Dark Matter Direct Detection
Status and Prospects

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European Strategy for Particle Physics Update
Granada, ES
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Big Questions for the Dark Sector

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

- what are the most promising experimental programs, approved or proposed, to cover different regions of parameter space?

2) What are the main differences between light Hidden Sector DM and WIMPs? How broad is the parameter space for the QCD axion?

3) How to compare results of different experiments in a more model-independent way?

- should one draw limits from direct, indirect, and collider searches on the same plot?

4) How will Direct and Indirect DM Detection experiments inform/guide accelerator searches and vice-versa?

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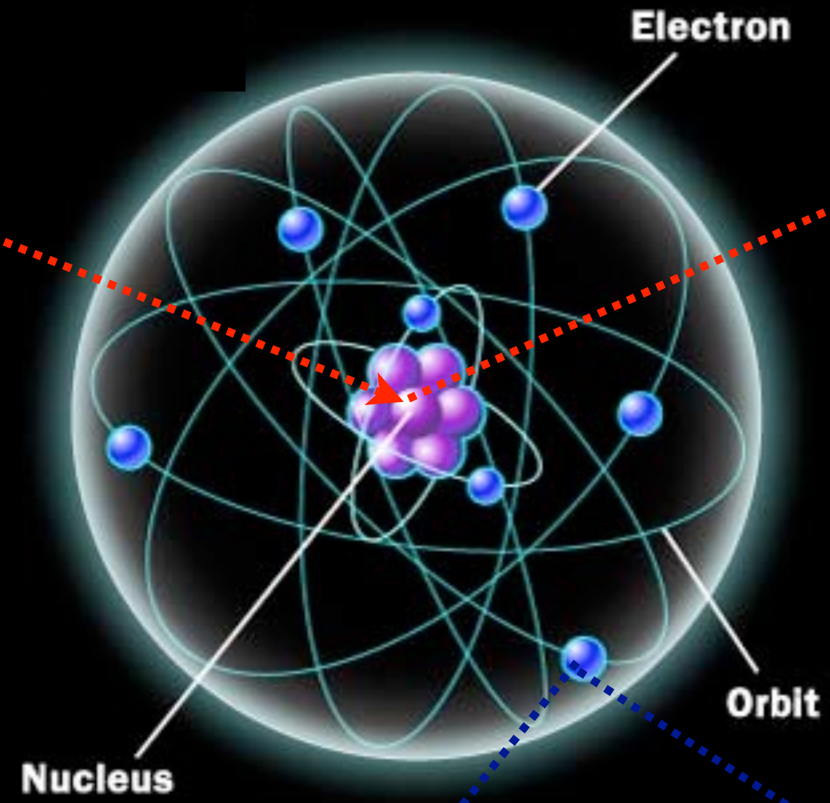
3) How will Direct and Indirect DM Detection experiments inform/guide accelerator searches and vice-versa?
    - what else might we see in Direct Detection DM experiments?

4) WIMP Community input to the ESPPU

Dark Matter Direct Detection

Signal: $\chi N \rightarrow \chi N$



Backgrounds:

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

$n\ N \rightarrow n\ N$

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

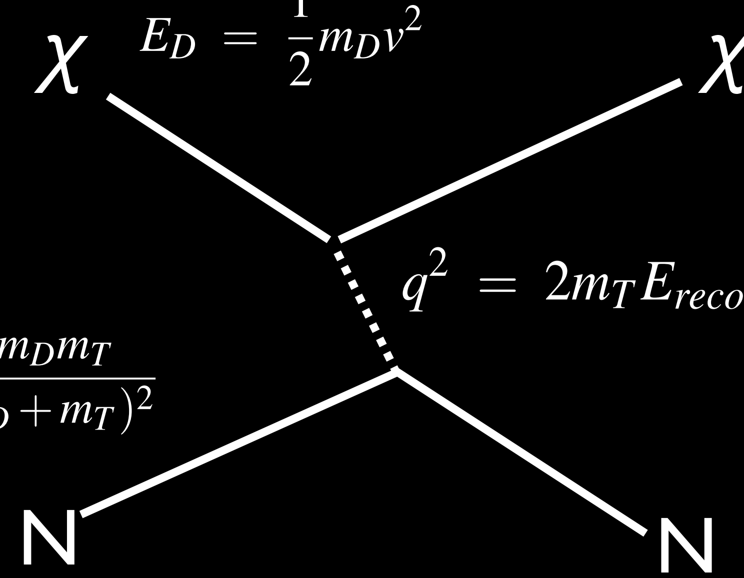
$\nu\ N \rightarrow \nu\ N$

experimental requirements: particle ID for recoil N, e-, alpha, n (multiple) final states

WIMP Scattering

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

recoil angle strongly correlated with incoming WIMP direction



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

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

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

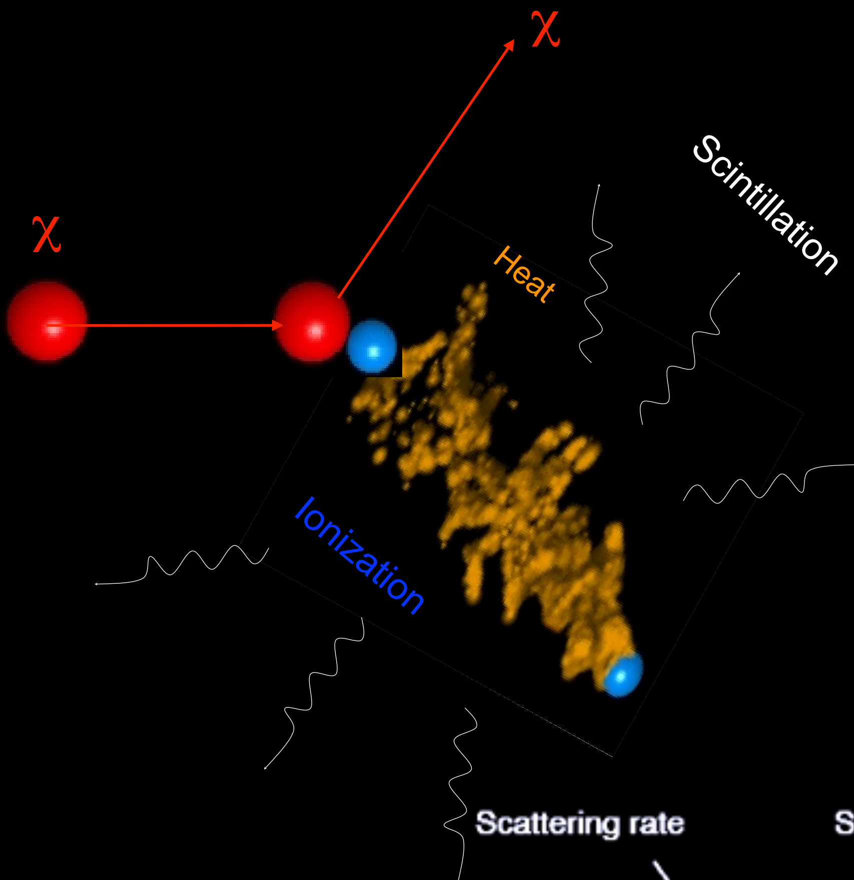
$$E_{recoil} = E_D r \frac{(1 - cos\theta)}{2}$$

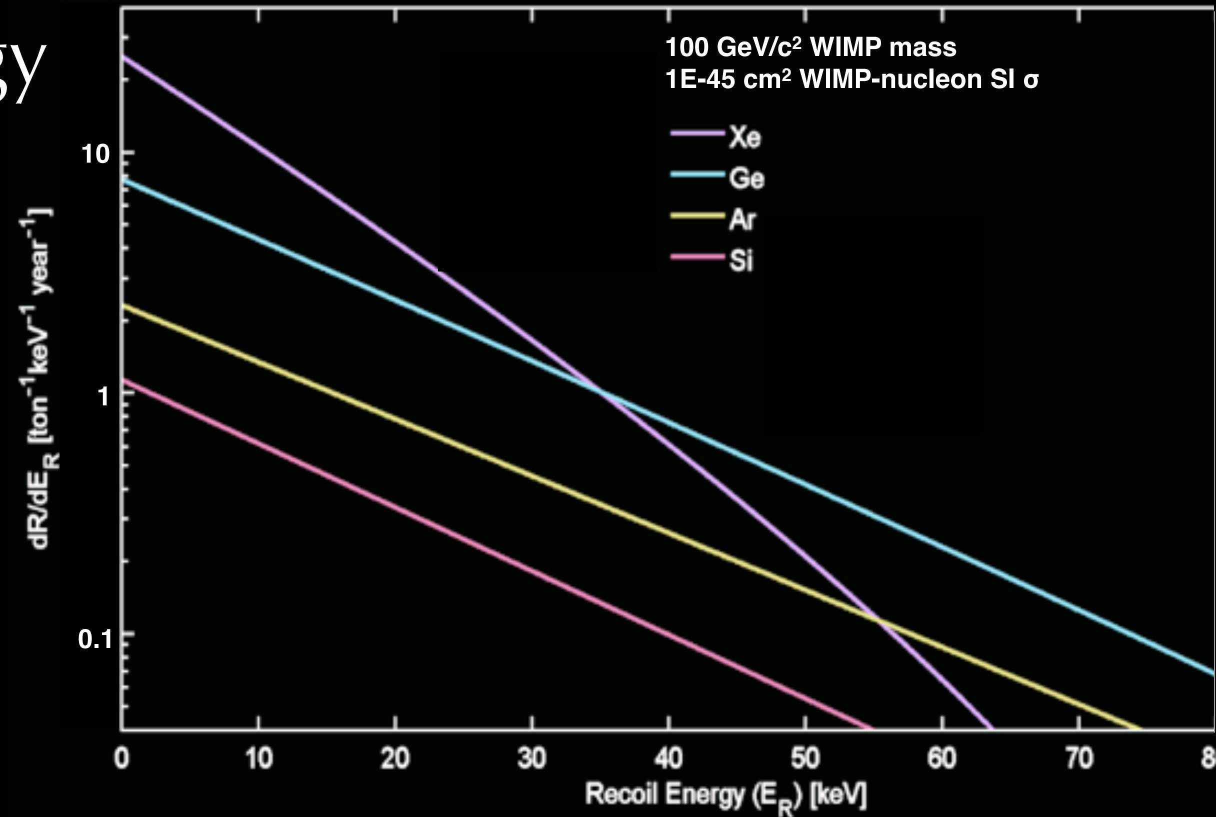
<u>Spin Independent:</u>
χ scatters coherently off of the entire nucleus A: $\sigma \sim A^2$
D. Z. Freedman, PRD 9, 1389 (1974)

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

experimental requirements: measure recoil energy, time, +angle

Observable: Recoil Energy





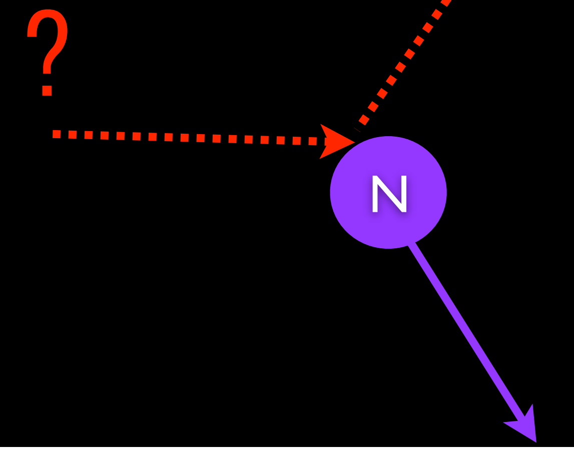
Scattering rate | Sun's velocity around the galaxy | WIMP velocity distribution

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

WIMP energy density, 0.3 GeV/cm³ | Form factor

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

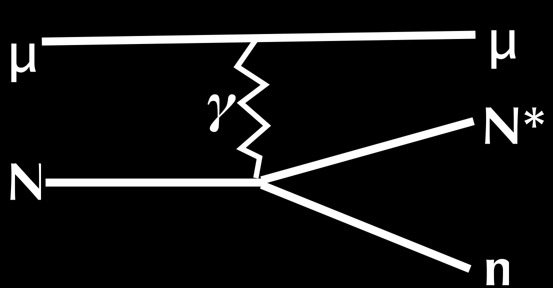
Backgrounds

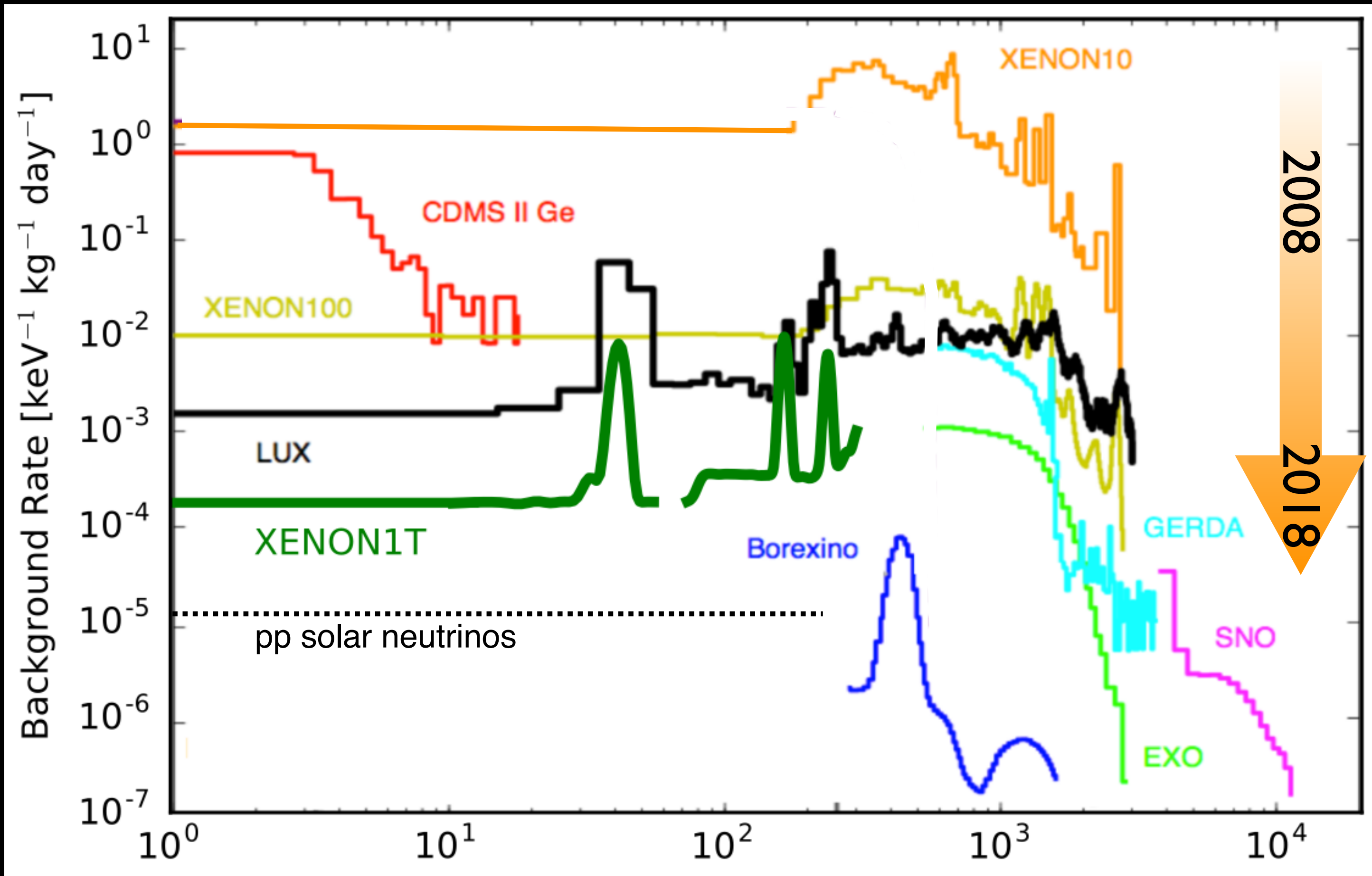


Gamma ray interactions: electron recoil final states
rate ~ N_e x (gamma flux), O(1E7) events/(kg day)
mis-identified electrons mimic nuclear recoils

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

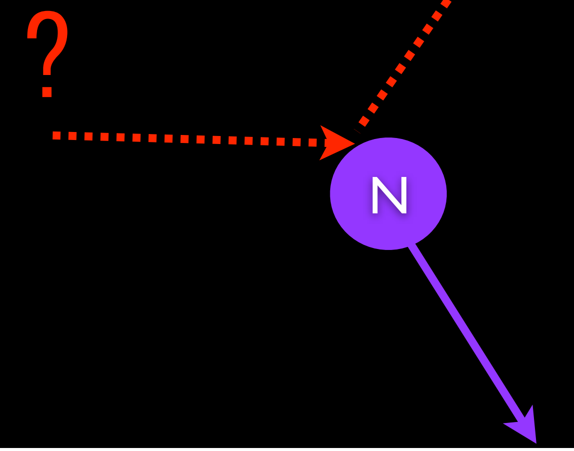
Neutrons:
Nuclear recoil final state.
(alpha,n), U, Th fission,
cosmogenic spallation





Thanks to L. Baudis

Backgrounds



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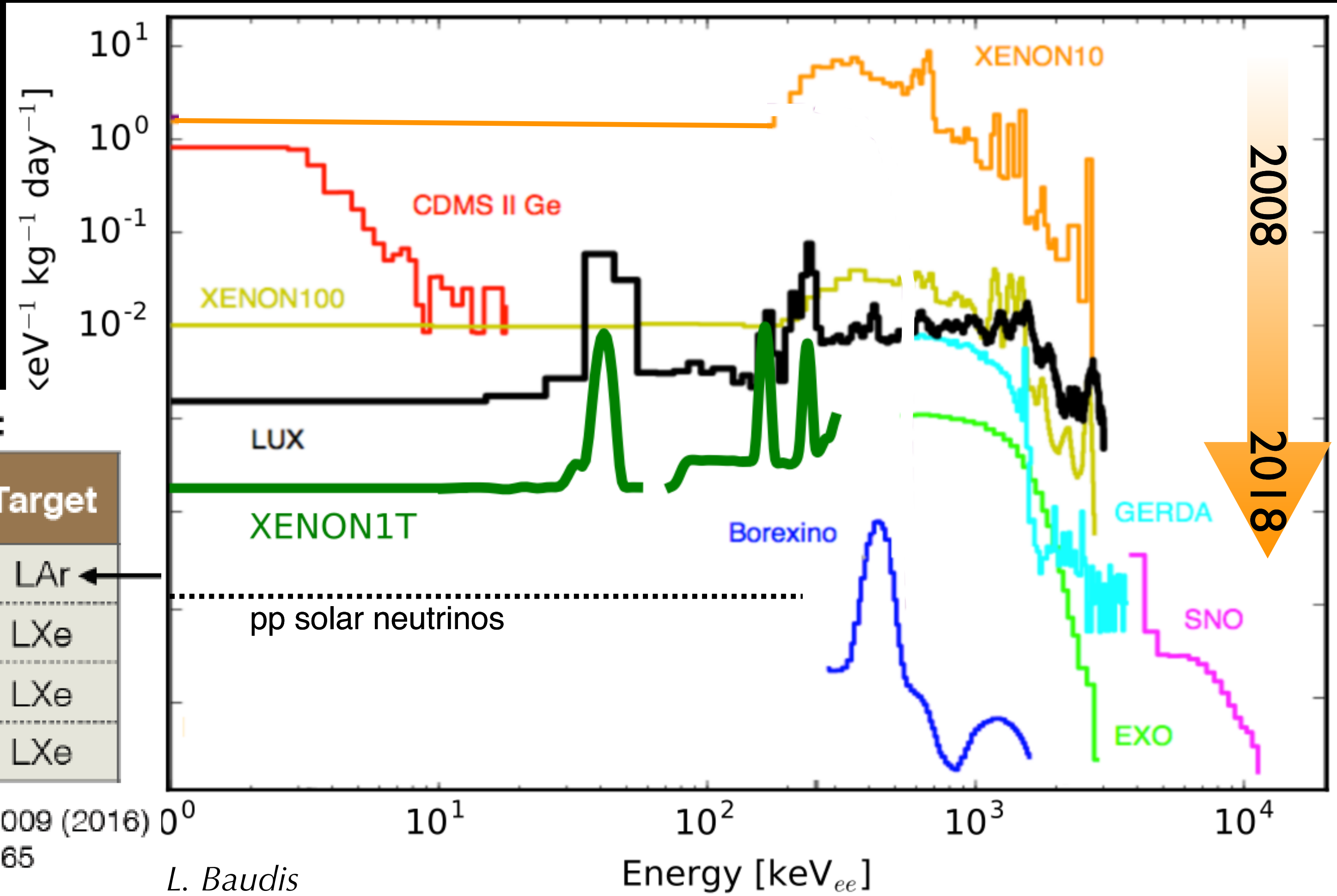
<u>*Contamination*</u>:
^{238}U and ^{232}Th decays,
recoiling progeny and
mis-identified alphas, betas
mimic nuclear recoils

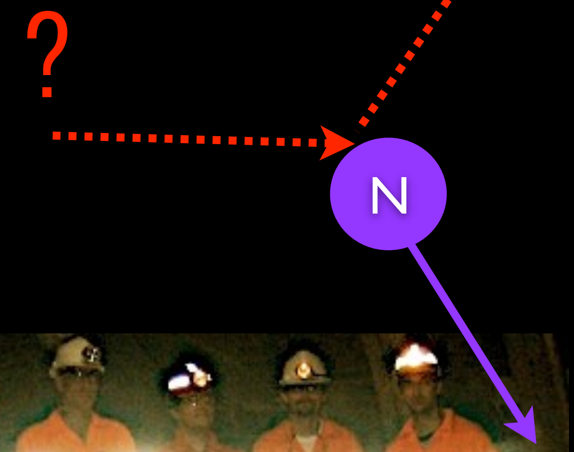
^{222}Rn in Dark Matter experiments:

Experiment	Activity / rate	Target
DEAP-3600	≈0.2 μBq / kg	LAr
PandaX-II	6.6 μBq / kg	LXe
LUX	66 μHz / kg	LXe
XENON1T	10 μBq / kg	LXe

- PandaX-II: PHYSICAL REVIEW D 93, 122009 (2016)
- LUX: Physics Procedia 61 (2015) 658 – 665
- XENON1T: XeSAT 2017 talk [link]



Backgrounds



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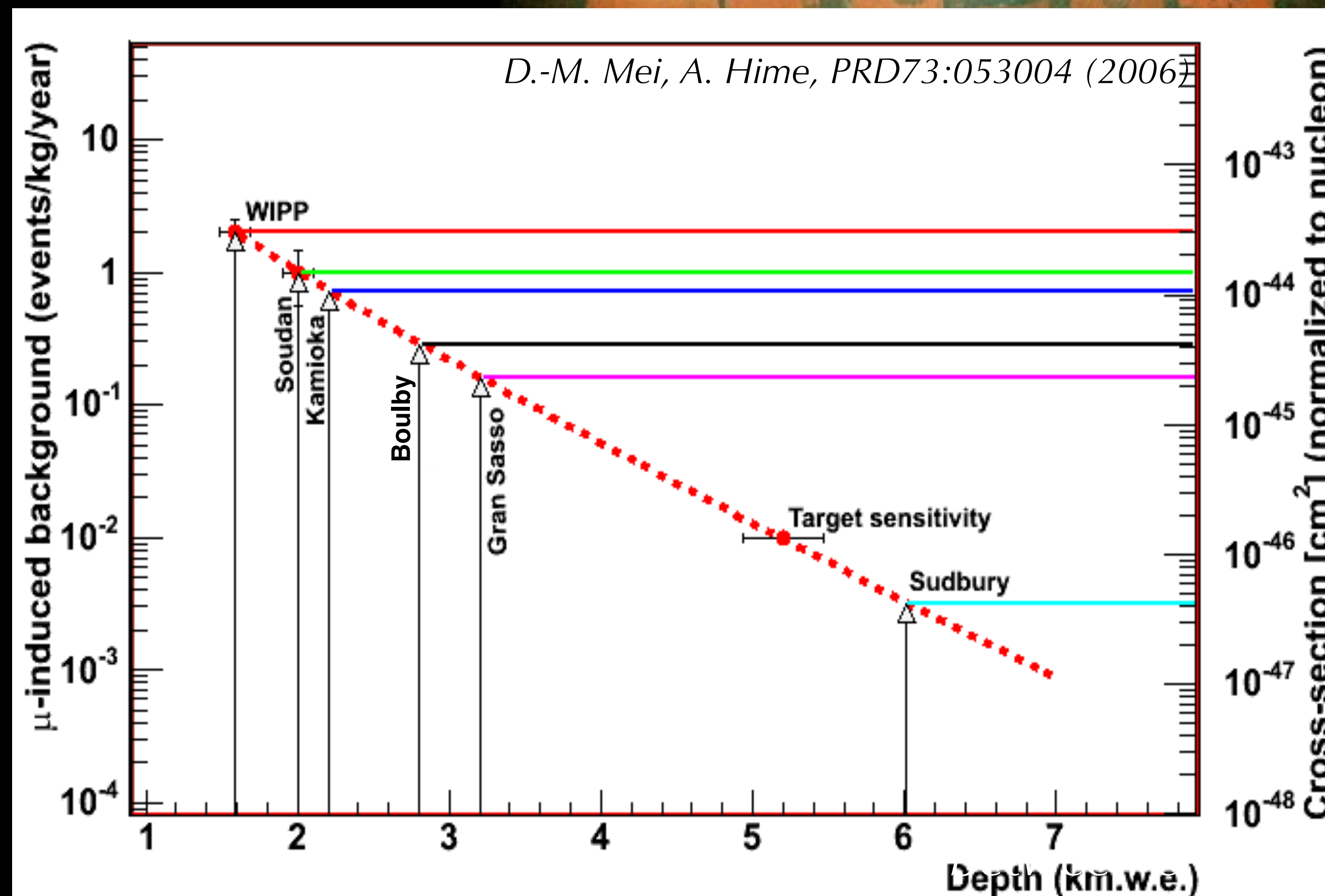

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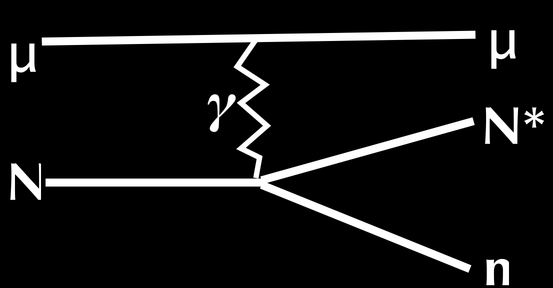
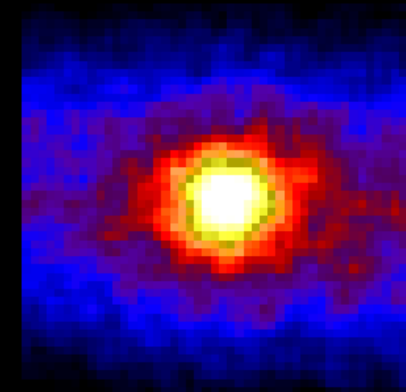


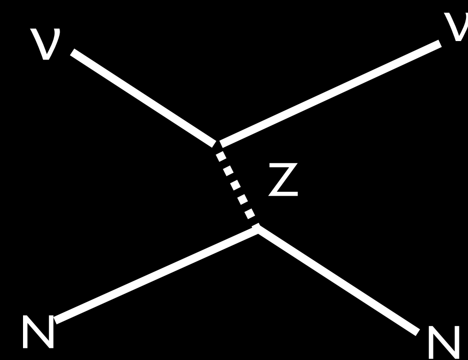
+ large, active neutron shielding

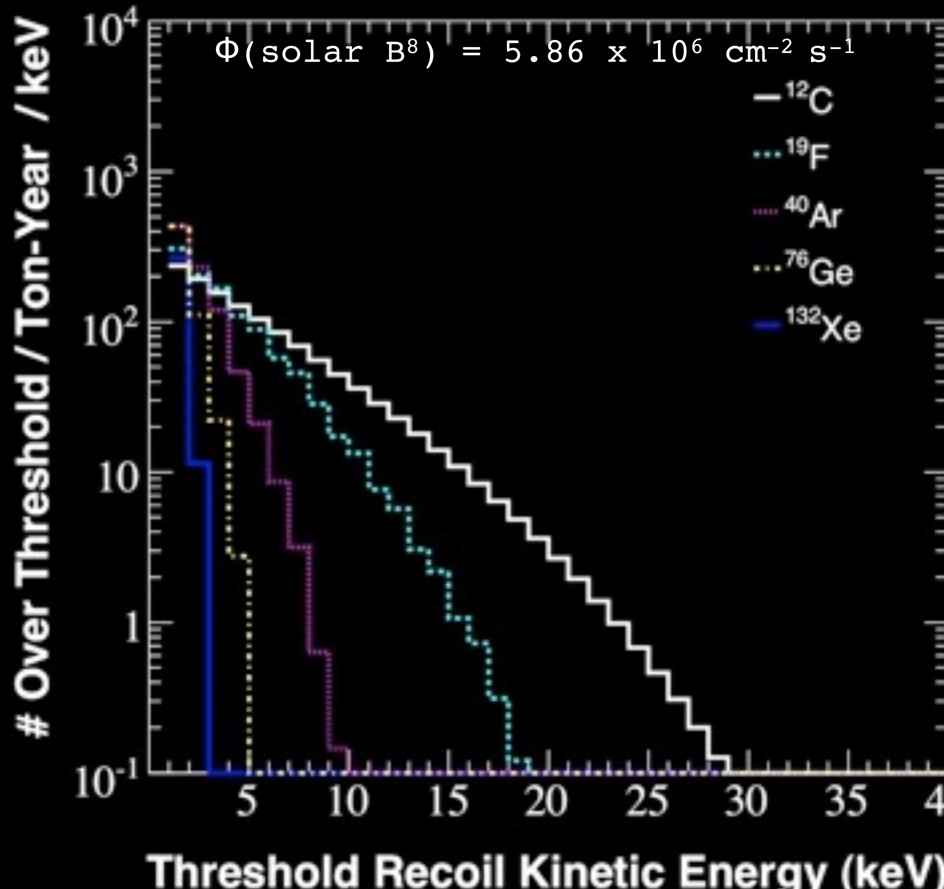
Irreducible Backgrounds



impossible to shield a detector from coherent neutrino scattering!

