Pauli's messengers:
Looking at the sky in neutrinos

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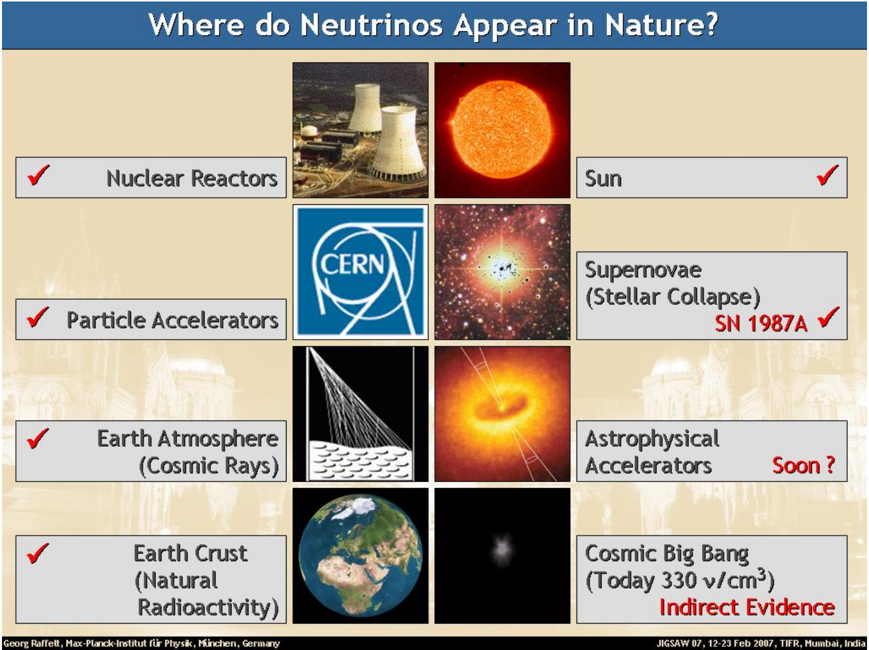
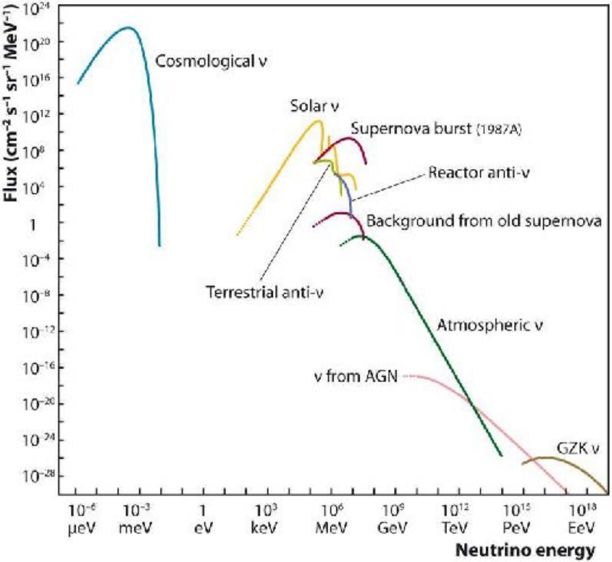
Multi-messenger Astronomy session,
ASI meeting, Srinagar, May 13th, 2016

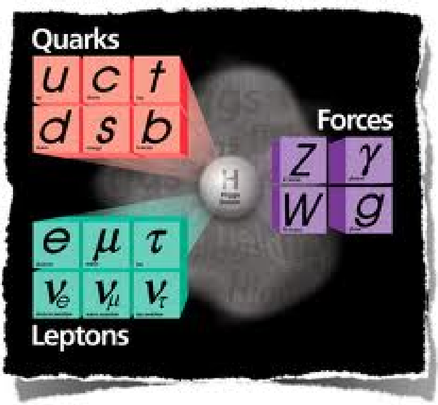
Omnipresent neutrinos



Energy spectra of neutrino sources



The Standard Model of Particle Physics

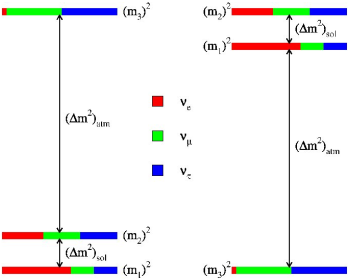


- 3 neutrinos: ν_e, ν_μ, ν_τ
- chargeless fermions
- almost massless ($m_\nu \lesssim 0.5$ eV)
- only weak interactions

- Second-most abundant particles next to photons: cosmic neutrino background of 330 ν/cc with $T \sim 2K$

The three-neutrino mixing picture

Mixing of $\nu_e, \nu_\mu, \nu_\tau \Rightarrow \nu_1, \nu_2, \nu_3$ (mass eigenstates)



- $\Delta m^2_{\rm atm} \approx 2.4 \times 10^{-3}$ eV^2
- $\Delta m^2_{\odot} \approx 8 \times 10^{-5}$ eV^2
- $\theta_{\rm atm} \approx 45^\circ$
- $\theta_{\odot} \approx 32^\circ$
- $\theta_{\rm reactor} \approx 9^\circ$

Mass ordering: Normal (N) or Inverted (I) ?

