Experimental Techniques in Dark Matter and Neutrino Physics
Rare Event Searches

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Invisibles School 2023
Bad Honnef, DE

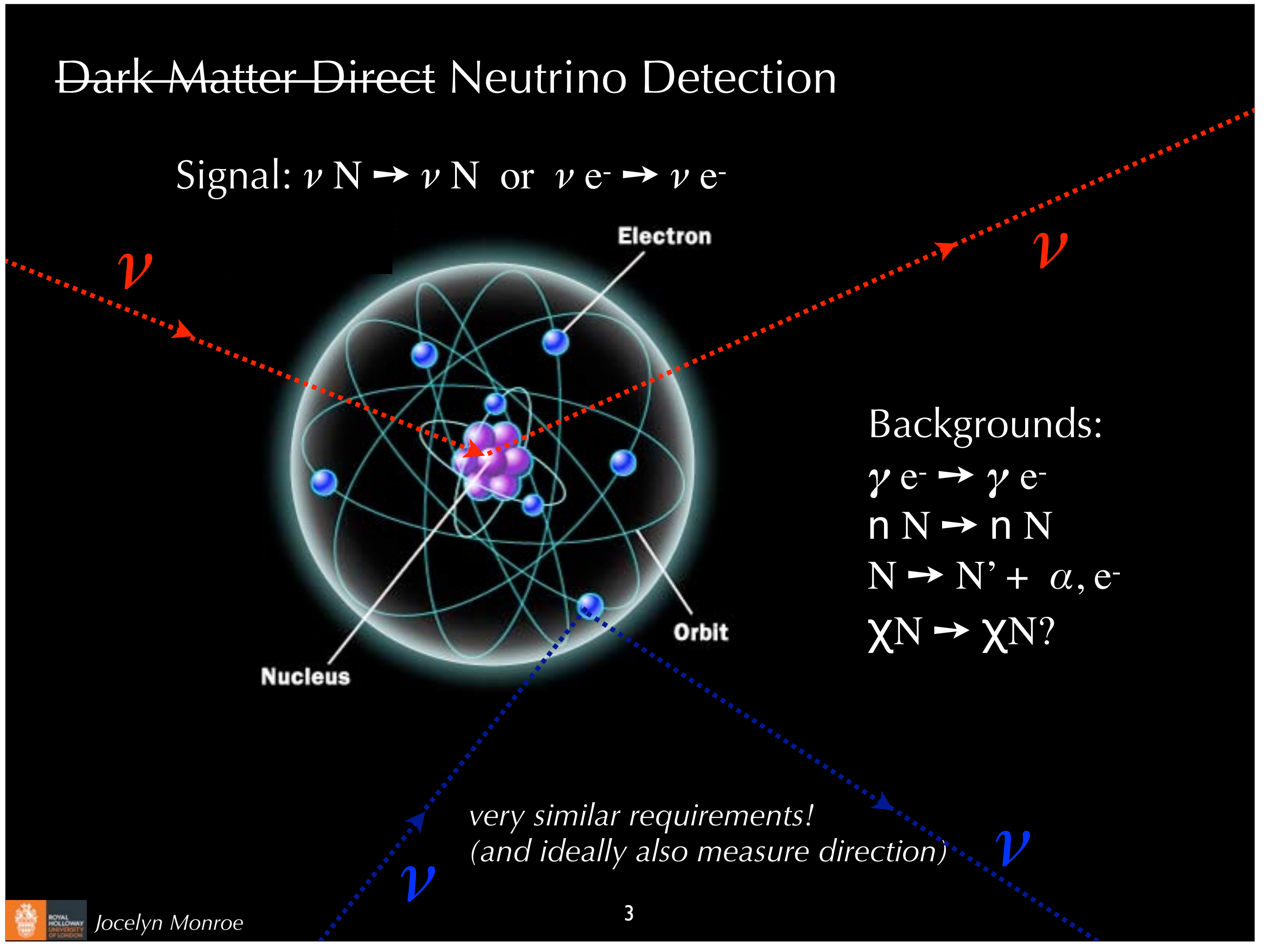
Outline

1. The Evidence for Dark Matter

2. Dark Matter Detection Experimental Techniques

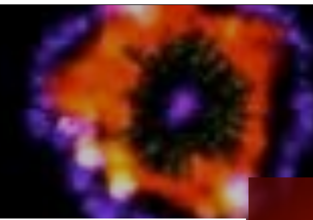
3. Dark Matter Search Status and Prospects

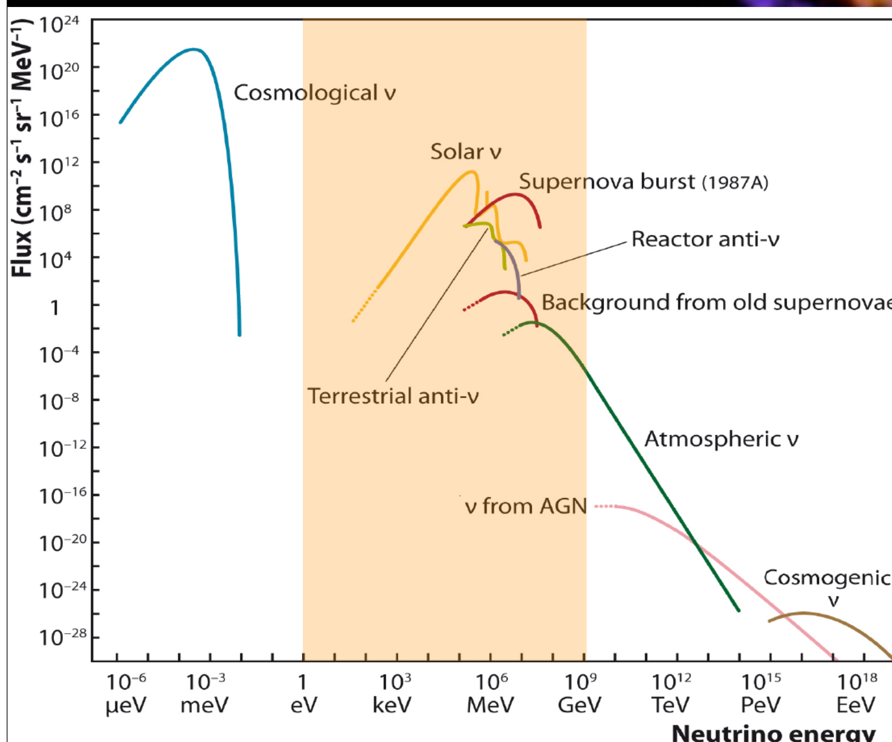
4. Neutrino Physics in Dark Matter Detectors

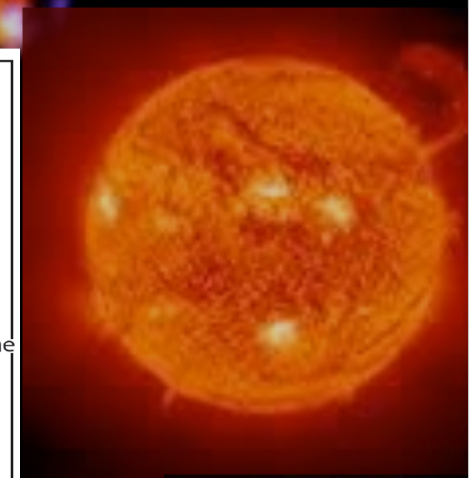


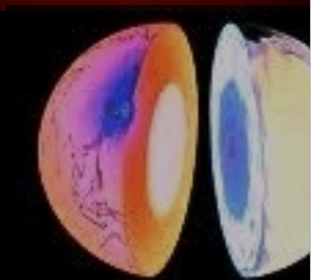
in that sense the neutrino experiments pioneered the low background frontier

What ν sources can dark matter detectors see?





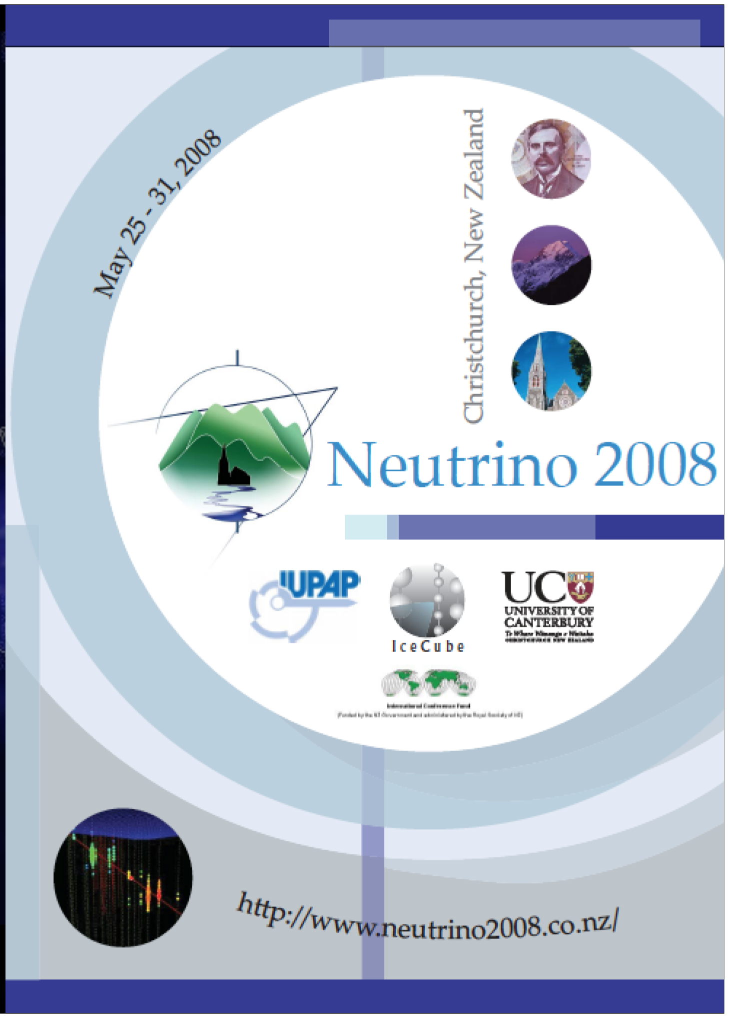




https://masterclass.icecube.wisc.edu/en/learn/detecting-neutrinos

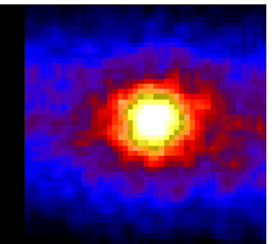
Neutrino Backgrounds to Dark Matter Searches and Directionality

