Neutrinos in Astrophysics

- ❑ Neutrino connections: Los Alamos, me, and my friend Frank
- ❑ Solar neutrinos: Multi-messenger astrophysics and neutrino mass
- ❑ Astrophysical neutrinos: Supernovae and kilonovae

Wick Haxton, UC Berkeley

Hidden Neutrinos

May 19 2023

Cal GOLDEN BEARS

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

NSF

BERKELEY LAB

Los Alamos circa 1980: A Bit of a Sanctuary for Neutrino Physics

- The lab's neutrino legacy dated from the days of Cowan and Reines

- In 1972 LAMPF produced an 800 MeV proton beam. With Louie Rosen as Director, Los Alamos took on responsibility for the first true national NP users facility
  - produced the world's then most intense muon and neutrino beams

  - E225, led by Herb Chen, 1975-93: $\nu_e + e^- \to \nu_e + e^-$
    probed the interference between neutral and charge-changing weak currents
    measured: $\nu_e + {}^{12}\mathrm{C} \to \nu_e + {}^{12}\mathrm{C}^*$

  - E645, E764, 1980-92: oscillation experiments using p, ${}^{12}\mathrm{C}$ targets
    $\nu_e,\ \bar{\nu}_e$ appearance in $\nu_\mu,\ \bar{\nu}_\mu$ beams

  - E31, 1975-1980: charged current reactions $\bar{\nu}_e + p,\ \nu_e + D$
    test of family number conservation

- E1173, 1989-1999: the LSND experiment $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ appearance, …

- E1213, 1990-1999: $\nu_e + {}^{37}\mathrm{Cl} \rightarrow e^- + {}^{37}\mathrm{Ar}, \quad \nu_e + {}^{127}\mathrm{I} \rightarrow e^- + {}^{127}\mathrm{Xe},$
  solar neutrino detector calibration experiments

- In 1977 I finished my thesis on Semi-leptonic Weak Interactions on Nuclei
  - one of applications was to analyze what would be learned were E1213 done with a Cl target
  - after a year as a postdoc in Germany, this connection and the LAMPF neutrino beam drew me to Los Alamos, as a T5 postdoc (the theory group for LAMPF)

  - epilog: a decade later I wrote a paper pointing out that an experiment using iodine would be a twin of the Cl experiment, but with a rate 10 times higher
    - Ken Lande used this target in E1213

  - Los Alamos created an amazing environment that coupled theorists and experimentalists in a way that I have not seen duplicated elsewhere

Louie Rosen

LAMPF

Bob Berman, Don Cochran, Jean Duclos, Peter Nemethy (E31)

Marvelous opportunities for a theorist with an interest in experiment

- I met George Cowan, and we worked on exotic ideas to do new kinds of solar neutrino experiments that would test the thermal stability of the Sun over the Kelvin time

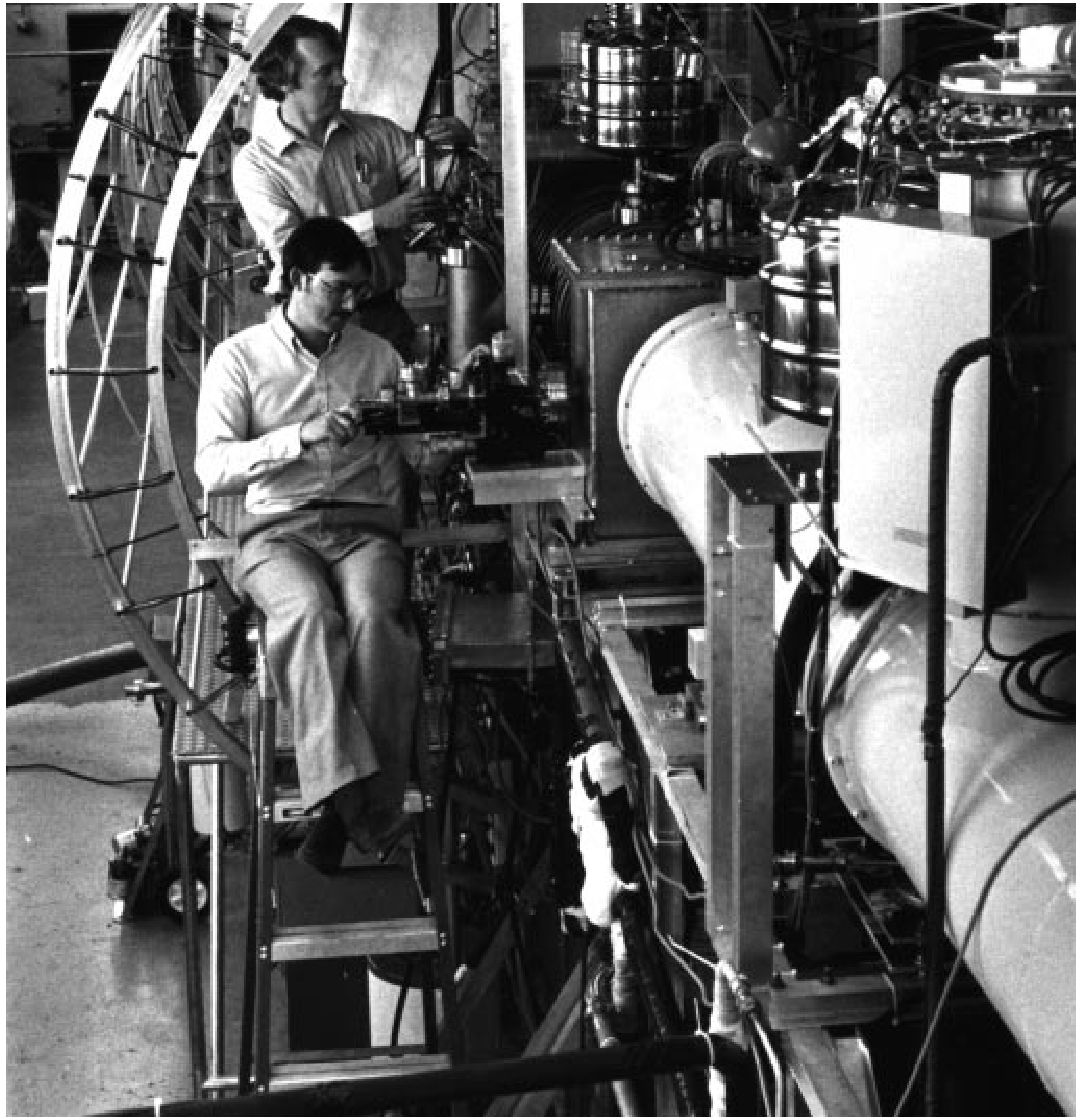
- Became interested in nuclear and atomic tests of parity and time reversal
  - led me to interact with Eric Adelberger, Jules Deutsch, and Art McDonald when they visited — all of whom were interested in similar problems

- And someone told me it was a good time to think about the nuclear and particle physics of a process called double beta decay

My subsequent involvement with double beta decay led to my friendship with Frank

- The Physics Division was not only involved in LAMPF oscillations physics, but other aspects of neutrinos
- Tritium decay neutrino mass measurements of Bowles, Robertson, Wilkerson…
- SAGE solar neutrino experiment
- Currently, LEGEND, BEST, …

Frank was a frequent visitor to Los Alamos, and called to arrange for us to meet due to our shared interest in double beta decay



Tom Bowles and Hamish Robertson

- Frank and I have shared a friendship as well as interests in $\beta\beta$ decay and DM searches for forty years

- From one of our Los Alamos interactions, I wound up doing the data analysis for an axion experiment he, Frank Calaprice, and others performed with an intense ^{65}Zn neutrino source fabricated by Ray Davis

TAUP 2013, Asilomar

Hamish-Fest, Seattle (with Baha Balantekin)

And because of our shared interest in US underground science, twice we co-organized the TAUP meeting

My science theme today is Neutrinos in Astrophysics

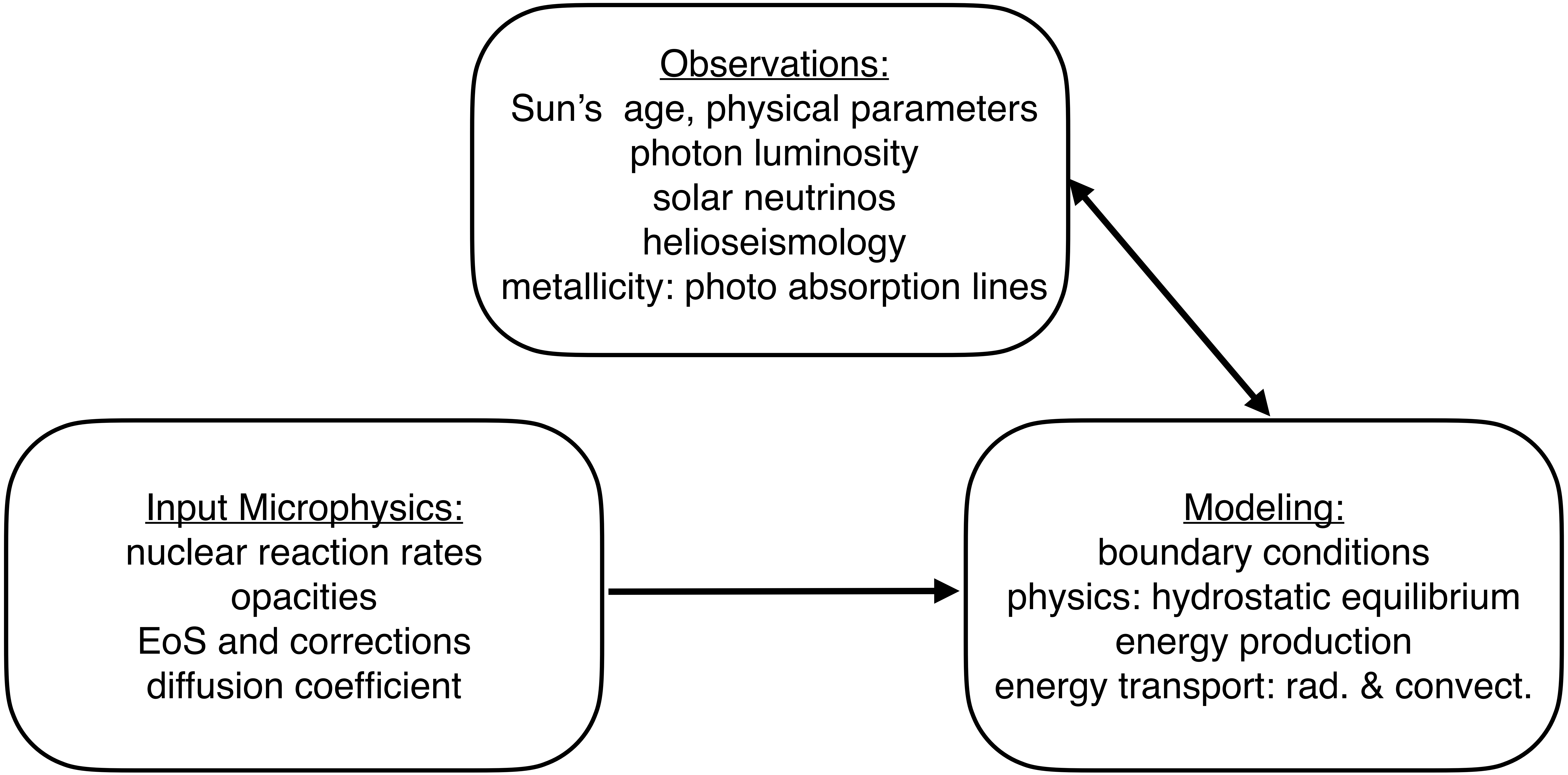
- Laboratory efforts on neutrino mass, oscillations, and lepton number conservation were linked from the beginning to neutrino astrophysics

- The first serious exploration of Pontecorvo's idea to build a radiochemical Cl neutrino detector (1946) was done by L. Alvarez in 1949
  - — goal: to look for the wrong-sign lepton process $\bar{\nu}_e^{\mathrm{reactor}} + {}^{37}\mathrm{Cl} \rightarrow e^- + {}^{37}\mathrm{Ar}$
  - — pre-parity-violation, this was a test of a Majorana neutrino

- Ray Davis, Harmer, and Hoffman perfected the technology, built the detector, applied it to solar neutrinos, and got the "wrong" result for the flux (1968)

- Pontecorvo suggestion of oscillations among massive neutrinos (1957) became the leading particle-physics explanation for the solar neutrino problem

Solar Neutrinos as the first Example of Multi-Messenger Astrophysics



Observations:
Sun’s age, physical parameters
photon luminosity
solar neutrinos
helioseismology
metallicity: photo absorption lines

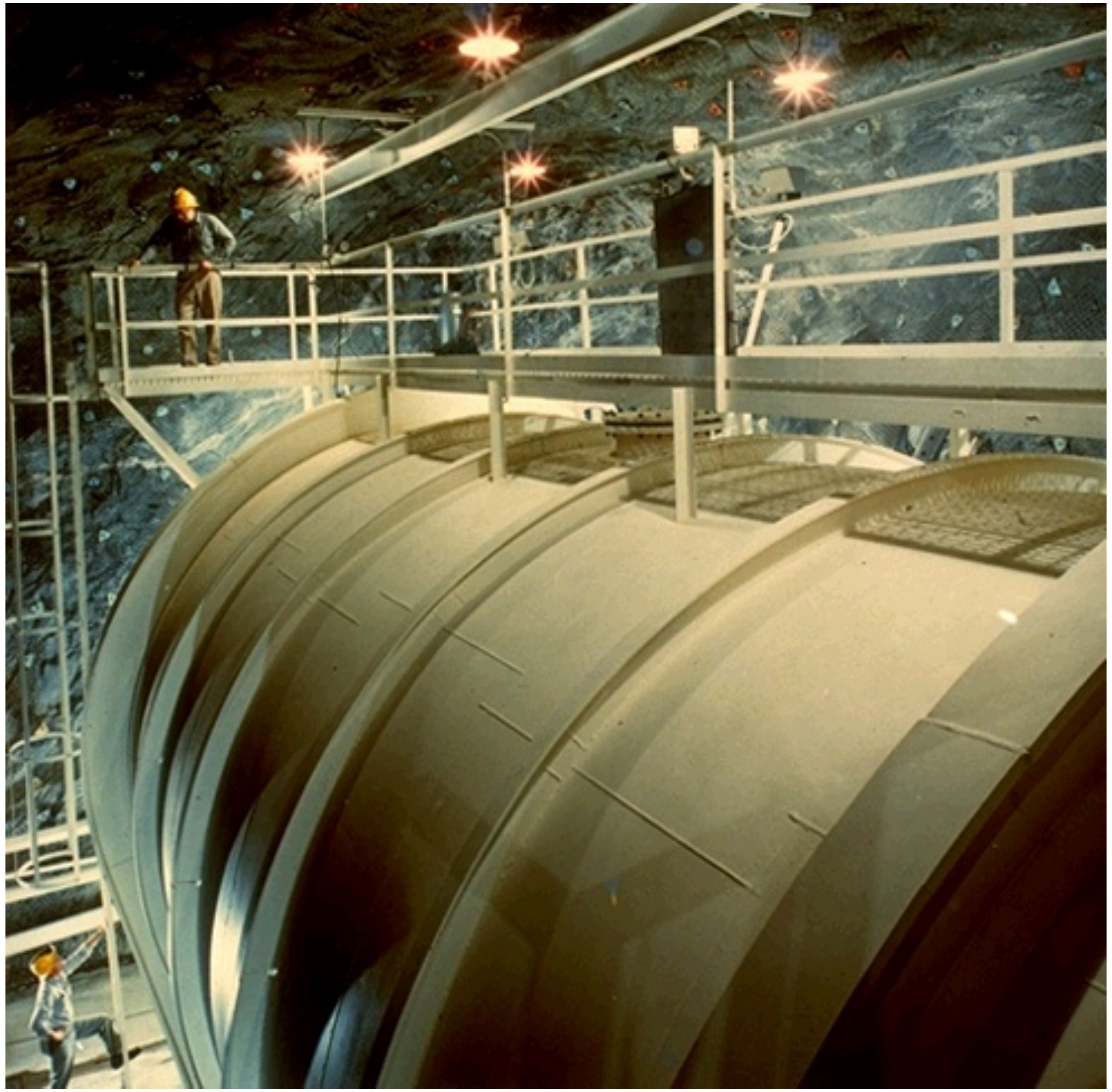
Input Microphysics:
nuclear reaction rates
opacities
EoS and corrections
diffusion coefficient

Modeling:
boundary conditions
physics: hydrostatic equilibrium
energy production
energy transport: rad. & convect.

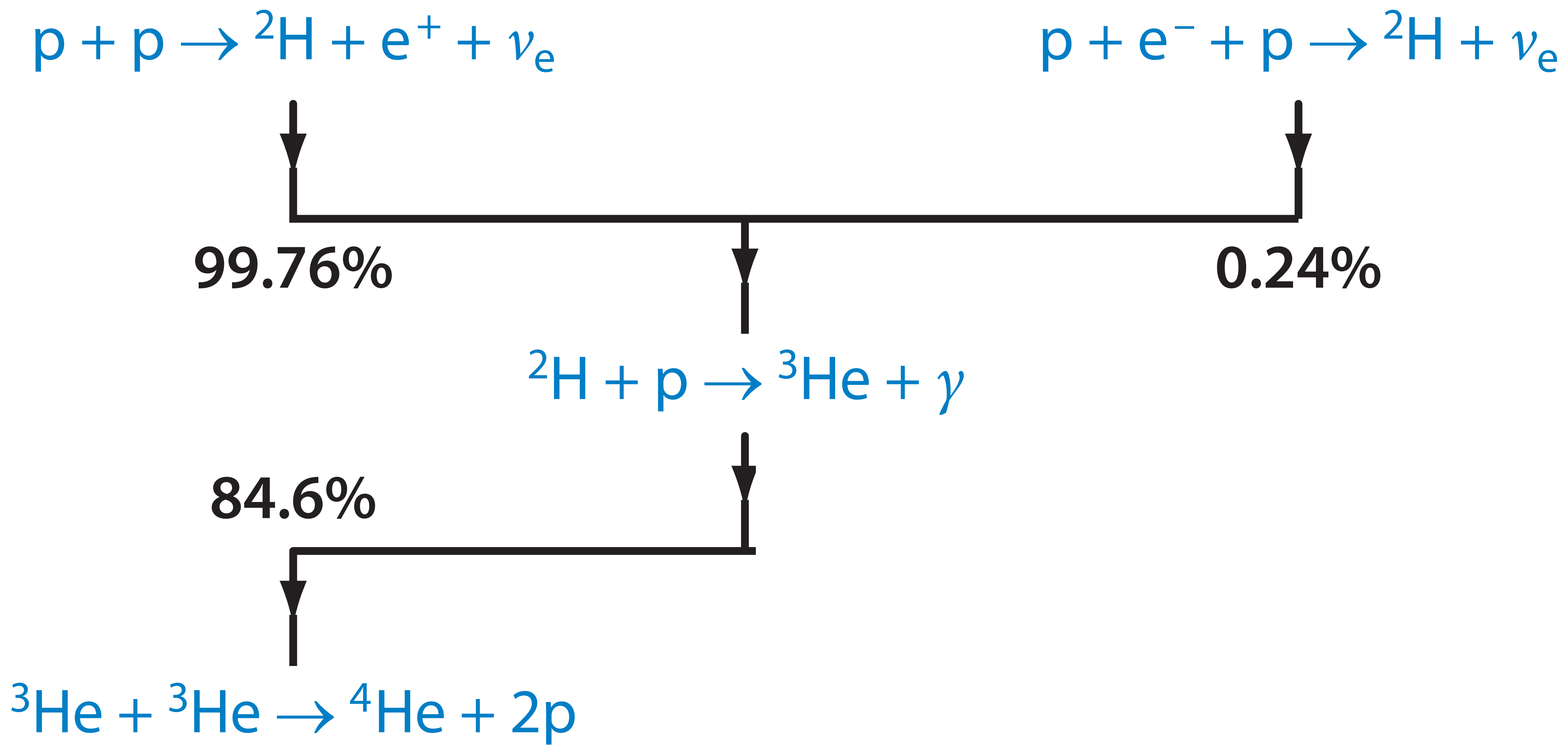
But things did not start out this way.