- From particle physics: oscillation experiments (e.g. INO)
- From cosmology: $\sum m_\nu$
- From astrophysics: neutrinos from core-collapse supernova

Looking at the sky in neutrinos

1. Neutrinos from the sun (1-10 MeV)
2. Neutrinos from a core collapse supernova (5-50 MeV)
3. High energy astrophysical neutrinos ($\gtrsim$ TeV)
4. Big–bang relic neutrinos: ($E \sim$ meV)
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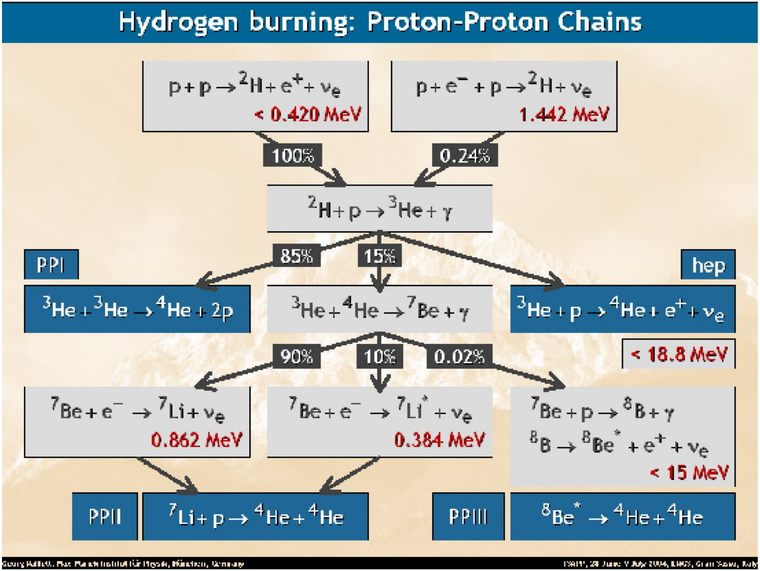
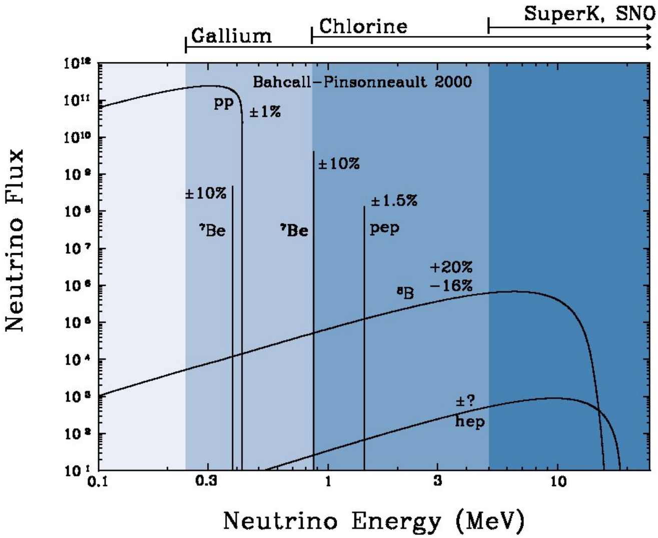
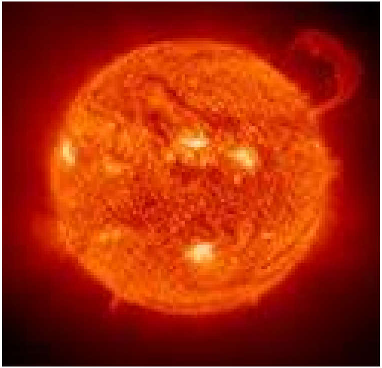
Neutrino production inside the Sun

