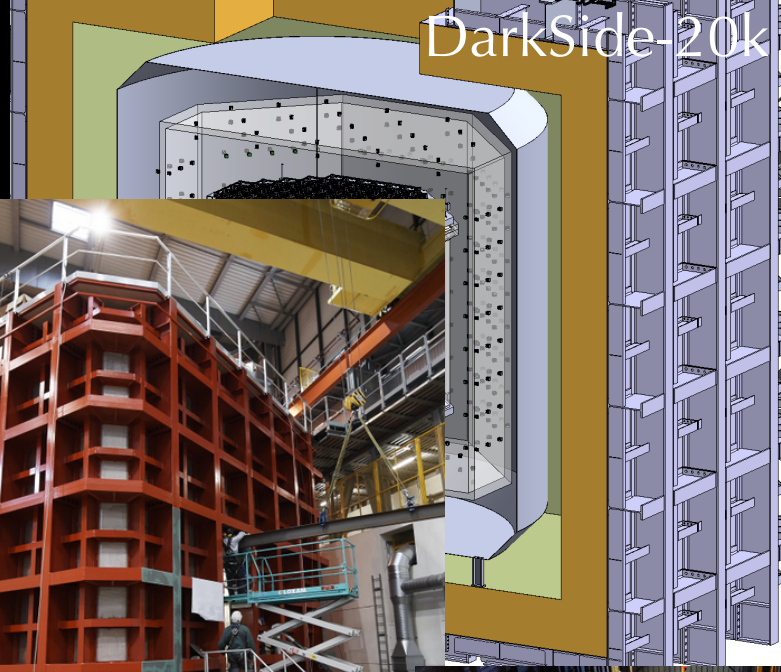
***Future: ARGO**: 400 t*

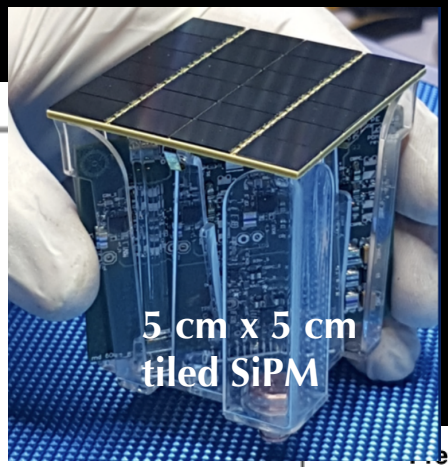
Technology Synergies

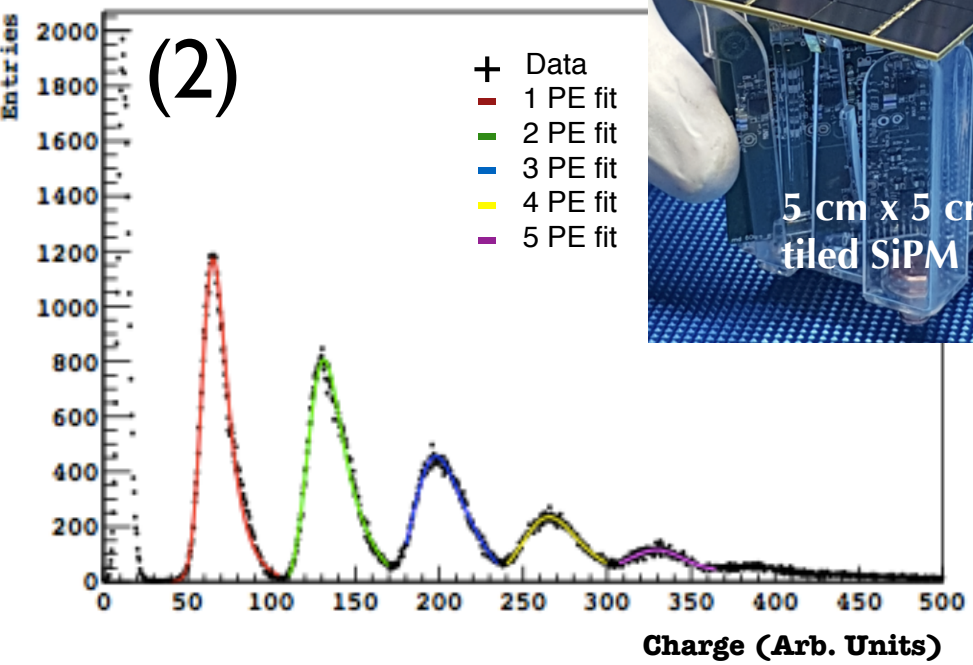
1. Cryostat technologies: DarkSide-20k cryostat uses technology developed for ProtoDUNEs

2. Photon sensors: low noise, high efficiency, cryo Si sensors developed by DarkSide-20k with FBK (LHC Si)

3. Isotopic enhancement: ARIA facility for depletion of Ar-39 in UAr, CERN Vacuum Group collaboration

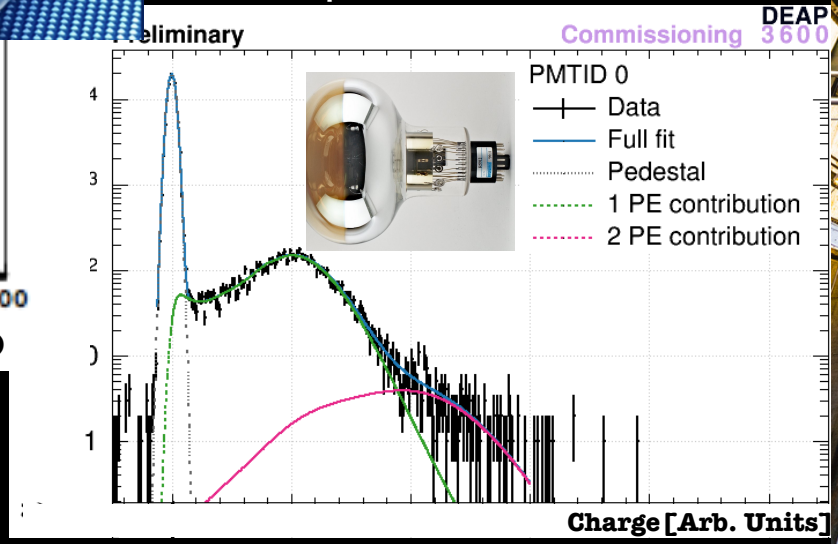




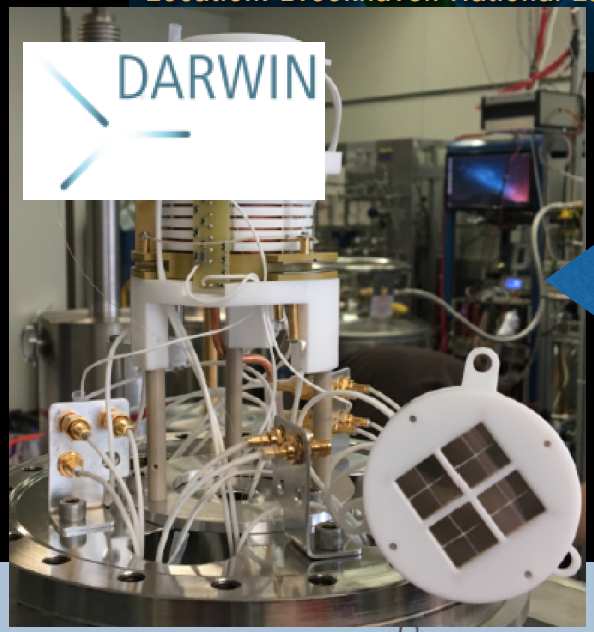


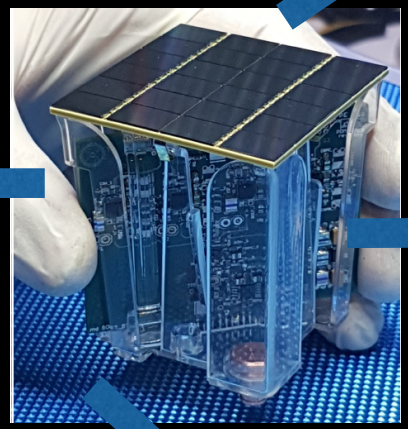
Aalseth, et al. JINST 12 (2017) no.09, P09030

for comparison:

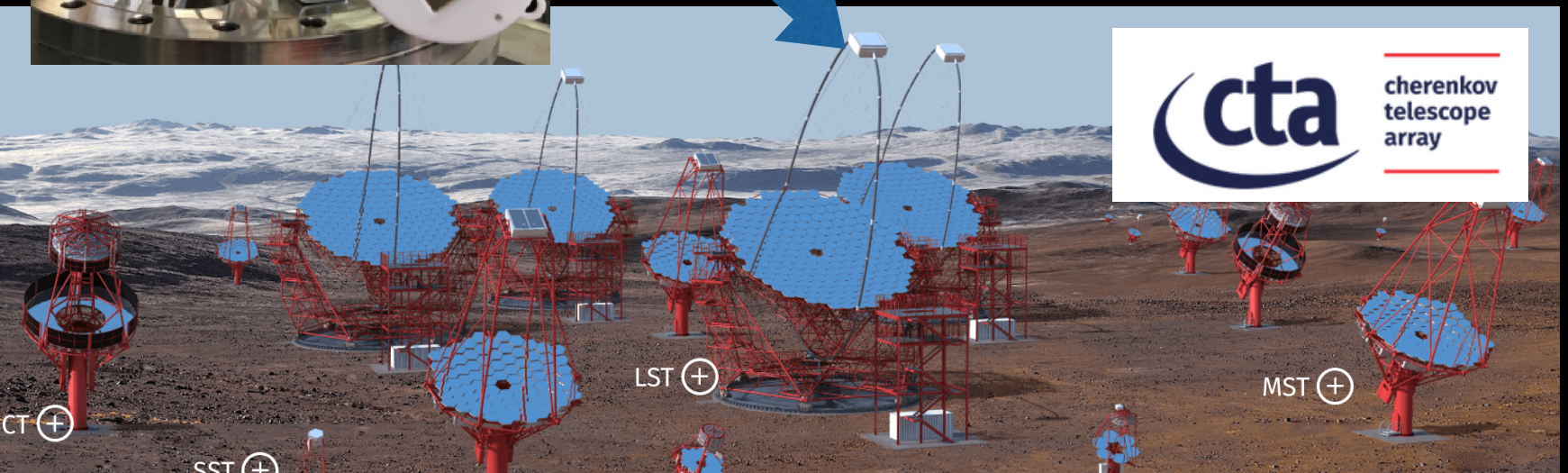


Experiments Exploring Cryogenic SiPM Technology





LEGEND
Large Enriched Germanium Experiment for Neutrinoless ββ Decay

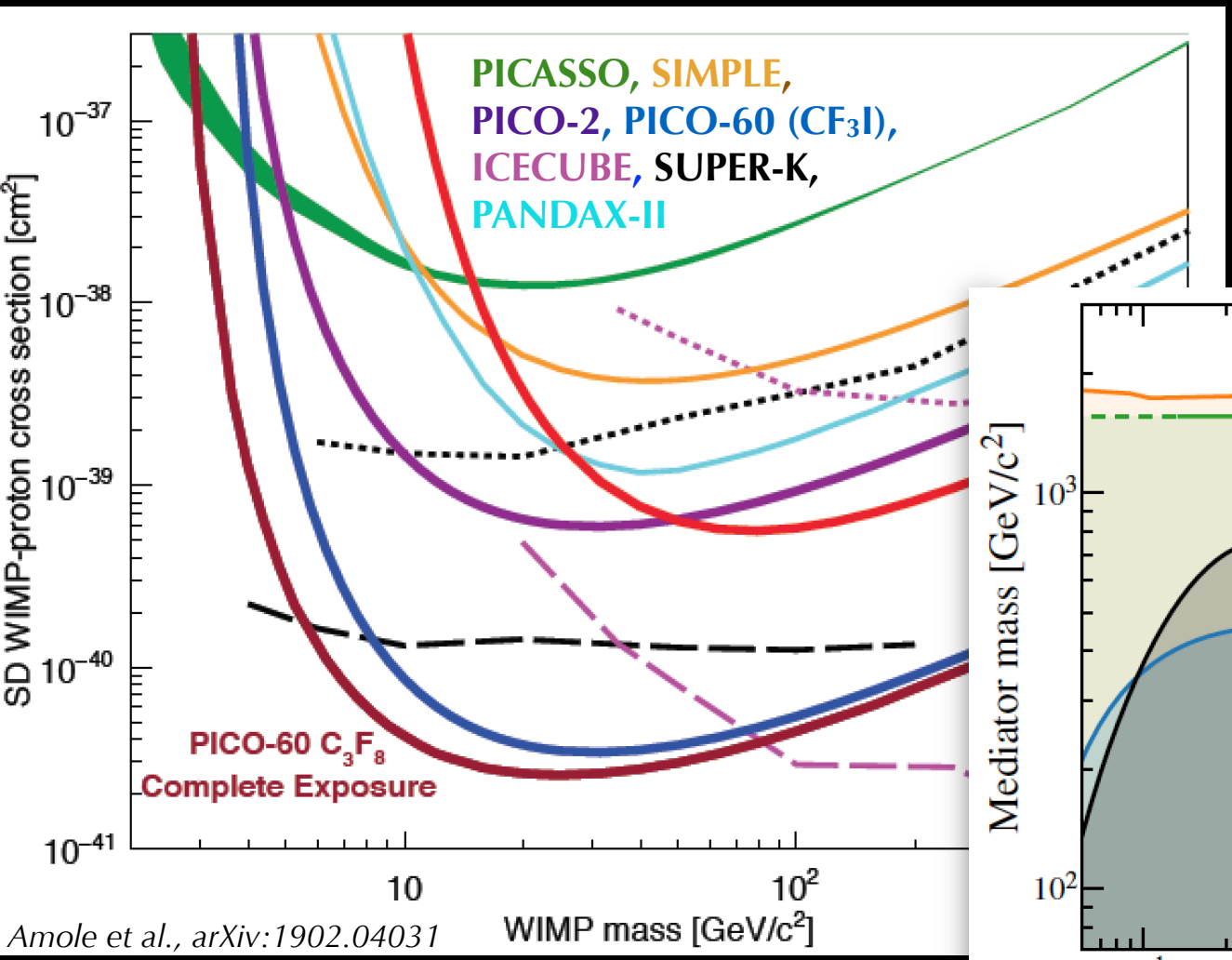


+ medical imaging, environmental monitoring, automated navigation (LIDAR) …

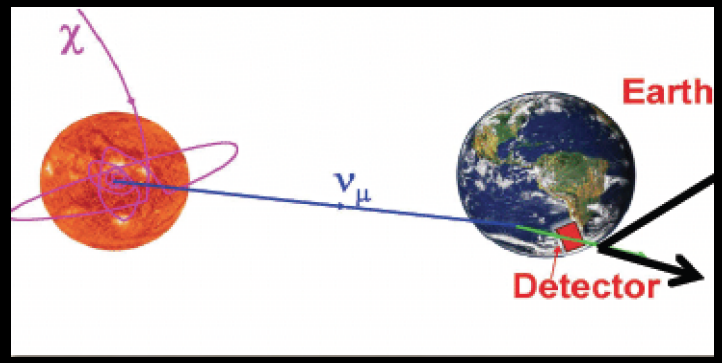
Spin-Dependent Interactions

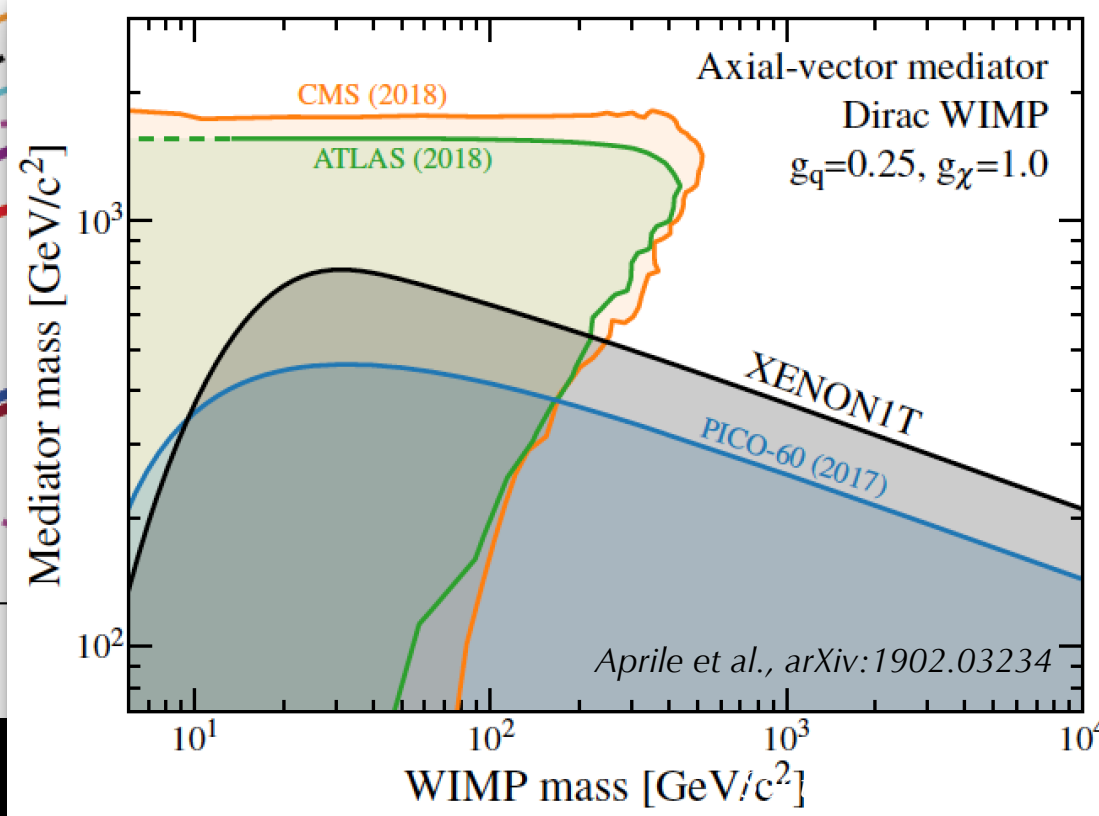
Direct Detection: leading WIMP-p limit at low mass from PICO-60, 500 kg upgrade planned. Best WIMP-n limits at high mass from Xenon-1T, at low mass from collider searches (for specific operators)

Indirect Detection: leading WIMP-p limit at high mass from neutrino telescopes, via WIMP scattering on p, +capture in the sun, leading to annihilation signatures.



