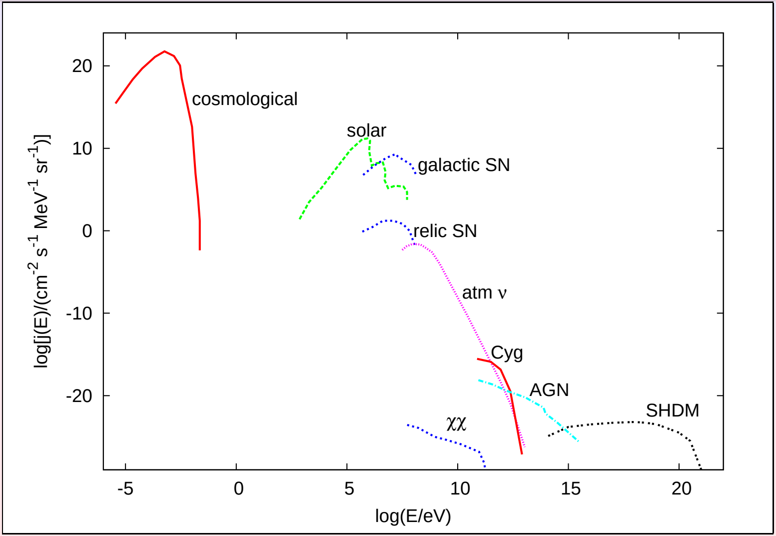
Cosmic Neutrinos

Michael Kachelrieß

Neutrino opportunities:



Neutrinos: what we do know

- neutrino oscillations are solution to
  - solar neutrino problem
  - atmospheric neutrino anomaly

$\Rightarrow$ neutrinos have mass and mix

$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = U_{\alpha i} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}$$

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$$U = \underbrace{\begin{bmatrix} 1 & 0 & 0 \\ 0 & c_a & s_a \\ 0 & -s_a & c_a \end{bmatrix}}_{\text{atm. osc.}} \underbrace{\begin{bmatrix} c_x & 0 & s_x e^{-i\delta} \\ 0 & 1 & 0 \\ -s_x e^{i\delta} & 0 & c_x \end{bmatrix}}_{\theta_x \equiv \theta_{13}} \underbrace{\begin{bmatrix} c_s & s_s & 0 \\ -s_s & c_s & 0 \\ 0 & 0 & 1 \end{bmatrix}}_{\text{solar osc.}} \underbrace{\text{diag}(1, \phi_2, \phi_3)}_{\text{Majorana phases}}$$

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- absolute scale of neutrino masses
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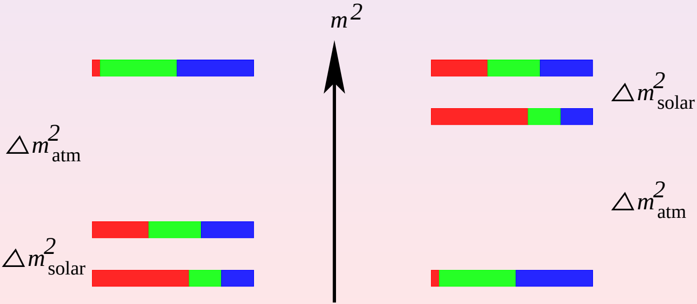
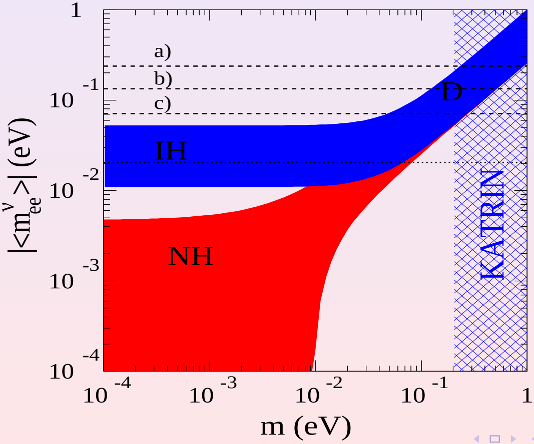
- value of θ_{13}
- hierarchy of masses: normal or inverted? $(\nu_e, \nu_\mu, \nu_\tau)$



Impact of mass hierarchy:

- constraint for models of neutrino mass
- neutrinoless double-beta decay:



