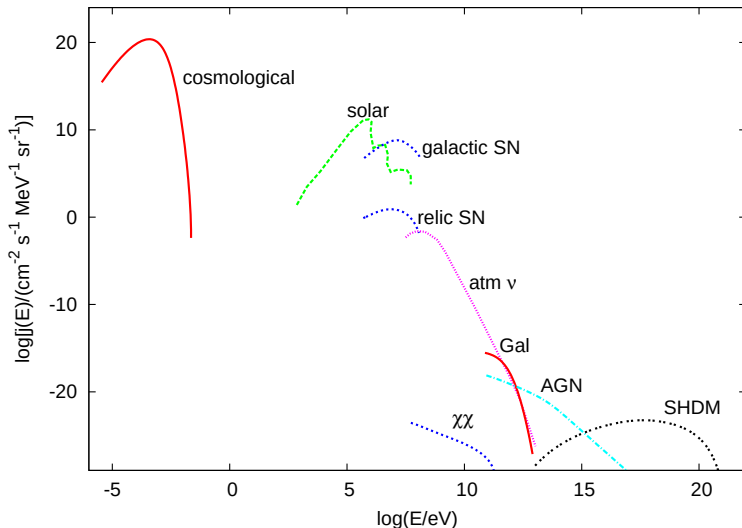


Particle Physics and Astrophysics with Cosmic Neutrinos

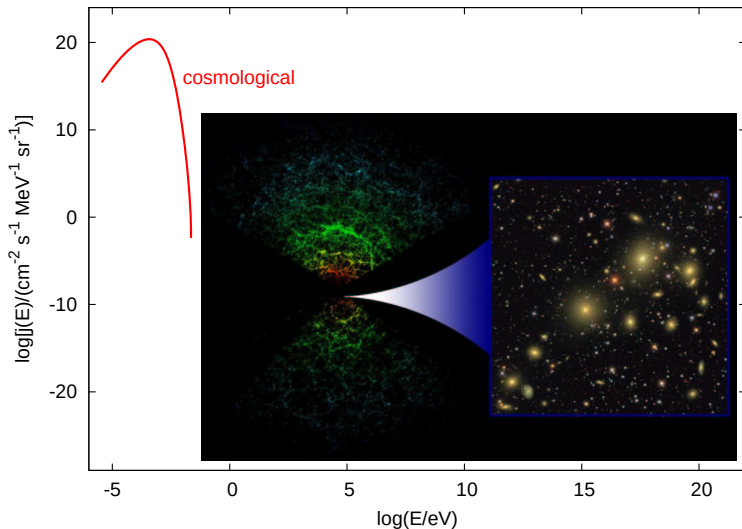
Michael Kachelrieß

NTNU Trondheim

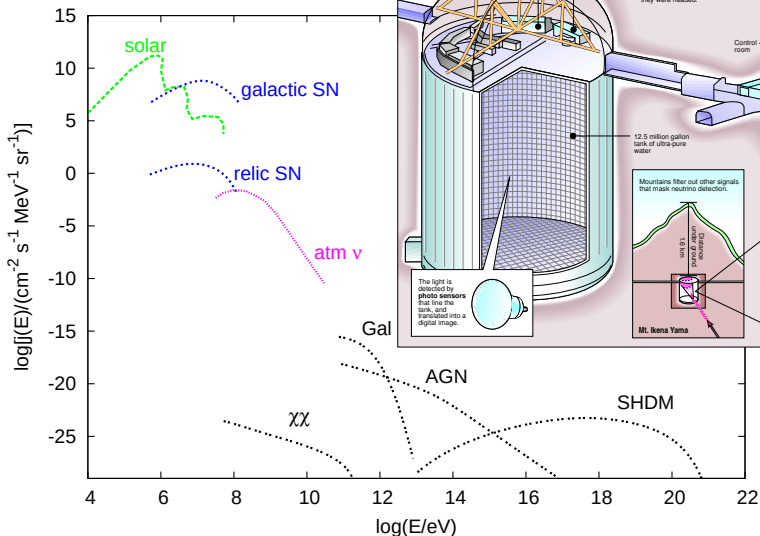
Neutrino opportunities:



