Particle Physics and Supernovae

Past, Present and Future

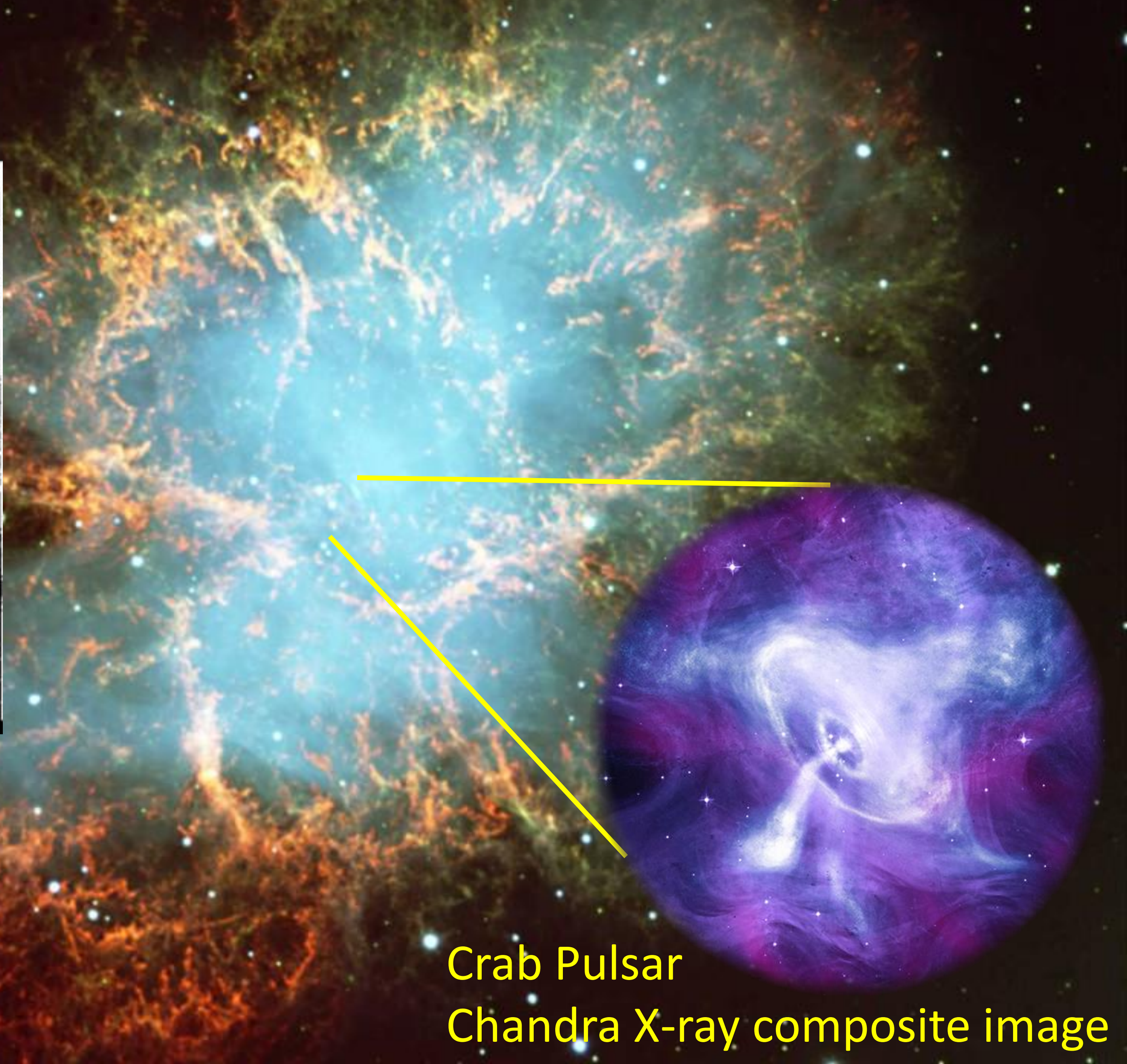
GGI Neutrino Frontiers,
25 June–19 July 2024, Florence

Georg Raffelt, Max-Planck-Institut für Physik, Garching

Crab Nebula – Remnant of SN 1054

凡十一日没三年三月乙巳出東南方大中祥符四
年正月丁丑見南斗魁前天禧五年四月丙辰出軒轅
前星西北大如桃速行經軒轅太星入太微垣掩右執
法犯次將歷屛星西北凡七十五日入濁没明道元
年六月乙巳出東北方近濁有芒彗至丁巳凡十三
日没至和元年五月己丑出天關東南可數寸歲餘
稍没熙寧二年六月丙辰出箕度中至七月丁卯犯
箕乃散三年十一月丁未出天囷元祐六年十一月
辛亥出參度中犯掩側星壬子犯九游星十二月癸
酉入奎至七年三月辛亥乃散紹興八年五月守婁

宋史志卷九



Crab Pulsar
Chandra X-ray composite image

George Gamow and Mário Schoenberg (1940, 1941)

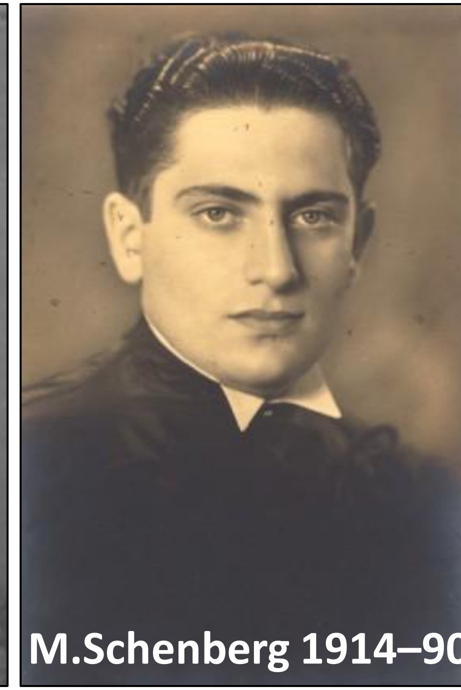
- **The Possible Role of Neutrinos in Stellar Evolution**, Phys. Rev. 58 (1940) 1117 (1 column letter to the editor)
- **Neutrino Theory of Stellar Collapse** Phys. Rev. 59 (1941) 539

As we suggested in a recent publication,[5] this very fast removal of energy from the interior of the star can be understood on the basis of the present ideas on the role of neutrinos in nuclear transformations involving emission or absorption of β-particles. In fact, when the temperature and density in the interior of a contracting star reach certain values depending on the kind of nuclei involved, we should expect processes of the type

$$\begin{cases} {}_{Z}N^{A}+e^{-}\rightarrow {}_{Z-1}N^{A}+\text{antineutrino} \\ {}_{Z-1}N^{A}\rightarrow {}_{Z}N^{A}+e^{-}+\text{neutrino}, \end{cases} \quad (3)$$

which we shall call, for brevity, "urca-processes." The neutrinos formed in the above processes[6] absorb a considerable part of the transformation energy (about $\frac{2}{3}$), and escape with practically no difficulty through the body of the star.


G.Gamow 1904–68

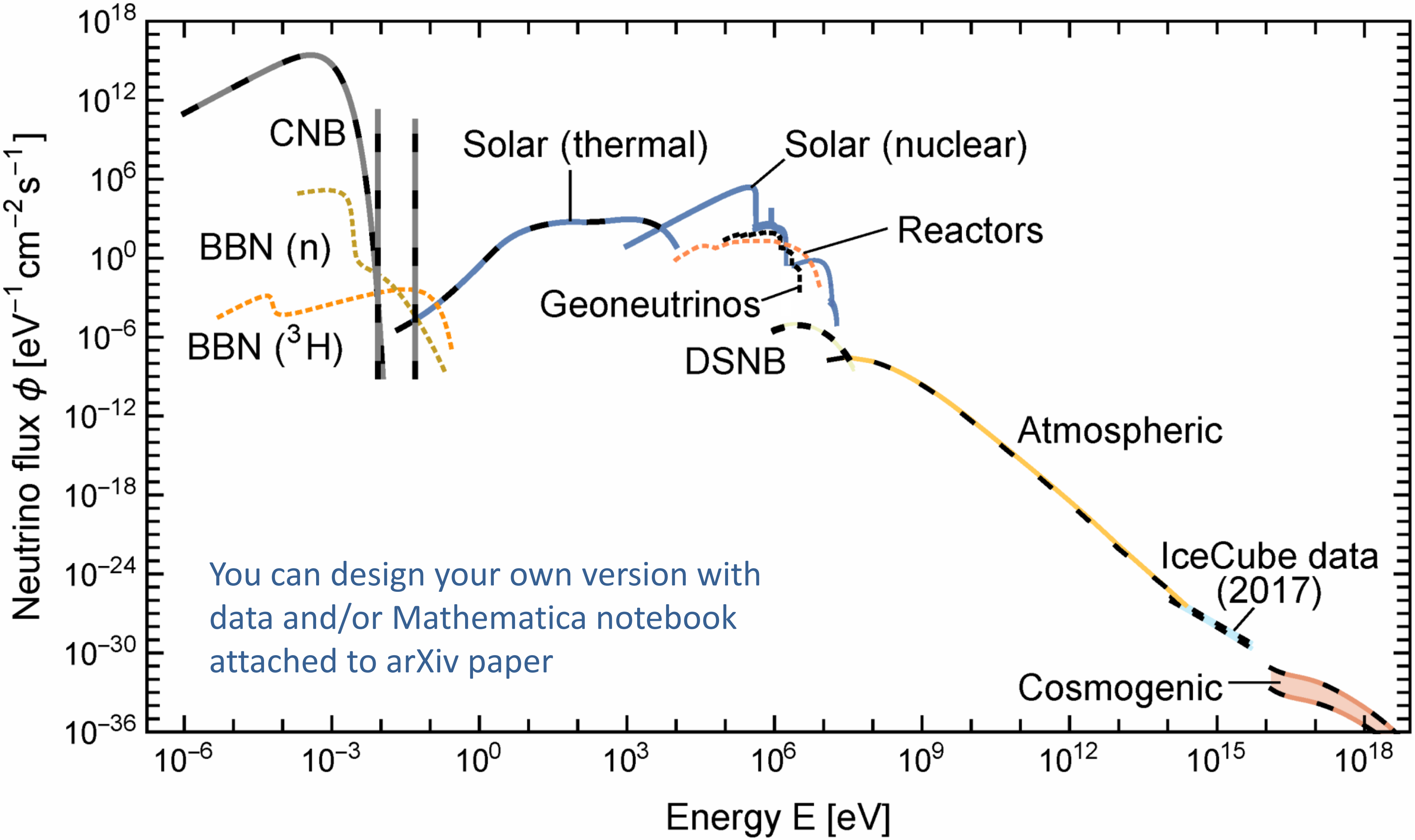

M.Schenberg 1914–90

Introducing urca processes

Named after a casino in Rio de Janeiro, but not explained in the paper.
(The bank always wins!)
Sch(o)enberg was Brazilian from São Paolo

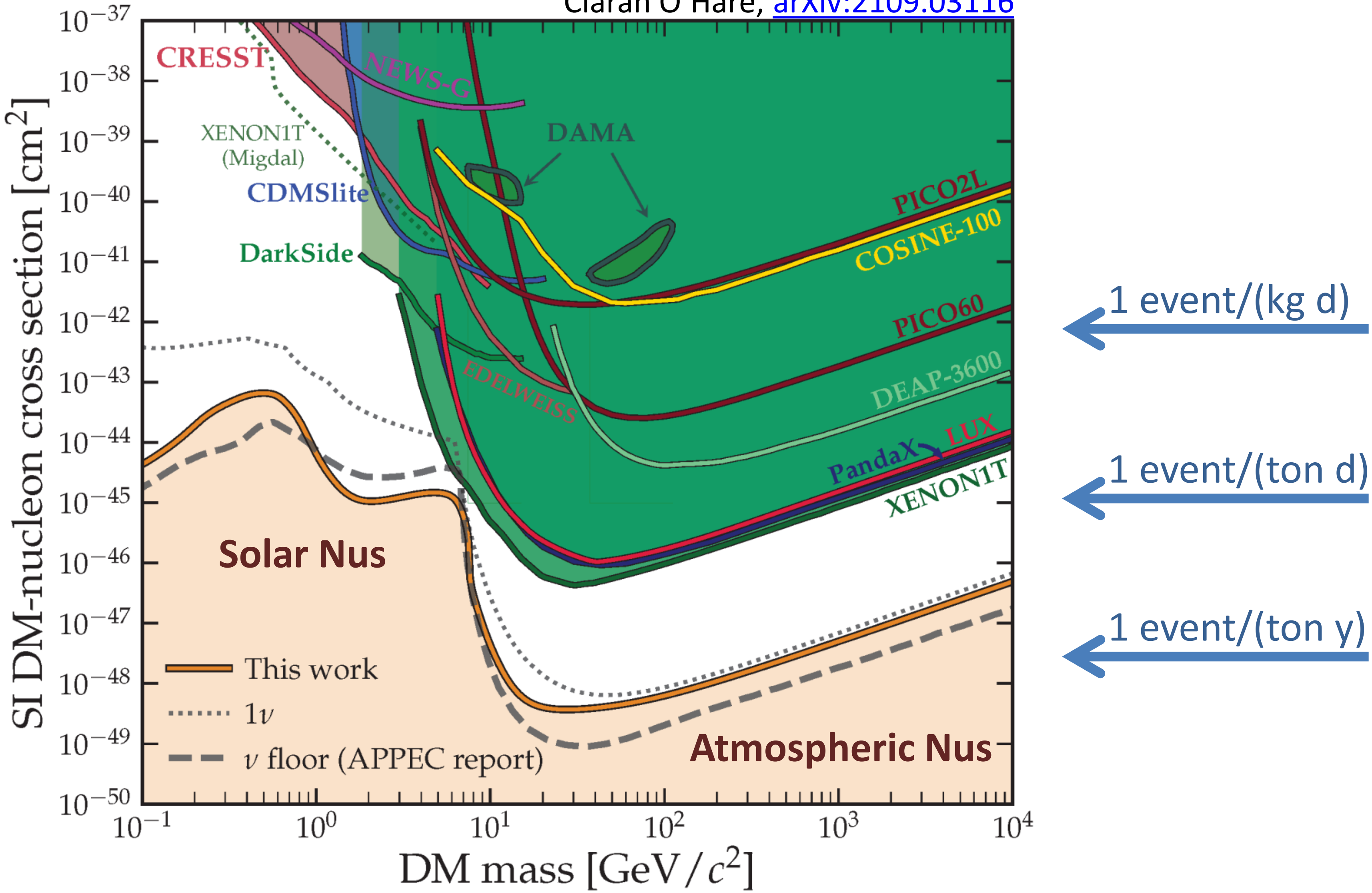
Grand Unified Neutrino Spectrum (GUNS) at Earth