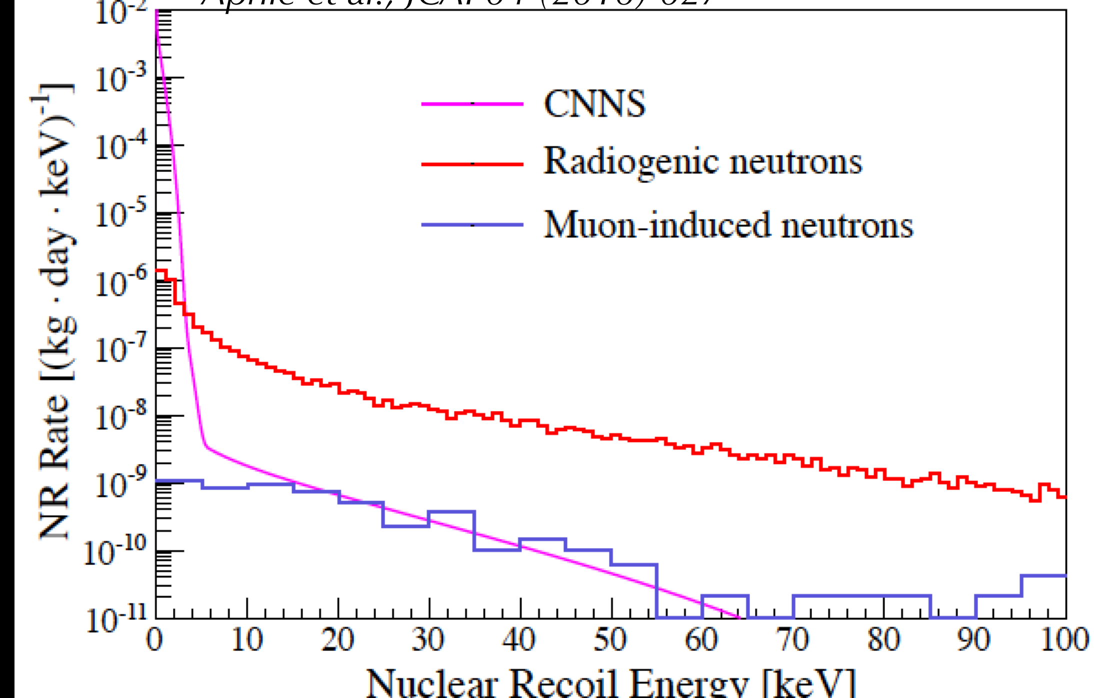
- "neutrino floor:" both ν-N and ν-e contribute backgrounds



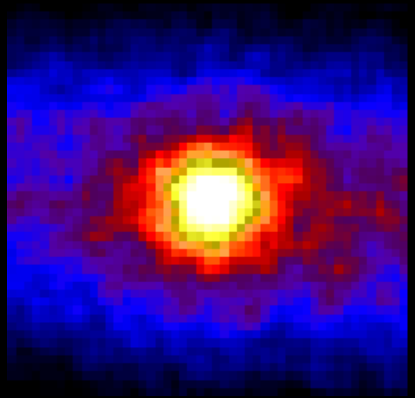


JM, P. Fisher, PRD76:033007 (2007)

Aprile et al., JCAP04 (2016) 027



Irreducible Backgrounds



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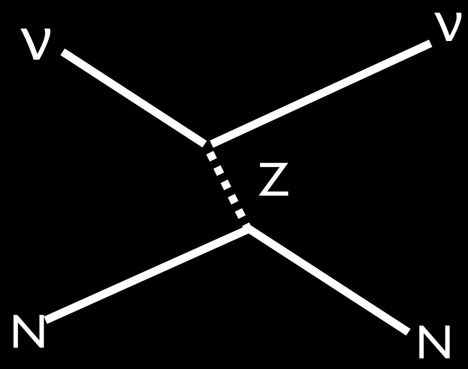

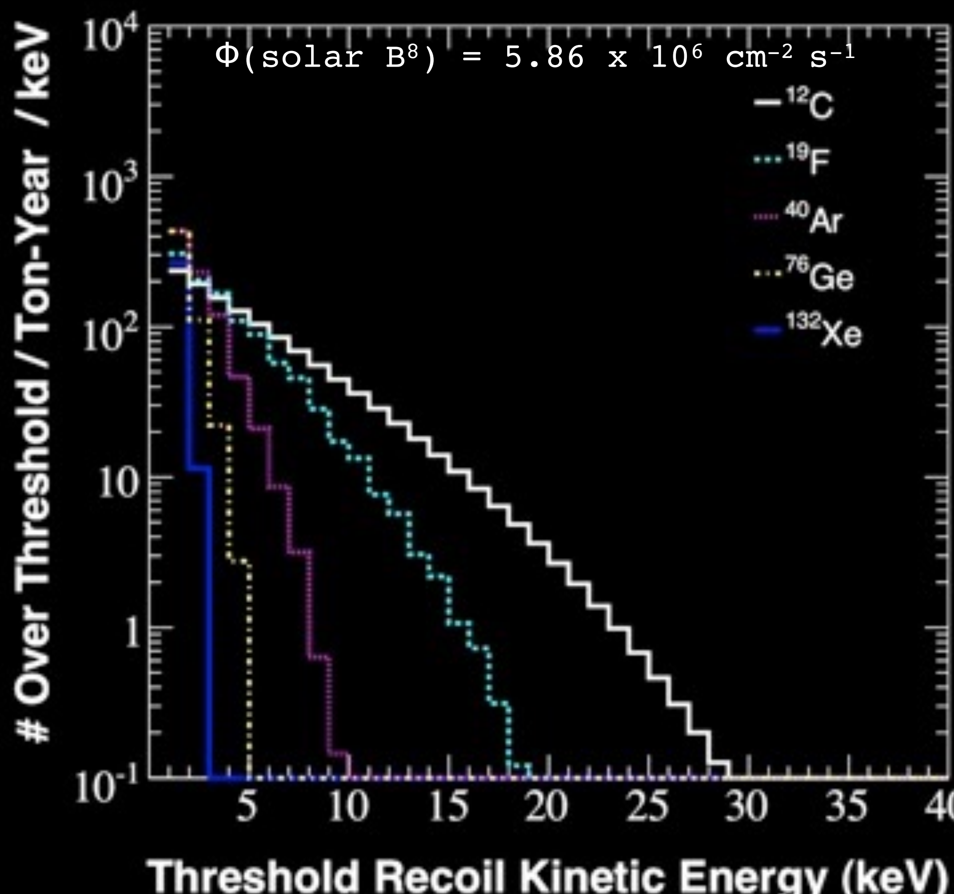

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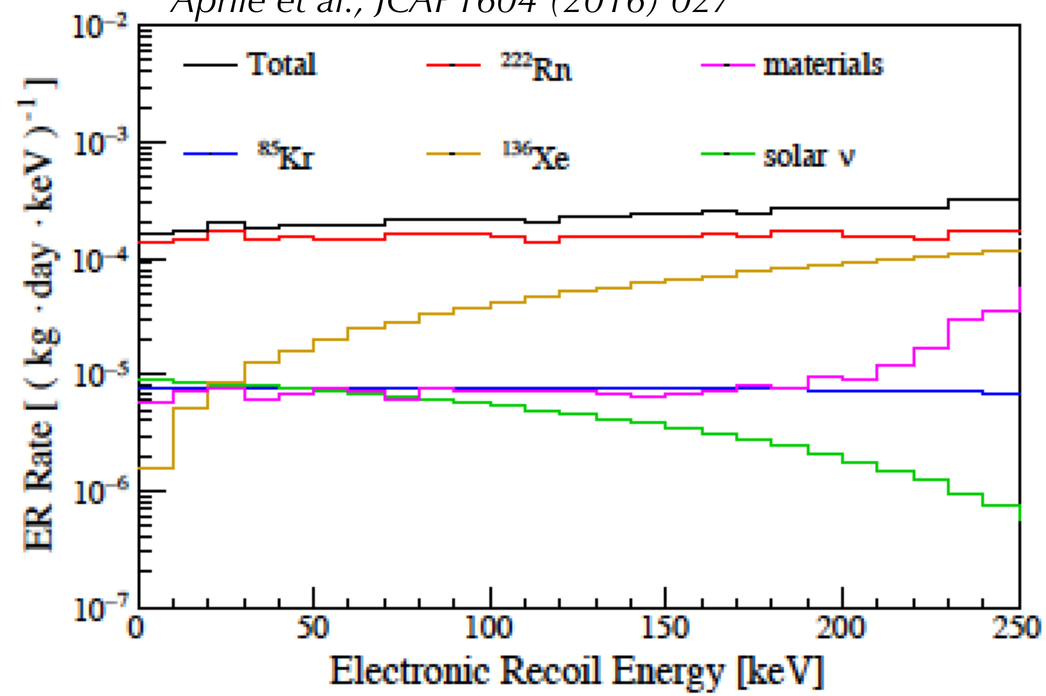
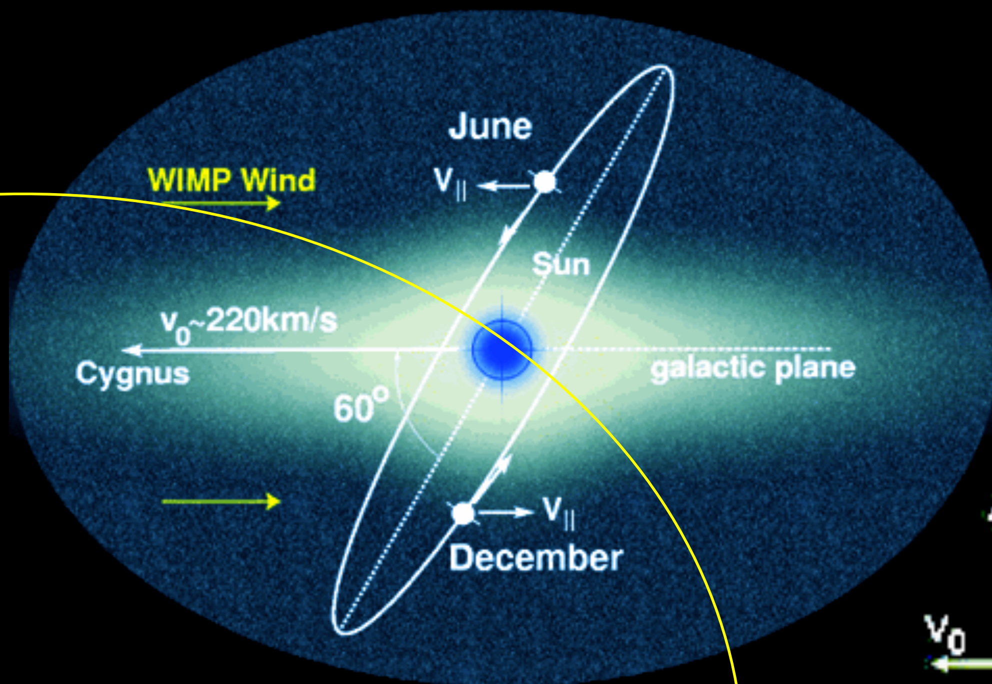


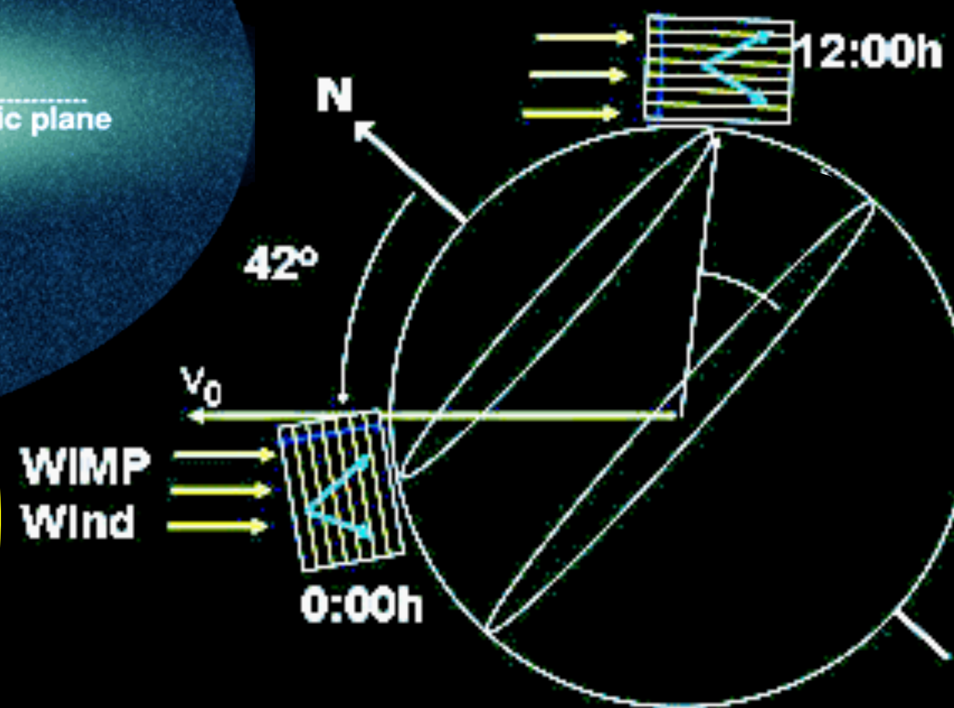
Aprile et al., JCAP1604 (2016) 027

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.

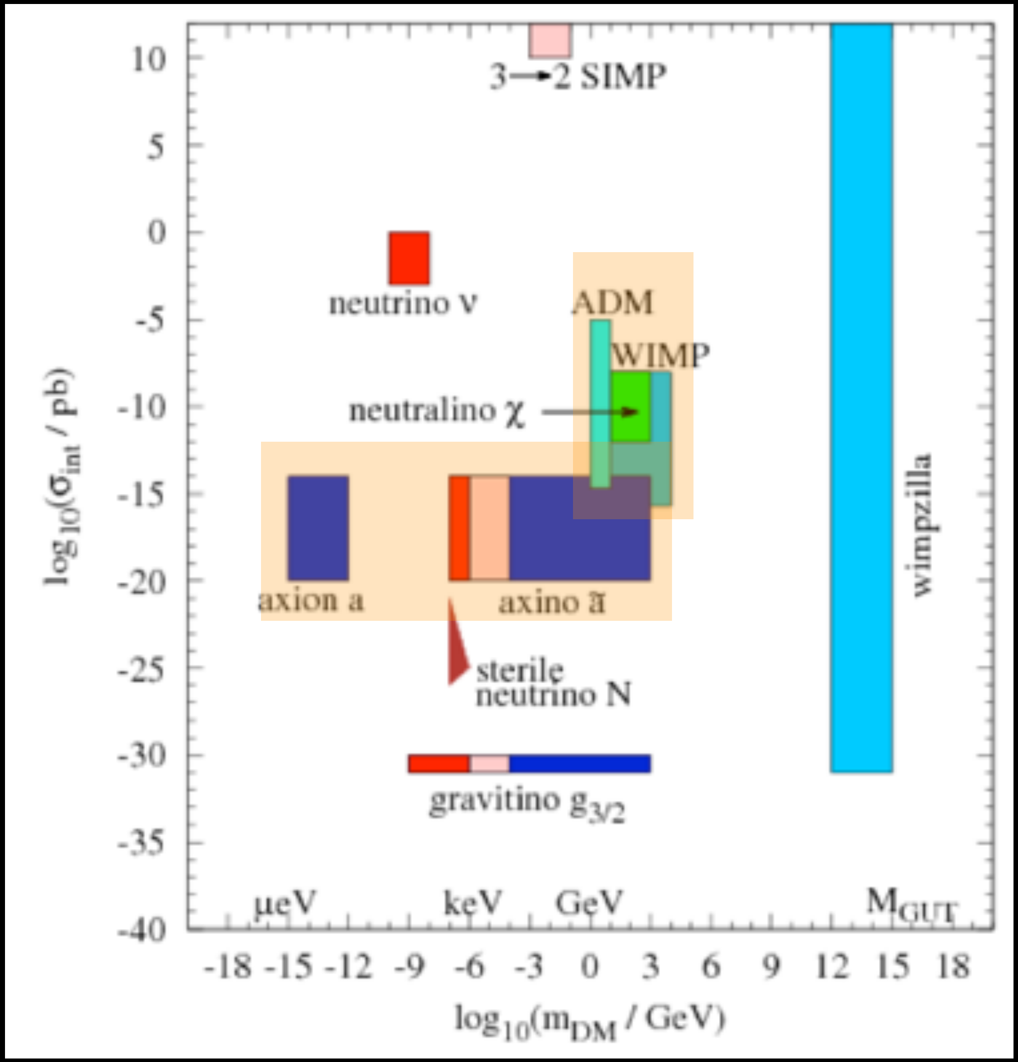
Spergel, Phys. Rev. D36:1353 (1988)

need precise detector stability, + readout capable of direction measurement

Model Space

Wide range of parameters!

Direct detection searches generally optimised for WIMP sensitivity...



Baer et al., arXiv:1407.0017

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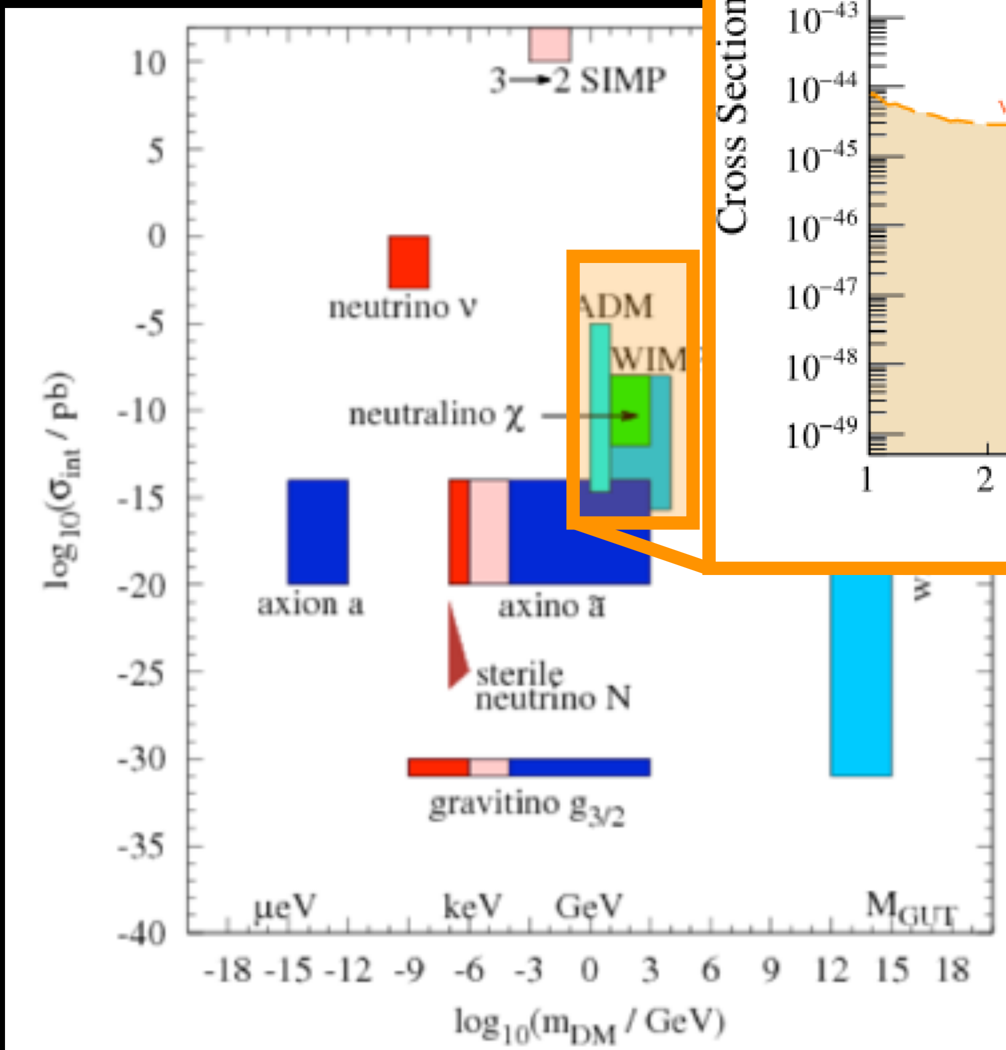

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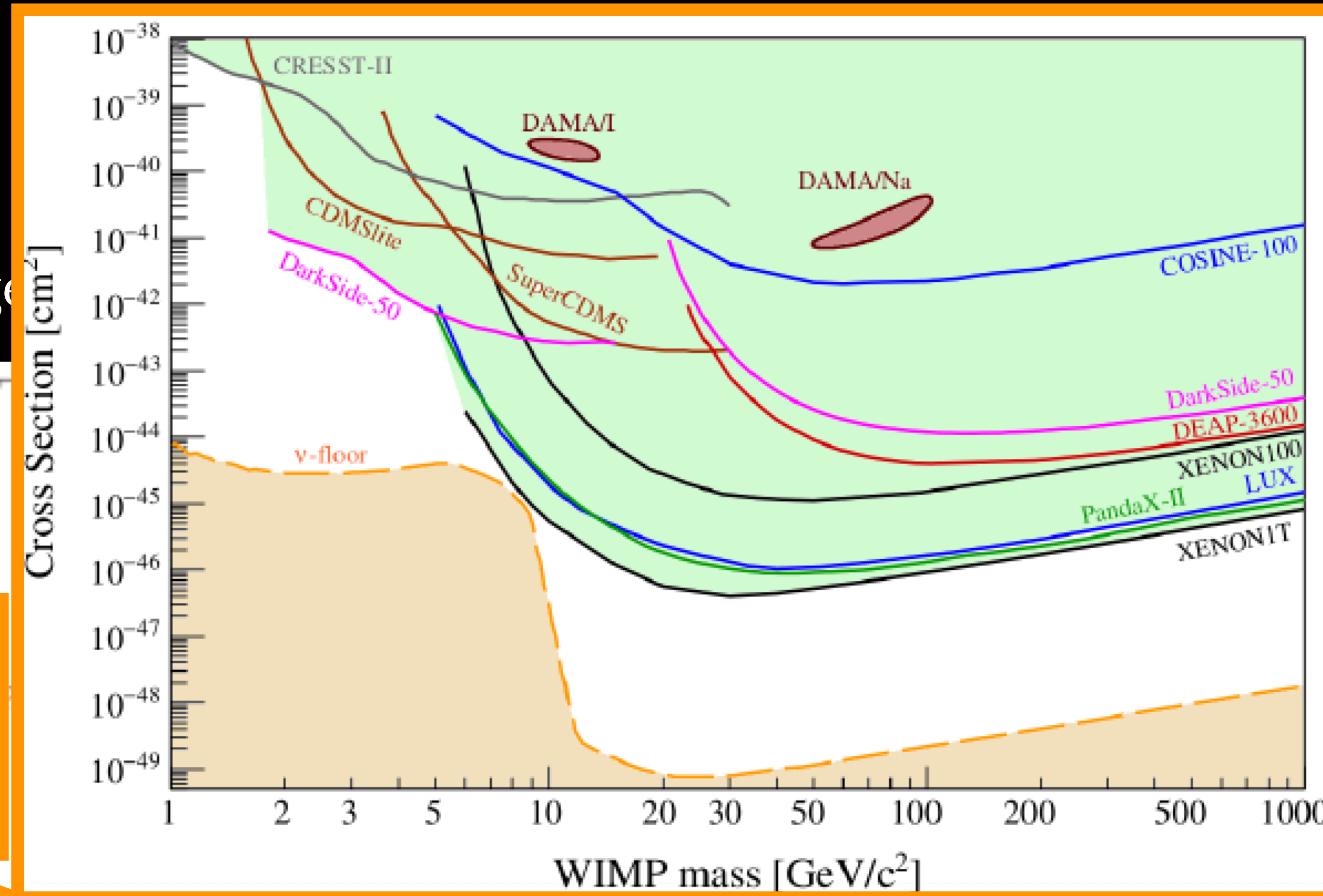

Schumann, arXiv:1903.03026

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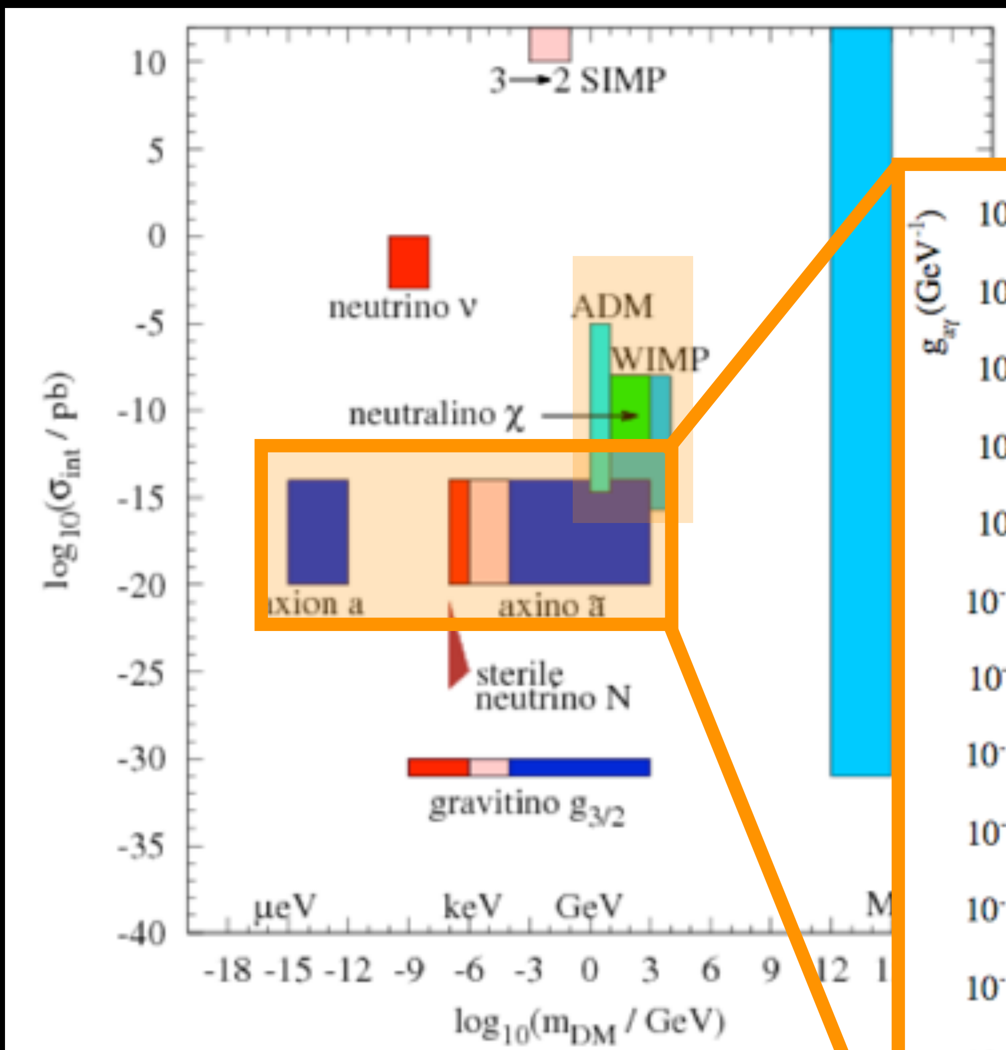
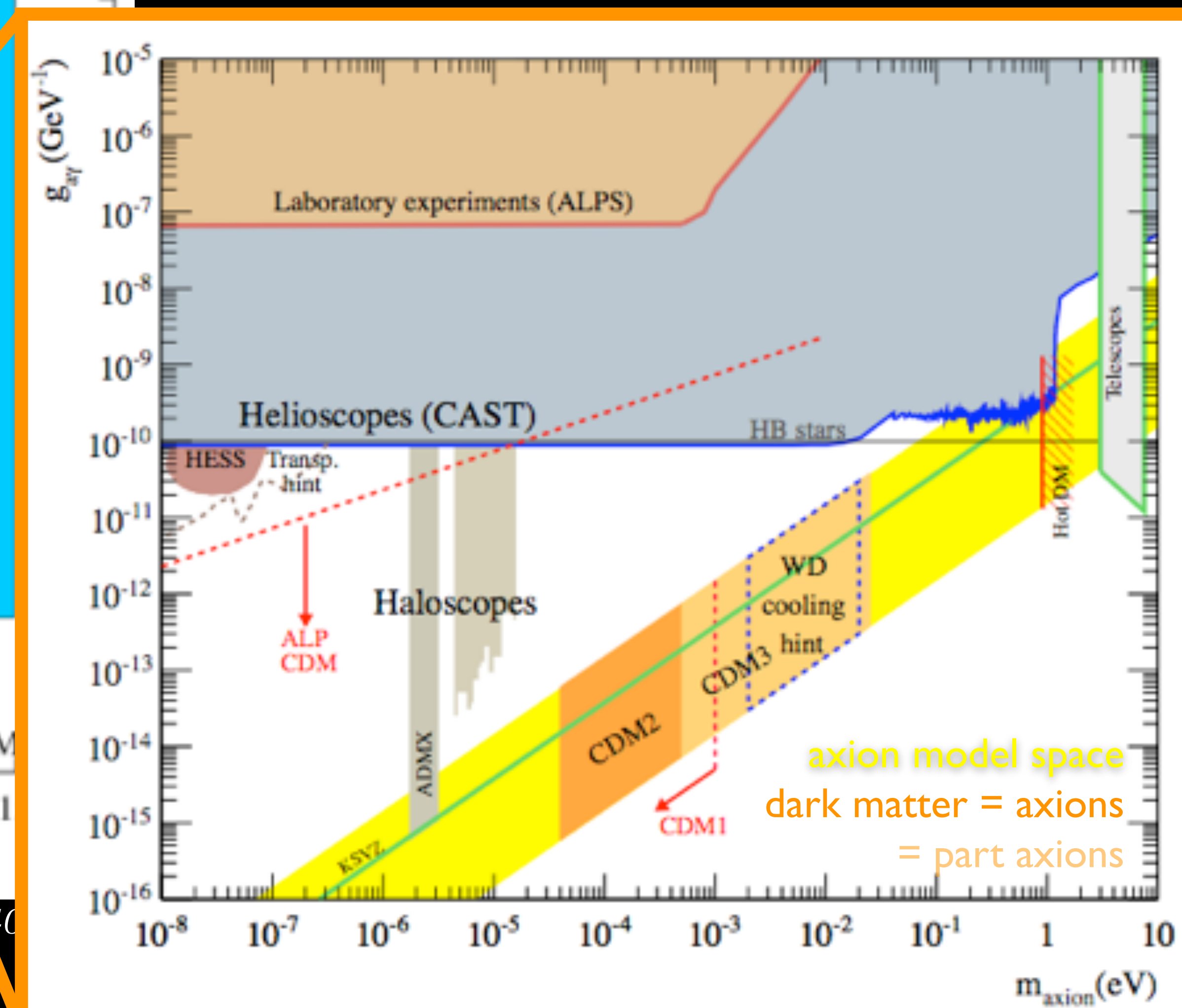


starting to look for axion-like particles too!



Baer et al., arXiv: 140

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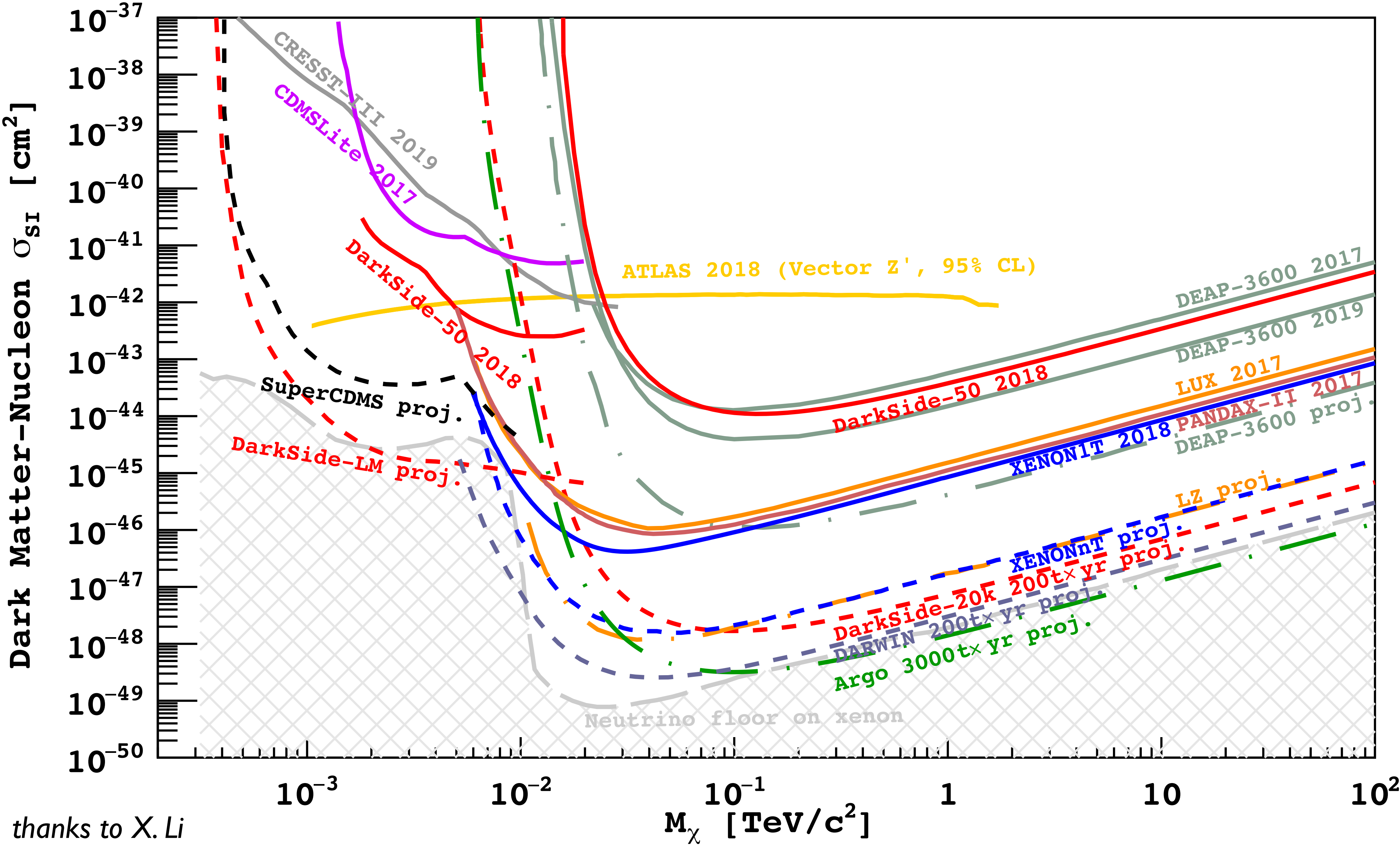
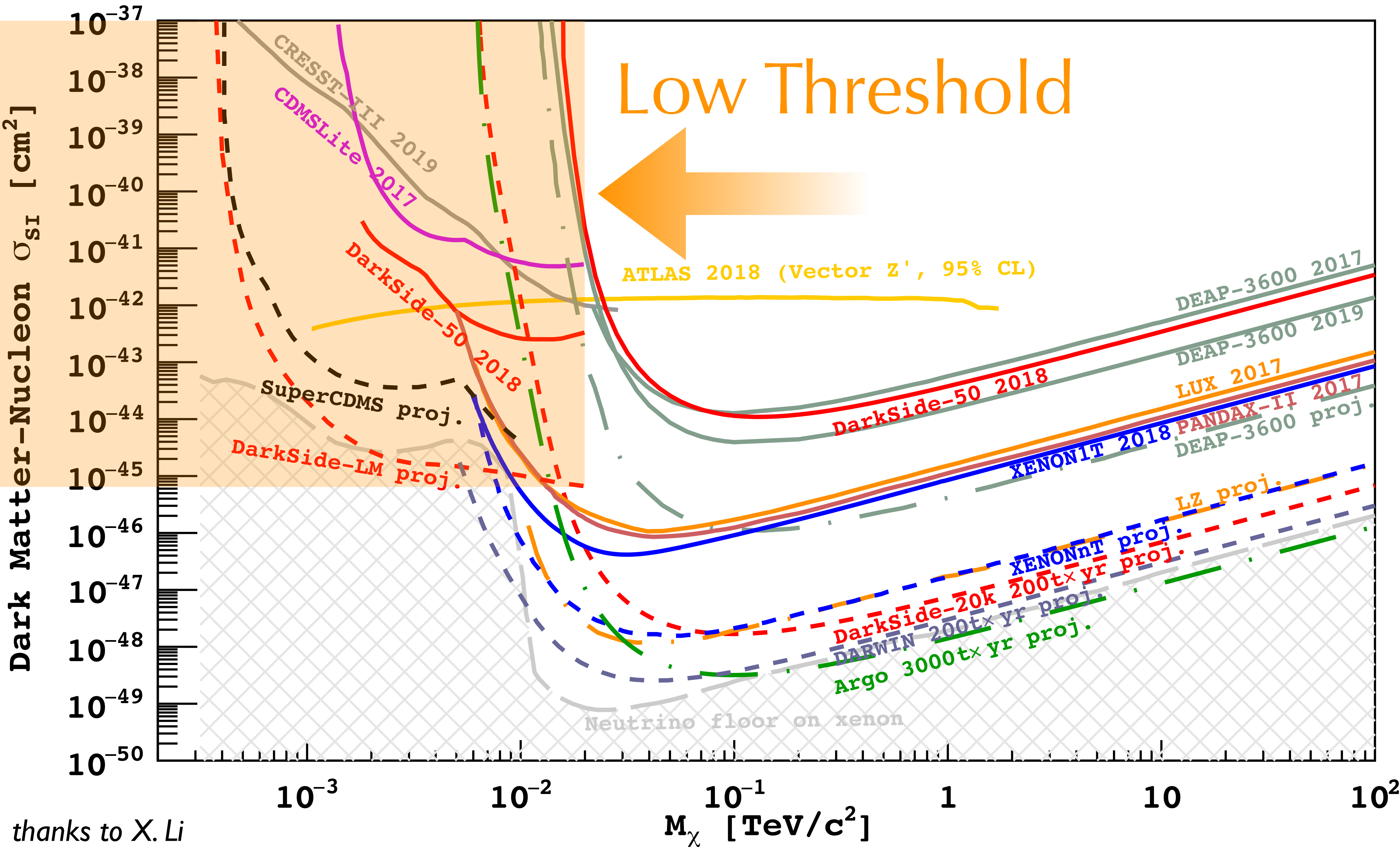
Direct Detection Status and Prospects