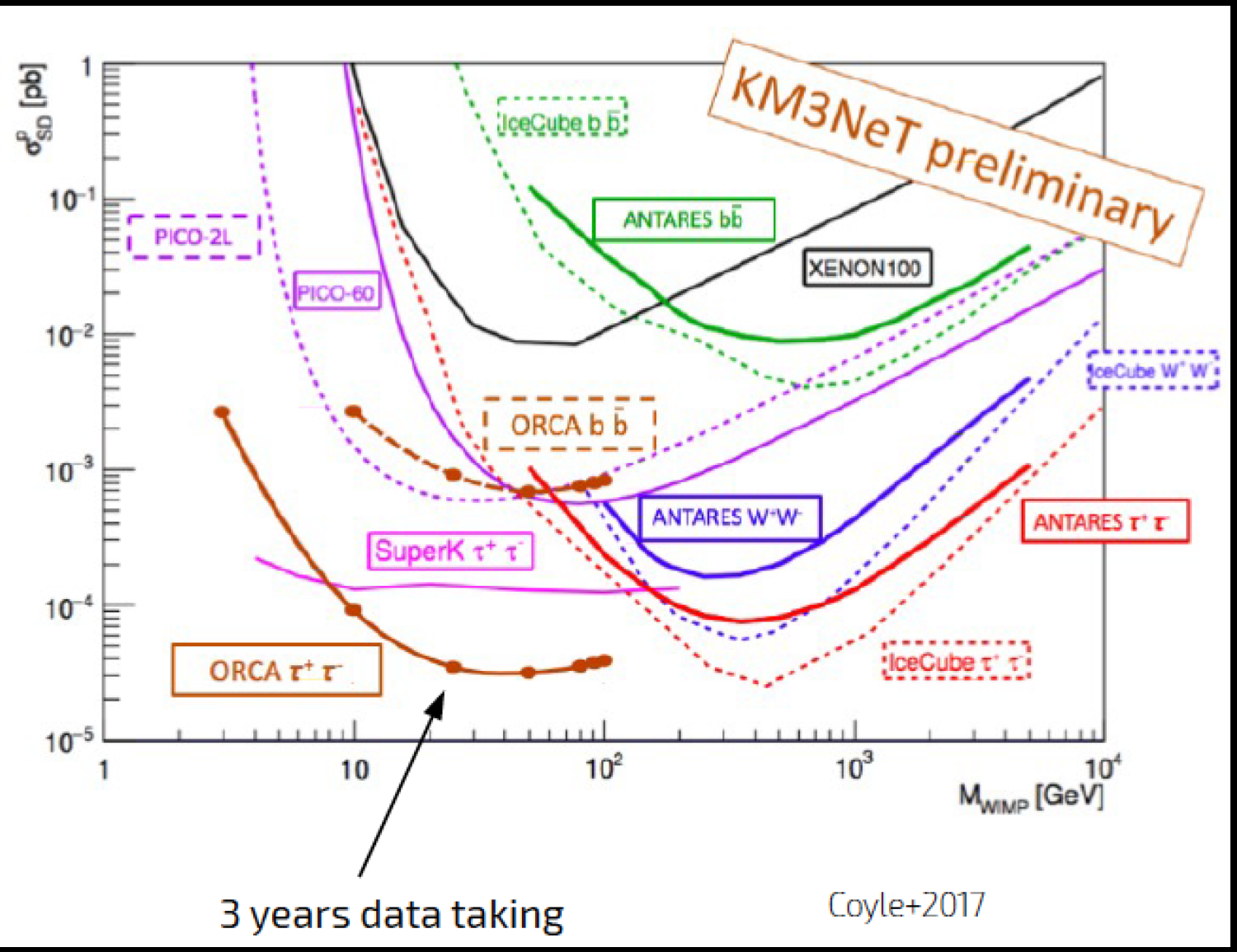
Amole et al., arXiv:1902.04031





Aprile et al., arXiv:1902.03234

Spin-Dependent Interactions: Prospects



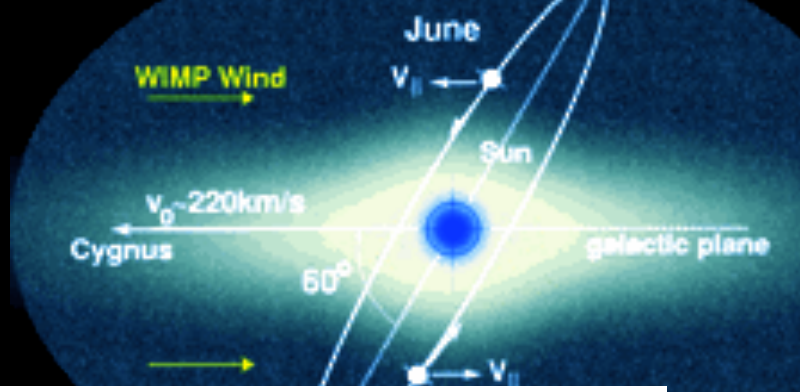
+PINGU sensitivity extends reach 1-2 orders of magnitude at low mass (<10 GeV)

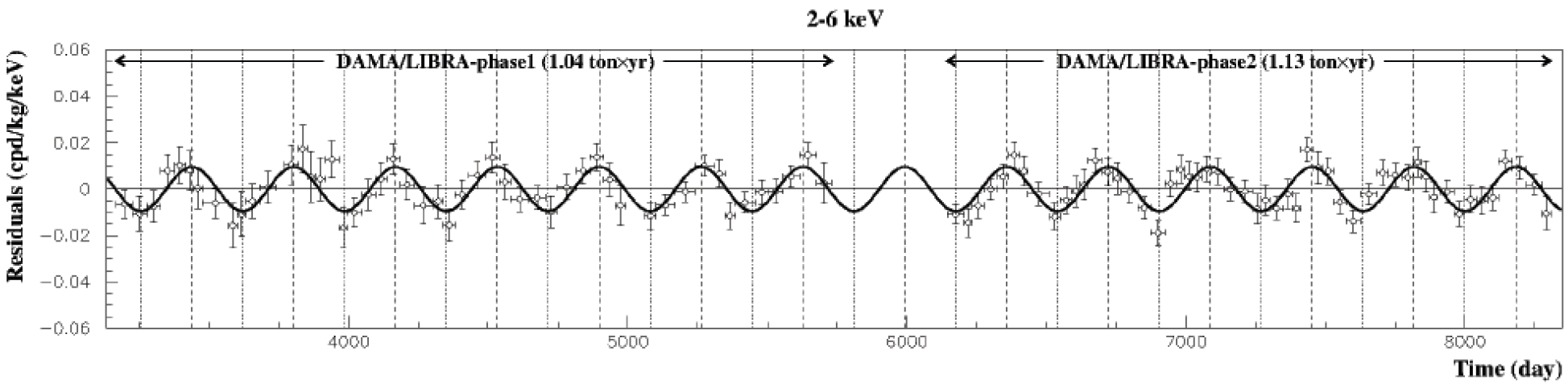
+Hyper-K galactic center search can approach the thermal relic bound

Direct Detection: Candidate Signal

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

DAMA/LIBRA: measure (0.0095±0.0008) cpd/kg/keV,
t_0 = (145±5) d in 2.17 tonne-yr.



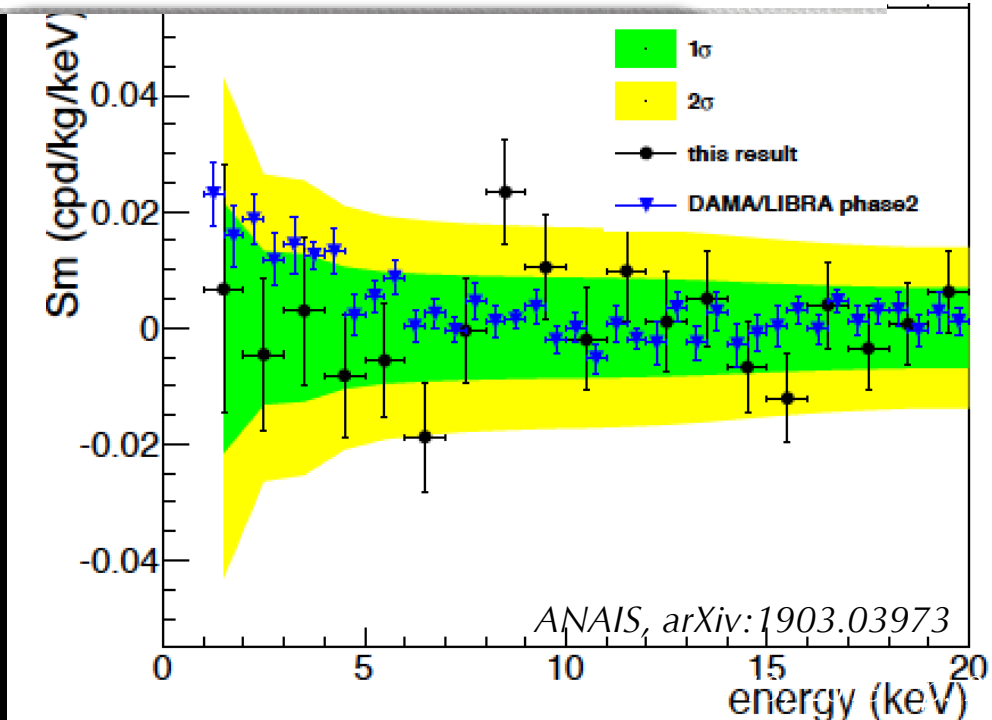


CSLNGS, March 2018

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*

Using the same target (NaI):
ANAIS (LSC), **SABRE** (AU), **COSINE-100** (Y2L)
~consistent at 1σ, project 3σ test in 5 years.



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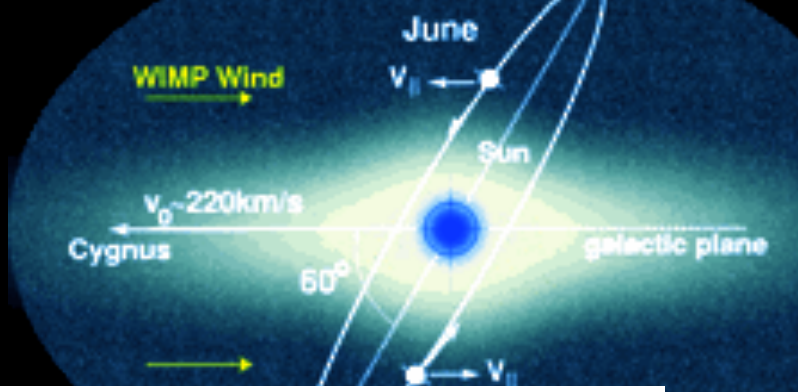

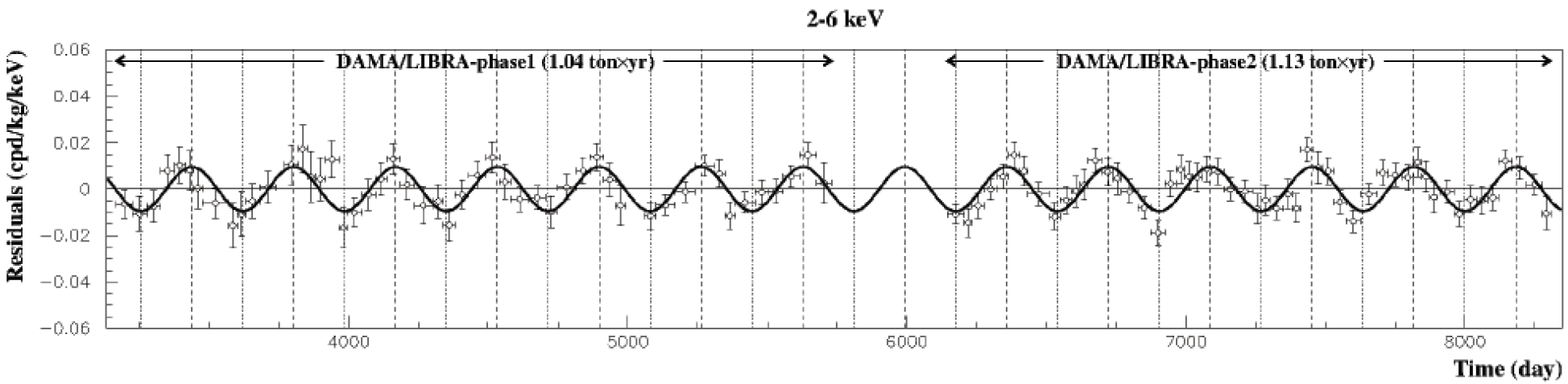

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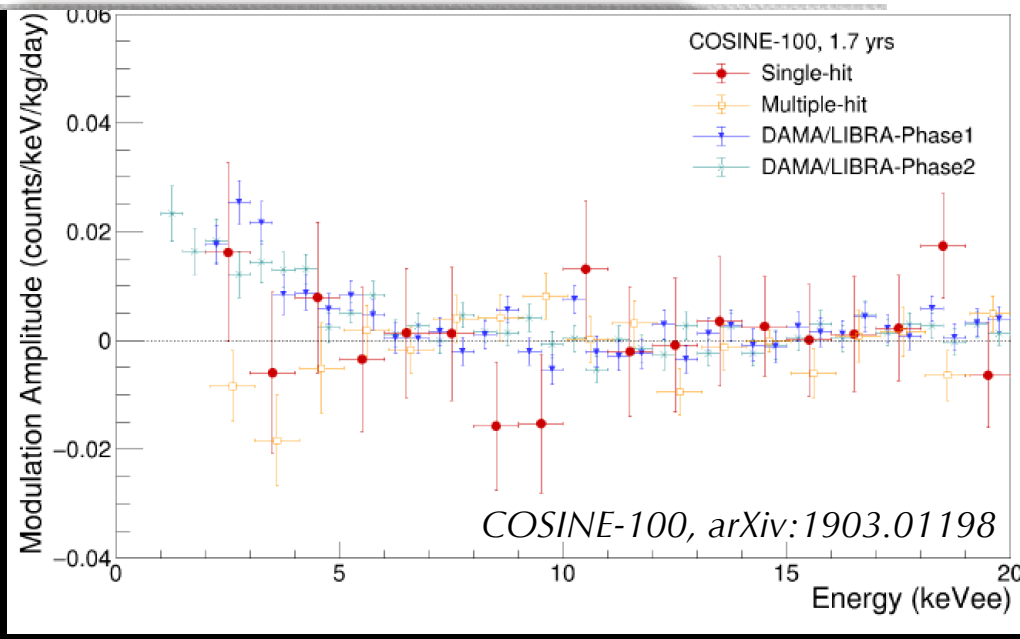
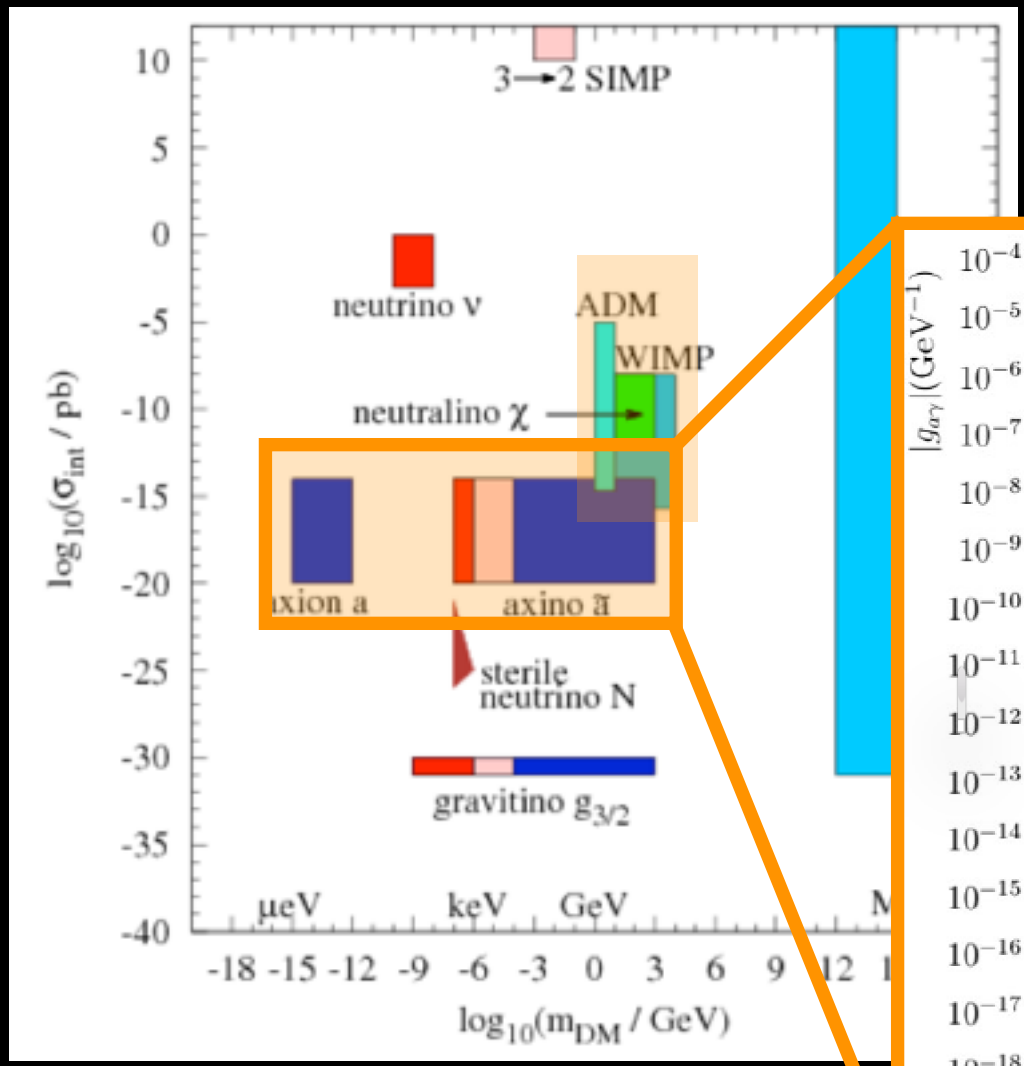


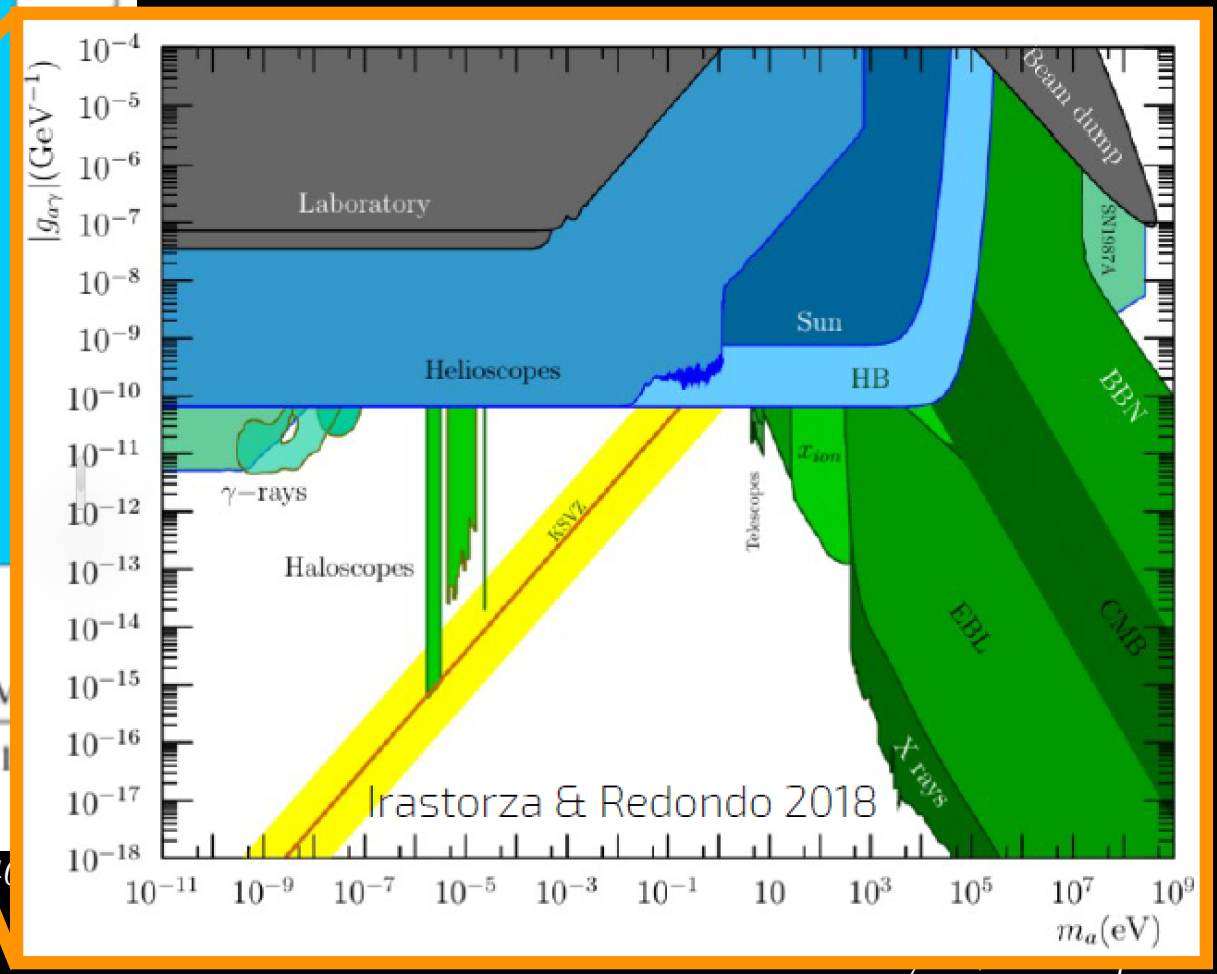
Direct Detection Status

Wide range of parameters!

Direct detection searches historically optimised for WIMP sensitivity...



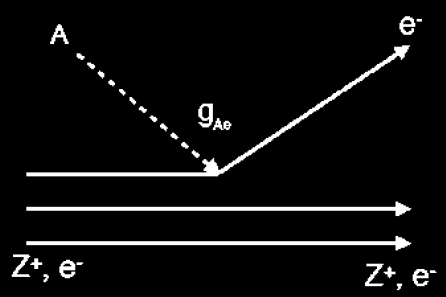
+big recent expansion of interest in laboratory axion searches!