When the Homestake experiment was proposed, little was known about the nuclear reactions powering the Sun: it was unclear whether the Sun was powered by the pp chain or the CNO cycle

The modeling was immature, with no quantitative estimate of the Sun's core temperature, the most critical parameter in determining neutrino fluxes



$$4\mathrm{p} \rightarrow {}^4\mathrm{He} + 2e^+ + 2\nu_e + 26.7\ \mathrm{MeV}$$



$\mathrm{p} + \mathrm{p} \rightarrow {}^2\mathrm{H} + \mathrm{e}^+ + \nu_\mathrm{e}$

$\mathrm{p} + \mathrm{e}^- + \mathrm{p} \rightarrow {}^2\mathrm{H} + \nu_\mathrm{e}$

99.76%

0.24%

${}^2\mathrm{H} + \mathrm{p} \rightarrow {}^3\mathrm{He} + \gamma$

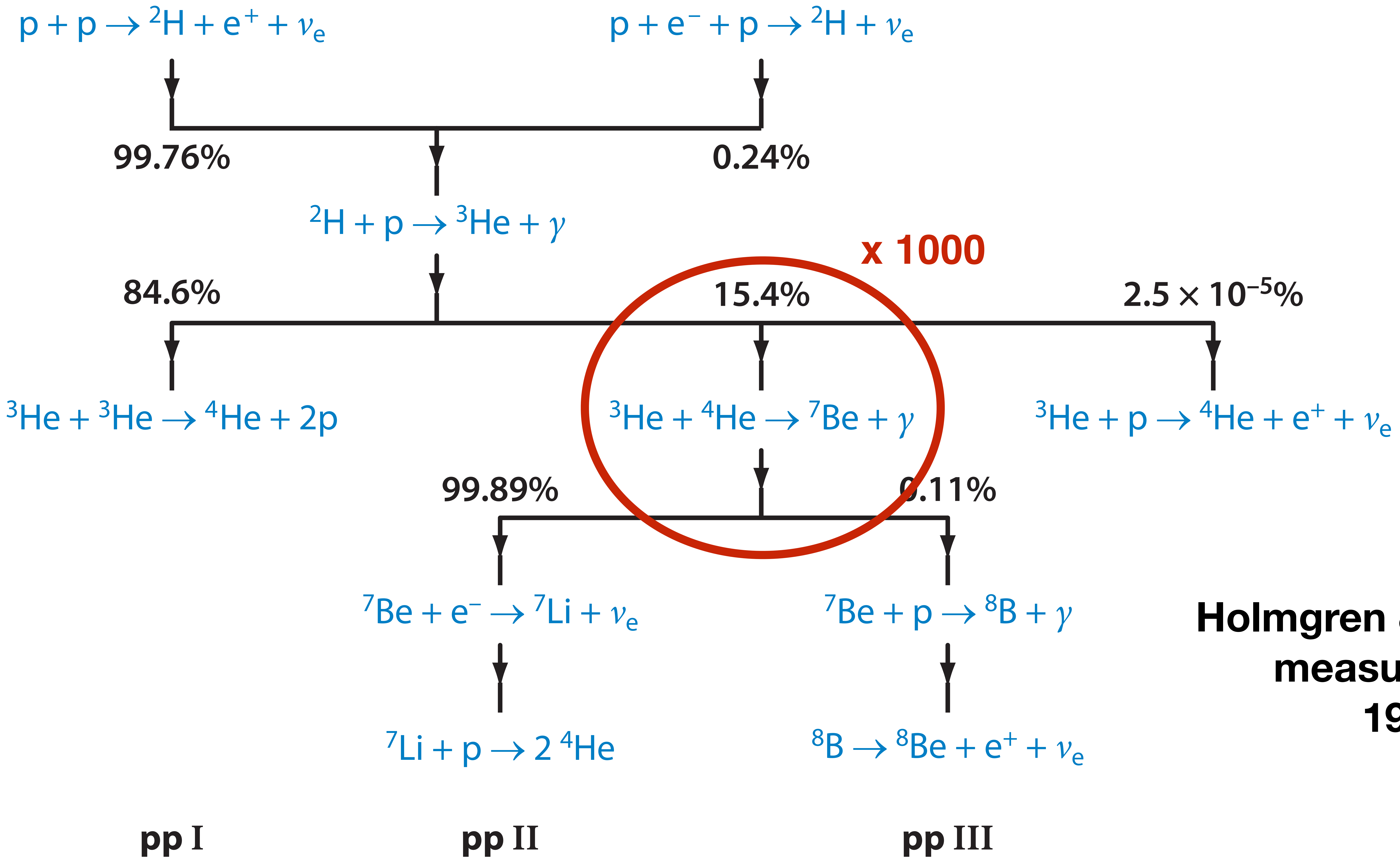
84.6%

${}^3\mathrm{He} + {}^3\mathrm{He} \rightarrow {}^4\mathrm{He} + 2\mathrm{p}$

Prior to 1959: solar neutrinos
though to be too low in
energy for detection in
the chlorine detector

pp I

$$4\mathrm{p} \rightarrow {}^{4}\mathrm{He} + 2e^{+} + 2\nu_e + 26.7\ \mathrm{MeV}$$



$\mathrm{p} + \mathrm{p} \rightarrow {}^{2}\mathrm{H} + \mathrm{e}^{+} + \nu_\mathrm{e}$

$\mathrm{p} + \mathrm{e}^{-} + \mathrm{p} \rightarrow {}^{2}\mathrm{H} + \nu_\mathrm{e}$

99.76%

0.24%

${}^{2}\mathrm{H} + \mathrm{p} \rightarrow {}^{3}\mathrm{He} + \gamma$

x 1000

84.6%

15.4%

$2.5 \times 10^{-5}\%$

${}^{3}\mathrm{He} + {}^{3}\mathrm{He} \rightarrow {}^{4}\mathrm{He} + 2\mathrm{p}$

${}^{3}\mathrm{He} + {}^{4}\mathrm{He} \rightarrow {}^{7}\mathrm{Be} + \gamma$

${}^{3}\mathrm{He} + \mathrm{p} \rightarrow {}^{4}\mathrm{He} + \mathrm{e}^{+} + \nu_\mathrm{e}$

99.89%

0.11%

${}^{7}\mathrm{Be} + \mathrm{e}^{-} \rightarrow {}^{7}\mathrm{Li} + \nu_\mathrm{e}$

${}^{7}\mathrm{Be} + \mathrm{p} \rightarrow {}^{8}\mathrm{B} + \gamma$

${}^{7}\mathrm{Li} + \mathrm{p} \rightarrow 2\ {}^{4}\mathrm{He}$

${}^{8}\mathrm{B} \rightarrow {}^{8}\mathrm{Be} + \mathrm{e}^{+} + \nu_\mathrm{e}$

pp I

pp II

pp III

Holmgren & Johnston
measurement
1959

- Willy Fowler immediately recognized the opportunity that had opened for the chlorine detector

- Had stellar modelers Iben and Sears at Caltech: He brought in a young John Bahcall to help with the weak interaction/neutrino physics

- The result was a model that yielded a core temperature that was used by John to make a first estimate of solar neutrino fluxes, off line

- That model has been refined over the last 50 years, with significant modifications continuing even in this decade

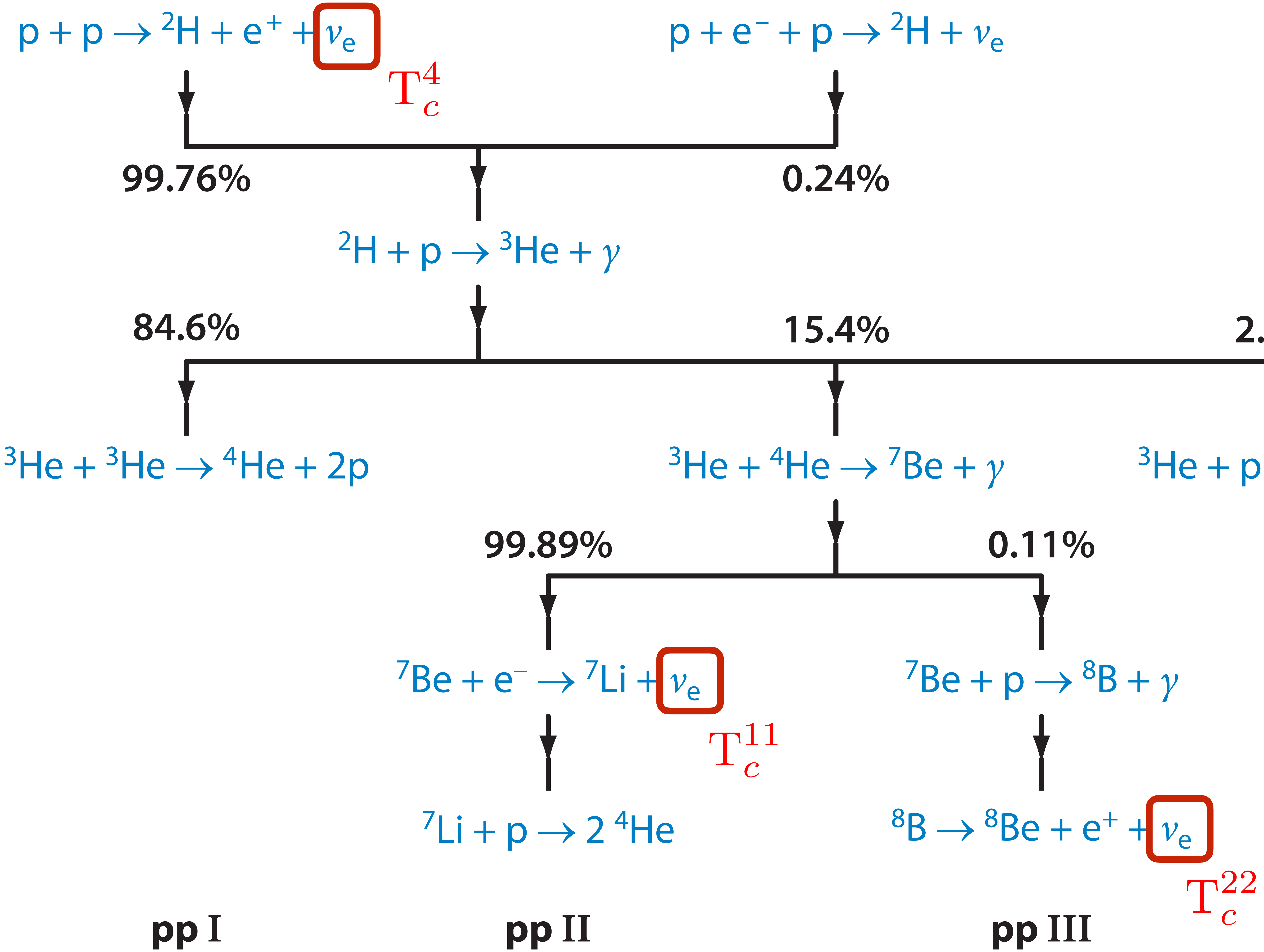
The Standard Solar Model

- Origin of solar neutrino physics: desire to test our model of low-mass, main-sequence stellar evolution
  - local hydrostatic equilibrium: gas pressure gradient counteracting gravitational force
  - hydrogen burning: 4p → 4He + energy (+ neutrinos)
  - energy transport by radiation (interior) and convection (envelope)
  - boundary conditions: today's mass, radius, luminosity, …

- The implementation of this physics requires
  - an electron gas EoS
  - cross sections for the very low energy nuclear reactions
  - radiative opacity
  - some means of fixing the composition at ZAMS, including the ratios H:He:metals

This model describs 70% of the stars in the Milky Way, critical to the interpretation of modern surveys like those of the ESA's Plato Mission

$$4\mathrm{p} \rightarrow {}^4\mathrm{He} + 2e^+ + 2\nu_e + 26.7\ \mathrm{MeV}$$



$\mathrm{p} + \mathrm{p} \rightarrow {}^2\mathrm{H} + \mathrm{e}^+ + \boxed{\nu_\mathrm{e}}$ T_c^4

$\mathrm{p} + \mathrm{e}^- + \mathrm{p} \rightarrow {}^2\mathrm{H} + \nu_\mathrm{e}$

99.76%

0.24%

${}^2\mathrm{H} + \mathrm{p} \rightarrow {}^3\mathrm{He} + \gamma$

84.6%

15.4%

2.5×10^{-5}%

${}^3\mathrm{He} + {}^3\mathrm{He} \rightarrow {}^4\mathrm{He} + 2\mathrm{p}$

${}^3\mathrm{He} + {}^4\mathrm{He} \rightarrow {}^7\mathrm{Be} + \gamma$

${}^3\mathrm{He} + \mathrm{p} \rightarrow {}^4\mathrm{He} + \mathrm{e}^+ + \nu_\mathrm{e}$

99.89%

0.11%

${}^7\mathrm{Be} + \mathrm{e}^- \rightarrow {}^7\mathrm{Li} + \boxed{\nu_\mathrm{e}}$ T_c^{11}

${}^7\mathrm{Be} + \mathrm{p} \rightarrow {}^8\mathrm{B} + \gamma$

${}^7\mathrm{Li} + \mathrm{p} \rightarrow 2\ {}^4\mathrm{He}$

${}^8\mathrm{B} \rightarrow {}^8\mathrm{Be} + \mathrm{e}^+ + \boxed{\nu_\mathrm{e}}$ T_c^{22}

pp I

pp II

pp III

dependence on the core temperature

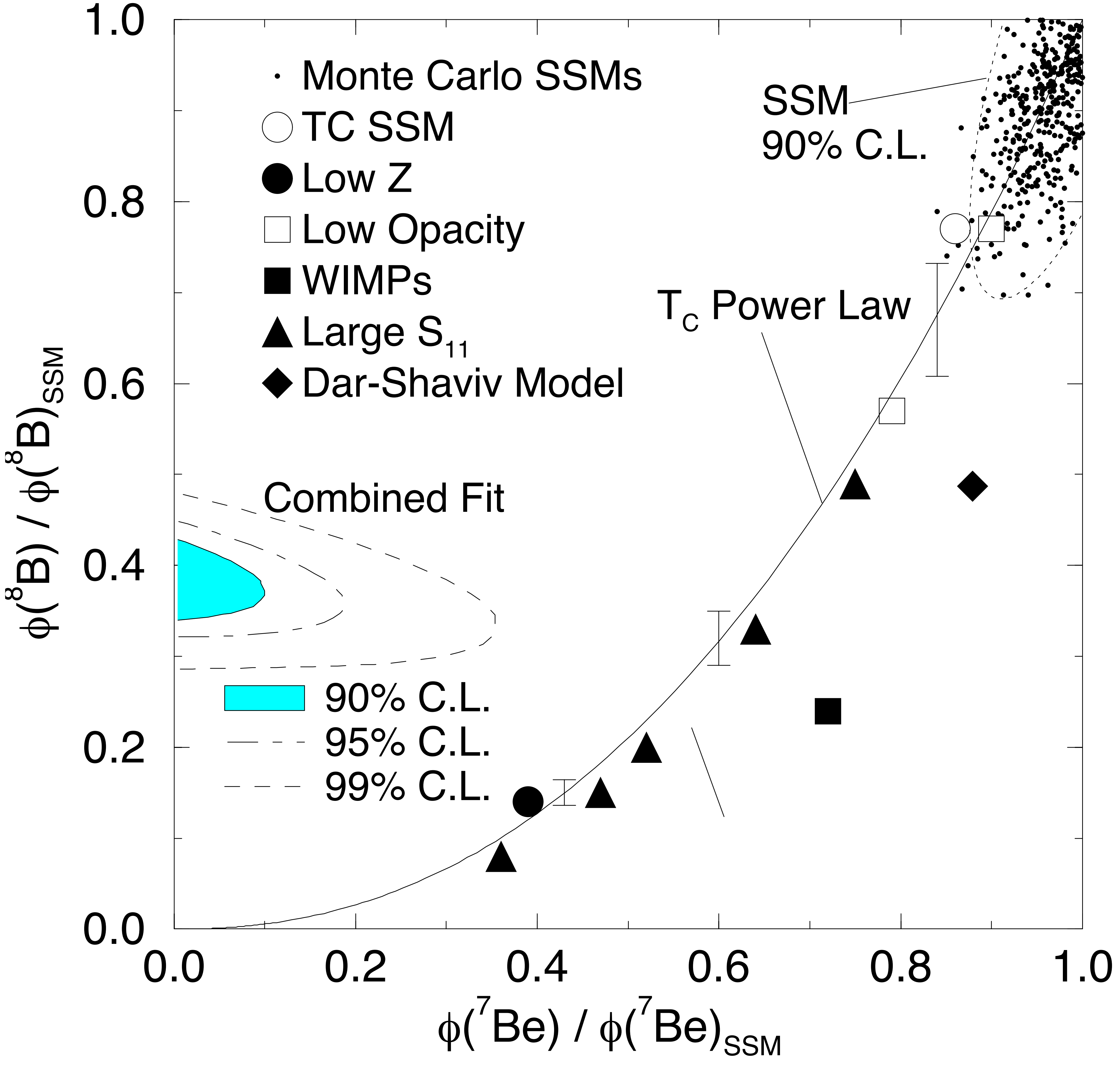
Have a neutrino thermometer capable of measuring the solar core temperature to 1%

- While the first results from the Homestake were announced in 1968, it took 20 years before other experiments were able to confirm the solar neutrino deficit

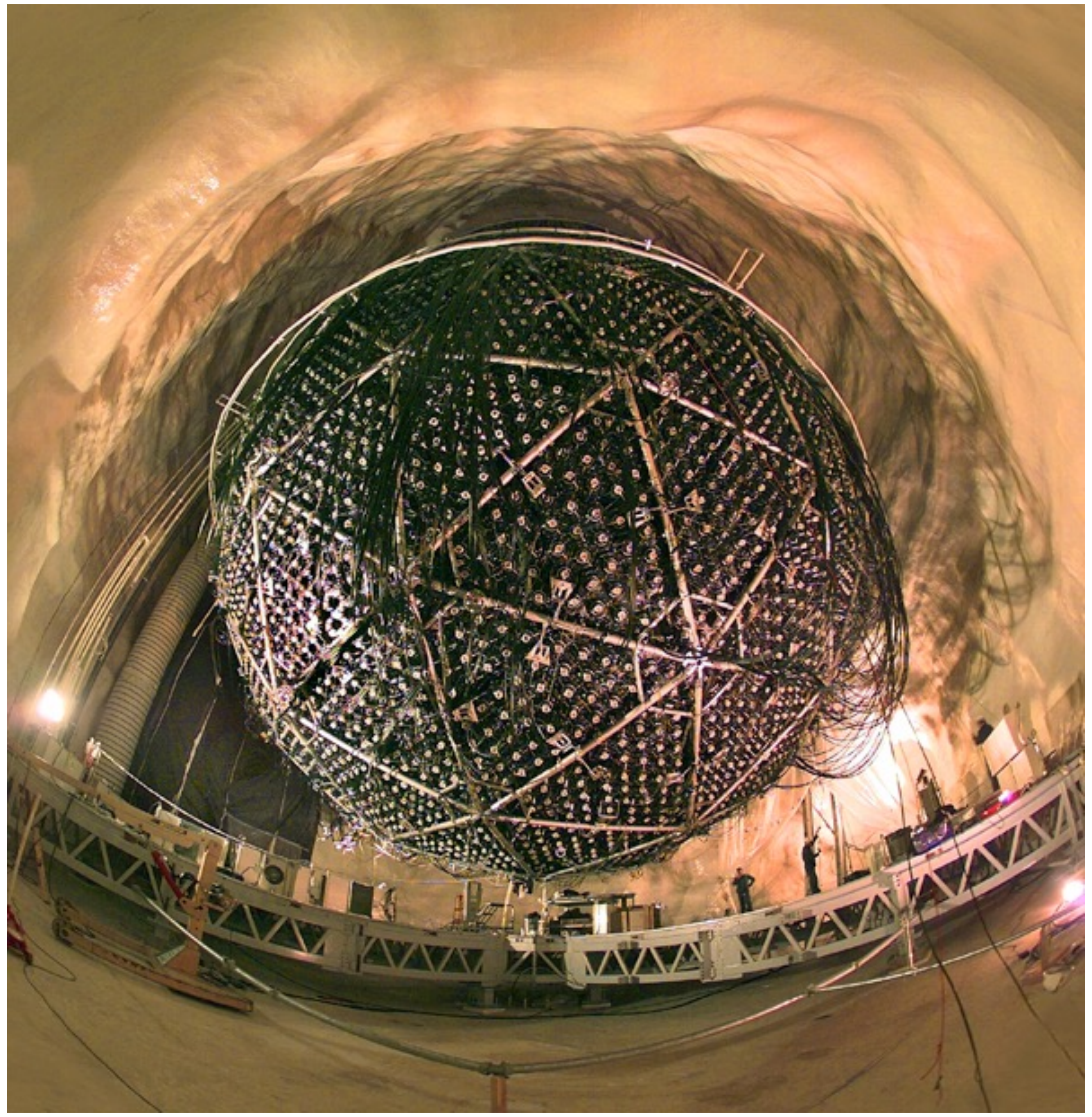
- This delay was not entirely scientific: Davis had developed procedures for both the Ga metal (SAGE) and GaCl (GALLEX) experiments, and pointed out that this experiment had the potential to definitively distinguish neutrino oscillation solutions from solar model solutions — but proposals for a US-based experiment were unsuccessful

- But when the chlorine, gallium, and Kamioka II/III results were confined, the significance of the solar neutrino problem became more apparent

The results were not compatible with the SSM or any reasonable variation thereof - something novel was going on



