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Neutrinos in astrophysics and cosmology

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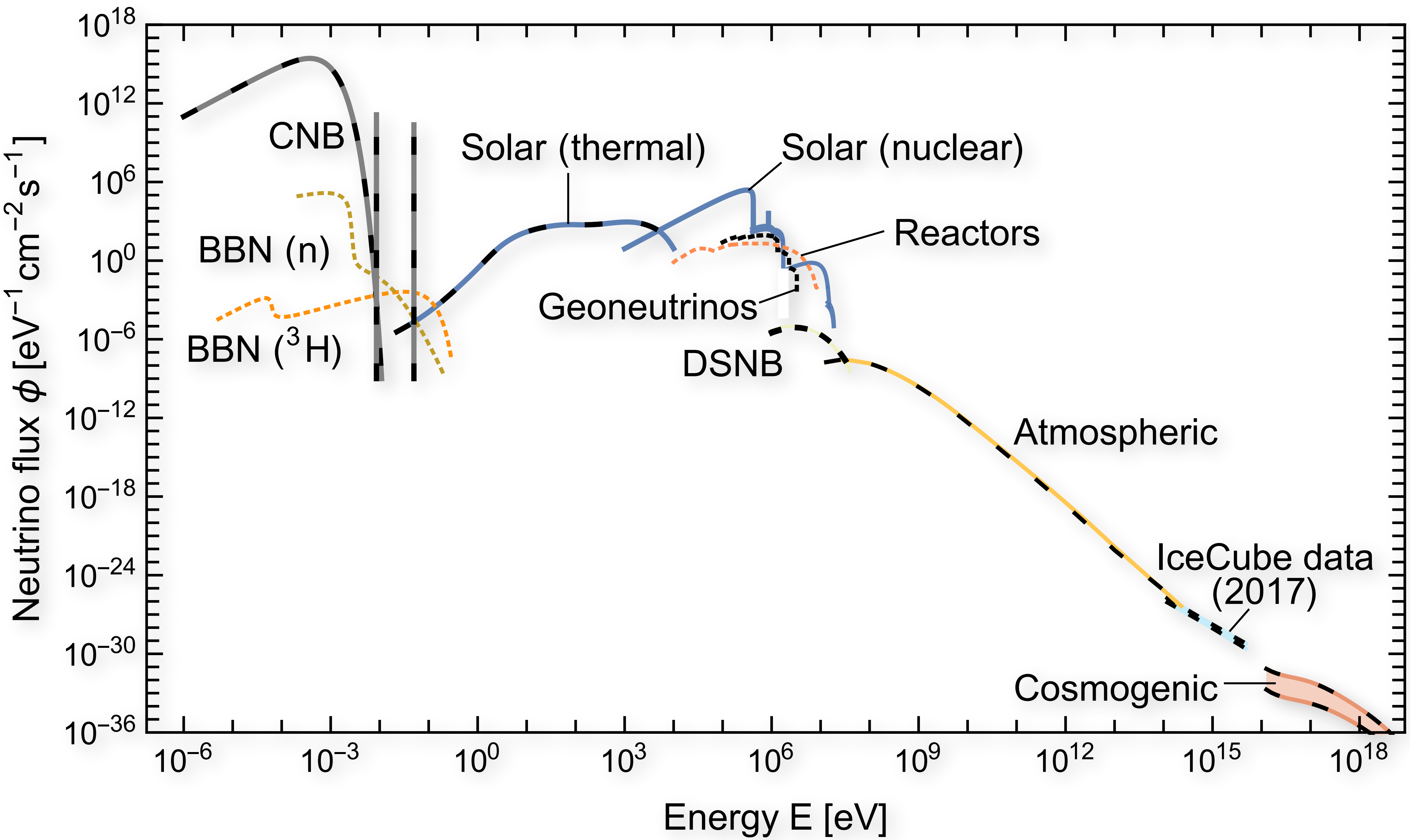
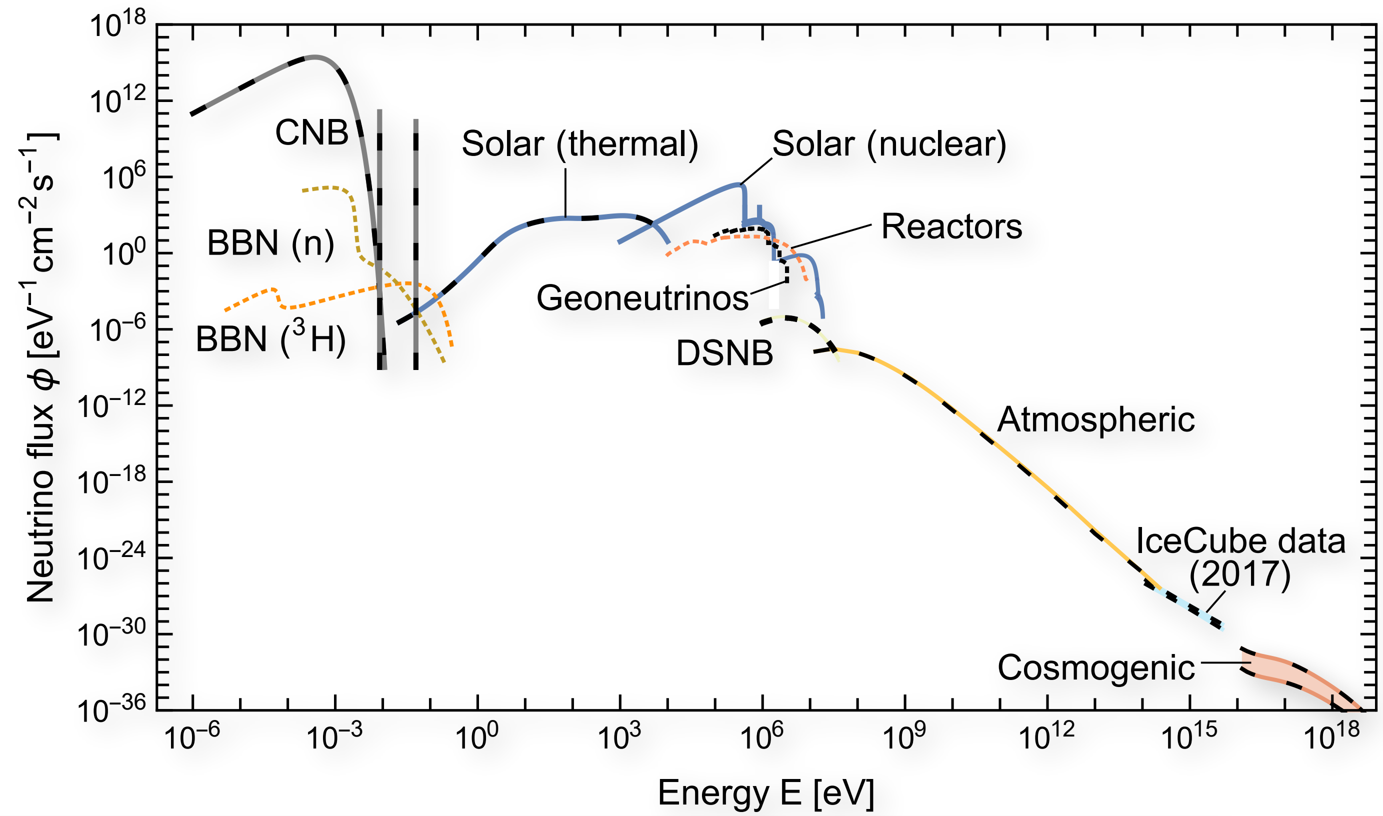
Our universe is filled with neutrinos



- "The Grand Unified Neutrino Spectrum at Earth" (update from Vitagliano et al, arXiv:1910.11878, original version by Cribier, Spiro, & Vignaud, 1995)

Let's look at the components

- Reactor, atmospheric, geoneutrinos -> locally produced
- Thermal neutrinos from stellar interiors:
    - energies in the several keV range (for the Sun), not directly detected,
    - but are clearly, if indirectly, observed in advanced stellar evolution stages



Woosley, Janka, Nature Physics V. 1, p. 147 (2005)

Table 1 Evolution of a 15-solar-mass star.

Stage	Timescale	Fuel or product	Ash or product	Temperature (10^9 K)	Density (gm cm^{-3})	Luminosity (solar units)	Neutrino losses (solar units)
Hydrogen	11 Myr	H	He	0.035	5.8	28,000	1,800
Helium	2.0 Myr	He	C, O	0.18	1,390	44,000	1,900
Carbon	2000 yr	C	Ne, Mg	0.81	2.8×10^5	72,000	3.7×10^5
Neon	0.7 yr	Ne	O, Mg	1.6	1.2×10^7	75,000	1.4×10^8
Oxygen	2.6 yr	O, Mg	Si, S, Ar, Ca	1.9	8.8×10^6	75,000	9.1×10^8
Silicon	18 d	Si, S, Ar, Ca	Fe, Ni, Cr, Ti, . . .	3.3	4.8×10^7	75,000	1.3×10^{11}
Iron core collapse*	$\sim$1 s	Fe, Ni, Cr, Ti, . . .	Neutron star	$>$7.1	$>7.3\times10^9$	75,000	$>3.6\times10^{15}$