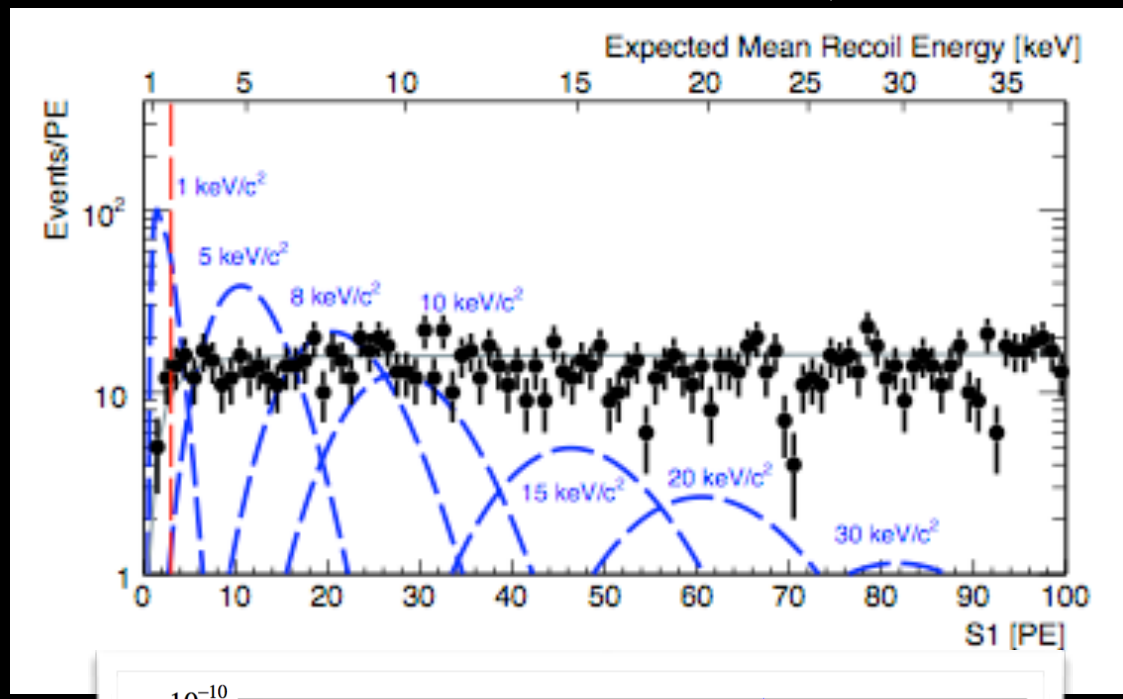
Baer et al., arXiv:1

Bump Hunts in Direct Detection

search for axio-electric effect:



XENON100, arXiv:1404.1455



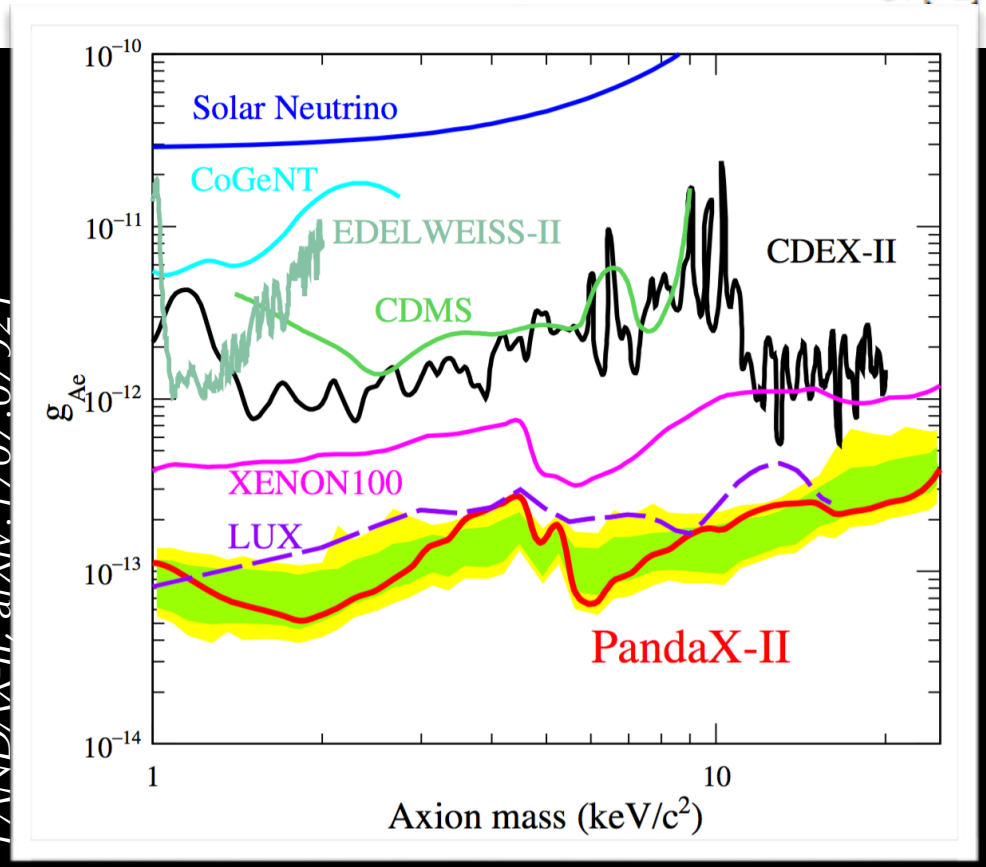
Signal: peak in electron recoil spectrum at axion-like particle (ALP) mass.

Backgrounds: electron recoils, ~1E-4/(keV kg day).

Contraints on new pseudoscalars at ~10 keV/c^2 via ALP-electron coupling. Projected reach of DARWIN is >x20.

Constraints on vector particles at 0.1-100 MeV/c^2 via limits on kinetic mixing to hidden sector. *(arXiv:1901.10478)*

Constraints on new scalar (and vector) bosonic SuperWIMPs in 10-100 keV/c^2 *(arXiv:1709.02222)*



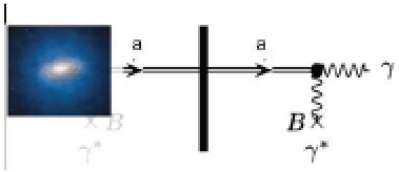
PANDAX-II, arXiv:1707.07921

Axion Searches

Axion/ALP searches: Mature Key Techniques

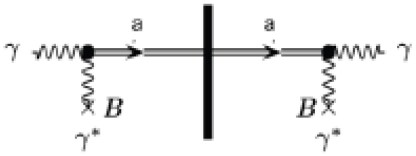
Helioscopes

- Build on success of CAST hosted by CERN
- Proposed BabyIAXO, leads to IAXO, with large discovery potential



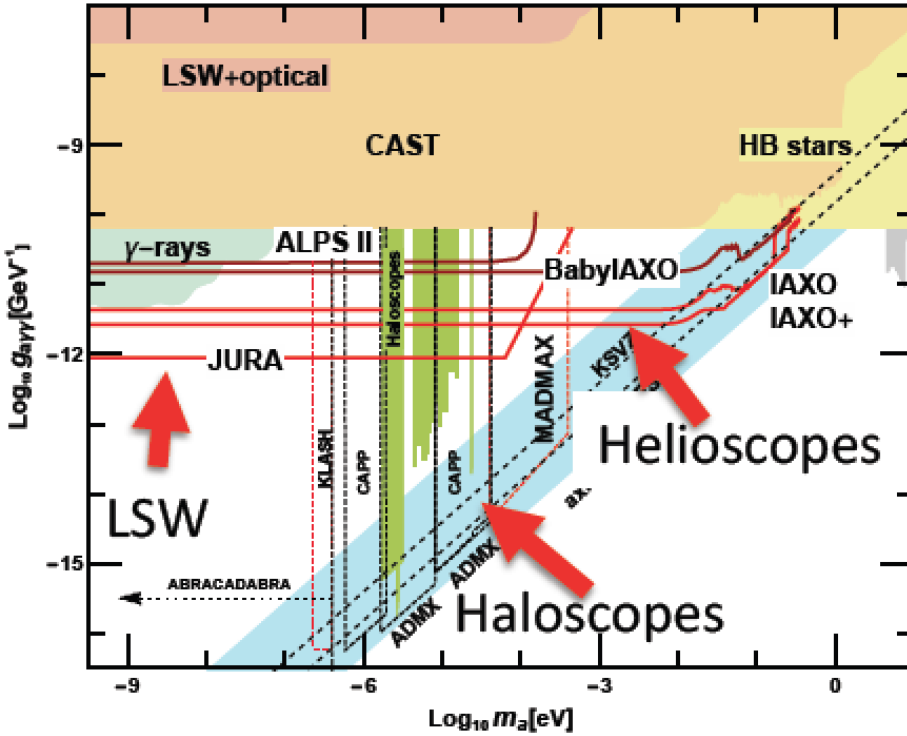
Haloscopes

- ADMX (US) is leading the field
- In Europe, MadMax is new key player
- Smaller efforts developing new techniques



Light-shining-through-walls

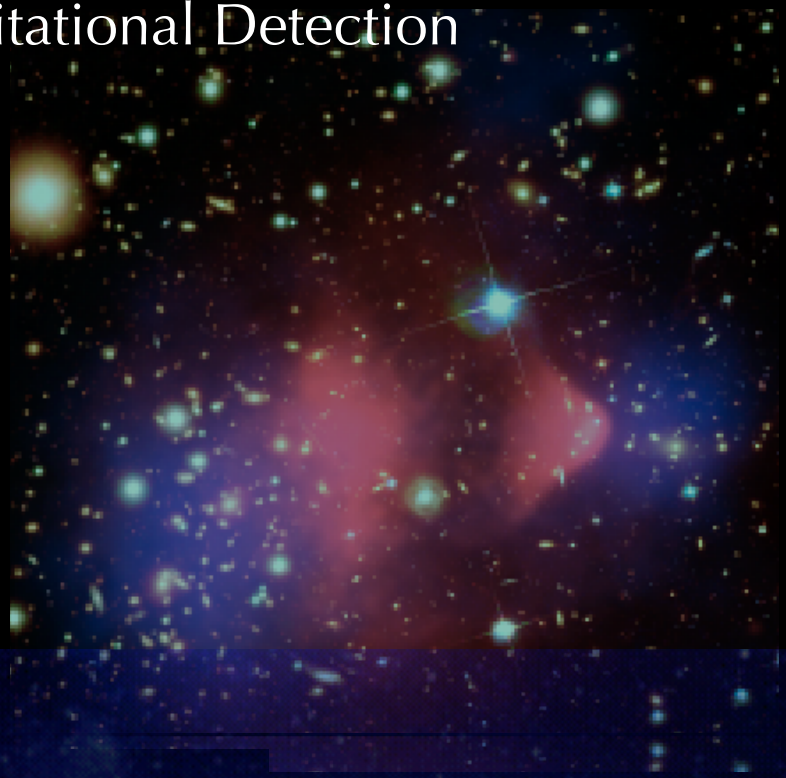
- ALPS II is well underway
- STAX is a new idea RF based
- JURA is long term plan



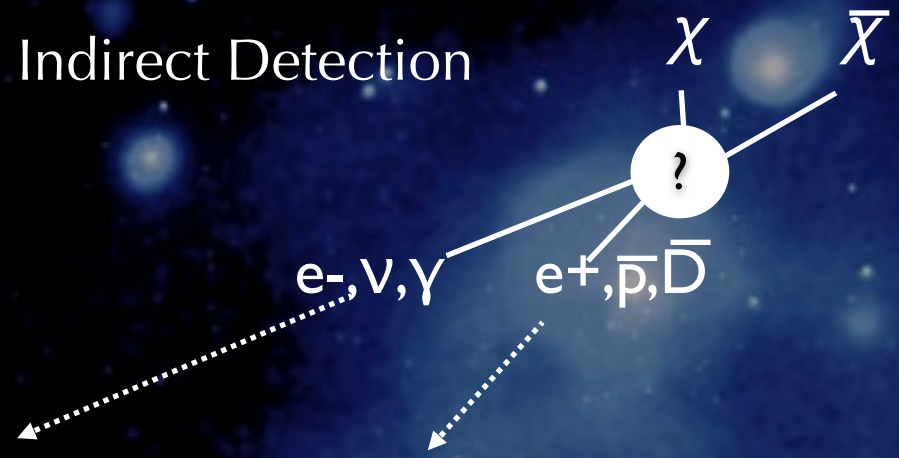
Searches relevant for both QCD Axions and more general Axion-like particles (ALPs)

+many interesting new ideas in quantum measurement techniques, atom interferometers, …

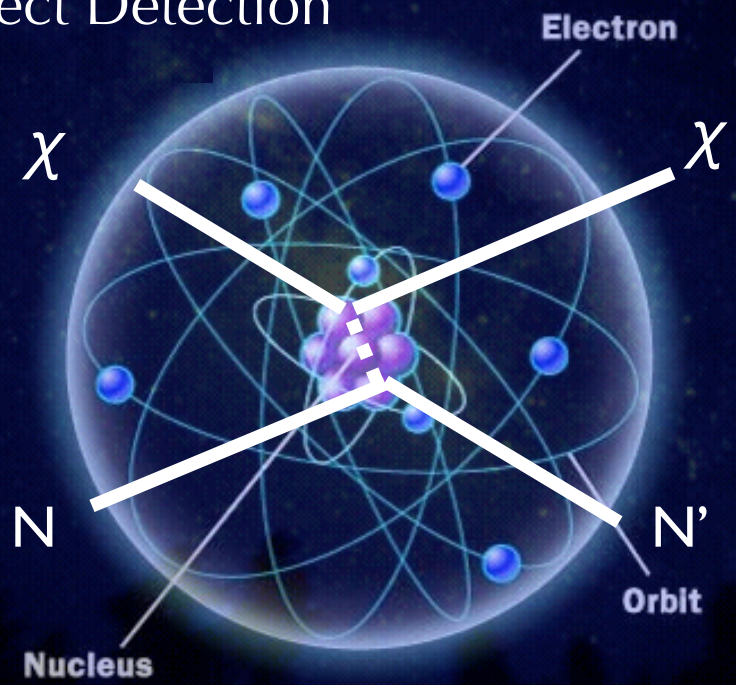
Gravitational Detection



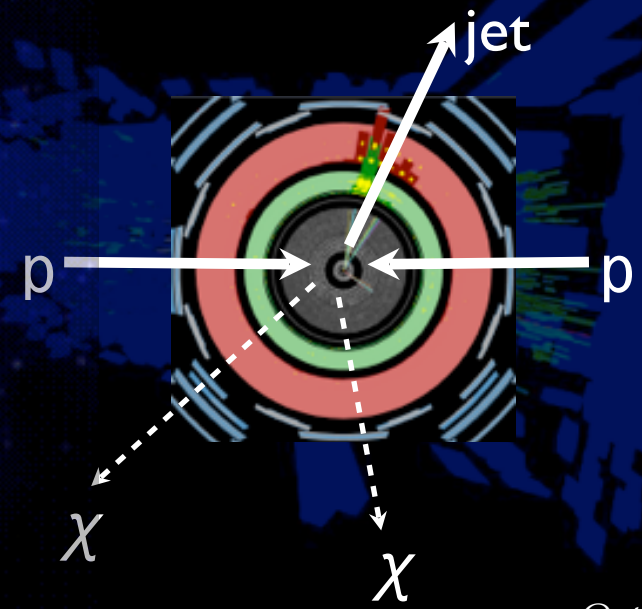
Indirect Detection



Direct Detection



Accelerator Production



Collider Searches, Complimentarity

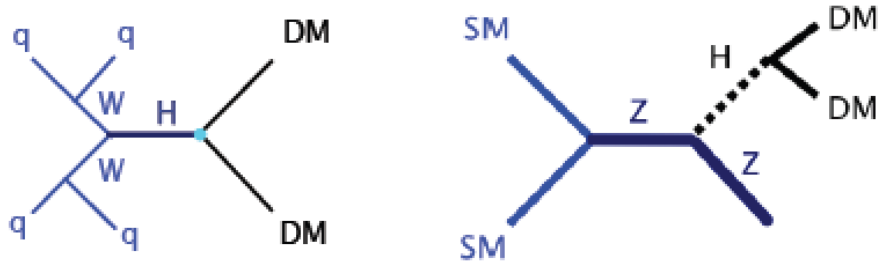
Ellis et al., ESPPU Physics Briefing Book, CERN-ESU-004 (2019)

- Limits on BR can be translated to limits in the DM-nucleon plane

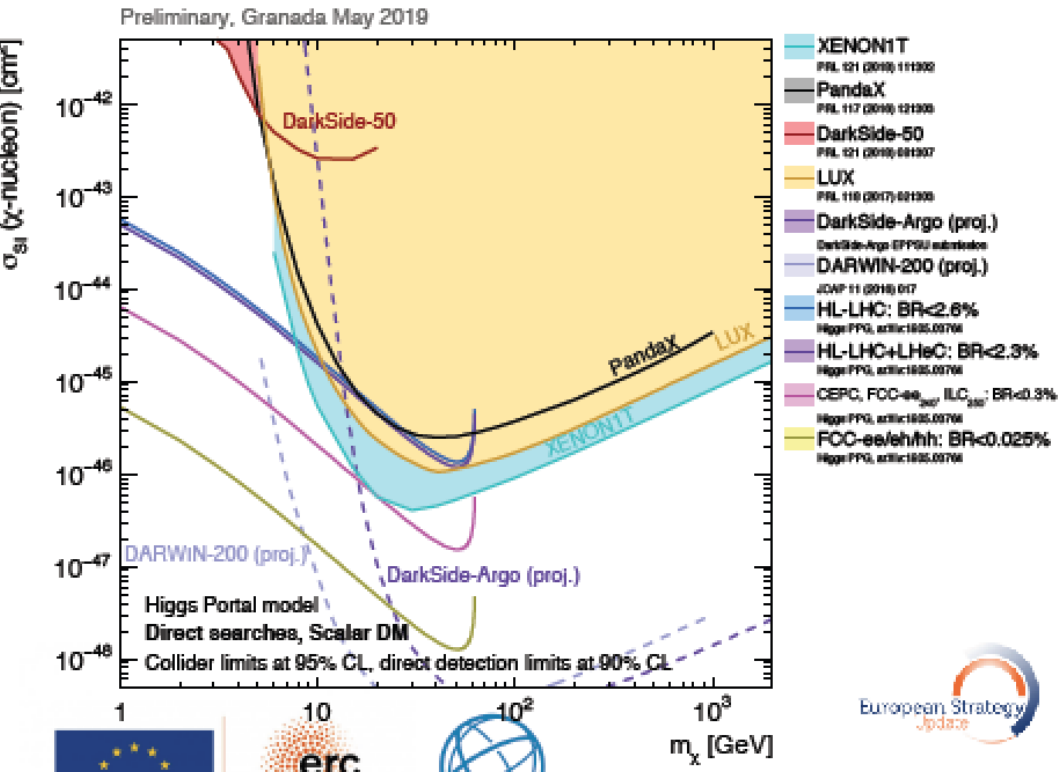
$$\sigma_{\chi N} = \Gamma_{\rm inv} \frac{8 m_N^4 f_N^2}{v^2 \beta m_h^3 (m_\chi + m_N)^2} g_\chi \left(\frac{m_h}{m_\chi}\right), \qquad (15)$$

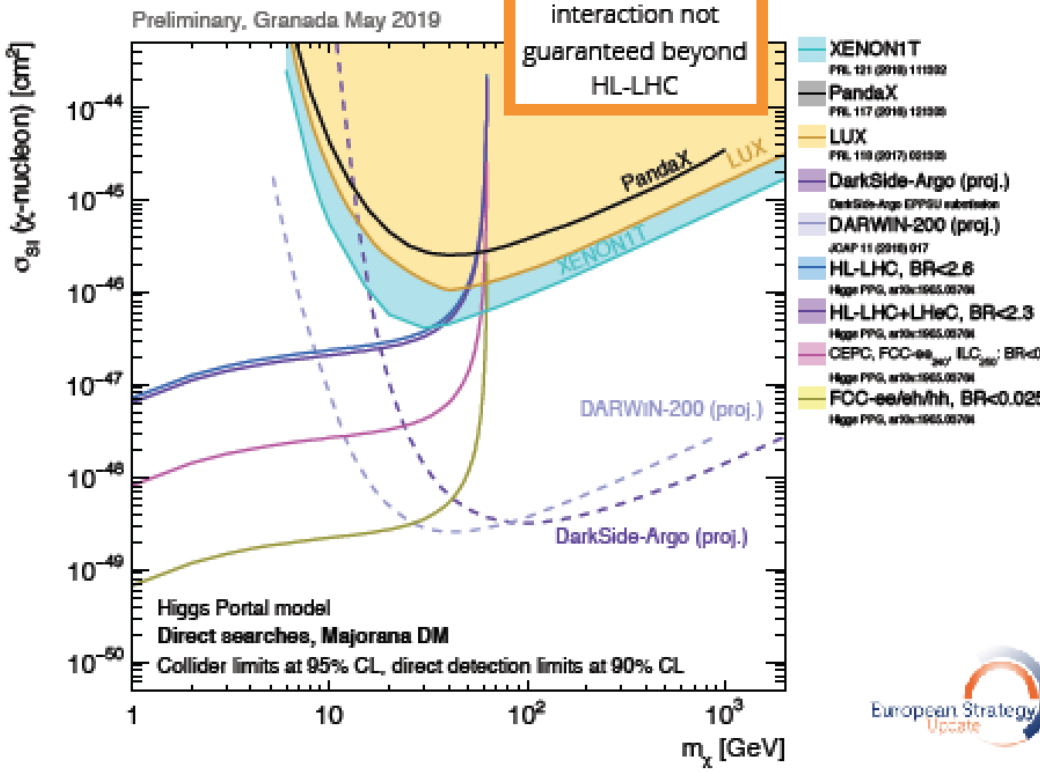
arXiv:1708.02245

where $g_S(x) = 1$,
$g_f(x) = 2/(x^2-4)$, $\beta = \sqrt{1-4m_\chi^2/m_h^2}$, $v = 246\,\mathrm{GeV}$