From Hata

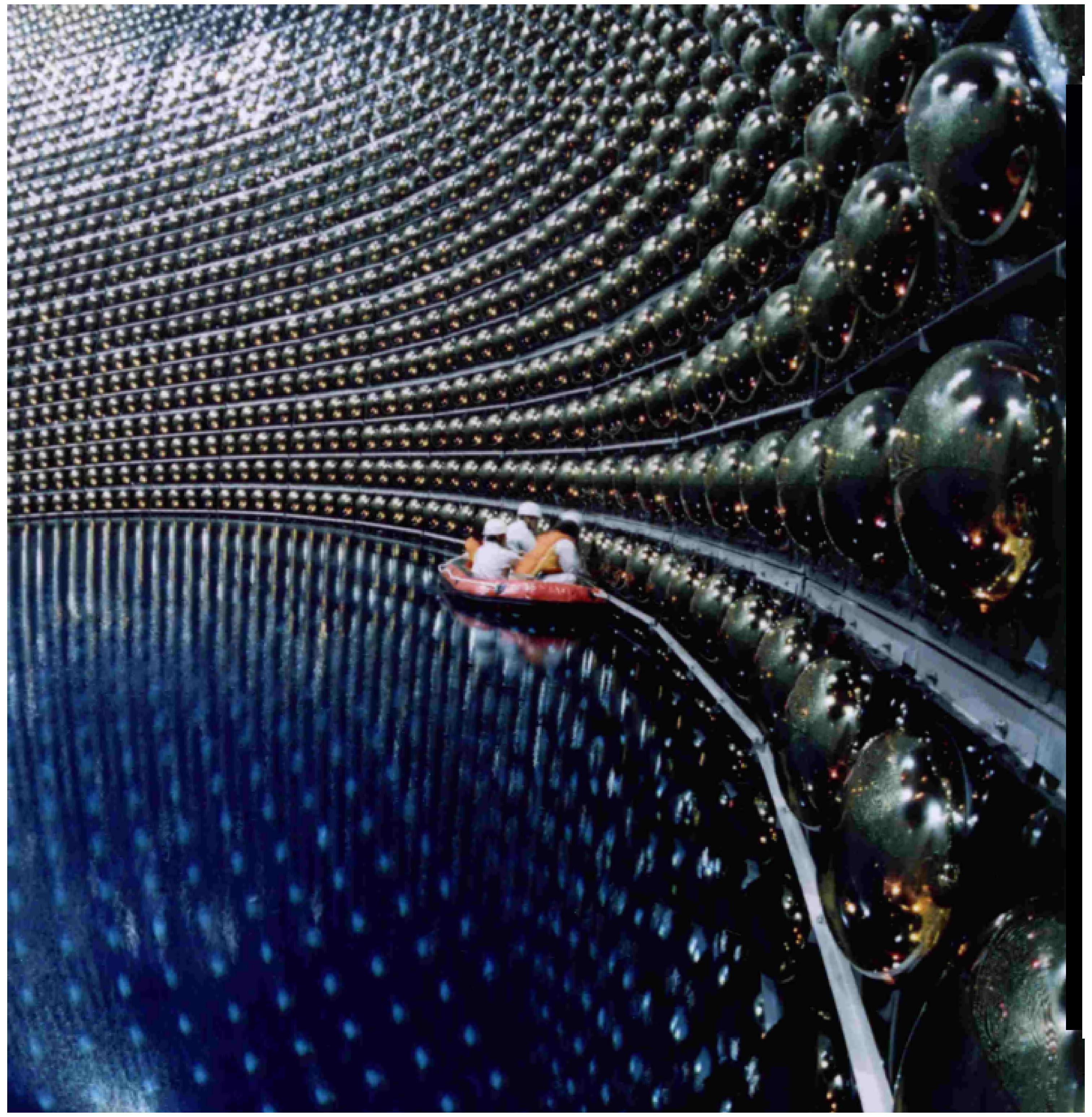


SNO

$$\nu_x + e^- \to \nu_x + e$$

$$\nu_e + d \to e^- + p + p$$

$$\nu_x + d \to \nu_x + n + p$$



Super-Kamiokande

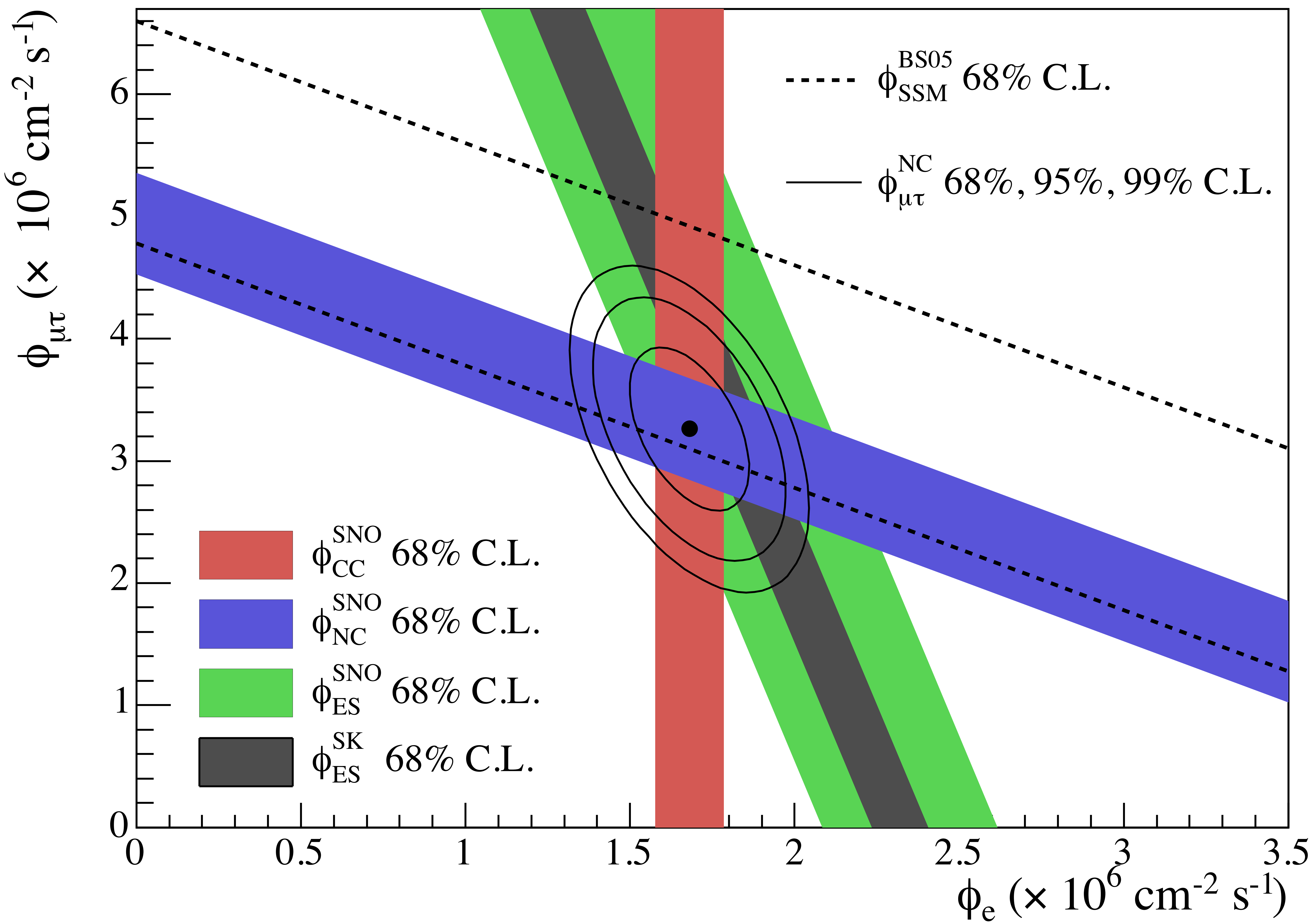
50 kilotons

yielded a neutrino
“photograph” of the Sun

Borexino

3 kiltons of ultra pure scintillator

pp, pep, ^{7}Be, ^{8}B, CNO



SNO Collaboration

the SNO results showing the flavor conversion $\nu_e \rightarrow \nu_{heavy}$

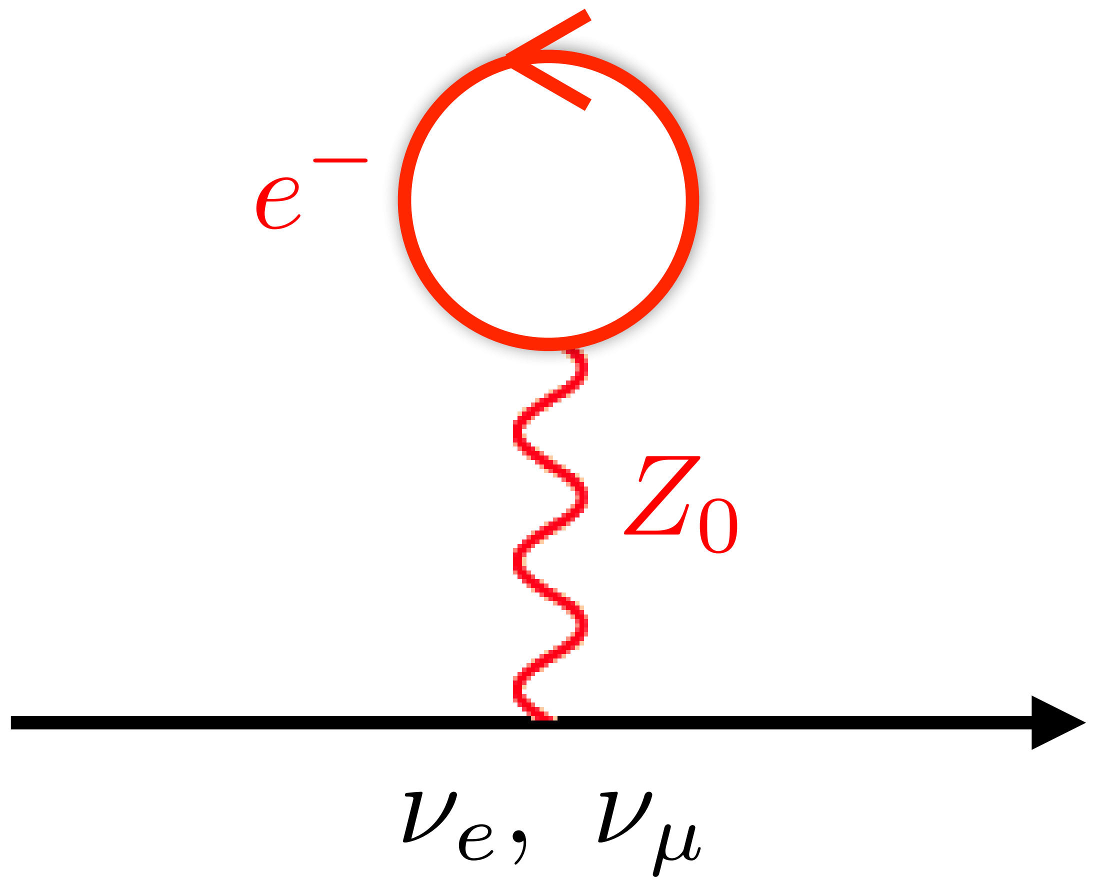
requires massive neutrinos and an extension of the SM

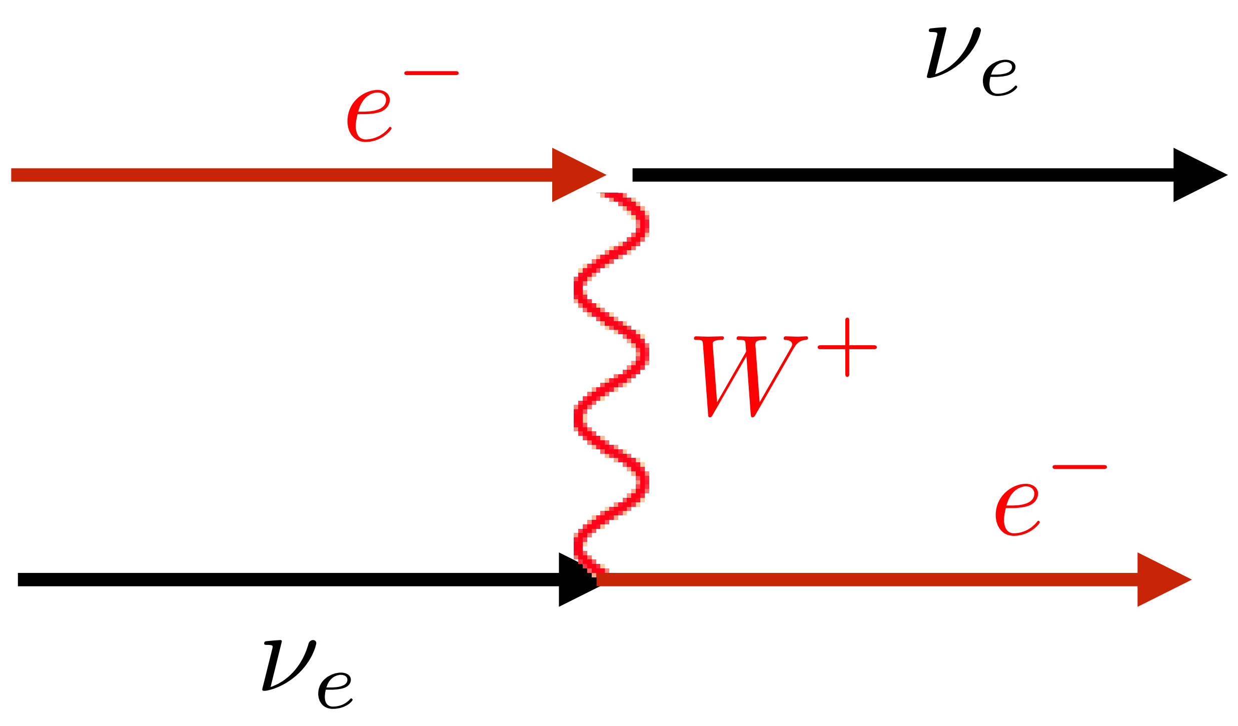
Super-K
found the same physics
in its zenith-angle mapping
of atmospheric neutrinos

Included the discovery of matter effects on oscillations

$$|\nu_e(t)\rangle = \exp\left[i\frac{\delta m^2_{12}(\rho)}{4E}\,t\right]\cos\theta_{12}(\rho)\,|v_1\rangle + \exp\left[-i\frac{\delta m^2_{12}(\rho)}{4E}\,t\right]\sin\theta_{12}(\rho)\,|v_2\rangle$$

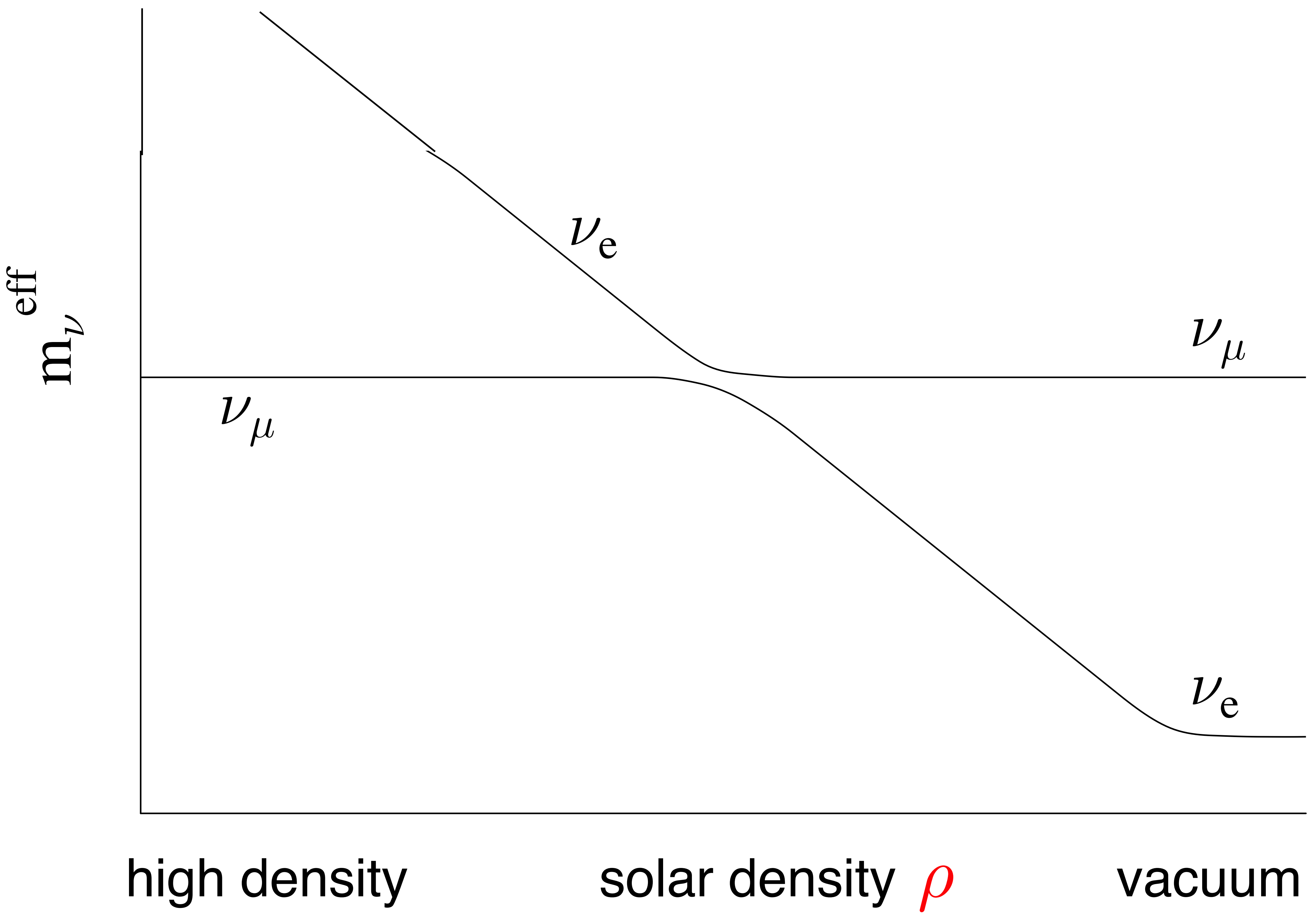
Just as the photon acquires a mass in water, neutrino masses (and mass differences) evolve with ρ_{solar}





⇒ the electron neutrino becomes <u>heavier</u> when surrounded by matter

$$|\nu_e(t)\rangle = \exp\left[i\frac{\delta m_{12}^2(\rho)}{4E}\ t\right]\cos\theta_{12}(\rho)|v_1\rangle\ + \exp\left[-i\frac{\delta m_{12}^2(\rho)}{4E}\ t\right]\sin\theta_{12}(\rho)\ |v_2\rangle$$



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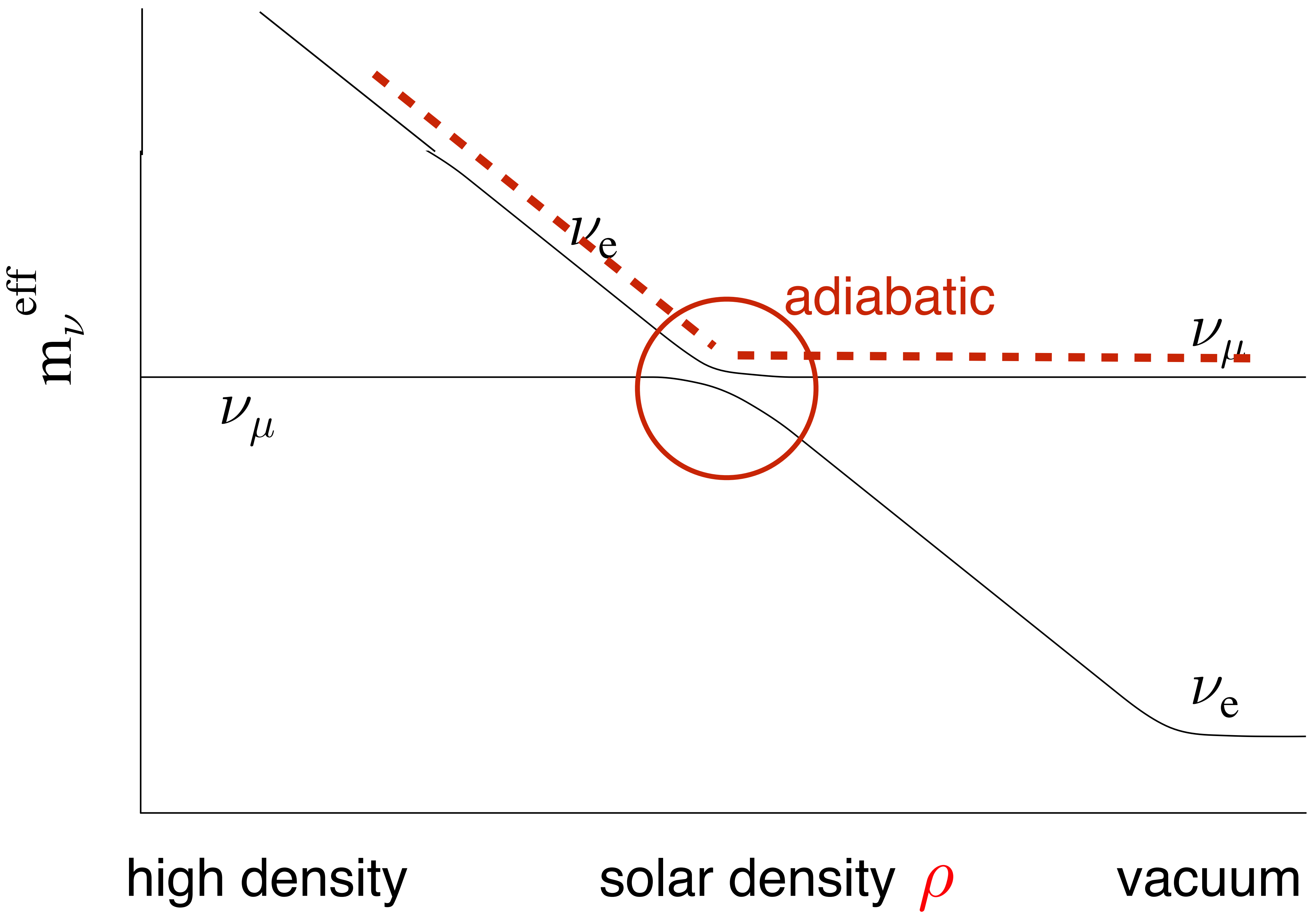
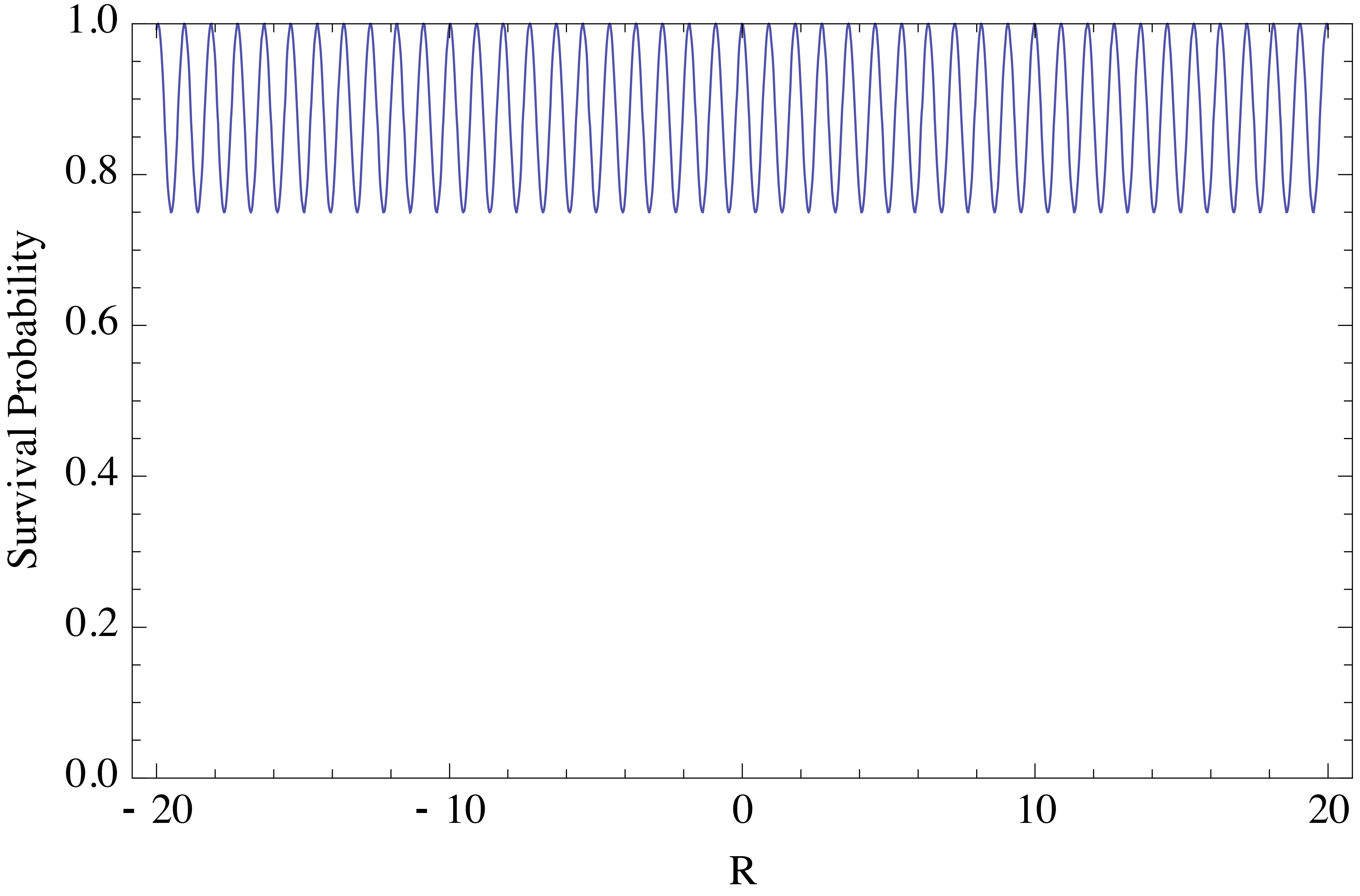