Jocelyn Monroe, MIT



Neutrino Signals
at Dark Matter Searches

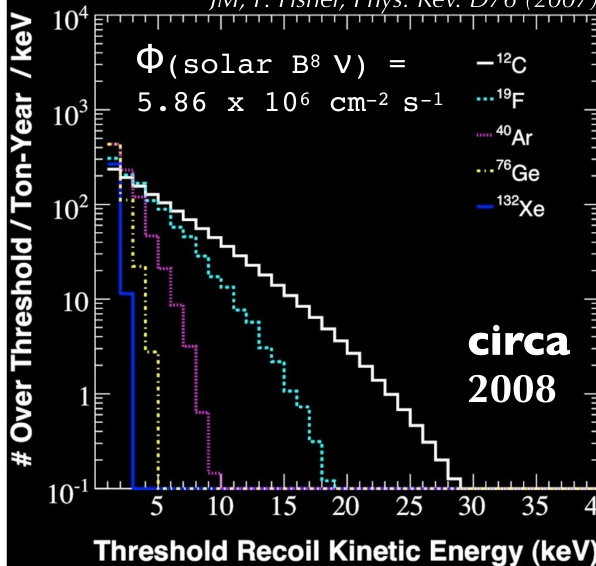
Jocelyn Monroe, RHUL

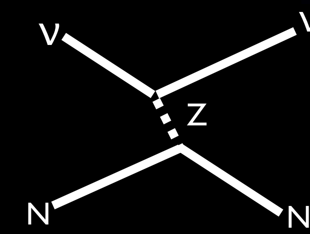


ν Cross Sections

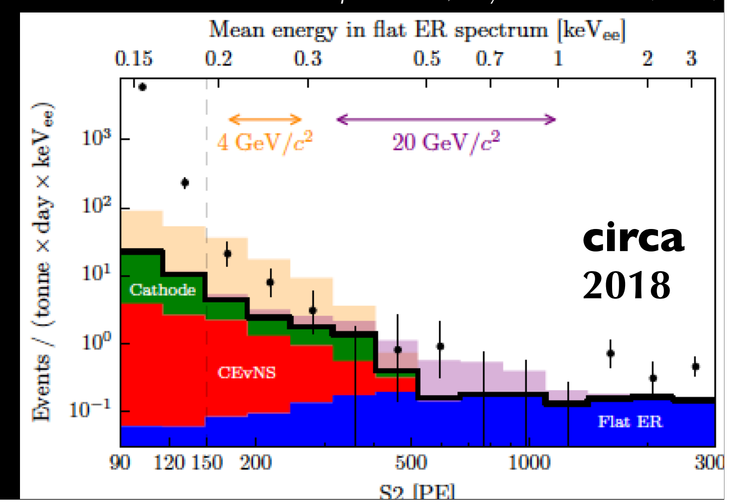
ν-N coherent scattering: ~ $A^2 \times (E_\nu/\mathrm{MeV})^2 \times 10^{-44}$ cm^2
recoils are O(10 keV) … *neutrino floor in DM searches*

JM, P. Fisher, Phys. Rev. D76 (2007)





Aprile et al., PhysRevLett 123 (2019)



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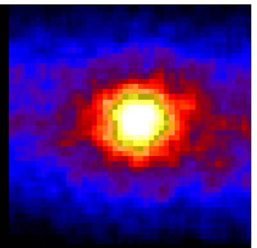
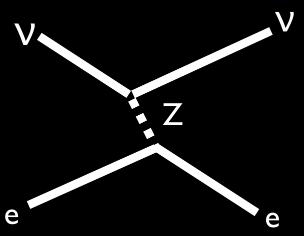
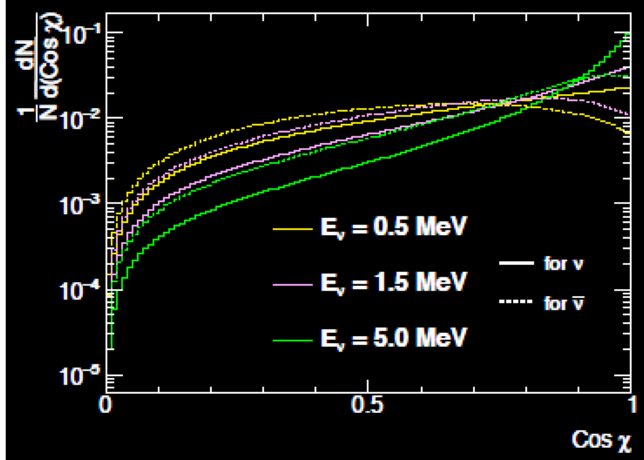
N ton detectors are next, and at some point experiments can't gain by lowering threshold since they run into new backgrounds (Xe is here already)

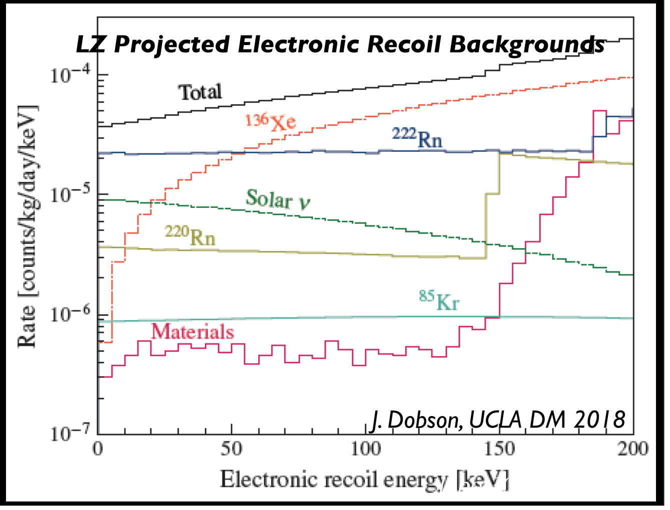
ν Cross Sections



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



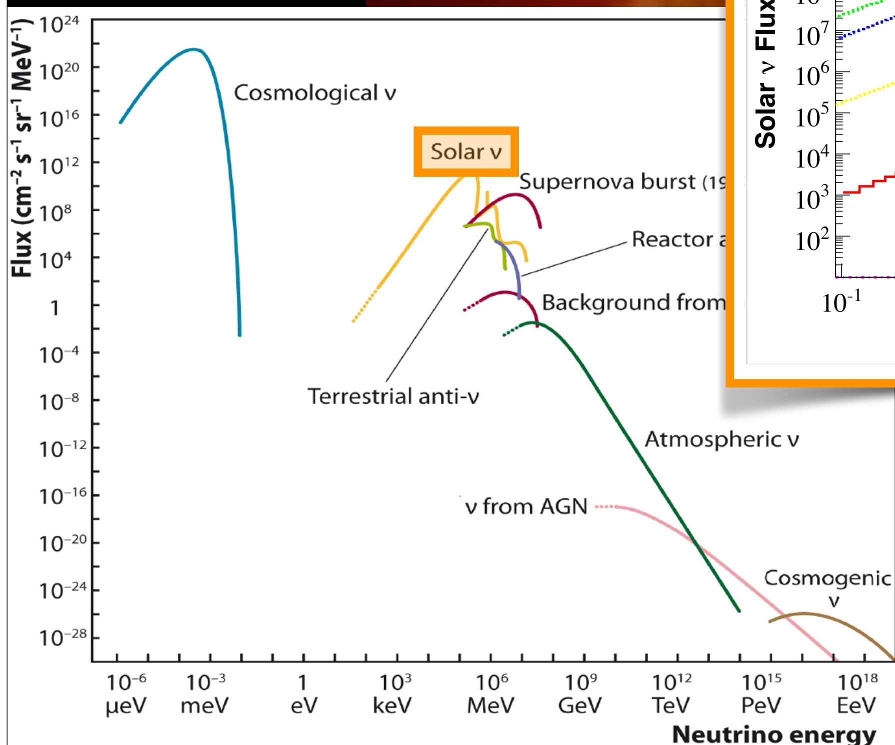


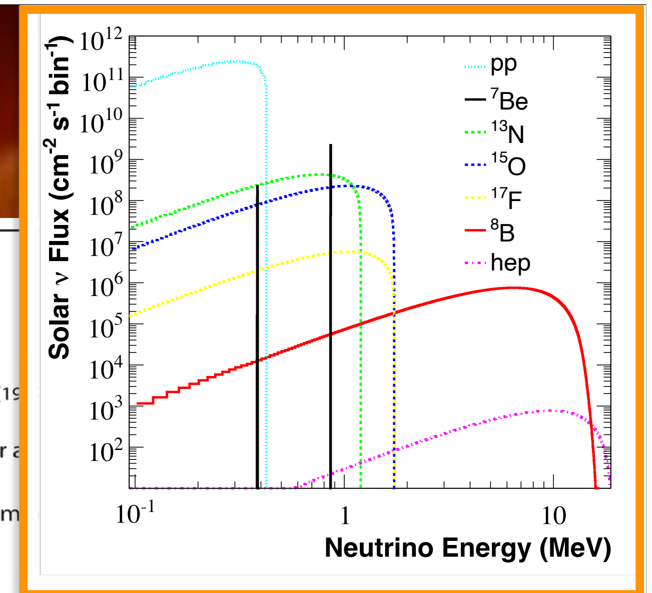


ν-e backgrounds: ν floor depends on e- discrimination

chi = angle between neutrino and recoil directions

What ν sources can dark matter detectors see?





