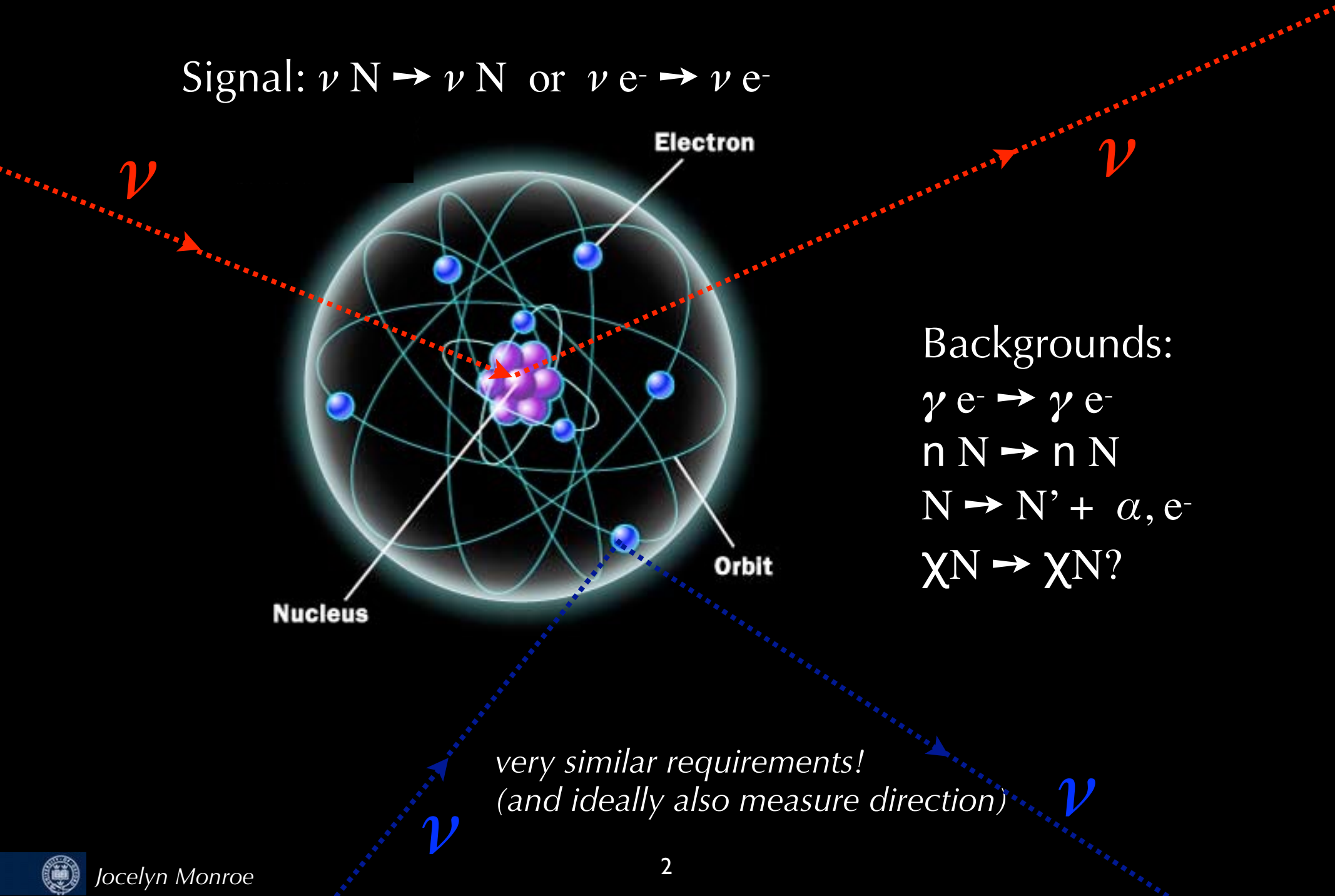
Outline

1. The Evidence for Dark Matter
2. Dark Matter Detection Experimental Techniques
3. Dark Matter Search Status and Prospects
4. **Neutrino Physics in Dark Matter Detectors**

~~Dark Matter Direct~~ Neutrino Detection

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



Backgrounds:

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

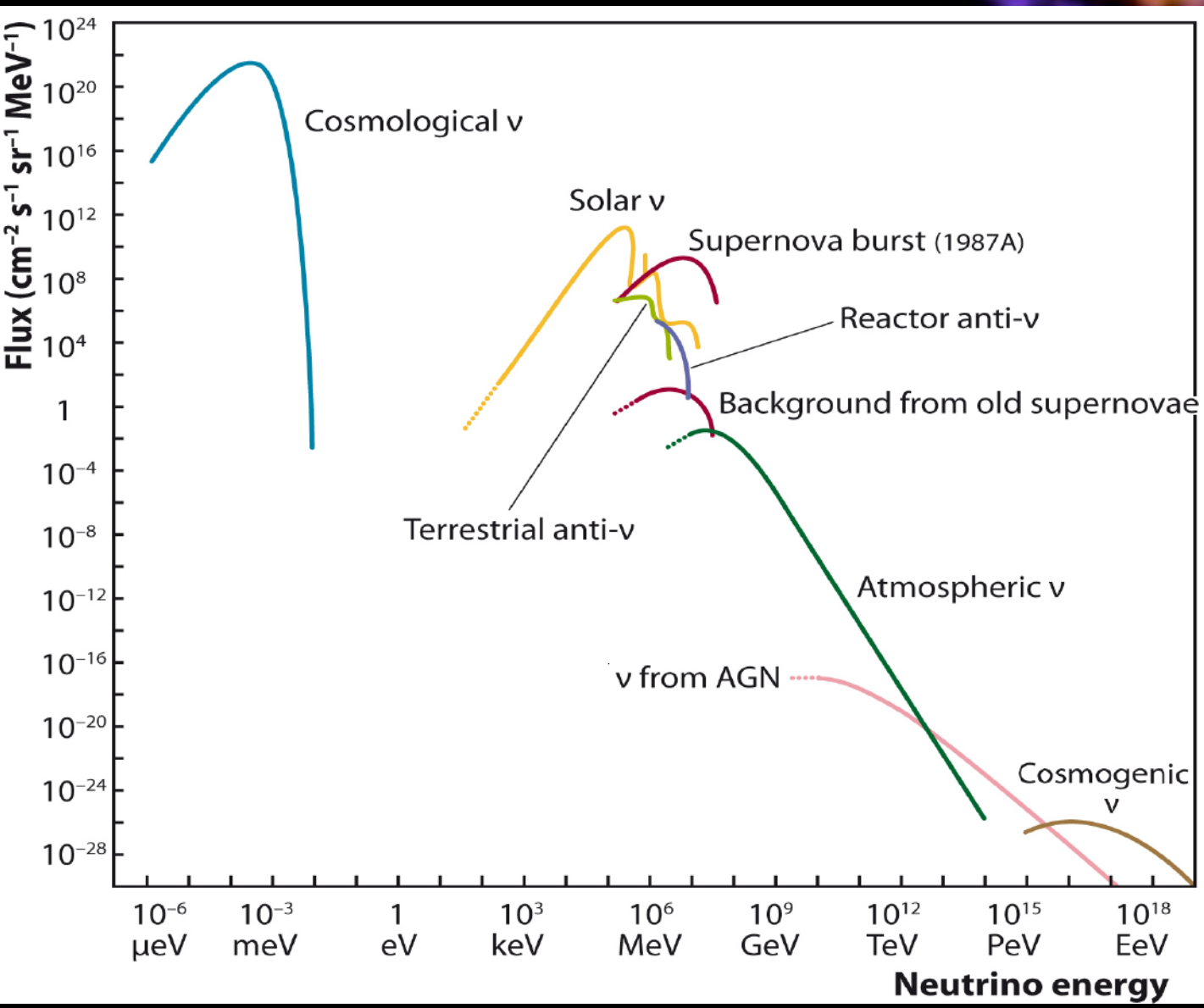
$n\, N \rightarrow n\, N$

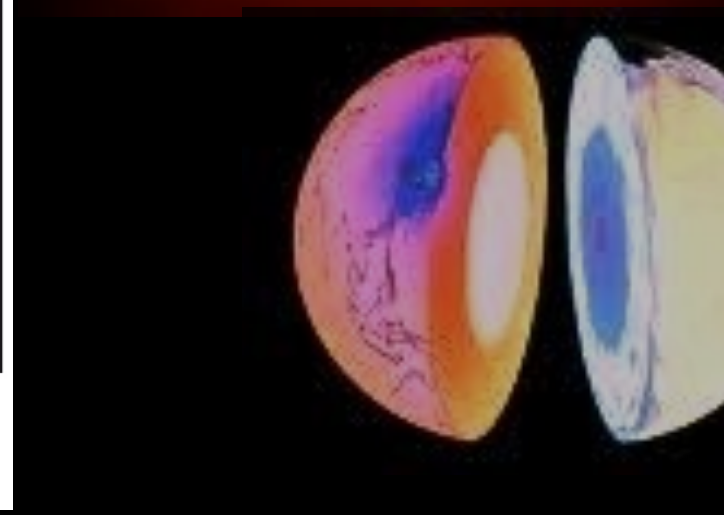
$N \rightarrow N' + \alpha, e^-$

$\chi N \rightarrow \chi N$?

very similar requirements!
(and ideally also measure direction)

What ν sources can dark matter detectors see?





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

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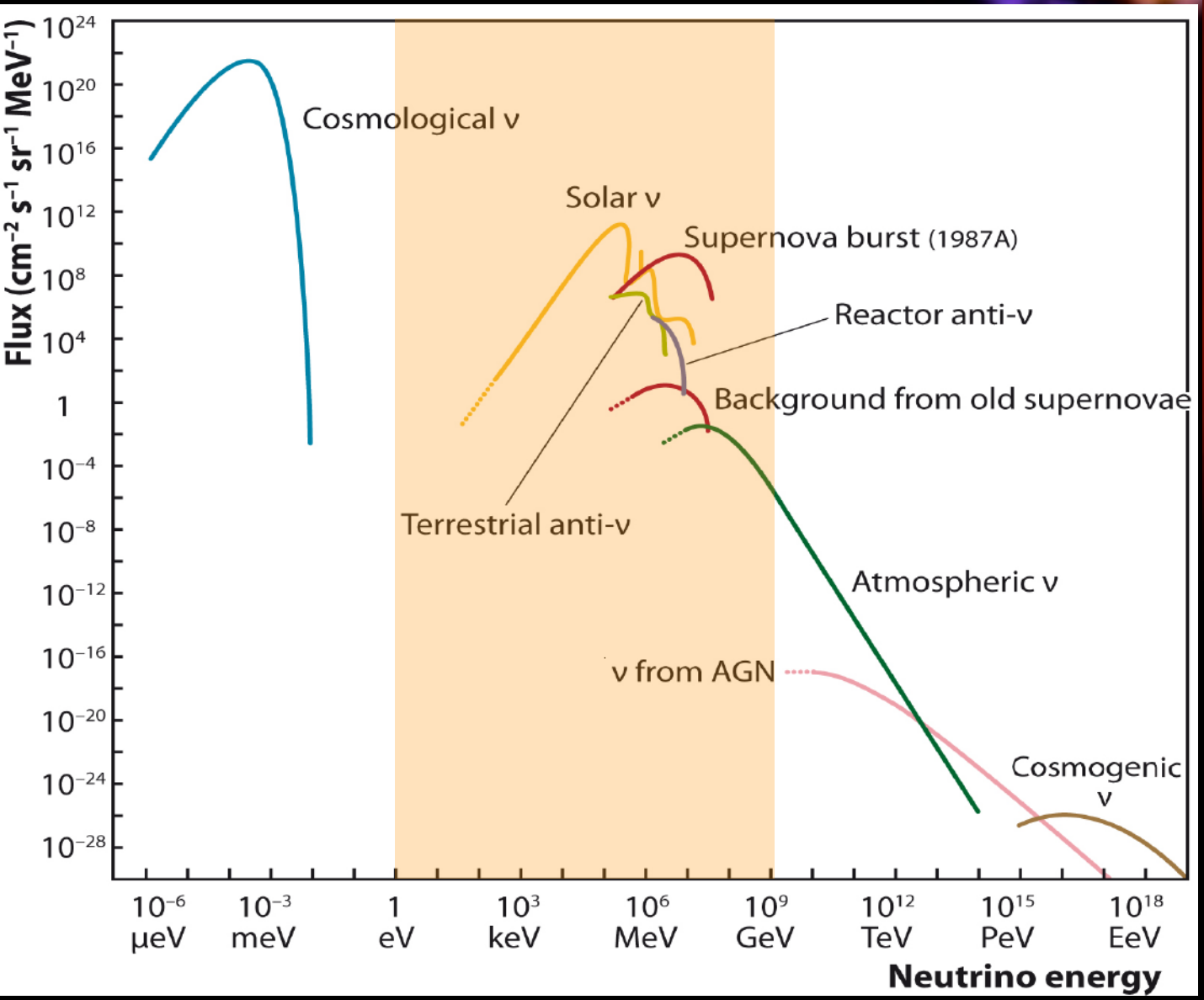

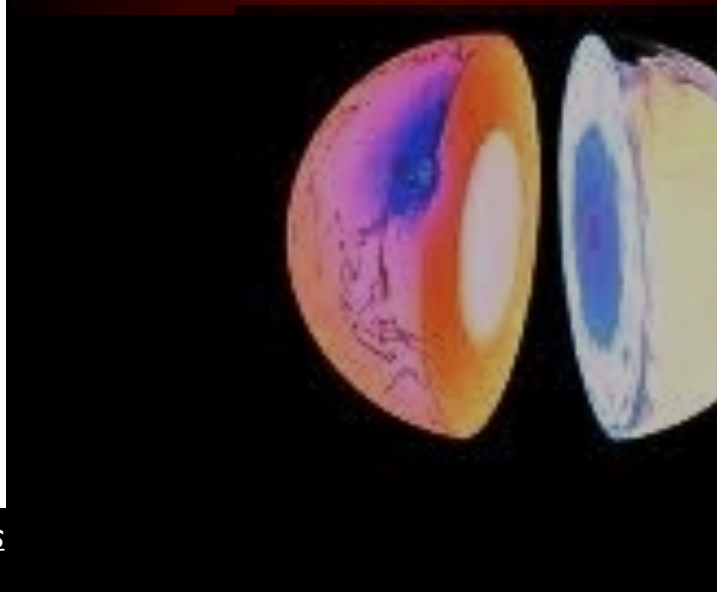

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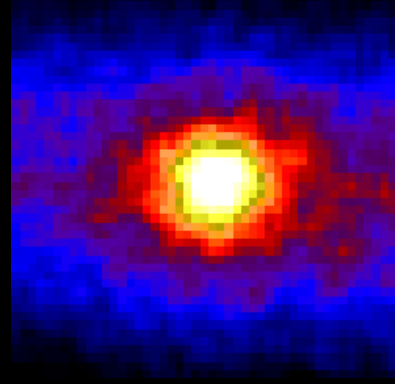
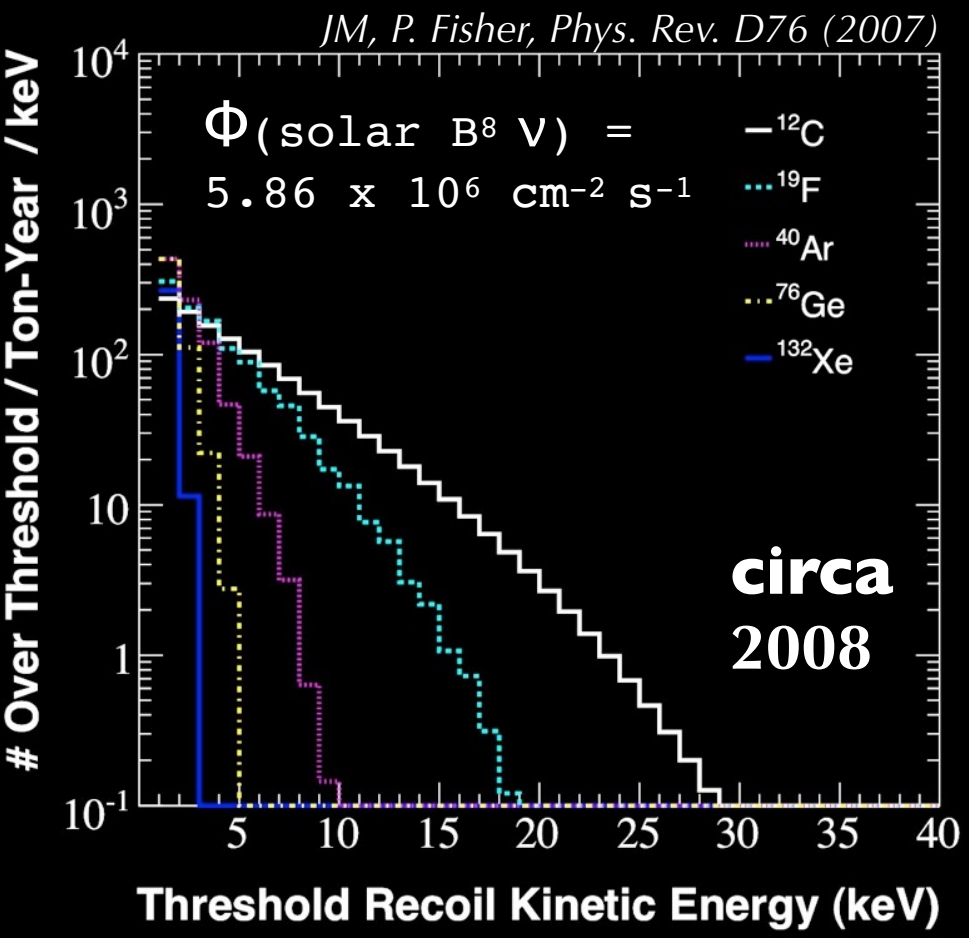
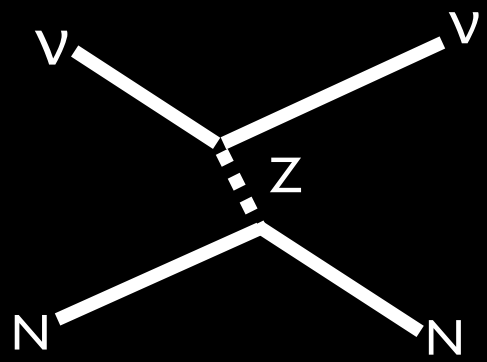
ν Cross Sections

ν-N coherent scattering: ~ $A^2 \times (E_\nu/\mathrm{MeV})^2 \times 10^{-44}$ cm^2

