Neutrinos in Astrophysics and Cosmology

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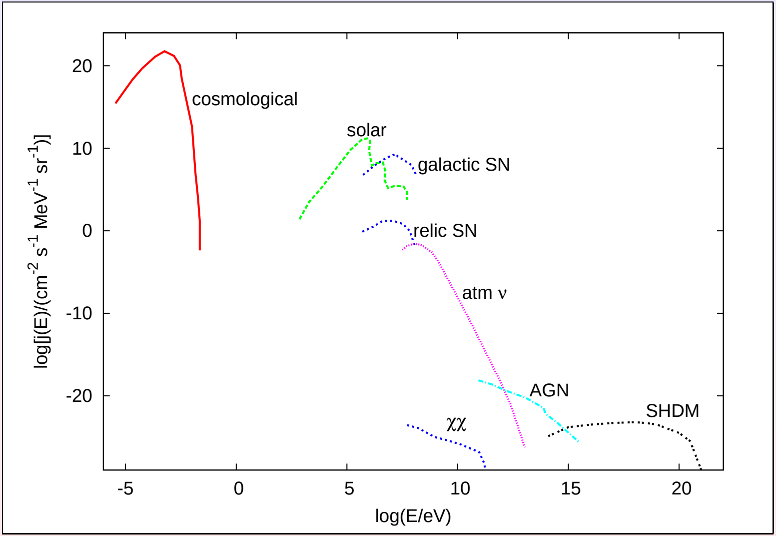
Neutrino opportunities:



Structure formation:

- structure formation operates via gravitational instability
- primordial spectrum from inflation is adiabatic, Gaussian, nearly scale-invariant with density contrast $\delta(x) \equiv (\rho(x) - \bar{\rho})/\bar{\rho}$:

$$\delta_k \propto \int d^3x \, e^{-ikx} \delta(x) \propto k^{n_s} \quad \text{with} \quad n_s \approx 1$$

- transfer function $T(k)$ describes nonlinear evolution of primordial power spectrum $P_0(k) = |\delta_k|^2$,

$$P(k) = T(k) P_0(k)$$

Neutrinos as Hot Dark Matter:

- light neutrinos are relativistic at decoupling ($T \sim$ MeV)
- free-streaming erases perturbations on scales $< \lambda_{FS} = 30\text{Mpc}/(\Omega_\nu h^2)$

Neutrinos as Hot Dark Matter:

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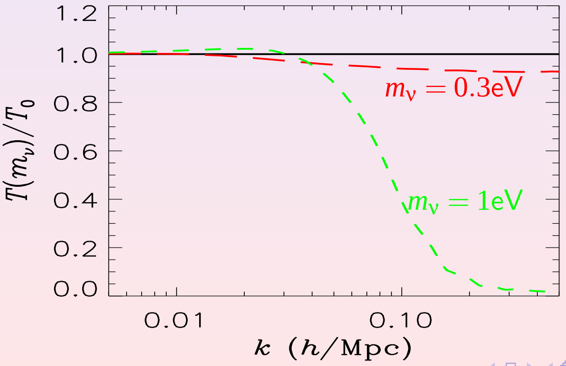
- free-streaming erases perturbations on scales $< \lambda_{FS}$
- on small scales,