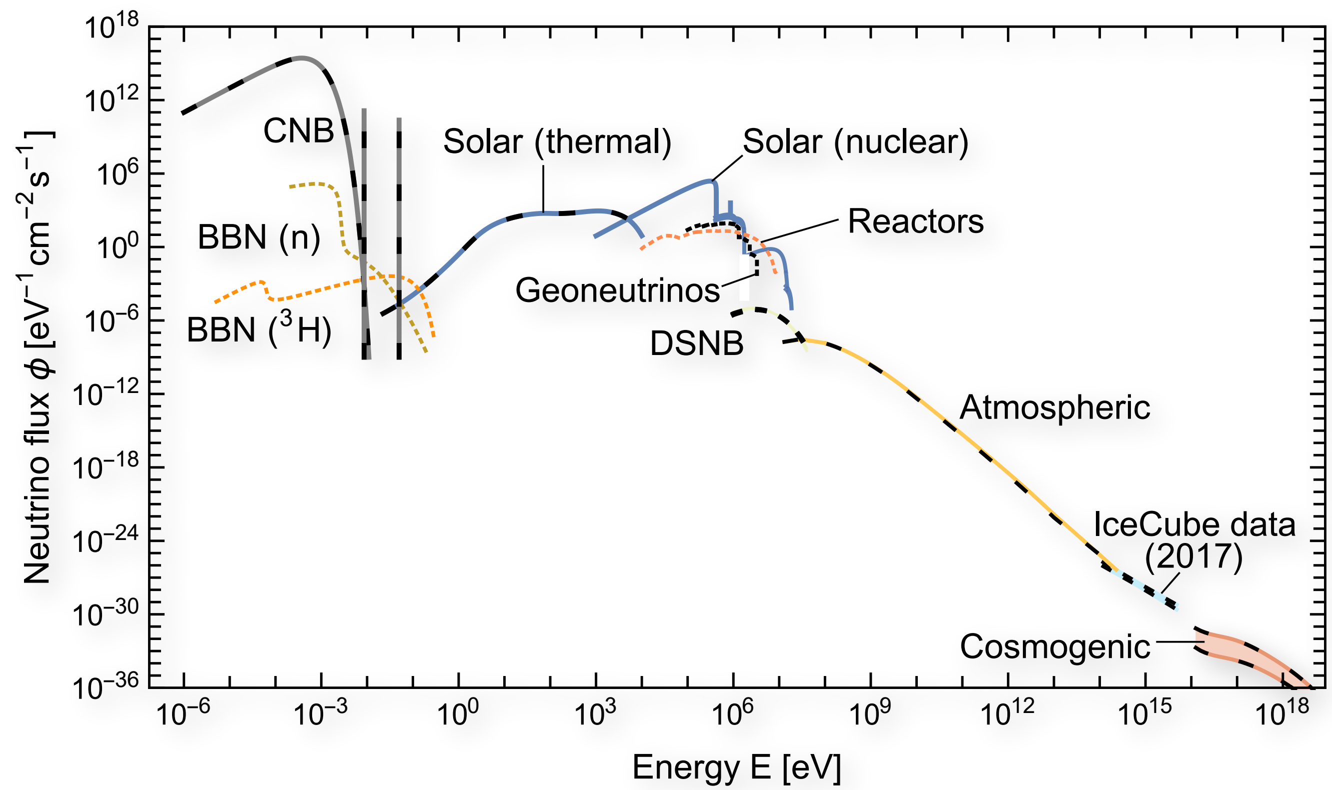
* The pre-supernova star is defined by the time at which the contraction speed anywhere in the iron core reaches 1,000 km s^{-1}.

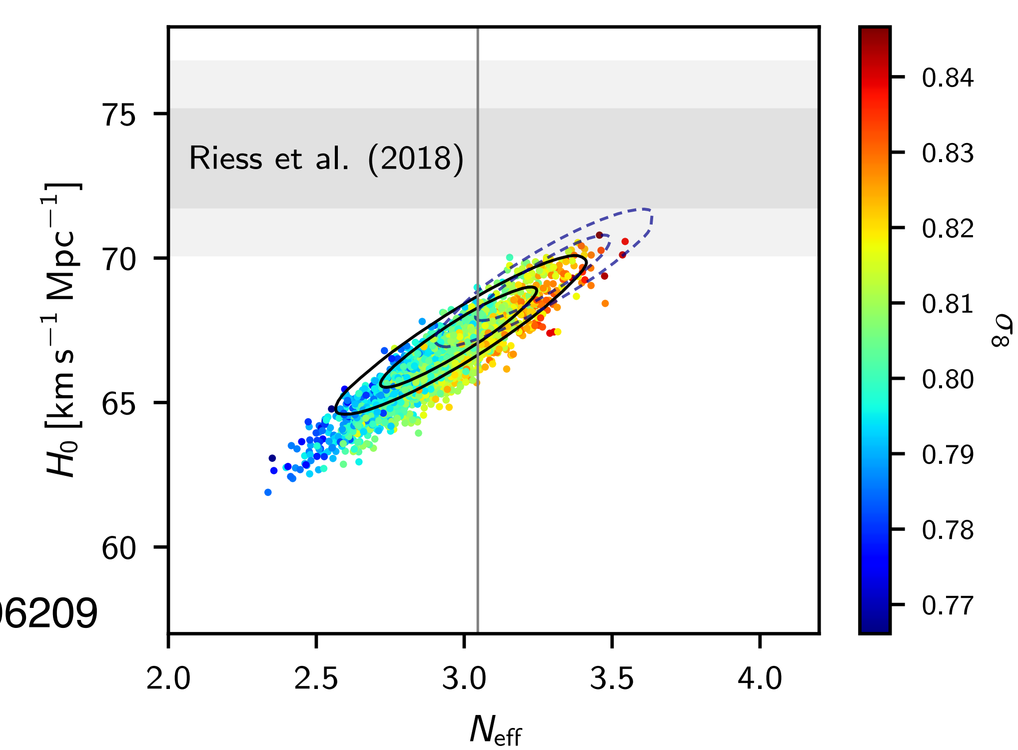
Relic neutrinos

- Cosmic Neutrino Background: the figure assumes the lightest state is massless, the other two are 8 meV and 50 meV (solar and atmospheric splittings) -> presently non-relativistic