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



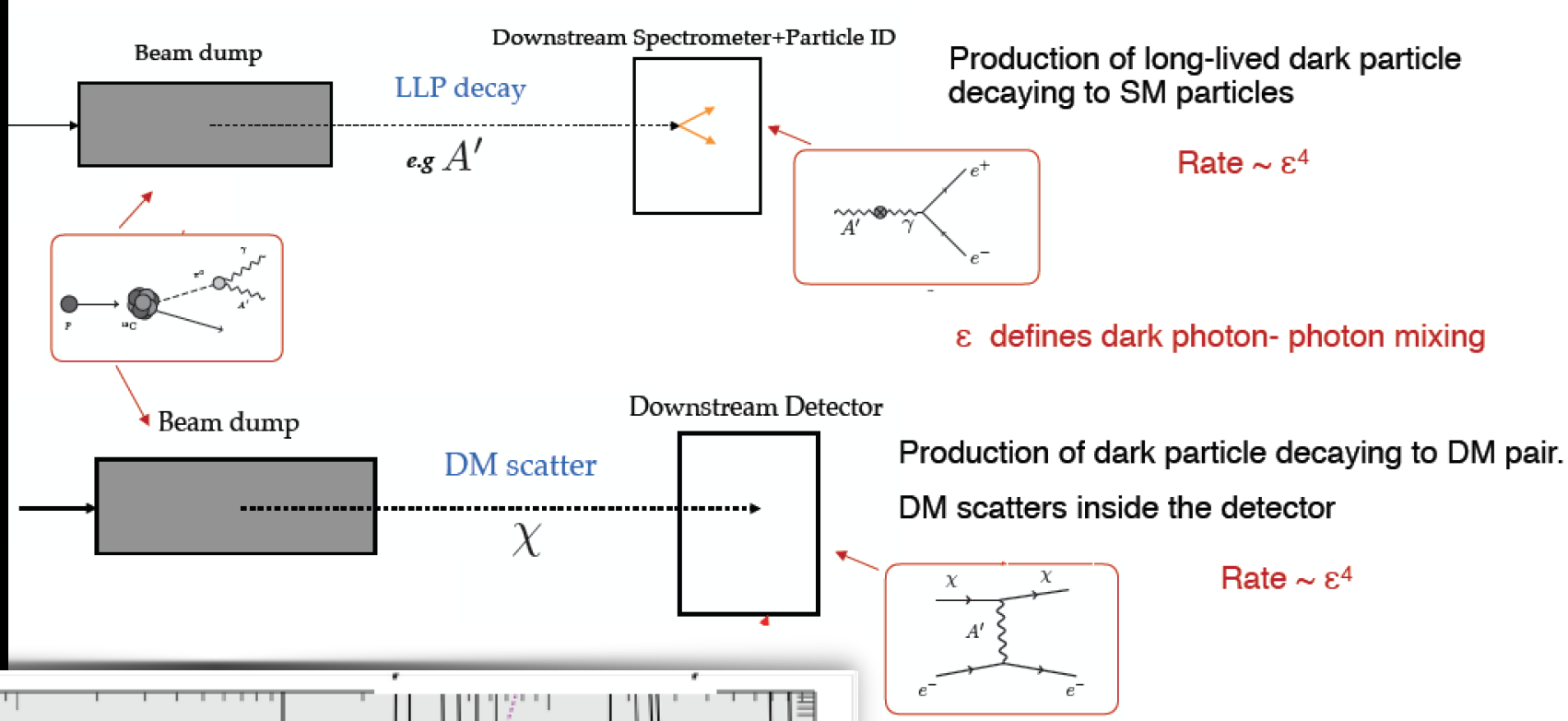


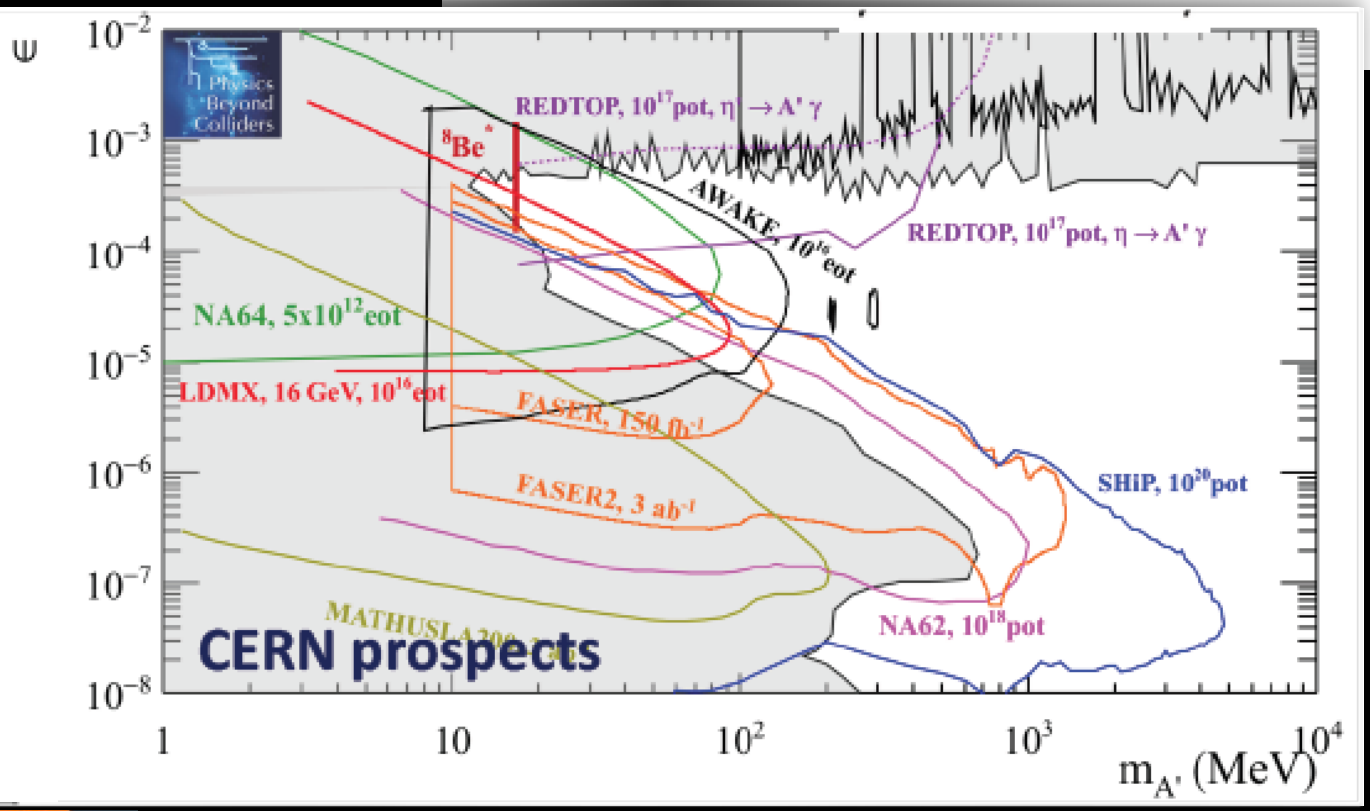
Caterina Doglioni - 2019/05/13 - European Strategy Update 24

Fixed-Target Searches

Renaissance of the fixed-target!

New sociology of DM searches.





Many new experiments planned or proposed for hidden sector searches.

Major synergistic topic of Dark Sectors group at ESPPU.

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

Big Questions for the Dark Sector

(a la European Strategy for Particle Physics Update 2019)

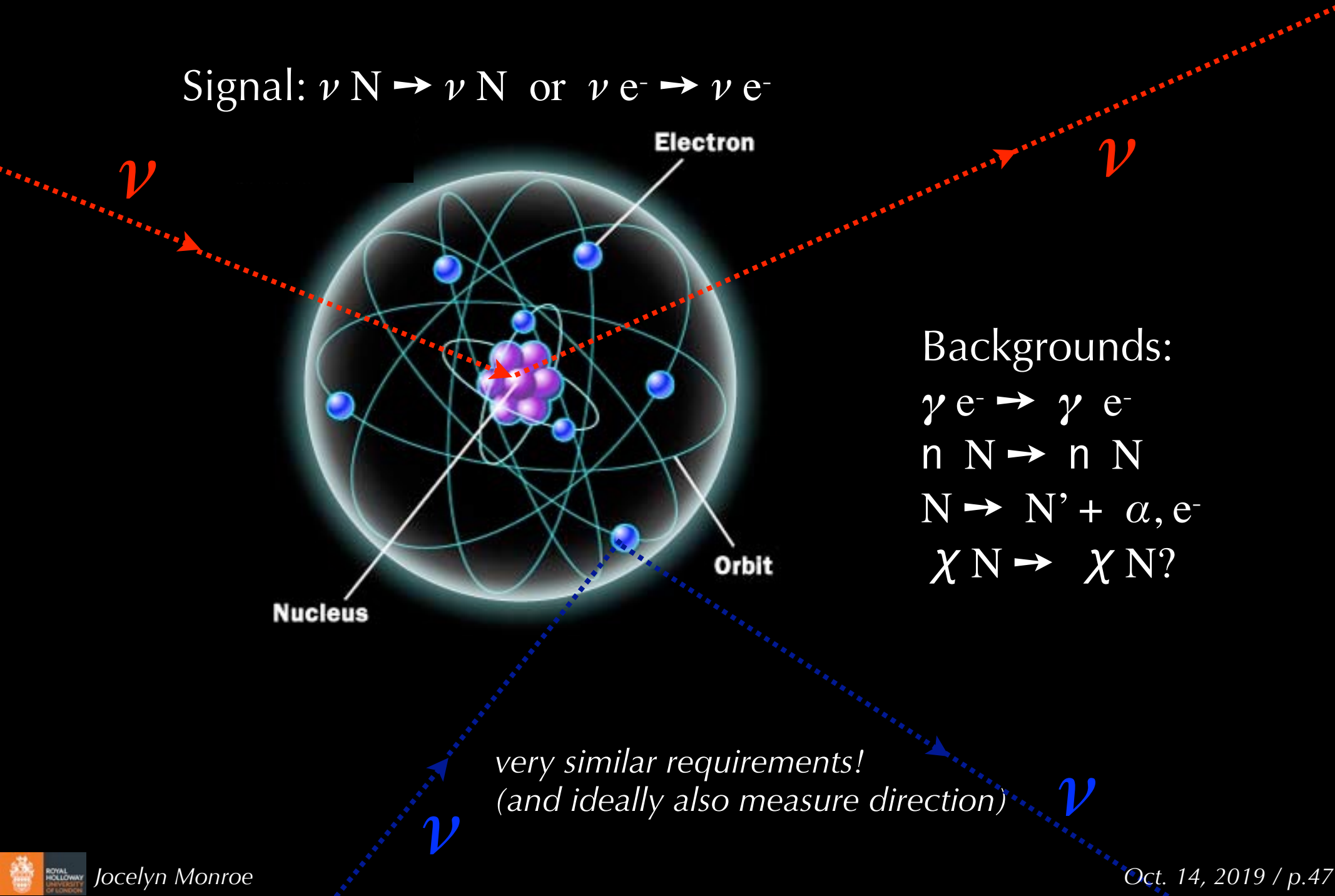
1) How do we search for dark matter, depending on its properties?

2) What are the highlights and challenges of the experimental programs, current or near-future, that address different regions of parameter space?

3) How can dark matter detection experiments inform/guide energy and **intensity** frontier experiments, and vice versa?

~~Dark Matter Direct~~ Neutrino Detection

Signal: $\nu\, N \rightarrow \nu\, N$ or $\nu\, e^- \rightarrow \nu\, e^-$



Backgrounds:

$\gamma\, e^- \rightarrow \gamma\, e^-$

$n\, N \rightarrow n\, N$

$N \rightarrow N' + \alpha, e^-$

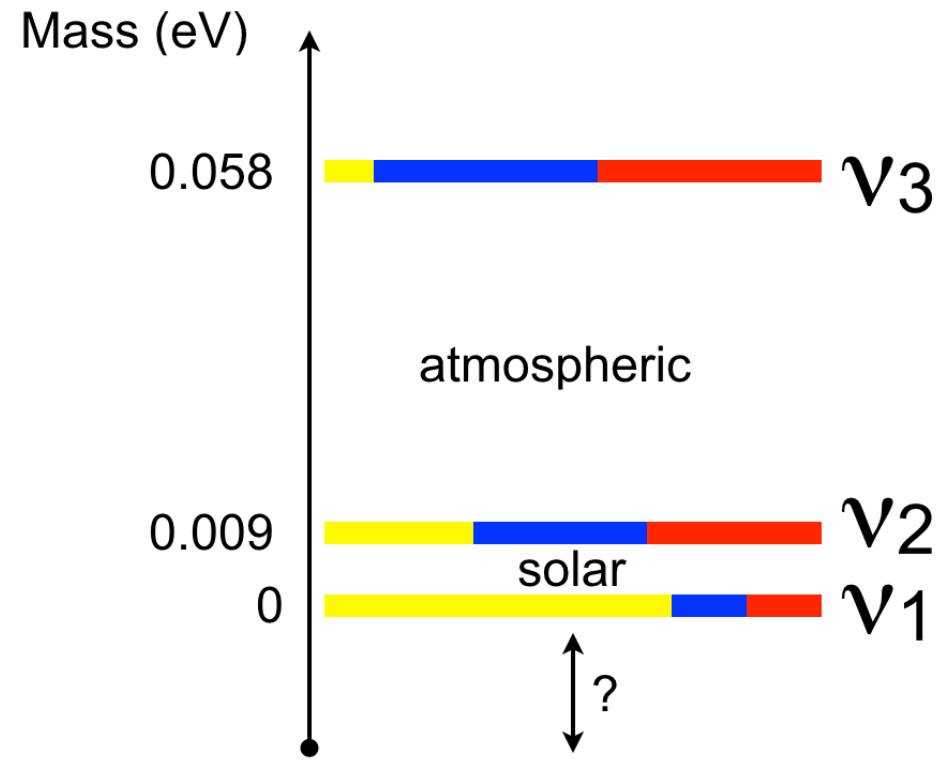
$\chi\, N \rightarrow \chi\, N$?

very similar requirements!
(and ideally also measure direction)

What can future dark matter direct detection experiments tell us about the neutrino?

Open Questions

- What is absolute mass scale?
- Details of neutrino oscillation?
  - Is $\theta_{23} = 45°$?
  - CP violation?
- Mass hierarchy?
- Why is m_ν so small?
- Majorana or Dirac?
- Are there sterile neutrinos?



flavour key:

ν_e ν_μ ν_τ

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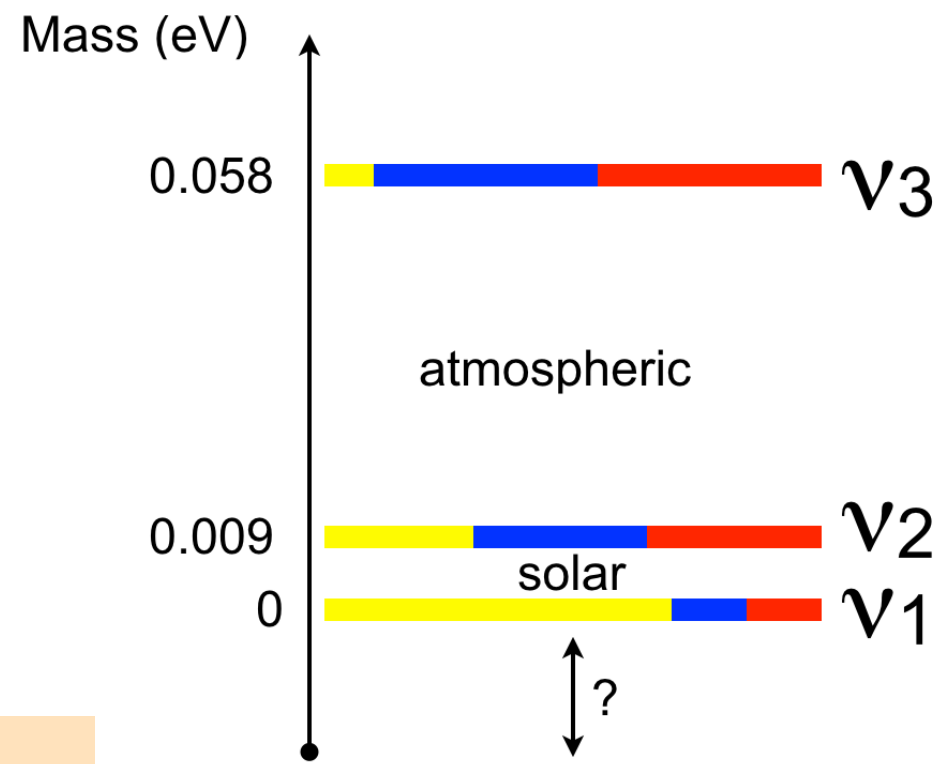
(Xe)
(Ar)

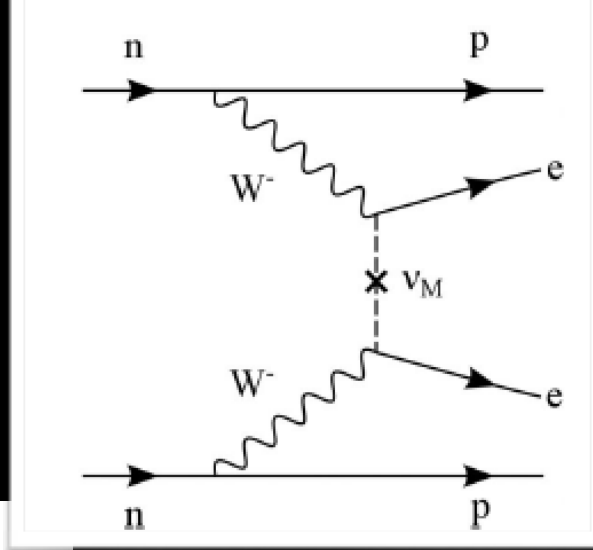


flavour key:

ν_e ν_μ ν_τ

ν-less Double Beta Decay

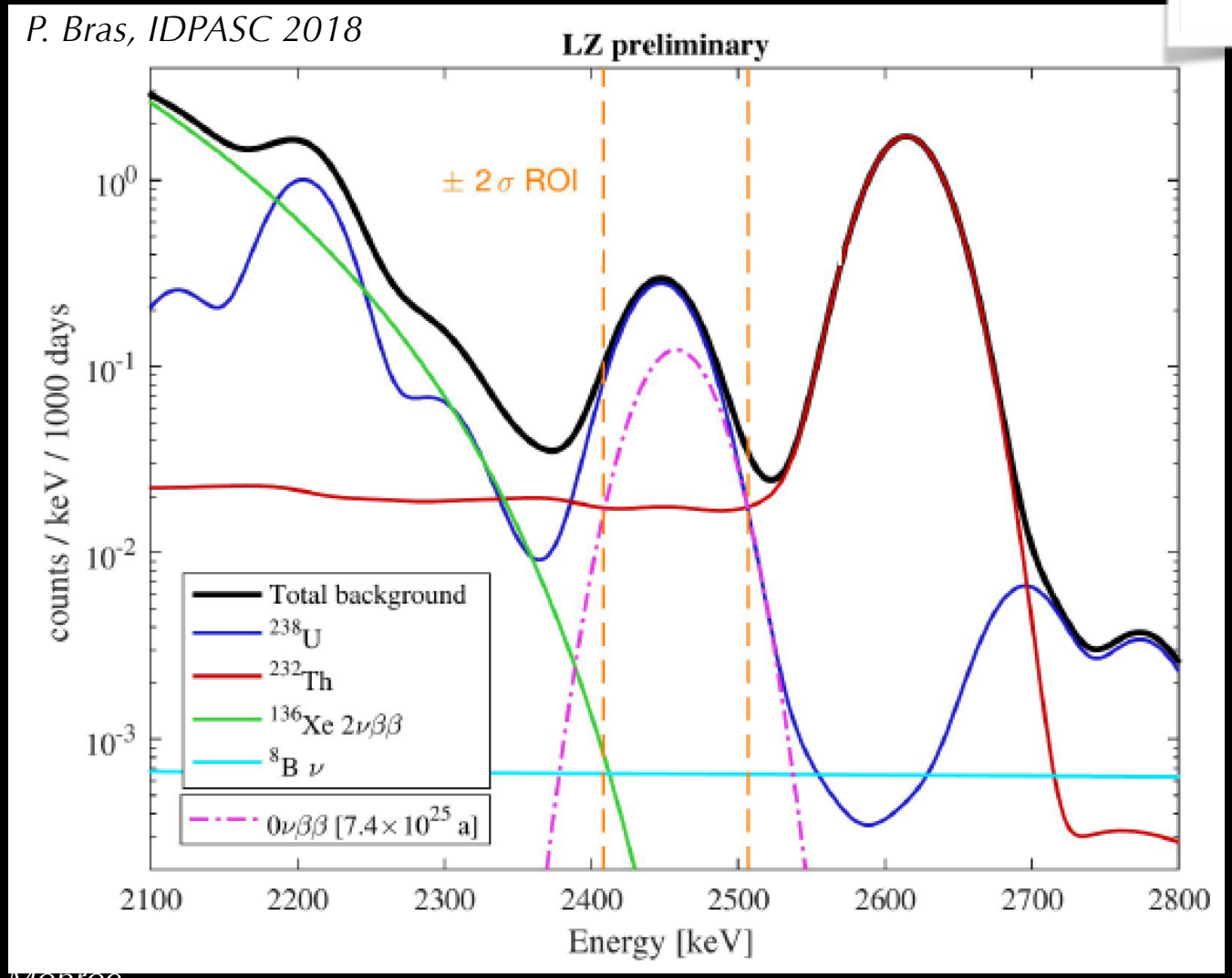
The liquid Xenon dark matter searches aim for competitive sensitivity to neutrinoless double beta decay.



example: projected sensitivity in **LZ**:

Q-value= 2458 keV

P. Bras, IDPASC 2018



<u>big opportunity:</u>
significant Xe-136 target mass (~600 kg)

