Neutrino signatures of supernova turbulence

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Outlines

- Background
  - SN neutrino flavor transformation
- Signature of shock passage through resonance (existing work)
- Turbulence
  - Motivation, status of simulations
  - Neutrino evolution in Kolmogorov turbulence
- Implications for observed signal

Core collapse supernovae

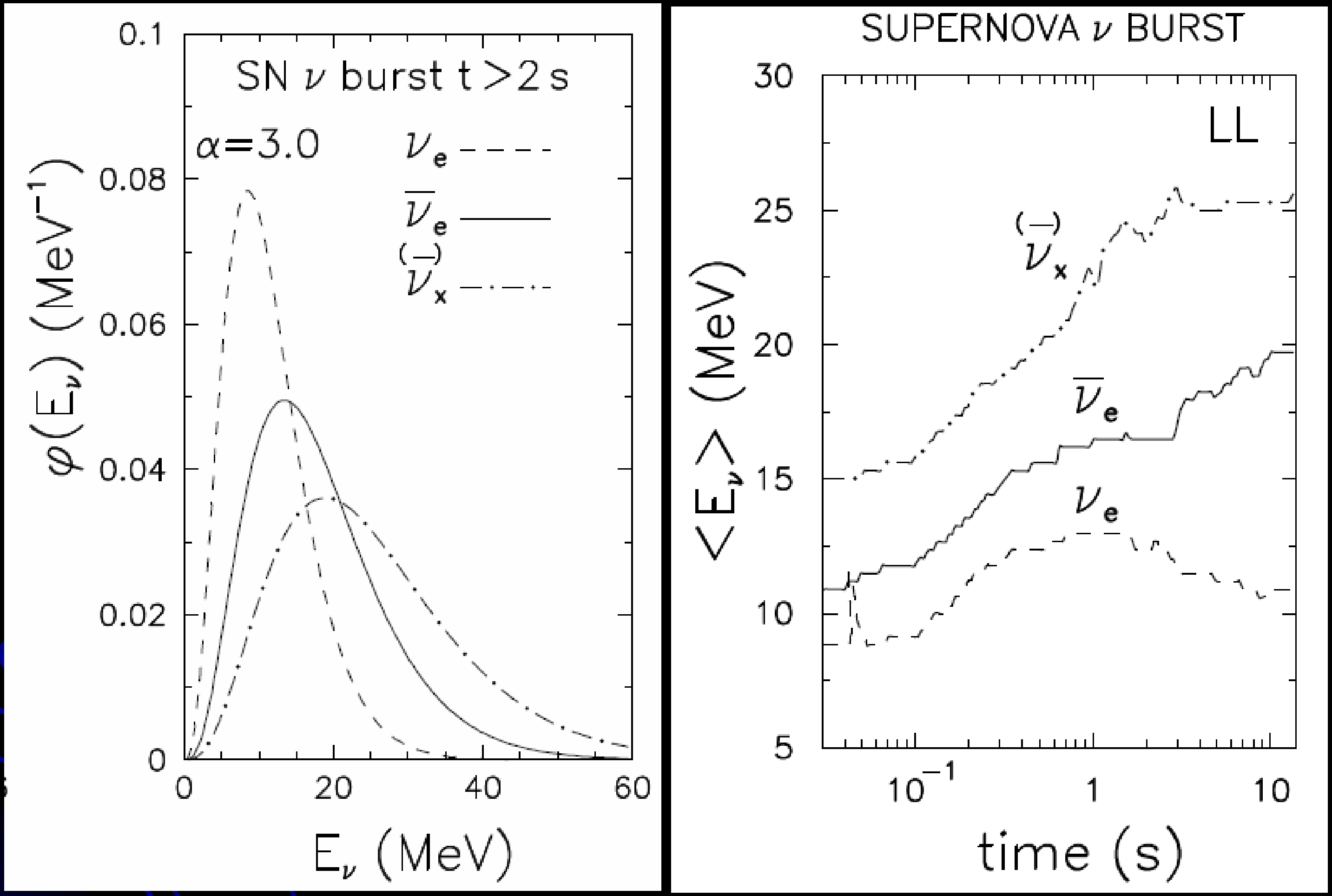
- Gravitational binding energy of the collapsed core, $G_N M^2/r \sim 3\times10^{53}$ ergs, is 10% of its rest mass
- This energy is released in neutrinos and antineutrinos of all three active flavors
  - Visible explosion only 1-2 $\times10^{51}$ ergs, $\lesssim$ 1% of the total energy
- -> SN is basically a gravity powered neutrino explosion
- Instantaneously as bright as the rest of the luminous Universe
- Very rich physics:
  - Energy transport and deposition by neutrinos
  - Matter at very high (nuclear) densities (EOS, cross sections, etc)
  - Convection (fluid instabilities)
  - Magnetic fields? Rotation?
- No clear single dominant process -> 40 years of active research

For accessible review and refs, see, e.g., Woosley & Janka, Nature Physics 1, 147-154 (2005)

MSW effect and explosion

- It would be great if the neutrino signal could be used to learn about the explosion
- This talk will focus on one particular late-time signature, modification of MSW flavor transformation by the explosion
- Rules of the game: only known physics!
  - No sterile neutrinos
  - No non-standard interactions
  - No magnetic moments
  - Just 3 known active flavors; the only unknowns are θ_{13} and the type of neutrino mass hierarchy