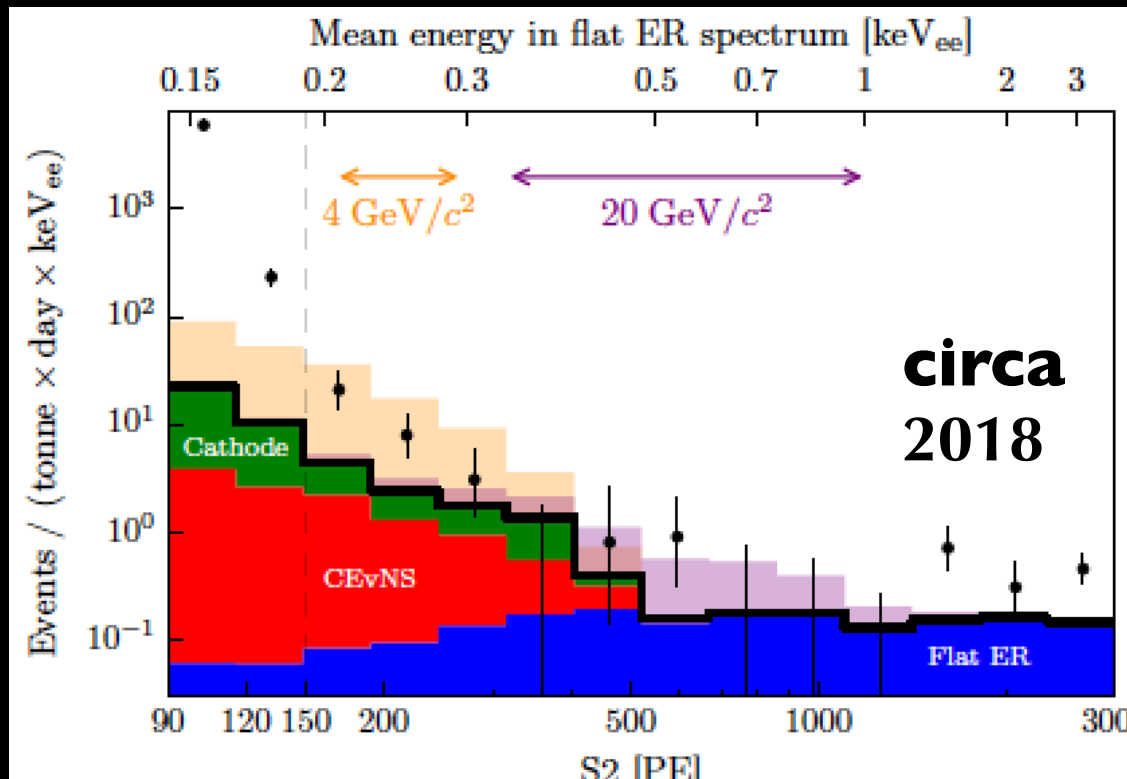
recoils are O(10 keV) … *neutrino floor in DM searches*





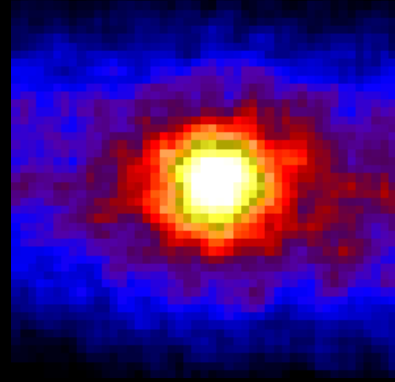


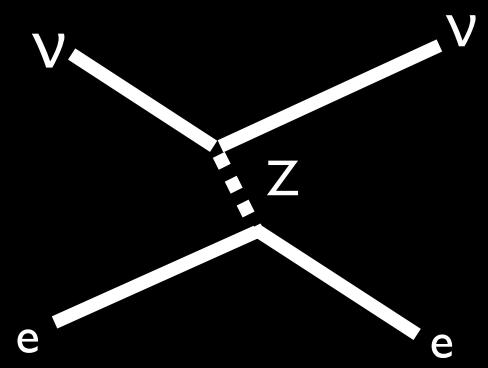
Aprile et al., PhysRevLett 123 (2019)

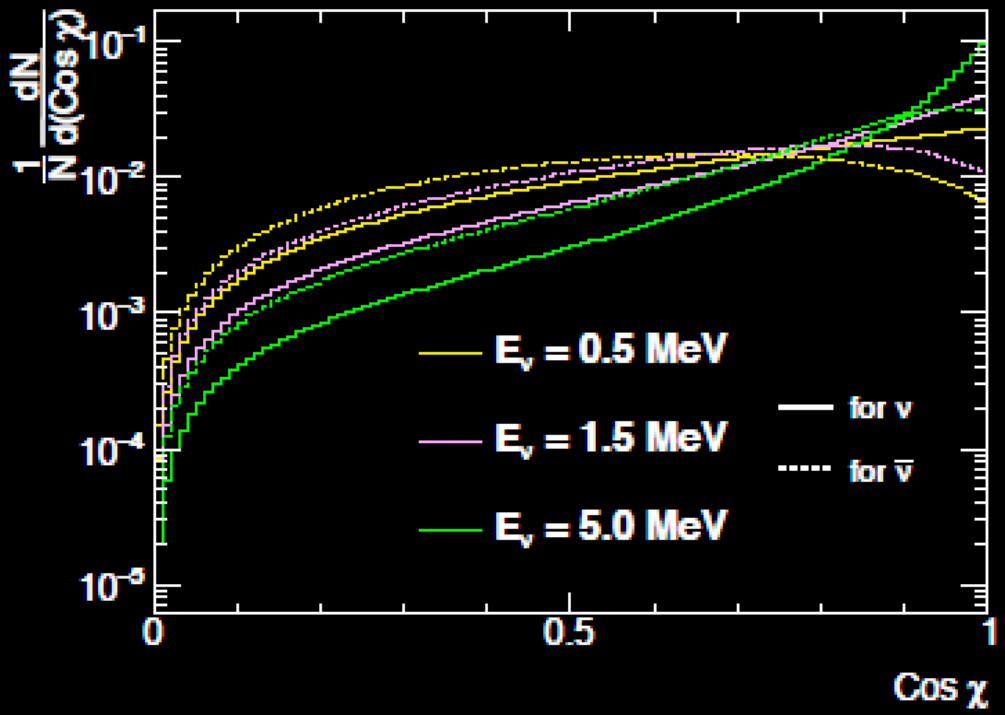


ν Cross Sections

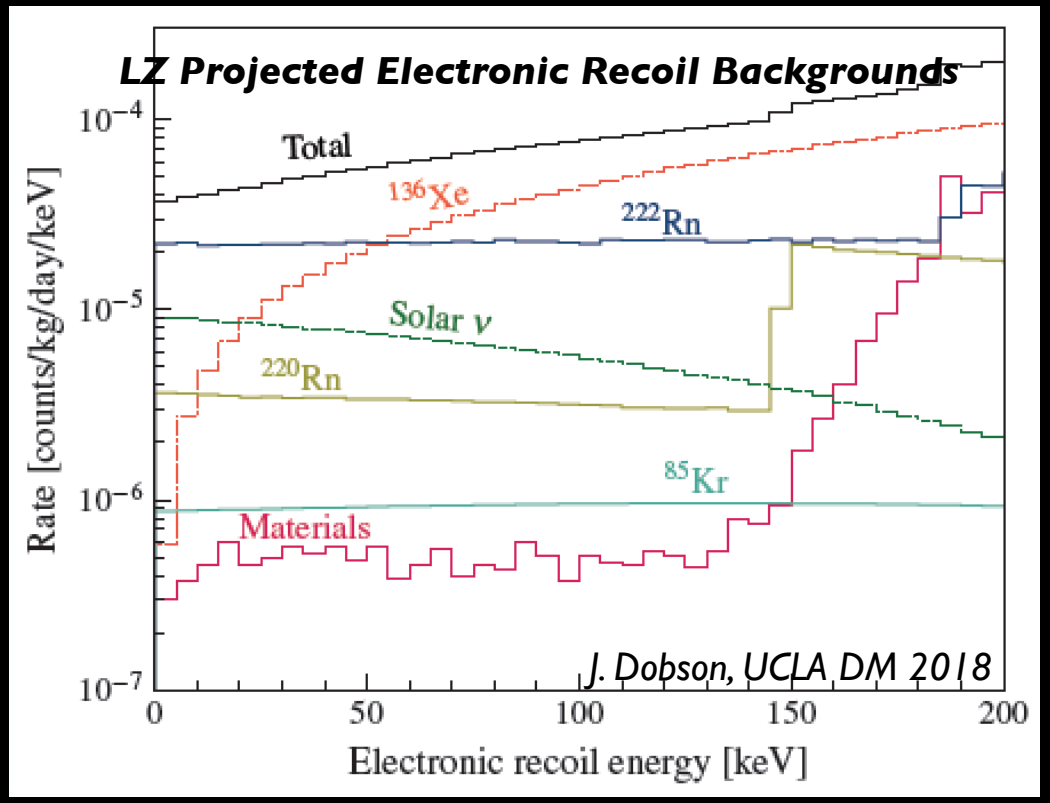
ν-e elastic scattering: smaller by ~ (m_e / E_ν)
but recoils are "high" energy ~ E_ν
and directional!







ν-e backgrounds: ν floor depends on e- discrimination



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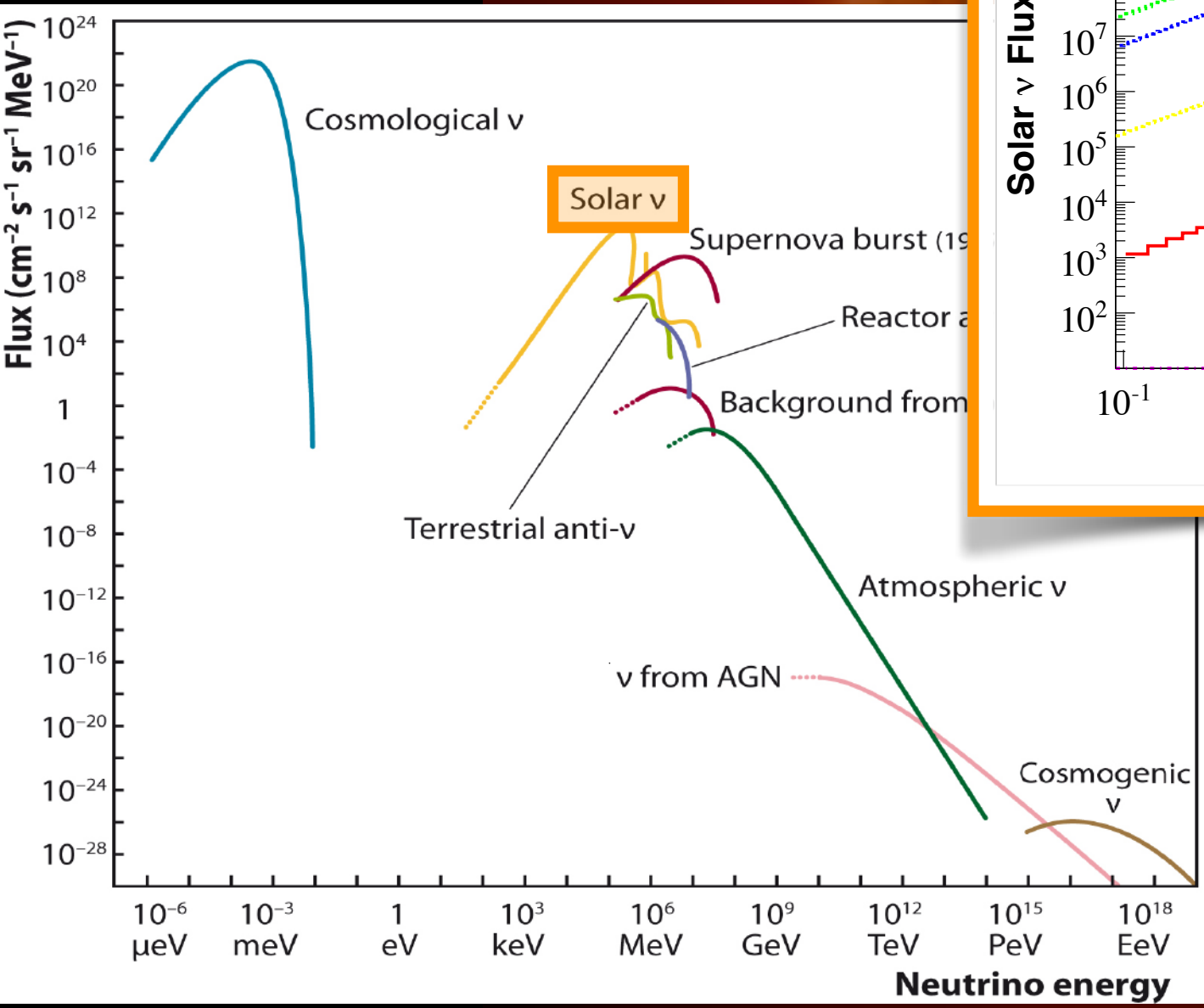
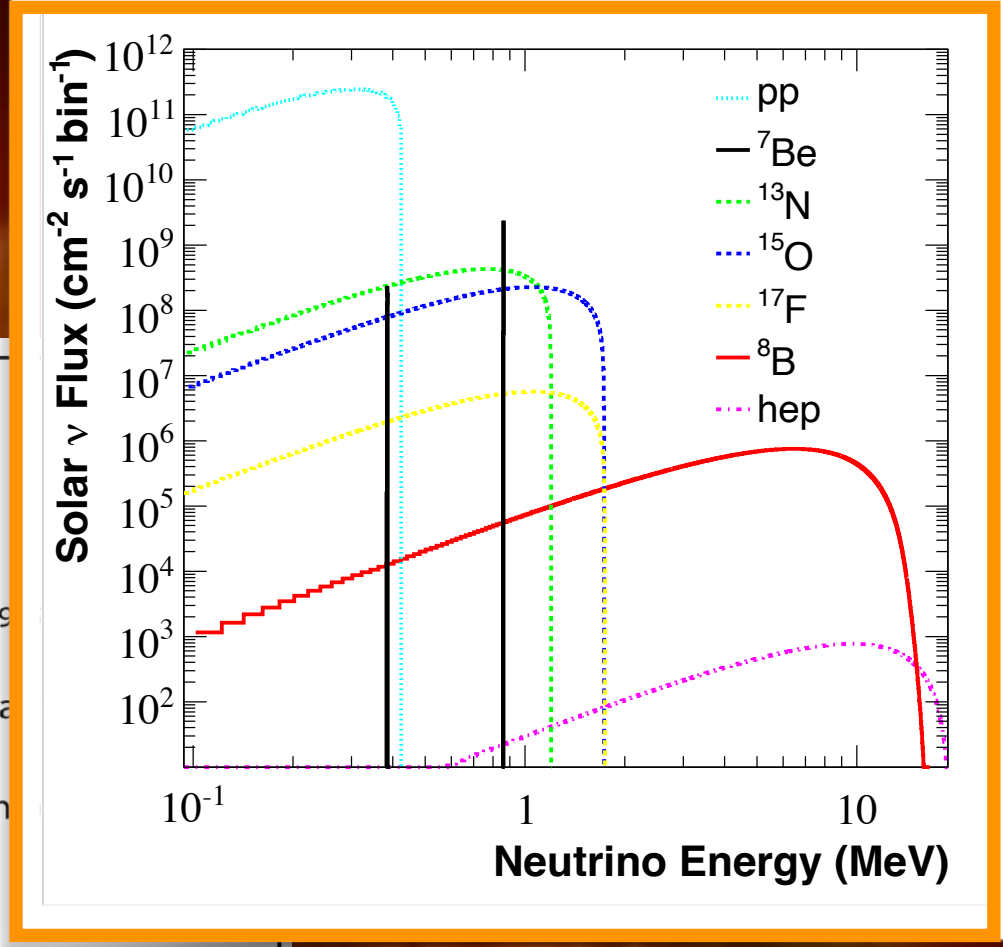




DarkSide-20k:10k solar **ν-e** scatters /100 tonne-yrs

In 400 t-yr:
CNO ~12%, Be-7~2%

Franco et al., JCAP 08 (2016) 017

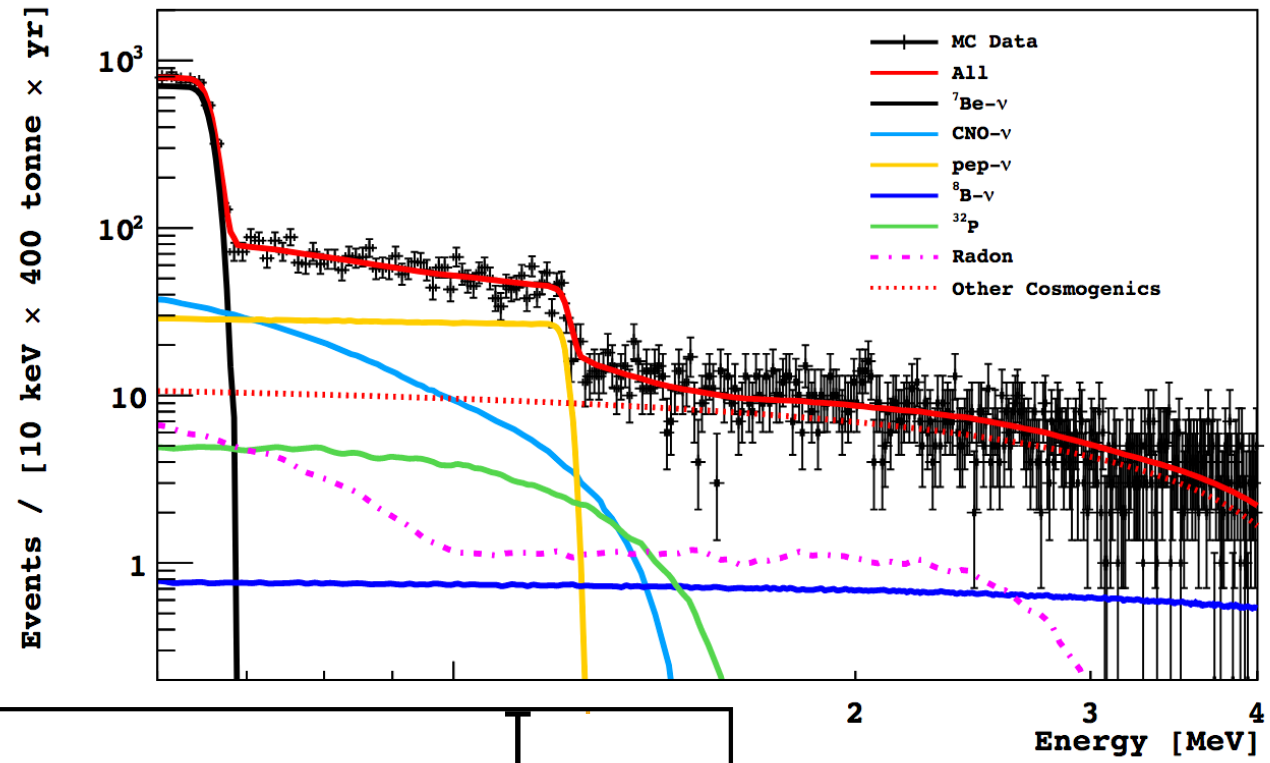
https://masterclass.icecube.wisc.edu/en/learn/detecting-neutrinos