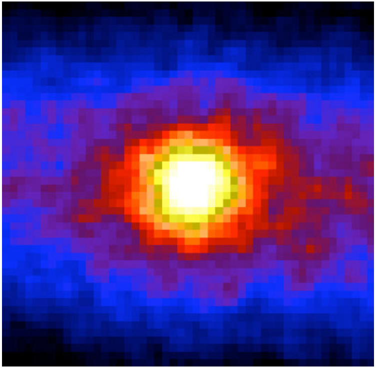


Spectrum of solar neutrinos (at production)



Sun in light and neutrinos





Scale: $\sim 1^\circ$ | $\sim 30^\circ$

Exposure: $\sim 1/100$ s | ~ 10 years at a 50 kt detector

Neutrino physics $\leftrightarrow$ solar astrophysics

- Standard Solar Model (SSM) predicts neutrino fluxes
- Solar neutrino experiments find a deficit in the number of neutrinos
- Neutrino theorists propose neutrino masses and oscillations
- Solar and reactor experiments confirm neutrino oscillation picture
- Accurate measurements of neutrino fluxes and mixing parameters help fine-tune the Standard Solar Model

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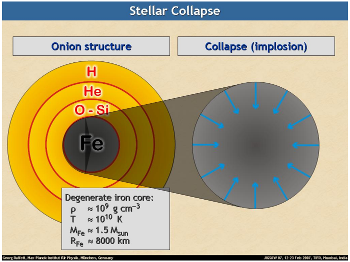
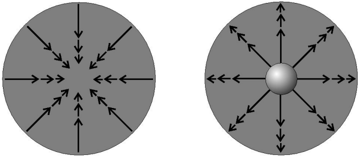
The death of a star: role of different forces

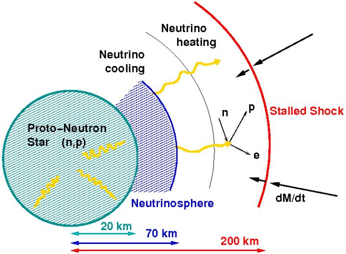
Gravity ⇒



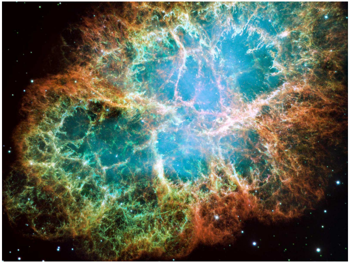
Nuclear forces ⇒



Neutrino push ⇒

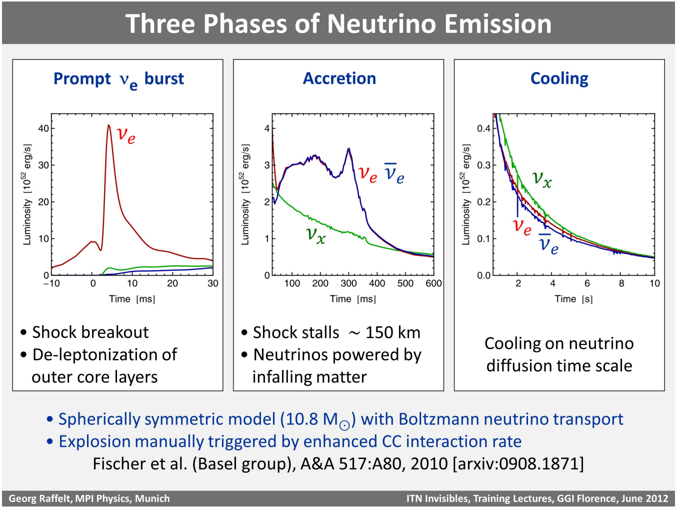


Hydrodynamics ⇒



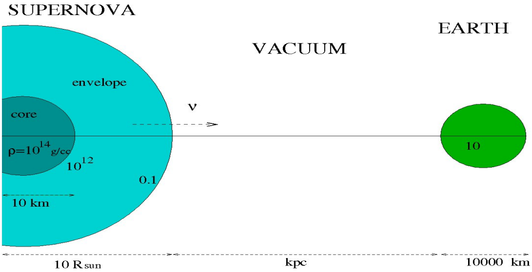
(Crab nebula, SN seen in 1054)

Neutrino fluxes: $\sim 10^{58}$ neutrinos in 10 sec



- Escaping neutrinos: $\langle E_{\nu_e} \rangle < \langle E_{\bar{\nu}_e} \rangle < \langle E_{\nu_x} \rangle$

Neutrino oscillations in matter of varying density



Inside the SN: *flavour conversion*

Non-linear "collective" effects and resonant matter effects

Between the SN and Earth: *no flavour conversion*

Neutrino mass eigenstates travel independently

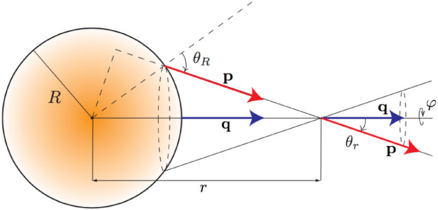
Inside the Earth: *flavour oscillations*