$$\frac{\delta T}{T} \approx -\frac{8\Omega_\nu}{\Omega_m}$$



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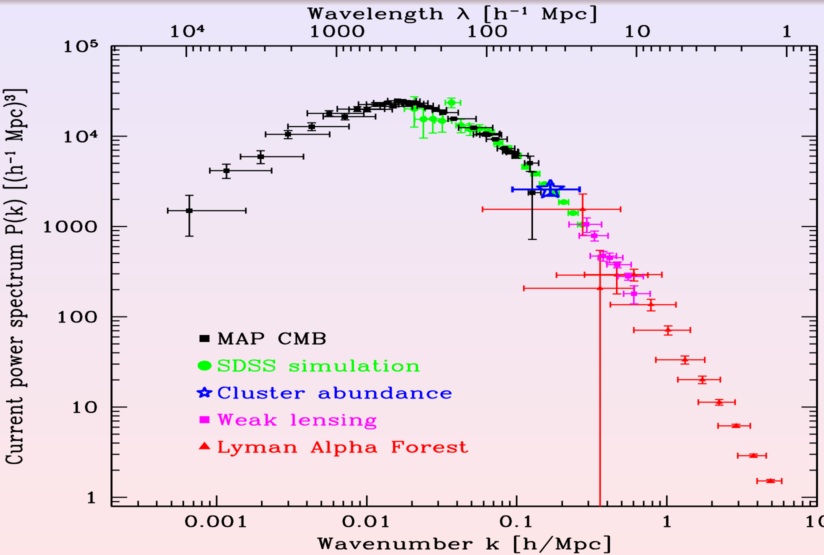
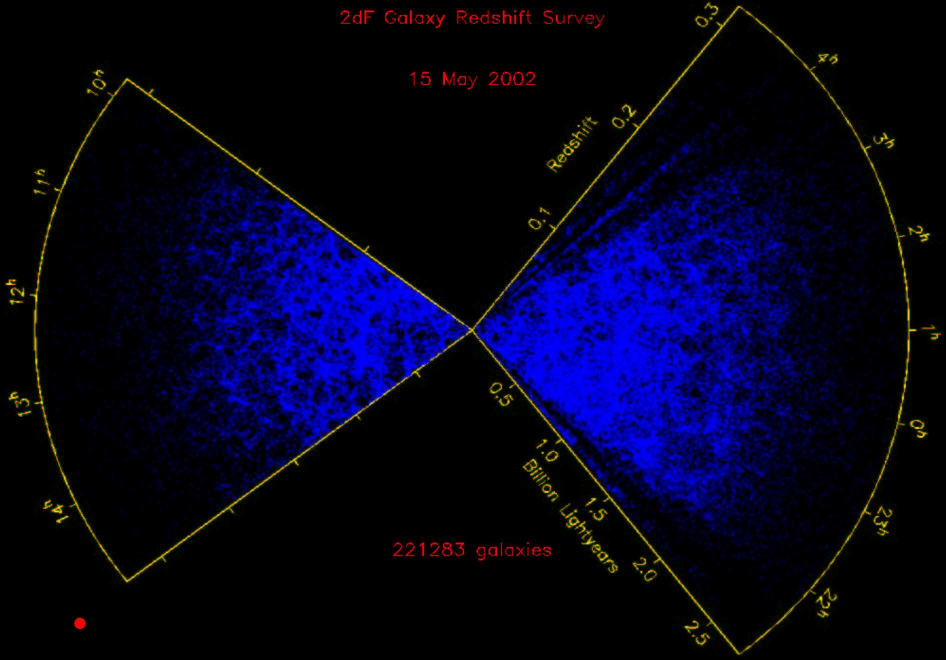
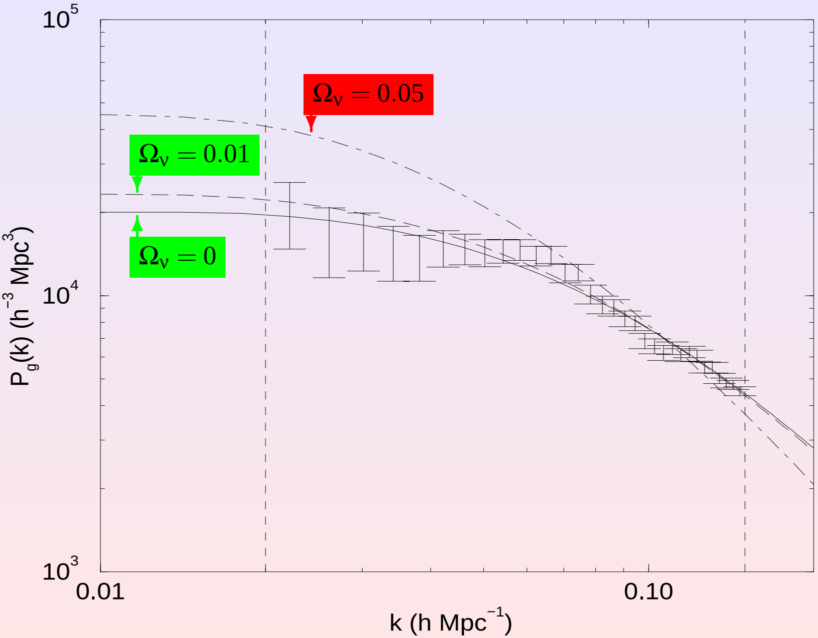
- most sensitive data for m_ν probe $k^{-1} \lesssim 10\,\mathrm{Mpc}$
- to fix normalization and exclude parameter degeneracies also data at larger scales needed