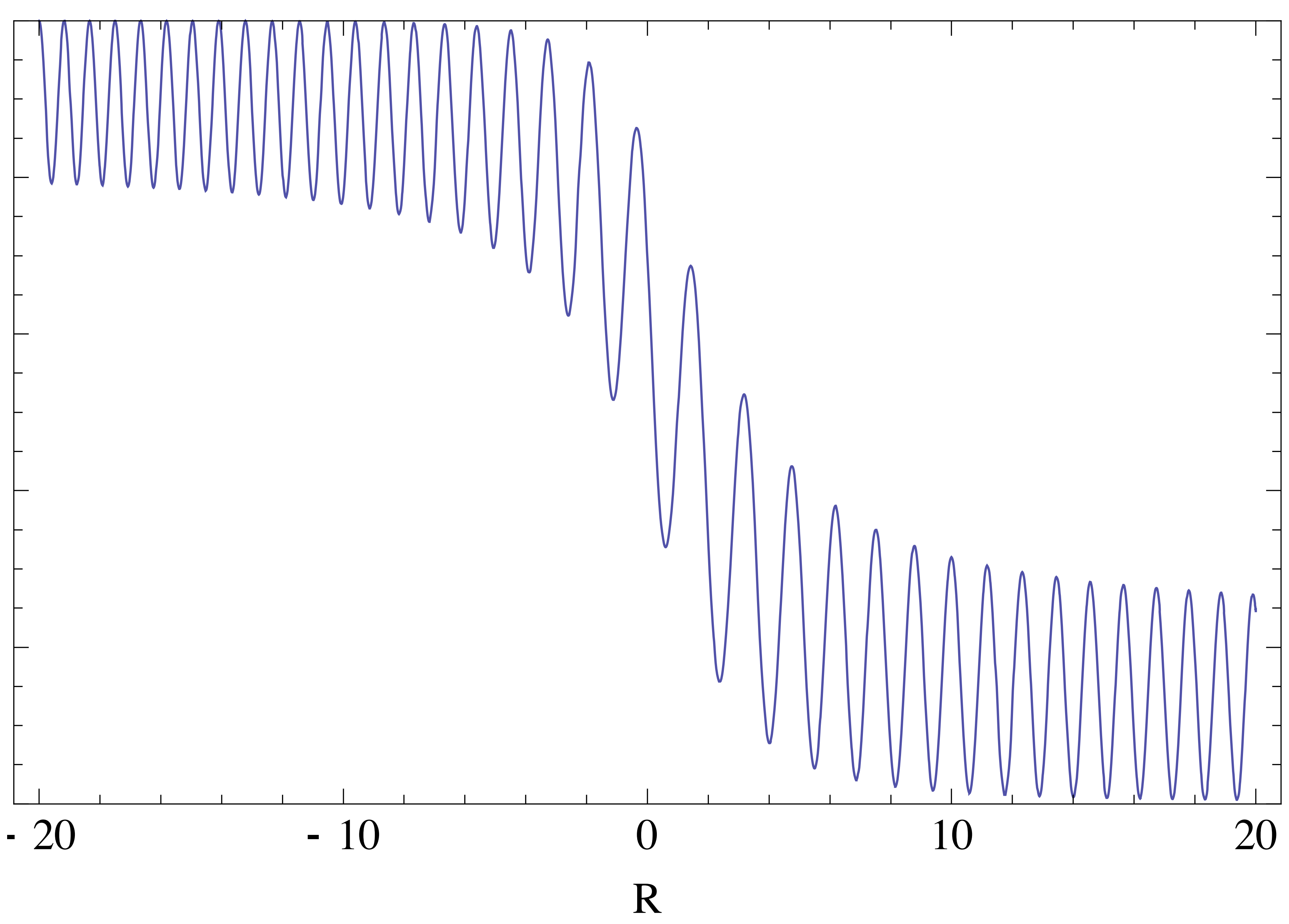
level crossing must be adiabatic: neutrino oscillation wavelength — maximal at the cross point — must be shorter than the solar density scale height

$$|\nu_e(t)\rangle = \exp\left[i\frac{\delta m_{12}^2(\rho)}{4E}\ t\right]\cos\theta_{12}(\rho)|v_1\rangle + \exp\left[-i\frac{\delta m_{12}^2(\rho)}{4E}\ t\right]\sin\theta_{12}(\rho)\,|v_2\rangle$$



in vacuum

$\Rightarrow$

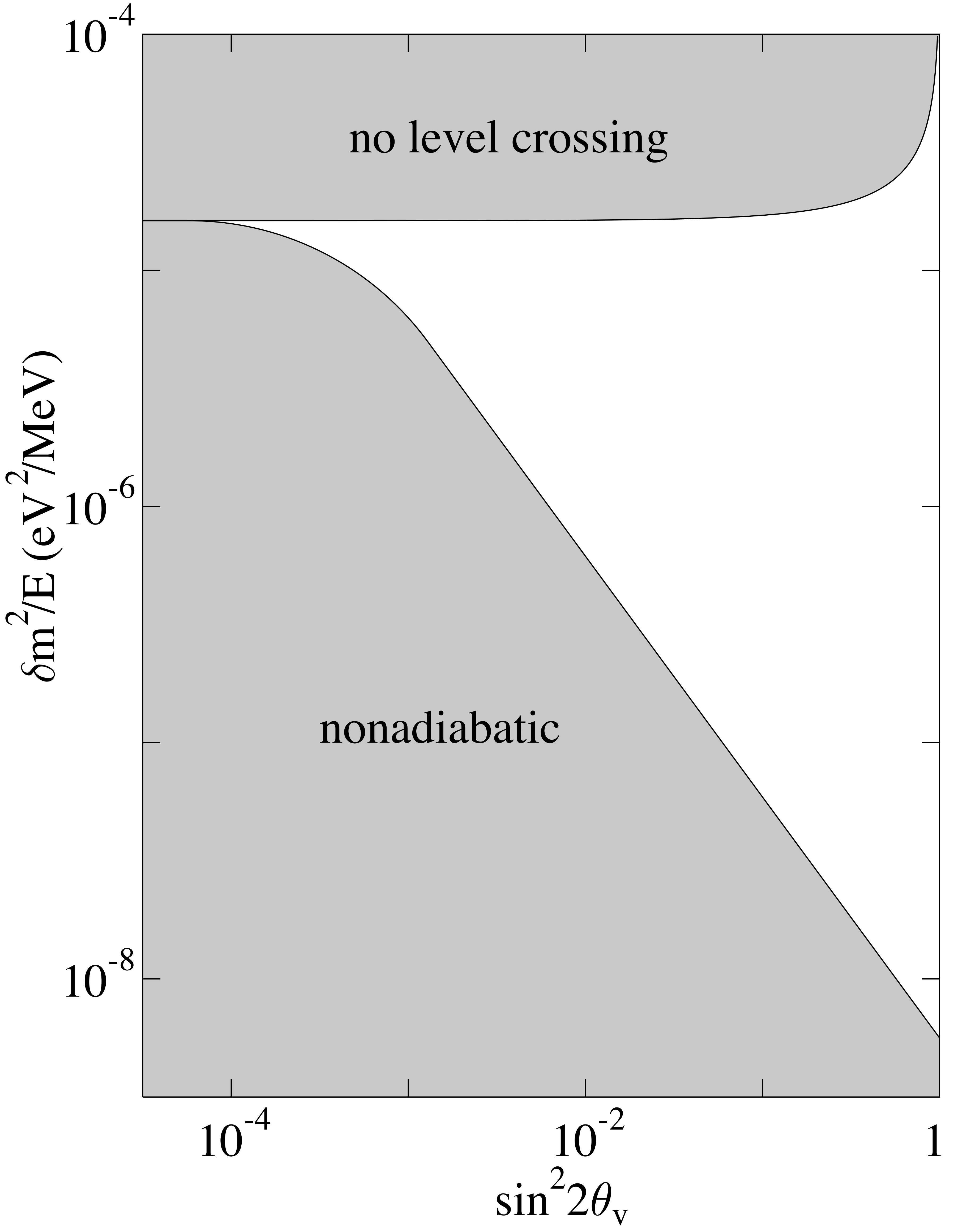


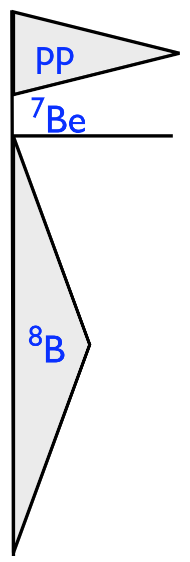
in matter:

MSW Mechanism:

put the level-crossing and adiabatic conditions on a graph

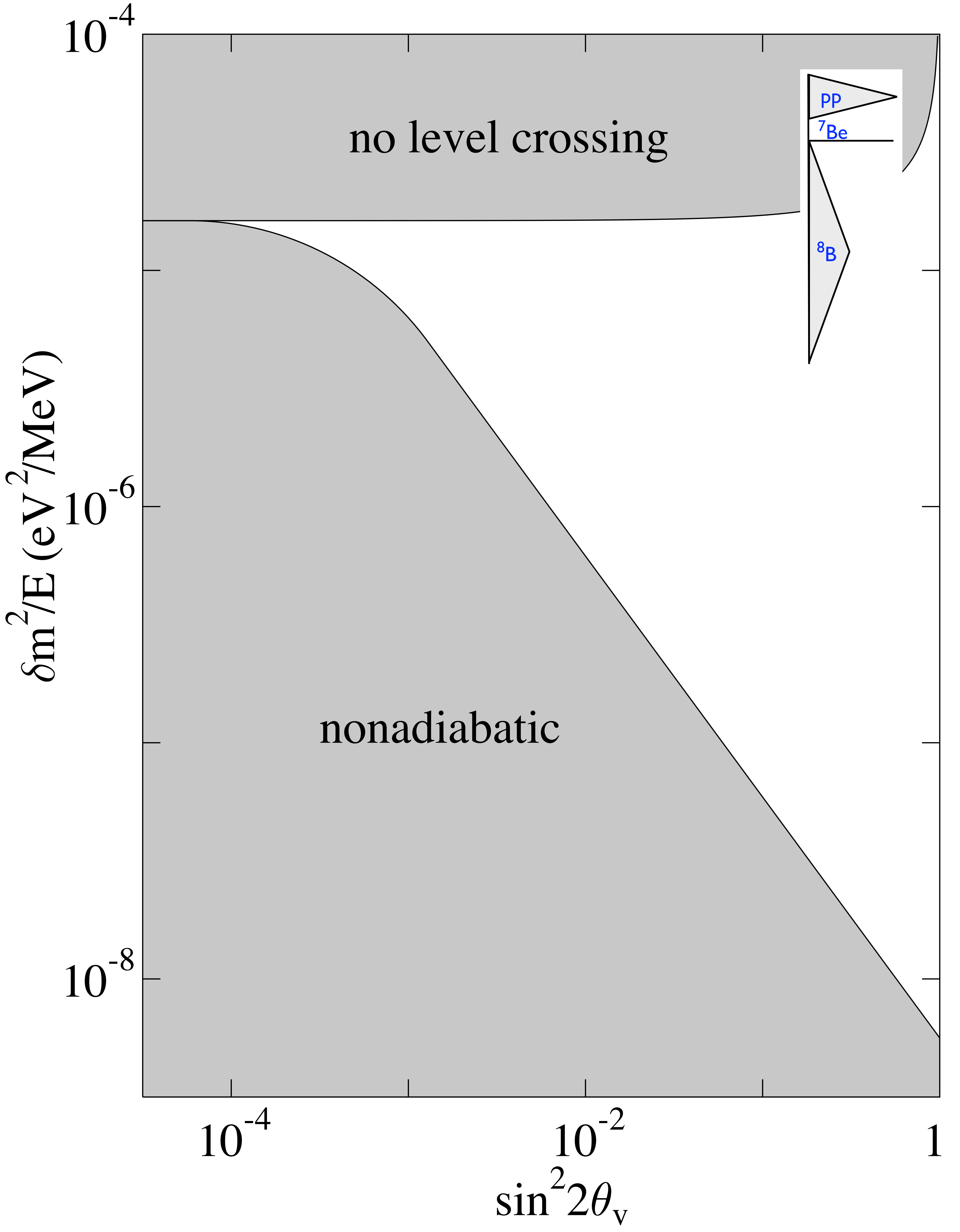
the white triangle shows the neutrino parameters where the MSW mechanism operates effectively in the Sun





$\sin^2 2\theta_{12} \sim 0.85$

MSW Mechanism



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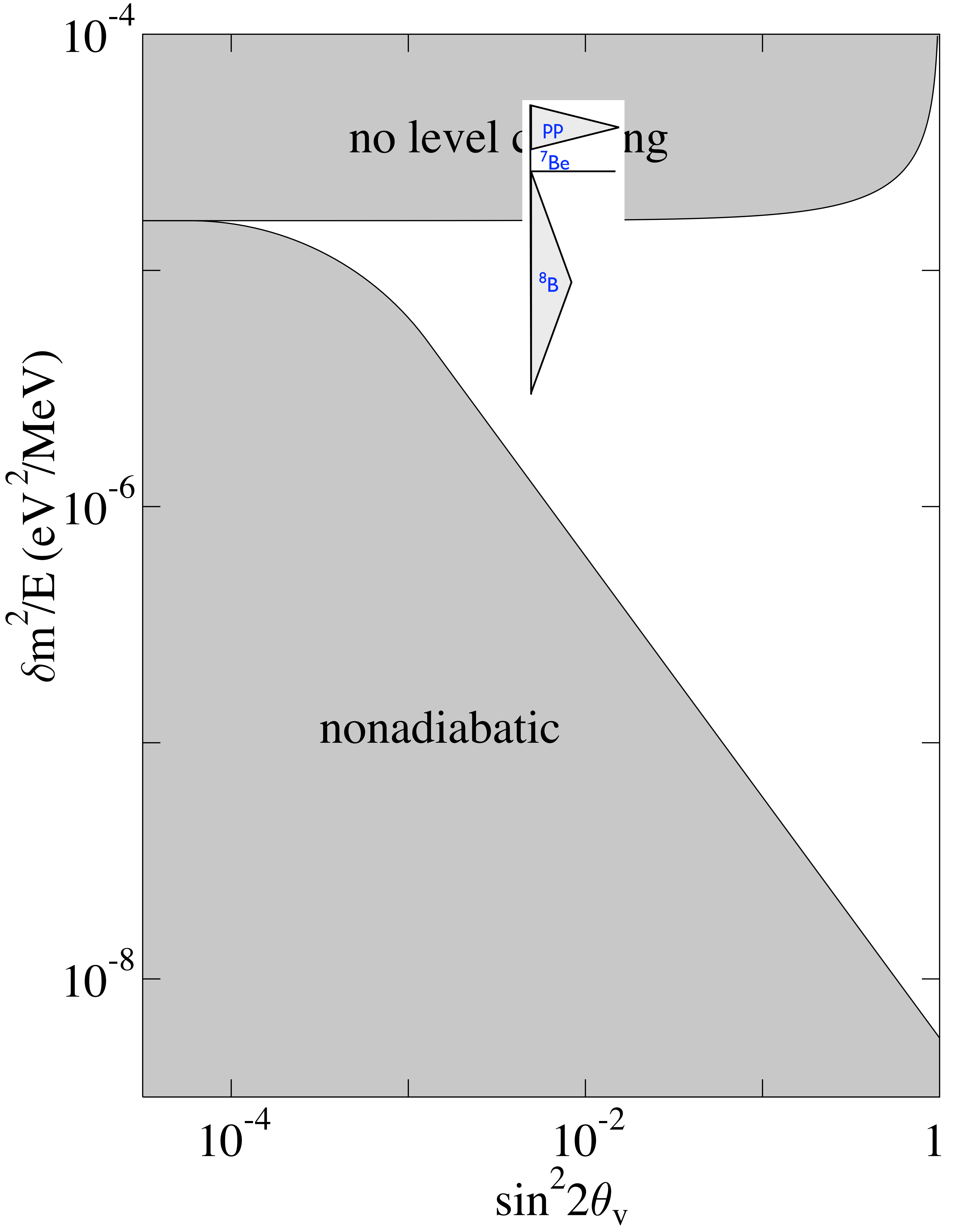

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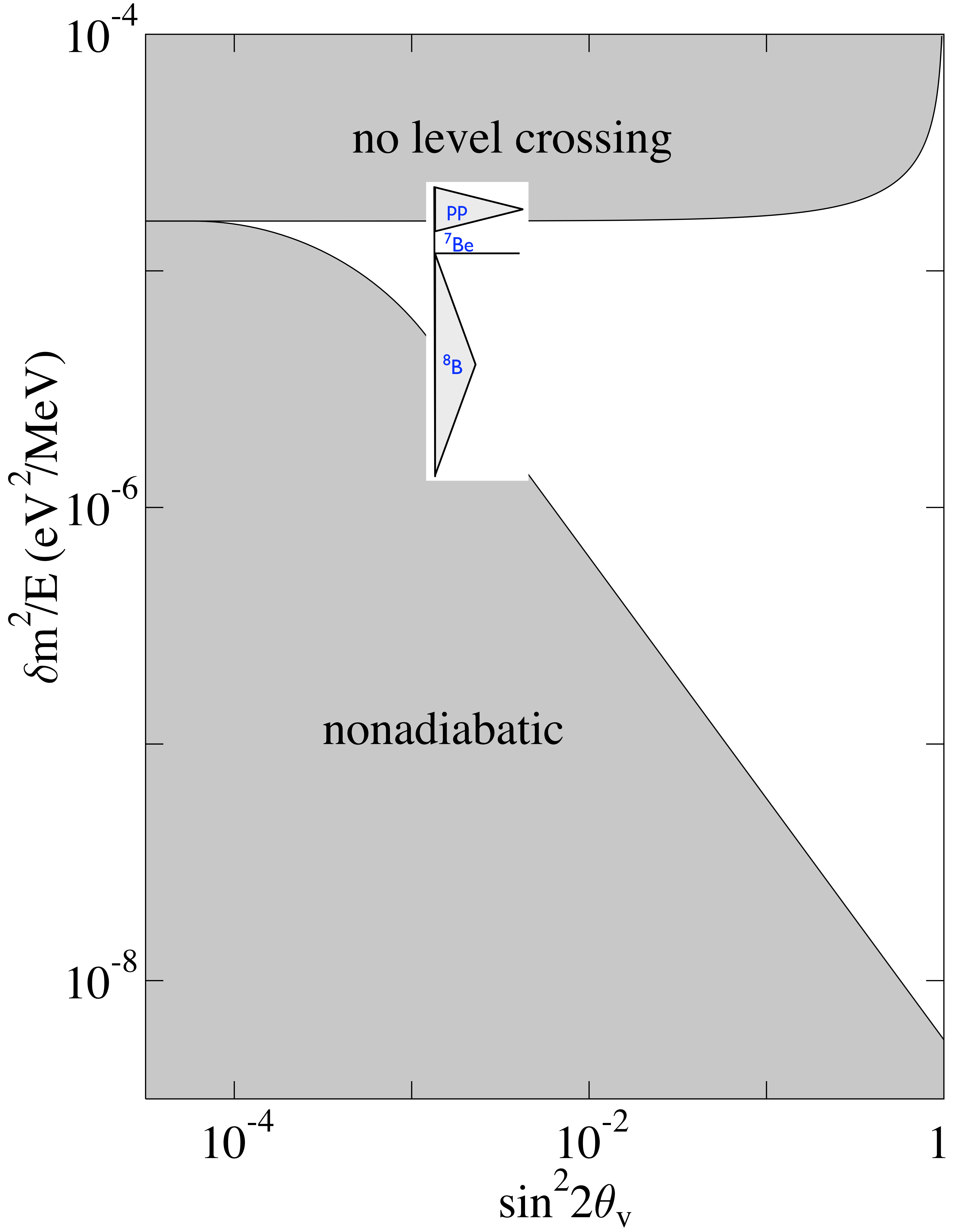