Resonant matter effects (*if detector is shadowed by the Earth*)

Non-linearity from neutrino-neutrino interactions

- Effective Hamiltonian: $H = H_{vac} + H_{MSW} + H_{\nu\nu}$

$$H_{vac}(\vec{p}) = M^2/(2p)$$
$$H_{MSW} = \sqrt{2}G_F n_{e^-}\, diag(1,0,0)$$
$$H_{\nu\nu}(\vec{p}) = \sqrt{2}G_F \int \frac{d^3q}{(2\pi)^3}(1-\cos\theta_{pq})(\rho(\vec{q})-\bar{\rho}(\vec{q}))$$



Duan, Fuller, Carlson, Qian, PRD 2006

- Equation of motion:

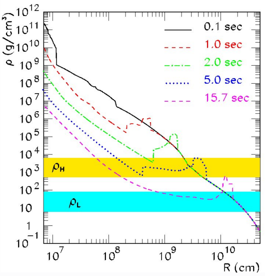
$$\frac{d\rho}{dt} = i\,[H(\rho),\rho]$$

Further MSW flavor convensions inside the star

MSW resonances

- *H* resonance: $\rho \sim 10^3$–10^4 g/cc
  - In $\nu(\bar{\nu})$ for normal (inverted) hierarchy
- *L* resonance: $\rho \sim 10$–100 g/cc
  - Always in ν

Shock effects



- During shock wave propagation, adiabaticity momentarily lost ⇒ fluctuations in spectra.

Schirato, Fuller 2002

- Large amplitude turbulence in outer layers of the star may obscure usual signatures, but give rise to some new ones...

Kneller, Lund 2013

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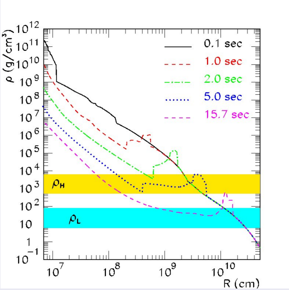

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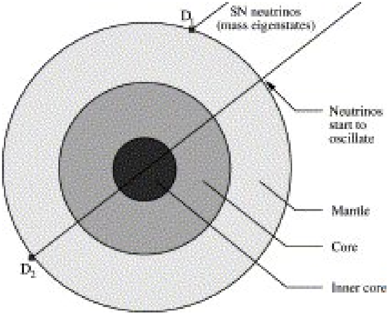
Earth matter effects

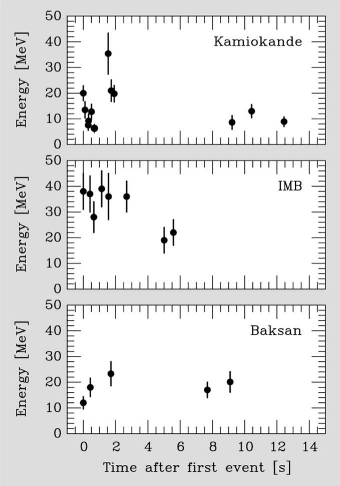


- If the detector is shadowed by the Earth, matter-induced flavor oscillations inside the earth produce spectral modulations.

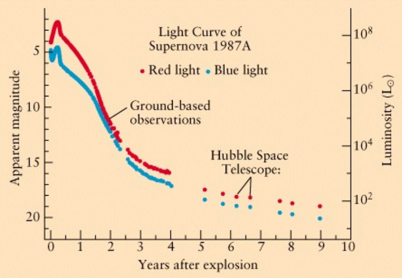
AD, Smirnov 2000, Lunardini et al, 2001, Tomas et al 2004

SN1987A: neutrinos and light

Neutrinos: Feb 23, 1987



Light curve: 1987-1997

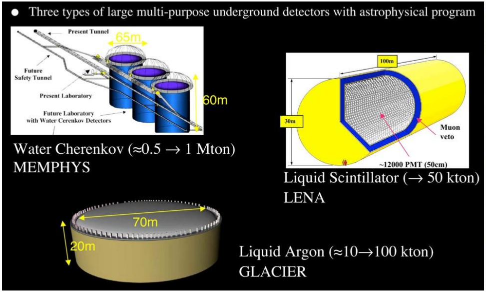


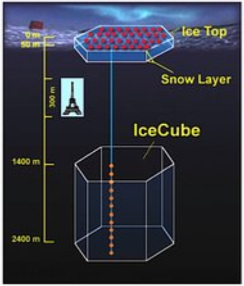
SN1987A: what did we learn ?