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

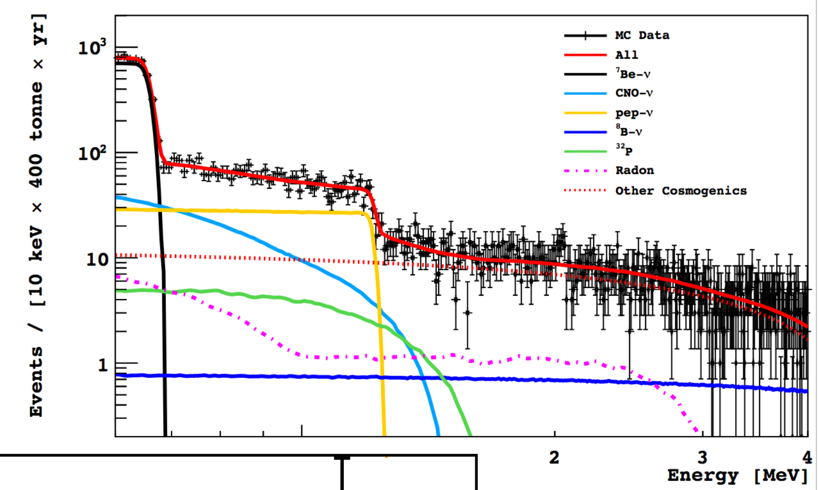
https://masterclass.icecube.wisc.edu/en/learn/detecting-neutrinos

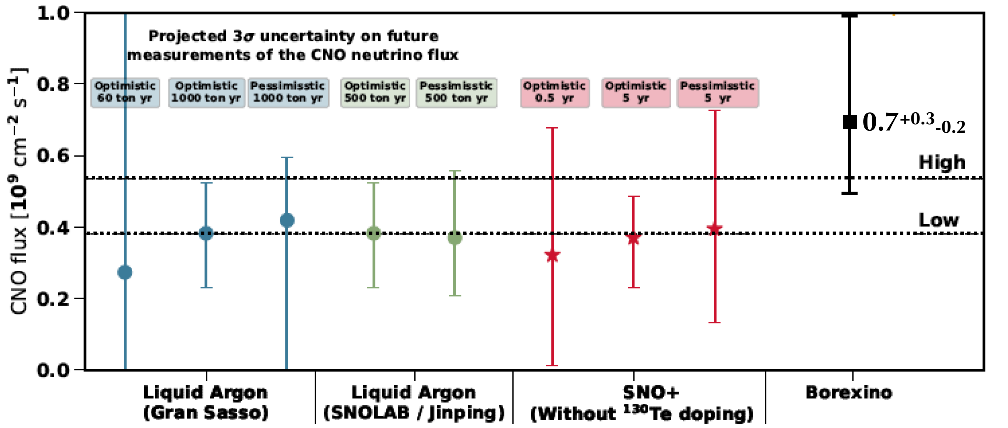
Solar ν-e Scattering

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



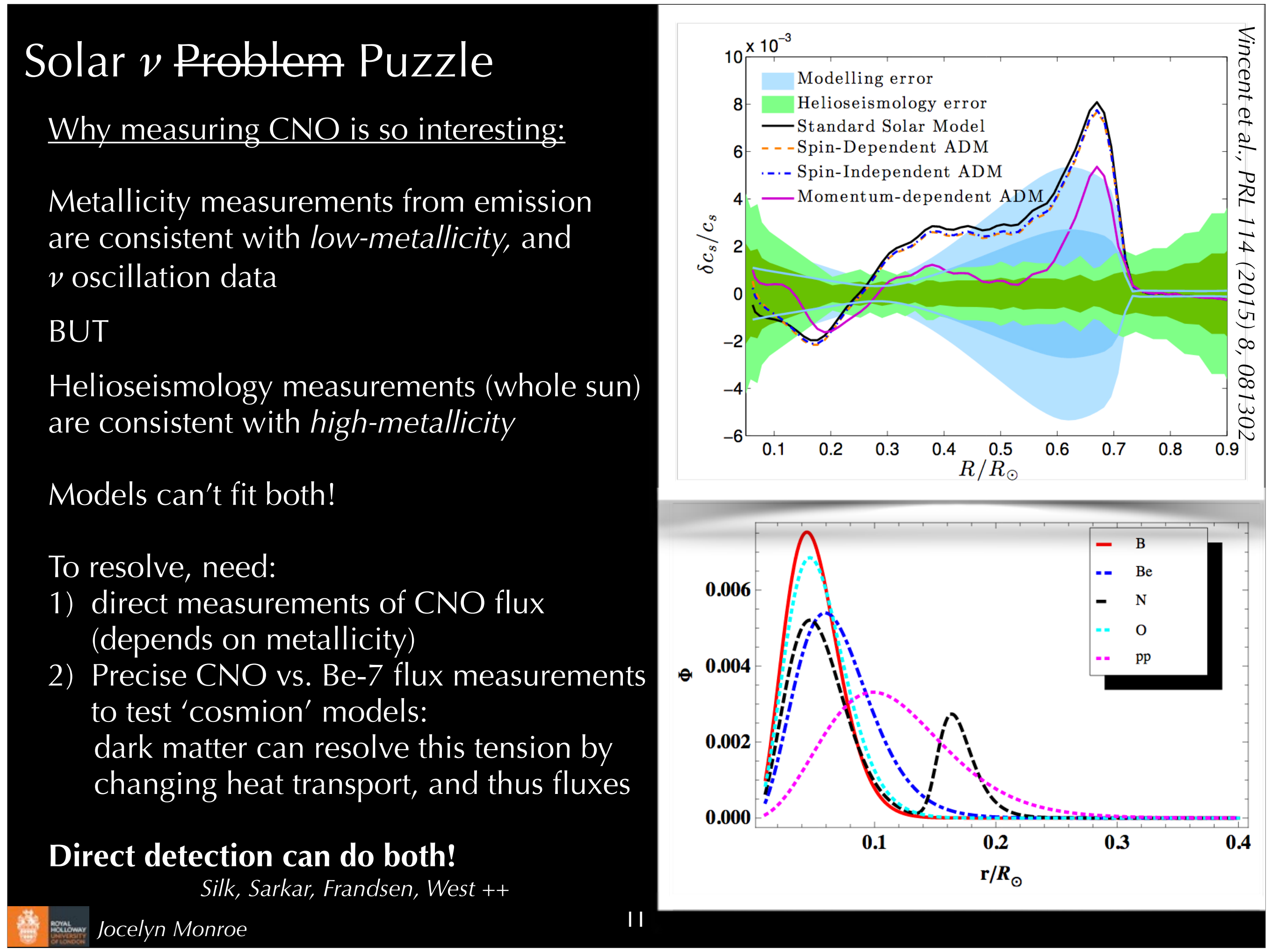


<u>big opportunity:</u> distinguish between high vs. low metallicity.

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

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

complementarity between SNO+ and DarkSide



top fig: deviation of the radial sound speed profile (sun - model)/sun in the solar interior from the values inferred from helioseismological data, for the SSM and 3 models of asmmetric dark matter. colored reigions indicate 1 and 2 siga errors in modelling (blue) and on helioseismological inversions (green band). The combination of (m_x, sigma) are chosen for each model to the best improvement w.r.t. the SSM

https://arxiv.org/pdf/2009.00663.pdf

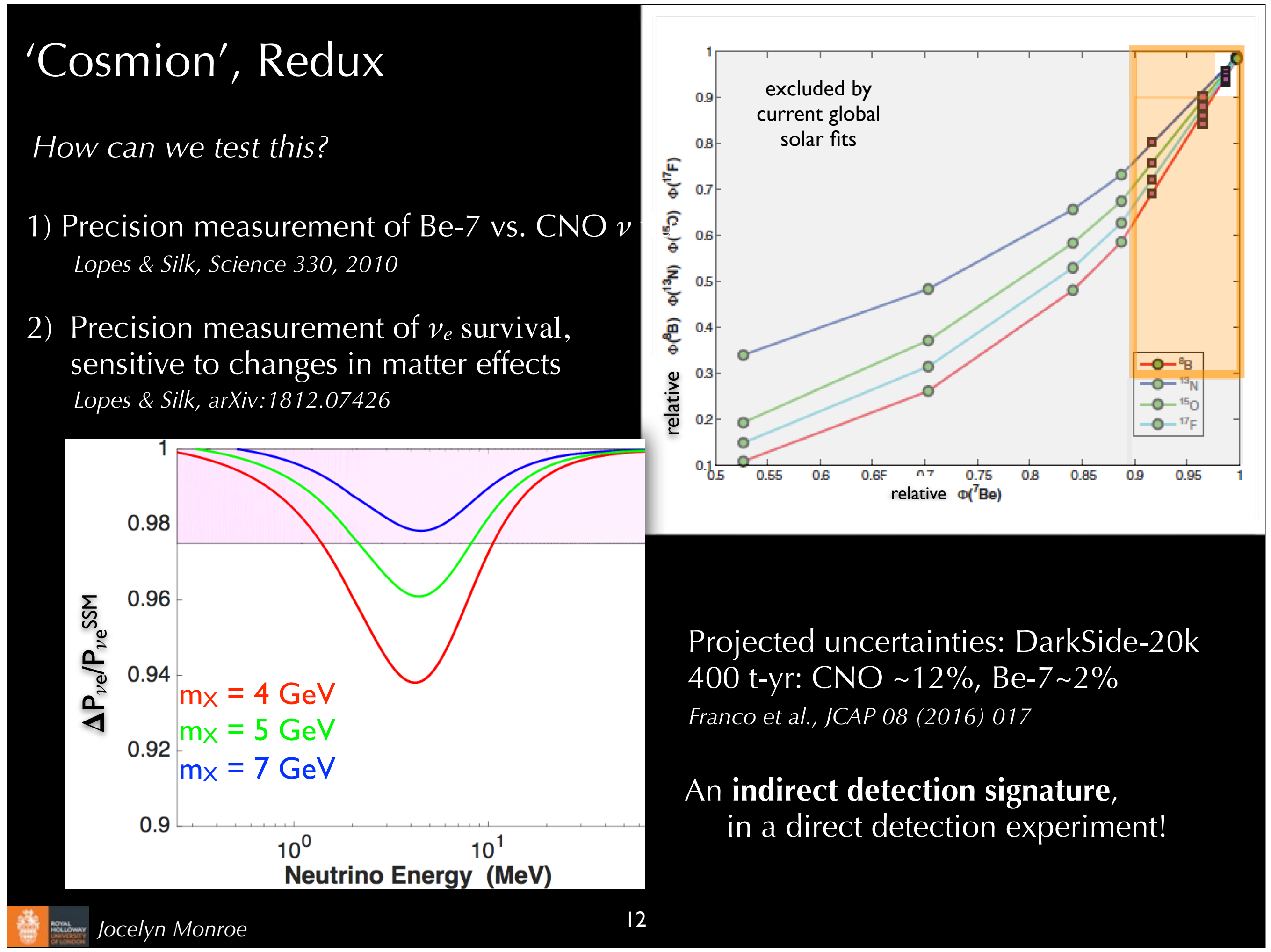
If present in the lab, elastic scattering between DM and nuclei must also occur in natural systems.The largest nearby target for such an effect is the Sun: at 2×1030kg and exposuret= 4.57Gyr, itconstitutes a truly titanic (if noisy) detector. Indeed, if DM scattering off solar nuclei brings it belowthe local escape velocity, the DM will become gravitationally bound and settle into an equilibriumconfiguration near the core. Depending on the nature of the DM itself, it may then suffer one of threepossible fates: 1) if it is too light, it will "evaporate" from momentum exchanges large enough to bringit above the local escape velocity12) if it is self-conjugate, or if sufficient quantities of "anti-DM" arepresent in the star, it will annihilate, or 3) if it is sufficiently heavy and asymmetric [5], it can act as aheat conductor [6], thanks to its long mean free path inside the solar plasma

