Neutrino signatures of supernova turbulence

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With Andrei Gruzinov (NYU)
astro-ph/0607244 + in prep.

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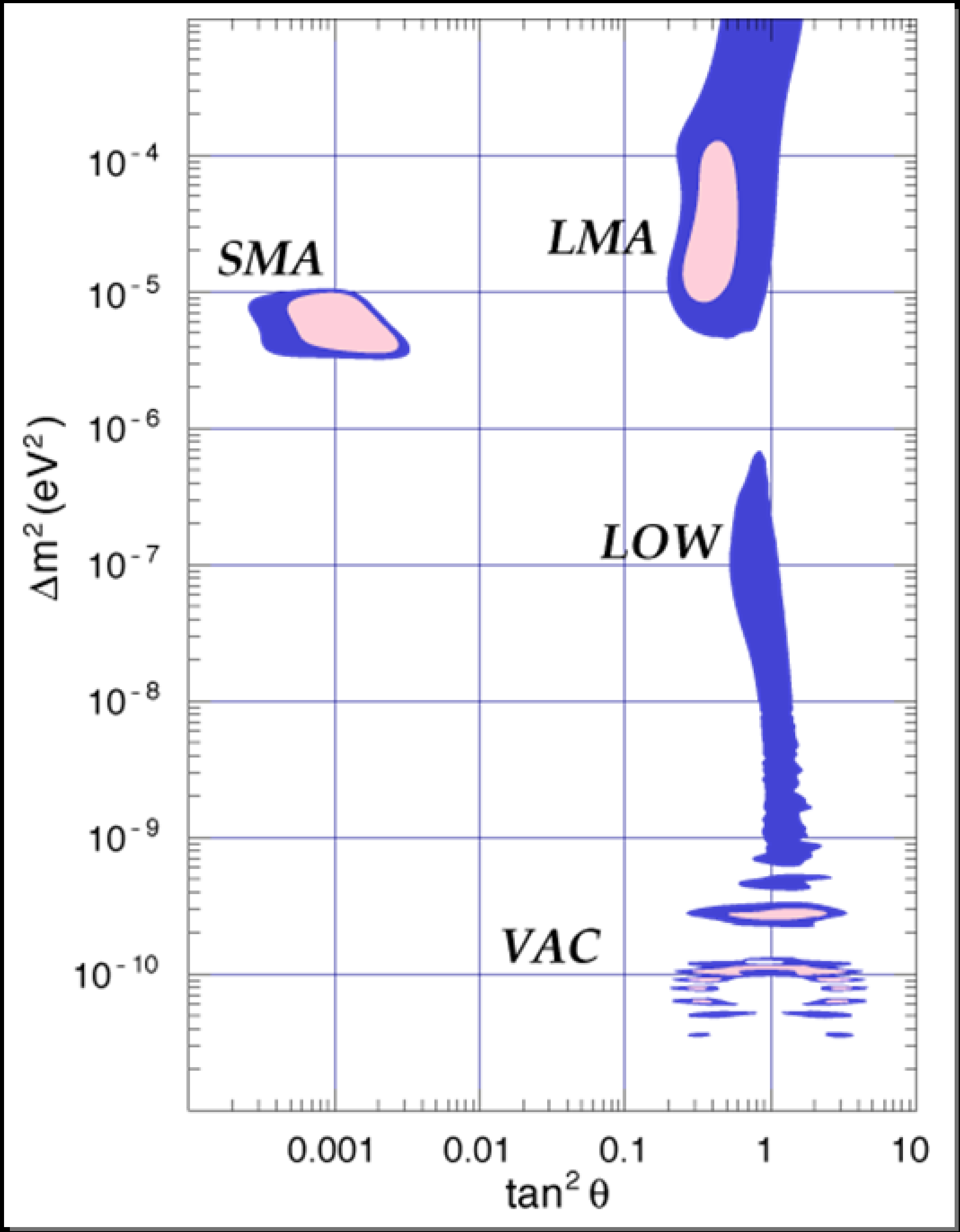
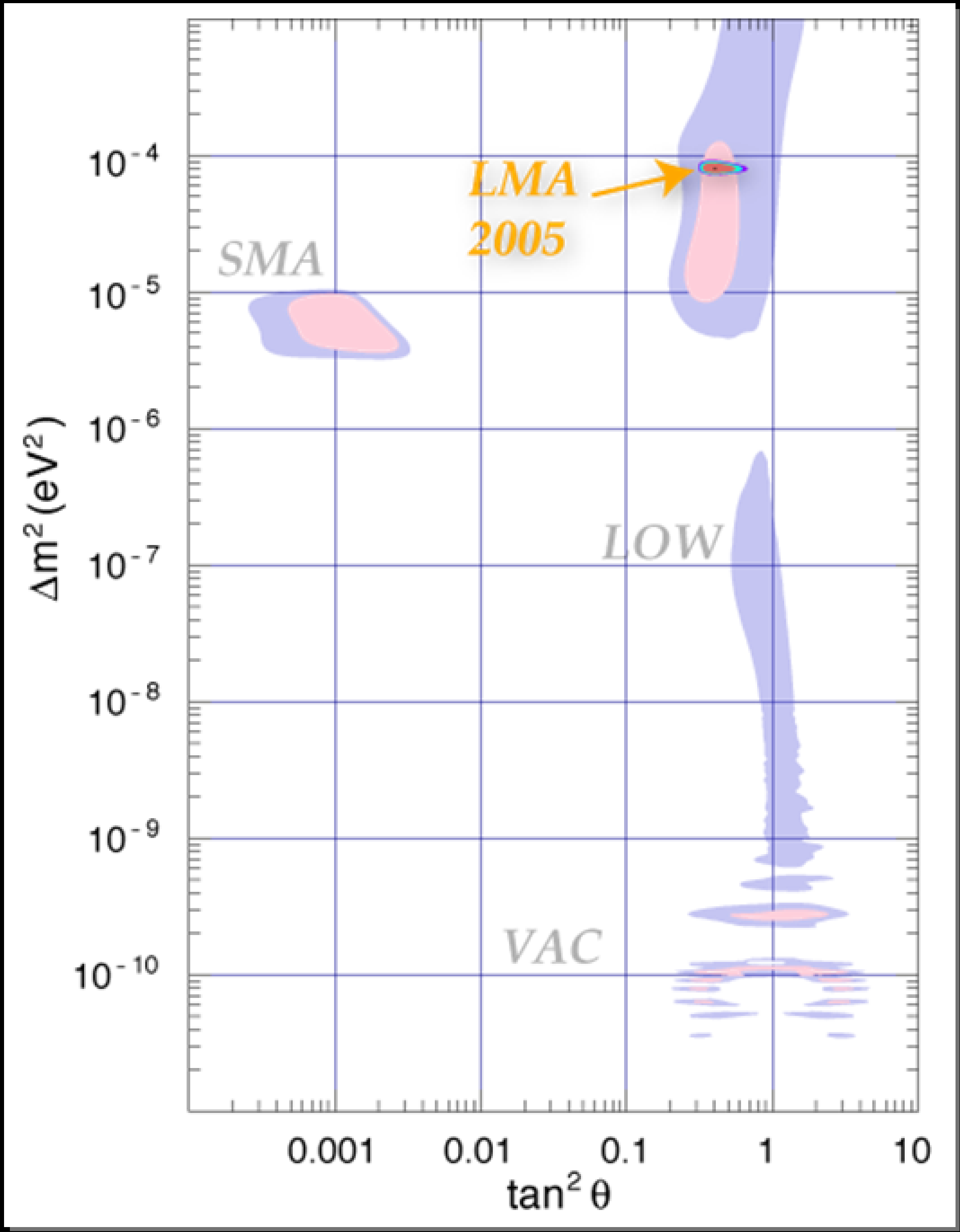
- Evgeny Akhmedov (Munich -> MPI Heidelberg), Sterling Colgate (LANL), Chris Fryer (LANL), George Fuller (UCSD), Wick Haxton (INT), Thomas Janka (MPI, Garching), Cecilia Lunardini (INT, Seattle), Georg Raffelt (MPI, Munich), Timur Rashba (MPI, Munich), Sanjay Reddy (LANL) and Mark Wise (Caltech) for helpful conversations

- In the last seven years, neutrino physics has seen astonishing progress!

Just compare this fit to the solar neutrino data circa 2000…



- … to the situation 5 years later!



Neutrinos from core-collapse supernovae

- Progress in our understanding of neutrinos from core-collapse SN has likewise been remarkable! *Incomplete* list:
  - circa 2000: SN ν's undergo relatively simple flavor transformations in a smooth profile of the progenitor star, unaffected by the explosion, neutrino self-refraction, etc.
  - 2002: the front shock reaches the resonance densities while ν's are being emitted!
    - R. Schirato, G. Fuller, astro-ph/0205390
  - 2004: maybe more than one shock
    - R. Tomas et al, astro-ph/0407132
  - 2005-2006: neutrino self-refraction matters
    - H. Duan, G. Fuller, Y.-Zh. Qian, astro-ph/0511275 and subsequent work
  - 2005: bubbles of low density matter
    - J. Kneller, G. McLaughlin, hep-ph/0509356
  - 2006: neutrinos may come from an accretion disk, not just protoneutron star
    - G. McLaughlin, R. Surman, astro-ph/0605281
  - 2006: turbulent density fluctuations matter!
    - A.F., A. Gruzinov, astro-ph/0607244 + in prep ← We are here!
  - …

The progress continues!

