Neutrinos: The Ghost Supernova Particles

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Invisibles Journal Club
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Outline

- ★ Supernova neutrino signal and neutrino oscillations
- ★ Diffuse supernova neutrino background
- ★ Neutrinos and nucleosynthesis
- ★ Conclusions

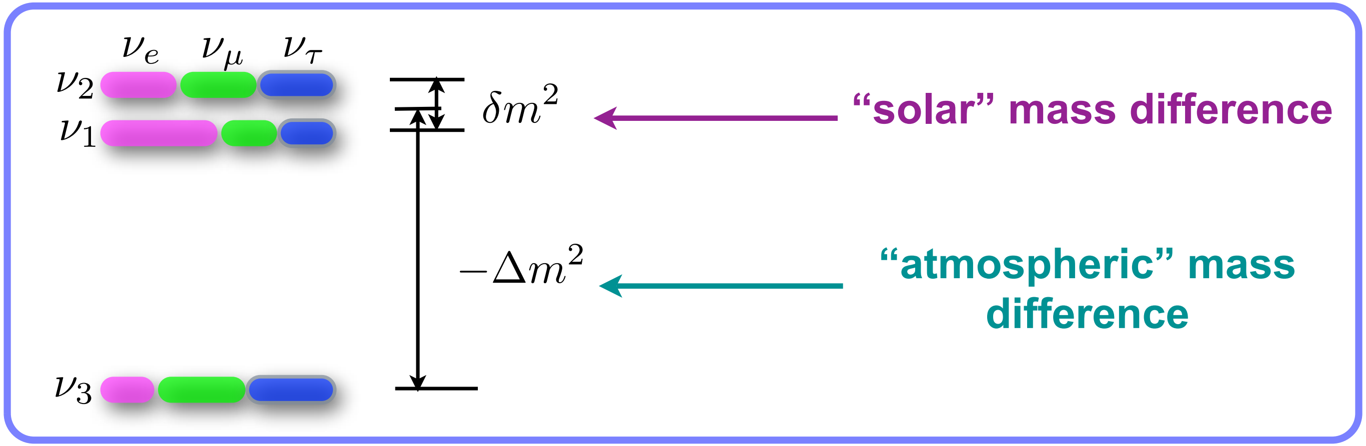
Neutrino Oscillations

Neutrino masses and neutrino flavors

Neutrino flavor eigenstates are linear combinations of mass eigenstates by means of three mixing angles and one CP-phase

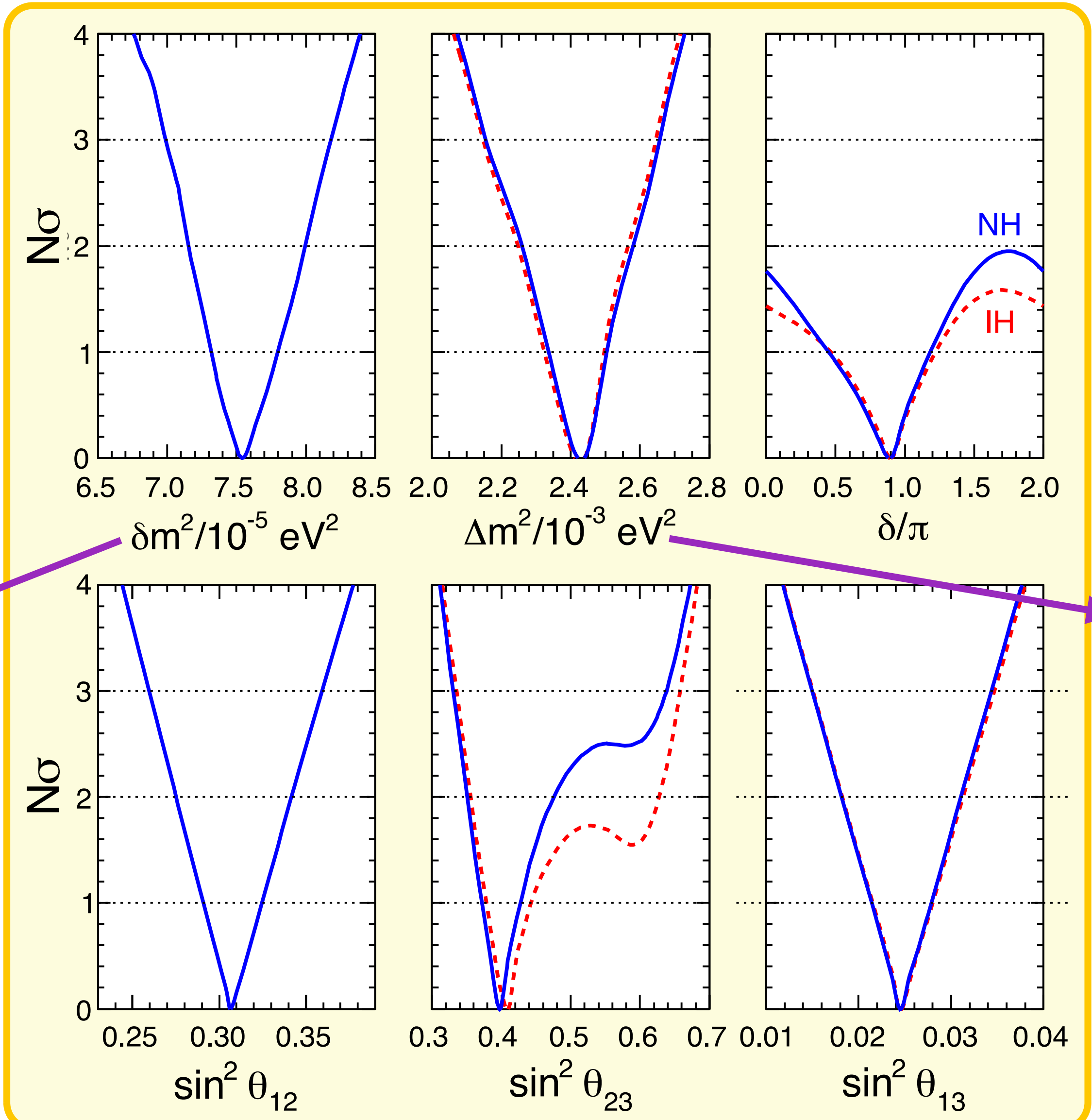
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U(\theta_{12}, \theta_{13}, \theta_{23}, \delta) \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Neutrino mass eigenstates differ by two mass differences. The sign of the biggest one is still unknown [normal hierarchy: $+\Delta m^2$, inverted hierarchy:$-\Delta m^2$].
For example, in inverted hierarchy:



Typical supernova neutrino energies are below threshold for μ and τ production via CC.
ν_μ and ν_τ behave in a similar way and are often denoted by ν_x.

Neutrino Masses and Mixing Angles



"solar" mass difference

"atmospheric" mass difference

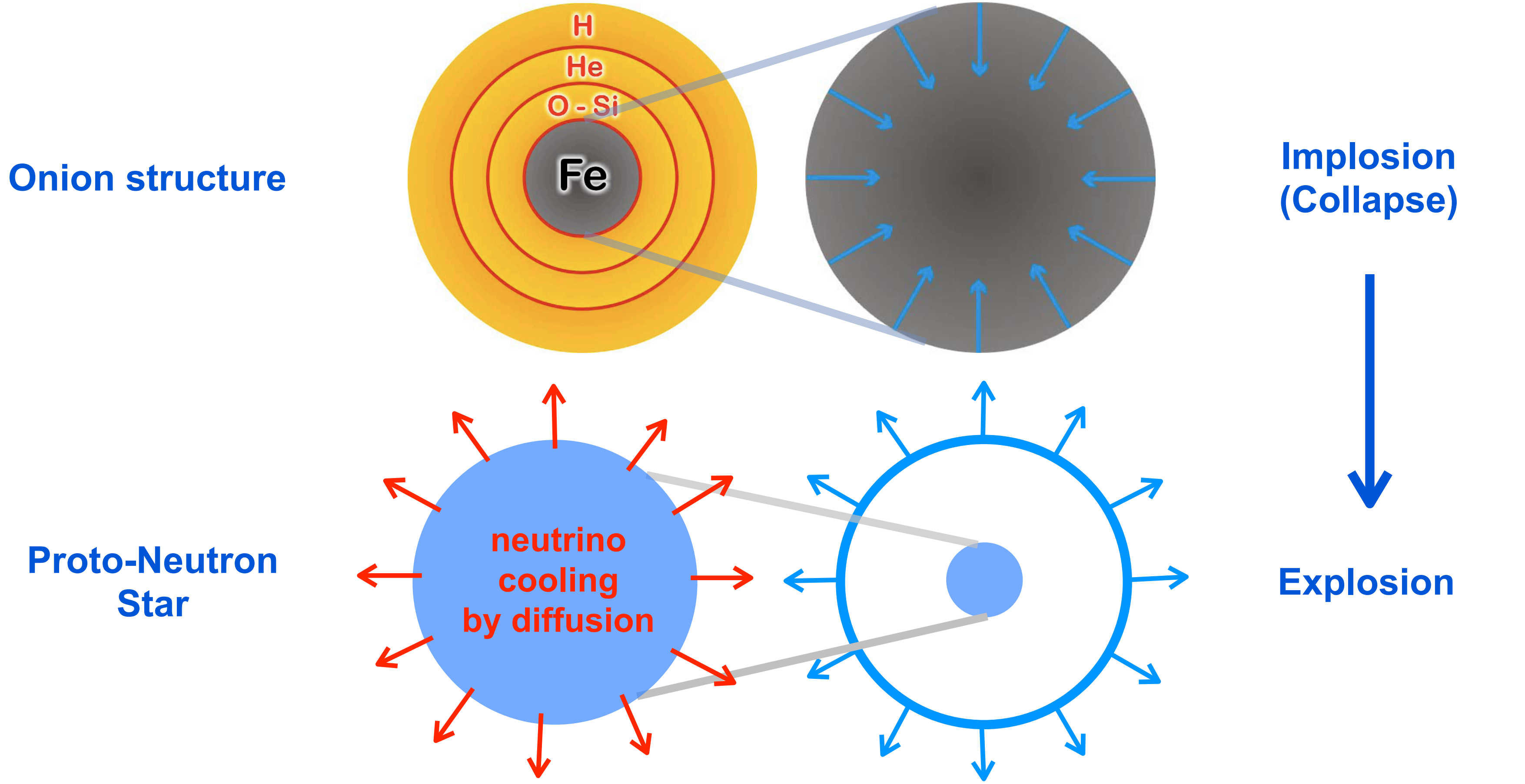
mixing angles

* G.L. Fogli et al., arXiv: 1205.5254.

Core-Collapse Supernovae as Neutrino Sources

Stellar collapse and Supernova Explosion

Core-collapse supernovae: terminal phase of massive stars [$M \geq 8M_{\odot}$]. At the end of their life, these stars collapse ejecting the outer mantle by means of shock-wave driven explosions.



Energy scale: **99% of the released energy** (~ 10^{53} erg) is **emitted by neutrinos and antineutrinos** of all flavors (energies ~ 15 MeV).

Time scale: neutrino emission lasts ~ 10 s. **Expected rate**: 1-3 SN/century in our galaxy (~ 10 kpc).

SN 1987A

The last known core-collapse supernova near our galaxy is the SN 1987A.
Its neutrino burst observation was the first verification of stellar evolution mechanism.

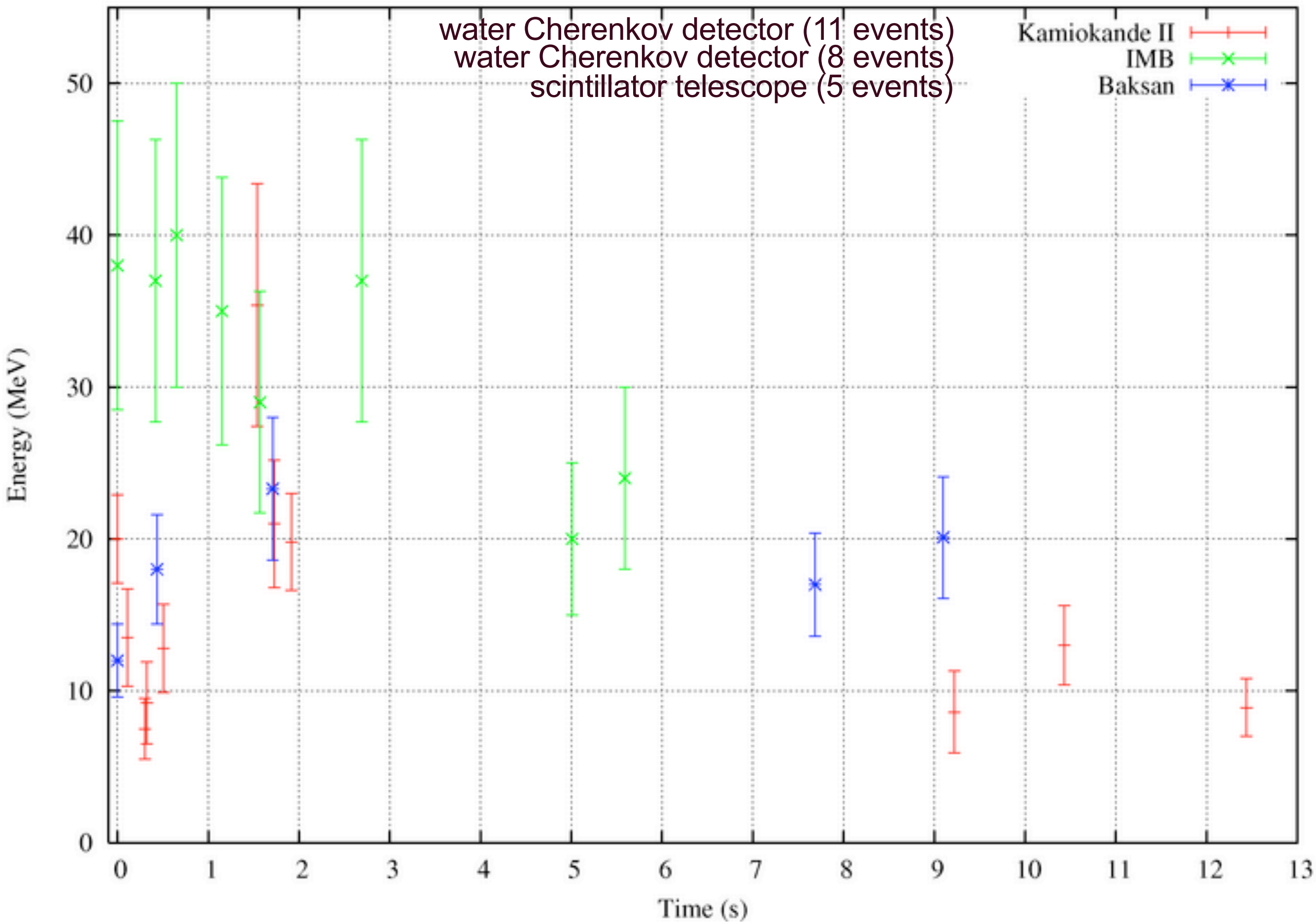
Sanduleak -69° 202

SN 1987A (Feb. 23, 1987)

SN 1987A

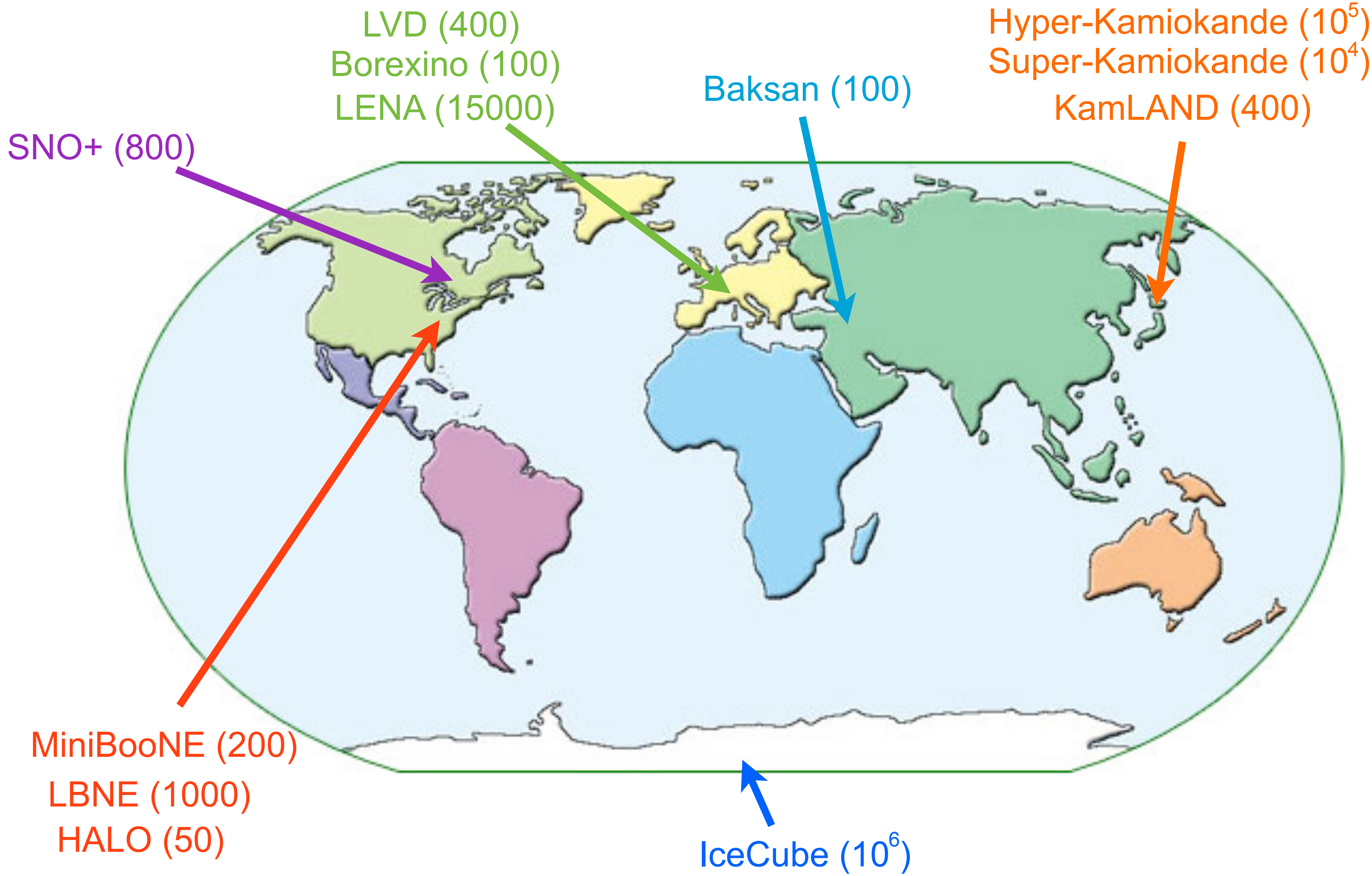
Unfortunately, only few detectors were able to detect SN 1987A neutrinos. The first neutrinos were contemporaneous within time uncertainties.