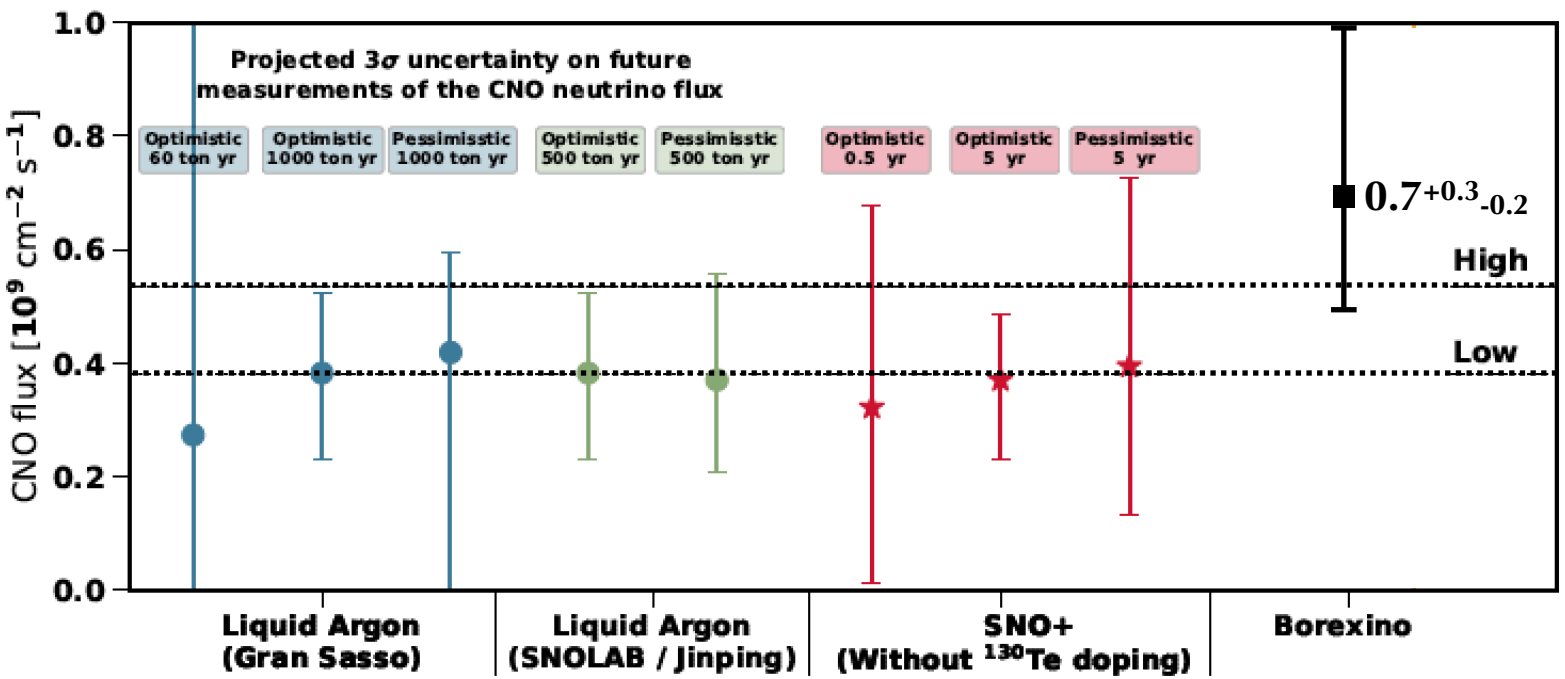
Solar ν-e Scattering

dark matter experiments can measure CNO (via spectral deformation)

+with 500 t-y, study the solar metallicity puzzle

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





*1-2 sigma discrimination possible in Xe, *Baudis et al., arXiv:2006.03114*

<u>big opportunity:</u>
distinguish between high vs. low metallicity.

<u>big challenges:</u>
Rn background suppression and uncertainty on cosmogenics

Solar ν ~~Problem~~ Puzzle

<u>Why measuring CNO is so interesting:</u>

Metallicity measurements from emission are consistent with *low-metallicity,* and ν oscillation data

BUT

Helioseismology measurements (whole sun) are consistent with *high-metallicity*

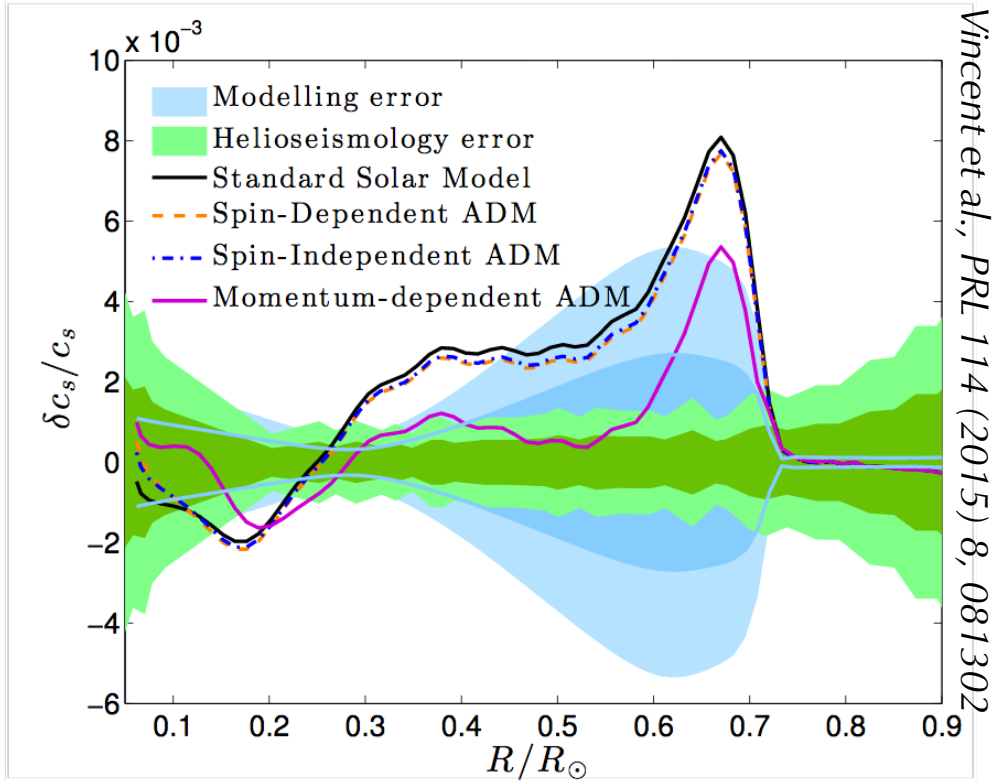
Models can't fit both!

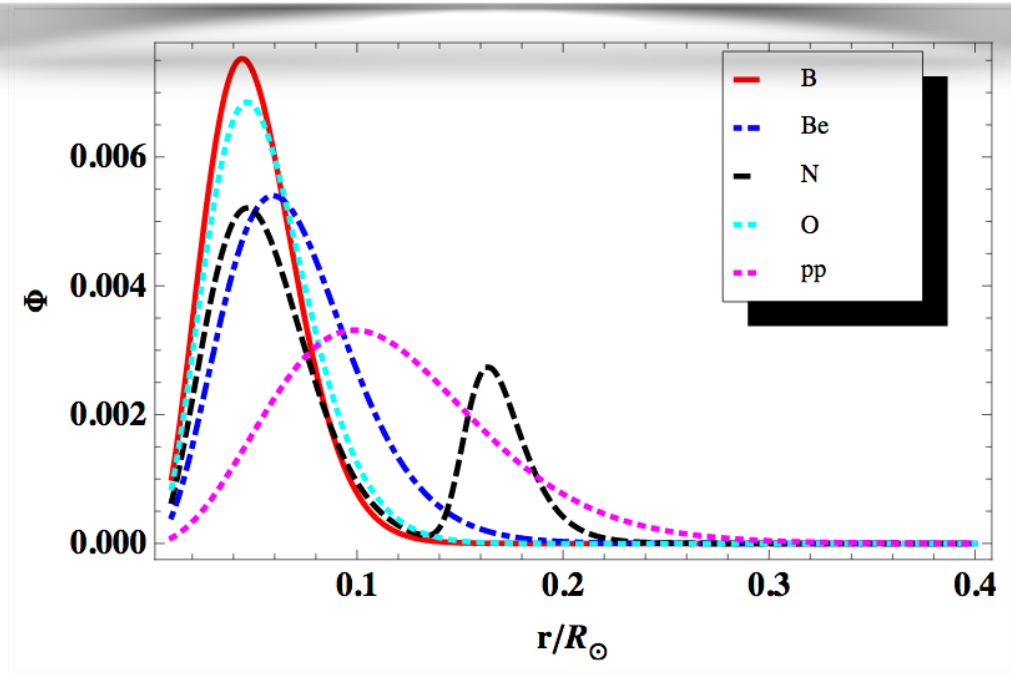
To resolve, need:

1) direct measurements of CNO flux (depends on metallicity)
2) Precise CNO vs. Be-7 flux measurements to test 'cosmion' models:
   dark matter can resolve this tension by changing heat transport, and thus fluxes

Direct detection can do both!

Silk, Sarkar, Frandsen, West ++





‘Cosmion’, Redux

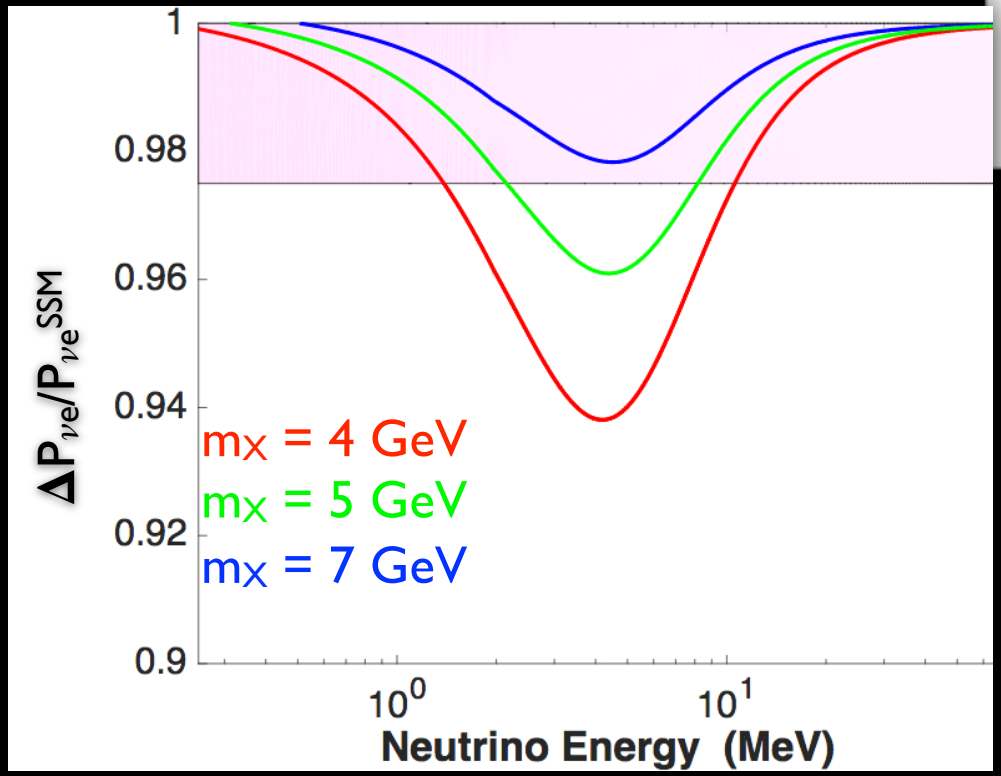
How can we test this?

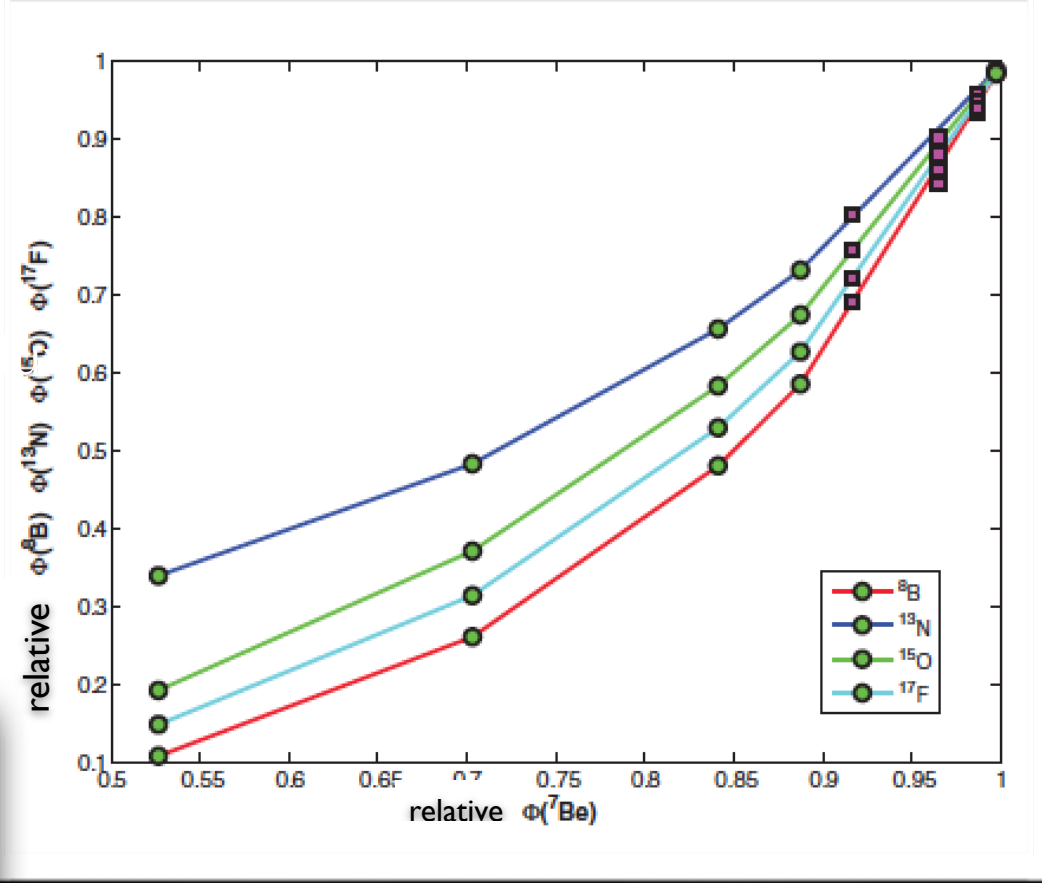
1) Precision measurement of Be-7 vs. CNO ν

Lopes & Silk, Science 330, 2010

2) Precision measurement of ν_e survival, sensitive to changes in matter effects

Lopes & Silk, arXiv:1812.07426





Projected uncertainties: DarkSide-20k 400 t-yr: CNO ~12%, Be-7~2%

Franco et al., JCAP 08 (2016) 017

An **indirect detection signature**, in a direct detection experiment!

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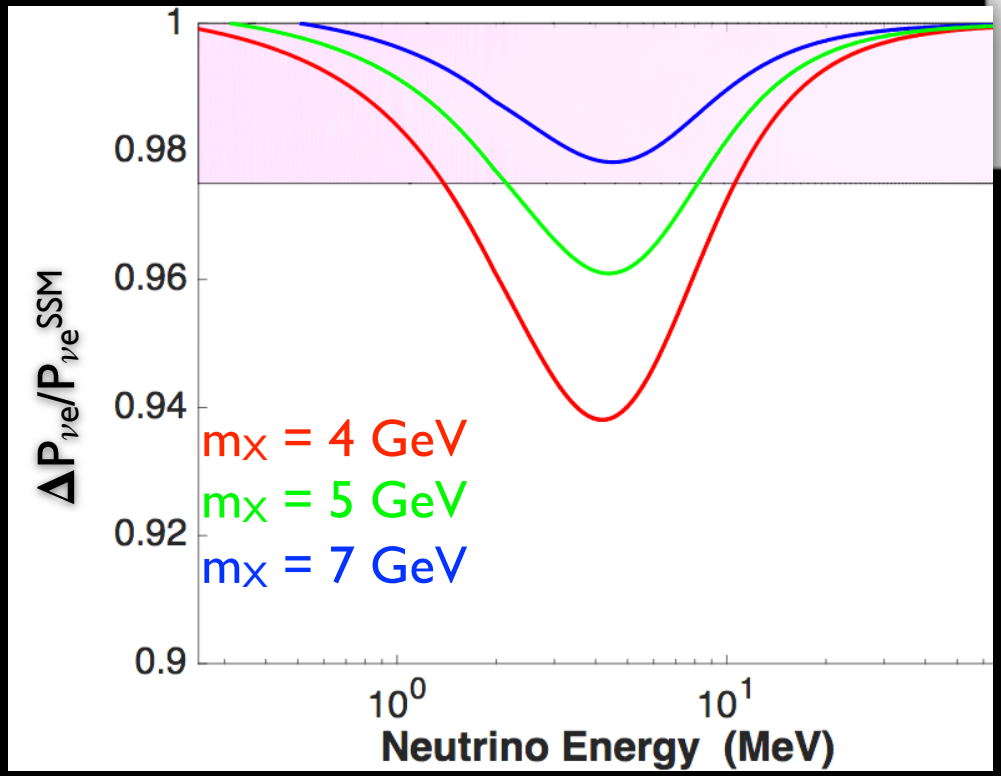