Vitagliano, Tamborra & Raffelt, arXiv:1910.11878

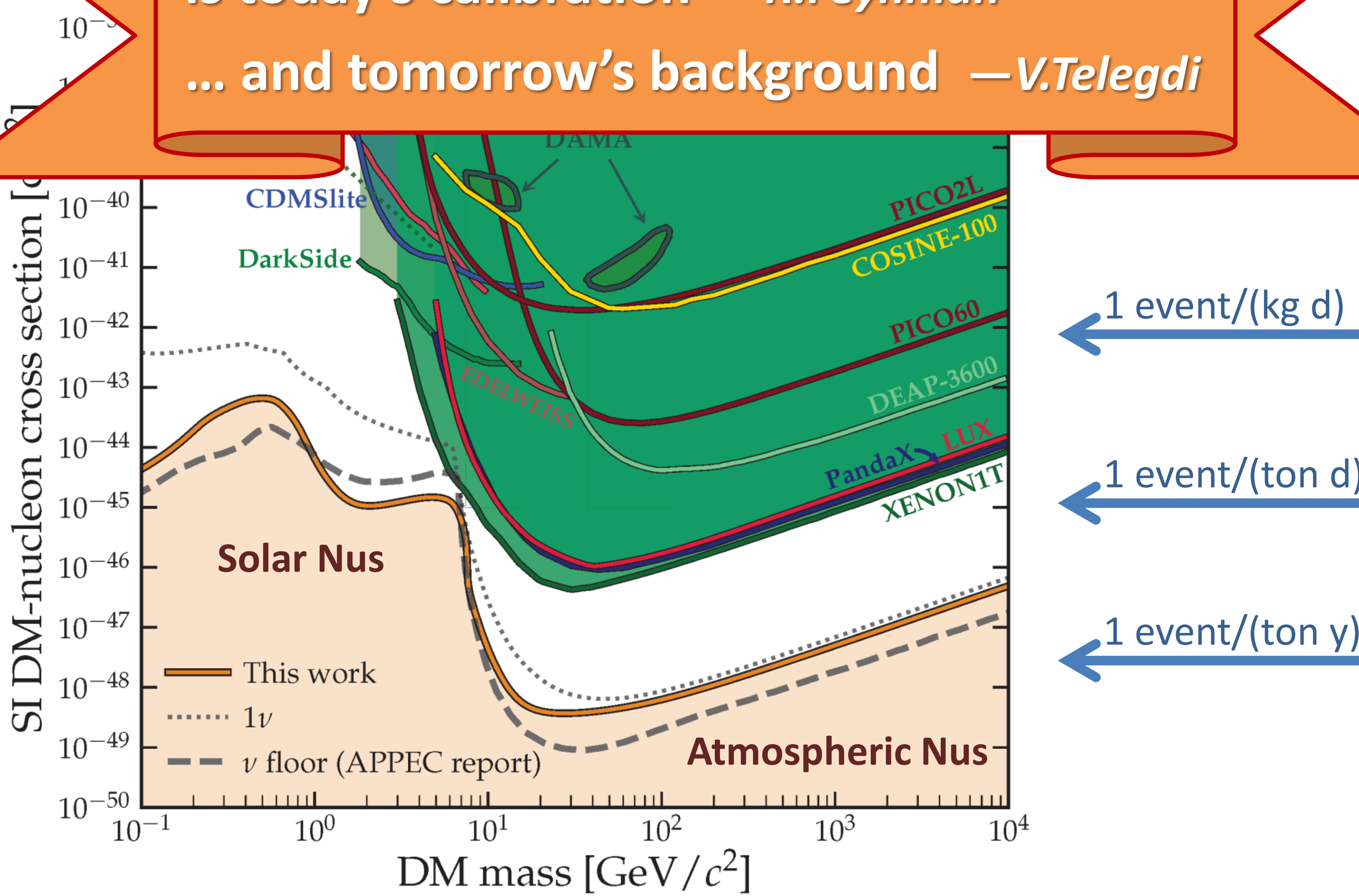


Neutrino Fog for WIMP Dark Matter Detection

Ciaran O'Hare, arXiv:2109.03116



Yesterday's sensation
is today's calibration —*R.Feynman*
… and tomorrow's background —*V.Telegdi*



XENON

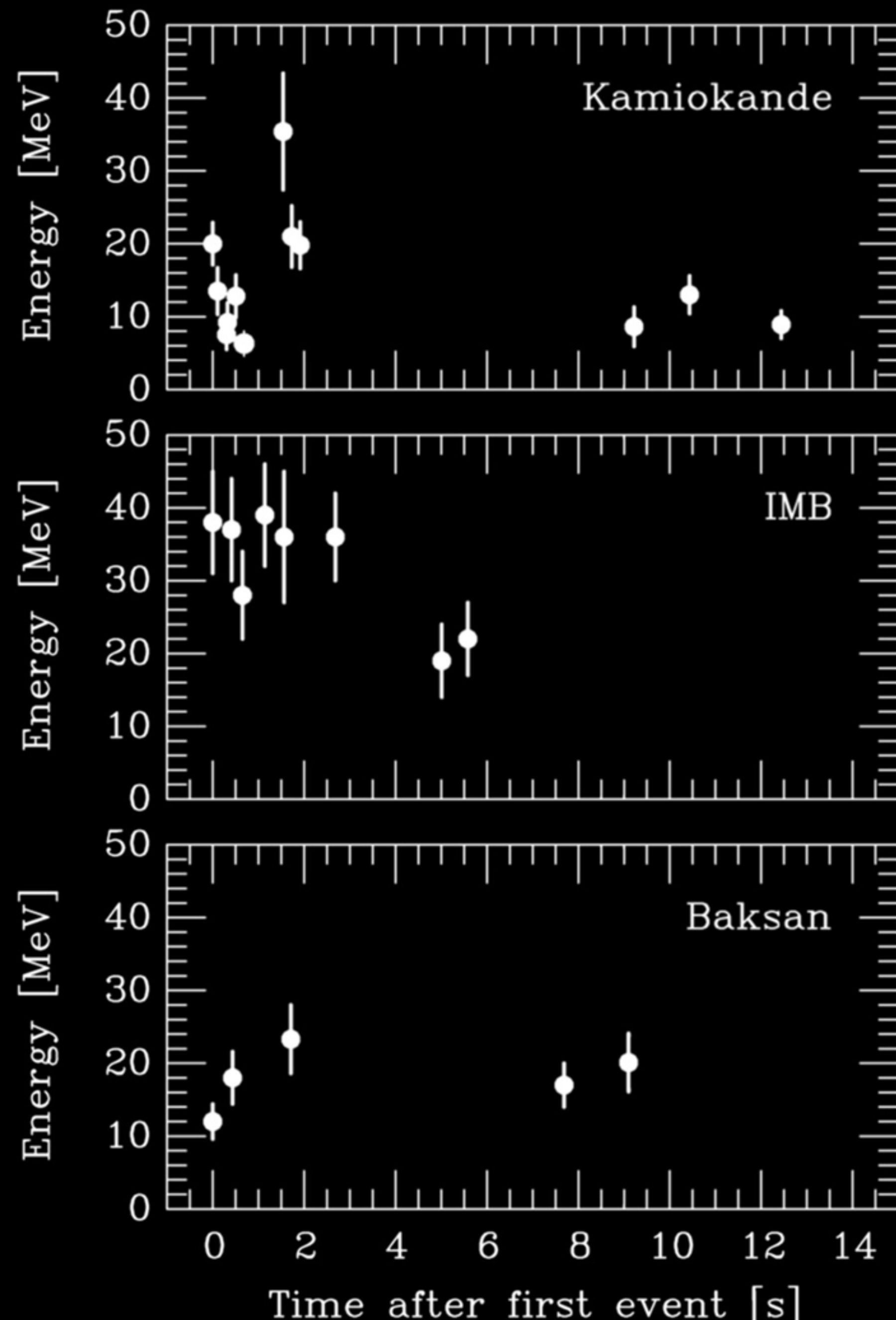
清華大學
Tsinghua University

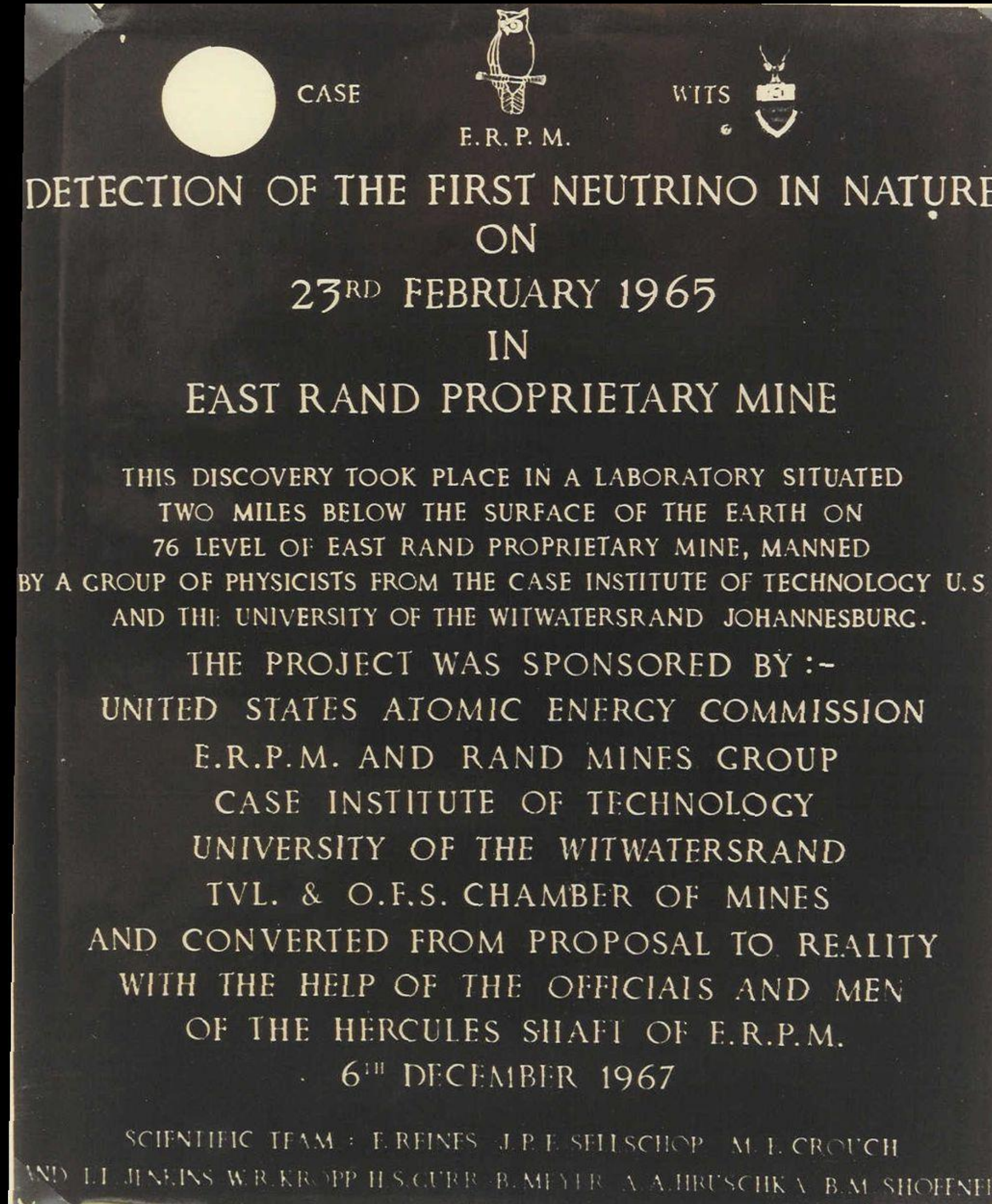
First Measurement of Coherent Elastic Neutrino Nucleus Scattering of Solar ^{8}B Neutrinos in XENONnT

Fei Gao, Tsinghua University
on behalf of the XENON Collaboration

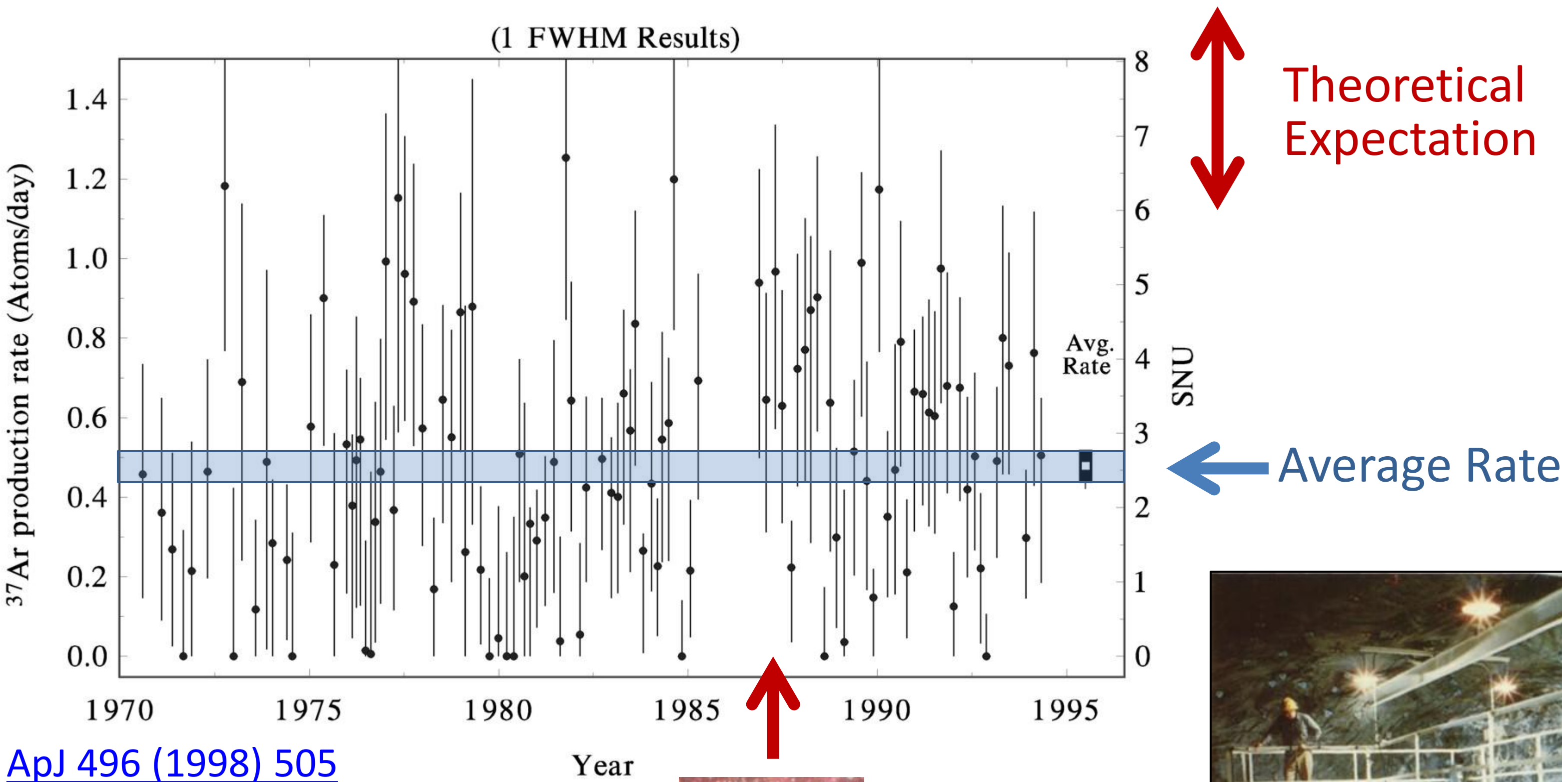
15th International Workshop on the Identification of Dark Matter
July 8-12, 2024, L'Aquila