Hubble image: now

- Confirmed the SN cooling mechanism through neutrinos
- Number of events too small to say anything concrete about neutrino mixing
- Some constraints on SN parameters obtained
- Strong constraints on new physics models obtained (neutrino decay, Majorans, axions, extra dimensions, ...)

Preparing for future SN neutrino detection





- Water Cherenkov / liquid scintillator / liquid Ar detectors for tracking individual neutrinos
- Large-volume ice Cherenkov for determining luminosity to a high accuracy (integrated Cherenkov glow)

What a galactic SN can tell us

On neutrino masses and mixing

- Instant identification of neutrino mass ordering (N or I), through
  - Neutronization burst: disappears if I
  - Shock wave effects: in ν ($\bar{\nu}$) for N (I)

On supernova astrophysics

- Locate a supernova hours before the light arrives
- Track the shock wave through neutrinos while it is still inside the mantle (Not possible with light)
- Possible identification of QCD phase transition, SASI (Standing Accetion Shock) instabilities.
- Identification of O-Ne-Mg supernovae
- Hints on heavy element nucleosynthesis (r-process)

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Sources of HE/UHE neutrinos

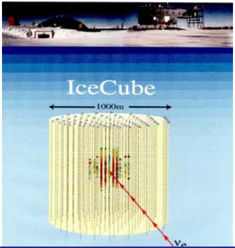
Secondaries of cosmic rays

- Primary protons interacting within the source or with CMB photons $\Rightarrow \pi^{\pm} \Rightarrow$ Decay to ν
- At GZK energies, secondary neutrino flux comparable to the primary cosmic ray flux (Waxman-Bahcall bound) $E^2 dN/dE \lesssim (10 - 50)\ \mathrm{eV\ cm^{-2}\ sr^{-1}\ s^{-1}}$
- $\pi^{\pm}$ produced $\Rightarrow \pi^0$ produced $\Rightarrow \gamma$ that shower. Observation of gamma rays near $\sim$ 100 GeV $\Rightarrow$ $E^2 dN/dE \lesssim 100\ \mathrm{eV\ cm^{-2}\ sr^{-1}\ s^{-1}}$

AGNs and GRBs

- Neutrinos produced by particle decays / nuclear reactions / pair production in extreme environments
- AGNs can give measurable diffused flux in near future
- Flux possible during the precursor phase, the emission phase as well as the afterglow phase of GRBs

Detection of HE neutrinos: water/ice Cherenkov



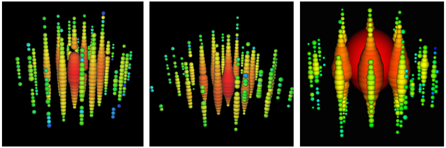
- Thresholds of $\sim$ 100 GeV, controlled by the distance between optical modules
- Track for ν_μ
- Cascade for ν_e, hadrons, ν_τ
- Double-bang for ν_τ ?

Detection estimates

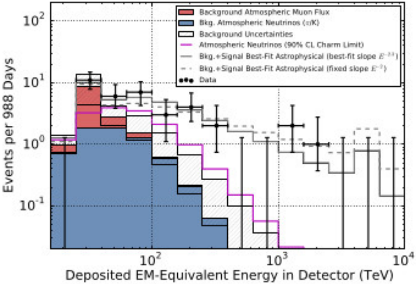
- $E \lesssim 10^{16}$ eV: only up-going ν useful since prohibitive background from atmospheric muons
- $E \gtrsim 10^{16-17}$ eV: only down-going neutrinos available since more energetic neutrinos get absorbed in the Earth
- Diffused flux sensitivity to $E^2 dN/dE \sim 2$ eV cm^{-2} sr^{-1} s^{-1} after 3 years of full Icecube
- AGNs emitting at $E \sim 10^{16}$ eV detectable if $E^2 dN/dE \gtrsim 10^2$ eV cm^{-2} sr^{-1} s^{-1}

G. Sigl, 1202.0466

The three PeV events at Icecube



Bert Ernie Big Bird

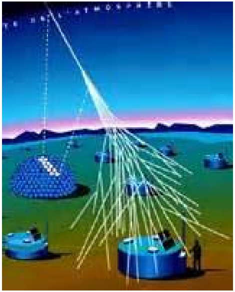


- Three events at $\sim 1, 1.1, 2.2$ PeV energies found
- Cosmogenic ? X Glashow resonance? X atmospheric ?