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- complete understanding of SN dynamics

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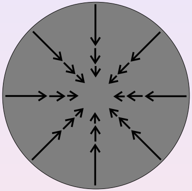
open: sources for HE neutrinos

- Galaxy, AGN's, . . .
- decay/annihilations of cosmic relics

Core collapse supernovae:

- gravitational core collapse:



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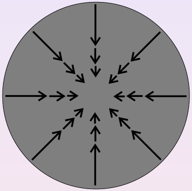
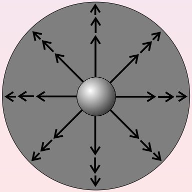
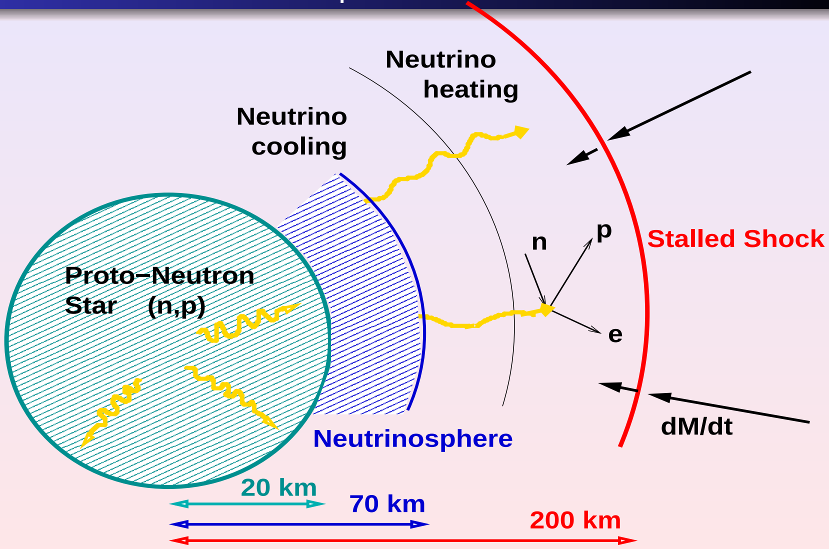


- reflection for $\rho > \rho_{\rm nuc}$, generation of out-going shock wave



Neutrino emission from proto-neutron stars



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SN neutrino spectra are model dependent:
how can mixing parameters be determined reliably?

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solution

use only things in which you are sure:

- shock wave
- Earth matter effect
- neutronization burst

Neutrino oscillations and matter effects

- SN core $\rightarrow$ envelope $\rightarrow$ interstellar medium $\rightarrow$ Earth

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- consider effective Hamiltonian in (ν_e, ν_μ) basis:

$$H = \frac{1}{4E} \begin{pmatrix} -\Delta m^2 \cos 2\theta + A & \Delta m^2 \sin 2\theta \\ \Delta m^2 \sin 2\theta & \Delta m^2 \cos 2\theta \end{pmatrix}, \qquad A \propto \pm 2E\rho$$

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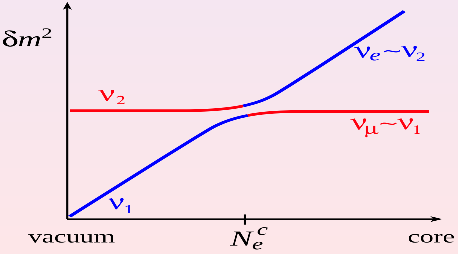
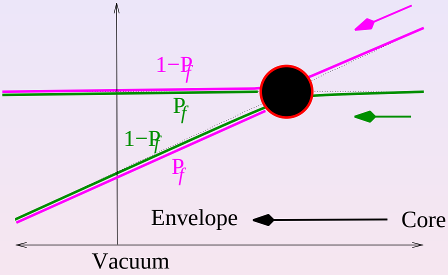
- eigenvalues: $m_i^2 = \frac{A}{2} \mp \sqrt{(\Delta m^2 \cos 2\theta - A)^2 + (\Delta m^2 \sin 2\theta)^2}$



Adiabaticity at resonance:



$$P_c \approx \exp\left(-\frac{\pi}{2}\gamma\right) , \qquad \gamma \equiv \frac{\Delta m^2}{2E}\,\frac{\sin^2 2\theta}{\cos 2\theta}\left(\frac{1}{n_e}\,\frac{dn_e}{dr}\right)^{-1}_{\text{res}}$$