- Neutrino astrophysics is a rapidly developing field
  - see other talks at this workshop
  - putting together all *known* effects for supernova neutrino still remains to be done, as stressed by George Fuller
    - state-of-the-art SN models (multi-D hydro, neutrino transport and decoupling, nuclear equation of state, etc)
    - neutrino oscillations MUST be there
    - neutrino self-refraction
    - front shock
    - turbulence
    - accretion disks/fallback
    - …
  - whoever tells you "neutrino physics is done" doesn't know what he's talking about! ;-)

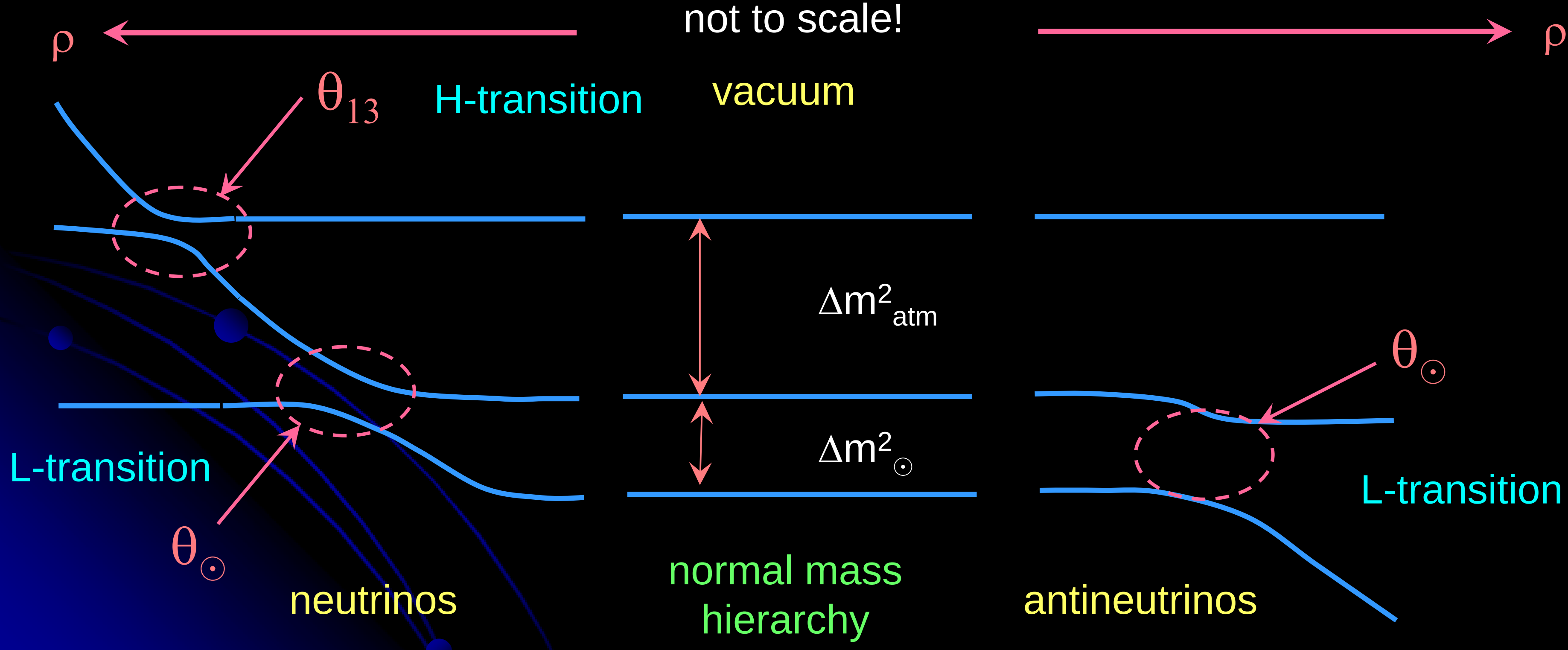
Goal of this talk

- This talk will focus on one particular effect, modification of the MSW flavor transformation by the turbulence of the explosion
- Rules of the game: known physics!
  - No sterile neutrinos
  - No non-standard interactions
  - No magnetic moments
  - 3 known active flavors with known oscillation parameters; the only unknowns are θ_{13} and the type of neutrino mass hierarchy
  - In future, needs to be combined with other effects
- Results may have applicability beyond the SN set-up

MSW transformations in SN: simplest case – smooth profile

- see, e.g., A. Dighe, A. Smirnov, hep-ph/9907423

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



MSW transformations in SN: simplest case – smooth profile

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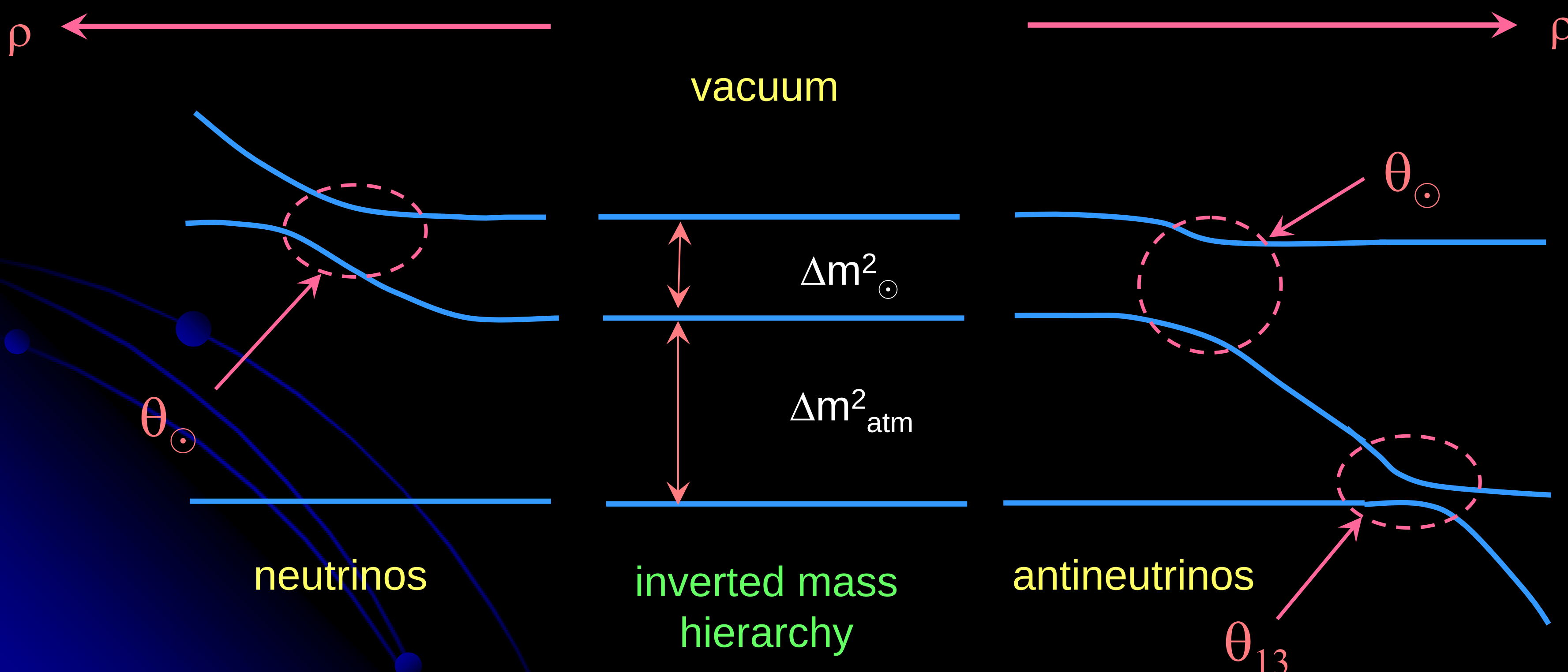


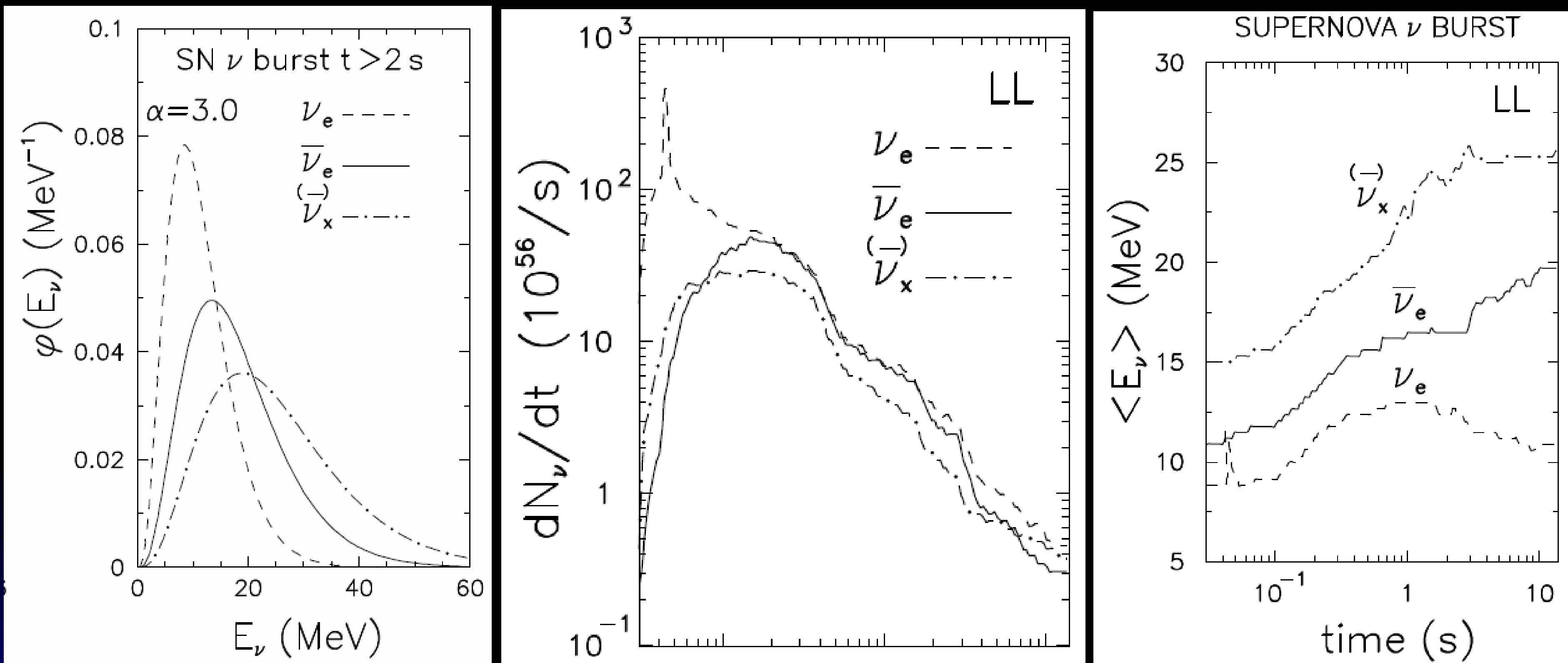
Flavor transformations in the first few seconds