The latter two fates have observable consequences. DM annihilation into SM products and theirsubsequent decays into neutrinos can produce observable signals at underground (or under-ice) neu-trino telescopes. Indeed, the strongest bounds on DM-nucleon scattering for certain DM candidatescome from this channel. Heat transport can have more subtle consequences: by flattening the temper-ature gradient in the inner Sun, neutrino fluxes can be reduced, and the pressure and density profileof the Sun can be modified, changing helioseismology observables such as the convective zone ra-diusrCZ, the surface helium composition, and the inferred sound speed profile [7]. In other mainsequence stars, convective cores can be erased, and with large enough concentrations, evolutionarytrajectories on the Hertzsprung-Russel (HR) diagram can be severely modified.

Silk et al
https://arxiv.org/pdf/1812.07426.pdf
if light DM is presentin the solar core, the amount of electron-neutrinosconverted toother flavors will be different from the value found in the stan-dard solar model [SSM, e.g.,25,26], and consequently theirtotal neutrino fluxes and neutrino spectra will also be differentfrom the SSM.

The presence of darkmatter in the Sun's core could help solve the long-running so-lar composition problem [35], a discrepancy between the solarstructure inferred from helioseismology and the one computedfrom a SSM by inputting the most up-to-date photosphericabundances

Frandsen & Sarkar
https://arxiv.org/abs/1003.4505



error on B-8: 0.007 but below Ar-39 endpoint so statistical separation

B-8 plot caption:

the ratio of several B-8 survival probablities of electron neutrinos of DM solar models in relation to the standard solar model. The colour curves correspond to an halo of DM particles with m_x = 4 GeV and sigma_SI = 1E-37 cm2 (red), m=5 GeV and sigma_SI = 1E-35cm2 (green), and m=7 GeV and sigma_SI = 1E-35 cm2 (blue).

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Frandsen & Sarkar

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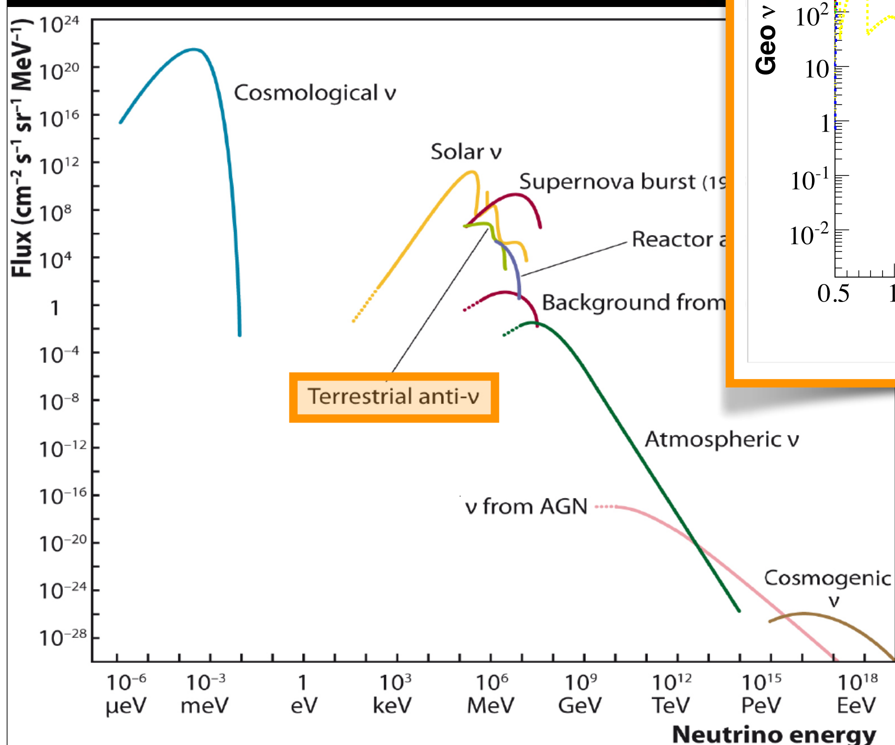
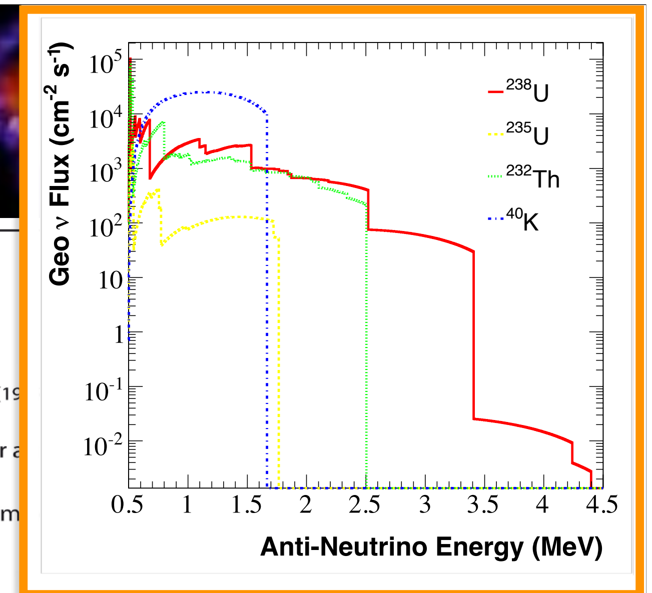
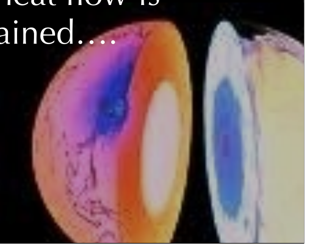
What ν sources can dark matter detectors see?





K-40 flux never measured

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



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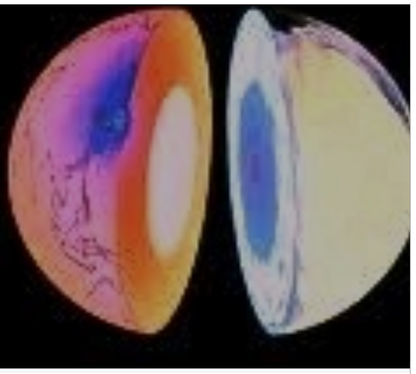
https://masterclass.icecube.wisc.edu/en/learn/detecting-neutrinos

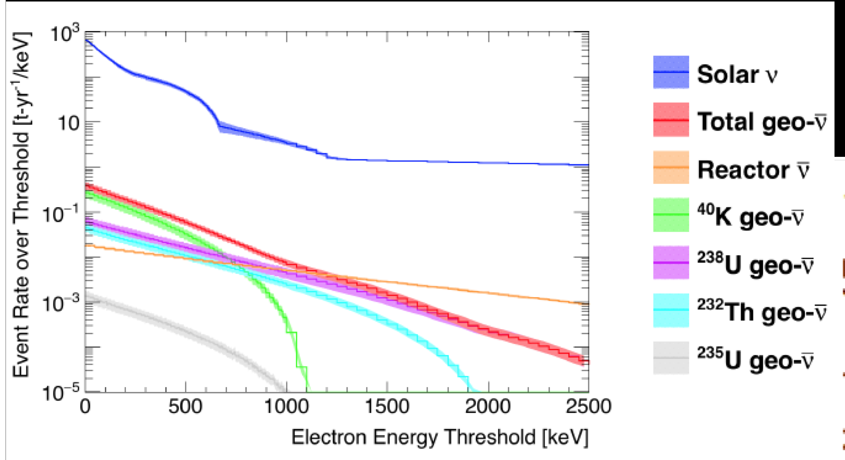
in a 10^n T-year exposure…

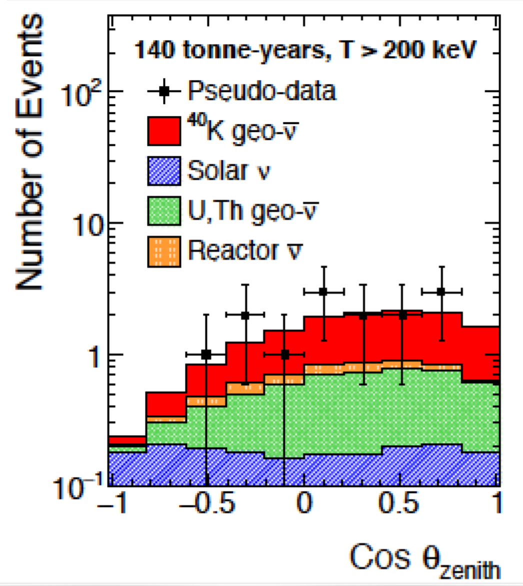
low E dominated by the un-measured K-40 geoneutrino flux

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

to the *earth*!