Time distribution of SN 1987A events



Are we ready for the next explosion?

Today, several detectors are (or will be soon) waiting for the next explosion.

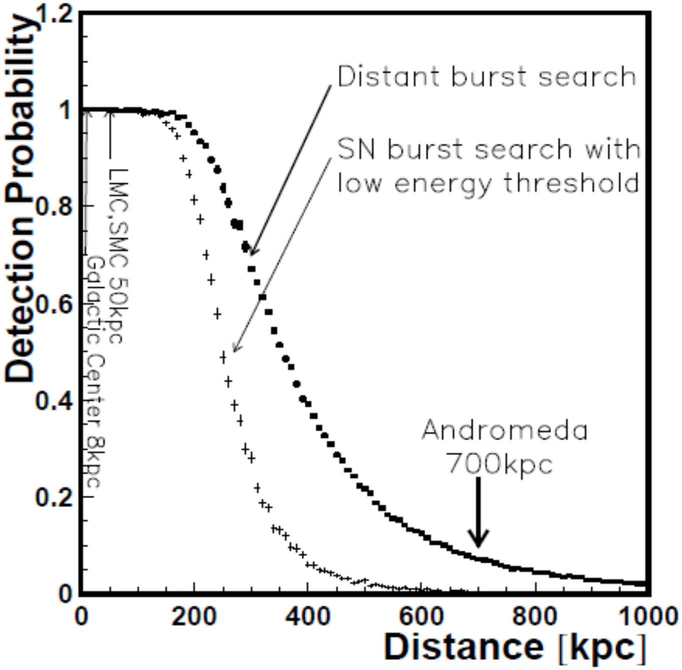


The expected number of events is estimated for a galactic supernova (10 kpc).

Are we ready for the next explosion?

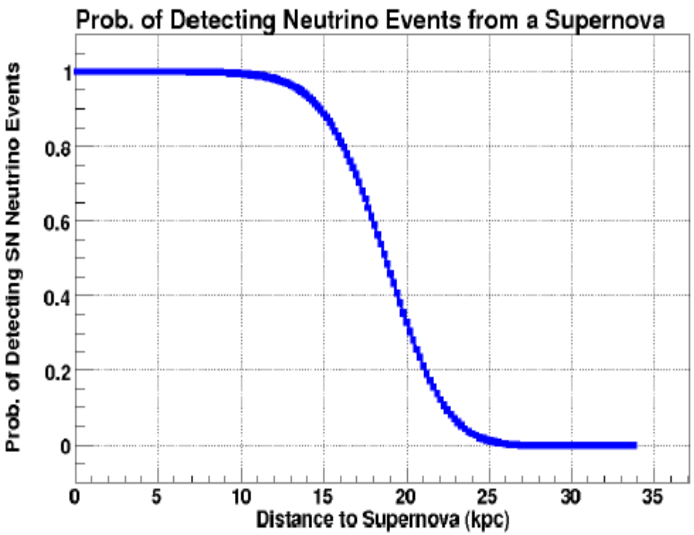
Neutrino bursts from galactic explosions will be detected helping us to improve our knowledge about SN physics.

Super-Kamiokande



Upper limit: 0.32 SN/year
for d < 100 kpc (90% CL).*

Mini-BooNE



Upper limit: 0.69 SN/year
for d < 13.5 kpc (90% CL).**

* Super-Kamiokande Collaboration, arXiv: 0706.2283

** MiniBooNE Collaboration, arXiv: 0910.3182

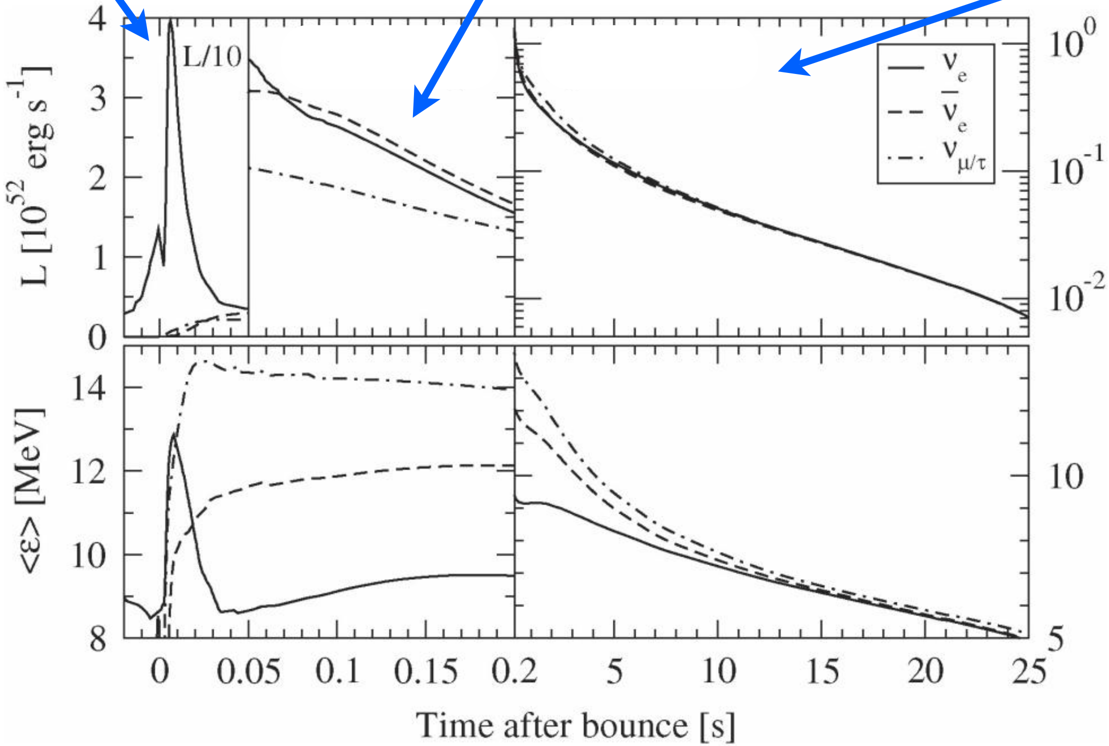
Characteristics of Neutrino Signal

Characteristics of Neutrino Signal

De-leptonization burst
(large ν_e luminosity peak)

Accretion phase
(large fluxes and
large $\bar{\nu}_e - \bar{\nu}_x$ flux differences)

Cooling phase
(small fluxes and small
$\bar{\nu}_e - \bar{\nu}_x$ flux differences)

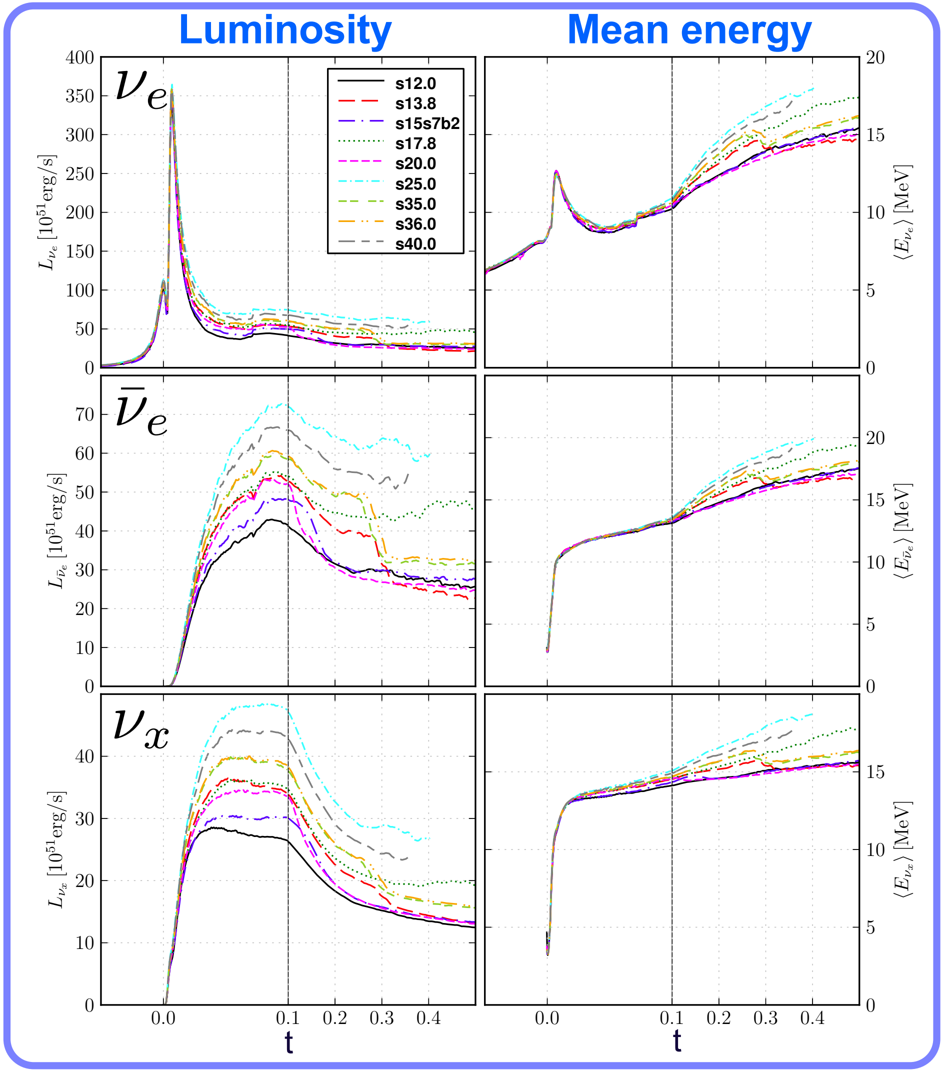


Exploding 1D electron-capture supernova simulation ($M = 8.8\ M_\odot$).

* L. Huedepohl et al. (Garching group), arXiv: 0912.0260

Accretion Phase

Set of 1D simulations for different SN masses (Garching models)



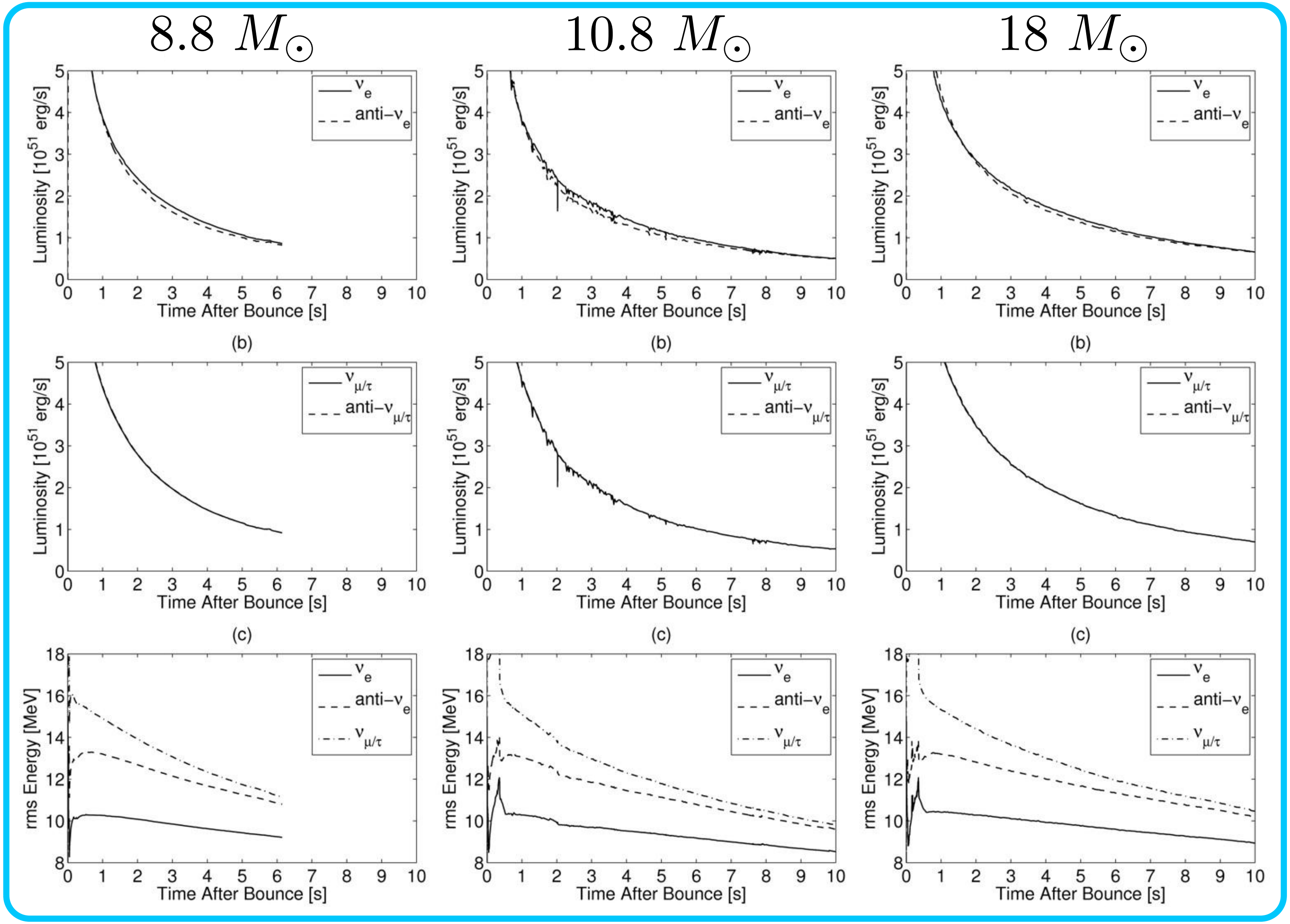
★ During the de-leptonization burst the neutrino signal is independent on the SN mass and the equation of state. SNe might be adopted as **standard candles**.

★ During the accretion phase the differences among the fluxes of different flavors are large.

★ **Consequences of neutrino oscillations are relevant.**

* For details see http://www.mpa-garching.mpg.de/ccsnarchive/, M. Kachelriess et al., astro-ph/0412082.

