Exploring the universe with neutrinos

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Neutrinos as messengers

Messenger properties

- No bending in magnetic fields $\Rightarrow$ point back to the source
- Minimal obstruction / scattering $\Rightarrow$ can arrive directly from regions from where light cannot come.
- This messenger may have unknown interesting properties !

Sources

- Stars, Earth's atmosphere and crust
- Astrophysical phenomena with large ν flux
- Diffused fluxes accumulated over the lifetime of universe

Detectors

- Water / ice Cherenkov, scintillators, liquid Ar, Lead
- Big, bigger and still bigger size !
- Energy resolution, time resolution, and directionality

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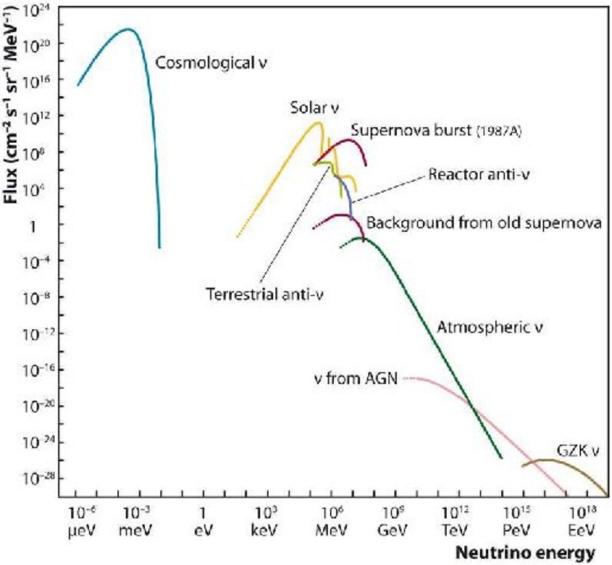
Neutrino fluxes at different energies



We have seen a lot of these...

Atmospheric neutrinos ($E \sim$ GeV)

- Neutrino oscillations: the first BSM signal
- Measurements of $|\Delta m^2_{31}|$ and θ_{23}
- Can also provide sign(Δm^2_{31}), now that θ_{13} is large

Solar neutrinos ($E \sim$ MeV)

- Neutrino oscillations in matter
- Measurements of Δm^2_{21} and θ_{12}
- Can be used to probe the interior of the sun

Geoneutrinos ($E \sim$ MeV)

- Understanding radioactivity inside the Earth

Talks by Silvia Pascoli, Gemma Testera

Exploring the universe in neutrinos

1. High / ultra-high energy neutrinos ($E \gtrsim$ TeV)
2. Neutrinos from a core-collapse SN ($E \sim MeV$)
3. Big–bang relic neutrinos: ($E \sim$ meV)

Neutrinos and SN astrophysics

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Sources of HE/UHE neutrinos

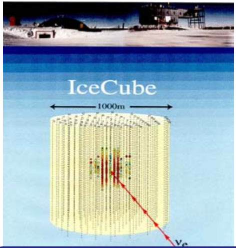
Secondaries of cosmic rays

- 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 ?

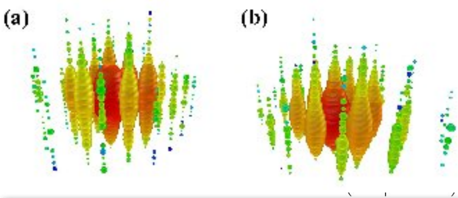
Detection estimates

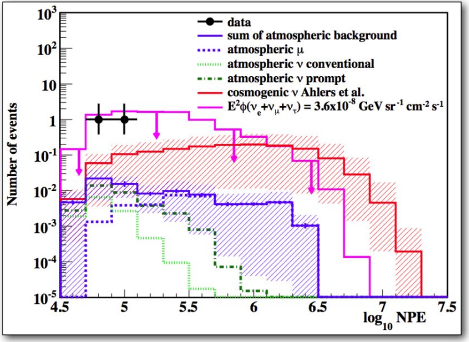
- Down-going neutrinos: atmospheric muon background becomes insignificant only for $E \gtrsim 10^{16-17}$ eV
- Up-going neutrinos: $E \lesssim 10^{16}$ eV, since more energetic neutrinos get absorbed in the Earth
- Diffused flux sensitivity to $E^2 dN/dE \sim 2$ eV cm^{-2} sr^{-1} s^{-1} after 3 years 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 two PeV events at Icecube

Talk by Darren Grant





- Two events at $\sim$ 1 PeV energies found
- Cosmogenic ? X Glashow resonance? X atmospheric ?

Roulet et al 2013 ++ many

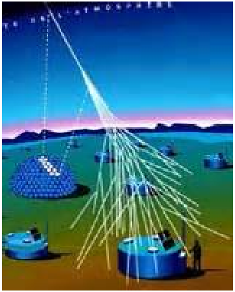
- IceCube analyzing 28 events from 30 TeV to 1.1 PeV

Details in talk by Darren Grant

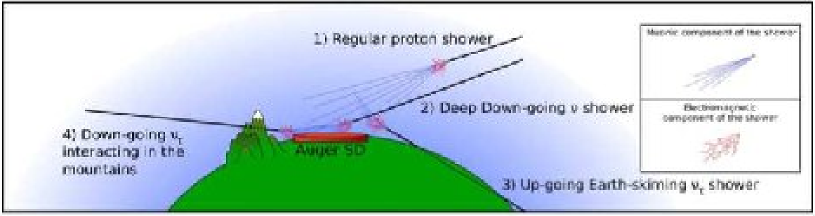
- Constraints on Lorentz violation: $\delta(v^2-1) \lesssim \mathcal{O}(10^{-18})$

Borriello, Chakraborty, Mirizzi, 2013

Detection of UHE neutrinos: cosmic ray showers



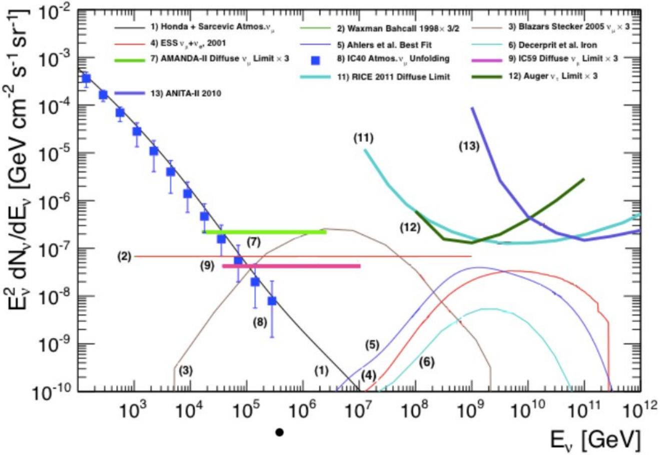
- Neutrinos with $E \gtrsim 10^{17}$ eV can induce giant air showers (probability $\lesssim 10^{-4}$)
- Deep down-going muon showers
- Deep-going ν_τ interacting in the mountains
- Up-going Earth-skimming ν_τ shower



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



Talk by Darren Grant

Waxman-Bahcall, AMANDA, ANITA, RICE, Auger, IceCube

Also expect complementary info from: NEMO, NESTOR, ANTARES, KM3NET ...

Flavor information from UHE neutrinos

- Neutrino flavor ratio $\nu_e : \nu_\mu : \nu_\tau$ from primary sources:
  Neutron source $1 : 0 : 0$,
  Pion source $1 : 2 : 0$,
  Dense sources that absorb muons $0 : 1 : 0$
- L/E large $\Rightarrow$ oscillations change the flavor ratio.
  Pion source: approx $1 : 1 : 1$
  Muon-absorbing sources: $1 : 2 : 2$
- 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

(The numbers obtained with bimaximal mixing)

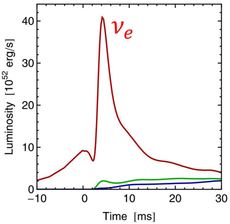
Neutrinos and SN astrophysics

1. High / ultra-high energy neutrinos ($E \gtrsim$ TeV)
2. Neutrinos from a core-collapse SN ($E \sim MeV$)
3. Big–bang relic neutrinos: ($E \sim$ meV)

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

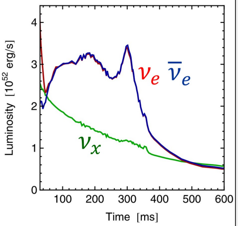
Three Phases of Neutrino Emission

Prompt ν_e burst



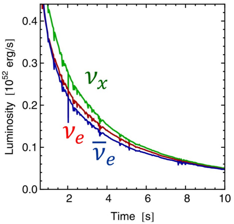
- Shock breakout
- De-leptonization of outer core layers

Accretion



- Shock stalls $\sim$ 150 km
- Neutrinos powered by infalling matter

Cooling

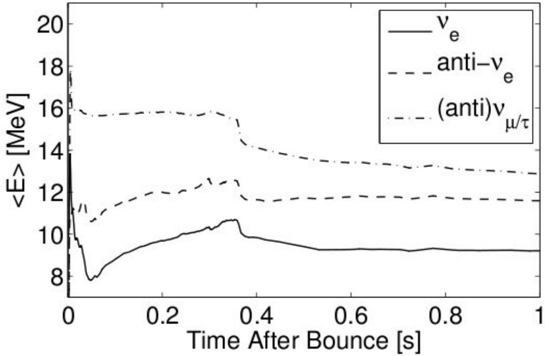


Cooling on neutrino diffusion time scale

- Spherically symmetric model (10.8 $M_\odot$) with Boltzmann neutrino transport
- Explosion manually triggered by enhanced CC interaction rate

Fischer et al. (Basel group), A&A 517:A80, 2010 [arxiv:0908.1871]

Neutrino fluxes: energy spectra

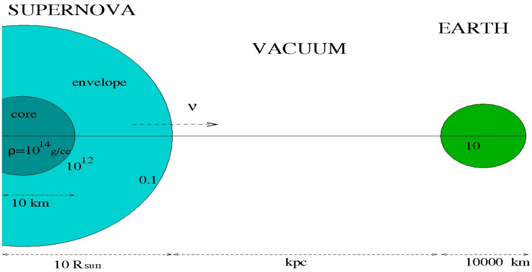


$10.8 M_\odot$ star

Fischer et al, arXiv:0908.1871

- Approximately thermal spectra
- $\langle E_{\nu_e} \rangle < \langle E_{\bar{\nu}_e} \rangle < \langle E_{\nu_\mu, \nu_\tau, \bar{\nu}_\mu, \bar{\nu}_\tau} \rangle$

Neutrino propagation



Inside the SN: *flavor conversion*

Collective effects and MSW matter effects

Between the SN and Earth: *no flavor conversion*

Mass eigenstates travel independently

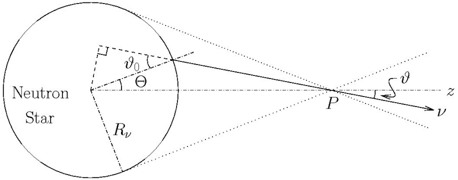
Inside the Earth: *flavor oscillations*

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

Non-linearity from neutrino-neutrino interactions

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

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



Duan, Fuller, Carlson, Qian, PRD 2006

- Equation of motion:

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

Note: ρ is a 3×3 matrix

"Collective" effects: qualitatively new phenomena

Synchronized oscillations:

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

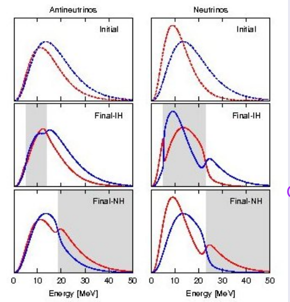
S. Pastor, G. Raffelt and D. Semikoz, PRD65, 053011 (2002)

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)

Problems and open questions in collective effects

- New non-linear effects: can they be understood/modelled in terms of other phenomena (like superconductivity) ?

Pehlivan, Balentekin et al, 2011

- Many answers known only with the single-angle approximation (all neutrinos at a point face the same average $\nu\nu$ potential [effective averaging of $(1 - \cos\theta_{pq})$]). How good is this approximation ?
- Multi-angle effects seem to suppress collective effects, or make them appear earlier / later, or smoothen out their effects on the spectra.

Duan, Friedland, 2011, Mirizzi, Serpico 2012

- Normal matter at high densities also seems to give rise to additional suppression. What will be the net effect ?

Chakraborty et al, 2011

Some recent theoretical progress

- Linearized stability analysis: focussing on the onset of collective oscillations

  Banerjee, AD, Raffelt 2011, Sarikas Raffelt 2011

- Neutrinos that undergo scattering outside the neutrinosphere can have an effect on oscillations (Halo effect)

  Cherry et al 2012, Sarikas et al 2012

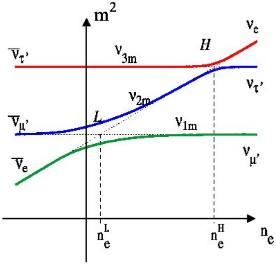
- Large amplitude turbulence in outer layers of the star may obscure usual signatures, but give rise to some new ones...

  Kneller, Lund 2013

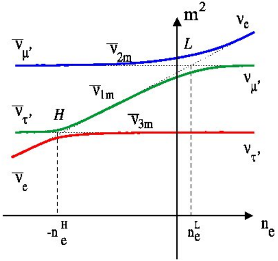
- “Collective” work in progress....