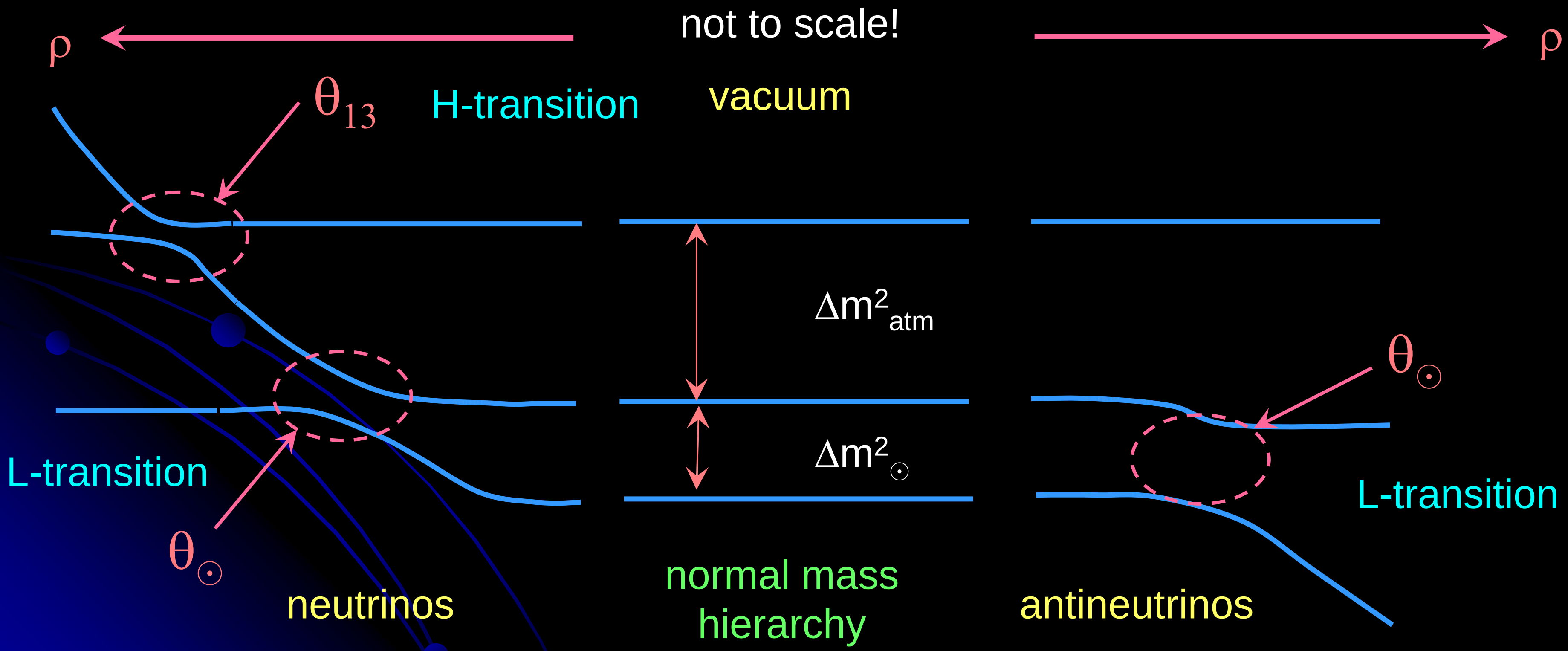
"Typical" spectra



- from hep-ph/0412046; after T. Totani, K. Sato, H.E. Dalhed, and J.R. Wilson

MSW effect in SN: original spectra get permuted

- Flavor transformations occur for both ν's and anti-ν's
- Depend on the type of mass hierarchy



not to scale!

ρ

ρ

θ_{13}

H-transition

vacuum

Δm^2_{atm}

$\theta_{\odot}$

L-transition

$\Delta m^2_{\odot}$

$\theta_{\odot}$

L-transition

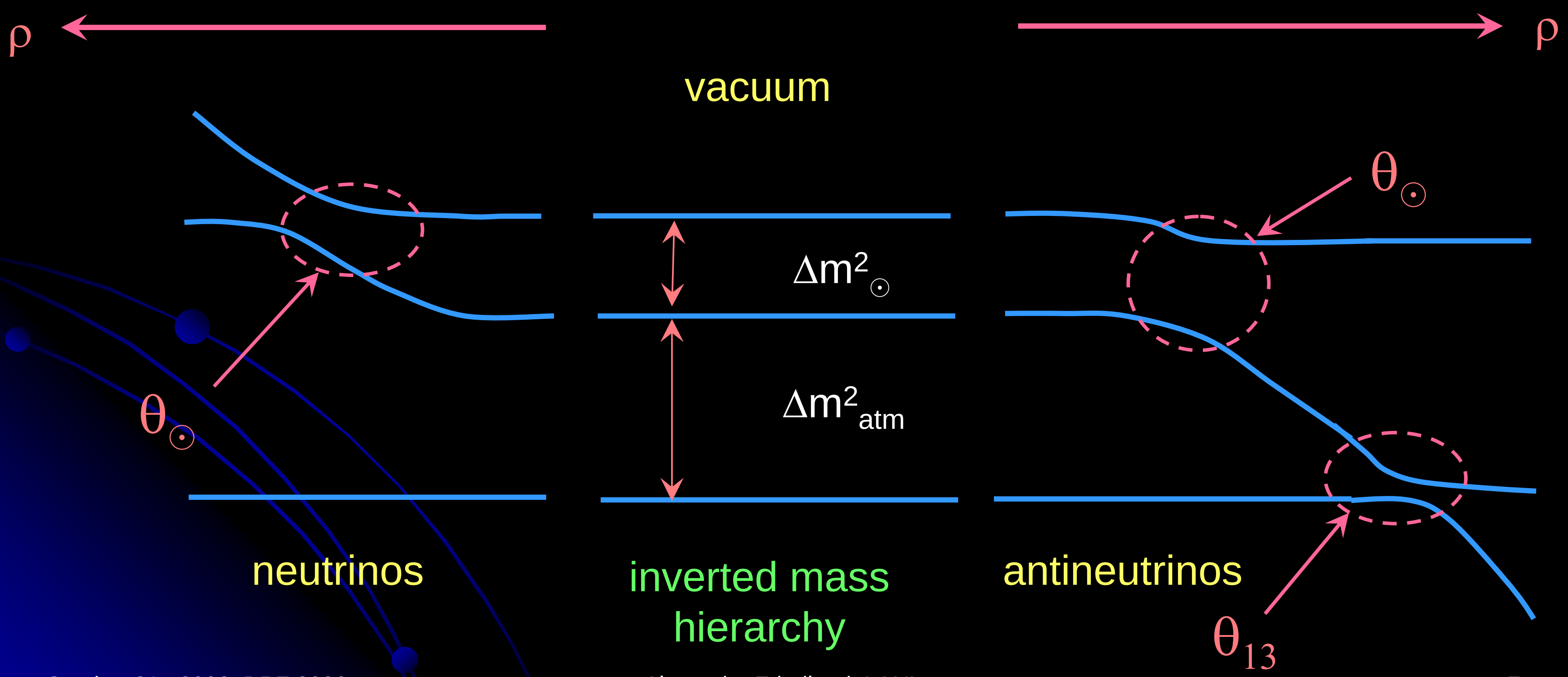
neutrinos

normal mass hierarchy

antineutrinos

MSW effect in SN: basics

- Flavor transformations for both ν's and anti-ν's
- Depend on the type of mass hierarchy