- Again, no direct detection

- But overwhelming indirect evidence in the CMB

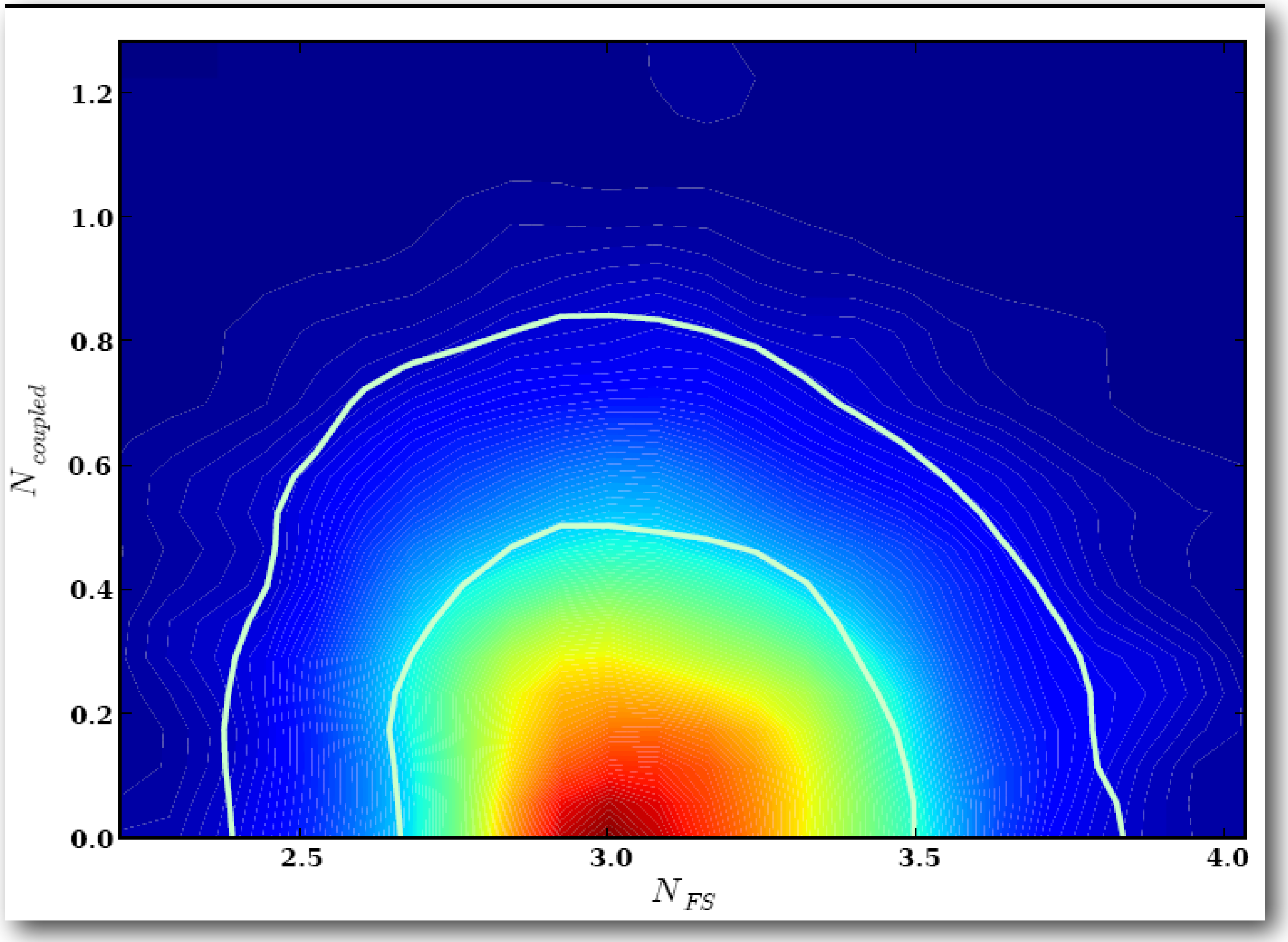




Planck 2018,
arXiv: 1807.06209

Relic neutrinos

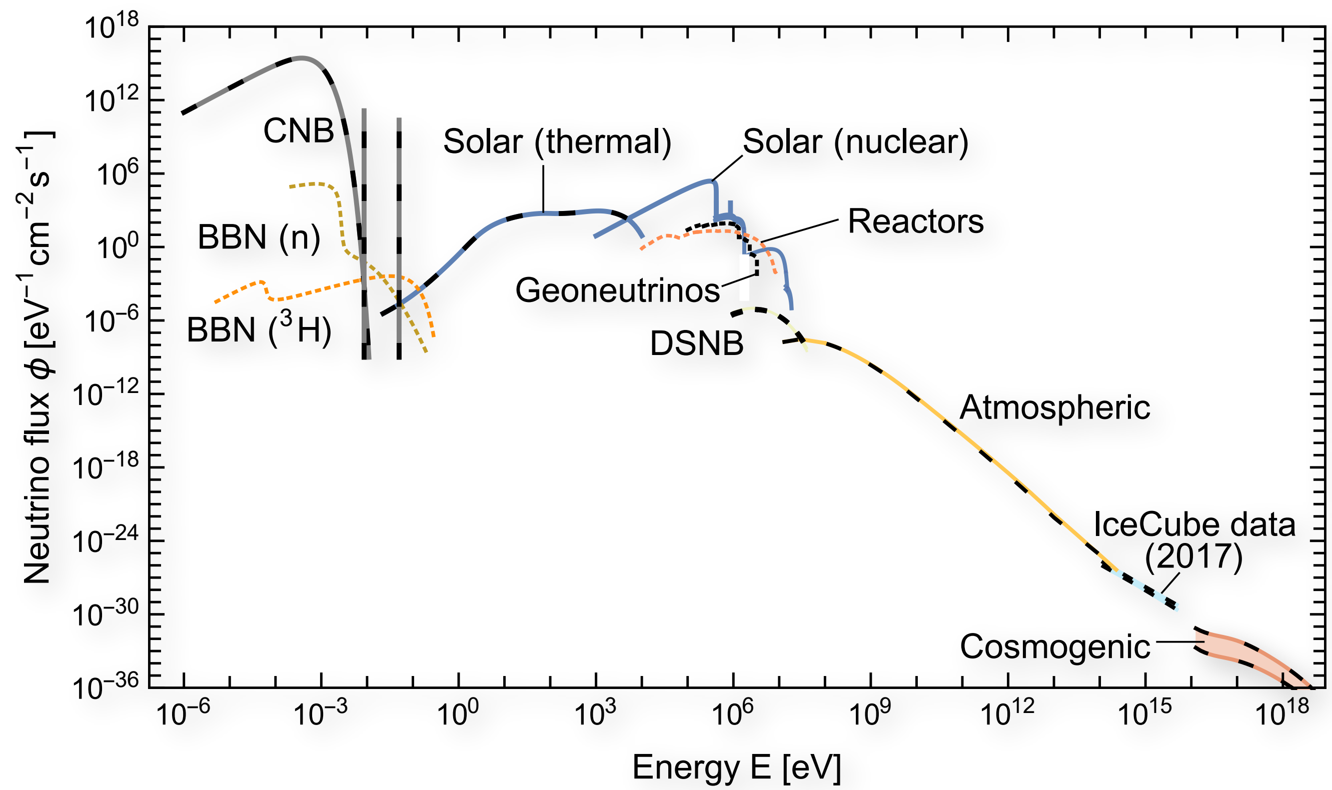
- We know not only that about three neutrino species were present at the time of the CMB formation, but also that they were (mostly) streaming freely, not coupled to plasma like photons

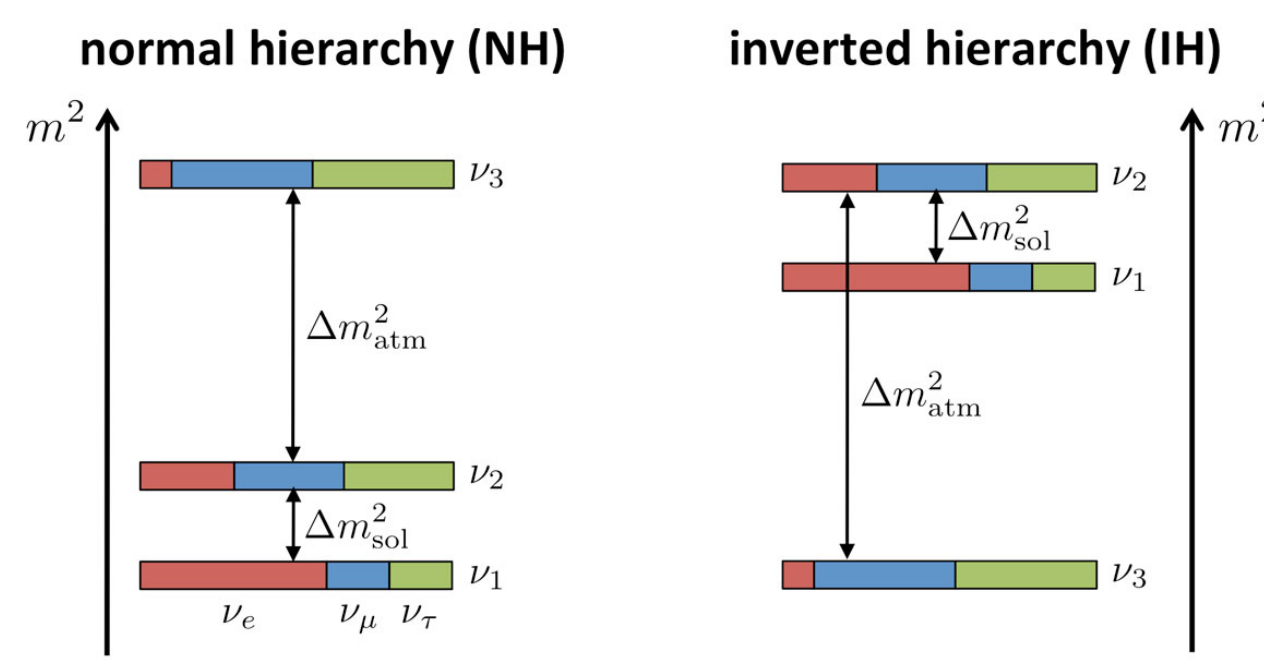


Friedland, Zurek, Bashinsky, 0704.3271

Tau neutrinos?

- So, are there nonrelativistic tau neutrinos in this room?
- Thinking about them as “tau neutrinos” is not right!
- Proper particles are mass eigenstates, ν_1, ν_2, ν_3, each with the tau component
- Wavepackets separate over long distances, any flavor oscillations stop
- Same is true, btw, for all astrophysical neutrinos





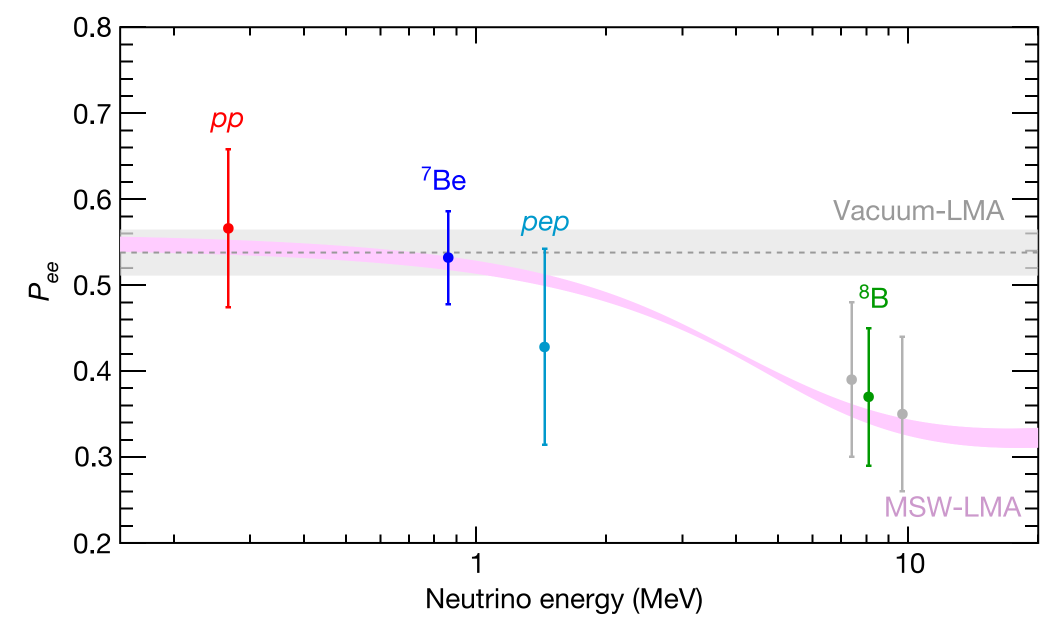
Solar neutrinos

- Also arrive in mass eigenstates

- In fact, thanks to the adiabatic matter effect (MSW), ^{8}B neutrinos arrive as almost exclusively ν_2. Flavor composition independent of the Earth-Sun distance

- The solution to the solar neutrino problem is neutrino oscillations (Nobel Prize 2015), yet to be technically correct, ^{8}B solar neutrinos don't oscillate.