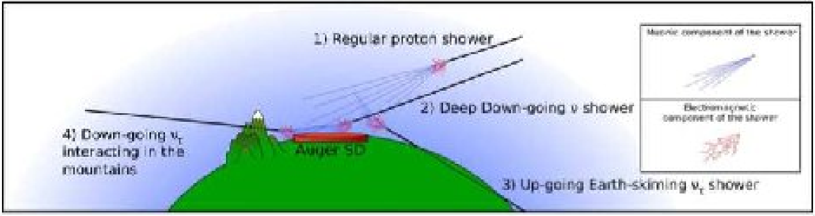
  Roulet et al 2013 ++ many
- IceCube analyzing 54 events from 30 TeV to 10 PeV
- Constraints on Lorentz violation: $\delta(v^2 - 1) \lesssim \mathcal{O}(10^{-18})$

  Borriello, Chakraborty, Mirizzi, 2013

Detection of UHE neutrinos: cosmic ray showers



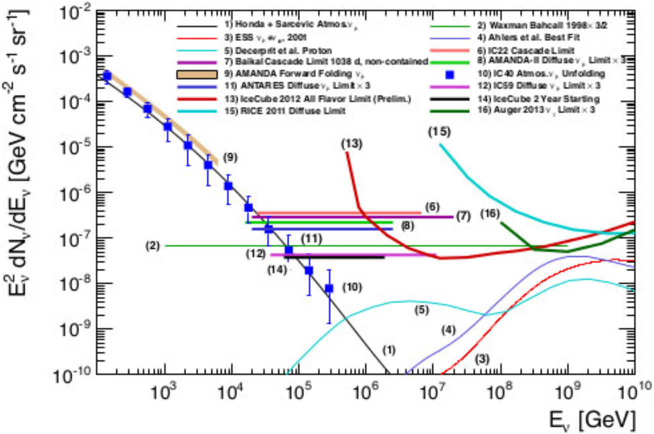
- Neutrinos with $E \gtrsim 10^{17}$ eV can induce giant air showers (probability $\lesssim 10^{-4}$)
- Deep down-going muon showers
- Deep-going ν_τ interacting in the mountains
- Up-going Earth-skimming ν_τ shower



Detection through radio waves: ANITA

- Charged particle shower $\Rightarrow$ Radio Askaryan: charged clouds emit coherent radio waves through interactions with $\mathbf{B}_{\rm Earth}$ or Cherenkov
- Detectable for $E \gtrsim 10^{17}$ eV at balloon experiments like ANITA

Limits on UHE neutrino fluxes



Waxman-Bahcall, AMANDA, Antares, RICE, Auger, IceCube
Also expect complementary info from: ANITA, NEMO, NESTOR, KM3NET ...

Flavor information from UHE neutrinos

Flavor ratios $\nu_e : \nu_\mu : \nu_\tau$ at sources

- Neutron source (nS): $1 : 0 : 0$
- Pion source (πS): $1 : 2 : 0$,
- Muon-absorbing sources (μDS): $0 : 1 : 0$

Flavor ratios at detectors

- Neutron source: $\approx 5 : 2 : 2$
- Pion source: $\approx 1 : 1 : 1$
- Muon-absorbing sources : $\approx 4 : 7 : 7$

New physics effects

- Decaying neutrinos can skew the flavor ratio even further: as extreme as $6 : 1 : 1$ or $0 : 1 : 1$
  Ratio measurement $\Rightarrow$ improved limits on neutrino lifetimes

Beacom et al, PRL 2003

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Source: abundance and temperature

- Relic density: $\sim$ 110 neutrinos /flavor /cm^3
- Temperature: $T_\nu = (4/11)^{1/3} T_{\rm CMB} \approx 1.95\ {\rm K} = 16.7\ {\rm meV}$
- The effective number of neutrino flavors:
  $N_{\rm eff}({\rm SM}) = 3.074$. Planck $\Rightarrow$ $N_{\rm eff} = 3.30 \pm 0.27$.
- Contribution to dark matter density:

$$\Omega_\nu/\Omega_{\rm baryon} = 0.5 \left(\sum m_\nu/{\rm eV}\right)$$

- Looking really far back:

	Time	Temp	z
Relic neutrinos	0.18 s	$\sim$ 2 MeV	$\sim 10^{10}$
CMB photons	$\sim 4 \times 10^5$ years	0.26 eV	1100

Lazauskas, Vogel, Volpe, 2008

The inverse beta reaction

- Need detection of low-energy neutrinos, so look for zero-threshold interactions
- Beta-capture on beta-decaying nuclei:

$$\nu_e + N_1(A, Z) \rightarrow N_2(A, Z+1) + e^-$$

End-point region ($E > M_{N_1} - M_{N_2}$) background-free.
Energy resolution crucial.