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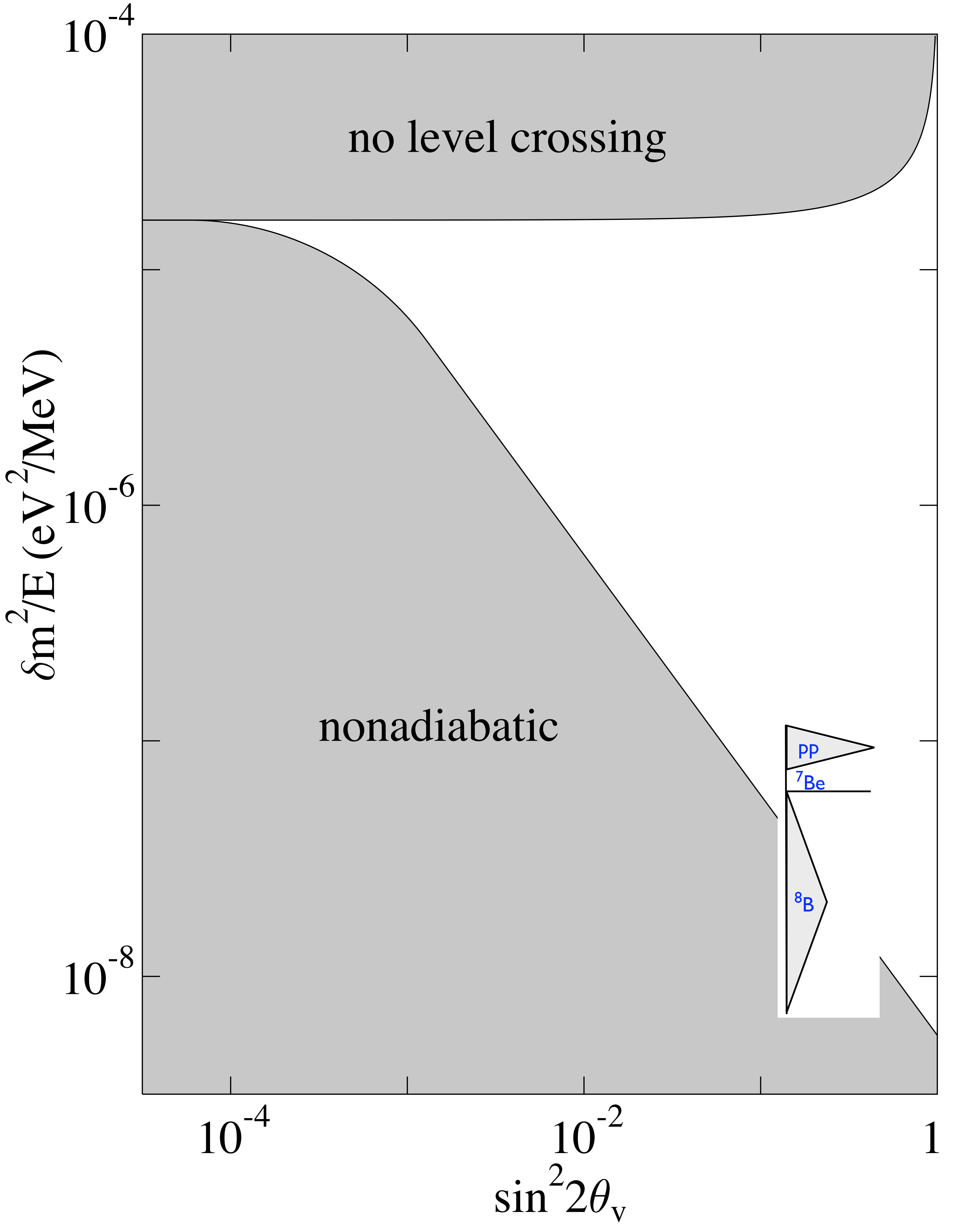

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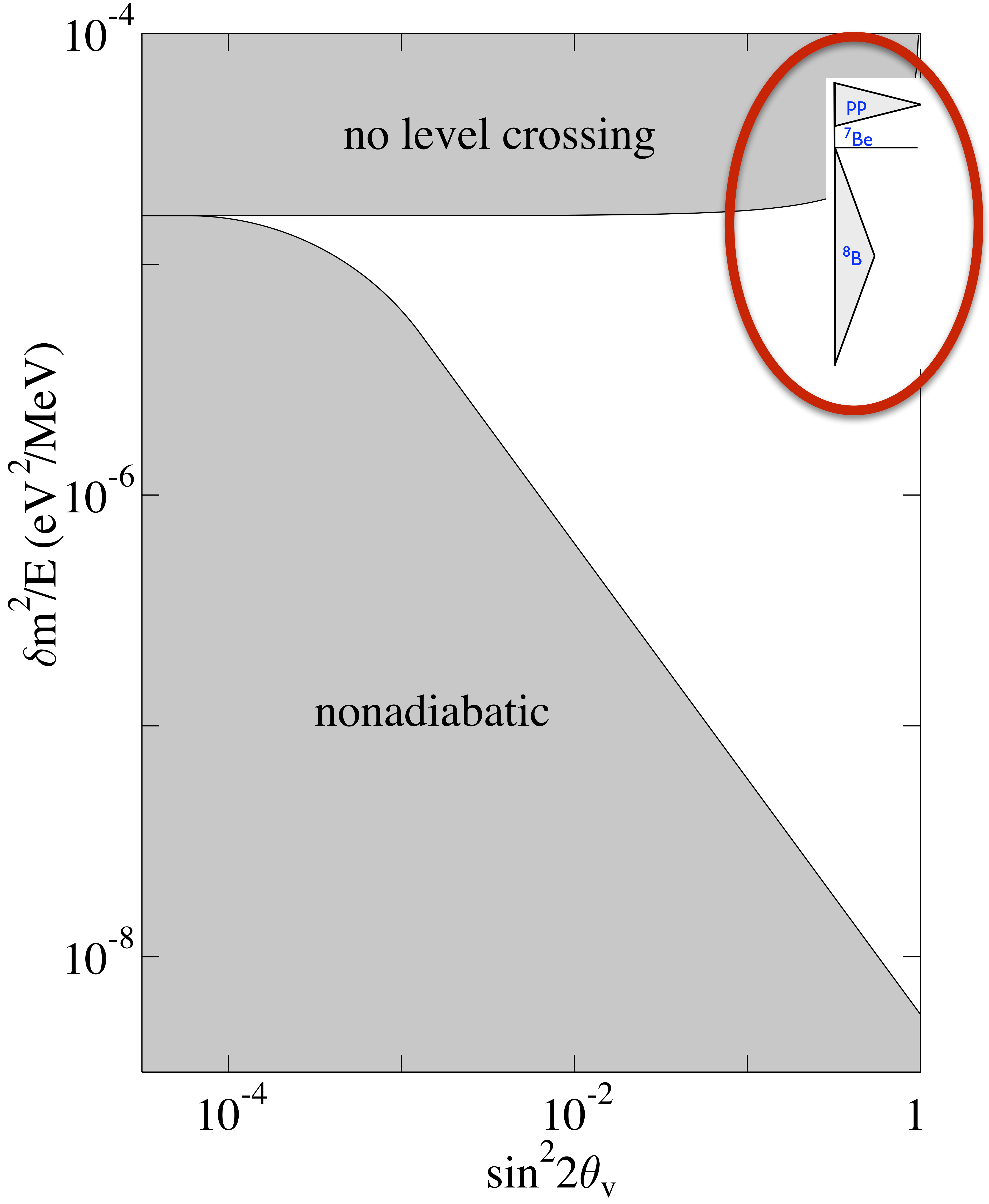
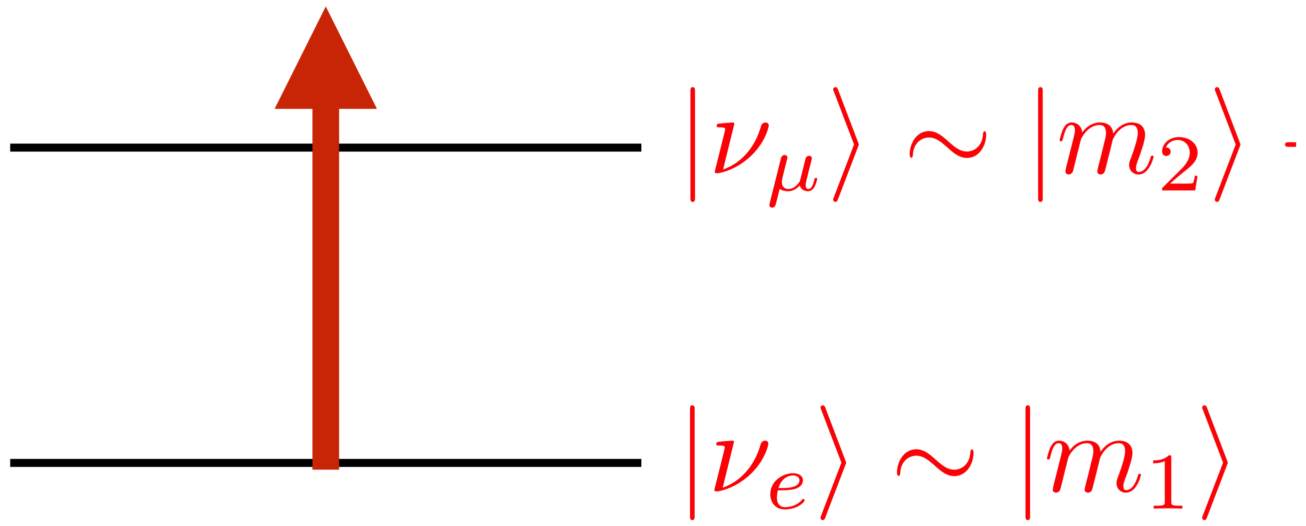


$\sin^2 2\theta_{12} \sim 0.85$

How extremely fortunate! The level crossing — which depends on $\delta m_{12}^2/E$ — occurs in the middle of the solar neutrino spectrum. We can effectively turn on/off matter effects.

Consequently the Sun provides information on the ordering of the mass eigenstates:

Crossing

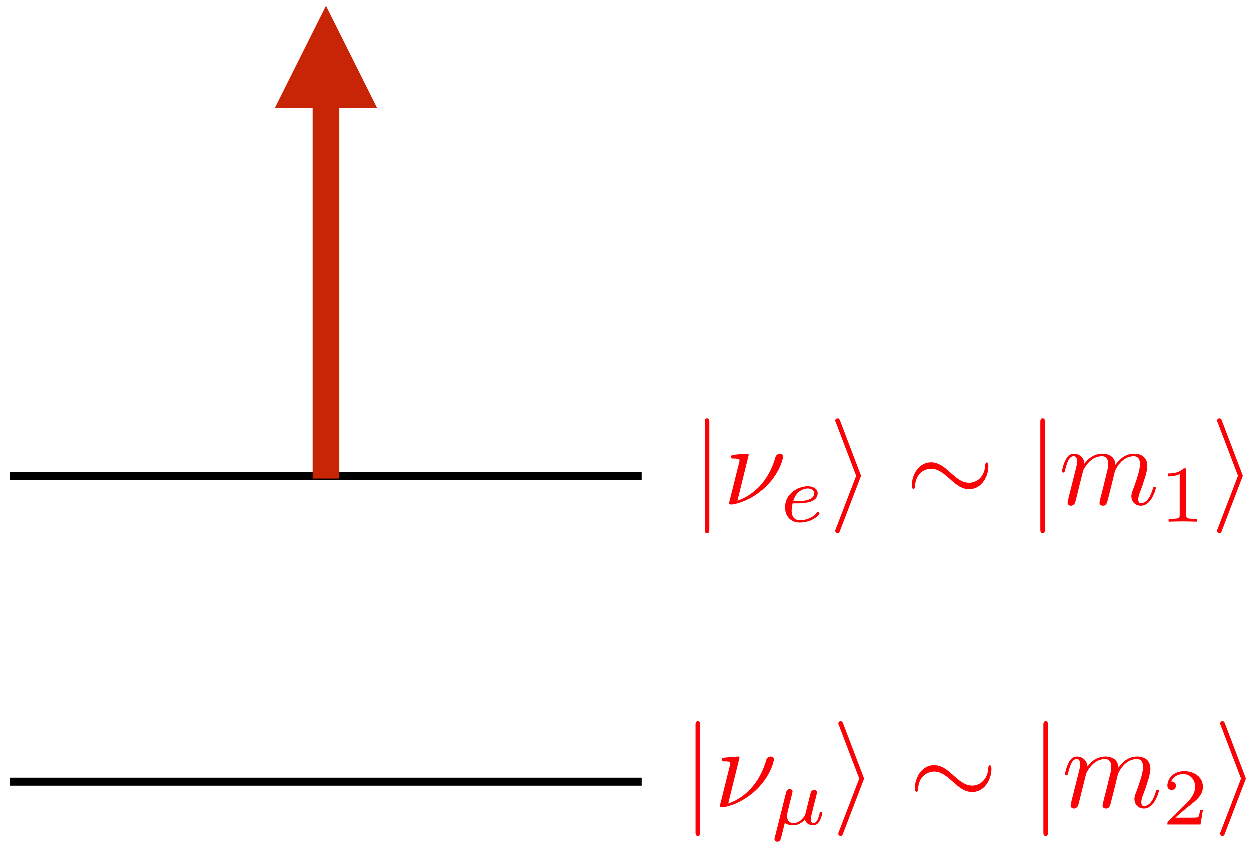


$|\nu_\mu\rangle \sim |m_2\rangle$

$|\nu_e\rangle \sim |m_1\rangle$

mass difference decreased:
oscillation length increased

No Crossing



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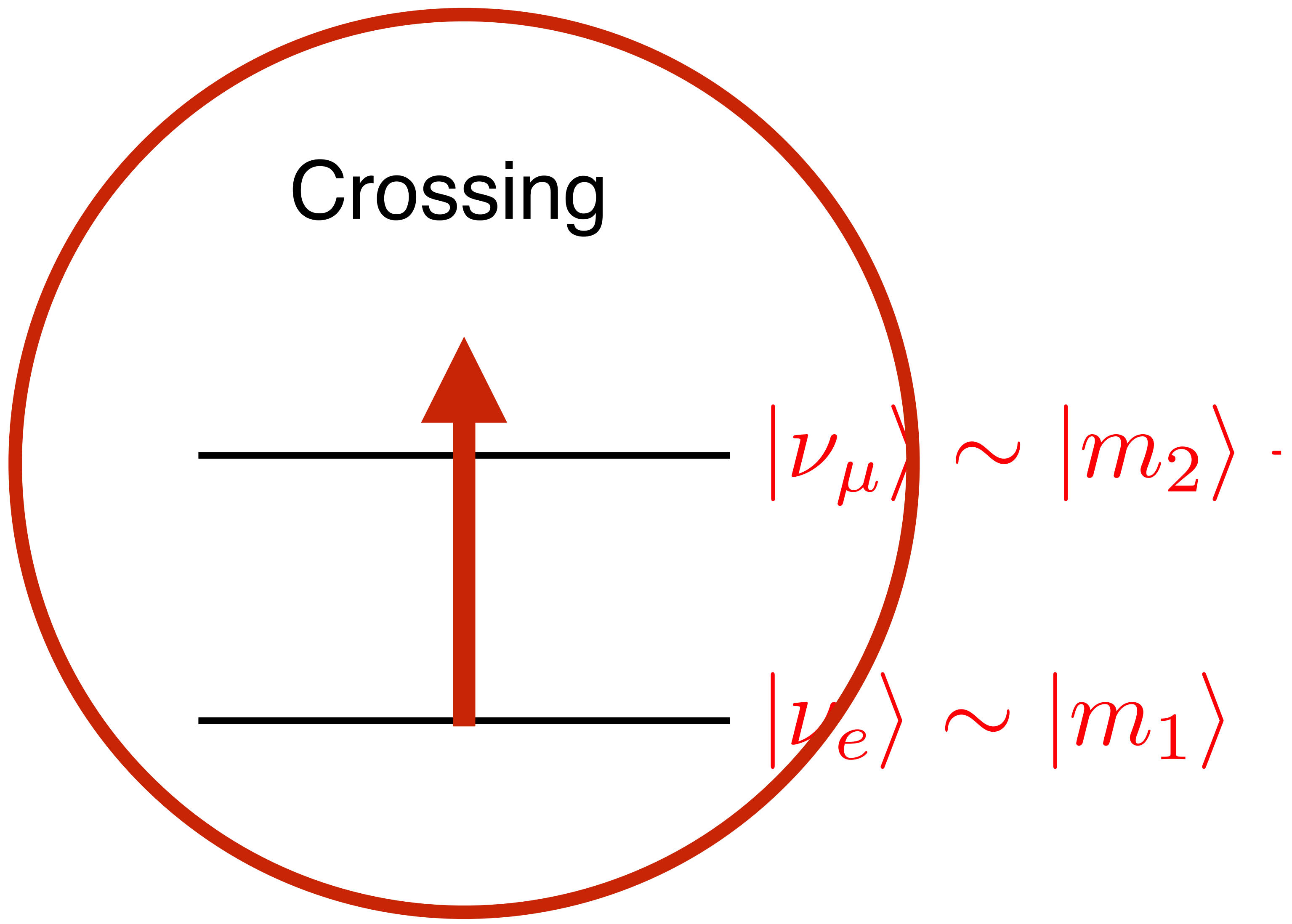

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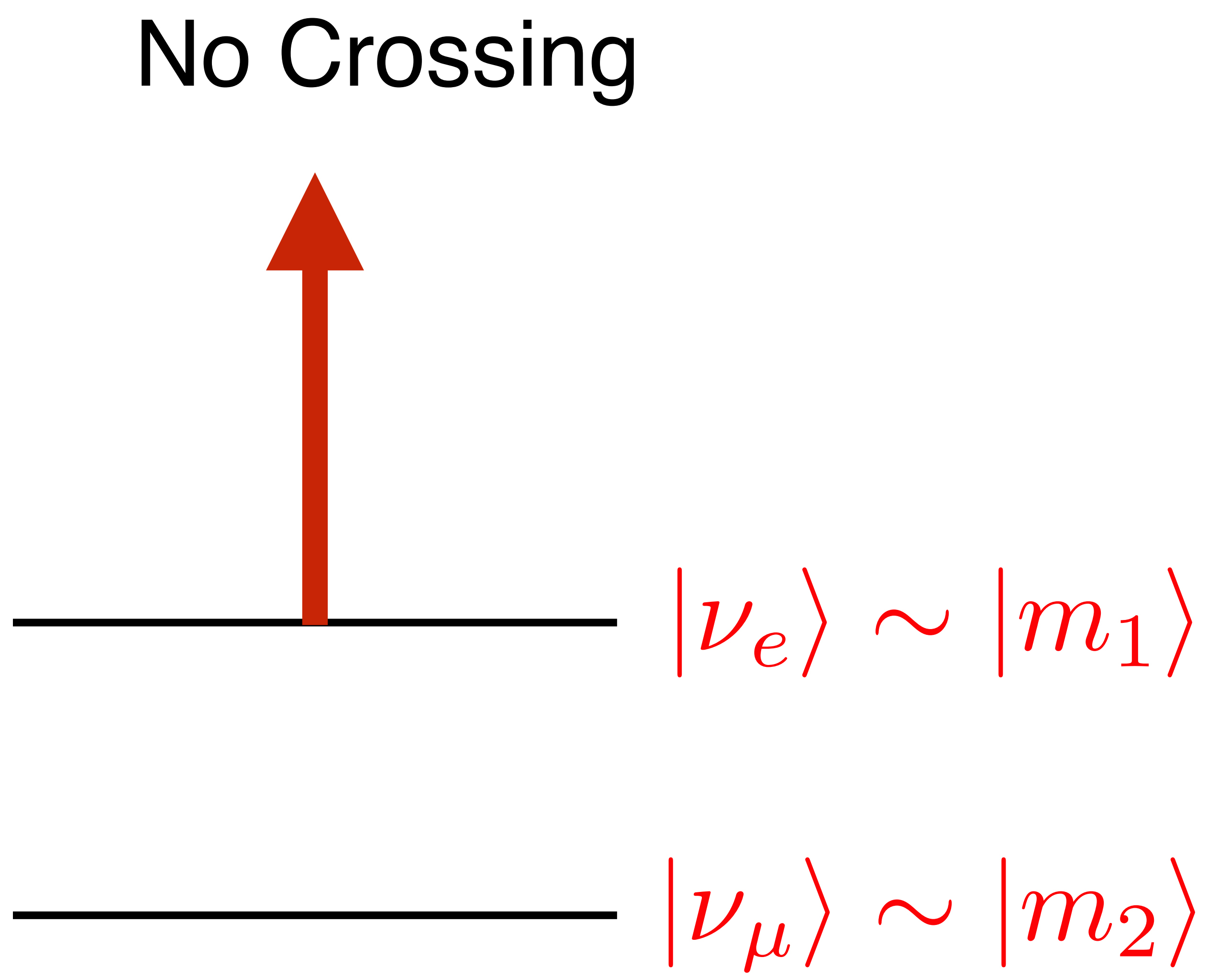

No Crossing

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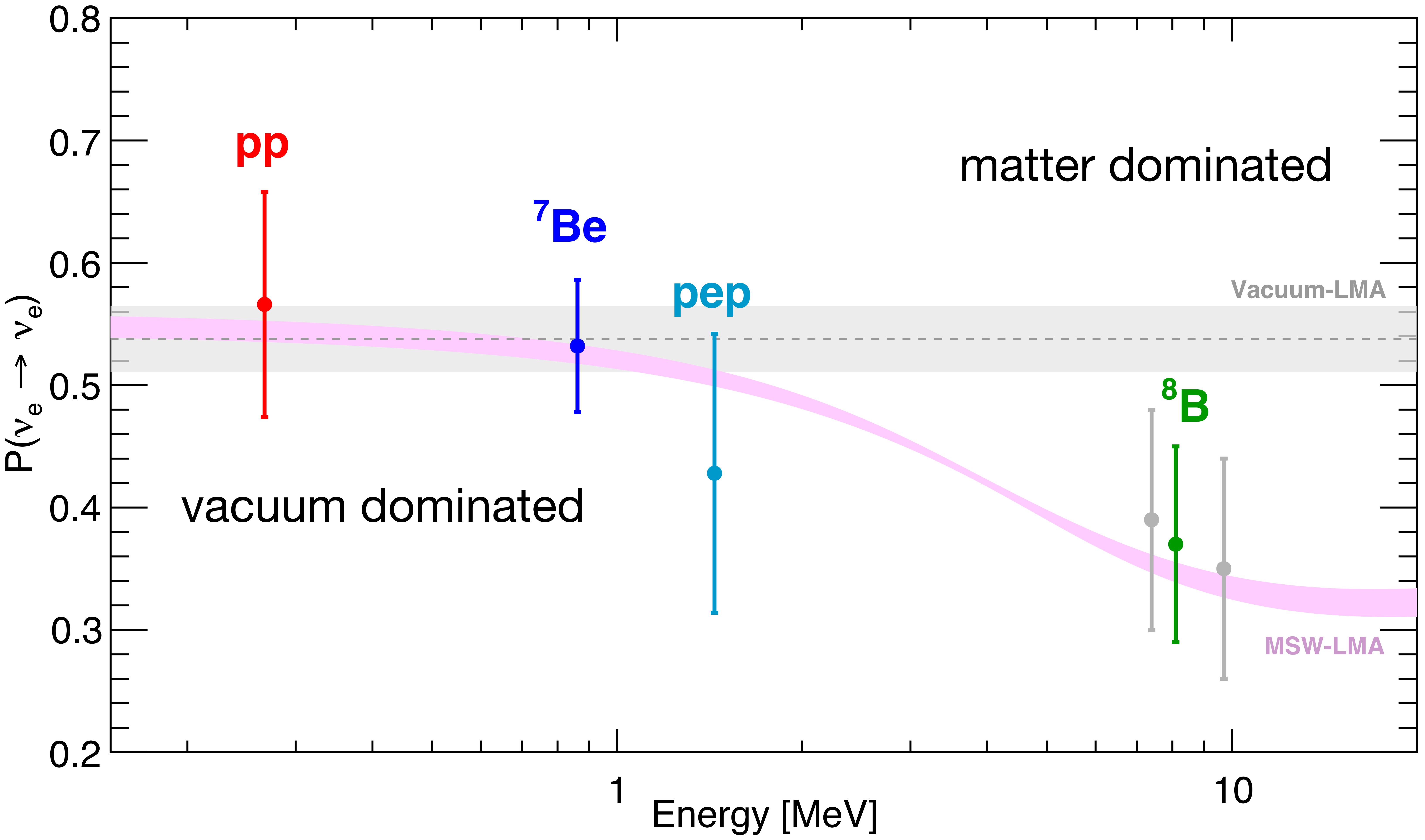
Borexino patiently mapped out the vacuum → matter oscillation transition



We may not be quite done with the Sun and solar neutrinos

Two basic assumptions in the SSM should be better tested — to high precision

- the equivalence of the sun’s electromagnetic (photon) and weak (neutrino) luminosities: only tested to $\sim 10\%$: leads room for anomalous cooling through new particle physics, solar variability, etc.