Supernova 1987A
23 February 1987




CASE
E.R.P.M.
WITS
DETECTION OF THE FIRST NEUTRINO IN NATURE
ON
23RD FEBRUARY 1965
IN
EAST RAND PROPRIETARY MINE
THIS DISCOVERY TOOK PLACE IN A LABORATORY SITUATED
TWO MILES BELOW THE SURFACE OF THE EARTH ON
76 LEVEL OF EAST RAND PROPRIETARY MINE, MANNED
BY A GROUP OF PHYSICISTS FROM THE CASE INSTITUTE OF TECHNOLOGY U.S
AND THE UNIVERSITY OF THE WITWATERSRAND JOHANNESBURG.
THE PROJECT WAS SPONSORED BY :-
UNITED STATES ATOMIC ENERGY COMMISSION
E.R.P.M. AND RAND MINES GROUP
CASE INSTITUTE OF TECHNOLOGY
UNIVERSITY OF THE WITWATERSRAND
TVL. & O.F.S. CHAMBER OF MINES
AND CONVERTED FROM PROPOSAL TO REALITY
WITH THE HELP OF THE OFFICIALS AND MEN
OF THE HERCULES SHAFT OF E.R.P.M.
6TH DECEMBER 1967
SCIENTIFIC TEAM : F. REINES J.P.F. SELLSCHOP M.F. CROUCH
AND T.L. JENKINS W.R. KROPP H.S. GURR B. MEYER A.A. HRUSCHKA B.M. SHOFFNER

Chlorine Solar Neutrino Experiment (Homestake)



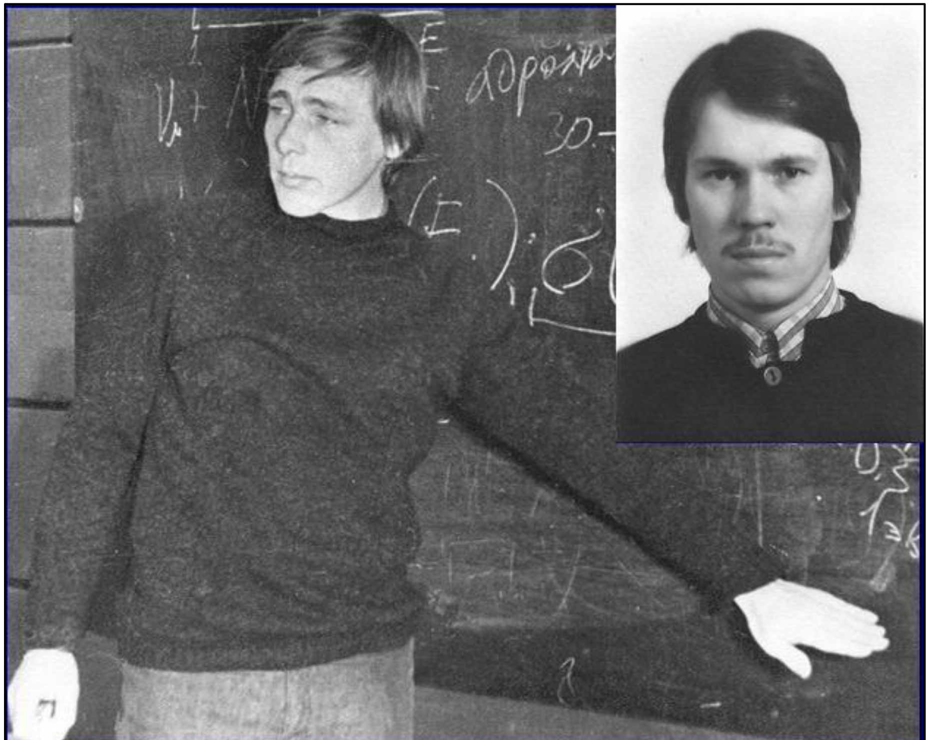
[ApJ 496 (1998) 505]

Inverse beta decay of chlorine

$$\nu_e + {}^{37}\mathrm{Cl} \to {}^{37}\mathrm{Ar} + e^-$$

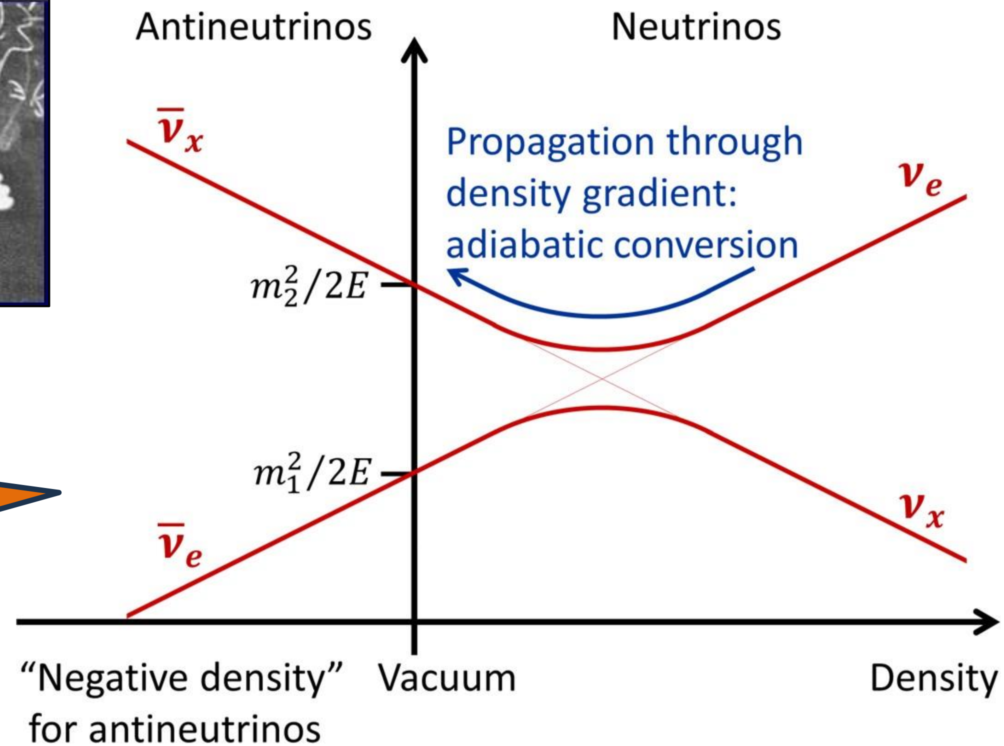
Extraction of argon atoms

Mikheev-Smirnov-Wolfenstein (MSW) effect

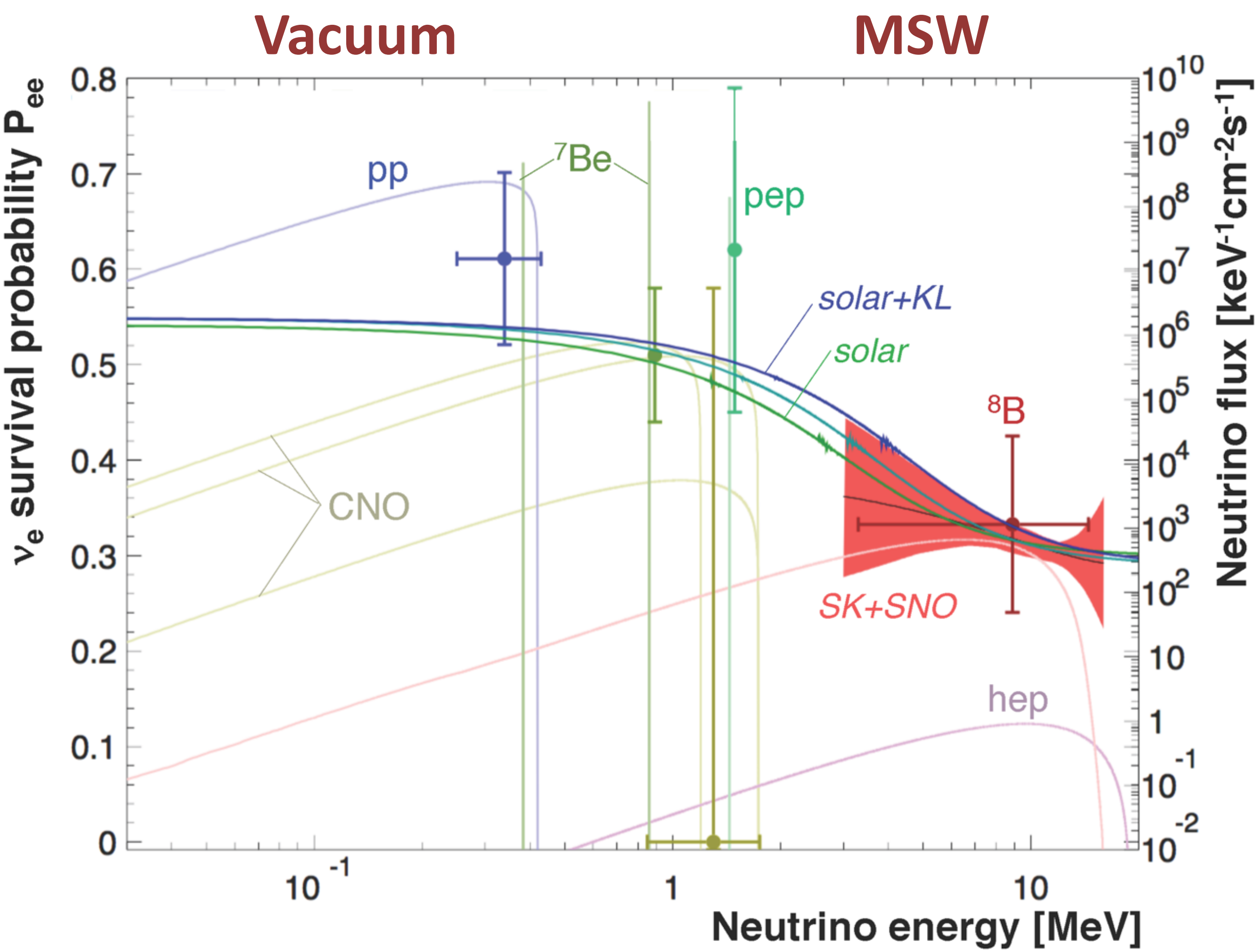


Slide for Smirnov Fest
June 2012 at GGI

Eigenvalues of Hamiltonian for
2-flavor oscillations



Solar Neutrino Spectroscopy with Borexino



Energy-dependent flavor conversion probability confirms neutrino refraction in matter!

M.Wurm, Solar Neutrino Spectroscopy, arXiv:1704.06331

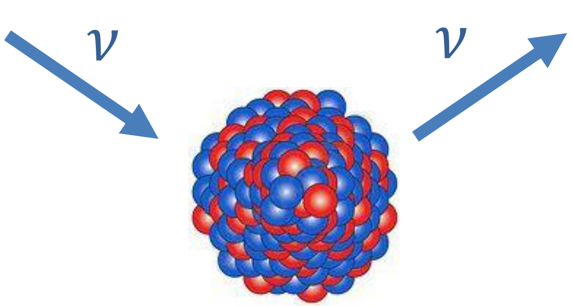
PHYSICAL REVIEW D VOLUME 9, NUMBER 5 1 MARCH 1974

Coherent effects of a weak neutral current

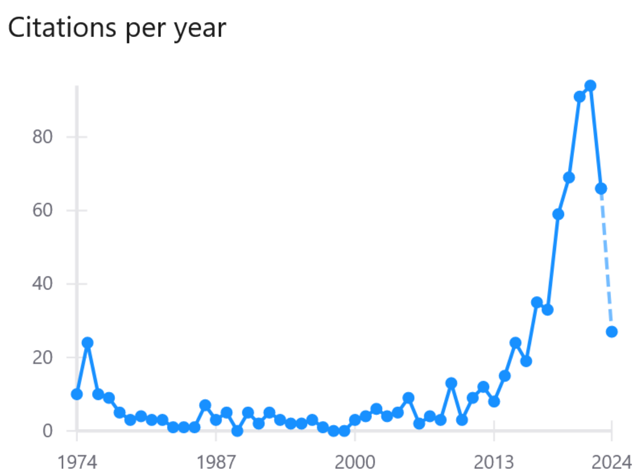
Daniel Z. Freedman†
National Accelerator Laboratory, Batavia, Illinois 60510
and Institute for Theoretical Physics, State University of New York, Stony Brook, New York 11790

(Received 15 October 1973; revised manuscript received 19 November 1973)

If there is a weak neutral current, then the elastic scattering process $\nu + A \rightarrow \nu + A$ should have a sharp coherent forward peak just as $e + A \rightarrow e + A$ does. Experiments to observe this peak can give important information on the isospin structure of the neutral current. The experiments are very difficult, although the estimated cross sections (about 10^{-38} cm^2 on carbon) are favorable. The coherent cross sections (in contrast to incoherent) are almost energy-independent. Therefore, energies as low as 100 MeV may be suitable. Quasi-coherent nuclear excitation processes $\nu + A \rightarrow \nu + A^*$ provide possible tests of the conservation of the weak neutral current. Because of strong coherent effects at very low energies, the nuclear elastic scattering process may be important in inhibiting cooling by neutrino emission in stellar collapse and neutron stars.

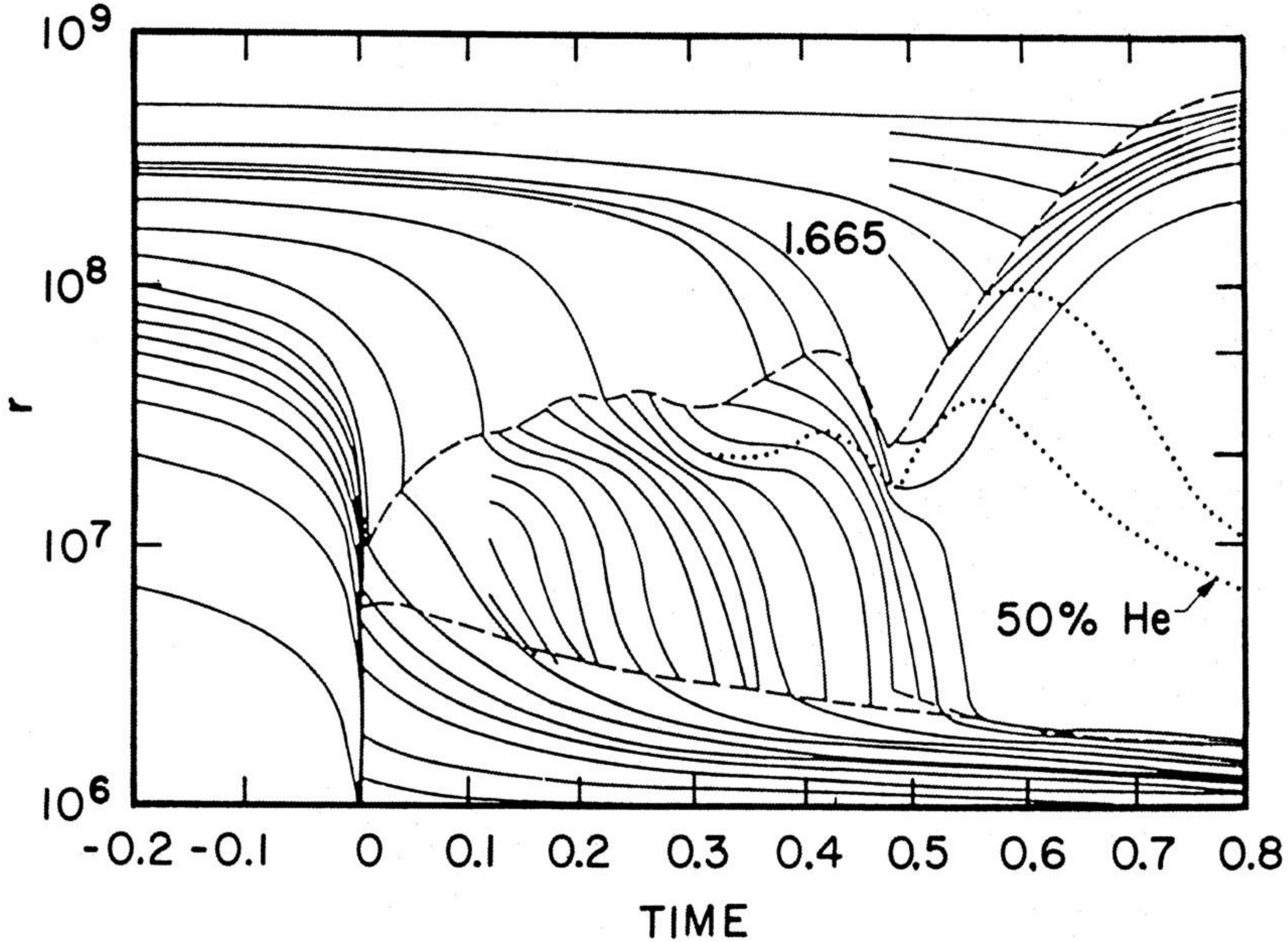


Enhancement by
$N^2 + Z^2(1 - 4\sin^2\Theta_W)$



Coherent Elastic Neutrino Nucleus Scattering (CENNS=CEνNs, "seventh")
now a major industry with reactor $\overline{\nu}_e$ (eg arXiv:2203.07361)