thanks to X. Li

Direct Detection Status and Prospects



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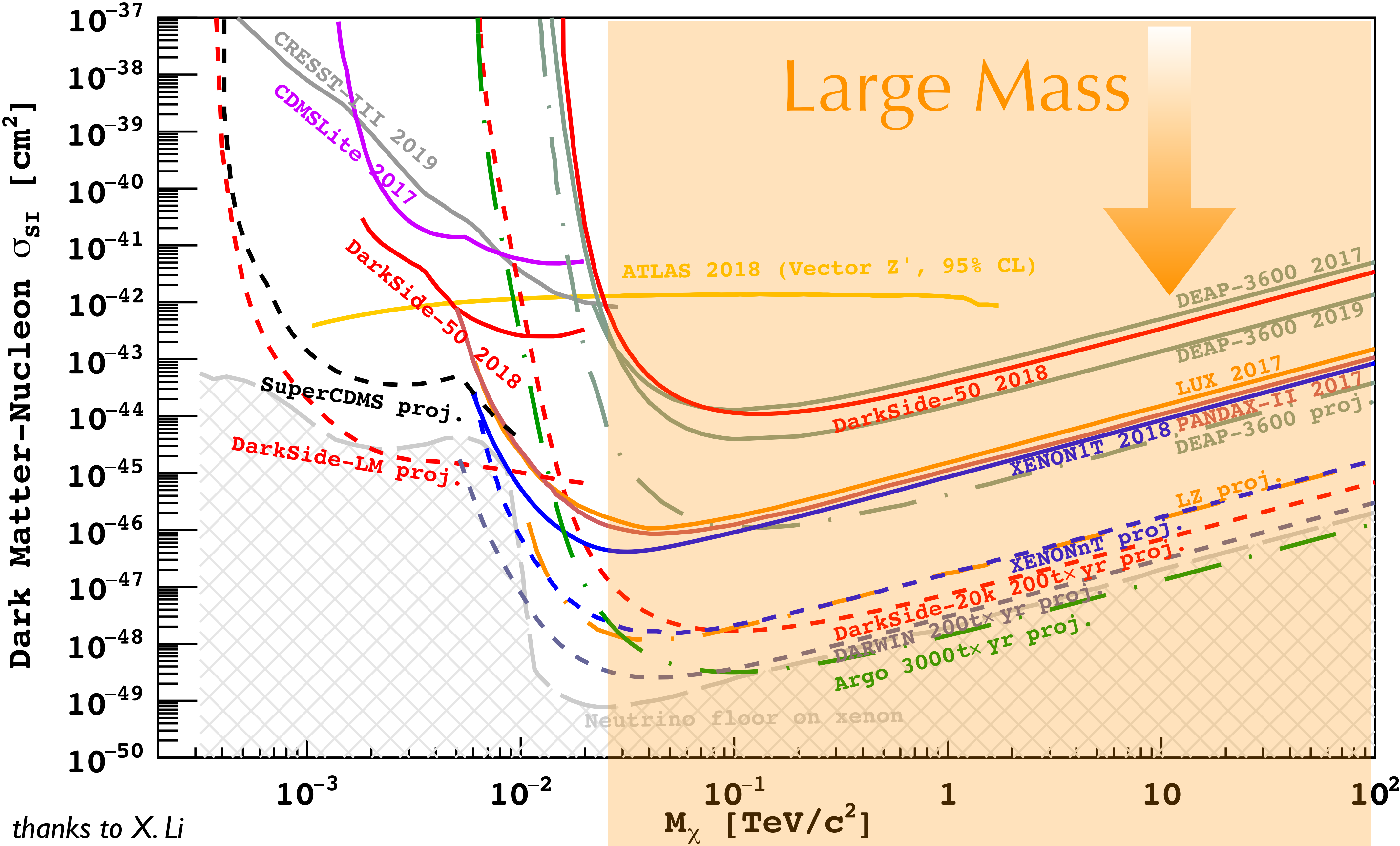
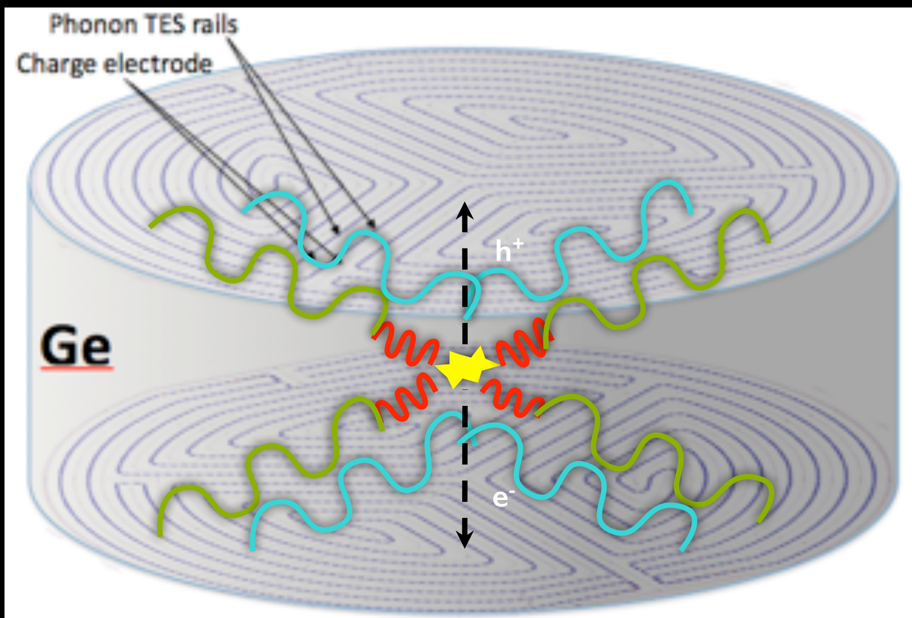
Direct Detection Status and Prospects



thanks to X. Li

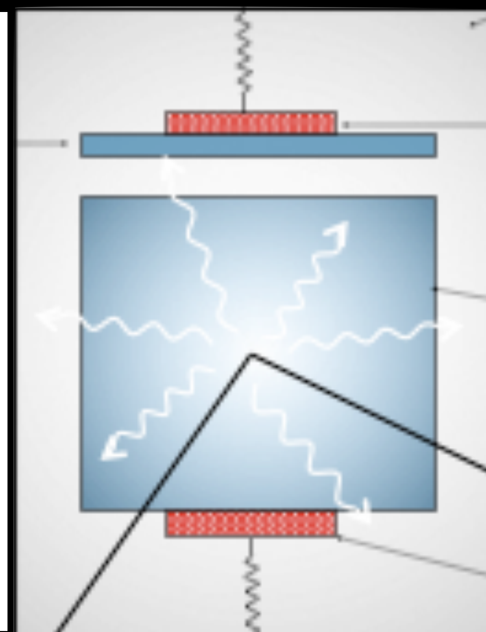
Solid State Dark Matter Detectors

Phonon rails: 1400 gm (**SuperCDMS**) or 800 gm (**EDELWEISS**) Ge, TES for E_{recoil} & R (timing)



Charge electrodes: biased at +/- 2V, measure E_{recoil}, configured to reject surface events

Phonon side: 300 gm $CaWO_4$ (**CRESST**), TES for E_{recoil}l



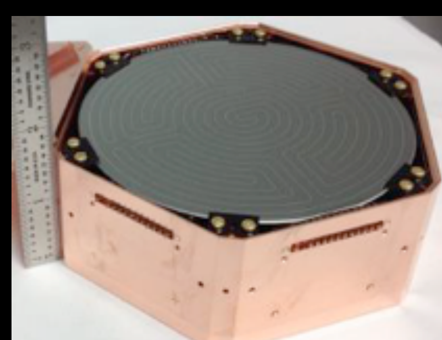
Scintillation side: TES for particle ID

Detector Technology:

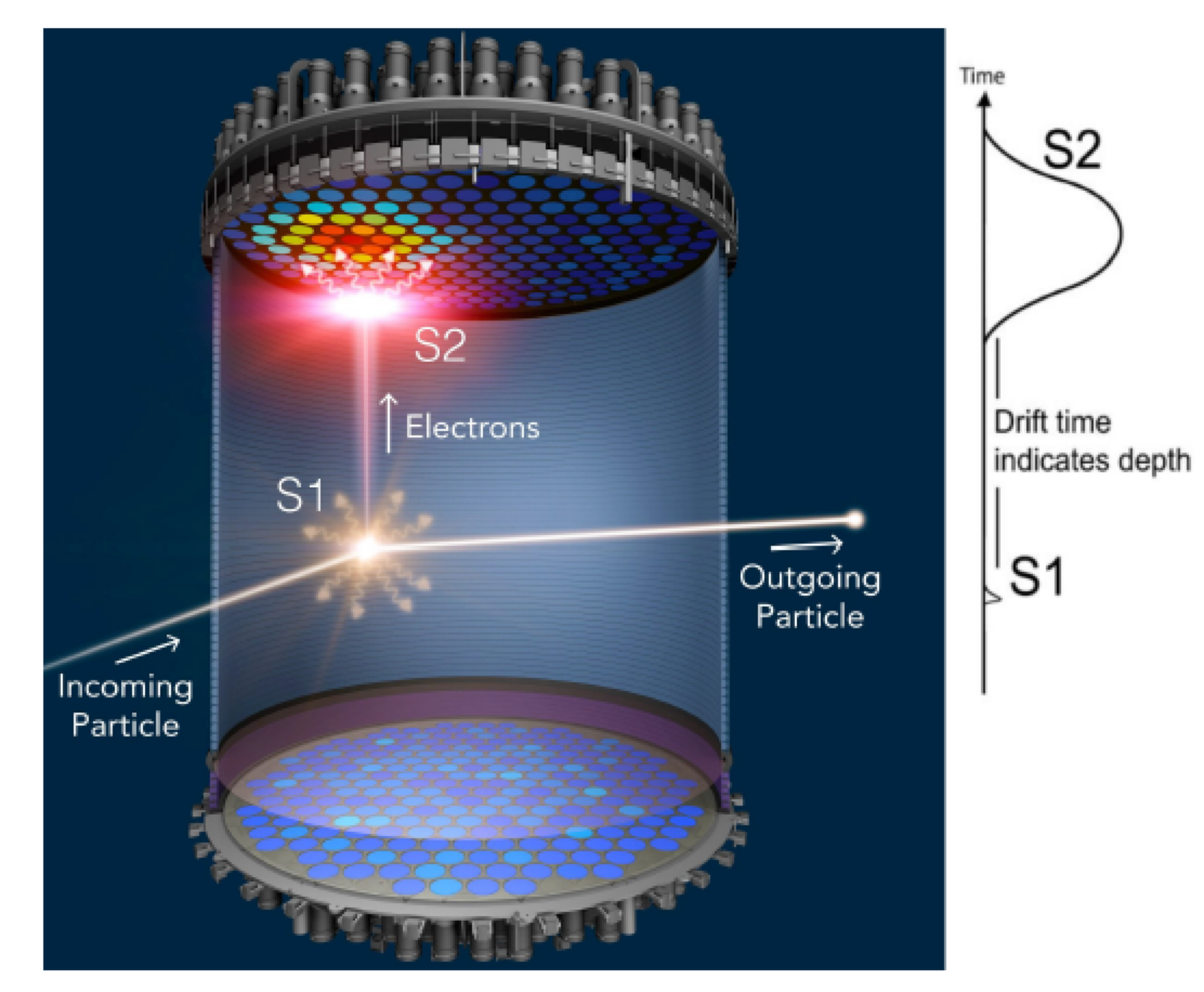
crystal bolometers with Transition Edge Sensor readout at O(10 mK) for phonon detection + scintillation/ionization

\+ many new ideas

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



Large-Mass Dark Matter 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"

Goal: zeptobarn ->
yoctobarn sensitivity
to dark matter!

Liquid Noble Targets

particle identification:
light vs. time depends on ionization density.

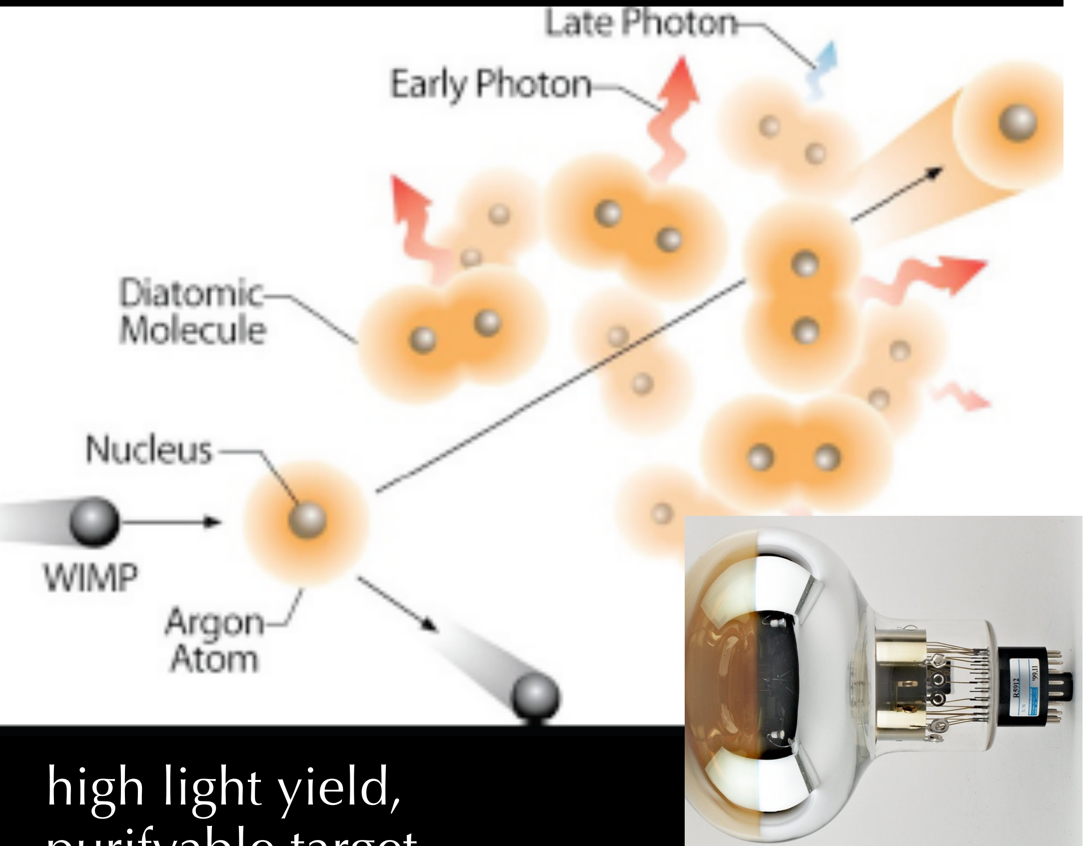
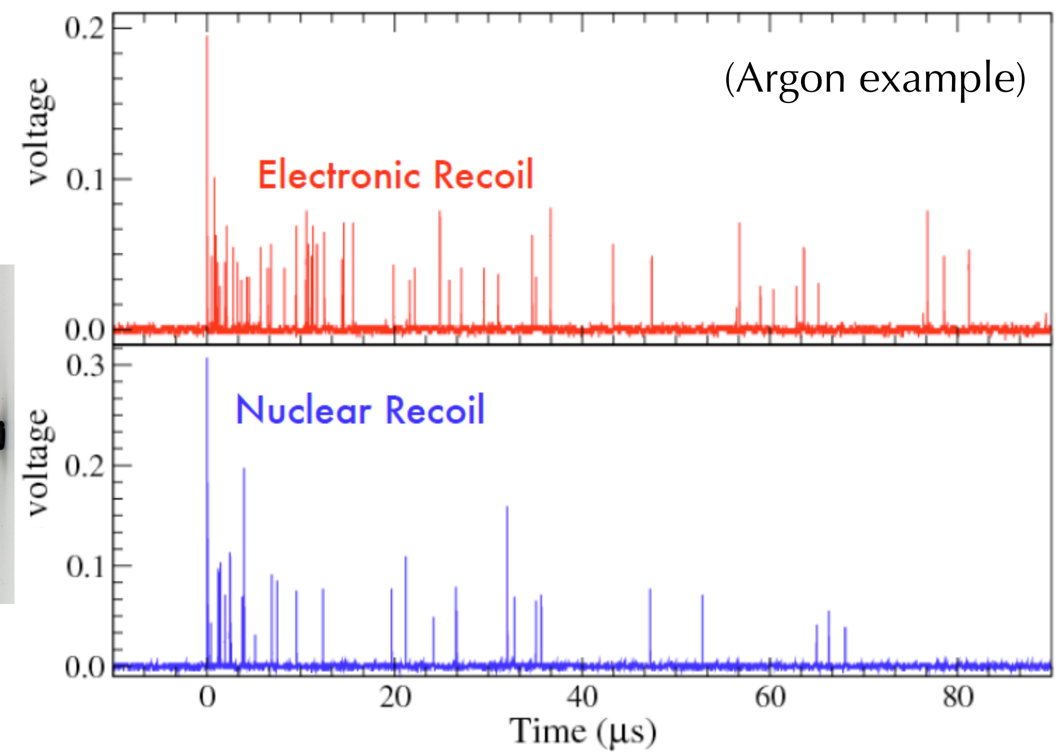


Table 3: Scintillation parameters for liquid neon, argon, and xenon.

Parameter	Ne	Ar	Xe
Yield ($\times 10^4$ photons/MeV)	1.5	4.0	4.2
prompt time constant τ_1 (ns)	2.2	6	2.2
late time constant τ_3	15 μs	1.59 μs	21 ns
I_1/I_3 for electrons	0.12	0.3	0.3
I_1/I_3 for nuclear recoils	0.56	3	1.6
λ(peak) (nm)	77	128	174
Rayleigh scattering length (cm)	60	90	30



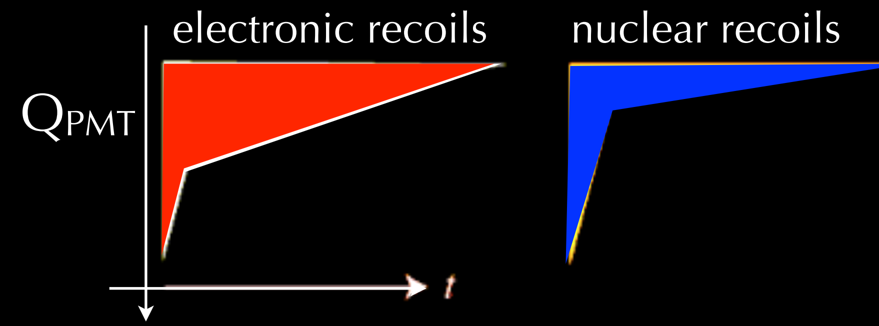
Amaudruz et al. Astropart.Phys. 85 (2016) 1-23

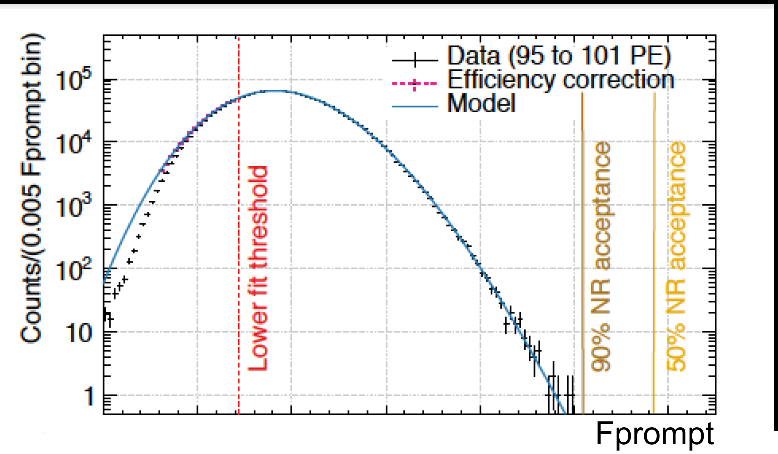
high light yield,
purifyable target,
self-shielding,
transparent to VUV scintillation,
…

Argon Detectors

Liquid Ar TPCs developed for neutrino oscillation searches

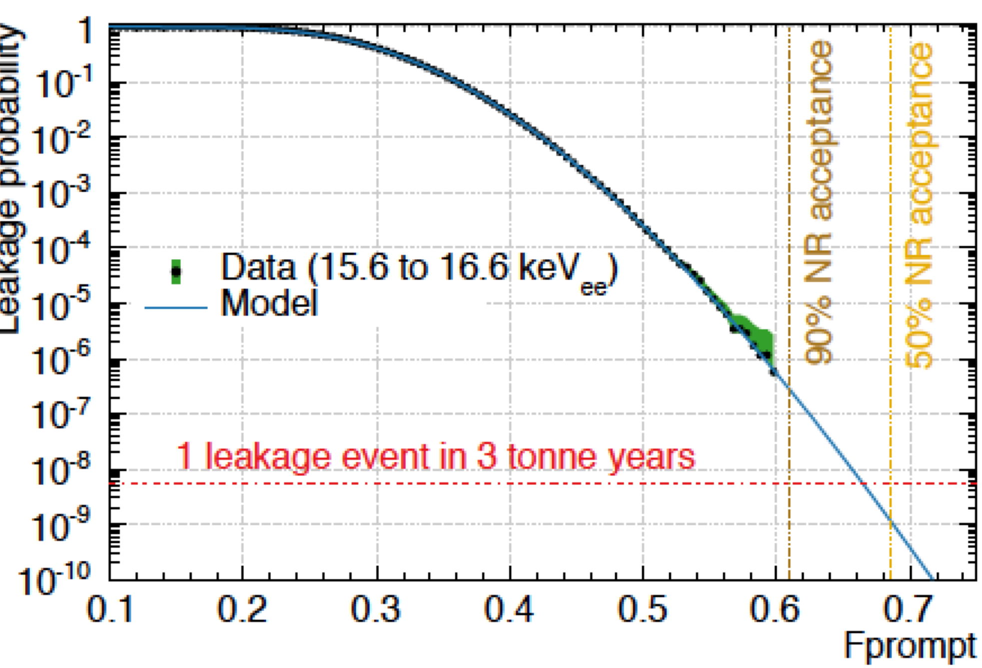
DM searches: background ID power from light vs. time

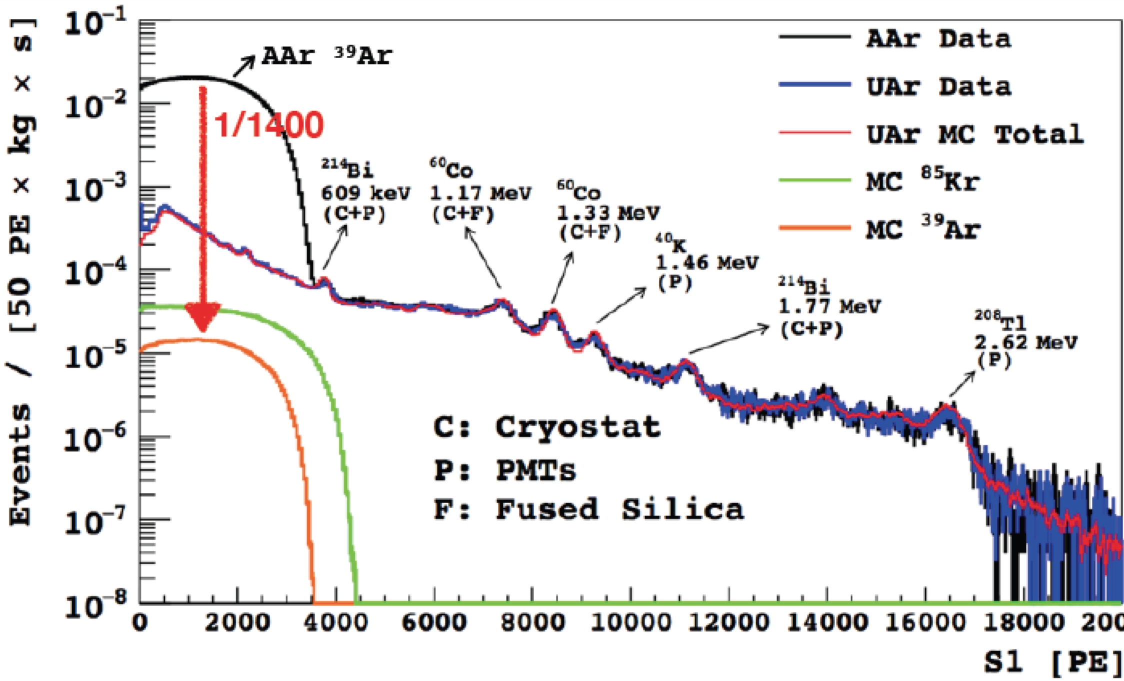




DEAP: electron-nuclear recoil discrimination at 15 keVee threshold is **3.5E-11** (50% nuclear recoil acceptance)

DarkSide-50: developed underground argon (UAr) extraction & distillation to deplete Ar in Ar-39 by >x1000

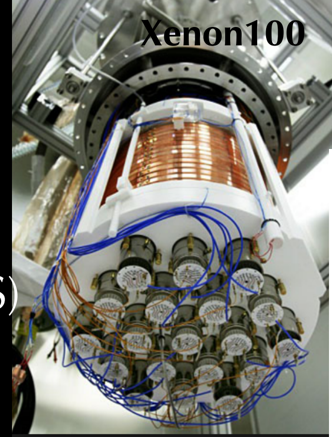




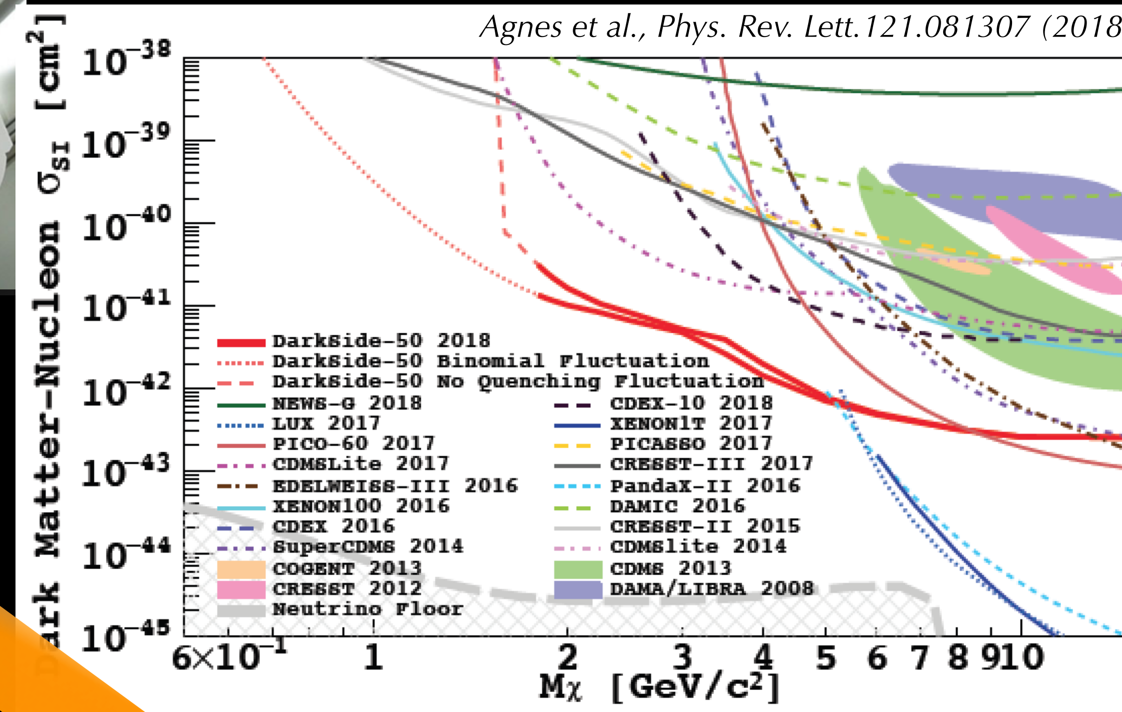
Ajaj et al, arXiv:1902.04048

Agnes et al, Phys. Rev. D.93.081101 (2015)

Argon Detectors



DarkSide-50: leading SI limit at 1-5 GeV/c² for WIMP-nucleus and WIMP-e scattering



2010

10 kg

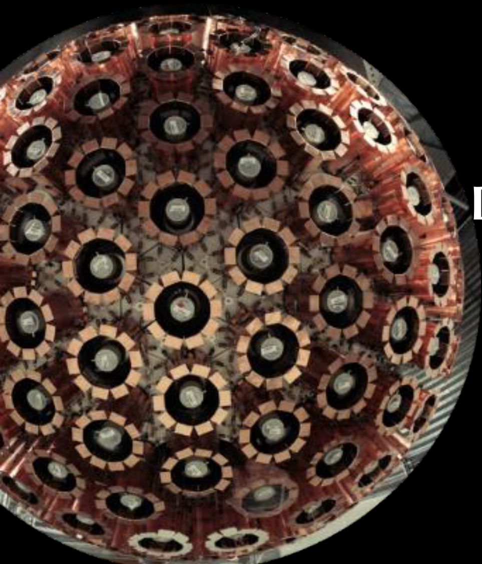
DarkSide-50
(50 kg, LNGS)

100 kg

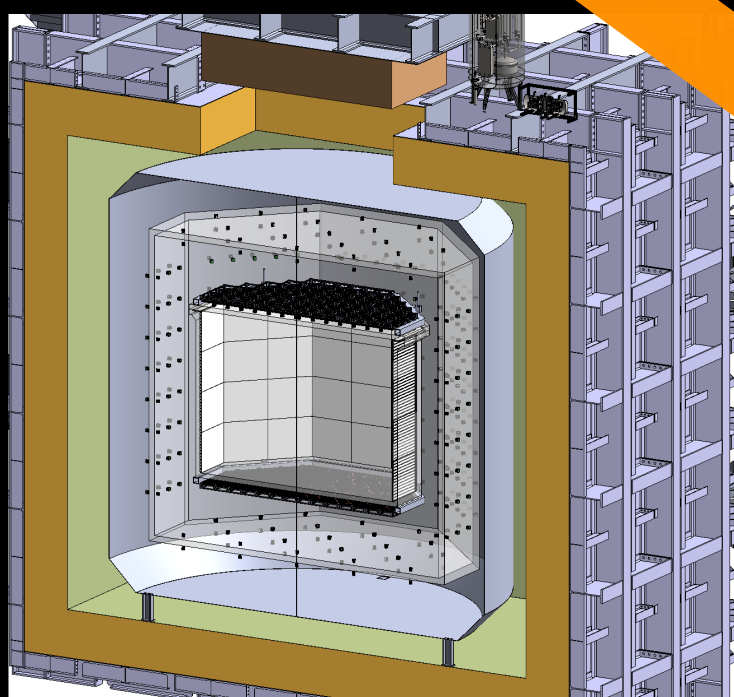
ArDM
(1t, LSC)

2015

1000 kg



DEAP-3600 (3.6t, SNOLAB)



2020

Global Argon Dark Matter Collaboration formed:

APPEC

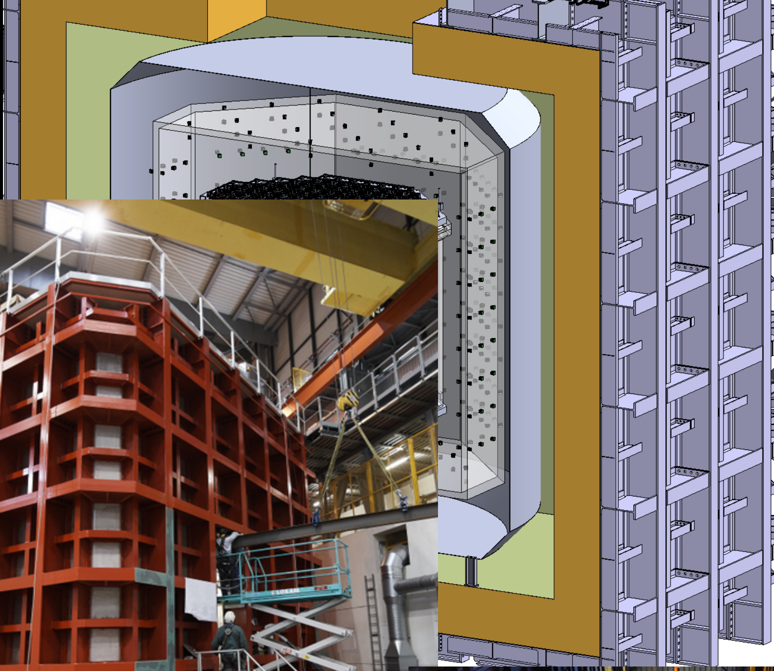
DarkSide-20k
(50t, LNGS)

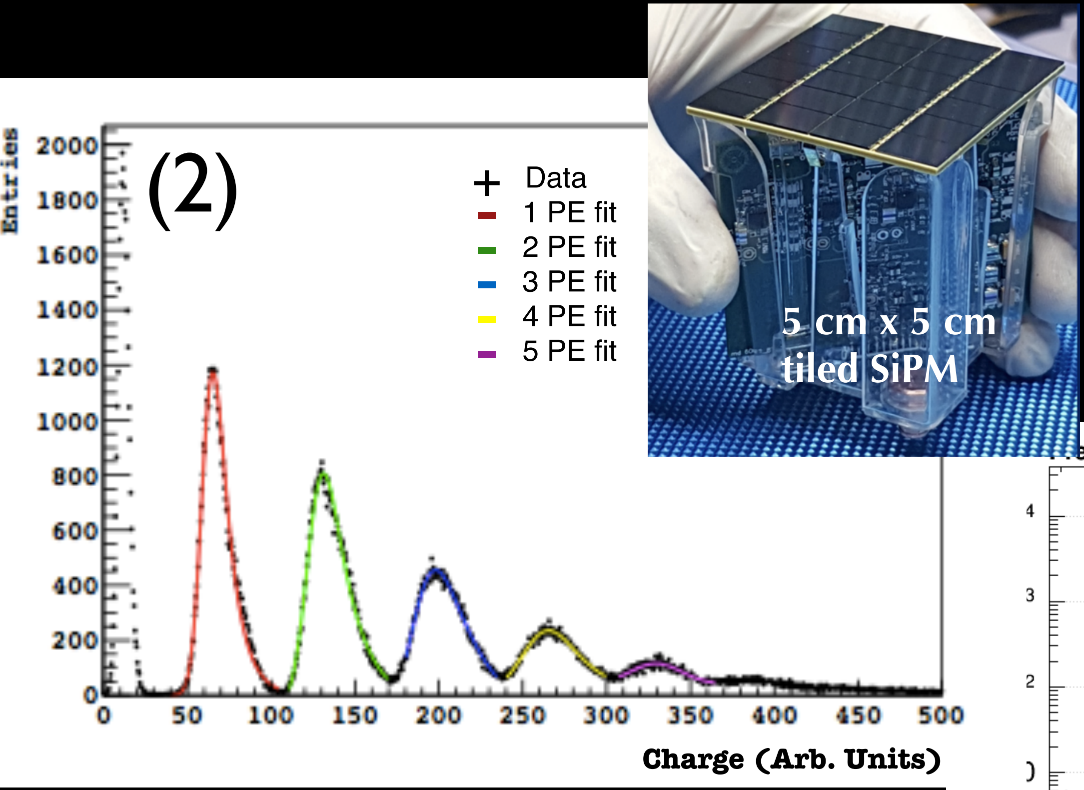
100000 kg

ARGO: 400 t,
ESPPU Document #97

Technology Synergies

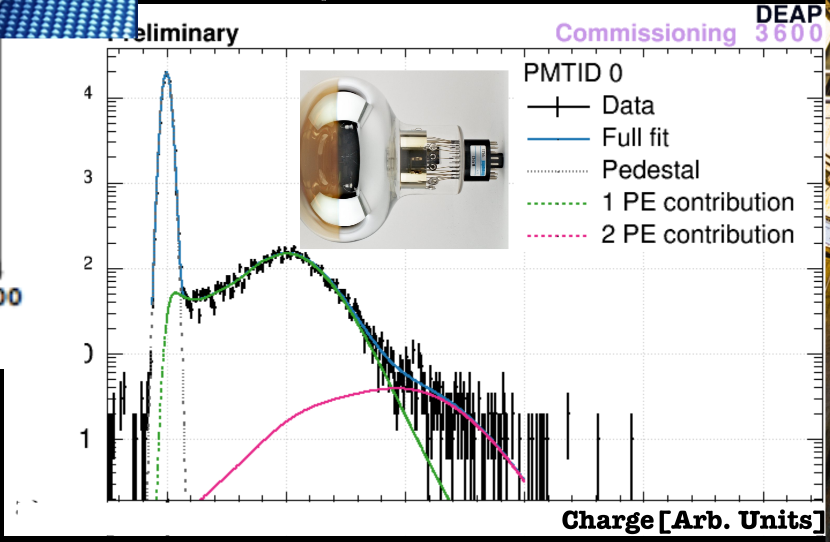
1. Cryostat technologies: DarkSide-20k cryostat uses technology developed for ProtoDUNEs
2. Photon sensors: low noise, high efficiency, cryo Si sensors developed by DarkSide-20k with FBK (LHC Si)
3. Isotopic enhancement: ARIA facility for depletion of Ar-39 in UAr, CERN Vacuum Group collaboration



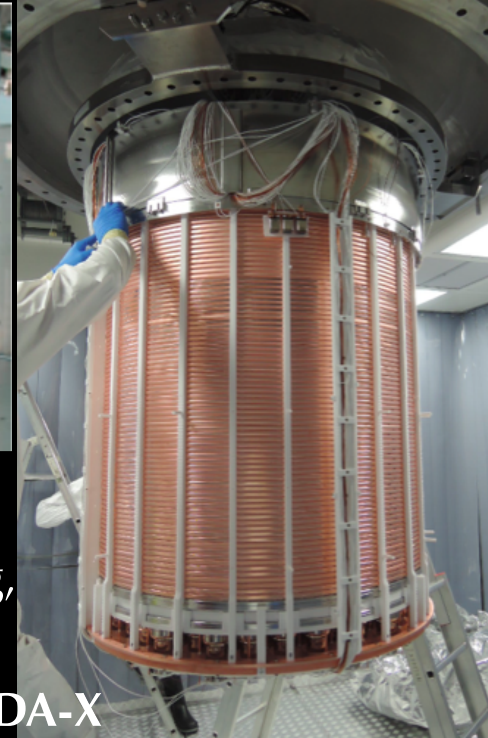


Aalseth, et al. JINST 12 (2017) no.09, P09030

for comparison:



Xenon Detectors



XENON 10 (LNGS)
ZEPLIN II (Boulby)
ZEPLIN III (Boulby)

10 kg

2010

XENON 100 (LNGS)

100 kg

LUX (250 kg, SURF),

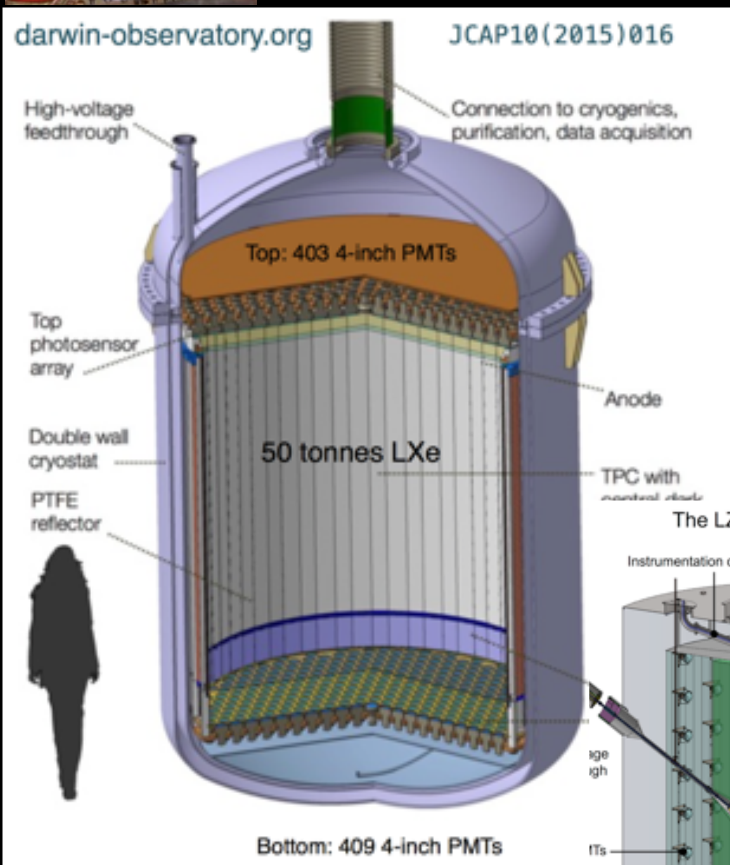
PANDA-X (500 kg, CJPL)

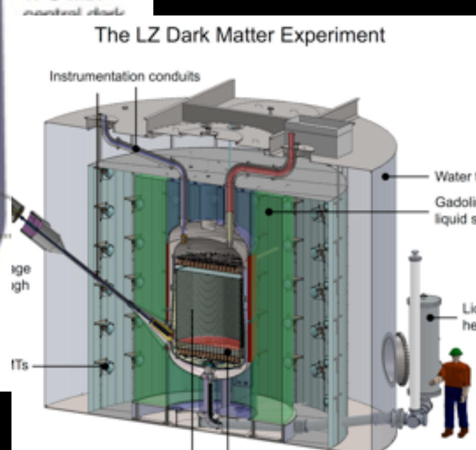
2015

XMASS (0.8t, Kamioka)

1000 kg

XENON 1T (1t, LNGS)





PandaX-4:(4t, CJPL)

2020

XENONnT: (6t, LNGS)

LZ: (7t, SURF)

10000 kg

DARWIN: 50 t,
ESPPU Document #62

Xenon TPCs

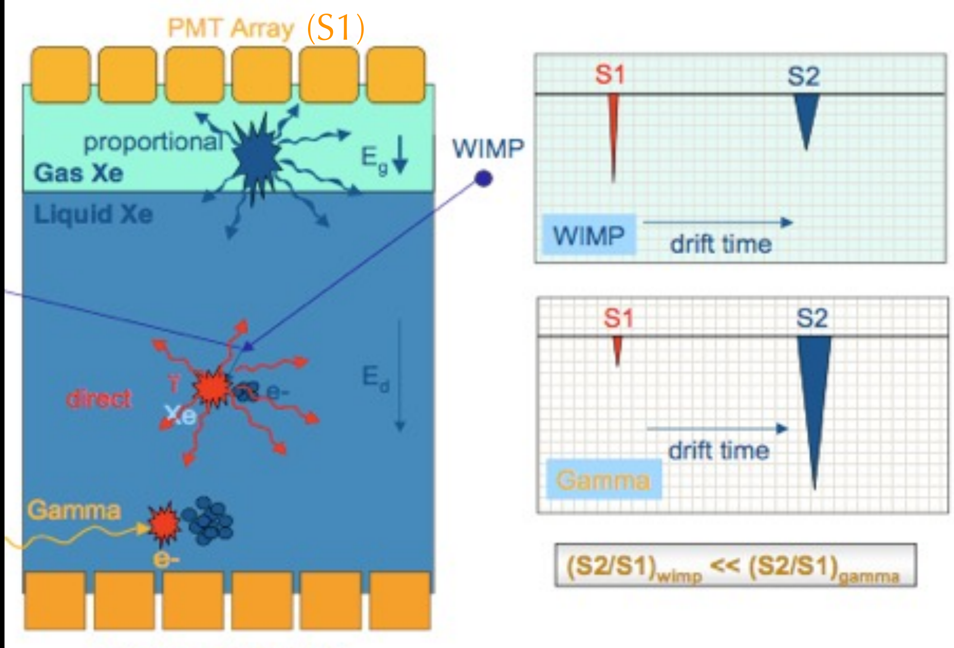
technique developed for gamma ray astrophysics balloon experiments

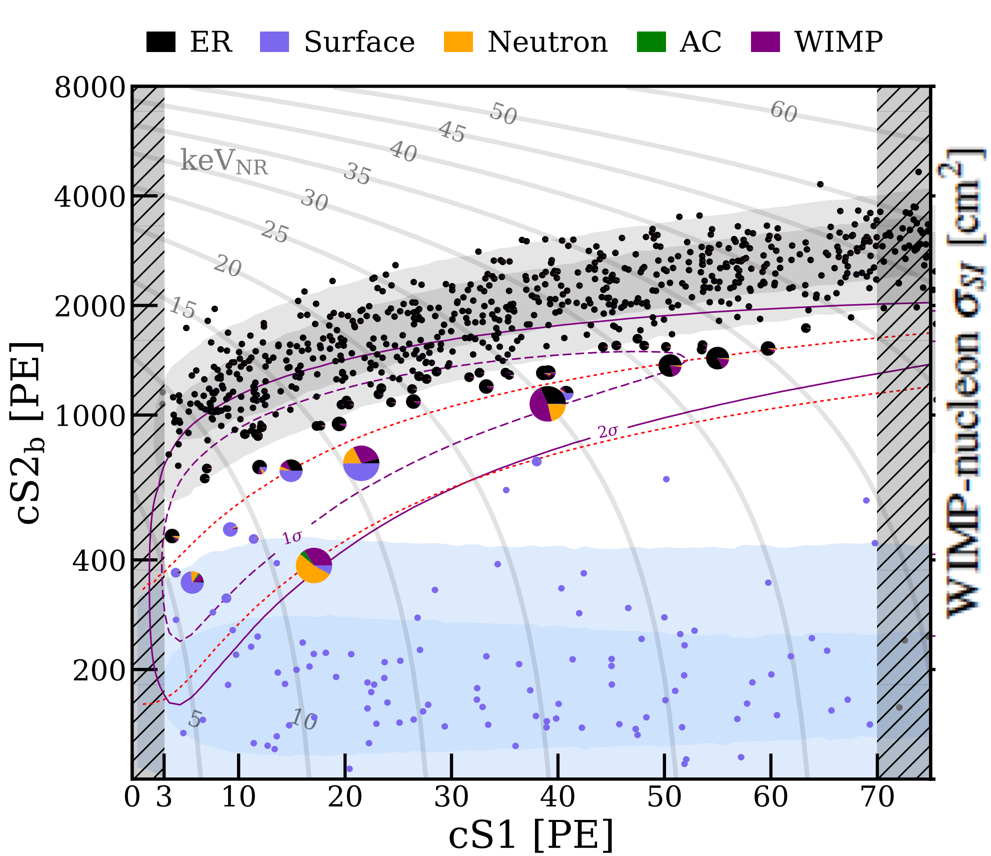
electron-nuclear recoil discrimination from S1/S2 of **3x10^{-2}** at 1.4 keVee threshold

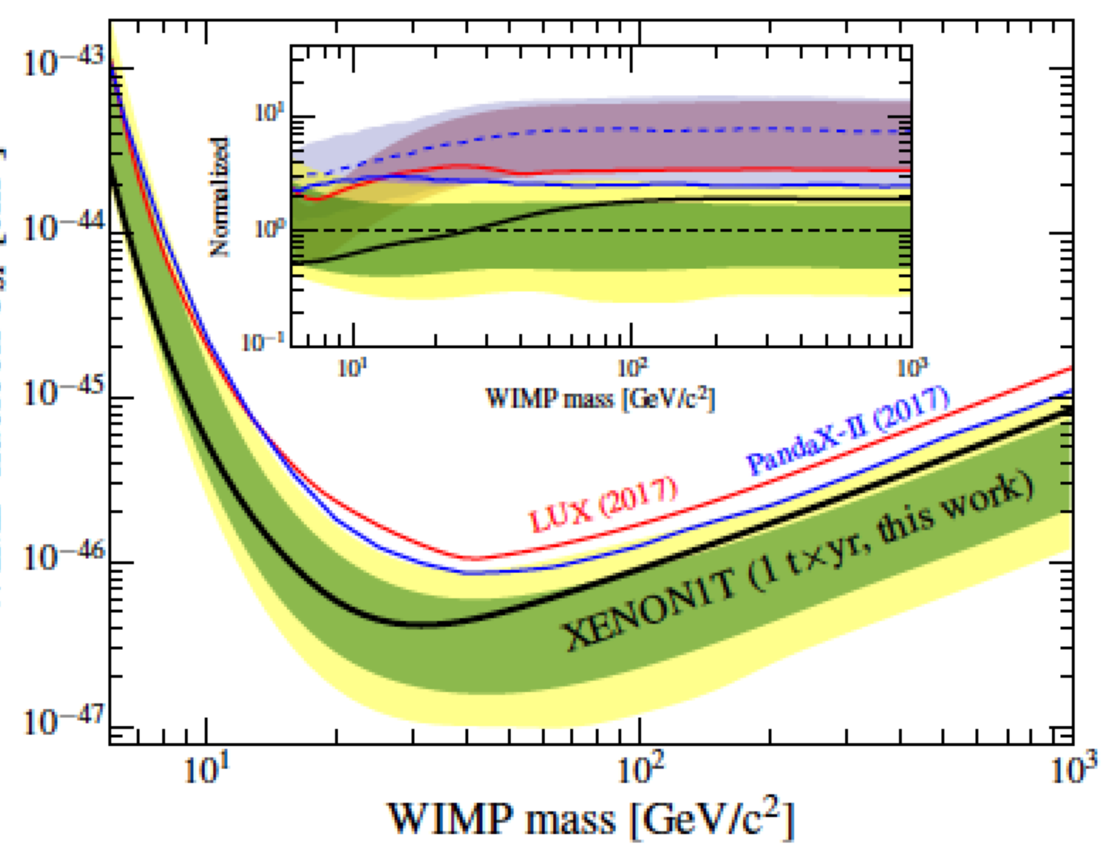
"S1": primary scintillation

"S2": amplified, drifted, ionization signal

XENON1T: leading SI constraint at >30 GeV/c^2



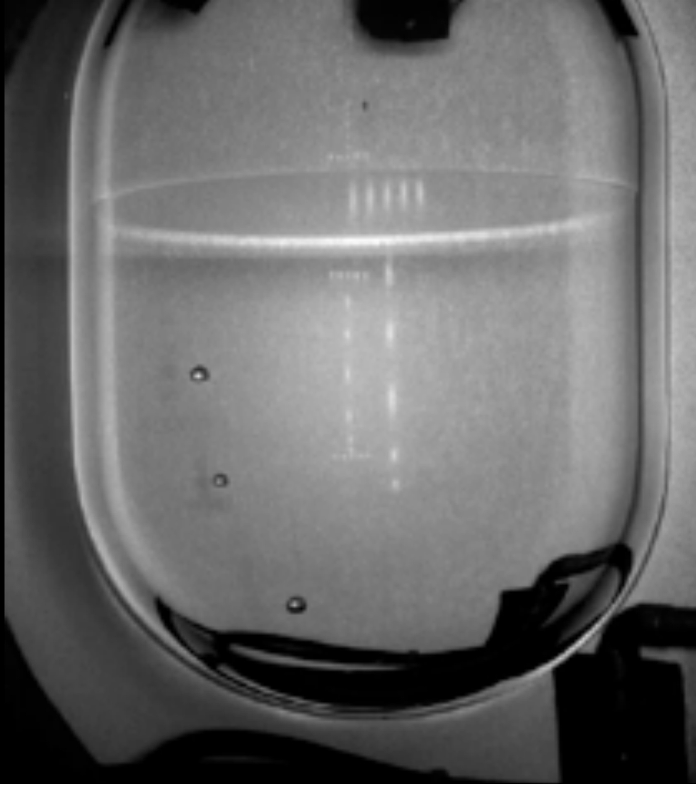


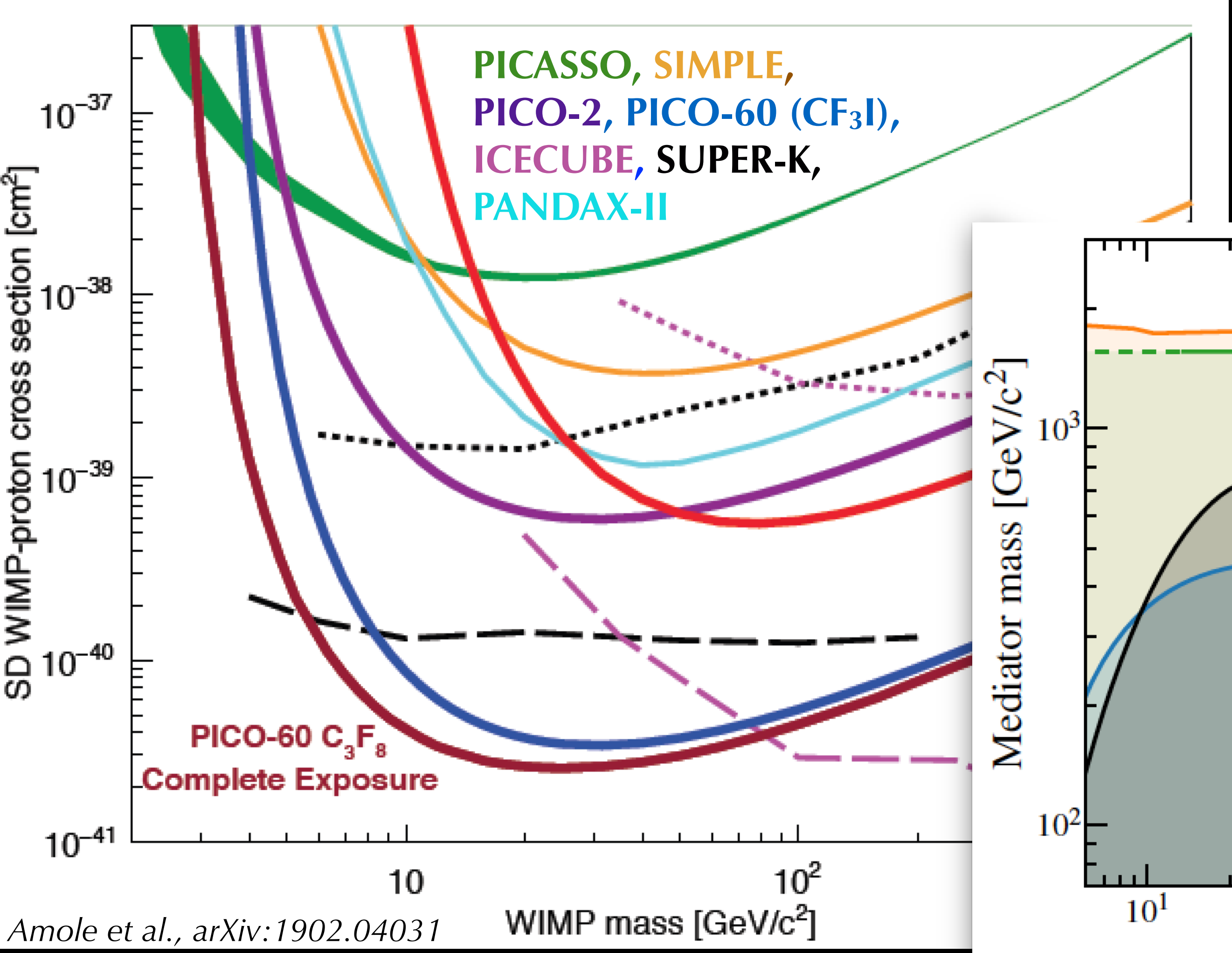


Spin-Dependent Interactions, Prospects

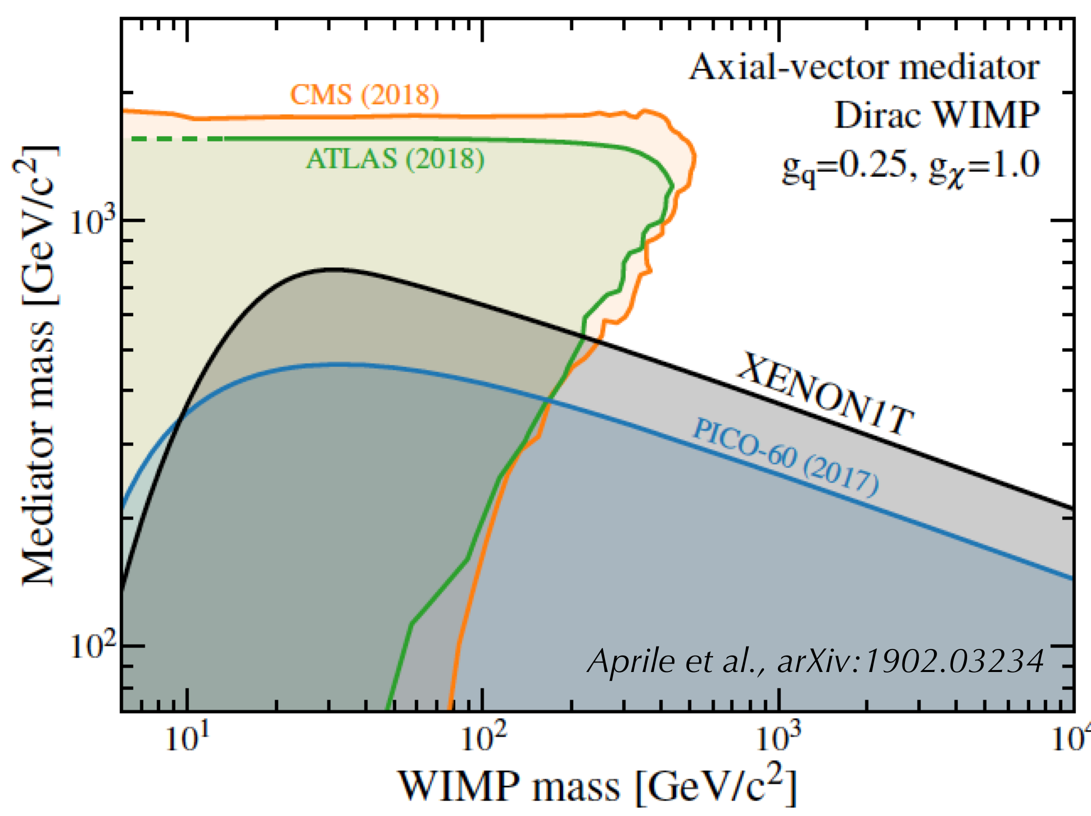
Detector Technology: superheated target (C_NF_M), camera + acoustic readout, background rejection based on topology $O(10^{-2})$, measure counts above threshold when dE/dx > nucleation, **SIMPLE** (GESA), **PICASSO+COUPP** = **PICO** (SNOLAB)

PICO-60: leading WIMP-p limit, C_4F_8 target (60 kg), 500 kg planned. leading WIMP-n limits from Xe 2-phase TPCs.





Amole et al., arXiv:1902.04031

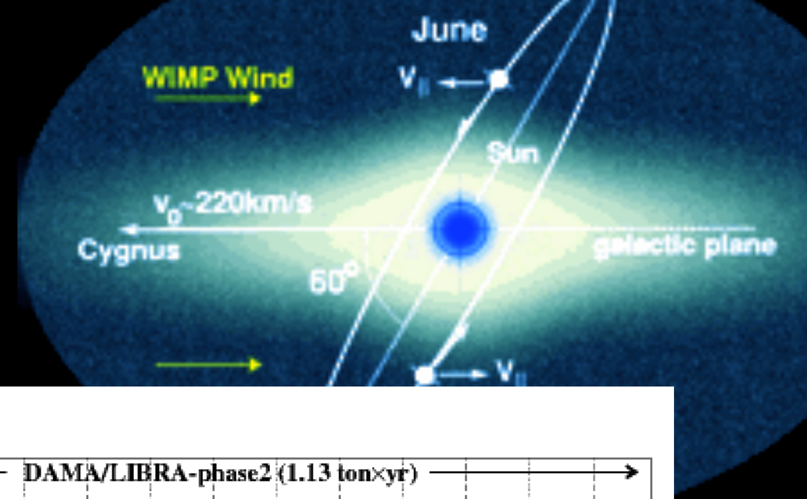


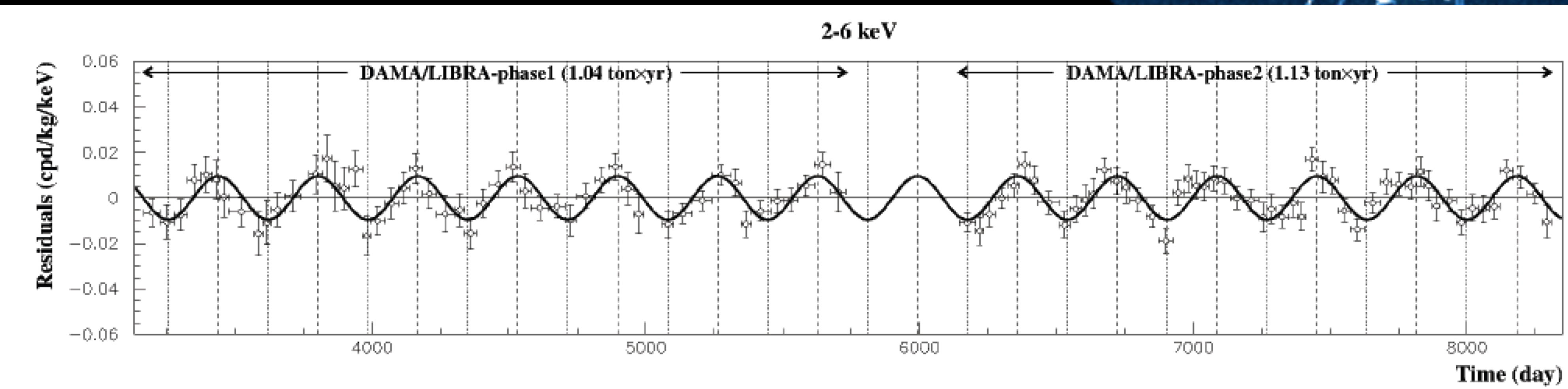
Aprile et al., arXiv:1902.03234

Annual Modulation Searches

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.



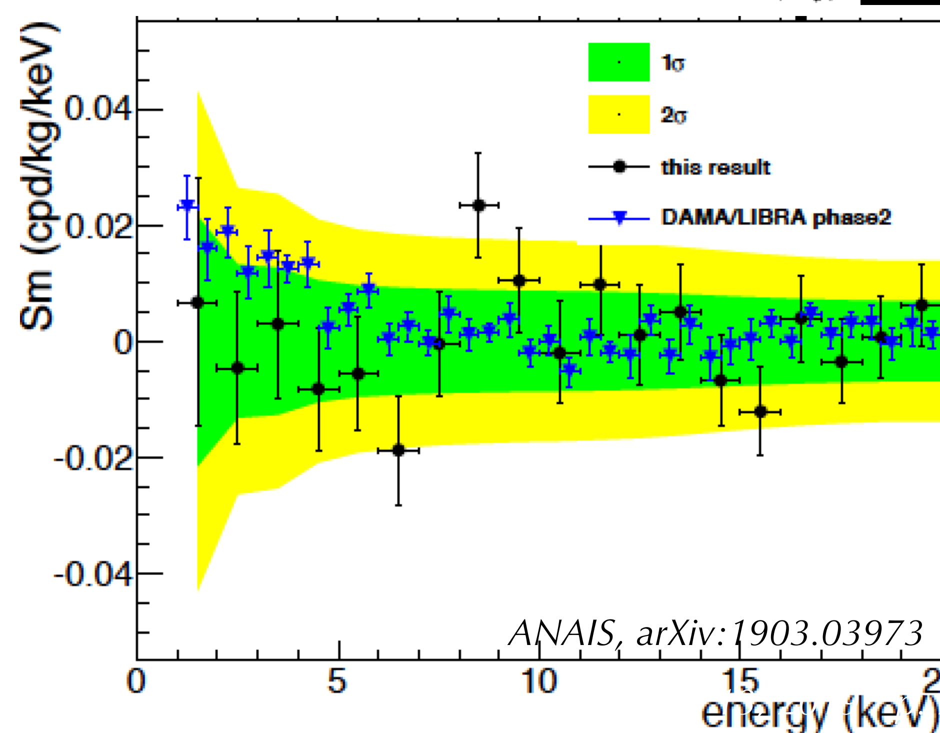


CSLNGS, March 2018

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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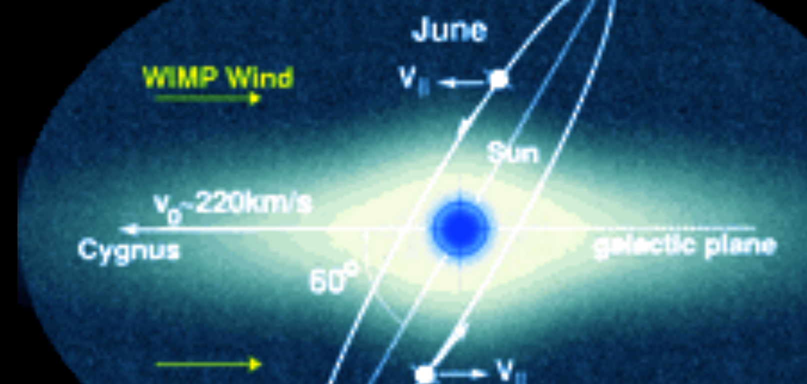

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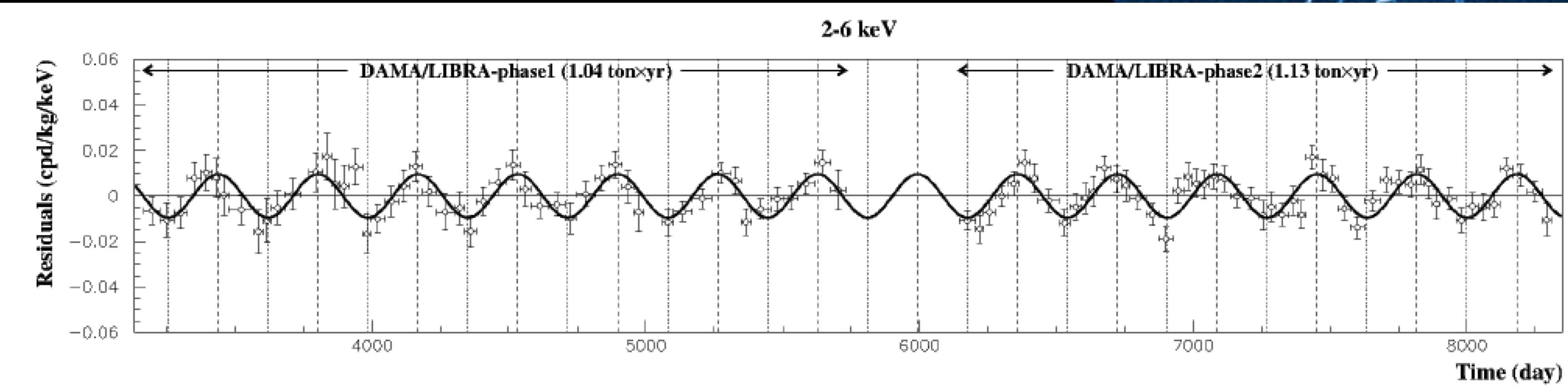

CSLNGS, March 2018

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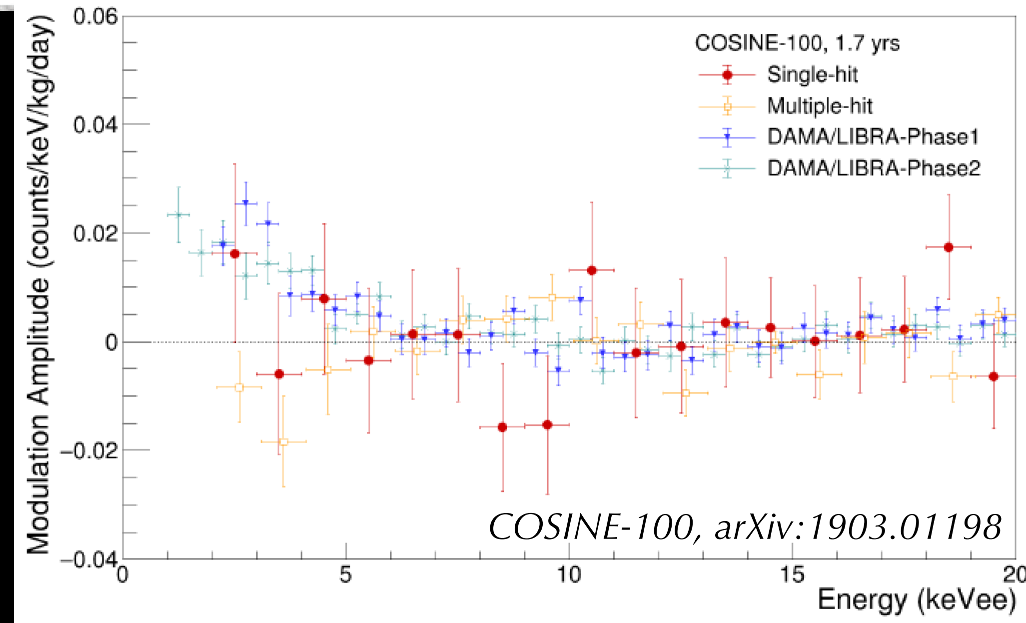

COSINE-100, arXiv:1903.01198

Outline

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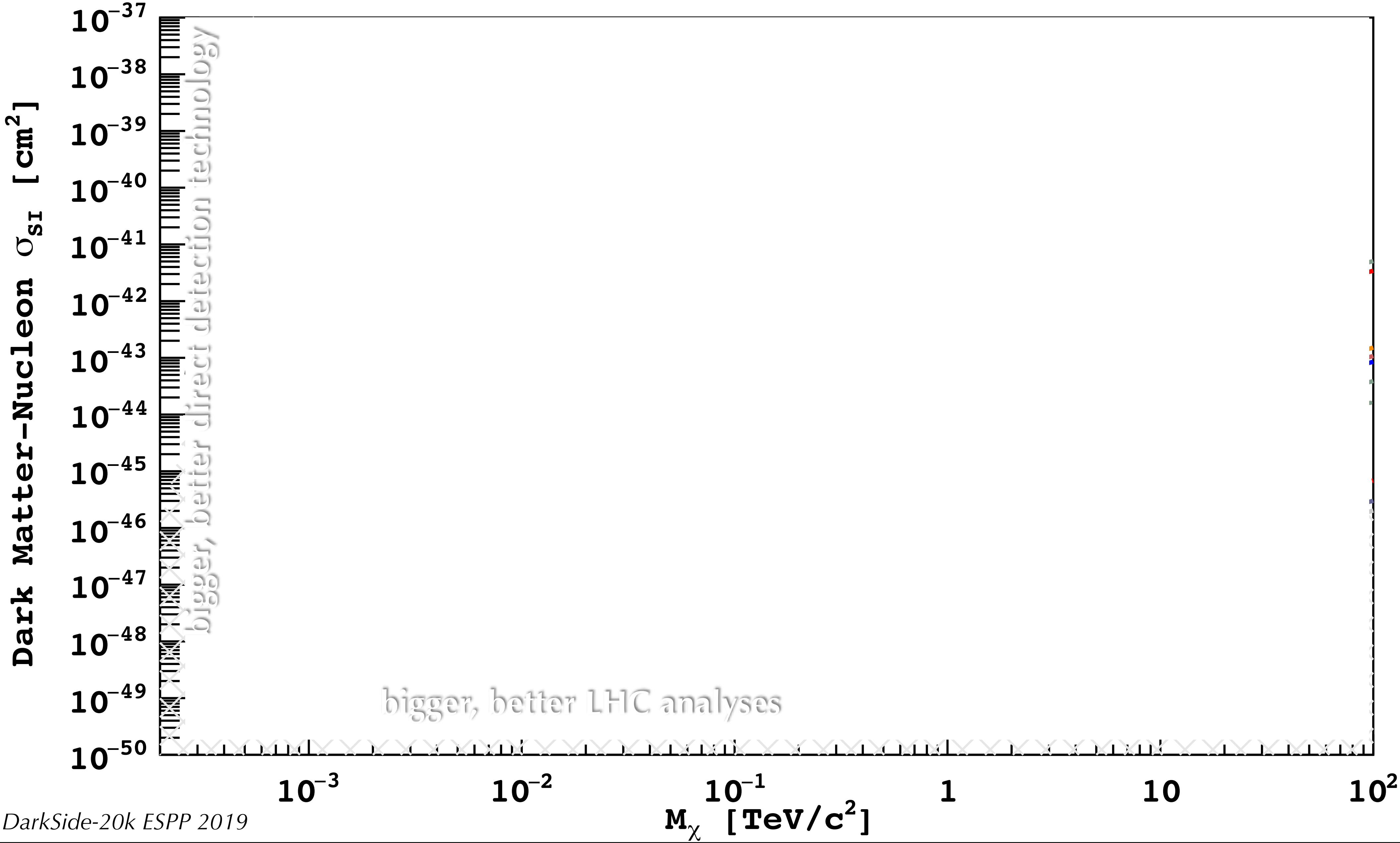
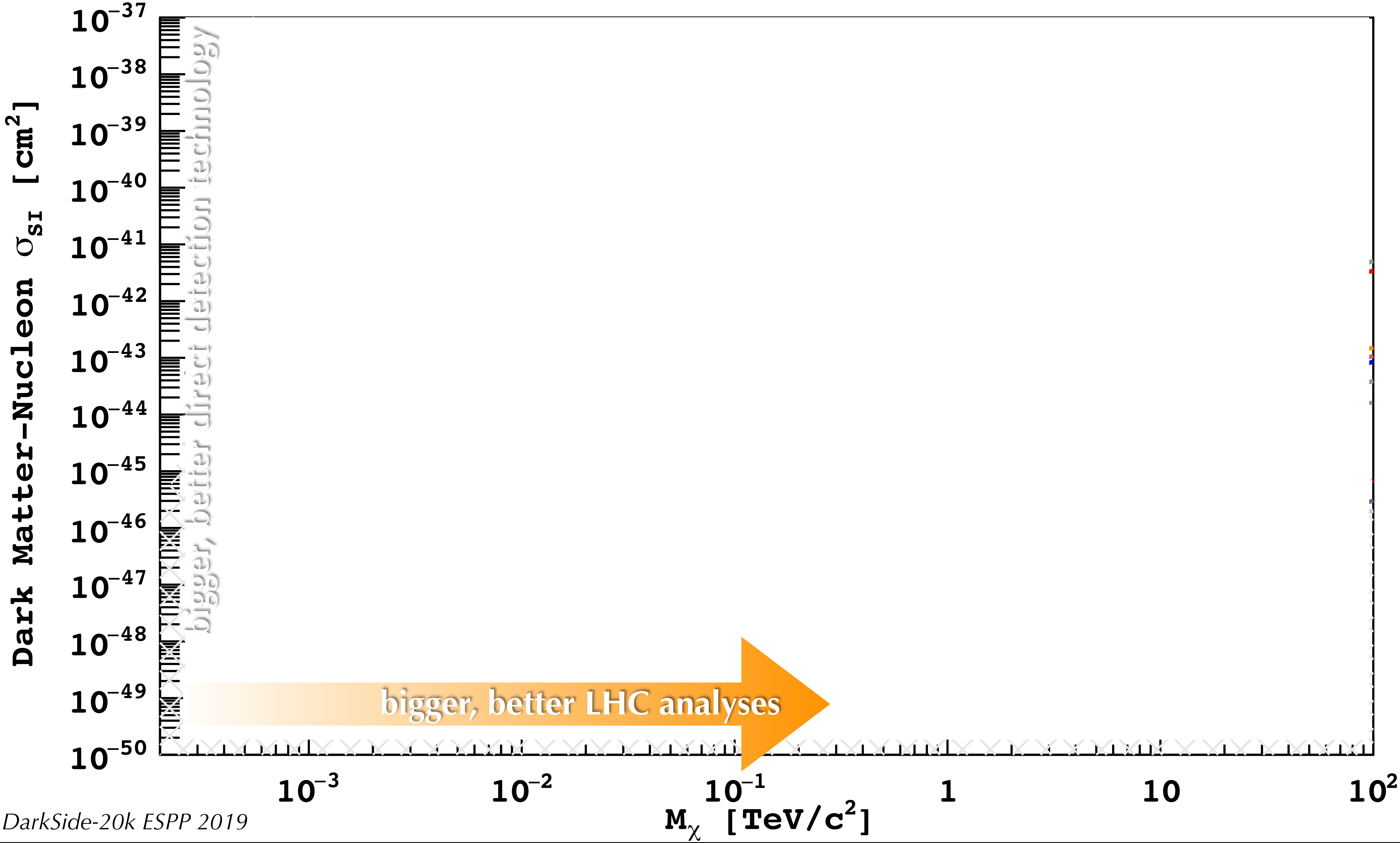
4) WIMP Community input to the ESPPU

Complementarity, a view towards ESPPU 2024



DarkSide-20k ESPP 2019

Complementarity, a view towards ESPPU 2024



DarkSide-20k ESPP 2019

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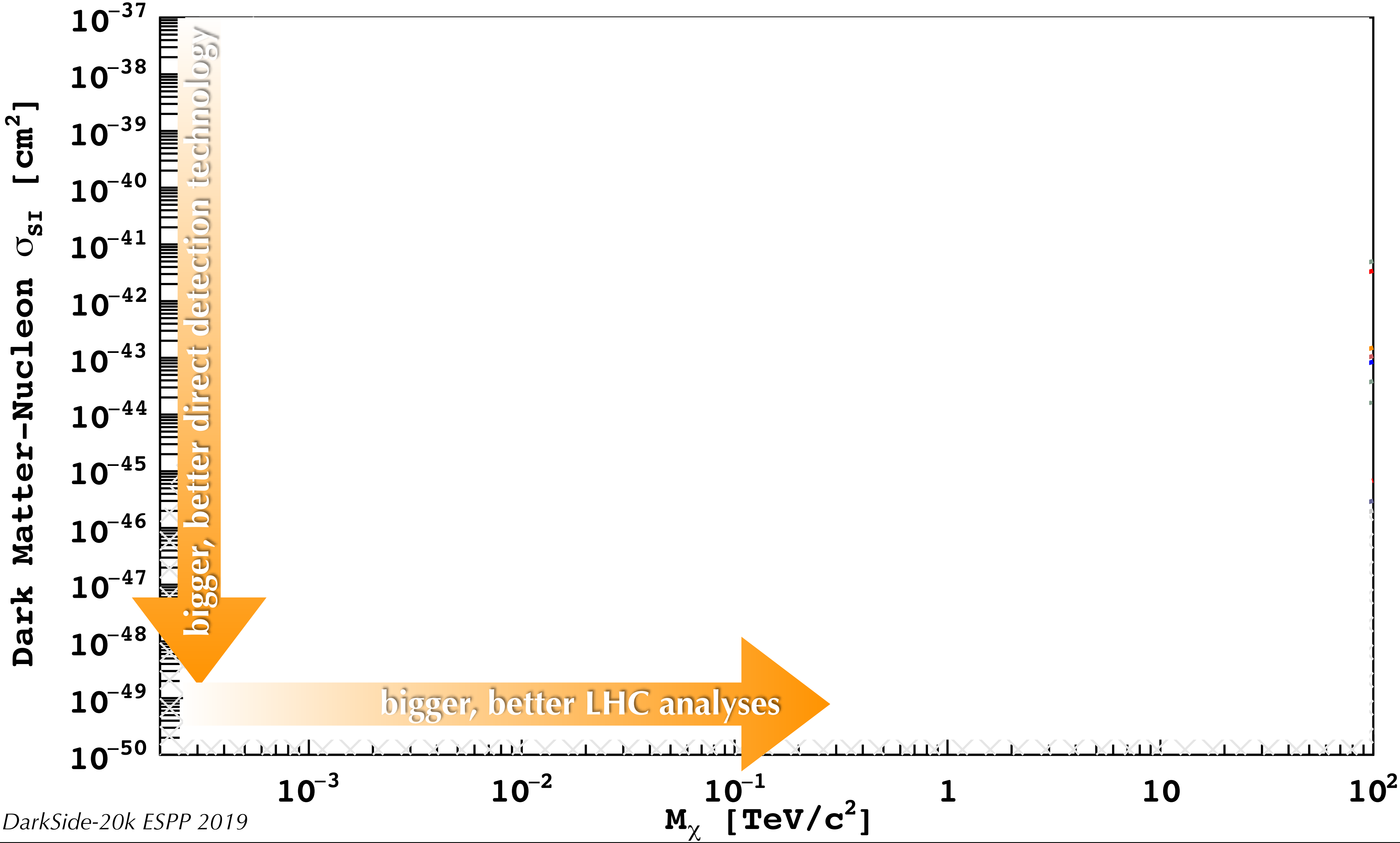

DarkSide-20k ESPP 2019

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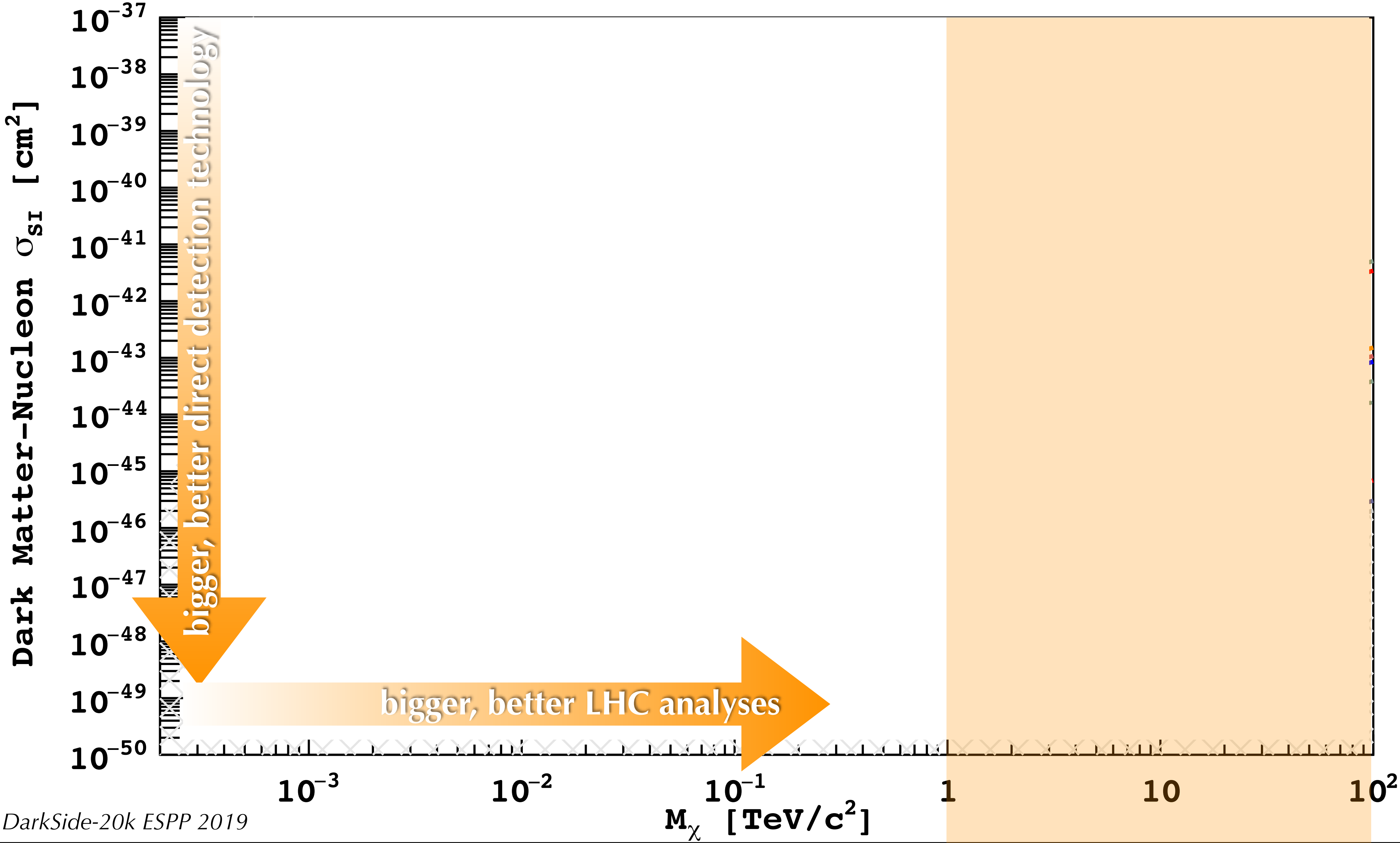

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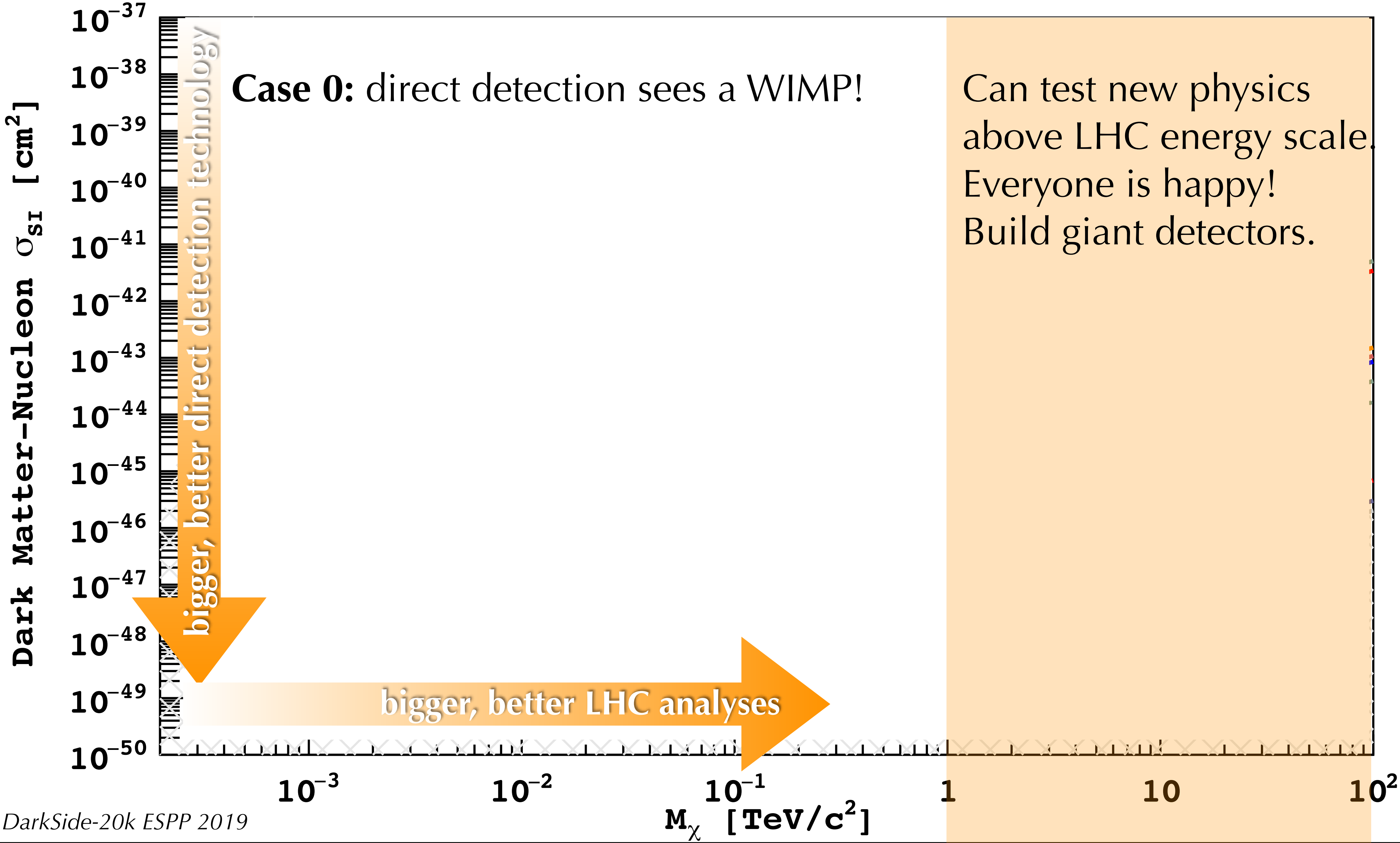

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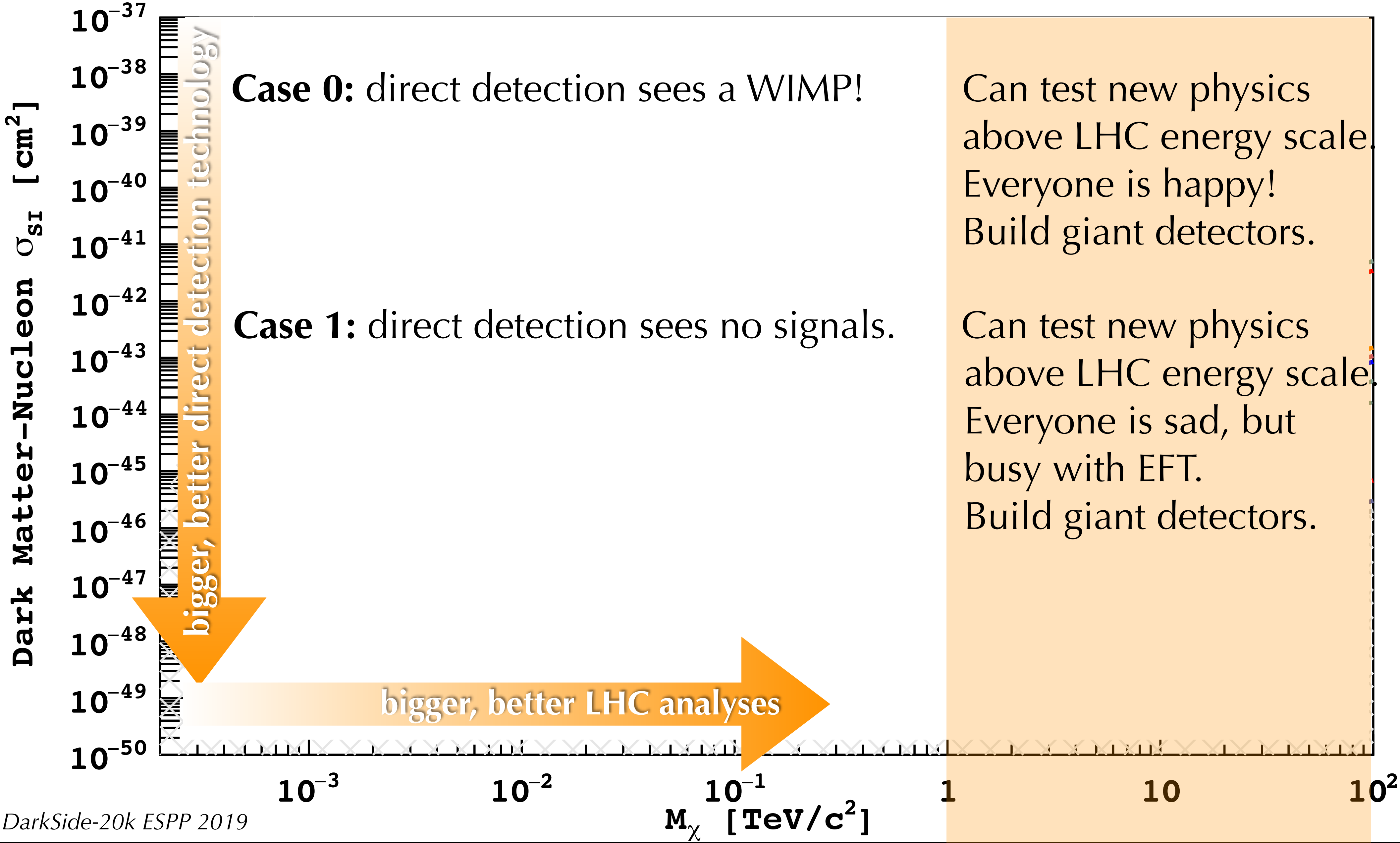

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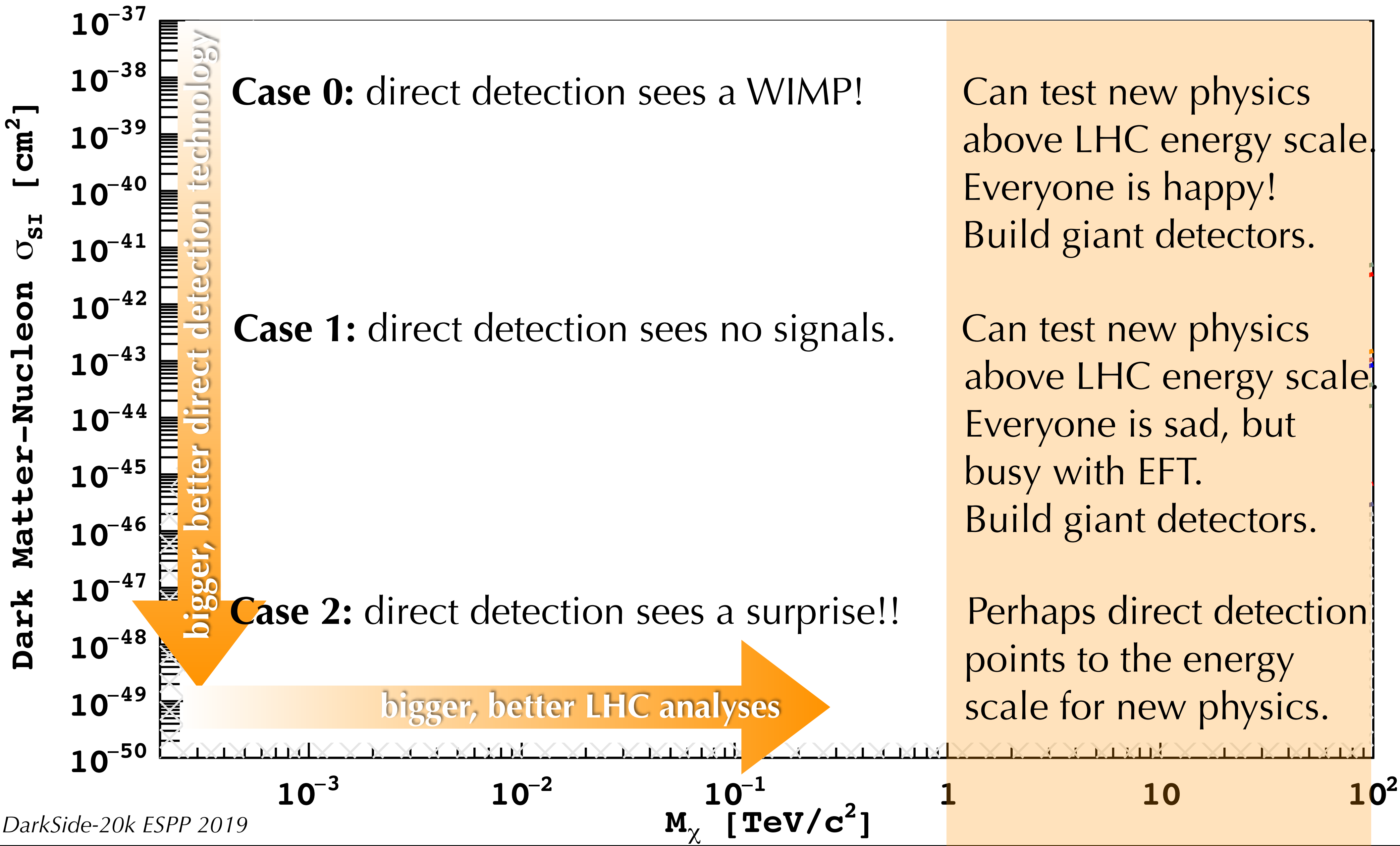


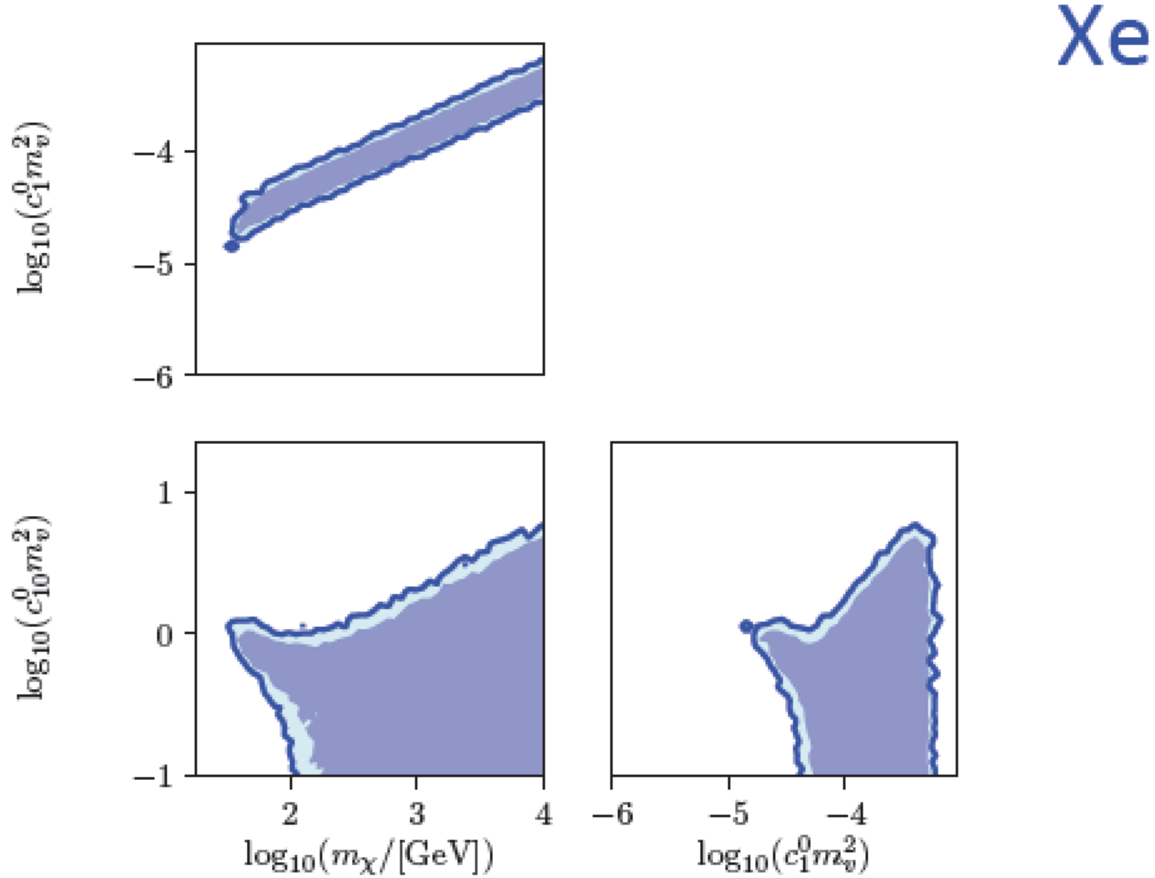
DarkSide-20k ESPP 2019

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



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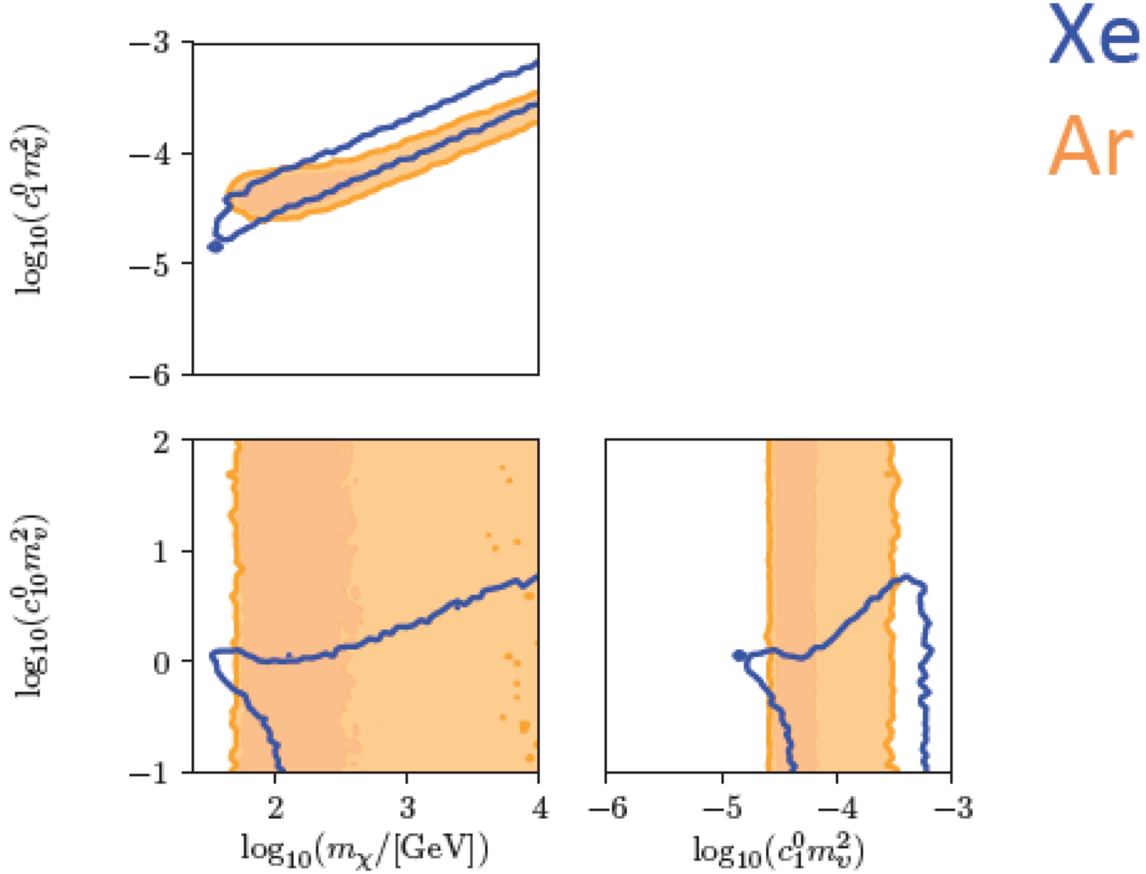

D. Cerdeno, IPPP April 2018

Complementarity: Case 0 Example

Example: Scalar DM – Scalar Mediator
m = 100 GeV

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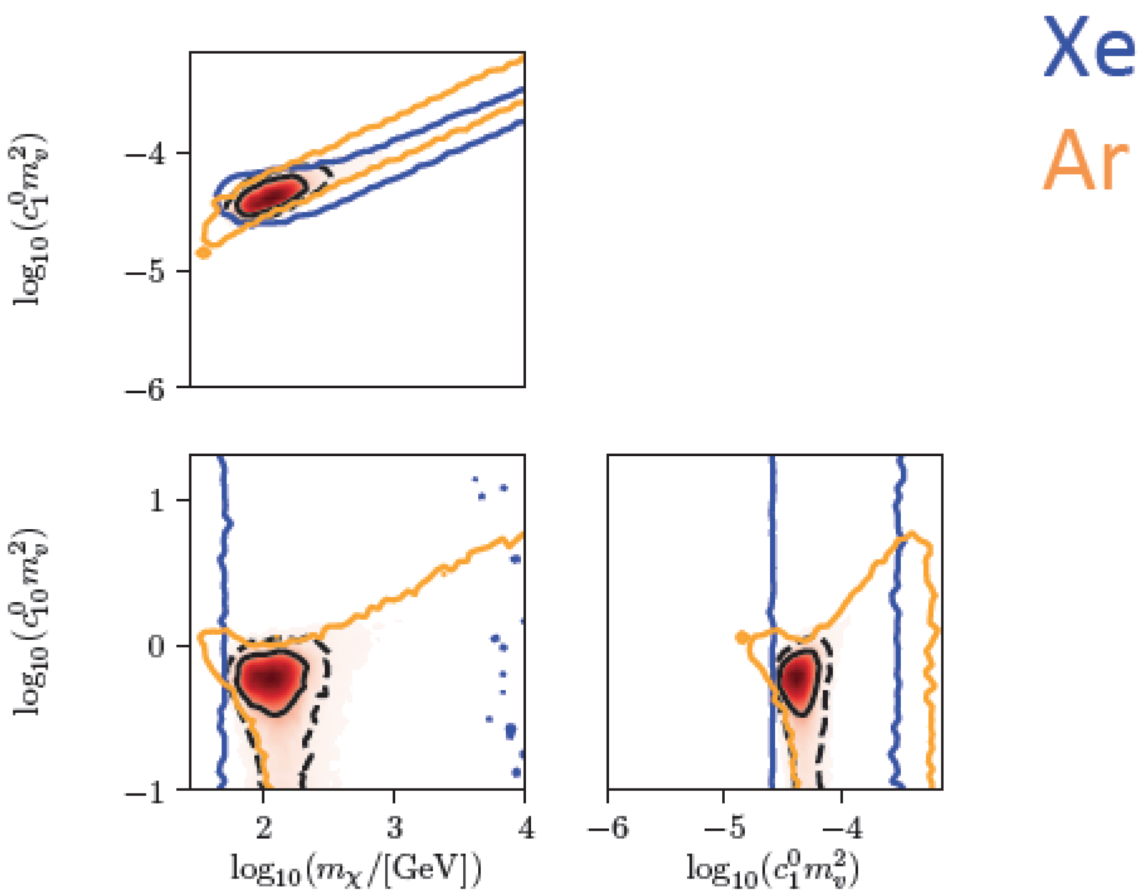
The experimental response is very sensitive to the target

Combining data some degeneracies can be removed

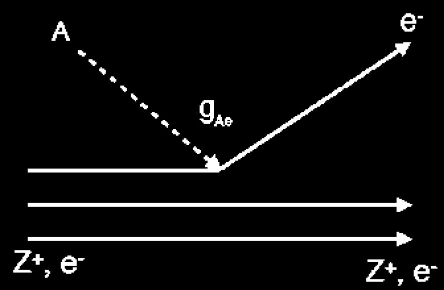


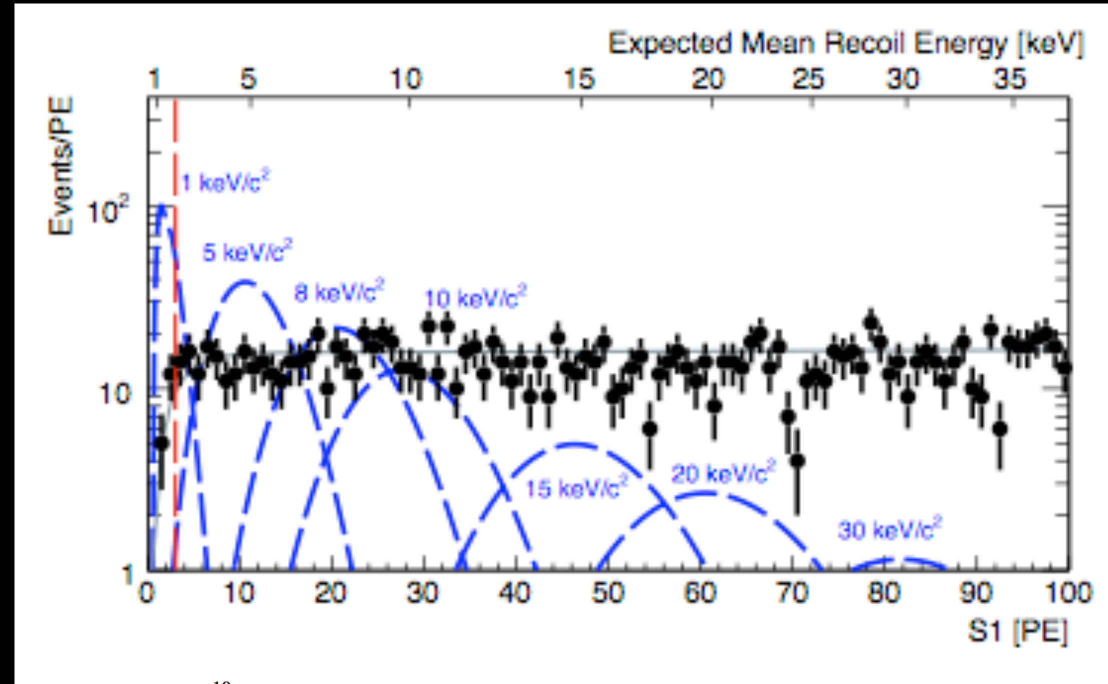
D. Cerdeno, IPPP April 2018

Bump Hunts in Direct Detection

XENON100, *arXiv:1404.1455*

search for axio-electric effect:





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

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

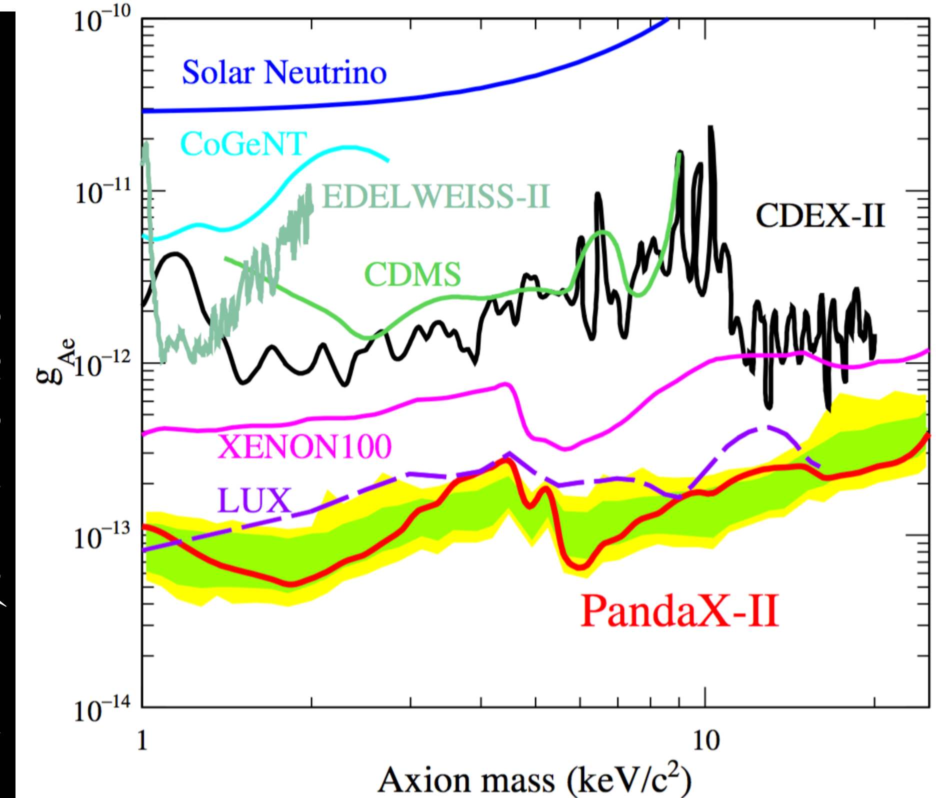
Analysis: bump hunt.

Current leading limit on new pseudoscalars at ~10 keV/c² via ALP-electron coupling from PANDAX-II. Projected reach of DARWIN is >x20.

Constraints on vector particles at 0.1-100 MeV/c² via limits on kinetic mixing to hidden sector *(arXiv:1901.10478)*

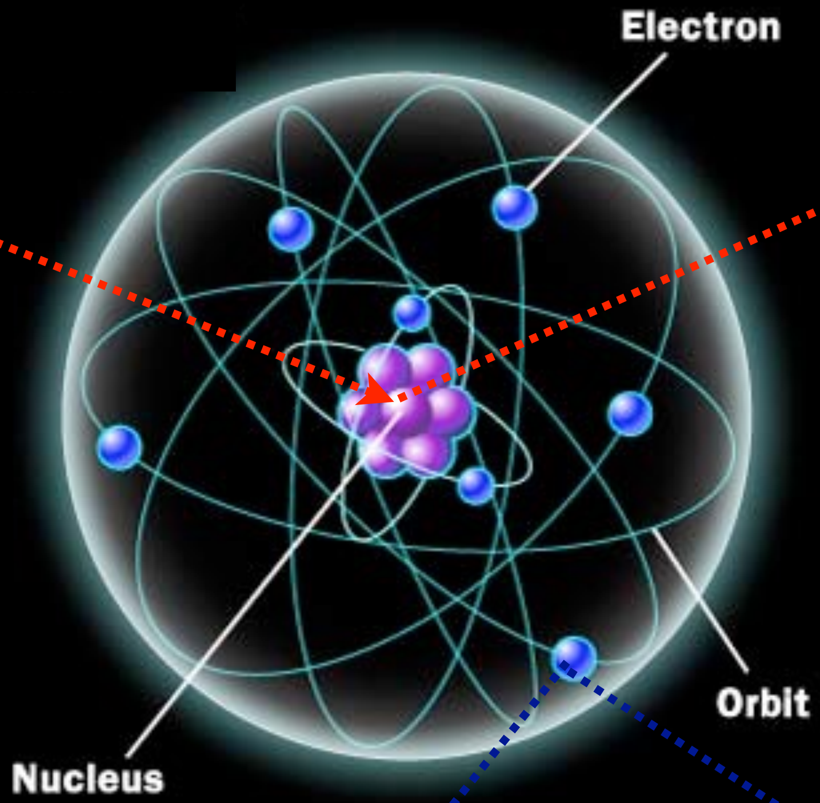
Constraints on new scalar (and vector) bosonic SuperWIMPs in 10-100 keV/c² *(arXiv:1709.02222)*

PANDAX-II, arXiv:1707.07921



~~Dark Matter Direct~~ Neutrino Detection

Signal: ν N $\rightarrow$ ν N or ν e^- $\rightarrow$ ν e^-



Backgrounds:

γ e^- $\rightarrow$ γ e^-

n N $\rightarrow$ n N

N $\rightarrow$ N' + α, e^-

χ N $\rightarrow$ χ N?

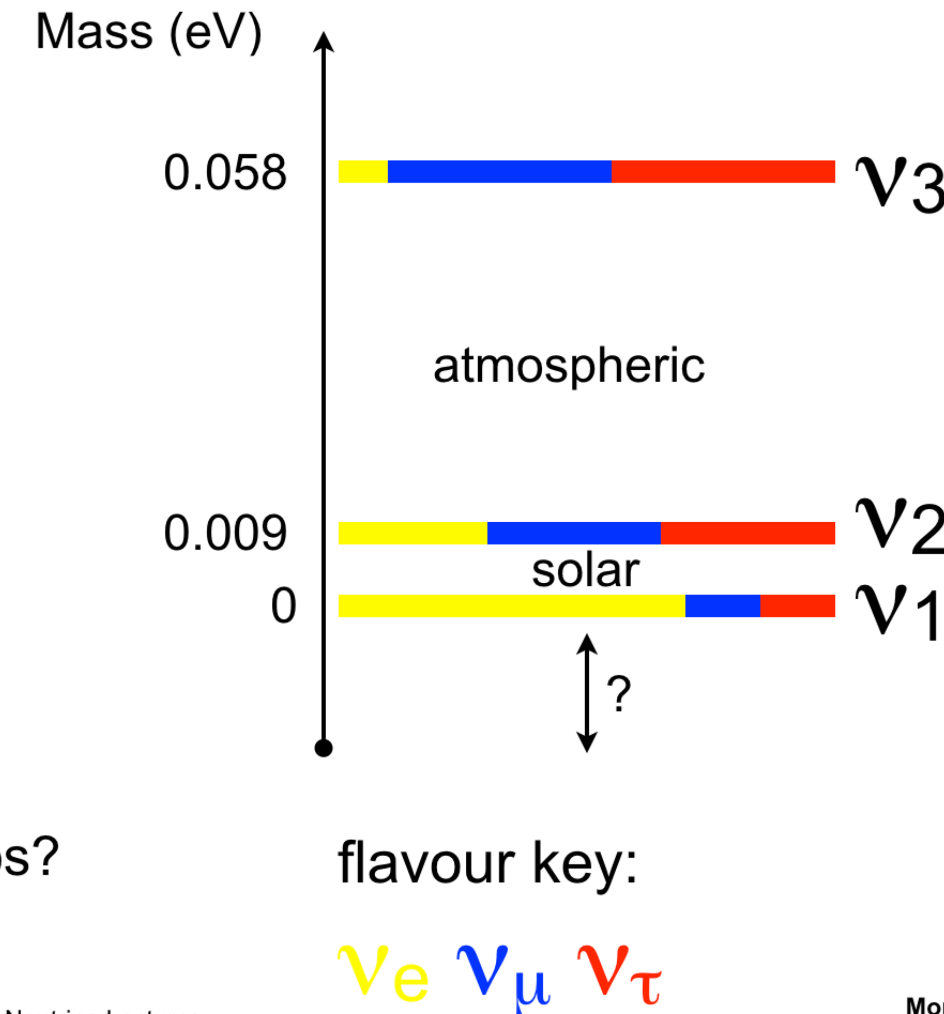
very similar requirements!
(and ideally also measure direction)

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?



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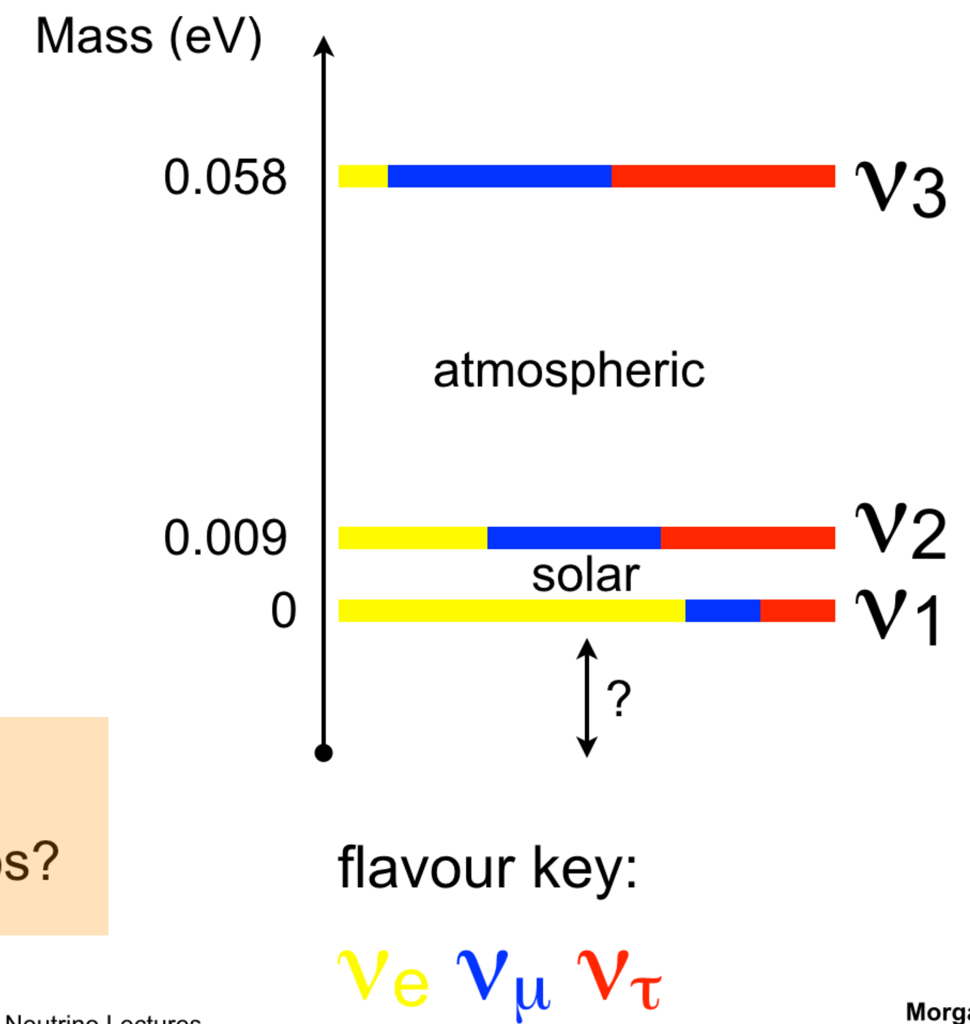
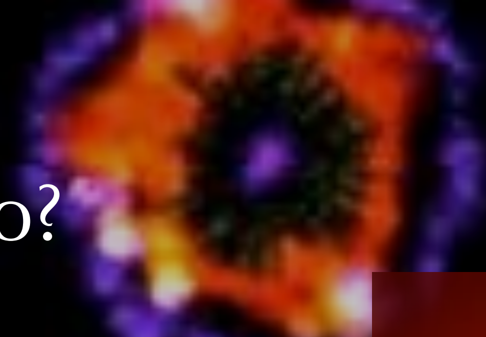
Open Questions

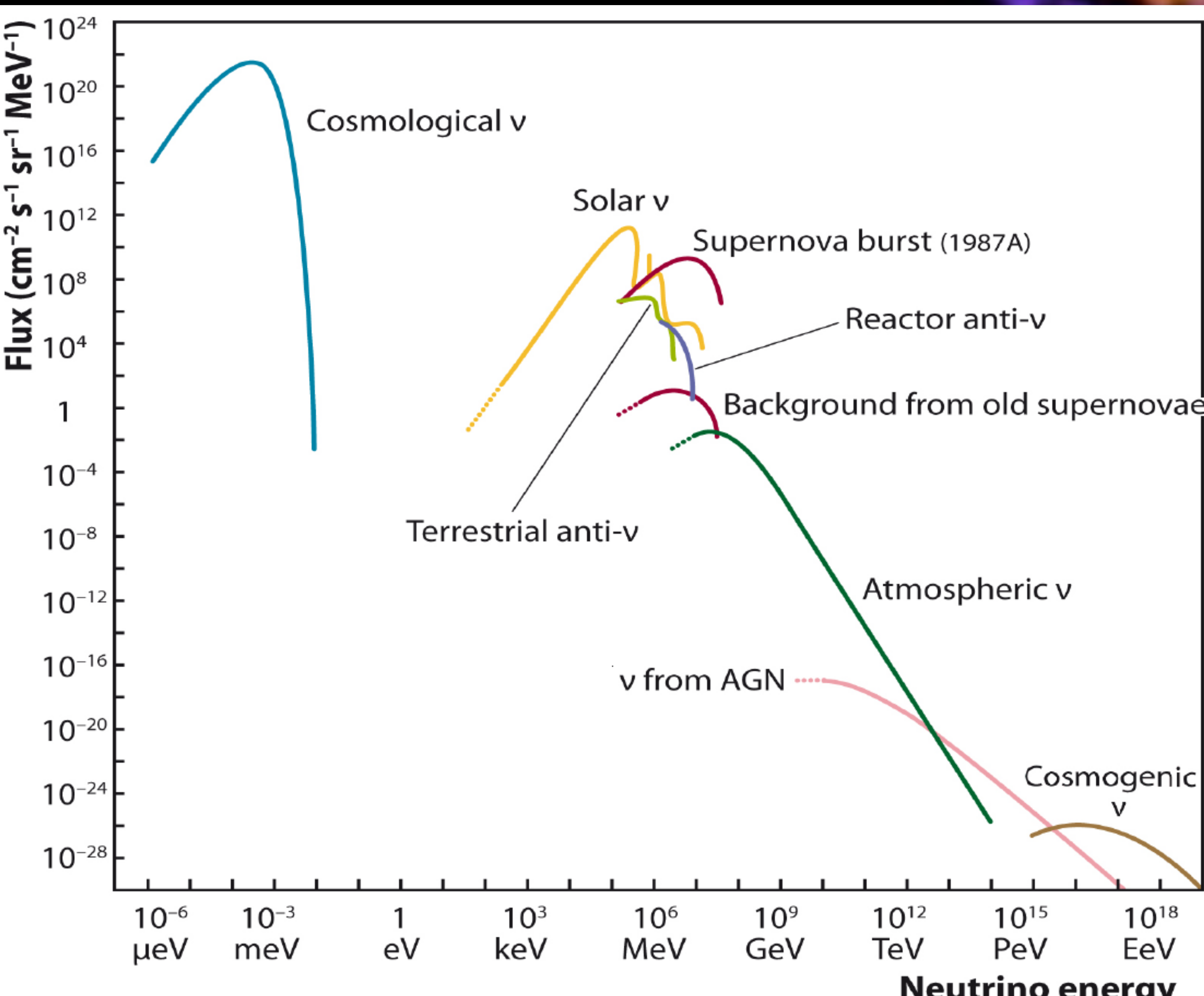
What is absolute mass scale?

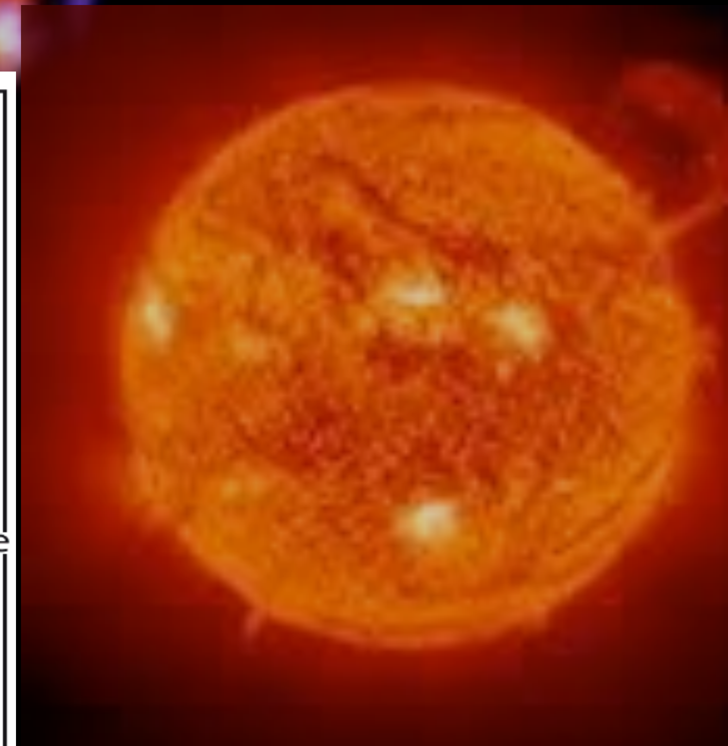
- Details of neutrino oscillation?
  - Is θ_{23} = 45°?
  - CP violation?
- Mass hierarchy?
- Why is m_ν so small?
- Majorana or Dirac? (Xe)
- Are there sterile neutrinos? (Ar)

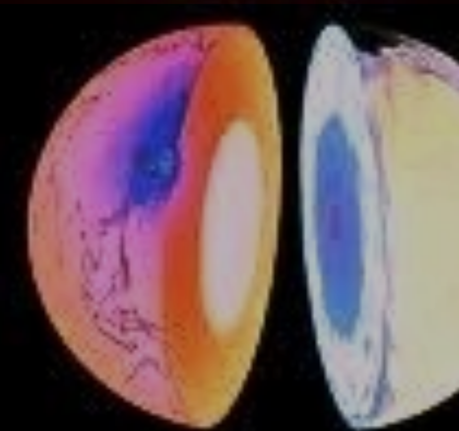


What ν physics can future dark matter detectors do?









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

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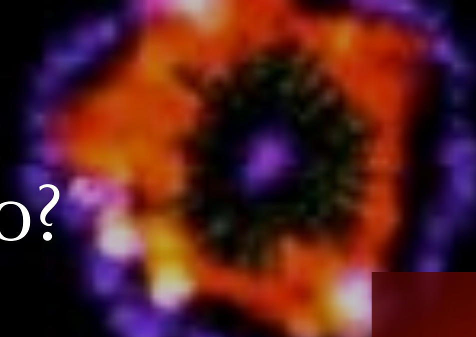

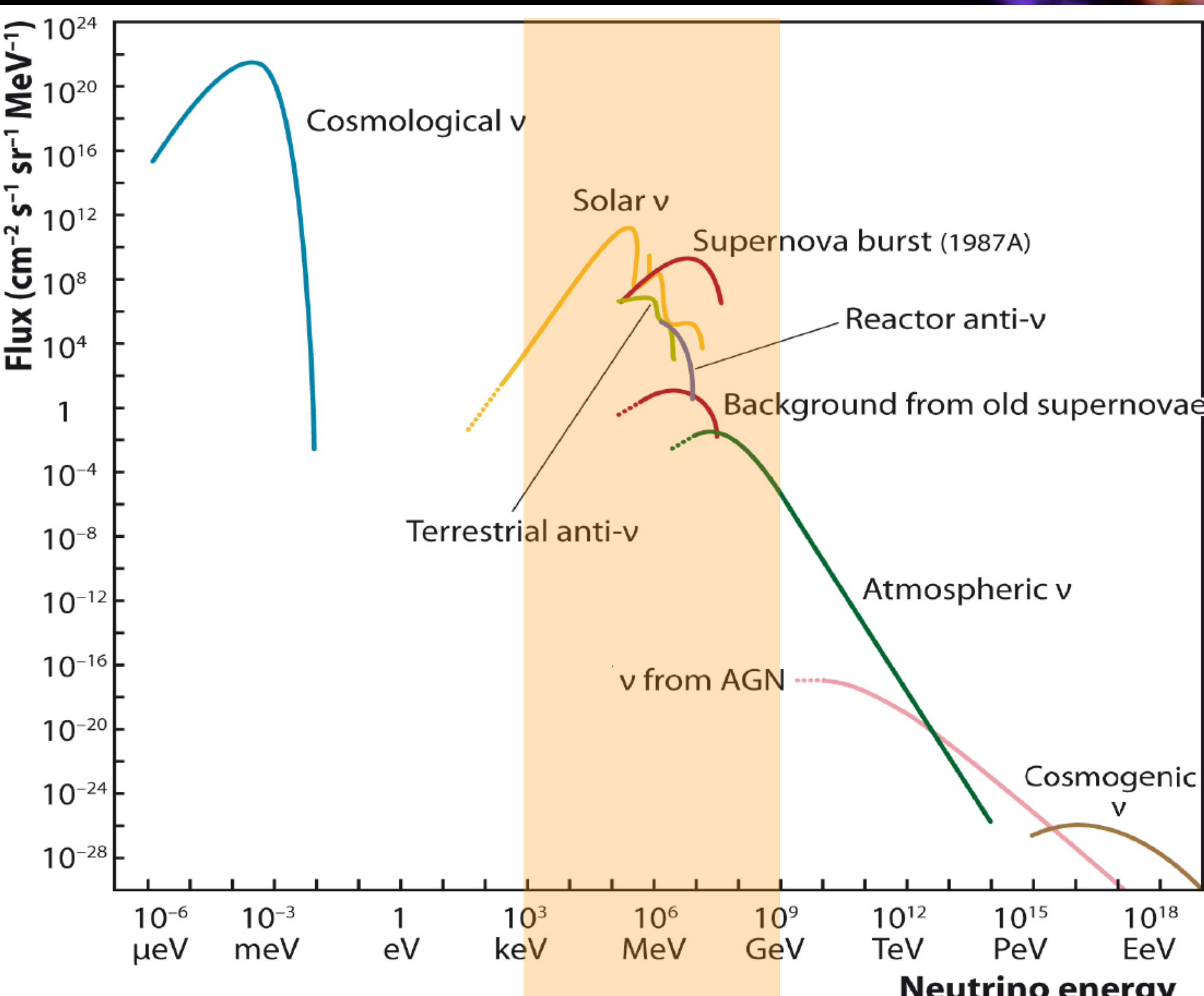

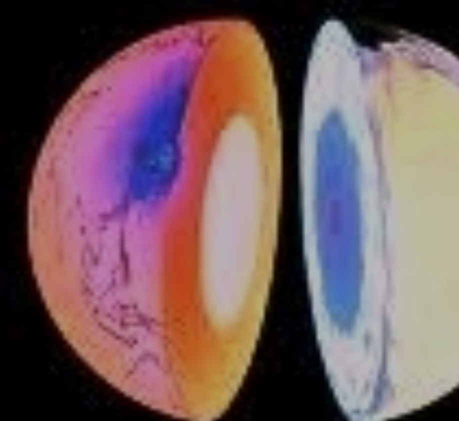

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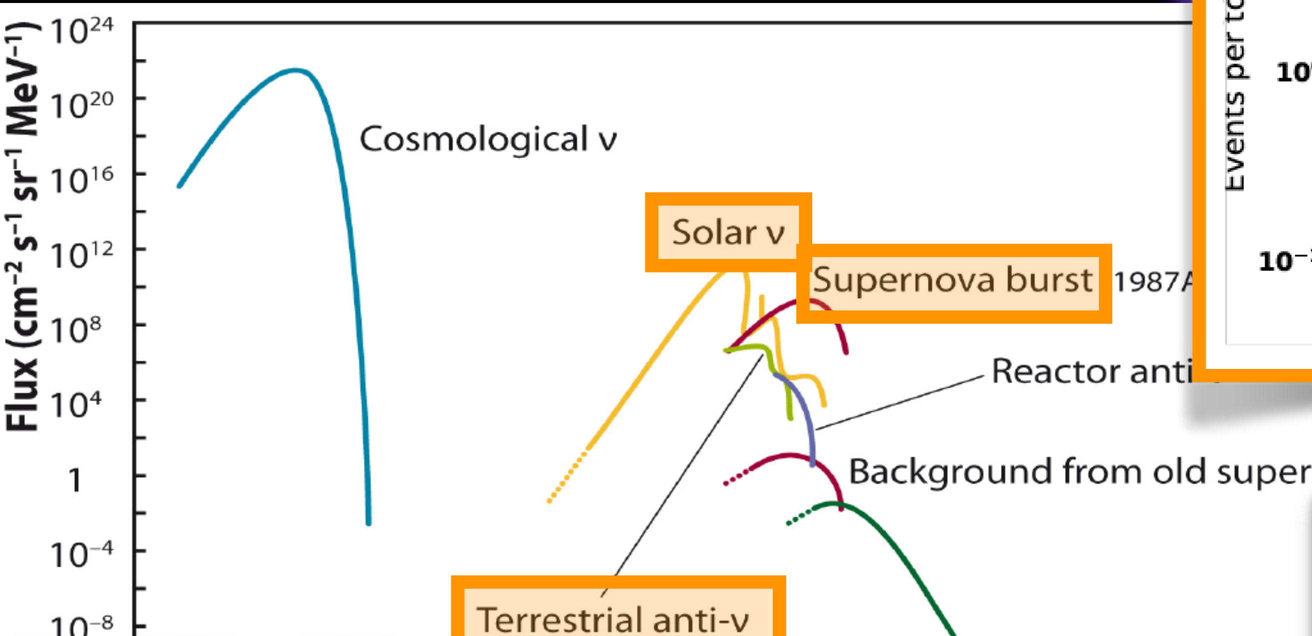
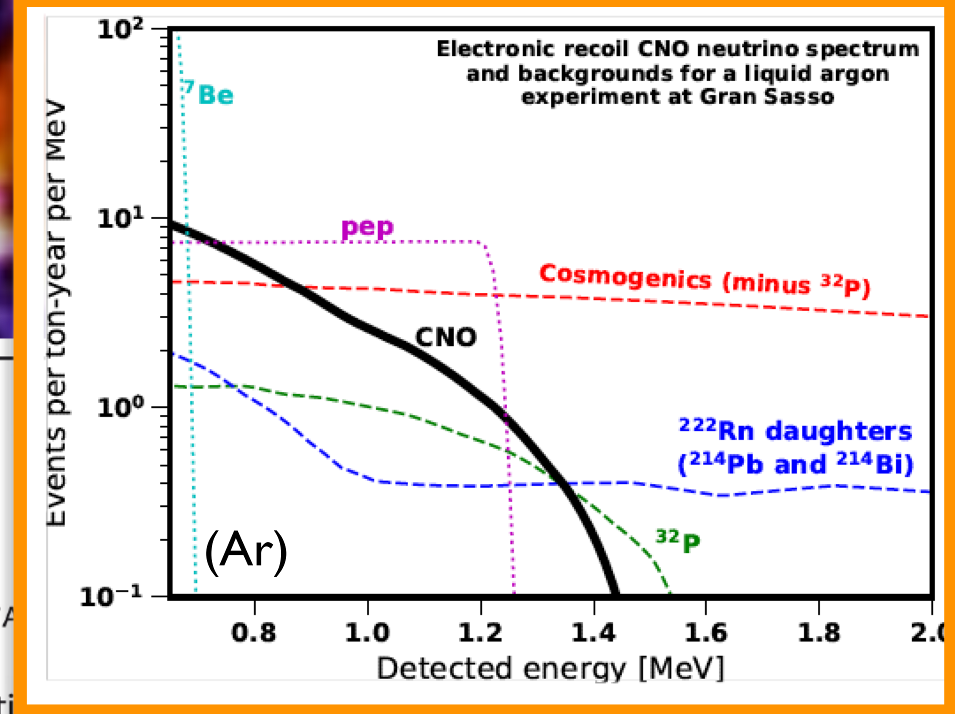
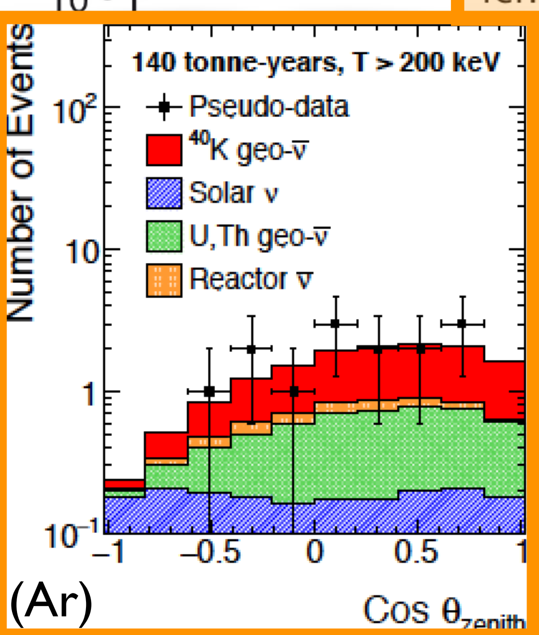
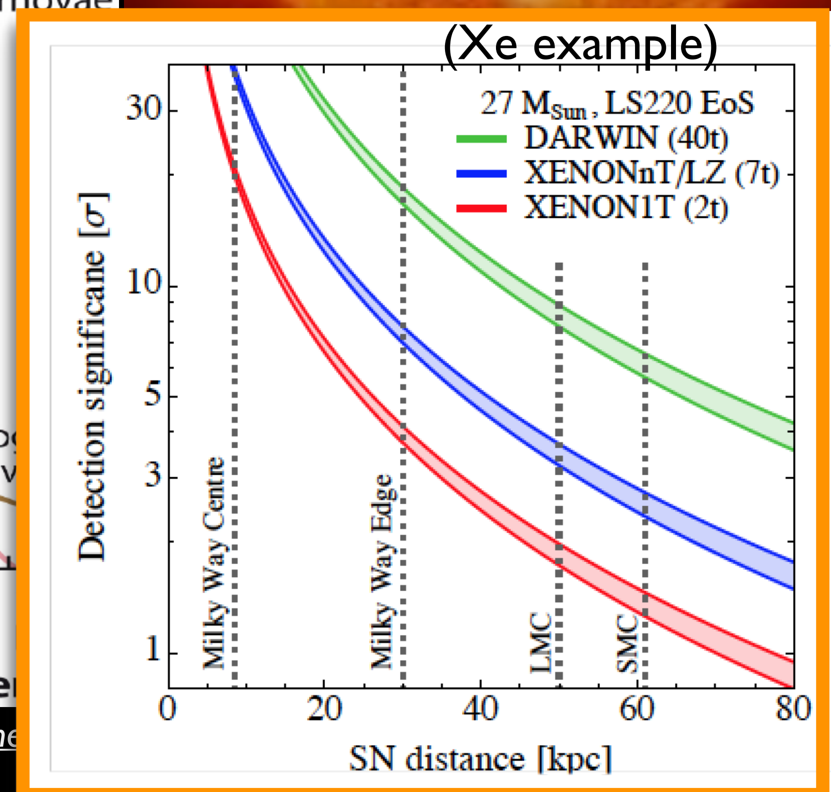


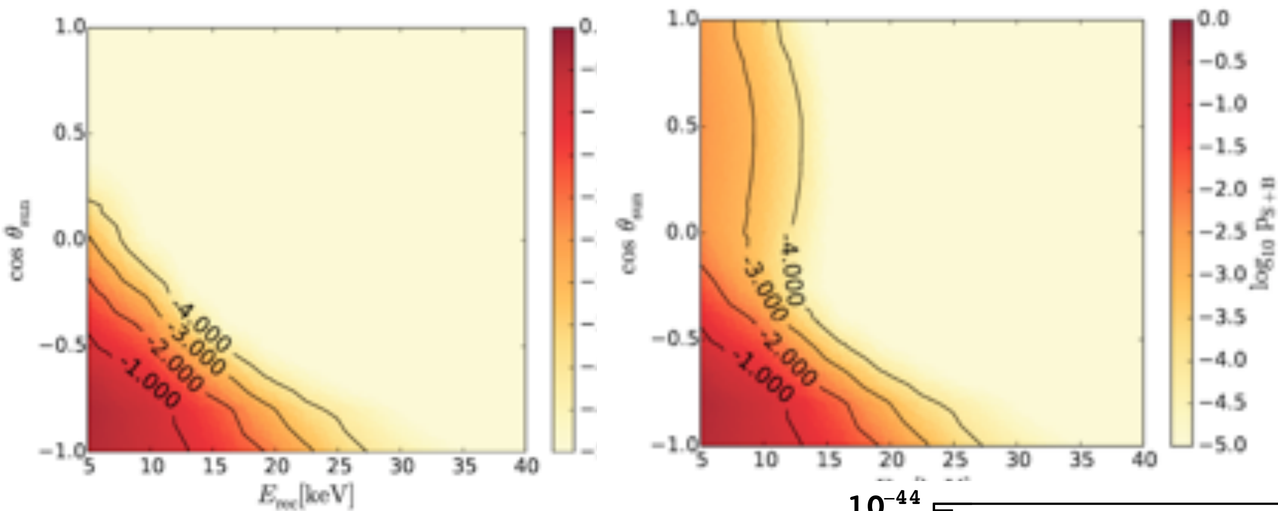






Is the Neutrino Bound the End? No.

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



PDFs in (energy, angle, time) of event for coherent solar neutrino background vs. background + DM signal are different!

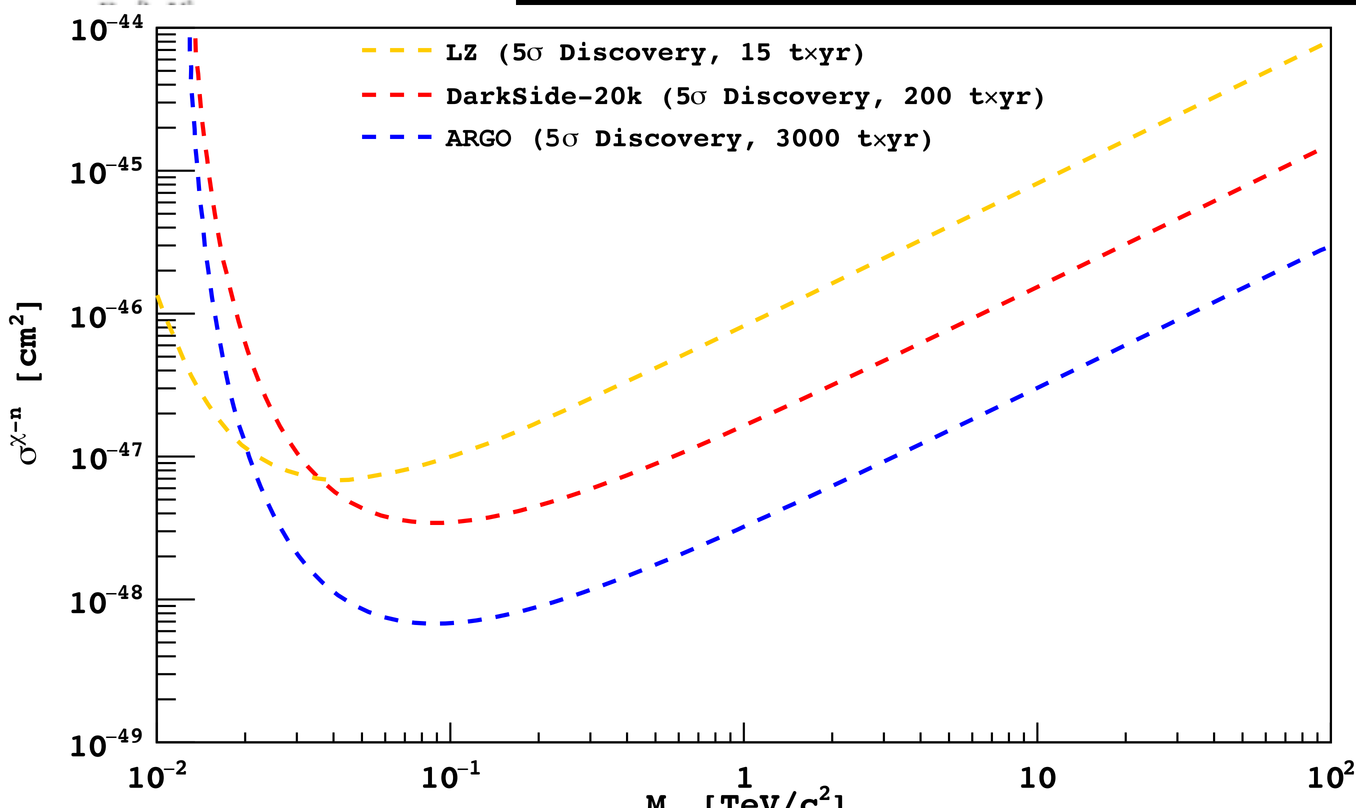
- no ν bound for directional detectors

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

A ν background paradigm…

(for non-directional detectors)

where the 'neutrino floor' impact on discovery sensitivity depends on electron discrimination power against ν-e scatters



Jocelyn Monroe

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WIMP Community Input to the ESPPU

9 submissions to ESPPU 2019 in track “dark matter”,
2 focussed around direct detection (in Europe):
DARWIN and Global Argon Dark Matter Collaboration

Submissions are on ‘observatory’-scale programmes, with multiple physics goals (dark matter of many kinds, neutrinos, rare processes) and decade-long time scales for operations

Submissions identify areas of strong technical synergy across search strategies:

- cryostat technology
- large-volume cryogenics and purification
- TPC design and optimization, high voltage delivery
- silicon detectors for photon detection
- low-noise, cold readout electronics
- common challenges with LAr neutrino detectors (DAQ, optics, etc.) + large overlap of European LAr neutrino and dark matter communities.

WIMP Community Input to the ESPPU

Submissions aim for increased interaction between this community and CERN.

DARWIN:

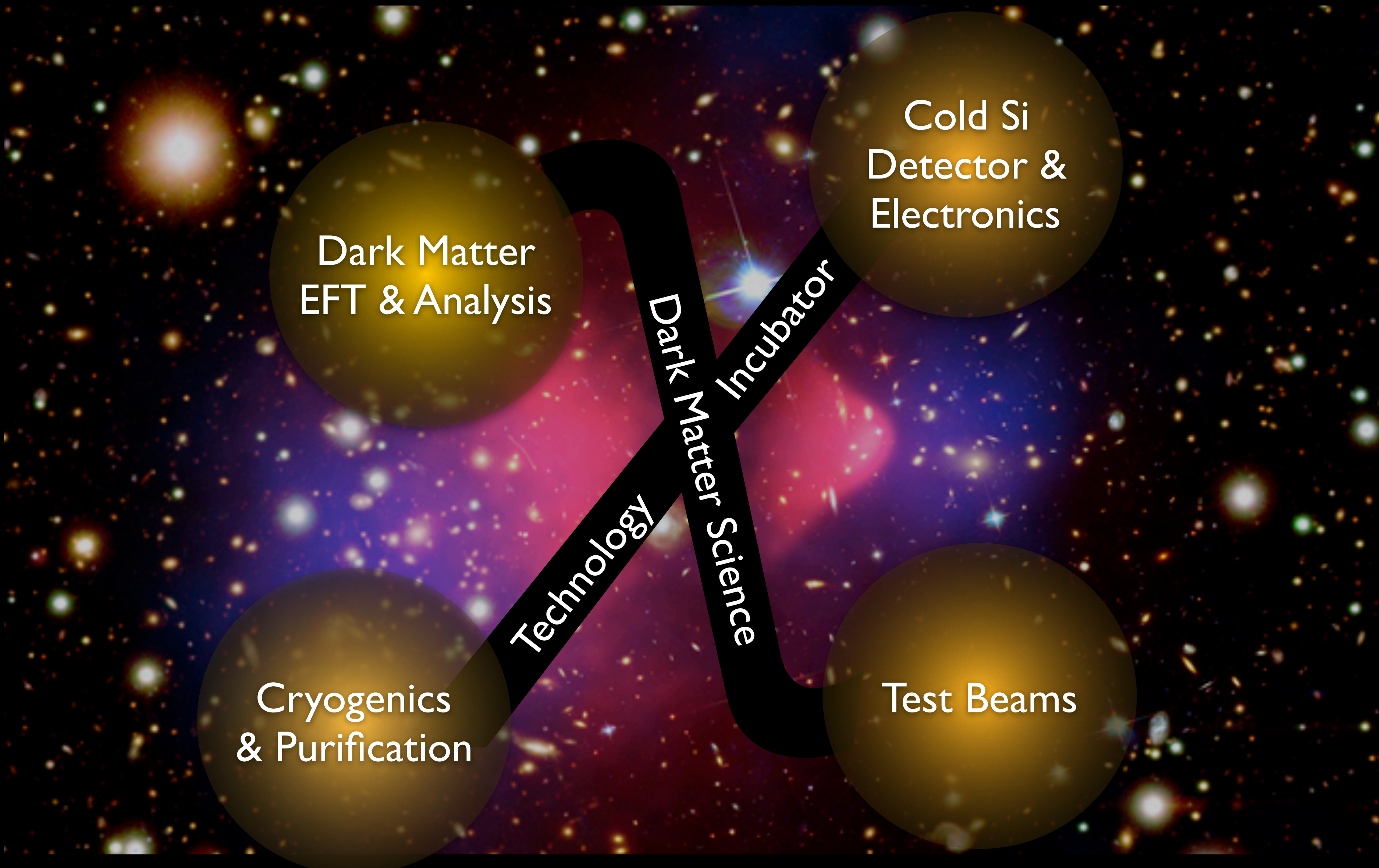
The DARWIN experiment is a cornerstone of the European Astroparticle Physics program and should be considered as an essential part of the European Strategy for Particle Physics, especially in light of the complementarity of its dark matter program to the HL-LHC. DARWIN presents a unique opportunity to realize an observatory for low-background, low-threshold astroparticle physics in Europe, under European leadership. On the path towards becoming reality, DARWIN could directly benefit from the unique CERN expertise on cryogenics, large-scale vacuum systems, engineering, electronics, computing, etc. The collaboration would also benefit from interacting with the CERN theory group in designing new potential physics channels for the observatory, and with high-energy experimentalists and phenomenologists for combined data analysis projects.

Global Argon Dark Matter Collaboration:

We emphasize the importance of the infrastructure and expertise of CERN in underpinning the European research program in both dark matter and neutrino physics using liquid argon. Synergy with the Neutrino Platform cryostat developments has led to a significant design evolution of the DarkSide-20k detector. We encourage the European Strategy to recognize the importance of these shared technological developments and the role of CERN as an extraordinary catalyzing factor of discovery and feedback concerning the future directions to follow in the Argo program.

A *Dark Matter Science and Technology Incubator* at CERN would support the European community's leadership in dark matter direct detection, encompassing the common technical challenges and the phase transition to next-generation of experiments.

- CERN can play a unique role to catalyze the community to come together



Conclusions & Outlook

Direct detection of dark matter is key to identifying whether new particle content makes up the astrophysical missing mass.

- Direct detection experiments aim to reach the neutrino floor within the coming decade.
- Direct detection probes above the center of mass energy of the LHC, perhaps can tell us the next energy scale in particle physics!
- Dark matter is a field of rapid detector technology innovation, which supports detector R&D and technology development across particle physics.

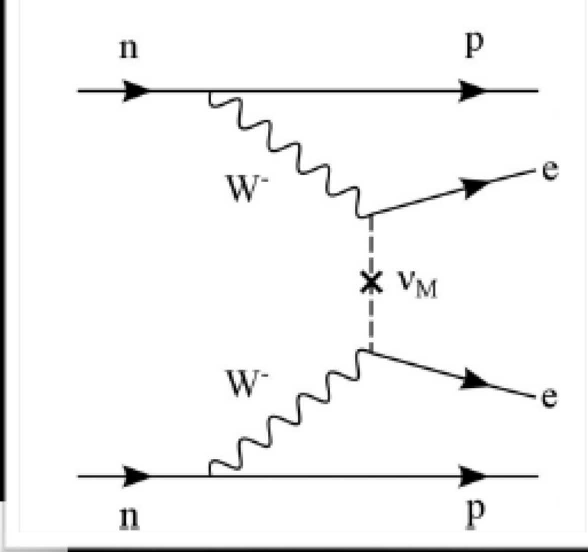
Should we re-evaluate search strategies beyond WIMPs? Yes.

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

More Slides

ν-less Double Beta Decay

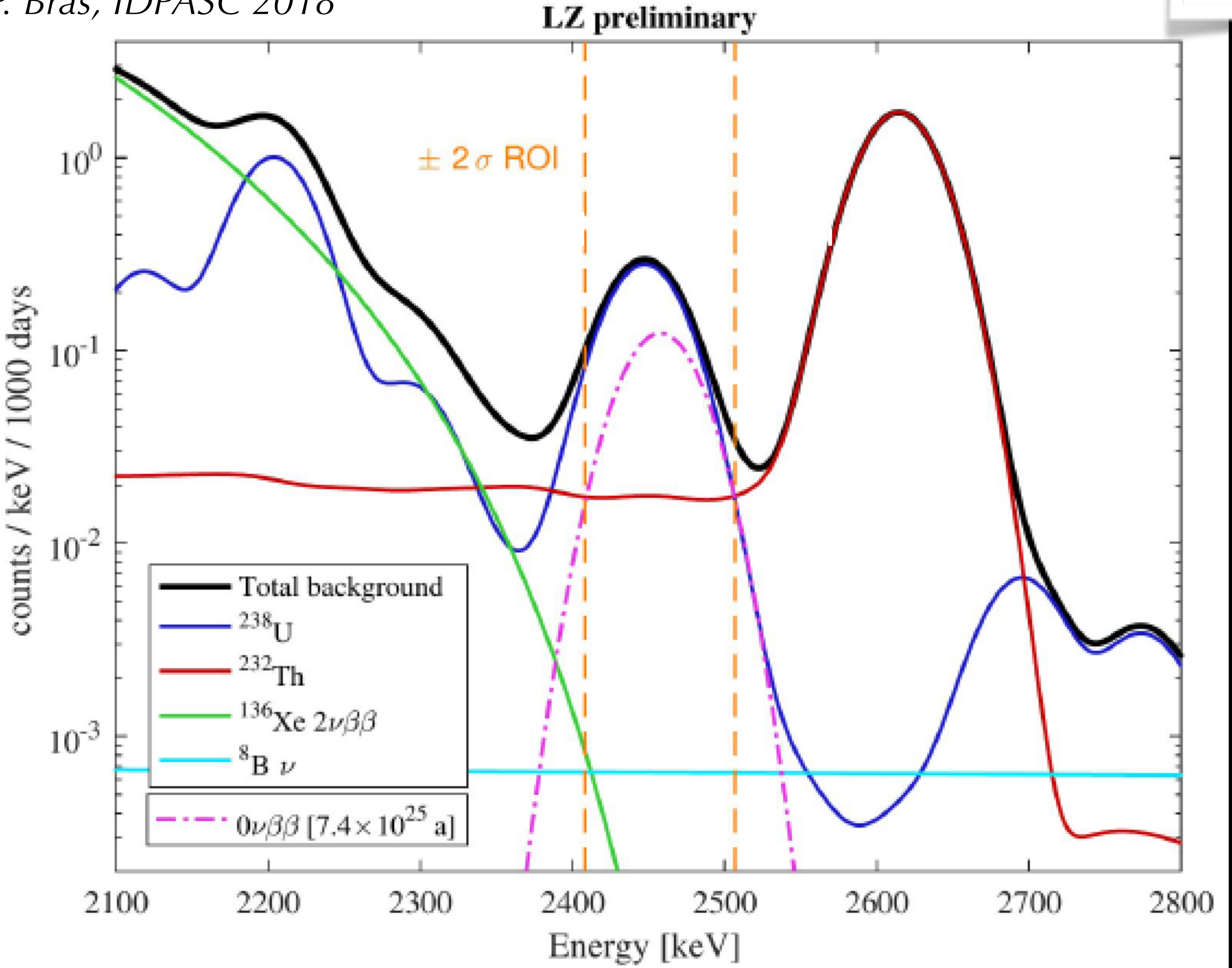
The liquid Xenon dark matter searches aim for competitive sensitivity to neutrinoless double beta decay, via restricted fiducial volume (inner 1 t) to reduce backgrounds, and projected **1%** energy resolution at the 2ν beta decay endpoint in Xe.



example: projected sensitivity in **LZ**:

Q-value= 2458 keV

P. Bras, IDPASC 2018



big opportunity:
significant Xe-136 target mass (~600 kg)

big challenges:
Th background suppression, achieving target energy resolution, and nuclear matrix element uncertainty

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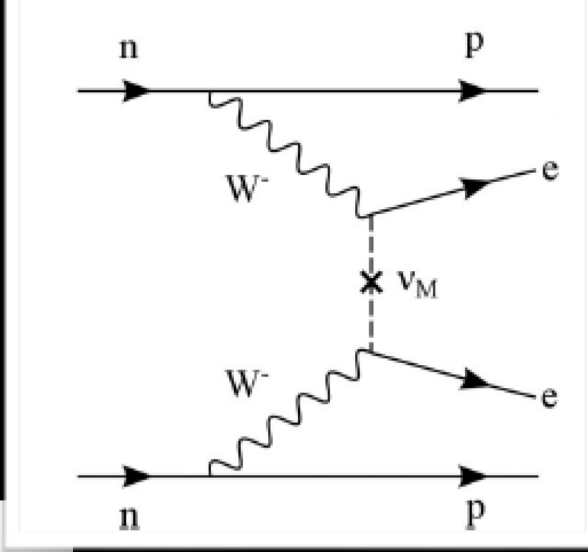
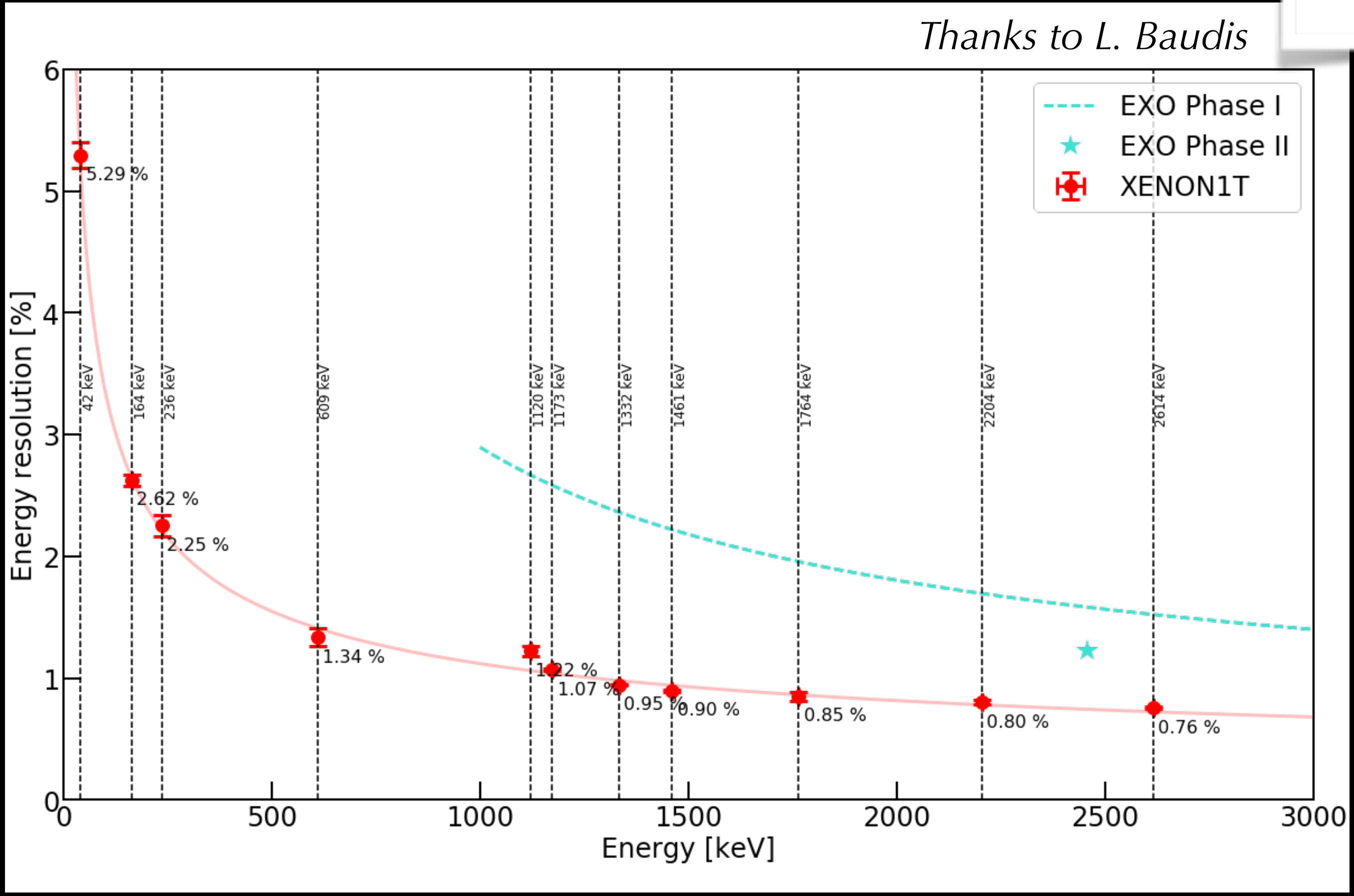


example: **Xenon1T** energy resolution

Q-value= 2458 keV



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

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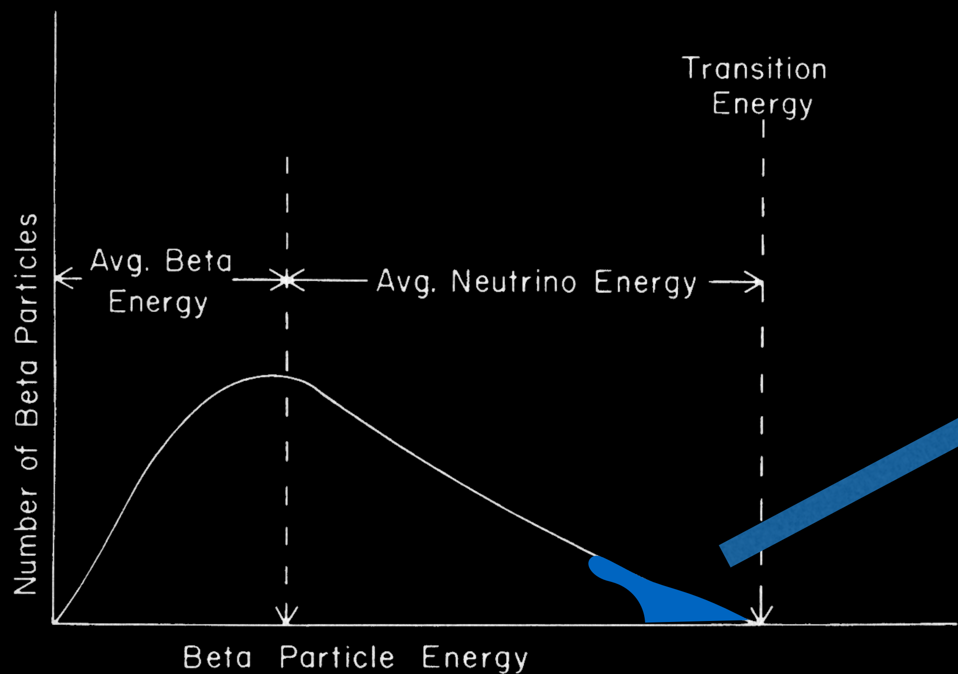
significant Xe-136 target mass (~600 kg)

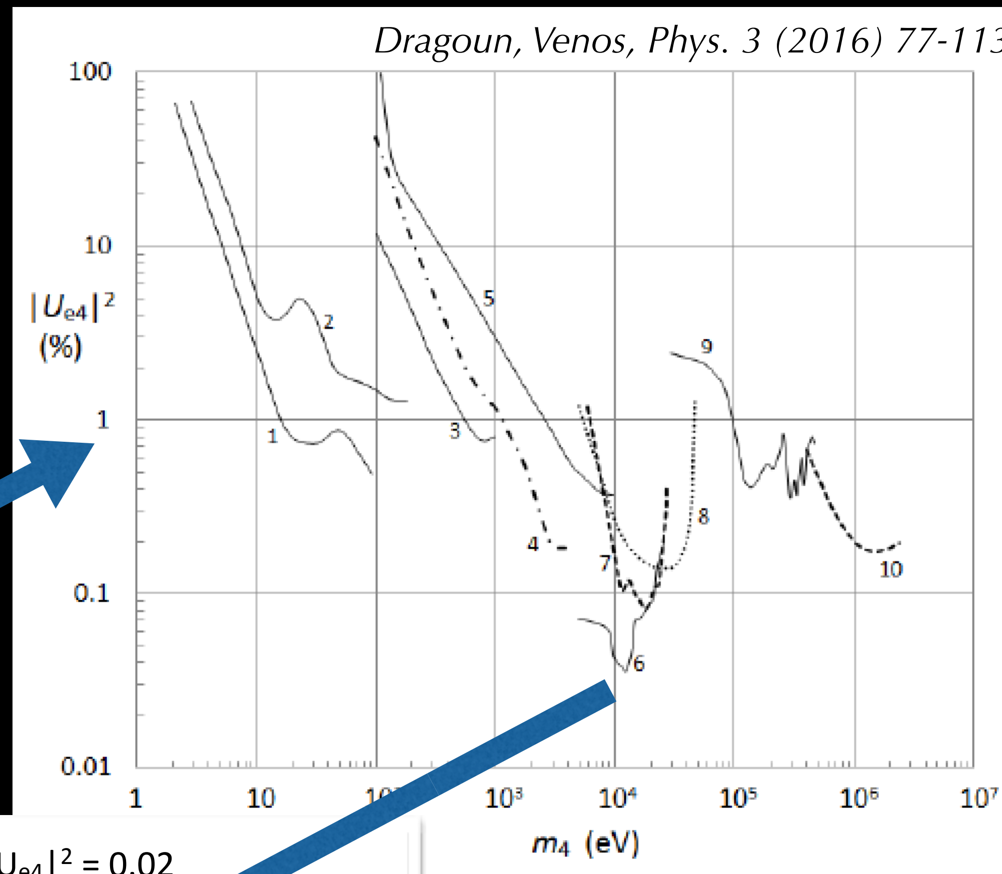
<u>big challenges:</u>
Th background suppression, achieving target energy resolution, and nuclear matrix element uncertainty

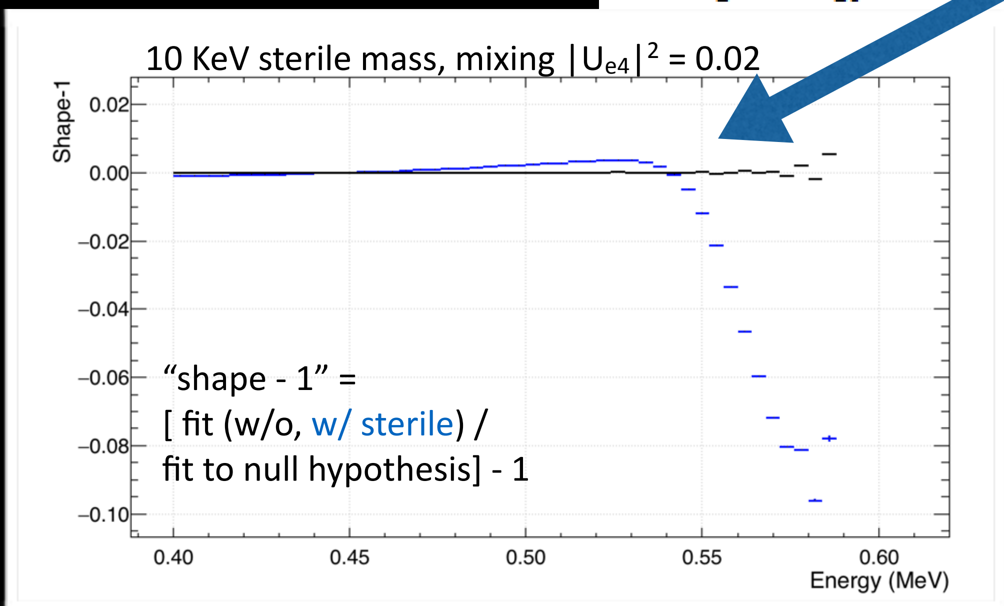
Sterile ν Signatures

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

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





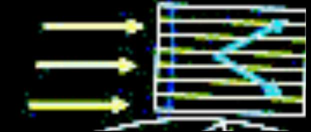


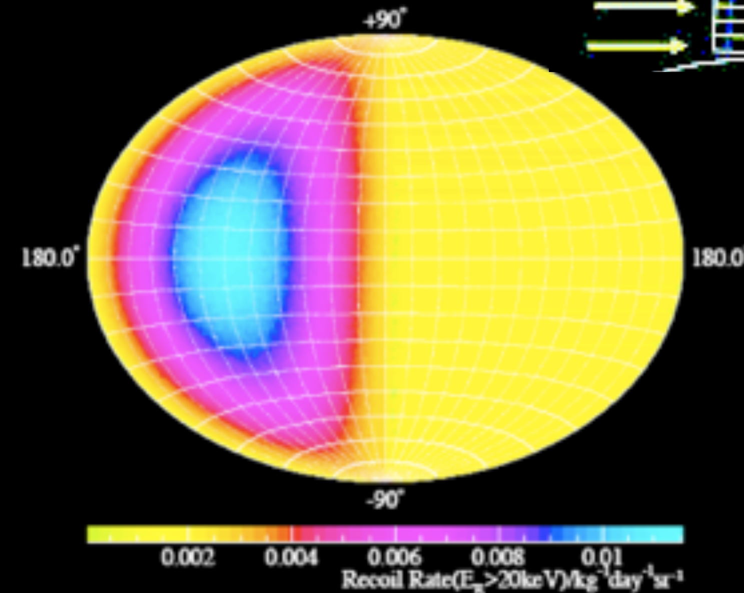
<u>big opportunity:</u>
high Q-value beta decays of backgrounds (e.g. Ar-39) with good energy resolution have sensitivity to 10-100 keV sterile νs

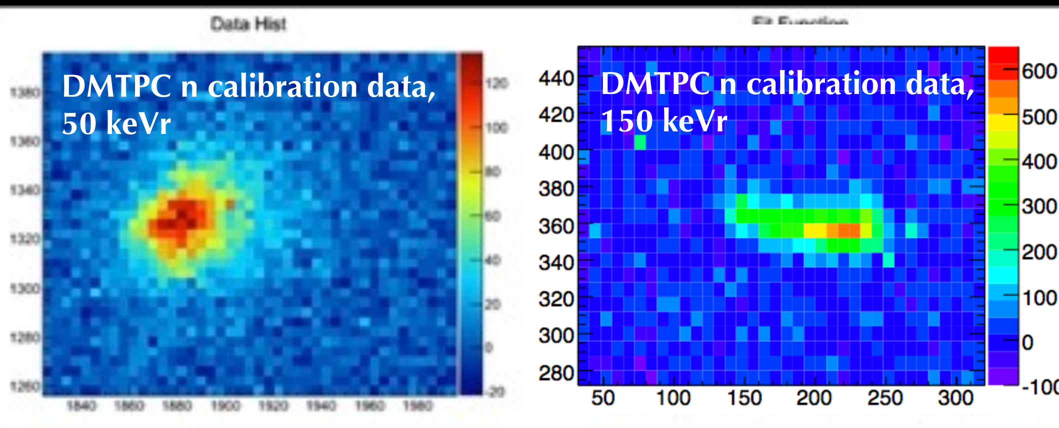
<u>big challenges:</u>
nuclear physics uncertainties on beta spectrum shape, understanding energy resolution at % level

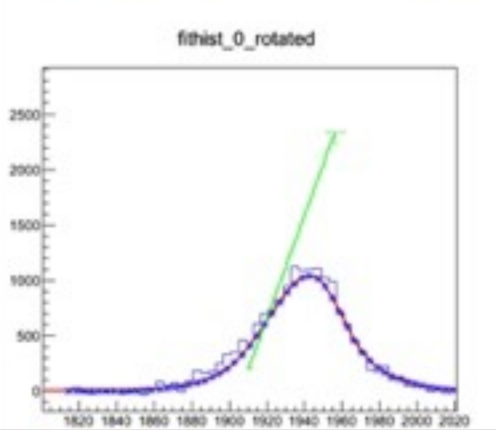
Directional Detection

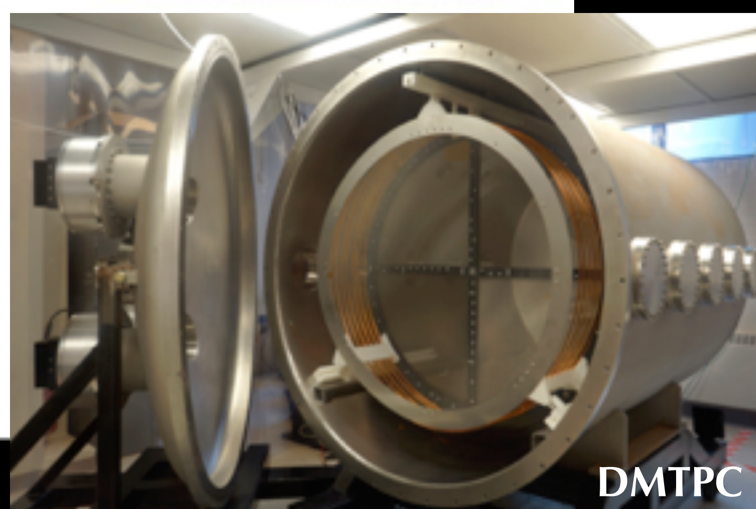
R&D towards recoil *direction measurement* to correlate a signal with the galactic halo











Many R&D efforts:

DRIFT, DMTPC, MIMAC, NEWS-DM, RED++...

largest are 1m³ (O(100g) target).