$\gamma \gg 1 \Rightarrow P_c \ll 1 \Rightarrow$ adiabatic resonance

depends on $\Delta m^2/E$, mixing angle, density profile

more

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- inverted hierarchy: "atm. resonance" in anti-neutrino sector

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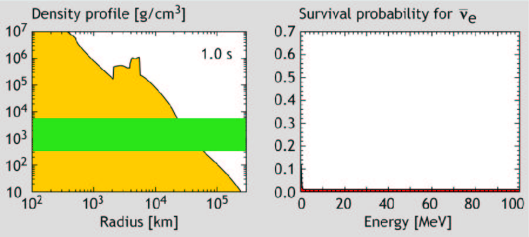
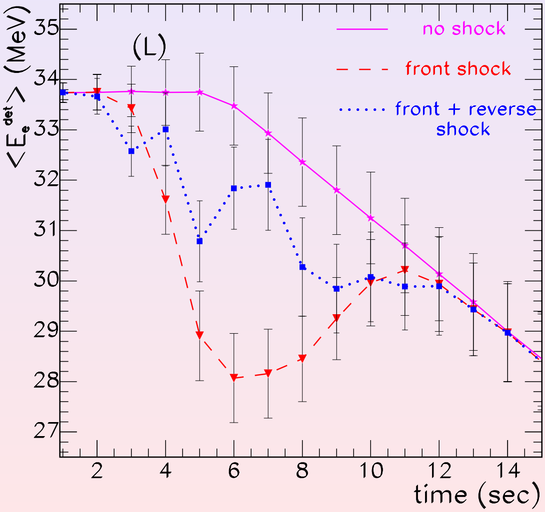
- inverted hierarchy: "atm. resonance" in anti-neutrino sector
- large θ_{13}: "atm. resonance" is adiabatic for progenitor profile
- shock waves passing through resonance break adiabaticity
- position of resonance is energy dependent
  $\Rightarrow$ energy binned $\bar{\nu}_e$ spectra allows tomography of SN

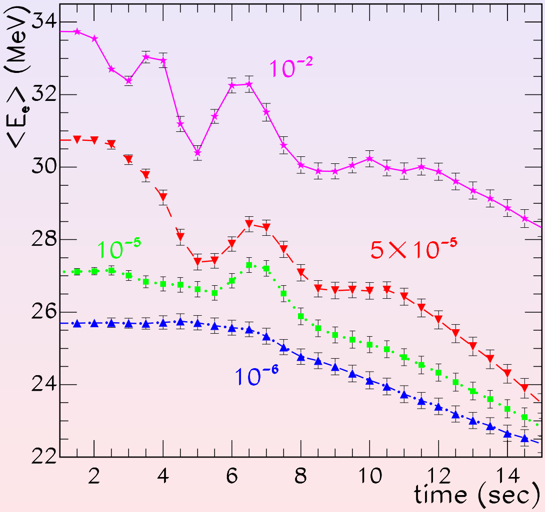


[Tomàs, MK, Raffelt, Dighe, Scheck, Janka '04]

Statistical significance: SuperKamiokande



Statistical significance: HyperKamiokande



Observable 2: Earth matter effects

- fast oscillations in the Earth superimpose wiggles on the primary spectra

$F^0_{\nu_e}$ $F^0_{\nu_x}$ F_{ν_e}

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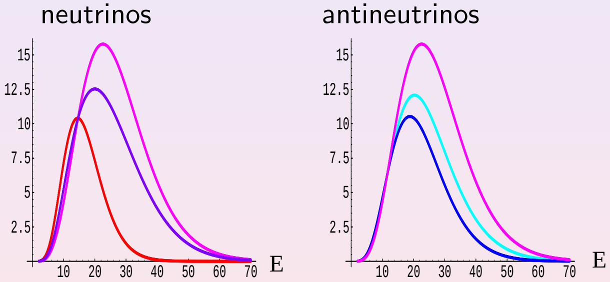