Weinberg 1962, cocco, Mangano, Messina 2008, Lazauskas et al 2008, Hodak et al 2009

- Possible at ^{3}H experiments with 100 g of pure tritium but atomic tritium is neeed to avoid molecular energy levels
- ^{187}Re at MARE also suggested, but a lot more material will be needed....

Lazauskas, Vogel, Volpe 2009, Hodak et al 2011

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Multi-messenger astronomy: role of neutrinos

Neutrinos as messengers

- No bending in magnetic fields ⇒ point back to the source
- Minimal obstruction / scattering ⇒ can arrive directly from regions from where light cannot reach us.

Supernova neutrinos

- Early warning of a galactic SN (SNEWS network)
- Instant identification of mass hierarchy possible
- Signals of shock propagation, QCD phase transition, SASI instabilities, BH formation...
- Gravitational waves ?? hidden supernovae ??

High-energy astrophysical neutrinos

- Simultaneous detection with EM-observed events
- Flavor identification for sources and ν properties

Cosmological ultra-low energy neutrinos

- Testing prediction of standard big-bang cosmology

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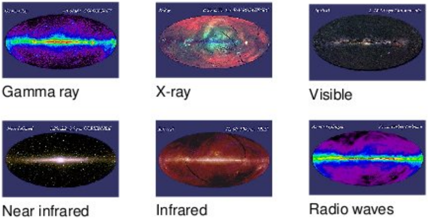
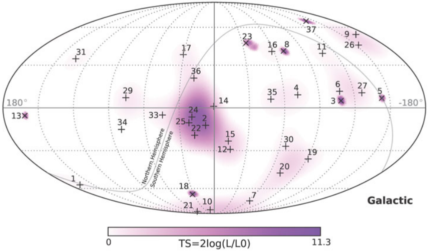
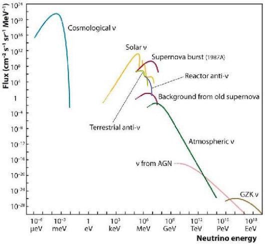
The dawn of neutrino astronomy



Neutrinos are entering this domain, slowly but surely...

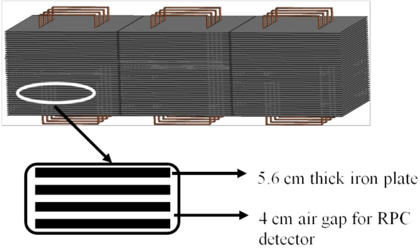




... and should be adding more colors to the universe...

Backup slides

Coming soon inside a mountain near you: INO



India-based Neutrino Observatory

- In a tunnel below a peak (Bodi West Hills, near Madurai)
- 1 km rock coverage from all sides
- 50 kiloton of magnetized iron (50 000 000 kg)
- Can distinguish neutrinos from antineutrinos
- Determining mass hierarchy from atmospheric neutrinos

“Collective” effects: qualitatively new phenomena

Synchronized oscillations:

ν and $\bar{\nu}$ of all energies oscillate with the same frequency

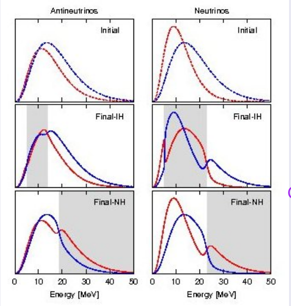
S. Pastor, G. Raffelt and D. Semikoz, PRD65, 053011 (2002)

Bipolar/pendular oscillations:

Coherent $\nu_e \bar{\nu}_e \leftrightarrow \nu_x \bar{\nu}_x$ oscillations

S. Hannestad, G. Raffelt, G. Sigl, Y. Wong, PRD74, 105010 (2006)

Multiple spectral split/swap:



ν_e and ν_x ($\bar{\nu}_e$ and $\bar{\nu}_x$) spectra interchange completely,
but only within certain energy ranges.