Long-Term Cooling



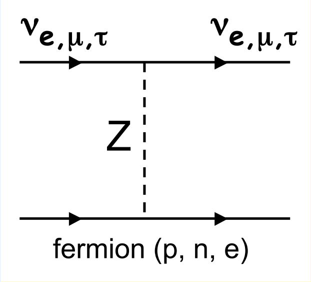
During the cooling phase the fluxes of different flavors are similar. **Therefore detailed oscillation physics is not crucial since it should be responsible only for small variations.**

* Fisher et al. (Basel group), arXiv: 0908.1871 [astro-ph.HE]

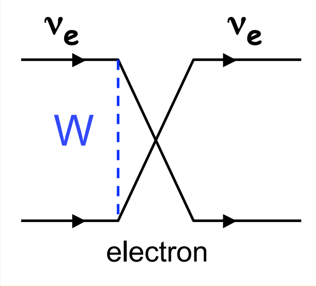
Neutrino Oscillations in Supernovae

Neutrino interactions

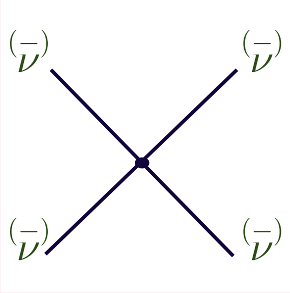
Neutrinos interact with matter and among themselves...



Neutral current (NC) interactions with matter background



e-flavor has charged current (CC) interactions too



$\nu - \nu$ interactions

Equations of motion

The equations of motion for neutrinos and antineutrinos describing the time evolution in a homogeneous medium for each energy mode E and angle ϑ are

$$i\,\dot{\varrho}_{E,\vartheta} = [\mathsf{H}_{E,\vartheta}, \varrho_{E,\vartheta}] \quad \text{and} \quad i\,\dot{\bar{\varrho}}_{E,\vartheta} = [\bar{\mathsf{H}}_{E,\vartheta}, \bar{\varrho}_{E,\vartheta}]$$

with the neutrino Hamiltonian defined as

$$\mathsf{H}_{E,\vartheta} = \frac{\mathsf{UM}^2\mathsf{U}^\dagger}{2E} + \sqrt{2}G_\mathrm{F}\ \mathsf{N}_l + 2\pi\sqrt{2}G_\mathrm{F}\int dE' \int d\cos\vartheta'\ \left(\varrho_{E',\vartheta'} - \bar{\varrho}_{E',\vartheta'}\right)(1-\cos\vartheta\cos\vartheta')$$

vacuum term
(with opposite sign
for antineutrinos)

matter term
$\mathsf{N}_\ell = \mathrm{diag}(n_e - n_{\bar{e}}, n_\mu - n_{\bar{\mu}}, n_\tau - n_{\bar{\tau}})$

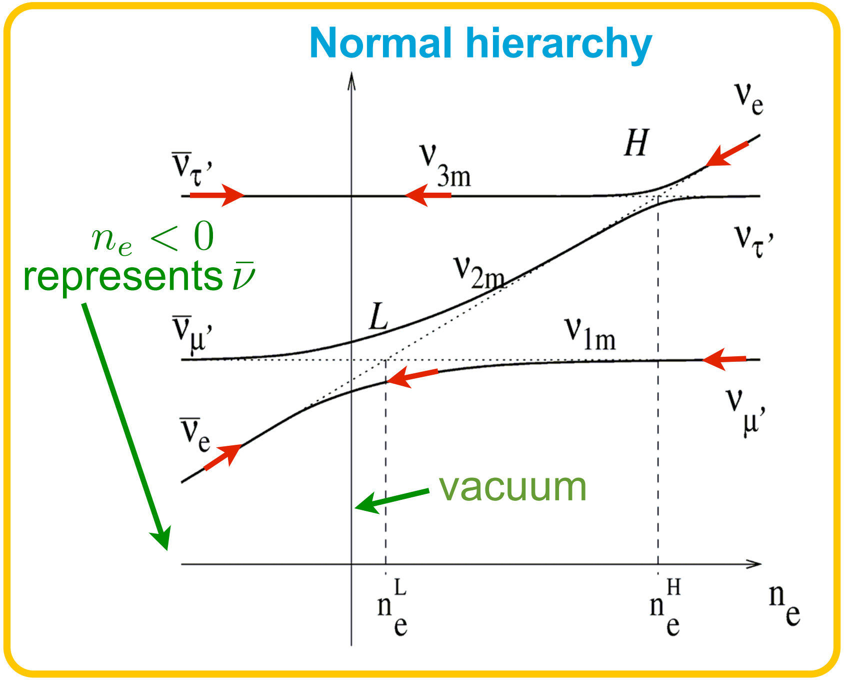
$\nu-\nu$ interaction term

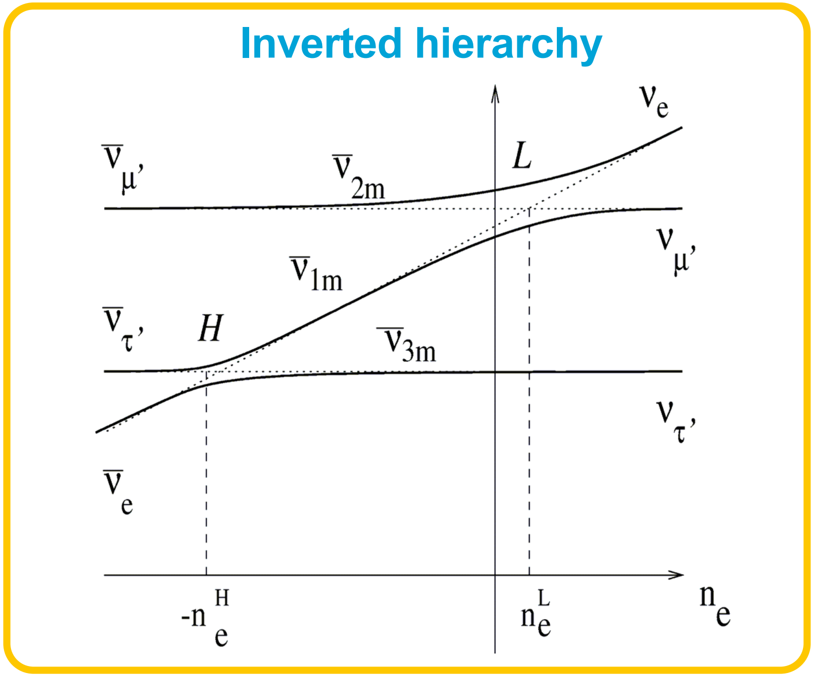
The Hamiltonian for antineutrinos has the vacuum term with opposite sign.

Neutrino Interactions with Matter (MSW)

When the vacuum term is in resonance with the matter term maximal flavor conversions occur (MSW effect).

Eigenvalue diagram of 3 x 3 Hamiltonian matrix for 3-flavor oscillations





Δm^2 resonance for neutrinos
δm^2 resonance for neutrinos

Δm^2 resonance for antineutrinos
δm^2 resonance for neutrinos

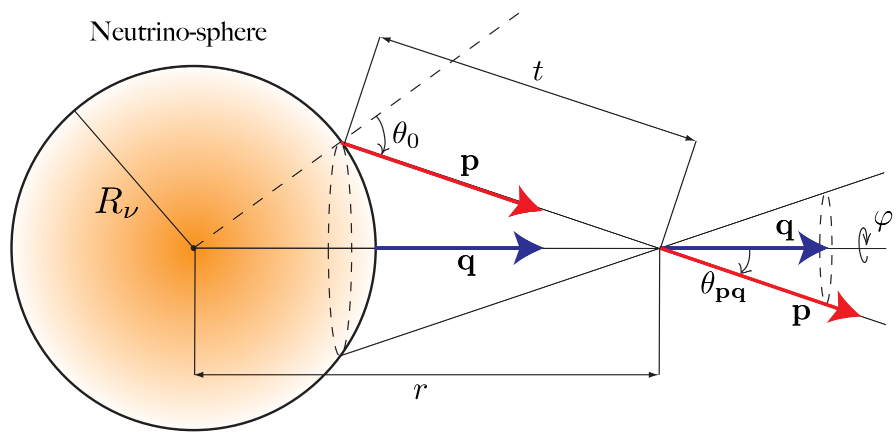
* For details see: A. Dighe and A. Yu. Smirnov, arXiv: hep-ph/9907423

Neutrino-neutrino Interactions

The $\nu - \nu$ term is non linear and it depends on the relative angle between colliding neutrinos

$$\mathsf{H}_{E,\vartheta} = \frac{\mathsf{UM}^2\mathsf{U}^\dagger}{2E} + \sqrt{2}G_{\mathrm{F}}\ \mathsf{N}_l + 2\pi\sqrt{2}G_{\mathrm{F}} \int dE' \int d\cos\vartheta' \ \left(\varrho_{E',\vartheta'} - \bar{\varrho}_{E',\vartheta'}\right)(1 - \cos\vartheta\cos\vartheta')$$

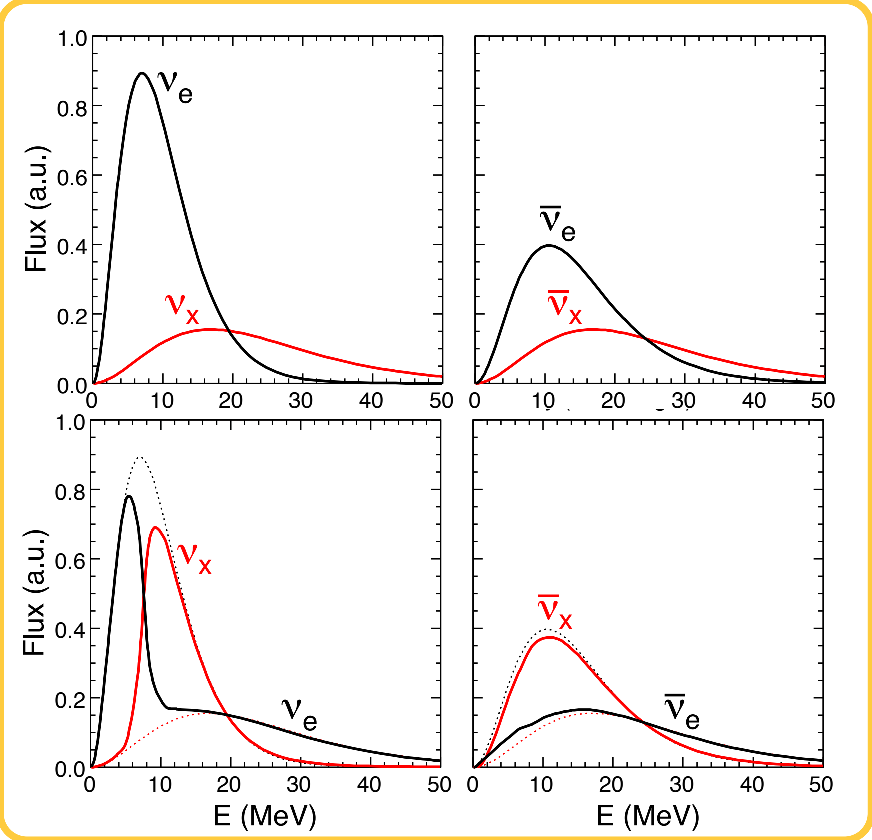
We assume the “bulb model”*: the neutrino-sphere emits neutrinos of all flavors from each point in the forward solid angle uniformly and isotropically.



Only lately, we are learning to appreciate the role of the angle among colliding neutrinos.

* For details see: H. Duan et al., arXiv: astro-ph/0606616

Spectral splits



The immediate signature of collective effects is the "**spectral split**": for energies above a critical value, a full flavor swap occurs*.

non-oscillated fluxes

fluxes after collective effects in *inverted hierarchy*

fluxes after collective effects = non-oscillated fluxes in *normal hierarchy*

The appearance and the number of splits are strictly dependent on:

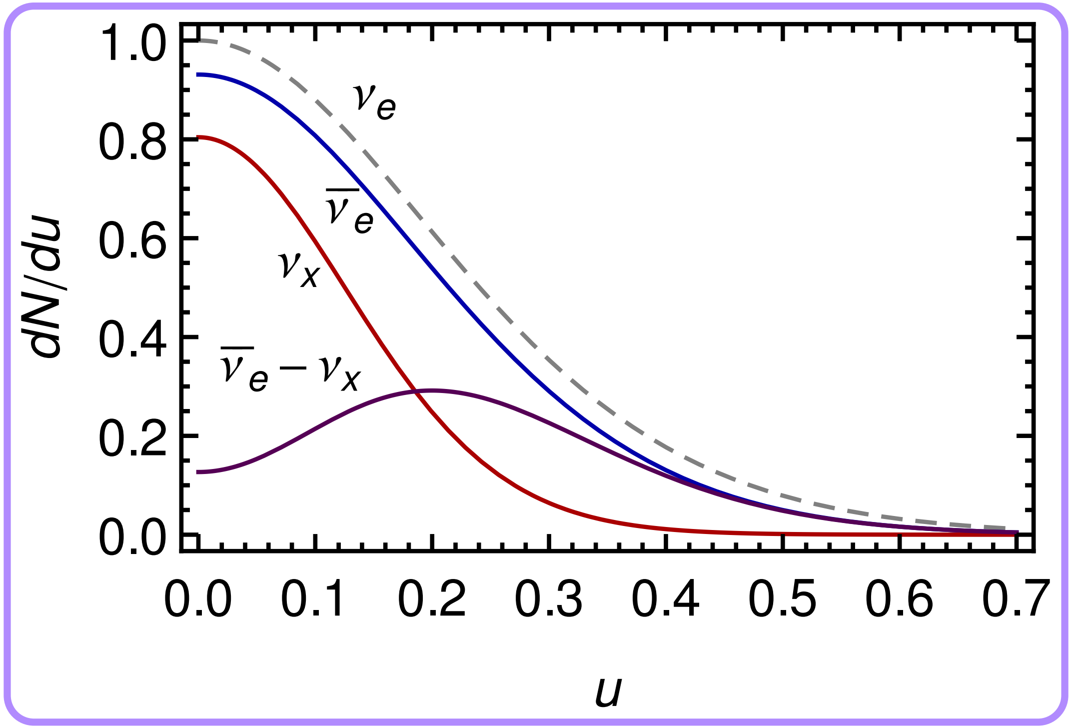
★ the ratio among the fluxes of different flavors
★ the **geometry of the neutrino angular emission**
★ the neutrino mass hierarchy.

* For details see: G.L. Fogli, E. Lisi, A. Marrone, A. Mirizzi, I. Tamborra arXiv: 0707.1998, 0808.0807
G.G. Raffelt and A. Yu. Smirnov, arXiv: 0705.1830, 0709.4641, H. Duan et al., arXiv: 0706.4293

Angular distributions

Lately, realistic angular distributions of neutrino emission have become available.
The neutrino angular distributions are flavor dependent and non-isotropic.

Angular emission spectra for different flavors for a SN with $15\ M_{\odot}, 280\mathrm{ms}$

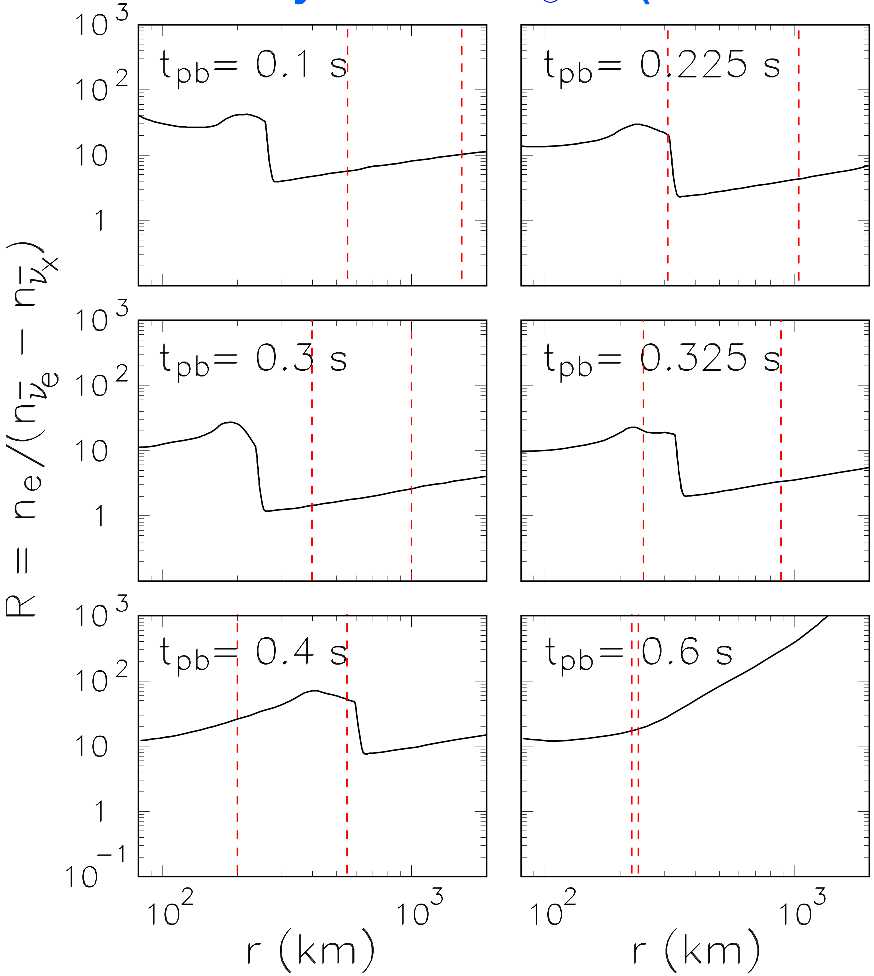


with the angular variable $u = \sin^2\theta_R$ and θ_R the neutrino emission angle at the neutrino-sphere.