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

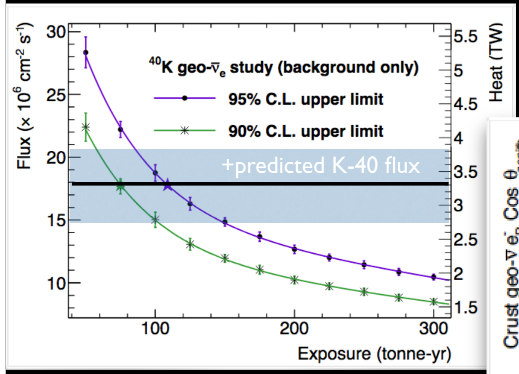
Leyton, Dye, JM, Nature Commun. 8 (2017) 15989

ν-N scattering:

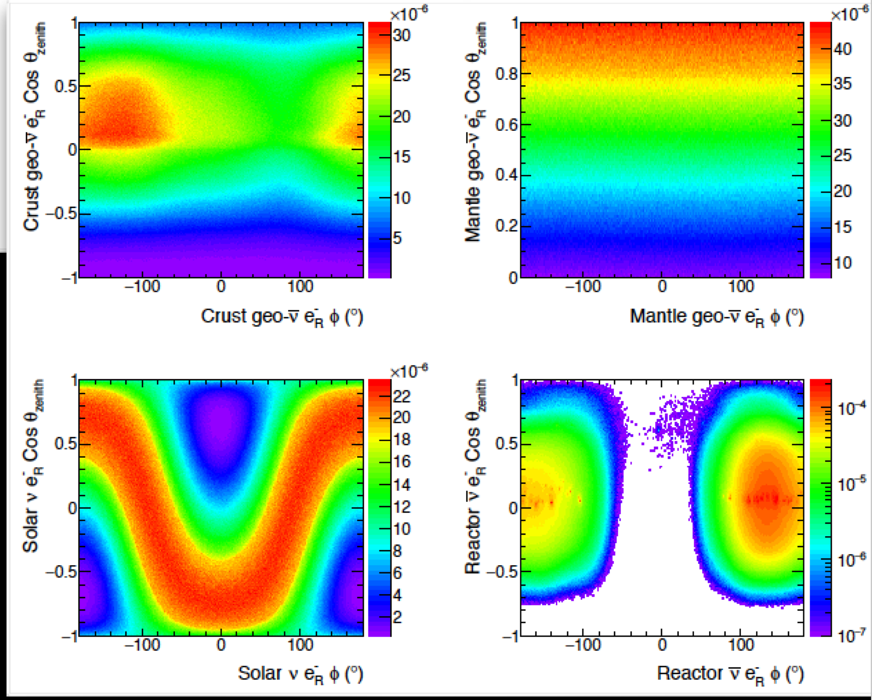
Gelmini et al, arXiv:1812.05550

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.

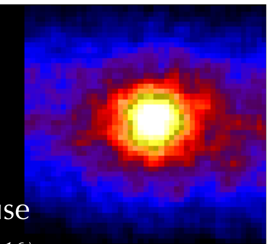


example: geo-, solar-, reactor-ν -induced electron recoil directions, at LNGS.

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

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

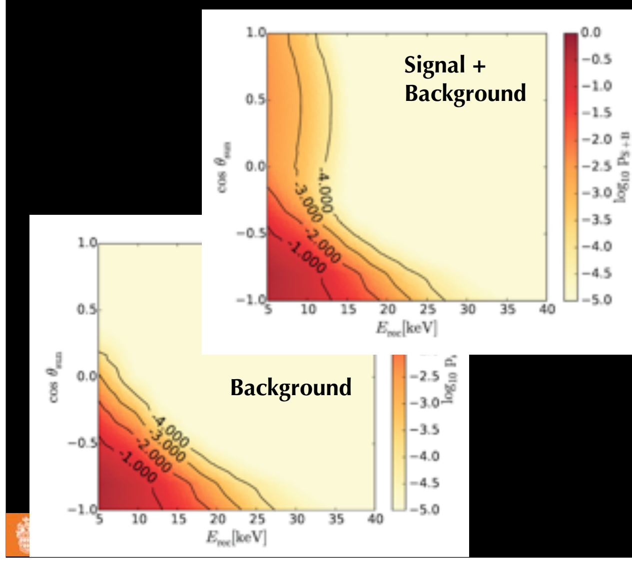
Recoil Directionality

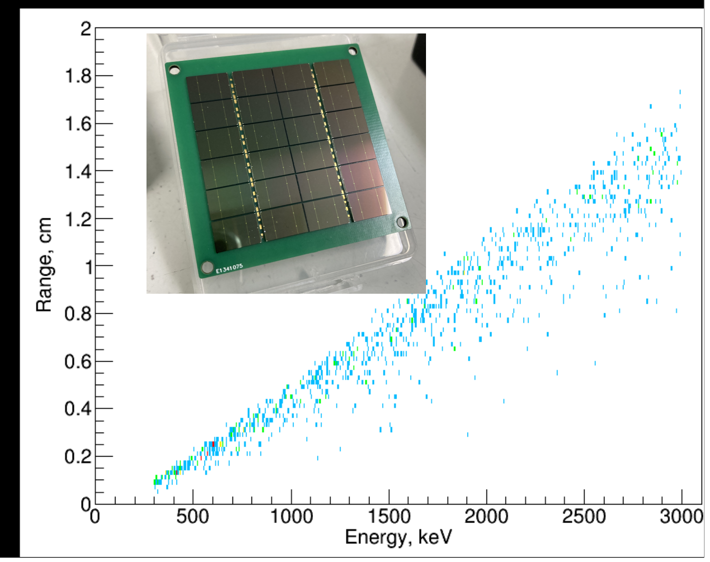


- directional dark matter detection studies show 1D direction reconstruction for χN ➙ χN nuclear recoils gains 10x over non-directional measurements, because (energy, angle, time) of signal != background. *Mayet, JM et al., Phys.Rept. 627 (2016)*

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

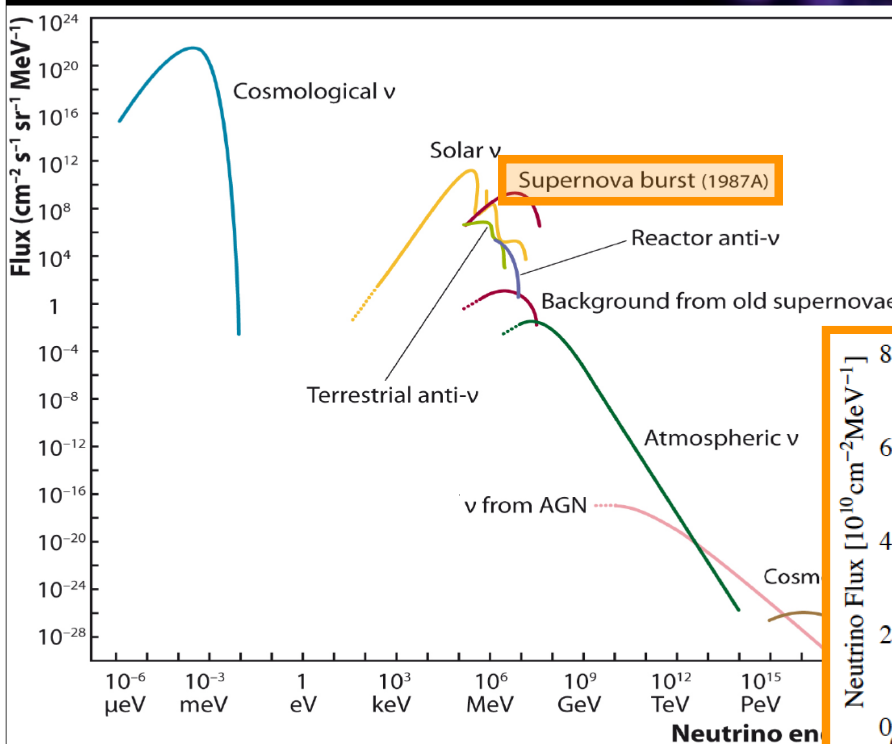
  mm sampling pitch in drift direction, demonstrated, makes direction reconstruction of ~cm length electron recoils *feasible* in 1D. Transverse pitch is a challenge tackled by 3DdSiPM readout R&D…





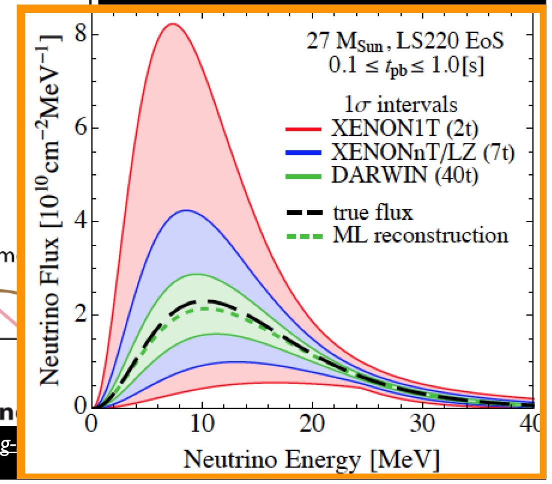
What ν sources can dark matter detectors see?

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.

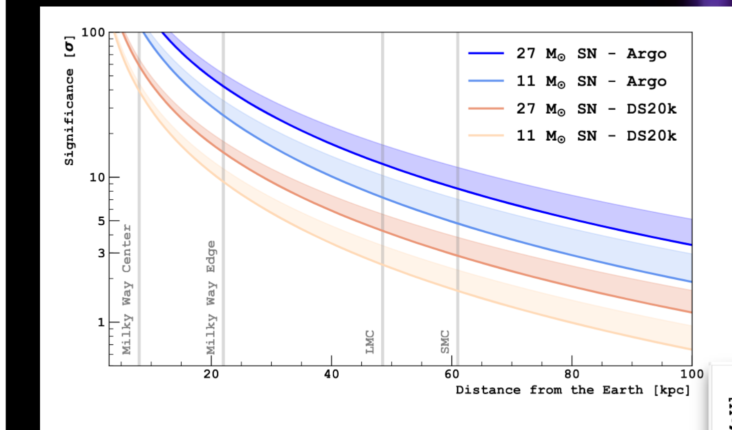
(if lucky!)