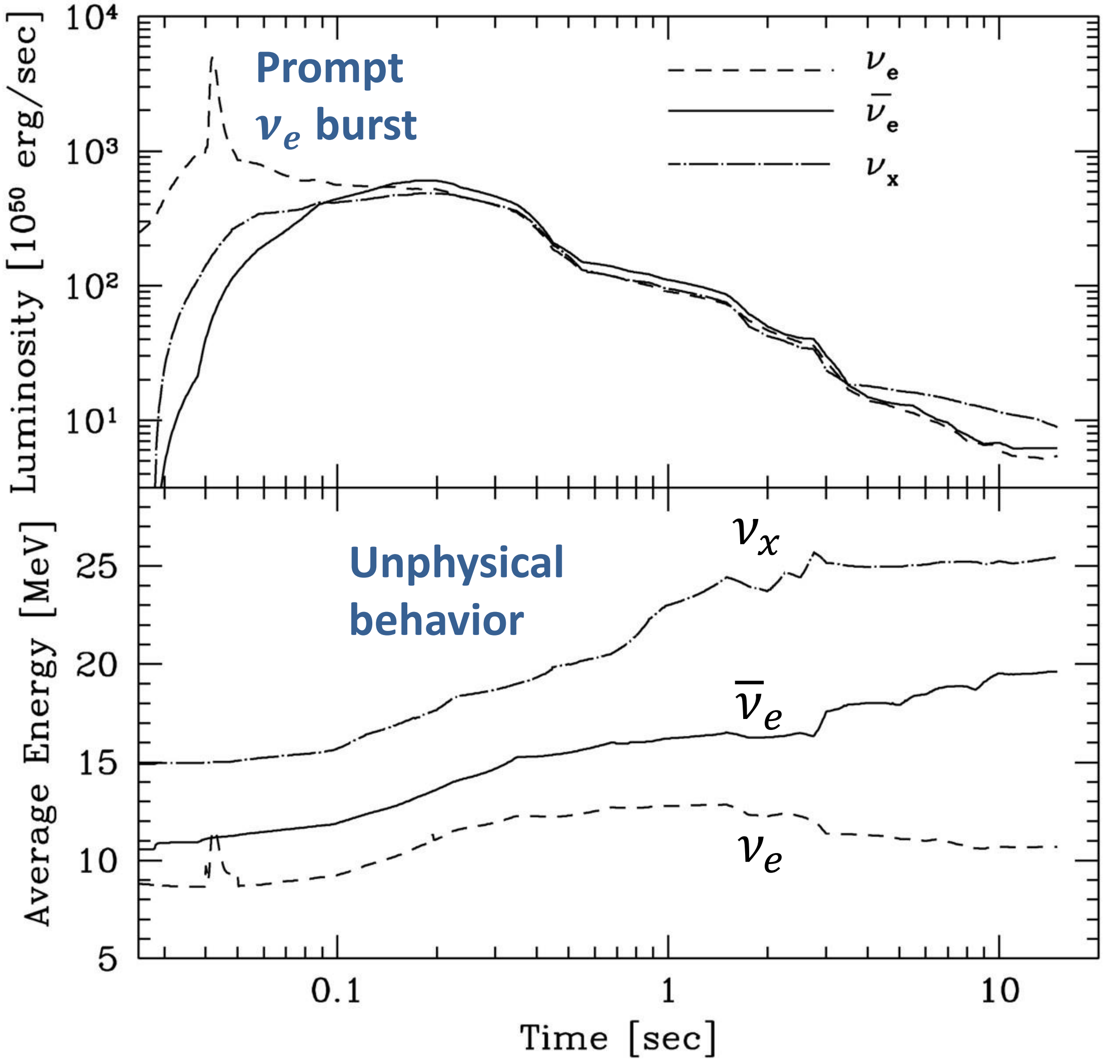
Delayed (Neutrino-Driven) Explosion



Wilson, Proc. Univ. Illinois Meeting on Num. Astrophys. (1982)
Bethe & Wilson, ApJ 295 (1985) 14

Livermore Fluxes and Spectra

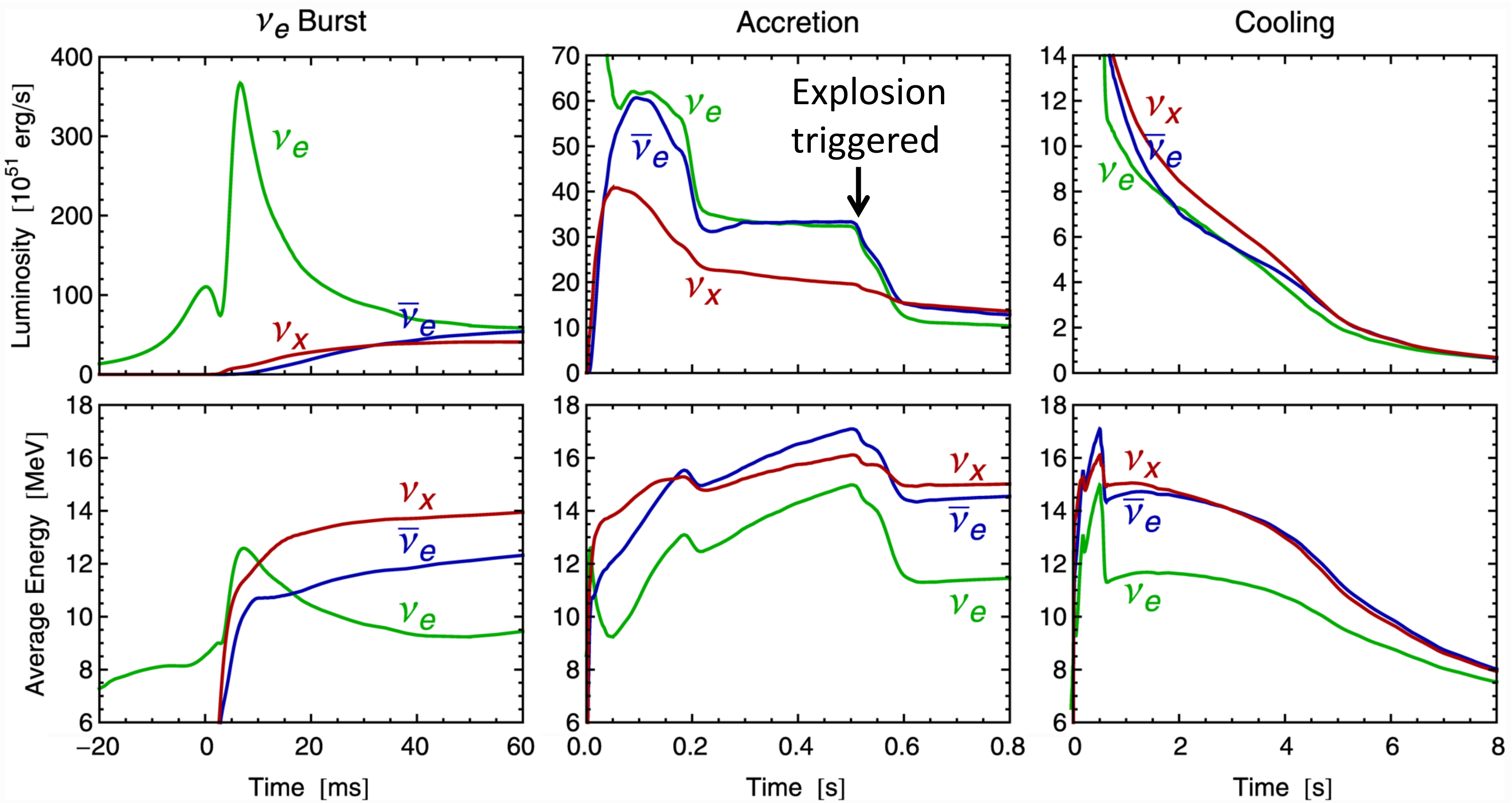
Livermore numerical model, ApJ 496 (1998) 216



Pioneering work, but today only of historical interest

- Transport of ν_μ and ν_τ only schematic
- Incomplete microphysics
- Schematic numerics to couple nu transport with hydro code

Three Phases of Neutrino Emission



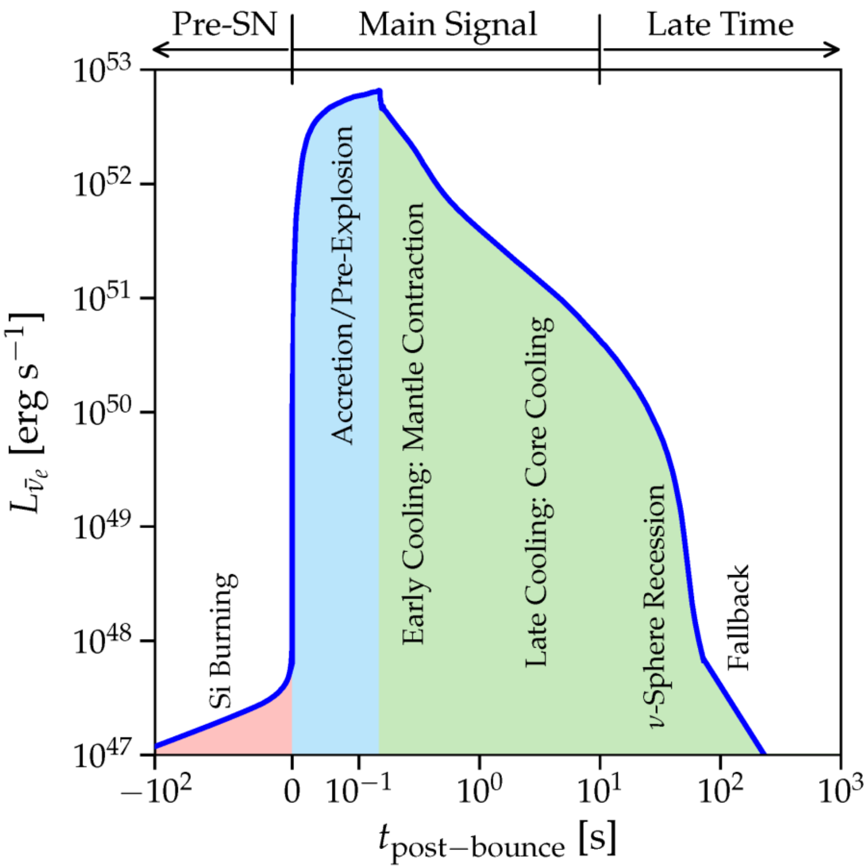
- Shock breakout
- De-leptonization of outer core layers

- Shock stalls ~ 150 km
- Neutrinos powered by infalling matter

Cooling on neutrino diffusion time scale

Spherically symmetric Garching model (25 $M_\odot$) with Boltzmann neutrino transport

Opportunities with the Next Galactic Supernova

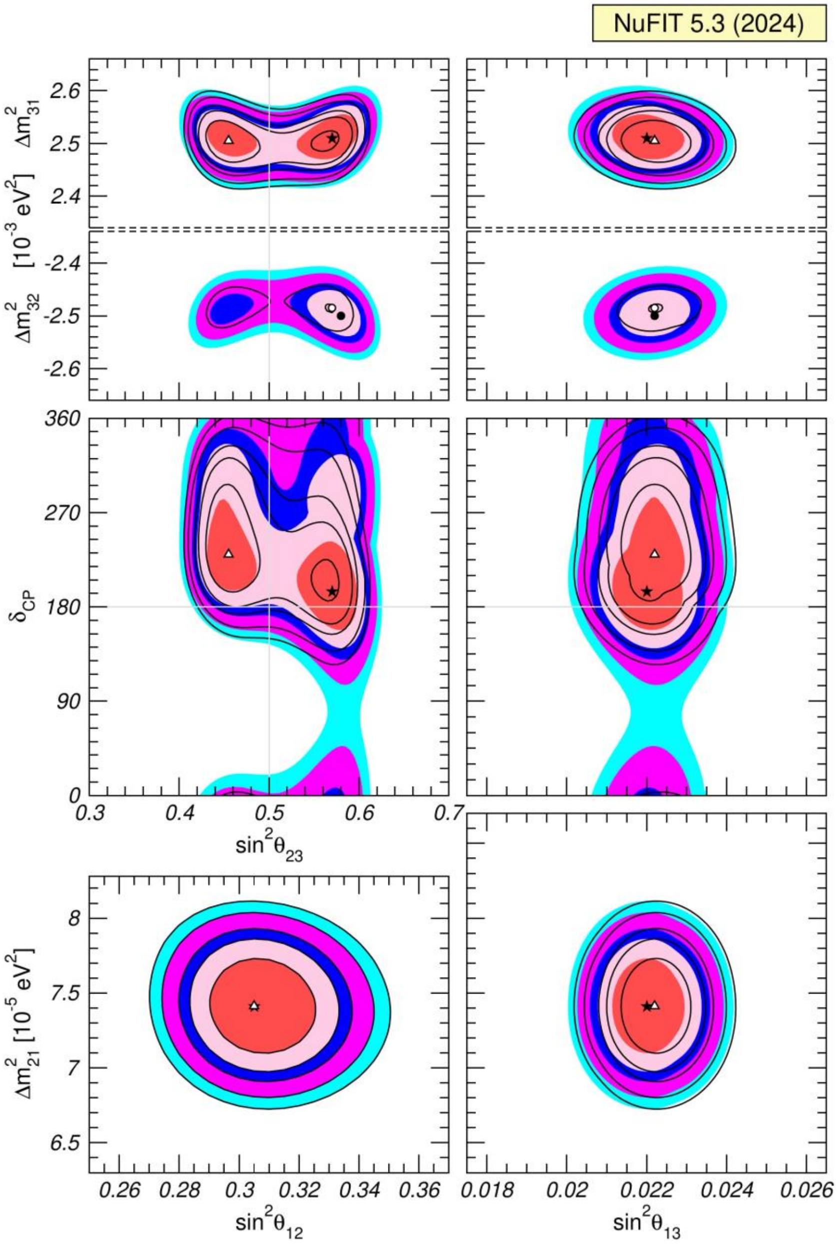


Phase	Physics Opportunities
Pre-SN	early warning, progenitor physics
Neutronization	flavor mixing, SN distance, new physics
Accretion	flavor mixing, SN direction, multi-D effects
Early cooling	equation of state, energy loss rates, PNS radius, diffusion time, new physics
Late cooling	NS vs. BH formation, transparency time, integrated losses, new physics

TABLE I. Key physics opportunities from detecting supernova neutrinos in different phases.