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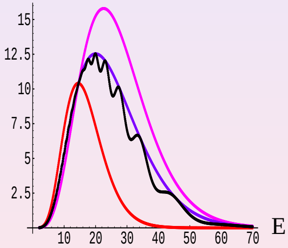
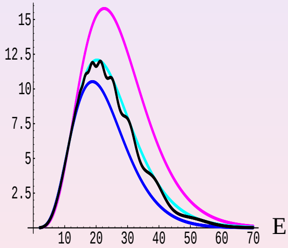
neutrinos



antineutrinos



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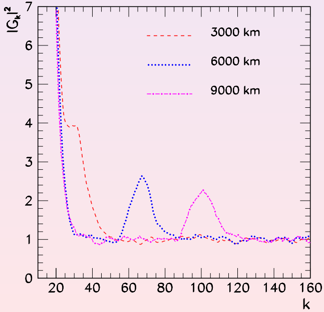
- Fourier transform of "inverse" energy spectrum $y = 1/E$

[Dighe, MK, Raffelt, Tomàs '04]



$$G(k) = \frac{1}{\sqrt{N}} \sum_{\text{events}} e^{iky}$$

more +1

SN neutrino summary

Hierarchy	$\sin^2\theta_{13}$	Earth effects	Shocks	ν_e burst
Normal	$\gtrsim 10^{-3}$	$\bar{\nu}_e$	ν_e	absent
Inverted	$\gtrsim 10^{-3}$	ν_e	$\bar{\nu}_e$	present
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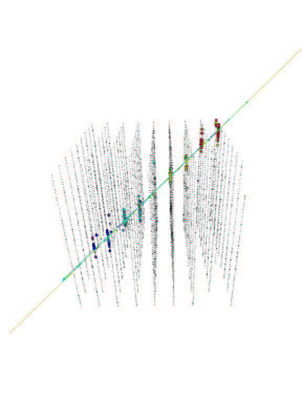
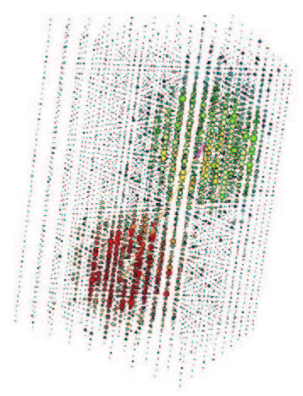
galactic SN & water Cherenkov/scintillation detector allows

- identification of neutrino mixing scenario
- a lot of astrophysics

Neutrino telescopes and neutrino mixing

- neutrino telescopes can distinguish muon neutrinos from electron and tau neutrino events:





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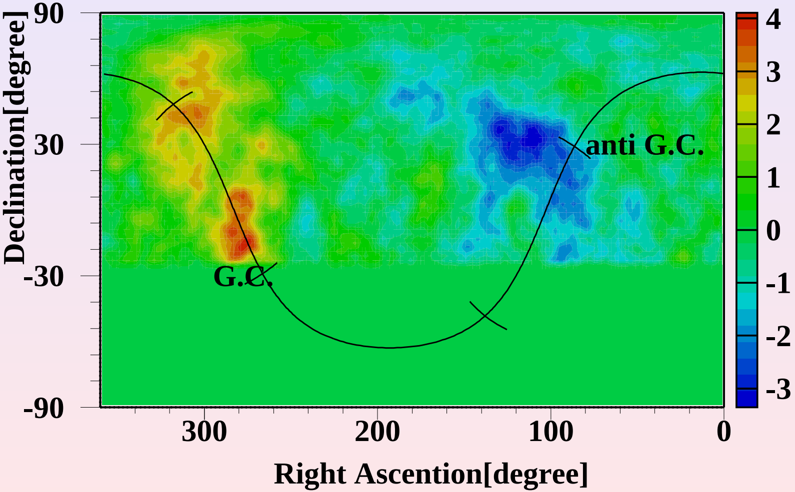
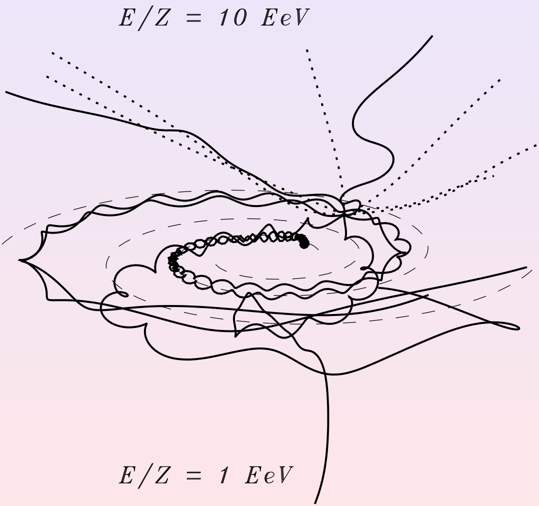
- example: galactic CR source near Cygnus region, if nuclei are accelerated [*MK, P. Serpico '05*]