<u>big challenges:</u>
backgrounds, energy resolution, and nuclear matrix element uncertainty

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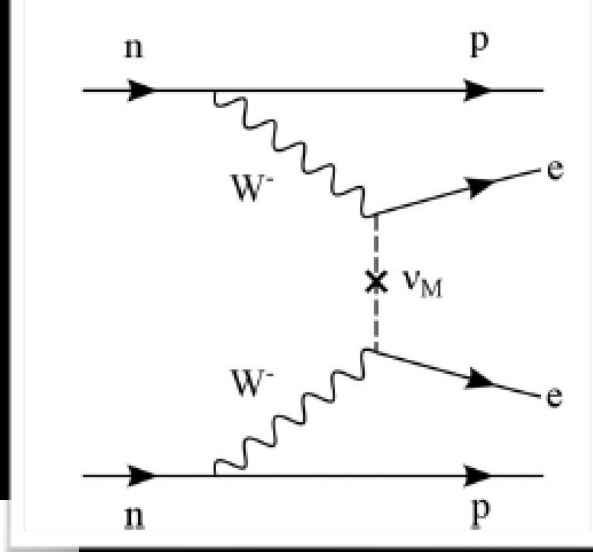
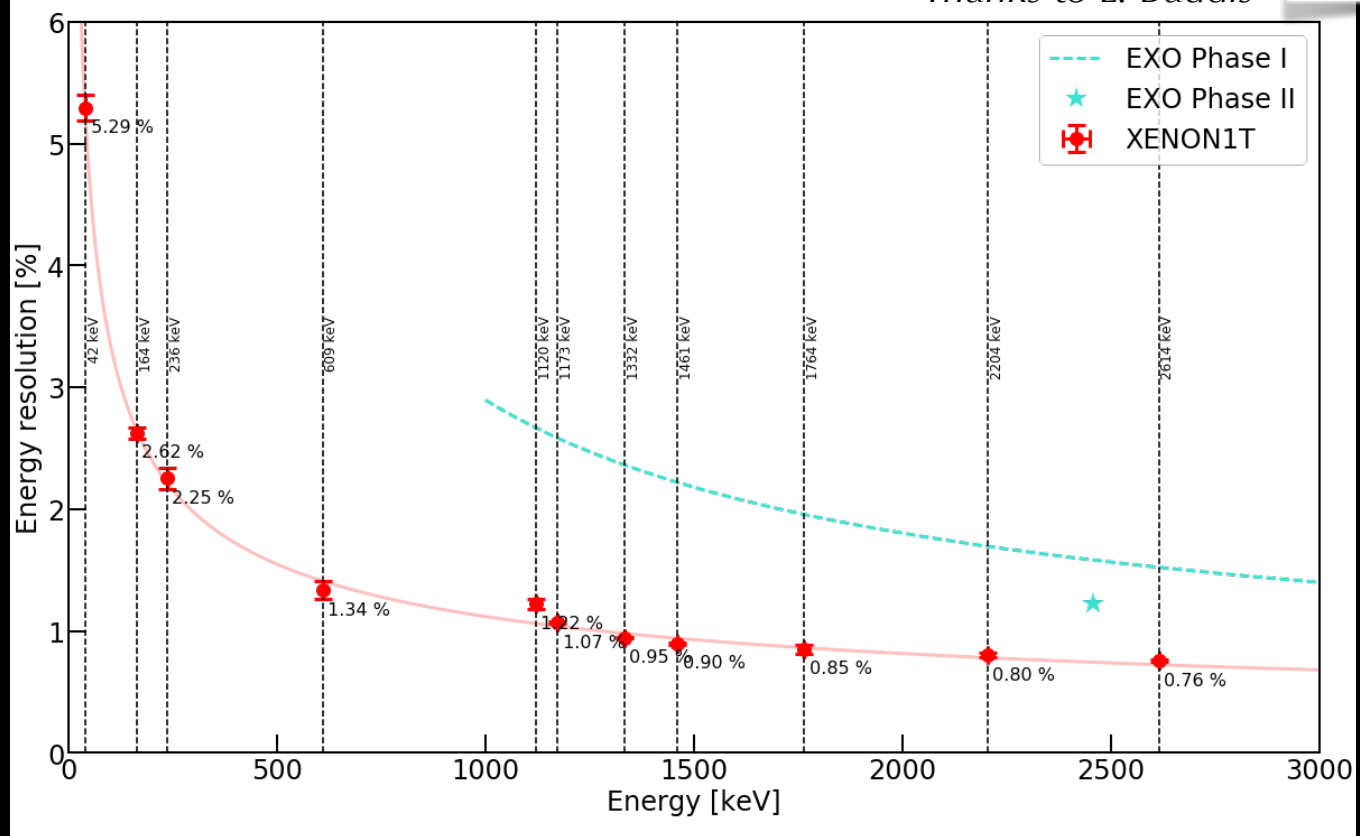


example: **Xenon1T** energy resolution

Q-value= 2458 keV

Thanks to L. Baudis



recent demonstration of sensitivity to ***rare*** processes: Xe-124 two-neutrino double e- capture, *arXiv:1904.11002*

<u>big opportunity:</u>
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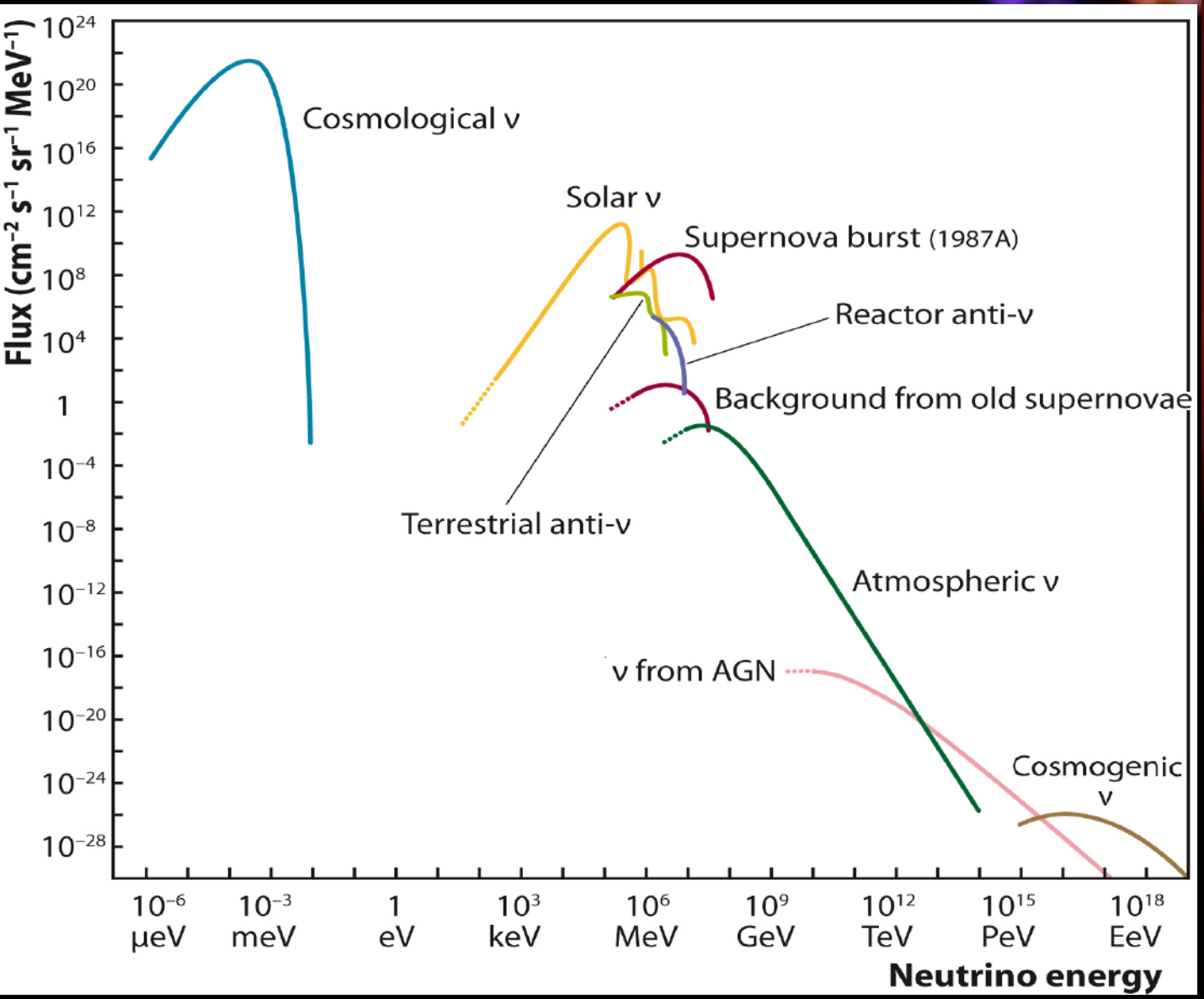
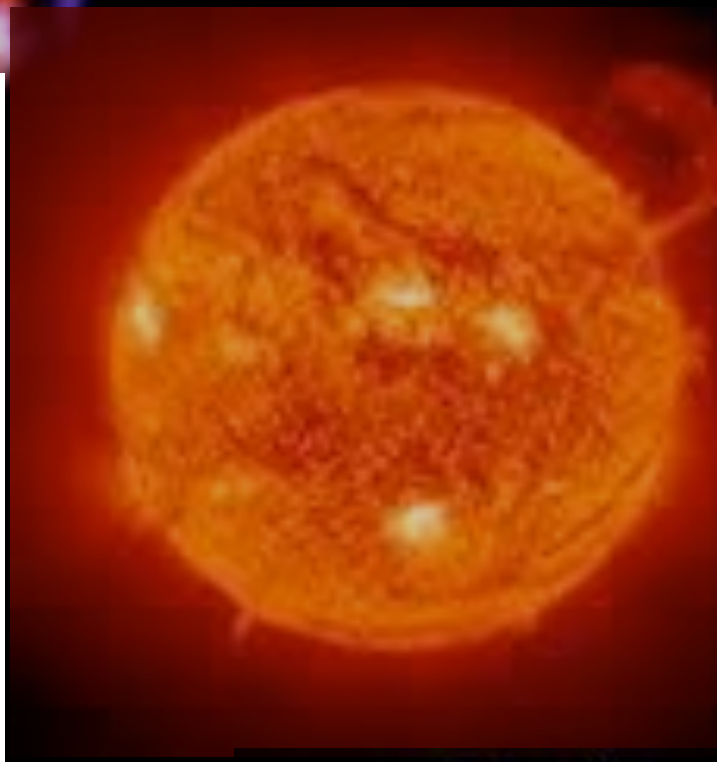
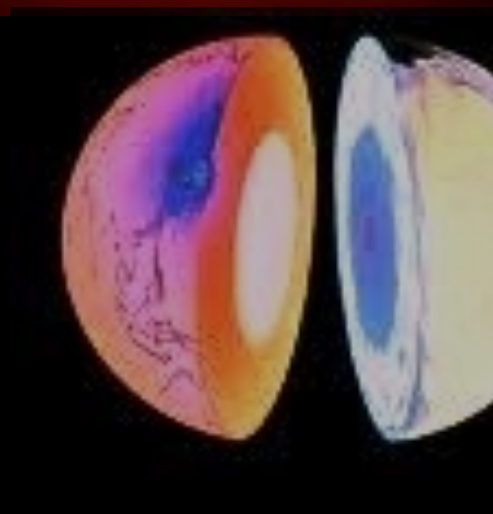
backgrounds, energy resolution, and nuclear matrix element uncertainty

What ν physics can future dark matter detectors do?







https://masterclass.icecube.wisc.edu/en/learn/detecting-neutrinos

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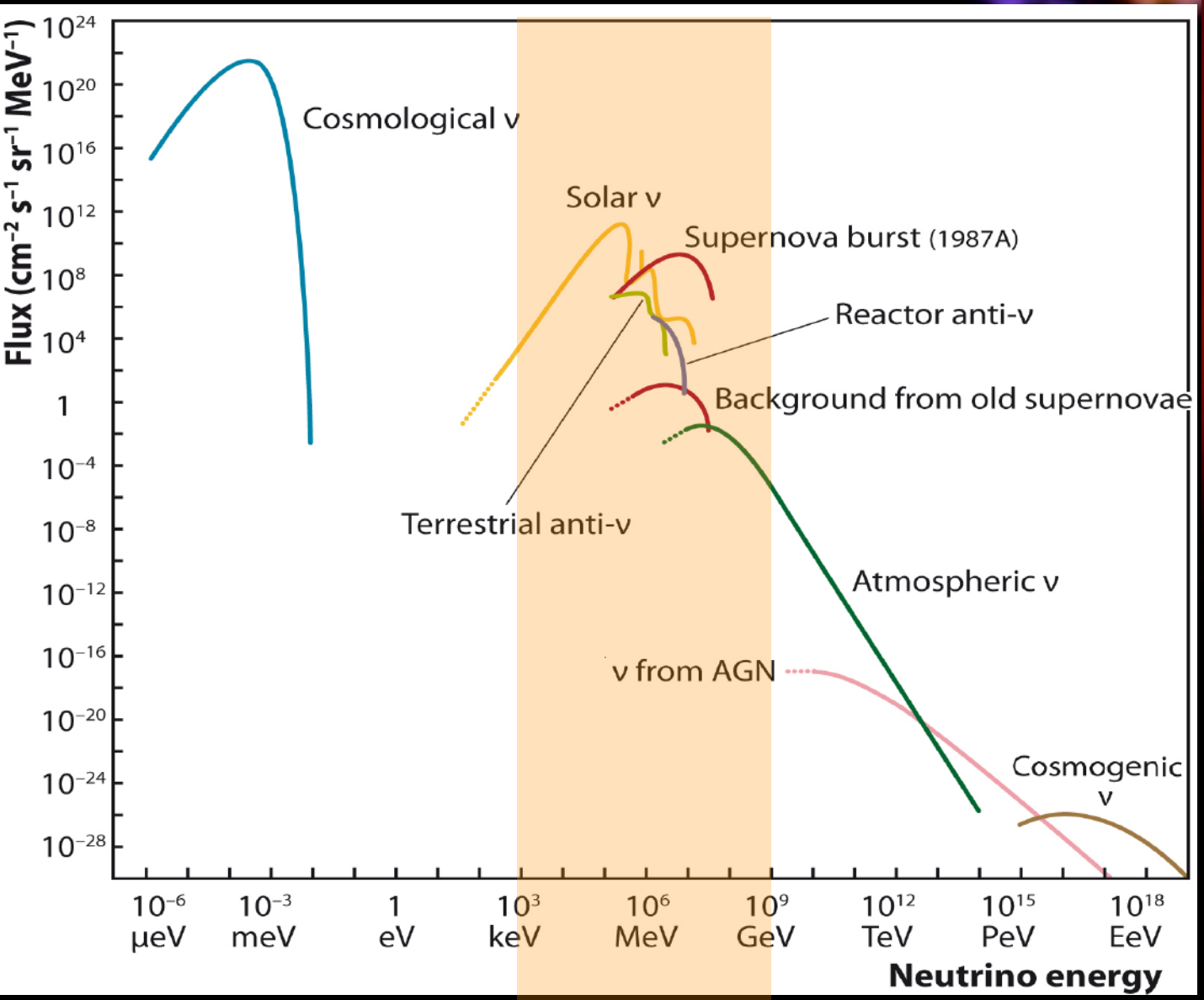

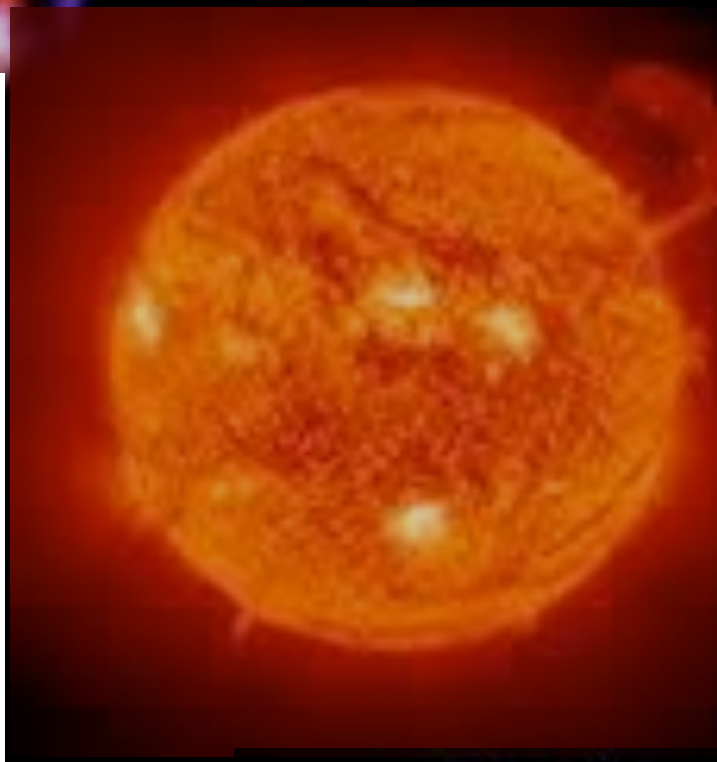

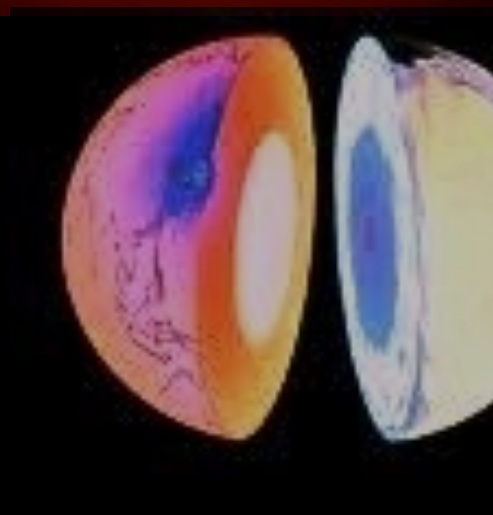

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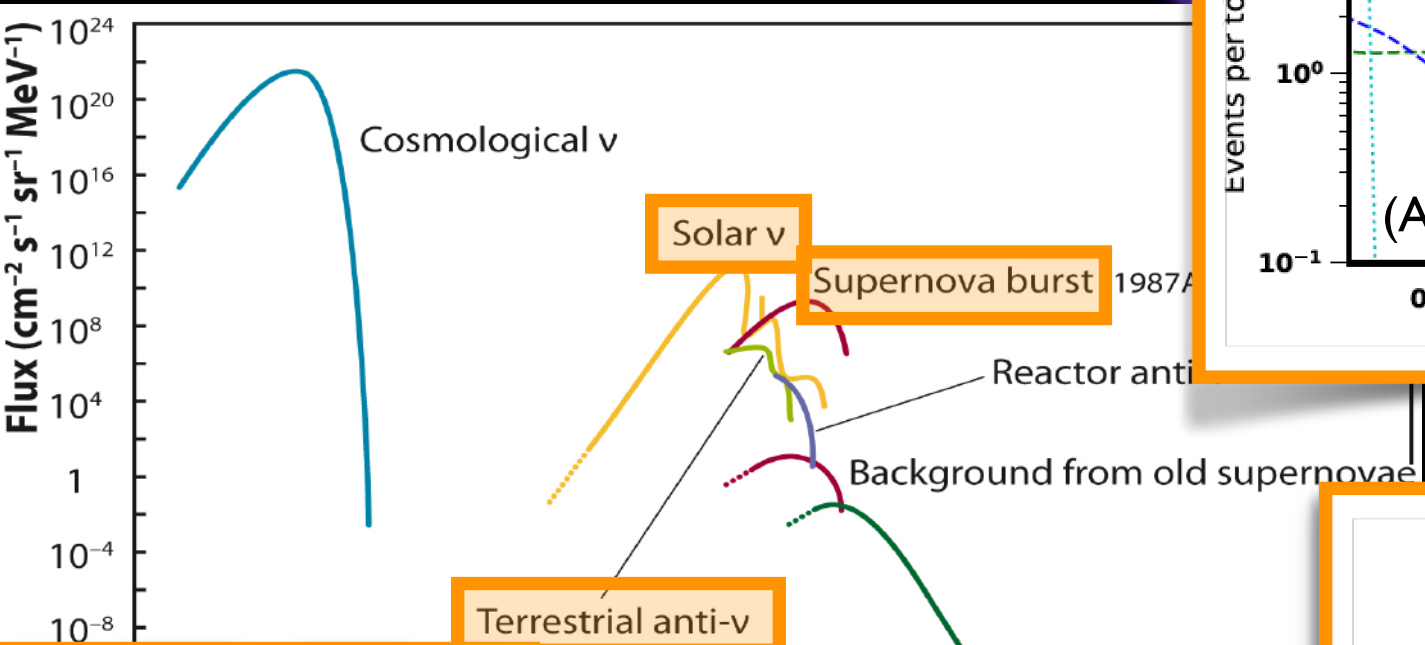