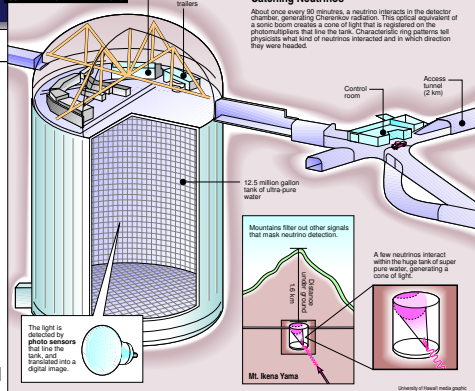
Neutrino opportunities:



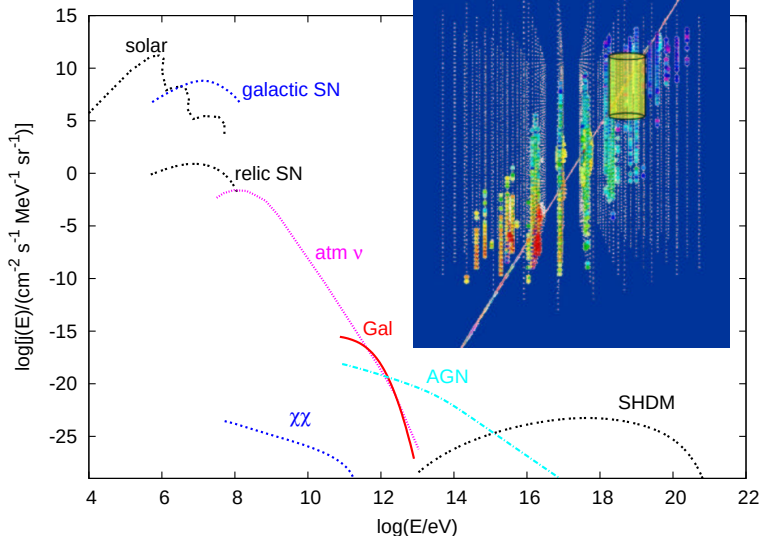
Neutrino opportunities:



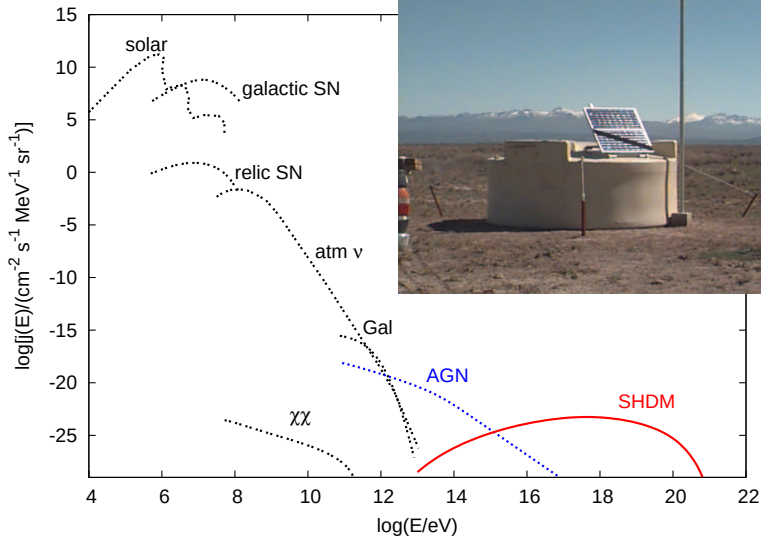
SUPERKAMIOKANDE DETECTOR



Neutrino opportunities:



Neutrino opportunities:



Neutrinos: what we do know

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

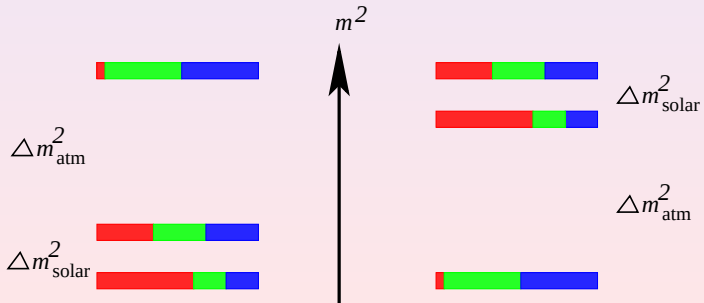
⇒ neutrinos have mass and mix

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

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

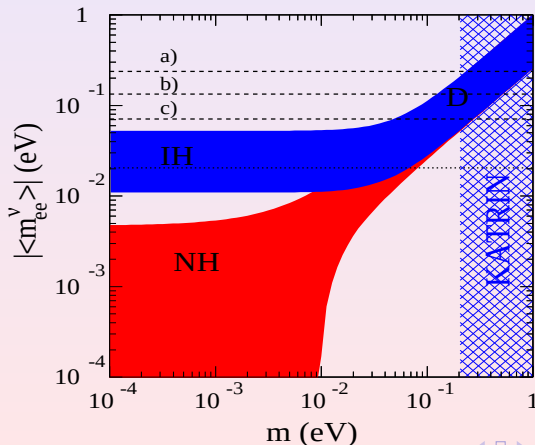
Neutrinos: what we do not know

- Dirac or Majorana particles?
- absolute scale of neutrino masses
- CP violation
- value of θ_{13}
- hierarchy of masses: normal or inverted? (ν_e, ν_μ, ν_τ)



Impact of mass hierarchy:

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



Neutrinos: what we do not know

only 2 confirmed neutrino sources

- the Sun
- SN 1987A

open:

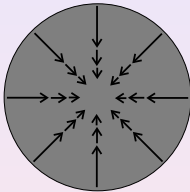
- complete understanding of SN dynamics

open: sources for HE neutrinos

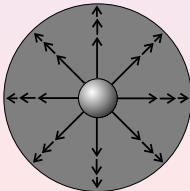
- Galaxy, AGN's, ...
- decay/annihilations of cosmic relics

Core collapse supernovae:

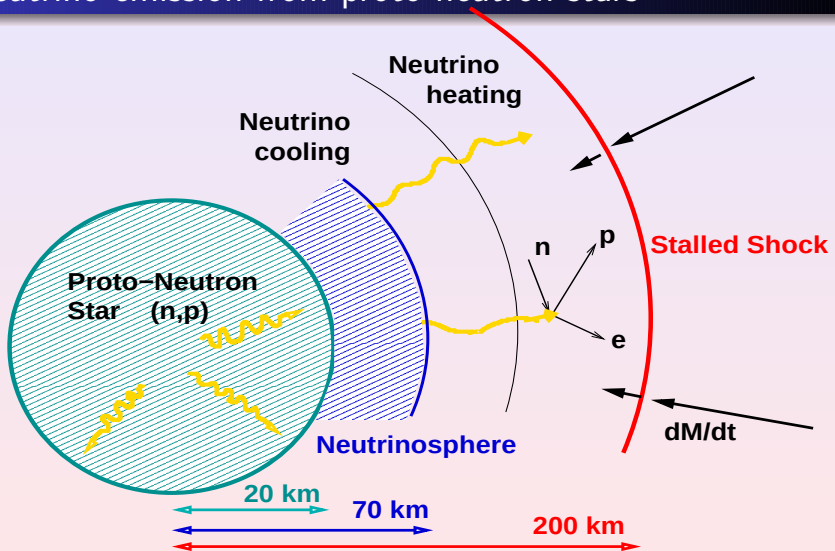
- gravitational core collapse:



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



Neutrino emission from proto-neutron stars



problem

SN neutrino spectra are model dependent:

how can mixing parameters be determined reliably?

↔ necessary for determination of primary spectra

solution

use only things in which you are sure:

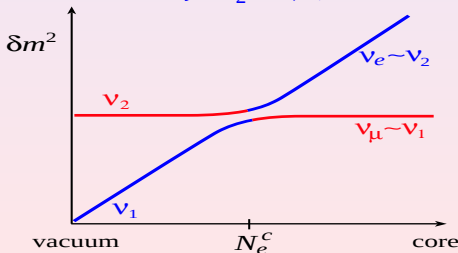
- shock wave
- Earth matter effect
- neutronization burst

Neutrino oscillations and matter effects

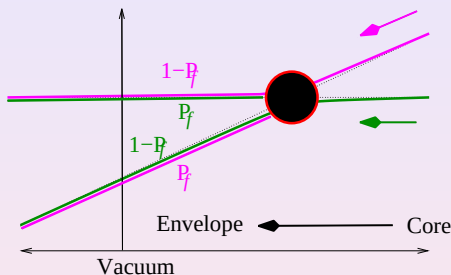
- SN core $\rightarrow$ envelope $\rightarrow$ interstellar medium $\rightarrow$ Earth
- consider effective Hamiltonian in (ν_e, ν_μ) basis:

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

- 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:



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

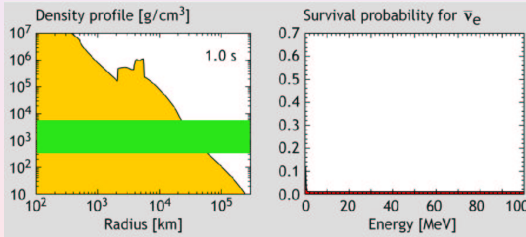
$$\gamma \gg 1 \Rightarrow P_c \ll 1 \Rightarrow \text{adiabatic resonance}$$

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

more

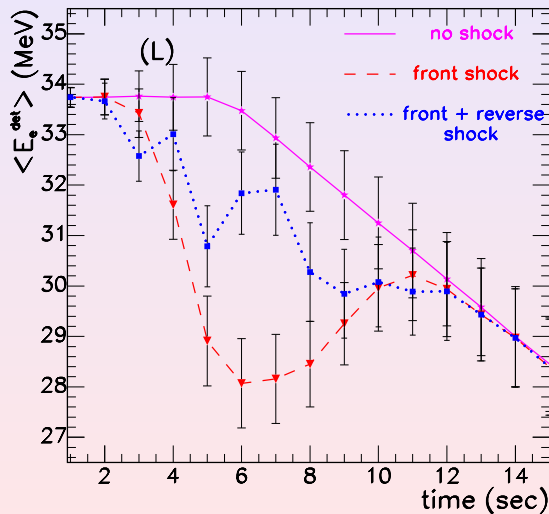
Observable 1: SN shock wave propagation

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

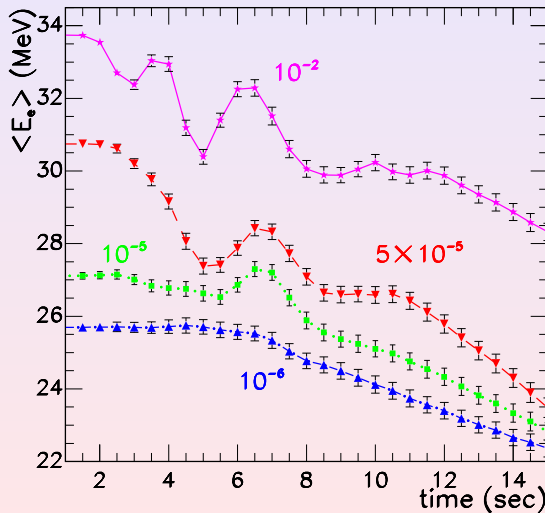


[Tomàs, MK, Raffelt, Dighe, Scheck, Janka '04]

Statistical significance: SuperKamiokande



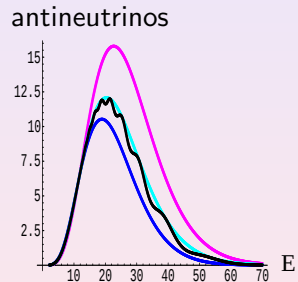
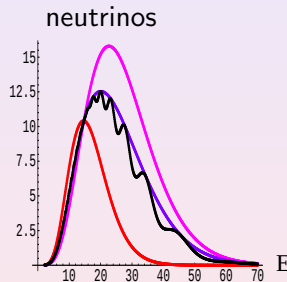
Statistical significance: HyperKamiokande



Observable 2: Earth matter effects

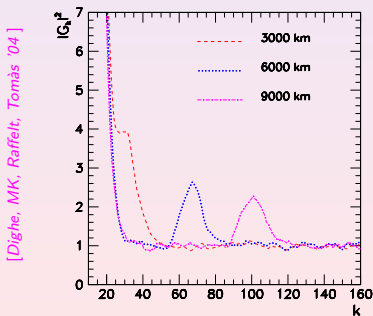
- fast oscillations in the **Earth** superimpose **wiggles** on the primary spectra

$$\begin{array}{lll}
 F_{\nu_e}^0 & F_{\nu_x}^0 & F_{\nu_e} \\
 F_{\nu_e}^0 & F_{\nu_x}^0 & F_{\bar{\nu}_e}
 \end{array}$$



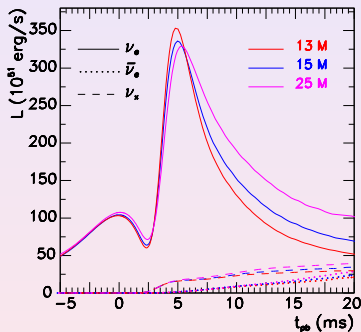
Observable 2: Earth matter effects

- oscillations in the Earth superimpose wiggles on spectra
- frequencies are
 - analytically known
 - independent of the primary neutrino spectra
- Fourier transform of “inverse” energy spectrum $y = 1/E$



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

Observable 3: ν_e neutronization burst



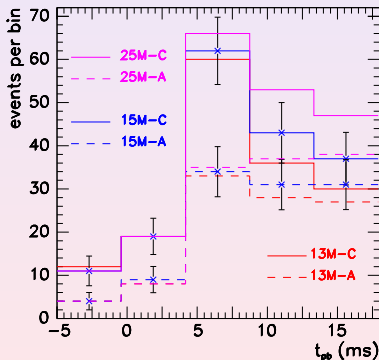
independent from

- progenitor mass
- EoS
- simulation

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

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]

SN neutrino summary

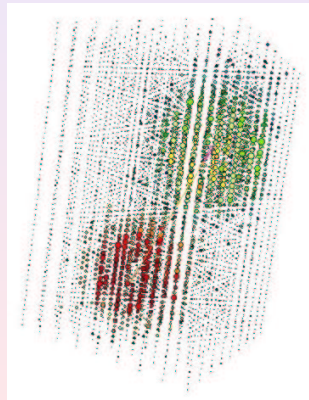
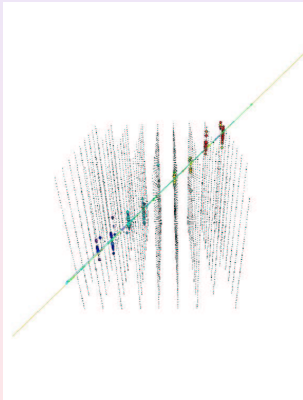
Hierarchy	$\sin^2 \theta_{13}$	Earth effects	Shocks	ν_e burst
Normal	$\gtrsim 10^{-3}$	$\bar{\nu}_e$	ν_e	absent
Inverted	$\gtrsim 10^{-3}$	ν_e	$\bar{\nu}_e$	present
Any	$\gtrsim 10^{-5}$	ν_e and $\bar{\nu}_e$	—	present

galactic SN & water Cherenkov/scintillation detector

- allows identification of neutrino mixing scenario
- goldmine for astrophysics

Neutrino telescopes and neutrino mixing

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



Neutrino telescopes and neutrino mixing

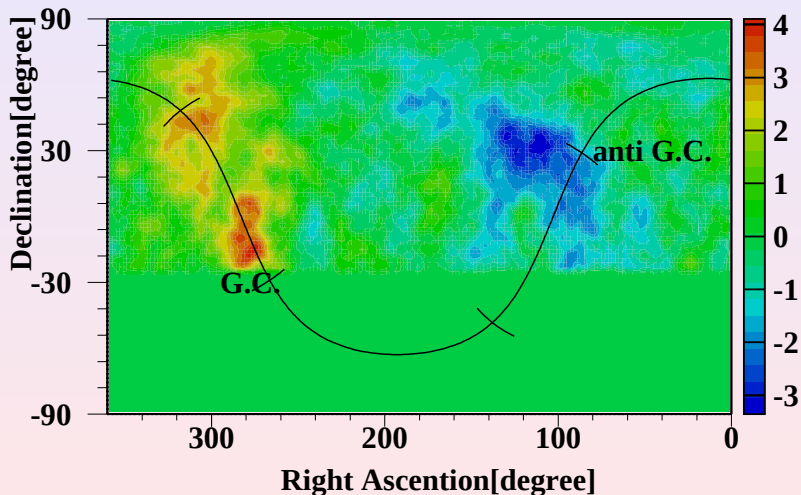
- neutrino telescopes can distinguish muon neutrinos from electron and tau neutrino events:
- but maximal mu-tau mixing washes-out flavor information for $l \gg l_{\text{osc}}$:

$$\phi_e : \phi_\mu : \phi_\tau = 1 : 2 : 0 \quad \Rightarrow \quad \phi_e : \phi_\mu : \phi_\tau = 1 : 1 : 1$$

- exception: e.g. beta beam from neutron decay
- example: galactic CR source near Cygnus region, if nuclei are accelerated

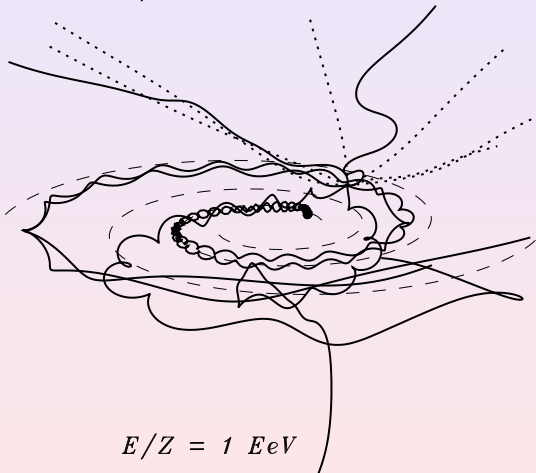
[MK, P. Serpico '05]

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



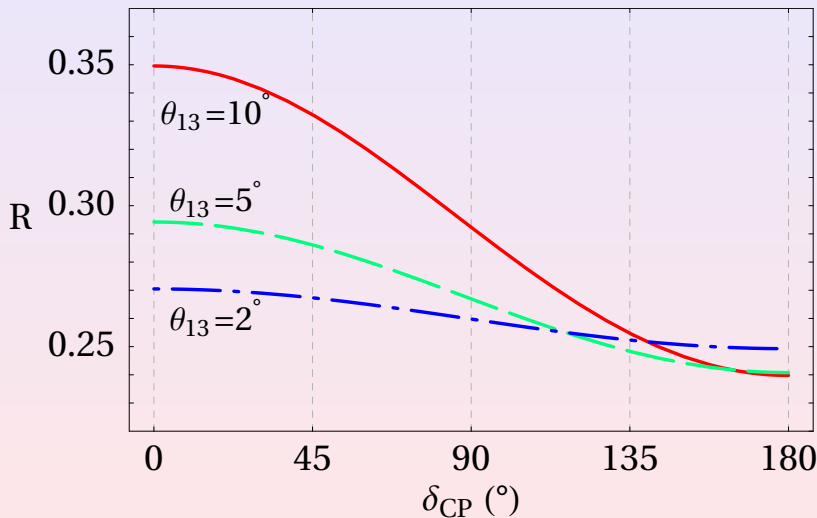
Deflection of charged particles in Galactic B -field:

$$E/Z = 10 \text{ EeV}$$



$$E/Z = 1 \text{ EeV}$$

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



Sensitivity of ICECUBE:

statistical significance of Cyg detection:

- with $\ell = 25^\circ$ angular resolution for ν_e and ν_τ :
 4.2σ for 10 years measurement
- with $\ell = 10^\circ$ angular resolution for ν_e and ν_τ :
 3.3σ 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:

- $\Omega_{\text{SHDM}} \sim 1$ for $M_X \sim 10^{13}$ GeV, independent of X properties
- theoretically motivated; testable predictions
- motivated by UHECRs beyond GZK cutoff:
if $X \in \text{CDM}$, no GZK-cutoff

Fragmentation of heavy particles

- Consider Bremsstrahlung, $X \rightarrow \bar{f}fV$:

soft and collinear singularities generate $\ln^2(m_V^2/m_X^2)$ for $m_X^2 \gg m_V^2$

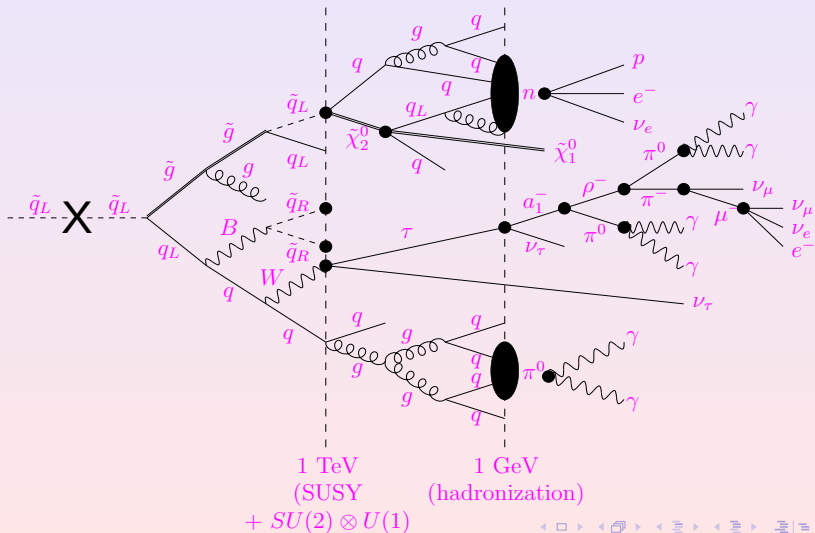
$\Rightarrow$ they can compensate the small couplings g^2 ,

$$g^2 \ln^2(m_X^2/m_V^2) \approx 1$$

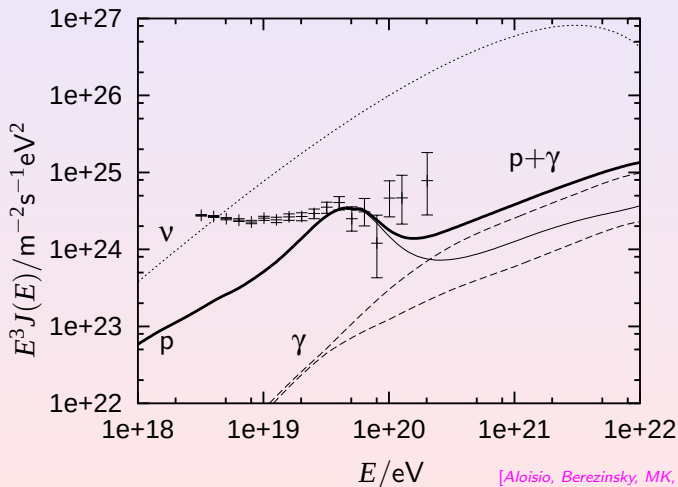
- $M_X \gtrsim 10^6$ GeV, $\Rightarrow$ naive perturbation theory breaks down: electroweak and SUSY sector have a QCD-like behavior (“jets”)

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

Fragmentation of heavy particles



Neutrino fluxes from topological defects:



[Aloisio, Berezhinsky, 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