ρ

ρ

vacuum

$\Delta m^2_\odot$

Δm^2_{atm}

$\theta_\odot$

$\theta_\odot$

θ_{13}

neutrinos

inverted mass hierarchy

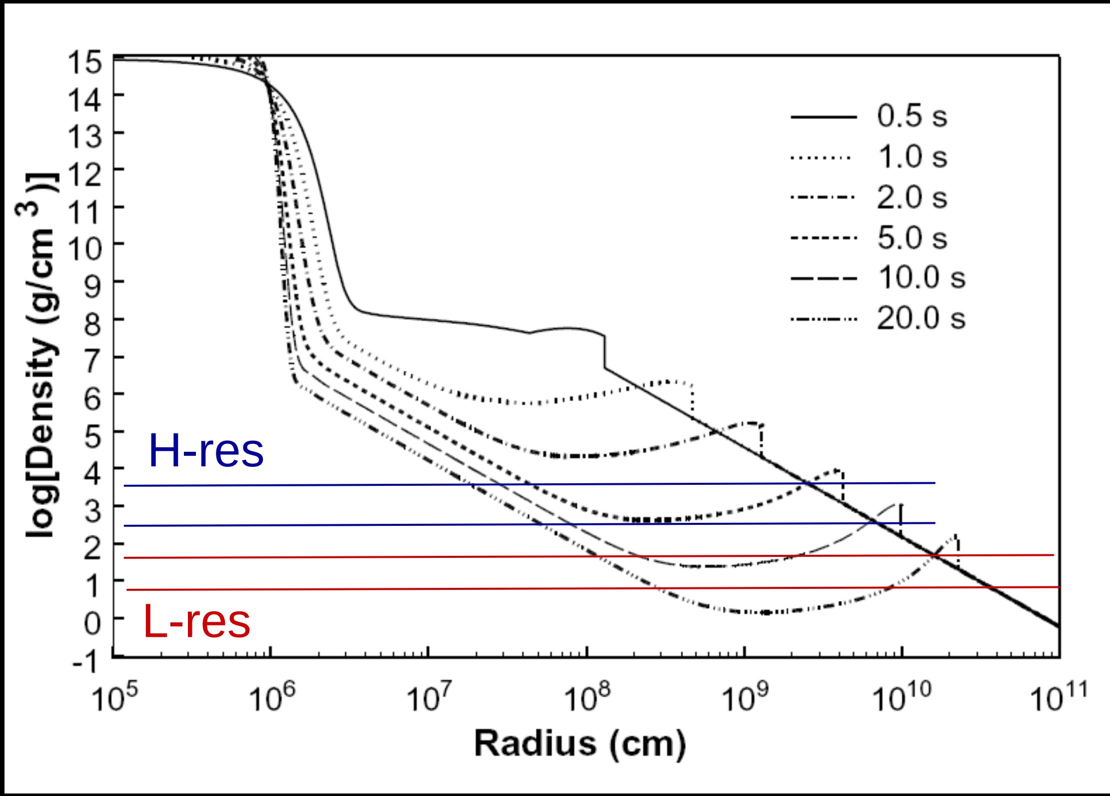
antineutrinos

Flavor transformations in the first few seconds

- Resonance regions at a few × 10^9 cm, a few × 10^{10} cm, density profile unperturbed by the explosion
- Density gradients in progenitor sufficiently smooth
  - the H-resonance is adiabatic so long as $\sin^2\theta_{13} \gtrsim 10^{-4}-10^{-3}$
  - the L-resonance is adiabatic (solar angle known)
- Original anti-ν_e are converted into anti-ν_μ and anti-ν_τ (and vice versa) -> hotter observed spectrum

Shock reaches the resonant layer

- At 3-5 seconds, shock reaches the H-resonant layer, while neutrinos are still streaming out of the protoneutron star
- Shock is very steep (photon mean free path) -> transition changes to maximally nonadiabatic