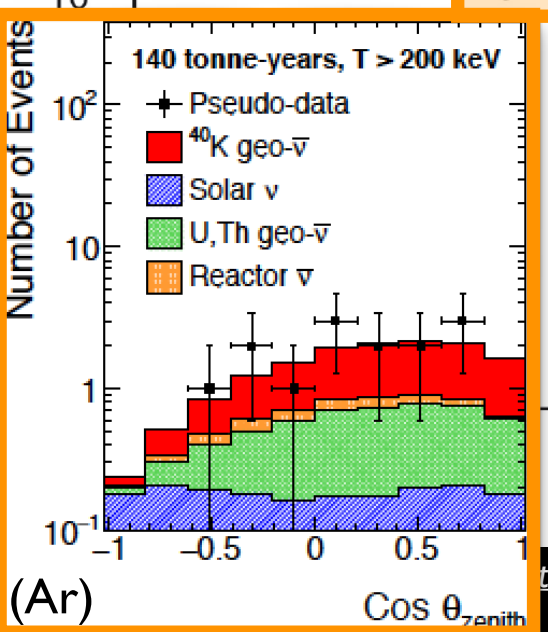

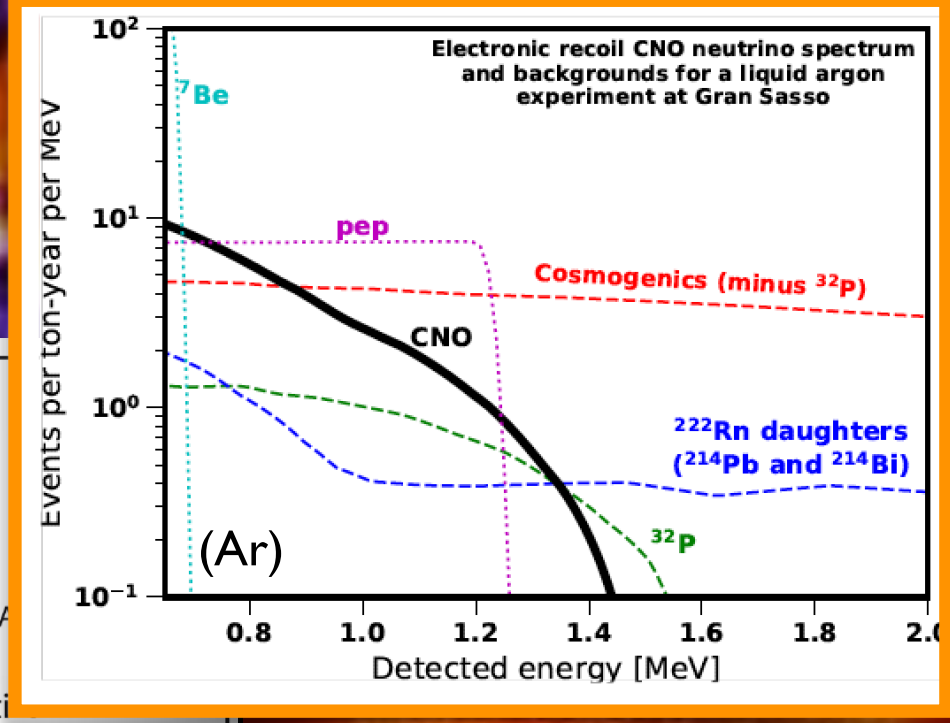

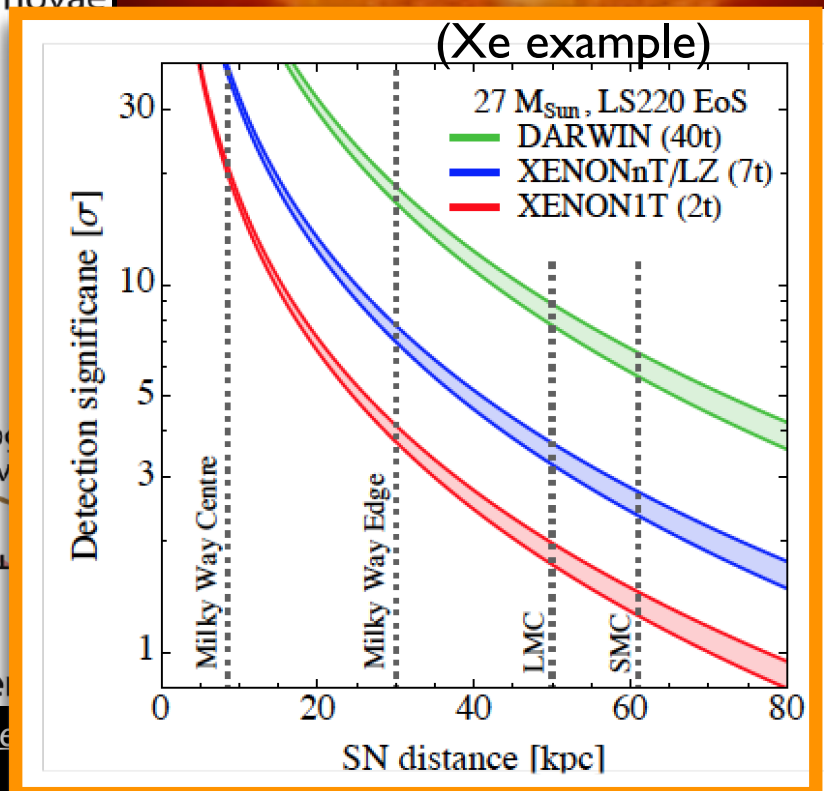

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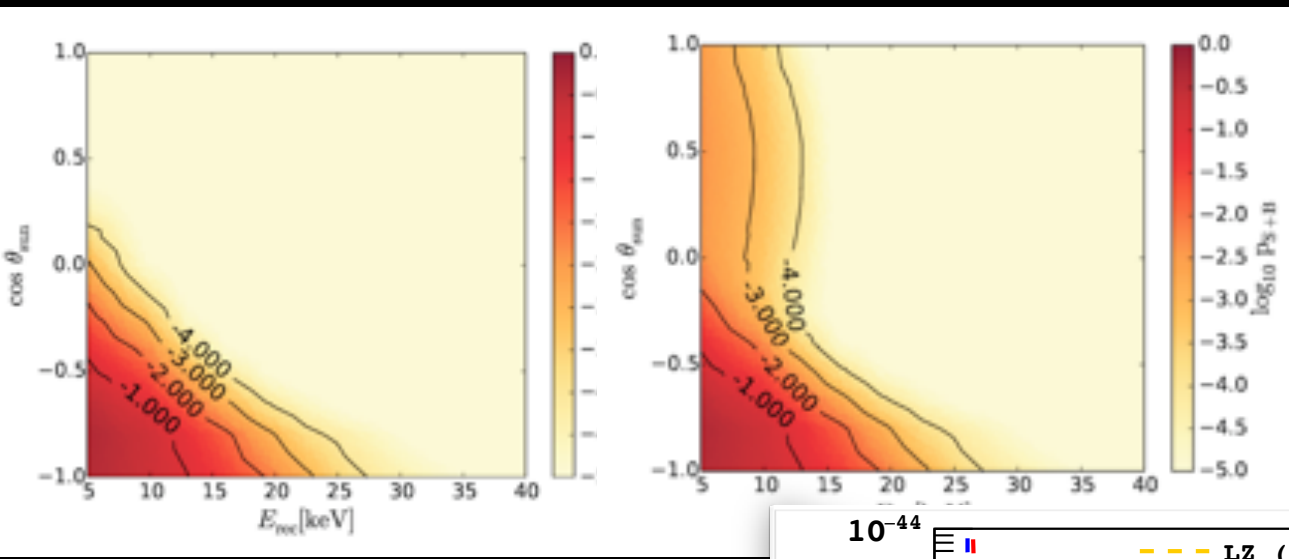
Is the Neutrino Bound the End? No.

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



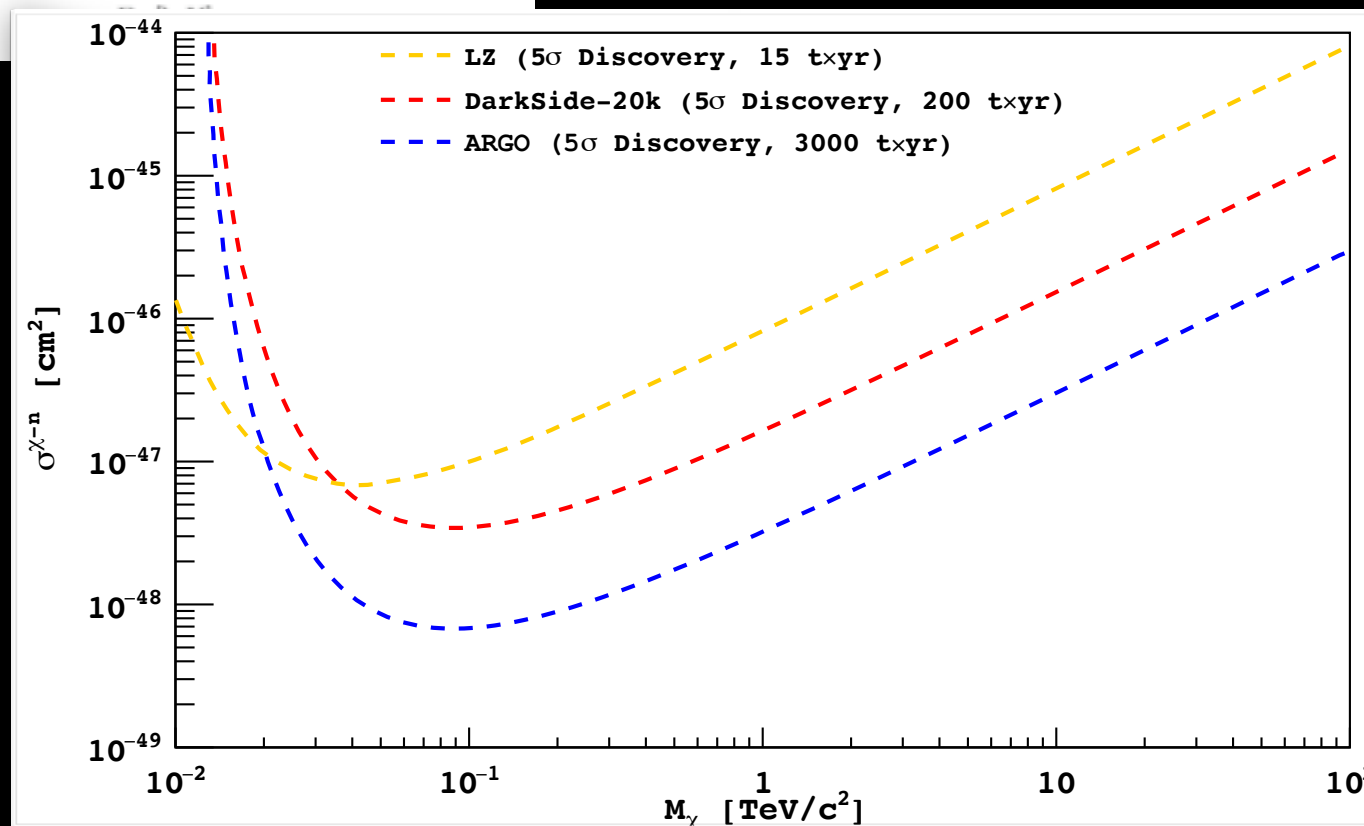
(energy, angle, time) of neutrino background vs. DM signal differ.

- 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.



Conclusions & Outlook

Astroparticle experiments show that the Standard Model is incomplete!

- Dark matter searches have synergies across ApPEC, ECFA, NuPPEC science.
- Dark matter searches drive rapid detector technology innovation, which supports detector R&D and technology development across fields.
- Astroparticle physics probes above the center of mass energy of the LHC, perhaps can tell us the next energy scale for new physics!

Astroparticle experiments continue to have outstanding discovery potential.

- Many new ideas for non-standard searches in new kinds of experiments … and today's background may be tomorrow's signal. *(T. Kajita, 2015)*

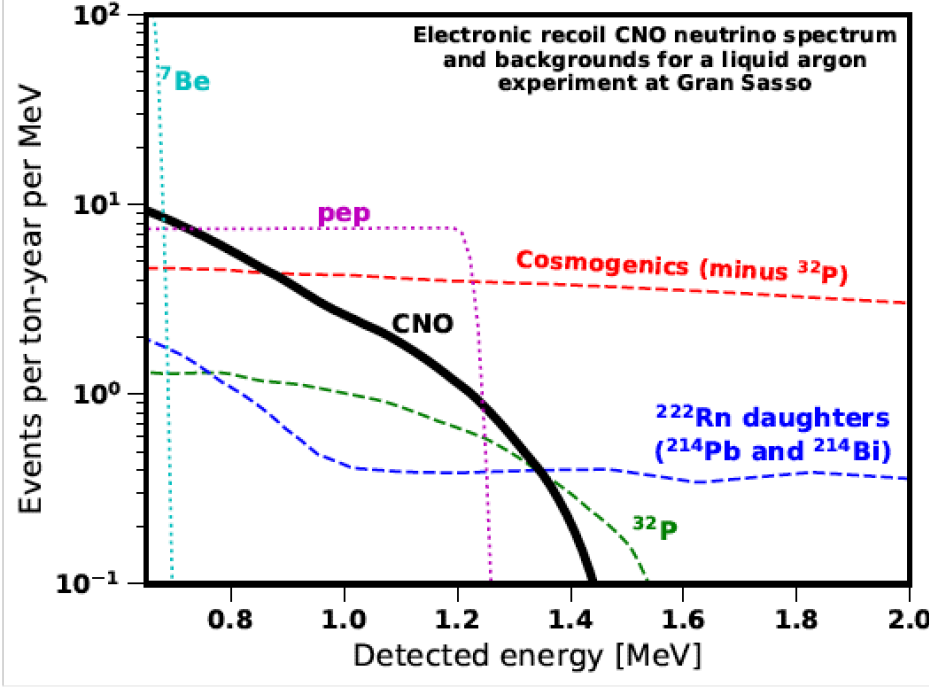
More Slides

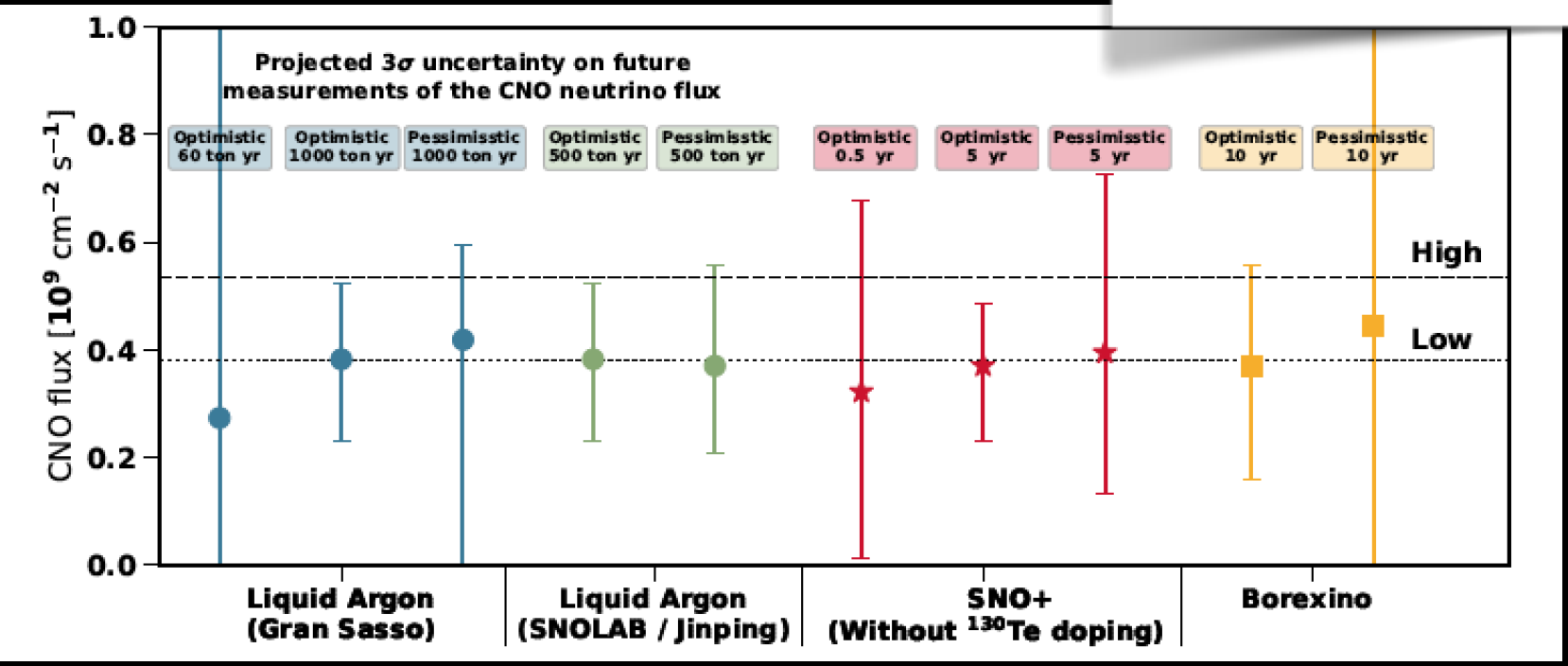
Solar ν-Electron Scattering

Via neutrino-electron elastic scattering, LAr dark matter experiments can observe the unmeasured CNO solar neutrino flux! (via spectral deformation)

+with O(500 t-y), study the "solar metallicity problem".

Franco et al., JCAP 1608 (2016) 08
Cerdeno, Davis, Fairbairn, Vincent, JCAP 1804 (2018) 37



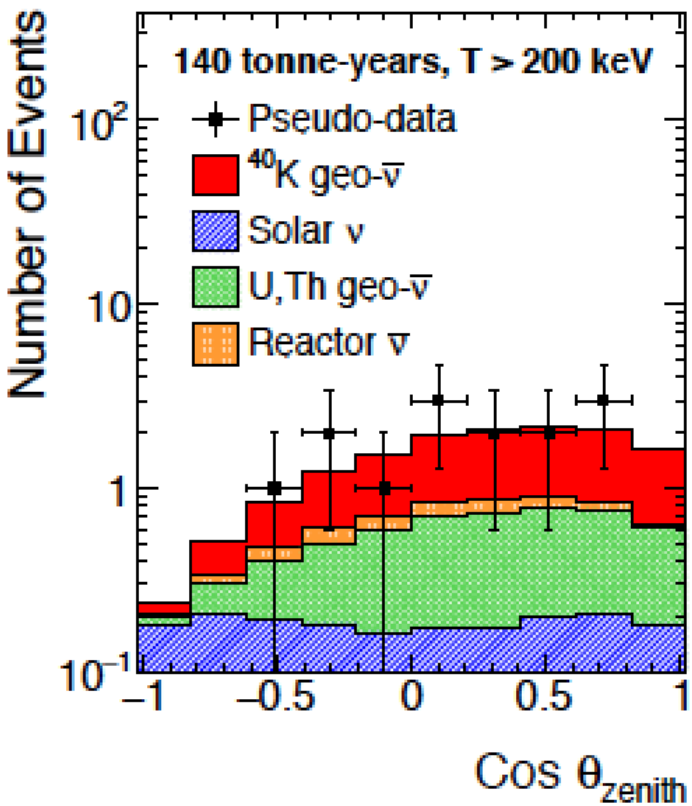


big opportunity:
distinguish between high vs. low metallicity.

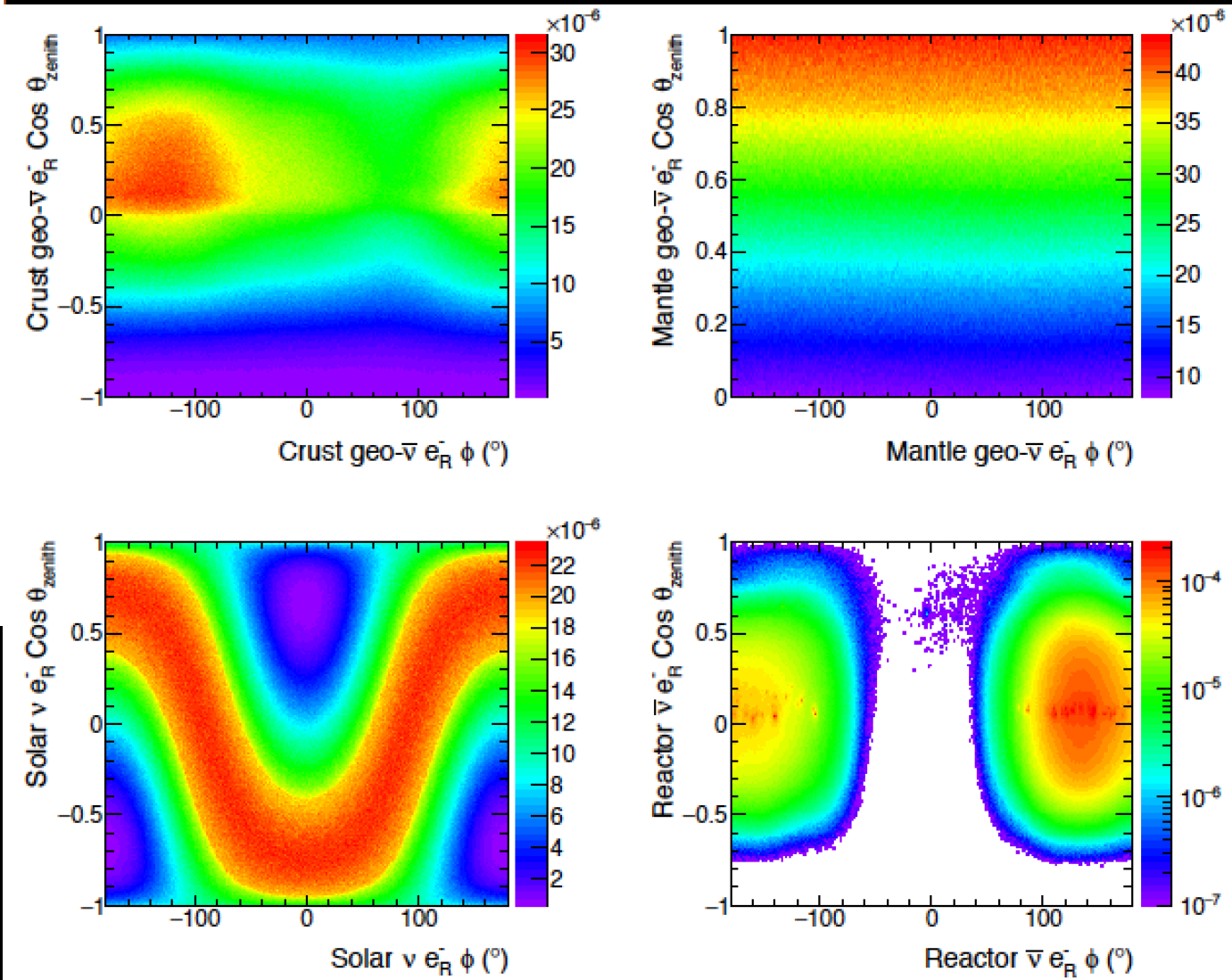
big challenges:
Rn background suppression and uncertainty on cosmogenics

*Xe-136 background makes LXe CNO challenging
Baudis et al., JCAP 1401 (2014) 044,

Geo ν-Electron Scattering



PLR analysis of energy, time, and *direction* shows sensitivity at 95% CL to measure K-40 geo-neutrino flux with O(100) t-yr exposure.