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

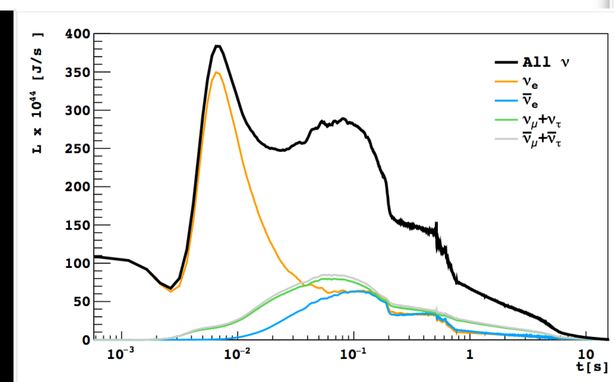
Agnes, JM et al., arXiv:2011.07819

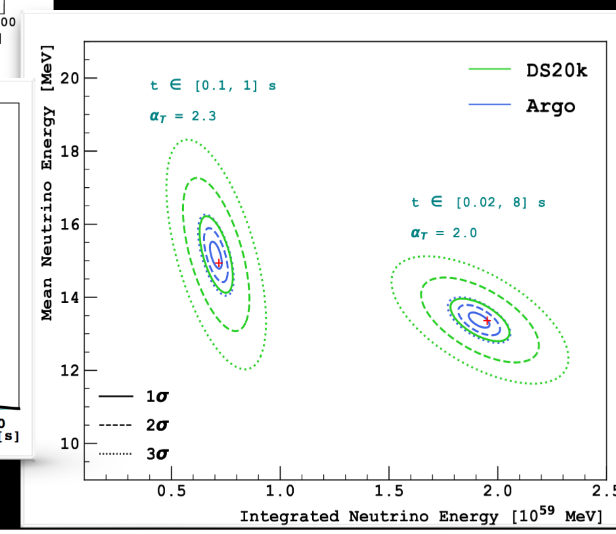
Supernova ν in DarkSide-20k



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

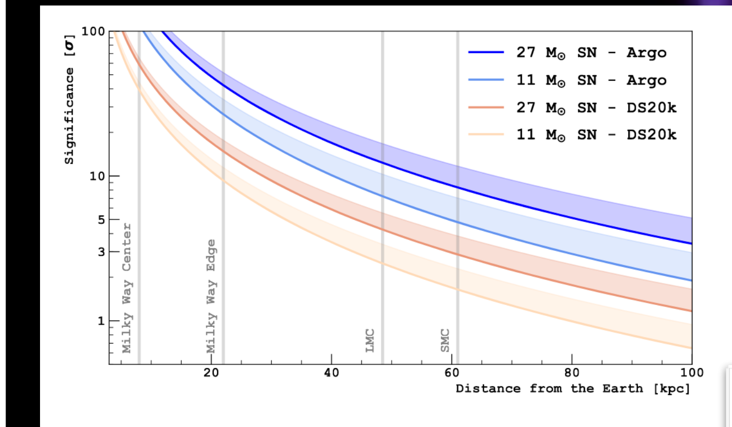
- measure all flavors via NC
  sensitive to total SN energy in ν





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
- measure ν_e via ν_e ^{40}Ar → e^- ^{40}K*
  sensitive to ν mass hierarchy

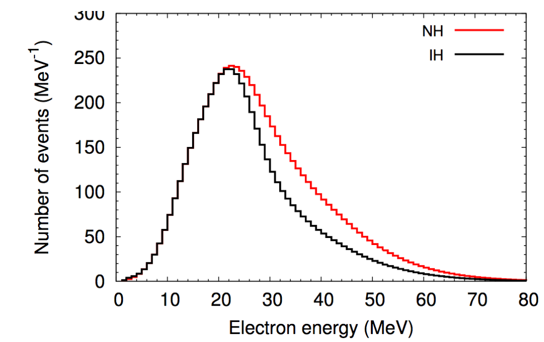
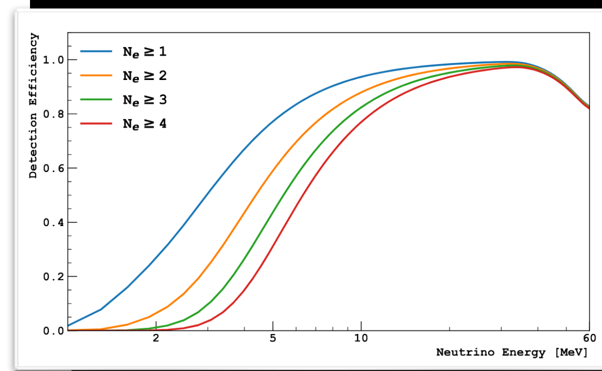


Fig. 33. – Observable SN ν_e spectra in a 40-kton LAr TPC for benchmark fluxes as in Fig. 28 in both the mass hierarchies. (Figure adapted from [356]; courtesy of B. Dasgupta.)



supernova distance measurement with ν?

Mirizzi et al., arXiv:1508.00785

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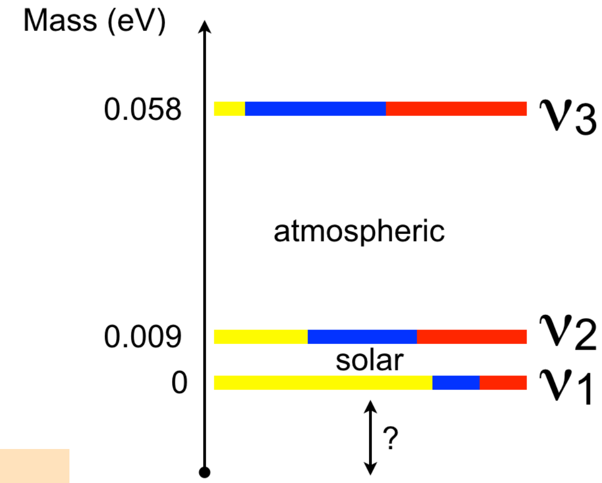
5.9 MeV threshold for nu-e CC process on Ar-40

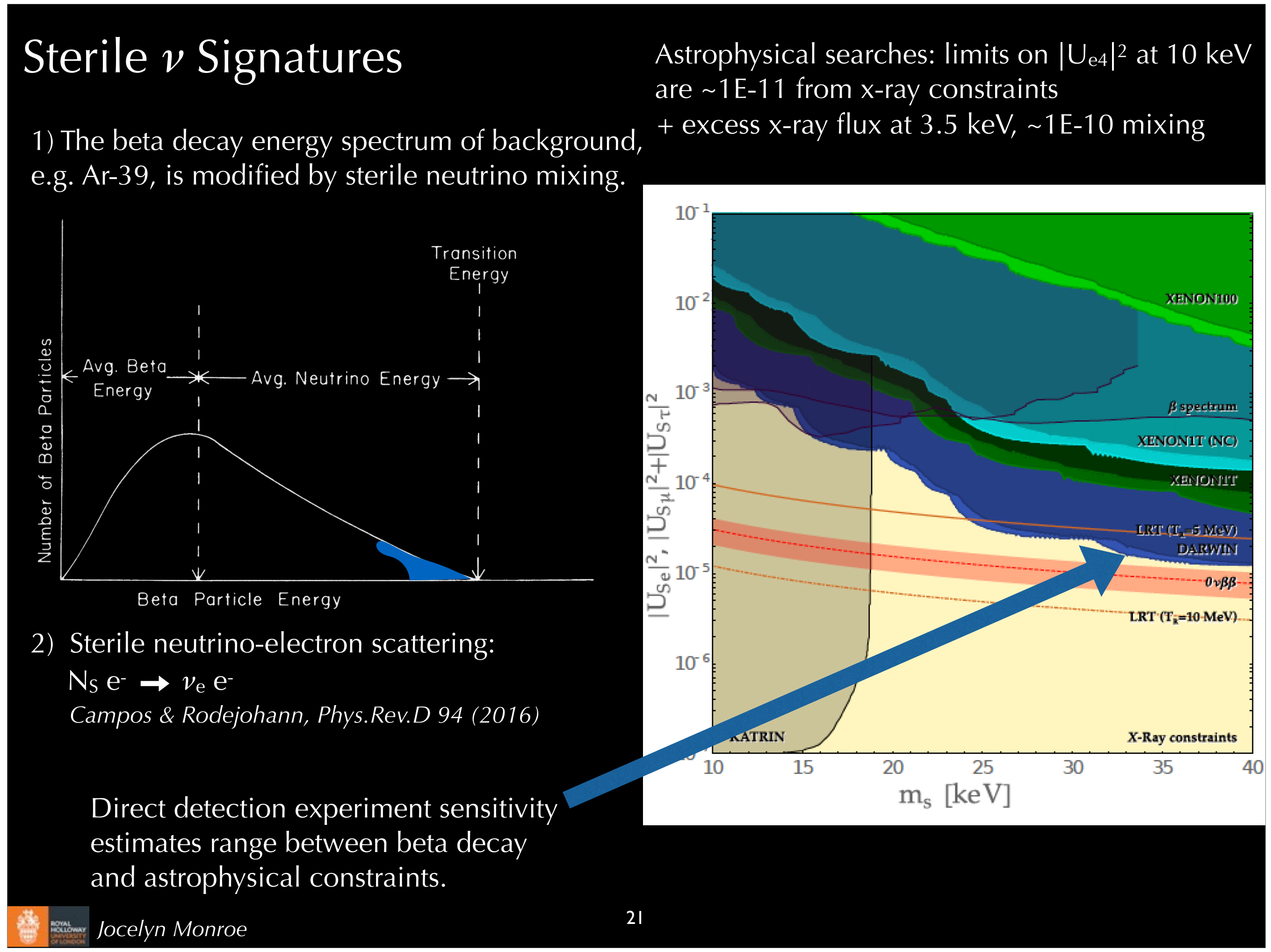
Open Questions

- 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?
- Are there sterile neutrinos?



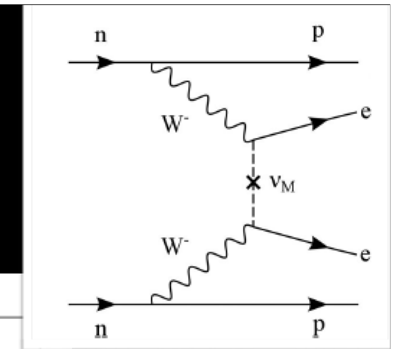
flavour key:

ν_e ν_μ ν_τ



uMbooNe off top left of plot…

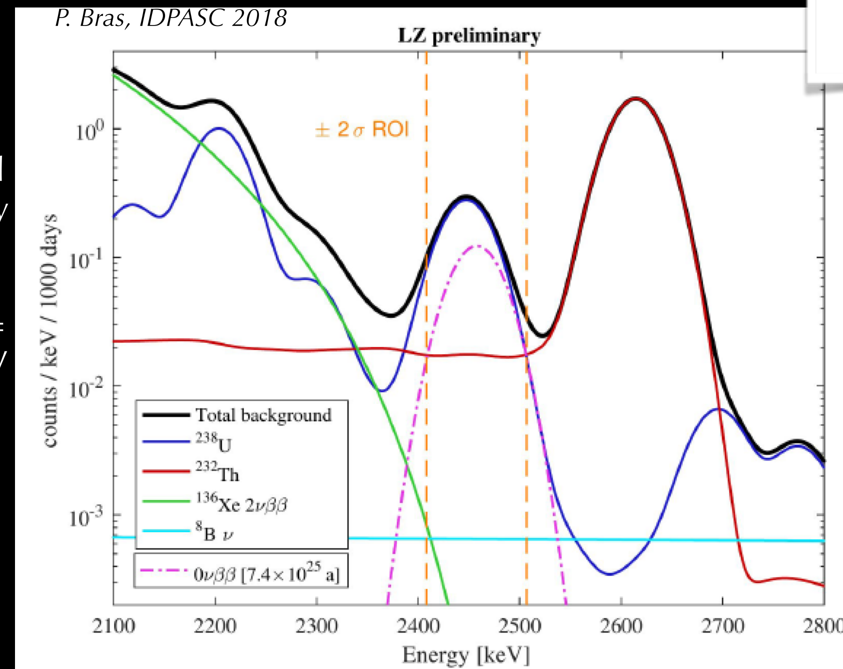
ν-less Double Beta Decay



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

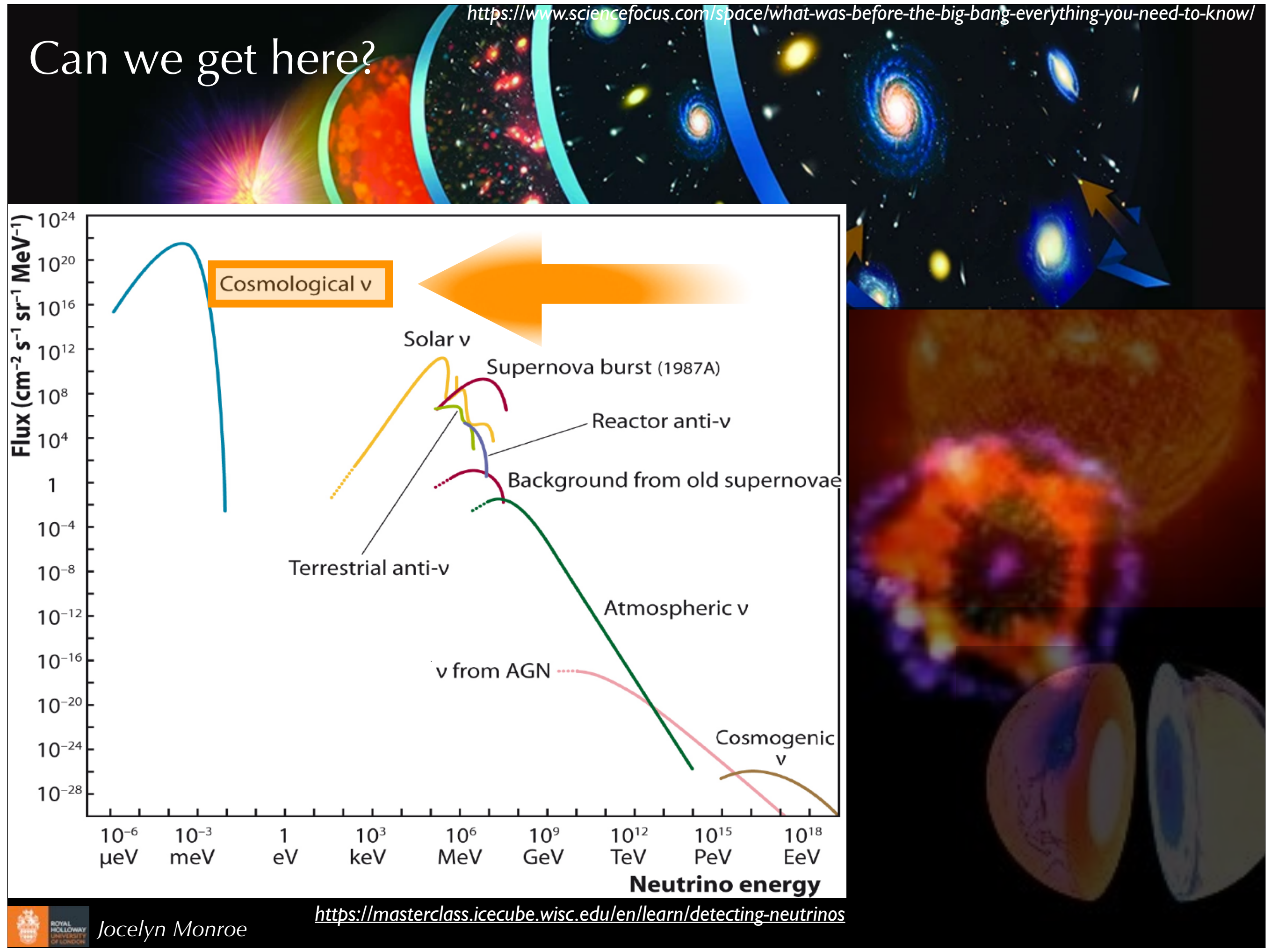
example: projected sensitivity in LZ:

Q-value= 2458 keV



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

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



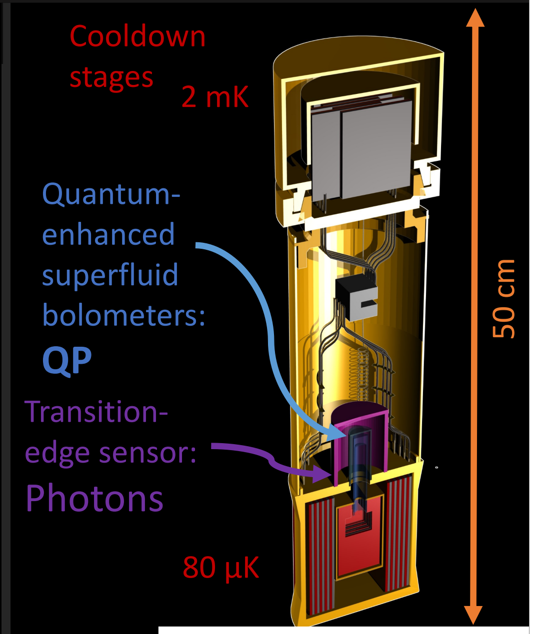
flavor blind vs. nu_e on tritium

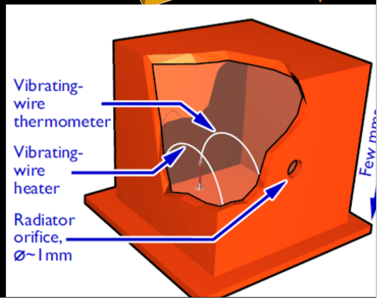
Quantum Enhanced Superfluid Technologies for Dark Matter and Cosmology

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

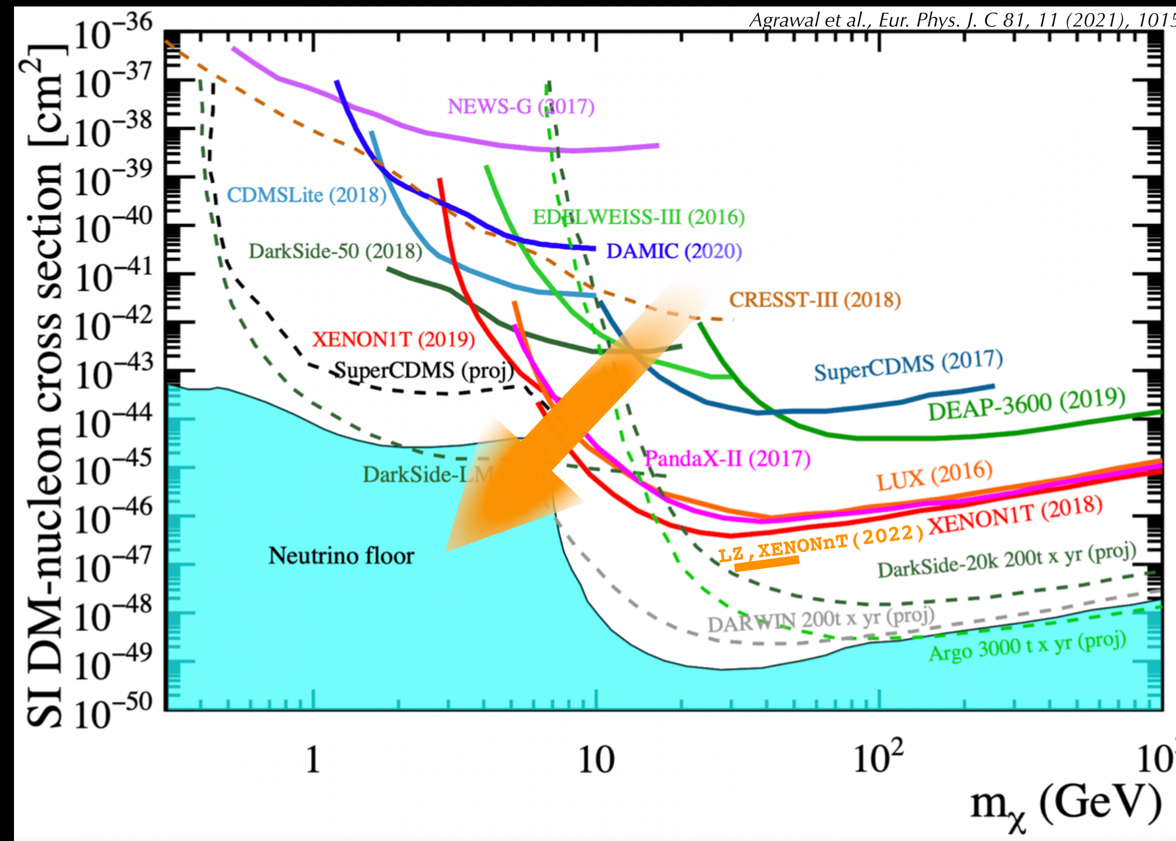
Heat partition measurement
- Quasiparticles "shake" a nano-electromechanical resonator (NEMS), coupled to SQUID, readout reaching quantum-limited displacement measurement





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

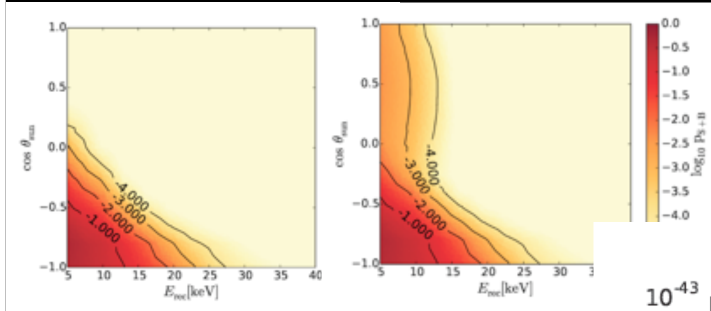
What happens when we get here?



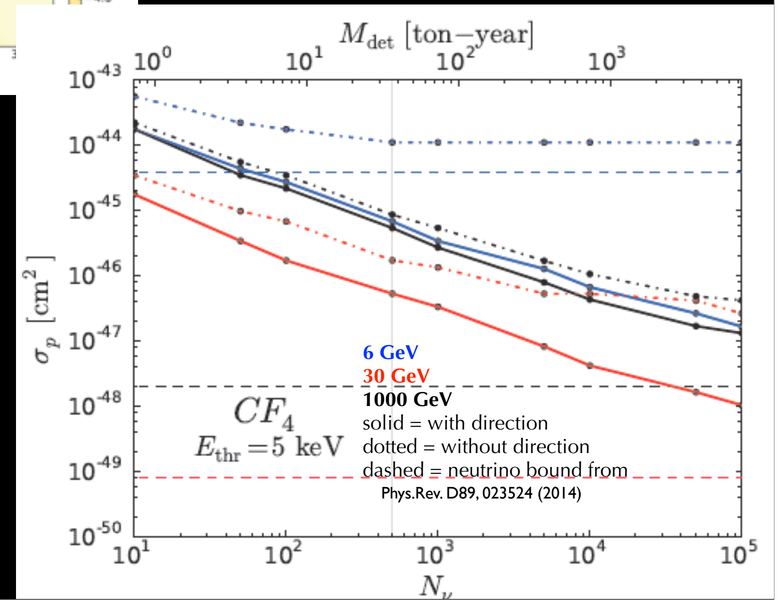
challenges: backgrounds, need a very large detector (scalability)
… if signal at current limit, need 1E-47 sensitivity to get 1000 events to measure mass, xsec

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*

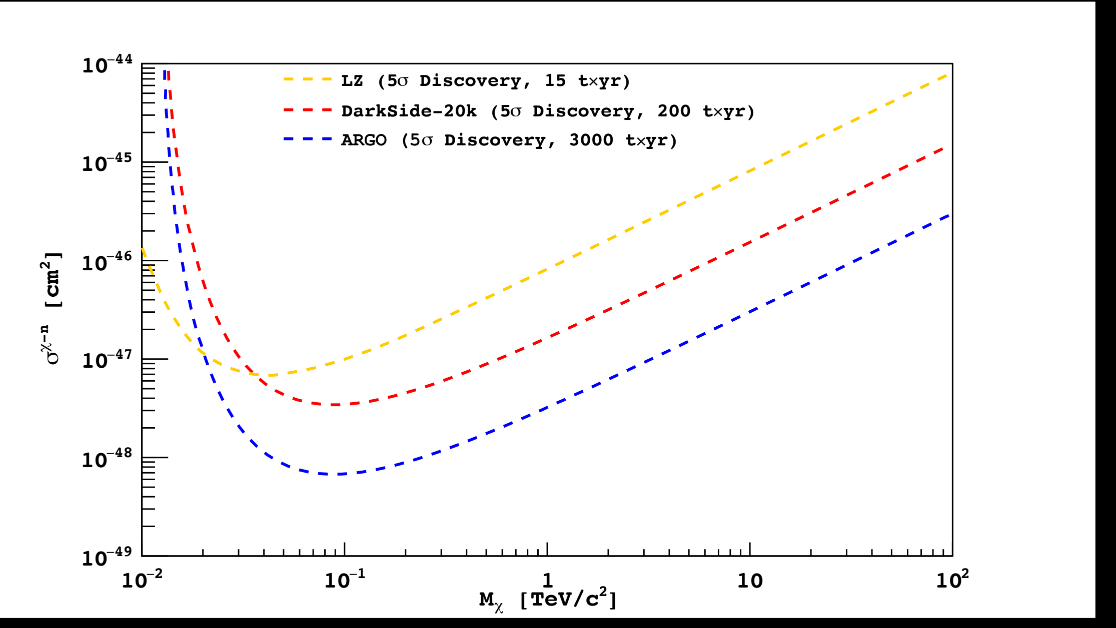
Jocelyn Monroe

this is the number of signal events required (so you have to run longer to get these at 100 keV than 50 keV)

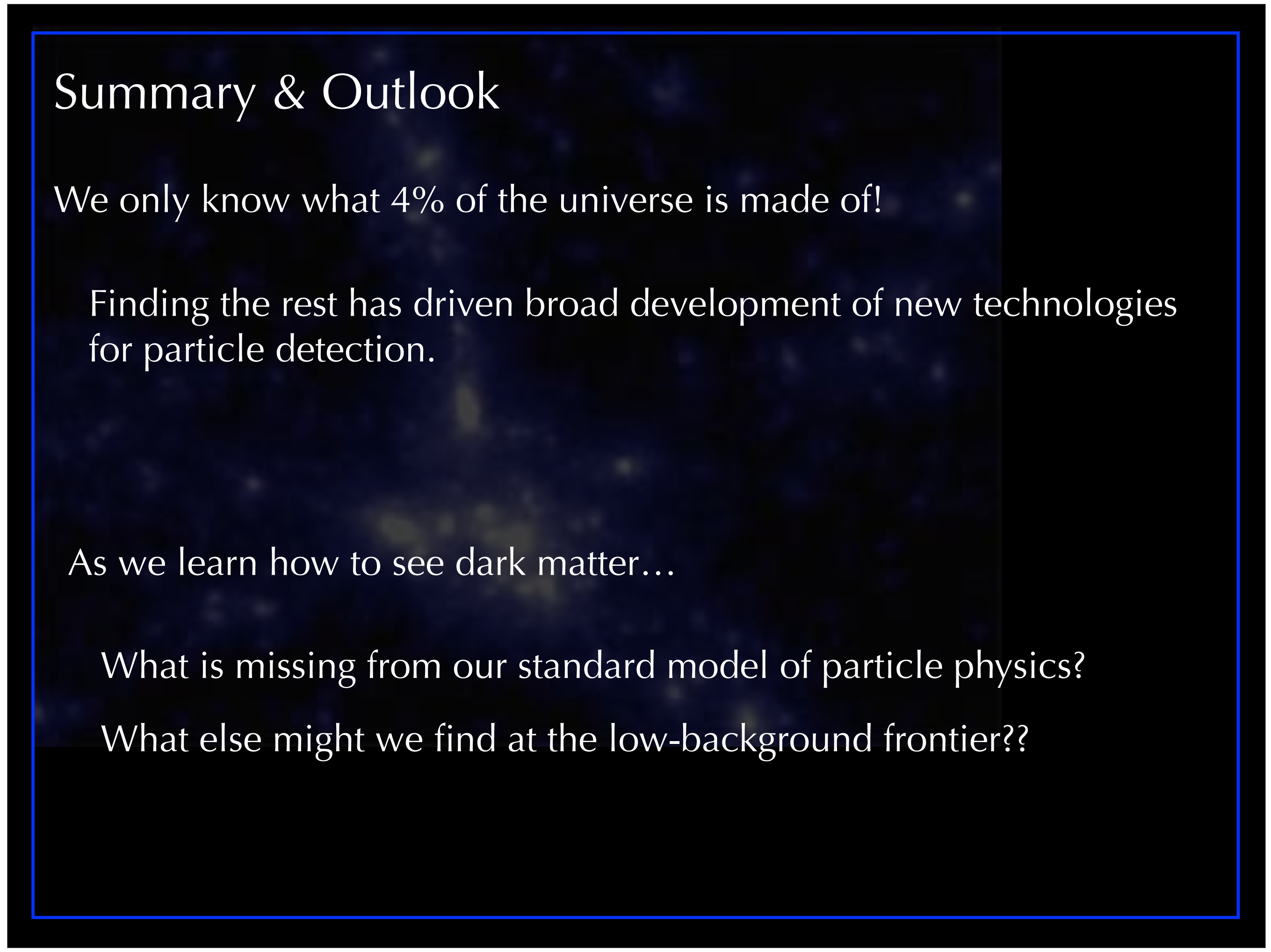
-vector is such a big improvement over axial because the statistic (Rayleigh power) is proportional to the mean direction to the 4th power.
-how much does axial improve over counting only? best counting only can be is 3 events
assume both signal and background are poisson distributed, you observe zero background, so the mean of the bgnd distribution is 2.3, and therefore you need more than 3 signal events to claim discovery at 90% CL
-compare 3D directional with 3D axial, 2D directional with 2D axial
-reduced angles=projected direction of solar motion subtracted = angle w.r.t. direction to cygnus

What happens when we get here?

We enter a nu background paradigm…



where the 'neutrino floor' depends on ER discrimination power



as we learn to see dark matter, we can study profound and fascinating questions...