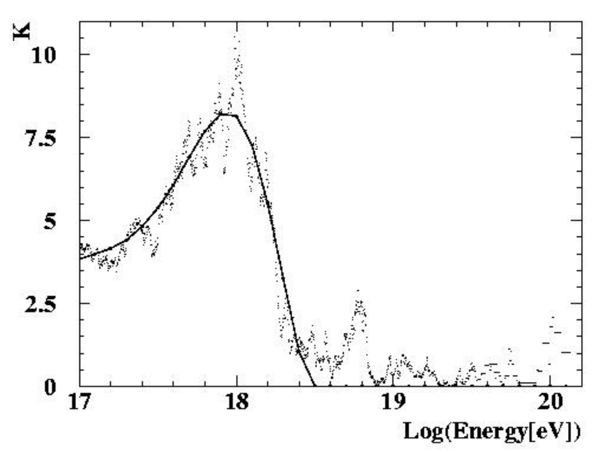
Galactic anisotropy around $E = 10^{18}$eV: significance



Deflection of charged particles in Galactic B-field:



Fit of neutron source at GC in Leaky Box model:



best fit with

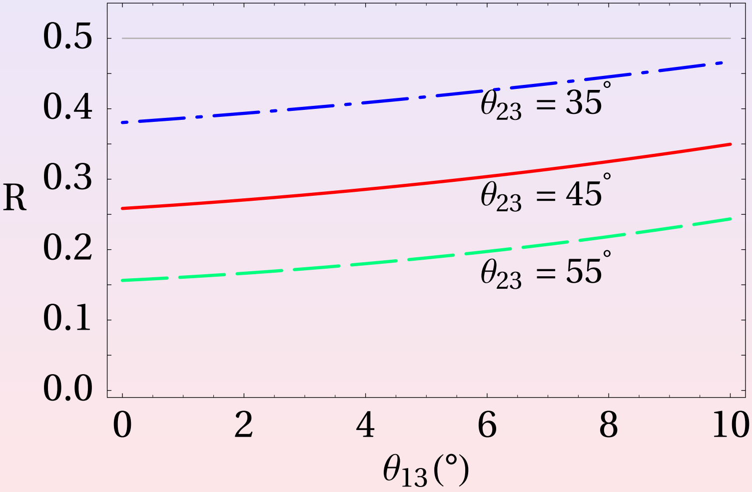
$dN/dE \propto E^{-2.5}$

distance 10kpc

$E_{\rm max} = 10^{18.5}$eV

[AGASA '98]

Neutrino telescopes and neutrino mixing: $R = \phi^\mu / \phi^{e+\tau}$



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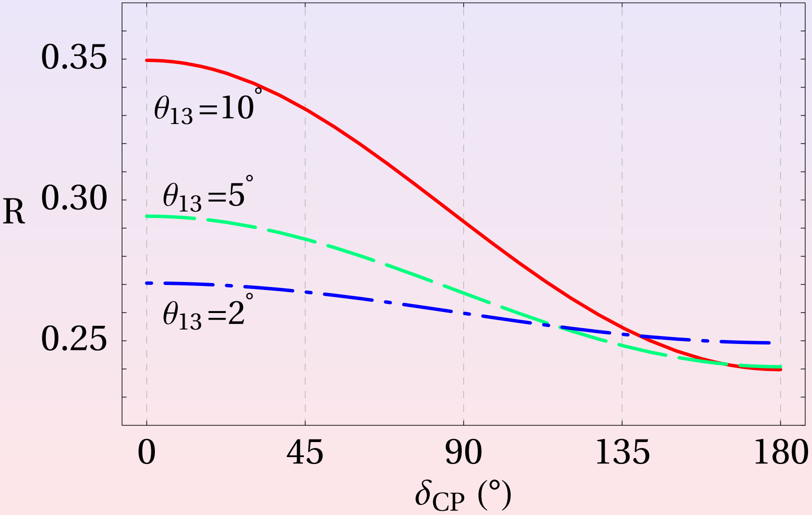