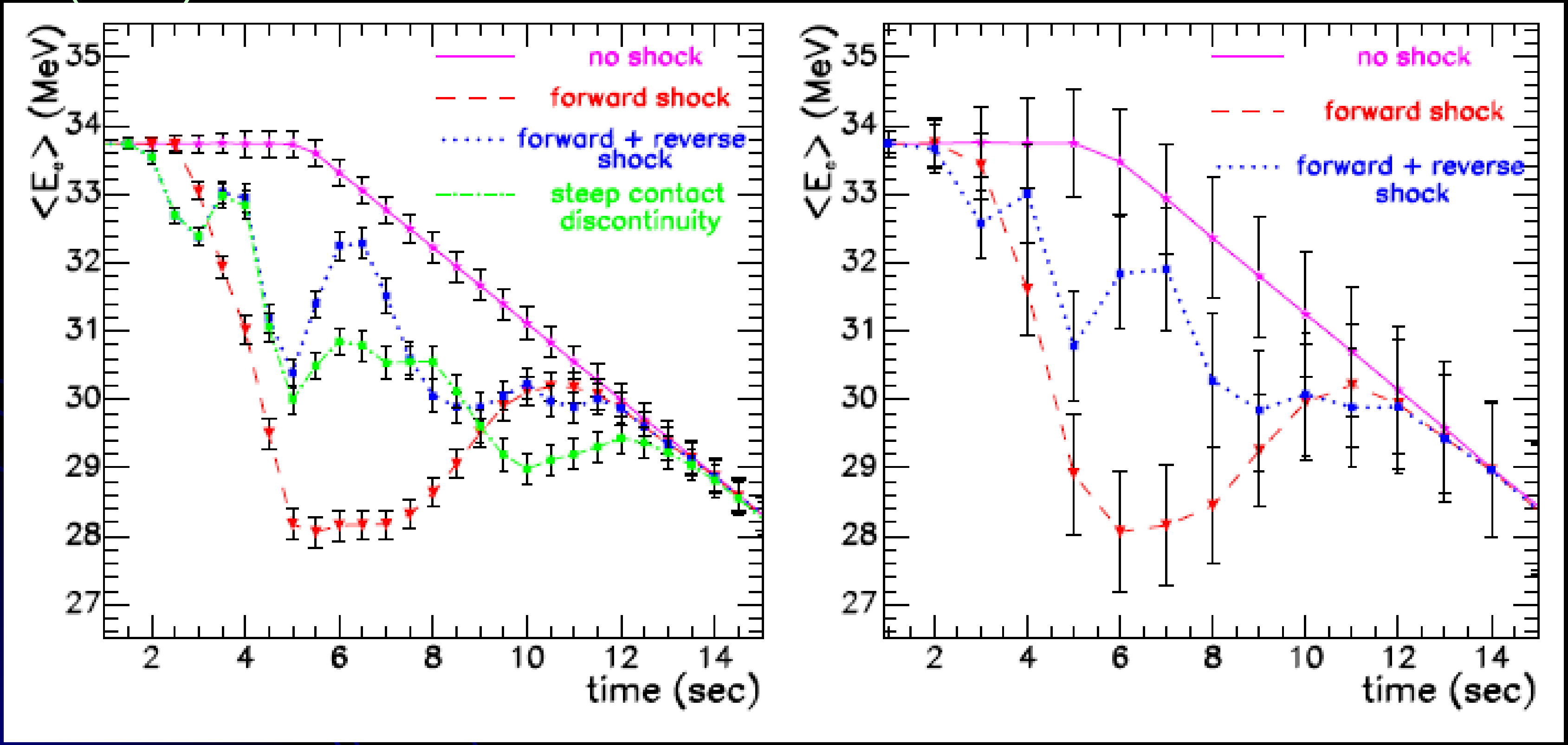
Schirato & Fuller, astro-ph/0205390

Notable follow-up work

- Thomas, Kachelrieß, Raffelt, Dighe, Janka and Scheck, JCAP09, 015 (2004), reverse shock in 1-dim simulations
- Kneller&McLaughlin, hep-ph/0509356, density bubble
- Fogli, Lisi, Mirizzi, Montanino, JCAP 0504:002,2005, detailed investigation of front/reverse shock signatures
- this year: Fogli, Lisi, Mirizzi, hep-ph/0603033 (ad-hoc) delta-correlated noise

Predicted signatures at Super-K and megaton water-Cherenkov detector

- from Thomas, Kachelrieß, Raffelt, Dighe, Janka and Scheck, JCAP09, 015 (2004)

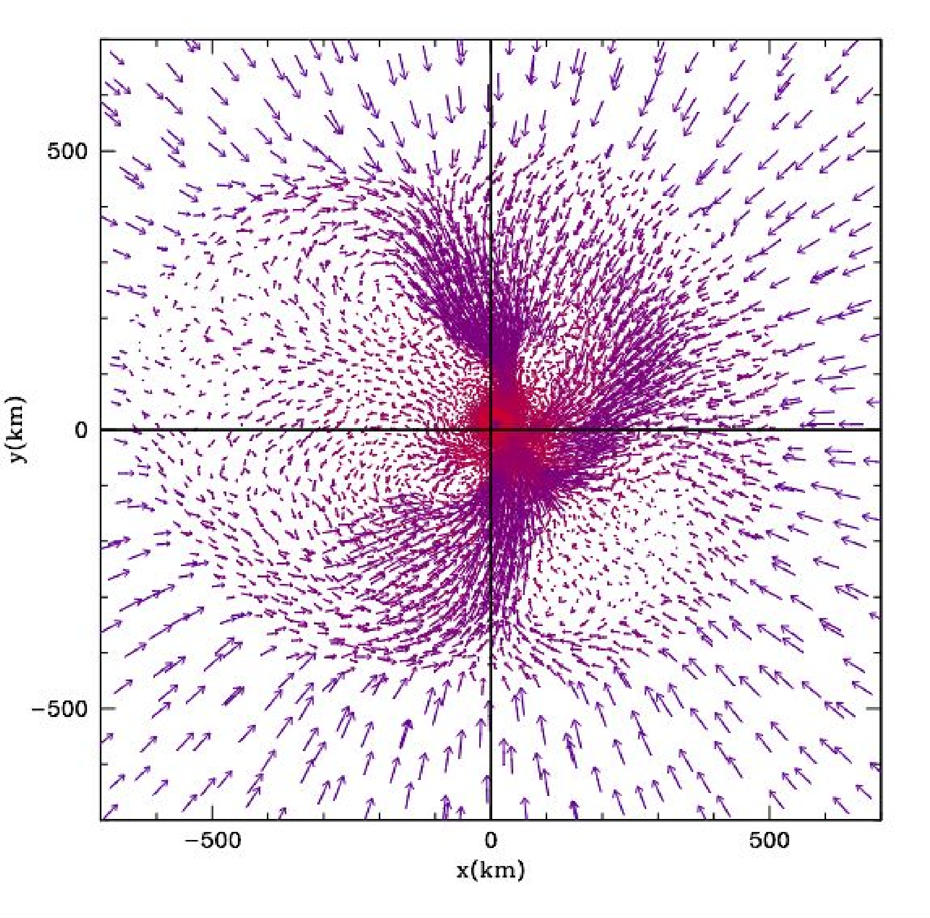


Correct cartoon?

- What do actual models of the explosion look like?
- Are the cartoons used so far the right cartoons? What features are important for neutrinos?

Explosion

- Actual simulations show vigorous turbulence behind the shock front at early times



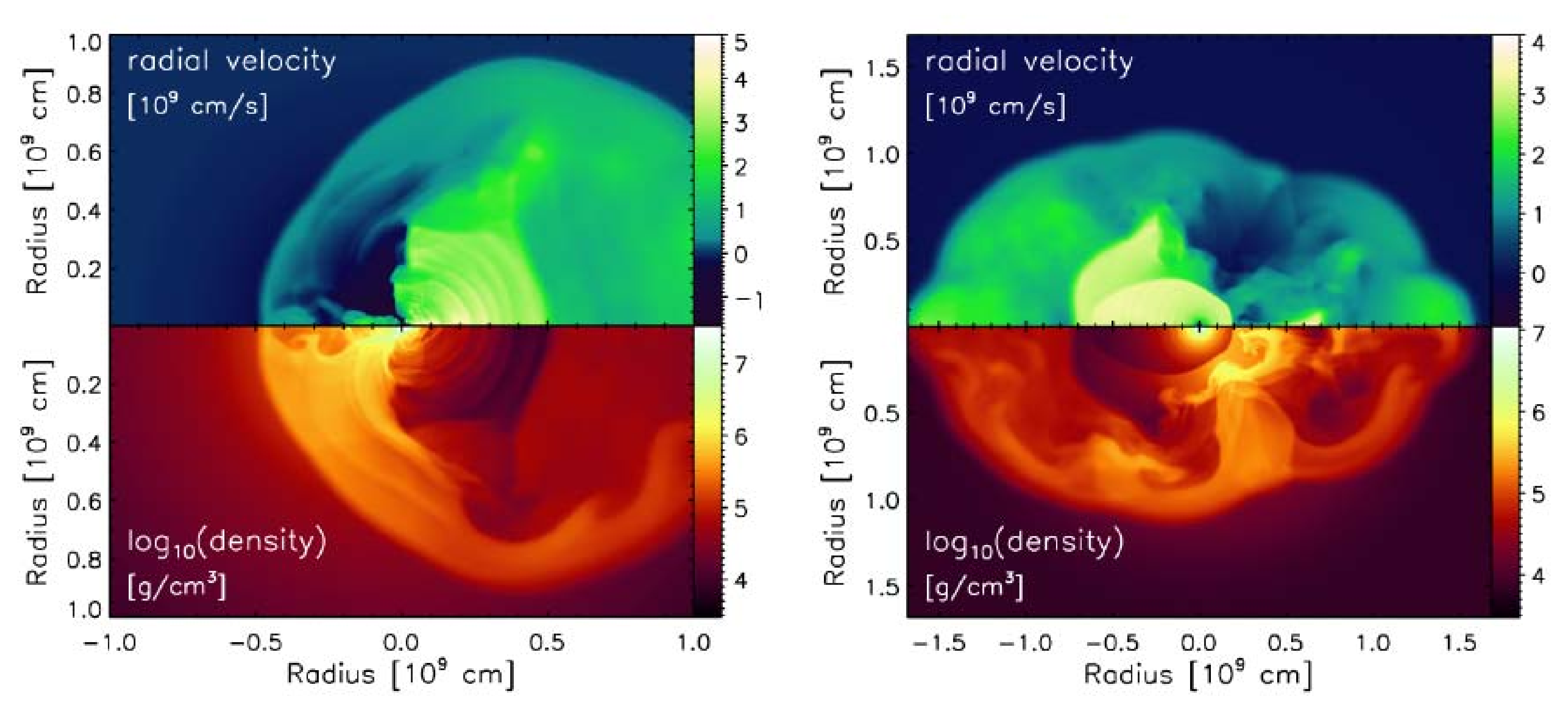
Snapshot of a 3D simulation
at t=340 ms
by Chris Fryer

Convection essential for the explosion mechanism!

Herant, Benz, Hix, Fryer, Colgate
Ap. J. 435, 339 (1994)

Explosion

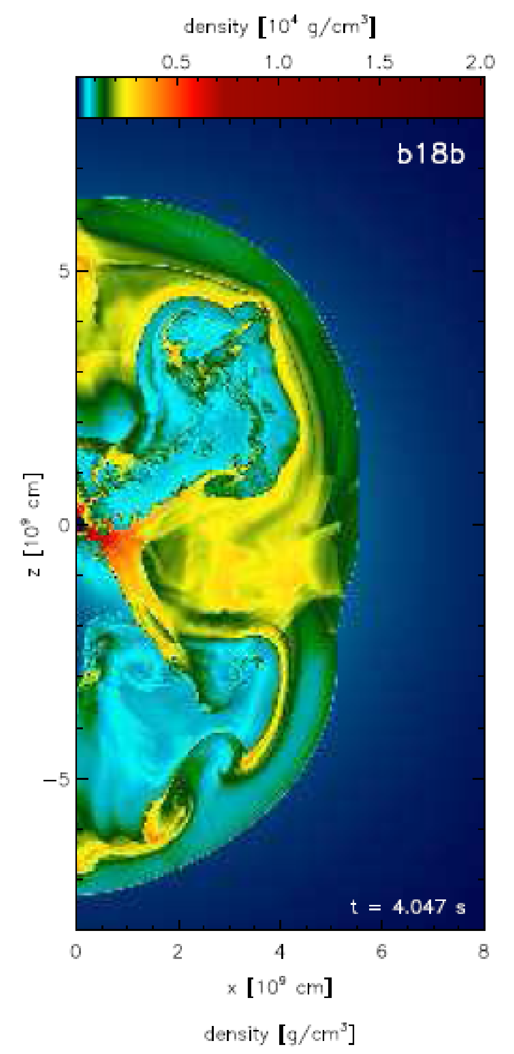
- Convection develops during the first second, creates large density/velocity fluctuations behind the shock

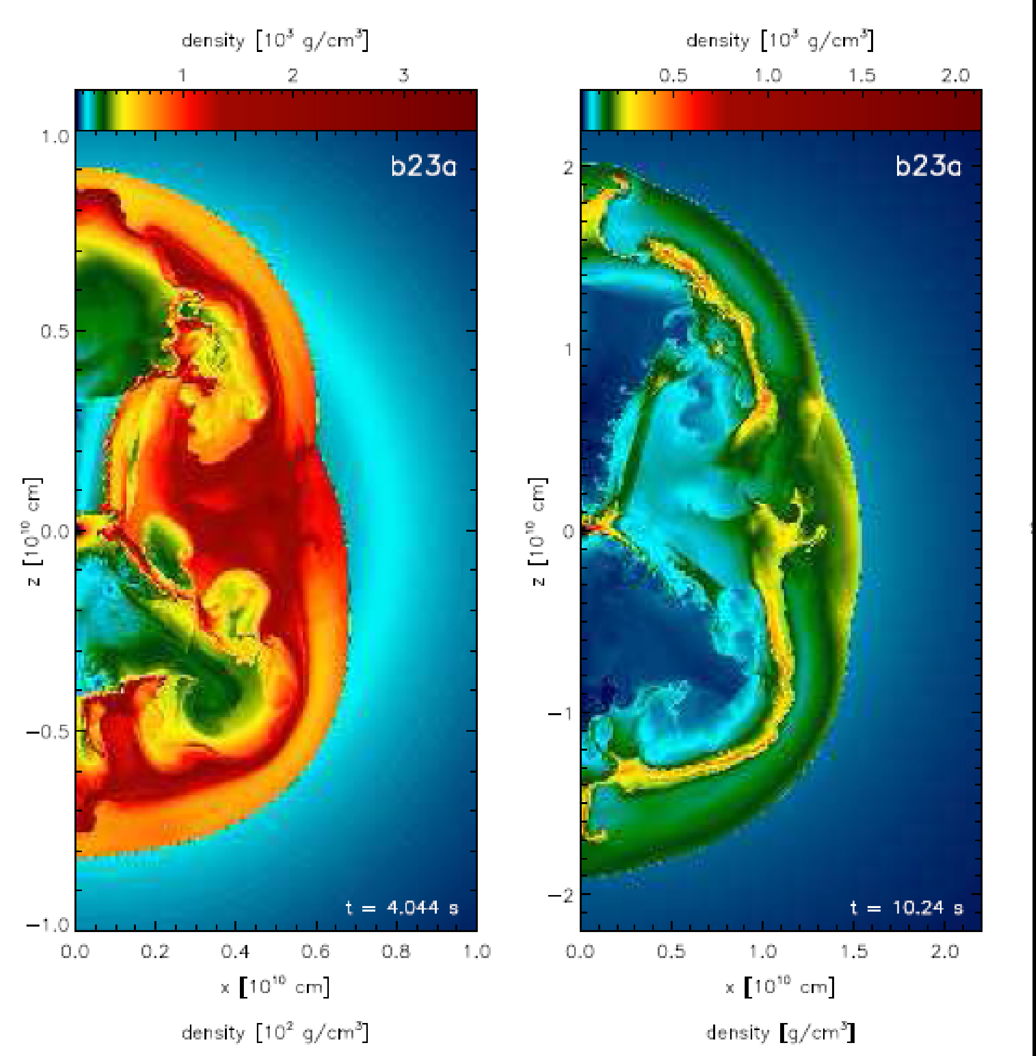


Scheck, Plewa, Janka, Kifonidis, and Muller, Phys. Rev. Lett. .92, 011103 (2004)

“Pulsar Recoil by Large-Scale Anisotropies in Supernova Explosions”

Turbulent fluctuations persist to later times

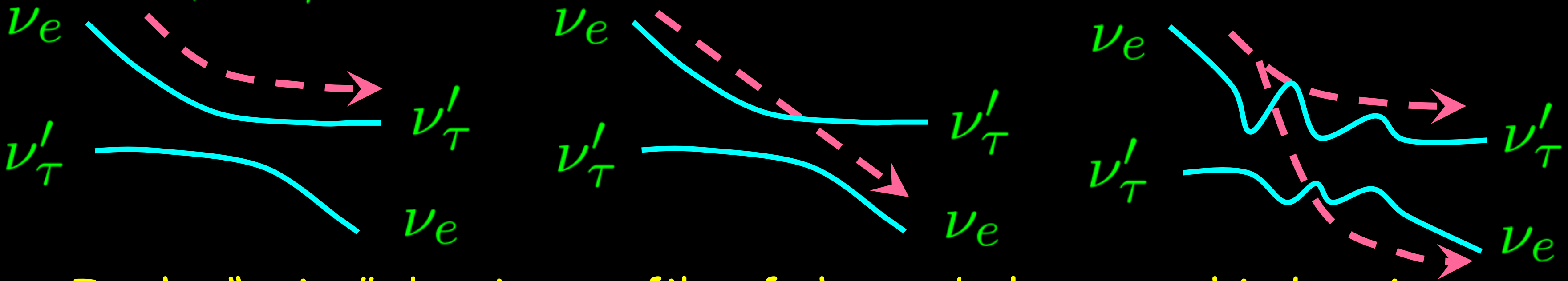




Density fluctuations can be important for neutrinos!

- Smooth profile: adiabatic or non-adiabatic

$$\nu'_\tau \equiv \nu_\mu \sin\theta_{atm} + \nu_\tau \cos\theta_{atm}$$



- In the "noisy" density profile of the turbulence, a third option: at densities near resonant, neutrinos may undergo "flavor depolarization".
  - Random walk on a sphere in flavor space
  - Effect known for a long time
    - A.Schafer, S. Koonin, Phys. Lett. B 185, 417 (1986)
    - W. Haxton, W-M. Zhang, Phys. Rev. D 43, 2484 (1991)
    - … many others

Can't we just apply existing analytical results in the literature?

- No, we can't!
- Exist analytical treatments of neutrino evolution in "delta-correlated noise" $\langle \delta n(x)\, \delta n(y) \rangle = n_0^2 L_0\, \delta(x-y)$
  - Nicolaidis, Phys. Lett. B 262, 303 (1991)
  - Loreti & Balantekin, Phys. Rev. D 50, 4762 (1994)
  - Loreti, Qian, Fuller, Balantekin, Phys. Rev. D 52 6664 (1995)
  - Balantekin, Fetter & Loreti, Phys. Rev. D 54, 3941 (1996)
  - Burgess & Michaud, Annals Phys. 256, 1 (1997)
  - …
- Turbulent fluctuations are not described by the delta-correlated noise. (Taken literally, delta-correllated noise is unphysical.)
  - No way to connect to large scale features observed in simulations.

Spin precession in turbulent magnetic field treated nicely in Miranda, Rashba, Rez, Valle, Phys.Rev.D70:113002,2004

Kolmogorov theory of turbulence

- Kolmogorov:
  - Energy pumped on large scales, dissipated on small scales
  - Between these two scales (in the "inertial range"), a turbulent cascade is formed, carrying energy from large to small scales
  - Relevant distance scales for neutrinos lie in the inertial range, dissipation scale much smaller
  - In the inertial range density (temperatures) fluctuations follow a power law, $\rho_\lambda \sim \rho_0 (\lambda/r_0)^\beta$
  - Kolmogorov: $\beta \simeq 1/3$ for velocities
- Is turbulence seen in realistic simulations strong enough to affect neutrinos?

Analytical solution, "noisy" resonance

- First, check if the evolution in the absence of the fluctuations would be adiabatic
- If not, that means that density change is very abrupt, adding turbulence to it doesn't change the result
- ->if the adiabaticity parameter

$$\gamma \equiv \frac{\pi(\Delta m^2 \sin 2\theta_{13}/4E)^2}{G_F|dn_0/dr|/\sqrt{2}} < 1$$

neutrino evolution is unaffected by the noise

  - Adiabaticity fulfilled for $\sin^2\theta_{13} \gtrsim 10^{-4}$-$10^{-3}$.

Analytical solution, "noisy" resonance II

- If $\gamma \gg 1$, the (perturbative) probability of a transition between mass eigenstates is given by

$$P_{perturb} \simeq \frac{G_F}{\sqrt{2} n'_0} \int dk C(k) G\left(\frac{k}{2\kappa}\right) \qquad \kappa \equiv \frac{\Delta m^2}{4E} \sin 2\theta_{13}$$

- Here $C(k)$ is a Fourier transform of the correlation function of the noise

$$C(k) \equiv \int dx \langle \delta n(0) \delta n(x) \rangle e^{-ikx}$$

- and the spectral response function $G(p)$ is given by

$$G(p) \simeq \frac{\Theta(p-1)}{p\sqrt{p^2-1}} \qquad \text{for } \gamma \gg 1$$

General properties of the solution

- The spectral response function $G(2E\, k/\Delta m^2 \sin 2\theta_{13})$ is peaked at $k \sim \Delta m^2 \sin 2\theta_{13}/2E$, up to a factor equals to inverse neutrino oscillation length
- For fluctuations on longer distance scales, the response is approximately zero (exp. suppressed); those fluctuations are followed adiabatically
- Contributions of fluctuations on shorter scales are power-law suppressed ($\sim k^{-2}$)
- Previously known analytical result for delta-correlated noise $\langle \delta n(0)\, \delta n(x) \rangle = n_0^2\, L_0\, \delta(x)$ is correctly reproduced (in the region of applicability $P \ll 1$)

Solution and Kolmogorov spectrum

- For Kolmogorov turbulence

$$C(k) \equiv \int dx \langle \delta n(0) \delta n(x) \rangle e^{-ikx} = C_0 k^{-5/3}$$

we have

$$P_{perturb} \simeq \frac{G_F}{\sqrt{2} n'_0} C_0 \left(\frac{\Delta m^2 \sin 2\theta_{13}}{2E} \right)^{-2/3} \times 0.84$$

- This means

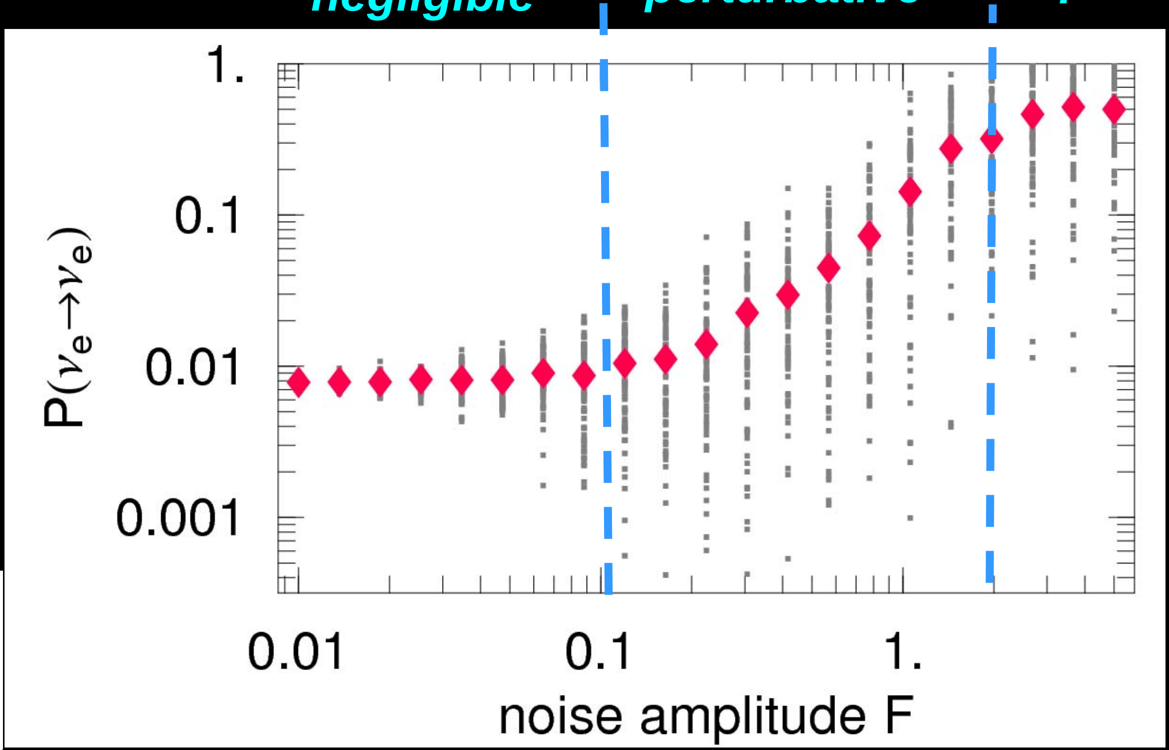
$$P \to \begin{cases} P_{perturb}, & P_{perturb} \ll 1/2, \gamma \gg 1 \\ \frac{1}{2}, & P_{perturb} \gtrsim 1/2, \gamma \gg 1 \\ 1, & \gamma \ll 1 \end{cases}$$

perturb. noise, adiabatic smooth
large noise, adiabatic smooth
nonadiabatic smooth

- See astro-ph/0607244 for details

Numerical check

- Check against direct calculations of neutrino conversion in simulated turbulence profile
- The three regimes are clearly seen

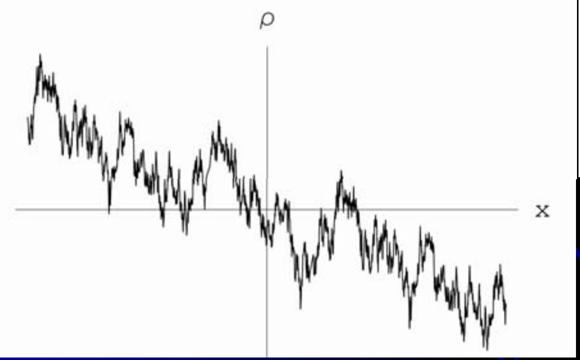


noise negligible

noise perturbative

complete depolarization

adiabatic

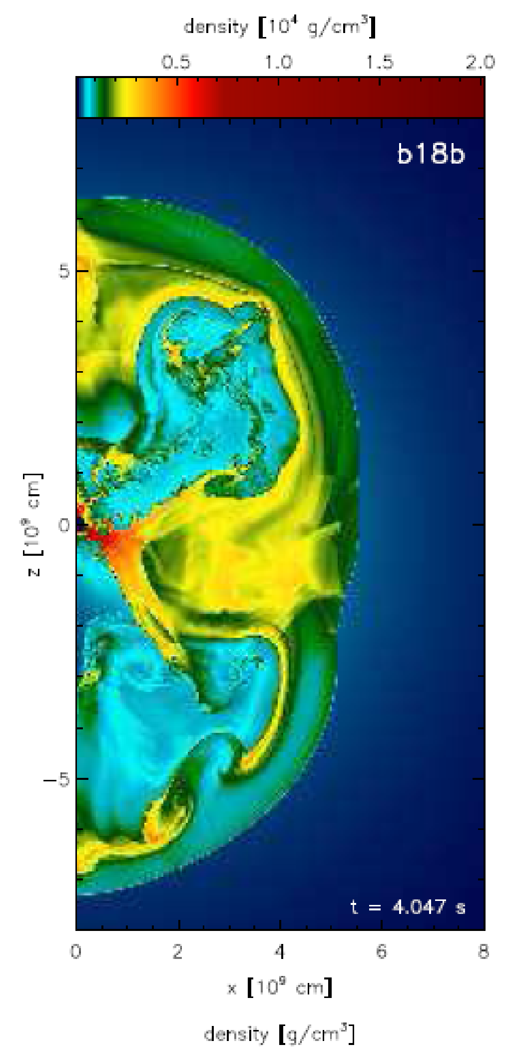


Implications

- Simulations see order one density variations on large scales r_0 -> use to fix C_0
- The noise amplitude on small scales turns out to be more than enough to insure complete depolarization by turbulence

$$\frac{\delta n_r}{n_r} > 0.1\ \theta_{13}^{1/3}$$

so long as the oscillation length stays below the scale height of the smooth component in the bubble (i.e. adiabaticity)



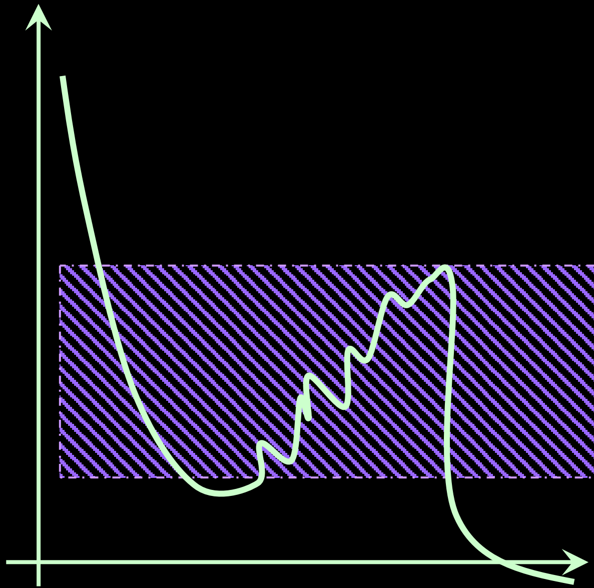
Off-resonance depolarization

- Since on resonance the effect is strongly oversaturated, but continuity expect that it becomes important before the density in the turbulence is diluted down to the resonance value
- -> The depolarization effect
  - starts setting in earlier, possibly at $\sim$ 3 seconds
  - Turns on gradually (more so than the shock effect)
- See astro-ph/0607244 for details

The shadow effect

- Turbulence produces 50/50 incoherent mixture of the two states
- Density matrix diag(1/2,1/2) commutes with any Hamiltonian -> any other features neutrino encounters, before or after turbulence, have no effect
- Sensitivity to front shock lost, replaced by the signal from turbulence

  Fogli, Lisi, Mirizzi, hep-ph/0603033
- Turbulence casts a shadow!
  - If neutrino encounters turbulence at resonant densities and in the absence of the turbulence transition would have been adiabatic, the shadow effect occurs
- At t∼ 8 sec the L-resonance also becomes depolarized -> no regeneration in Earth



Implications

- For neutrino properties:
  - Signal change (lowering of E_{av}, broadening of the spectrum, dip in the # of events) will occur *either* in the neutrino or antineutrino channel, indicating the sign of mass hierarchy
  - Lower bound on θ_{13} , at the level of $\sin^2\theta_{13} \gtrsim 10^{-4}$-$10^{-3}$.
- For understanding supernova physics
  - Observe the turbulence in the expanding hot bubble behind shock in real time -> confirm the key ingredient of the explosion mechanism
  - Spectrum swapping ν_e <-> $\nu_{\mu,\tau}$ will be incomplete -> be careful in inferring original temperatures
  - Signal may (strongly) depend on the direction!
- Others being worked on… Stay tuned!

Acknowledgments

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