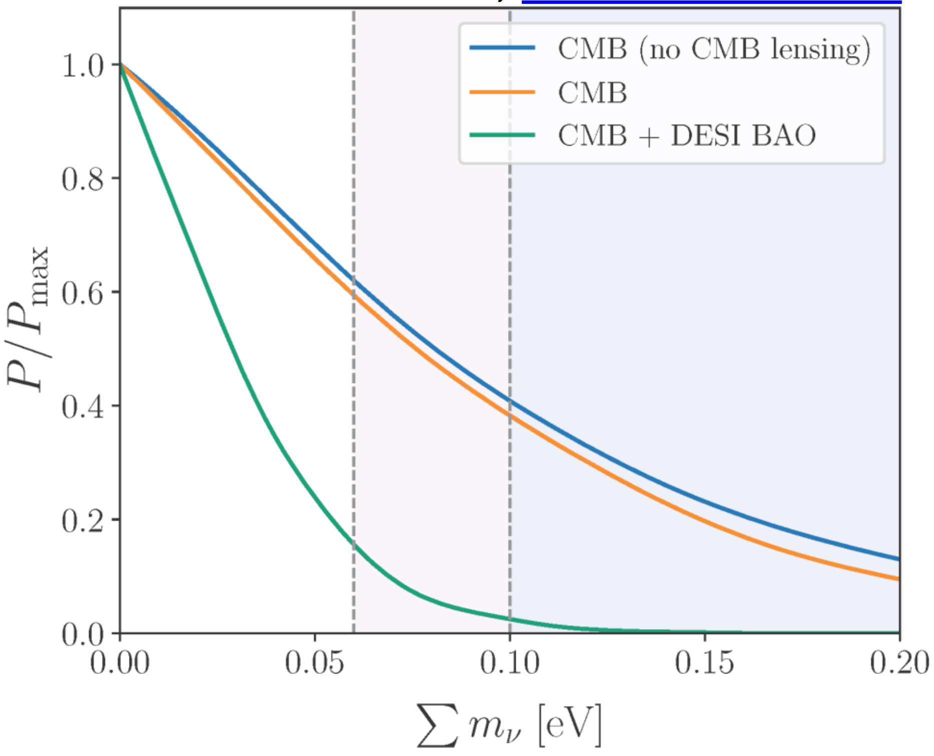
Li, Roberts & Beacom [arXiv:2008.04340]

Neutrinos in the Precision Era



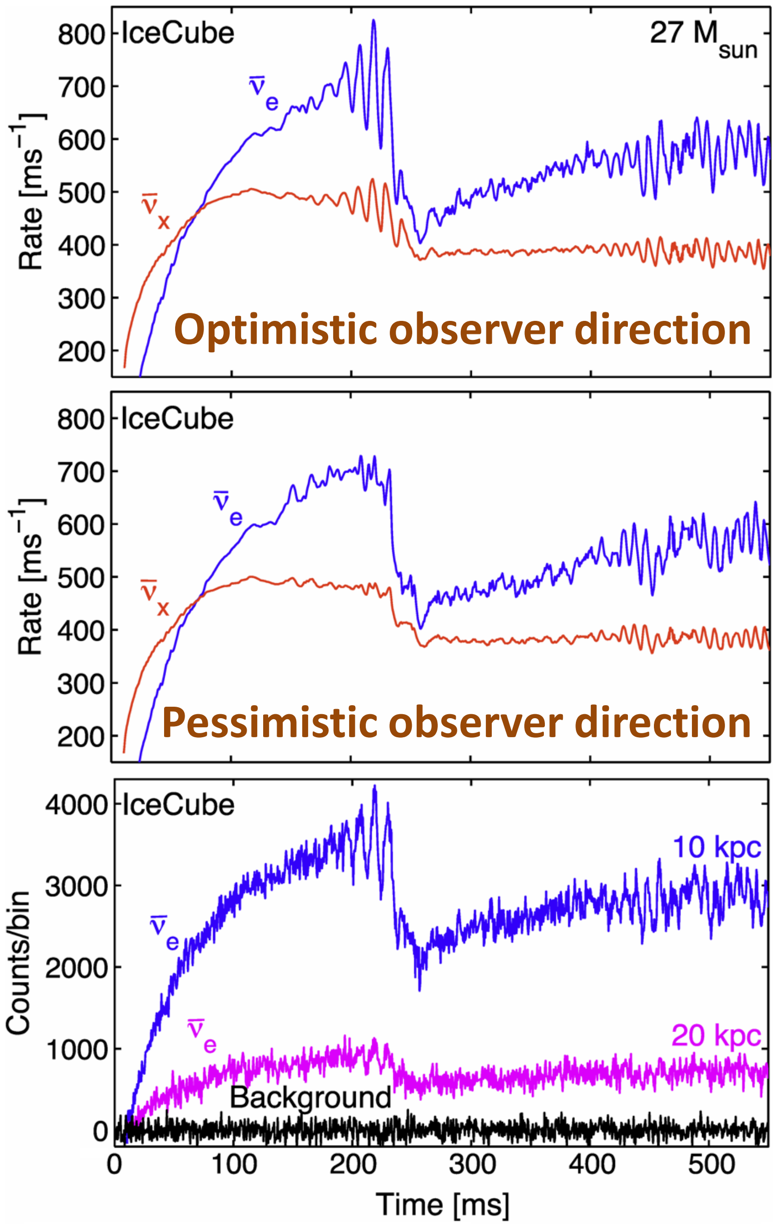
Mass scale constrained from cosmology
Soon to be measured?

DESI, arXiv:2404.03002



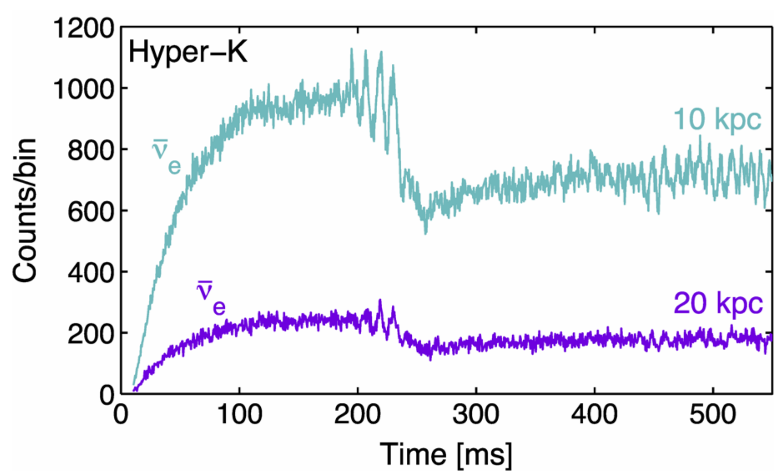
Mass ordering, CP-violation from upcoming oscillation experiments

SASI Detection Perspectives



Neutrino signal variations from hydro instabilities detectable for sub-eV neutrino masses

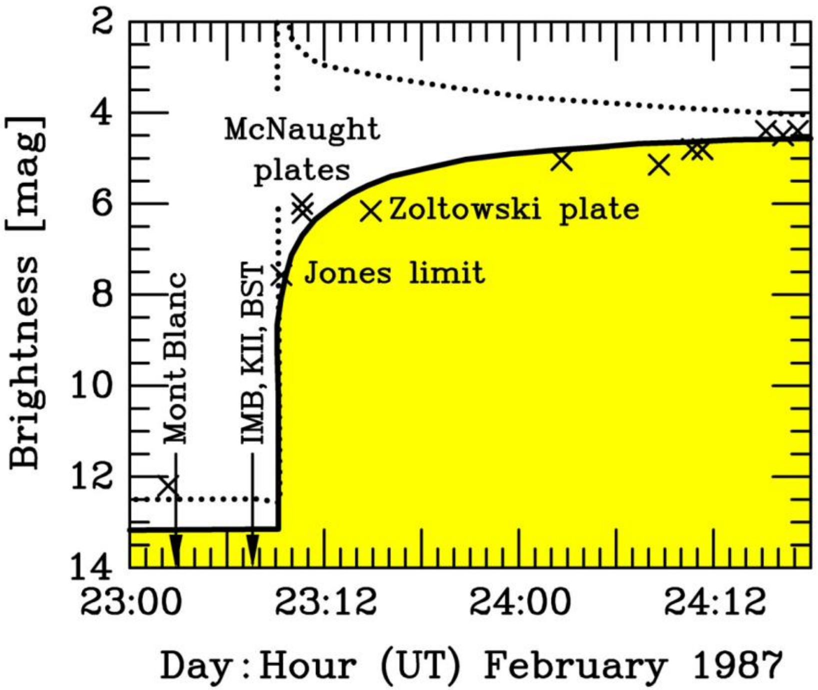
E.g. Lund+ [arXiv:1006.1889]
Tamborra+ [arXiv:1307.7936]
Walk+ [arXiv:1807.02366]



Includes shot noise

Do Neutrinos Gravitate?

Early light curve of SN 1987A



- Neutrinos arrived several hours before photons as expected
- Transit time for ν and γ same (160.000 yr) within a few hours

Shapiro time delay for particles moving in a gravitational potential

$$\Delta t = -2\int_A^B dt\,\Phi[r(t)]$$

For trip from LMC to us, depending on galactic model,

$$\Delta t \approx 1\text{–}5 \text{ months}$$

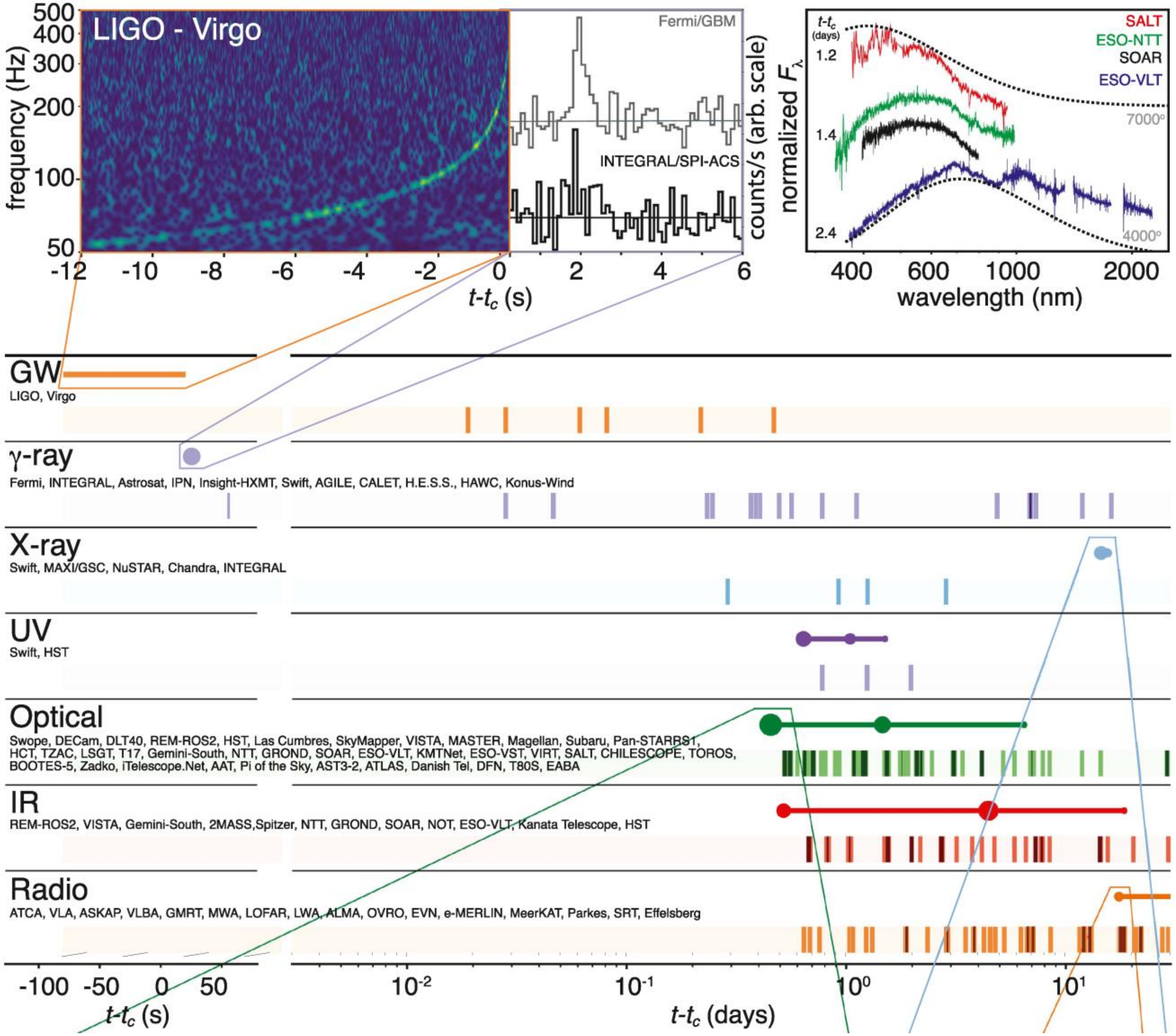
Neutrinos and photons respond to gravity the same to within

$$1\text{–}4\times 10^{-3}$$

Longo, PRL 60:173, 1988
Krauss & Tremaine, PRL 60:176, 1988

GW vs Gamma-Ray Shapiro Time Delay

[ApJ Lett. 848 (2017) L12](https://arxiv.org)