Power spectrum and data sets:




2dF Galaxy Redshift Survey
15 May 2002
221283 galaxies
Redshift
0.1
0.2
0.3
0.5
1.0
1.5
2.0
2.5
Billion Lightyears
10h
11h
12h
13h
14h
4h
3h
2h
1h
0h
23h
22h



$\Omega_\nu = 0.05$
$\Omega_\nu = 0.01$
$\Omega_\nu = 0$
10^5
10^4
10^3
$P_g(k)$ (h^{-3} Mpc^3)
0.01
0.10
k (h Mpc^{-1})

Present neutrino mass limits:

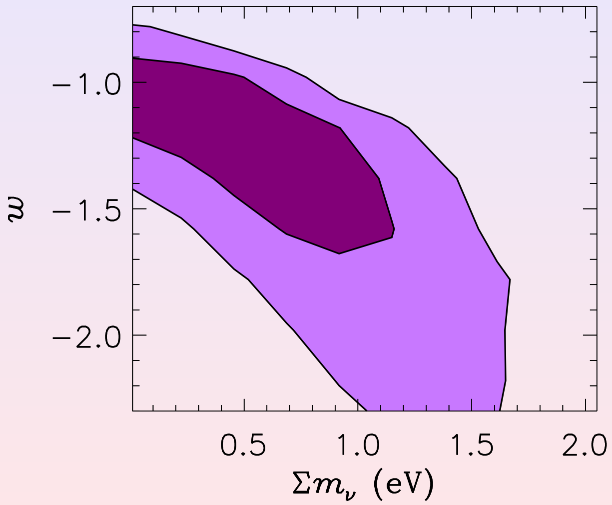
limits depend on

- priors
- free/fixed parameters
- chosen data-samples (LSS+CMB+Lyα+...)
- systematic uncertainties

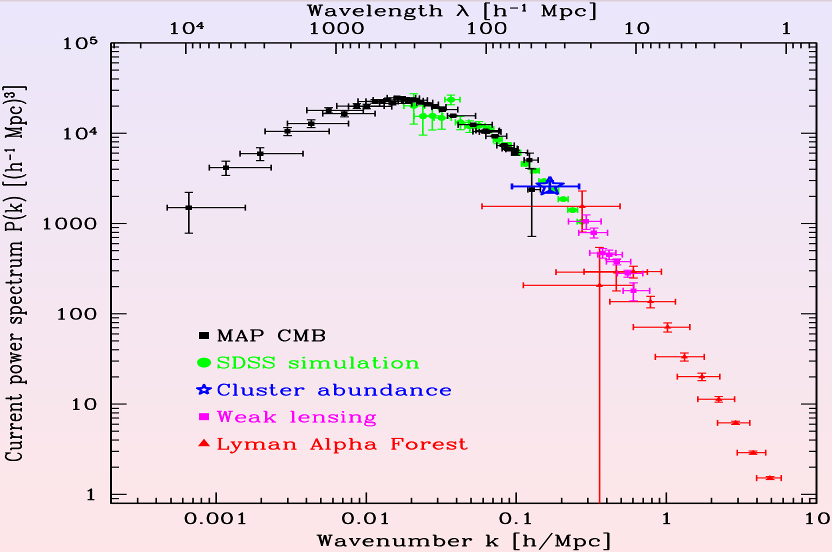
typical values

- CMB+LSS: $\sum m_i \lesssim 1.0\,\text{eV}$
- CMB+LSS+Lyα: $\sum m_i \lesssim 0.6\,\text{eV}$
- allowing for more free parameters: back $\sum m_i \lesssim 1.0\,\text{eV}$

w–m_ν degeneracy:

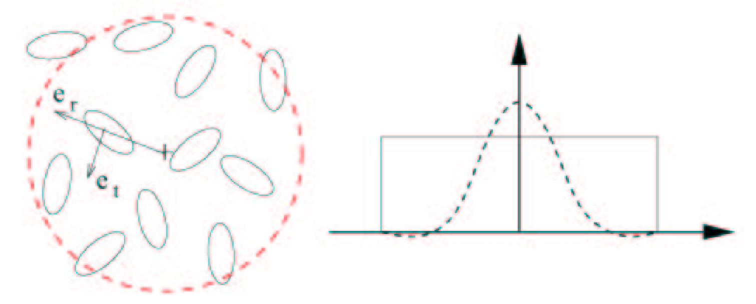


Future of neutrino mass limits: weak lensing:



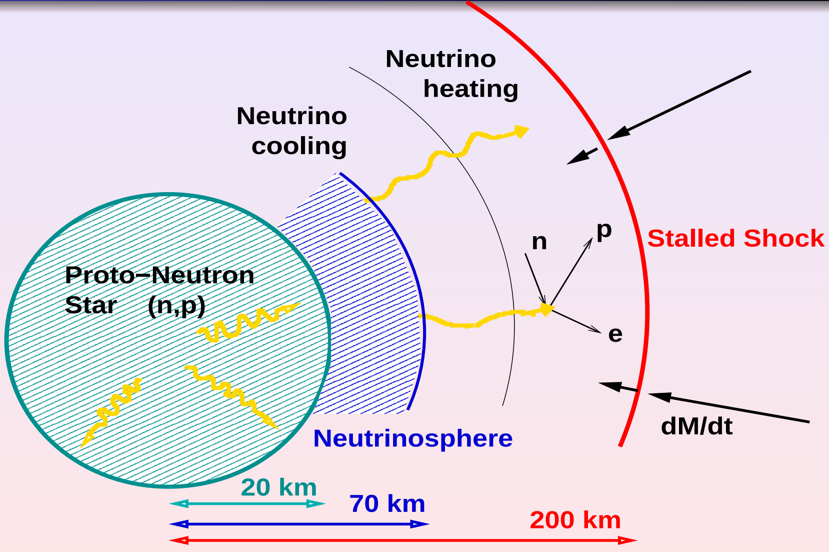
Future of neutrino mass limits: weak lensing:

- measure ellipticity of galaxies



- predicted sensitivity, $\sum m \lesssim 0.03\,\text{eV}$

Neutrino emission from SN cores:



problem

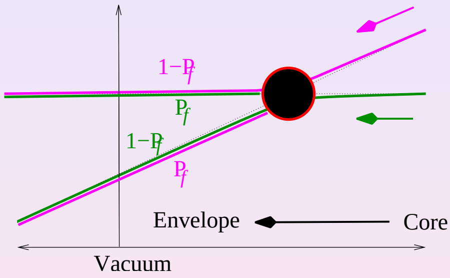
SN neutrino spectra are model dependent:
how can mixing parameters be determined reliably?

solution

use only features in which you are sure:

- shock wave
- Earth matter effect
- neutronization burst

Neutrino oscillations and matter effects



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

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

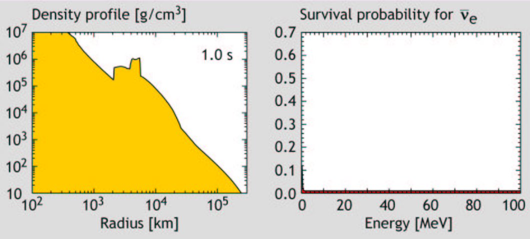
depends on $\Delta m^2/E$, mixing angle, density profile

more

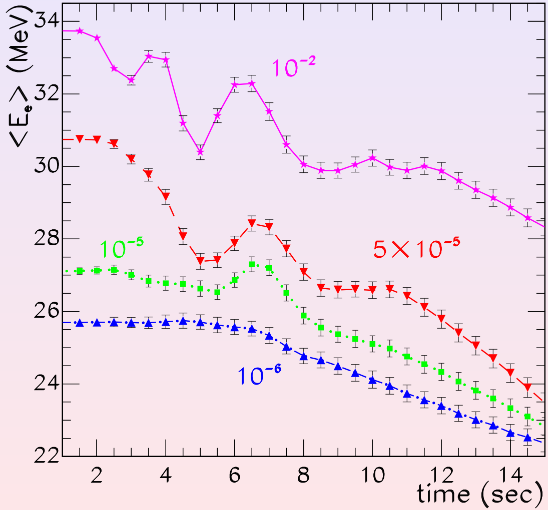
Example: SN shock wave propagation

- 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



Sensitivity to $\sin^2\theta_{13}$: HyperKamiokande



SN neutrino summary

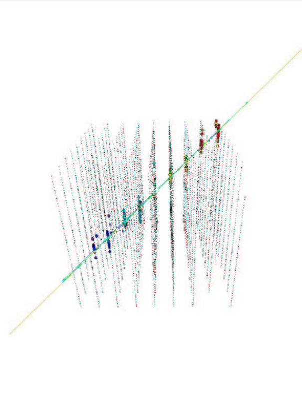
Hierarchy	$\sin^2\theta_{13}$	Earth effects	Shocks	ν_e burst
Normal	$\gtrsim 10^{-3}$	$\bar{\nu}_e$	ν_e	absent
Inverted	$\gtrsim 10^{-3}$	ν_e	$\bar{\nu}_e$	present
Any	$\lesssim 10^{-5}$	ν_e and $\bar{\nu}_e$	—	present

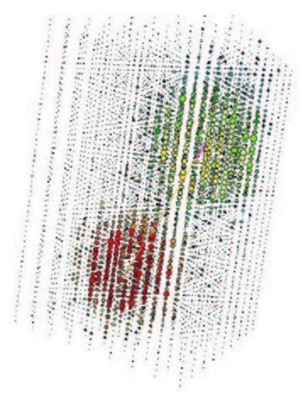
galactic SN & water Cherenkov/scintillation detector allows

- 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:





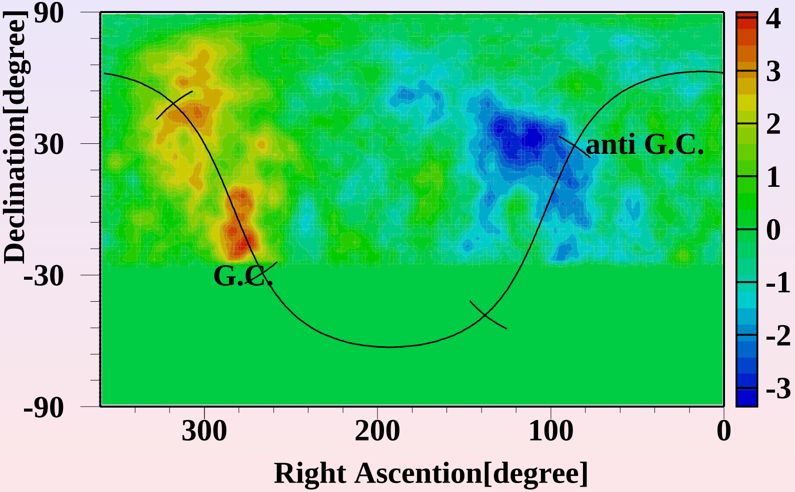
Neutrino telescopes and neutrino mixing

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

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

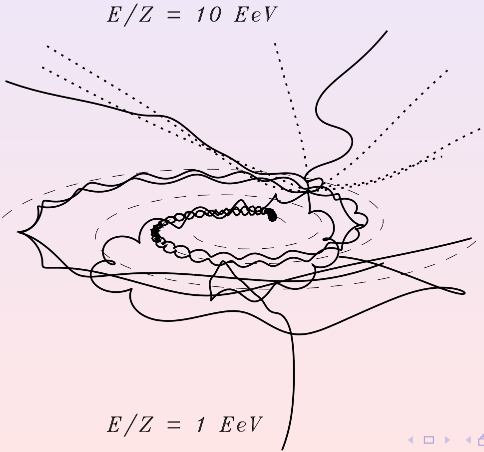
- exception: e.g. beta beam from neutron decay
- example: galactic CR source near Cygnus region, if nuclei are accelerated

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



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

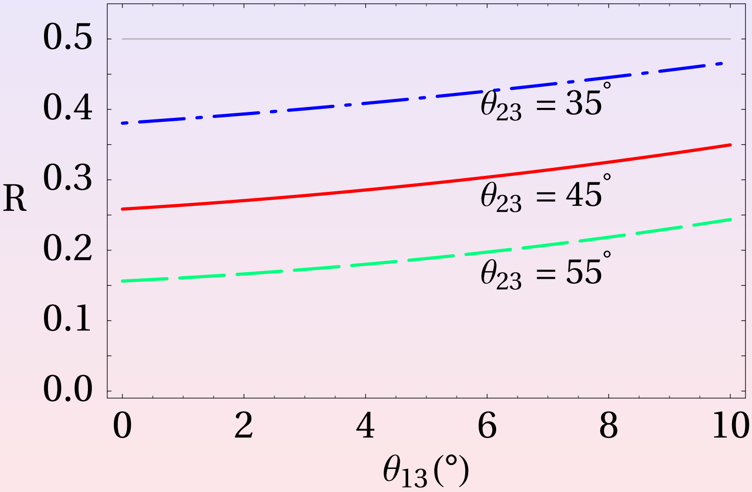
- charged particles with $E = 10^{18}$eV are strongly deflected by Galactic B-field



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

- charged particles with $E = 10^{18}$eV are strongly deflected by Galactic B-field
- neutron lifetime $c\gamma\tau \sim$ few kpc at $E = 10^{18}$eV
- likely source: photo-dissociation of nuclei
- neutrons with $E < 10^{18}$eV are source of pure $\bar{\nu}_e$ flux
- cosmic beta beam for free

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



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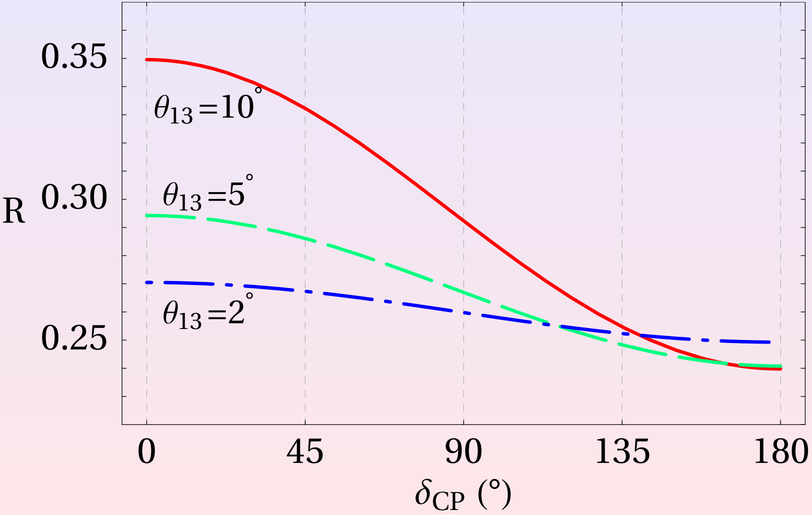


Neutrino telescopes and non-standard neutrinos

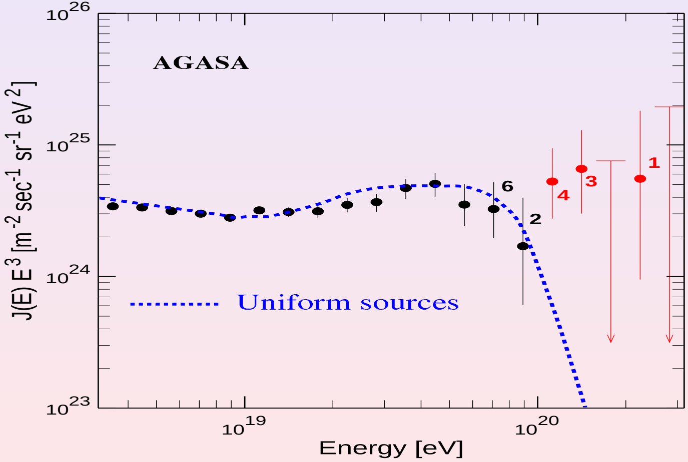
- neutrino telescopes can measure nucleon-neutrino cross section independent from neutrino flux
- constrains neutrino decays, decoherence, Lorentz invariance violation,. . .
- Ex. decoherence:
  space-time foam could lead to non-unitary time-evolution

$$\frac{\partial \rho}{\partial t} = -i[H,\rho] + D[\rho]$$

- measuring the flavor ratio improves by
  - 14 orders limits for decoherence,
  - 4 orders limits for decays, . . .

Z-bursts: UHE $\nu + \nu_{BR} \to Z \to$ hadrons

- orginal idea: explanation of UHECRs beyond GZK cutoff



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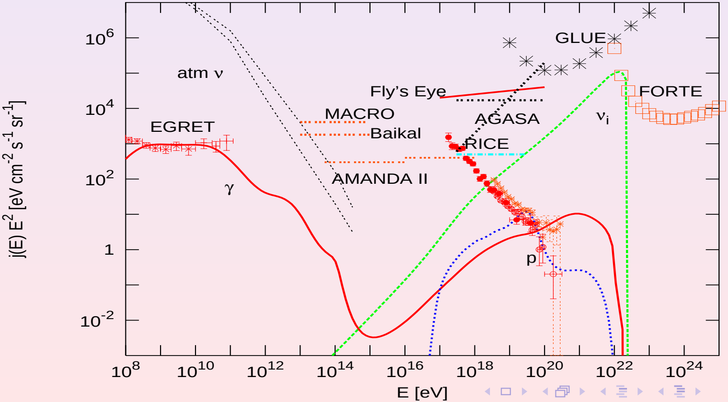
- for $E_\nu \sim 10^{23}$ eV, the mass of the relic neutrino should be $m_\nu = m_Z^2/(2E_\nu) \sim 0.1$ eV
- excluded by diffuse MeV-GeV photons and UHE neutrinos