Sensitivity of ICECUBE:

statistical significance of Cyg detection:

- with $\ell = 25^\circ$ angular resolution for ν_e and ν_τ:
  4.2 σ for 10 years measurement

⇒ end

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- with $\ell = 25^\circ$ angular resolution for ν_e and ν_τ:
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- with $\ell = 10^\circ$ angular resolution for ν_e and ν_τ:
  $3.3\,\sigma$ for 1 year measurement

⇒ end

Top-Down Models

UHECR primaries are produced by decays of supermassive particle X with $M_X \gtrsim 10^{12}$ GeV.

- topological defects: monopoles, strings, ...

  [*Hill '83; Ostriker, Thompson, Witten '86*]

- superheavy metastable particles

  [*Berezinsky, MK, Vilenkin '97; Kuzmin, Rubakov '97*]

Advantages:

- no acceleration problem
- no visible sources
- if $X \in$ CDM, no GZK-cutoff
- theoretically motivated; testable predictions

Fragmentation of heavy particles

- Consider Bremsstrahlung, $X \to \bar{f} f V$:

  soft and collinear singularities generate $\ln^2(m_V^2/m_X^2)$ for $m_X^2 \gg m_V^2$
  $\Rightarrow$ they can compensate the small couplings g^2,

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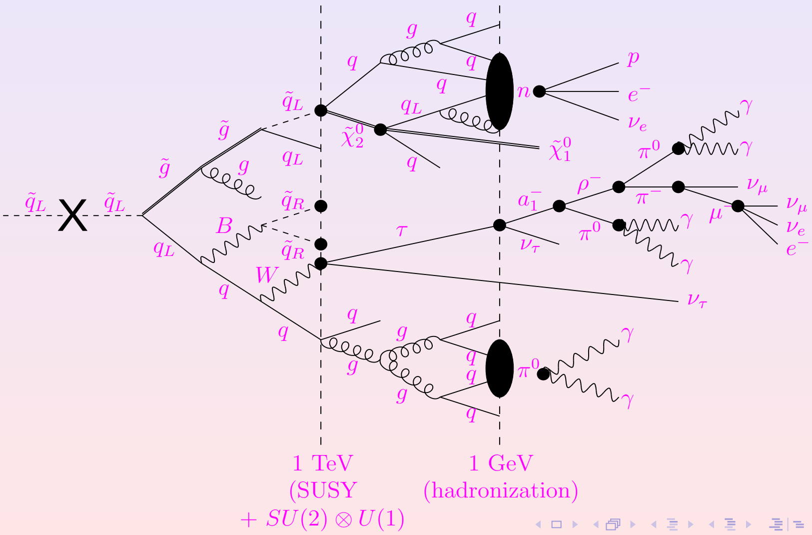
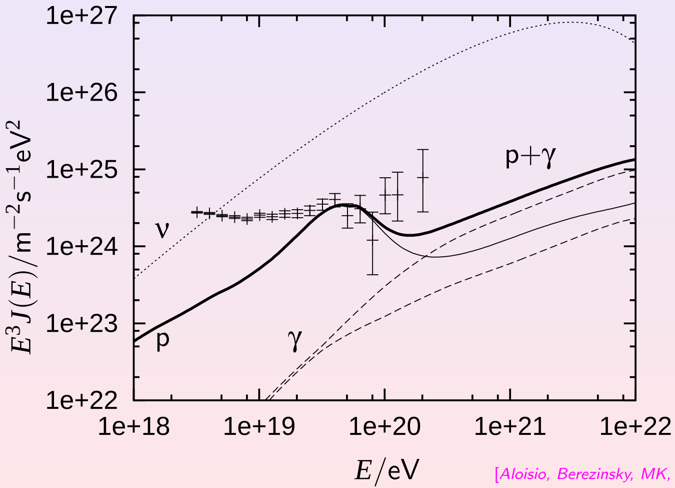
- $M_X \gtrsim 10^6$ GeV, $\Rightarrow$ naive perturbation theory breaks down: electroweak and SUSY sector have a QCD-like behavior ("jets")

[Berezinsky, MK '98, Berezinsky, MK, Ostapchenko '02)]