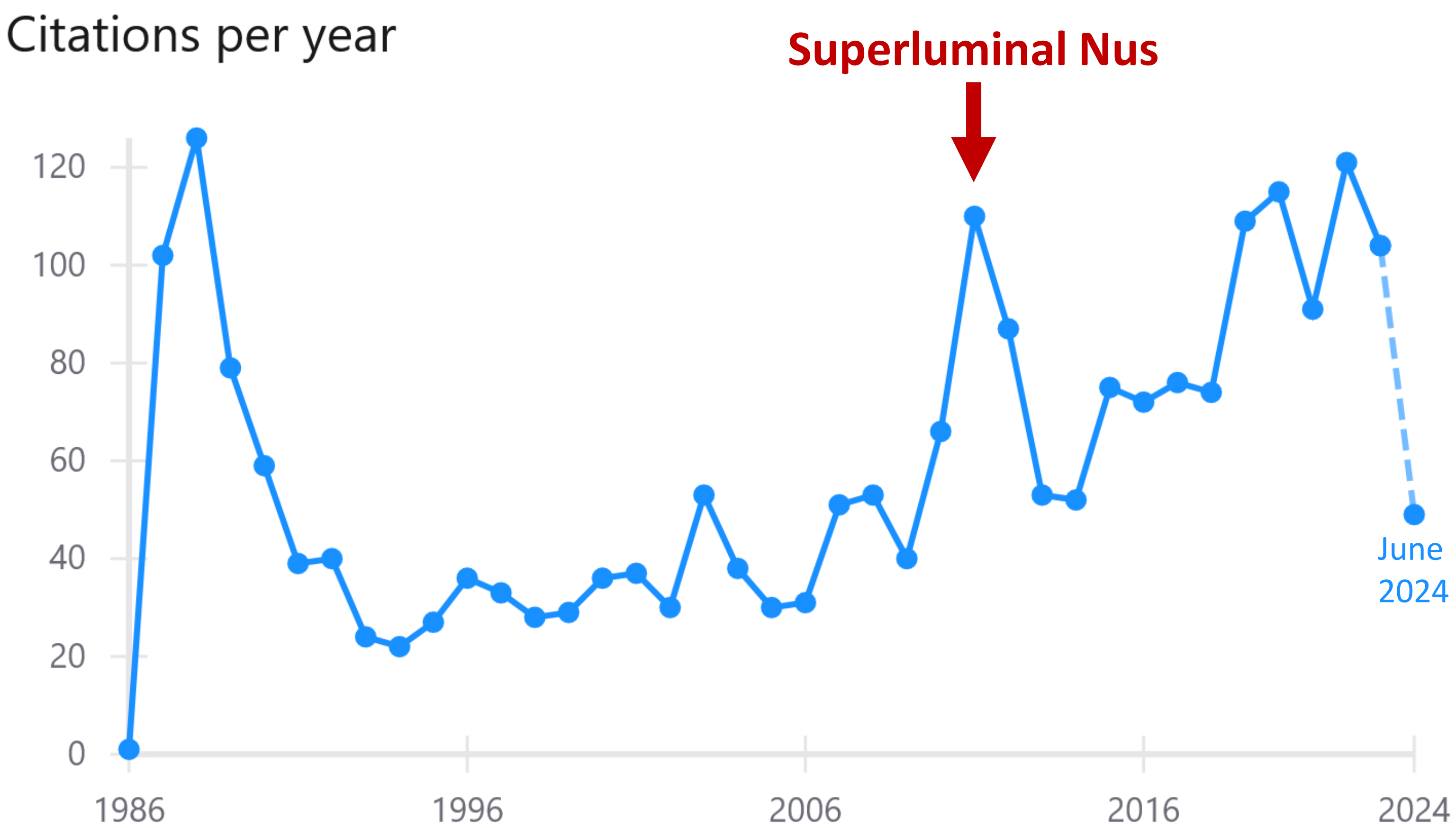
NS-NS Merger
- **GW170817**
- **GRB 170817A**

GWs & γ arrive within 2 s
Equal Shapiro time delay within $\sim 10^{-7}$

(Shoemaker & Murase [arXiv:1710.06427](https://arxiv.org/abs/1710.06427))

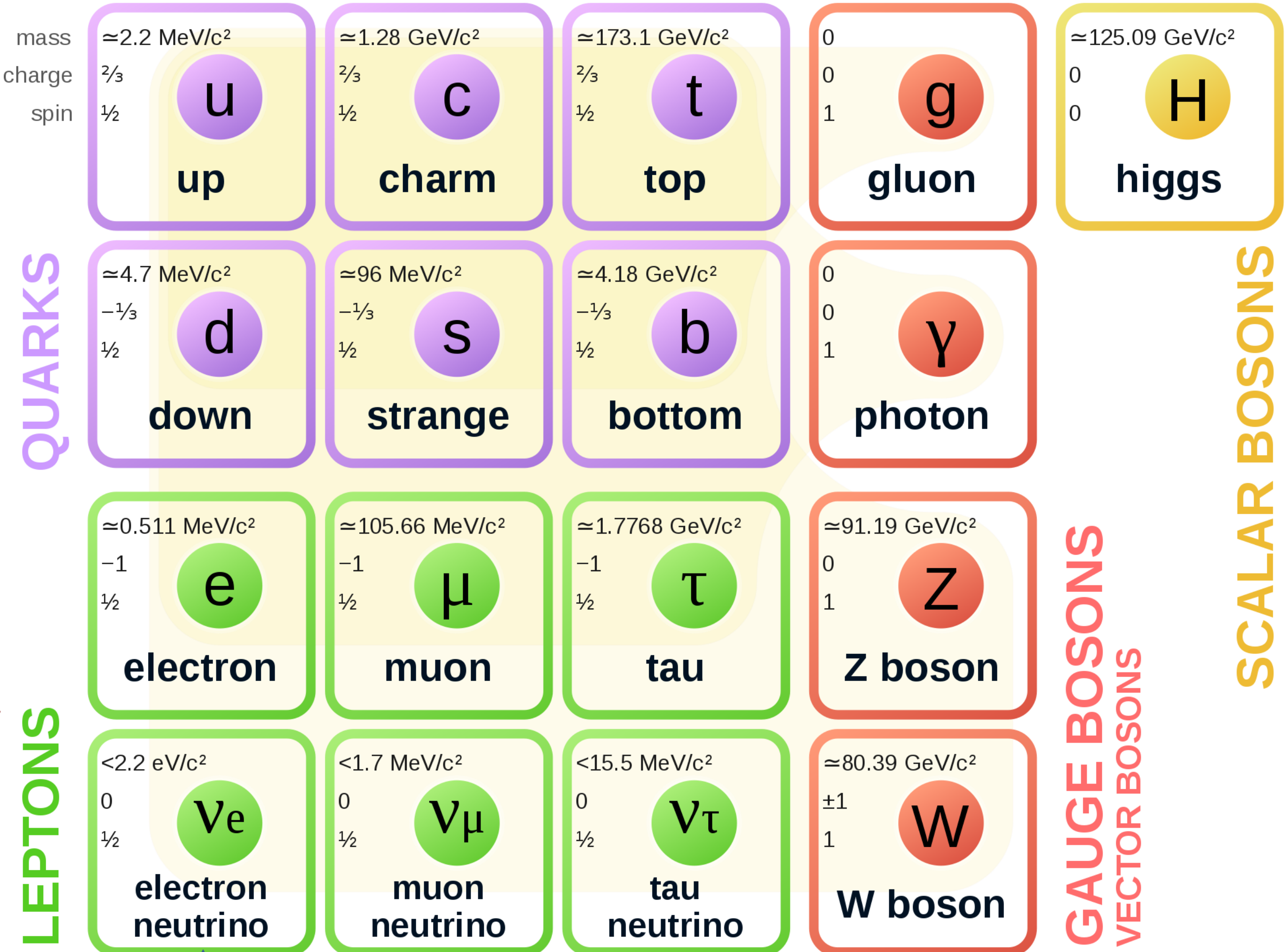
Continuing Interest in SN 1987A Neutrinos

- Hirata et al (Kamiokande-II), PRL 58 (1987) 1490
  Observation of a neutrino burst from the supernova SN1987A
- Bionta et al (IMB), PRL 58 (1987) 1494,   Observation of a Neutrino Burst in Coincidence with Supernova 1987A in the Large Magellanic Cloud



Second & Third Particle Generations in SN Physics

Early universe, stellar collapse & NS mergers naturally involve all flavor neutrinos →

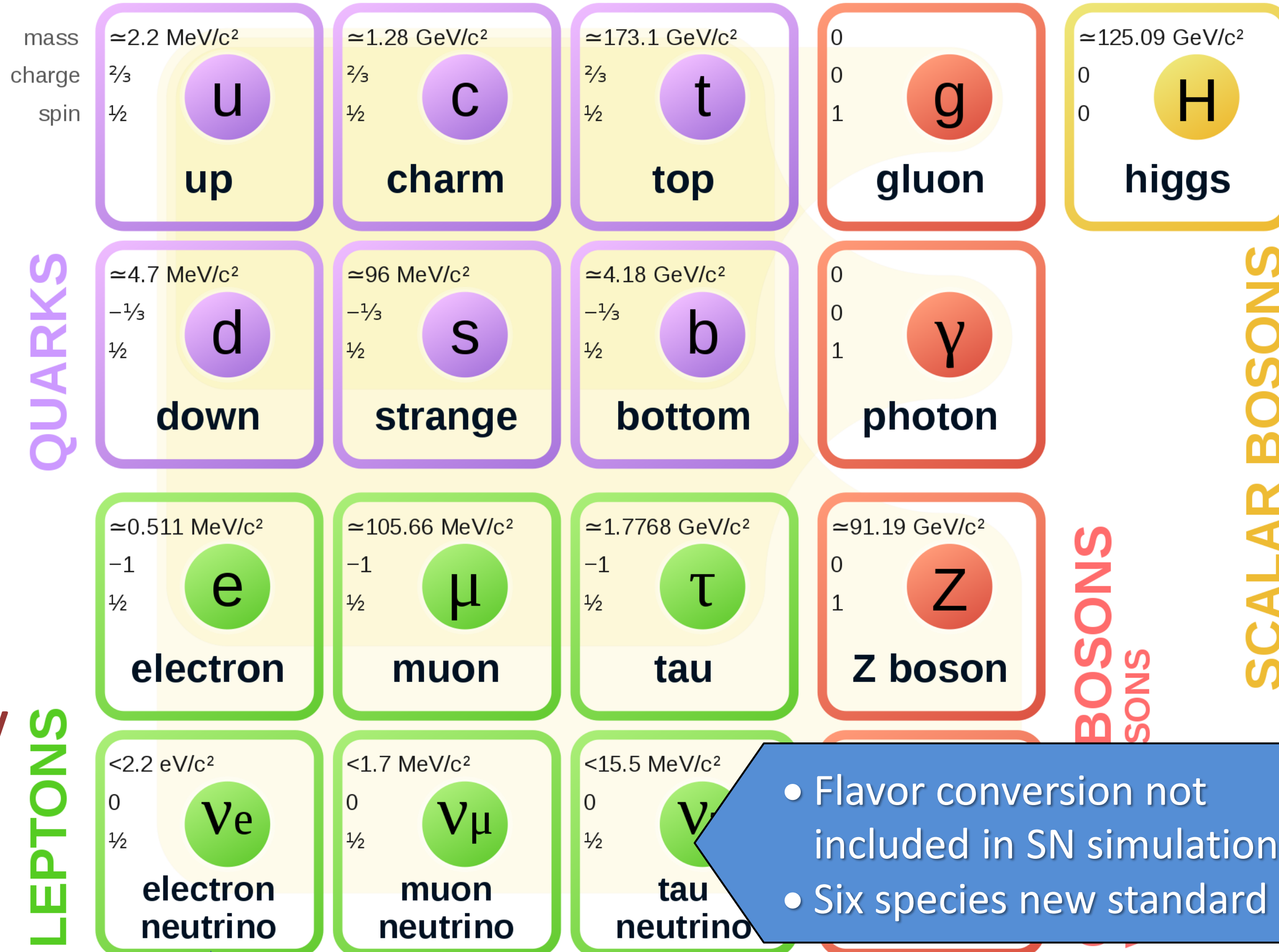


Everyday physics and astrophysics only first family of fermions

$\nu_x = \nu_\mu, \nu_\tau, \overline{\nu}_\mu, \overline{\nu}_\tau$

in old SN simulations

Second & Third Particle Generations in SN Physics



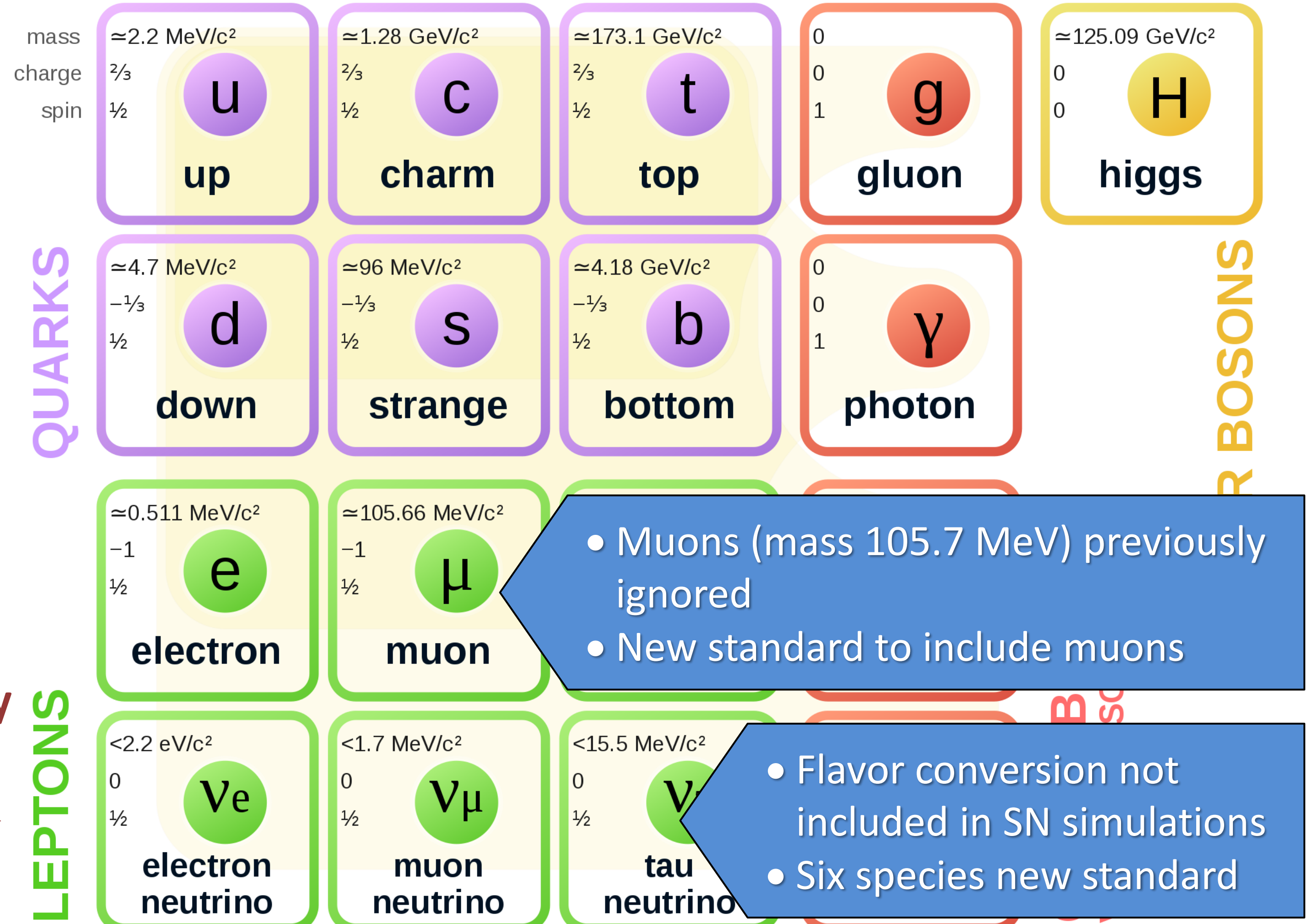
- Flavor conversion not included in SN simulations
- Six species new standard

Early universe, stellar collapse & NS mergers naturally involve all flavor neutrinos →

Everyday physics and astrophysics only first family of fermions

$\nu_x = \nu_\mu, \nu_\tau, \bar{\nu}_\mu, \bar{\nu}_\tau$
in old SN simulations

Second & Third Particle Generations in SN Physics



- Muons (mass 105.7 MeV) previously ignored
- New standard to include muons

- Flavor conversion not included in SN simulations
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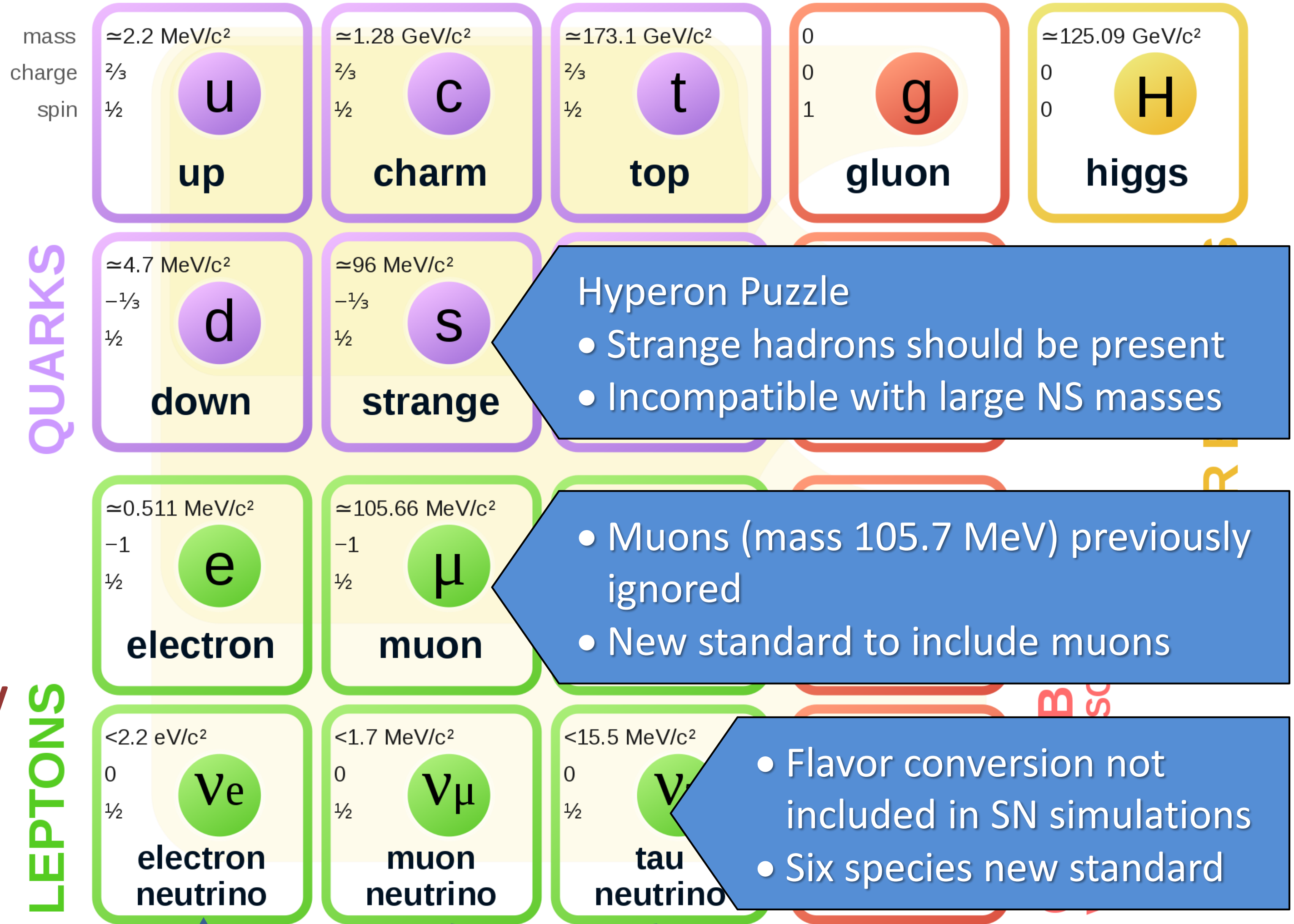
Early universe, stellar collapse & NS mergers naturally involve all flavor neutrinos →

Everyday physics and astrophysics only first family of fermions

$\nu_x = \nu_\mu, \nu_\tau, \bar{\nu}_\mu, \bar{\nu}_\tau$

in old SN simulations

Second & Third Particle Generations in SN Physics



Hyperon Puzzle
- Strange hadrons should be present
- Incompatible with large NS masses

- Muons (mass 105.7 MeV) previously ignored
- New standard to include muons

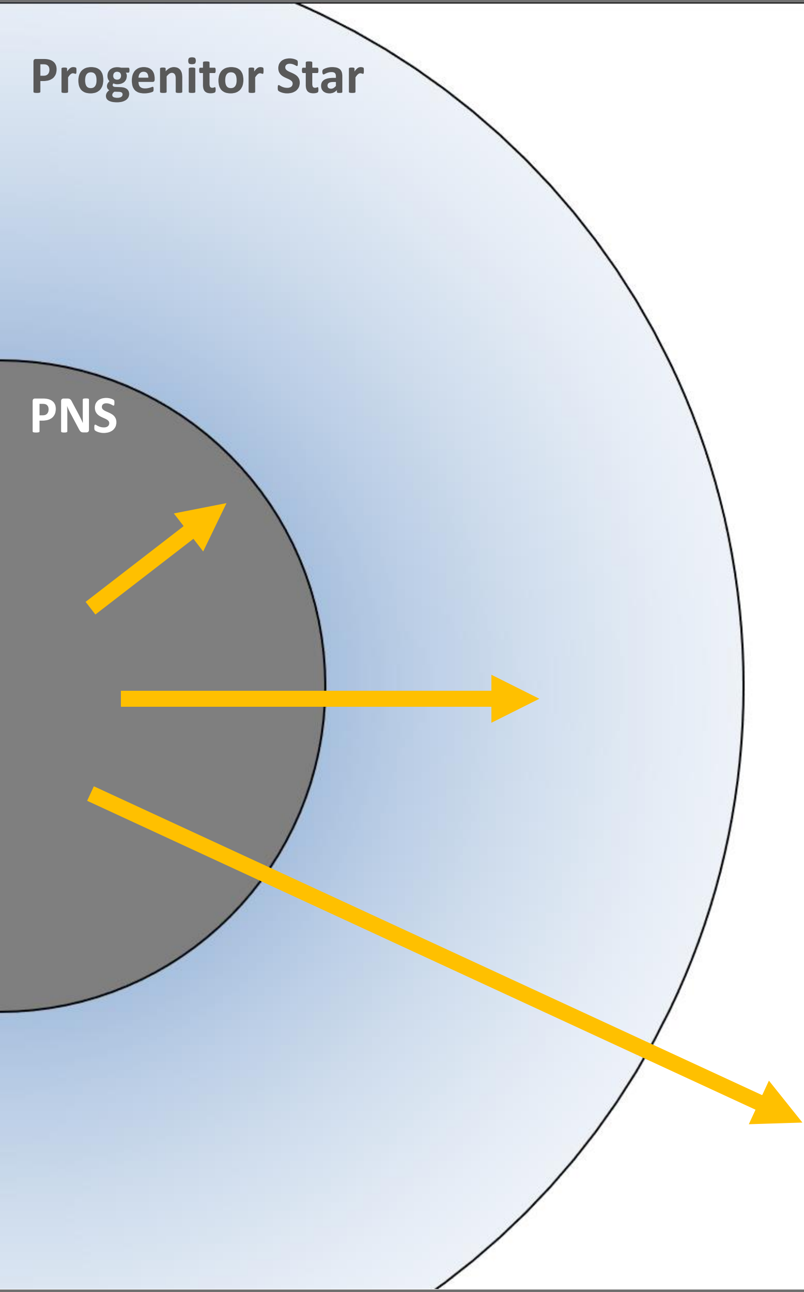
- Flavor conversion not included in SN simulations
- Six species new standard

Early universe, stellar collapse & NS mergers naturally involve all flavor neutrinos →

Everyday physics and astrophysics only first family of fermions

$\nu_x = \nu_\mu, \nu_\tau, \overline{\nu}_\mu, \overline{\nu}_\tau$
in old SN simulations

Impact of New Particles



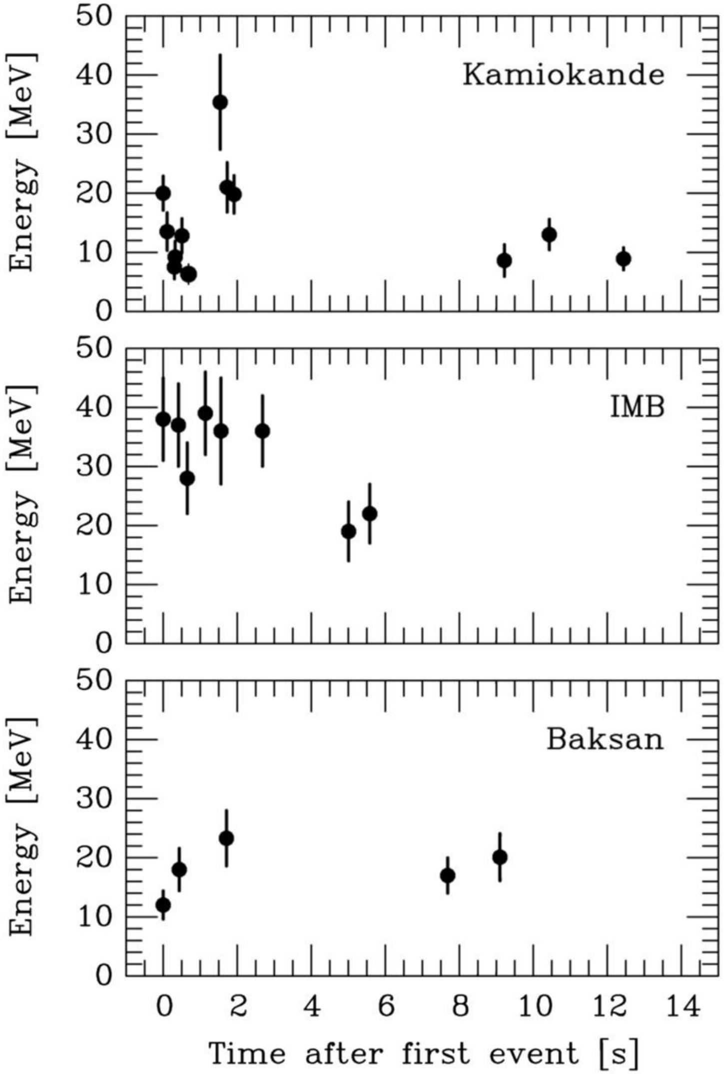
Energy and lepton transport within PNS

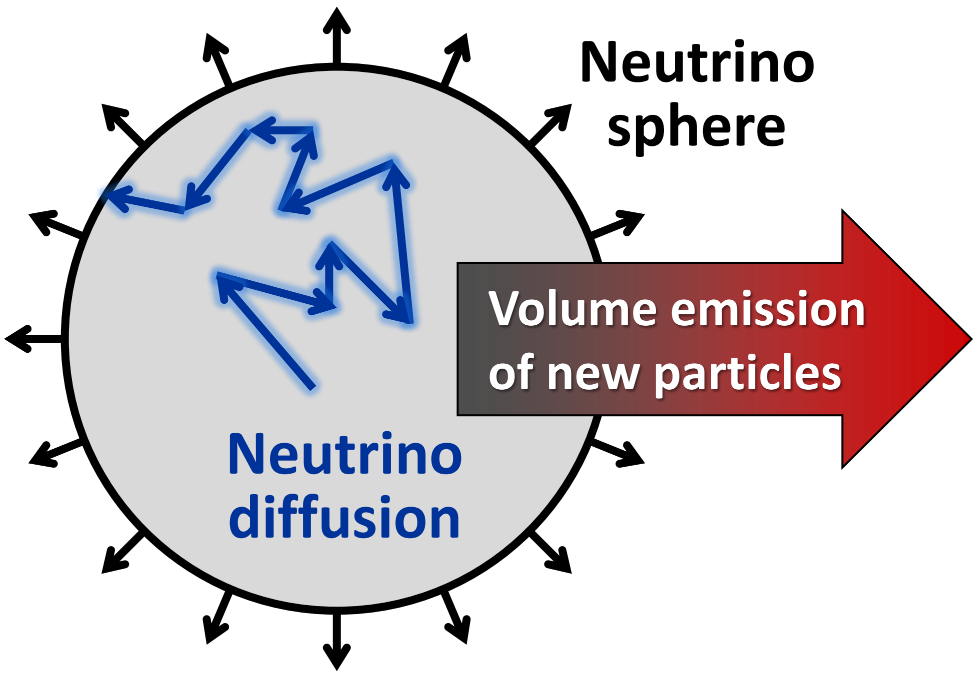
Energy transport beyond neutrino sphere (directly or decay products)
- Explosion
- Nucleosynthesis

Detection (direct or decay products)
- SN 1987A, next nearby SN
- Diffuse background from all past SNe

Supernova 1987A Energy-Loss Argument

SN 1987A neutrino signal



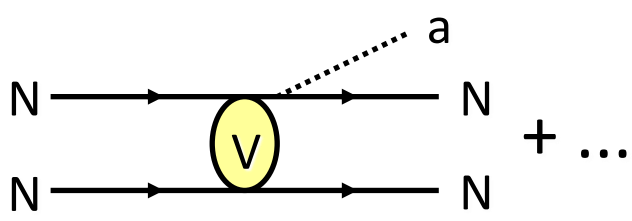


Emission of very weakly interacting particles would "steal" energy from the neutrino burst and shorten it.
(Early neutrino burst powered by accretion, not sensitive to volume energy loss.)

Late-time signal most sensitive observable

Axion Emission from a Nuclear Medium

Axion-nucleon interaction: $\mathcal{L}_{\rm int} = \frac{C_N}{2f_a}\,\overline{\Psi}_N\gamma_\mu\gamma_5\Psi_N\partial^\mu a = \frac{C_N}{2f_a} J_\mu^A \partial_a^\mu$



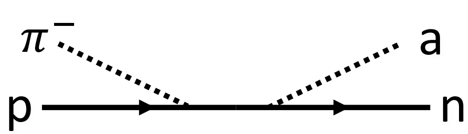
Nucleon-Nucleon
Bremsstrahlung

Axial-vector interaction implies dominance of spin-dependent process

- Interaction potential (one-pion exchange OPE often used, but too simplistic)
- In-medium coupling constants
- In-medium effective nucleon properties
- Correlation effects (static and dynamical spin-spin correlations)

→ **For latest discussion see Carenza et al. arXiv:1906.11844**

Thermal π^- contribute significant (dominant?)

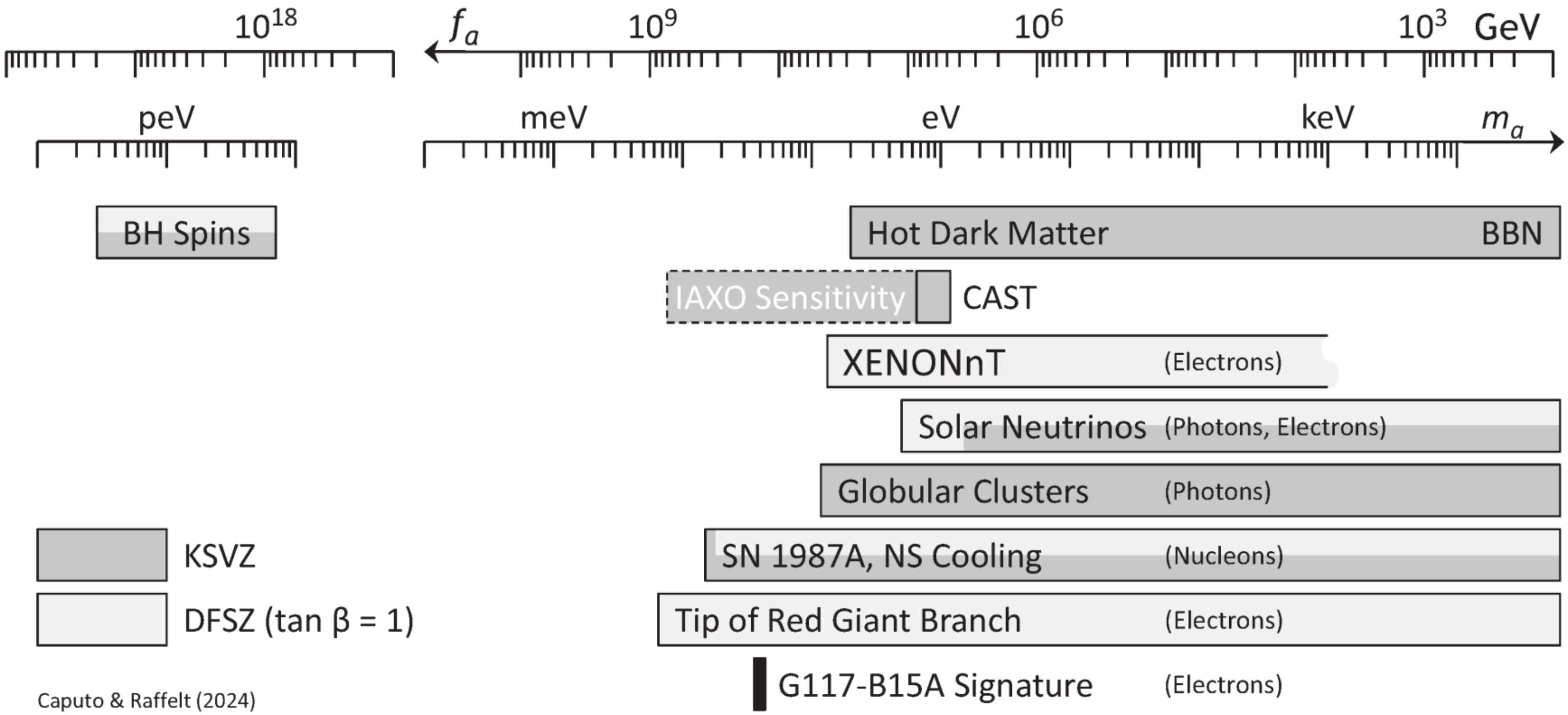


→ **For latest discussion see Carenza et al. arXiv:2010.02943**

Brand New

Astrophysical Axion Bounds

The 2024 Edition, Caputo & Raffelt, arXiv:2401.13728, 24 Jan 2024



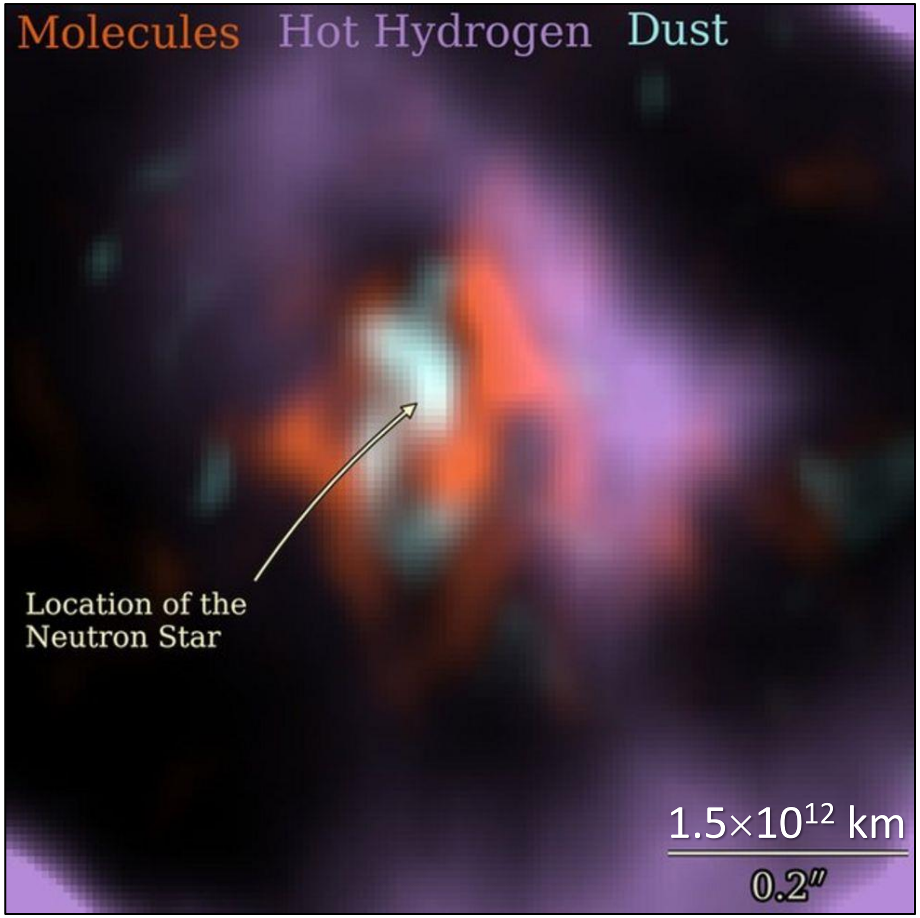
- Many improvements over the years, but overall picture the same
- Specific QCD axion signatures hard to expect from cooling effects
- Best stellar detection opportunity probably (Baby)IAXO

Where is the Neutron Star of SN 1987A?

No pulsar or neutron star has been seen until now (35 years later)

- Infra-red excess observed by ALMA: In "the blob" strong indication for NS
  Expected position, remnant hidden by dust [Cigan+ arXiv:1910.02960]
- Most plausible model: Thermally cooling non-pulsar NS [Page+ arXiv:2004.06078]

https://www.bbc.com/news/science-environment-50473482



Atacama Large Millimeter/Submillimeter Array (ALMA) at ESO in Chile

SN 1987A Signal Duration Too Long?

Fiorillo+ arXiv:2308.01403

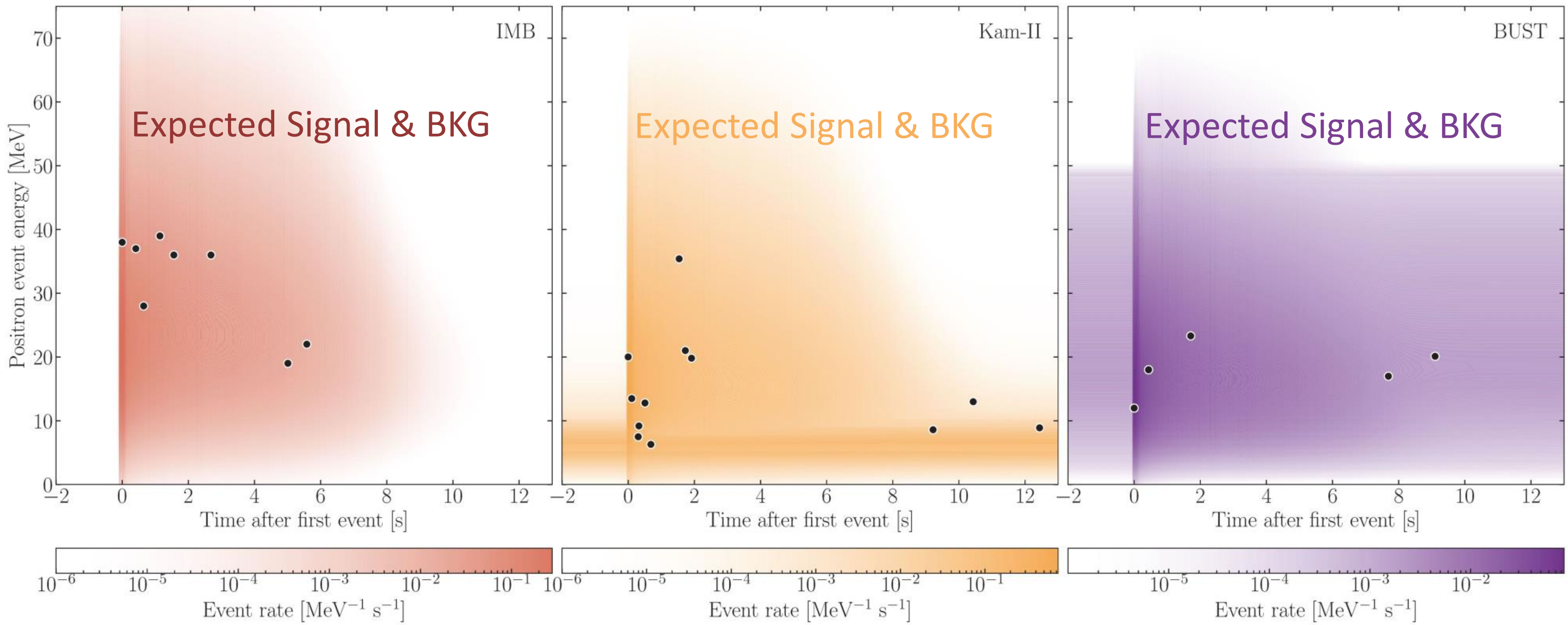
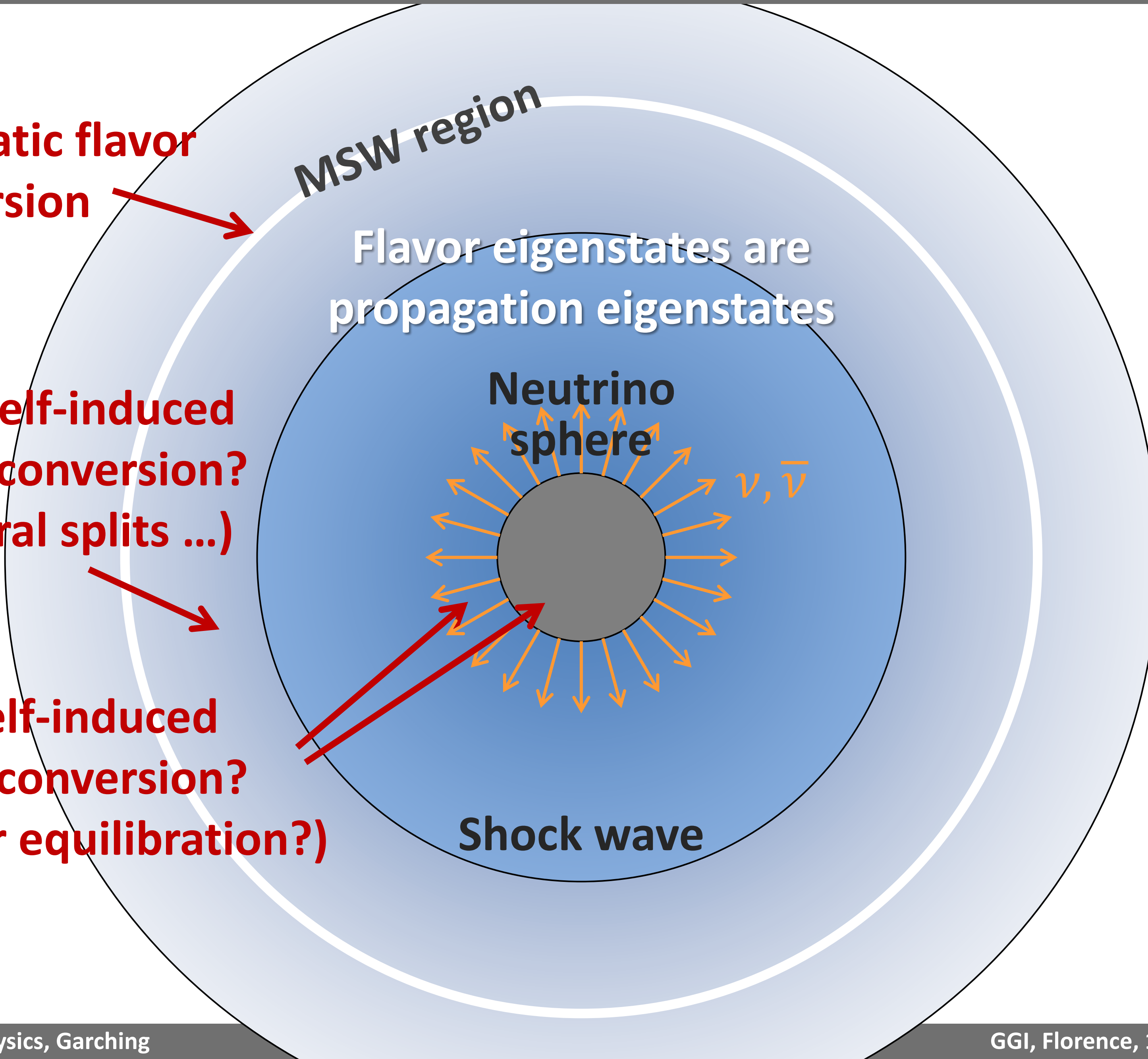


FIG. 17. Differential event distribution (signal and background) at each experiment, compared with the observations. Results are shown for model 1.44-SFHo without flavor swap; the offset time for each experiment is chosen as the best-fit value reported in Table VII.

- **In a suite of Garching models (no axions), expected signal always too short (PNS convection!)**
- **Deserves dedicated study**

Flavor Conversion in Core-Collapse Supernovae

- Adiabatic flavor conversion
- Slow self-induced flavor conversion? (Spectral splits …)
- Fast self-induced flavor conversion? (Flavor equilibration?)



Short History of Collective Neutrino Oscillations

1992–1993 Off-diagonal refraction (Pantaleone 1992),
QKEs (Dolgov 1981, Rudzsky 1990, Sigl & Raffelt 1993)

1993–2005 Self-induced coherence, early universe (Samuel 1993)
Homogeneous systems evolving in time
But spontaneous breaking of homogeneity

2005–2015 Supernova neutrinos, bulb model: **static solutions evolving in space**
(Duan, Fuller, Qian 2005, Duan, Fuller, Carlson, Qian 2006)
Looking for signatures (spectral splits, ...)
But many symmetries ... get spontaneousy broken

2015–today **Full space-time problem** (everything done before is wrong?)
Time-dependent solutions (Abbar, Duan 2015, Dasgupta, Mirizzi 2015)
Fast flavor conversion (Sawyer 2015)
Dispersion relation in linear regime (Izaguirre, Raffelt, Tamborra 2017)
Similar to plasma physics (Capozzi, Dasgupta, Lisi, Marrone, Mirizzi 2017)

FFC local effect? Connection to slow oscillations?
Leads to equilibrium, even thermalization?
Effective implementation in SN codes?

A problem worthy of attack proves its worth by fighting back

Old Adage
(Paul Erdos?, Piet Hein?)

Many Open Questions ... It's Only the Beginning

'If it's what I think it is, we've got some work ahead of us.'

Need more GGI workshops on Neutrinos ☺


Thanks
especially to the
Organizers!