* S. Sarikas, G.G. Raffelt, L. Huedepohl, H.-T. Janka, arXiv: 1109.3601

Suppression of collective oscillations during the accretion phase

Matter density during the accretion phase vs. neutrino density for a $10.8 M_\odot$ SN (Basel model)



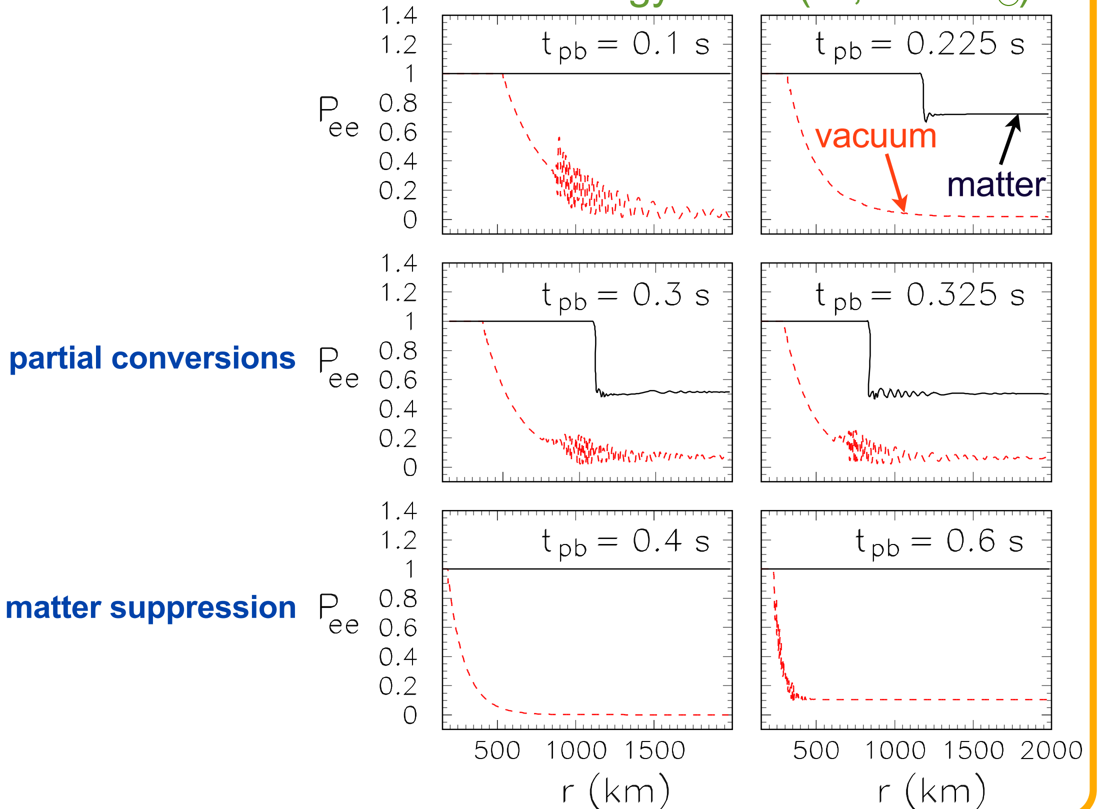
During the **accretion phase** the matter density is always larger than the neutrino one.
Multi-angle matter suppression of collective flavor conversions at small radii could occur.
Does this happen?

Yes, analytical estimations (stability analysis) and numerical simulations find multi-angle matter suppression of the collective oscillations during the accretion phase.

* For details see: Esteban-Pretel et al., arXiv: 0807.0659, S. Chakraborty et al., arXiv: 1104.4031, arXiv: 1105.1130, Banerjee, Dighe, Raffelt, arXiv: 1107.2308, S. Sarikas et al., arXiv: 1109.3601, arXiv: 1110.5572

Suppression of collective oscillations during the accretion phase

Electron survival probability for one energy mode (IH, $10.8\ M_{\odot}$)



Matter suppression of collective effects during the accretion -only MSW- (Basel models)

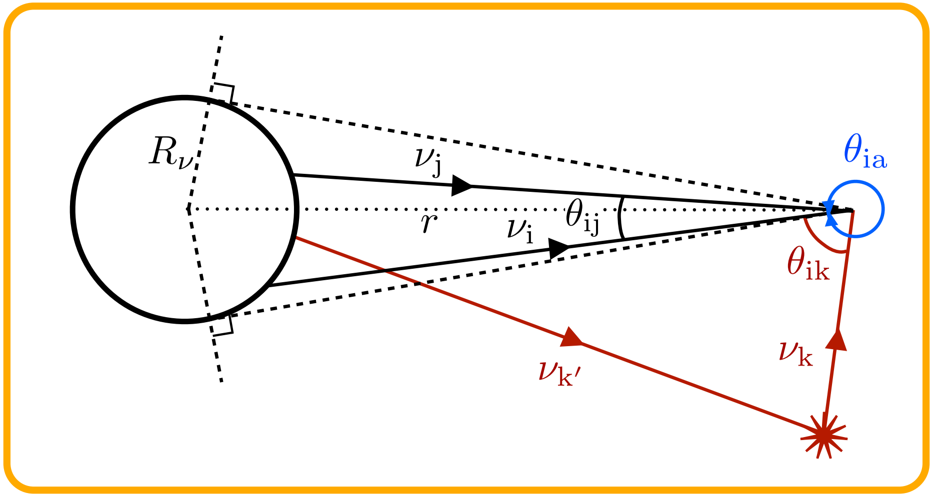
The high electron density suppresses collective flavor oscillation (no splits). Only MSW occurs.

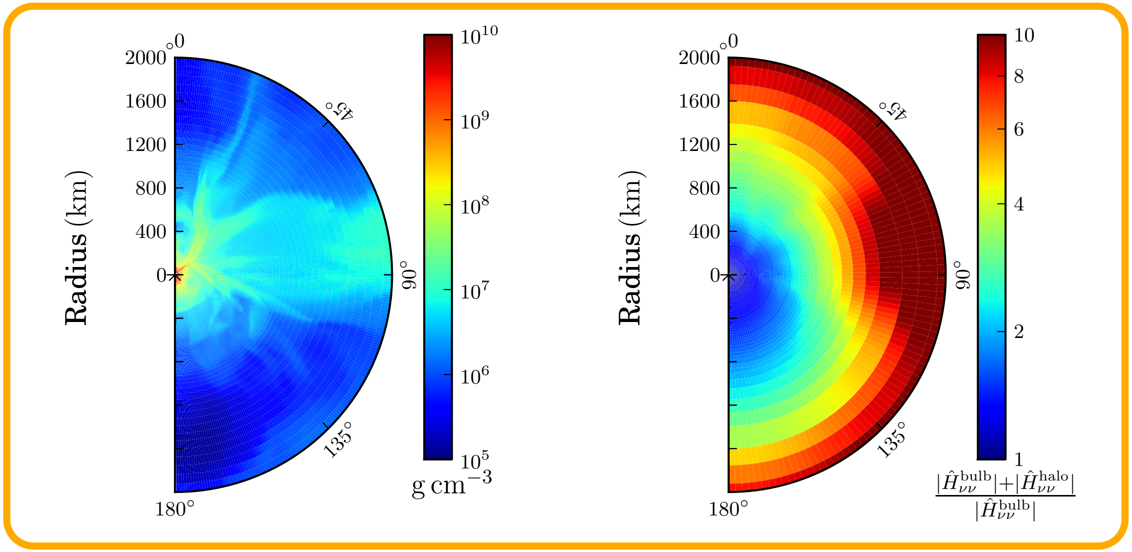
Note that the angular distribution is crucial for the flavor-oscillation suppression!

* For details see: S. Chakraborty et al., arXiv: 1104.4031, arXiv: 1105.1130, S. Sarikas et al., arXiv: 1110.5572, arXiv: 1109.3601

The “halo” contribution

During the **accretion phase,** collective interactions might be affected by the contribution of non-forward scattered neutrinos. How does the “halo” change the collective-oscillation paradigm?



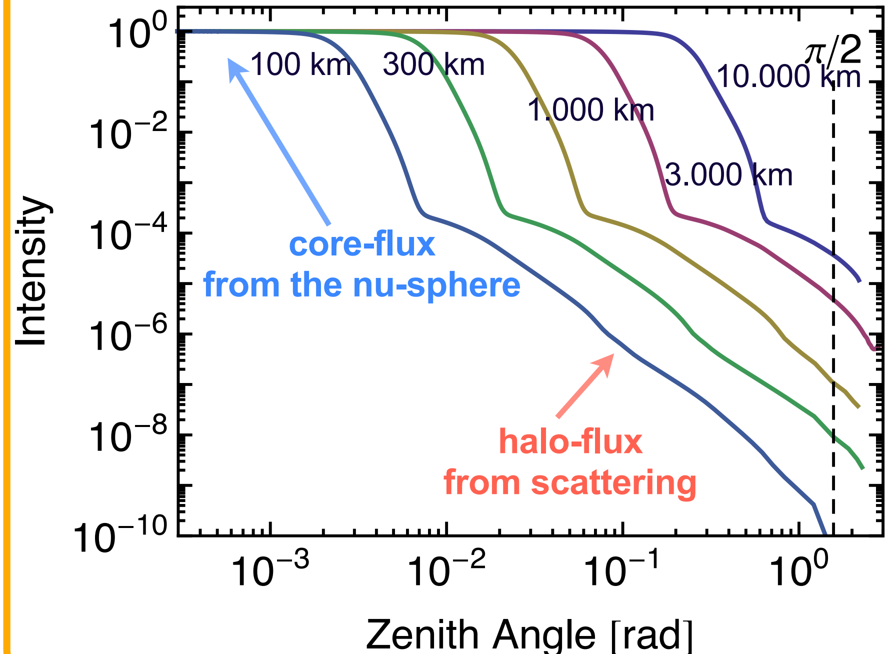


The “halo” contribution might be relevant only at large radii (r ~ 1000 km).

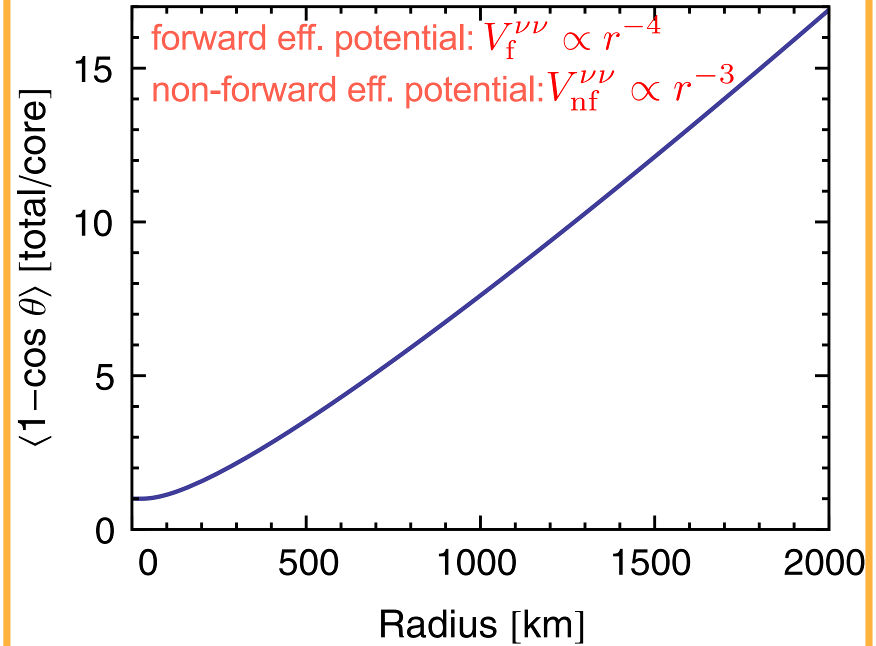
* For details see: J. F. Cherry et al., arXiv: 1203.1607

The “halo” contribution

Angular emission $\bar{\nu}_e$ spectra for a SN with $15 M_\odot, 280\ \mathrm{ms}$



Relative importance of the halo for the self-interaction potential

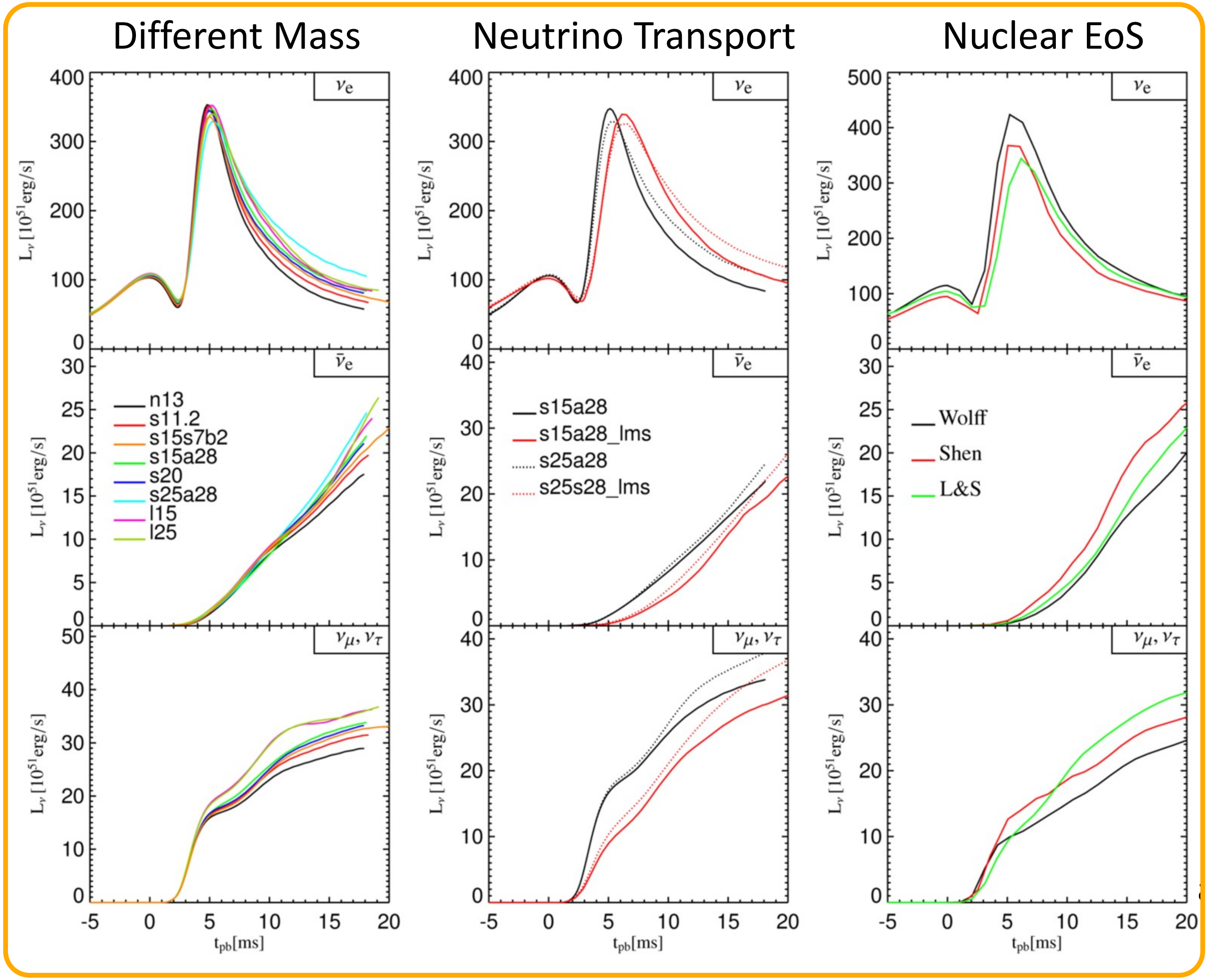


Analytical estimations on one Garching model ($15 M_\odot$, accretion): multi-angle matter suppression even after including the halo.

Attention! The halo might still affect flavor conversions for slightly low mass SNe or late accretion phase. More detailed analysis and numerical approaches are needed!

* For details see: S. Sarikas, I. Tamborra, G. Raffelt, L. Huedepol, T. Janka, arXiv: 1204.0971

Exploiting the neutronization burst....



Assuming the mixing scenario is known, we can use the neutronization burst to determine the SN distance.

* For details see: Kachelriess et al., arXiv: astro-ph/0412082.

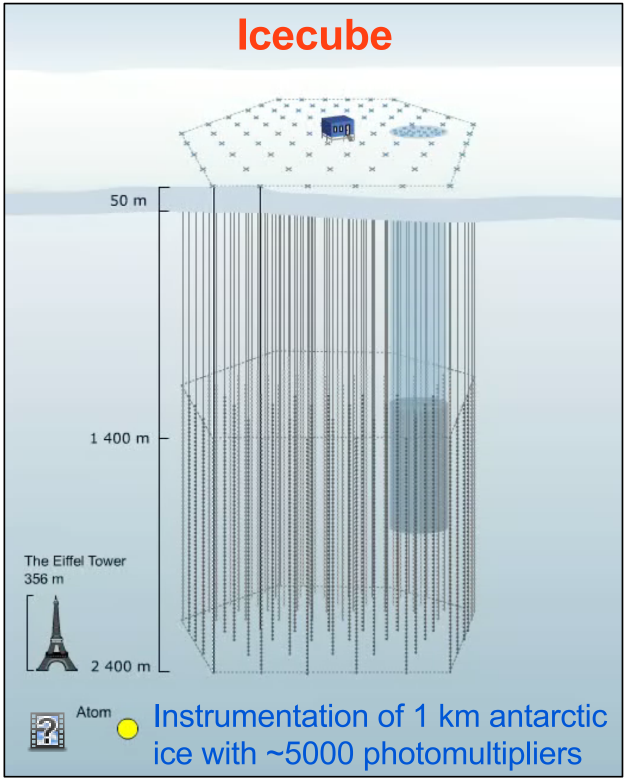
Exploiting the accretion phase ....

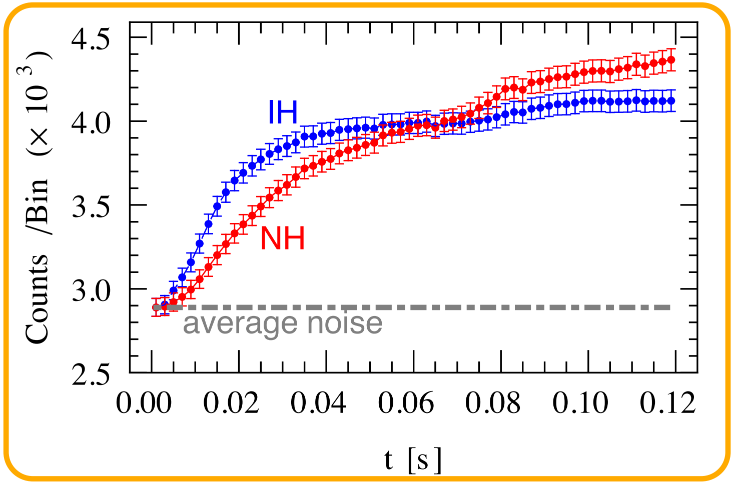
Because of the multi-angle matter suppression during the accretion phase and for large θ_{13}, one has

$$F^D_{\bar{\nu}_e} = \cos^2\theta_{12} F_{\bar{\nu}_e} + \sin^2\theta_{12} F_{\bar{\nu}_x} \quad \text{in NH}$$

$$F^D_{\bar{\nu}_e} = F_{\bar{\nu}_x} \quad \text{in IH}$$

A high-statistics measurement of the rise-time shape may distinguish the two scenarios!





The rise-time in IH is always faster than the NH one!

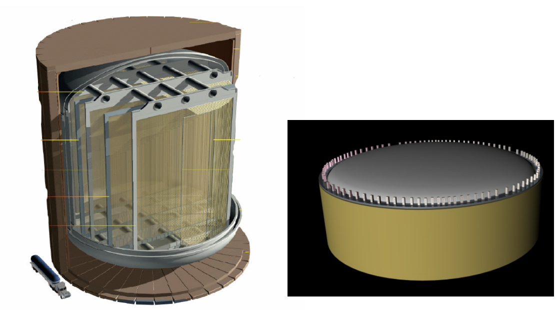
Available SN models suggest that one could unambiguously attribute the shape to NH or IH type (rise-time shapes robustly predicted). The correct hierarchy could be identified in 99% of the cases.
Is this true for all SN models?

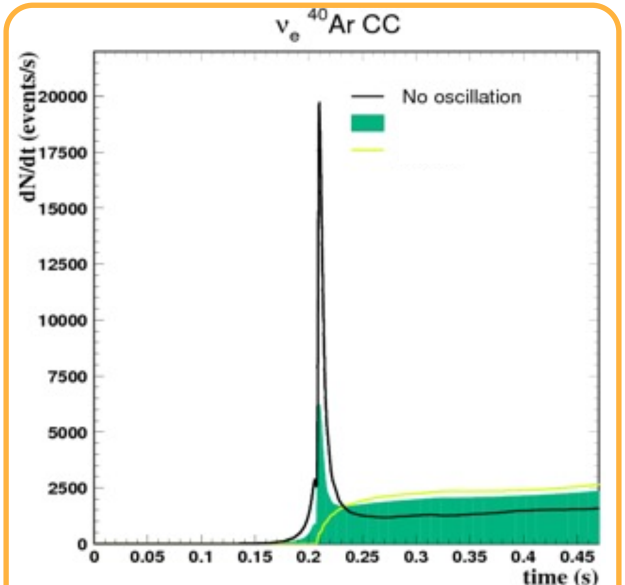
* For details see: P.D. Serpico et al., arXiv: 1111.4483, Abbasi et al., arXiv: 1108.0171.

Exploiting the accretion phase ....

Next generation large scale argon detectors could be very useful for SN neutrinos.

5-100 kton Liquid Argon TPC

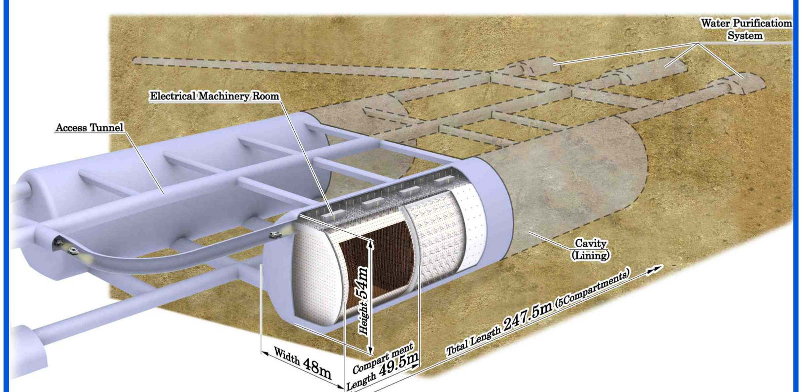


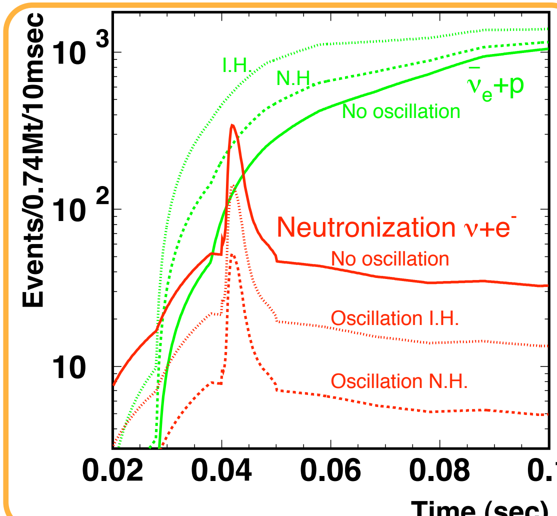


ICARUS - 70 kton LAr TPC

for large θ_{13}:
no peak → NH
peak → IH

Hyper-(and Super)Kamiokande

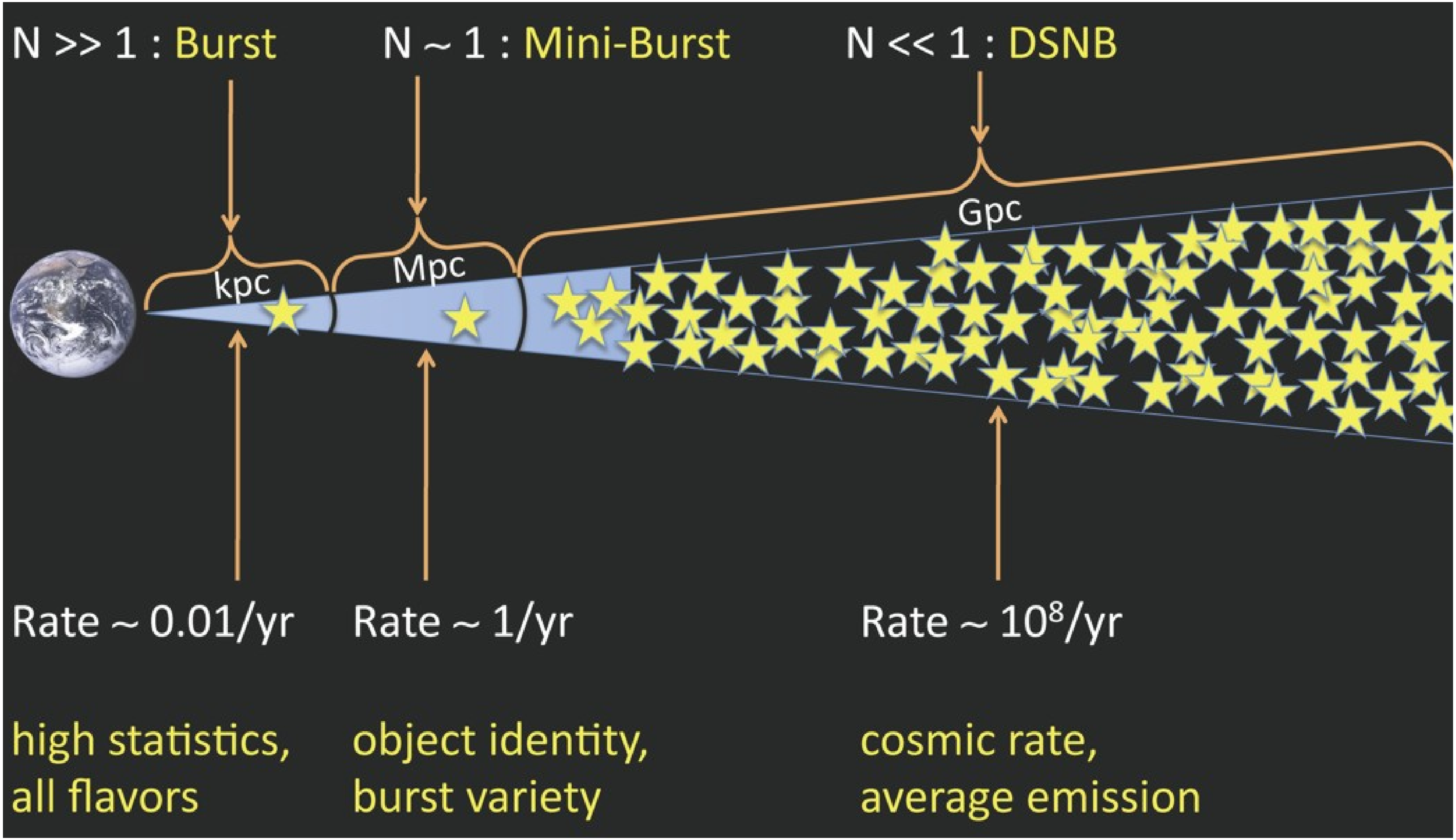




* For details see: I. Gil-Botella and A. Rubbia, hep-ph/0307244. K. Abe et al., arXiv: 1109.3262.

Diffuse Supernova Neutrino Background

Distance Scales and Detection Strategies



Adapted from Beacom's talk @ Neutrino 2012

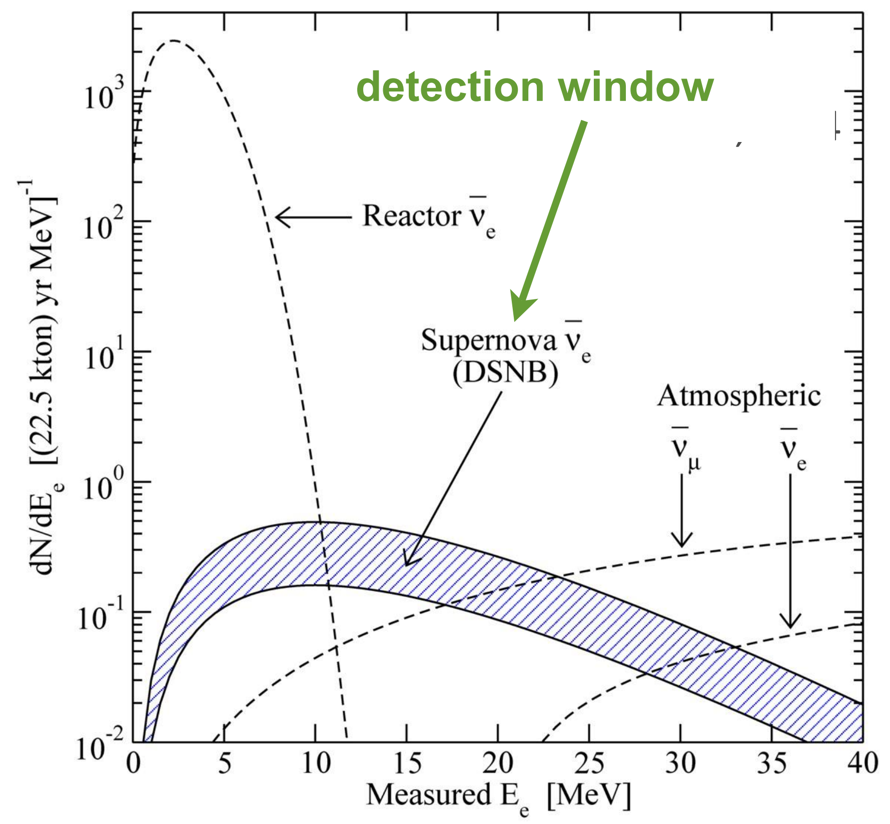
Why the DSNB?

Galactic supernova maybe rare but supernova explosions are quite common.
One supernova explosion occurs, on average, every second somewhere in the universe and these produce a diffuse supernova neutrino background (DSNB).

★ Detectable $\bar{\nu}_e$ flux at the Earth mostly from redshift z ~ 1

★ Test of supernova astrophysics

★ New frontiers for neutrino astronomy

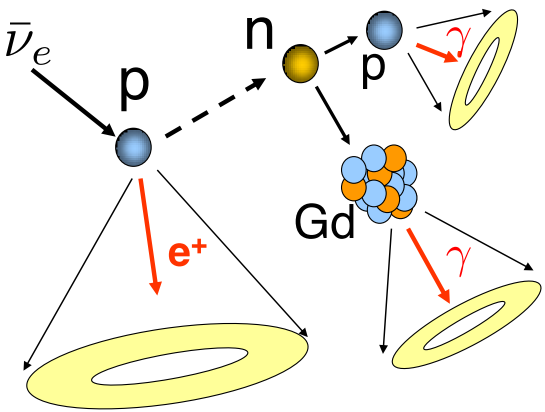


* Beacom and Vagins, arXiv: hep-ph/0309300

DSNB Detection

Neutron tagging in Gd-enriched WC detector (Super-K with 100 tons Gd to trap neutrons)

$\bar{\nu}_e + p \rightarrow n + e^+$

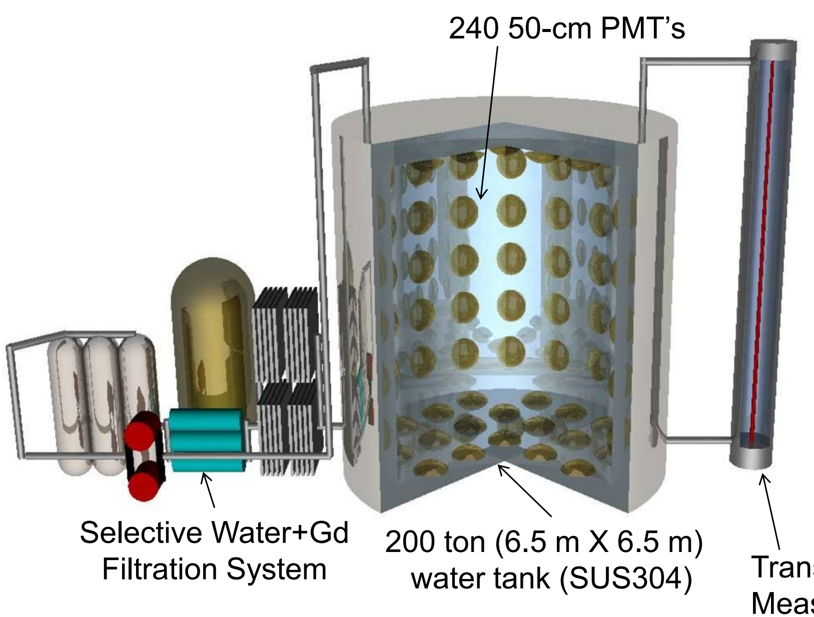


Positron and gamma ray vertices are within ~50cm.

$\bar{\nu}_e$ can be identified by delayed coincidence

spatial and temporal separation between prompt positron Cherenkov light and delayed Gd neutron capture gamma cascade

few clean events/yr in Super-K with Gd



*See talks by Vagins at Hanse 2011 and by Beacom at Neutrino 2012.

Ingredients

$$\Phi(E) = \frac{c}{H_0} \int_0^{z_{max}} R_{SN}(z) \frac{dN(E')}{dE'} \frac{dz}{\sqrt{\Omega_m (1+z)^3 + \Omega_\Lambda}}$$

cosmological supernova rate

oscillated neutrino flux corrected by redshift
[$E' = E(1+z)$]

cosmology

Cosmological Supernova Rate (SNR)

$$\boxed{R_{\rm SN}(z,M) = \frac{\int_{8M_\odot}^{125M_\odot} dM\ \eta(M)}{\int_{0.5M_\odot}^{125M_\odot} dM\, M\,\eta(M)}\,\dot{\rho}_\star(z)}$$

initial mass function
(mass distribution of stars at birth)

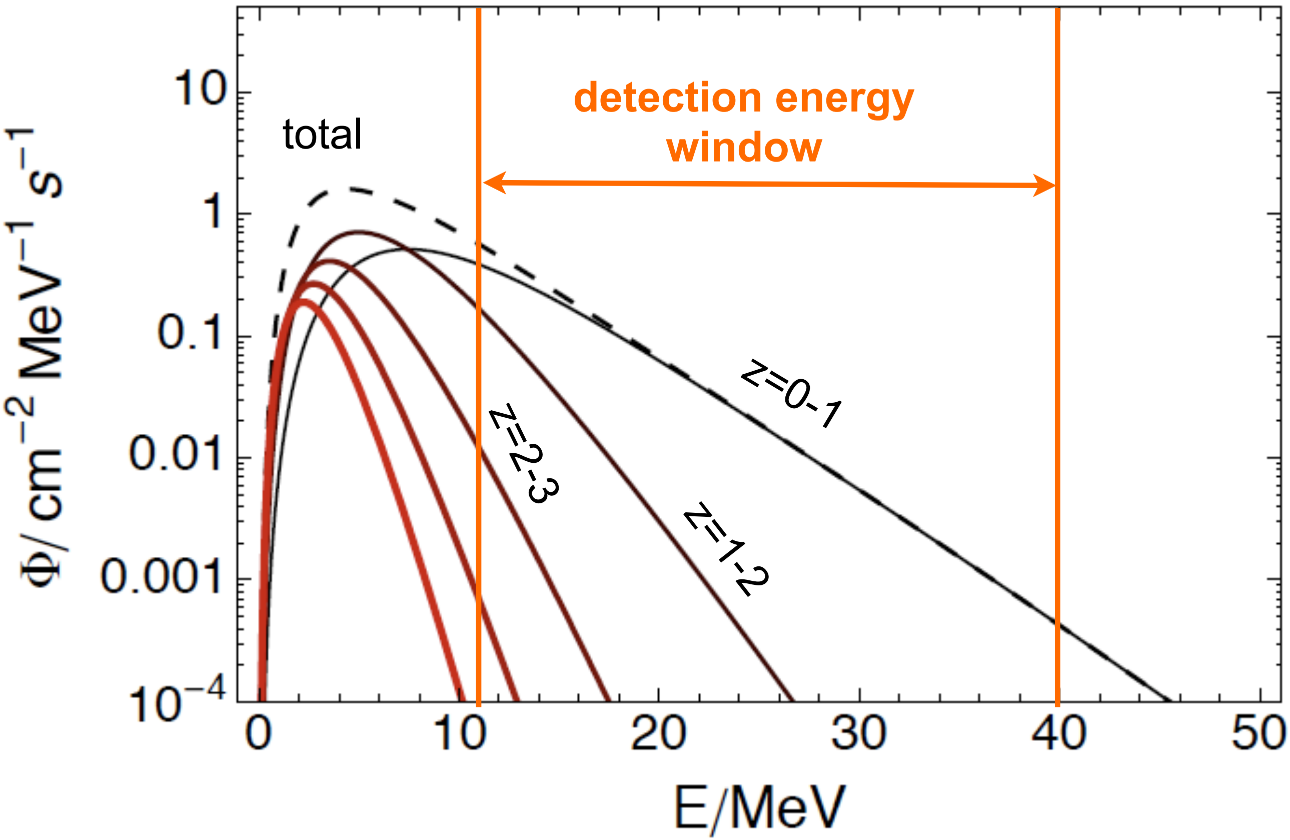
star formation rate

The initial mass function $\eta(M) \propto M^{-2.35}$. Therefore the flux is dominated by low mass stars.

The DSNB is dominated by the contribution of the closest ($z \leq 1$) and least massive ($M \simeq 8M_\odot$) stars and it depends only weakly on $M_{\rm max}$ and $z_{\rm max} \simeq 5$.

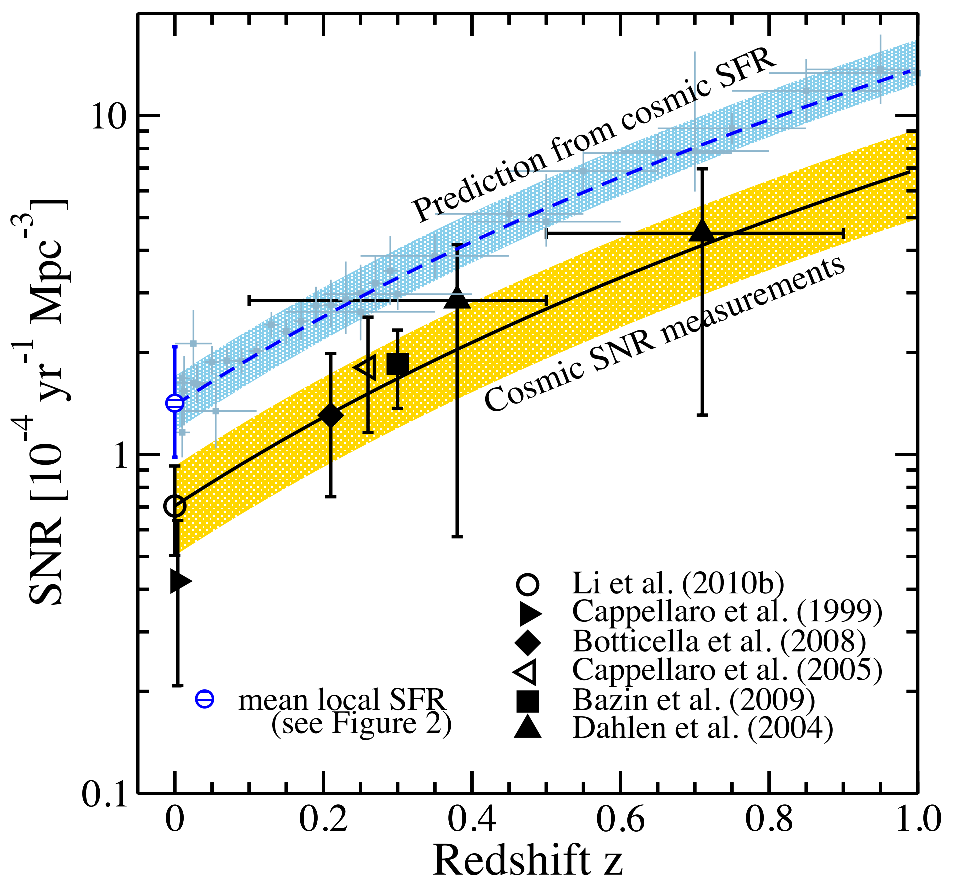
Cosmological Supernova Rate (SNR)

The redshift correction of energy is responsible for accumulating neutrinos of higher redshift at lower energies. Therefore the diffuse flux is dominated by the low z contribution ($z \leq 1$) in the energy window relevant for experiments (11 <E< 40 MeV).



See for details Ando, Sato, PLB 559 (2003) 113; Lunardini, arXiv: 1007.3252.

SNR: Measured Supernova Rate



The SNR is also given by direct SN observations.

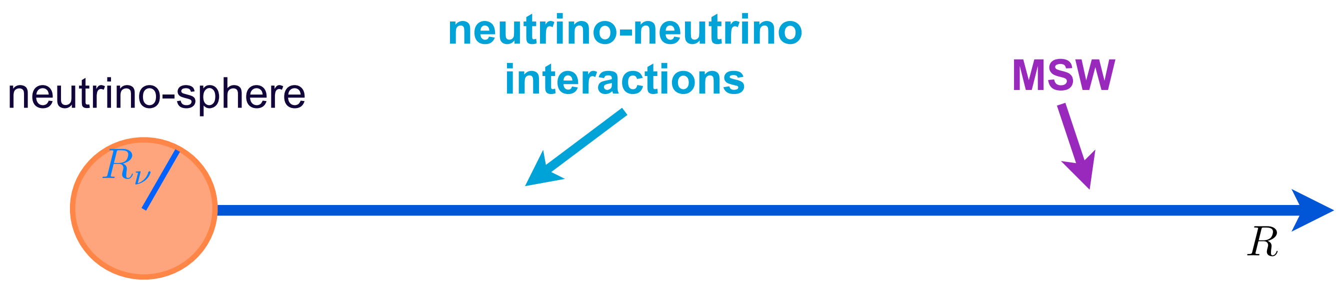
Surprisingly, **the normalization from direct SN observations is lower than that from SFR data by a factor ~ 2** and by a smaller factor at higher z.

Why? There are missing SNe - they are faint, obscured, or dark.

The existing measurements of the SNR and their uncertainties are dominated by normalization errors.

See Horiuchi et al., arXiv: 1102.1977; Botticella et al., arXiv: 1111.1692.

Oscillated Fluxes at the Earth



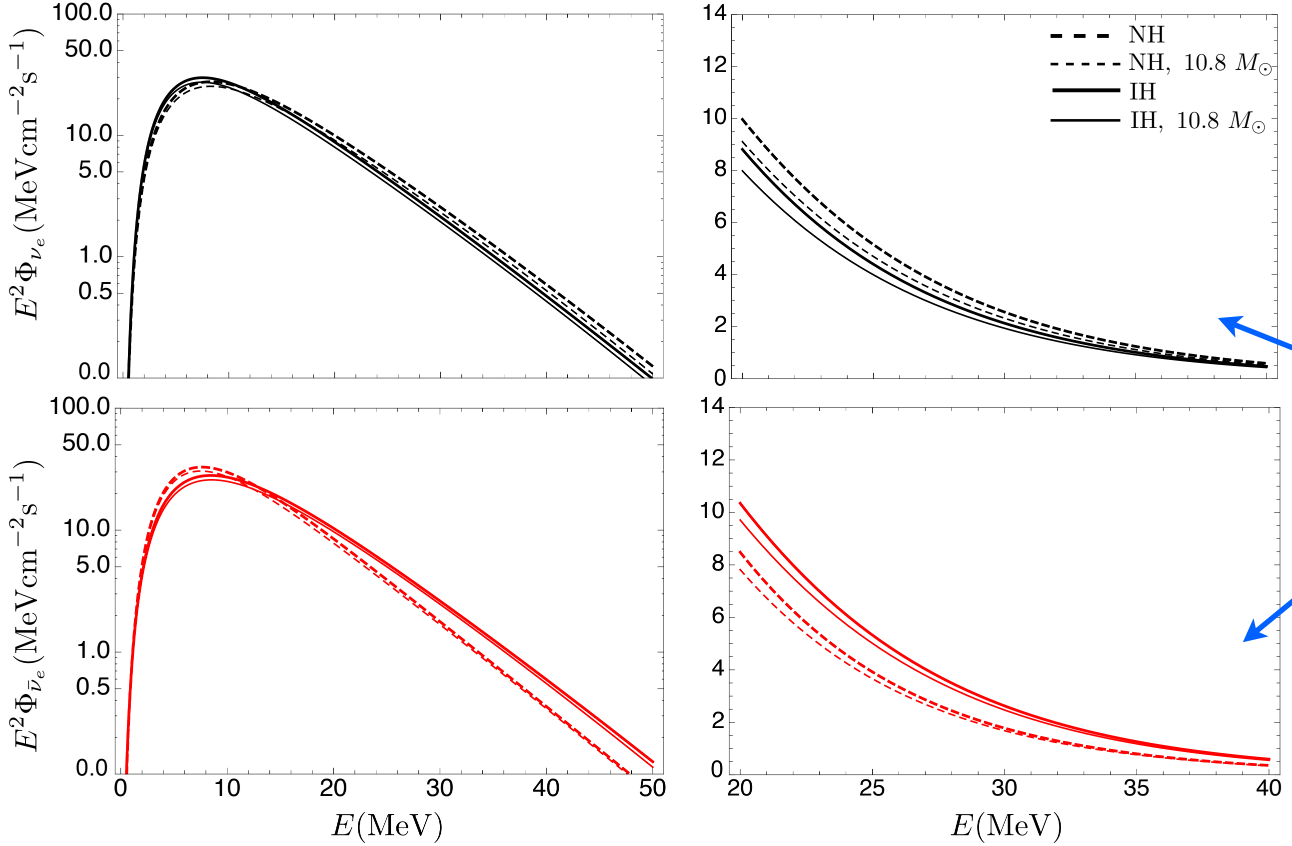
For large θ_{13} the oscillated fluxes are:

$$
\begin{aligned}
F_{\nu_e}^{\mathrm{NH}} &= \sin^2\theta_{12}[1 - P_c(F^c_{\nu_e}, F^c_{\bar{\nu}_e}, E)](F^0_{\nu_e} - F^0_{\nu_y}) + F^0_{\nu_y} \\
F_{\bar{\nu}_e}^{\mathrm{NH}} &= \cos^2\theta_{12}\bar{P}_c(F^c_{\nu_e}, F^c_{\bar{\nu}_e}, E)(F^0_{\bar{\nu}_e} - F^0_{\nu_y}) + F^0_{\nu_y} \ , \\
F_{\nu_e}^{\mathrm{IH}} &= \sin^2\theta_{12}P_c(F^c_{\nu_e}, F^c_{\bar{\nu}_e}, E)(F^0_{\nu_e} - F^0_{\nu_y}) + F^0_{\nu_y} \ , \\
F_{\bar{\nu}_e}^{\mathrm{IH}} &= \cos^2\theta_{12}[1 - \bar{P}_c(F^c_{\nu_e}, F^c_{\bar{\nu}_e}, E)](F^0_{\bar{\nu}_e} - F^0_{\nu_y}) + F^0_{\nu_y}
\end{aligned}
$$

Since self-induced flavor conversions and MSW resonances occur in well separated regions in most of the cases, we choose to factorize both the effects and treat them separately.

Diffuse Supernova Neutrino Background

A time-dependent analysis of the neutrino signal, including three different SN progenitors and oscillation physics at the best of our knowledge suggests that the largest uncertainties on the DSNB come from astrophysics.



region of interest for Super-Kamiokande detection

A maximum variation of 10-20% (at $E \simeq 20$ MeV) is related to the mass hierarchy.

For details see: C. Lunardini and I. Tamborra, arXiv: 1205.6292.

Diffuse Supernova Neutrino Background

★ The inclusion of time-dependent neutrino spectra is responsible for colder neutrino spectra in the DSNB (error ~5%).

★ The largest effect of flavor oscillations is due to MSW resonances (~50-60%), neutrino-neutrino interactions contribute at 5-10%. No energy-dependent signature of collective oscillations.

★ The dependence on the mass hierarchy is ~10-20% and it is stronger for antineutrinos.

★ Combining results for different progenitor stars (instead of using $10.8 M_\odot$ spectra for all stars), increases the DSNB by 5-10%.

★ The **DSNB is mainly affected by MSW effects and it can be used to extract astrophysical quantities.**

★ **The forthcoming detection of the DSNB will be an excellent benchmark to test models of neutrino spectra/emission and SNR!**

$$\Phi_{\rm tot}^{\nu_e,{\rm NH}} = 0.31\ {\rm cm}^{-2}{\rm s}^{-1} \text{ and } \Phi_{\rm tot}^{\nu_e,{\rm IH}} = 0.27\ {\rm cm}^{-2}{\rm s}^{-1}$$
$$\Phi_{\rm tot}^{\bar\nu_e,{\rm NH}} = 0.26\ {\rm cm}^{-2}{\rm s}^{-1} \text{ and } \Phi_{\rm tot}^{\bar\nu_e,{\rm IH}} = 0.32\ {\rm cm}^{-2}{\rm s}^{-1}$$

For details see: C. Lunardini and I. Tamborra, arXiv: 1205.6292.

