The Neutrino Floor

Kate Scholberg, Duke University
Dark Matter Searches in the 2020’s
November 11, 2019

OUTLINE

The Opaque Floor

- neutrino CEvNS background for WIMP-induced nuclear recoils [focus on these]
- CEvNS measurements [COHERENT and others]

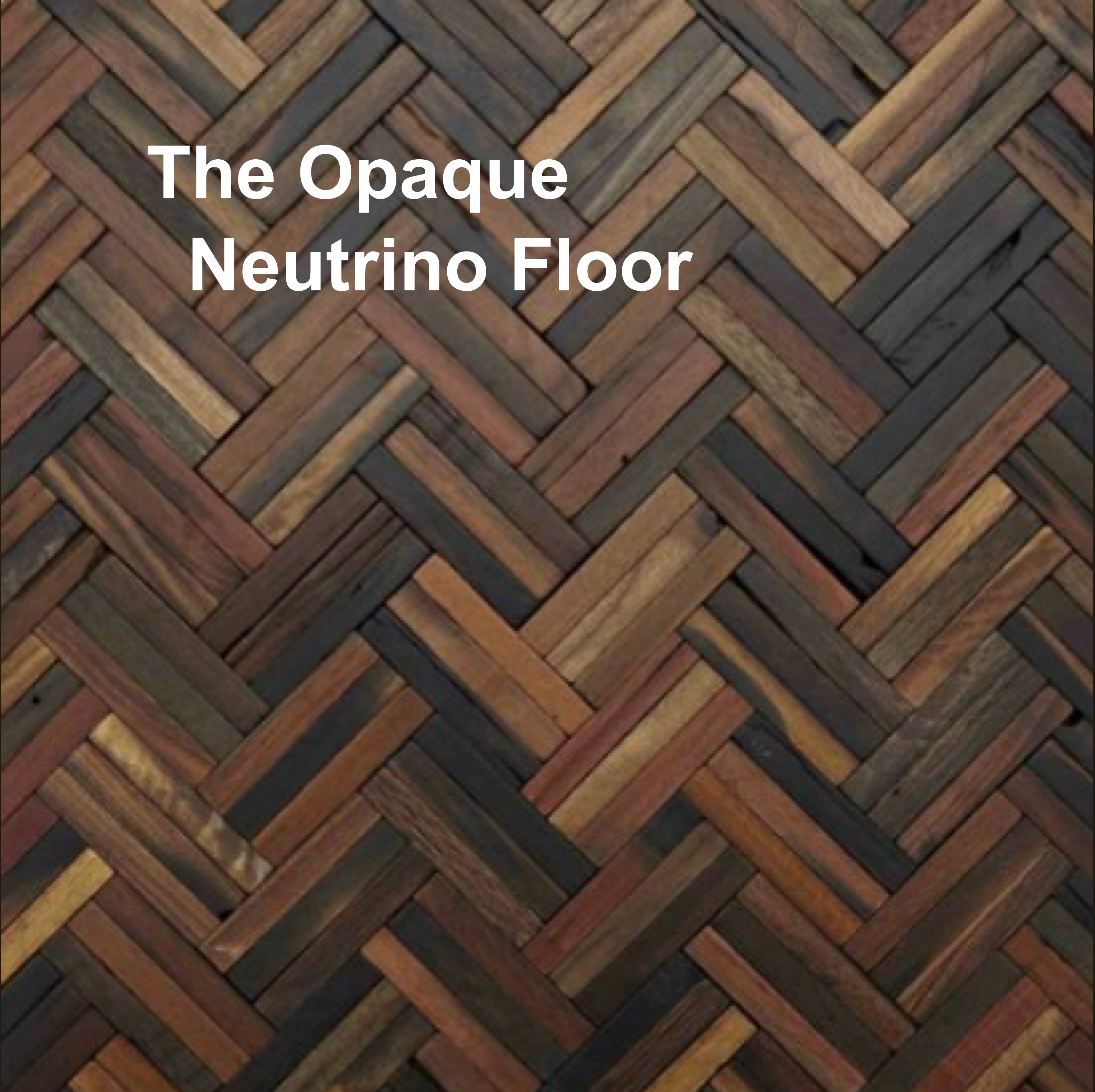
The Transparent Floor

- looking below with directionality

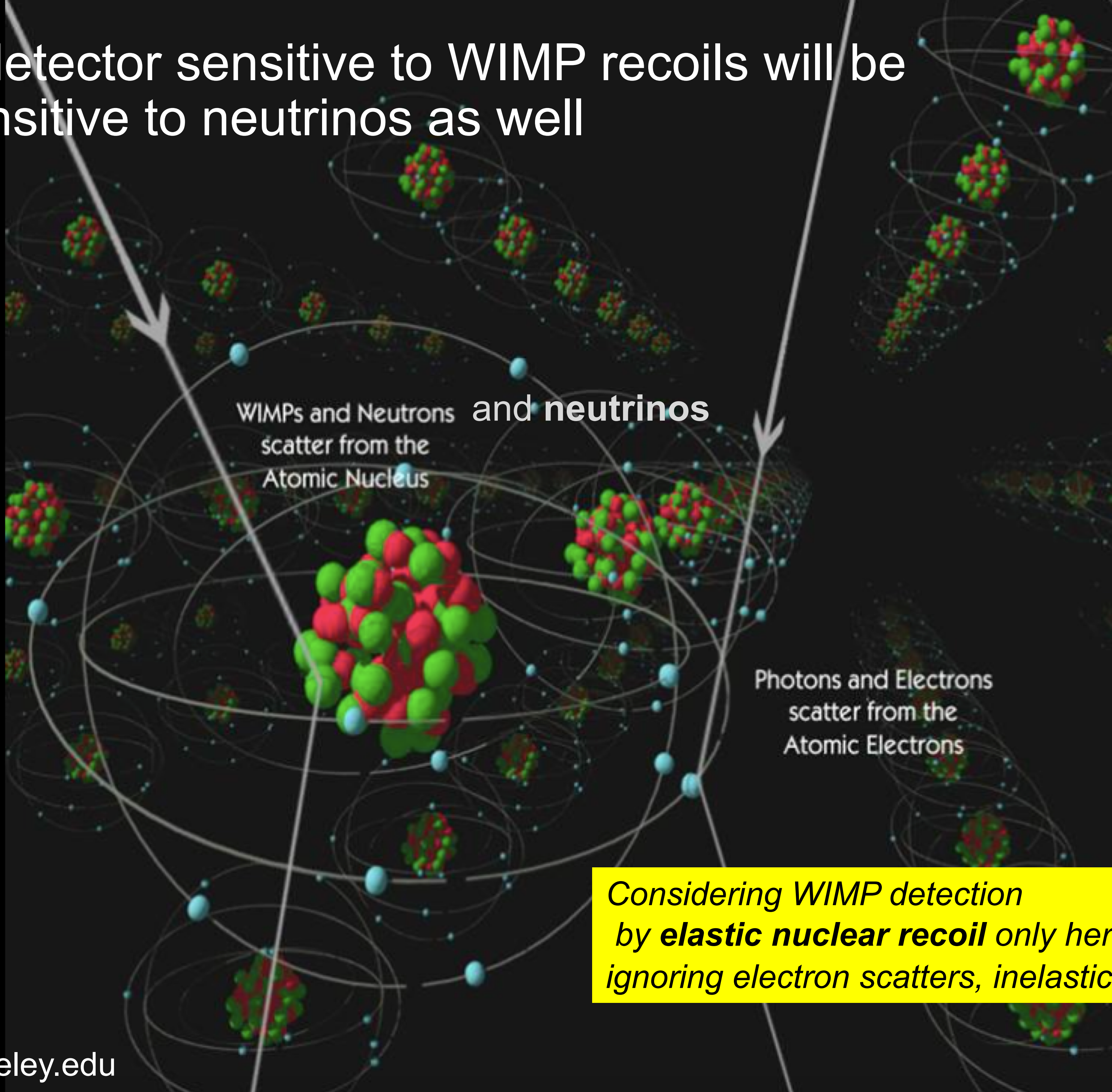
The Patterned Floor

- the floor as signal

The Opaque Neutrino Floor



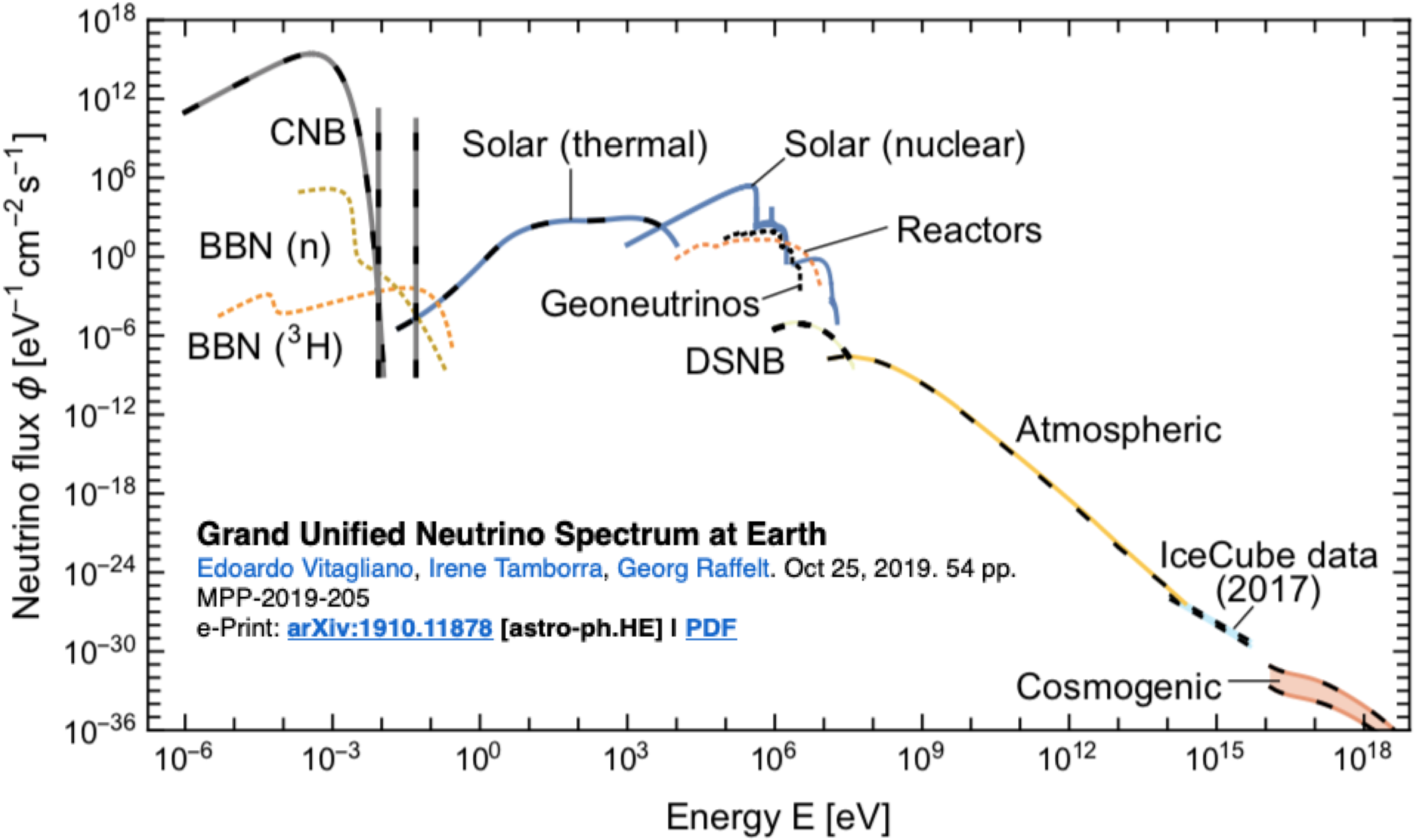
Any detector sensitive to WIMP recoils will be sensitive to neutrinos as well



Considering WIMP detection by ***elastic nuclear recoil*** *only here....*
ignoring electron scatters, inelastic, etc.

cdms.berkeley.edu

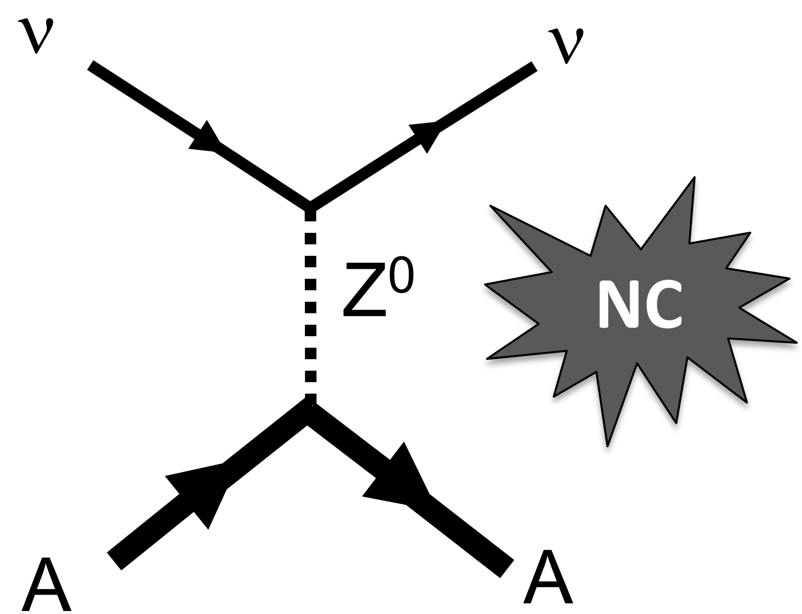
Neutrinos over many orders of magnitude in energy



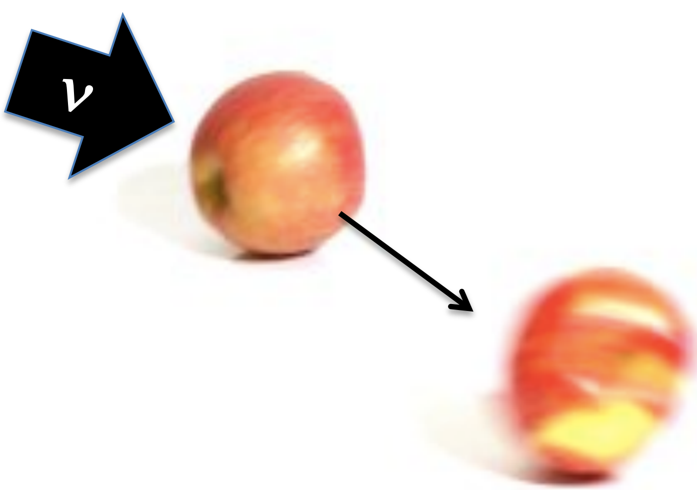
Mostly wild  ...but some “tame” 

Wild and tame neutrinos interact via **Coherent elastic neutrino-nucleus scattering (CEvNS)**

$$\nu + A \rightarrow \nu + A$$



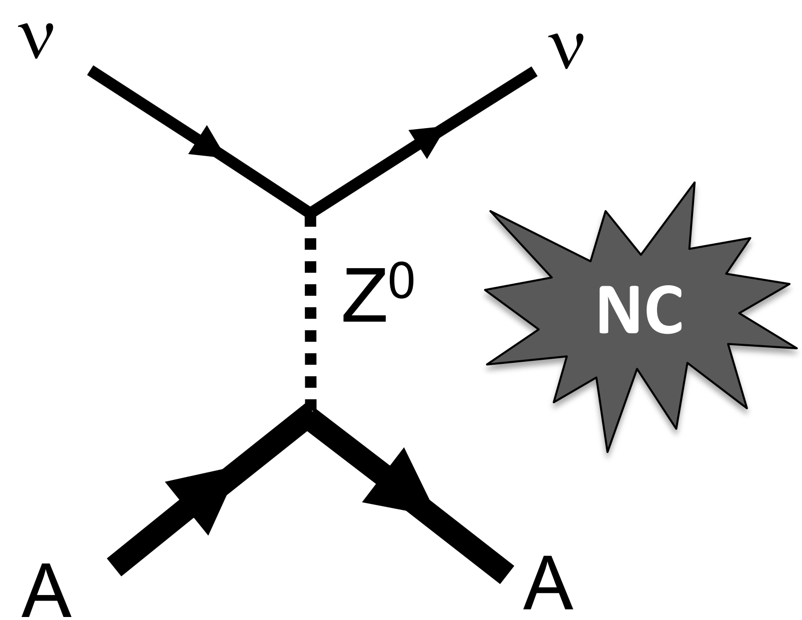
A neutrino smacks a nucleus via exchange of a Z, and the nucleus recoils as a whole; **coherent** up to $E_\nu \sim 50$ MeV



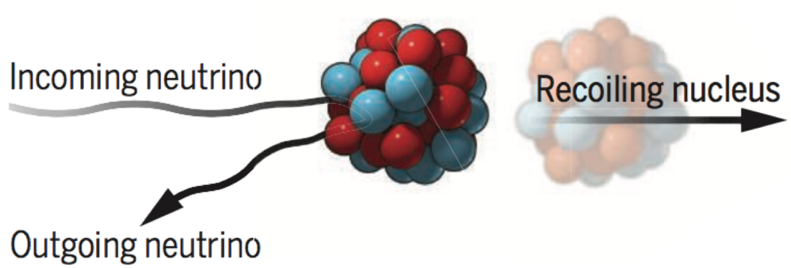
Wild and tame neutrinos interact via

Coherent elastic neutrino-nucleus scattering (CEvNS)

$$\nu + A \rightarrow \nu + A$$



A neutrino smacks a nucleus via exchange of a Z, and the nucleus recoils as a whole; **coherent** up to E_ν~ 50 MeV



Nucleon wavefunctions in the target nucleus are **in phase with each other** at low momentum transfer

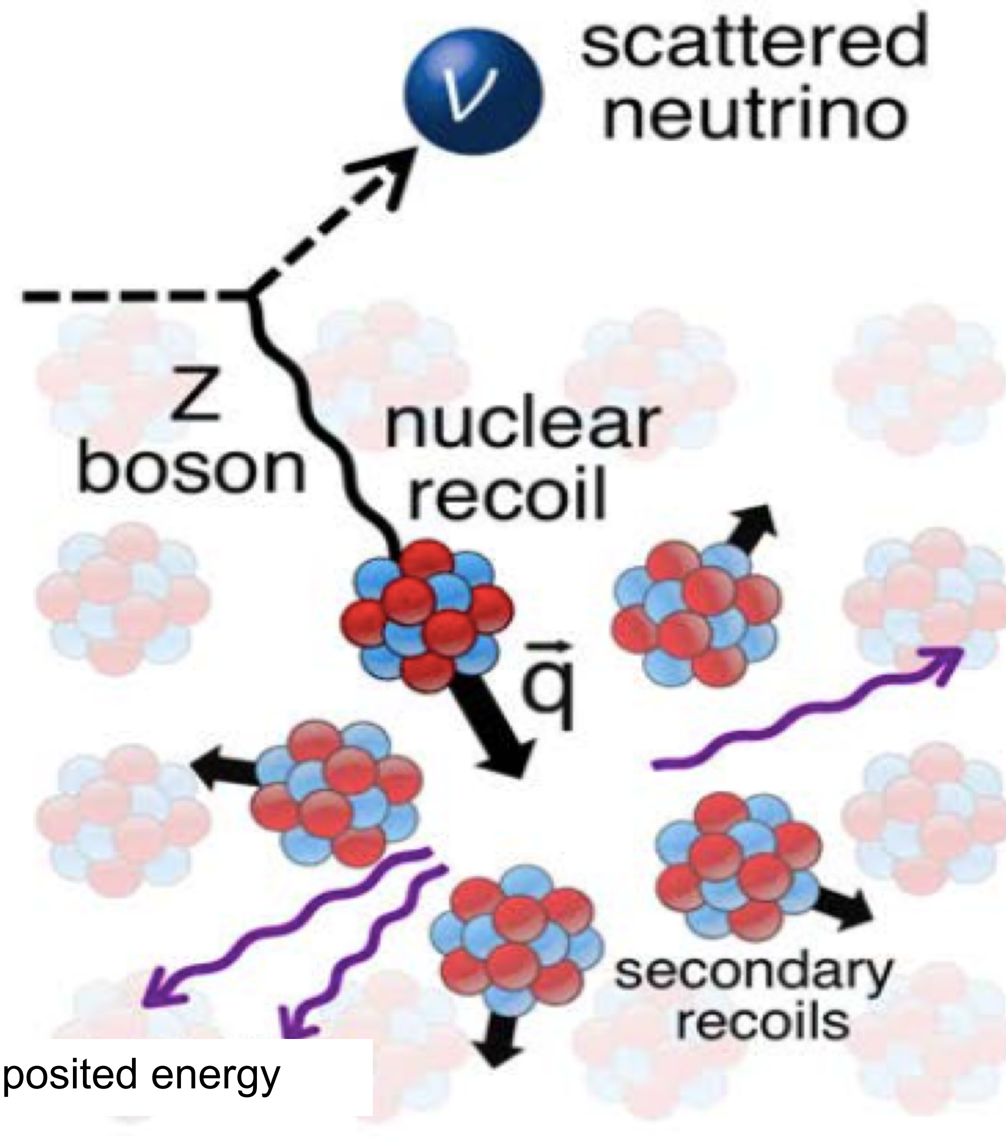
For $QR << 1$,

[total xscn] ~ A^2 * [single constituent xscn]

A: no. of constituents

Image: J. Link *Science* Perspectives

Just like a WIMP bump, the neutrino bump deposits a tiny bit of energy in the material...