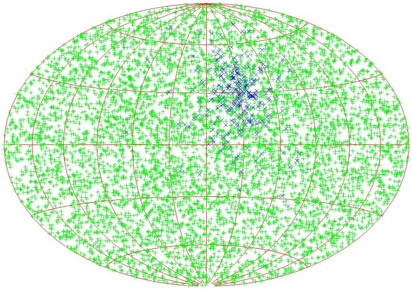
G.Raffelt, A.Smirnov, PRD76, 081301 (2007), PRD76, 125008 (2007)

B. Dasgupta, AD, G.Raffelt, A.Smirnov, PRL103,051105 (2009)

Pointing to the SN in advance

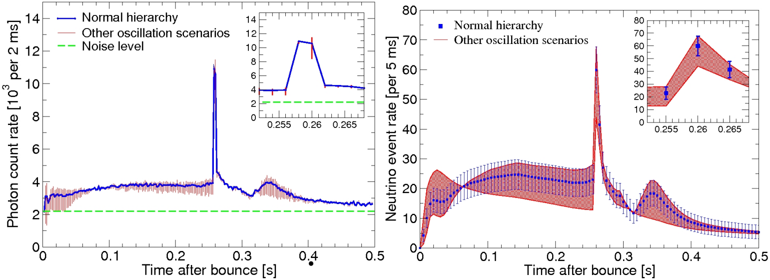
- Neutrinos reach 6-24 hours before the light from SN explosion (SNEWS network)
- $\bar{\nu}_e p \to n e^+$: nearly isotropic background
- $\nu e^- \to \nu e^-$: forward-peaked "signal"
- Background-to-signal ratio: $N_B/N_S \approx 30$–50
- SN at 10 kpc may be detected within a cone of $\sim 5^\circ$ at SK
- Adding Gd may make the pointing much better...

Beacom, Vogel 1999, Tomas et al 2003



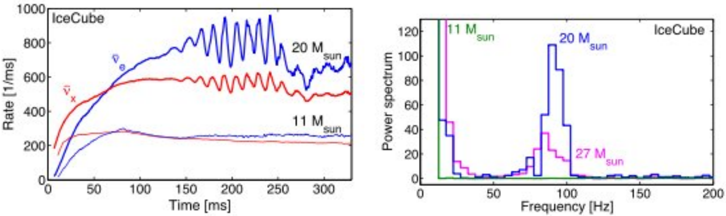
QCD phase transition (if it takes place)

- Sudden compactification of the progenitor core during the QCD phase transition
- Prominent burst of $\bar{\nu}_e$, visible at IceCube and SK



Dasgupta et al, PRD 2010

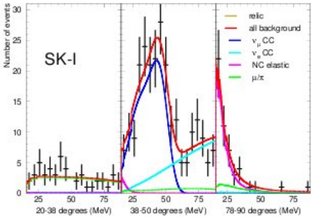
Detection of SASI instabilities

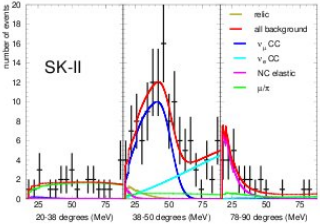


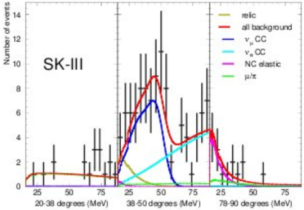
- Standing Accretion Shock Instability: global dipolar and quadrupolar deformations at the shock front
- Imprints even on top of the turbulent motion of matter
- Observable in Icecube event rate, as a high-frequency signal

Tamborra et al, PRL 2013

Diffused SN neutrino background







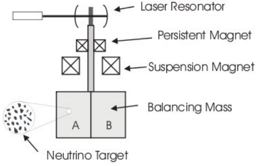
- Energy window: 17 MeV $\lesssim E \lesssim$ 50 MeV
- 90% C.L. limits on $\bar{\nu}$ flux: 2.9 cm^{-2} s^{-1} for $E > 17.3$ MeV

SK Collaboration, 2012

Predictions have a factor of 2-3 uncertainty. Collective effects and shock effects can affect predictions of the predicted fluxes by up to $\sim$ 50%

Chakraborty et al 2009, Galais et al 2010, Nakazato 2013

Detection of relic neutrinos: the torsion balance idea



- De Brogli wavelength of relic neutrinos: $\lambda \approx h/p \approx 1.5\text{mm}$.
- ν can interact coherently with a sphere of this size
- Measure force on such “spheres” due to the relic neutrino wind

- For iron spheres and 100 times local overdensity for ν, acceleration $a \lesssim 10^{-26}$ cm /s^2

Shvartsman et al 1982

- $\gtrsim$ 10 orders of magnitude smaller than the sensitivity of current torsion balance technology
- If neutrinos are Majorana, a further suppression by $v/c \approx 10^3$ (polarized target), $(v/c)^2 \approx 10^{-6}$ (unpolarized)

Hagmann, astro-ph/9901102

- The idea is essentially impractical.