Neutrinos and Nucleosynthesis

Electron fraction

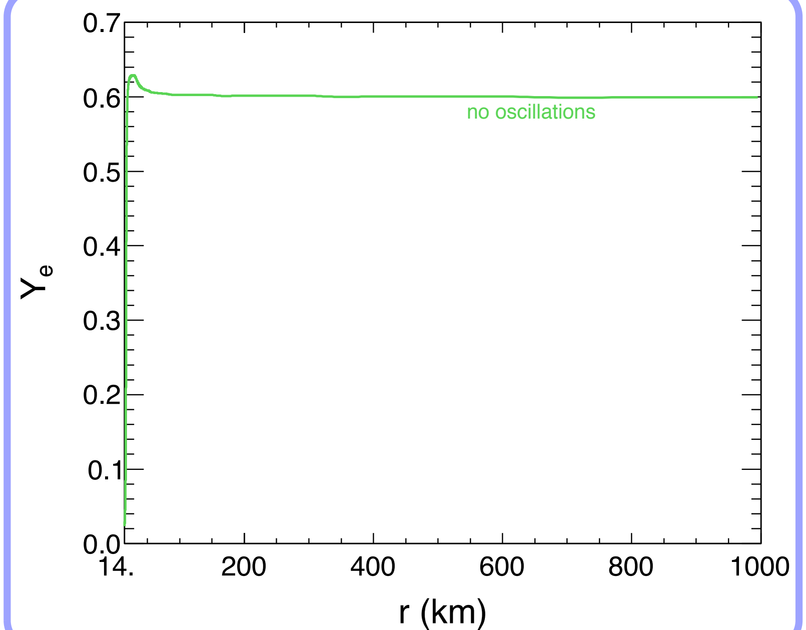
A hot problem in astrophysics is the location of the r-process nucleosynthesis (rapid neutron capture process generating elements with A >100).

Is the neutrino-driven matter outflow a good candidate site for the r-process nucleosynthesis in an electron-capture supernova?

To answer to this question, let's consider the evolution of the electron abundance:

$$\boxed{Y_e(r) = \frac{N_e(r)}{N_e(r) + N_n(r)}}$$

with $N_e(r)$ and $N_n(r)$ the effective electron and neutron densities.



$Y_e < 0.5 \Leftrightarrow$ more n than p $\Rightarrow$ r-process

Which is the impact of active-active and active-sterile oscillations on the electron abundance?

Electron fraction evolution

The electron abundance is set by the competition between the following neutrino and antineutrino capture rates on free nucleons

$$\boxed{\begin{aligned} &\nu_e + n \to p + e^- \\ &\bar{\nu}_e + p \to n + e^+ \end{aligned}}$$

and the associated reversed processes.

The electron abundance rate of change in an outflowing mass element may be written as

$$\boxed{\frac{dY_e}{dt} = v(r)\frac{dY_e}{dr} \simeq (\lambda_{\nu_e} + \lambda_{e^+})Y_n^f - (\lambda_{\bar{\nu}_e} + \lambda_{e^-})Y_p^f}$$

where $v(r)$ is the velocity of the outflowing mass element, t is the time parameter, λ_α is the forward rate of each process, and $Y^f_{n\ (p)}$ is the fraction of unbounded neutrons (protons).

The neutrino scattering rates are functions of the neutrino fluxes and then flavor oscillations cannot be neglected. λ_e is a function of the electron temperature and of the electron chemical potential.

Light sterile neutrinos in supernovae

★ Reactor $\bar{\nu}_e$ spectra are interpreted assuming the existence of ν_s with mixing parameters $(\sin^2 2\theta, \Delta m_s^2) \simeq (0.14, 1.5\ \mathrm{eV}^2)$.*

★ In a supernova, such parameters induce MSW $\nu_e - \nu_s$ conversions sensitively affecting the neutrino energy spectra.

★ A decrease of the ν_e flux by $\nu_e - \nu_s$ oscillations increases the neutron abundance and thus it can enable the r-nucleosynthesis **.

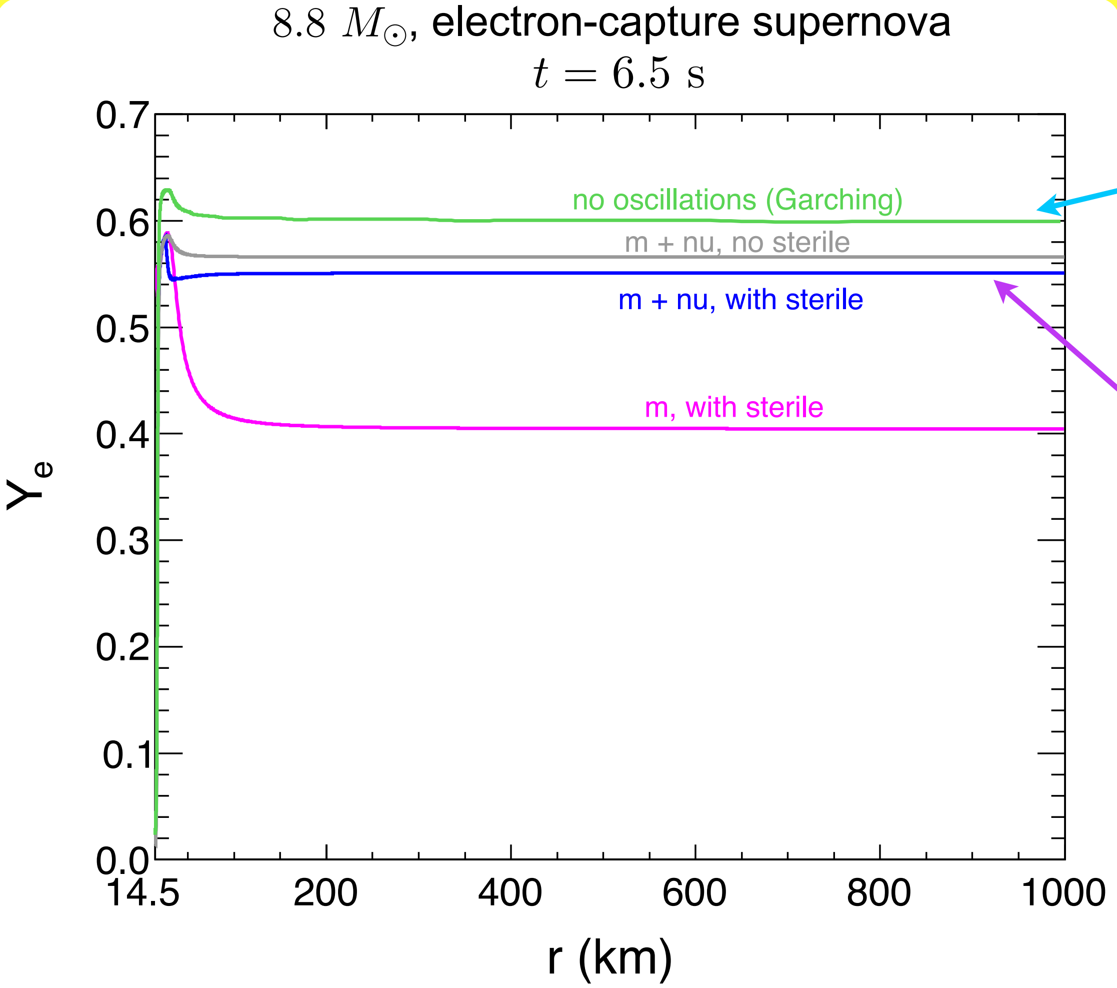
★ Using the new electron-capture supernova hydrodynamical simulations, we analyze (2 active+1 sterile) scenario with the anti-reactor mixing parameters.

less ν_e $\Rightarrow$ more n $\Rightarrow$ Y_e decreases

* Mention et al., PRD 83 (2011) 073006, Huber, PRC 84 (2011) 024617.
** See Fetter et al., Astrop. Phys. 18 (2003) 433, PRC 59 (1999) 2873 and references therein.

Sterile Neutrinos and Supernovae

Light sterile neutrinos could also affect the element formation in supernovae (impact on the r-process).



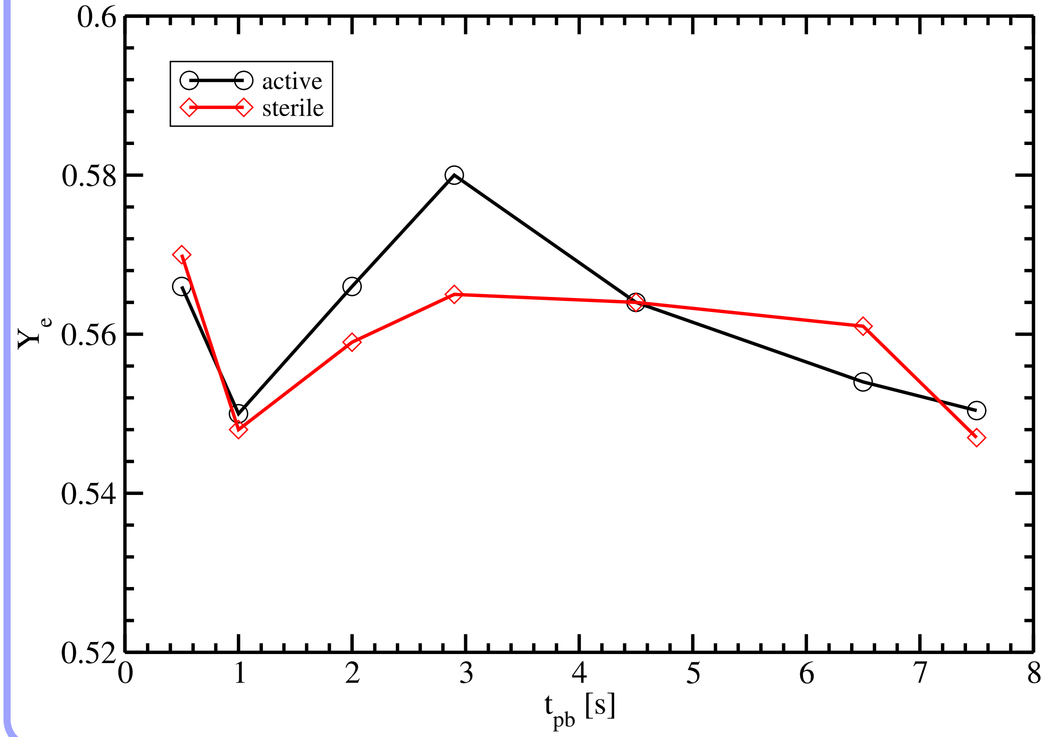
electron abundance in absence of neutrino oscillations

electron abundance in presence of oscillations, with eV-mass sterile neutrinos

* I. Tamborra, G. Raffelt, L. Huedepohl, H.-T. Janka, arXiv: 1110.2104.

Neutrinos and r-process

Asymptotic values of the electron abundance in presence of active-active and active-sterile oscillations



Oscillations do not drive the electron abundance below 0.5.

The alpha-effect is very strong.

Nucleosynthesis is very sensitive to neutrino oscillations, although the r-process is not enabled.

Caution! Extension to several progenitors required.

* E. Plumbii, I. Tamborra, S. Wanajo, T.-H. Janka, in preparation

Conclusions

★ Collective neutrino interactions are not negligible in neutrino dense media as SNe.

★ **The features of the oscillated neutrino fluxes are strictly dependent on the neutrino angular distribution, flux hierarchies and mass hierarchy.**

★ More supernova models needed to extract the standard features of the expected neutrino signal. More details on the neutrino-angle distributions needed.

★ De-leptonization burst and accretion phase: large differences among the neutrino fluxes. SN as standard candles. Accretion phase as laboratory to detect the neutrino mass hierarchy.

★ Cooling phase: small differences among the neutrino fluxes. Relevant for nucleosynthetic processes.

★ Good chances to detect the DSNB in the next future. Test for our SN astrophysics.

Thank you

for your attention!

Backup slides

Stability analysis

A powerful method to check whether flavor conversions are occurring during the accretion phase is the stability analysis criterion.

$$\boxed{i\partial_r \varrho_{E,u,r} = [\mathsf{H}_{E,u,r}, \varrho_{E,u,r}]}$$

Let us define $\omega = \Delta m^2/2E$, $u = \sin^2\vartheta_R = (1-\cos^2\vartheta_r)\, r^2/R^2$ and $v_{u,r}$ the radial velocity. The Hamiltonian and the density matrix in terms of these variables are

$$\mathsf{H}_{E,u,r} = \left(\frac{\mathsf{M}^2}{2E} + \sqrt{2}\,G_\mathrm{F}\mathsf{N}_\ell\right)\frac{1}{v_{u,r}} + \frac{\sqrt{2}\,G_\mathrm{F}}{4\pi r^2}\int_0^1 \mathrm{d}u' \int_{-\infty}^{+\infty}\mathrm{d}E'\left(\frac{1}{v_{u,r}v_{u',r}} - 1\right)\varrho_{E',u',r}$$

$$\varrho_{E,u} = \frac{\mathrm{Tr}\,\varrho_{E,u}}{2} + \frac{F^{\nu_e}_{E,u,R} - F^{\nu_x}_{E,u,R}}{2}\mathsf{S}_{E,u}$$

with the swapping matrix
$$\mathsf{S}_{E,u} = \begin{pmatrix} s_{E,u} & S_{E,u} \\ S^*_{E,u} & -s_{E,u}\end{pmatrix}$$

We expand the Hamiltonian for large distances from the core and small mixing angles

$$\begin{aligned}
H^{\mathrm{vac}}_{E,u} &= \frac{\mathsf{M}^2}{2E}\,v_u^{-1} \to \pm\frac{\omega}{2}\begin{pmatrix}\cos 2\theta & \sin 2\theta \\ \sin 2\theta & -\cos 2\theta\end{pmatrix} v_u^{-1} \to \pm\frac{\omega}{2}\begin{pmatrix}1 & 0 \\ 0 & -1\end{pmatrix}\left(1 + \frac{u}{2}\frac{R^2}{r^2}\right) \\
H^{\mathrm{m}}_{E,u} &= \sqrt{2}\,G_\mathrm{F}\begin{pmatrix} n_e - n_{\bar e} & 0 \\ 0 & 0\end{pmatrix} v_u^{-1} \to \frac{\tilde\lambda}{2}\begin{pmatrix}1 & 0 \\ 0 & -1\end{pmatrix}\left(1 + \frac{u}{2}\frac{R^2}{r^2}\right), \\
H^{\nu\nu}_{E,u} &\to \frac{\sqrt{2}\,G_\mathrm{F}\,R^2}{4\pi r^4}\int_0^1 \mathrm{d}u'\,\frac{u+u'}{2}\int_{-\infty}^{+\infty}\mathrm{d}E'\,\frac{F^e_{E,u,R} - F^x_{E,u,R}}{2}\,\mathsf{S}_{E',u'}\,.
\end{aligned}$$

* A. Banerjee, A. Dighe and G.G. Raffelt, arXiv: 1107.2308

Stability analysis

Expanding in the small-amplitude limit with $|S| \ll 1$ and normalizing the fluxes such that $\int_0^\infty \mathrm{d}E \int_0^1 \mathrm{d}u \, g_{E,u} = 1 + \varepsilon$, the equation of motion becomes

$$\boxed{\mathrm{i}\partial_r S_{\omega,u} = [\omega + u(\lambda + \varepsilon\mu)] \, S_{\omega,u} - \mu \int \mathrm{d}u' \, \mathrm{d}\omega' \, (u + u') \, g_{\omega' u'} \, S_{\omega',u'}}$$

This equation has solutions in the form

$$S_{\omega,u} = Q_{\omega,u} e^{-i\Omega r}$$

with $\Omega = \gamma + i\kappa$ and the eigenvector equation

$$(\omega + u\bar{\lambda} - \Omega) \, Q_{\omega,u} = \mu \int du' \, d\omega' \, (u + u') \, g_{\omega' u'} \, Q_{\omega',u'}$$

The solution has to be in the form

$$Q_{\omega,u} \propto \frac{1}{\omega + u\bar{\lambda} - \Omega}$$

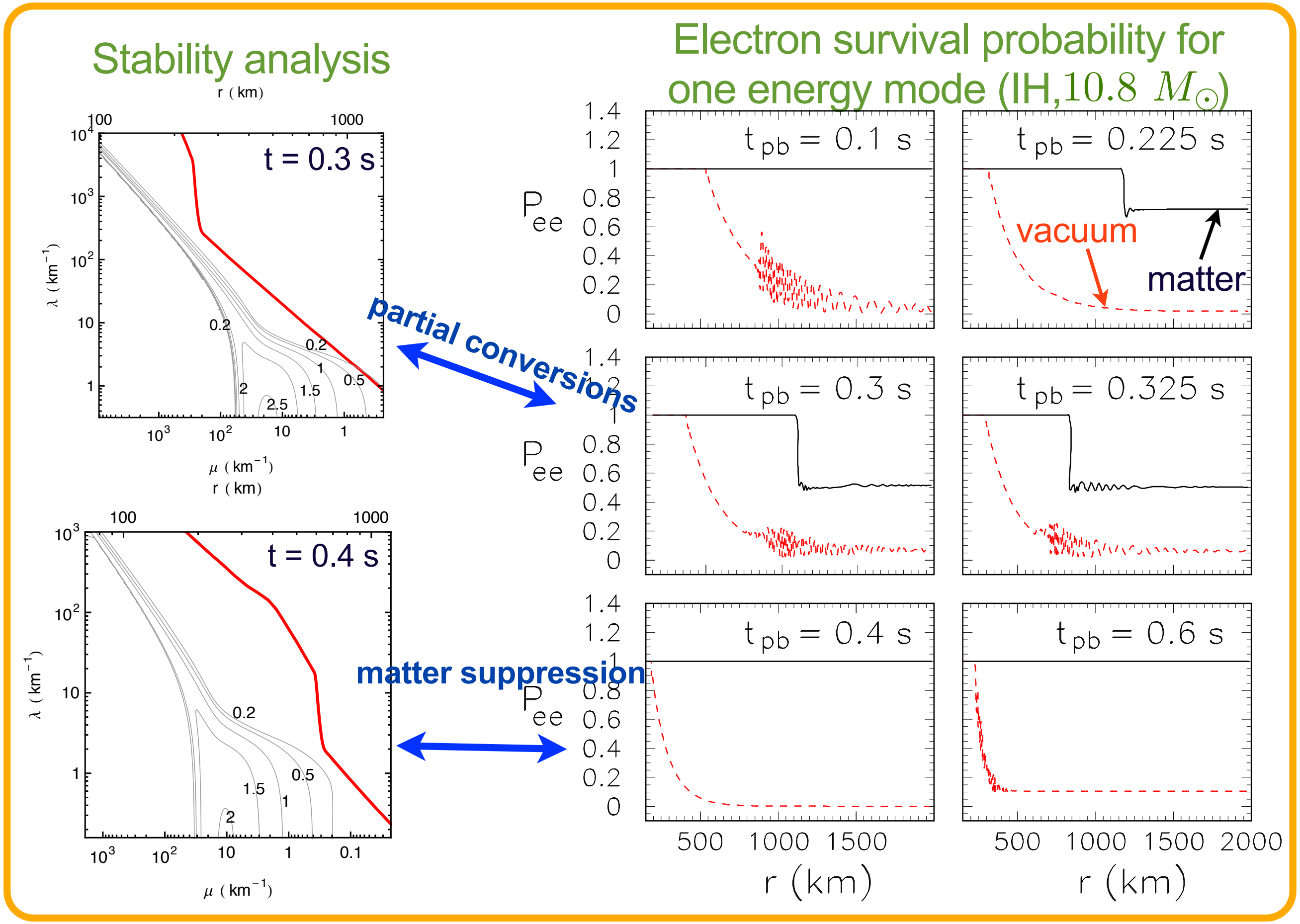
It can be proved that an instability occurs if

$$\boxed{\kappa = \mathrm{Im}(\Omega) \neq 0}$$

Therefore if we compute κ and we find a non-null value we should expect flavor conversions.

Note: the stability analysis only determines whether flavor conversions occur or not.

Suppression of collective oscillations during the accretion phase



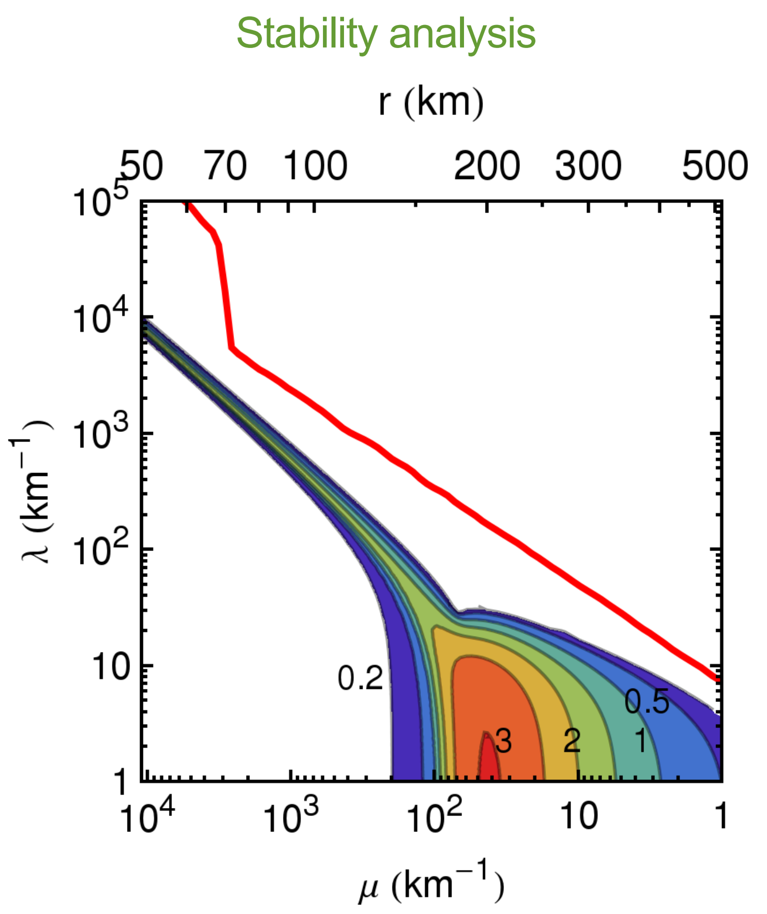
Matter suppression of collective effects during the accretion -only MSW- (Basel models)

The high electron density suppresses collective flavor oscillation (no splits). Only MSW occurs.

Note that the angular distribution is crucial for the flavor-oscillation suppression!

* For details see: S. Chakraborty et al., arXiv: 1104.4031, arXiv: 1105.1130, S. Sarikas et al., arXiv: 1110.5572, arXiv: 1109.3601

Application of the stability analysis



SN mass: $M = 15\ M_{\odot}$, t= 280 ms

Matter suppression of collective effects during the accretion -only MSW- (confirmed by Garching models)

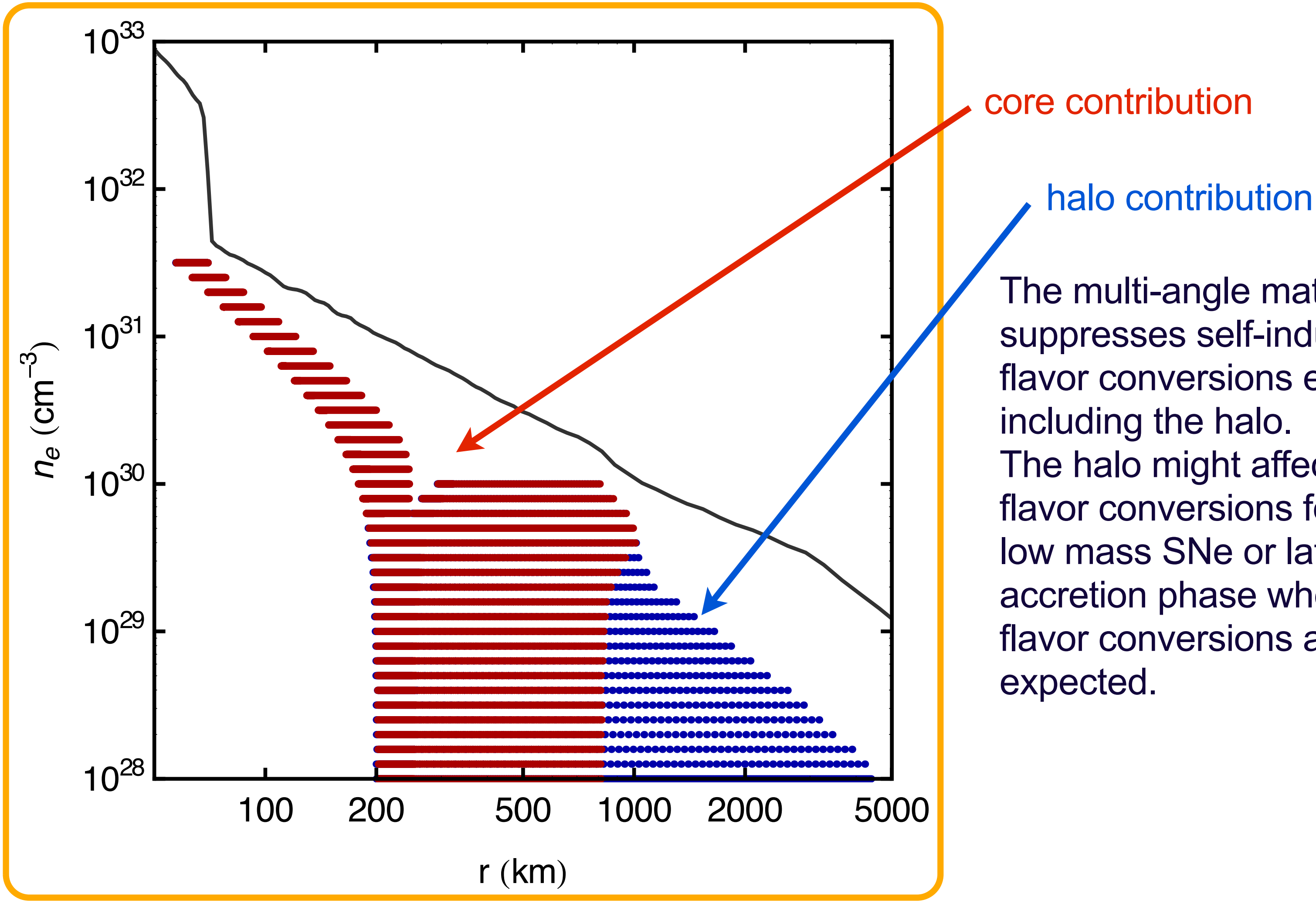
The high electron density suppresses collective flavor oscillation (no splits). Only MSW occurs.

Note that the angular distribution is crucial for the flavor-oscillation suppression!

* For details see: S. Sarikas, G.G. Raffelt, L. Huedepohl, H.-T. Janka, arXiv: 1109.3601

Application of the stability analysis

Stability analysis applied to a SN with $15\ M_\odot, 280\mathrm{ms}$ including the “halo” contribution.



The multi-angle matter effect suppresses self-induced flavor conversions even after including the halo.
The halo might affect the flavor conversions for slightly low mass SNe or late accretion phase where partial flavor conversions are expected.

* For details see: S. Sarikas, I. Tamborra, G. Raffelt, L. Huedepol, T. Janka, in preparation

DSNB Detection Perspectives

The DSNB has not been observed yet, the most stringent limit is from Super-Kamiokande (SK):

$$\phi_{\bar{\nu}_e} \leq 2.8 - 3.0 \text{ cm}^{-2}\text{s}^{-1}$$

computed for energies above 17.3 MeV.

Concept	energy window (MeV)	detection processes	experiment (location)	fiducial mass (kt)	events per year
H_2O	19.3 - 30 $[17.3 - 30]$	$\bar{\nu}_\mathbf{e}\ (\mathbf{p},\mathbf{n})\mathbf{e}^+$	SK (Japan)	22.5	0.25 - 1.40
		$\nu_e\ (^{16}O, X)e^-$	DUSEL WC (USA)	300	3.3 - 18.7
		$\bar{\nu}_e\ (^{16}O, X)e^+$	MEMPHYS (Europe)	440	4.9 - 27.5
		$\nu_w(e^-, e^-)\nu_w$	Hyper-K (Japan)	500	5.5 - 31.2
		$\nu_w(p, p)\nu_w$	Deep-TITAND (Japan)	$5\ 10^3$	55 - 312
		$\nu_w(^{16}O, X)\nu_w$			
$H_2O + Gd$	11.3 - 30	same as H_2O	GADZOOKS (Japan)	22.5	0.97 - 2.8
			DUSEL WC+Gd	300	12.9 - 37.2
			MEMPHYS+Gd	440	18.9 - 54.6
			Hyper-K+Gd	500	21.5 - 62.0
Scintillator	$\sim 8 - 30$	$\bar{\nu}_\mathbf{e}\ (\mathbf{p},\mathbf{n})\mathbf{e}^+$	LENA (Europe)	50	1.9 - 5.4
		$\nu_e\ (^{12}C, X)e^-$	Hano Hano (USA)	10	0.3 - 1.1
		$\bar{\nu}_e\ (^{12}C, X)e^+$			
		$\nu_w(e^-, e^-)\nu_w$			
		$\nu_w(p, p)\nu_w$			
		$\nu_w(^{12}C, X)\nu_w$			
Argon	$\sim 18 - 30$	$\nu_\mathbf{e}\ (^{40}\mathbf{Ar}, \mathbf{X})\mathbf{e}^-$	LANNDD (USA)	< 100	< 3.3
		$\bar{\nu}_e\ (^{40}Ar, X)e^+$	GLACIER (Europe)	100	0.9 - 3.3
		$\nu_w(e^-, e^-)\nu_w$			
		$\nu_w(^{40}Ar, X)\nu_w$			

For details see: C. Lunardini, arXiv: 1007.3252.

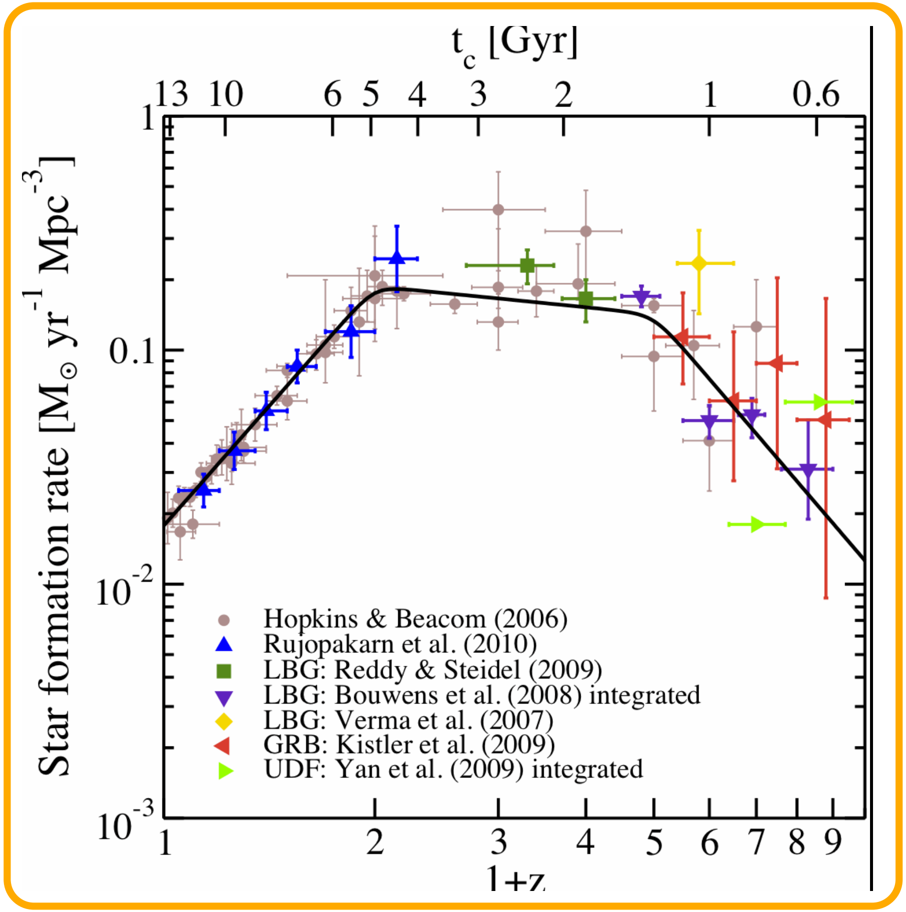
SNR: Predictions From Star Formation Rate

The SNR is proportional to the star formation rate (SFR), mass that forms stars per unit time per unit volume:

$$\dot{\rho}_\star \propto \begin{cases} (1+z)^\delta & z < 1 \\ (1+z)^\alpha & 1 < z < 4.5 \\ (1+z)^\gamma & 4.5 < z \end{cases}$$

The most precise way to measure the SNR is from data on the SFR.

The cosmic star formation history as a function of the redshift is pretty well known from data in the ultraviolet and far-infrared. Impressive agreement among results from different groups.



See for details Horiuchi, Beacom, arXiv: 1006.5751; Hopkins, Beacom, arXiv: astro-ph/0601463.