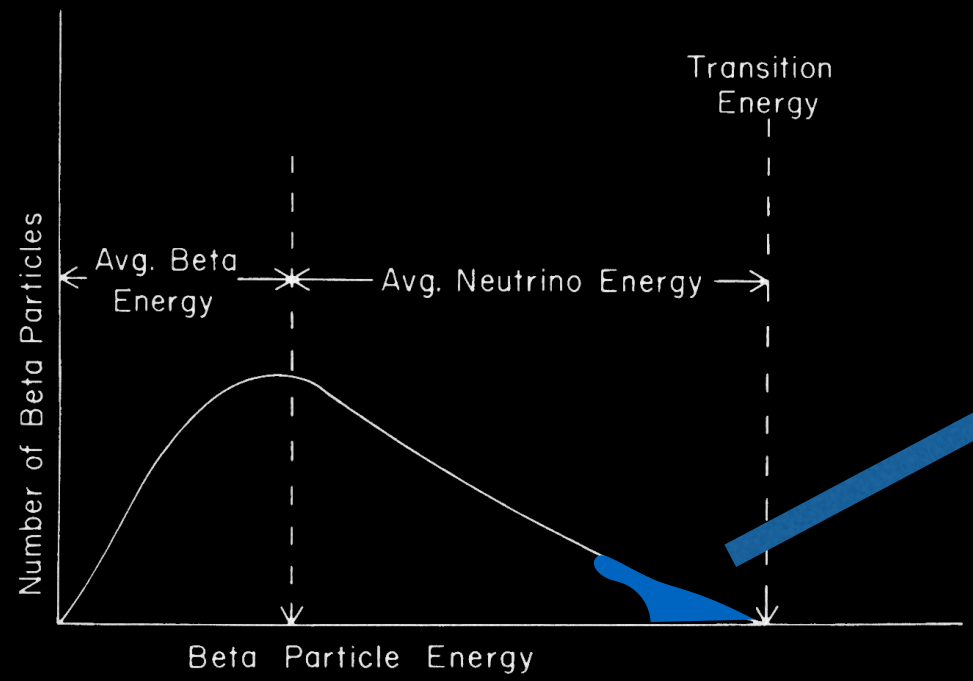
example: geo-, solar-, reactor-ν -induced electron recoil directions, at LNGS.

challenge: measure the *direction* of ~1 MeV e^- recoils..

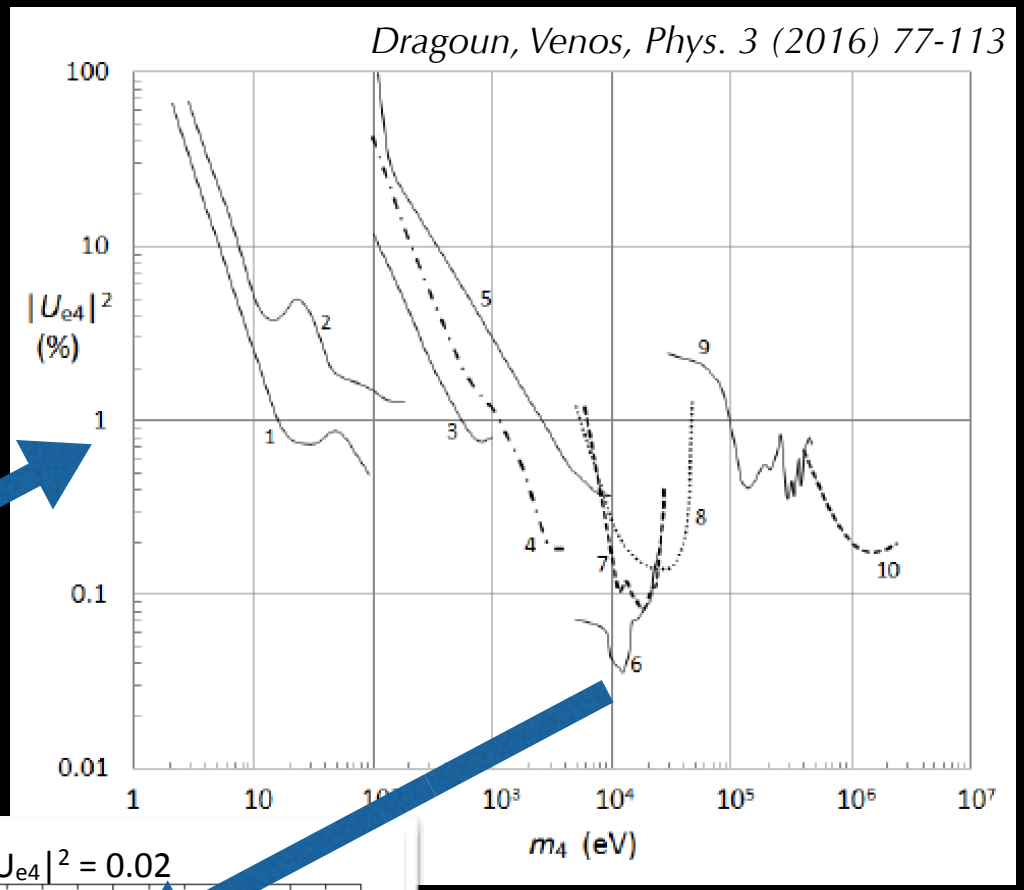
Leyton, Dye, JM, Nature Commun. 8 (2017) 15989

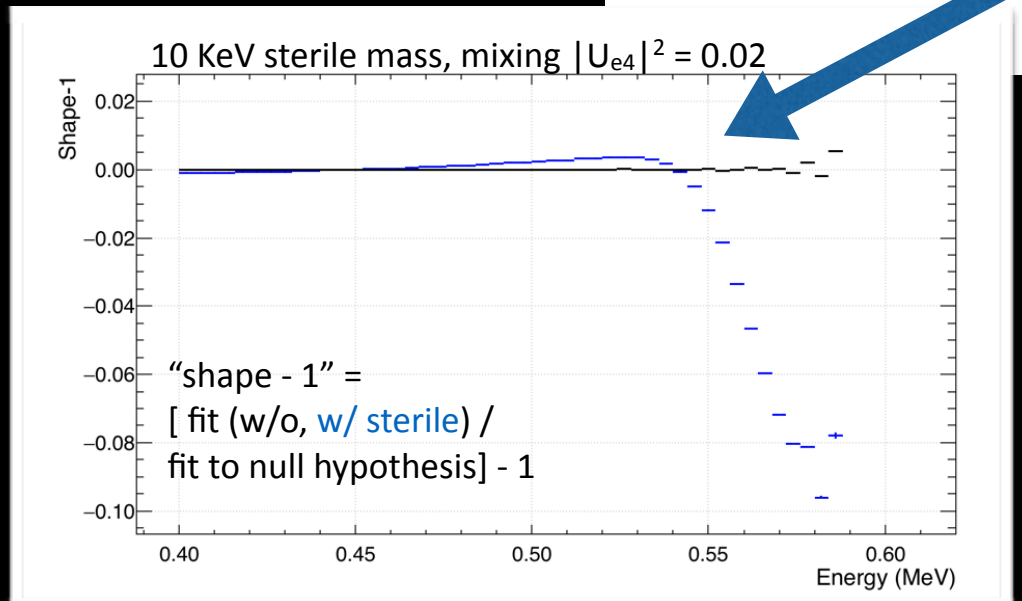
Sterile ν Signatures

The beta decay energy spectrum is modified by neutrino mass and mixing.



Upper limit on $|U_{e4}|^2$ at 10 keV mass ~ 0.02 at 90% CL from beta decay.





<u>big opportunity:</u>
high Q-value beta decays of backgrounds (e.g. Ar-39) with good energy resolution have sensitivity to 10-100 keV sterile νs

<u>big challenges:</u>
nuclear physics uncertainties on beta spectrum shape, understanding energy resolution at % level

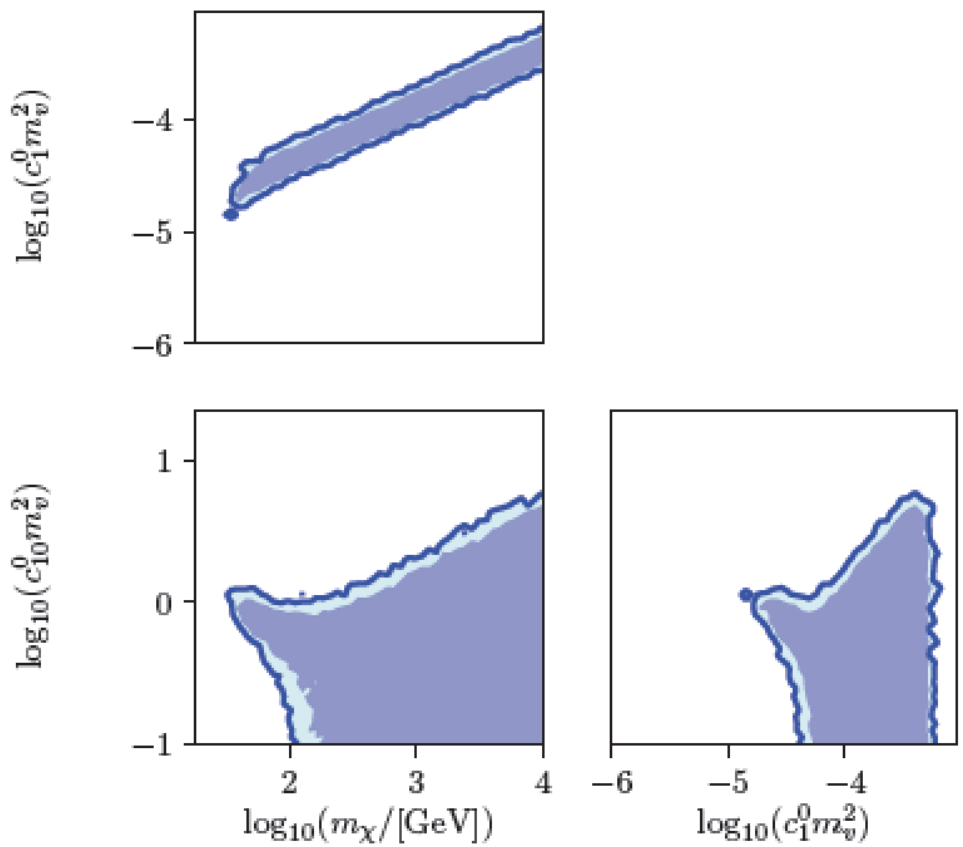
Complementarity: Case 0 Example

Newstead et al., PRD D 88, 076011 (2013)
DARWIN, JCAP 10 (2015) 016

Example: Scalar DM – Scalar Mediator
m = 100 GeV

A single target cannot determine the DM mass and couplings

Xe



D. Cerdeno, IPPP April 2018

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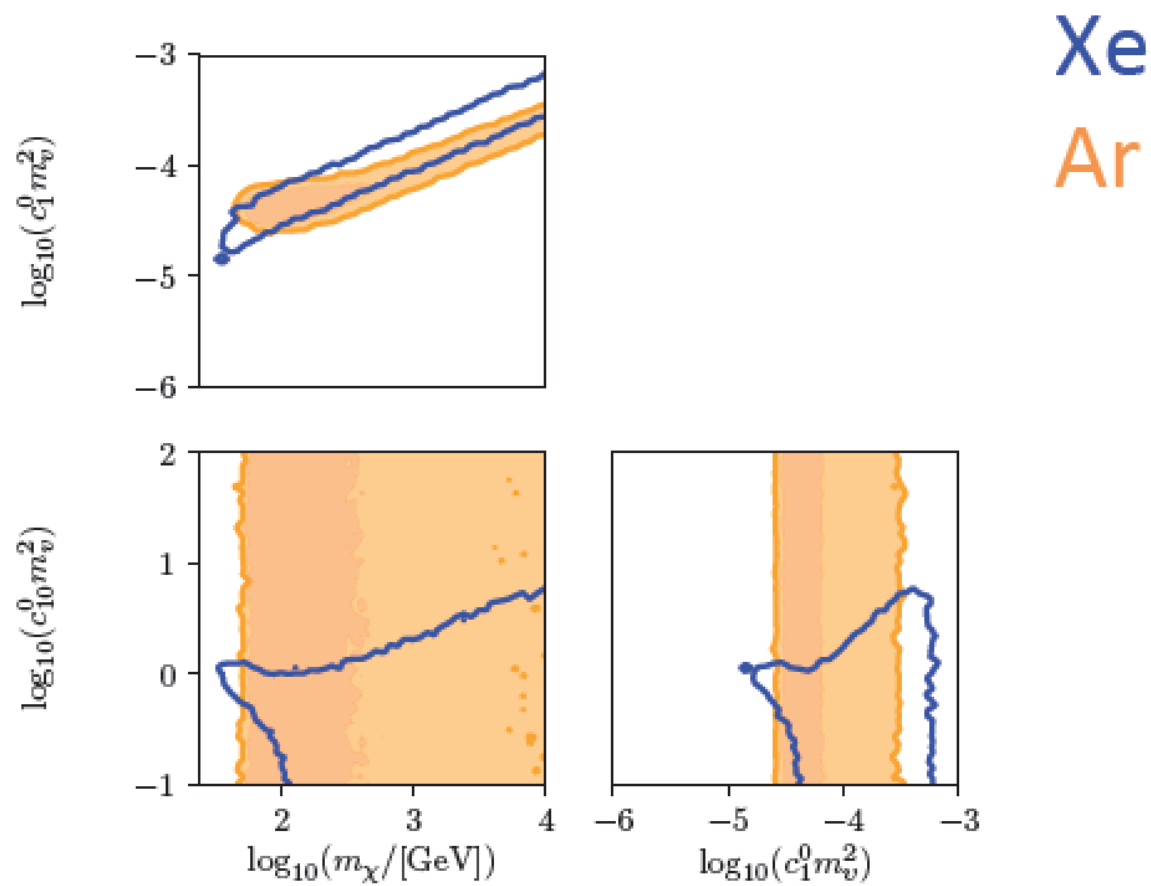
The experimental response is very sensitive to the target



D. Cerdeno, IPPP April 2018

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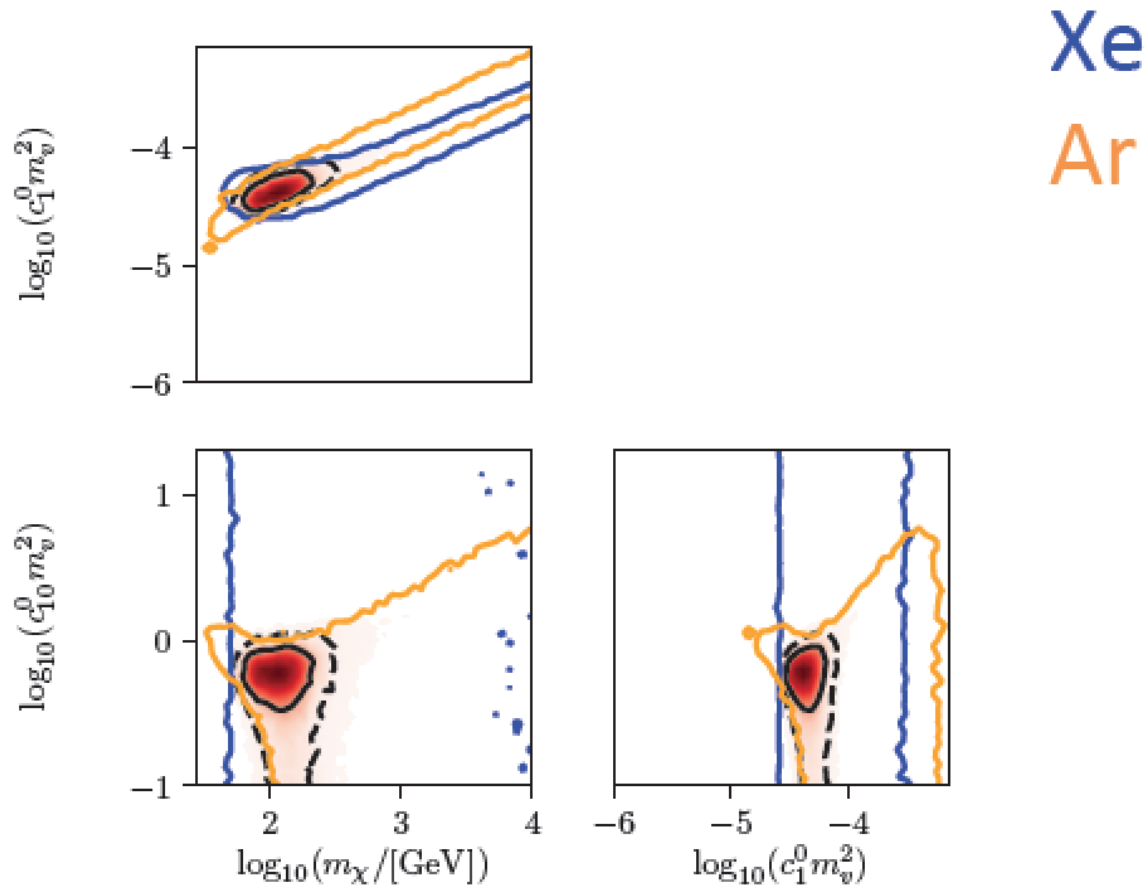
Example: Scalar DM – Scalar Mediator
m = 100 GeV

A single target cannot determine the DM mass and couplings

The experimental response is very sensitive to the target

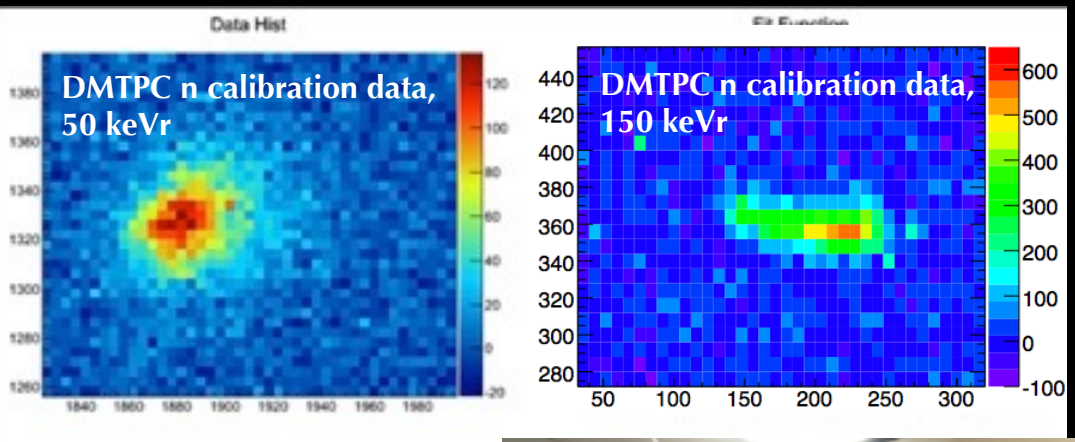
Combining data some degeneracies can be removed

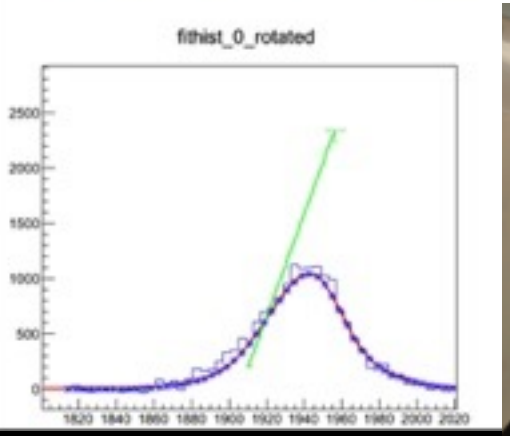


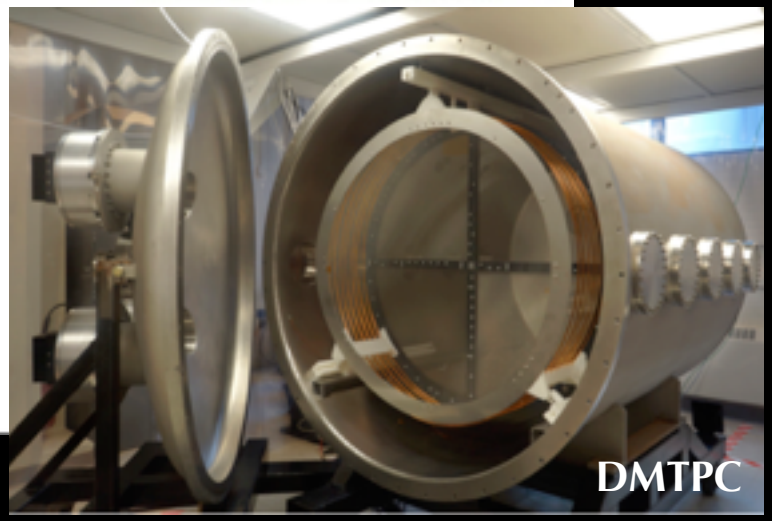
D. Cerdeno, IPPP April 2018

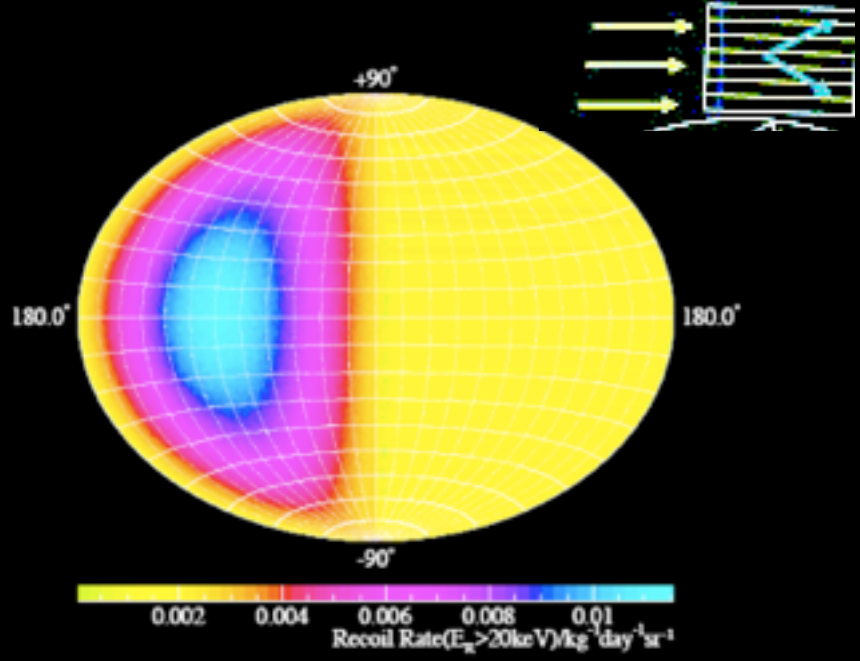
Directional Detection

R&D towards recoil *direction measurement* to correlate a signal with the galactic halo









Many R&D efforts:
DRIFT, DMTPC, MIMAC, NEWS-DM, RED, CYGNO++

largest are 1m^3 (O(100g) target).

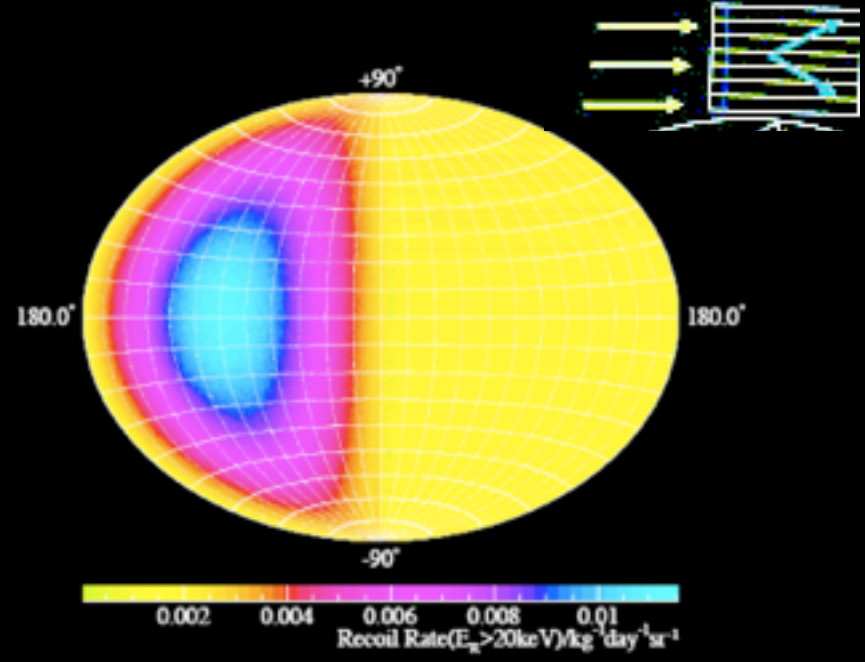
Majority use CF_4 gas; NEWS uses emulsions.

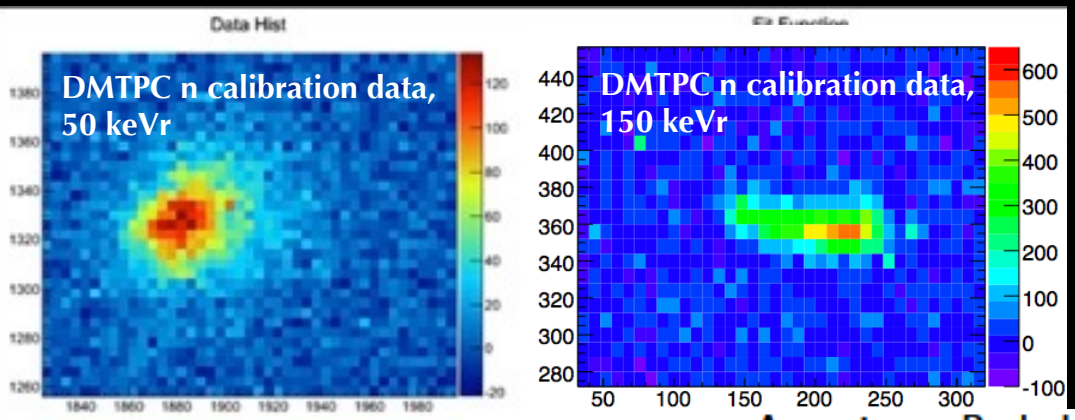
CYGNUS: global coordination towards a physics-scale directional experiment.
Physics Reports 2016, arXiv:1602.03781

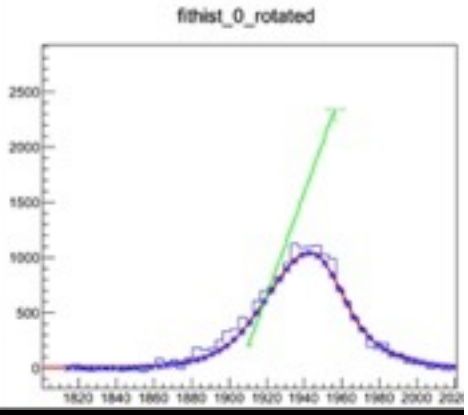
huge experimental challenge to measure direction of recoil tracks of O(10 keV): <mm length!

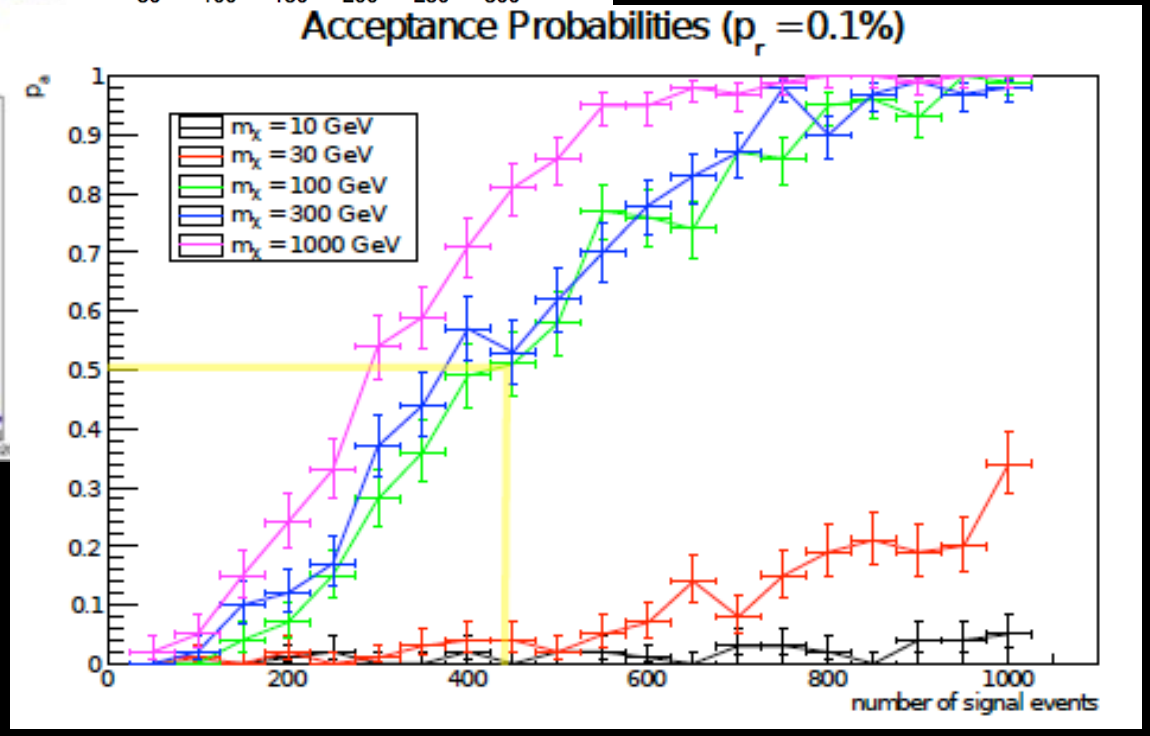
Directional Detection

R&D towards recoil *direction measurement* to correlate a signal with the galactic halo









detectors achieve angular resolution of ~35° at 50 keVr

with current best direction reconstruction, need 200-400 events to measure anisotropy at 3σ significance

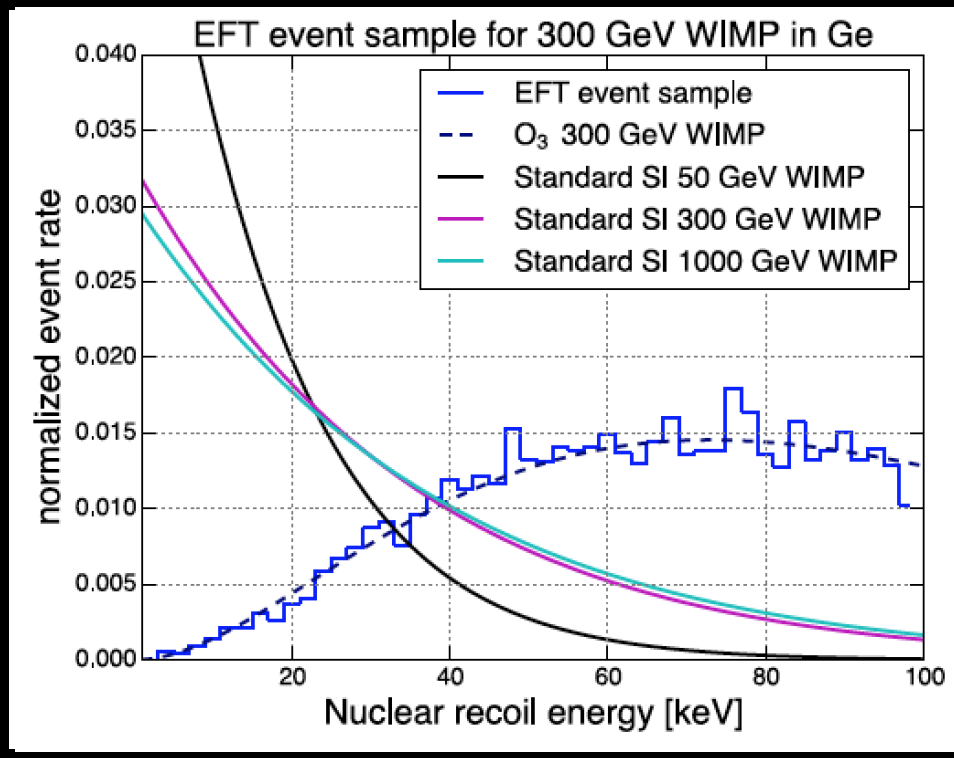
Phys.Rev.D95 (2017) 122002

Is High Mass Interesting? (1)

Yes. >few hundred GeV is above LHC reach, but accessible in direct detection experiments.

In EFT approach, the spectrum from possible interactions (e.g. momentum dependent) does not have the typical WIMP exponential.

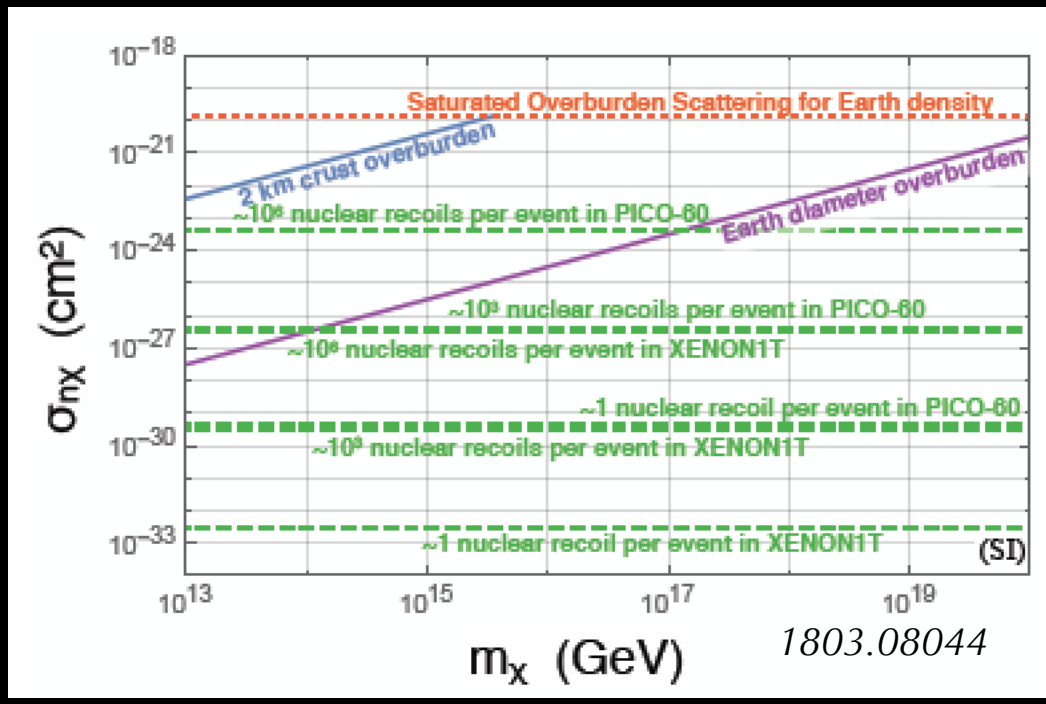
Information isn't only at threshold!



Beyond SUSY, variety of models can have DM candidates up to few TeV, e.g.

- little Higgs,
- warped extra dimensions,
- walking technicolor
- MIMPs
- composite states

…

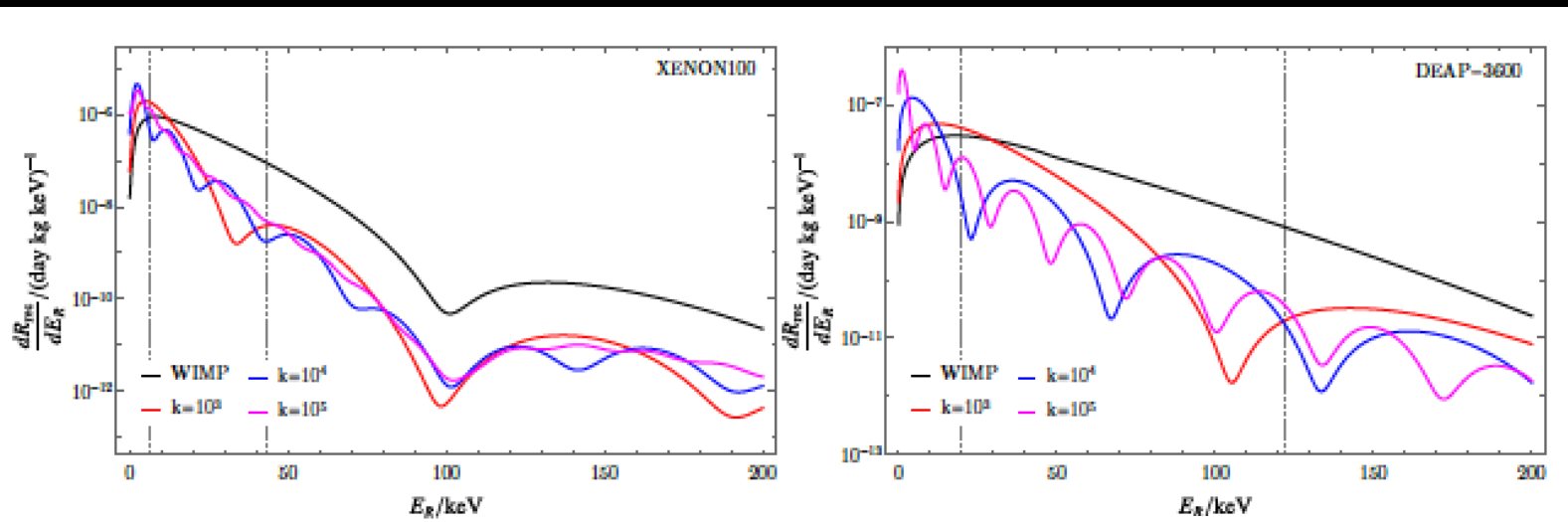


1803.08044

Is High Mass Interesting? (2)

Sensitivity to composite dark matter, e.g. *Hardy, Lazenby, March-Russell, West JHEP 07 (2015)*
dark nuclei, formed of *k* bound states of self-interacting light dark nucleons.

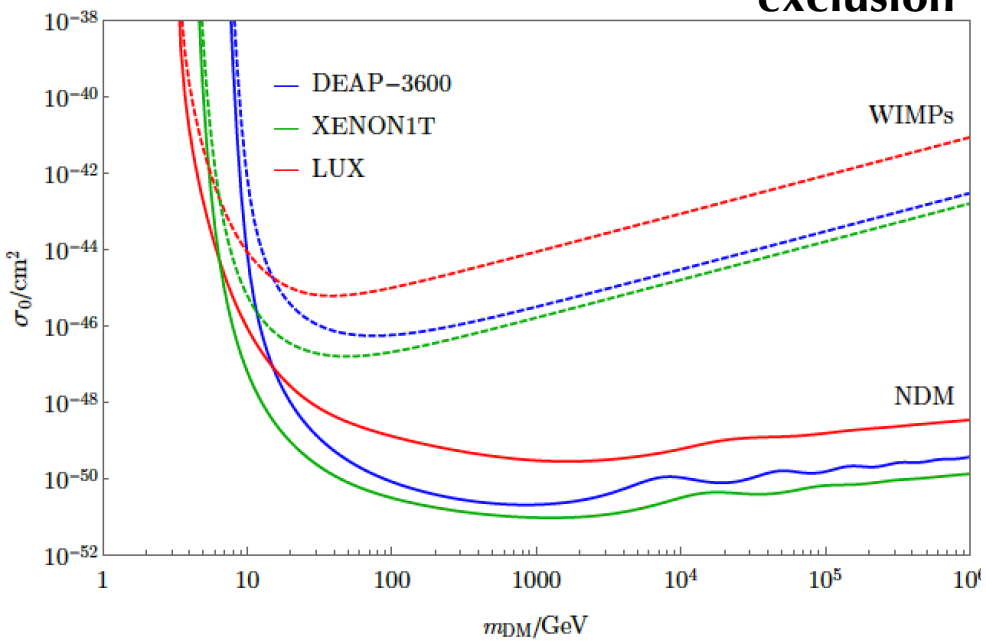
Scattering process now has a form factor from the nuclear dark matter and the target.



example: dark nucleon mass = 1 GeV, r = 1 fm, and per-SM nucleon xsec = 1E-46 cm^2.

Kirk, Butcher, JM, West, JCAP 1710 (2017) 10, 035

exclusion



detection