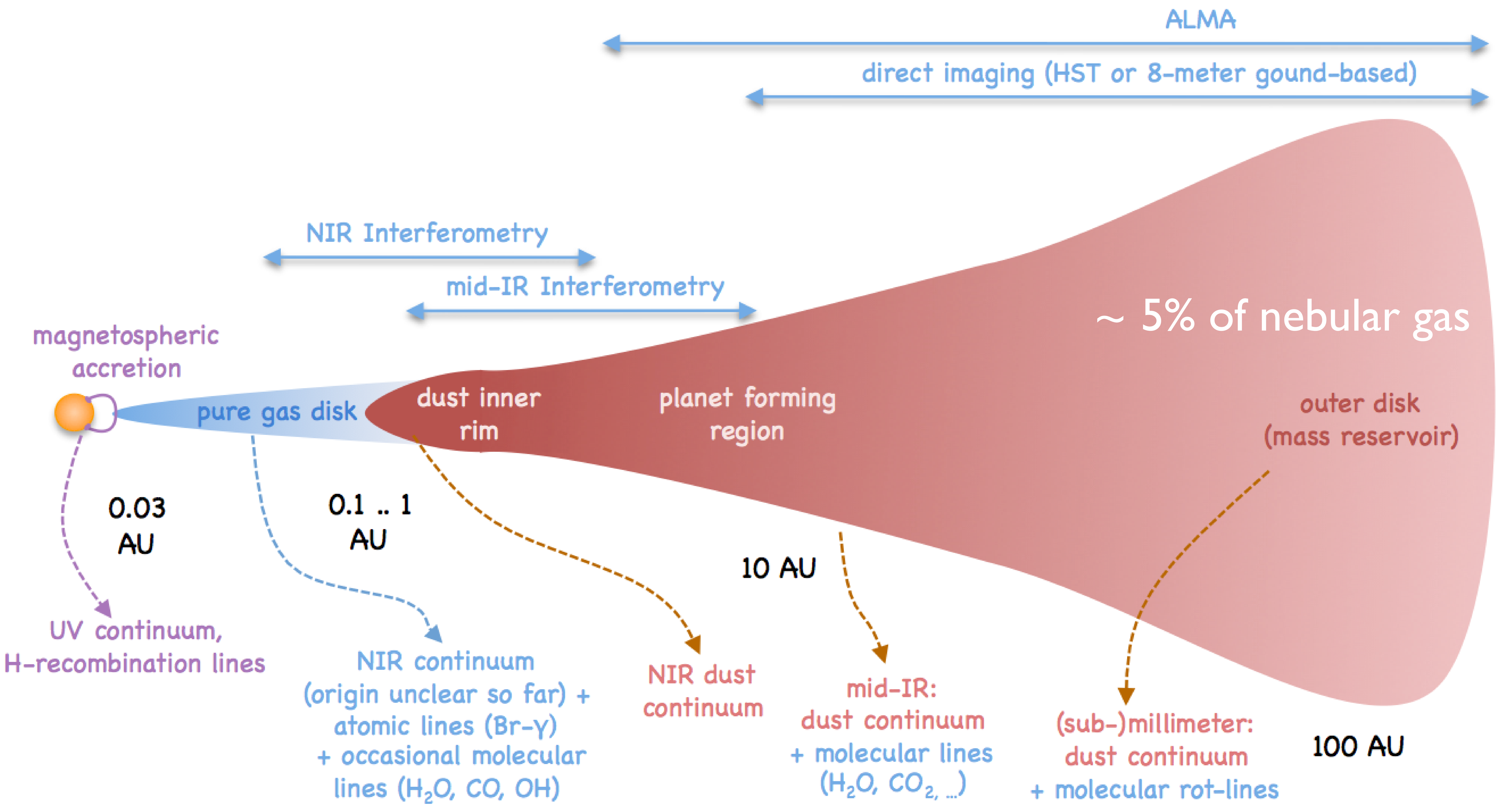
- the assumption that the Sun was homogeneous when it formed: critical to our understanding of our solar system, and to exoplanetary systems

“The solar abundance problem”: we can measure the early Sun’s metallicity in two ways - and in two places - but the measurements disagree

— in the photosphere (photo-absorption lines) → low from solar surface
— throughout the radiative zone (helioseismology) → high from core
— differ by 25%

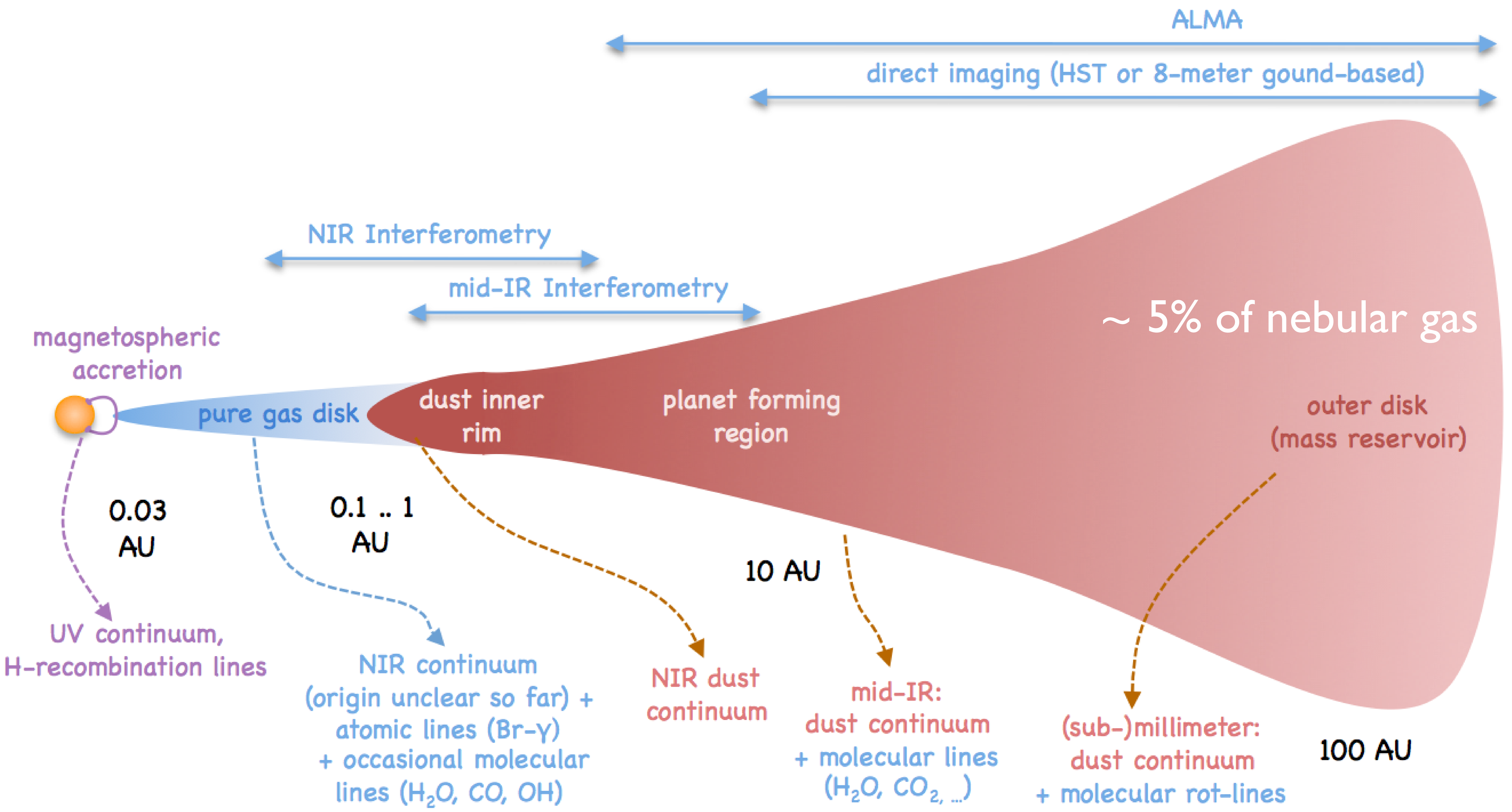
While a conventional resolution is quite possible, this difference has caused us to rethink whether we can treat the Sun in isolation

Was the Sun really homogeneous when it formed?



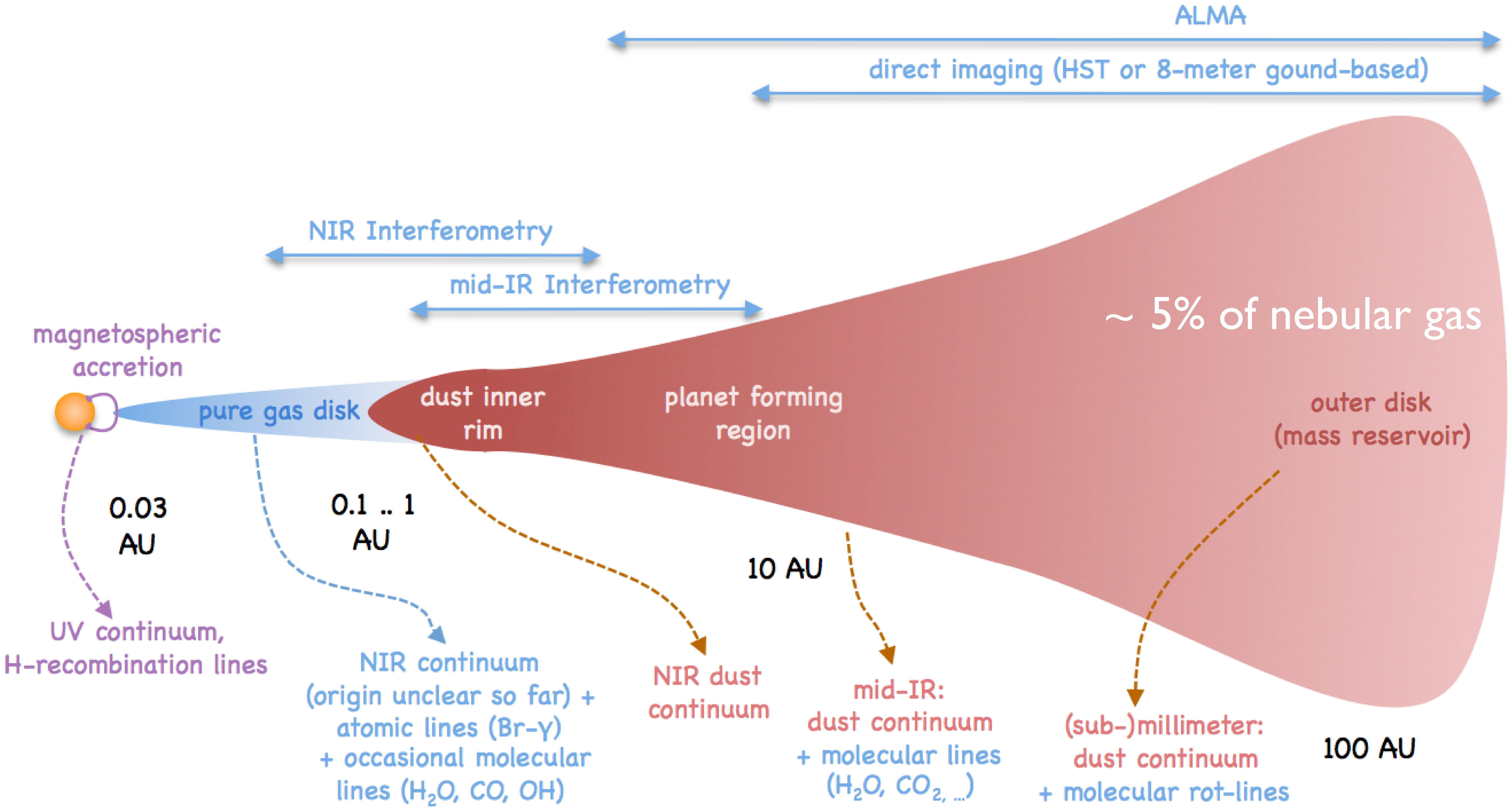
Dullemond and Monnier, ARA&A 2010

Was the Sun really homogeneous when it formed?



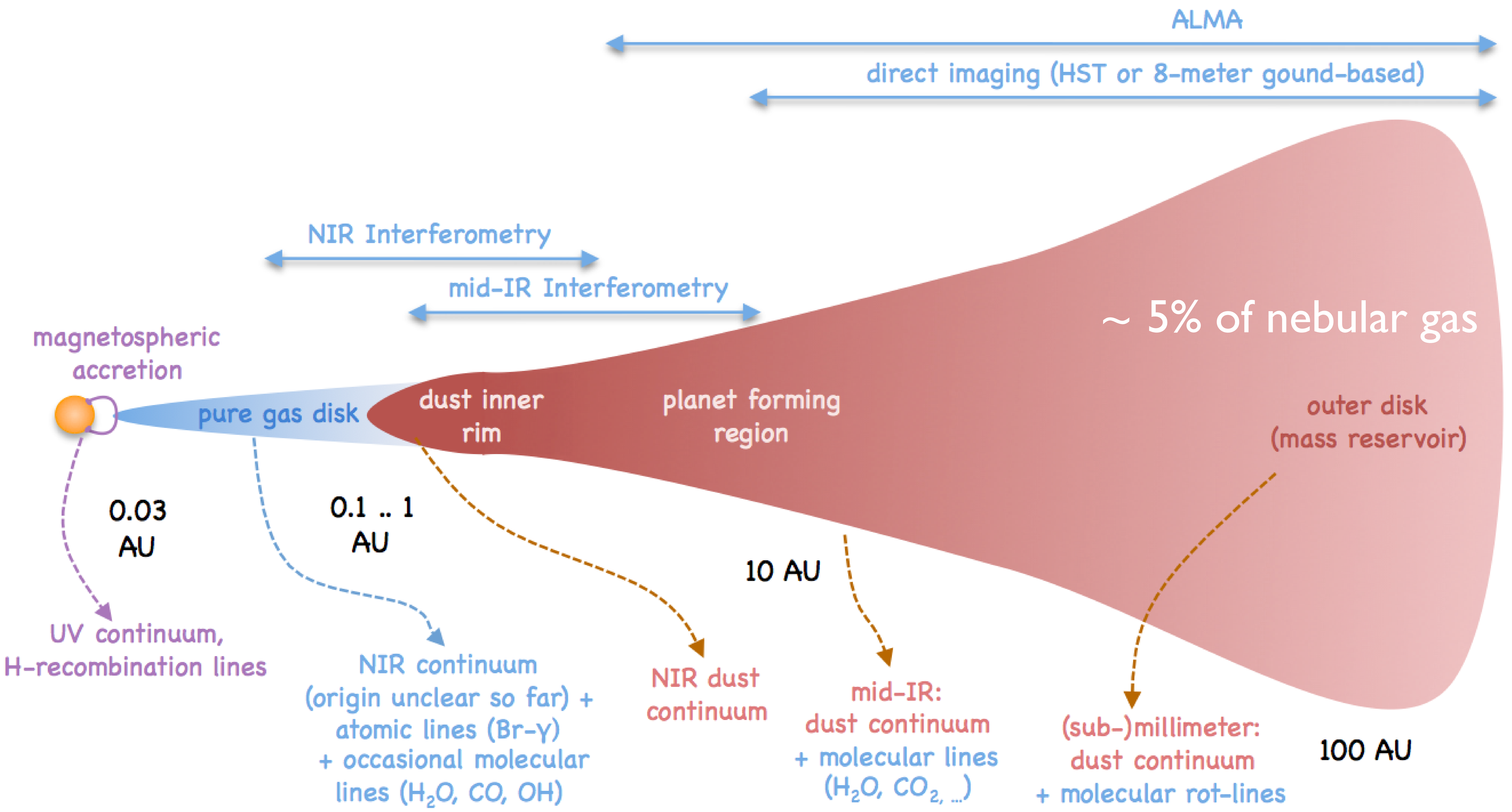
The argument in the affirmative comes from there passage of contracting Sun through the fully convective Hayashi phase

Was the Sun really homogeneous when it formed?



But when the Sun was 95% formed, the remaining 5% of the gas (which retains much of the Sun's original angular momentum) formed into a thin disk, with the planets forming in the disk's mid plane, sweeping out much of the dusty and ice that concentrated there

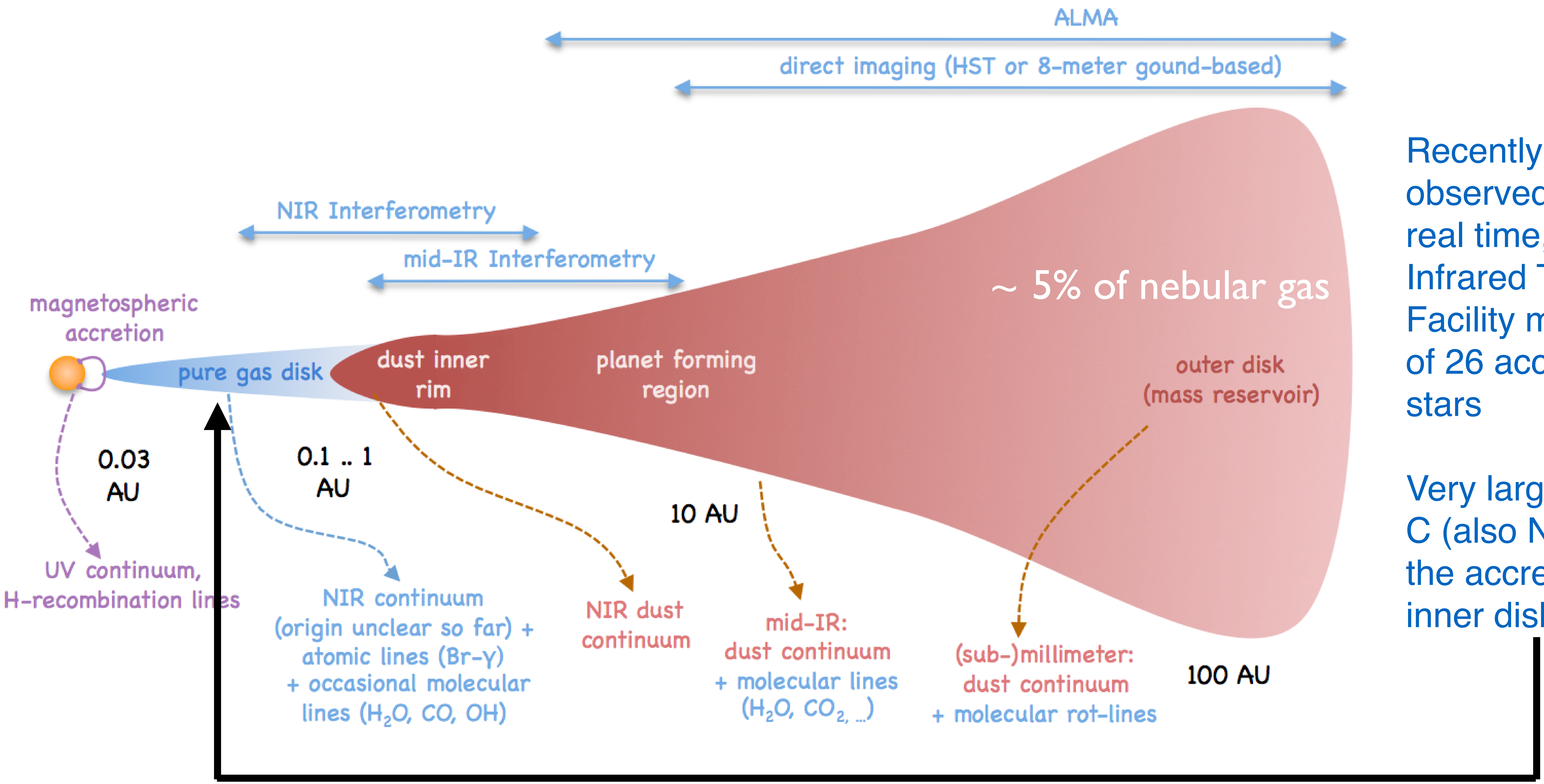
Was the Sun really homogeneous when it formed?