Fragmentation of heavy particles



Neutrino fluxes from topological defects:



[Aloisio, Berezinsky, MK, '03]

Summary

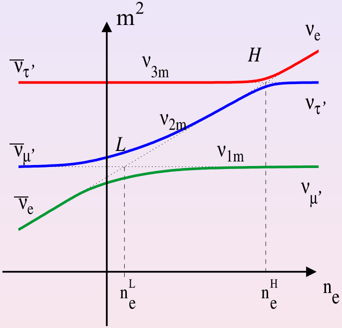
- Cosmic neutrinos encompass 24 orders in energy from 2.7 K relic background to UHE neutrinos with 10^{20} eV
- Relic neutrinos allow to test the absolute neutrino masses (LSS, Z-Burst model)
- SN neutrinos may identify mass hierarchy and θ_{13}
- Cygnus neutrinos as test for δ_{CP} and θ_{13}
- HE neutrinos as test for SUSY DM and new interactions
- UHE neutrinos are one of best tests for Lorentz invariance
- UHE neutrinos test superheavy dark matter or topological defects

  ...

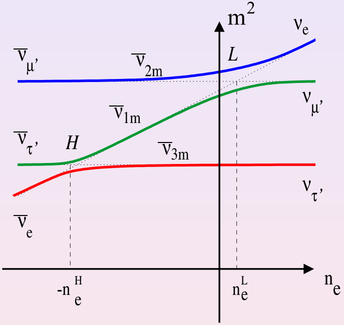
essential: interplay between particle physics, astrophysics and cosmology

3-ν level crossing schemes

normal mass hierarchy

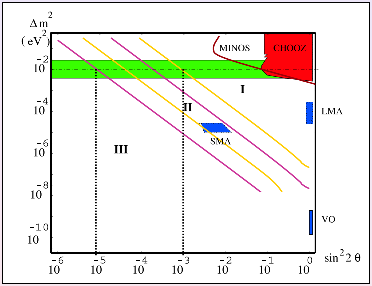


inverted mass hierarchy



- H-resonance: $(\Delta m^2_{\rm atm},\ \vartheta_{13})$, $\rho \sim 10^3$ g/cm^3
- L-resonance: $(\Delta m^2_\odot,\ \vartheta_\odot)$, $\rho \sim 10$ g/cm^3
- Δm^2 hierarchy $\Rightarrow$ resonances are independent

Adiabaticity at H and L resonances



- L always adiabatic
- H adiabatic for $|U_{e3}|^2 \gtrsim 10^{-3}$, non-adadiabatic for $|U_{e3}|^2 \lesssim 10^{-3}$
- H in ν_e channel for normal hierarchy
  H in $\bar{\nu}_e$ channel for inverted hierarchy

SN neutrino spectra sensitive for

- $|U_{e3}|^2 \gtrsim 10^{-3}$ or $|U_{e3}|^2 \lesssim 10^{-3}$
- normal or inverted mass hierarchy

Fluxes arriving at the Earth

Mixing of the emitted $\bar{\nu}_e$ flux:

$$F_{\bar{\nu}_e} = \bar{p} F^0_{\bar{\nu}_e} + (1-\bar{p}) F^0_{\nu_x}$$

Survival probability for different mixing scenarios:

case	hierarchy	$\sin^2\Theta_{13}$	$\bar{p}$
A	normal	$\gtrsim 10^{-3}$	$\cos^2\Theta_\odot$
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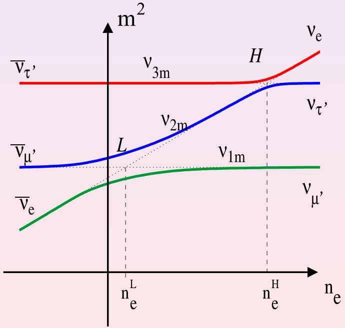

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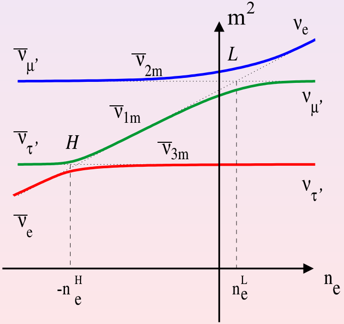