deposited energy

Magnificent CEvNS 2019

9-11 November 2019

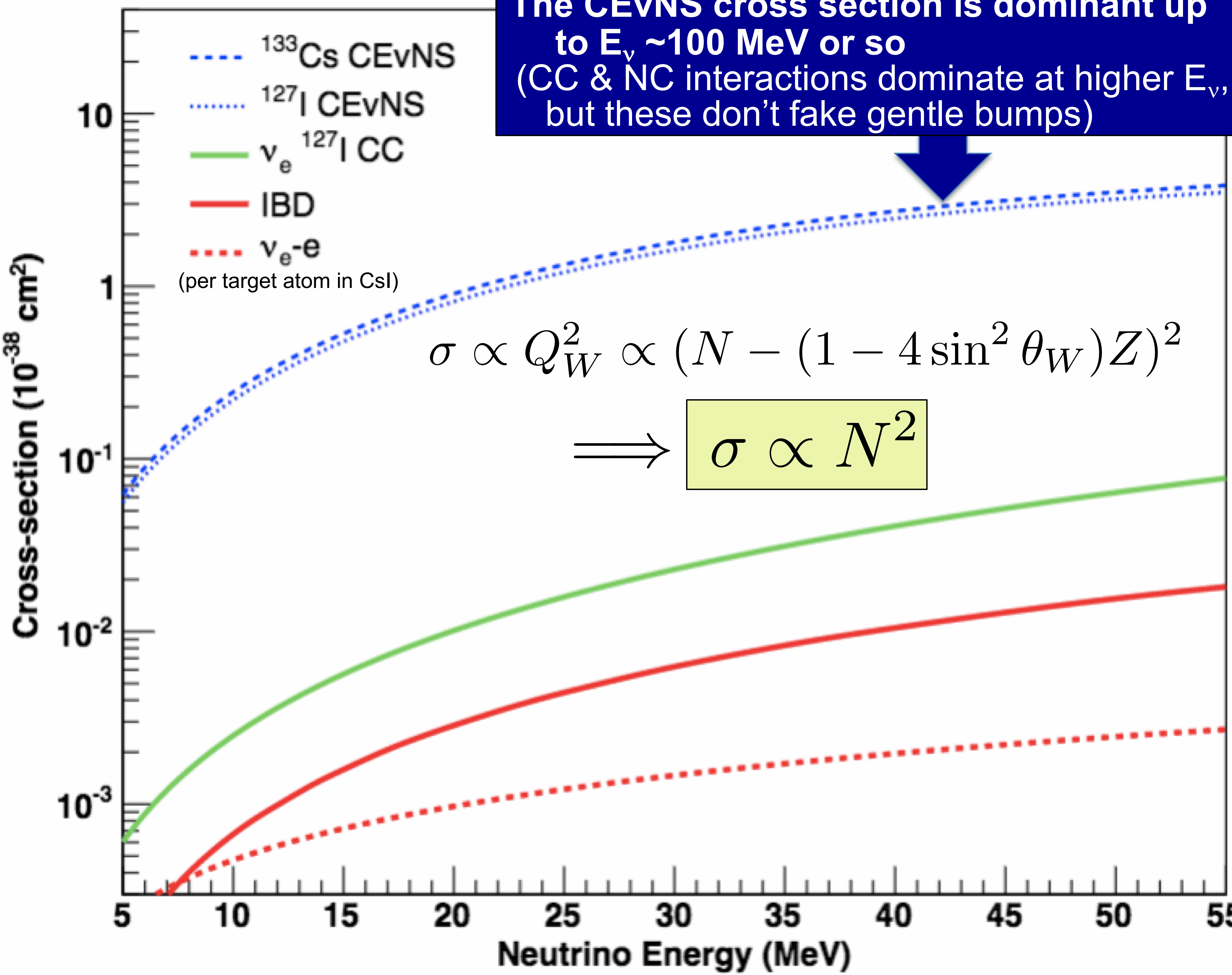
CEvNS is **“The Magnificent Background”**

-- Kentaro Miuchi

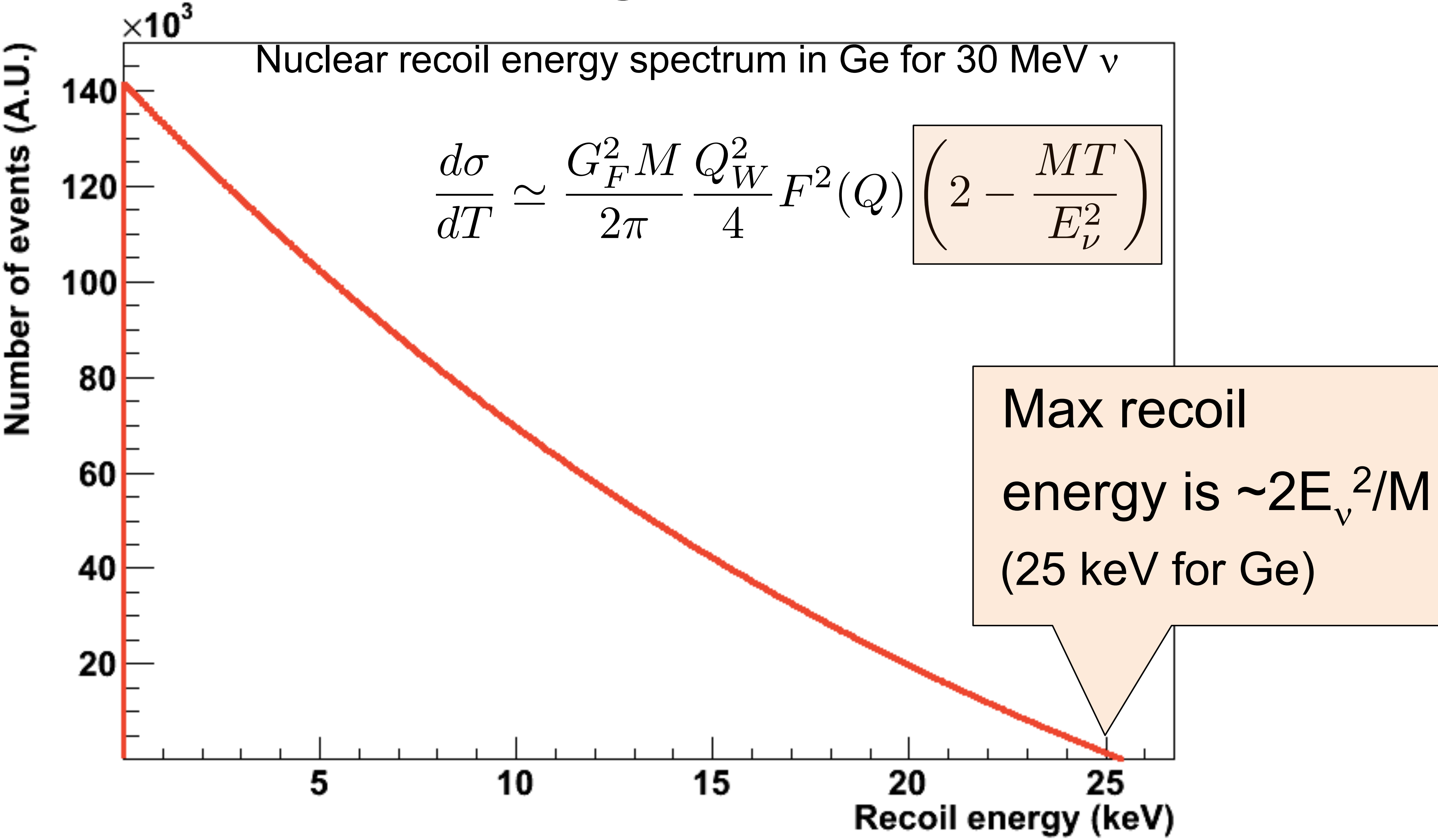
The CEvNS cross section is dominant up to E_ν ~100 MeV or so
(CC & NC interactions dominate at higher E_ν, but these don't fake gentle bumps)

$$\sigma \propto Q_W^2 \propto (N - (1 - 4\sin^2\theta_W)Z)^2$$

$$\Longrightarrow \boxed{\sigma \propto N^2}$$

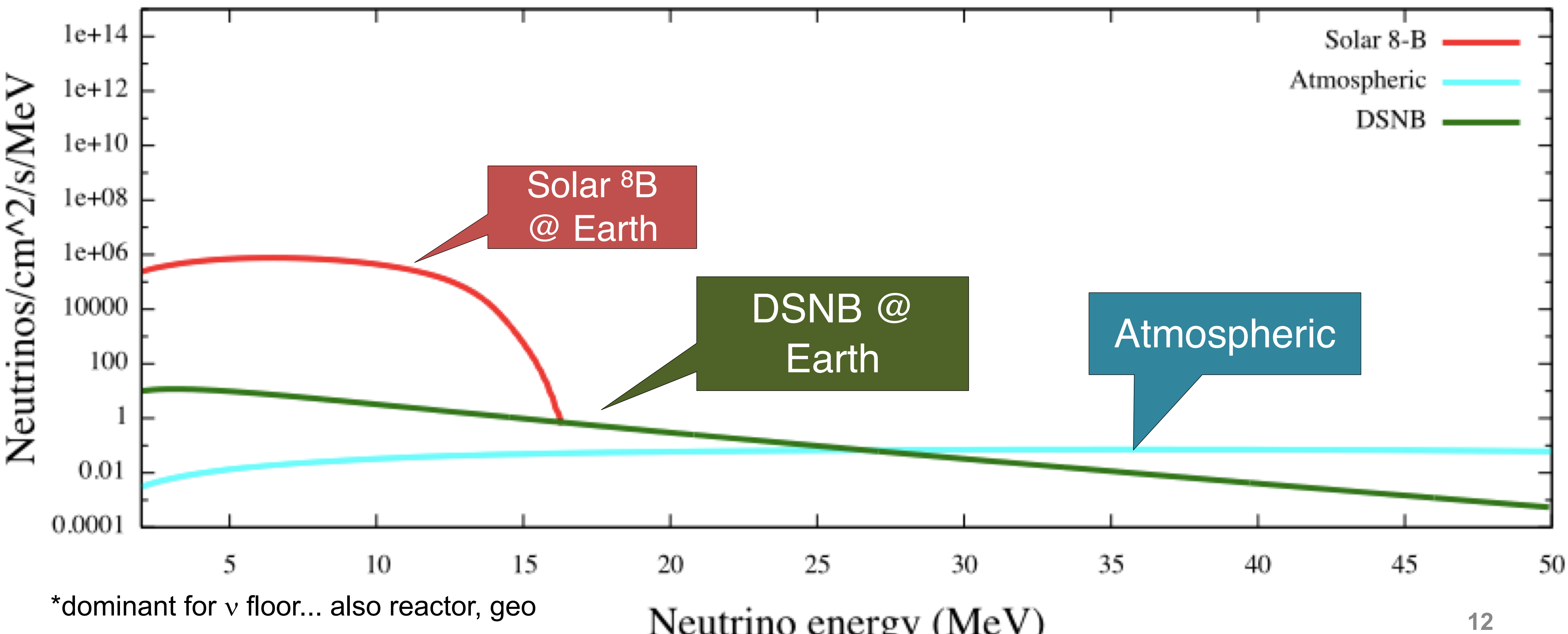


The cross section is large but the bump is small



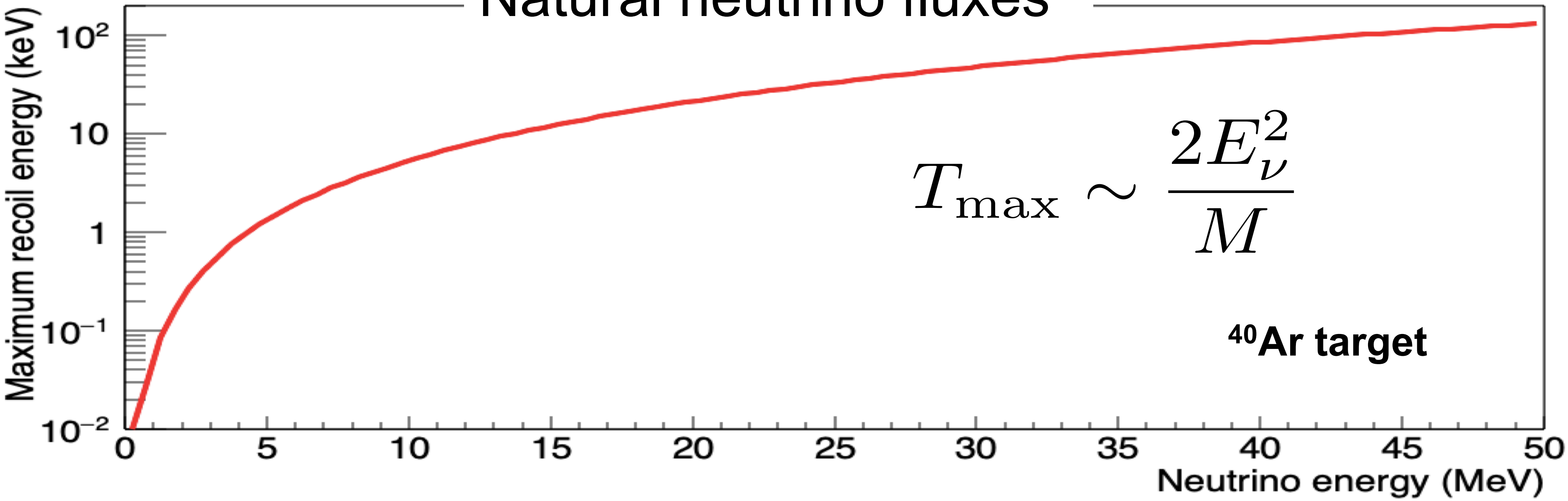
Not observable in "traditional" neutrino detectors (e.g. SK, KamLAND,...) w/ ~MeV thresholds... but will show up in WIMP detectors

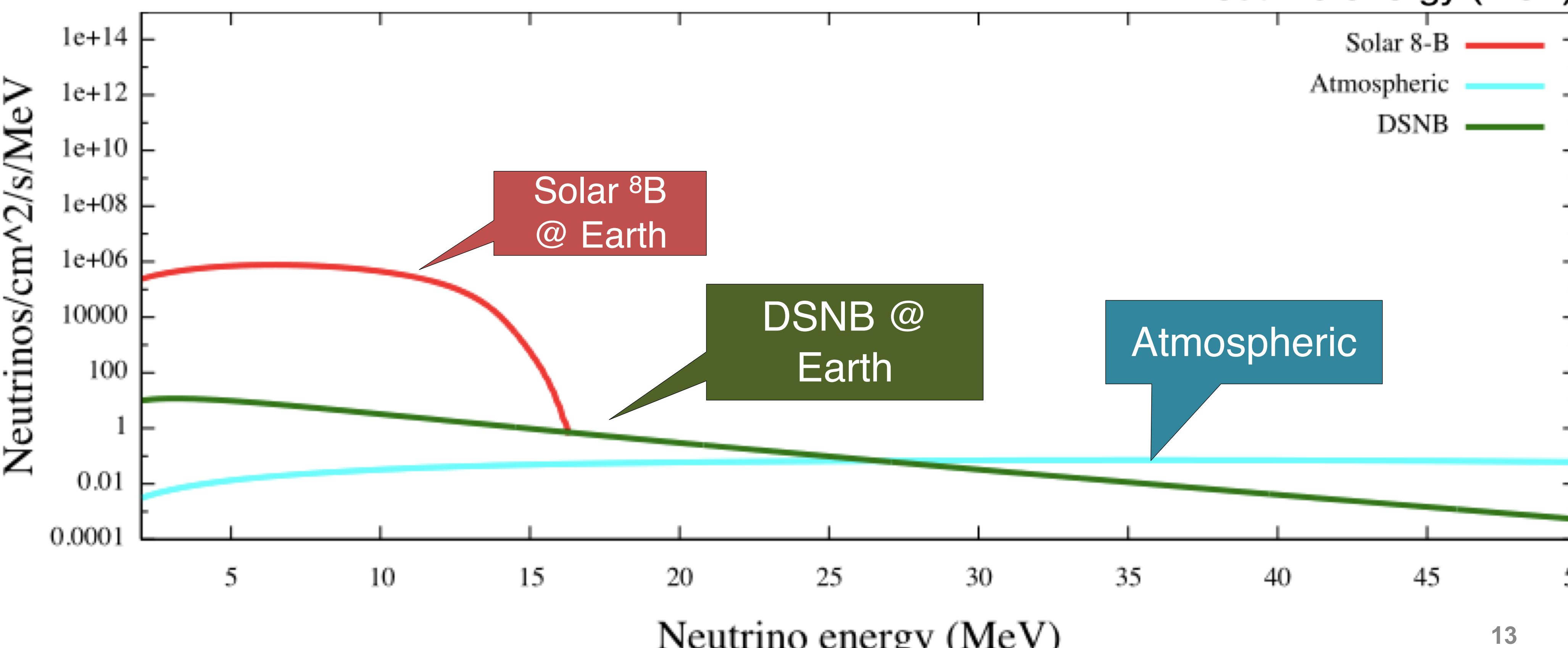
Natural neutrino fluxes*



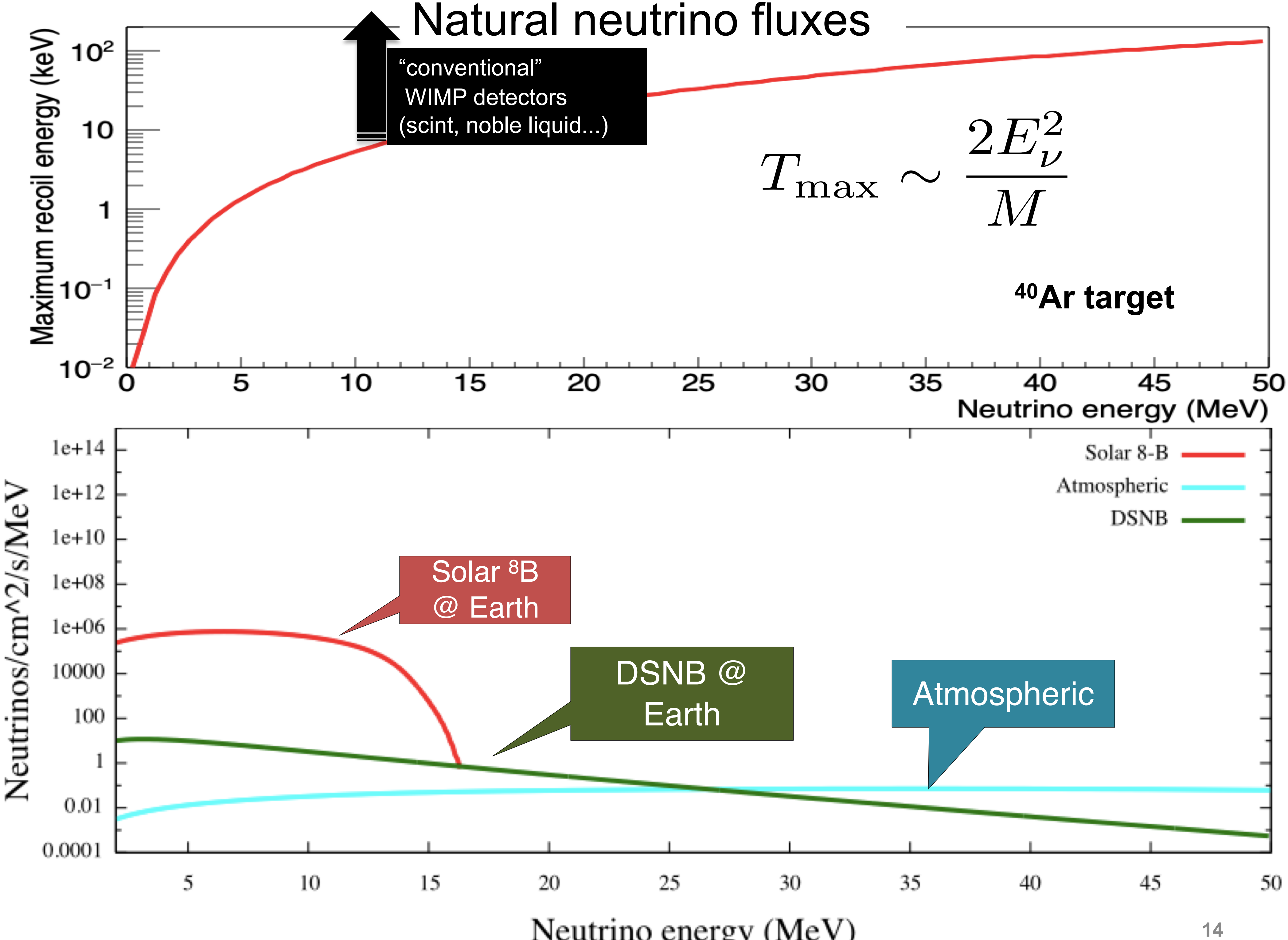
*dominant for ν floor... also reactor, geo

Natural neutrino fluxes

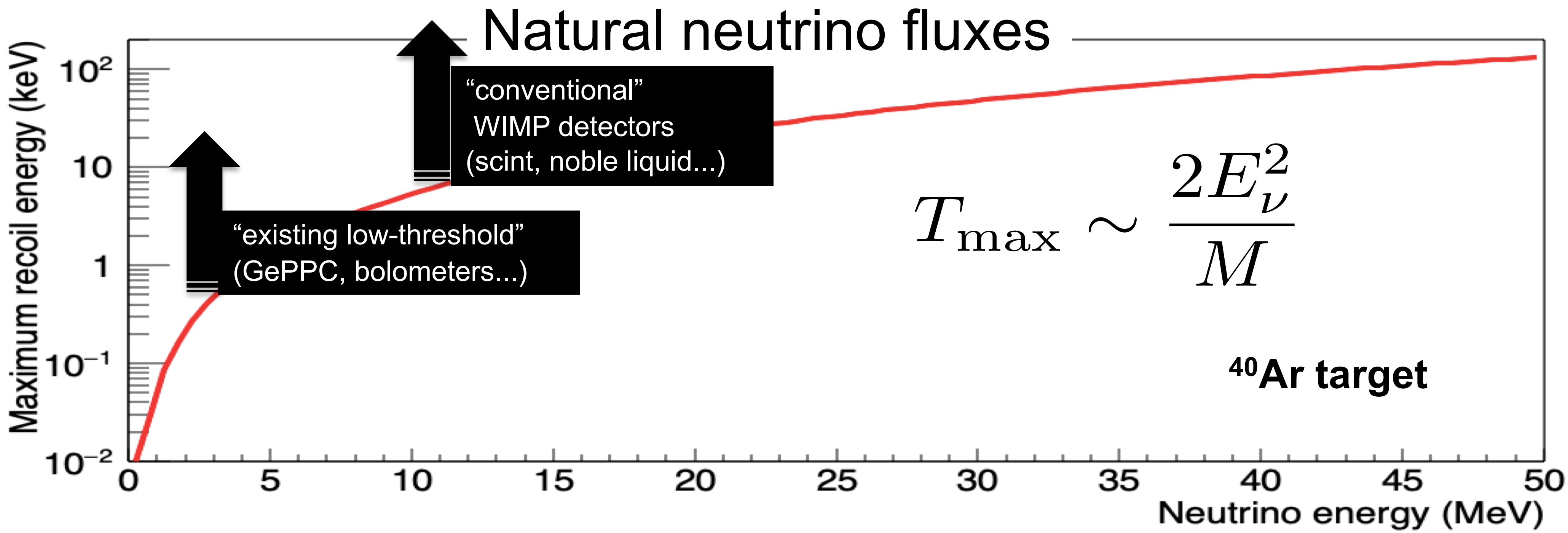


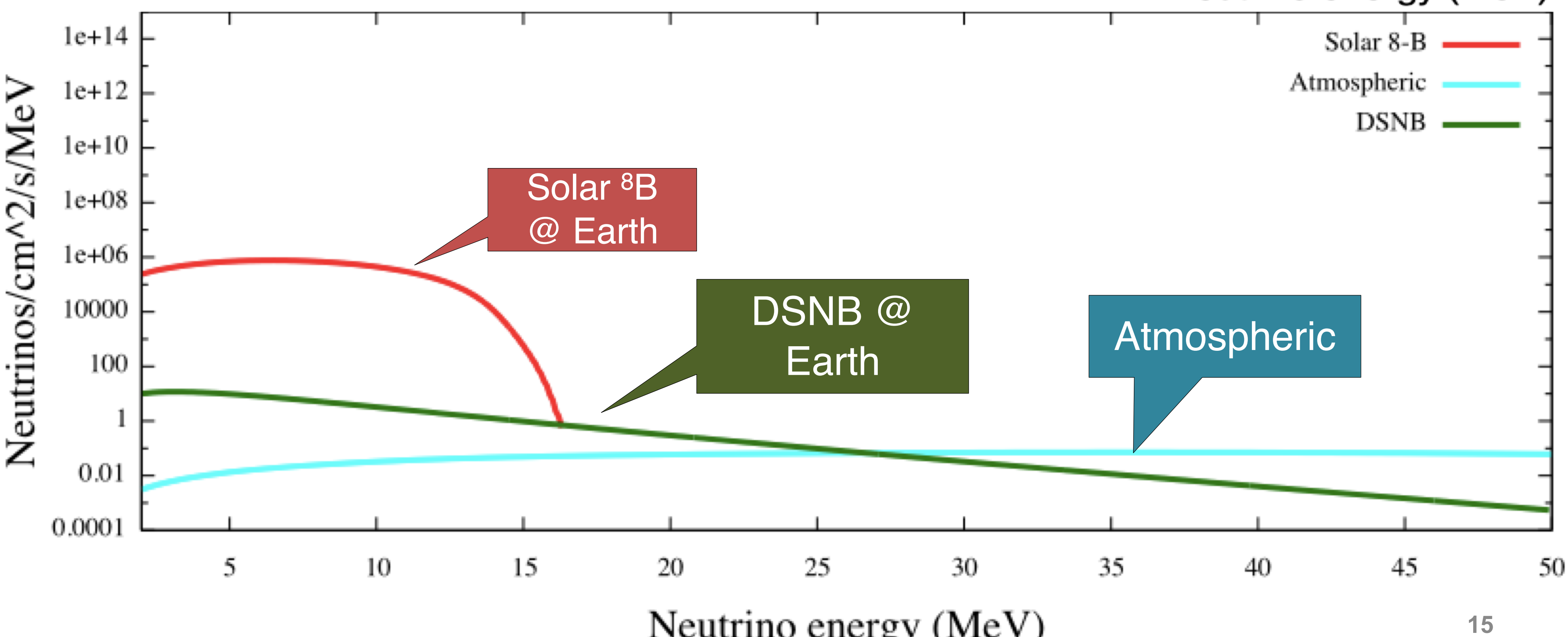


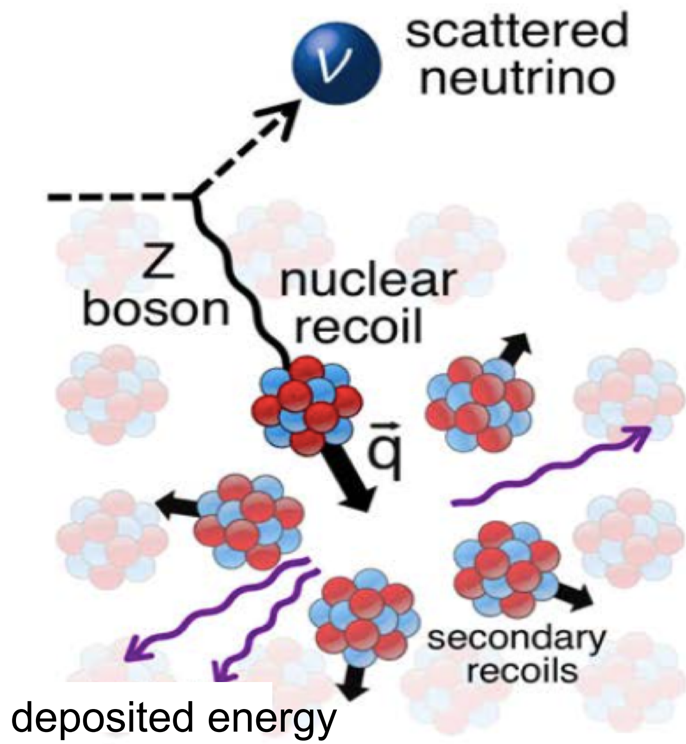
Natural neutrino fluxes



Natural neutrino fluxes





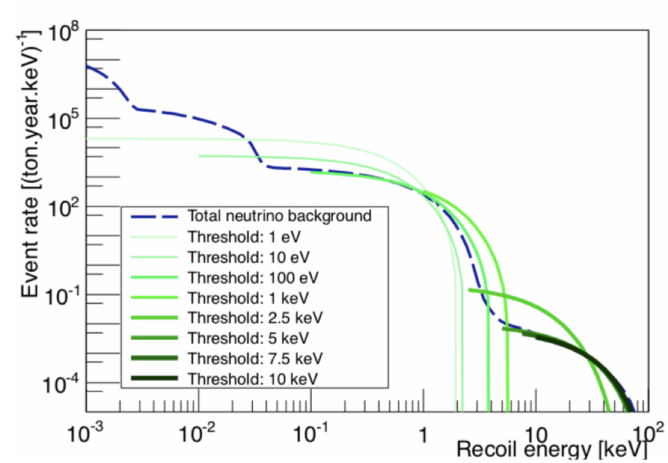


Event by event you can't tell the difference between a neutrino and a WIMP...

The only differences are *statistical*, in observables:

- Recoil spectral shape
  (lots of overlap between WIMPs & ν's...)
  ... depends on nature of WIMP interaction, nuclear target

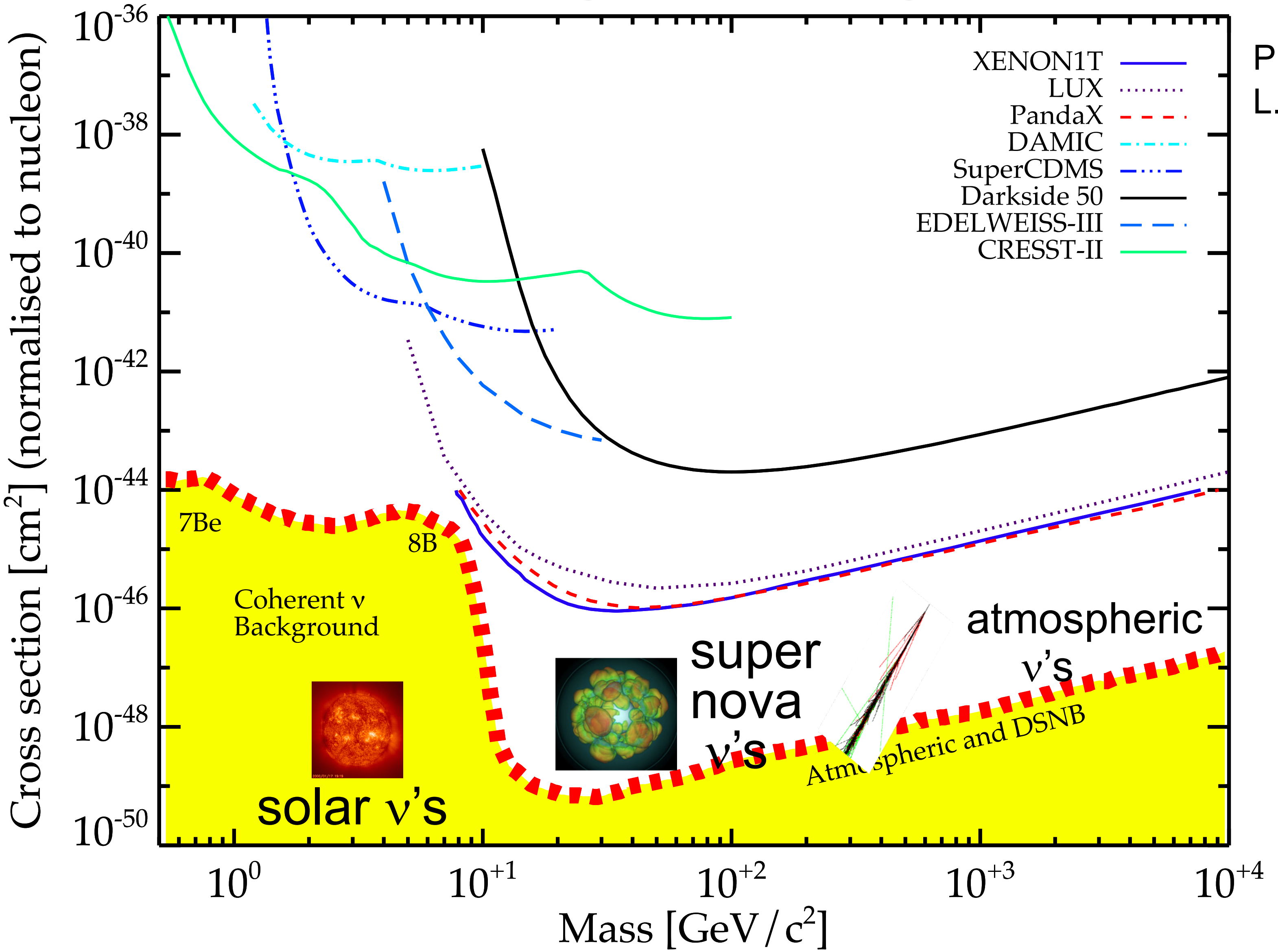
J. Billard, E. Figueroa-Feliciano, and L. Strigari, arXiv:1307.5458v2 (2013).



- Annual modulation, possibly
- Directional distribution
  (much less overlap between WIMPs & ν's)

The **"neutrino floor"** based on recoil spectral shape (target dependent)

J. Monroe & P. Fisher, 2007   J. Billard, E. Figueroa-Feliciano, and L. Strigari, arXiv:1307.5458v2 (2013).



Plot from L. Strigari

For WIMP parameters at which ν spectrum is ~degenerate; level set by statistical fluctuations of natural ν rate

How well do we know where the neutrino floor is?

$$\text{Rate} \propto \text{Flux} \otimes \text{Cross section}$$

Solar ^{8}B flux known to ~% level... others not so much...

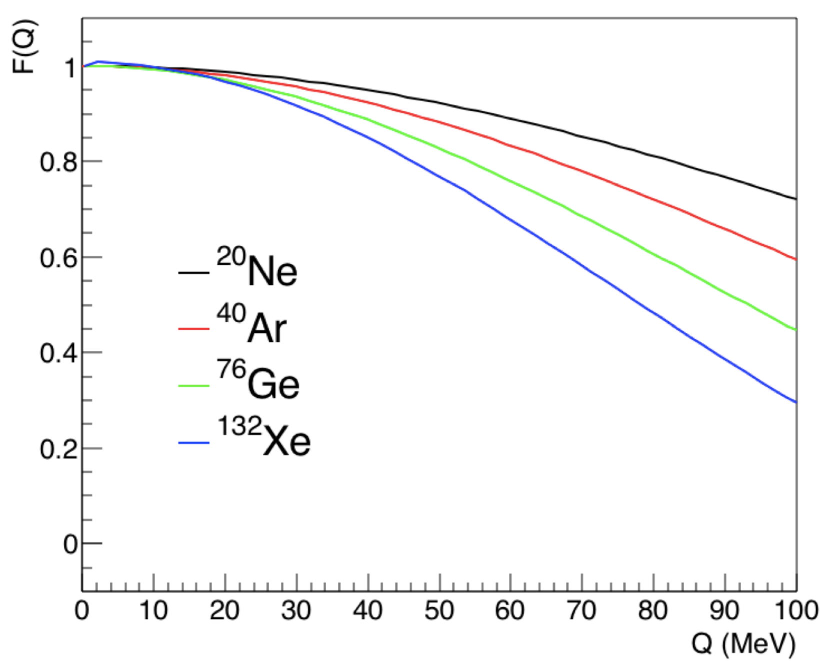
CEvNS xscn predicted at **few % level in SM**...

Standard Model CEvNS rate:

$$\frac{d\sigma}{dT} = \frac{G_F^2 M}{\pi} F^2(Q) \left[(G_V + G_A)^2 + (G_V - G_A)^2 \left(1 - \frac{T}{E_\nu}\right)^2 - (G_V^2 - G_A^2)\frac{MT}{E_\nu^2} \right]$$

E_ν: neutrino energy
T: nuclear recoil energy
M: nuclear mass
Q = √ (2 M T): momentum transfer
G_V, G_A: SM weak parameters

F(Q): nuclear **form factor** e.g., “Helm”



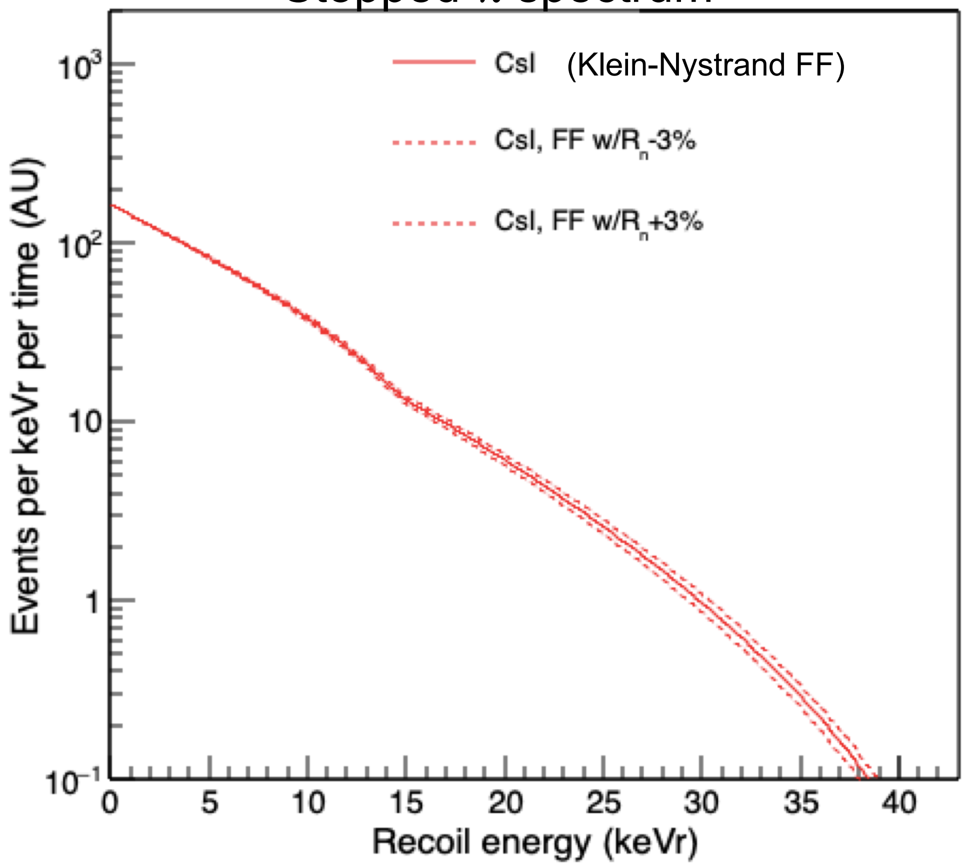
$$F(Q) = \frac{3}{QR_0}\left(\frac{\sin(QR_0)}{(QR_0)^2} - \frac{\cos(QR_0)}{QR_0}\right) e^{-Q^2 s^2/2}$$

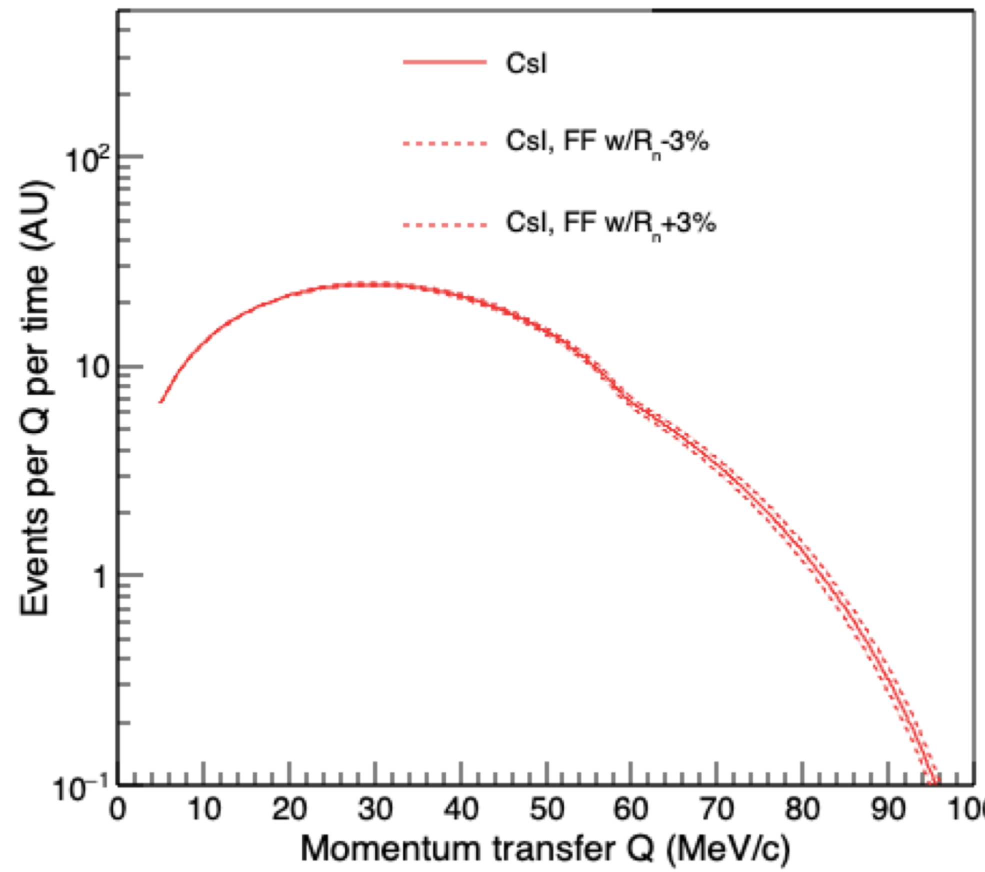
form factor suppresses cross section at large Q

Effect of form-factor *uncertainty* on the recoil spectrum: estimate as R_n +/- 3%

$$\frac{d\sigma}{dT} = \frac{G_F^2 M}{\pi} F^2(Q) \left[(G_V + G_A)^2 + (G_V - G_A)^2 \left(1 - \frac{T}{E_\nu}\right)^2 - (G_V^2 - G_A^2)\frac{MT}{E_\nu^2} \right]$$

Stopped-π spectrum





At current level of experimental precision, form factor uncertainty is small effect

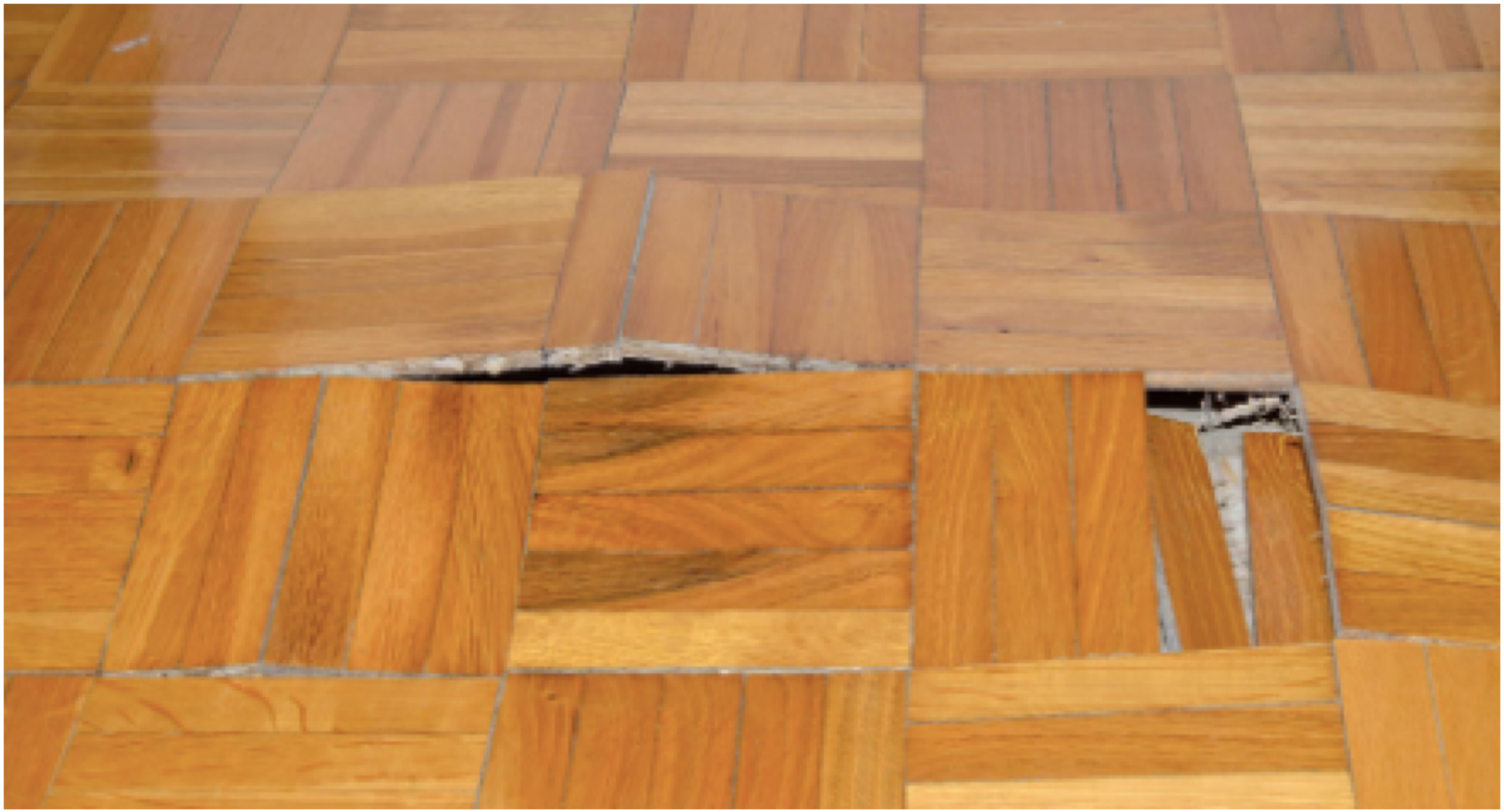
How well do we know where the neutrino floor is?

$$\text{Rate} \propto \text{Flux} \otimes \text{Cross section}$$

Solar ^8B flux known to ~% level... others not so much...

CEvNS xscn predicted at **few % level in SM**... some nuclear uncertainties, but small for most targets

But what if there's BSM physics?

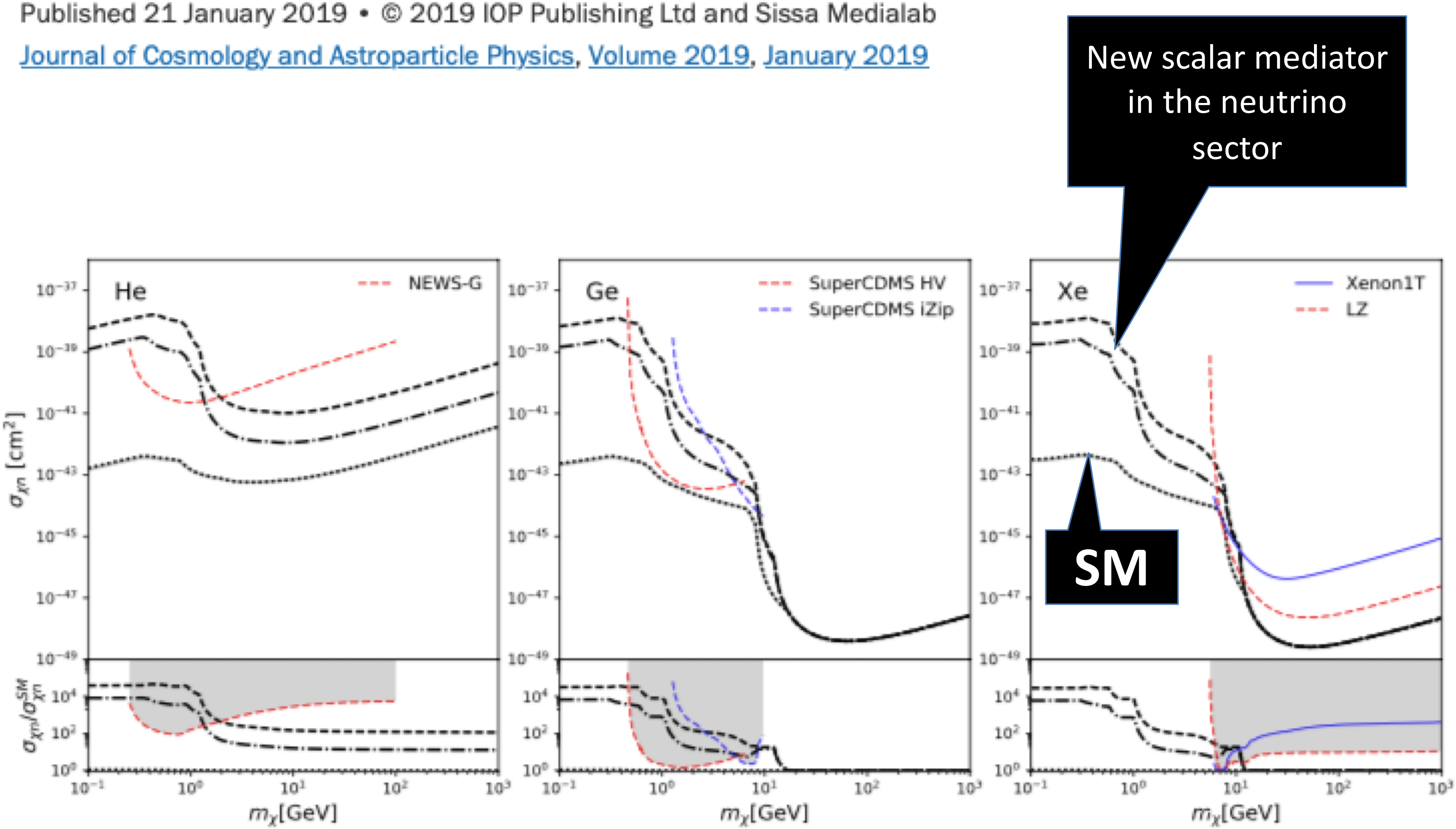


Non-standard interactions could raise the floor...

How high is the neutrino floor?

C. Bœhm[a,b], D.G. Cerdeño[c], P.A.N. Machado[d], A. Olivares-Del Campo[c], E. Perdomo[e] and E. Reid[c]

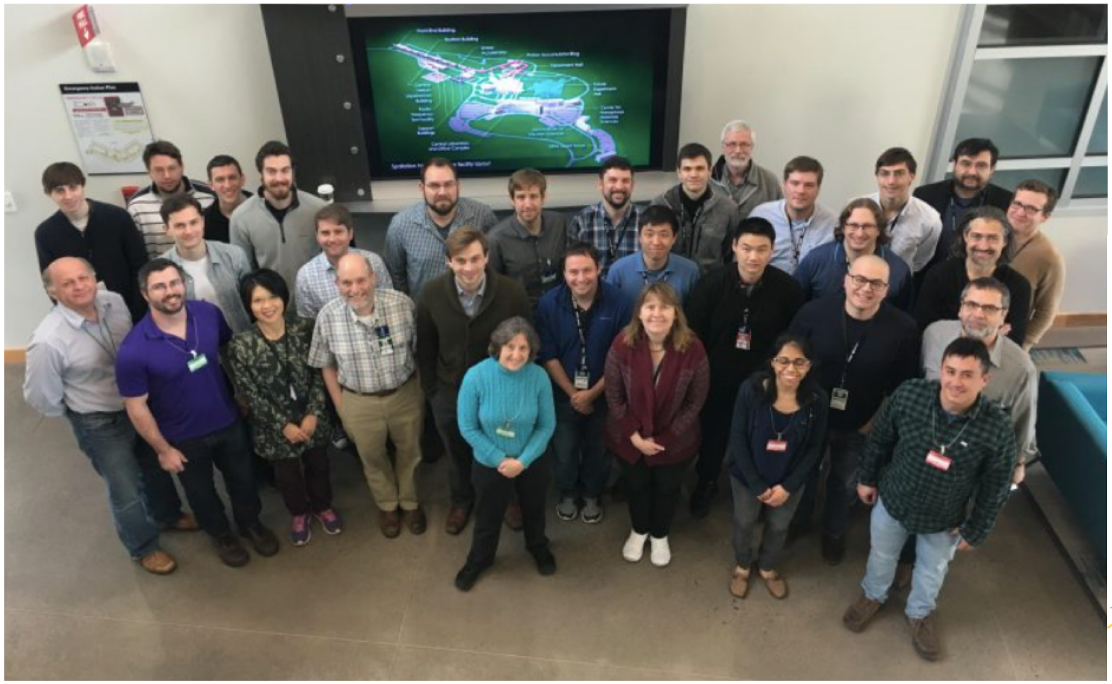
Published 21 January 2019 • © 2019 IOP Publishing Ltd and Sissa Medialab
Journal of Cosmology and Astroparticle Physics, Volume 2019, January 2019



We need to *measure* CEvNS!

The COHERENT collaboration

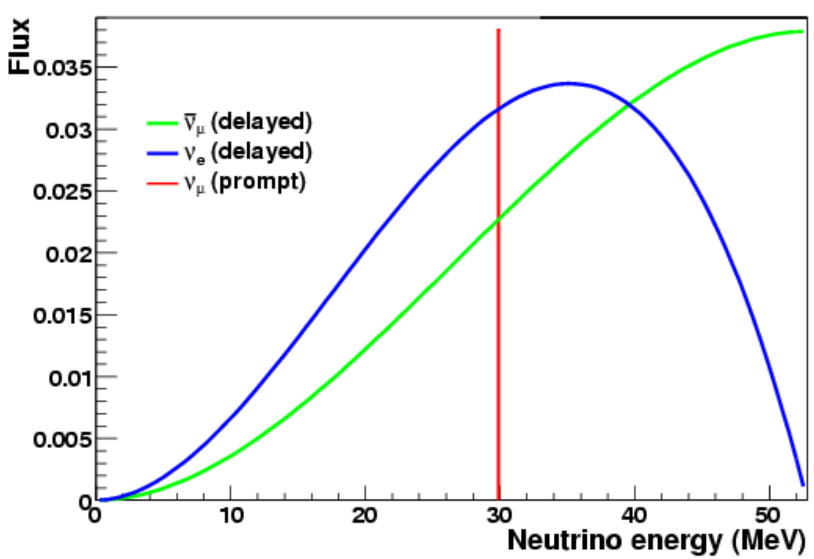
http://sites.duke.edu/coherent

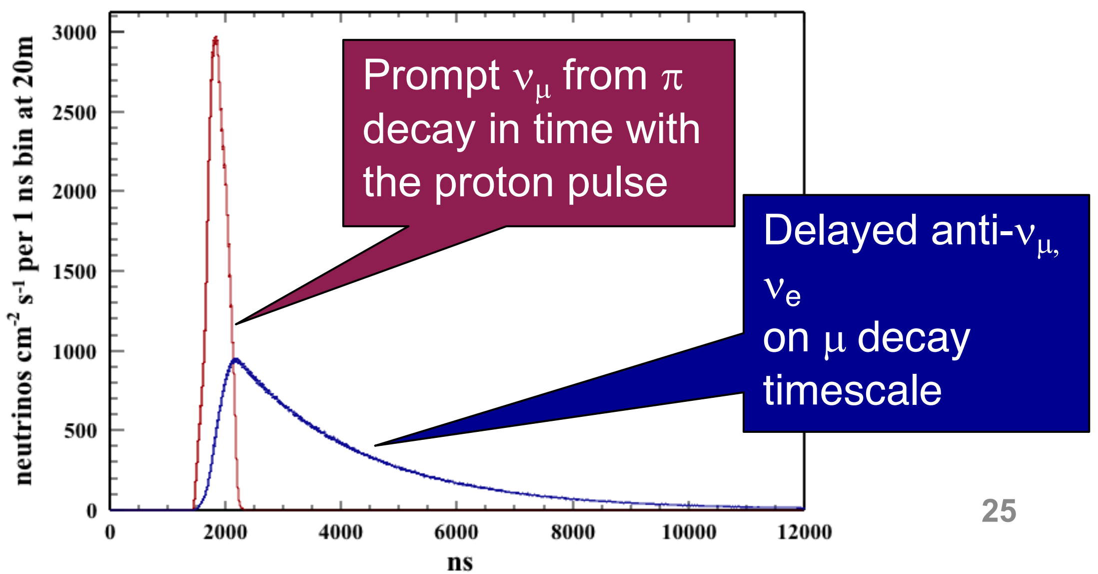


~90 members,
21 institutions
4 countries

arXiv:1803.09183v2

Free high-intensity, clean, pulsed stopped-pion neutrinos!

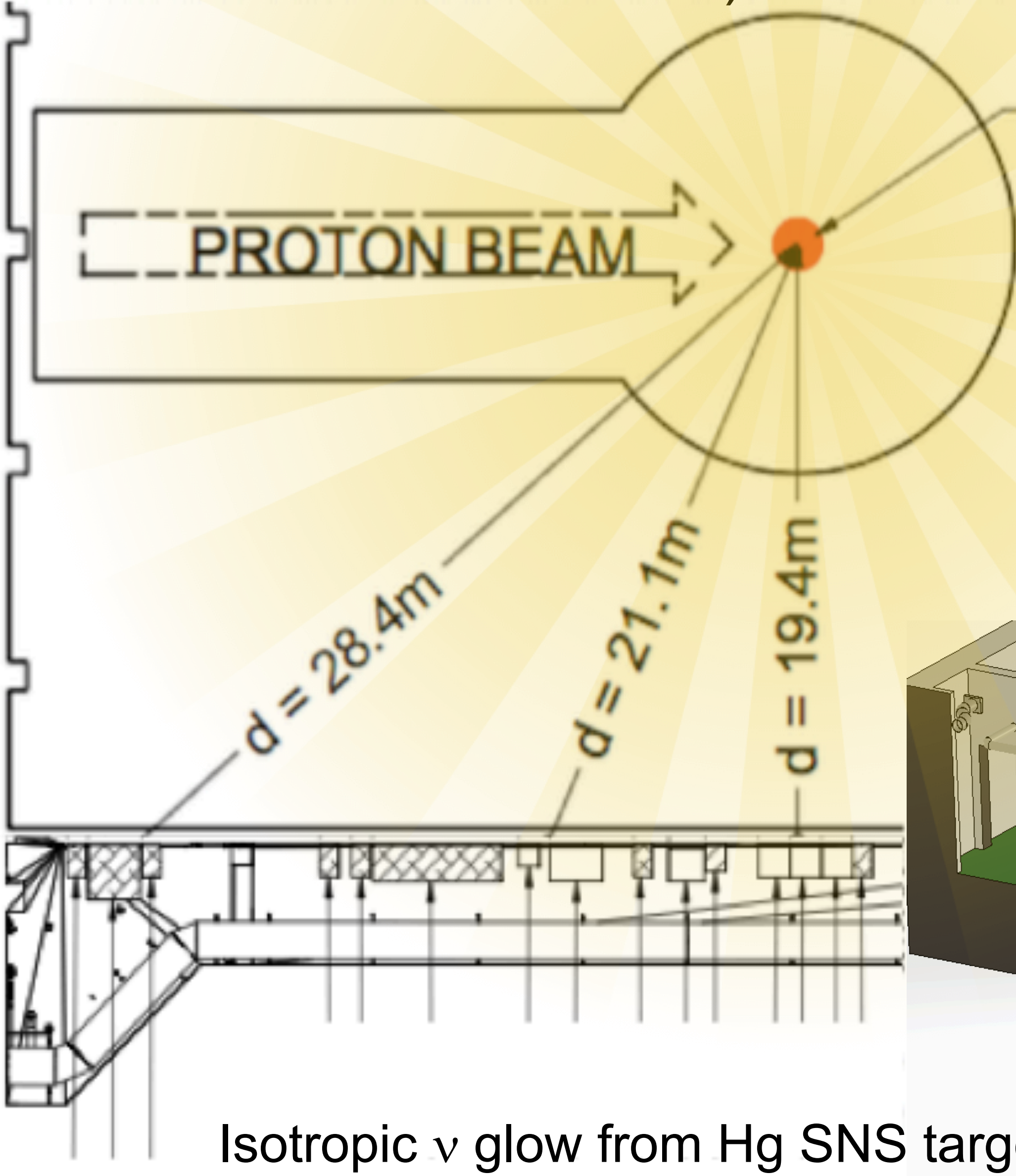


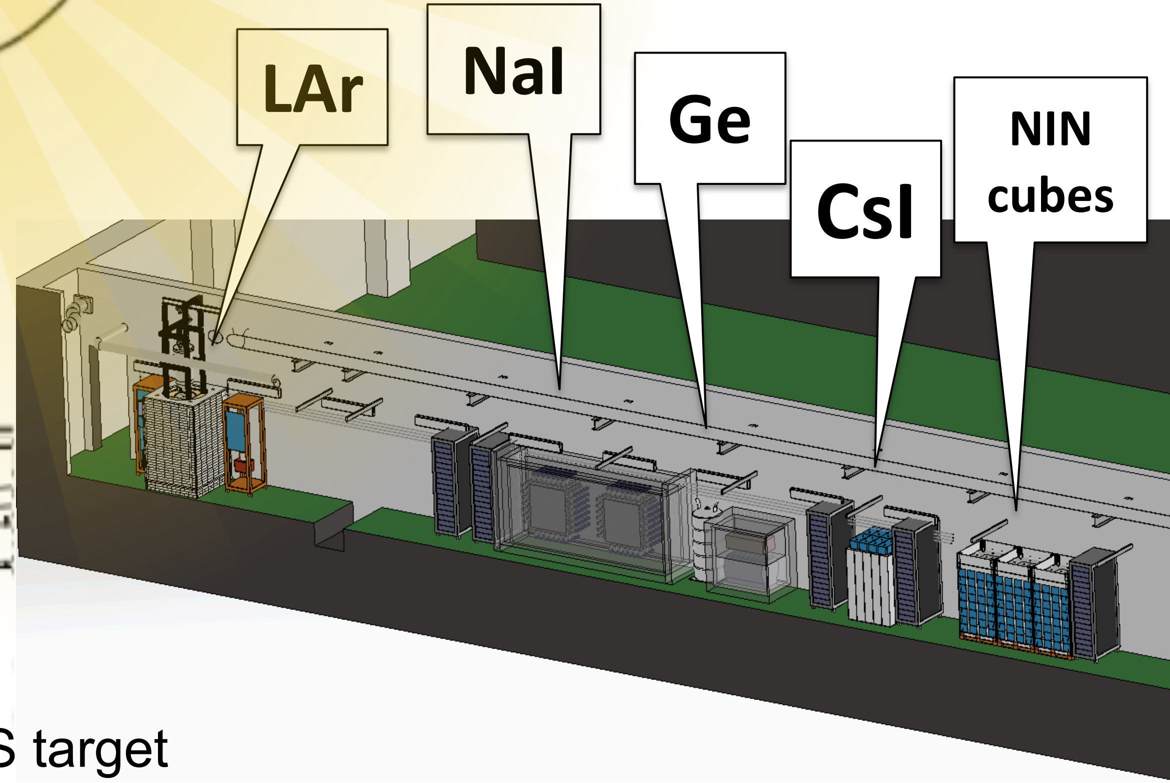


Siting for deployment in SNS basement

(measured neutron backgrounds low,

~ 8 mwe overburden)

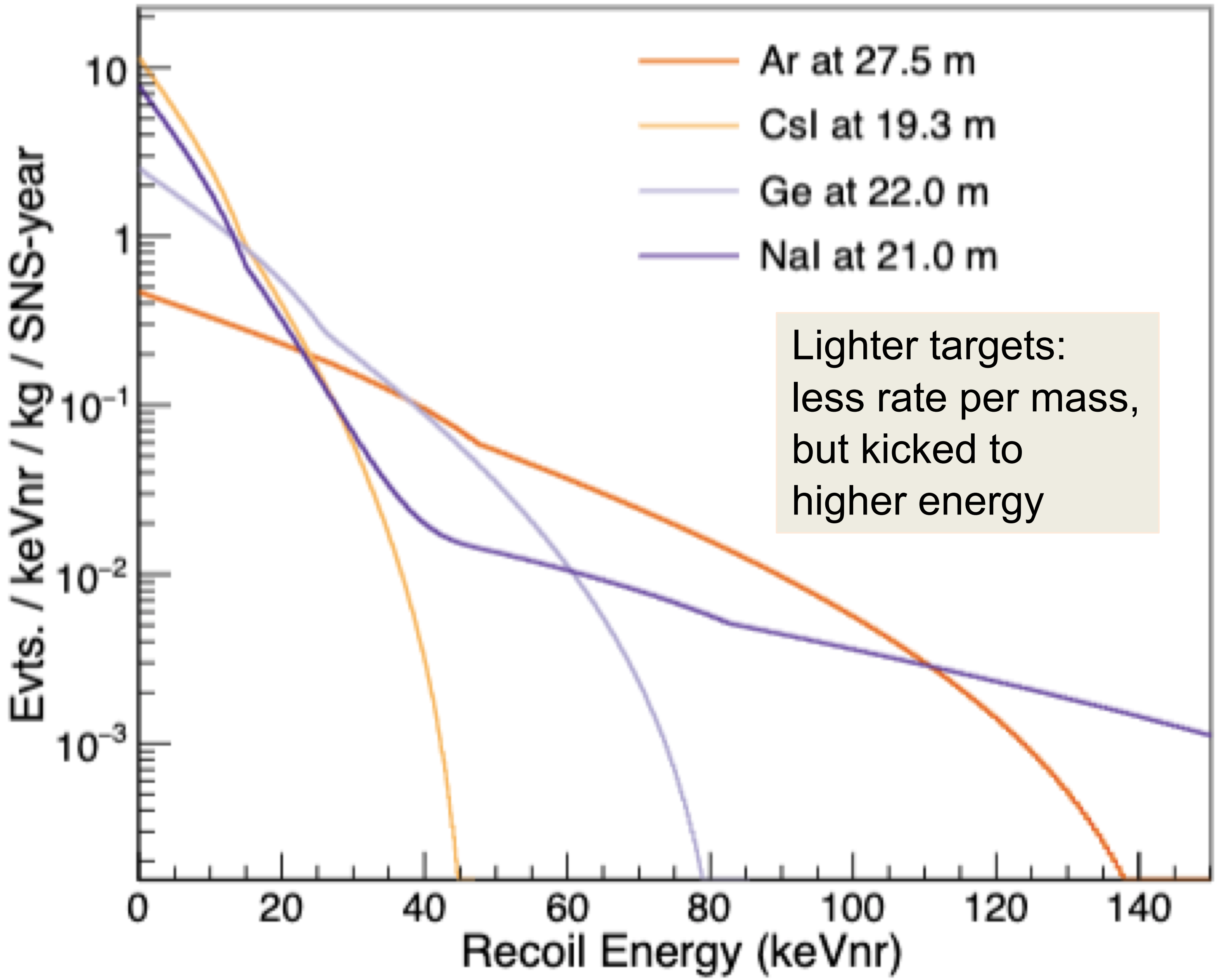




Isotropic ν glow from Hg SNS target

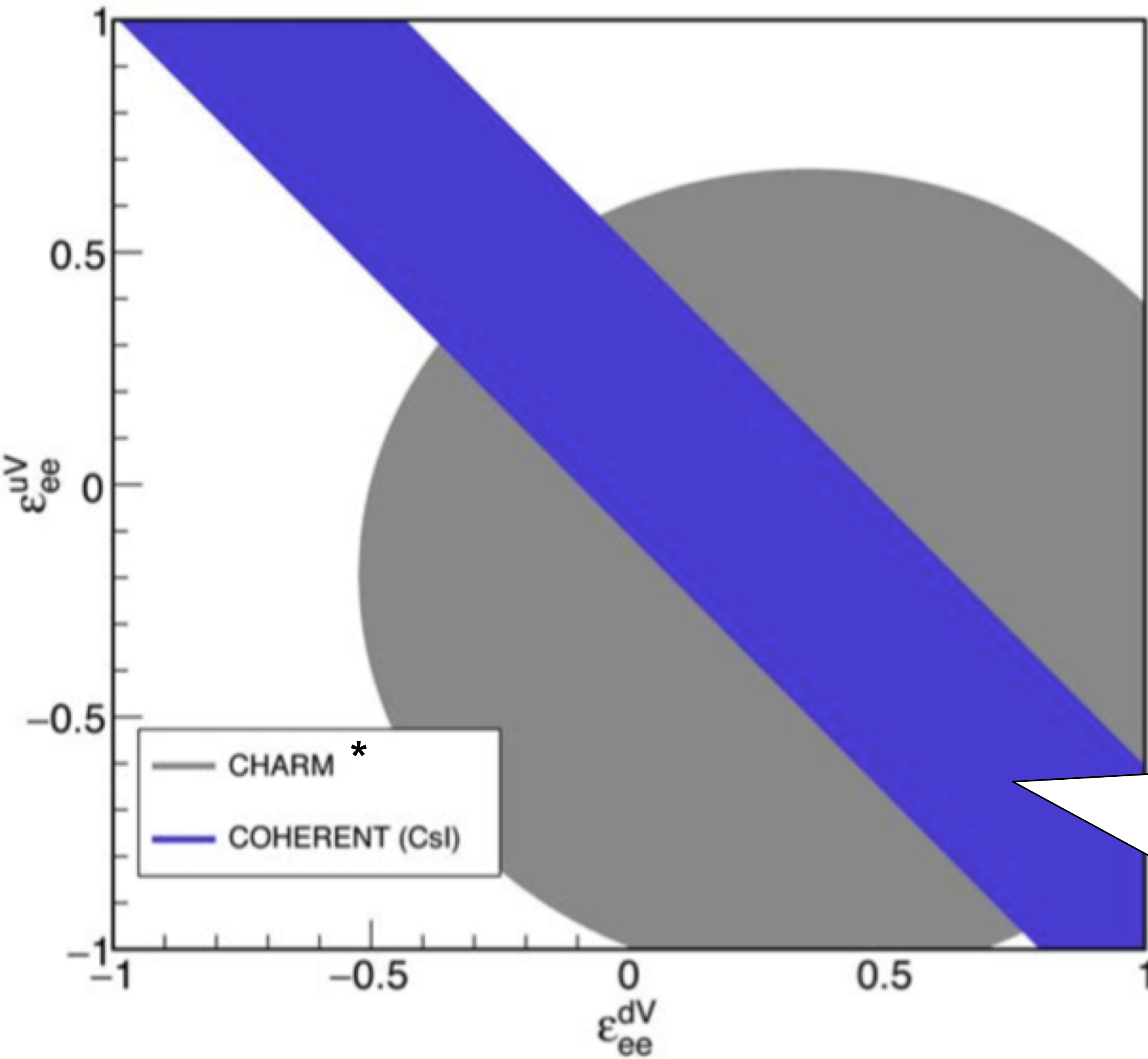
View looking down “Neutrino Alley”

Expected recoil energy distribution @SNS



Lighter targets:
less rate per mass,
but kicked to
higher energy

Neutrino non-standard interaction results for current CsI data set:

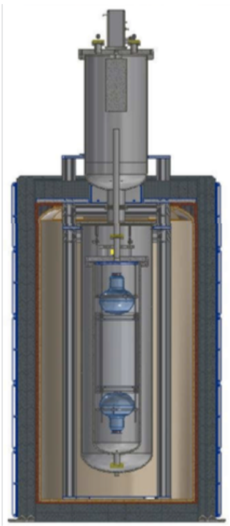


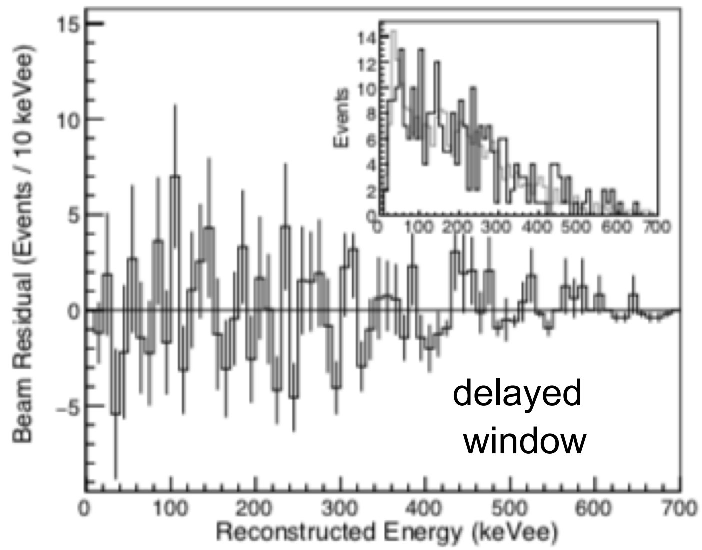
- Assume all other ε's zero

Parameters describing beyond-the-SM interactions outside this region disfavored at 90%

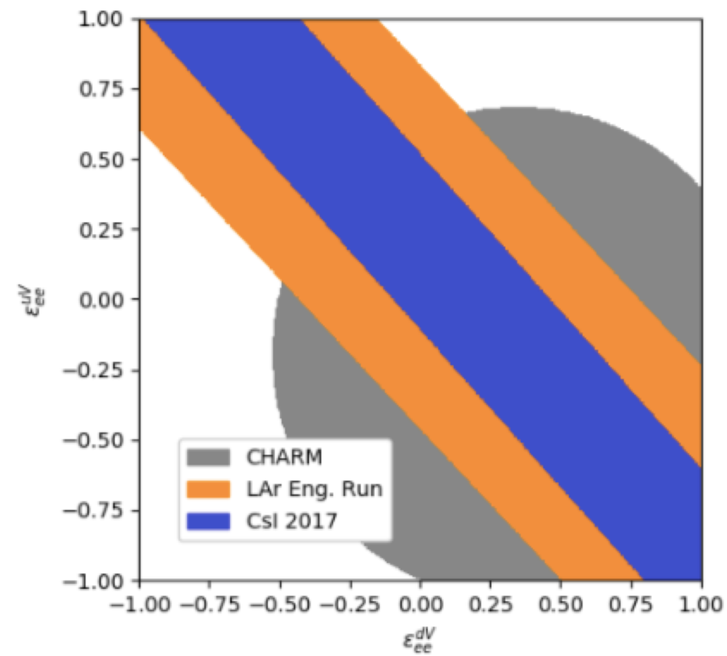
*CHARM constraints apply only to heavy mediators

COHERENT LAr Engineering Run Result





Matt Heath, Indiana U., thesis
APS April meeting
Just posted on arXiv

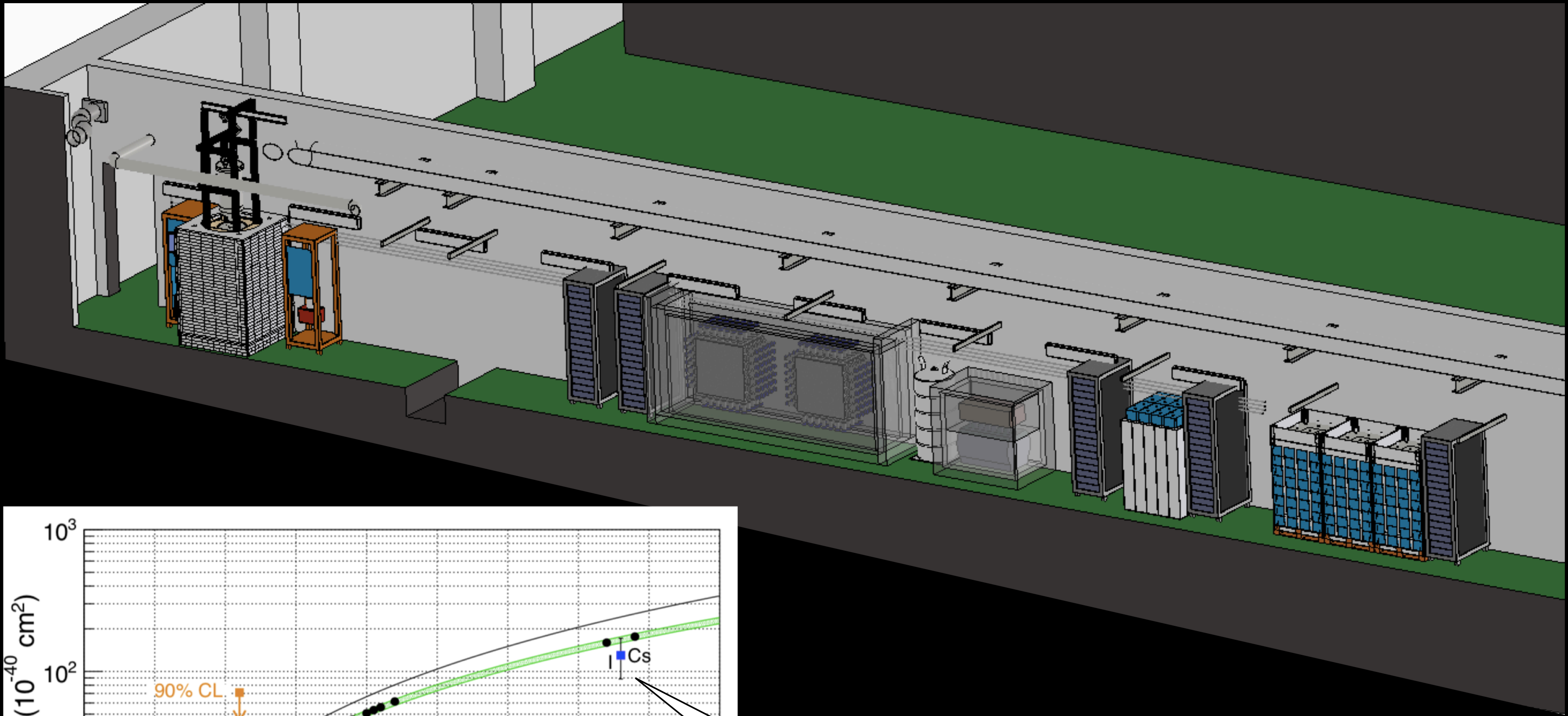


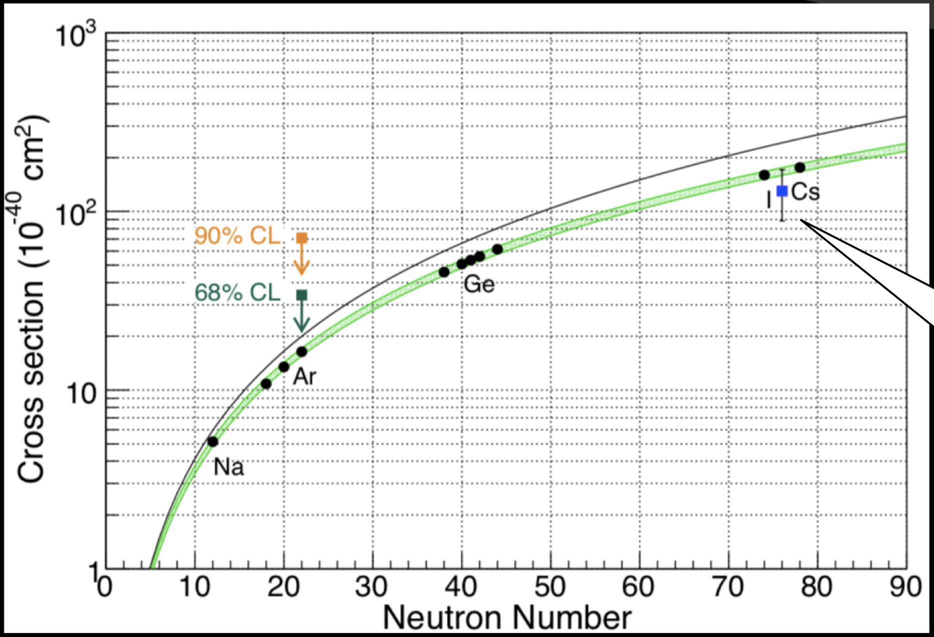
measure 1 ± 4 (stat), expect <1

$\sigma_{\text{flux-avg}} < 3.4 \times 10^{-39}\ \text{cm}^2$

- **Results from more CsI running,** improved QF & analysis
- **Results from 22-kg LAr detector**
- Treatment of shape systematics
- Accelerator-produced DM sensitivity

What's Next for COHERENT?

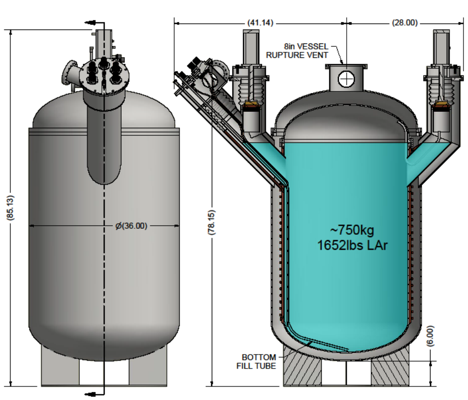


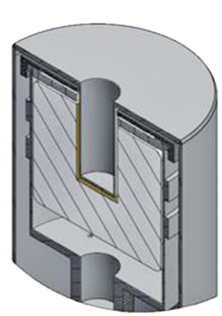


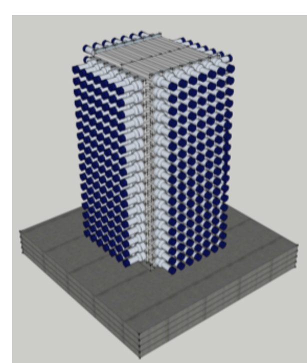
One measurement (and a limit) so far! Want to map out N^2 dependence

COHERENT **CEvNS** Detector Status and **Farther Future**

Nuclear Target	Technology	Mass (kg)	Distance from source (m)	Recoil threshold (keVr)	Data-taking start date	Future
CsI[Na]	Scintillating crystal	14.6	20	6.5	9/2015	Decommissioned
Ge	HPGe PPC	16	20	<few	2020	Funded by NSF MRI, in progress
LAr	Single-phase	22	20	20	12/2016, upgraded summer 2017	Expansion to **750 kg scale**
NaI[Tl]	Scintillating crystal	185*/ 3388	28	13	*high-threshold deployment summer 2016	Expansion to **3.3 tonne**, up to 9 tonnes



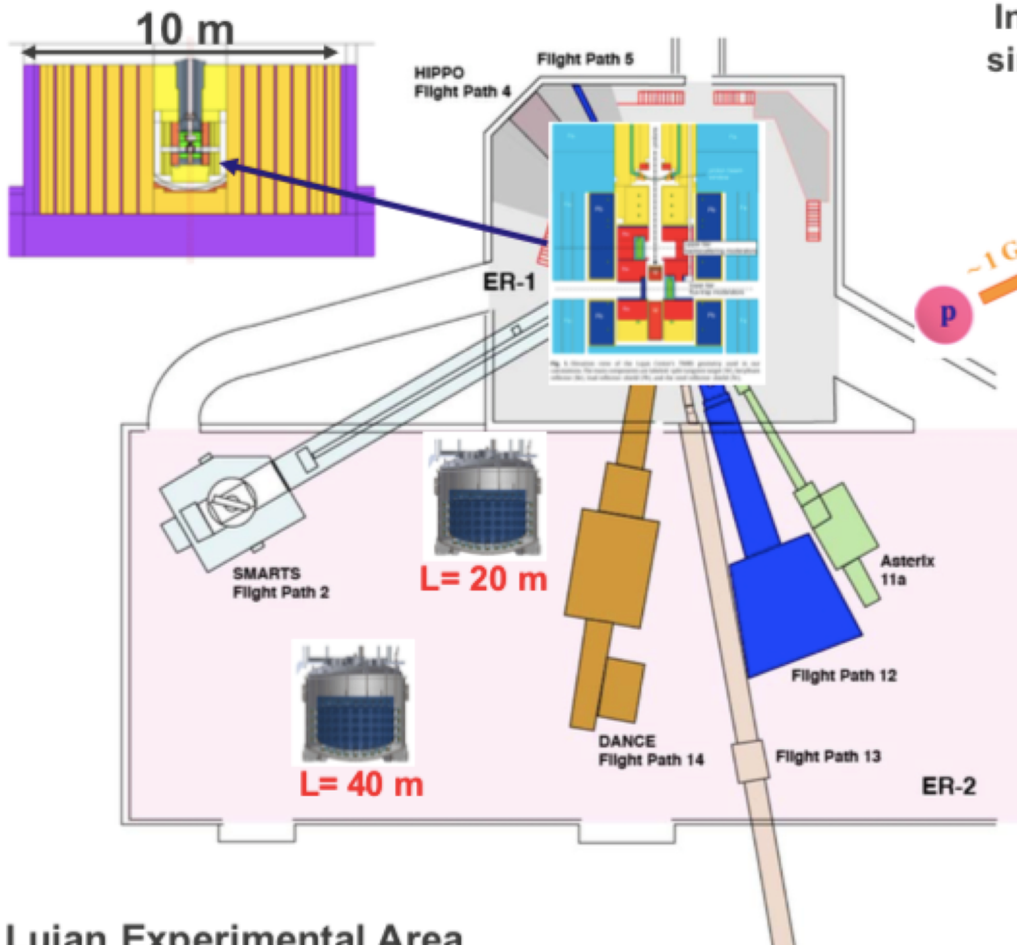




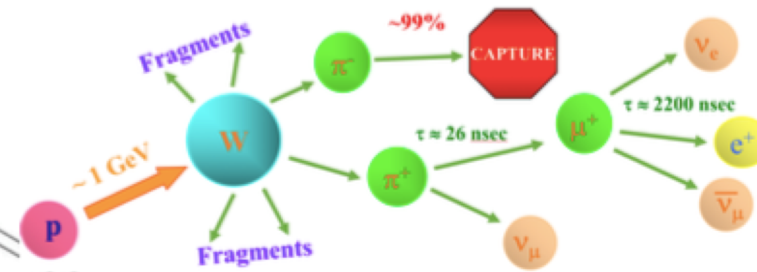
+D_2O for flux normalization
+ concepts for other targets...

Check out "The Magnificent CEvNS" workshop slides for more info!

Coherent Captain Mills @ Lujan: single-phase LAr



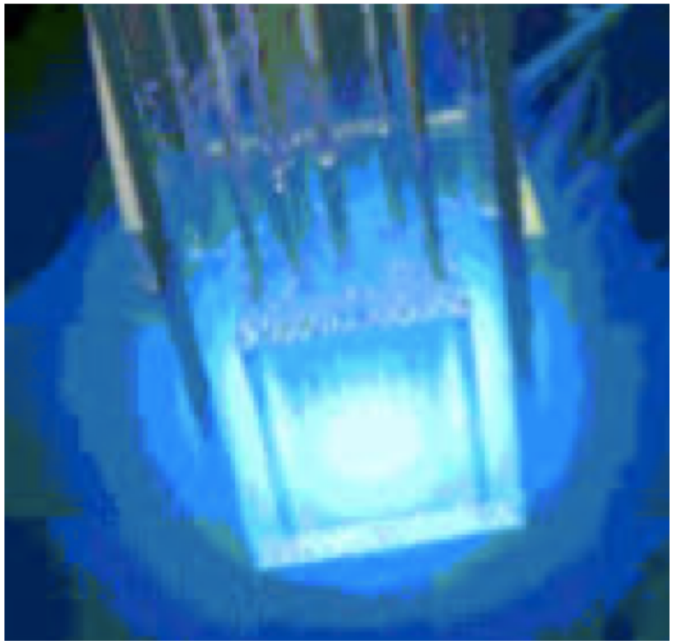
Intense source muon neutrinos: target MCNP simulation flux 4.74x10^5 ν/cm^2/s at 20 m

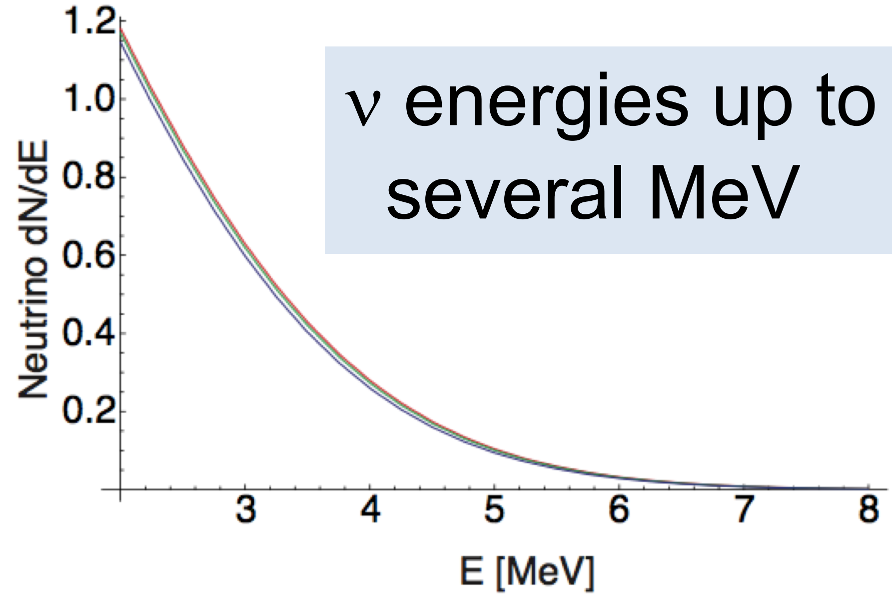


Lujan Experimental Area

- Space for large 10-ton liquid Argon ν detector.
- Run detector in multiple locations.
- Room to deploy shielding, large overhead crane, power, etc

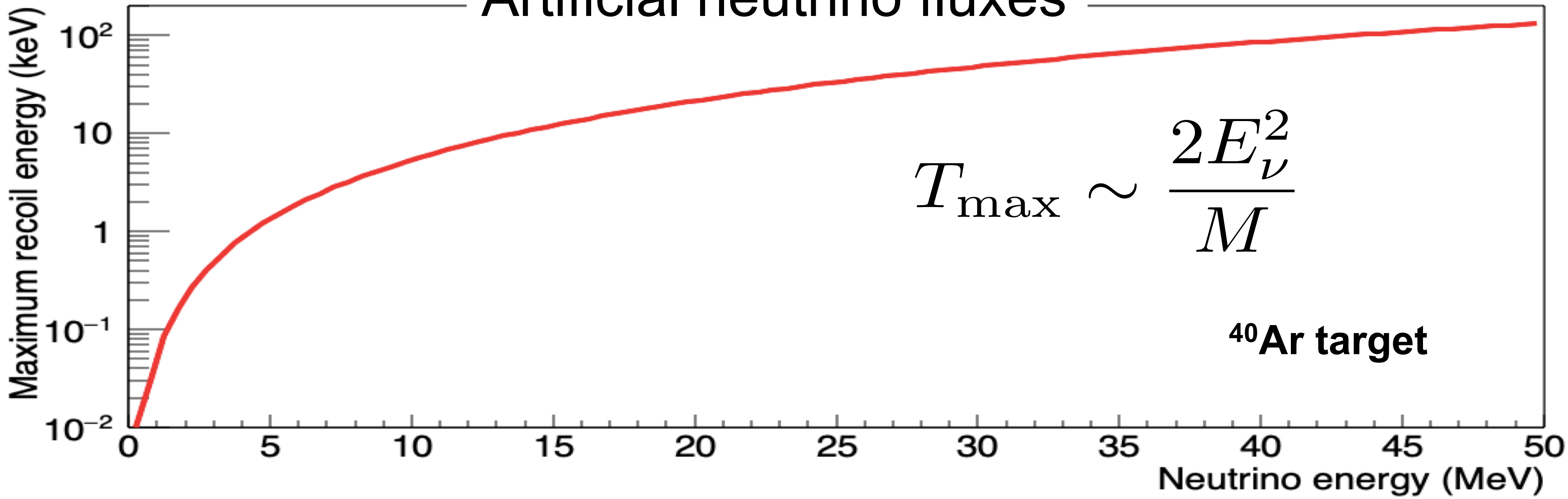
CEvNS with neutrinos from nuclear reactors

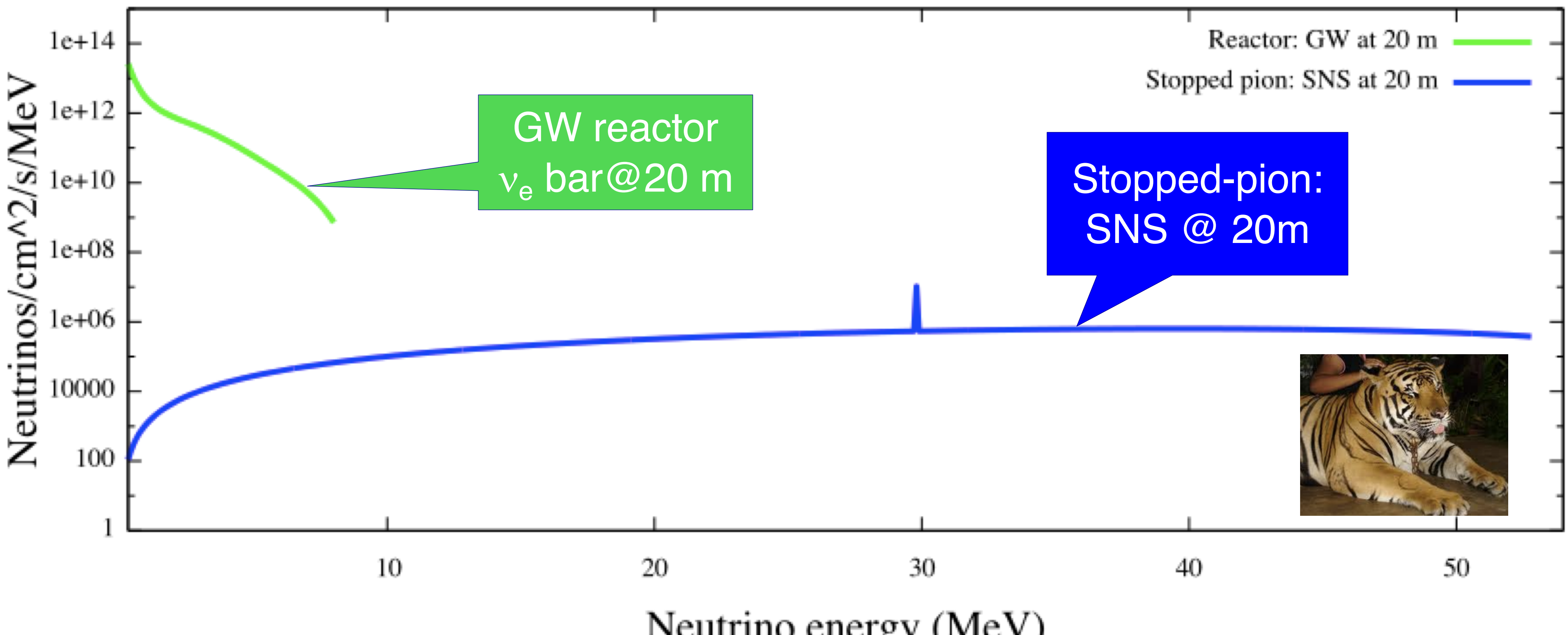




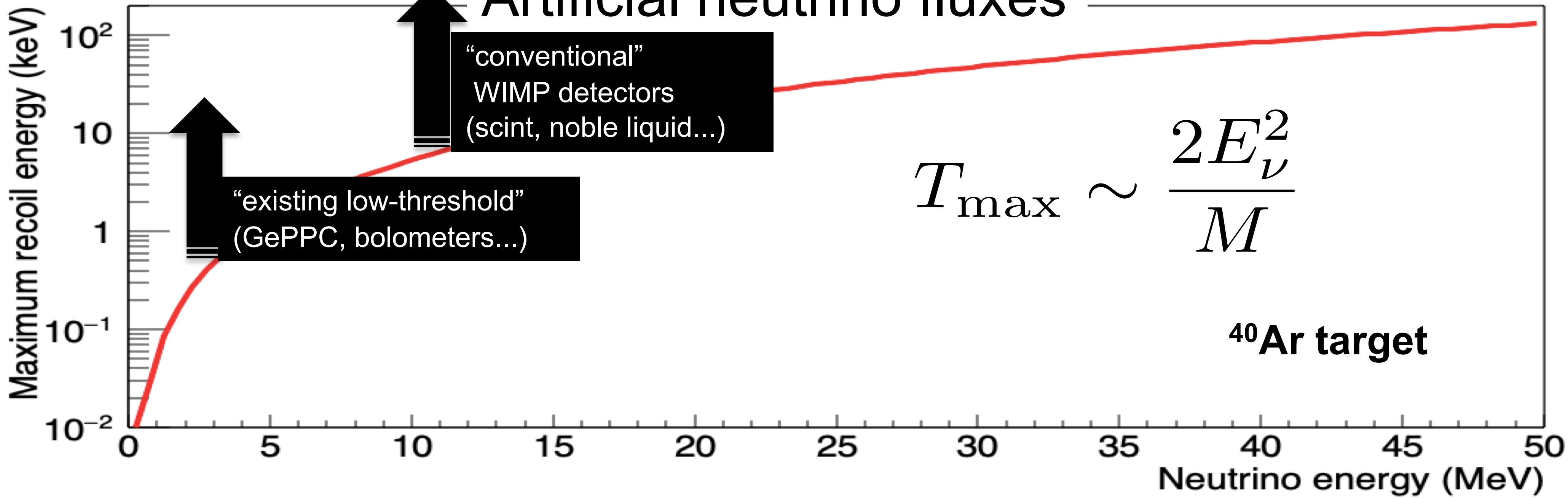
- ν_e-bar produced in fission reactions (one flavor)
- **huge fluxes possible**: ~$2x10^{20}$ s^{-1} per GW
- several CEvNS searches past, current and future at reactors, but **recoil energies<keV** and backgrounds make this very challenging

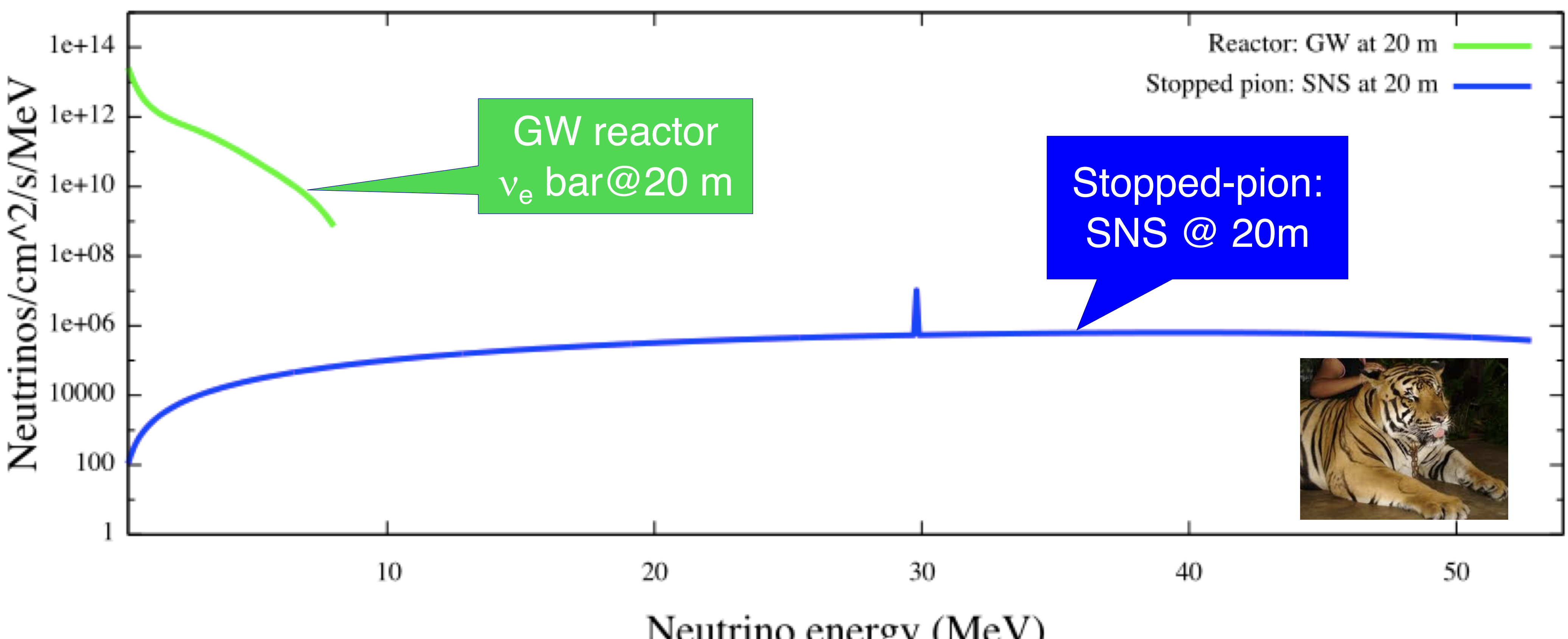
Artificial neutrino fluxes





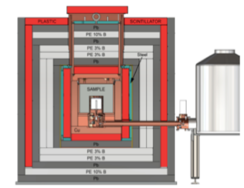
Artificial neutrino fluxes

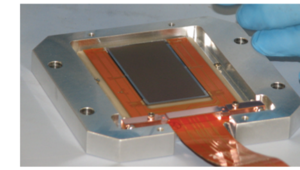


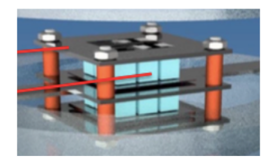


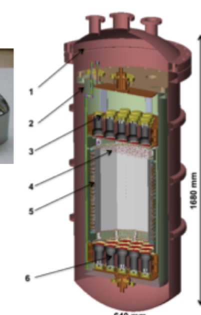
Reactor CEvNS Efforts Worldwide

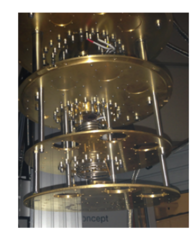
Experiment	Technology	Location
CONNIE	Si CCDs	Brazil
CONUS	HPGe	Germany
MINER	Ge/Si cryogenic	USA
Nu-Cleus	Cryogenic $CaWO_4$, Al_2O_3 calorimeter array	Europe
νGEN	Ge PPC	Russia
RED-100	LXe dual phase	Russia
Ricochet	Ge, Zn bolometers	France
TEXONO	p-PCGe	Taiwan

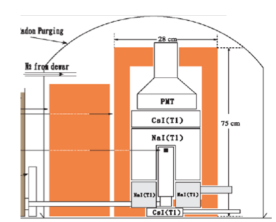










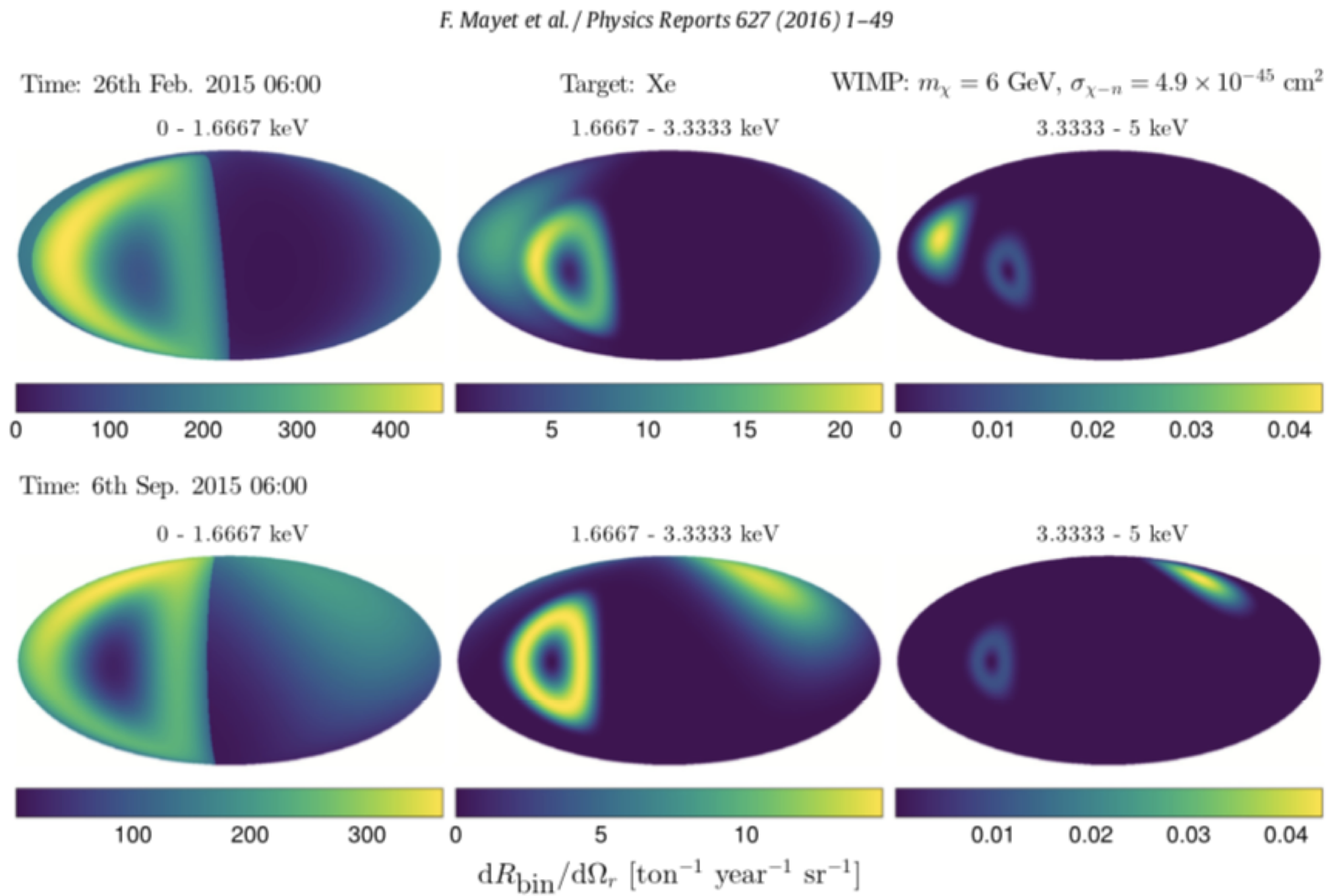


Many novel low-background, low-threshold technologies

See H. Wong, Nu2018 talk for a more detailed survey

Back to the neutrino floor...

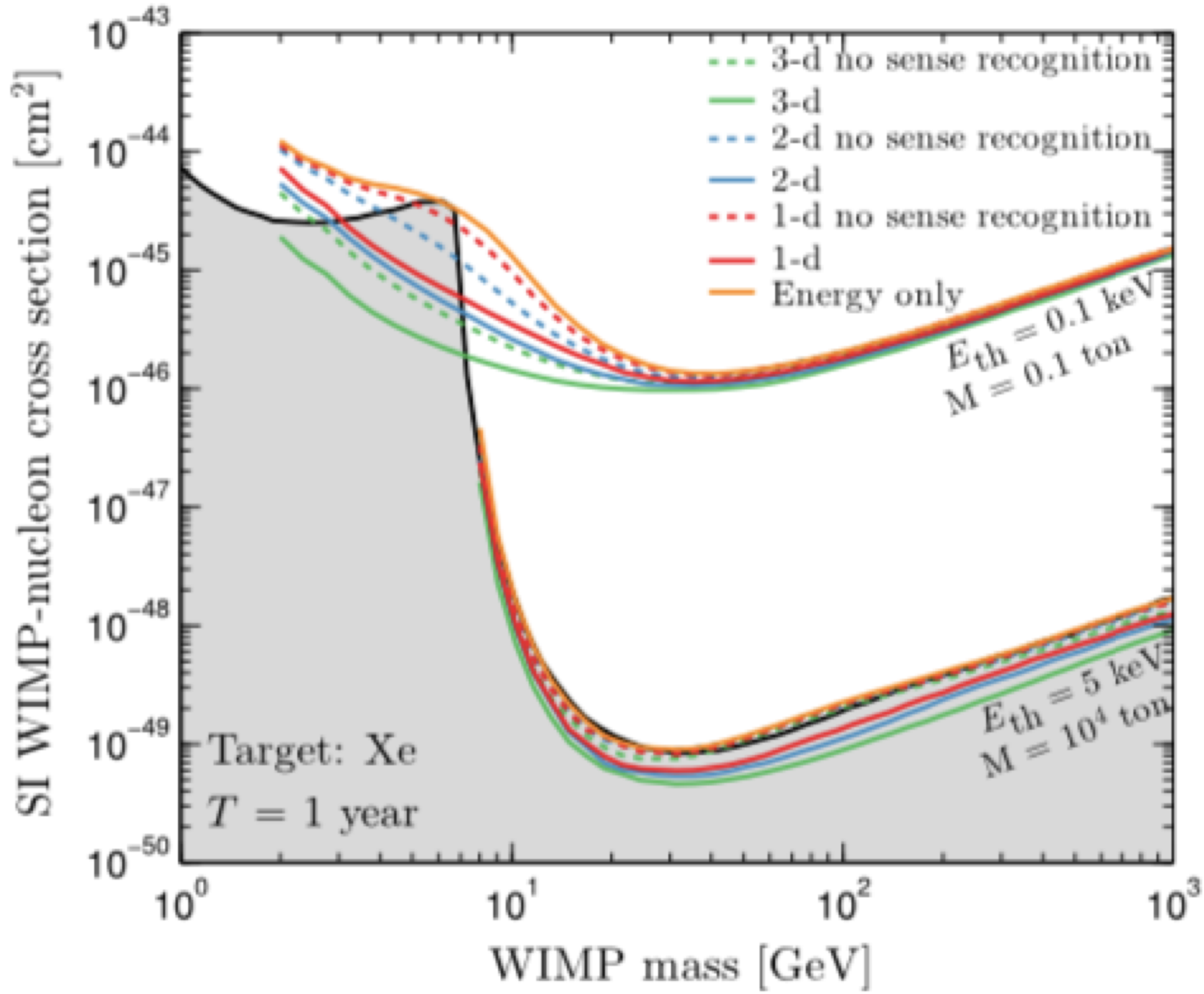
Directional recoil detection could help a lot...



The Sun and the WIMPs don't shine in the same parts of the sky

May see below the floor...

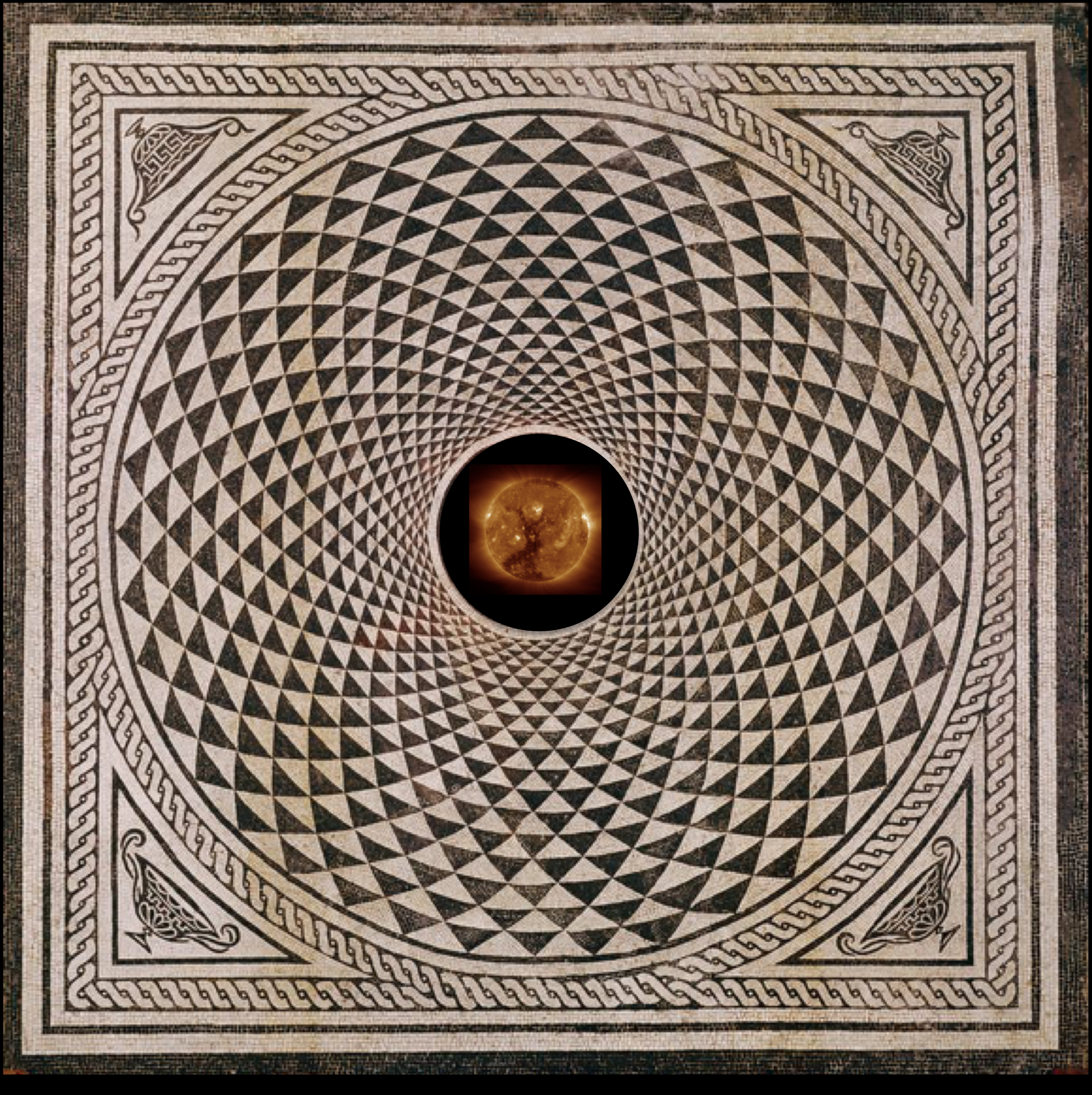
F. Mayet et al. / Physics Reports 627 (2016) 1–49



More in next talks by Ciaran O’Hare and Tatsuhiro Naka

The Patterned Neutrino Floor

Sometimes there are interesting things to see when you look down...

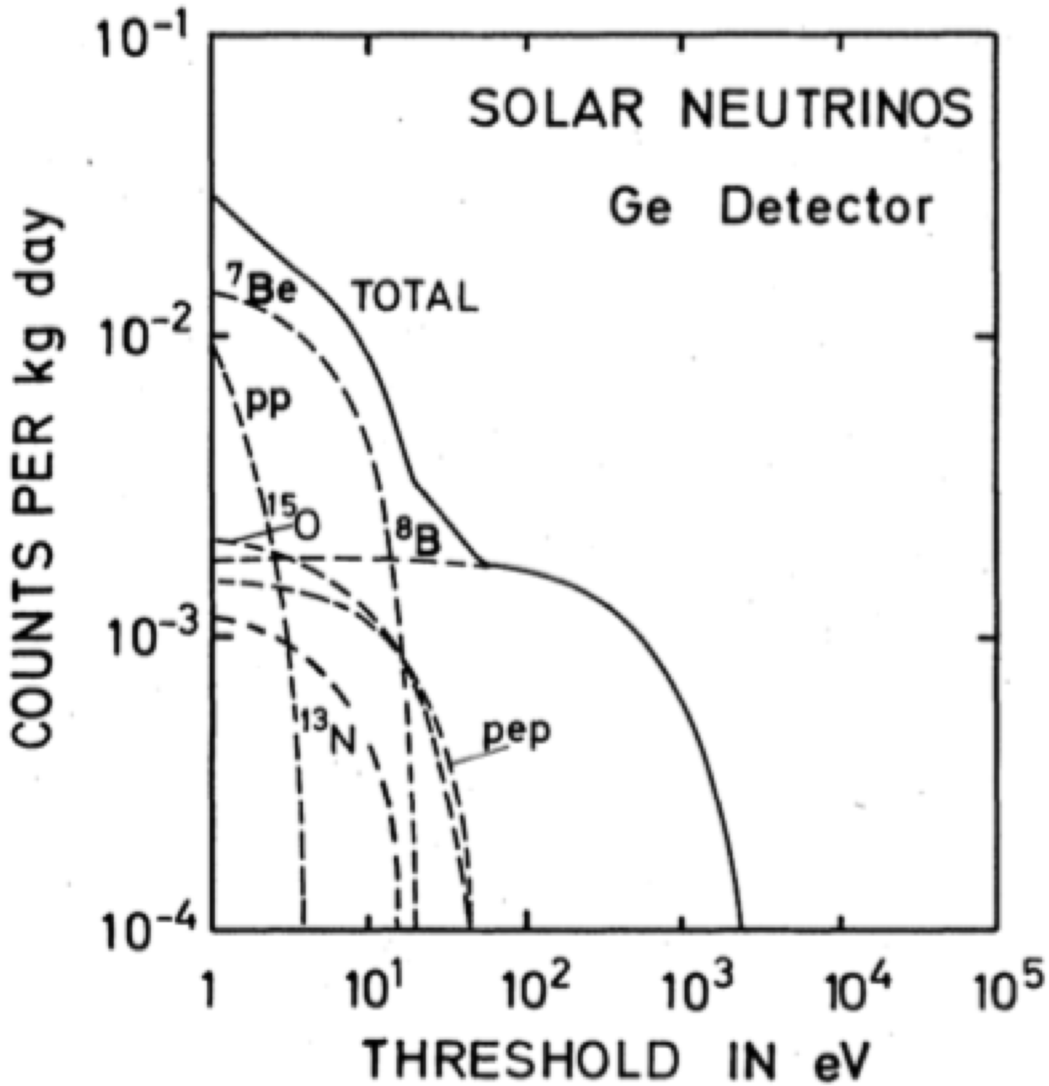


First suggestion for CEvNS as a solar neutrino *signal*

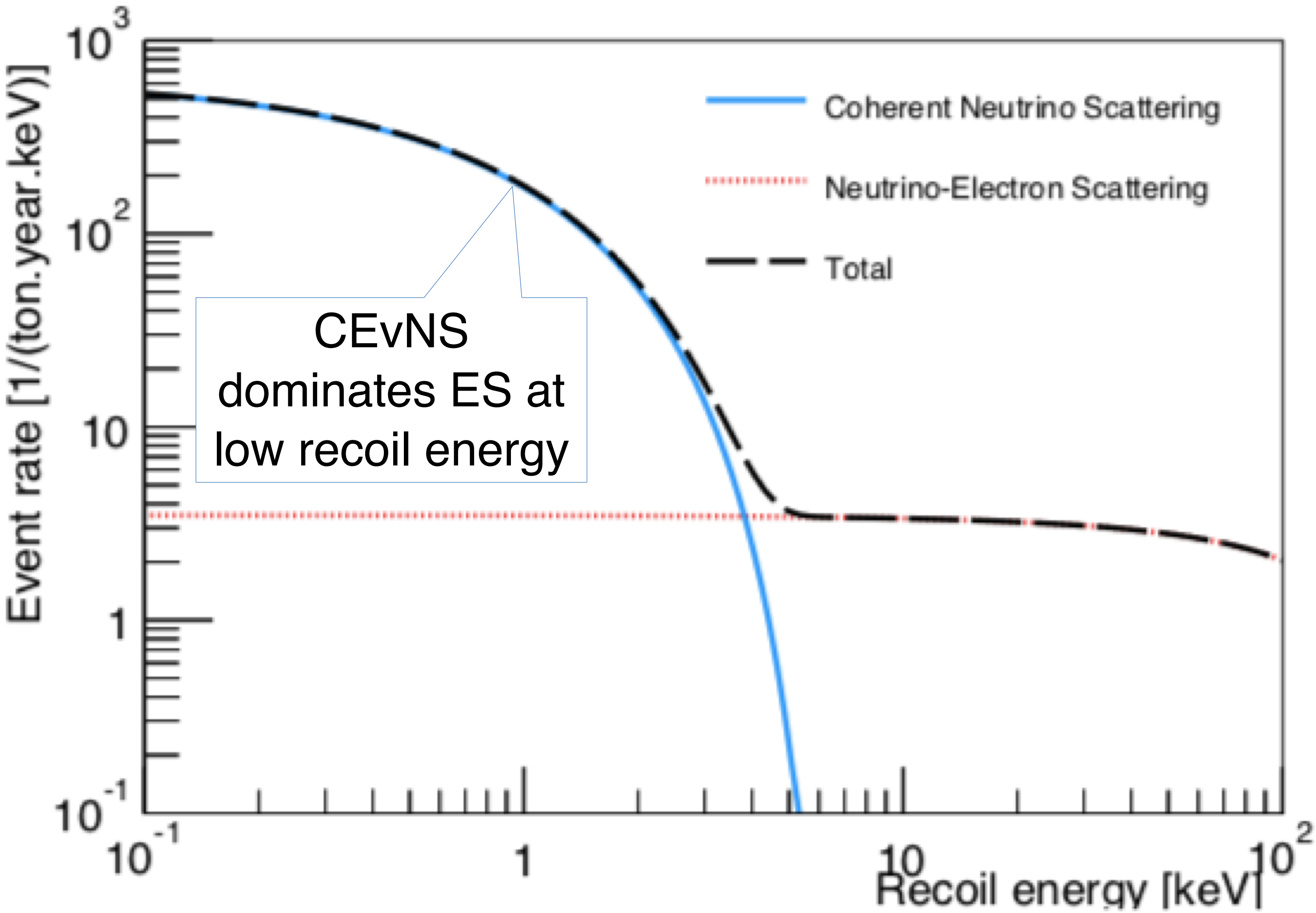
PHYSICAL REVIEW D VOLUME 30, NUMBER 11 1 DECEMBER 1984

Principles and applications of a neutral-current detector for neutrino physics and astronomy

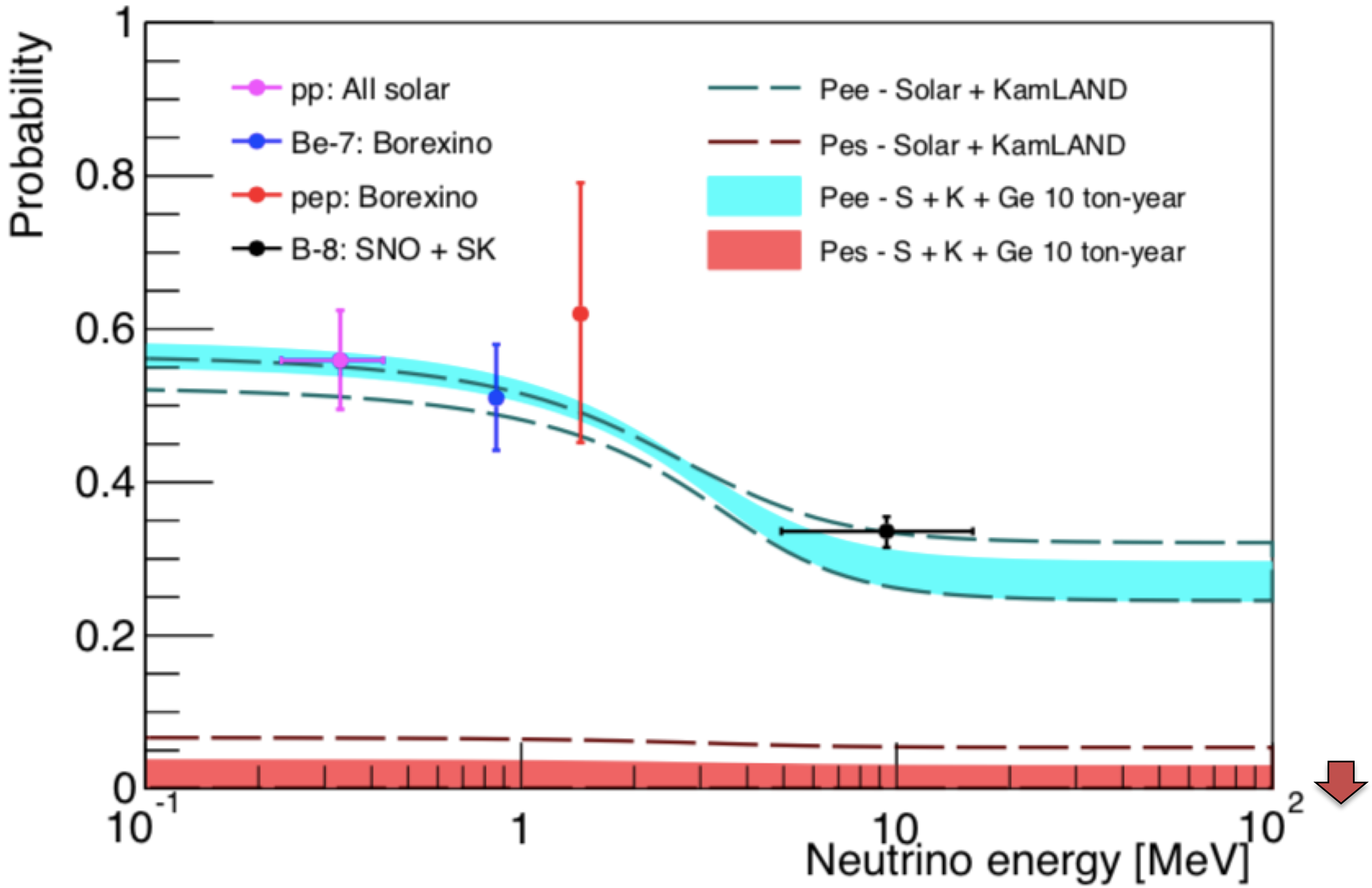
A. Drukier and L. Stodolsky
Max-Planck-Institut für Physik und Astrophysik, Werner-Heisenberg-Institut für Physik, Munich, Federal Republic of Germany
(Received 21 November 1983)



^{8}B solar neutrinos in germanium



J. Billard, L. Strigari, and E. Figueroa-Feliciano, Phys.Rev. D91 (2015) no.9, 095023



In principle, can better constrain sterile component in solar flux

(may need an unrealistic amount of Ge...)

J. Billard, L. Strigari, and E. Figueroa-Feliciano,
Phys.Rev. D91 (2015) no.9, 095023

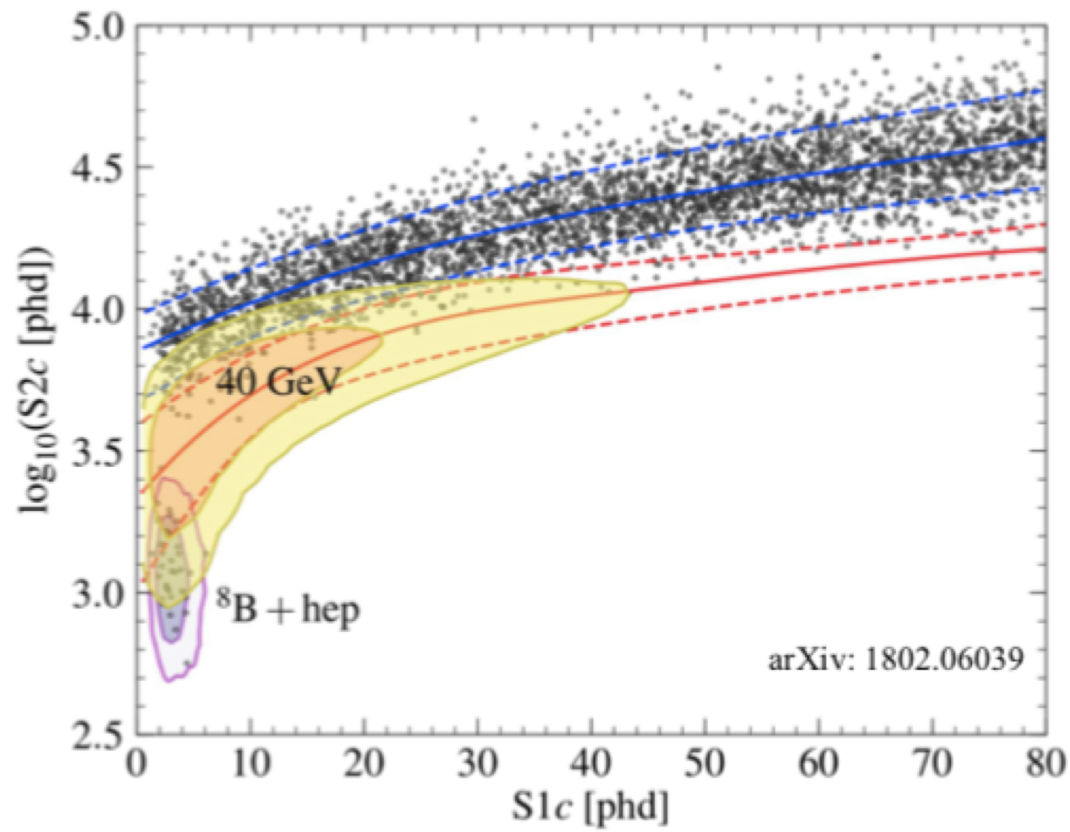
Solar neutrino detection in LXe

Expected CEvNS events in LZ

We expected ~35 CEvNS events in the whole LZ exposure

- The actual CEvNS rate will depend on the low-energy xenon recoil yield values and detector efficiencies
- The exact distribution of ^{8}B CEvNS events may shift if the yield values differ from current assumptions

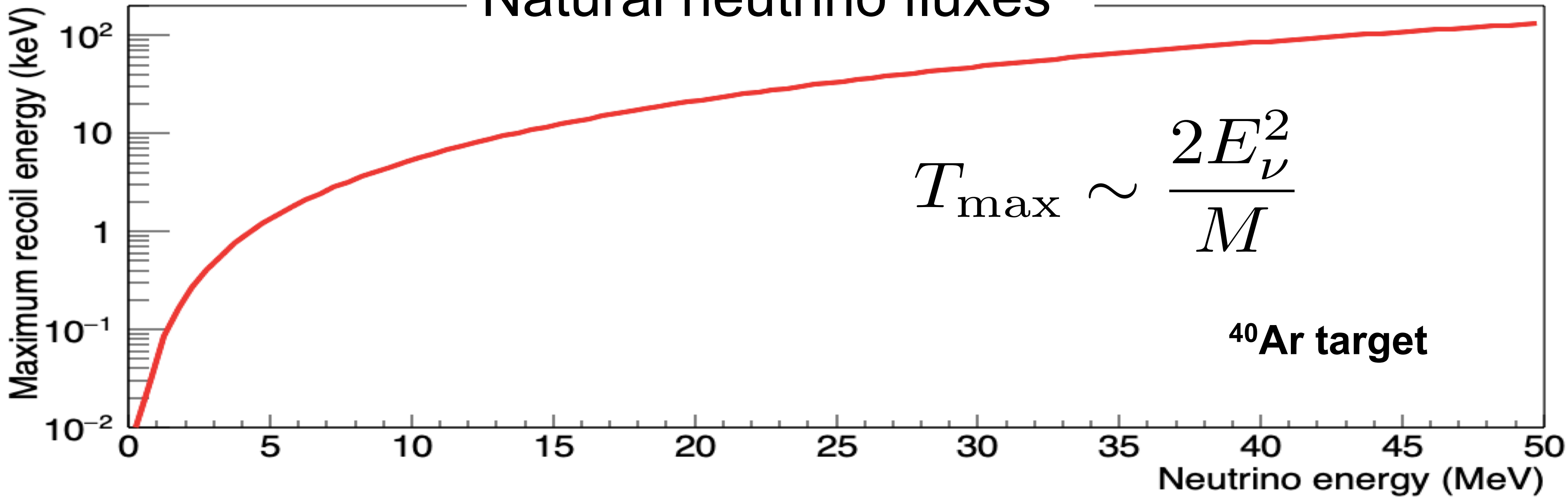
The event rate will be much higher if we can lower the analysis threshold (reduced S1 coincidence threshold, or S2-only)

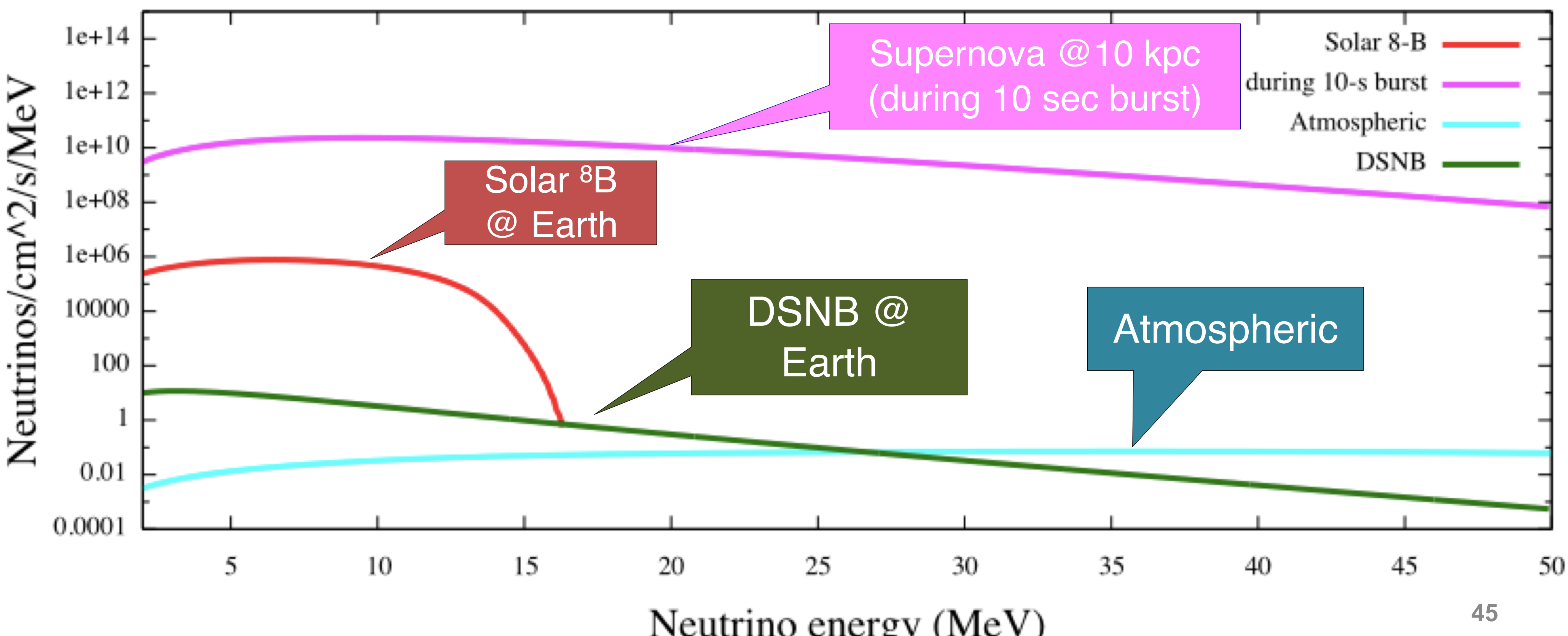


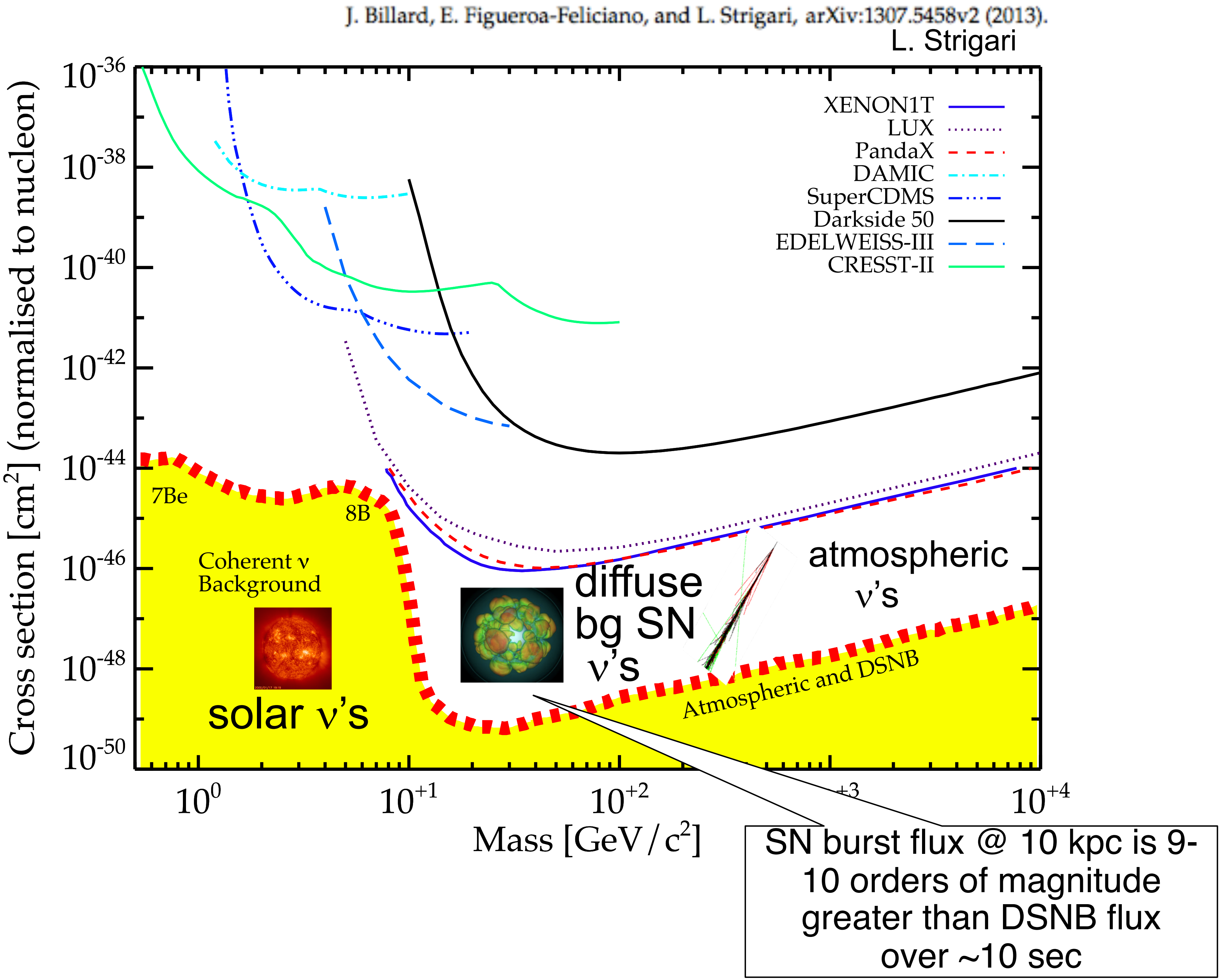
Anticipated distribution of CEvNS from 8B and hep neutrinos in the S2-S1 parameter space in LZ

Jingke Xu, Magnificent CEvNS 2019

Natural neutrino fluxes

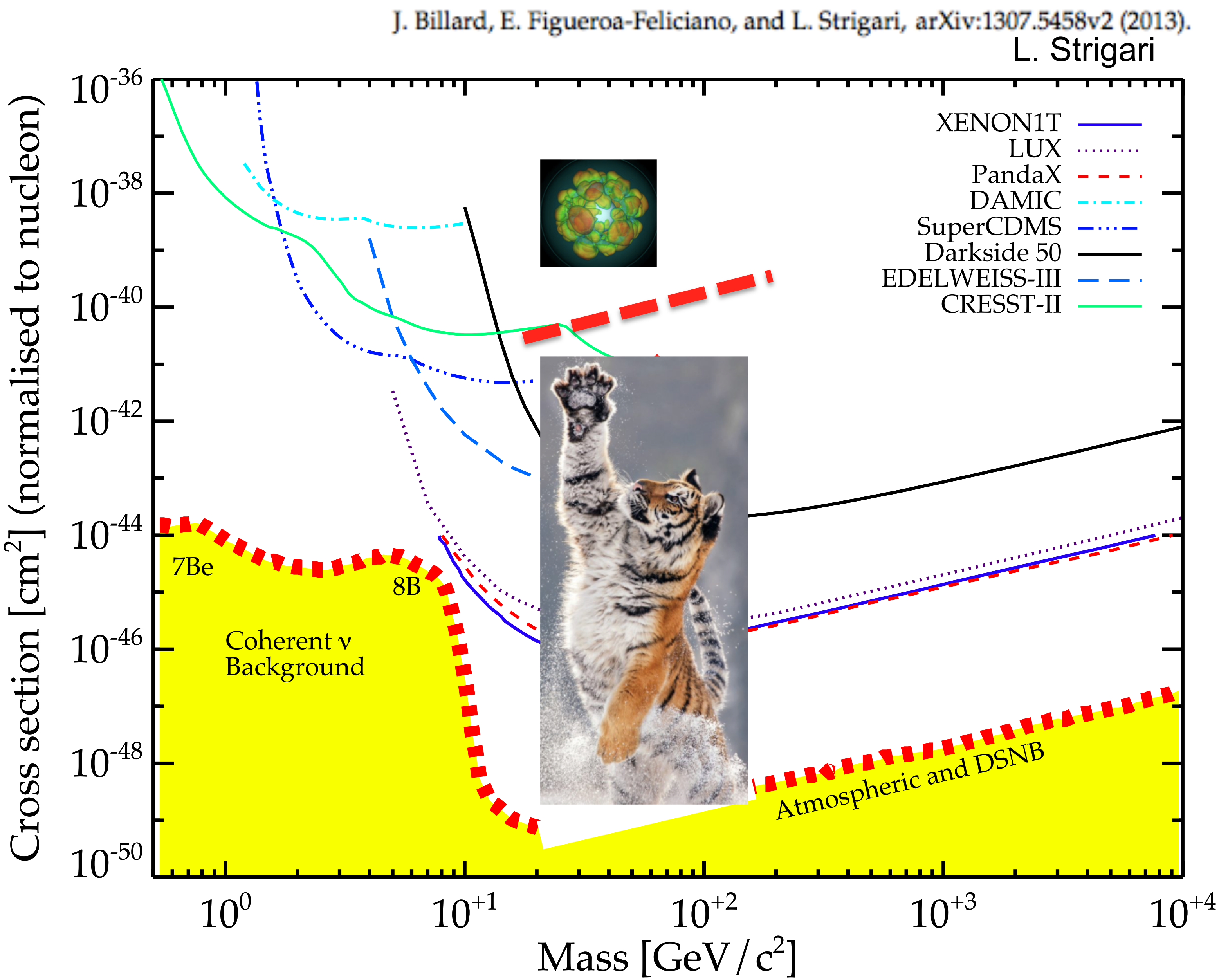




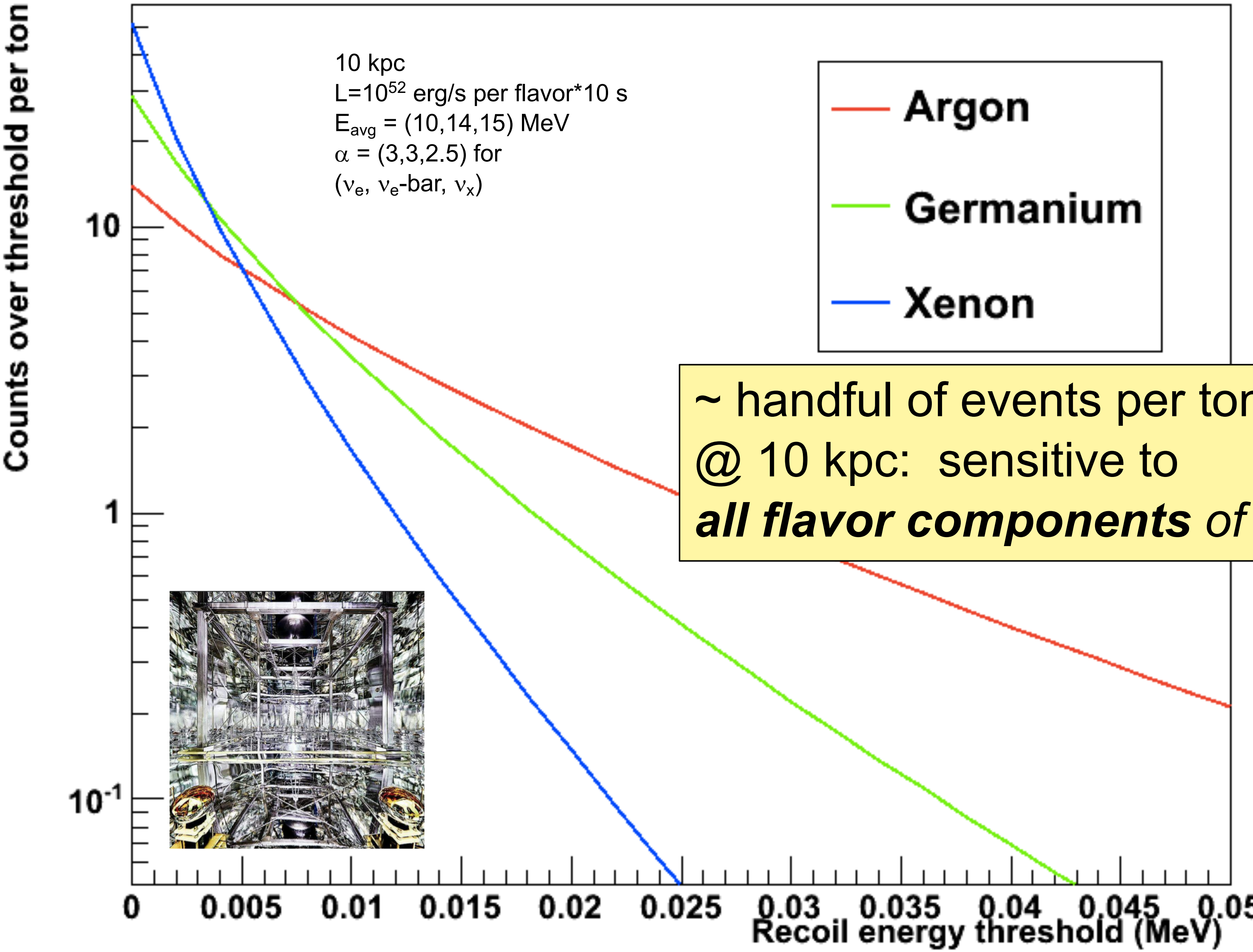


J. Billard, E. Figueroa-Feliciano, and L. Strigari, arXiv:1307.5458v2 (2013).
L. Strigari
Cross section [cm^2] (normalised to nucleon)
10^{-36}
10^{-38}
10^{-40}
10^{-42}
10^{-44}
10^{-46}
10^{-48}
10^{-50}
10^{0}
10^{+1}
10^{+2}
10^{+3}
10^{+4}
Mass [GeV/c^2]
XENON1T
LUX
PandaX
DAMIC
SuperCDMS
Darkside 50
EDELWEISS-III
CRESST-II
7Be
8B
Coherent ν Background
solar ν's
diffuse bg SN ν's
atmospheric ν's
Atmospheric and DSNB
SN burst flux @ 10 kpc is 9-10 orders of magnitude greater than DSNB flux over ~10 sec

Think of a SN burst as "**the ν floor reaching up to meet you**"



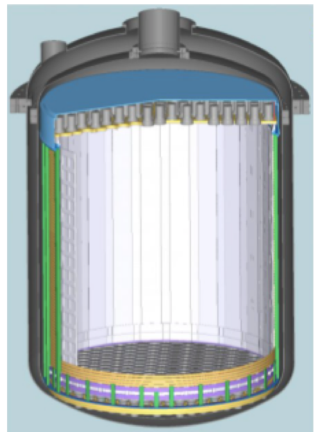
Supernova neutrinos in tonne-scale DM detectors

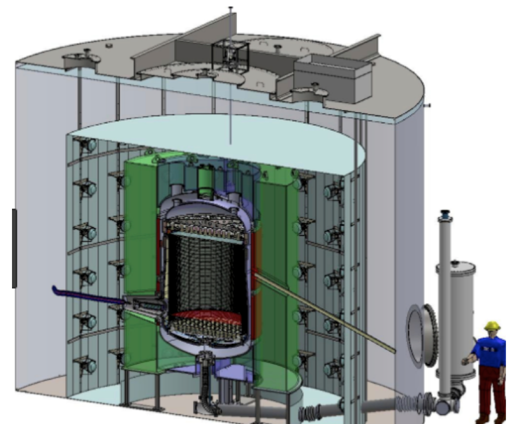


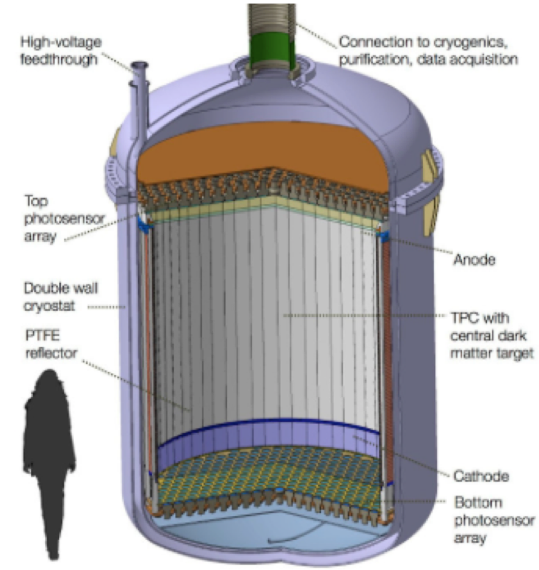
~ handful of events per tonne
@ 10 kpc: sensitive to
all flavor components *of the flux*

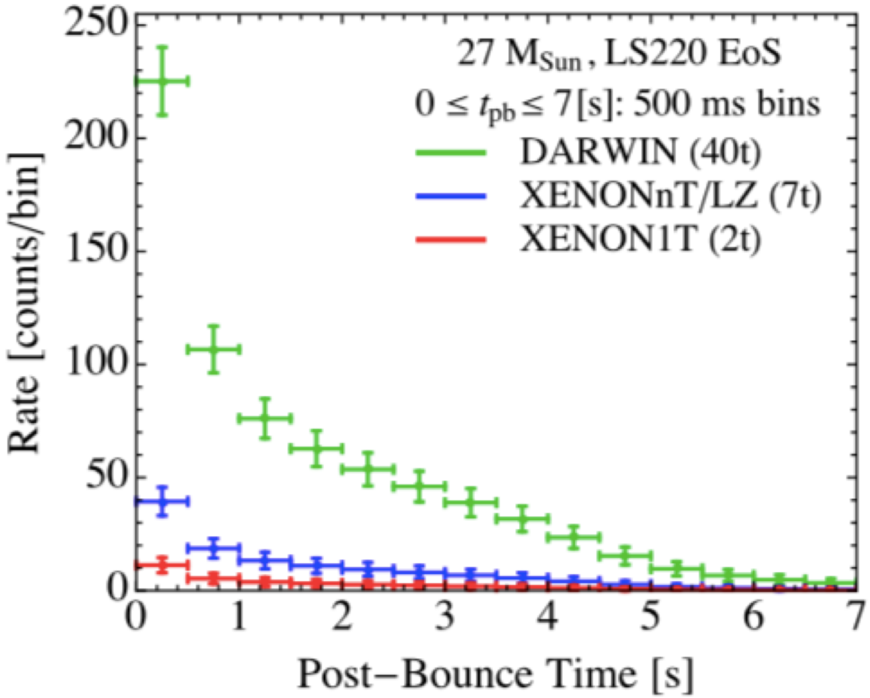
Detector example: **XENON/LZ/DARWIN**

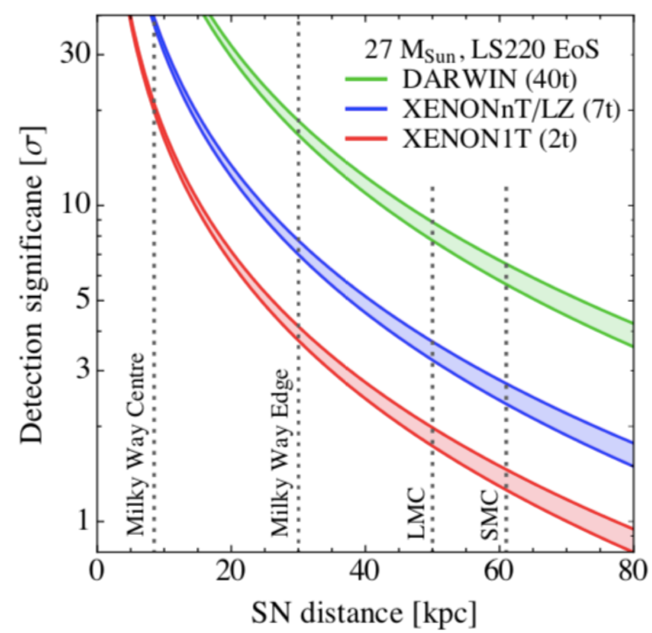
- dual-phase xenon time projection chambers











Lang et al.(2016). *Physical Review D*, *94*(10), 103009. http://doi.org/10.1103/PhysRevD.94.103009

Summary

The Opaque Floor:

- CEvNS may outshine DM for sensitive enough detectors
- *CEvNS measurements important to set the level of the floor*

The Transparent Floor:

- Directional detectors can help see below neutrino floor

The Patterned Floor:

- The floor is a signal too!
- Solar, SN (...) neutrinos are interesting physics targets for dark matter detectors