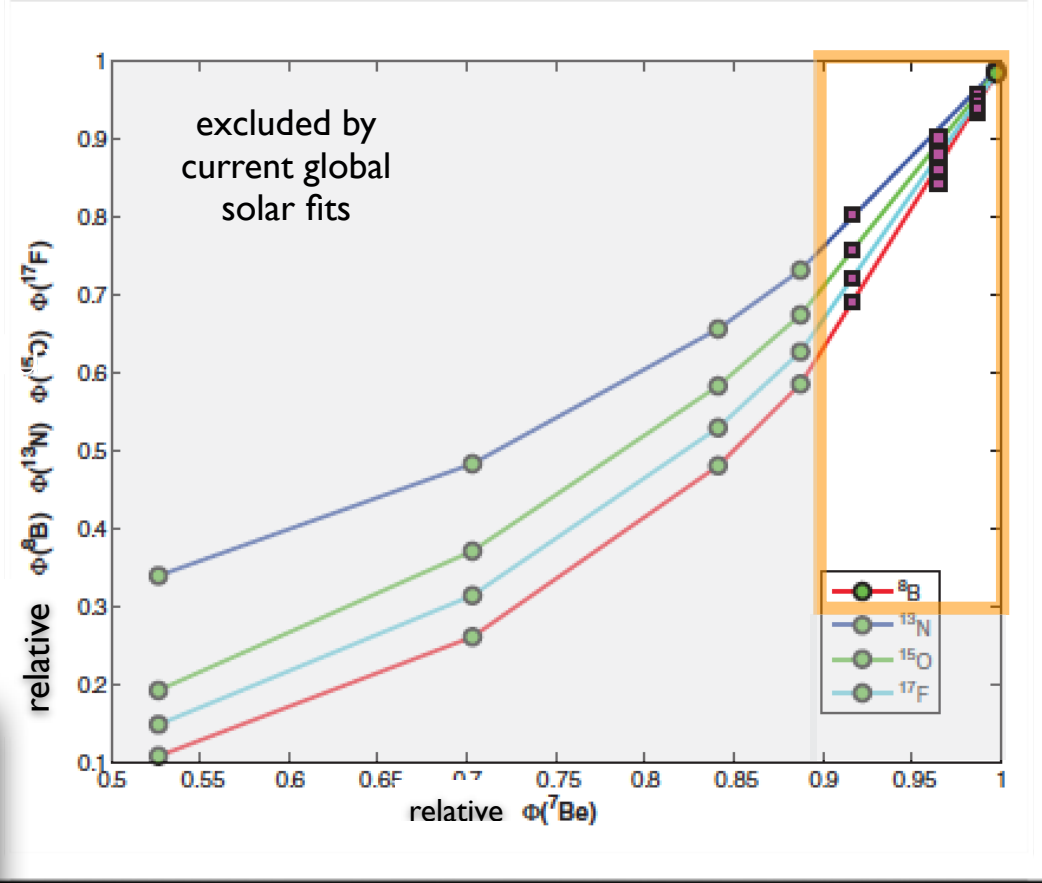

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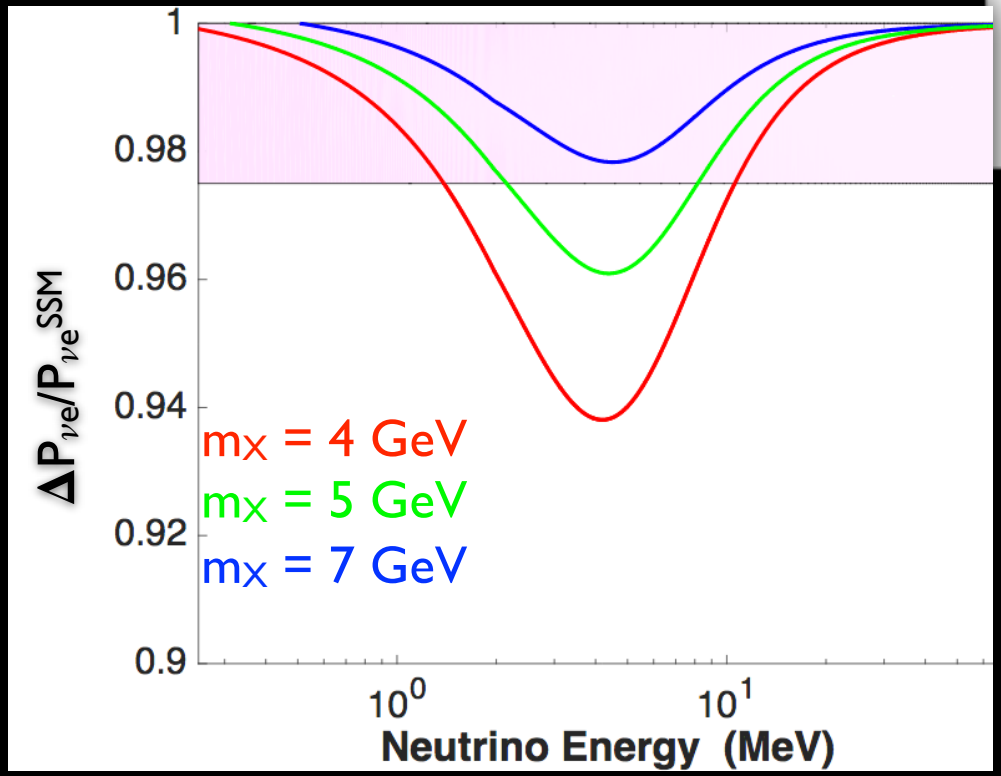

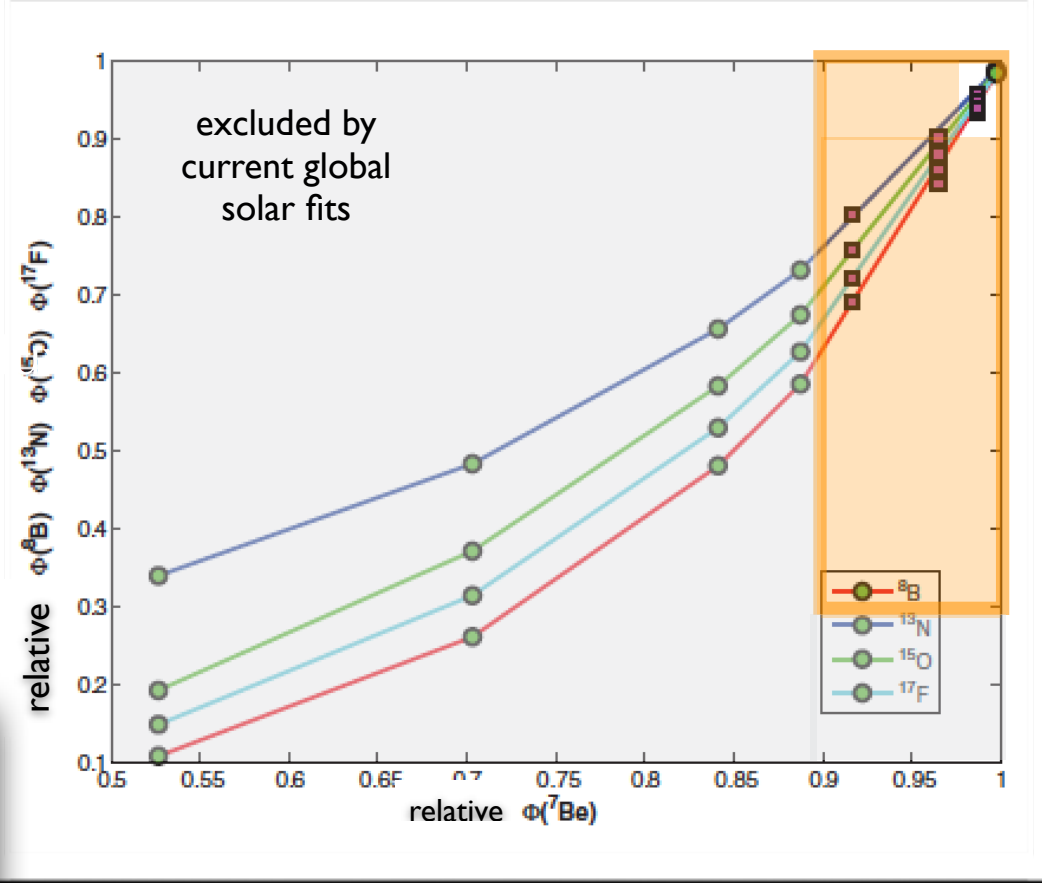

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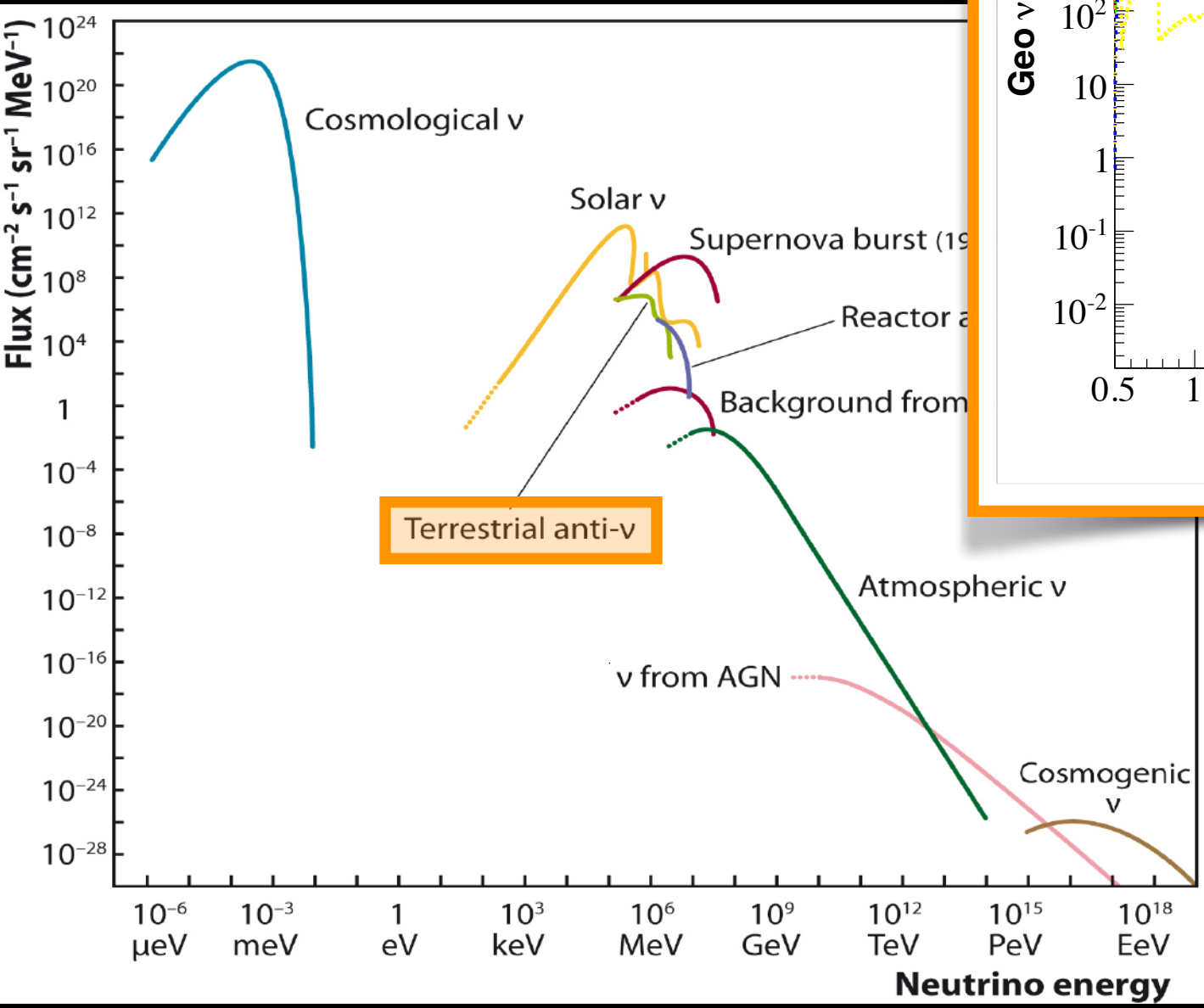
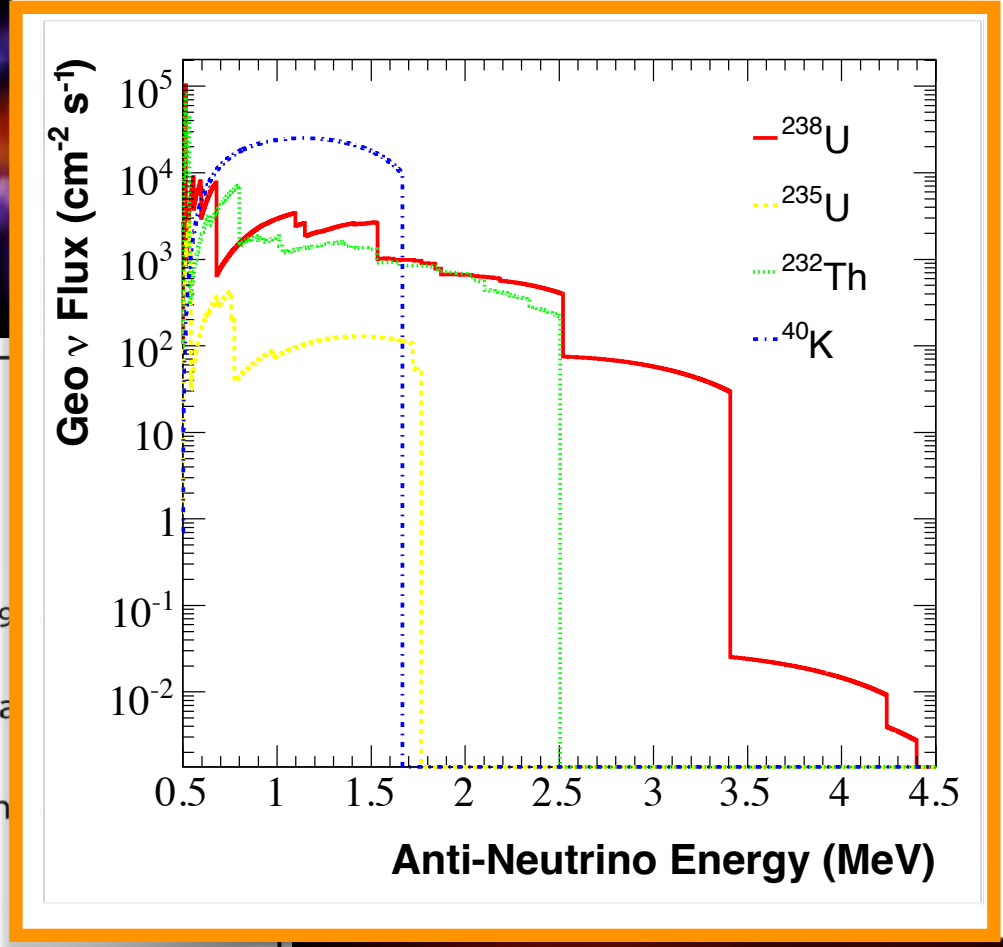
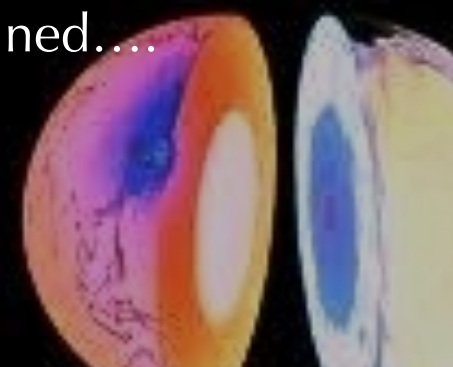




K-40 flux never measured

Half of the Earth's 33 TW of heat flow is unexplained….



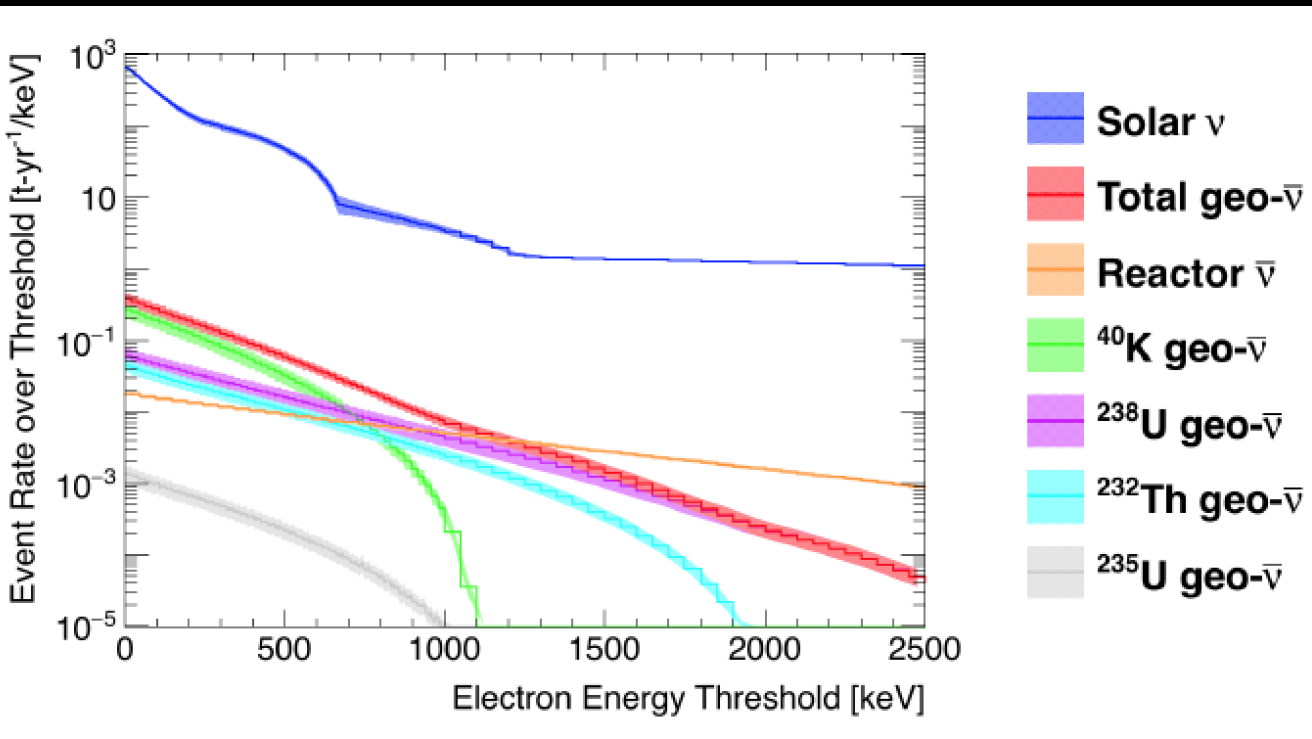
https://masterclass.icecube.wisc.edu/en/learn/detecting-neutrinos

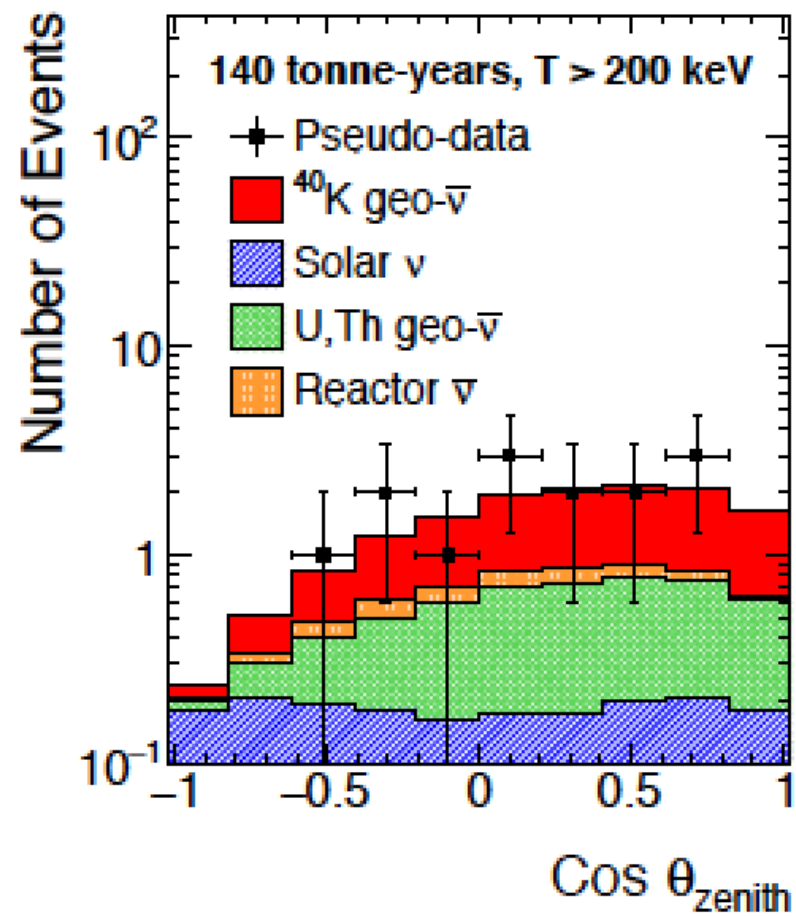
in a 10^n T-year exposure…

low E dominated by the un-measured K-40 geoneutrino flux

ν-e scattering has ~no threshold and geo-neutrinos point…

to the *earth*!





~15° angular resolution on electron recoil direction brings K-40 discovery within reach with 100 tonne-year scale exposure

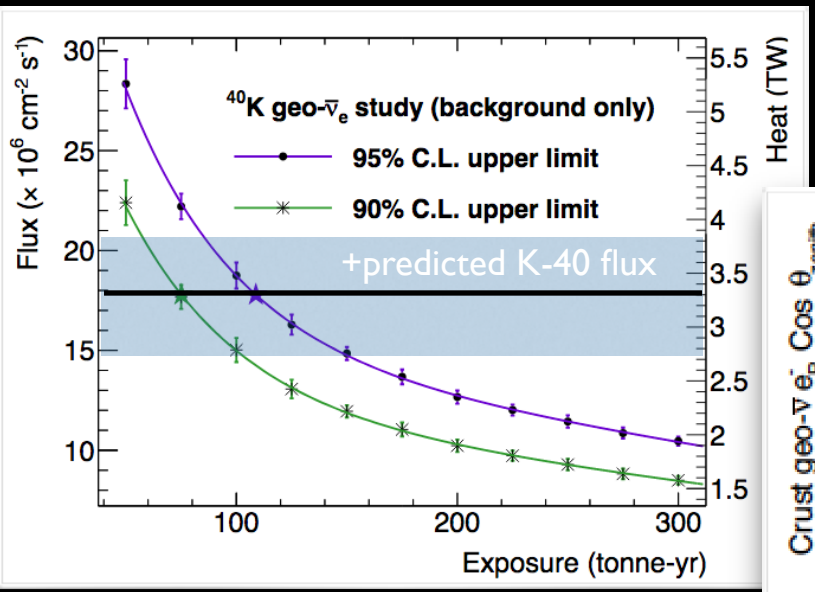
Leyton, Dye, JM, Nature Commun. 8 (2017) 15989

ν-N scattering:

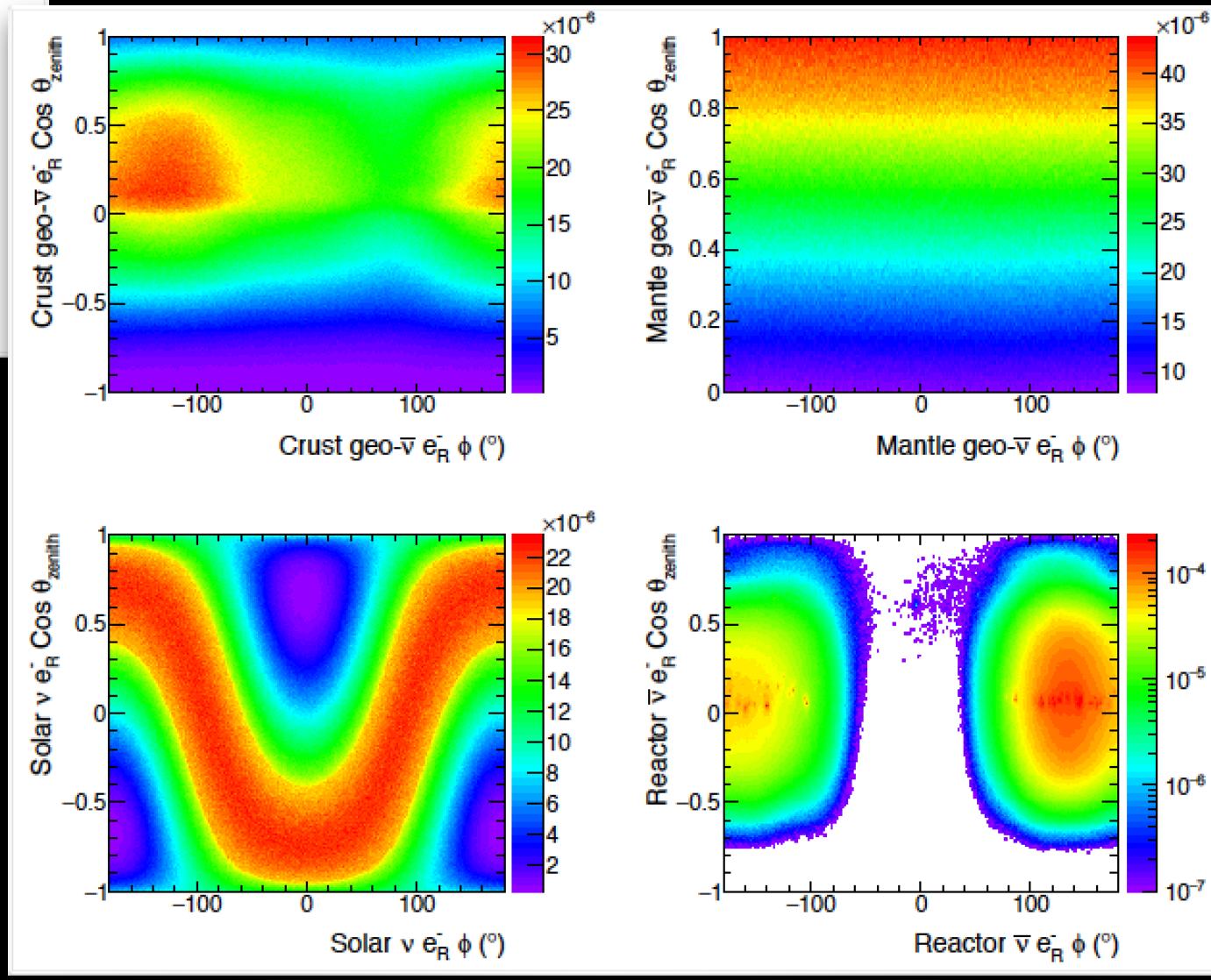
Gelmini et al, arXiv:1812.05550

Geo ν-Electron Scattering

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



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

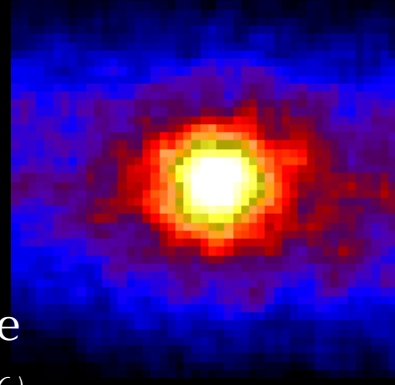


example: geo-, solar-, reactor-ν -induced electron recoil directions, at LNGS.

<u>challenge</u>: measure the *direction* of ~1 MeV e^- recoils

<u>opportunity</u>: + kt-yr exposures, potential for measurement of crust vs. mantle flux

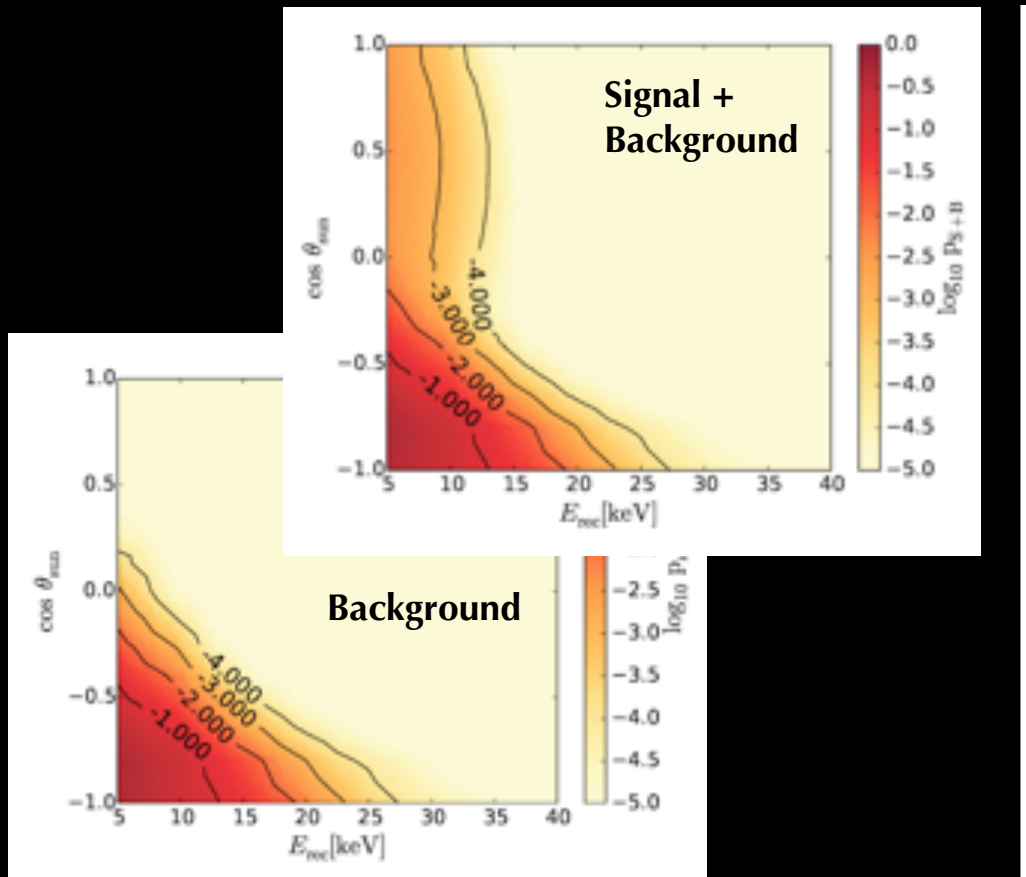
Recoil Directionality

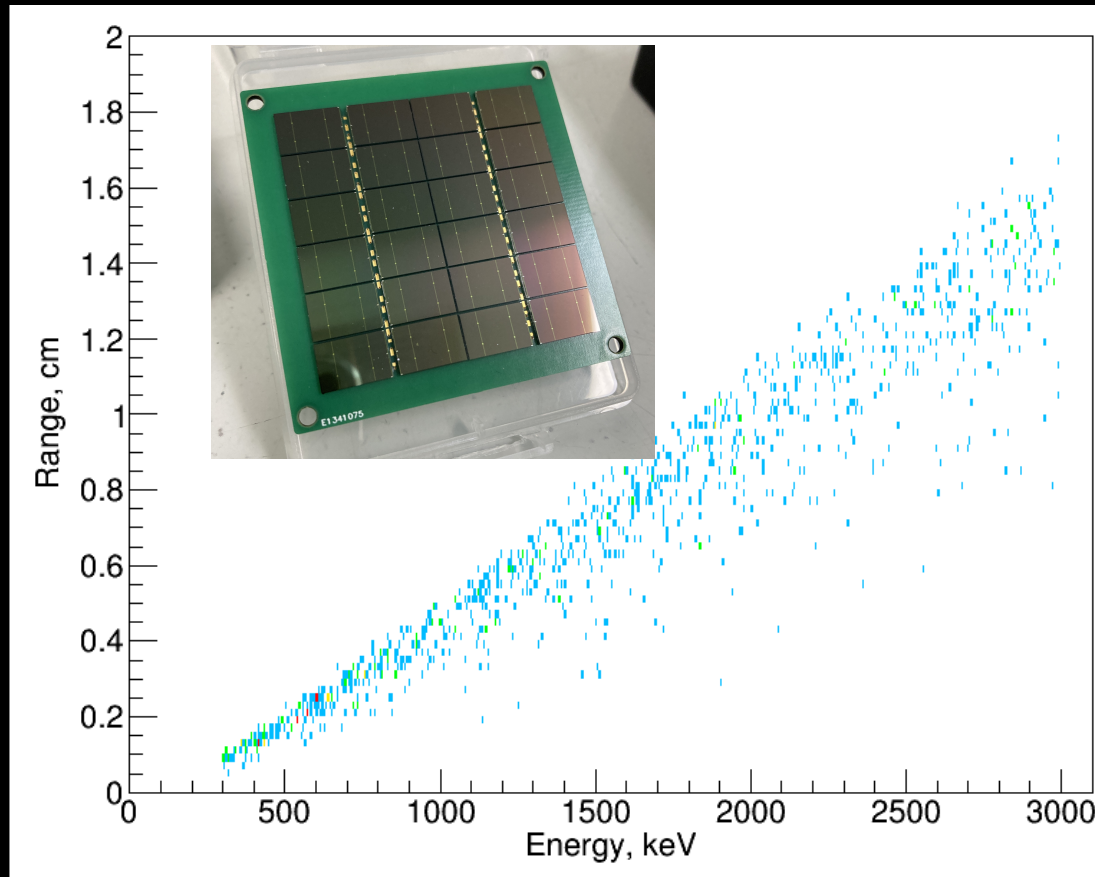


- directional dark matter detection studies show 1D direction reconstruction for $\chi N \rightarrow \chi N$ nuclear recoils gains 10x over non-directional measurements, because (energy, angle, time) of signal != background. *Mayet, JM et al., Phys.Rept. 627 (2016)*

- directionality could do the same for $\nu\, e \rightarrow \nu\, e$ signal sensitivity in the MeV ν energy range

  mm sampling pitch in drift direction, demonstrated, makes direction reconstruction of ~cm length electron recoils *feasible* in 1D. Transverse pitch is a challenge tackled by 3DdSiPM readout R&D…





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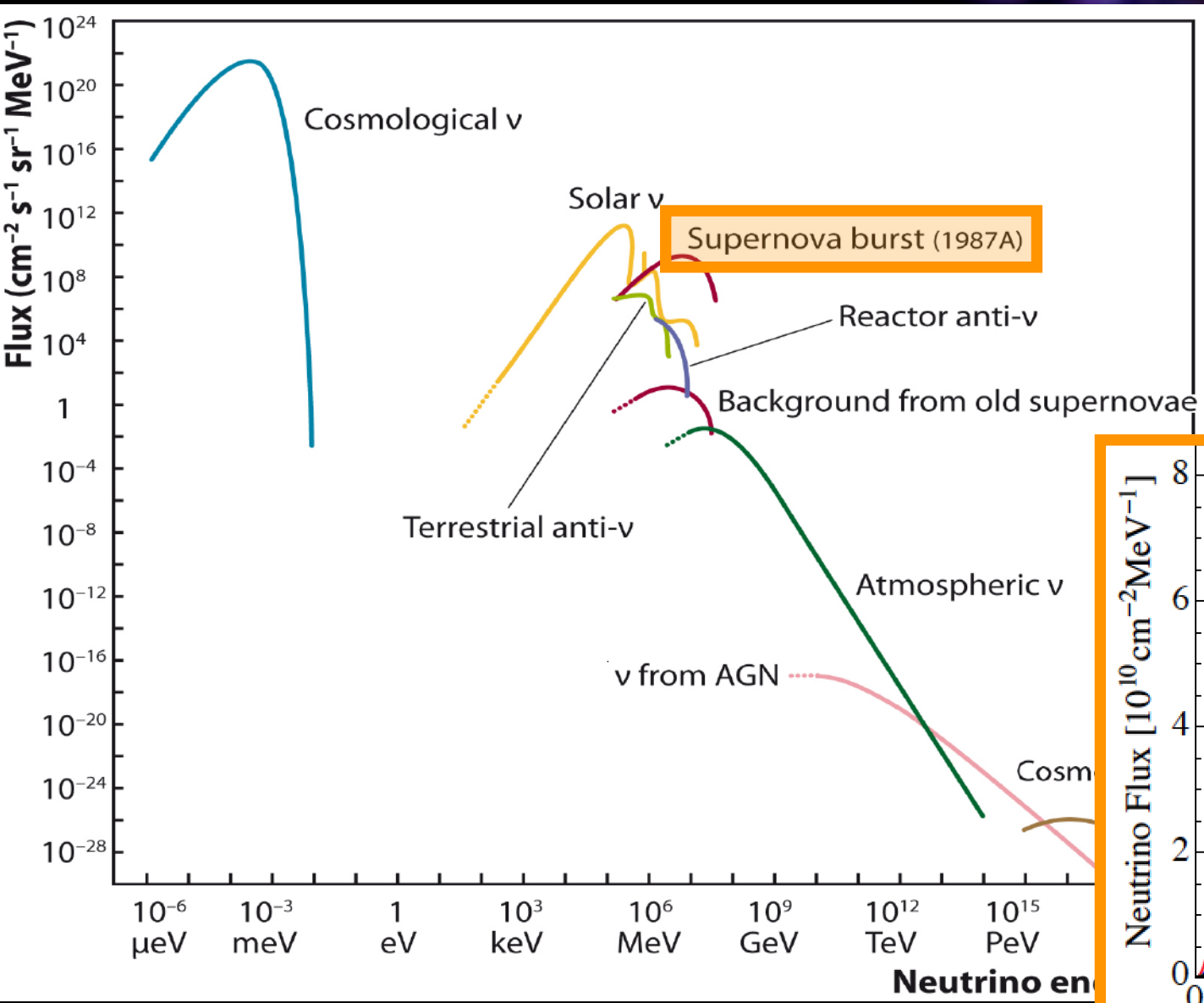
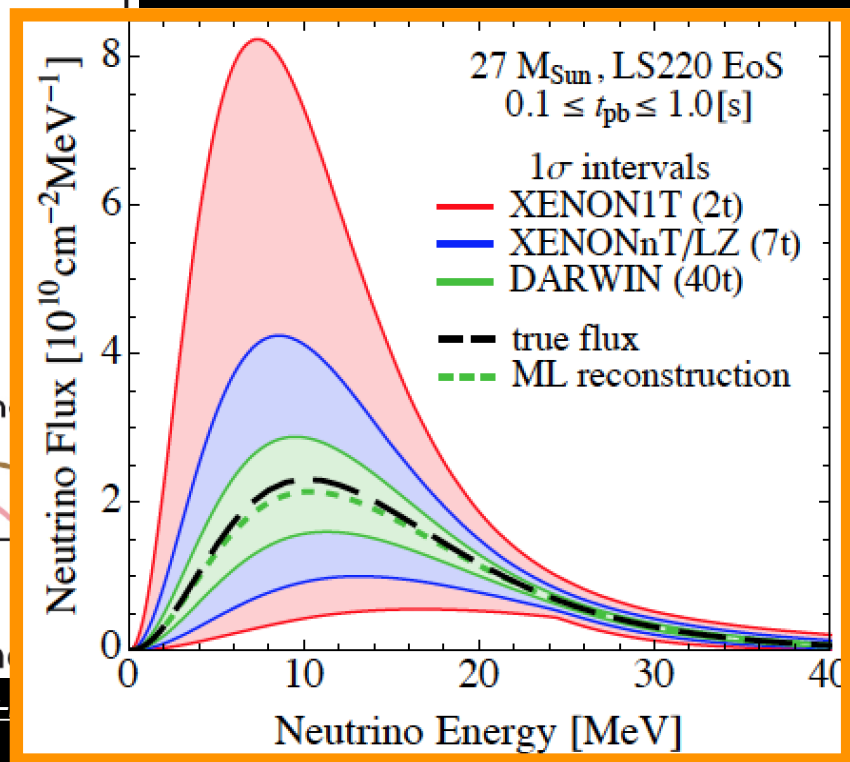
Lang et al., Phys. Rev. D 94 (2016)
Arnaud et al., Phys.Rev.D.65.033010



for a supernova at 10 kPc, expect 300-500 ν-N events in near-future experiments.

(if lucky!)



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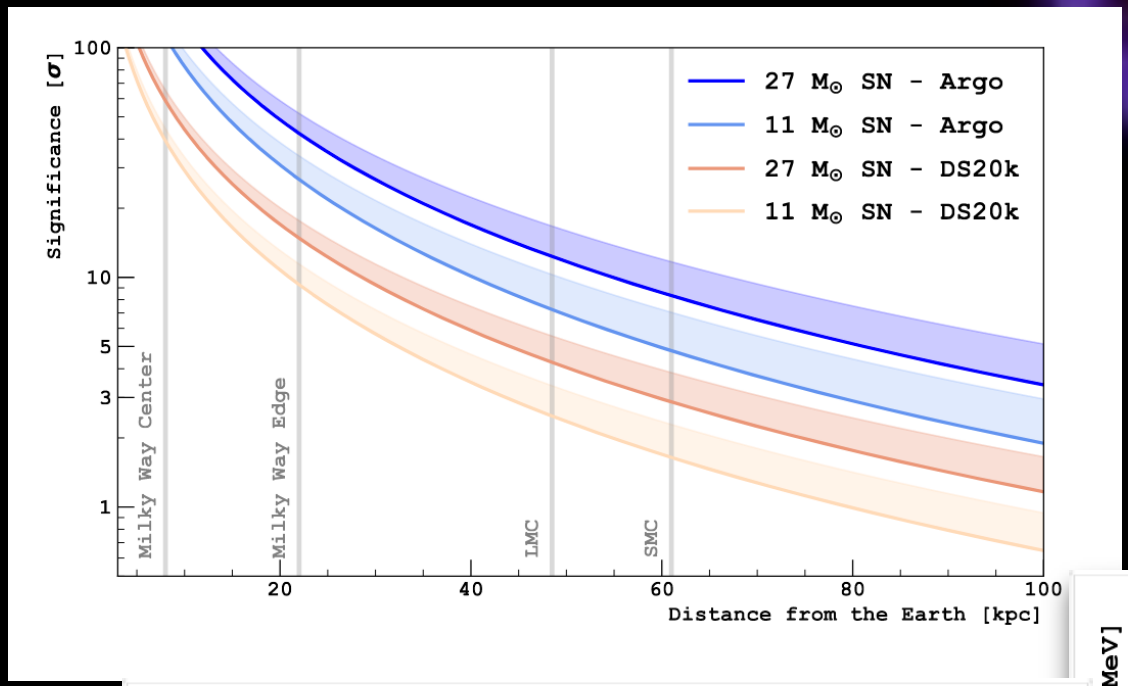
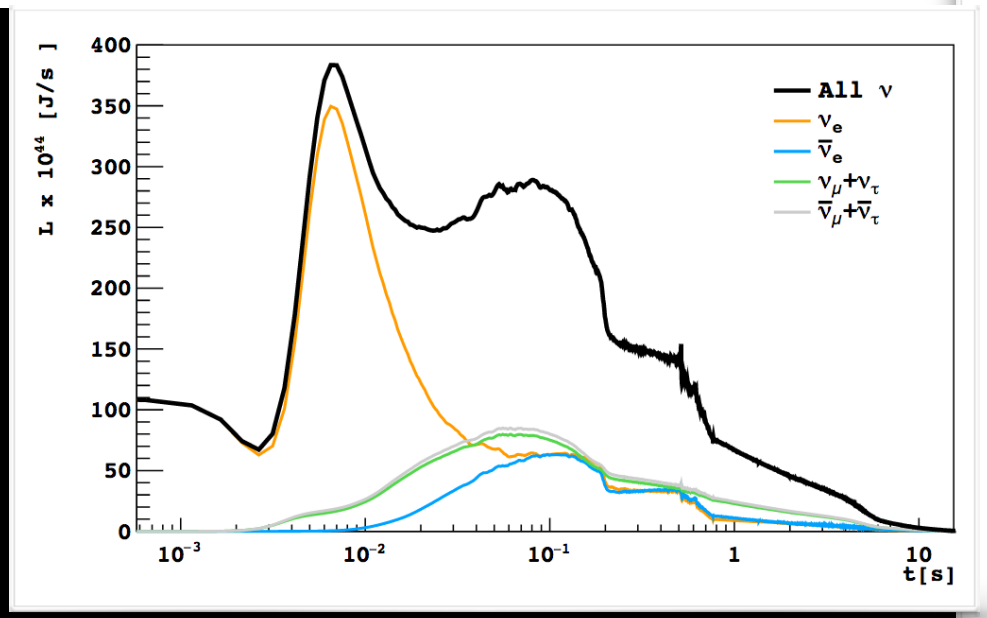
Supernova ν in DarkSide-20k

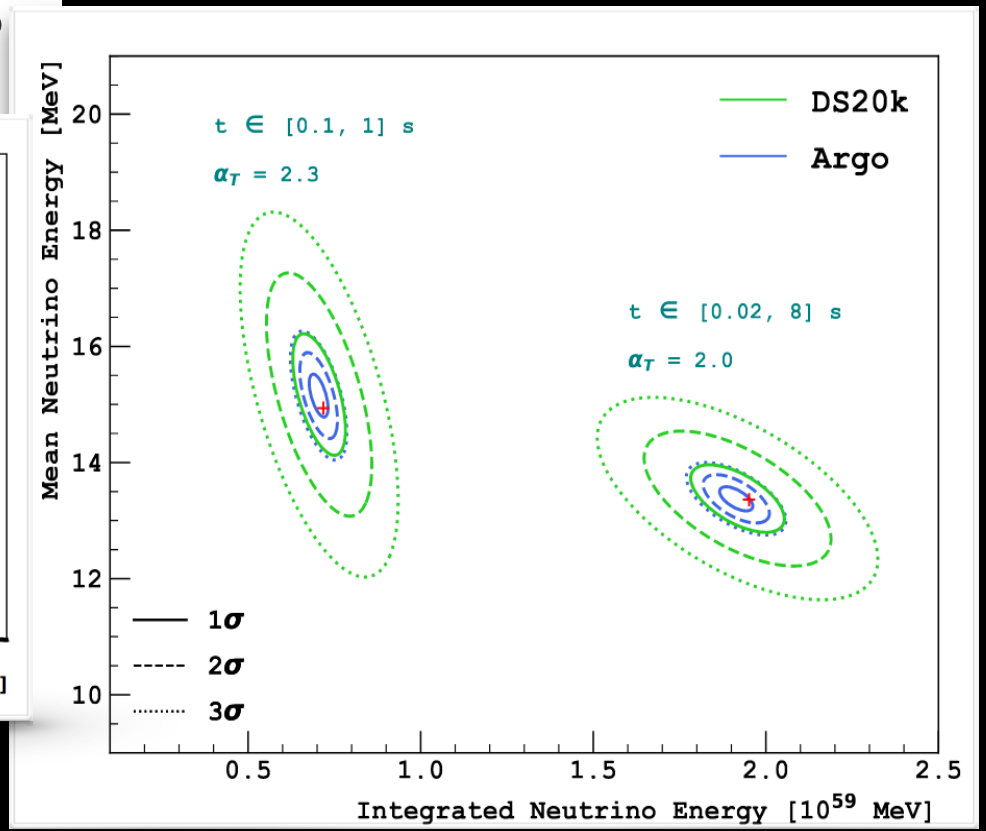
Agnes, JM et al., arXiv:2011.07819



e.g. 27 M_{sun} supernova at 10 kPc, ~300 ν-N events in DarkSide-20k

- measure all flavors via NC
  sensitive to total SN energy in ν





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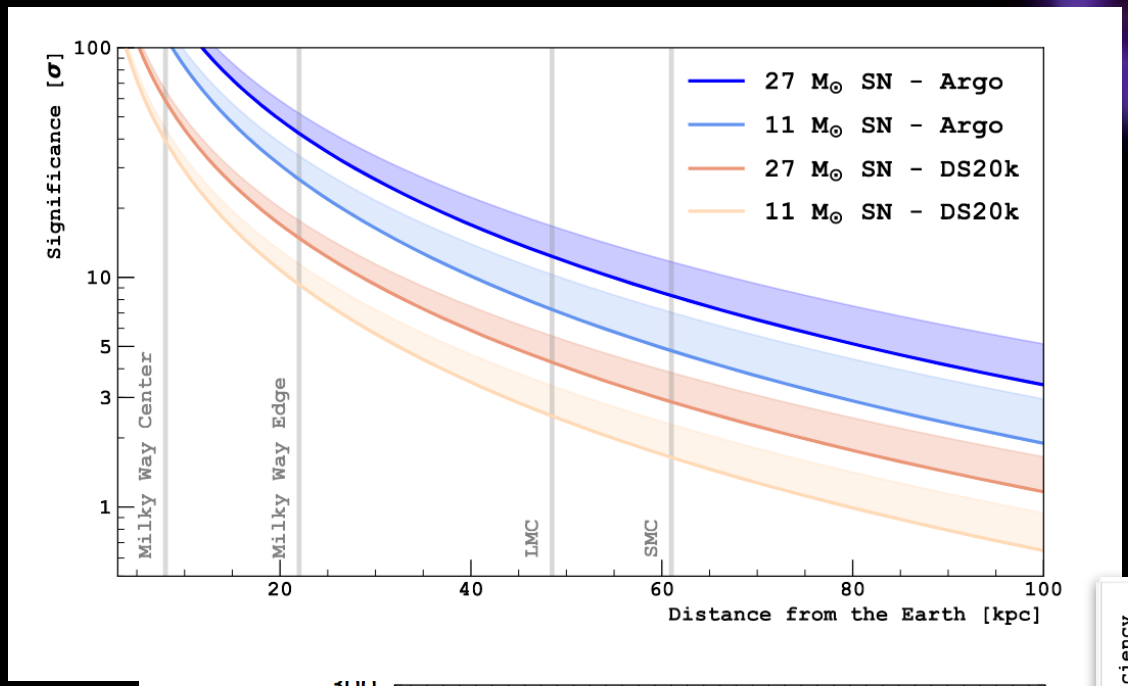
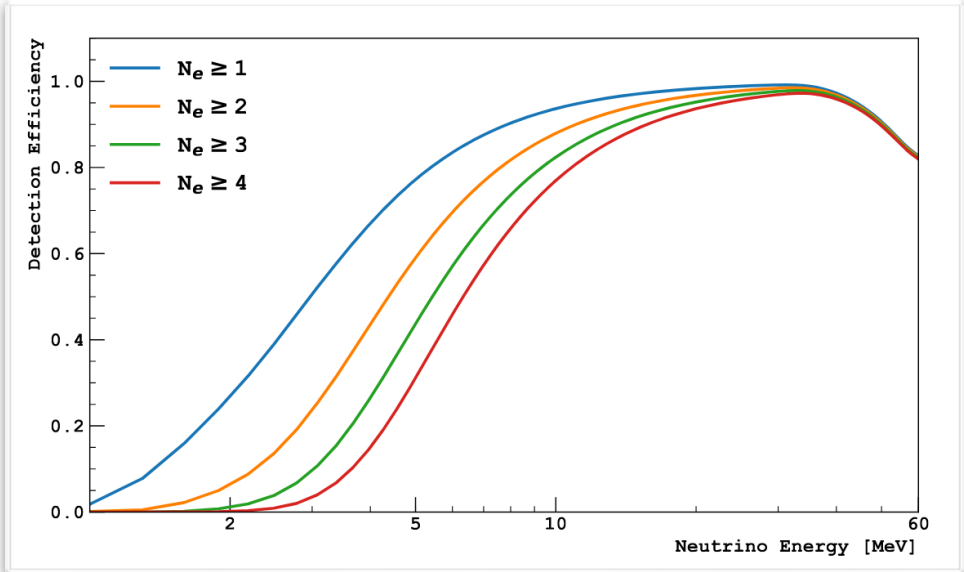
Agnes, JM et al., arXiv:2011.07819



e.g. 27 M_{sun} supernova at 10 kPc, ~300 ν-N events in DarkSide-20k

- measure all flavors via NC
  sensitive to total SN energy in ν
- measure ν_e via ν_e $^{40}Ar \rightarrow e^- \, ^{40}K^*$
  sensitive to ν mass hierarchy



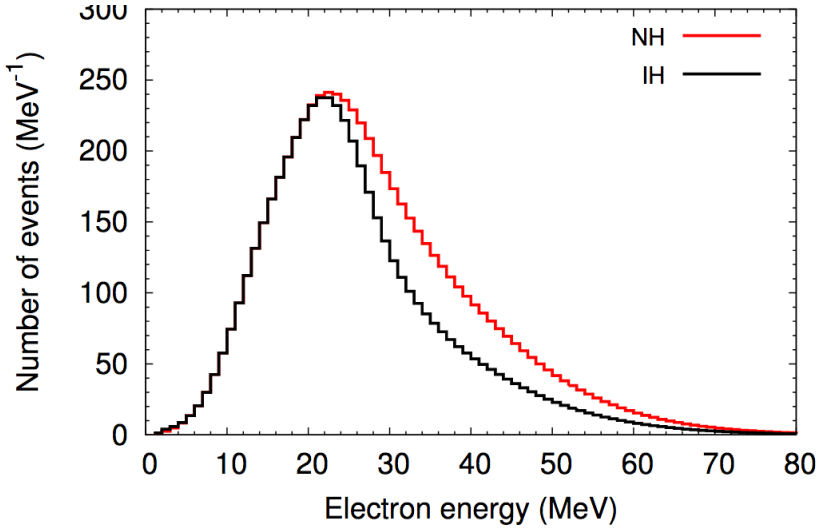


Fig. 33. – Observable SN ν_e spectra in a 40-kton LAr TPC for benchmark fluxes as in Fig. 28 in both the mass hierarchies. (Figure adapted from [356]; courtesy of B. Dasgupta.)

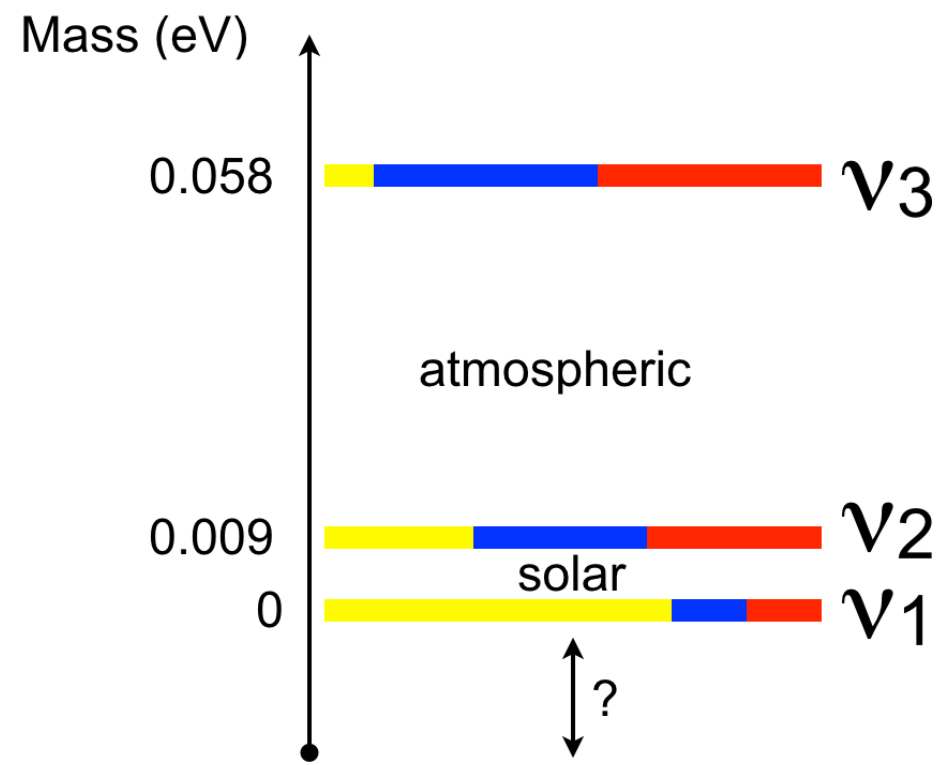
supernova distance measurement with ν?

Mirizzi et al., arXiv:1508.00785

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

What can future dark matter detectors tell us about the neutrino?

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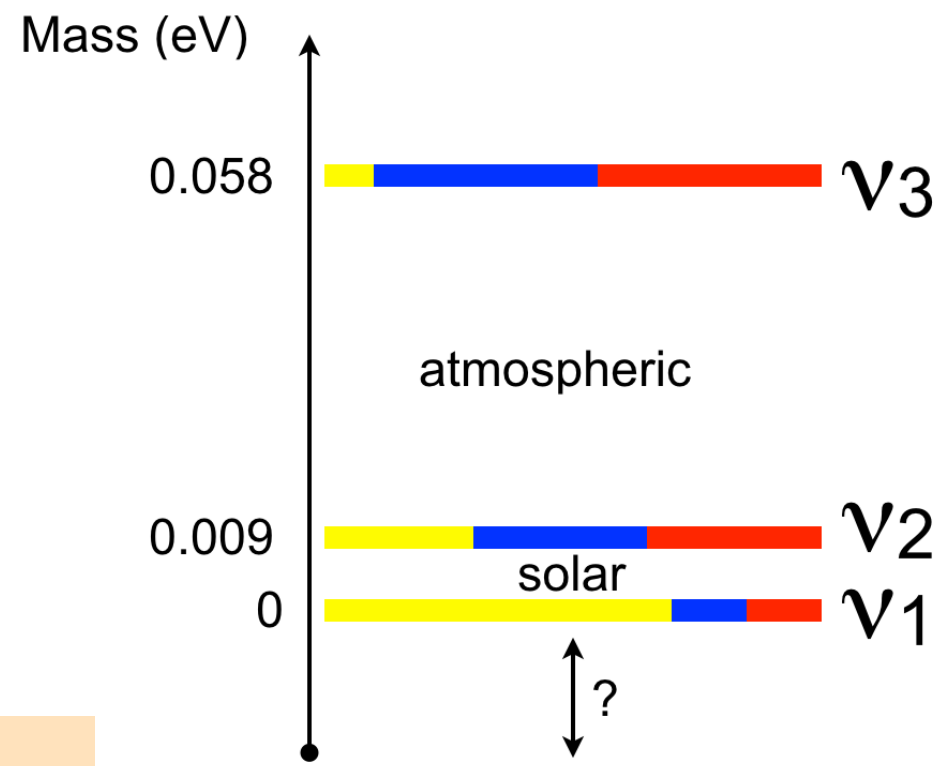

flavour key:

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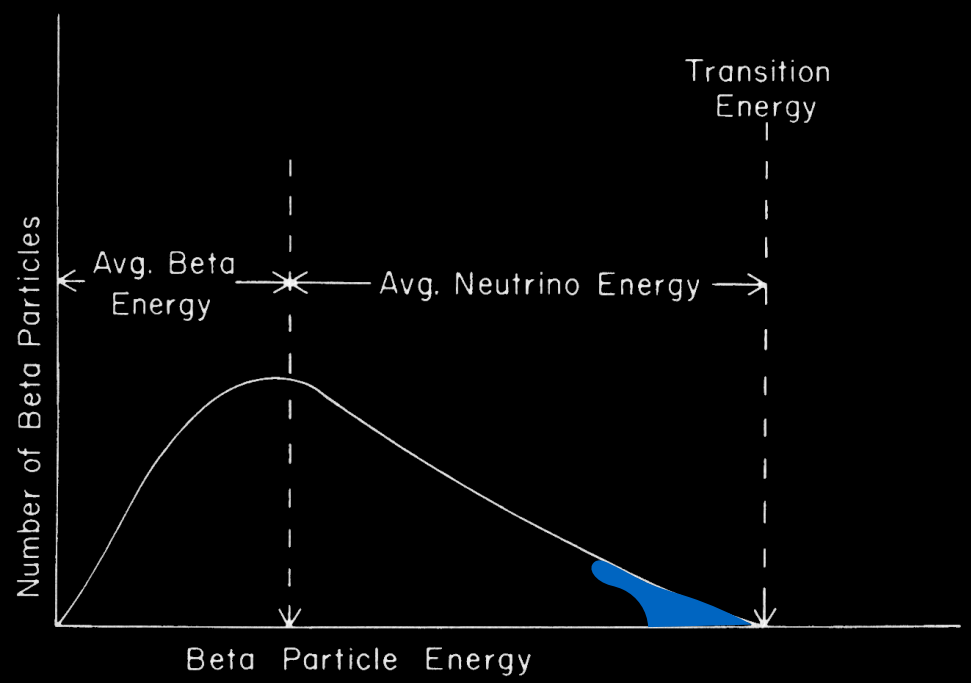
Sterile ν Signatures

Astrophysical searches: limits on $|U_{e4}|^2$ at 10 keV are ~1E-11 from x-ray constraints
+ excess x-ray flux at 3.5 keV, ~1E-10 mixing

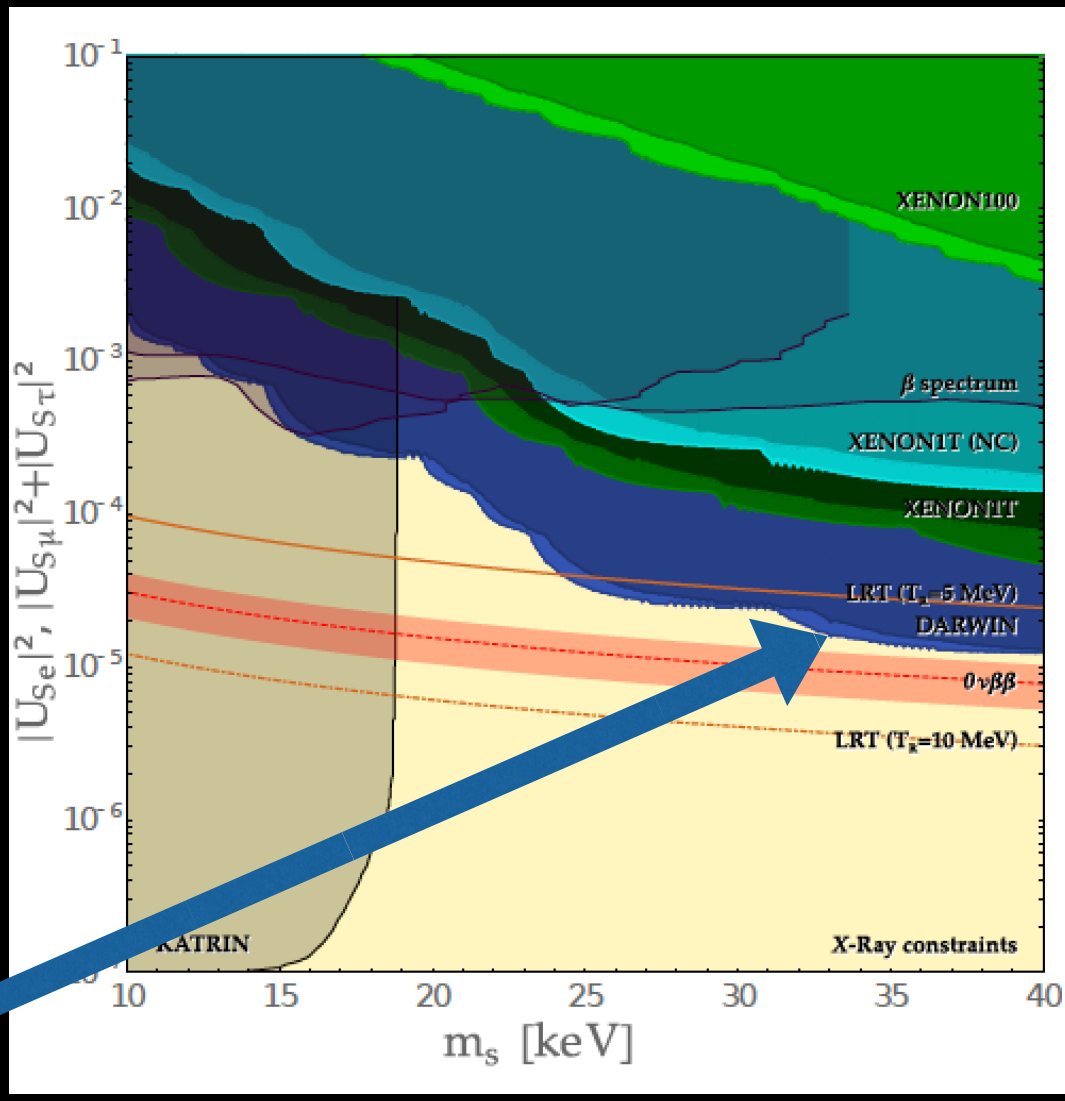
1) The beta decay energy spectrum of background, e.g. Ar-39, is modified by sterile neutrino mixing.



2) Sterile neutrino-electron scattering:

$N_S\ e^- \rightarrow \nu_e\ e^-$

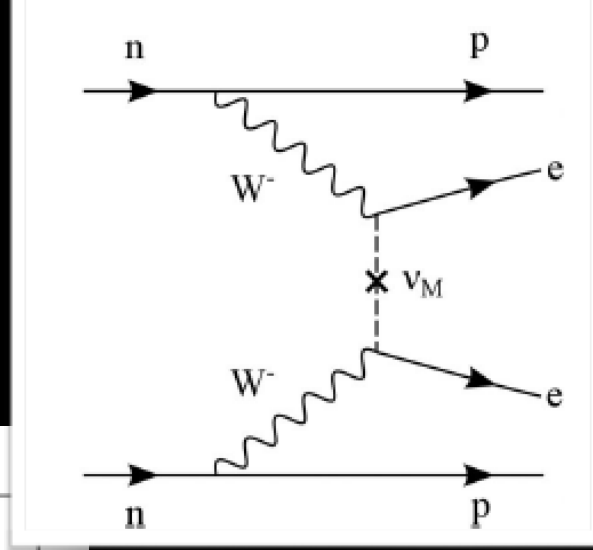
Campos & Rodejohann, Phys.Rev.D 94 (2016)



Direct detection experiment sensitivity estimates range between beta decay and astrophysical constraints.

ν-less Double Beta Decay

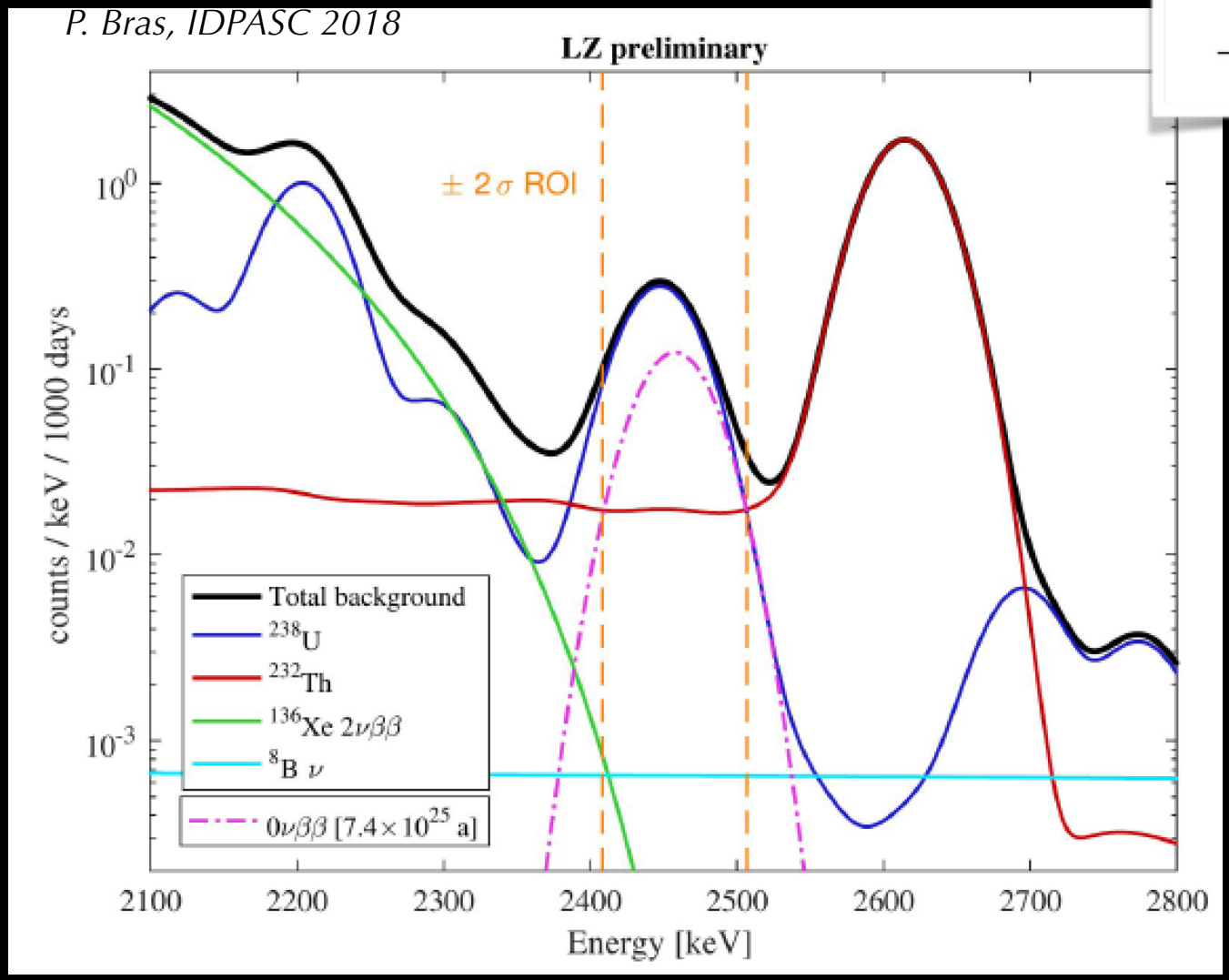
Xe dark matter searches aim for competitive sensitivity, via restricted fiducial volume (inner 1 t) to reduce backgrounds, and projected 1% energy resolution at the 2ν beta decay endpoint



example: projected sensitivity in LZ:

Q-value= 2458 keV

P. Bras, IDPASC 2018

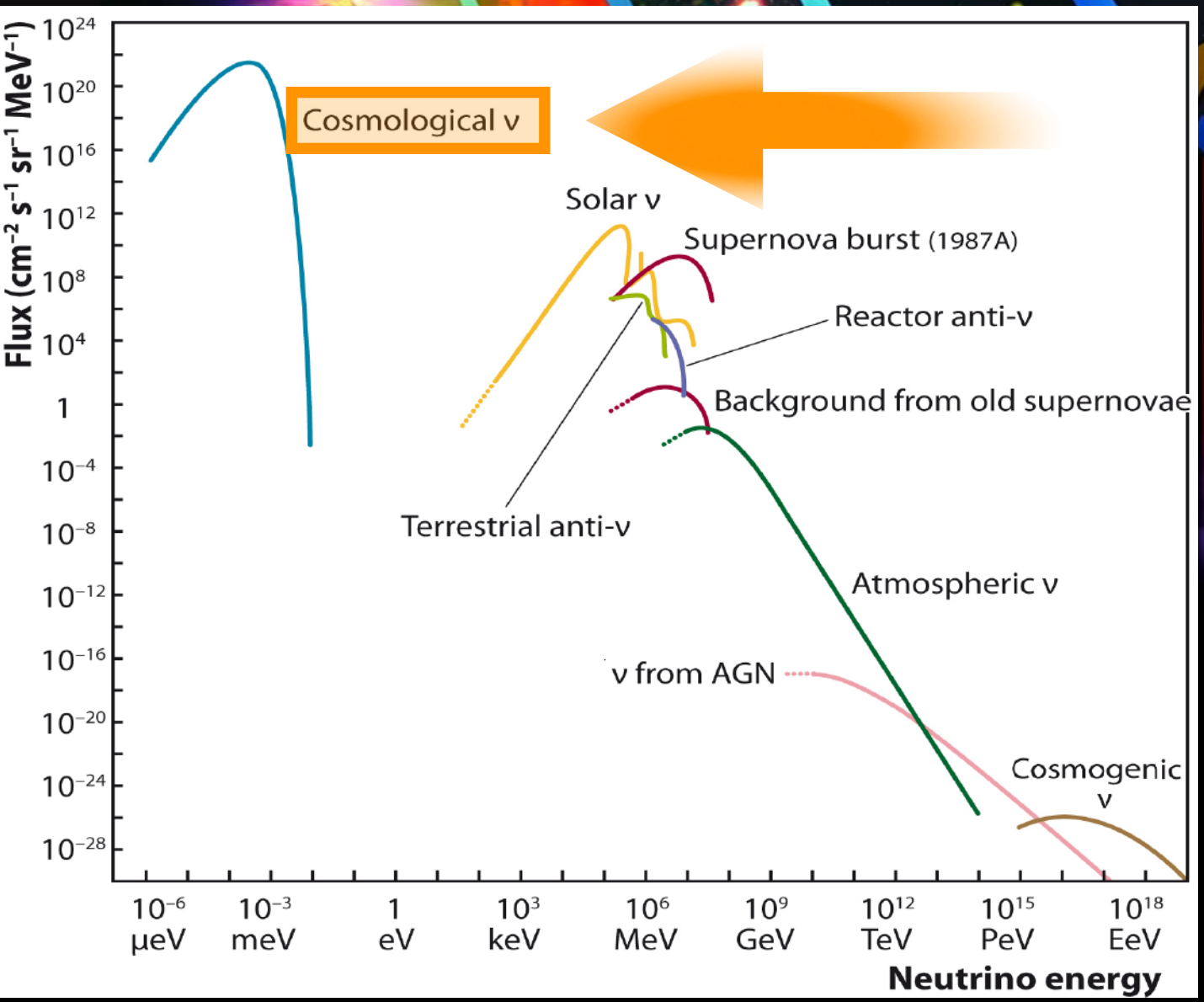


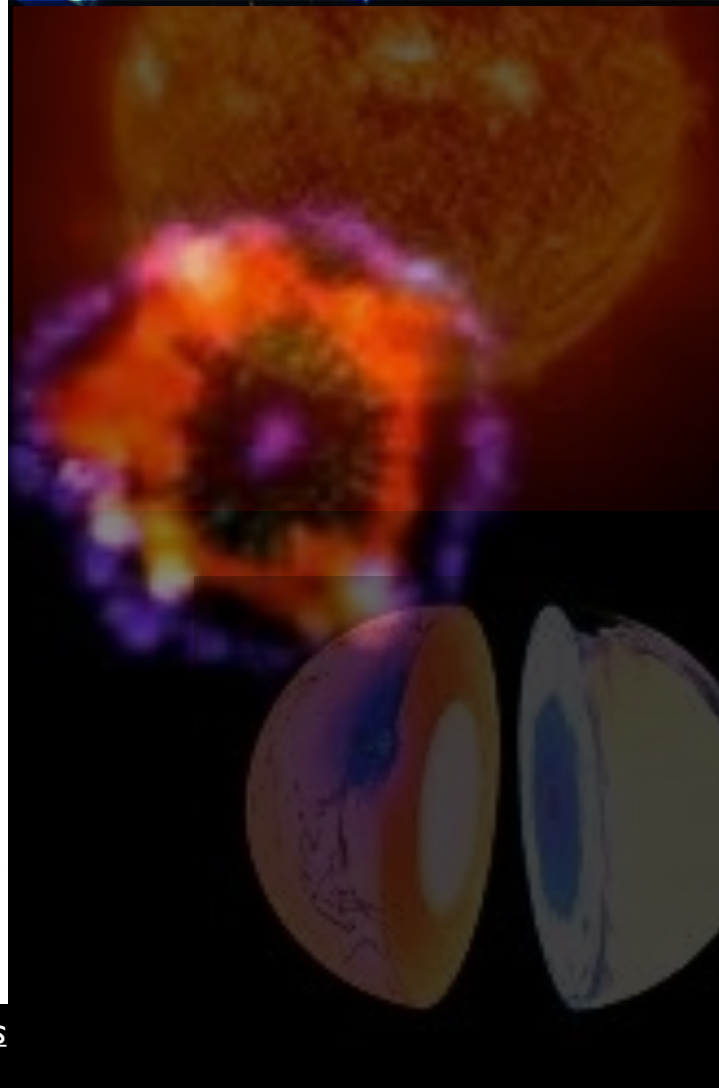
big opportunity:
significant Xe-136 target mass (~600 kg)

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

https://www.sciencefocus.com/space/what-was-before-the-big-bang-everything-you-need-to-know/

Can we get here?





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

Quantum Enhanced Superfluid Technologies for Dark Matter and Cosmology

Goal: reach sub-eV recoil energy threshold in spin-dependent dark matter search for scattering in Superfluid He-3 macroscopic quantum state

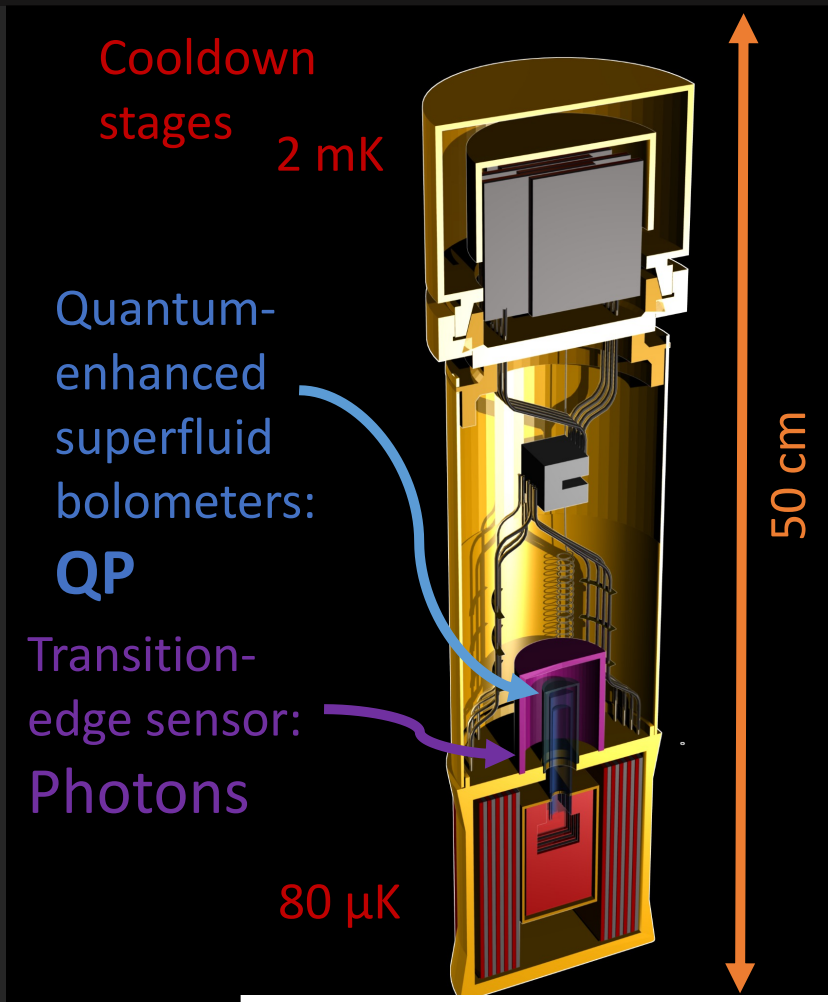
pairing energy ~1E-7 eV

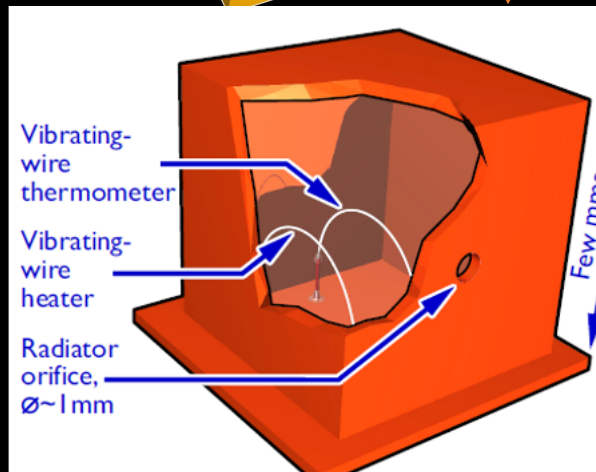
Ionisation partition measurement

- Detect scintillation in TES at mK stage

Heat partition measurement

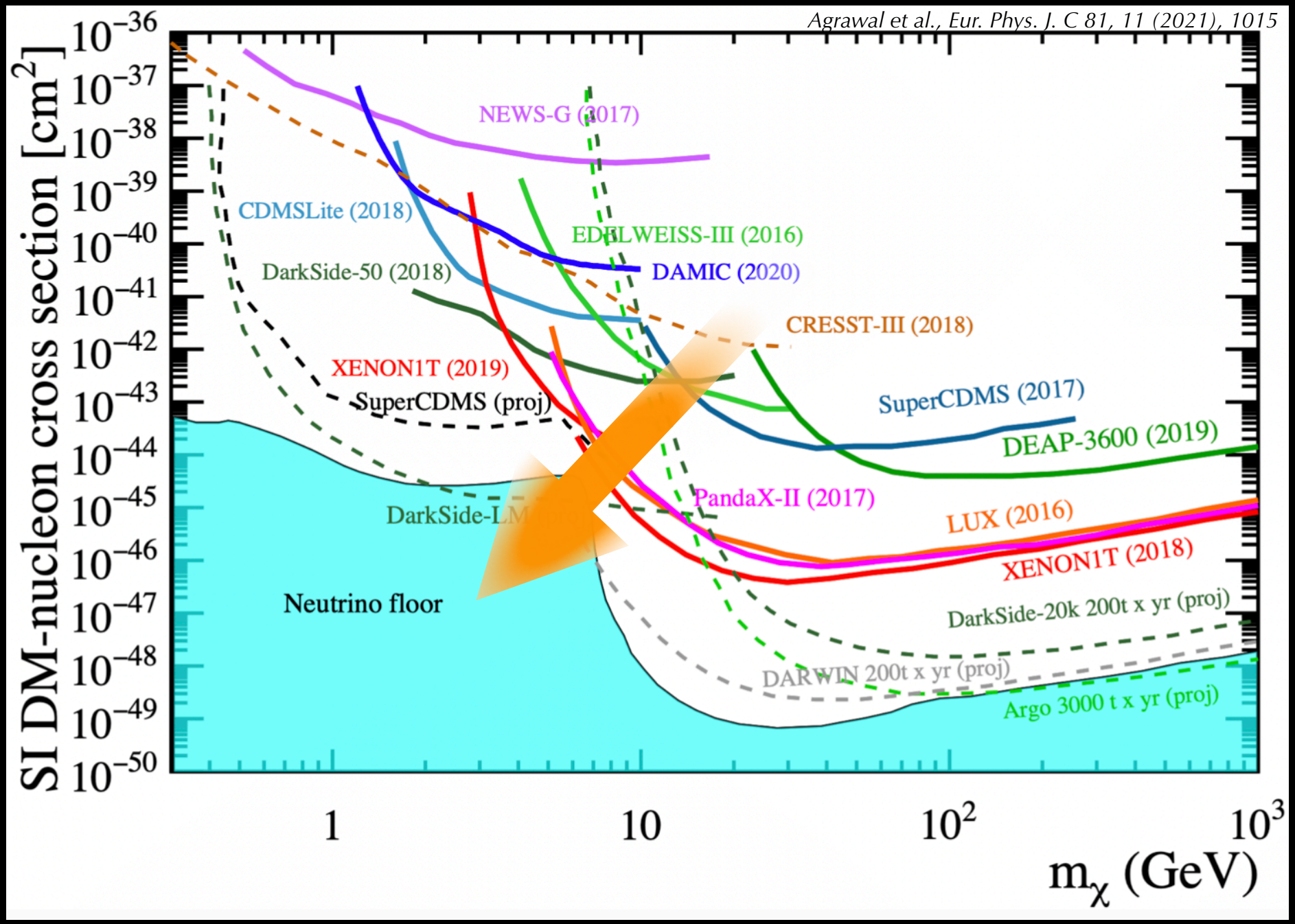
- Quasiparticles "shake" a nano-electromechanical resonator (NEMS), coupled to SQUID, readout reaching quantum-limited displacement measurement



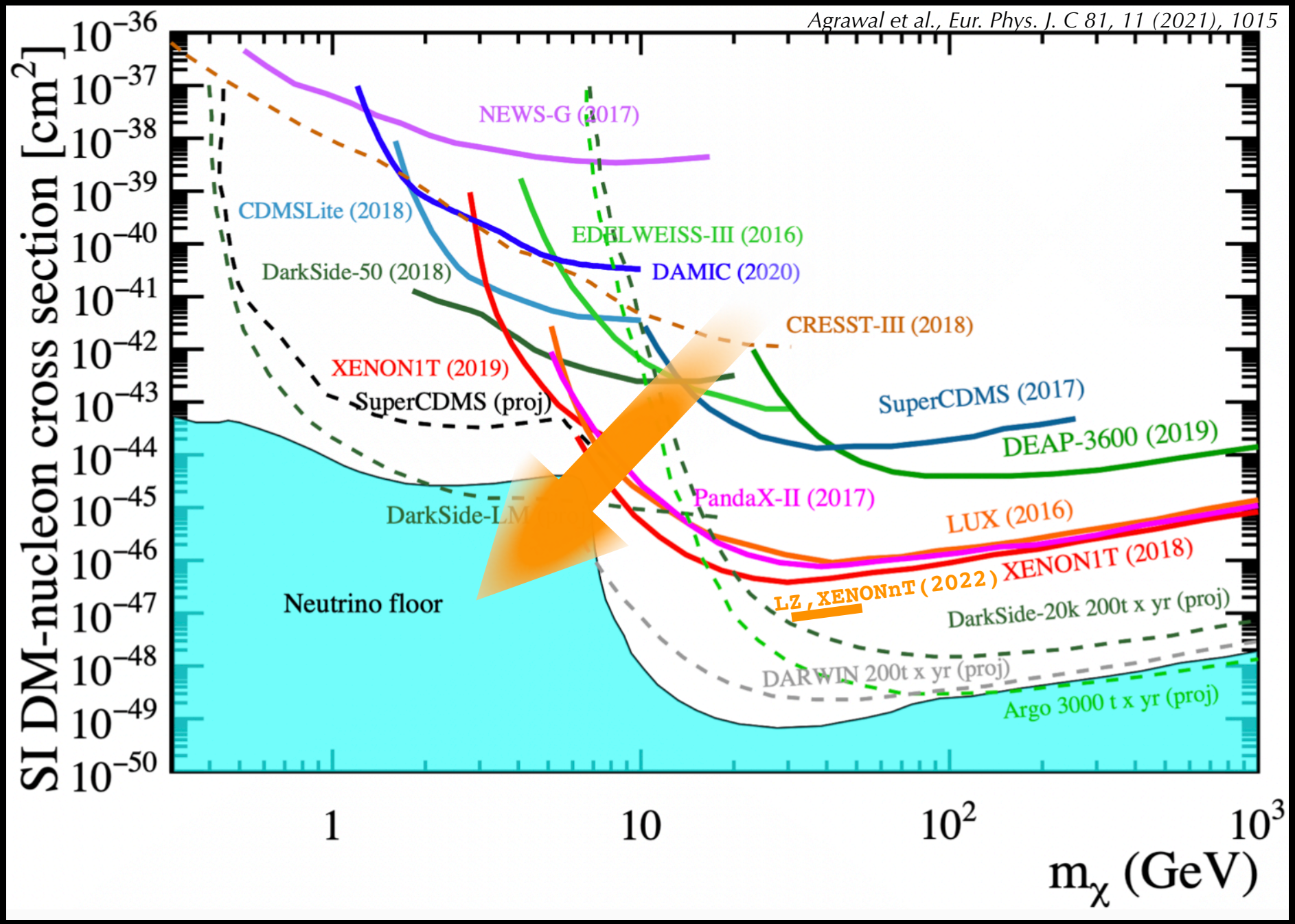


UK Quantum Technologies for Fundamental Physics project, builds on European Microkelvin Platform 80 uK infrastructure

What happens when we get here?

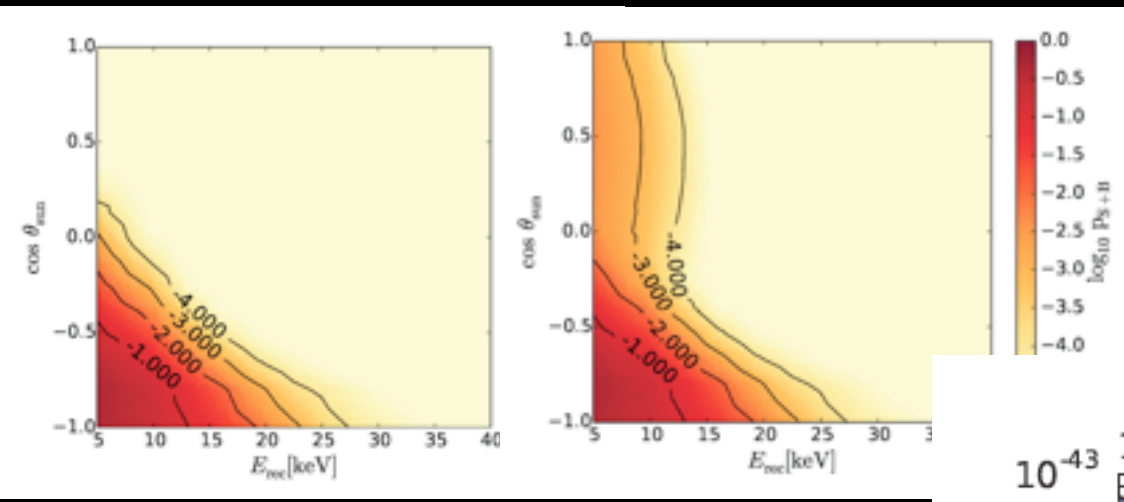


What happens when we get here?



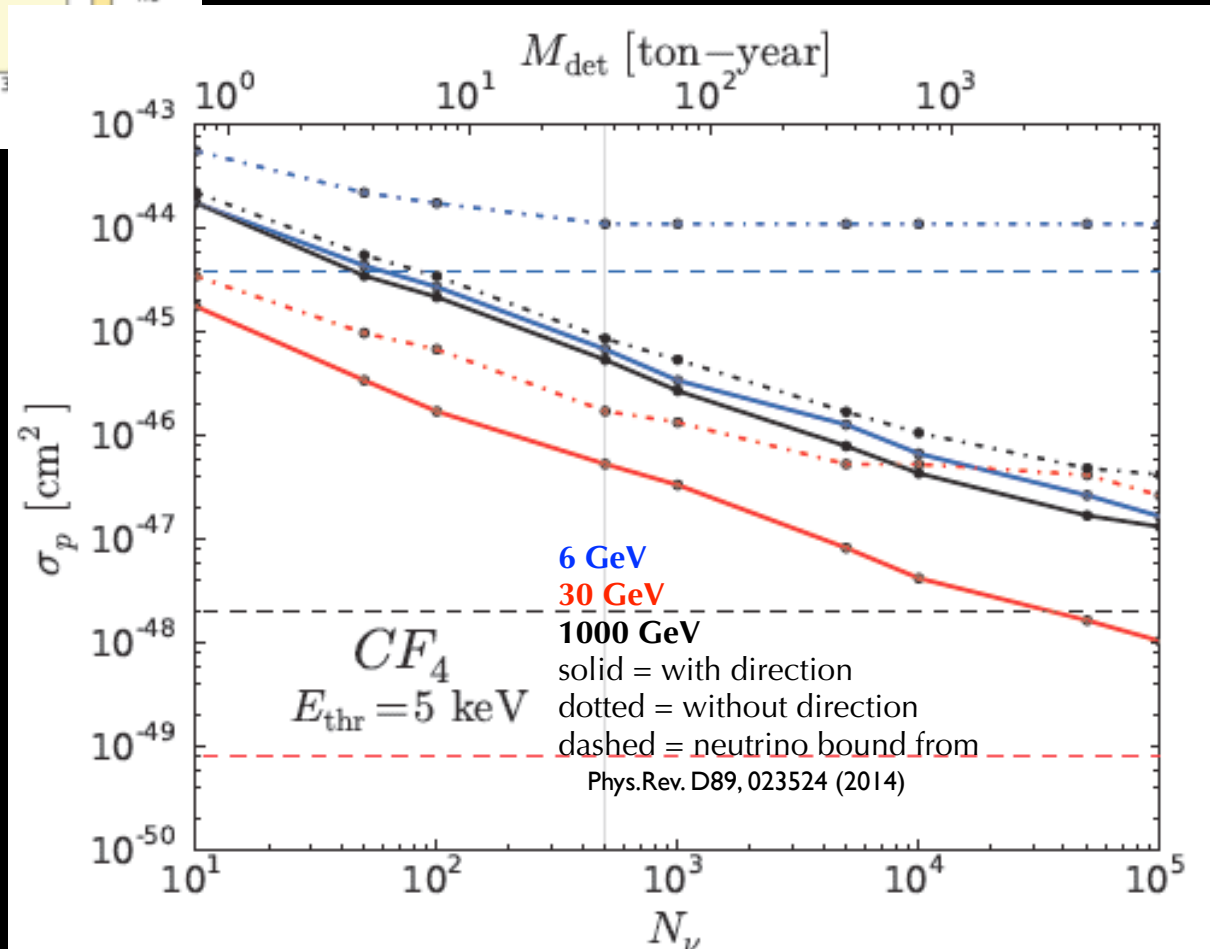
Is the Neutrino Bound the End? No.

sensitivity scales with sqrt(time) instead of linearly in time (with zero background)
… neutrino flux and cross section systematics become crucial



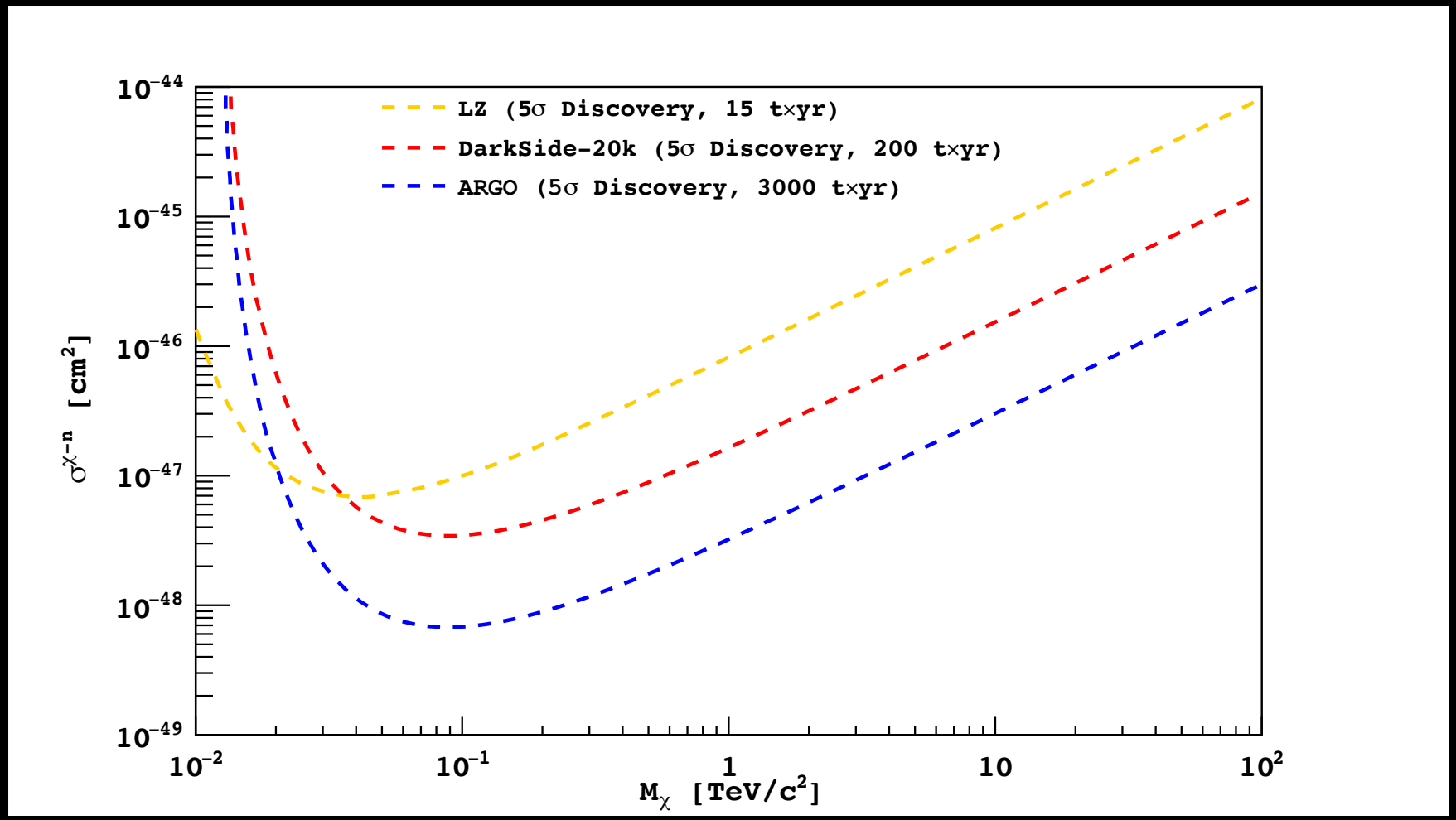
PDFs in (energy, angle, time) of event for coherent solar neutrino background vs. background + dark matter signal are different! (includes angular resolution)

- modulation signatures still contains information (annual, sidereal)
- directionality gains 10x in sensitivity in the presence of backgrounds
- no neutrino bound for directional detectors *Grothaus, Fairbairn, JM, Phys.ReV.D90 (2014) 055018*



What happens when we get here?

We enter a nu background paradigm…



where the 'neutrino floor' depends on ER discrimination power

Summary & Outlook

We only know what 4% of the universe is made of!

Finding the rest has driven broad development of new technologies for particle detection.

As we learn how to see dark matter…

What is missing from our standard model of particle physics?

What else might we find at the low-background frontier??