When we inventory the planets, we find that thy store an extra 50-90 earth masses of metals.

One concludes that the composition of the mass accreting onto the early Sun must have changed at that time, from metal rich to metal poor

Was the Sun really homogeneous when it formed?



Recently we have observed this process in real time, though Infrared Telescope Facility measurements of 26 accreting T Tauri stars

Very large depletions of C (also N, Si) found in the accreting gas of the inner disk

M. K. McClure, A&A 632 (2019) A32

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Multi-messenger Astrophysics

The effort to understand the Sun began long before we had evidence of new neutrino physics

A unique opportunity to study the best-known star to test whether we had a consistent model of hydrogen burning

Together with the Big Bang, the Sun provides perhaps our best example of multi-messenger astrophysics. Combines

— physical properties: the known age, mass, composition, and luminosity of the sun

— the neutrino fluxes: constraining the temperature of the core to 1%

— the heioseismology: maps the sound speed to sub-1% precision throughout most of the solar interior

— detailed input nuclear and atomic physics: laboratory measurements of nuclear cross sections, lab and QM determinations of opacities

There was no guarantee we would learn new fundamental physics by studying the Sun

Yet it was also a good bet that this might happen: Astrophysics provides extreme environments that cannot be duplicated on earth

The multi-messenger astrophysics strategy is to transform such environments into useful physics laboratories by constraining their properties through as many complementary measurements as possible

The Sun and the Big Bang (which gave us the baryon/photon ratio) are the best known examples of multi-messenger — but new ones are now emerging

* * *

Neutrino astrophysics: Supernovae and kilonovae

- In the Sun, neutrinos are a wonderful probe, but not a major player in solar dynamics or thermodynamics: they carry off about 1% of the energy

- This contrasts with the explosive environments generated by core-collapse supernovae and neutron star mergers and their kilonovae aftermaths
  - neutrinos control the transport of energy, lepton number, and entropy, as well p/n chemistry of the ejecta that is so crucial to nucleosynthesis

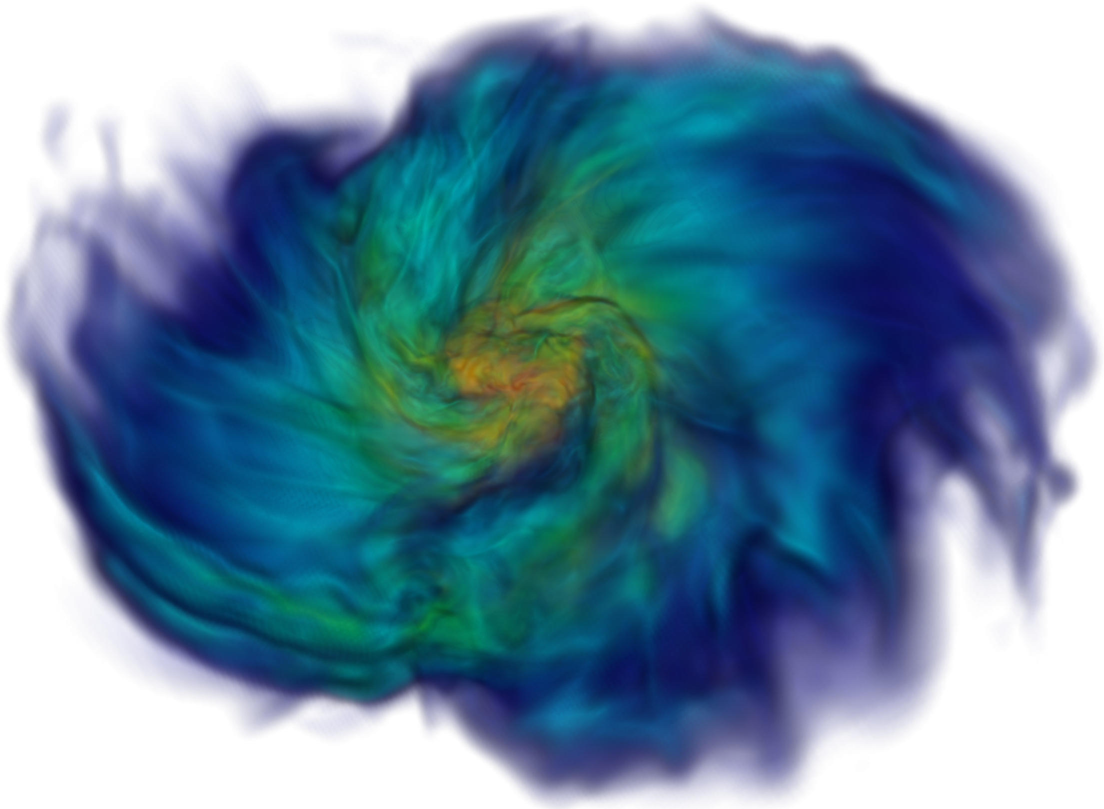
- With GW170817, such events became the new focus of multi-messenger astrophysics
  - gravitational waves tracking the early in-spiral
  - a variety of UV, optical, and IR measurements of the expanding, radioactively-powered kilonovae
  - a gamma ray burst
  - deductions about the type and quantity of heavy-element nucleosynthesis, due to the impact of the new metals on the light curve

- Opportunities include
  - the nuclear EoS under conditions not achievable in terrestrial labs (densities up to 4-6 ρ_0, temperatures ranging to 10^{11} K)
  - the impact of new particles on their evolution and cooling, or the impact of DM particle capture on the astrophysical evolution
  - neutrino physics not easily probed on earth

- Neutrinos may have roles as messengers, e.g.,
  - SuperK new phase running with Gd is motivated in part by the relic supernova neutrinos, whose detection would place a constraint on the entire cosmological history of neutrino emission in collapsing massive stars
  - if the event detected is galactic or near-galactic

- But for such events at cosmological distances, neutrinos are part of the microphysics the we must input to really understand the new astrophysical "laboratories" we now have available

Neutrino basics of SNe and NS mergers

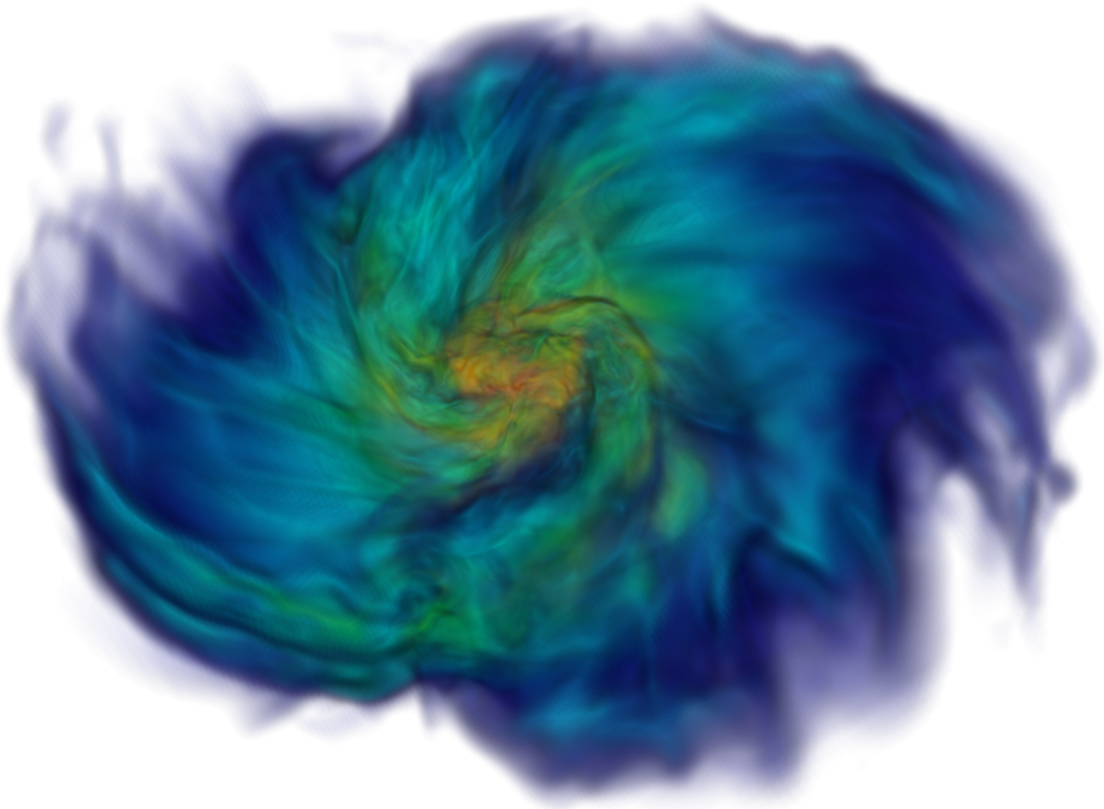


In other words,

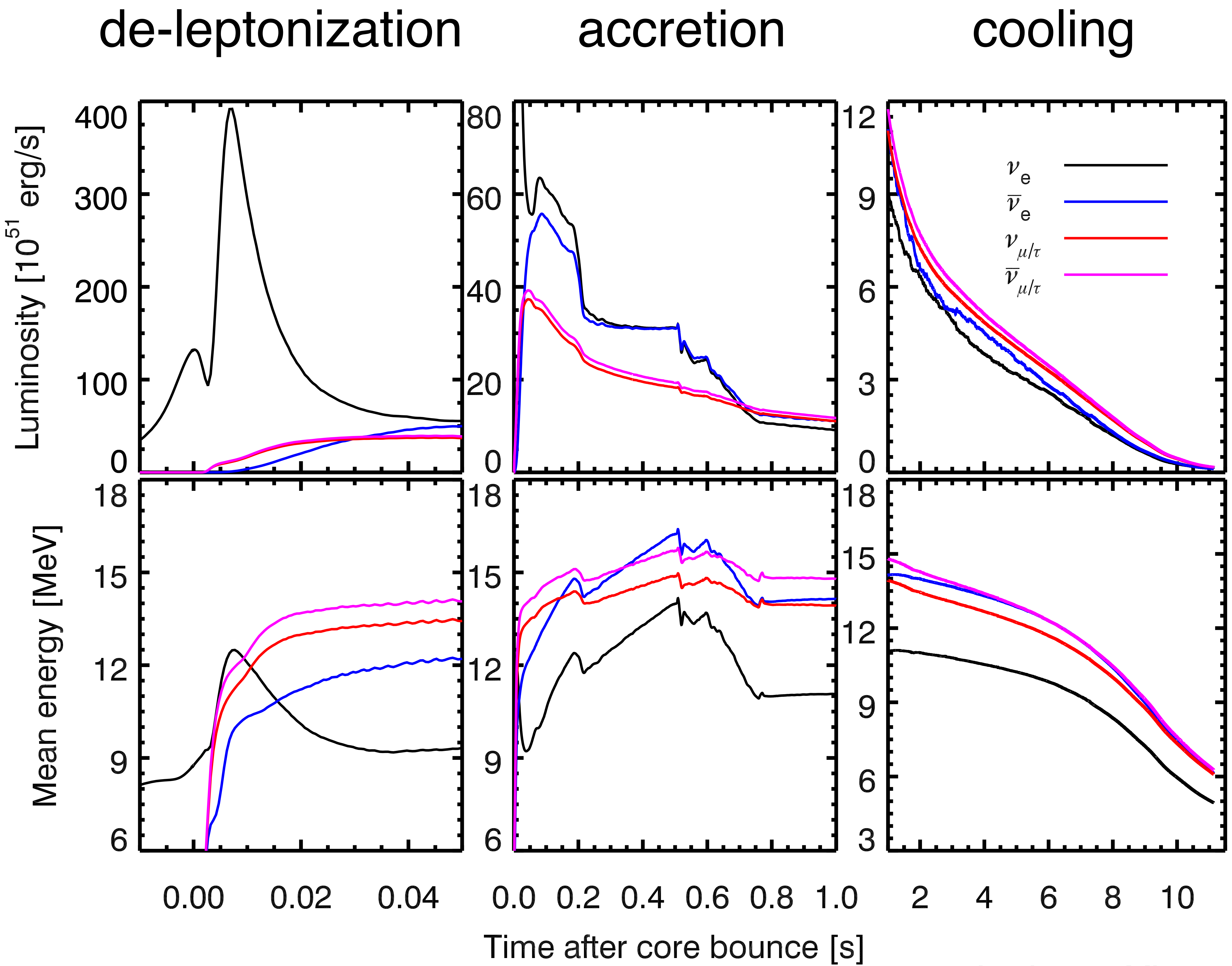
- One would like to find opportunities to do “clean” fundamental physics with the detectable neutrinos from nearby (galactic) SN neutrinos

- To get more value out of multi-messenger physics of gravitational waves and mergers/SNe from cosmological distances, we will need to understand the neutrino physics that controls the transport and nuclear chemistry of these explosions