$\Rightarrow$

Earth matter effects II

$\Rightarrow$

$$F_{\bar{\nu}_e} = \sin^2\Theta_{12} F^0_{\nu_x} + \cos^2\Theta_{12} F^0_{\nu_e} + \Delta F^0 \overline{A}_\oplus \sin^2(\overline{\Delta m^2_\oplus} L y)$$

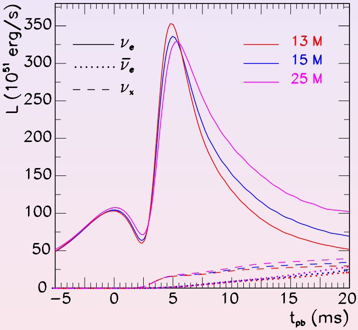
$\Delta F^0 = (F^0_{\nu_e} - F^0_{\nu_x})$, $\quad \overline{A}_\oplus = \sin 2\overline{\Theta}^\oplus_{12} \sin(2\overline{\Theta}^\oplus_{12} - 2\Theta_{12})$, $\quad y = (12.5/E)$

- coefficient $\Delta F^0 \overline{A}_\oplus$ varies slowly with E
- neutrino spectrum as function of $y \equiv 12.5/E$ oscillate with frequency $k_\oplus$ fast around primary spectrum

Oscillation frequency: $k_\oplus \equiv 2\overline{\Delta m^2_\oplus} L$

- completely independent of the primary neutrino spectra
- depends only on solar oscillation parameters, Earth density and the distance traveled through the Earth

Observable 3: ν_e neutronization burst



independent from

- progenitor mass
- EoS
- simulation

[MK, Tomàs, Buras, Janka, Marek, Rampp '04]

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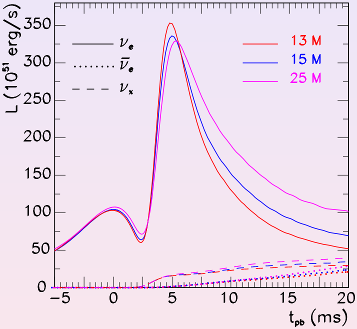


independent from

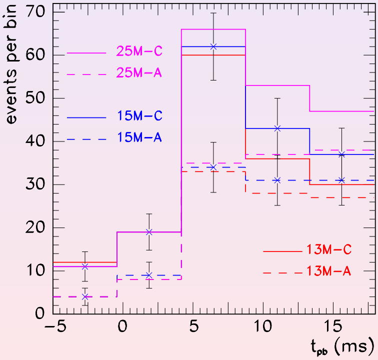
- progenitor mass
- EoS
- simulation

[MK, Tomàs, Buras, Janka, Marek, Rampp '04]

- allows to measure SN distance with 10% precision

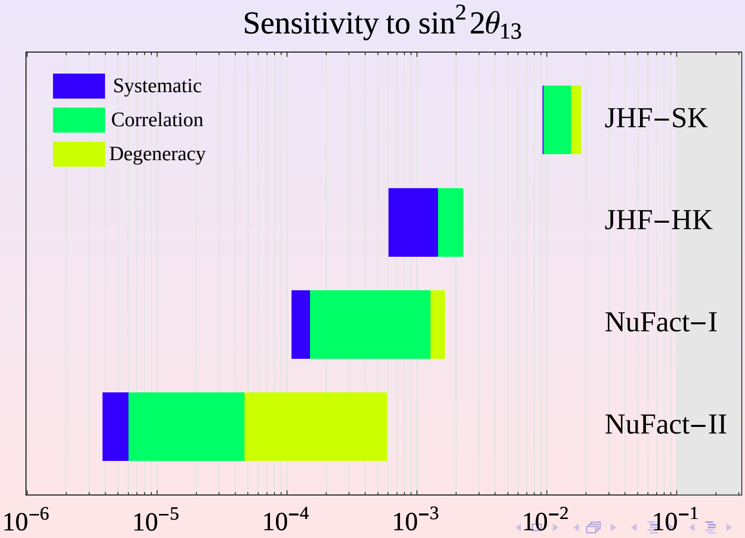
Observable 3: ν_e neutronization burst

- peak in time-binned spectra disappears for normal hierarchy and "large θ_{13}"



[MK, Tomàs, Buras, Janka, Marek, Rampp '04]

Sensitivity of future LBL experiments:



Scintillation vs. water Cherenkov detectors: