An Overview of Physics at Underground Laboratories

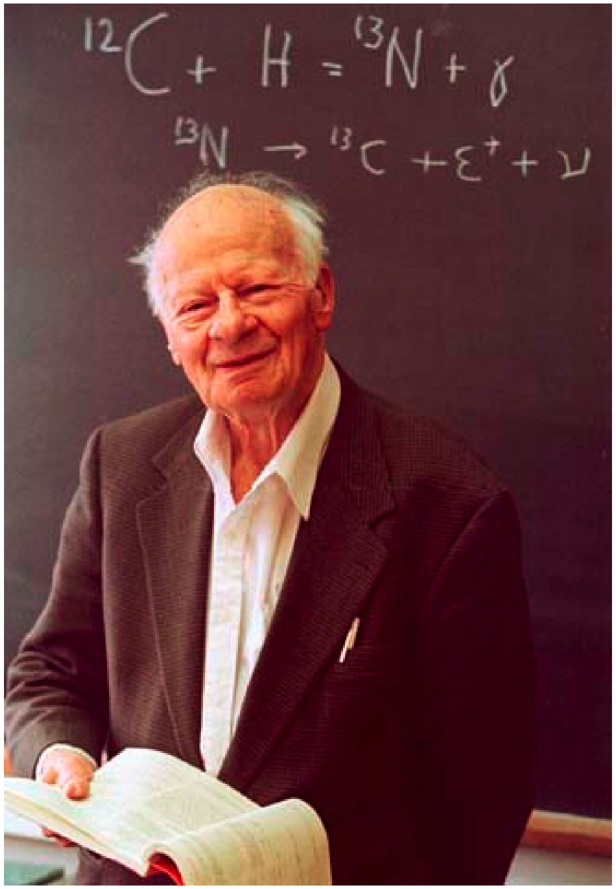
A.B. Balantekin

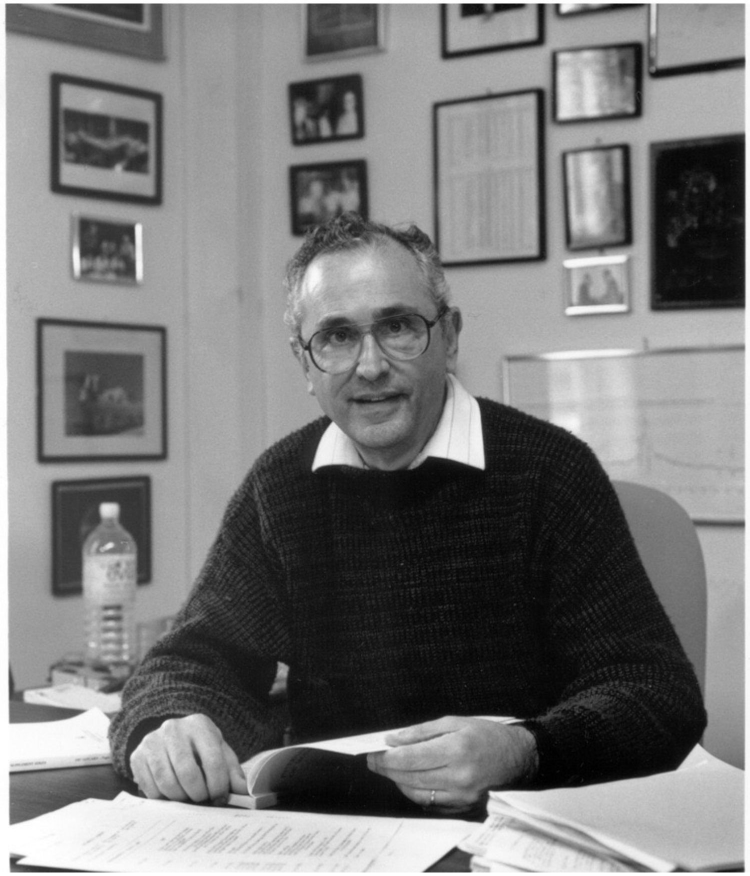
Conference on Science at the Sanford Underground Research Facility 2022

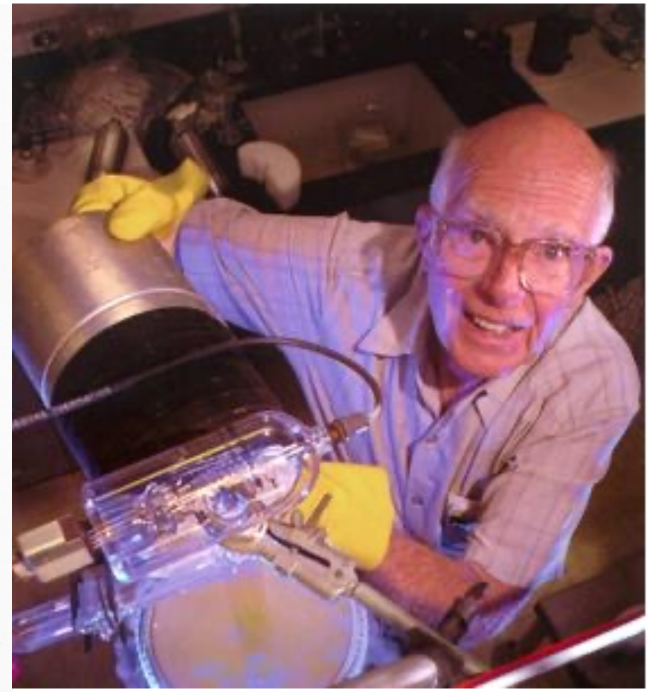
N3AS Network for Neutrinos, Nuclear Astrophysics, and Symmetries
PHYSICS FRONTIER CENTER


Right now we are in the middle of a
revolution in astrophysics and cosmology …


Right now we are in the middle of a
revolution in astrophysics and cosmology …
..which started not too
far from here in an
underground laboratory.



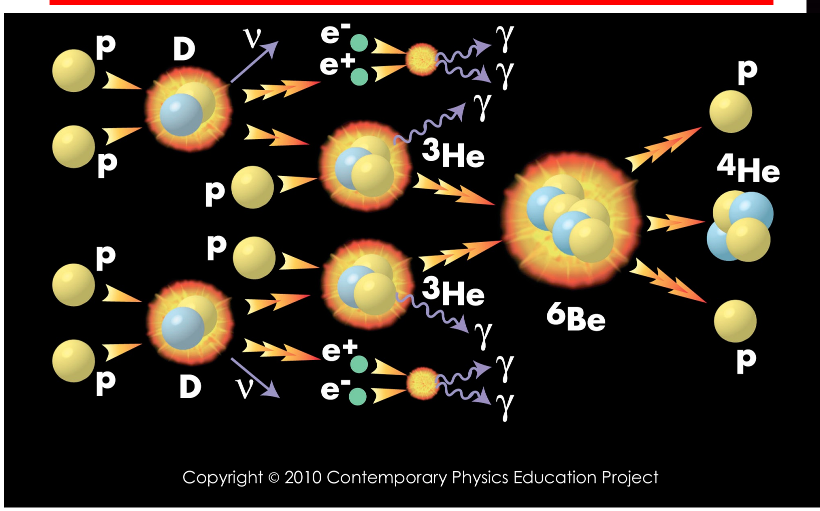


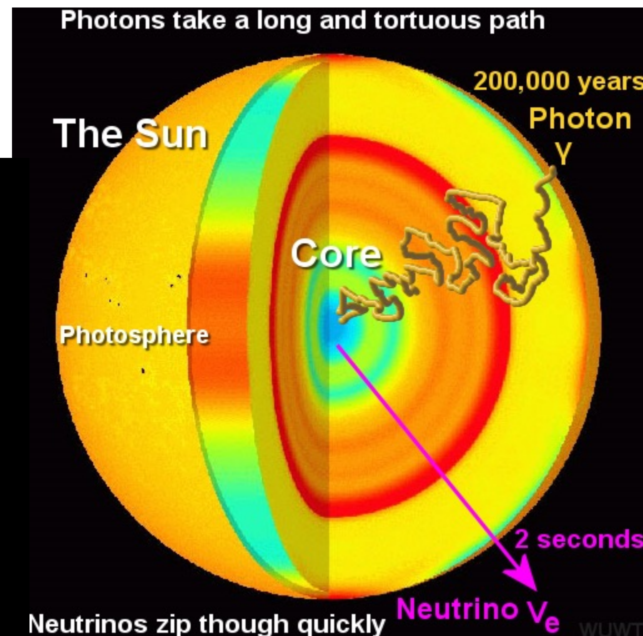


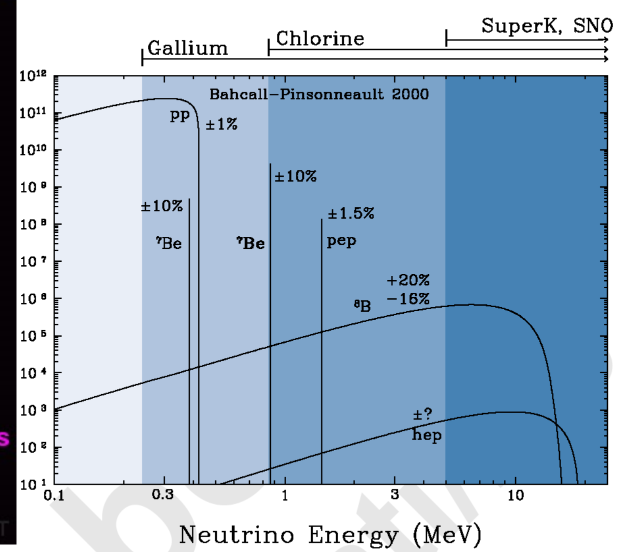
"...to see into the interior of a star and thus verify directly the hypothesis of nuclear energy generation.."

Bahcall and Davis, 1964

Solar Neutrinos

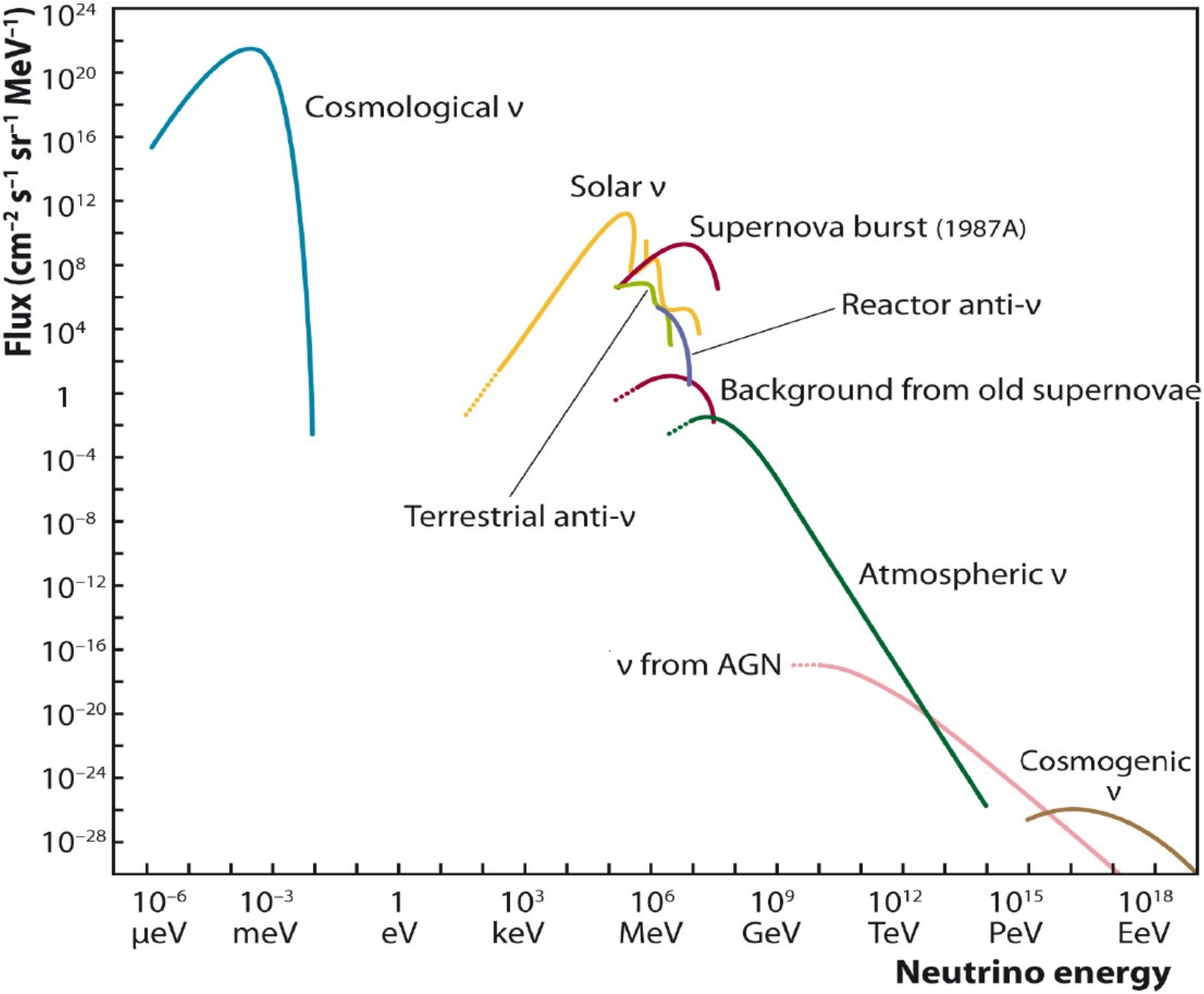






Scientific reach of the underground laboratories

- Physics at the intensity frontier: Violation of fundamental symmetries (time reversal, lepton number, baryon number); neutrino properties …
- Physics at the cosmic frontier: Particle and nuclear astrophysics; stellar and supernova neutrinos; nature of particle dark matter…
- Physics research carried at both frontiers is complementary to the research at the energy frontier.
- Low-background counting.
- Geophysics, dark life..



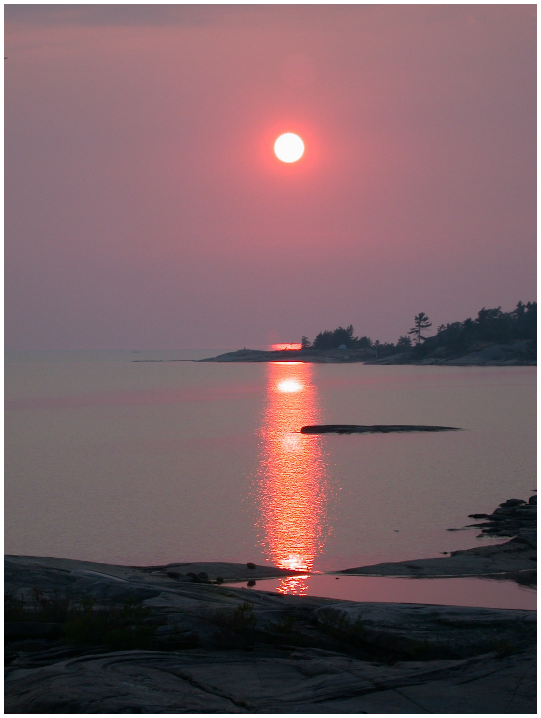
Flux (cm^{-2} s^{-1} sr^{-1} MeV^{-1})
10^{24}
10^{20}
10^{16}
10^{12}
10^{8}
10^{4}
1
10^{-4}
10^{-8}
10^{-12}
10^{-16}
10^{-20}
10^{-24}
10^{-28}
Cosmological ν
Solar ν
Supernova burst (1987A)
Reactor anti-ν
Background from old supernovae
Terrestrial anti-ν
Atmospheric ν
ν from AGN
Cosmogenic ν
10^{-6} μeV
10^{-3} meV
1 eV
10^{3} keV
10^{6} MeV
10^{9} GeV
10^{12} TeV
10^{15} PeV
10^{18} EeV
Neutrino energy

Mixing matrix for three flavors

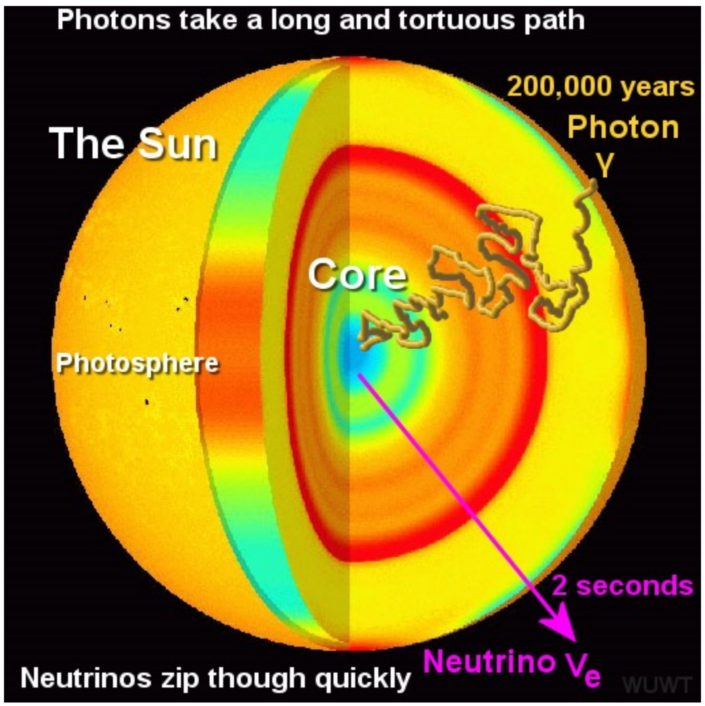
$$U = \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}}_{\text{Atmospheric neutrinos}} \underbrace{\begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\phi} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\phi} & 0 & c_{13} \end{pmatrix}}_{\text{Reactor neutrinos}}$$

$$\times \underbrace{\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\text{Solar neutrinos}} \underbrace{\begin{pmatrix} e^{i\alpha_1} & 0 & 0 \\ o & e^{i\alpha_2} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\text{Majorana phases}}$$

$$c_{ij} = \cos\theta_{ij} \quad s_{ij} = \sin\theta_{ij}$$

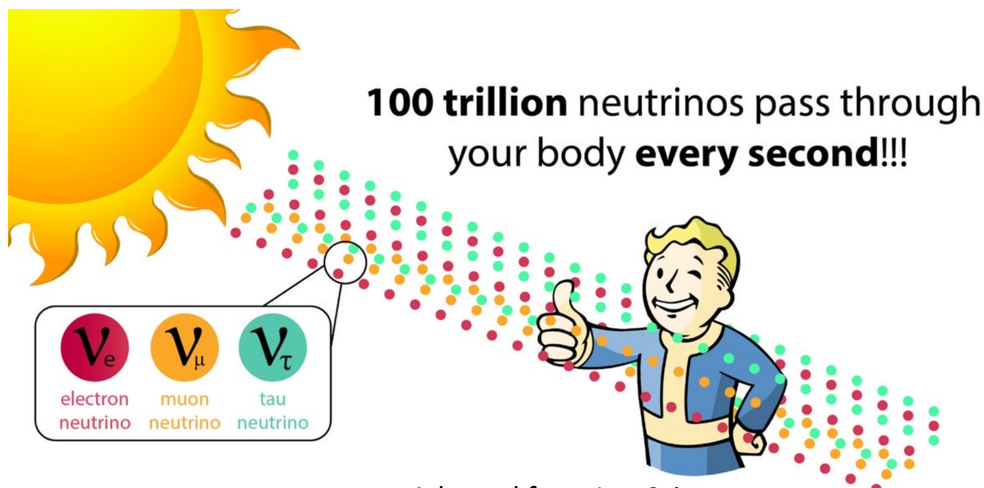


Sources of neutrinos: Sun

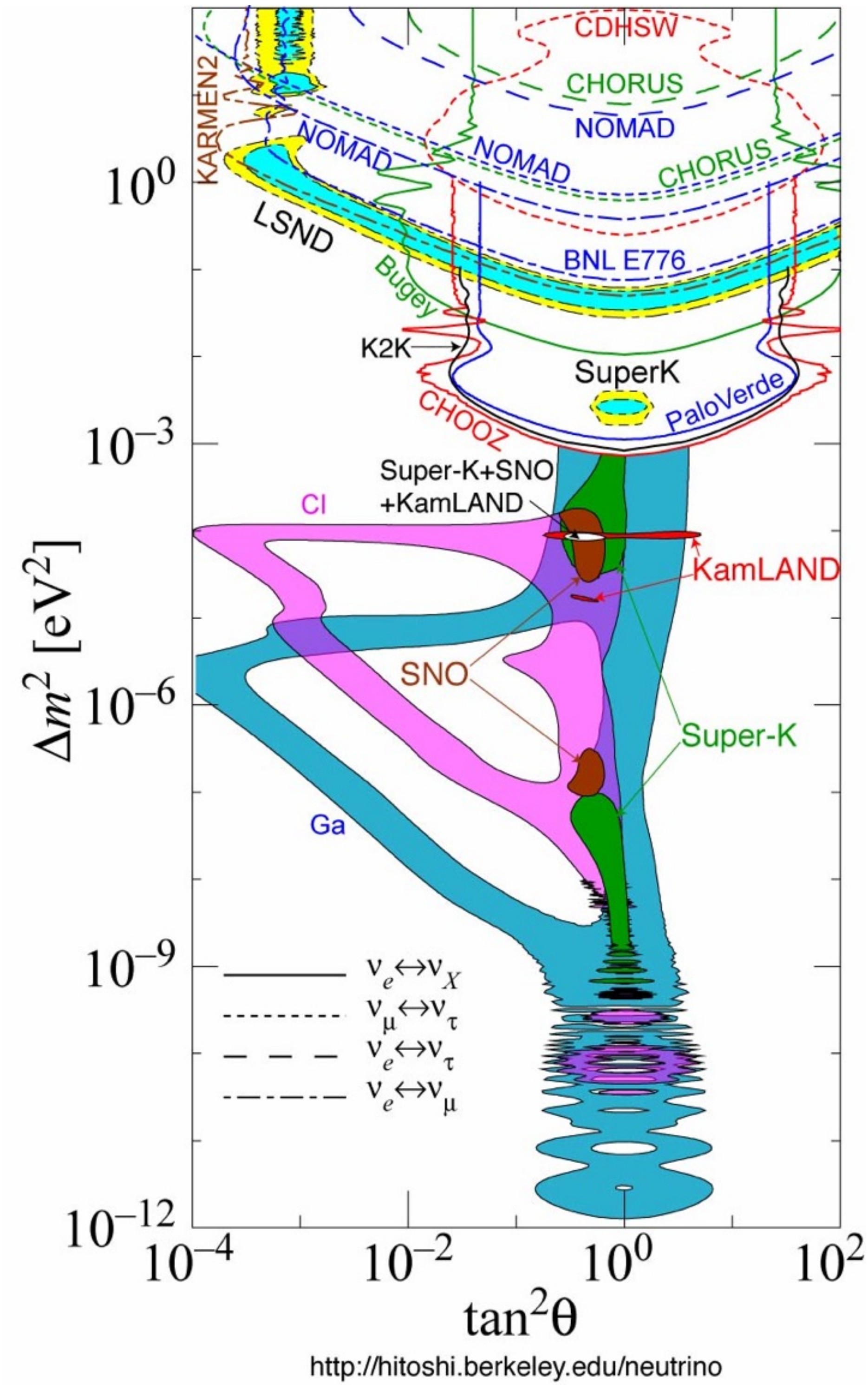


A minor league star (such as our Sun) produces neutrinos mainly through the reaction

$$p + p \rightarrow d + e^{+} + \nu_e$$



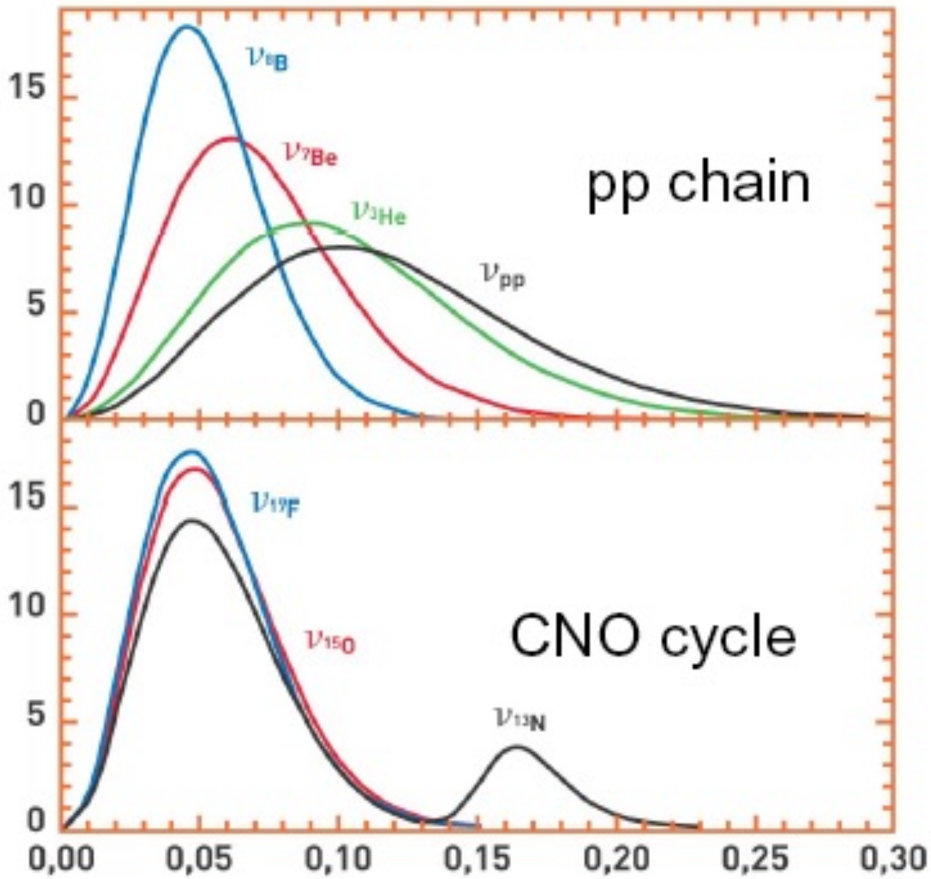
Adopted from Lux Science

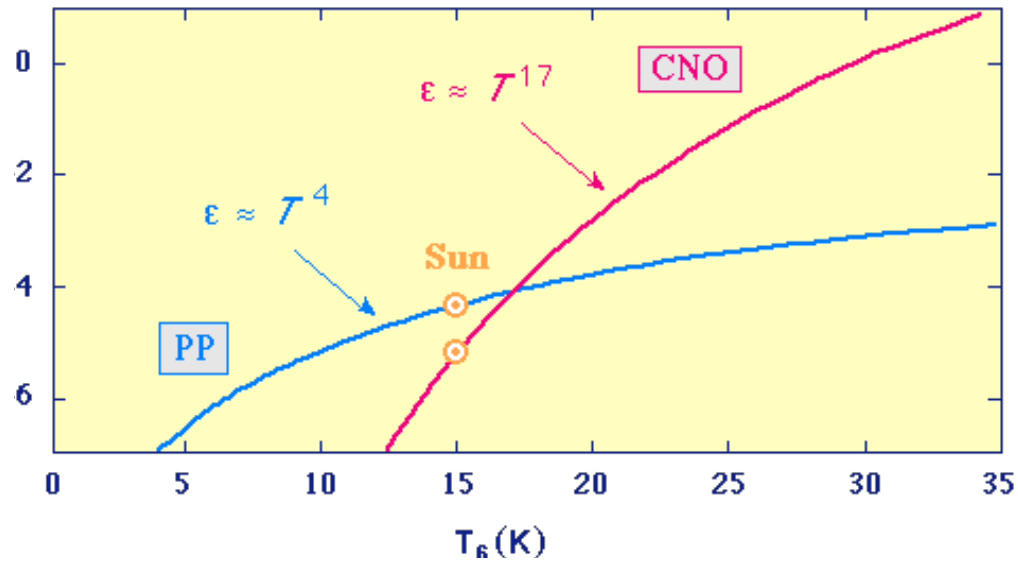


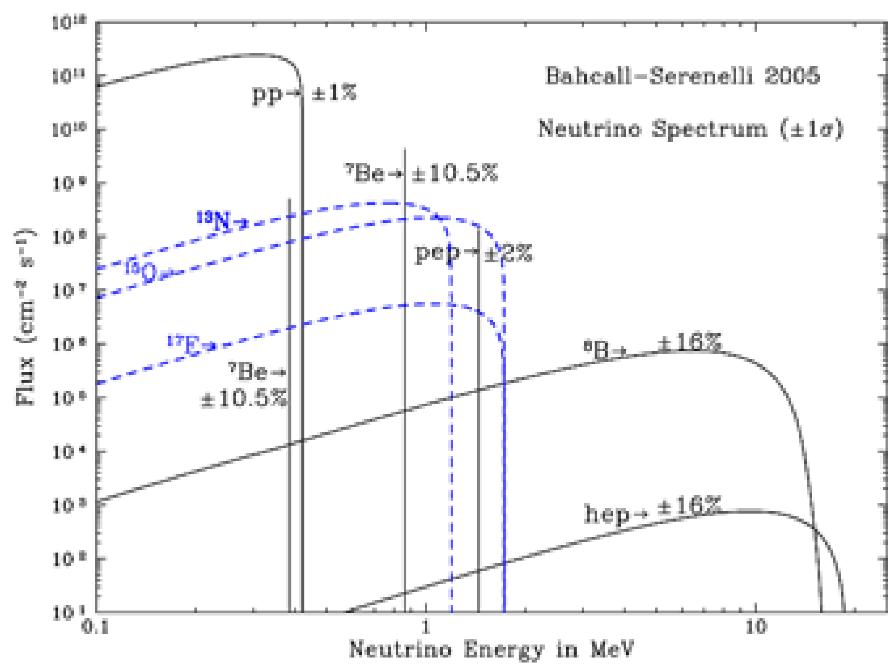
$\theta_{atmospheric}$ (primarily θ_{23})

θ_{solar} (primarily θ_{12})

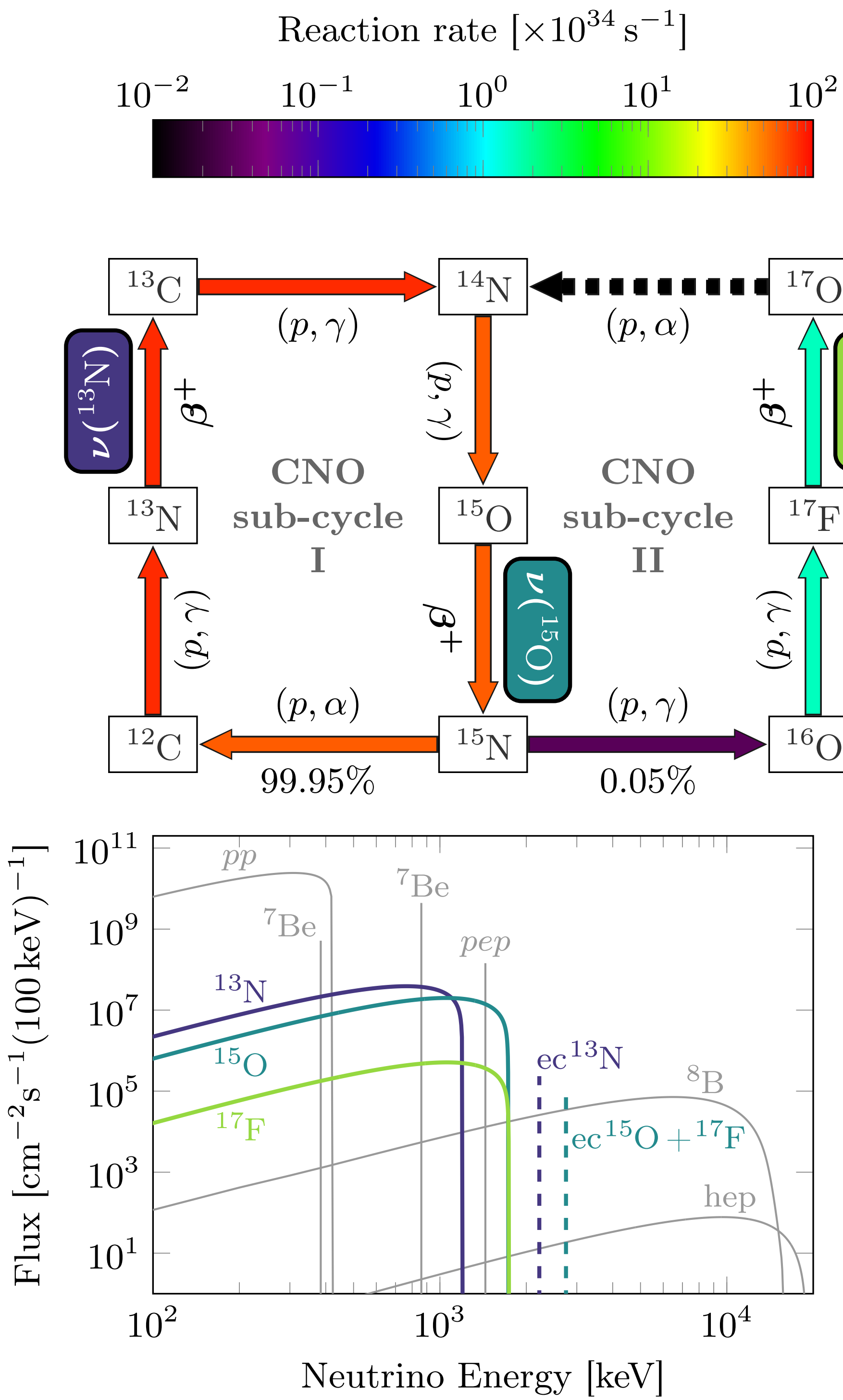
How much does the CNO cycle contribute in the Sun?





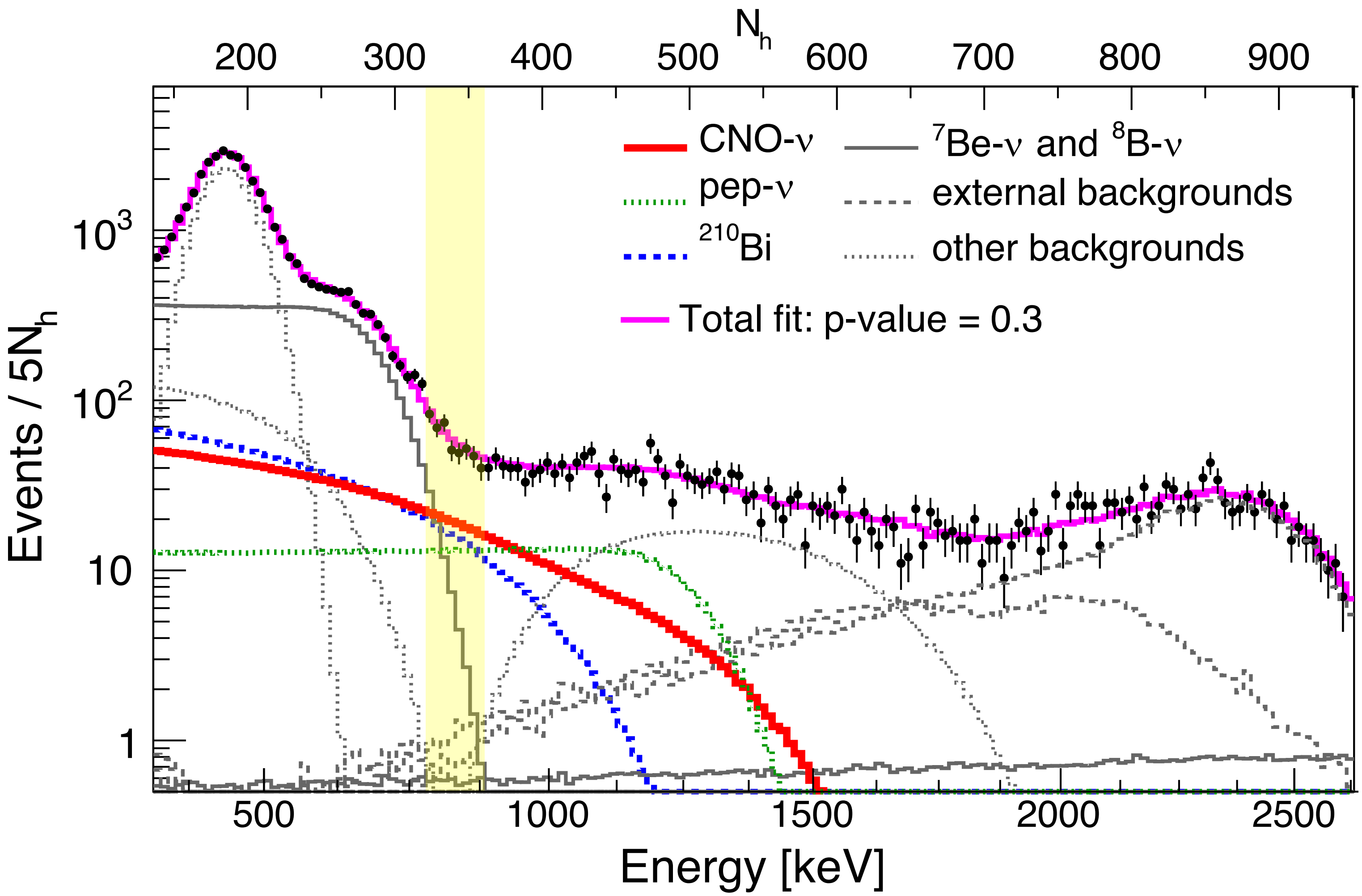


In SSM CNO cycle contribute about 0.8% of the neutrino flux. Data are consistent with this. A more precise measurement of the CNO contribution will provide a test of SSM.



CNO Neutrinos are now detected!

Borexino Collaboration
2006.15115 [hep-ex]



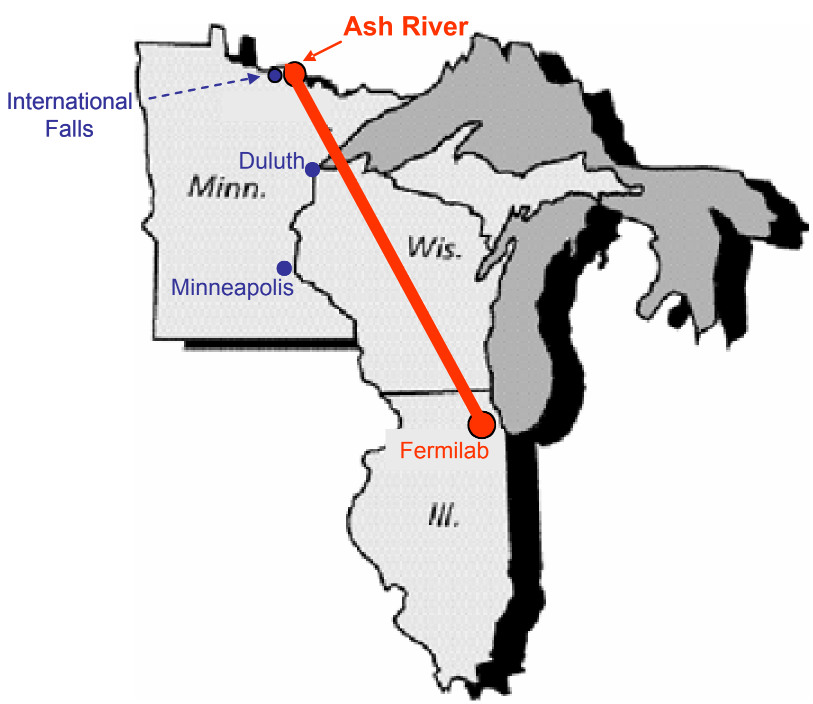
Borexino Collaboration
2006.15115 [hep-ex]

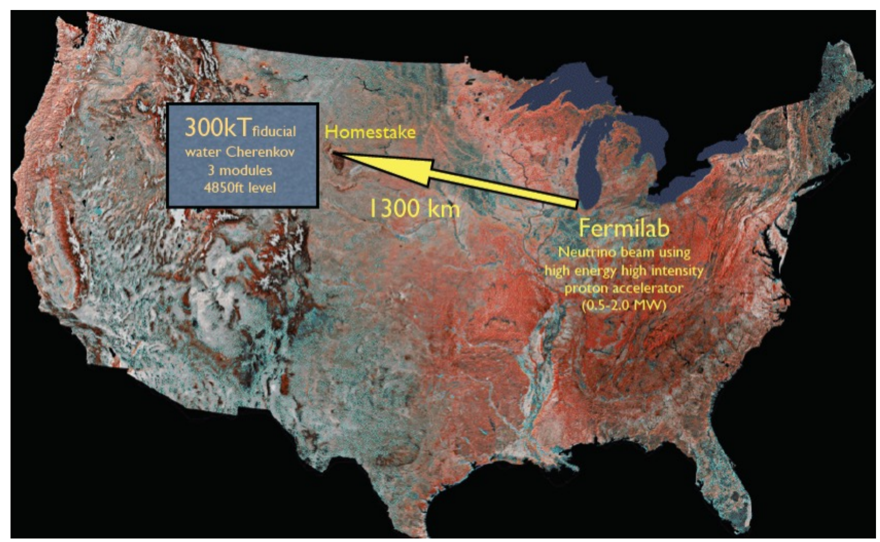
Long-baseline oscillations at GeV energies

Osc. max. $L \sim E$ **+** Flux at source $\sim E^2$; $\text{Flux}(L) = \text{Flux}(L=0)/L^2$

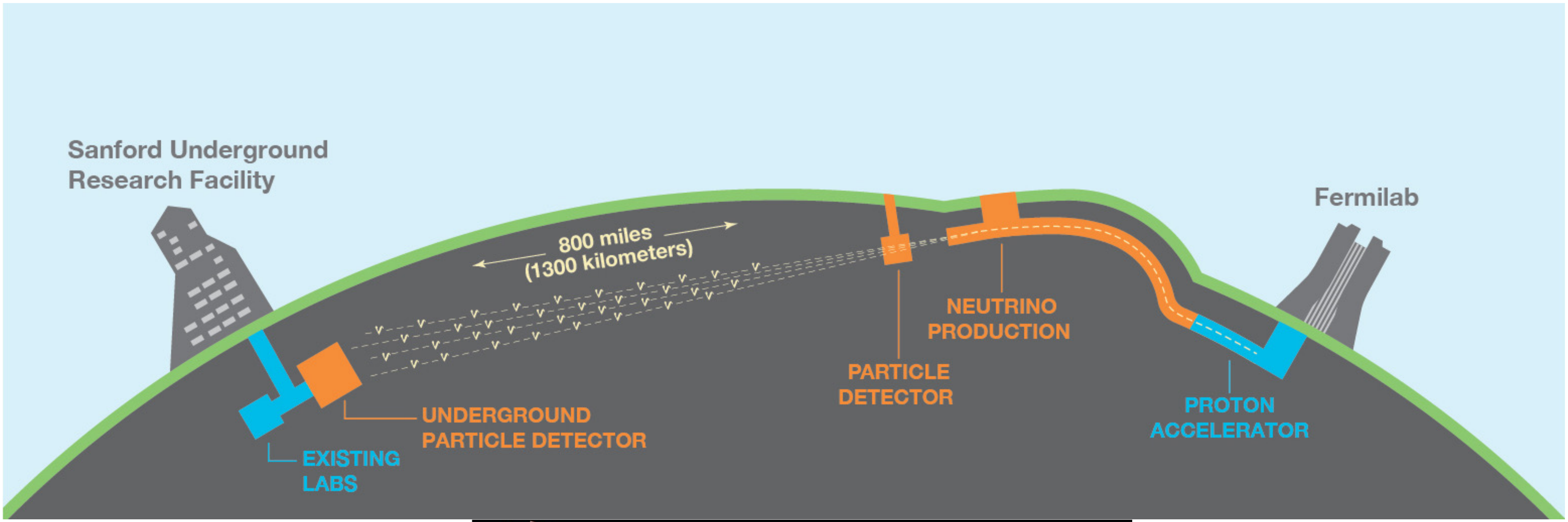
$\text{Flux}(L) \sim 1$ **+** $\sigma \sim E$ (DIS)

Event rate $\sim E$

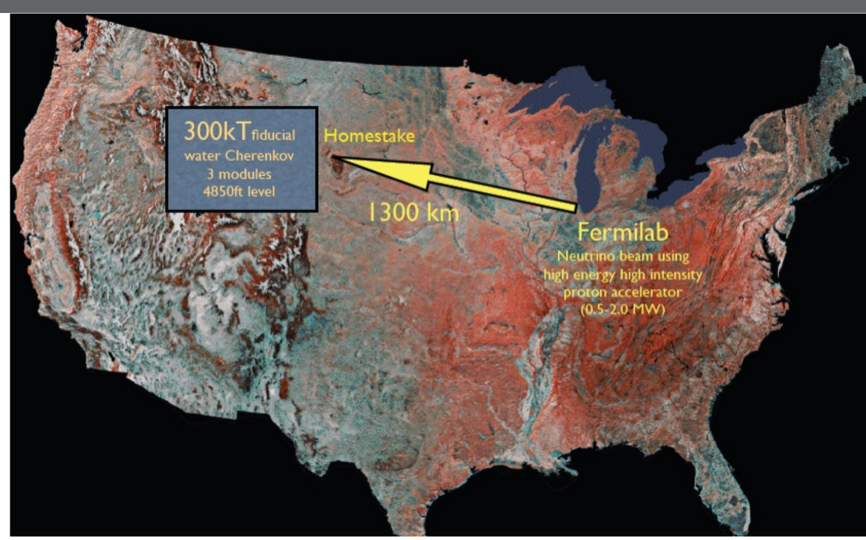




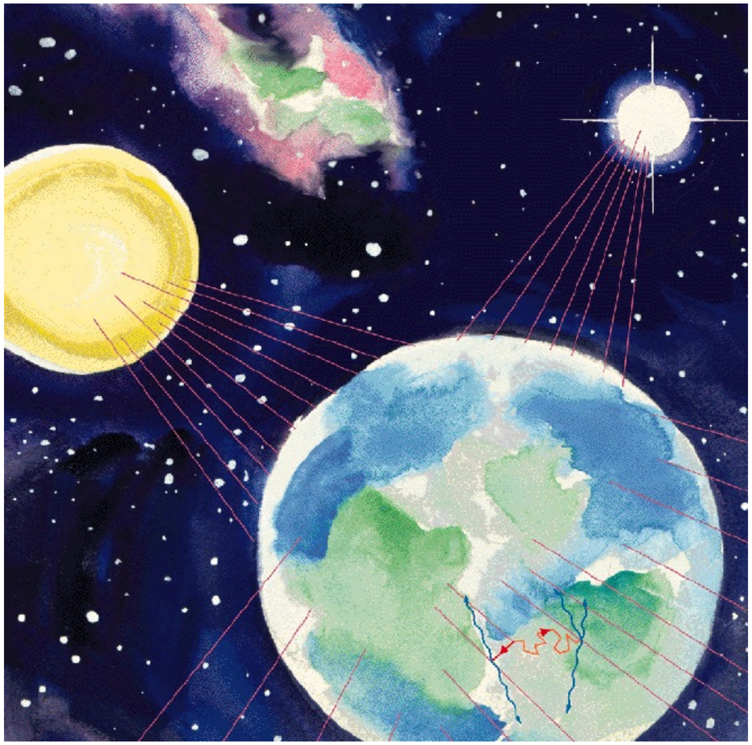
DUNE DEEP UNDERGROUND NEUTRINO EXPERIMENT



The flagship experiment…



Sources of neutrinos: Supernovae



A (hopefully distant enough) core-collapse supernova produces approximately 10^{58} neutrinos in about twenty seconds primarily via

$$\text{Gravitational binding energy} \rightarrow \nu_x + \bar{\nu}_x$$

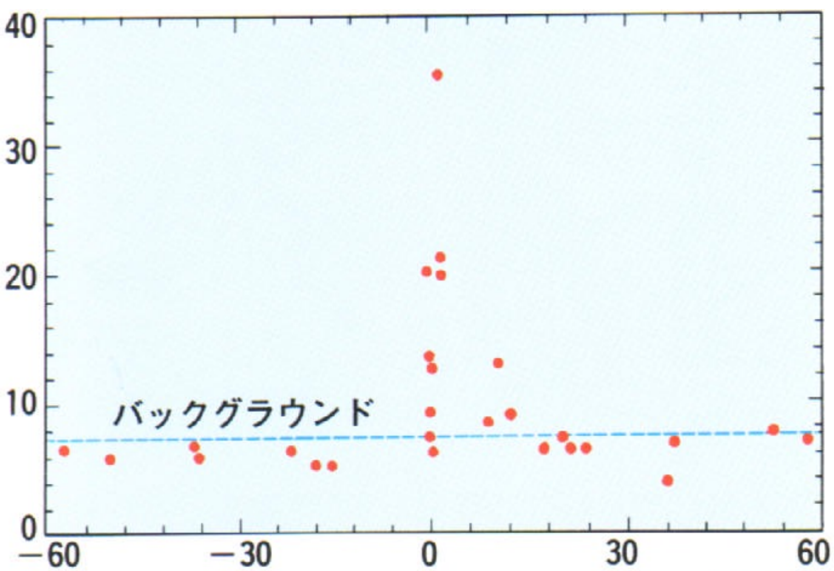
during the cooling and via

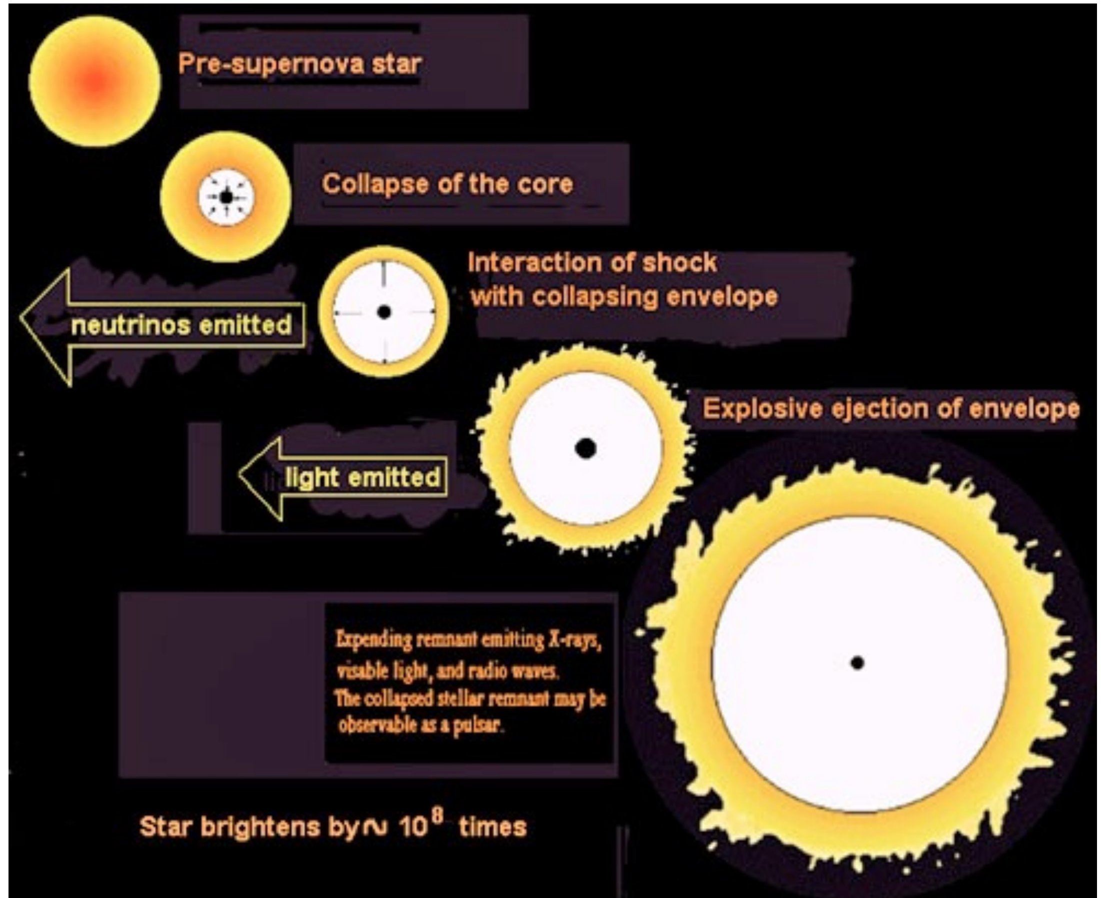
$$e^- + p \rightarrow n + \bar{\nu}_e$$

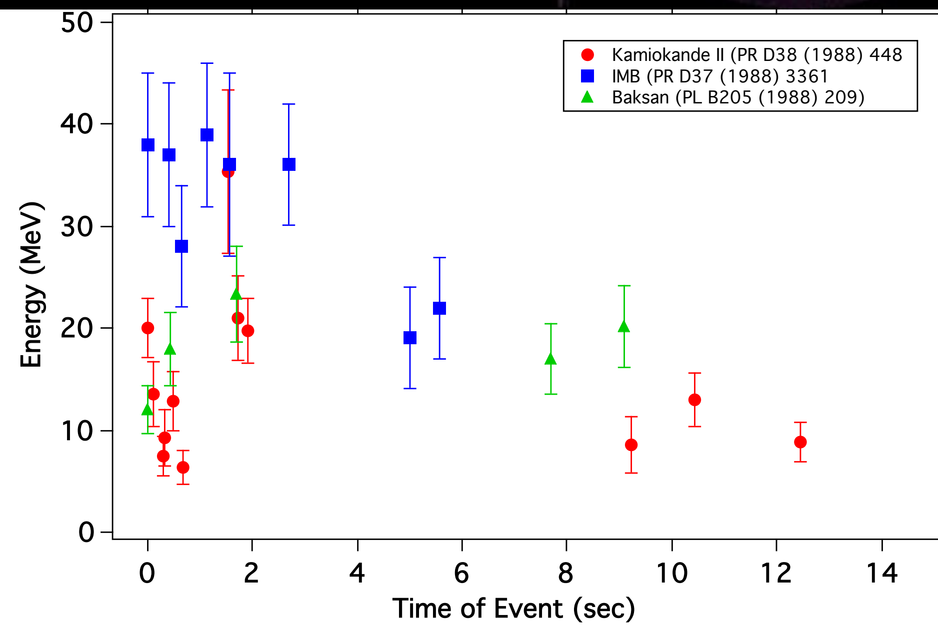
during the collapse.

Those neutrinos produced in supernova explosions since the beginning of the Universe still stick around, forming the "Diffuse Supernova Background"

Neutrinos from core-collapse supernovae





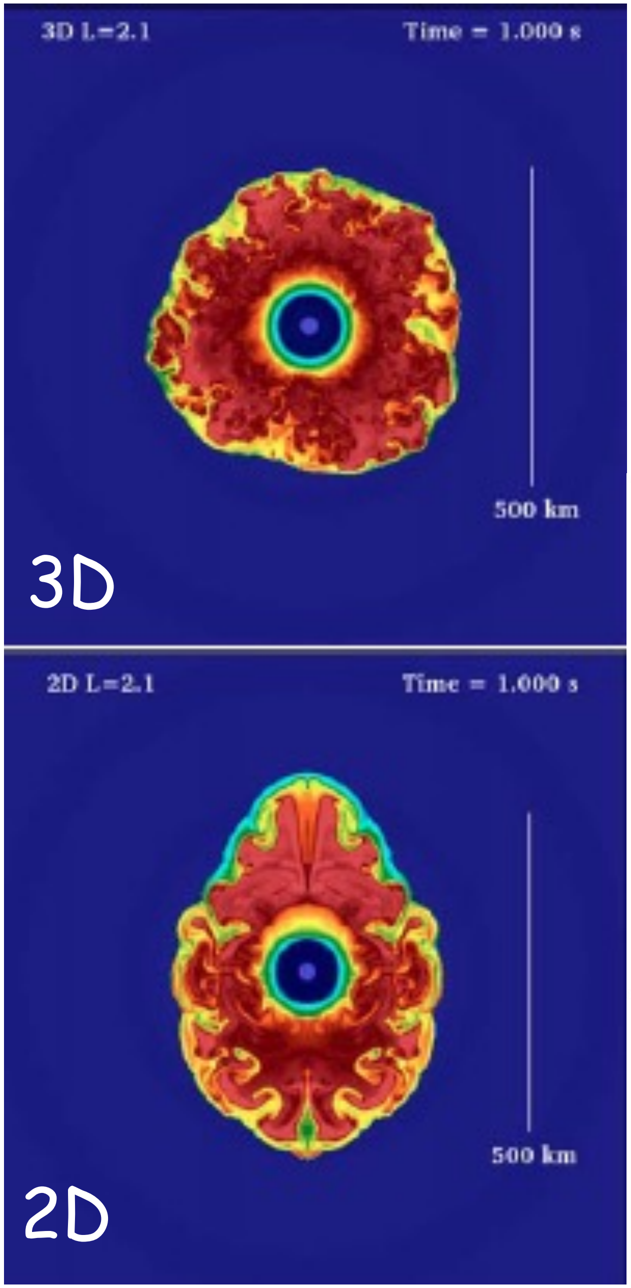


- $M_{prog} \geq$ 8 $M_{sun} \Rightarrow \Delta E \approx 10^{53}$ ergs $\approx 10^{59}$ MeV
- 99% of the energy is carried away by neutrinos and antineutrinos with $10 \leq E_\nu \leq 30$ MeV $\Rightarrow 10^{58}$ neutrinos

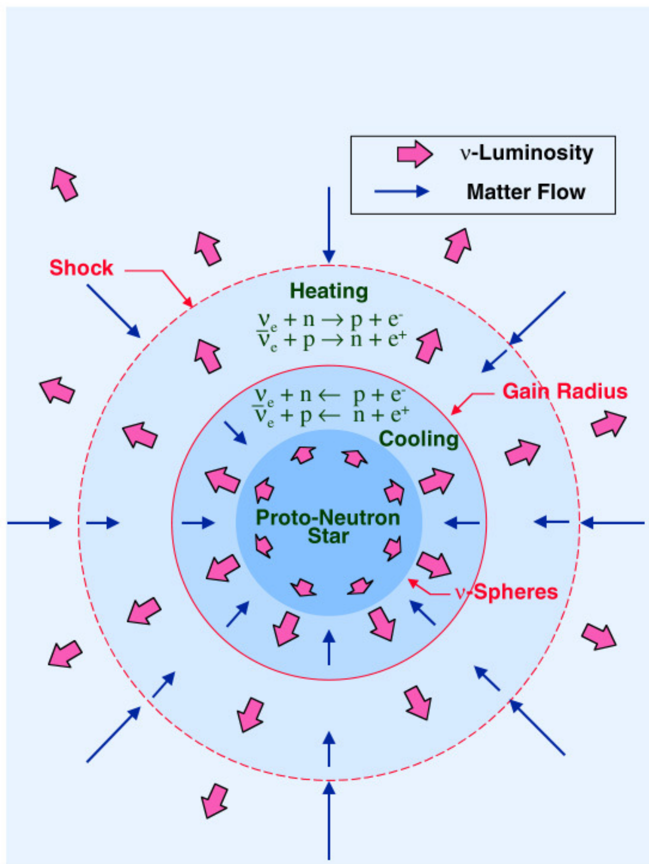
If we want to catch a supernova with neutrinos we'd better know what neutrinos do inside a supernova.

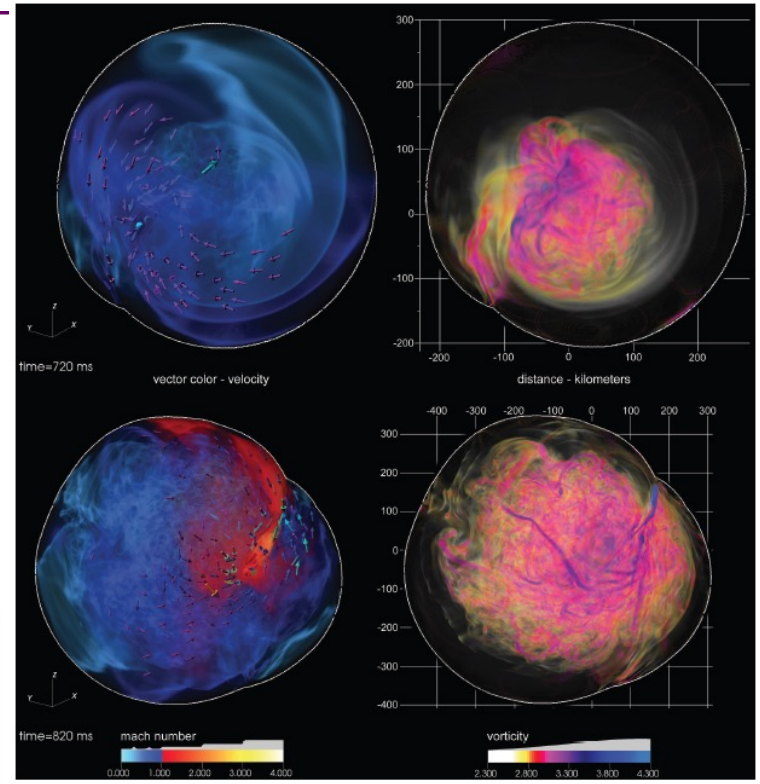
ORNL/UT

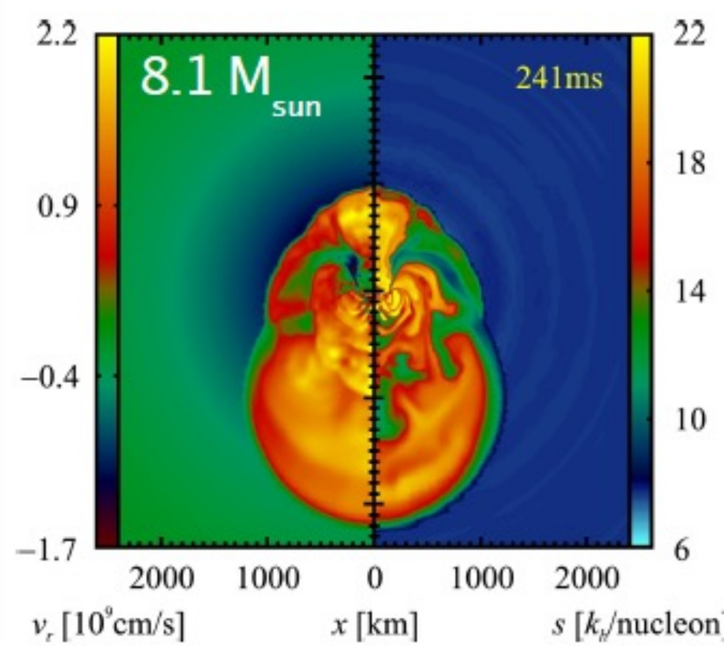
Development of 2D and 3D models for core-collapse supernovae: Complex interplay between turbulence, neutrino physics and thermonuclear reactions.



Princeton

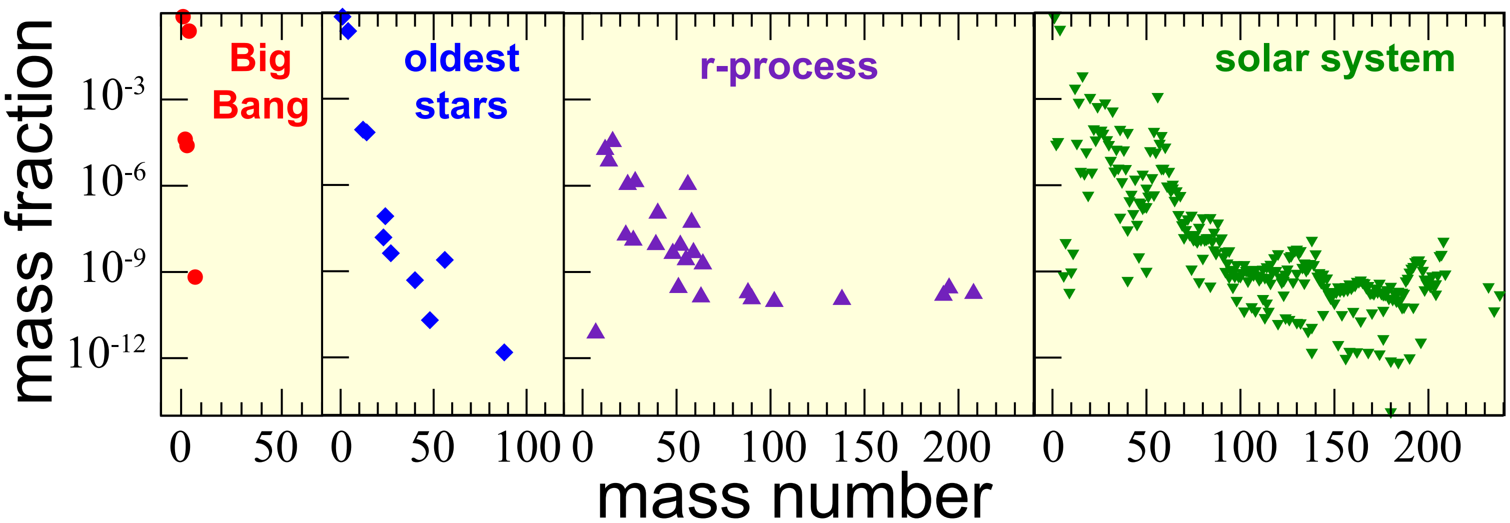


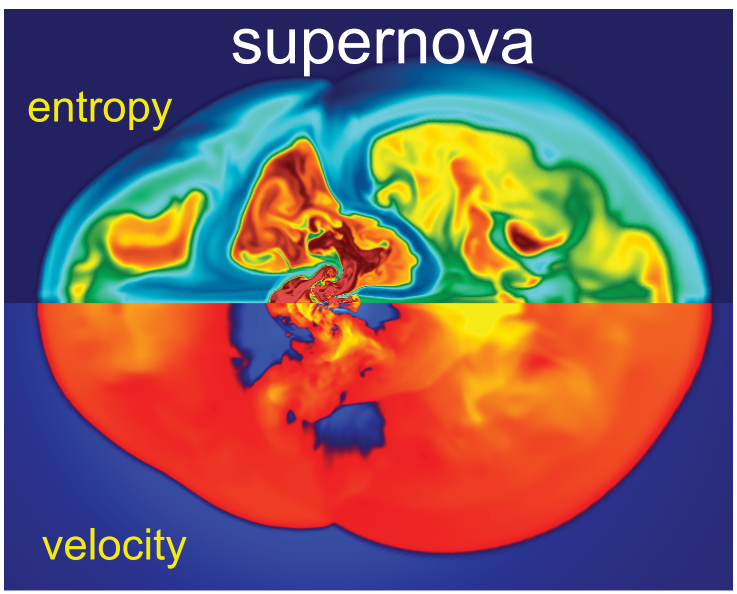


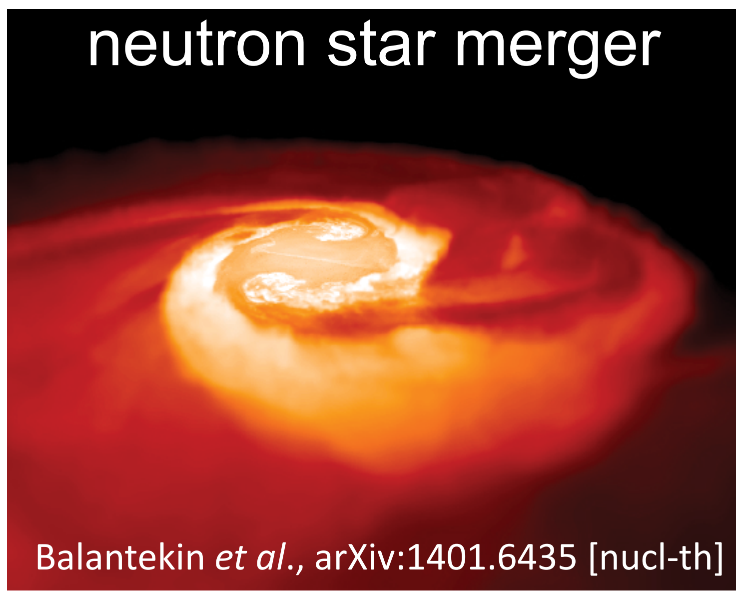


Munich

The origin of elements



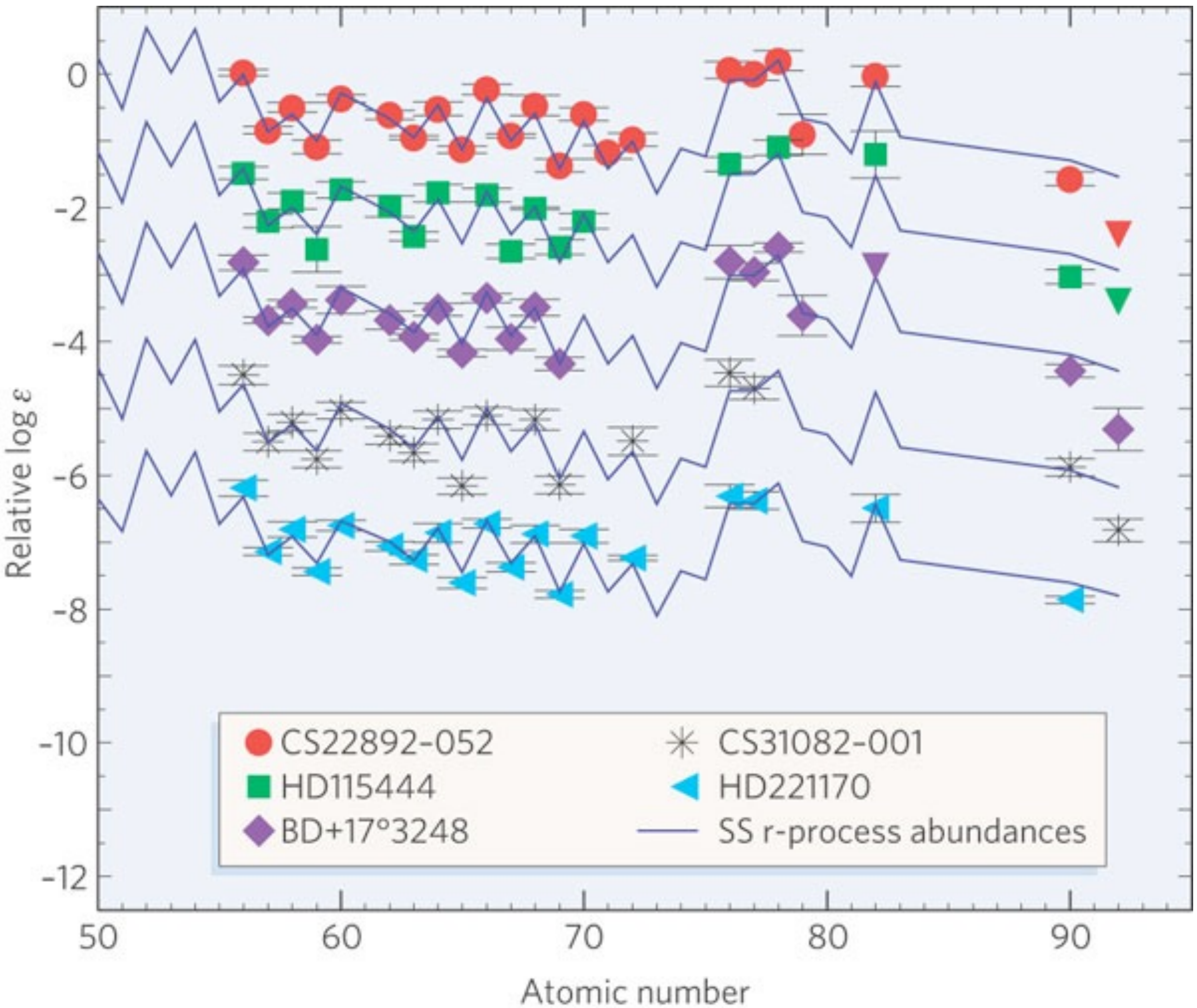


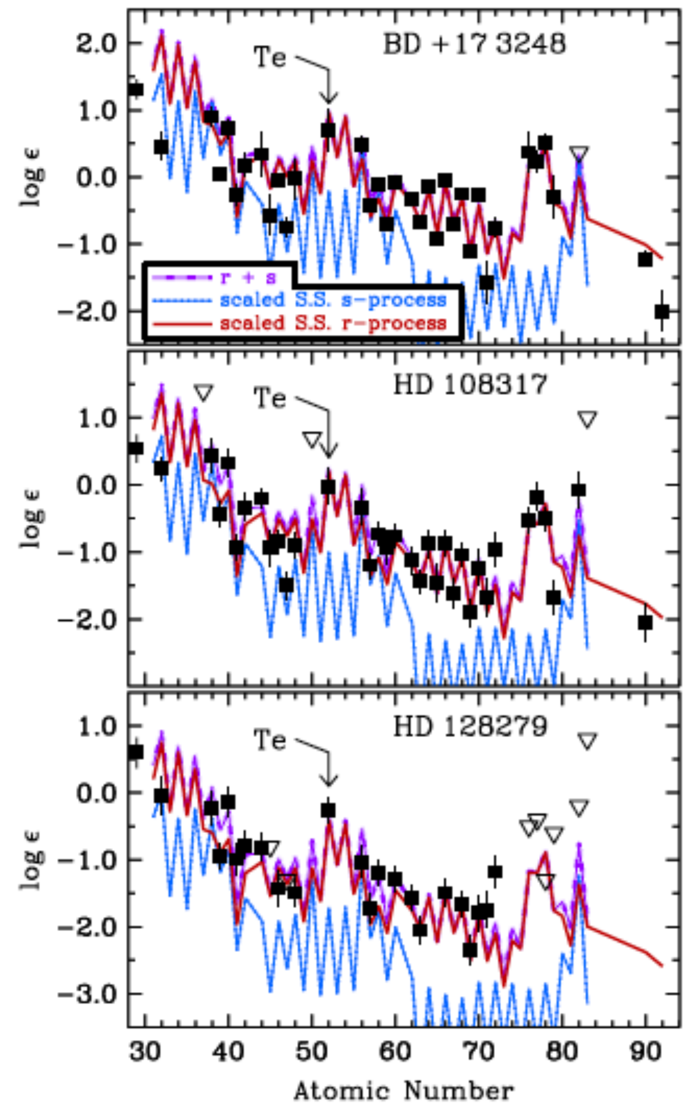


Possible sites for the r-process

Neutrinos not only play a crucial role in the dynamics of these sites, but they also control the value of the electron fraction, the parameter determining the yields of the r-process.

r-process nucleosynthesis



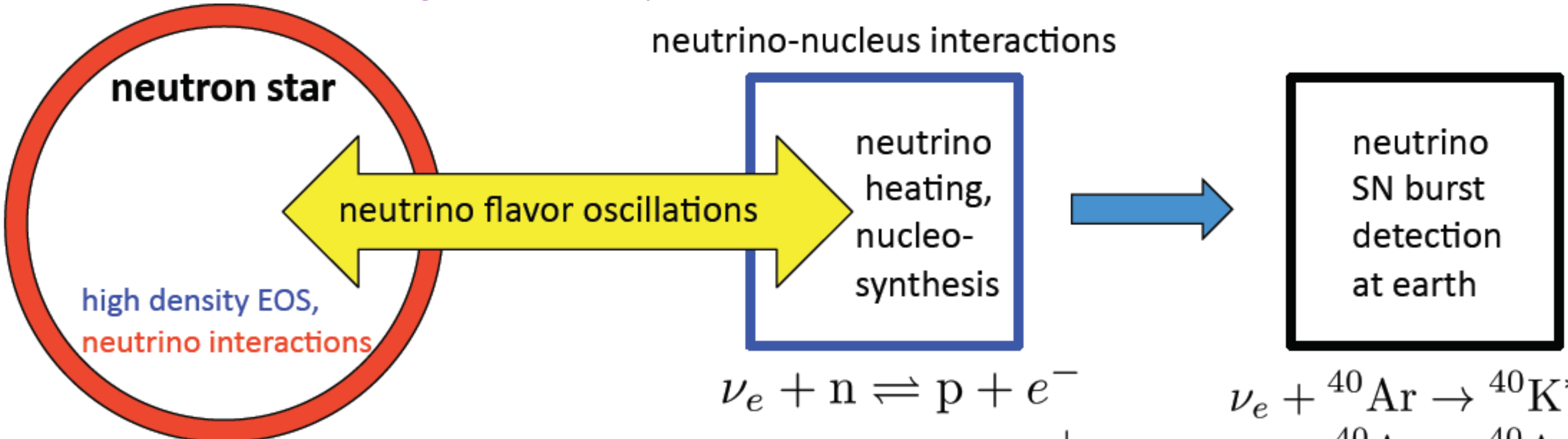


A > 100 abundance pattern fits the solar abundances well.

Roederer *et al.*, Ap. J. Lett. **747**, L8 (2012)

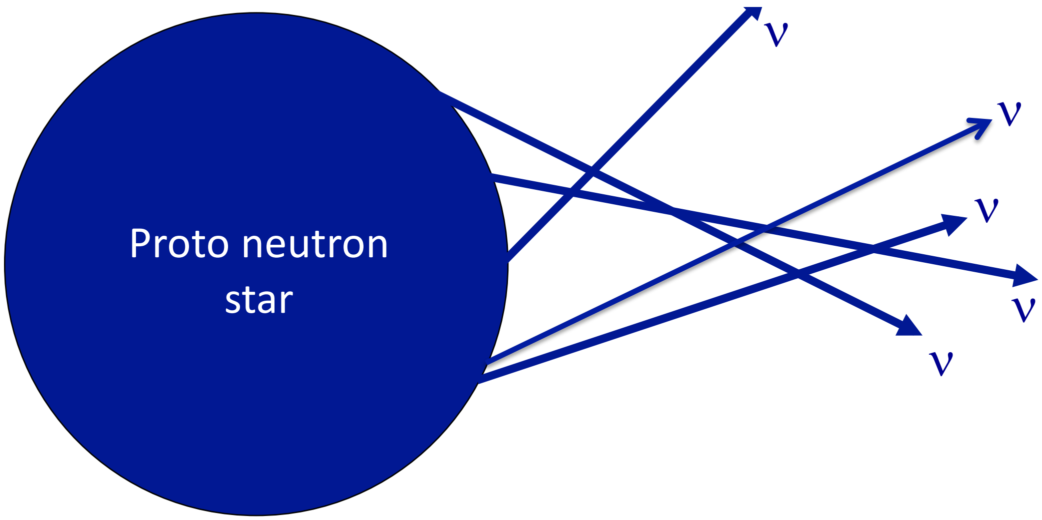
For example understanding a core-collapse supernova requires answers to a variety of questions some of which need to be answered, both theoretically and experimentally.

Balantekin and Fuller, Prog. Part. Nucl. Phys. **71** 162 (2013)



$$\nu_e + \mathrm{n} \rightleftharpoons \mathrm{p} + e^-$$
$$\bar{\nu}_e + \mathrm{p} \rightleftharpoons \mathrm{n} + e^+$$

$$\nu_e + {}^{40}\mathrm{Ar} \to {}^{40}\mathrm{K}^* + e^-$$
$$\nu_x + {}^{40}\mathrm{Ar} \to {}^{40}\mathrm{Ar}^* + \nu_x$$



Energy released in a core-collapse SN: $\Delta E \approx 10^{53}$ ergs $\approx 10^{59}$ MeV
99% of this energy is carried away by neutrinos and antineutrinos!
~ 10^{58} Neutrinos!
This necessitates including the effects of $\nu\nu$ interactions!

$$H = \underbrace{\sum a^\dagger a}_{\text{describes neutrino oscillations and interaction with matter (MSW effect)}} + \underbrace{\sum (1-\cos\theta) a^\dagger a^\dagger a a}_{\text{describes neutrino-neutrino interactions}}$$

The second term makes the physics of a neutrino gas in a core-collapse supernova a very interesting many-body problem, driven by weak interactions.

Neutrino-neutrino interactions lead to novel collective and emergent effects, such as conserved quantities and interesting features in the neutrino energy spectra (spectral “swaps” or “splits”).

Many neutrino system

This is the only many-body system driven by the weak interactions:

Table: Many-body systems

Nuclei	Strong	at most ~250 particles
Condensed matter	E&M	at most N_A particles
ν**'s in SN**	Weak	$\sim 10^{58}$particles

Astrophysical extremes allow us to test physics that cannot be tested elsewhere!

A system of N particles each of which can occupy k states (k = number of flavors)

Exact Solution → Mean-field approximation

Entangled and unentangled states → Only unentangled states

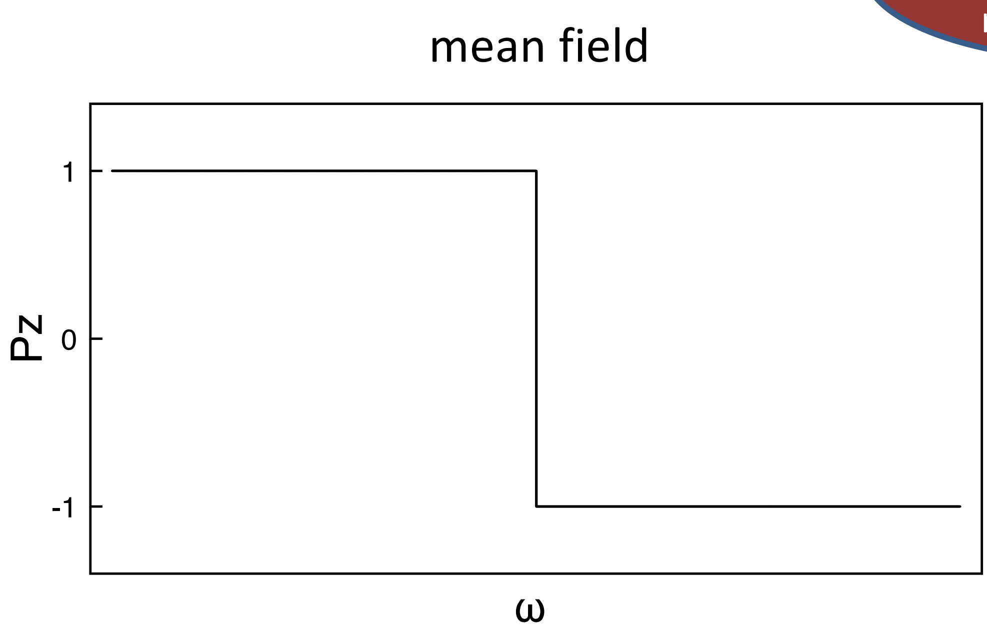
Dimension of Hilbert space: k^N

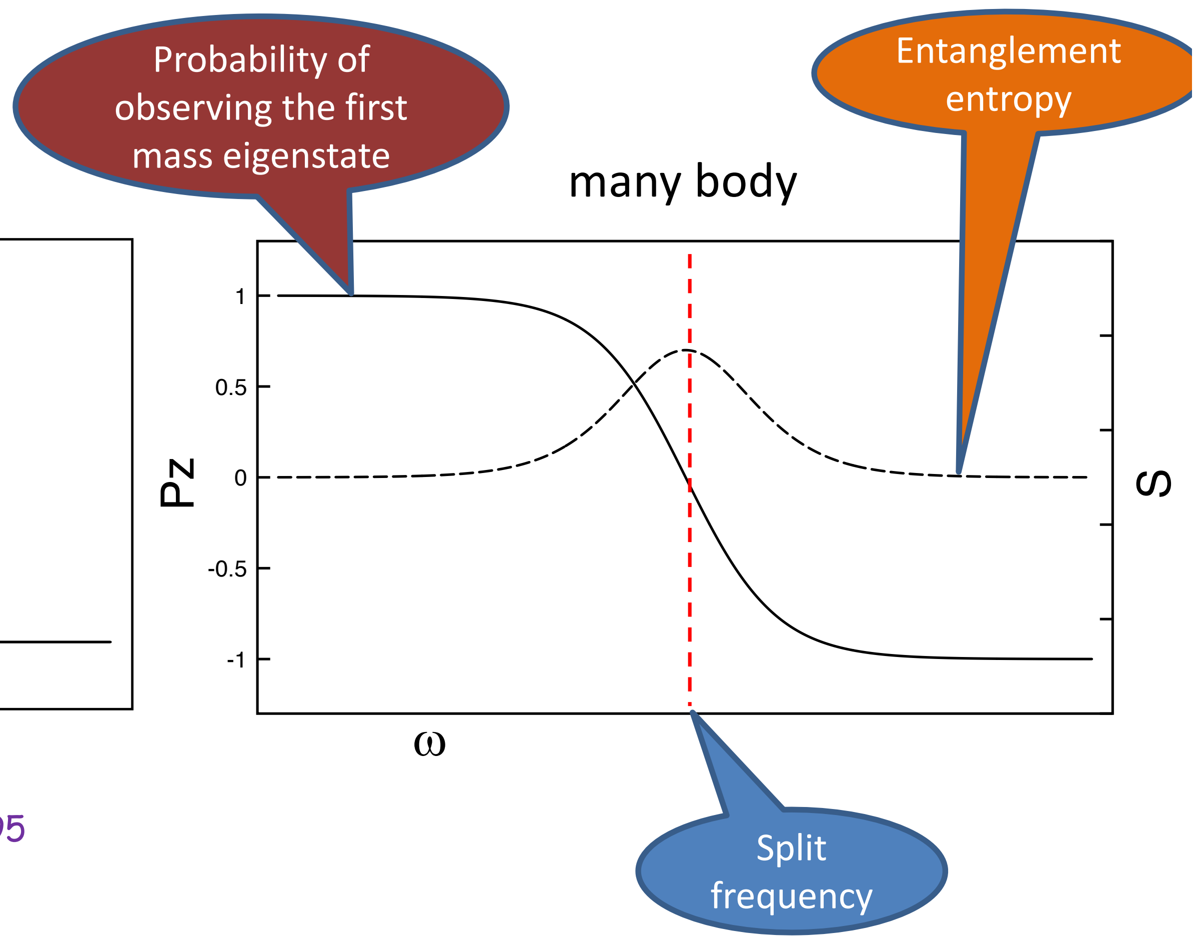
Dimension of the diagonalizing space: kN

von Neumann entropy $S = - \mathrm{Tr}\,(\rho \log \rho)$

	Pure State	Mixed State
Density matrix	$\rho^2 = \rho$	$\rho^2 \neq \rho$
Entropy	$S = 0$	$S \neq 0$

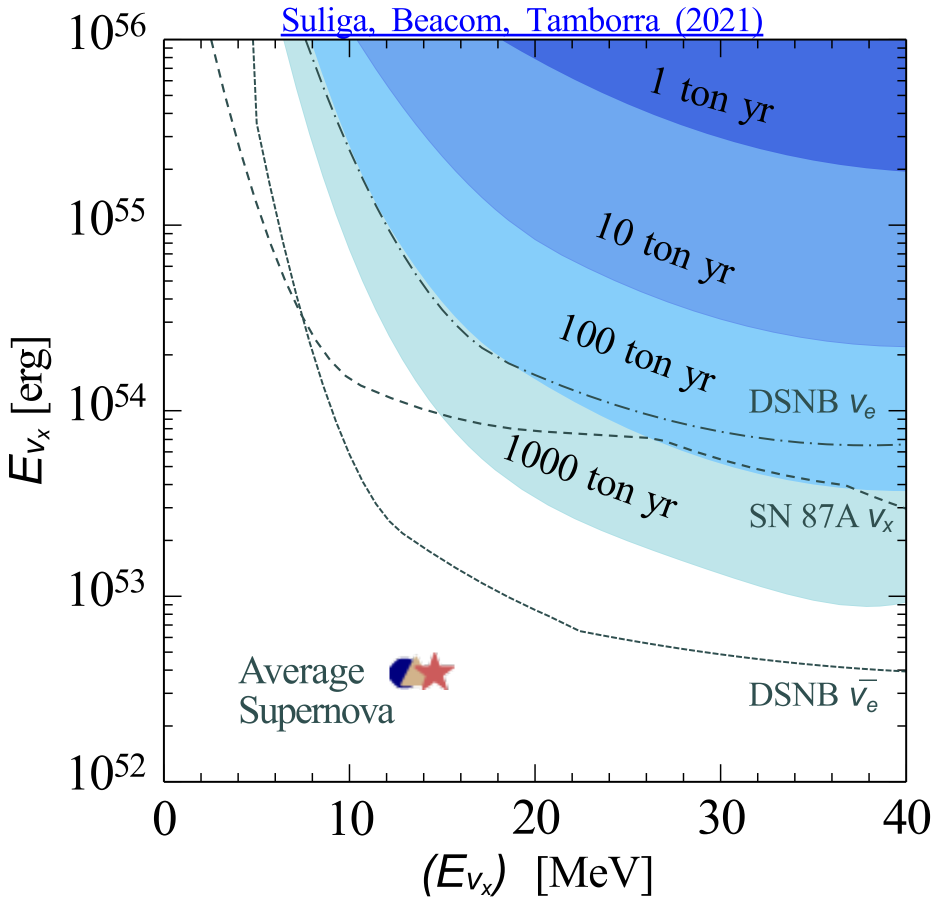
We find that the presence of spectral splits is a good proxy for deviations from the mean-field results





Patwardhan, Cervia, Balantekin, arXiv:2109.08995
Phys. Rev. D **104**, 123035 (2021)

Diffuse supernova neutrino background (DSNB)



- $\bar{\nu}_e$: soon to be detected by SK + Gd, JUNO
- ν_e: posssibly detectable by DUNE
- ν_x: CEνNS detectors can improve the existing limits to almost $\bar{\nu}_e$ level

Detection of all flavors required to

- rule out potential non-standard scenarios
- bring us closer to understaning the supernova physics

Guseinov (1967), Totani et al. (2009), Ando, Sato (2004), Lunardini (2009), Beacom (2010), Horiuchi et al. (2011), Lunardini, Tamborra (2012), Møller, Suliga, Tamborra, Denton (2018), Nakazato et al. (2018), Kresse et al. (2020) ...

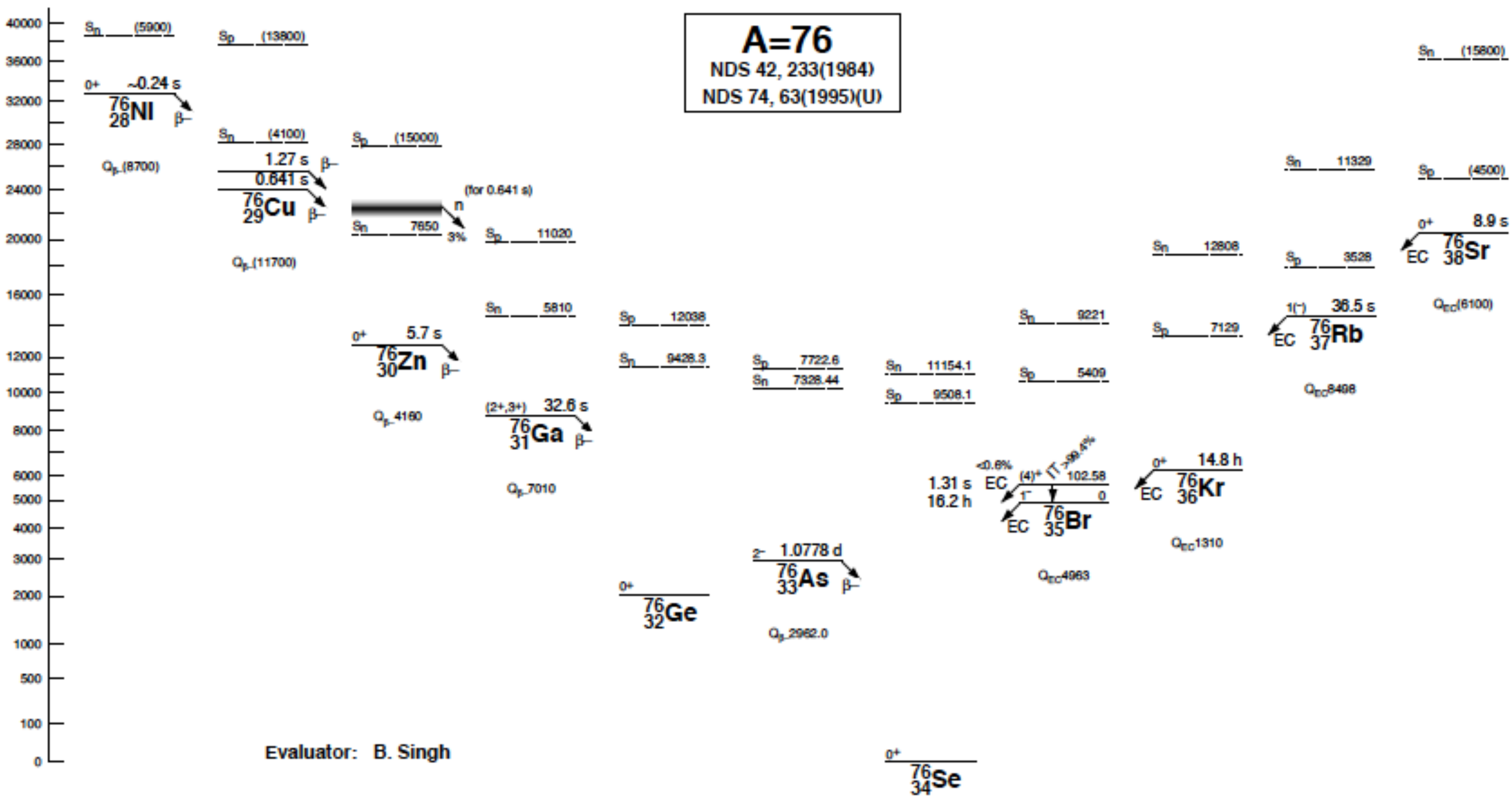
Double Beta Decay

The second order process, where two neutrinos are emitted, is also possible.

Maria Mayer, 1935

Maria Goeppert *Mayer* was *awarded* the 1963 *Nobel* for the nuclear shell model, the San Diego Union headline sadly read "*San Diego Housewife Wins Nobel Prize*".

Pairing gives rise to double beta decay:



Some measurements of 2ββ decay

Nucleus	Q-value (MeV)	$T_{1/2}$ (years)
^{48}Ca	4.276	$(3.9 \pm 0.7 \pm 0.6) \times 10^{19}$
^{76}Ge	2.039	$(1.7 \pm 0.2) \times 10^{21}$
^{82}Se	2.992	$(9.6 \pm 0.3 \pm 1.) \times 10^{19}$
^{100}Mo	3.034	$(7.11 \pm 0.02 \pm 0.54) \times 10^{18}$
^{116}Cd	2.804	$(2.8 \pm 0.1 \pm 0.3) \times 10^{19}$
^{128}Te	0.876	$(2.0 \pm 0.1) \times 10^{24}$
^{130}Te	2.529	$(7.6 \pm 1.5 \pm 0.8) \times 10^{20}$
^{136}Xe	2.467	$(1.1) \times 10^{25}$
^{150}Nd	3.368	$(9.2 \pm 0.25 \pm 0.73) \times 10^{21}$

Suggestion of neutrinoless double beta decay

Nuovo Cimento, **14**, pp 322-328 (1937)

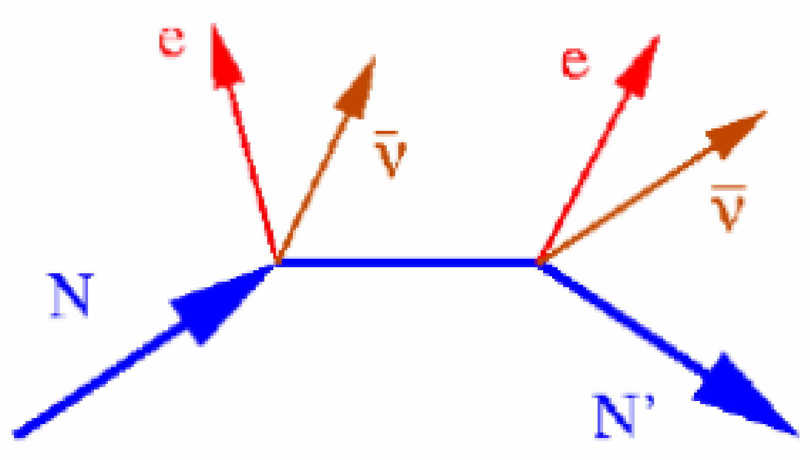
SULLA SIMMETRIA TRA PARTICELLE E ANTIPARTICELLE

Nota di GIULIO RACAH

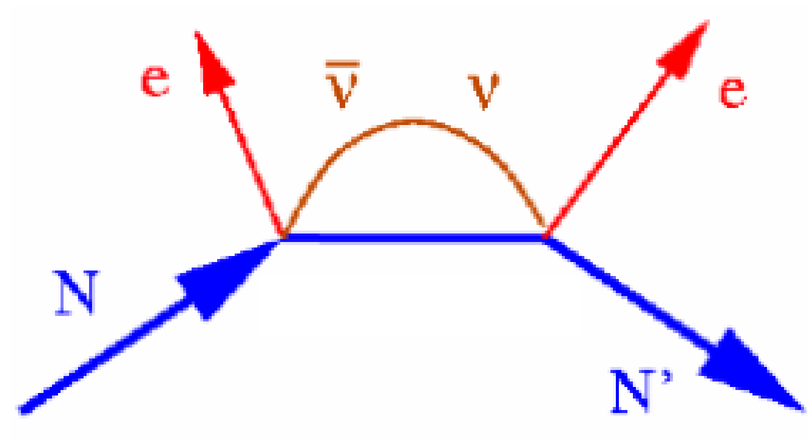
Sunto. - *Si mostra che la simmetria tra particelle e antiparticelle porta alcune modificazioni formali nella teoria di* FERMI *sulla radioattività* β, *e che l'identità fisica tra neutrini ed antineutrini porta direttamente alla teoria di* E. MAJORANA.

Summary - This article shows that the symmetry between particles and antiparticles leads some formal amendments in the theory of Fermi β radioactivity, and that the physical identity between neutrinos and antineutrinos leads directly to the theory of E. Majorana.

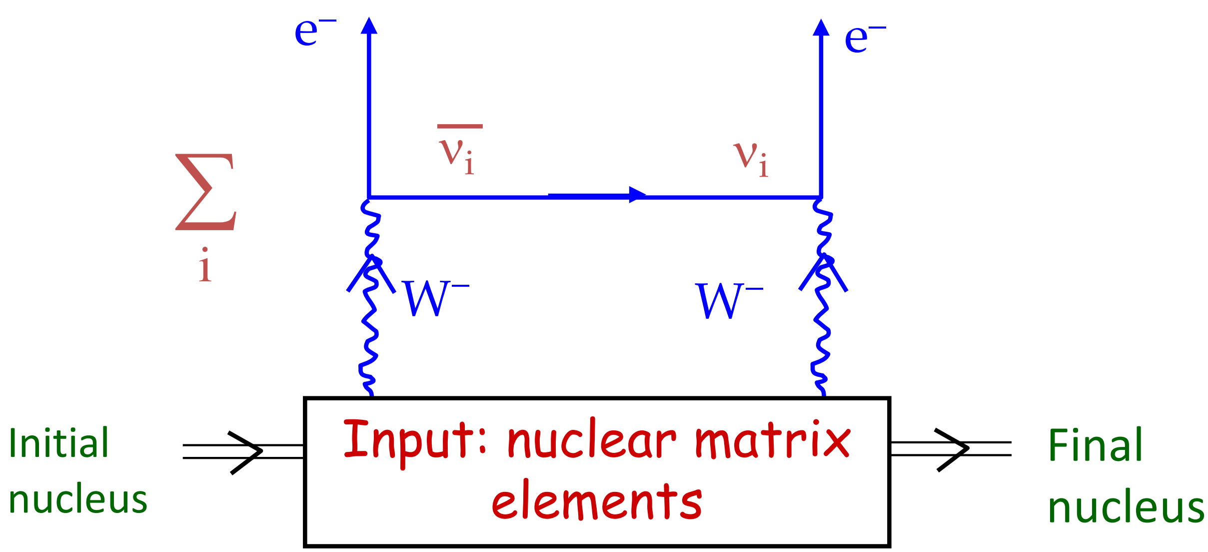
2νββ



0νββ



Majorana nature of the neutrinos permit neutrinoless double beta decay:



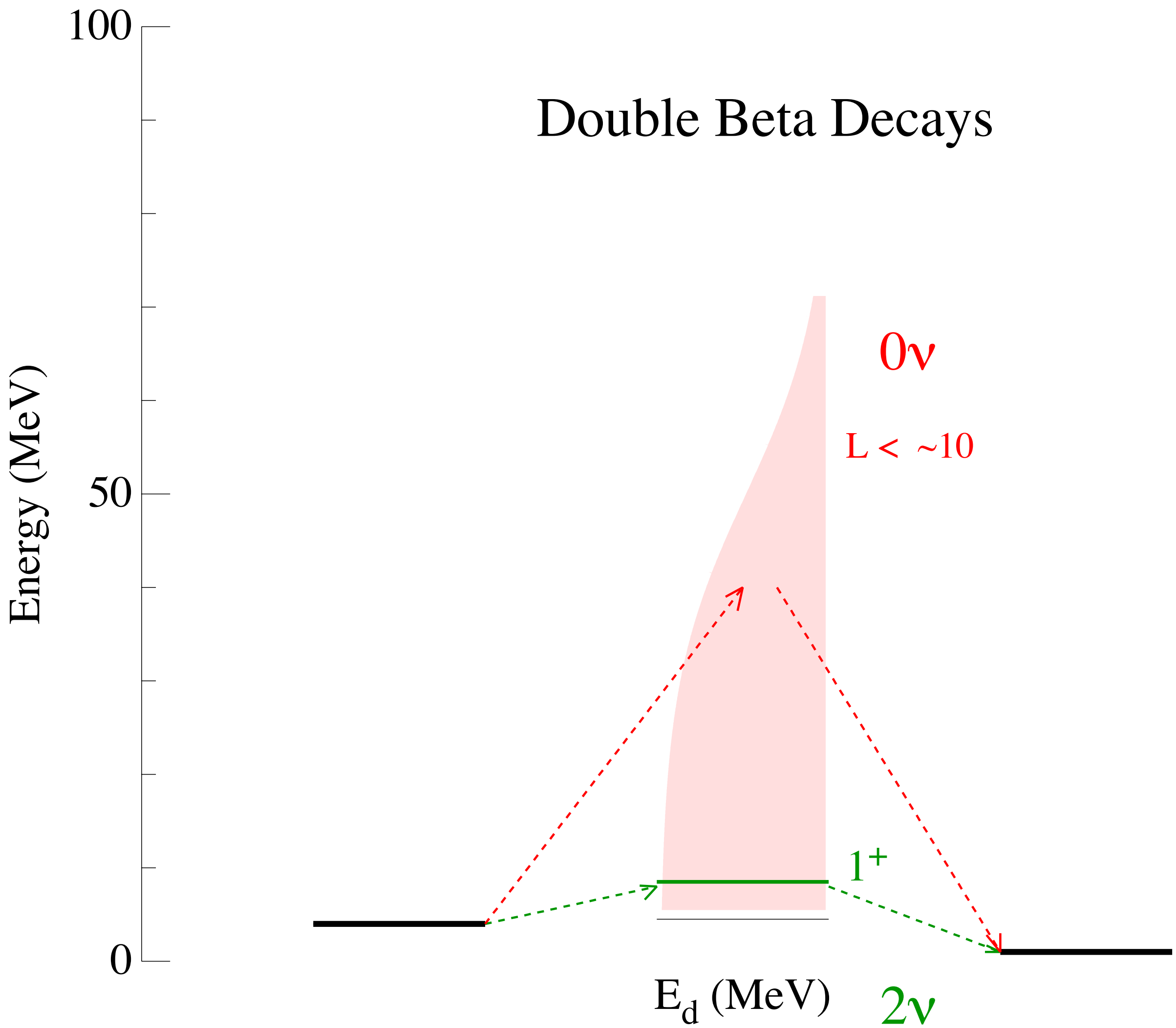
For Majorana neutrino exchange the leptonic part of the amplitude is given as a sum over mass eigenstates:

$$\mathcal{L}_{\mu\nu} = \sum_i [\bar{e}(x)]\gamma_\mu(1-\gamma_5)U_{ei}\nu_i(x)\overline{\nu_i^C}\,U_{ei}\gamma_\nu(1+\gamma_5)e^C(y)$$

Contracting the two neutrino fields gives $\dfrac{q_\mu\gamma^\mu - m_i}{q^2 - m_i^2}$

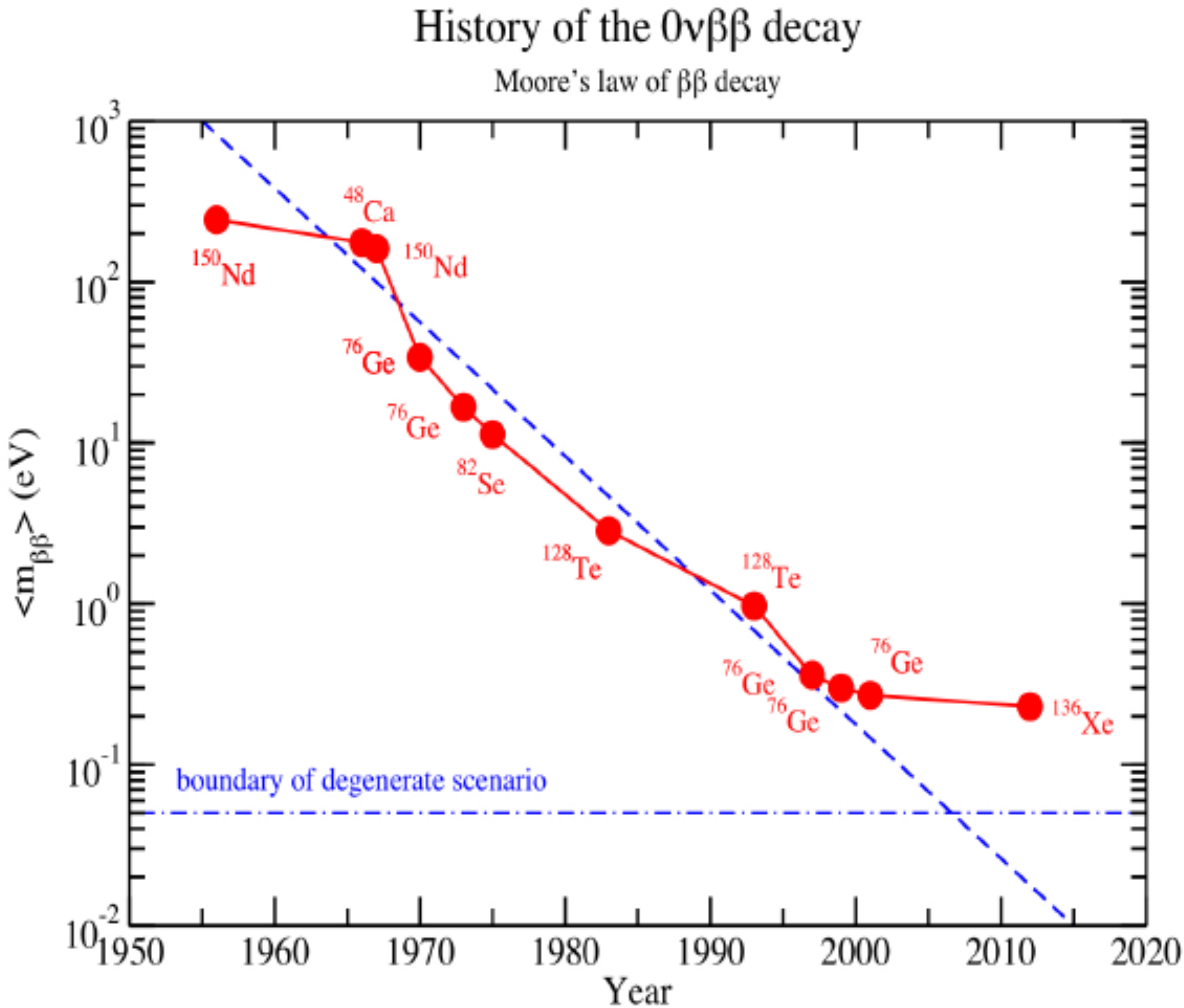
$q_\mu\gamma^\mu$ term does not contribute to the traces making leptonic tensor proportional to the quantity

$$m_{\beta\beta} = \sum_{i=1}^{3} U_{ei}^2 m_i$$

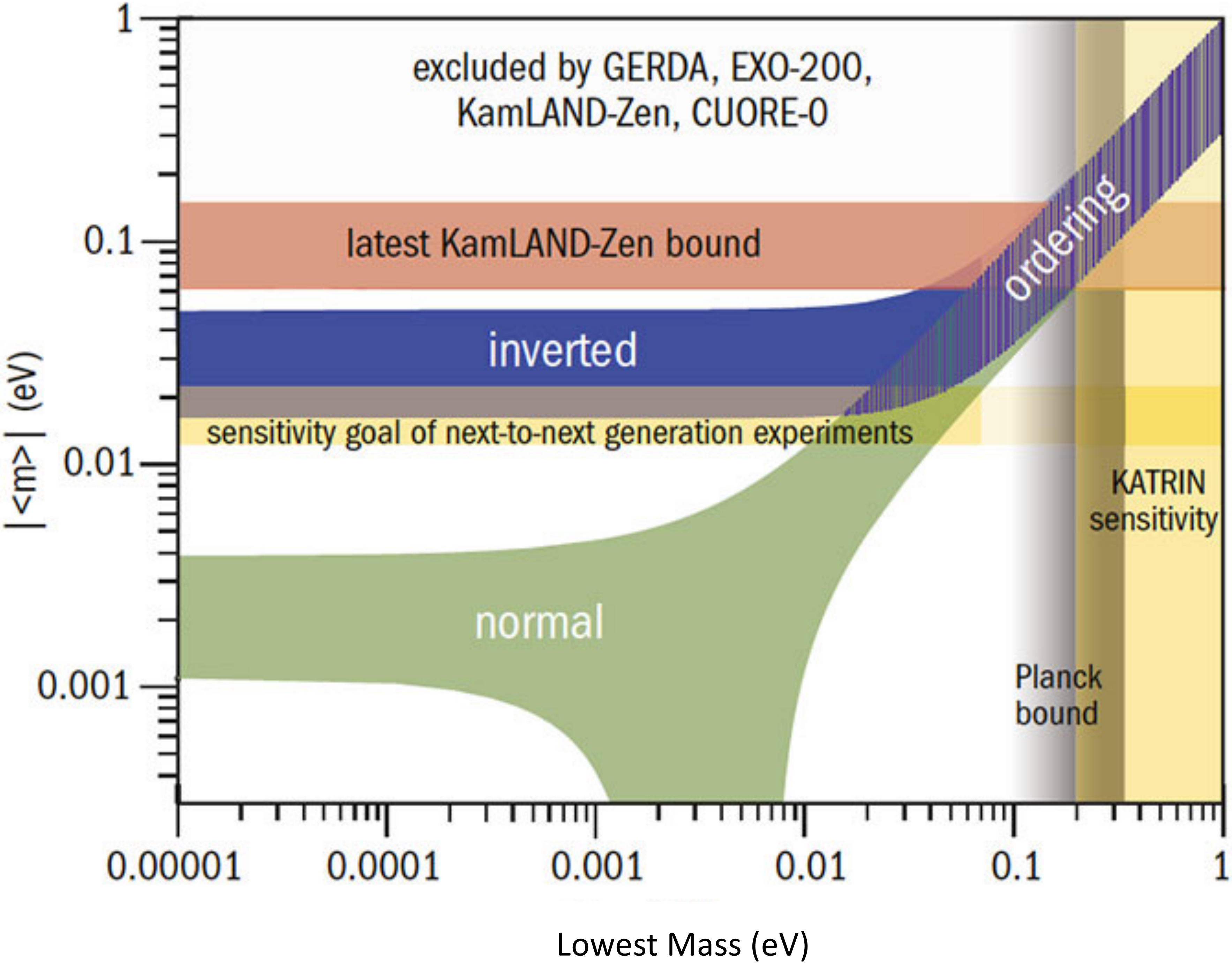


$$\frac{1}{T_{1/2}^{2\nu}} = G^{2\nu}(Q,Z)\left|M^{2\nu}\right|^2$$

$$\frac{1}{T_{1/2}^{0\nu}} = G^{0\nu}(Q,Z)\left|M^{0\nu}\right|^2\left|\sum_i U_{ei}^2 m_i\right|^2$$

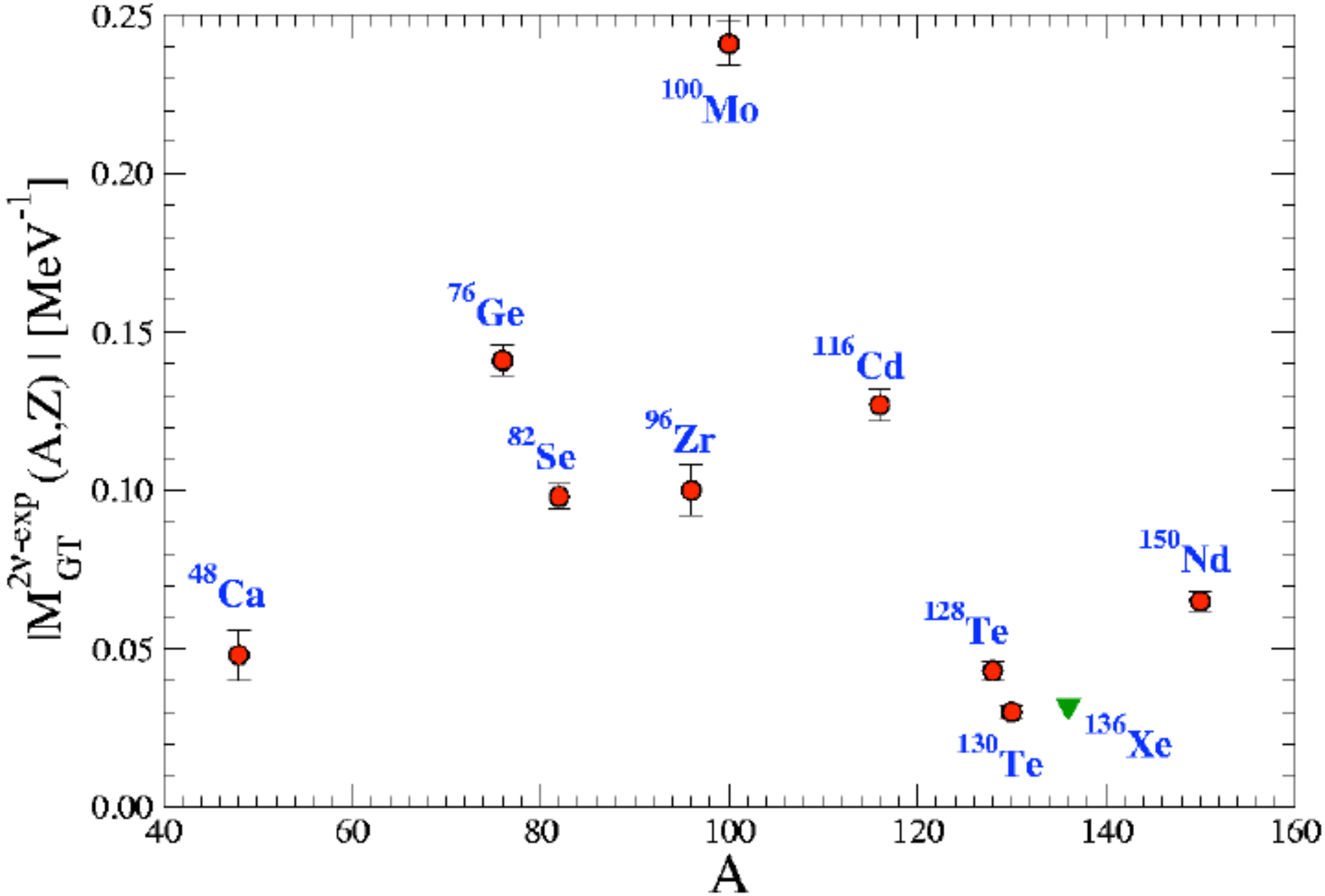

History of the 0νββ decay
Moore's law of ββ decay
<m_ββ> (eV)
Year
10^3
10^2
10^1
10^0
10^-1
10^-2
1950
1960
1970
1980
1990
2000
2010
2020
150Nd
48Ca
150Nd
76Ge
76Ge
82Se
128Te
128Te
76Ge
76Ge
76Ge
136Xe
boundary of degenerate scenario

Vogel



excluded by GERDA, EXO-200, KamLAND-Zen, CUORE-0
latest KamLAND-Zen bound
inverted
ordering
sensitivity goal of next-to-next generation experiments
KATRIN sensitivity
normal
Planck bound
|<m>| (eV)
1
0.1
0.01
0.001
0.00001
0.0001
0.001
0.01
0.1
1
Lowest Mass (eV)

For 2νββ there is a strong shell-model dependence of the matrix elements



Vogel

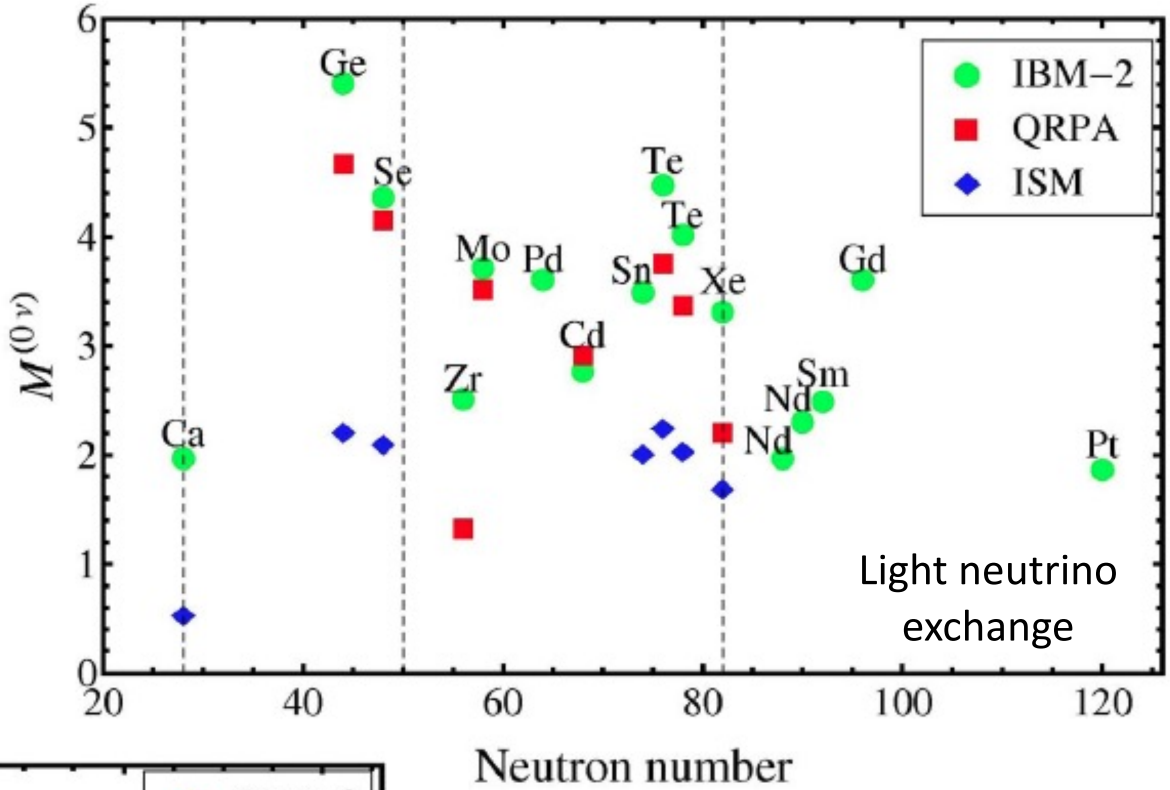
0ν double beta decay

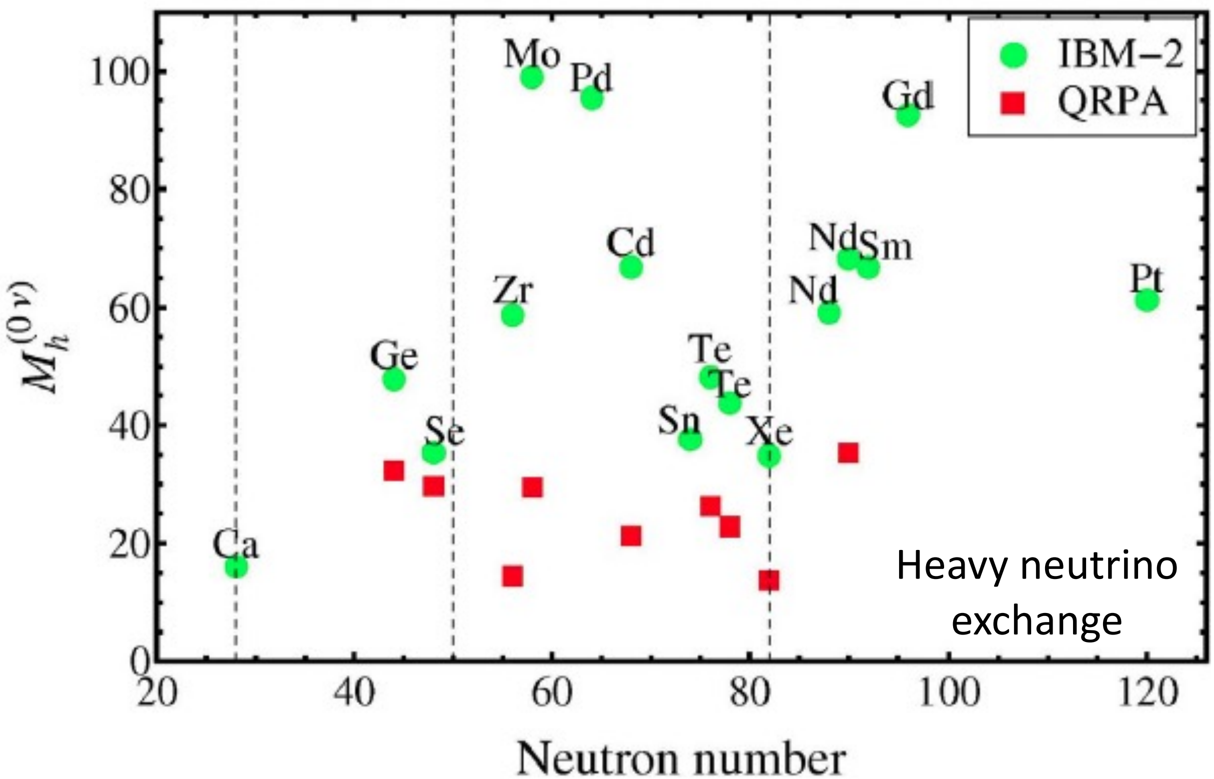
$(1/T_{1/2}) = G(E,Z)\, M^2 \langle m_{\beta\beta}\rangle^2$

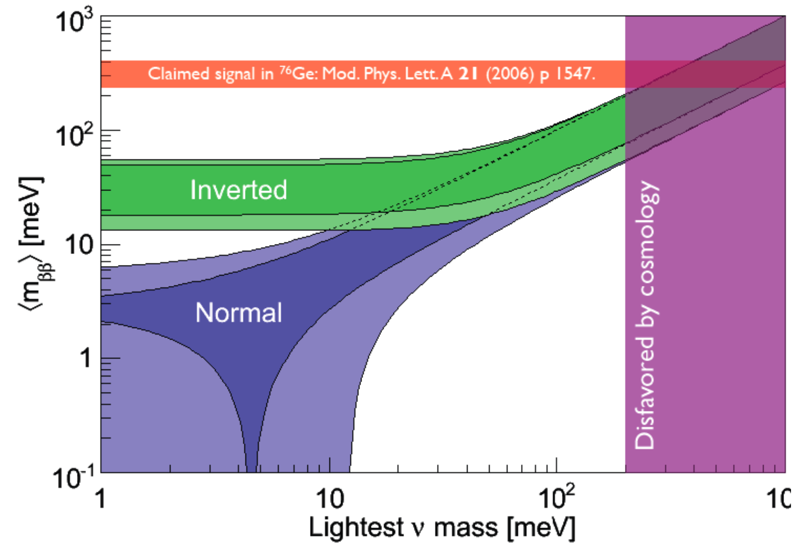
$G(E,Z)$: phase space

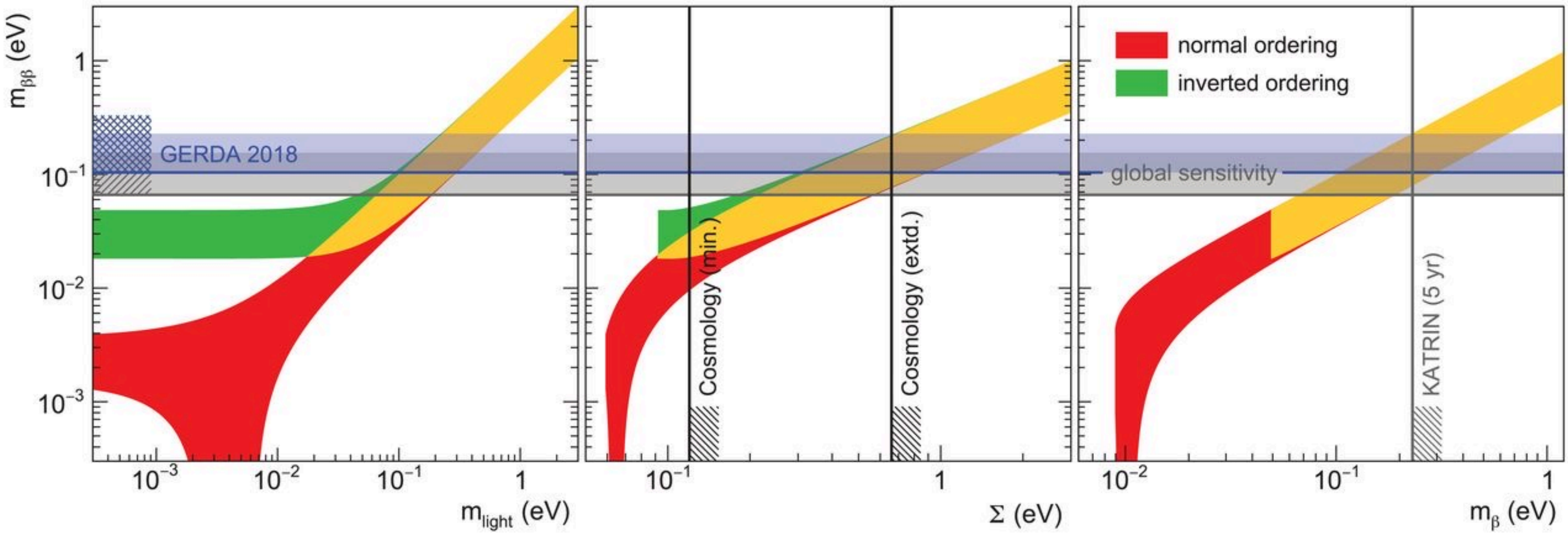
M : nuclear matrix element

$\langle m_{\beta\beta}\rangle = |\sum_j |U_{ej}|^2 m_j e^{i\delta(j)}|$









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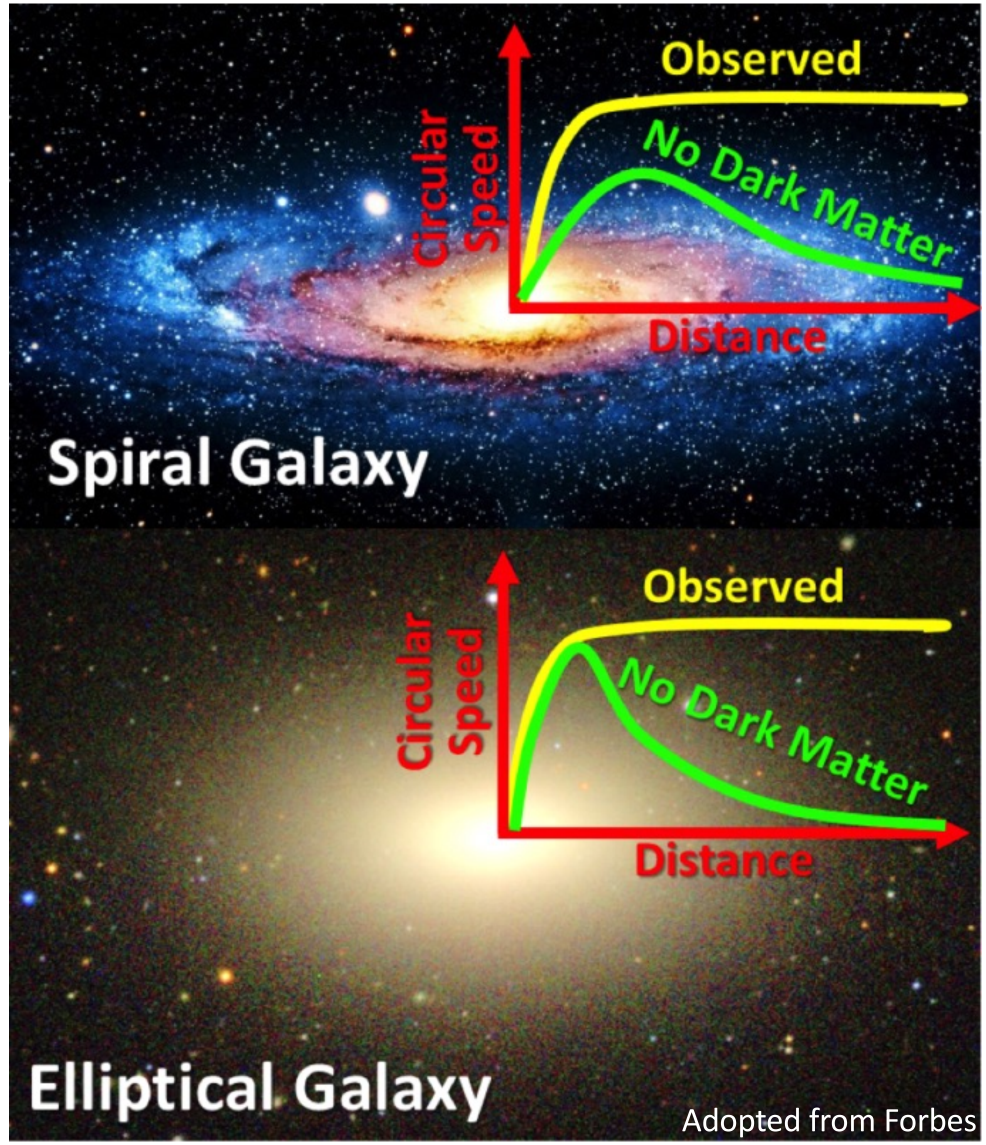
$$m_{\beta\beta} = \left| \sum_{i=1}^{3} U_{ei}^2 m_i \right|$$

$$m_\beta = \sqrt{\sum_i |U_{ei}^2| m_i^2}$$

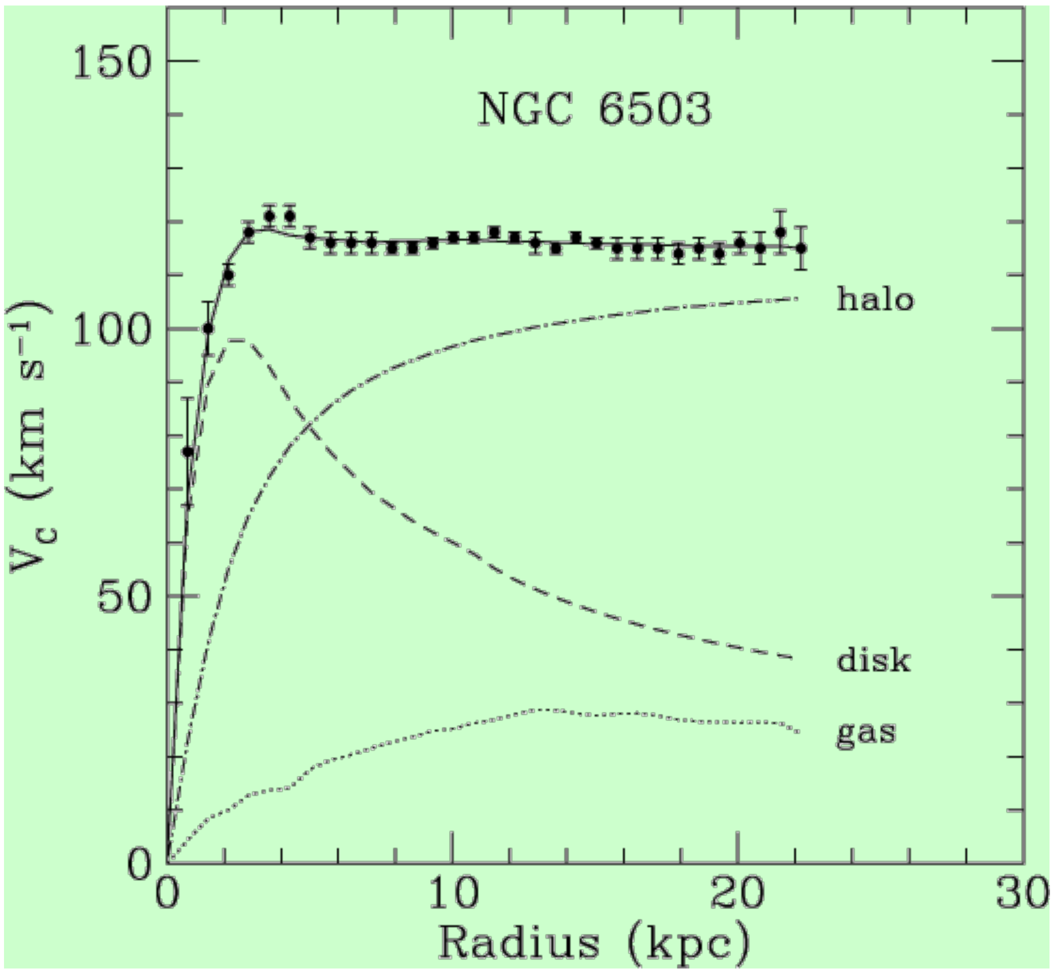
DARK MATTER

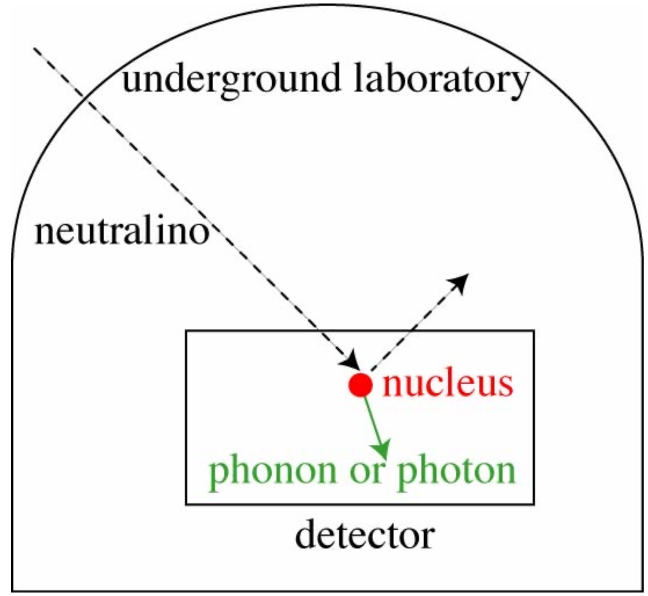
Zwicky

Rubin

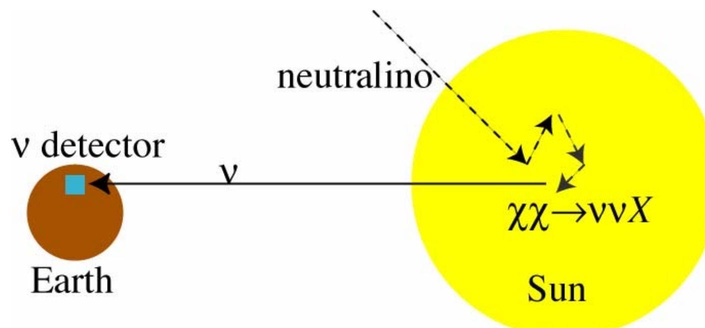


Observing the Dark Matter



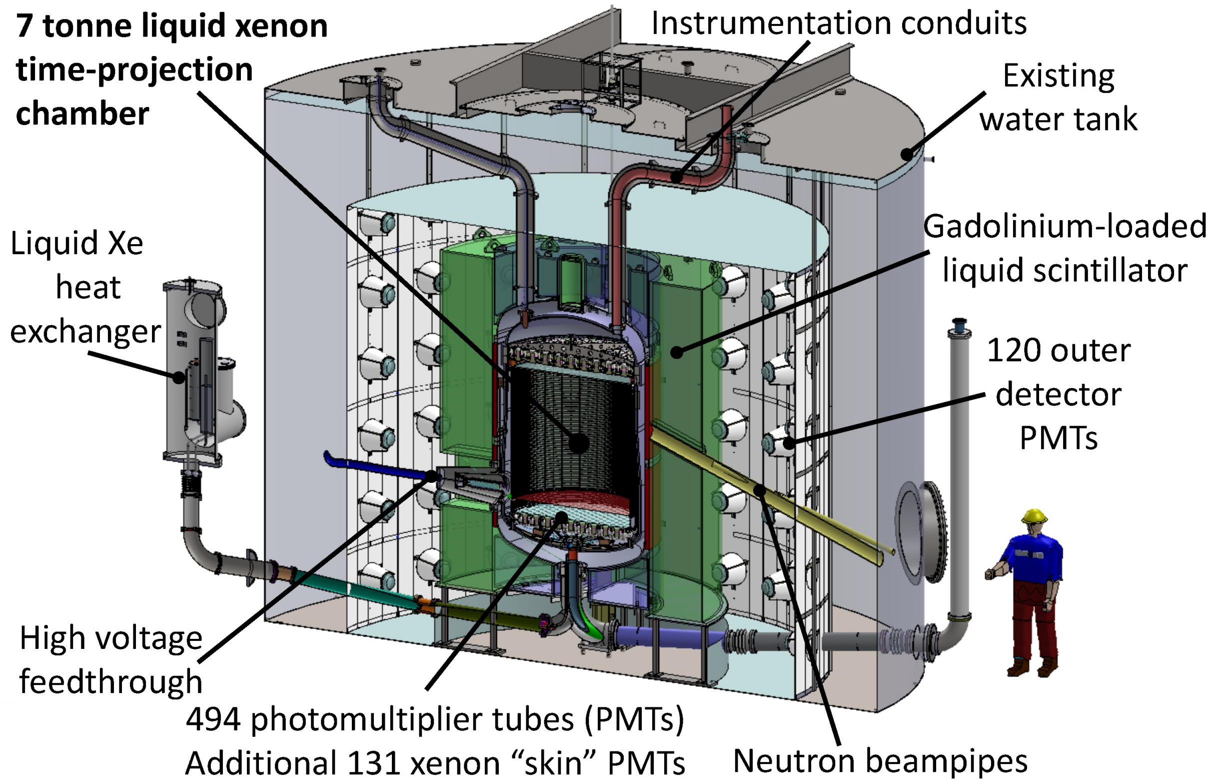


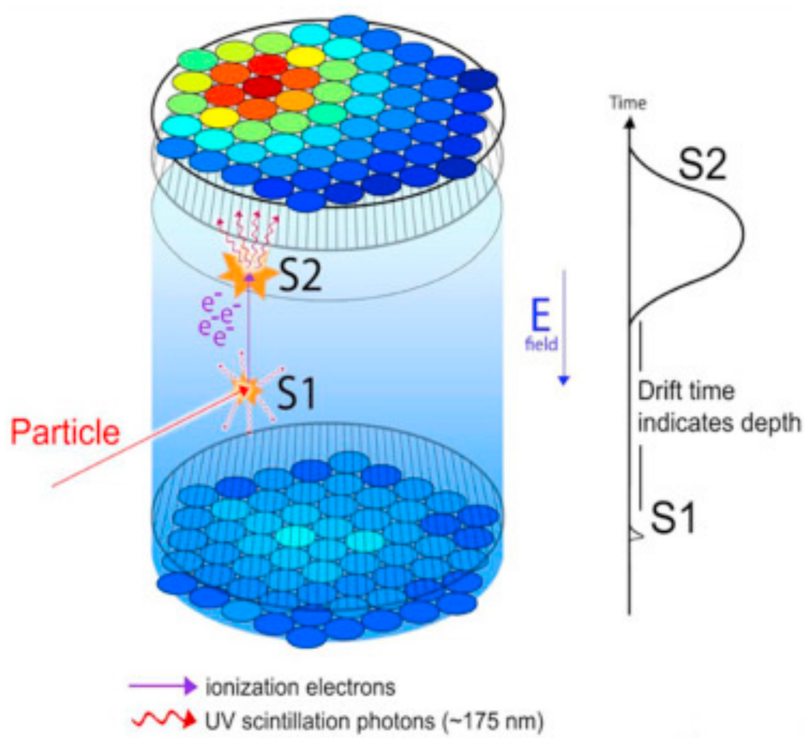
Direct detection



Indirect detection

The LZ Detector





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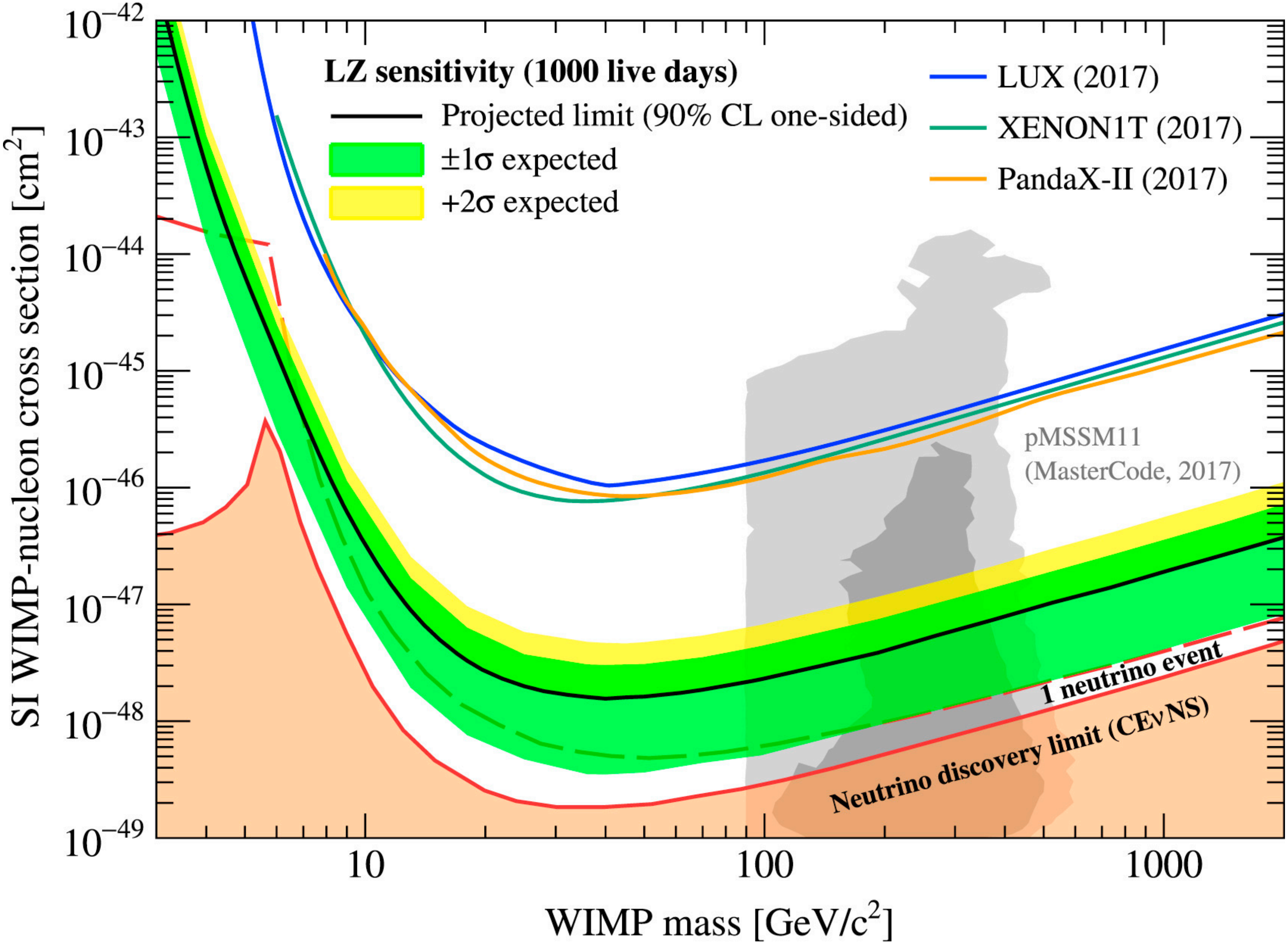


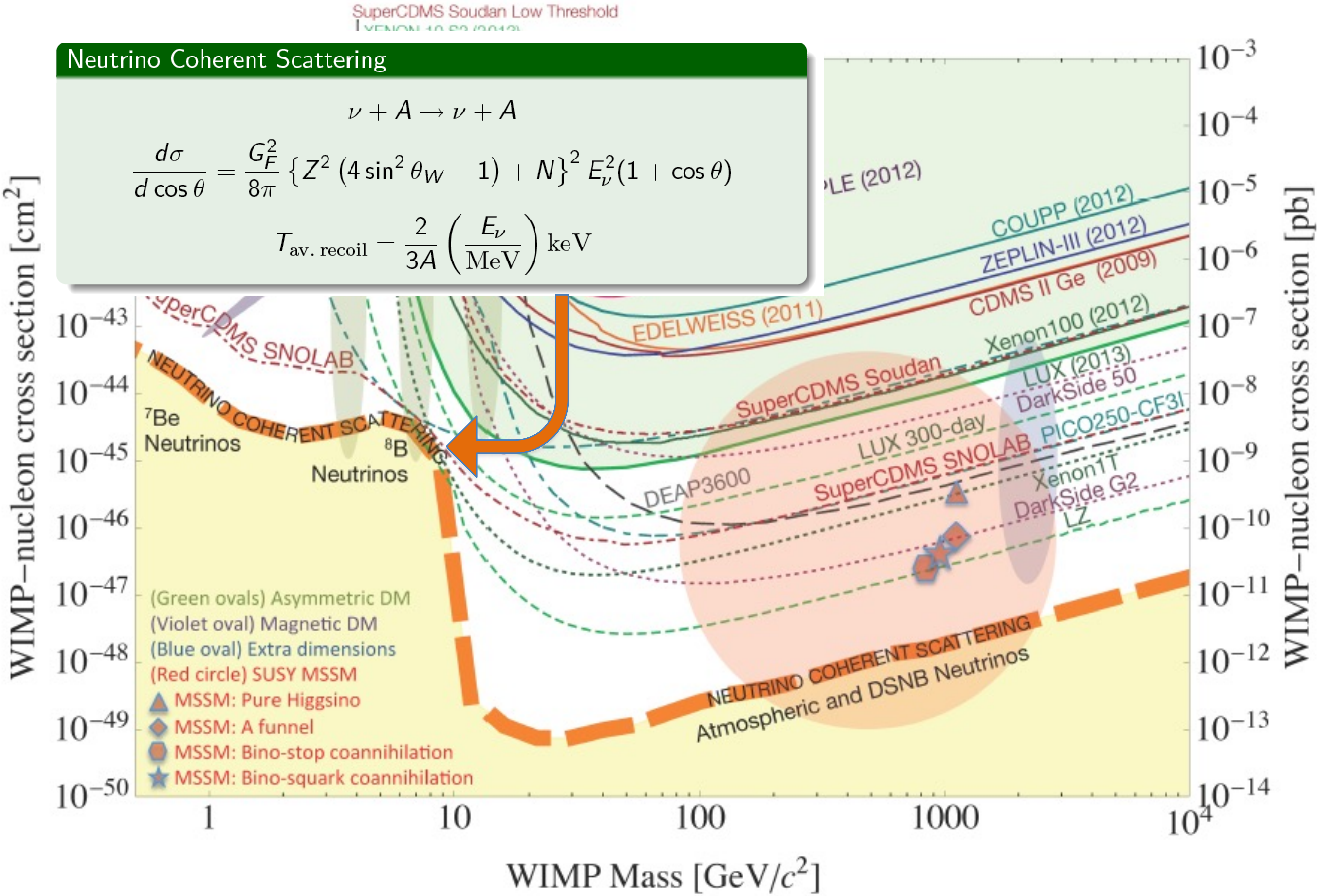
LZ sensitivity (1000 live days)
Projected limit (90% CL one-sided)
±1σ expected
+2σ expected
LUX (2017)
XENON1T (2017)
PandaX-II (2017)
pMSSM11
(MasterCode, 2017)
1 neutrino event
Neutrino discovery limit (CEνNS)
SI WIMP-nucleon cross section [cm^2]
WIMP mass [GeV/c^2]
10^{-42}
10^{-43}
10^{-44}
10^{-45}
10^{-46}
10^{-47}
10^{-48}
10^{-49}
10
100
1000

Neutrino Coherent Scattering

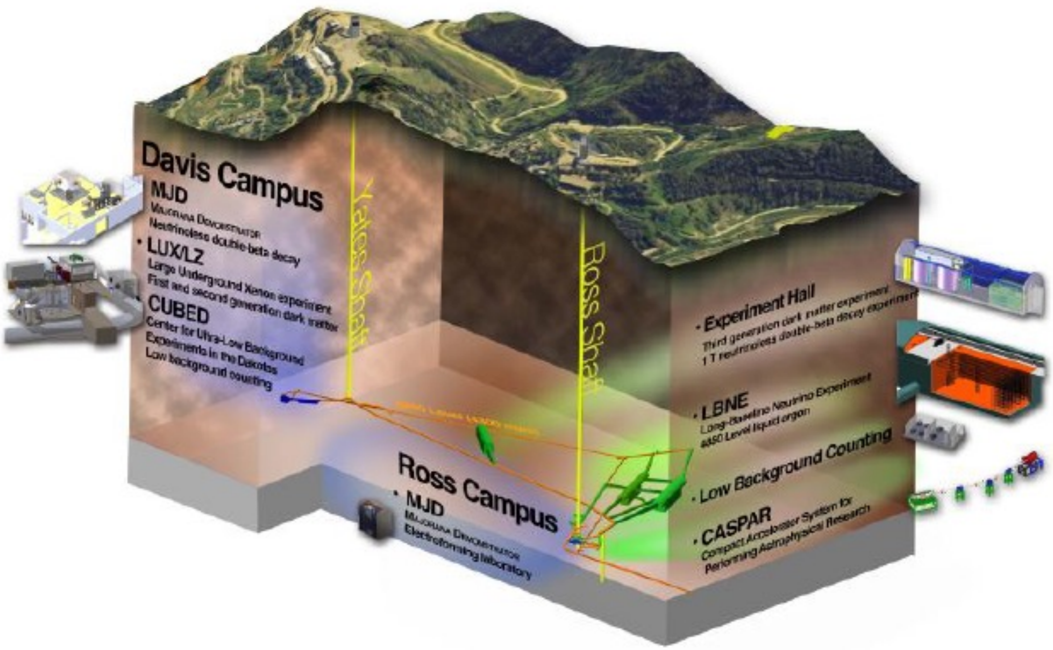
$$\nu + A \rightarrow \nu + A$$

$$\frac{d\sigma}{d\cos\theta} = \frac{G_F^2}{8\pi}\left\{Z^2\left(4\sin^2\theta_W - 1\right) + N\right\}^2 E_\nu^2(1+\cos\theta)$$

$$T_{\text{av. recoil}} = \frac{2}{3A}\left(\frac{E_\nu}{\text{MeV}}\right)\text{keV}$$

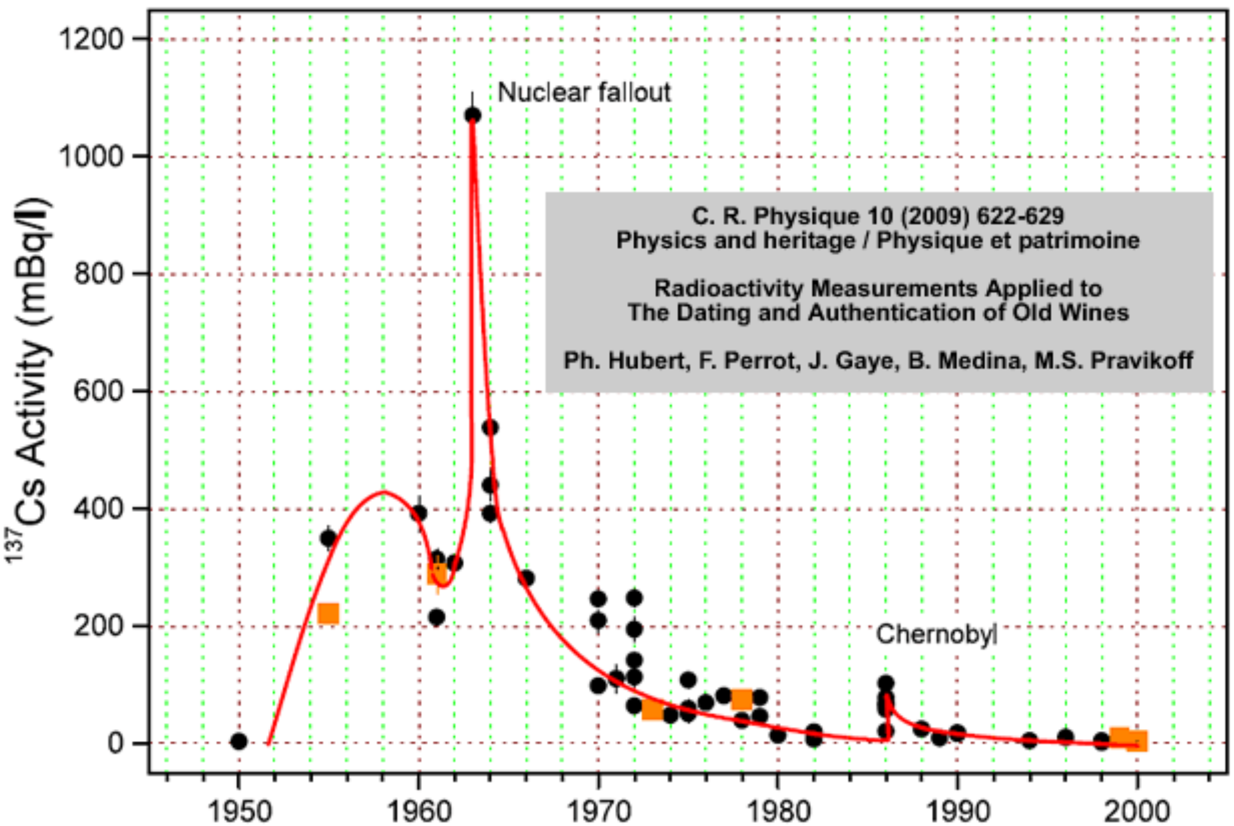


Compact Accelerator System for Performing Astrophysical Research (CASPAR)

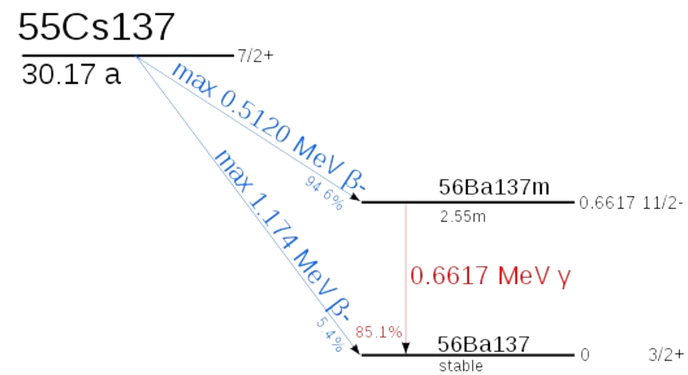


LUNA: Stellar Hydrogen burning
CASPAR: Helium burning in massive Red Giant stars or low-mass AGB stars
$^{13}C\ (\alpha,n)\ ^{16}O$
$^{22}Ne\ (\alpha,n)\ ^{25}Mg$

Sources of neutrinos: Wine



Activity (mBq/l) of the ^{137}Cs radioactive isotope as a function of the wine vintage.
All activities are for Bordeaux wines only, and are normalized to an arbitrary date, January 1st, 2000.
The solid circles correspond to measurements after reduction of the wine into ashes,
the orange squares correspond to nondestructive measurements, i.e., without opening the bottles.
Statistical errors are generally smaller than the dimension of the points.




Thank you