- Resonance regions at a few $\times$ 10^4 km, a few $\times$ 10^5 km, density profile unperturbed by the explosion
- This means density gradients in progenitor is very smooth, compared to the neutrino osc. length
- on resonance, $\lambda_{osc} \sim (\Delta m^2/(2E)\ \sin 2\theta)^{-1}$
  - 10^1 km for $E_\nu \sim 15$ MeV and atm. Δm^2

  -> the H-resonance is adiabatic so long as $\sin 2\theta_{13} \gtrsim 10^{-4}$-$10^{-3}$
  - a few $\times$ 10^2 km for $E_\nu \sim 15$ MeV and solar. Δm^2

  -> the L-resonance is guaranteed adiabatic (parameters known)
- Original anti-ν_e are converted into anti-ν_μ and anti-ν_τ (and vice versa) -> hotter observed spectrum

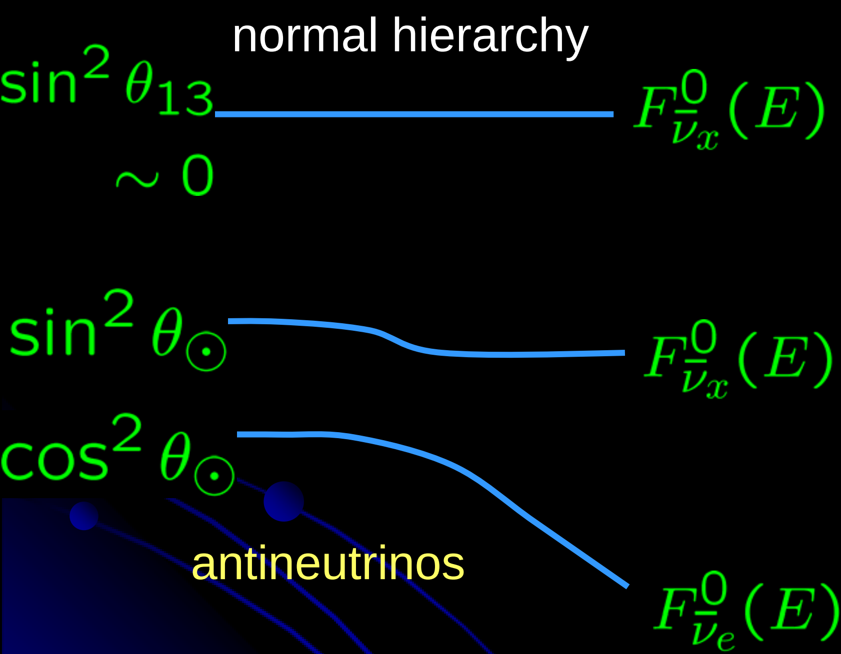
“Typical” spectra

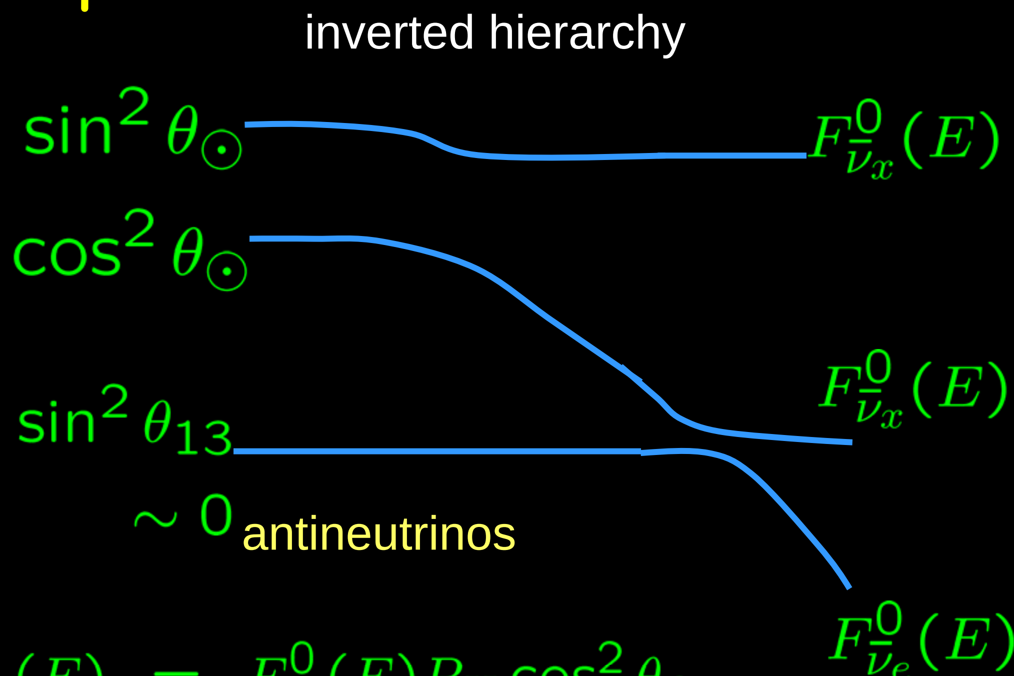


- from hep-ph/0412046; after T. Totani, K. Sato, H.E. Dalhed, and J.R. Wilson

Observed vs. original spectra

- electron antineutrino spectrum



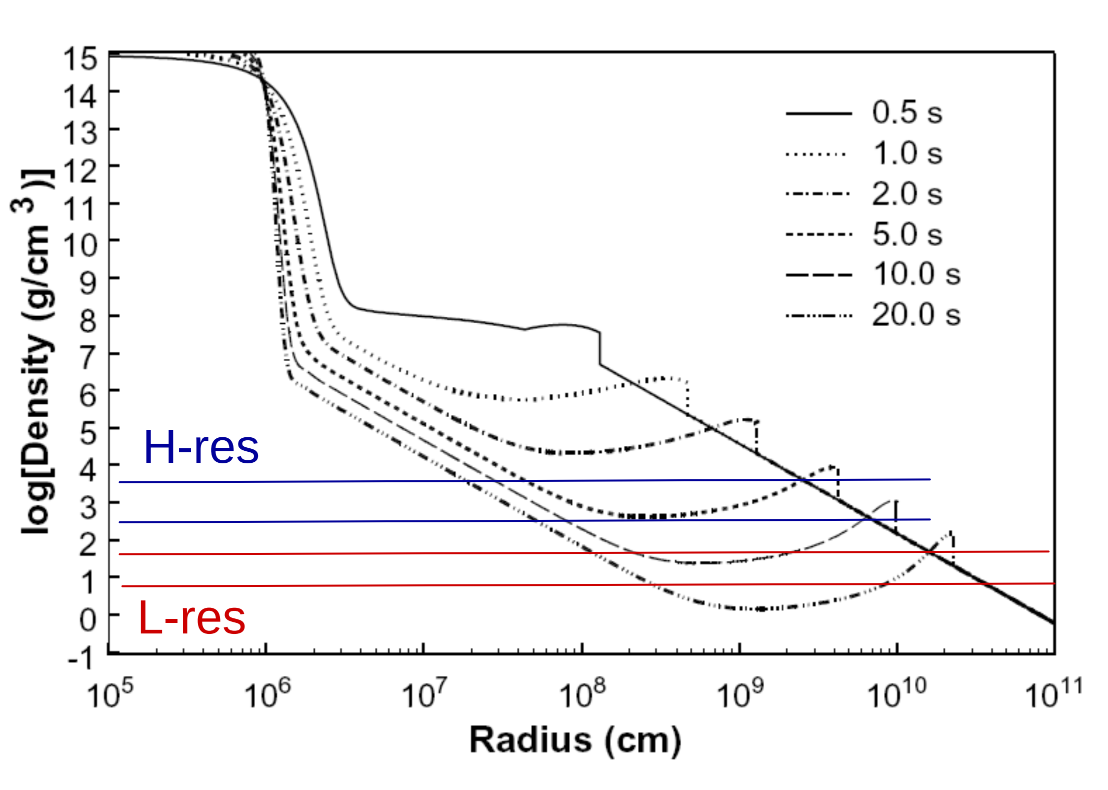


$$F_{\bar\nu_e}(E) = F^0_{\bar\nu_e}(E)\cos^2\theta_\odot + F^0_{\bar\nu_x}(E)\sin^2\theta_\odot$$

$$\begin{aligned} F_{\bar\nu_e}(E) &= F^0_{\bar\nu_e}(E) P_H \cos^2\theta_\odot \\ &+ F^0_{\bar\nu_x}(E)(1 - P_H)\cos^2\theta_\odot \\ &+ F^0_{\bar\nu_x}(E)\sin^2\theta_\odot \end{aligned}$$