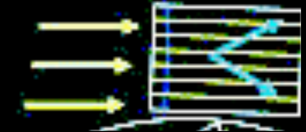
Majority use CF_4 gas; NEWS uses emulsions.

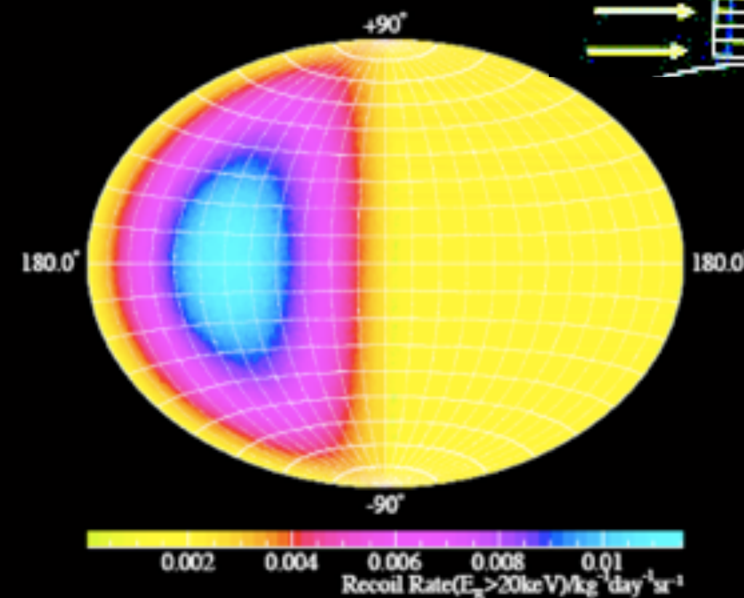
CYGNUS: global coordination towards a physics-scale directional experiment.

Physics Reports 2016, arXiv:1602.03781

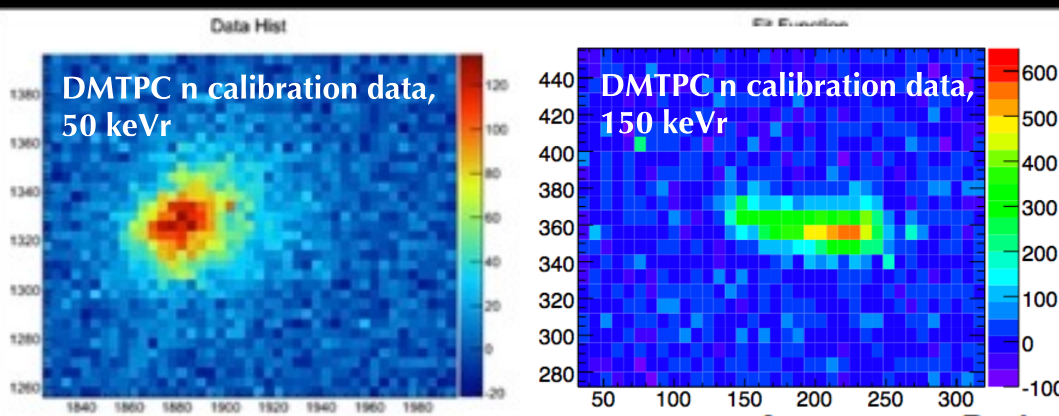
huge experimental challenge to measure direction of recoil tracks of O(10 keV): <mm length!

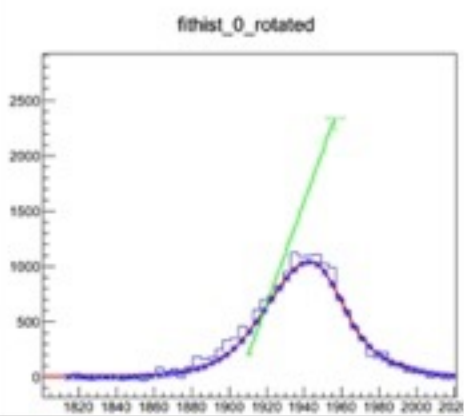
Directional Detection

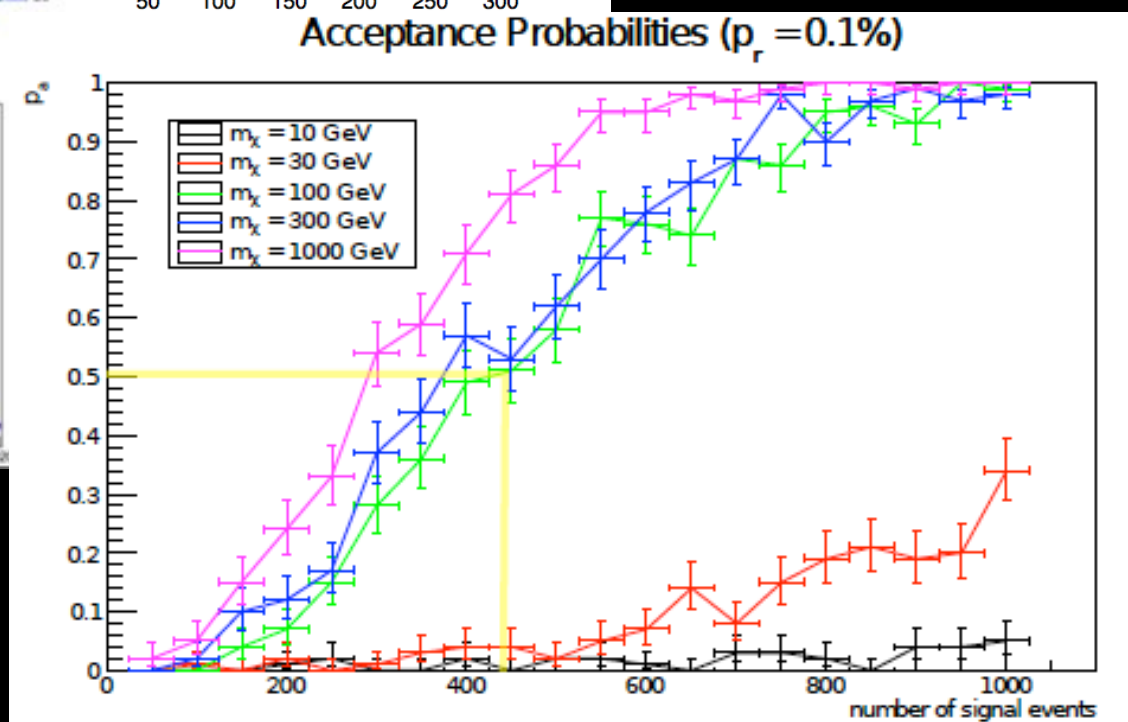




R&D towards recoil *direction measurement* to correlate a signal with the galactic halo







detectors achieve angular resolution of ~35° at 50 keVr

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

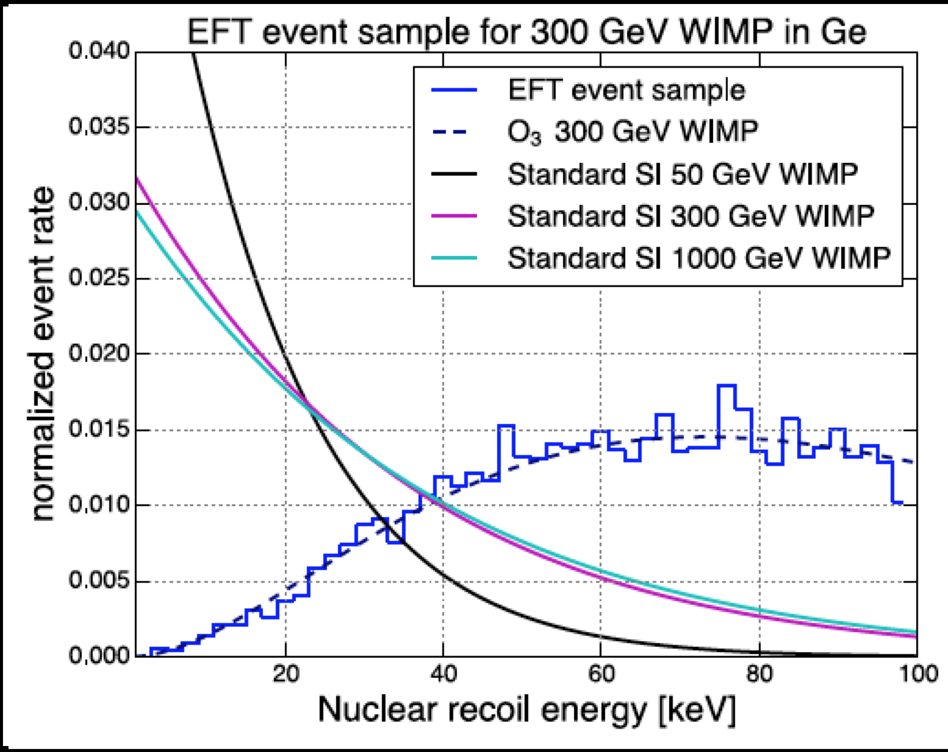
Phys.Rev.D95 (2017) 122002

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.

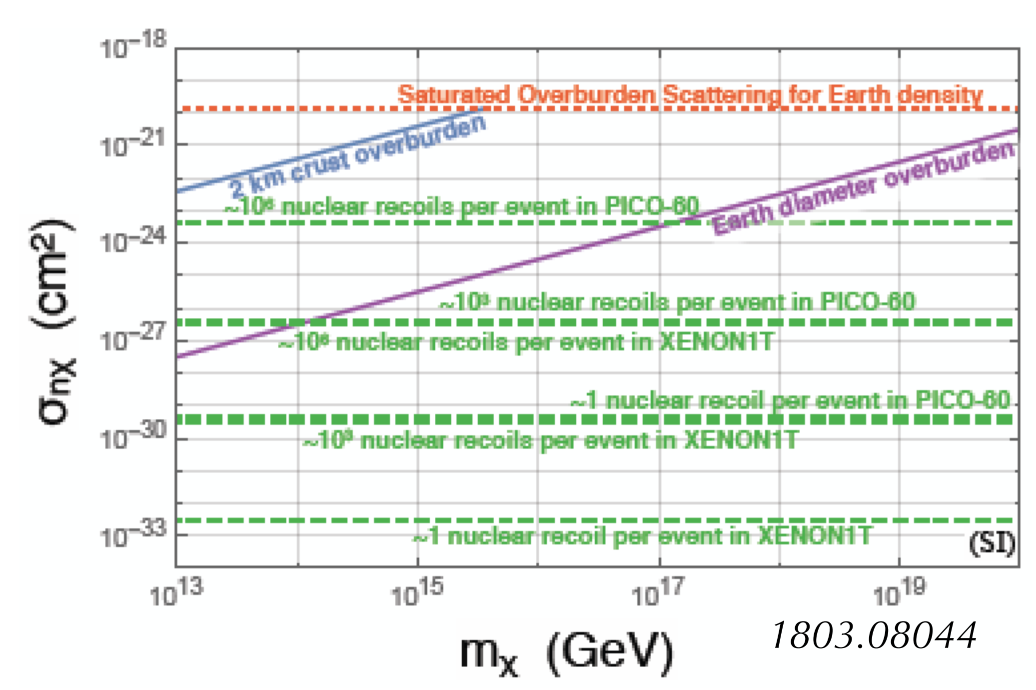
Information isn't only at threshold!



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

…

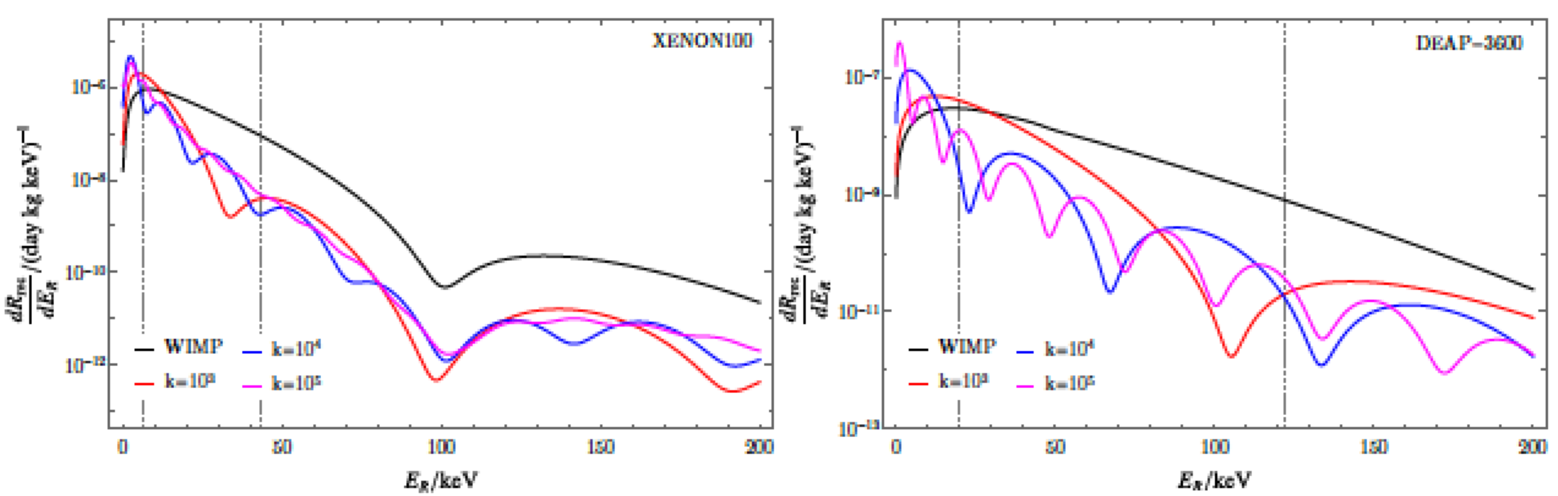


1803.08044

Is High Mass Interesting? (2)

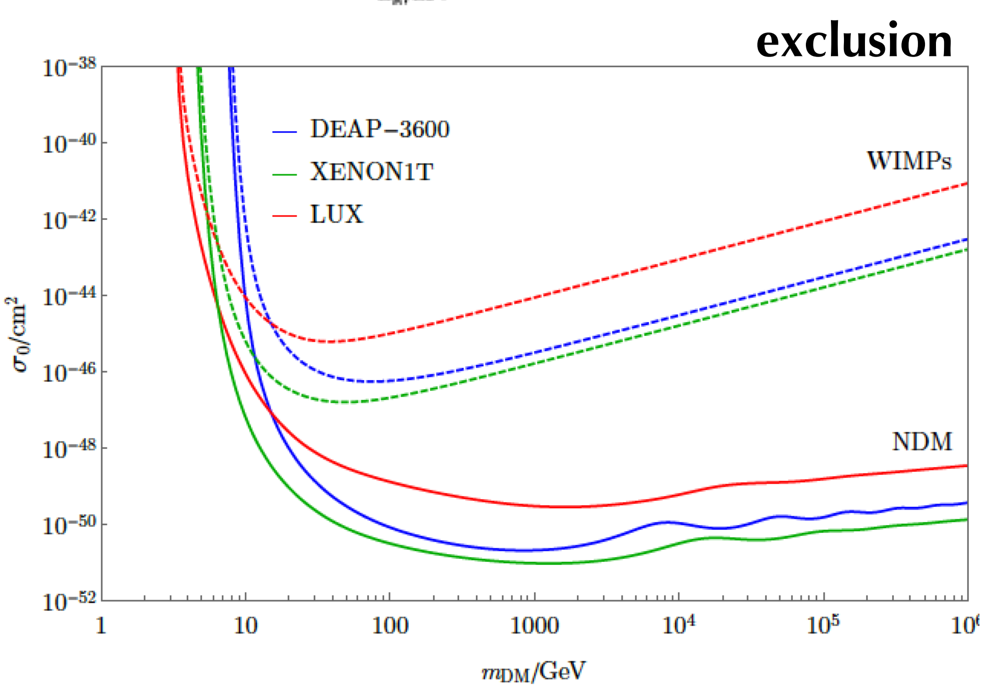
Sensitivity to composite dark matter, e.g. *Hardy, Lazenby, March-Russell, West JHEP 07 (2015)*
dark nuclei, formed of *k* bound states of self-interacting light dark nucleons.

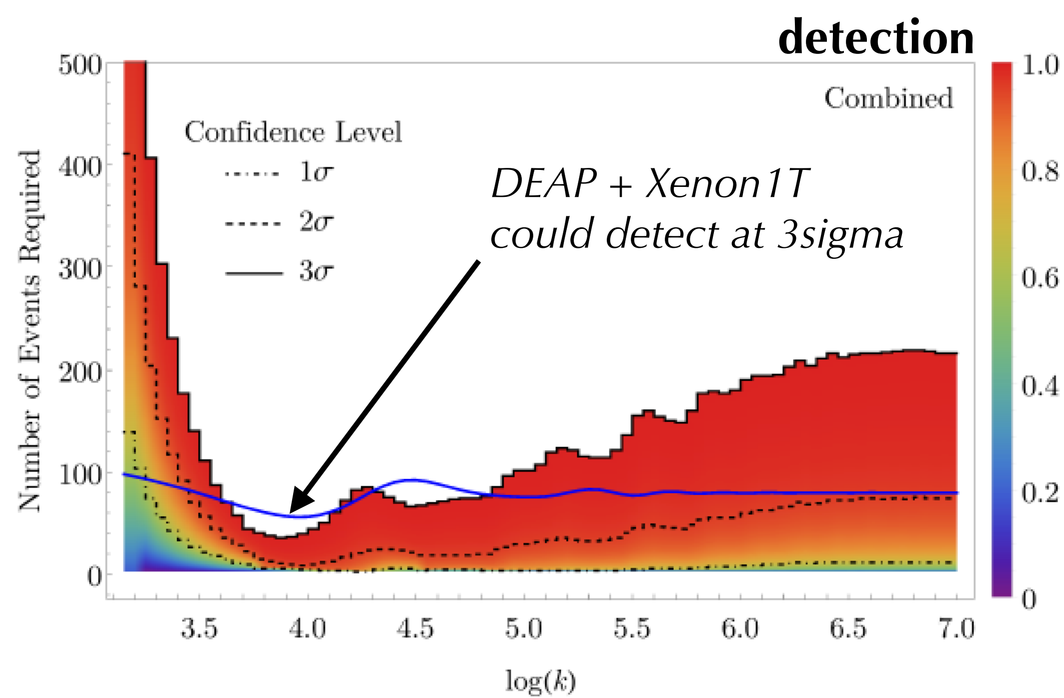
Scattering process now has a form factor from the nuclear dark matter and the target.



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



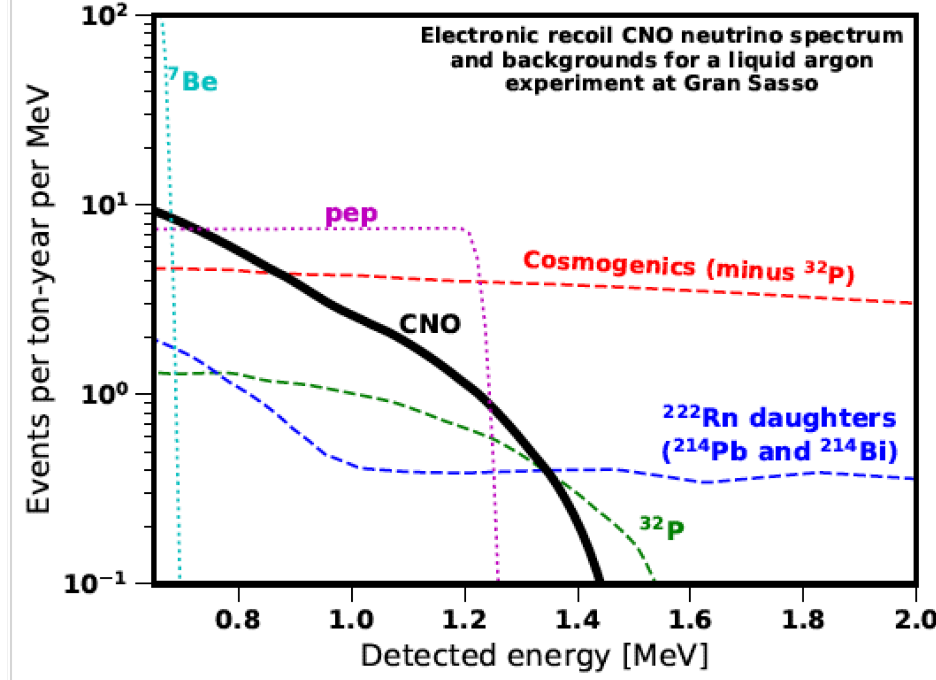


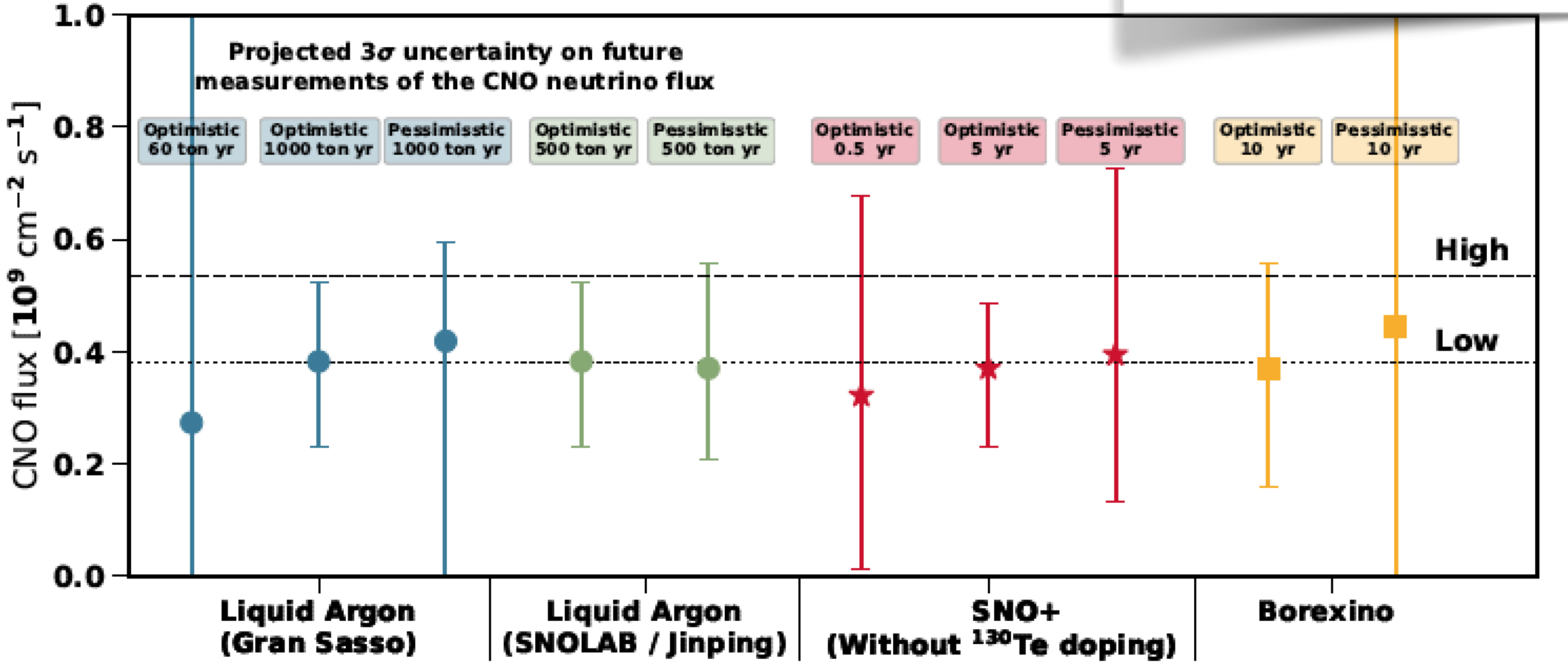
Solar ν-Electron Scattering

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



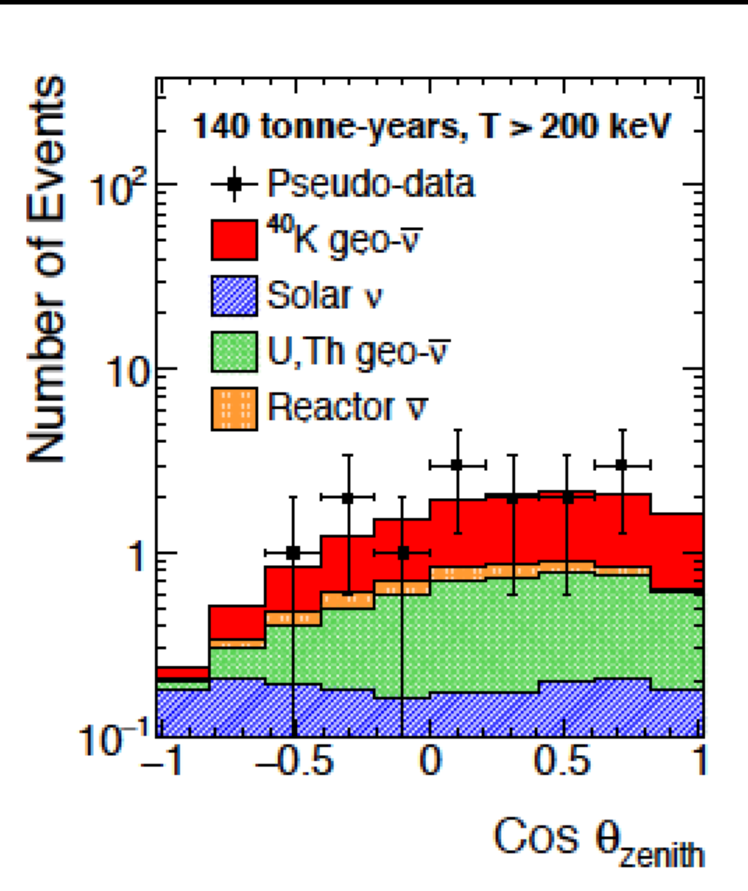


big opportunity:
distinguish between high vs. low metallicity.

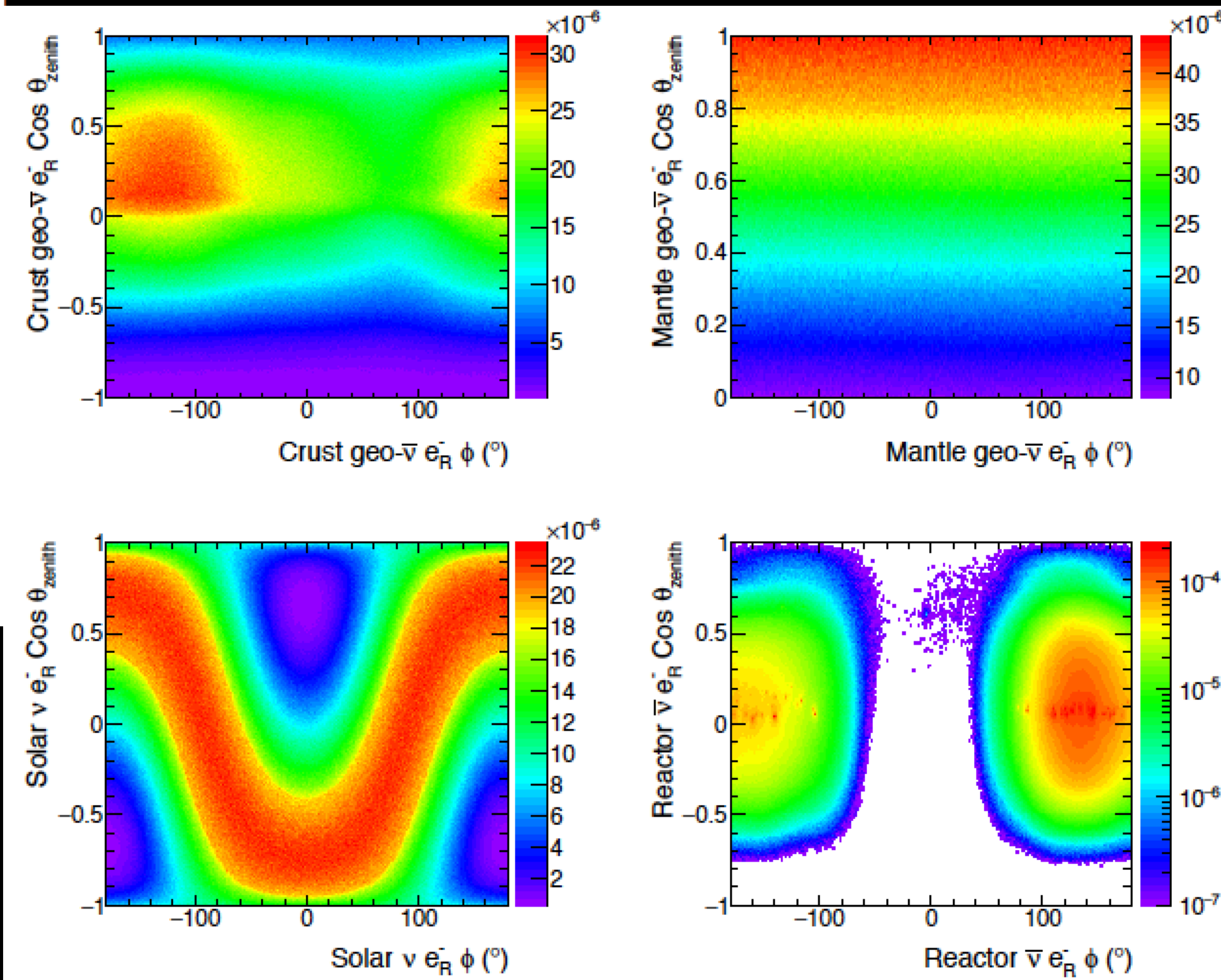
big challenges:
Rn background suppression and uncertainty on cosmogenics

*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