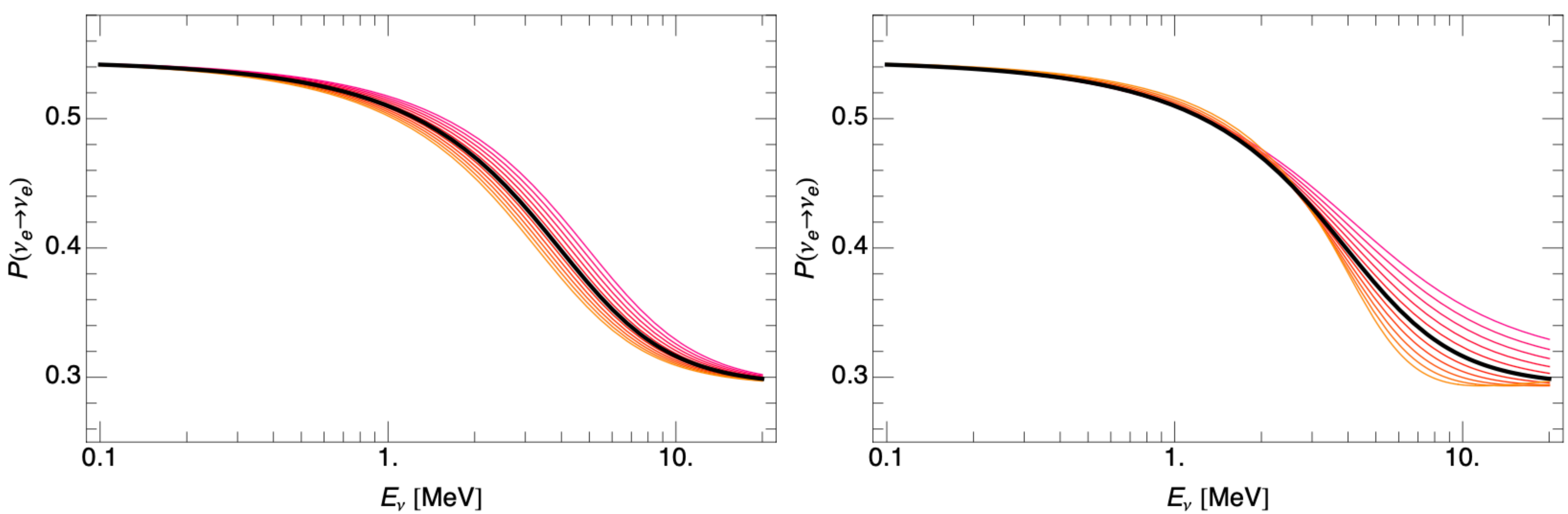
- Lower energy neutrinos, pp & ^{7}Be, do arrive as both ν_1 and ν_2. The transition between the MSW and averaged vacuum regimes in the middle of the solar neutrino spectrum is completely nontrivial: nature tunes $\Delta m_{12}/E_\nu$ to $G_F n_e^{\odot}$ (e.g., the solar neutrino density)



Borexino collab, Nature (2018)

Solar neutrinos as probes of BSM

- We are not really done with solar neutrinos
- It would be good to measure the transition regime better, because it is sensitive to new physics, e.g, NSI
- SNO+?

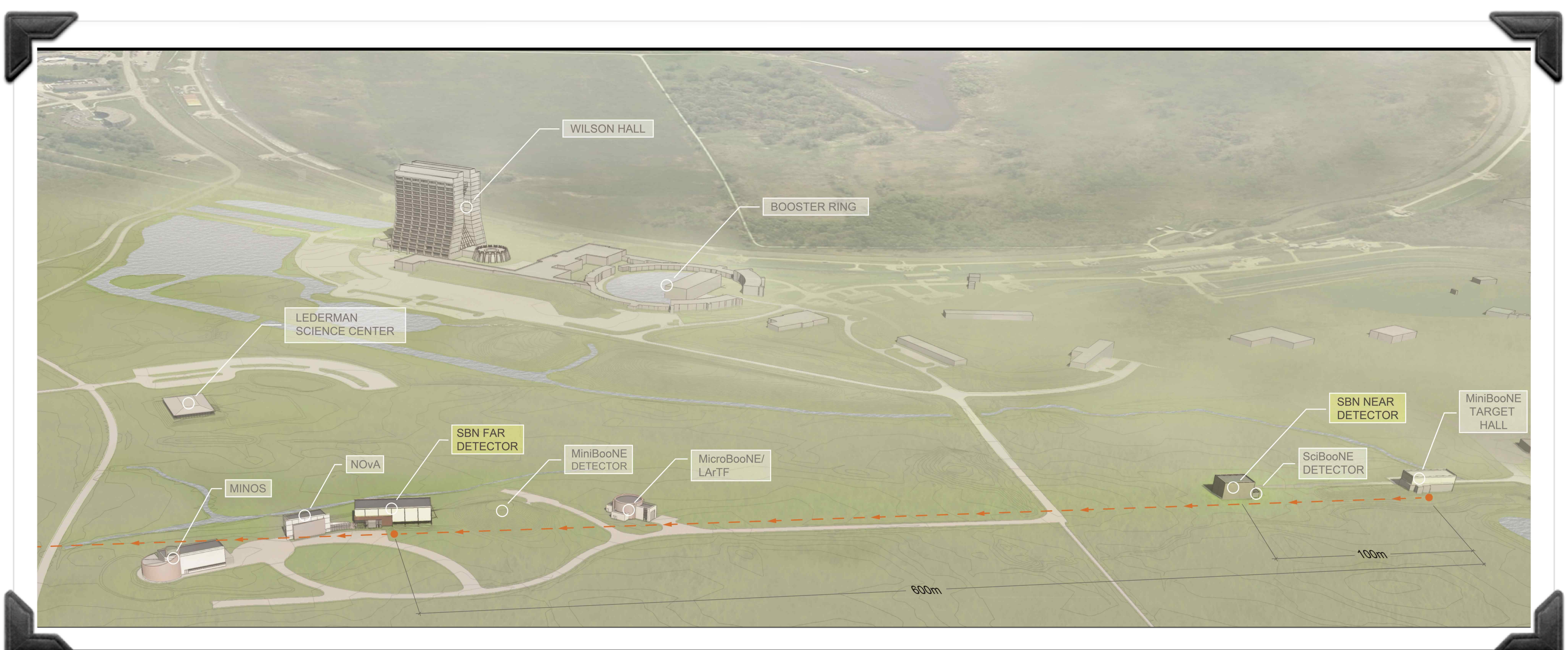


arXiv:1111.5331

Astrophysical neutrinos as probes of BSM

- Let's consider an example. If the short-baseline anomalies are due to a truly sterile neutrino, such a sterile neutrino would be completely thermalized with the active ones at T ~ several MeV -> $N_{eff}=4$ -> disfavored by Planck

- So what happens if a sterile neutrino is confirmed in the lab in the next 3-5 years? -> the physics is beyond minimal, life becomes interesting



Hidden interactions to the rescue?

- What if sterile neutrinos are actually not truly sterile, but interacting through their own force?

- Once there is some population of hidden neutrinos, this would induce an MSW potential that would suppress mixing between ν_a and ν_h . Would that shut off $\nu_a \rightarrow \nu_h$ thermalization?

- This is the Babu-Rothstein framework

  - Babu & Rothstein, Phys.Lett. B275 (1992) 112-118

  - Dasgupta & Kopp; Hannestad, Hansen, & T. Tram; plus a number of others

The physics here is actually subtle

- Different physical regimes must be carefully analyzed:
  - Heavy mediator, Light mediator, Resonant, Quantum Zeno, Non-freestreaming in CMB...
- We find that for the oscillation parameters suggested by the oscillation “anomalies” the thermalization temperature has a fundamental lower limit

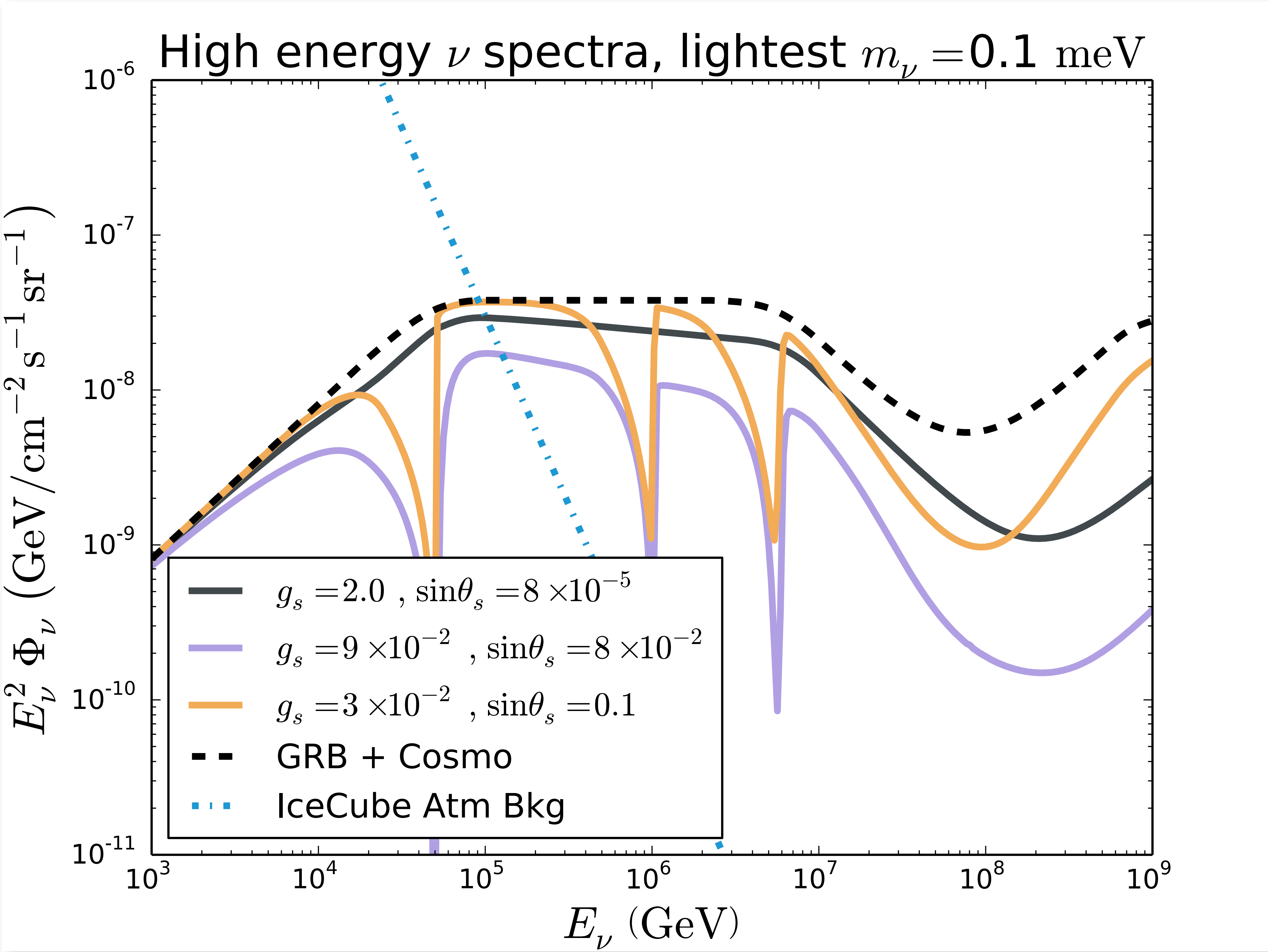
$$T_0 \sim (\sin^2 2\theta (\Delta m^2)^2 M_{pl})^{1/5} \sim 200\ \mathrm{keV}$$

- This is close to 1 MeV of weak decoupling. The BR mechanism is thus only marginally successful. Fractional deviation of Neff from 3 expected.
- The viable parameter space has mediator masses in the range ~ 10^{-3}-10^{2} MeV.
- This enter range will be probed with next-gen experiments.

Cherry, A. F., Shoemaker, arXiv:1605.06506

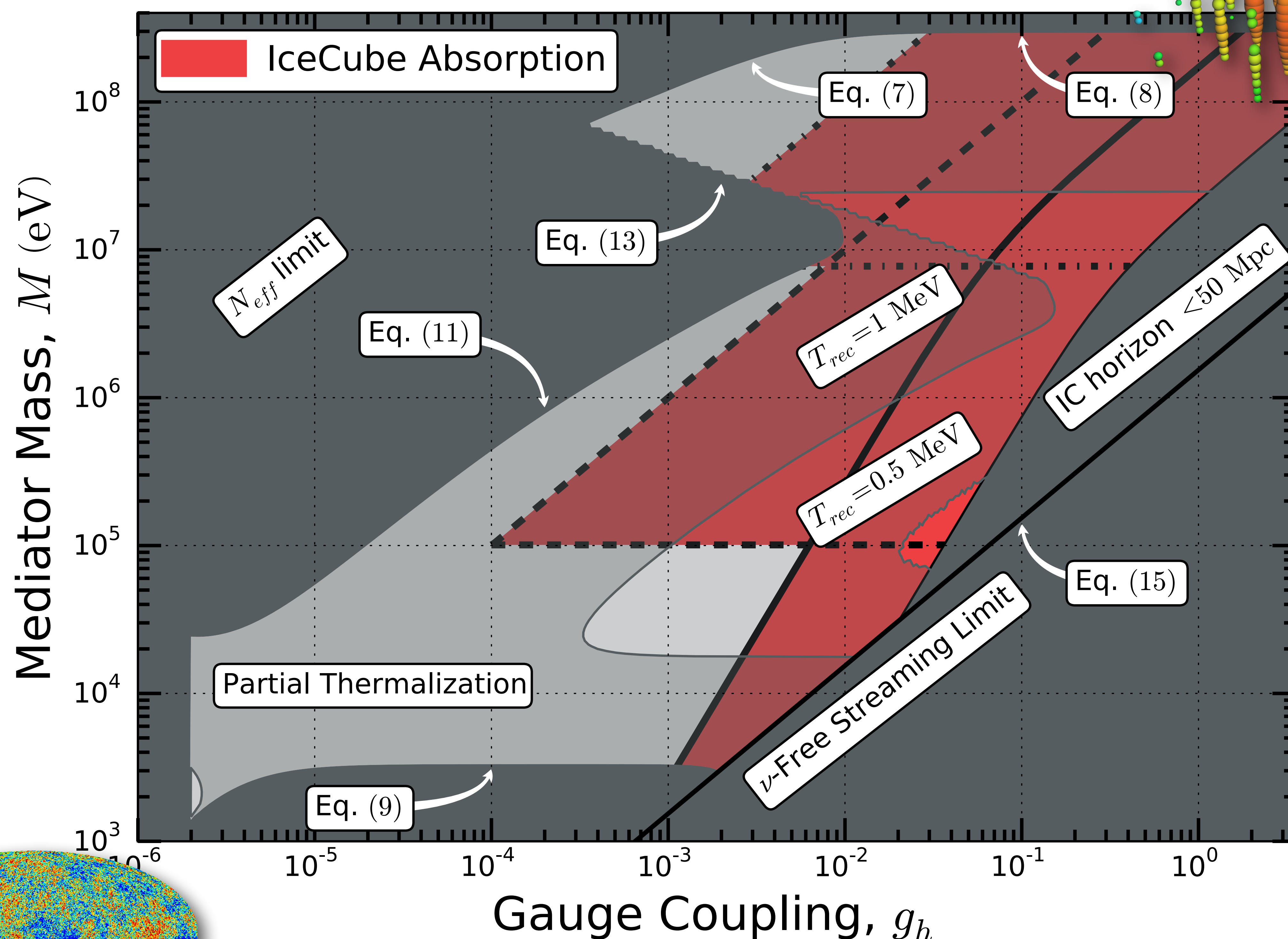
Testing this: neutrino-neutrino collider?

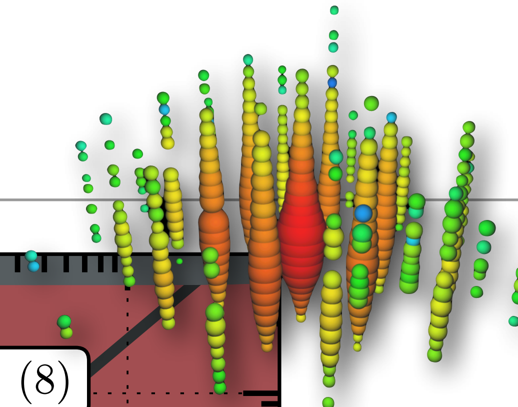
- We need to collide neutrino mass eigenstates, which have admixture of the "sterile" component that gives them new interactions
- Not feasible in the lab, but we can use the universe as the experimental setup
- **Icecube** has observed neutrinos in the PeV energy range, that likely originate from cosmological distances
- These neutrinos on their way to us travel through the relic neutrino background. Both the beam and the background had enough time to oscillate and separate into mass eigenstates.

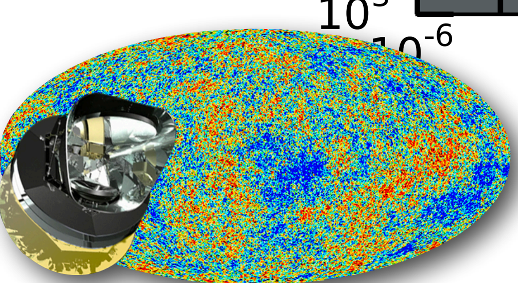


Example calculation

Compare absorption features w/ CNB spectrum earlier

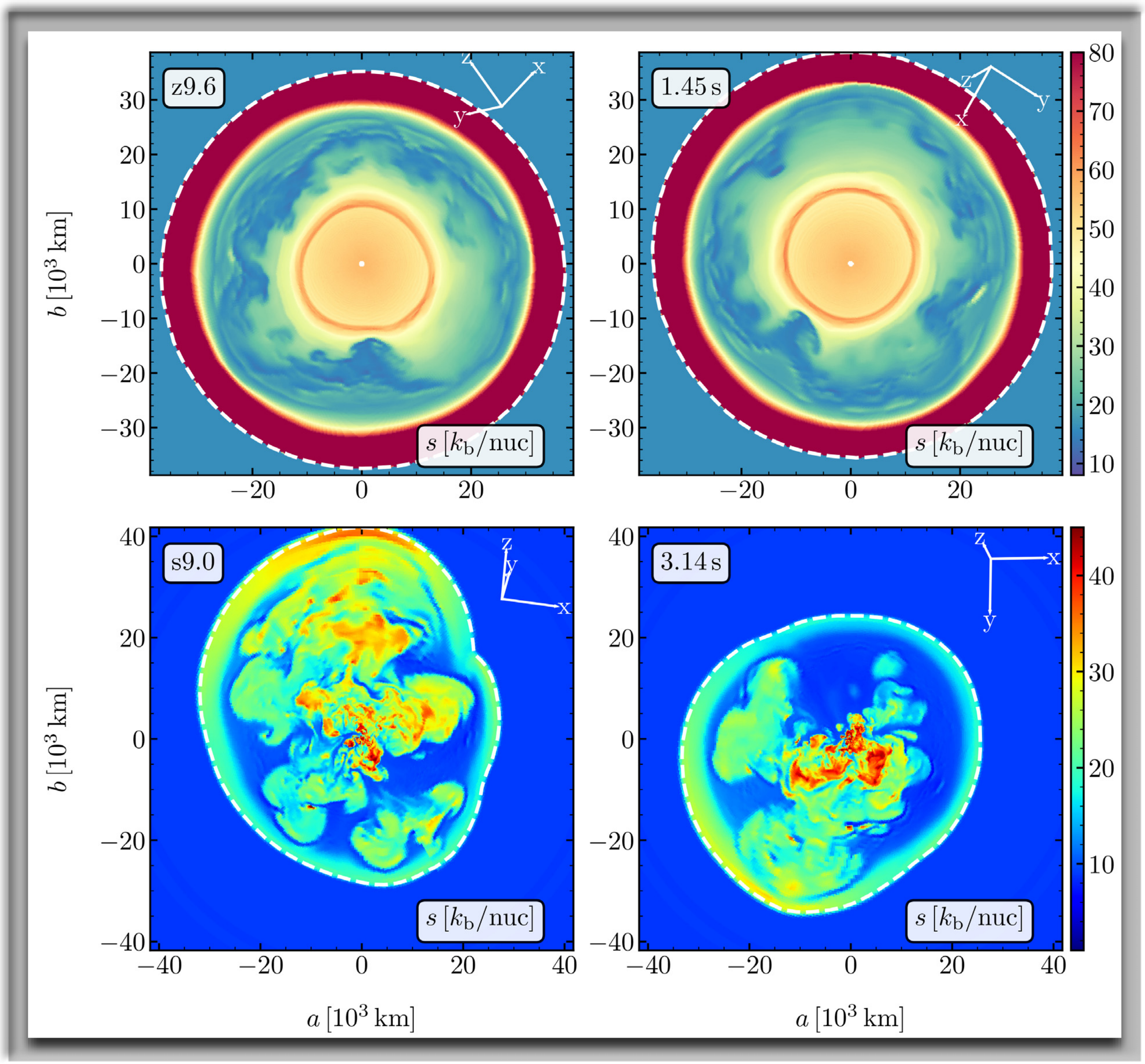






Details in arXiv:1605.06506

Last but not least, supernova neutrinos

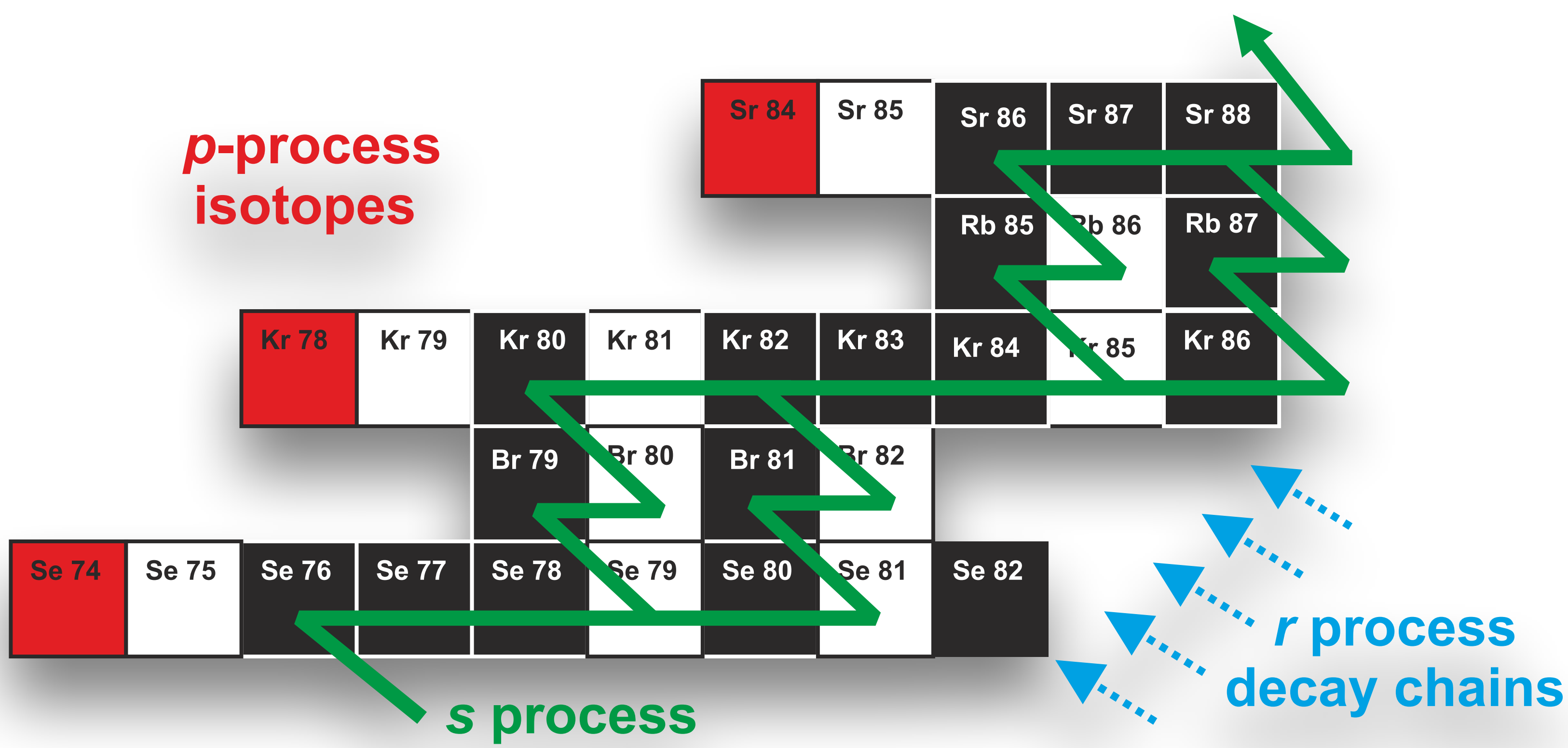


Core-collapse SN: Gravity-powered neutrino bomb

- Neutrinos carry away >99% of the energy (instantaneously, as all the stars in the universe)
  - Neutrino heating powers the expulsion of the envelope -> visible explosion
- Neutrinos are an essential ingredient in nucleosynthesis
  - Drive matter outflow from the PNS surface.
  - Set the electron fraction close to the PNS surface.
  - Drive weak processes in the entire outflow region.

Proton-rich isotopes: an enduring mystery

- Most elements heavier that iron are synthesized by neutron capture: the s- and r-processes
- A number of naturally occurring, proton-rich isotopes are bypassed by s- and r-processes, must be produced by different mechanisms



Rauscher et al (2013)

Leading proposal: the νp-process

- Proposed to operate in core-collapse SN, in a neutrino-driven outflow from the surface of protoneutron star [Frohlich et al (2005), Pruet et al (2005), Wanajo (2006)].

- The outflow is proton-rich and expands in the presence of a large flux of neutrinos

    - Key observation: neutrinos convert some of the protons into neutrons. These neutrons are immediately captured on proton-rich seed nuclei, helping bypass the beta-decay waiting points

Field in crisis?

Article

Enhanced triple-α reaction reduces proton-rich nucleosynthesis in supernovae

https://doi.org/10.1038/s41586-020-2948-7
Shilun Jin[1,2,3], Luke F. Roberts[1,2]✉, Sam M. Austin[1,2] & Hendrik Schatz[1,2]
Received: 9 March 2020

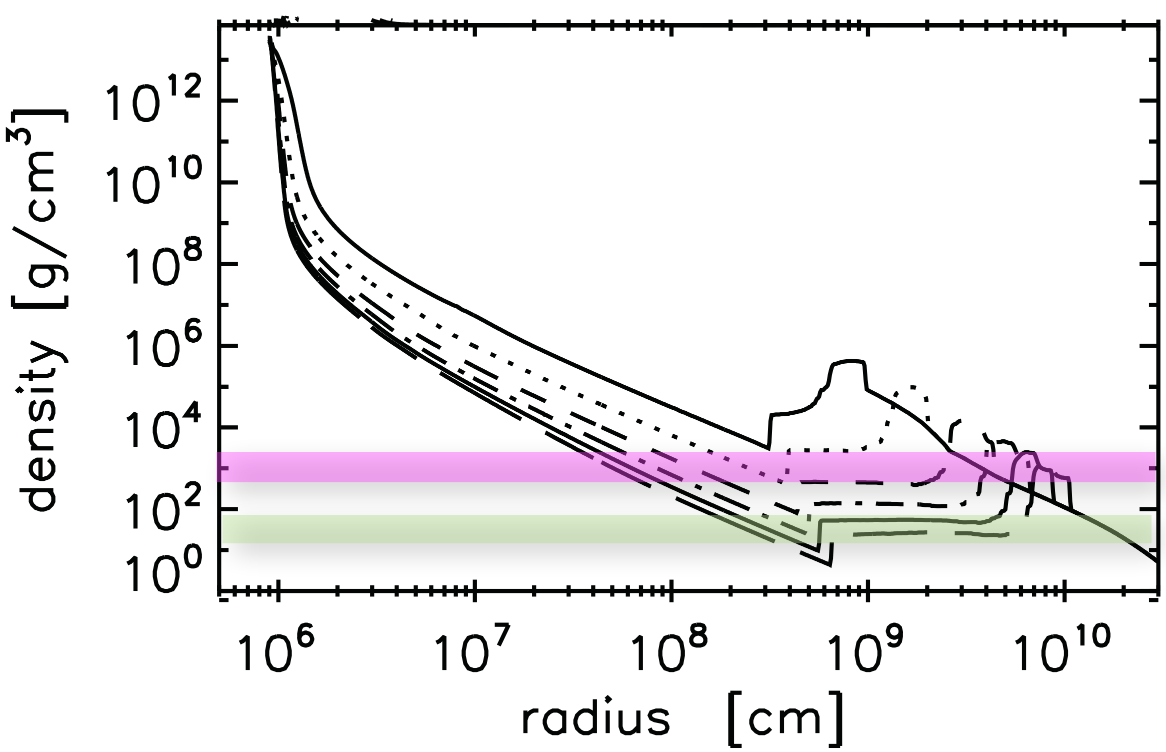
Dec. 2, 2020

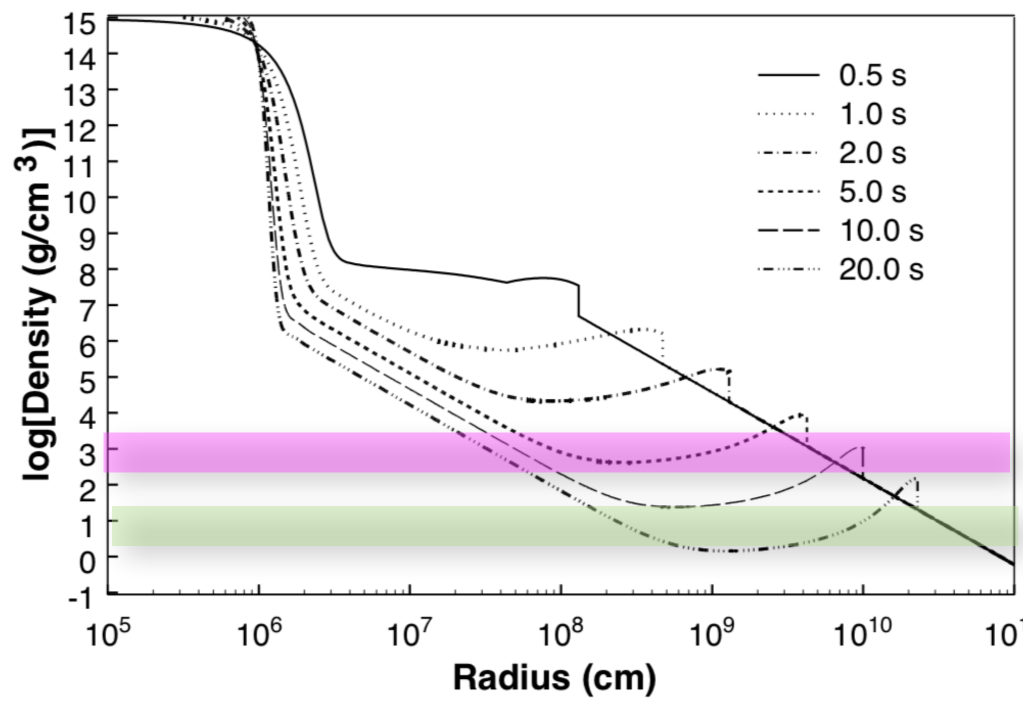
Supernova surprise creates elemental mystery

Michigan State University researchers have discovered that one of the most important reactions in the universe can get a huge and unexpected boost inside exploding stars known as supernovae.

This finding also challenges ideas behind how some of the Earth's heavy elements are made. In particular, it upends a theory explaining the planet's unusually high amounts of some forms, or isotopes, of the elements ruthenium and molybdenum.

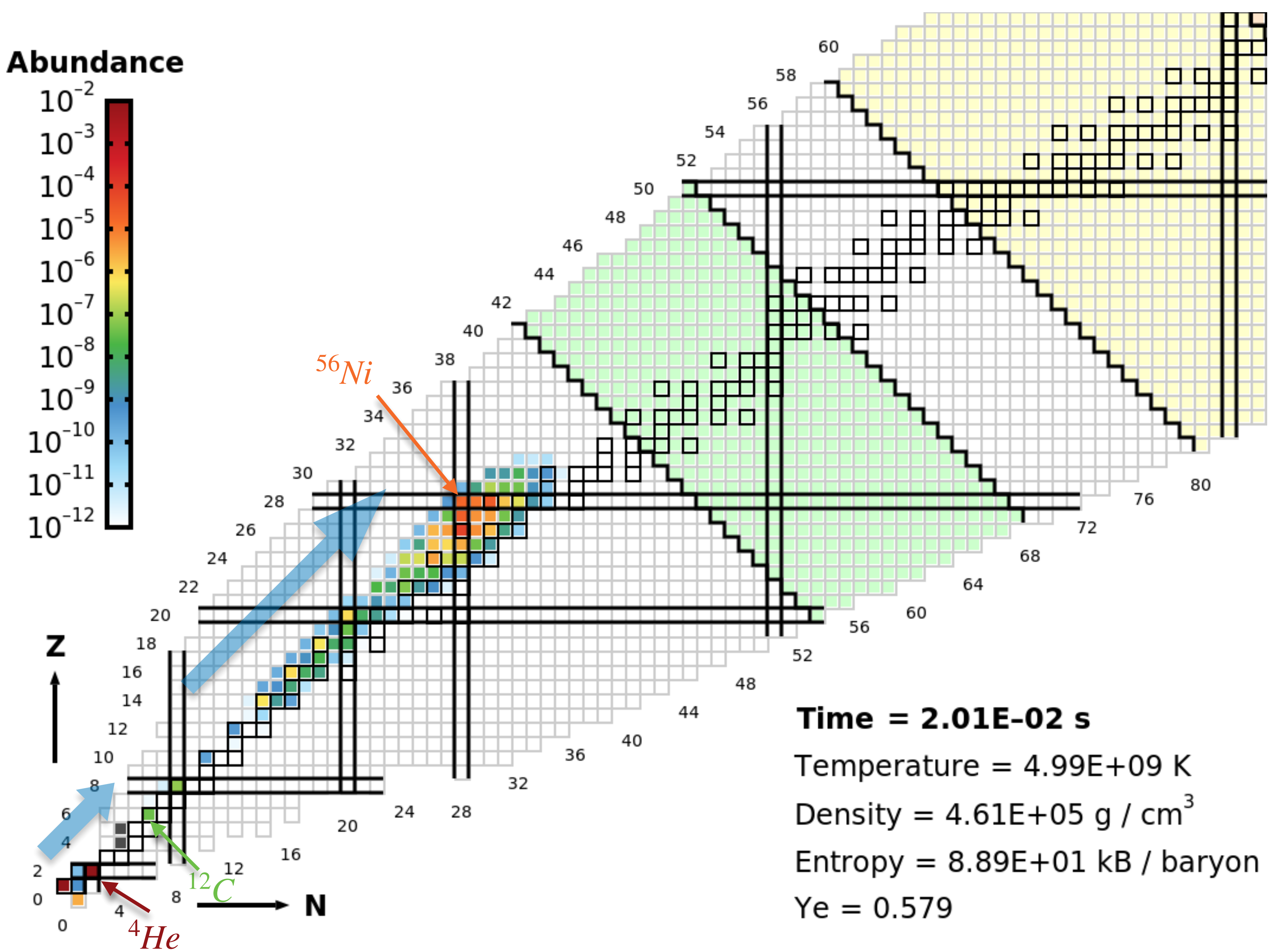
Physics of the outflows



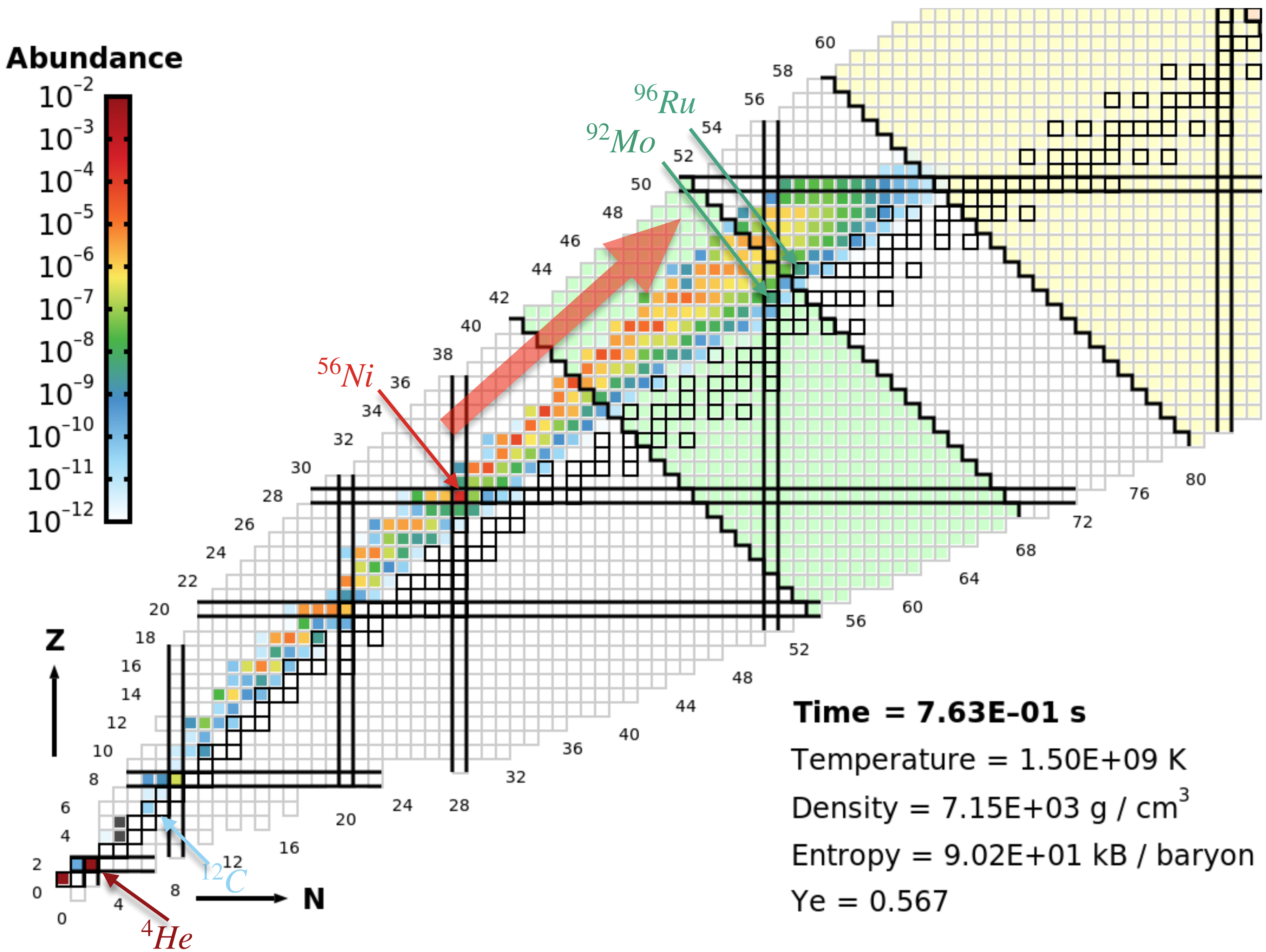


- The outflows can be subsonic (smooth) or supersonic (w/ termination shocks).
- The conditions in a supernova are special, such that both types can occur, depending on the exact conditions surrounding the core [A.F., Mukhopadhyay, PLB (2022)]
- Previous nucleosynthesis studies only considered supersonic
- But subsonic ones work perfectly fine! [A.F., Mukhopadhyay, Patwardhan, arXiv:2312.03208)]

Stages of the calculation



Stages of the calculation



Time = 7.63E-01 s

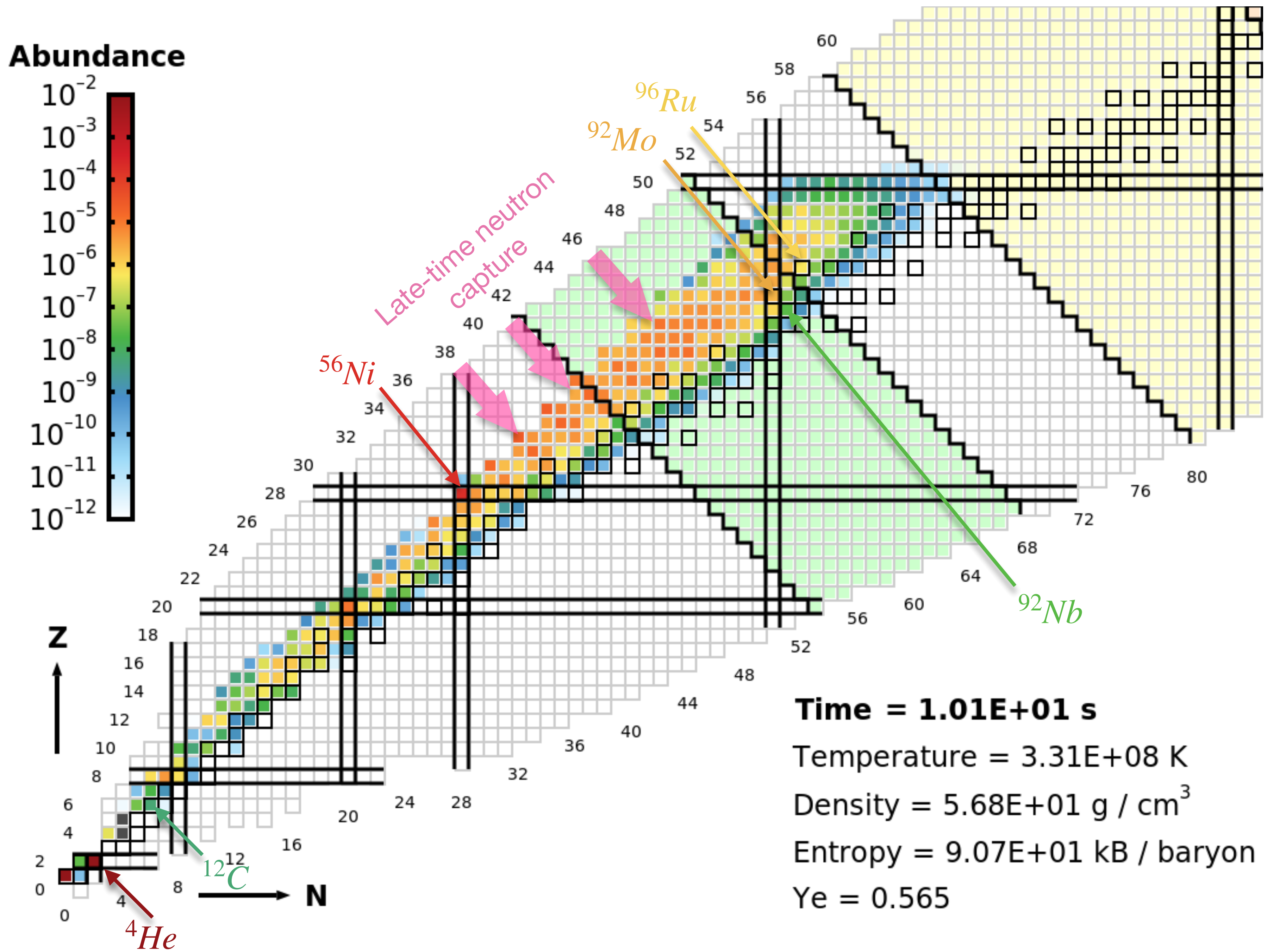
Temperature = 1.50E+09 K

Density = 7.15E+03 g / cm^3

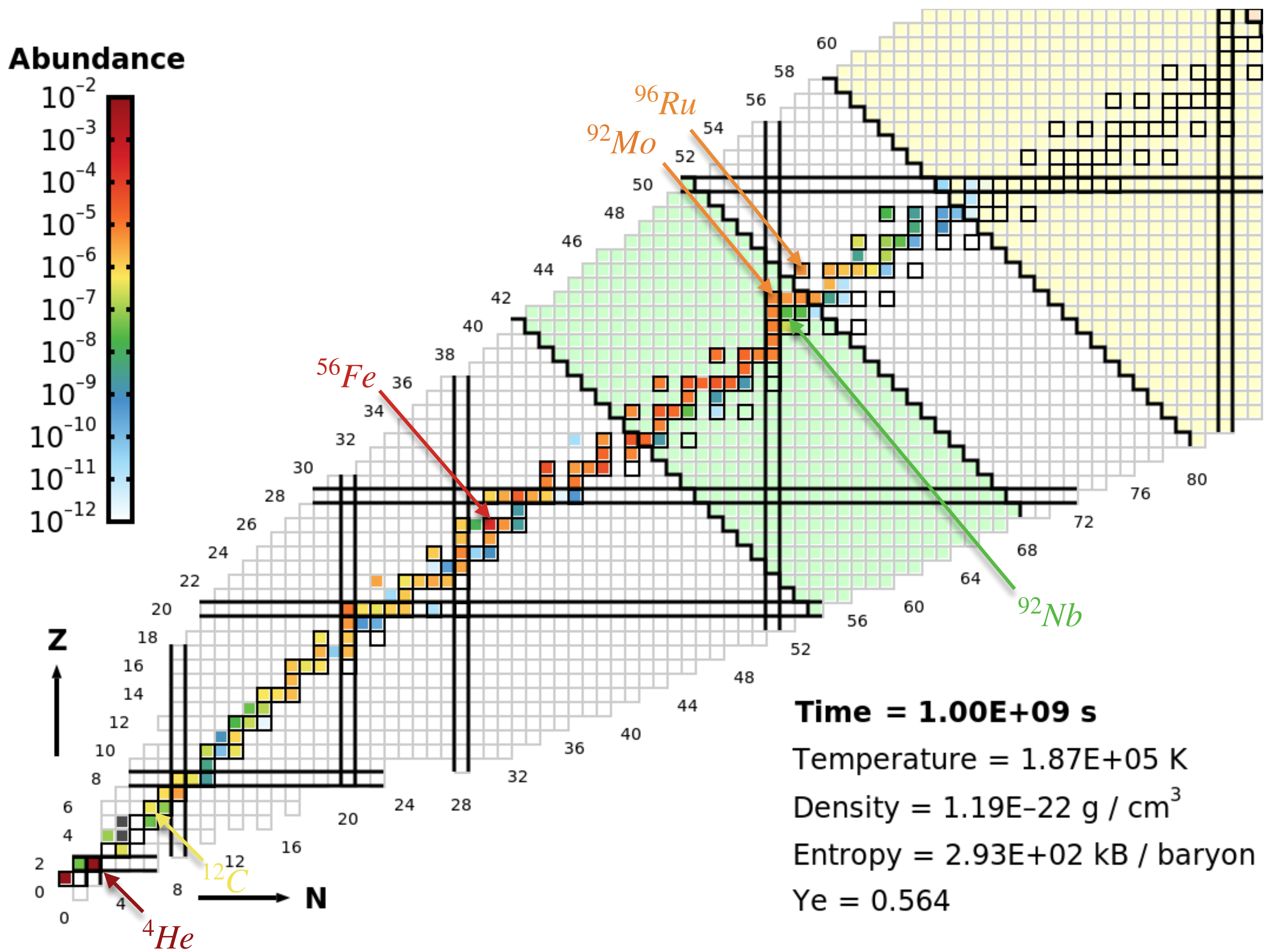
Entropy = 9.02E+01 kB / baryon

Ye = 0.567

Stages of the calculation



Stages of the calculation



Time = 1.00E+09 s

Temperature = 1.87E+05 K

Density = 1.19E−22 g / cm^3

Entropy = 2.93E+02 kB / baryon

Ye = 0.564

Conclusions

- Our universe is filled with neutrinos, with energies spanning more than two decades
- Sometimes these neutrinos can be measured directly, but often our measurements are indirect.
  - We see neutrino imprints in stellar evolution, in CMB fluctuations, or in the patterns of isotopes observed in the solar system
- The study of particle physics and astrophysics has gone hand in hand. Example: solar neutrinos. We learned about the solar interior and about particle physics.
  - Every reason to believe that the same will happen with supernova neutrinos or UHE neutrinos. They probe physical conditions that cannot be reproduced in the lab. There are lots of subtleties, but the payoff is potentially fantastic!