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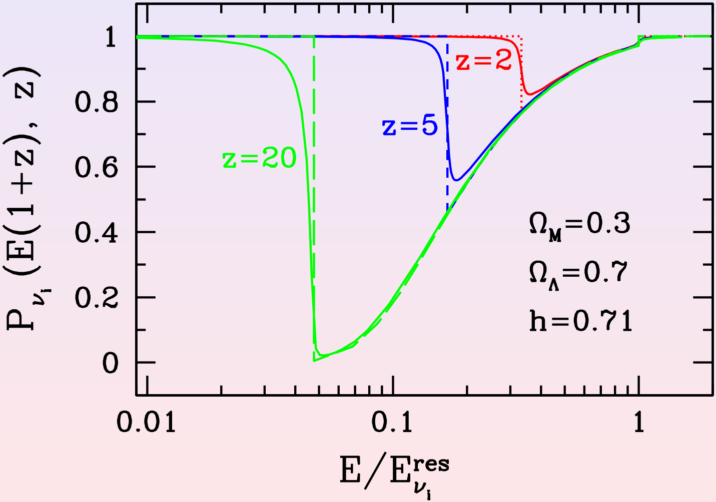
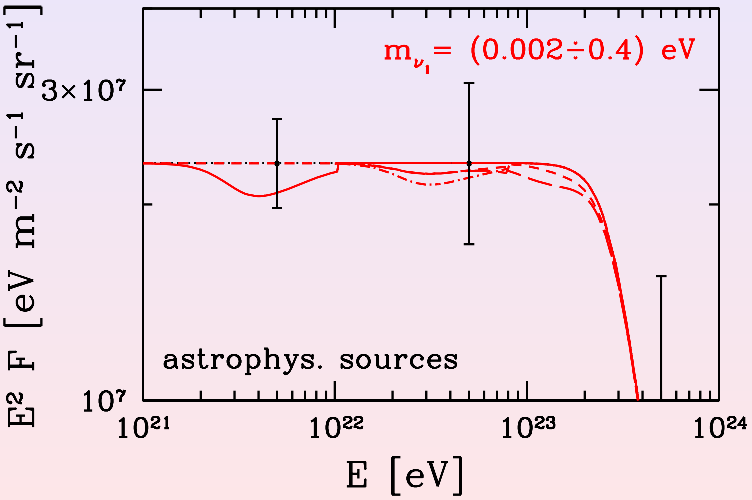
- possibility to detect relic neutrinos or even to measure m_ν?

Z-burst spectroscopy: Survival probability

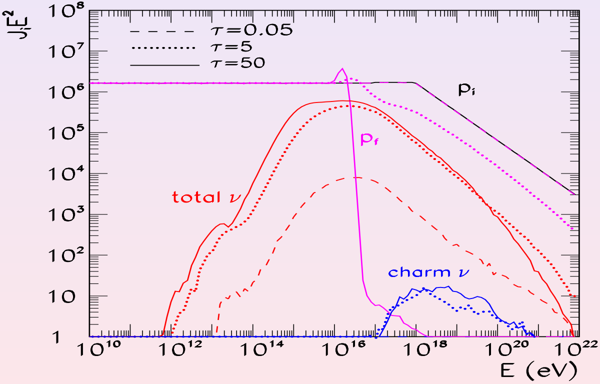


Z-burst spectroscopy: Diffuse neutrino flux



Can hidden sources of UHE neutrinos be constructed?

- hidden sources: $\tau \gg 1$
- evade limits from UHECR and γ-ray oberservations



- $\tau \gg 1$: UHE pions+muons scatter before decaying

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 small/large θ_{13}
- Cygnus neutrinos as test for δ_{CP} and θ_{13}
- HE neutrinos as test for SUSY DM, new interactions, decoherence, Lorentz invariance violation
- UHE neutrinos test superheavy dark matter or topological defects

  . . .

essential: interplay between particle physics, astrophysics and cosmology