Shock reaches the resonant layer

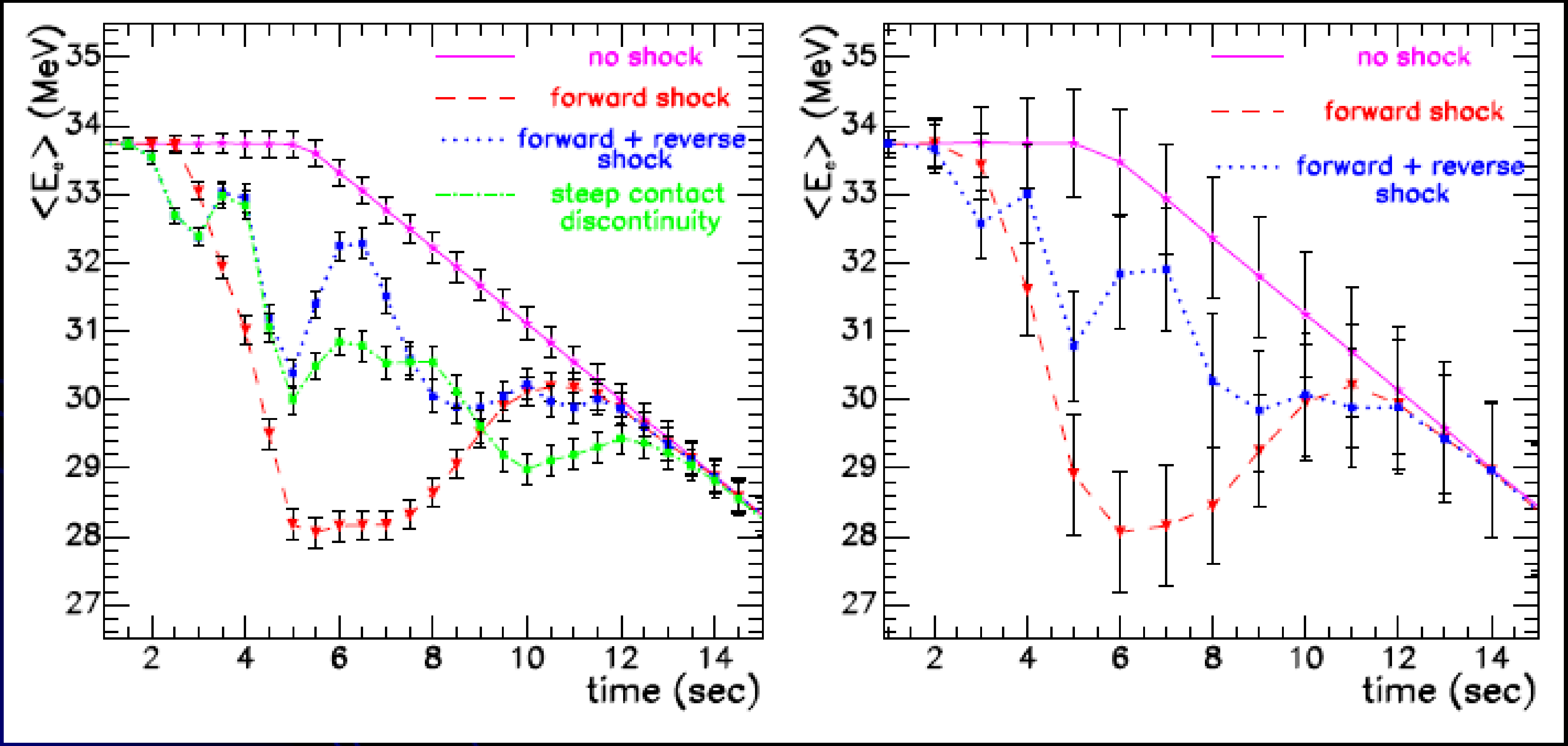
- At 3-5 seconds, shock reaches the H-resonant layer, while neutrinos are still streaming out of the protoneutron star
- Shock is very steep (photon mean free path) -> transition changes to maximally nonadiabatic



Schirato & Fuller, astro-ph/0205390

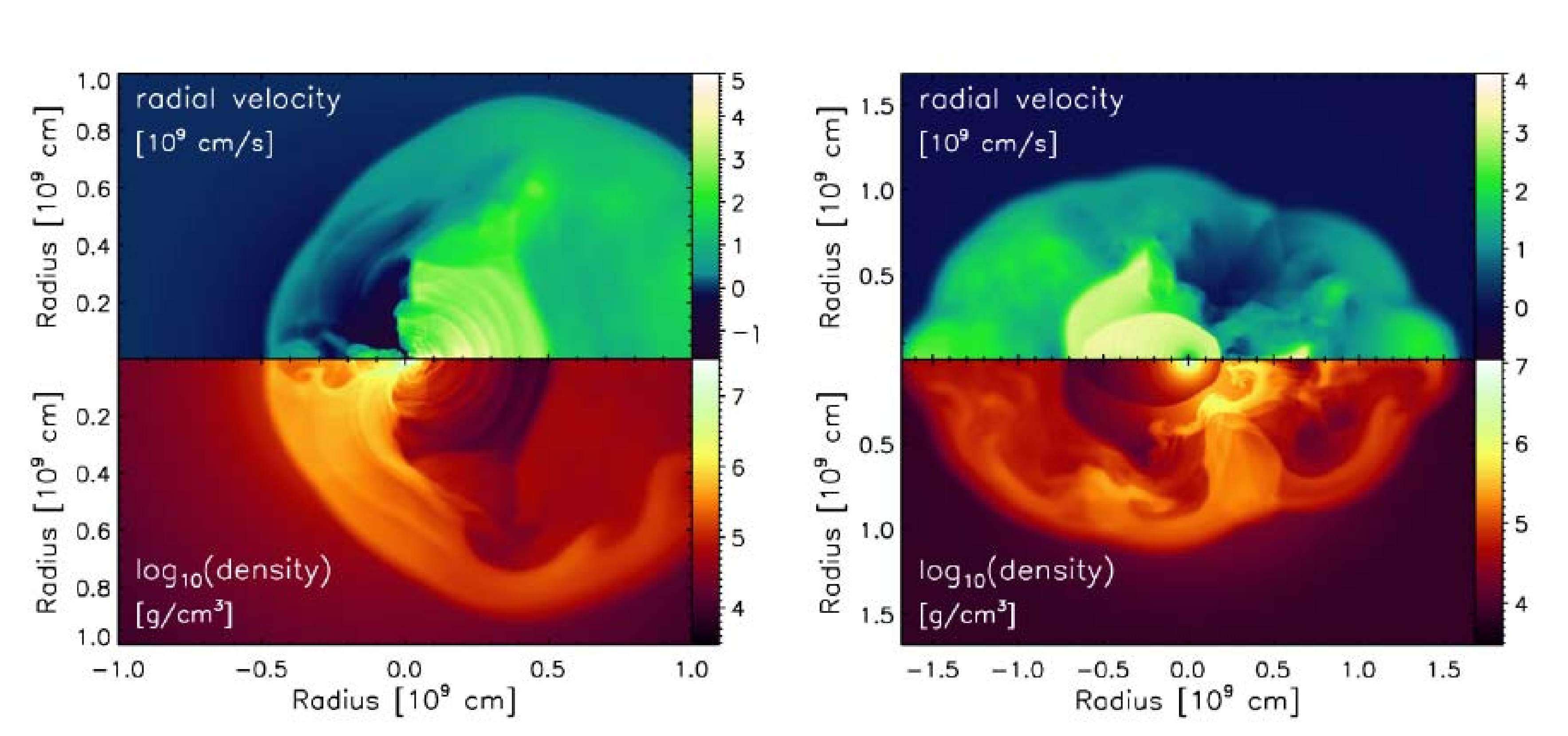
Predicted signatures at Super-K and megaton water-Cherenkov detector

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



Turbulence

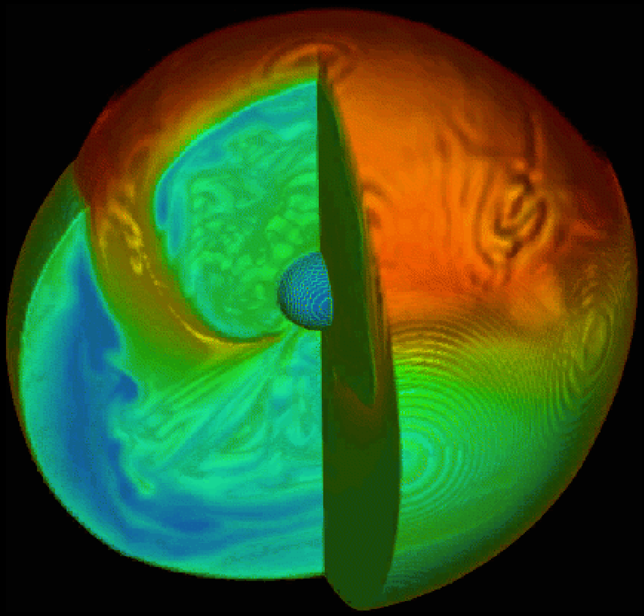
- Latest state of the art simulations show vigorous turbulence behind the shock front at early times



Scheck, Plewa, Janka, Kifonidis, and Muller, Phys. Rev. Lett. .92, 011103 (2004)
"Pulsar Recoil by Large-Scale Anisotropies in Supernova Explosions"

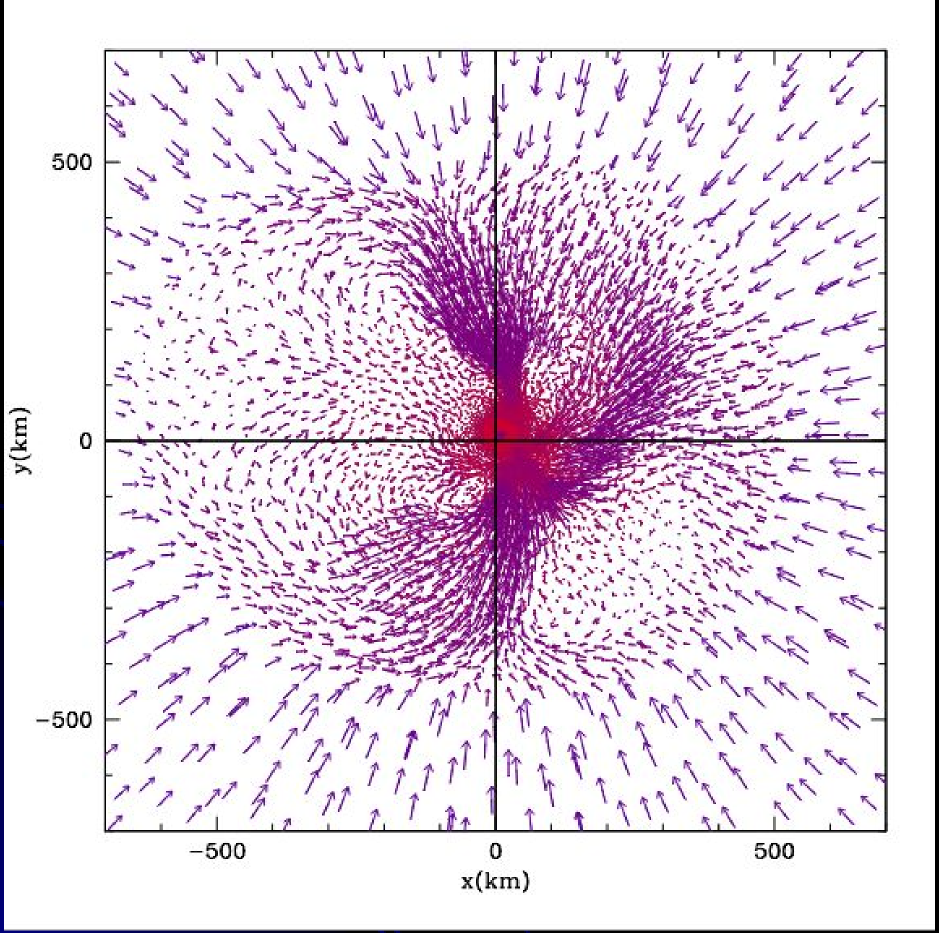
3D simulations by

- Blondin, Mezzacappa, & DeMarino
- Many thanks to the Oak Ridge group!
- `http://www.phy.ornl.gov/tsi/pages/simulations.html`



Very important for the explosion

- Convection not just a curiosity, essential for the explosion mechanism!

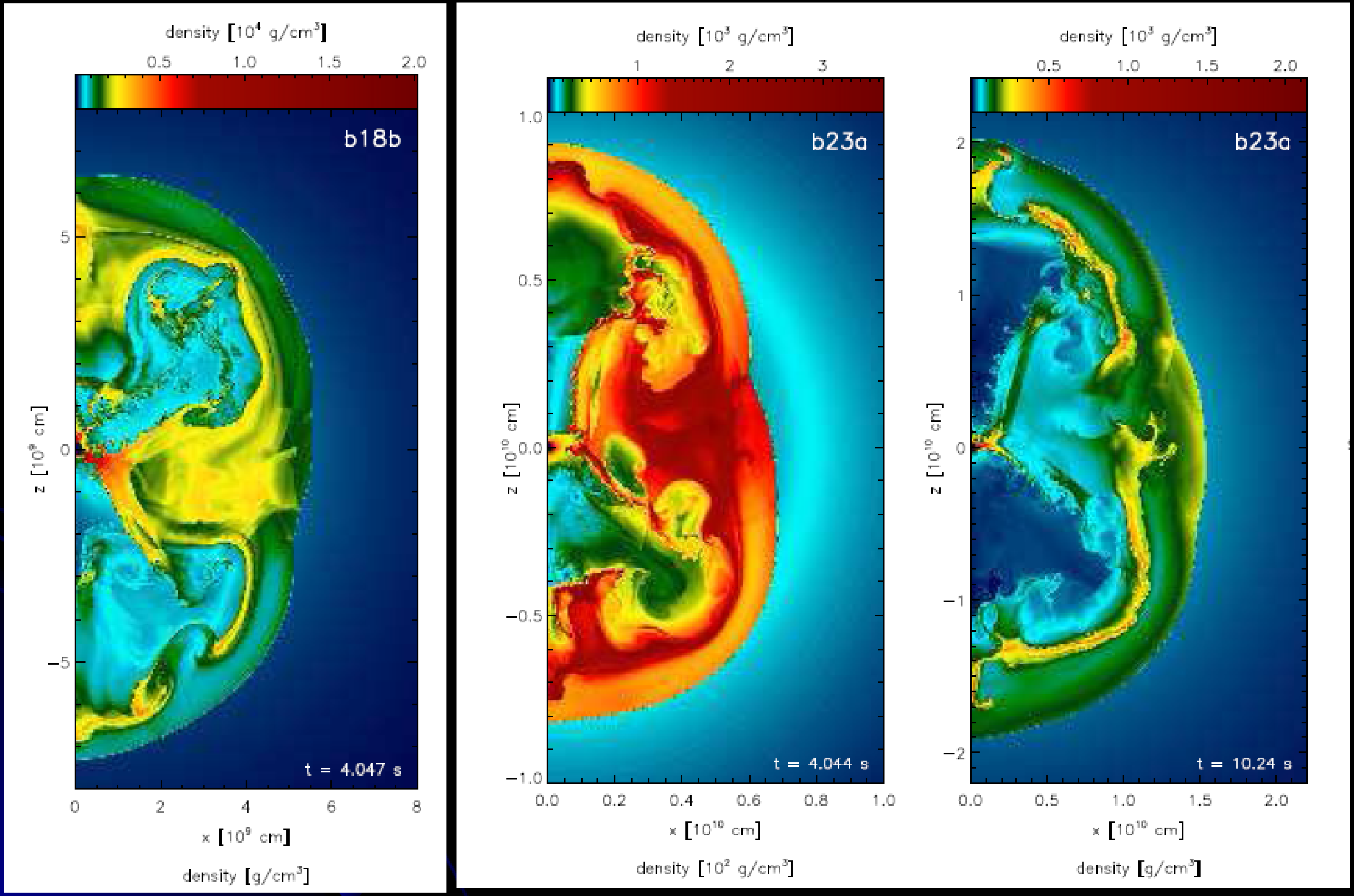


Snapshot of a 3D simulation at t=340 ms by Chris Fryer

Convection brings energy from the dense region near the proto-neutron star to the region behind the shock

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

Turbulence persists to later times



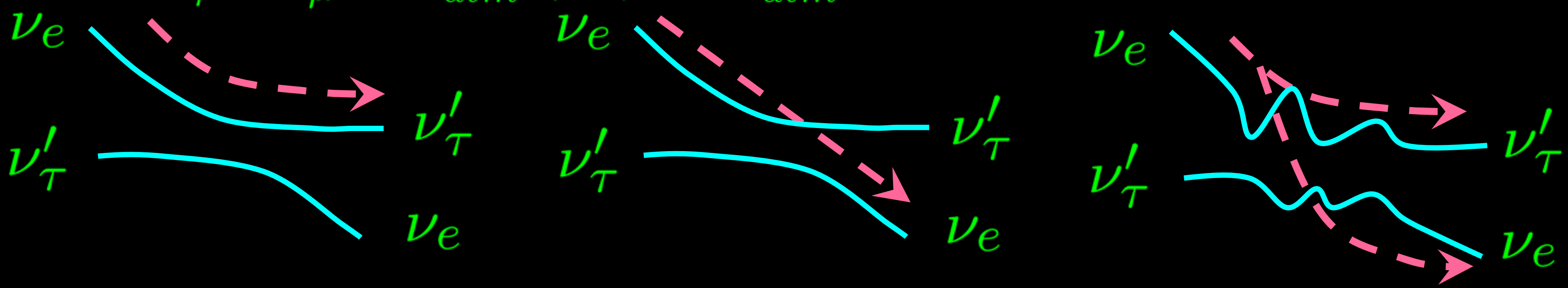
Reproduces many observed features

- SN1987A: final Fe group velocities, strong H/He mixing, prolate anisotropy of inner ejecta
- Pulsar kicks in excess of 1000 km/s possible
- "Many fundamental properties of observed supernovae and neutron stars might be traced back to the same origin, i.e. to non-radial hydrodynamic instabilities during the first second of a neutrino-driven SN explosion"
- For details see
  - Kifonidis, Plewa, Scheck, Janka, and Muller, astro-ph/0511369
  - Scheck, Kifonidis, Janka, Muller, astro-ph/0601302

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".
  - 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

Putting together simulations and our results on neutrino evolution

- As we will see, relevant fluctuations are those on scales $\lesssim$ 10 km $(0.3/\sin 2\theta_{13})(E_\nu/10\ \mathrm{MeV})$
- Simulations don't resolve, unless θ_{13} very small
- Also, the details of the turbulence may be quite different in 2D and 3D
- Need physical model of density fluctuations in supernova turbulence!
- Take only most basic (robust) features of the simulations

Use Kolmogorov

- Use Kolmogorov:
  - Energy pumped on large scales ("outer scale"), dissipated on small scales ("inner scale")
  - Between these two scales (in the "inertial range"), a turbulent cascade is formed, carrying energy from large to small scales
  - An eddy of a given size l fragments to smaller ones on the time scale of one turn, $\tau \sim l/v$
  - Energy is transported without piling up at any scale in the inertial range -> $v^2/(l/v)=const$
  - -> Velocities behave as a power law, $v_\lambda \sim v_0 (\lambda/r_0)^\beta$, with $\beta \simeq 1/3$ (incompressible fluid). Density (temperatures) should scale in a similar way.
  - Scales relevant for neutrinos lie in the inertial range.
  - Cascade forms quickly (on timescales of turn of large eddies)

How does neutrino flavor evolution proceed in Kolmogorov turbulence?

- Up to now, unsolved problem!
- It is well-known that density fluctuations *could* be important for neutrinos
  - A.Schafer, S. Koonin, Phys. Lett. B 185, 417 (1986)
  - W. Haxton, W-M. Zhang, Phys. Rev. D 43, 2484 (1991)
- 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)
  - ...
- Yet fluctuations in turbulence look nothing like delta-correlated noise. No way to connect to large scale features observed in simulations. (Taken literally, delta-corr. noise is unphysical.)

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

Task

- Is turbulence seen in realistic simulations strong enough to affect neutrinos?
- Understand qualitatively the physics of flavor evolution in Kolmogorov-like turbulence
- Derive analytical criterion for neutrino depolarization in turbulence
- Compare with fluctuation amplitudes seen in the simulations.

Step I: toy model

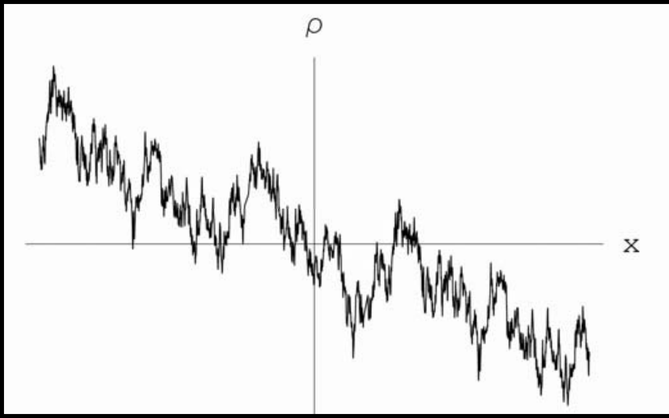
- Start with a toy model: noise $\delta n(x)$ with a Kolmogorov spectrum

$$\delta n(x) = F \sum_{k=1}^{600} k^{\beta} \cos[kx + \phi(k)],$$

$$\beta \sim -5/6,$$

superimposed on a smooth linear profile $n_0=x$ (justified since θ_{13} is small)

- Choose osc. parameters such that without noise evolution adiabatic
- Investigate what happens as the noise amplitude F changes



Numerical calculations repeated with random phases

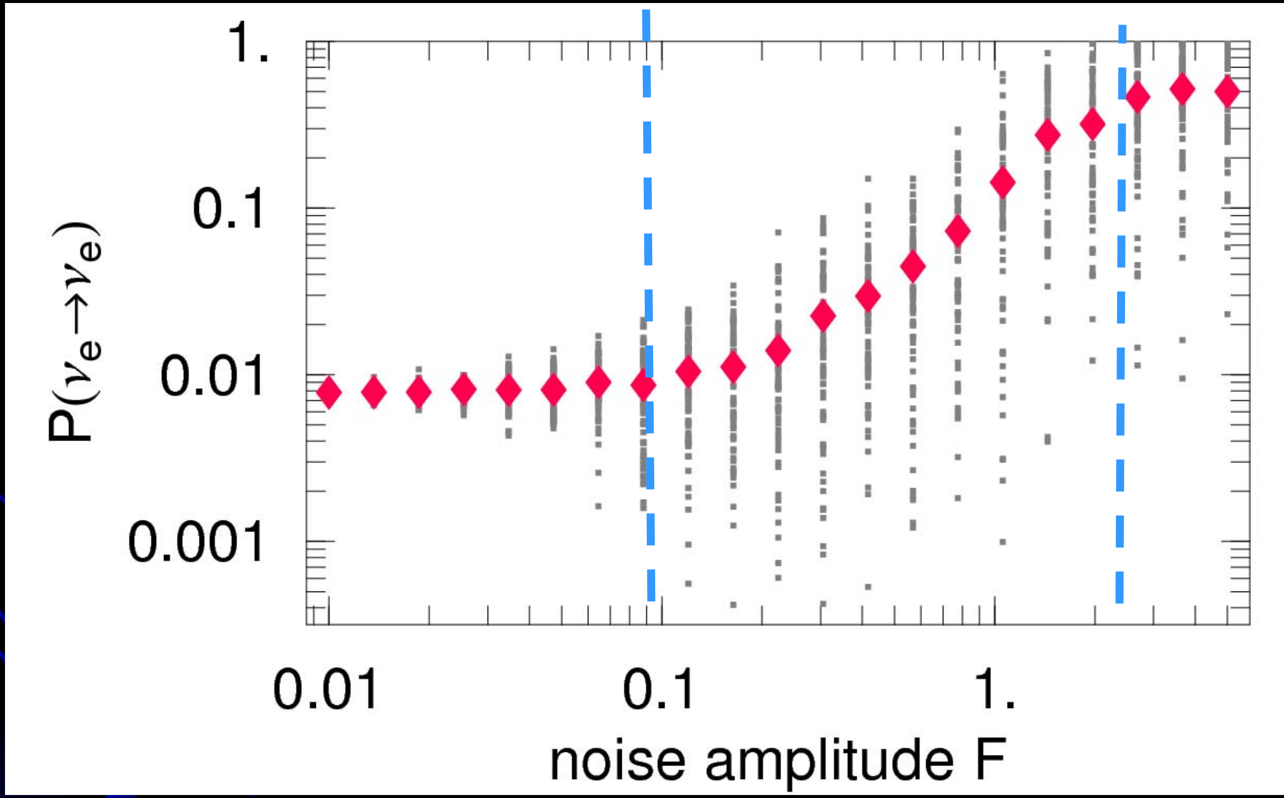
- Three regimes are clearly seen

noise negligible

noise perturbative

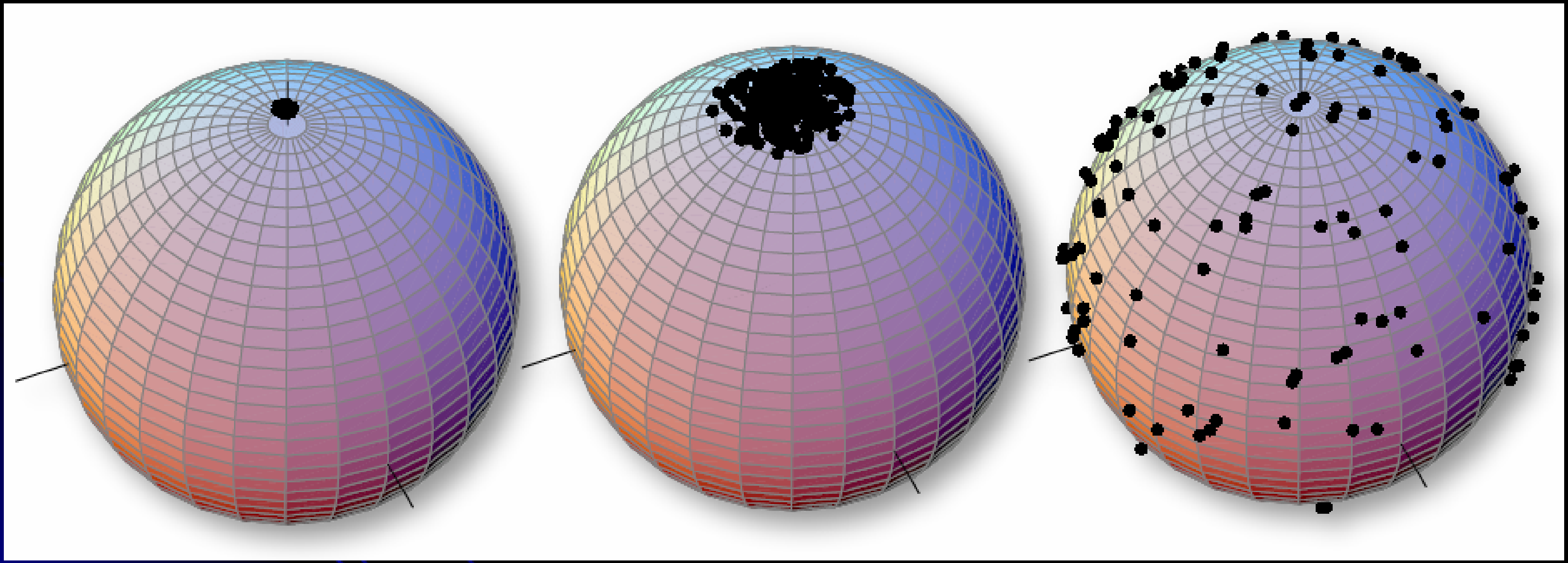
complete depolarization

adiabatic in the absence of fluctuations



Spin Analogy

- Density fluctuations -> fluctuating magnetic field -> spin random-walks on a sphere

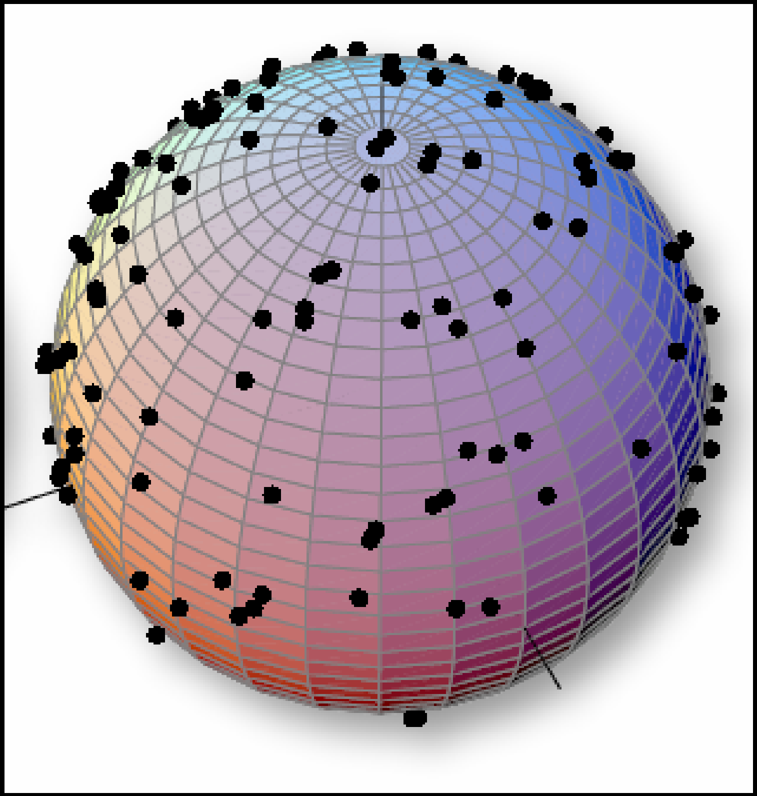


F=0.01 F=0.1 F=1

Depolarization limit

- For sufficiently large density fluctuations random walk covers the sphere: complete depolarization
- Either flavor equally likely. State described by the density matrix

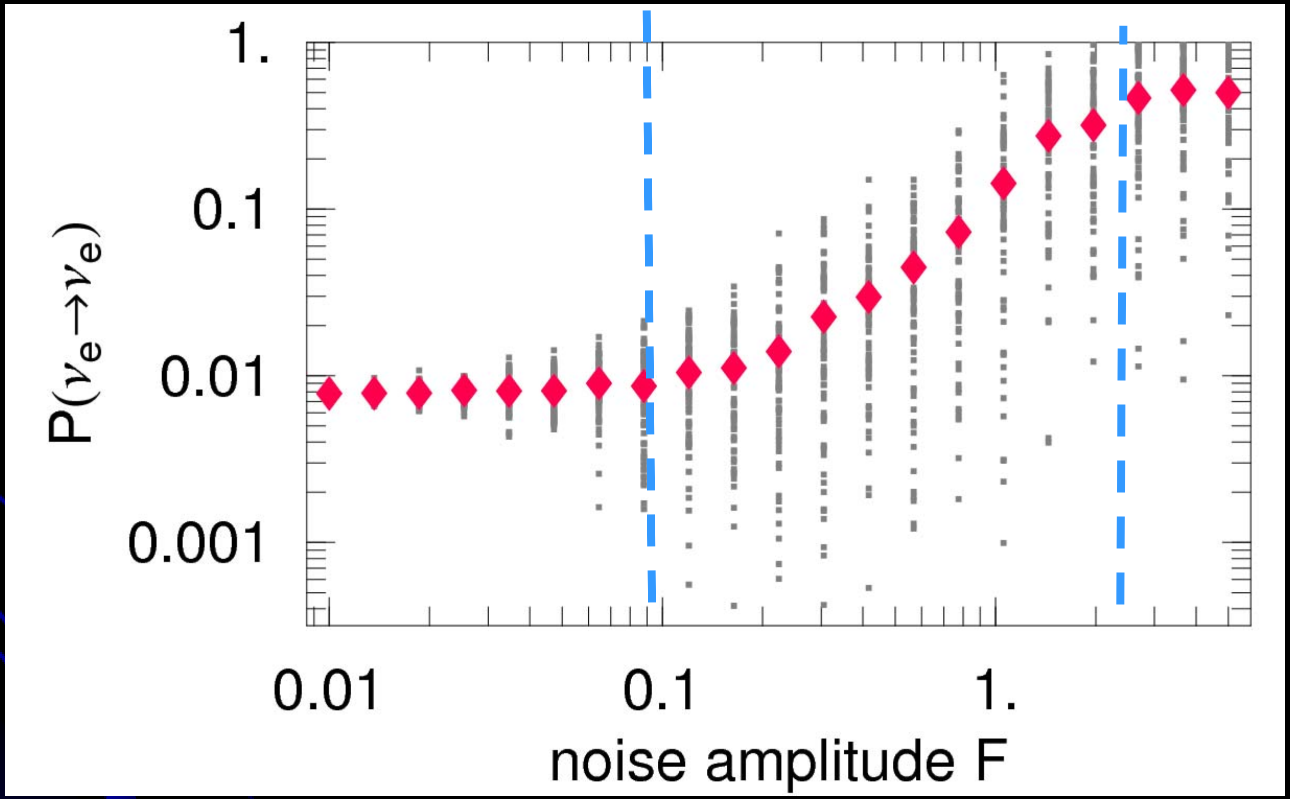
$$\rho = \begin{pmatrix} 1/2 & 0 \\ 0 & 1/2 \end{pmatrix}$$



F=1

Step II: Enough to find the probability in the perturbative regime

- If $P_{perturb} > \frac{1}{2}$ -> $P_{true} = \frac{1}{2}$ ->complete depolarization



Analytical result

- The (perturbative) probability of a transition between mass eigenstates is given by (saddle point approximation)

$$P_{perturb} \simeq \frac{G_F}{\sqrt{2}n_0'} \int dk C(k) G\left(\frac{k}{2\kappa}\right) \qquad \kappa \equiv \frac{\Delta m^2}{4E} \sin 2\theta_{13}$$

- 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

$$G(p) \simeq \frac{\Theta(p-1)}{p\sqrt{p^2-1}}$$

General properties of 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 $P \ll 1$)

What if non-adiabatic in smooth profile?

- In this case, neutrino oscillation length, $\lambda_{osc} \sim (\Delta m^2/(2E) \sin 2\theta)^{-1}$ is much greater than the outer scale of the turbulence (the radius of the shock) -> evolution non-adiabatic with or without turbulent fluctuations
- the adiabaticity parameter

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

Step III: 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

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

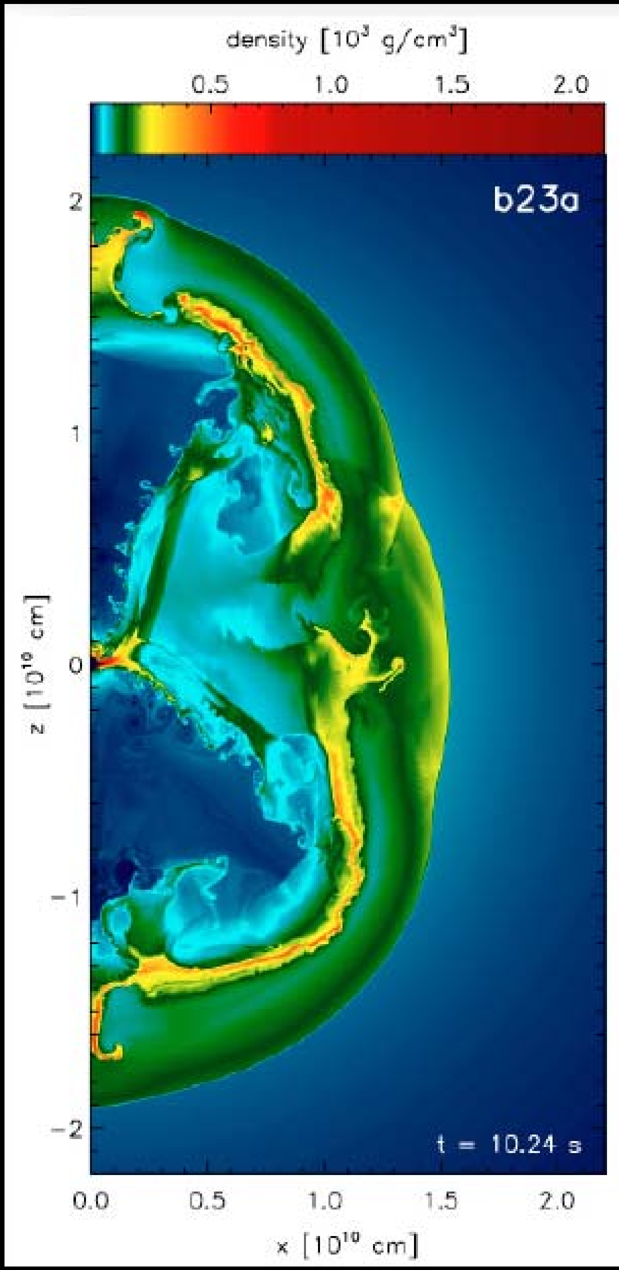
perturb. noise, adiabatic smooth
large noise, adiabatic smooth
nonadiabatic smooth

Step IV: Use simulations

- 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)



Robust with respect to the details of the spectrum

- For general noise exponent α in

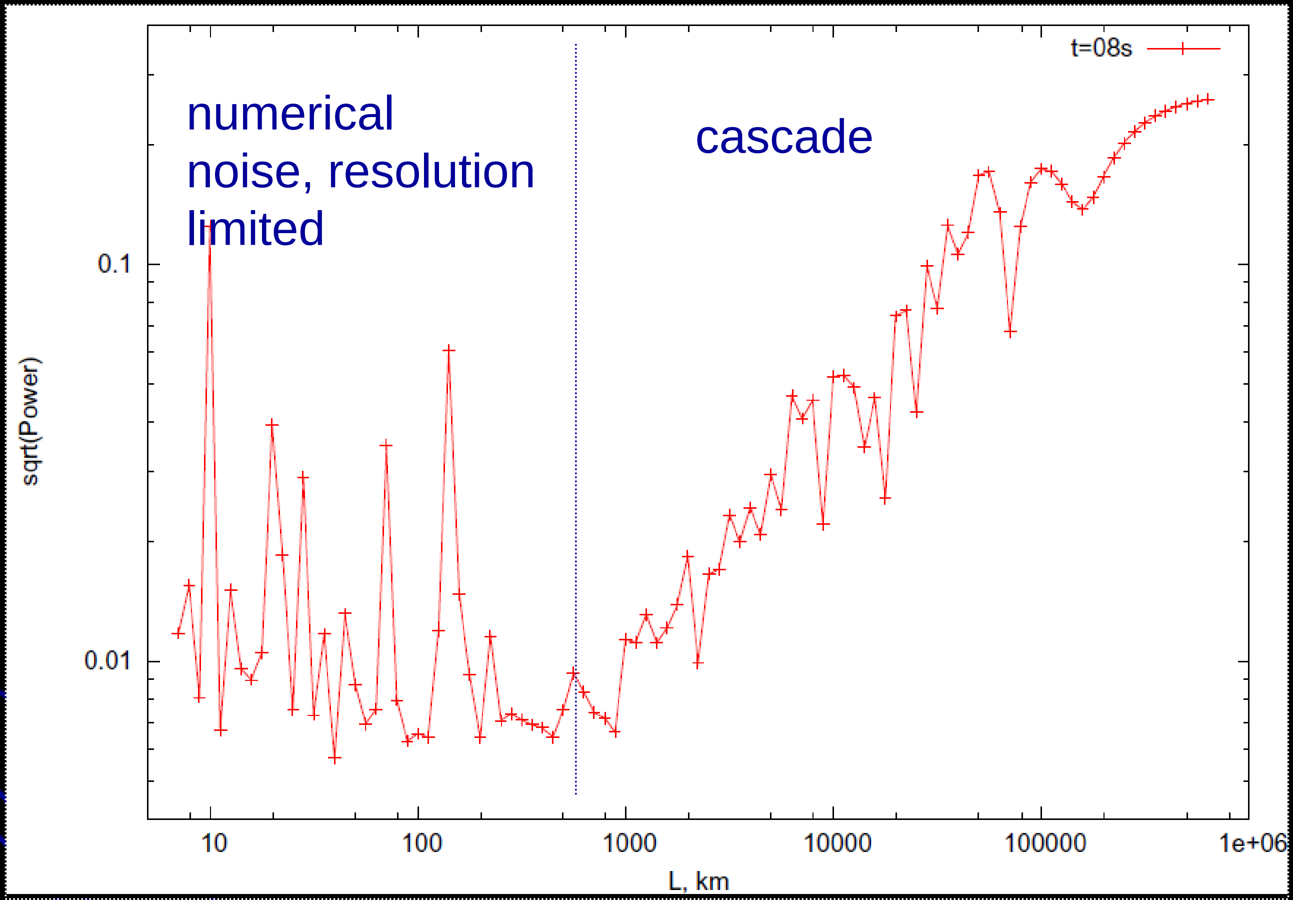
$$C(k) \equiv \int dx \langle \delta n(0) \delta n(x) \rangle e^{-ikx} = C_0 k^{\alpha}$$

we have

$$\delta n_L / n_L > f \; \theta_{13}^{-(\alpha+1)/2}$$

where the coefficient f varies from 0.04 to 0.25 as α varies from -1.5 to -2

Spectrum from the Janka group



- Many thanks to Timur Rashba!

Off-resonance depolarization

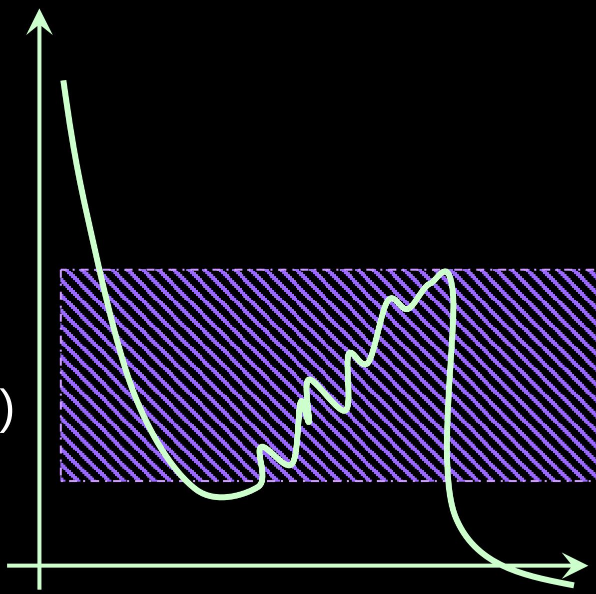
- Since on resonance the effect is strongly oversaturated, by continuity it should become important before the density in the turbulence is diluted down to the resonance value
- -> The depolarization effect
  - starts setting in earlier, possibly at $\sim$ 3 seconds
  - Turns on gradually (more so than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

Turbulence shadow

- 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

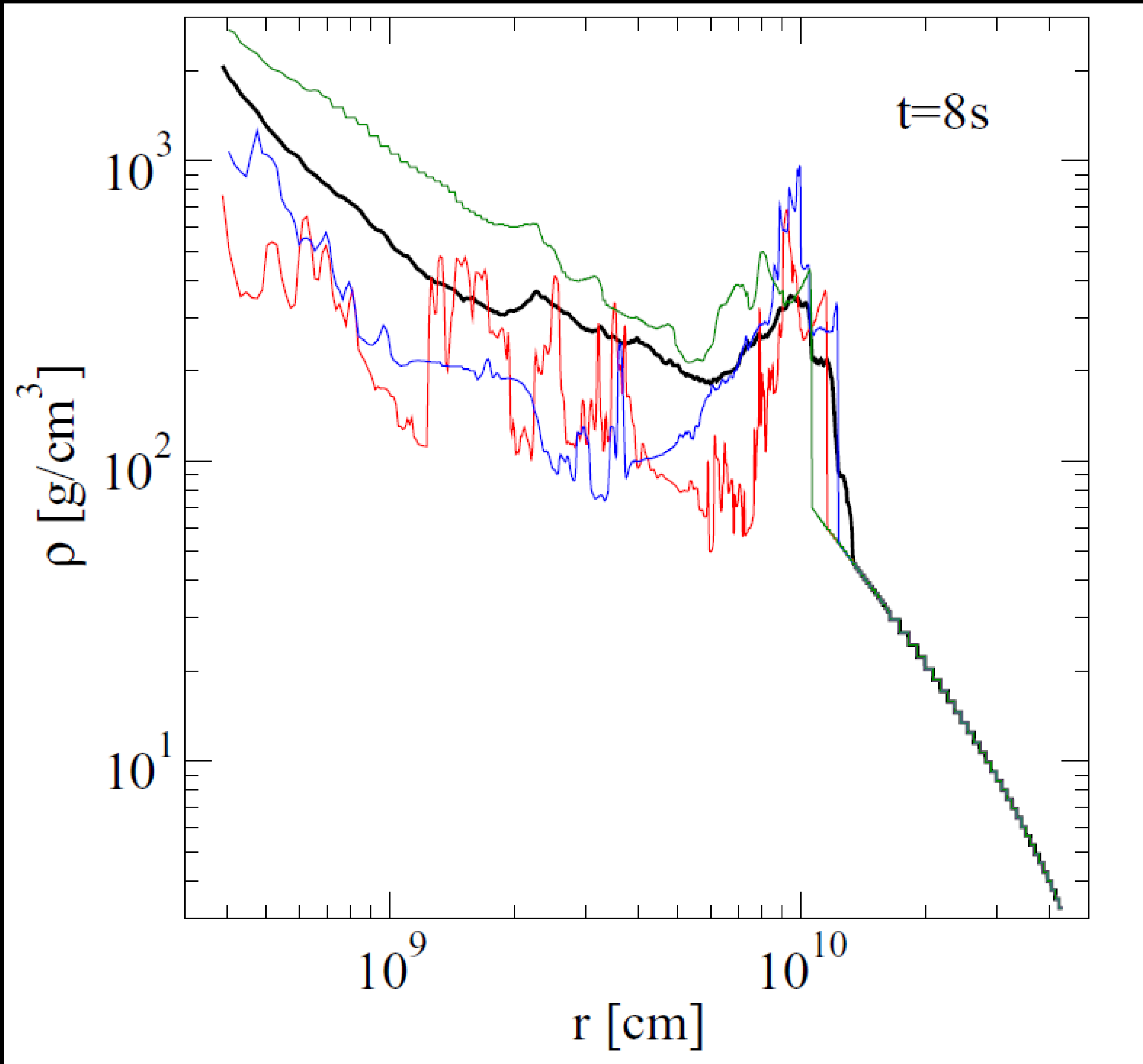
Fogli, Lisi, Mirizzi, hep-ph/0603033 (for δ-corr noise)

- 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$\sim$ 8 sec the L-resonance also becomes depolarized -> no regeneration in Earth



Turbulent shadow along different radial rays

- Still more thanks to Timur Rashba!!



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!
- More work needs to be done!