Neutrino basics of SNe and NS mergers

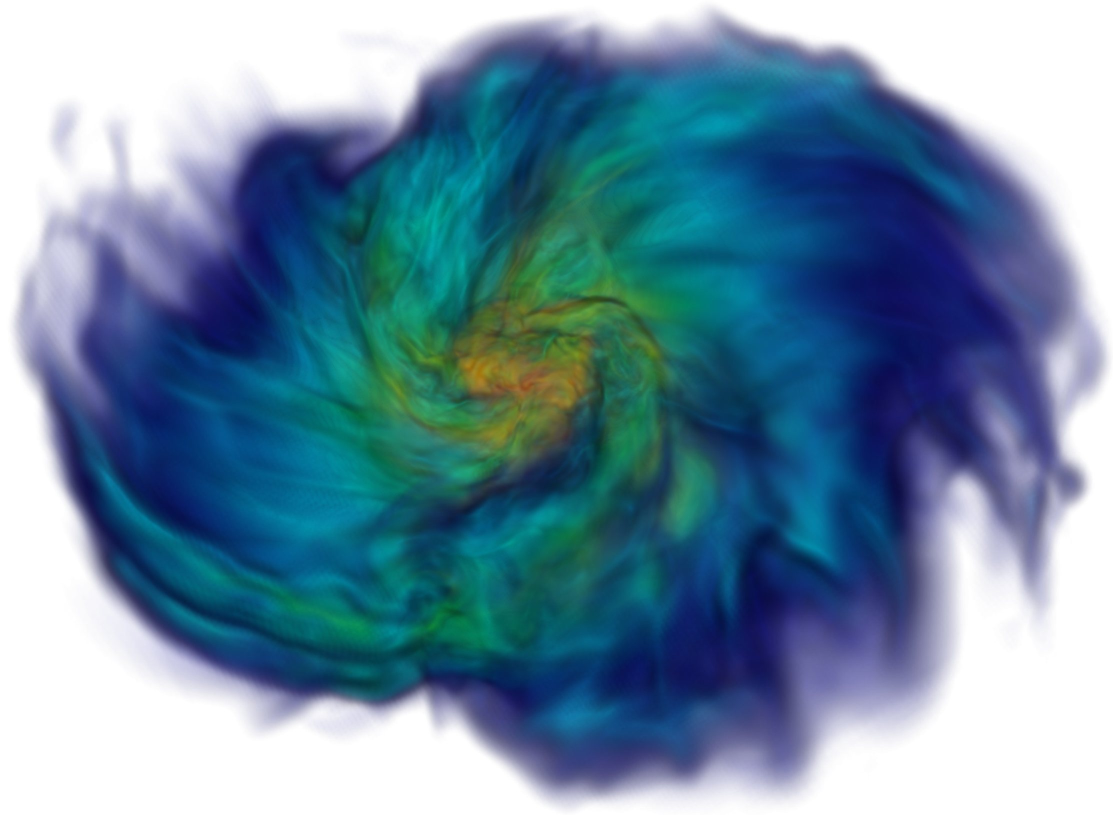


SN Neutrinos

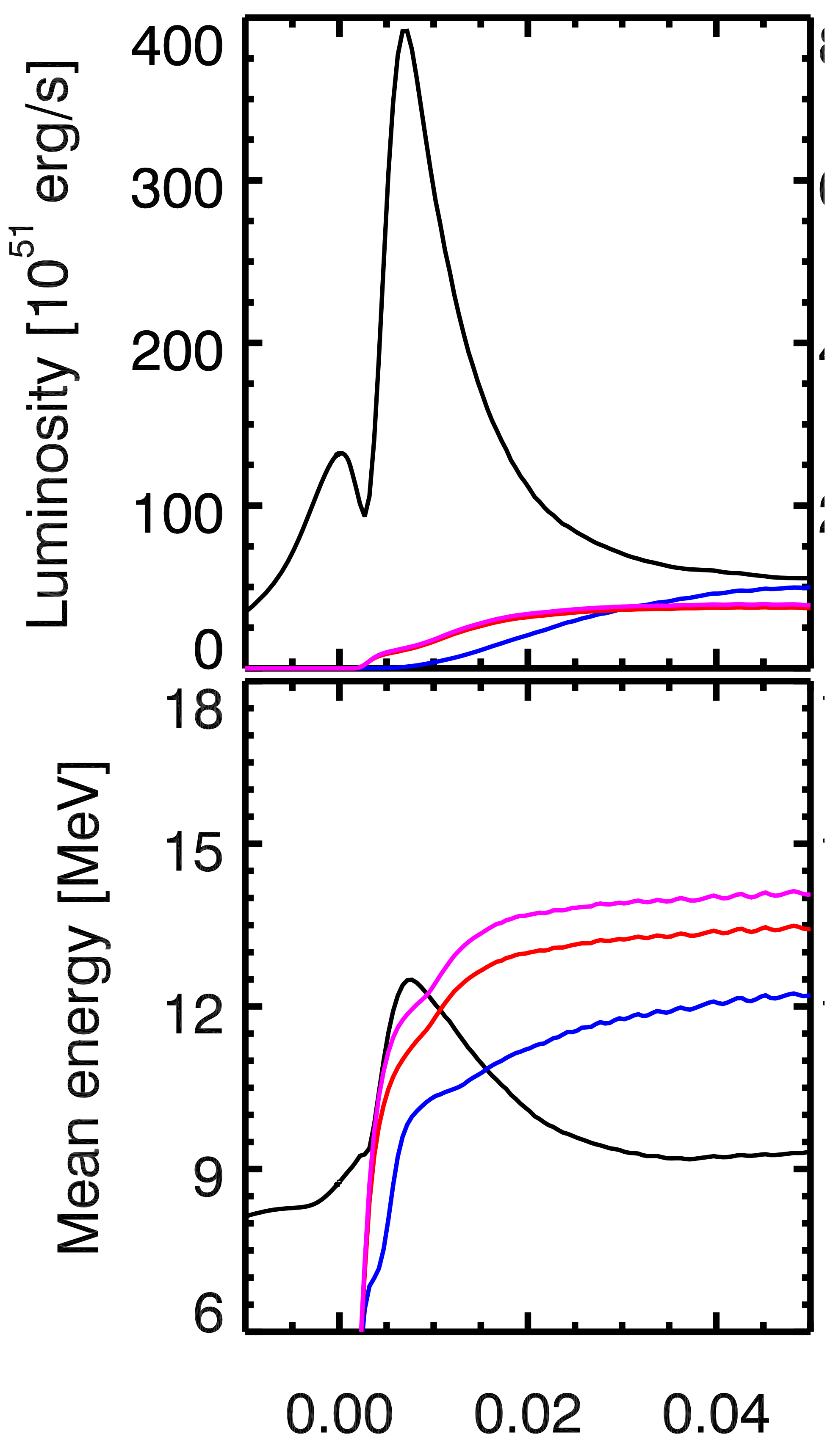


Janka arXiv:1702.08713

Neutrino basics of SNe and NS mergers

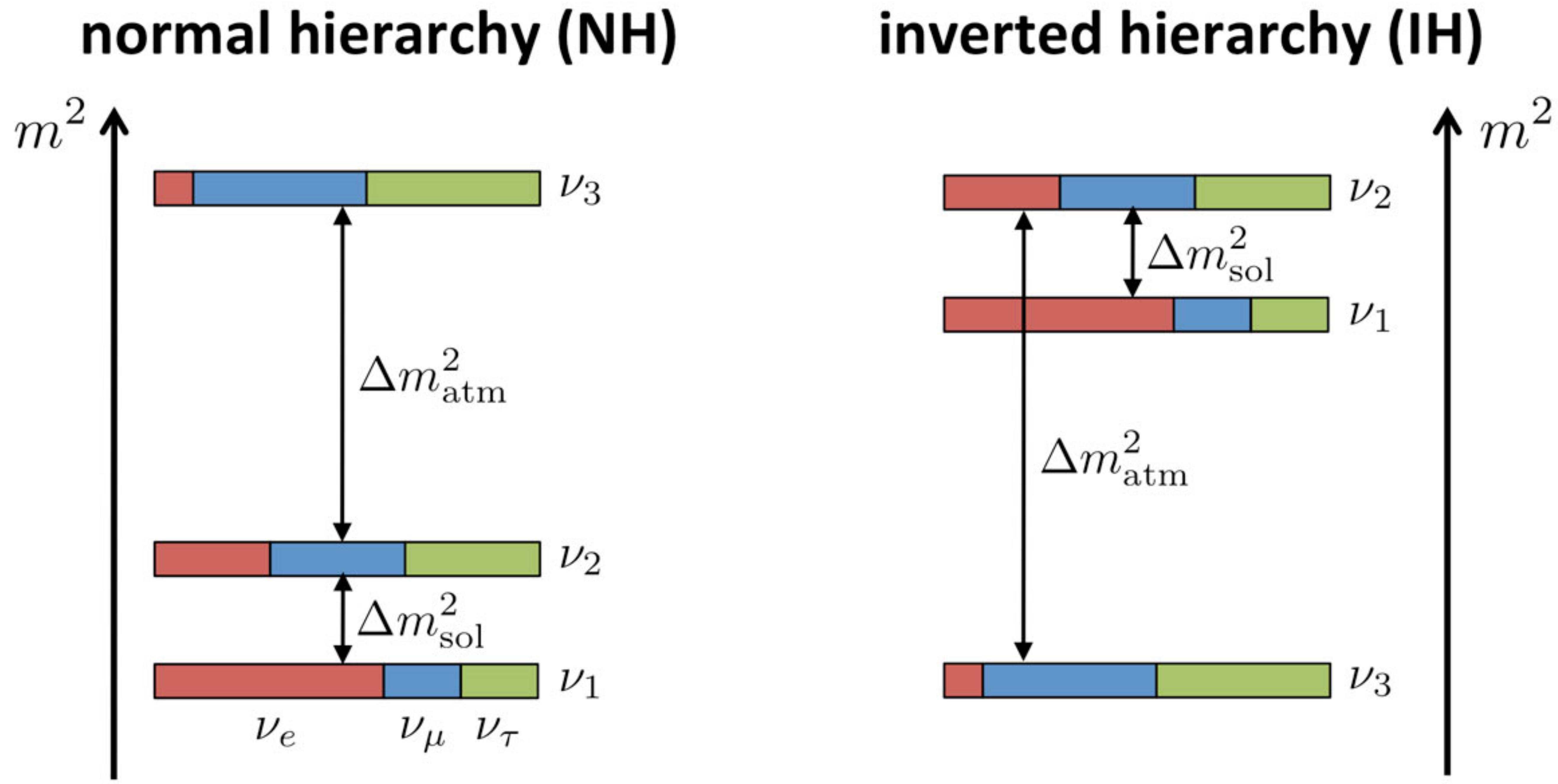


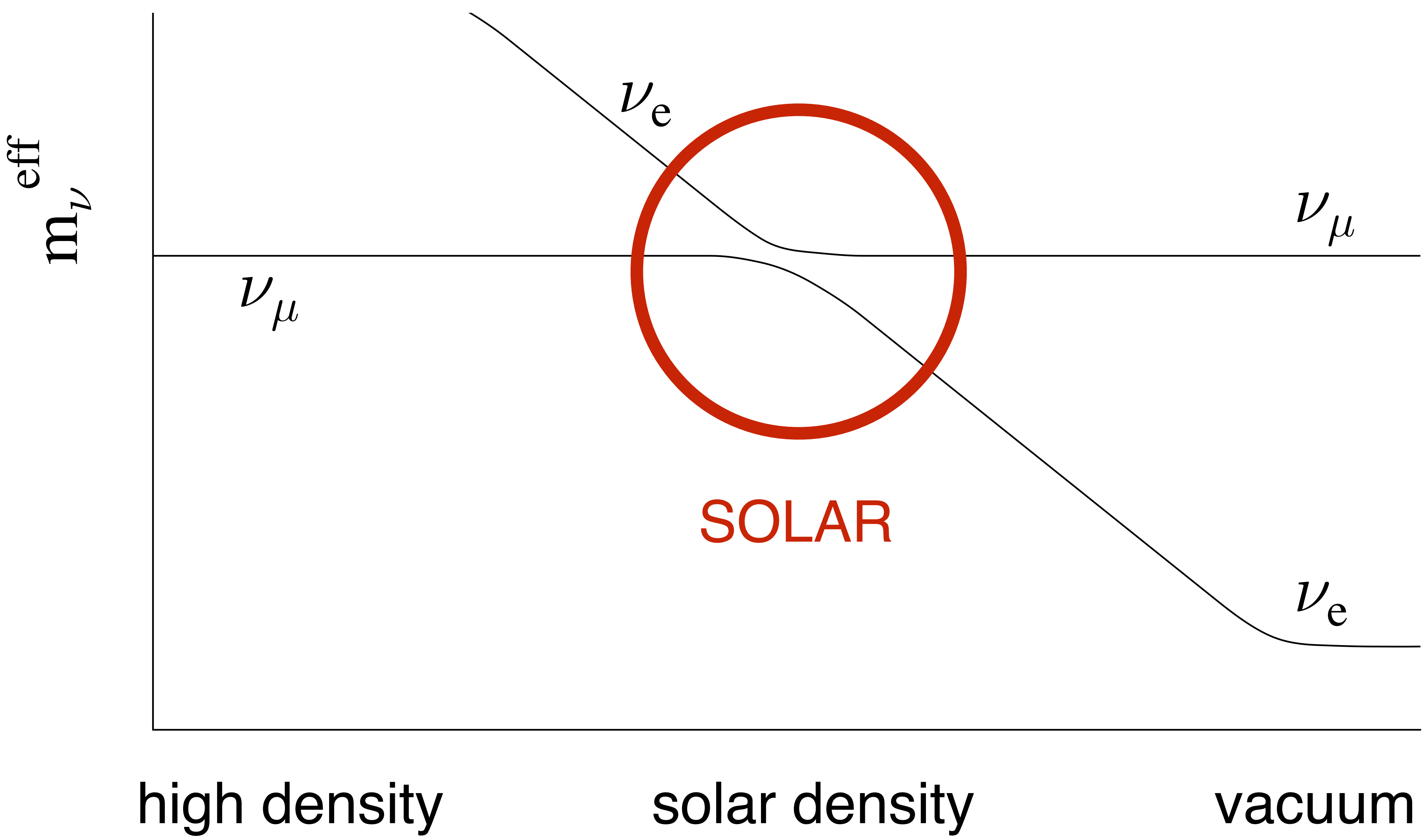
de-leptonization



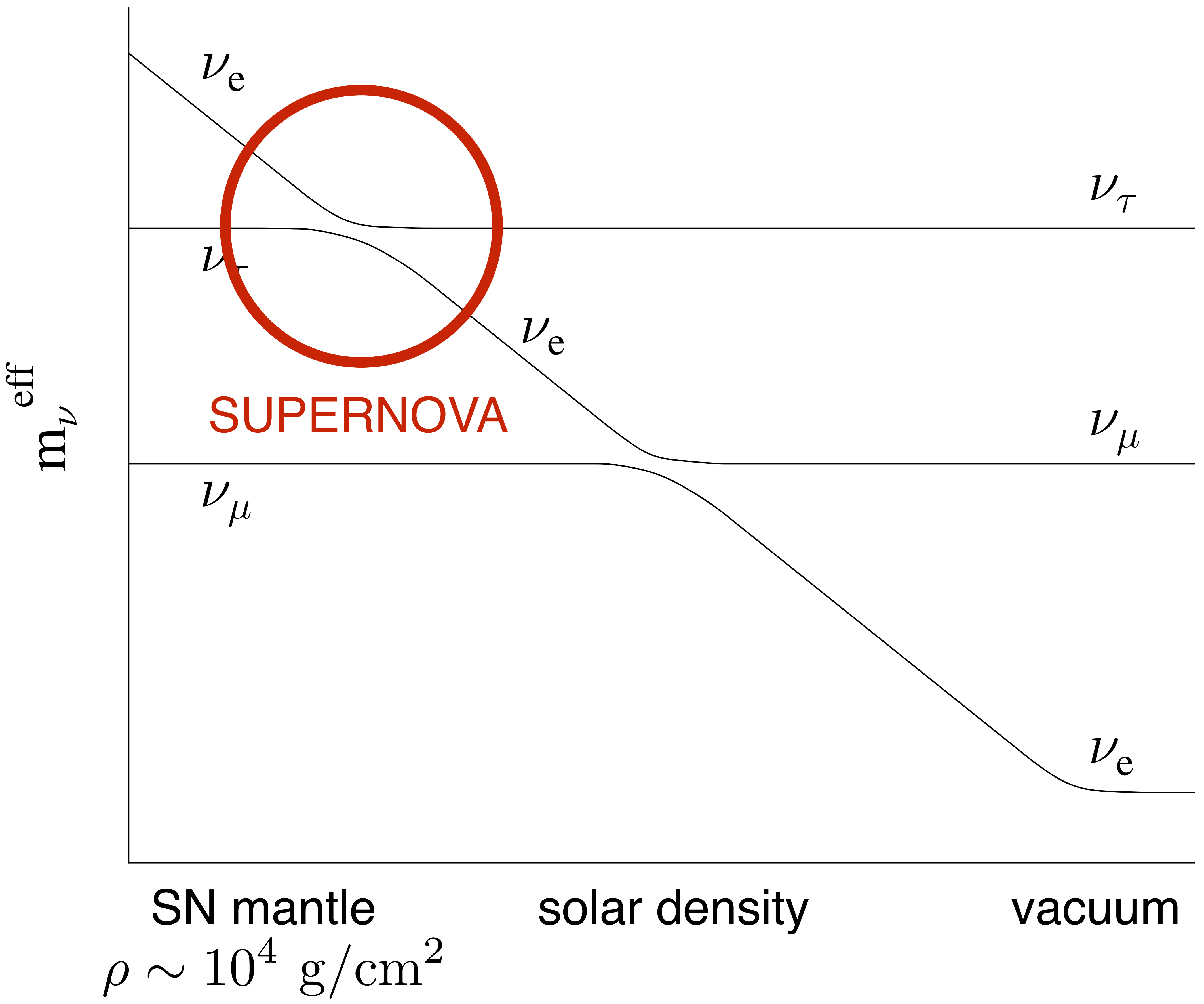
- high flux, modest fluency (1% of the neutrino emission)
- mean energy of about 12 MeV — readily detectable
- flavor purity quite good
- most important, created outside the SN's dynamical core — what we know about neutrinos today is adequate to model this source

In their role as messengers from nearby (galactic) events, perhaps the outstanding opportunity is the hierarchy — replicating what we did with solar neutrinos

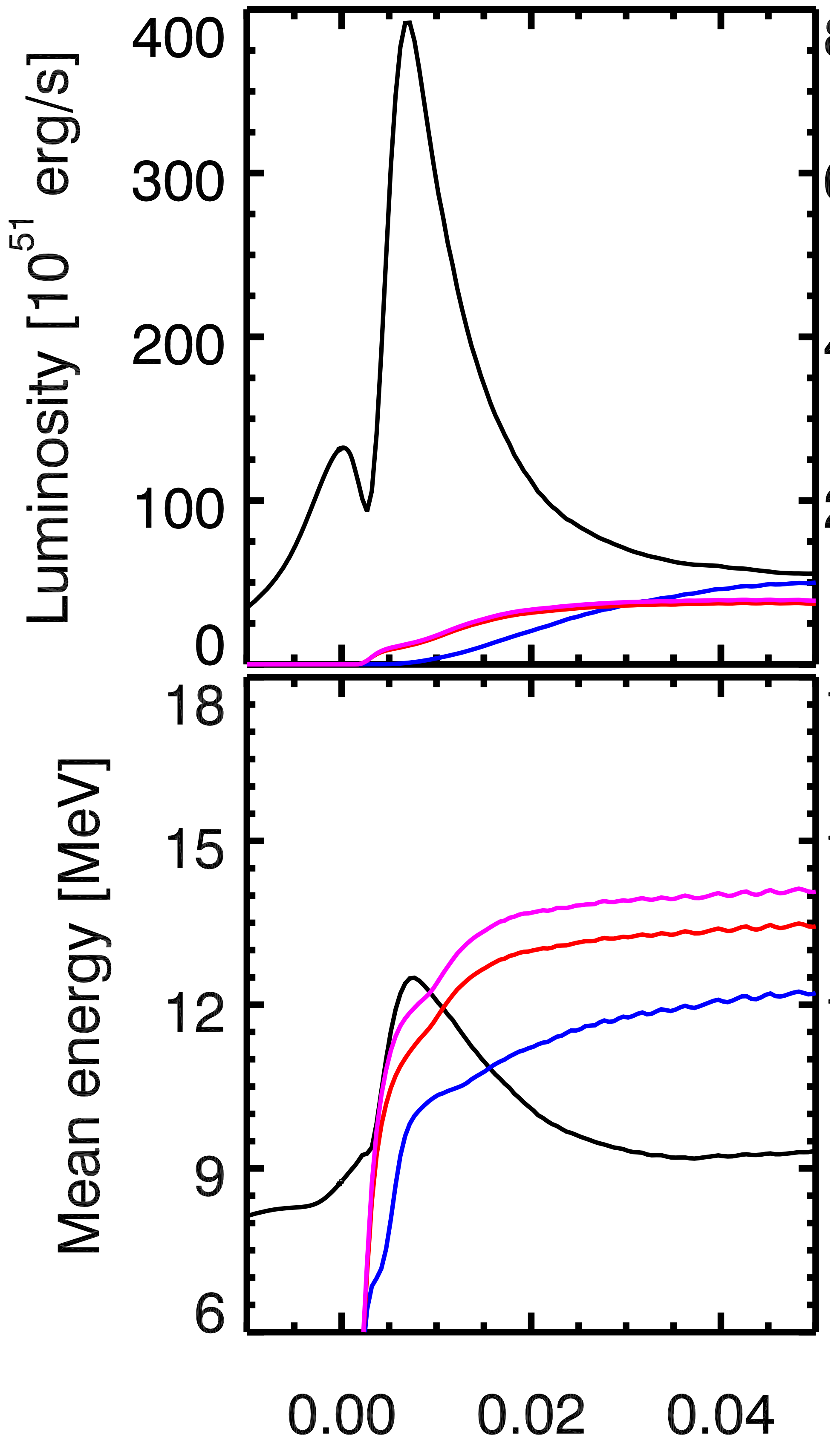




$\rho \lesssim 10^2 \ \text{g/cm}^3$



if the hierarchy is normal

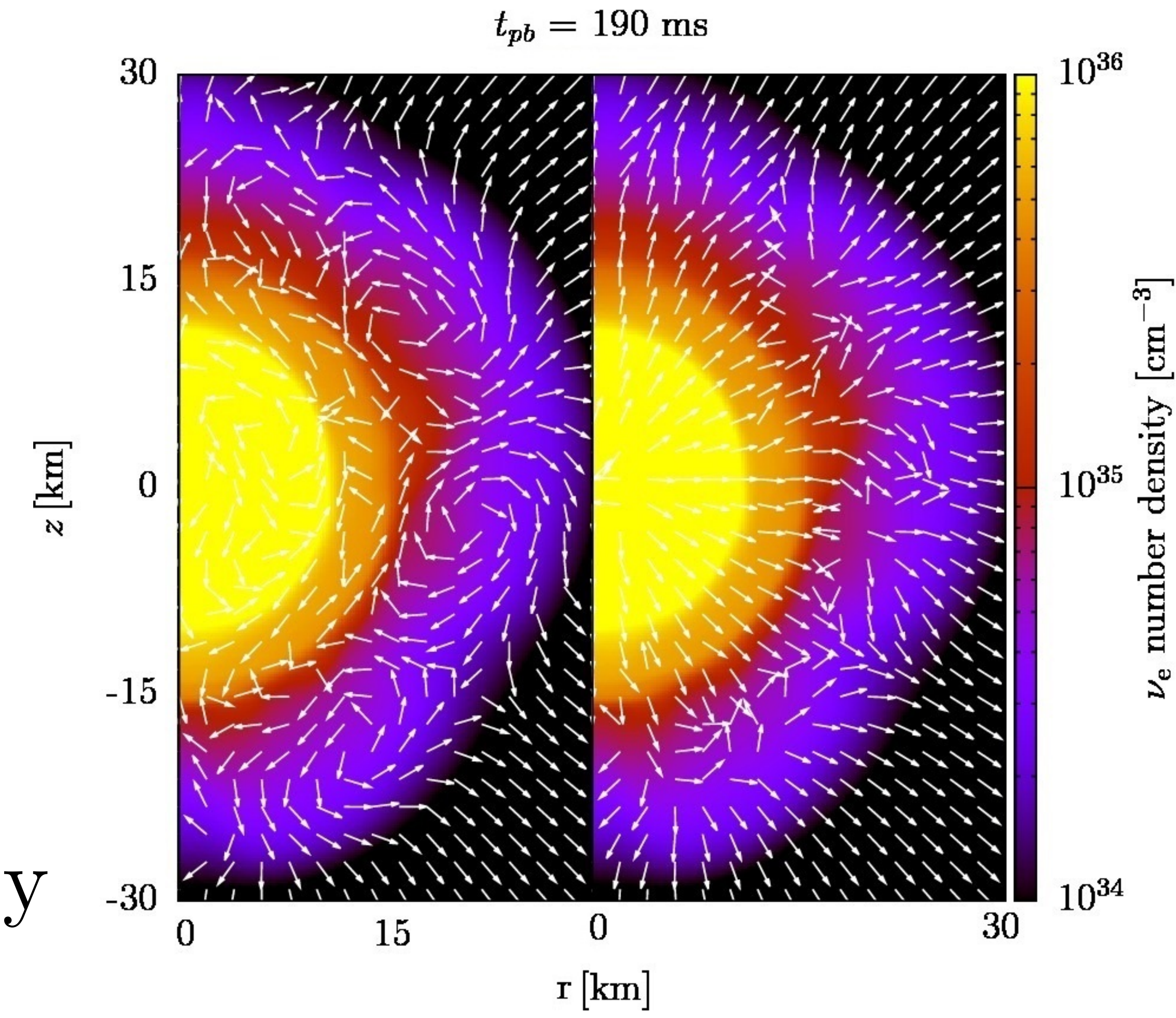


- The deleptonization neutrinos are created under conditions we believe we understand
- Generated during the infall phase, as the star begins to convert protons to neutrons
- They are trapped in the outer iron core by the high opacity, $\propto \mathrm{N}^2$, due to coherent scattering
- After core bounce, the stock wave stalls in the outer iron core, then is later revived by neutrino pressure
- The revived shock wave moves outwards, melting the outer iron core to nucleons, reducing the opacity by 1/N, releasing these
- These neutrinos are a good candidate for a hierarchy test, in a detector like DUNE that can see $\nu_e s$ in both NC and CC channels

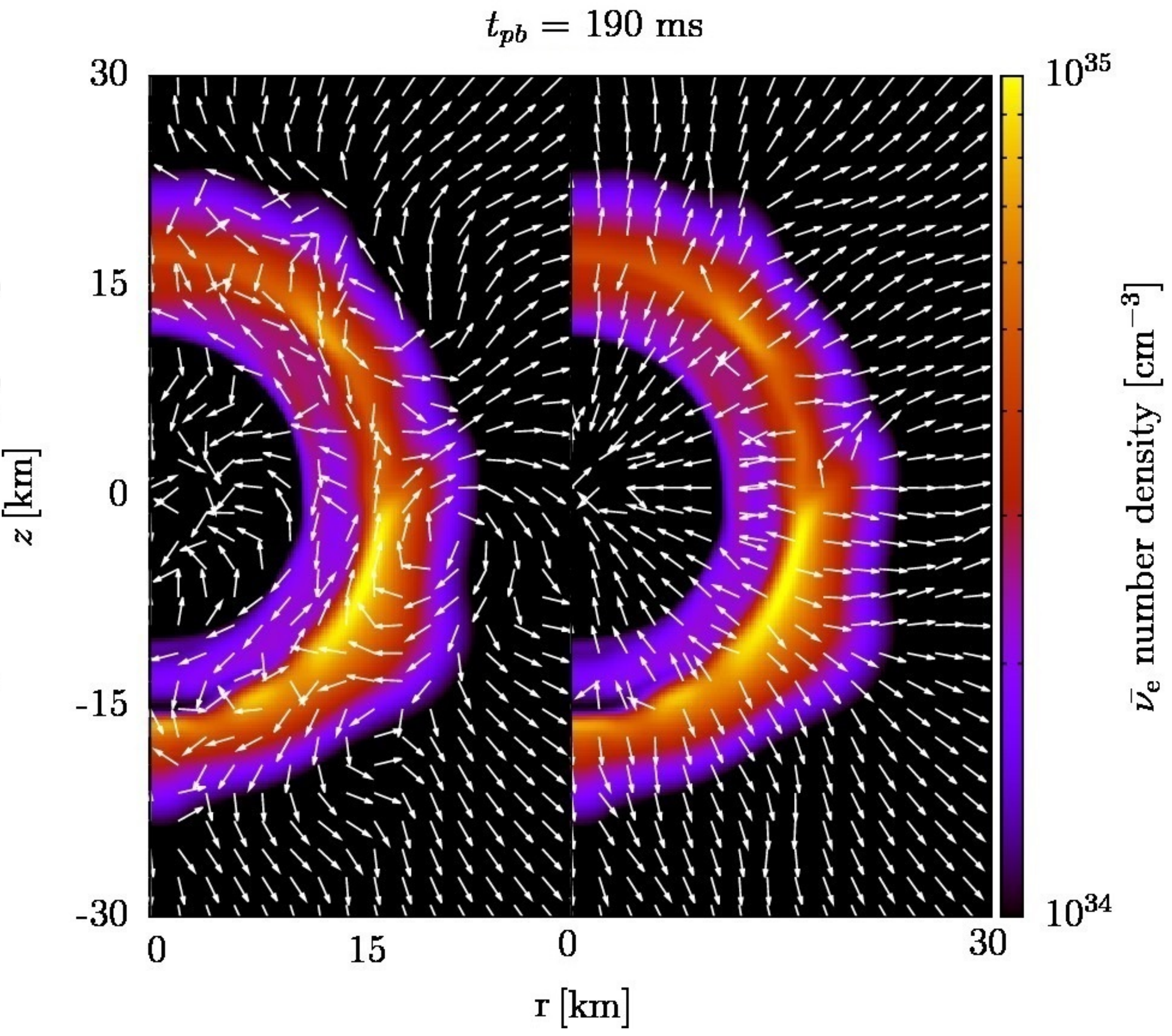
In contrast our understanding of the bulk of SN and merger neutrinos, that originate from deep within the dynamical cores of these explosioons, is more limited.

The MSW potential is dominated by the interactions of the neutrino with other trapped neutrinos : the oscillation phenomena are nonlinear, many-body, quantum entangled and fast, driven by lepton number asymmetries — we currently have no methods up to this task

Duan, Fuller, Qian,
ARNPS 60 (2010) 569



ν density



$\bar{\nu}$ density

Azari et al,
arXiv:1910.06176

This physics could affect many aspects of the dynamics - transport, energy deposition, nucleosynthesis: The challenge is to address this physics, just as Iben, Sears, and Bahcall were challenged to address the Sun

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

NSF

Closing Remarks

Frank has tenaciously pursued the neutrino throughout his long career

The neutrino has been equally tenacious in hanging on to its secrets

But the neutrino had the jump on Frank: that he is not the only nonagenarian here

The neutrino beat him to that birthday by two years!

Happy birthday, Frank!