MSW Resonances inside a SN

Normal mass ordering



Inverted mass ordering



AD, A.Smirnov, PRD62, 033007 (2000)

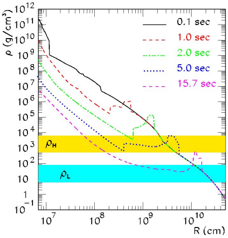
H resonance: $(\Delta m^2_{\rm atm}, \theta_{13})$, $\rho \sim 10^3$–10^4 g/cc

- In $\nu(\bar{\nu})$ for normal (inverted) hierarchy
- Now that θ_{13} is known to be large,
  adiabatic except during the passage of the shock wave

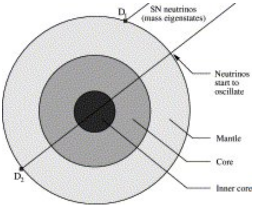
L resonance: $(\Delta m^2_{\odot}, \theta_{\odot})$, $\rho \sim 10$–100 g/cc

- Always adiabatic, always in ν

Further flavor conversions: shock and earth effects



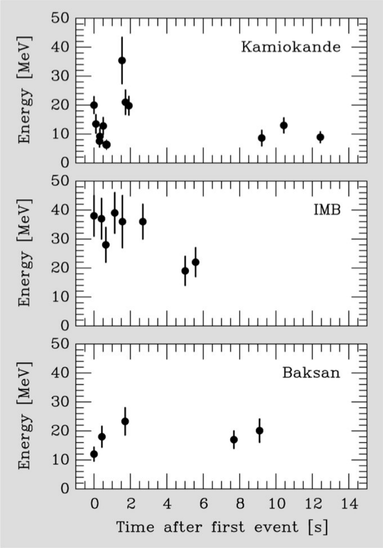
- During shock wave propagation, adiabaticity momentarily lost $\Rightarrow$ fluctuations in spectra.
- Turbulence behind the shock wave $\Rightarrow$ depolarization effects



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

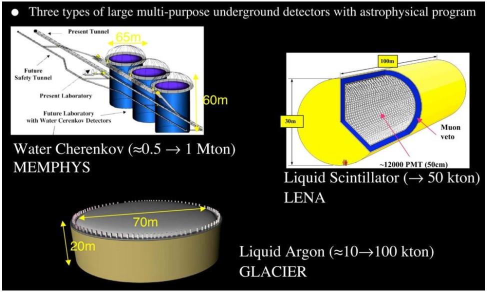
SN1987A: neutrinos and light

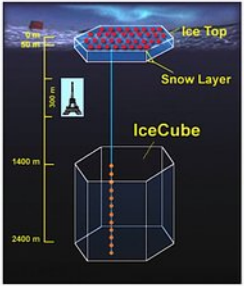
Neutrinos: Feb 23, 1987



- Neutrinos reached a few hours before the light
- Confirmed the SN cooling mechanism through neutrinos
- Number of events too small to say anything concrete about neutrino mixing
- Some constraints on SN parameters, strong constraints on new physics models (neutrino decay, Majorans, axions, extra dimensions, ...)

SN neutrino detection





- Water Cherenkov / liquid scintillator / liquid Ar detectors for tracking individual neutrinos (HK, LENA, ...)
- Large-volume ice Cherenkov for determining luminosity to a high accuracy (integrated Cherenkov glow)
- LBNE liquid Ar ? If it is underground...

Major reactions at the large detectors (SN at 10 kpc)

Water Cherenkov detector: size advantage (events at SK)

- $\bar{\nu}_e p \to n e^+$: ($\sim 7000 - 12000$)
- $\nu e^- \to \nu e^-$: $\approx 200 - 300$
- $\nu_e + ^{16}O \to X + e^-$: $\approx$ 150–800

Carbon-based scintillation detector: ΔE advantage

- $\bar{\nu}_e p \to n e^+$ ($\sim$ 300 per kt)
- $\nu + \ ^{12}C \to \nu + X + \gamma$ (15.11 MeV)
- $\nu p \to \nu p$

Liquid Argon detector: ν_e spectrum advantage

- $\nu_e + \ ^{40}Ar \to \ ^{40}K^* + e^-$ ($\sim$ 300 per kt)

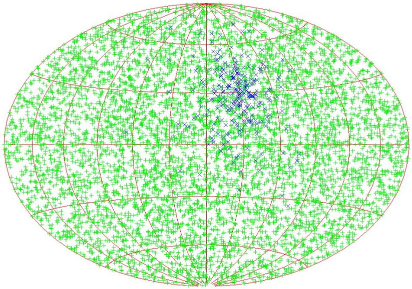
Lead detector:

- CC: $\nu_e +^{208}\mathrm{Pb} \to^{207}\mathrm{Bi} + n + e^-$,
  $\nu_e +^{208}\mathrm{Pb} \to^{206}\mathrm{Bi} + 2n + e^-$
- NC: $\nu_x +^{208}\mathrm{Pb} \to^{207}\mathrm{Pb} + n$, $\nu_x +^{208}\mathrm{Pb} \to^{206}\mathrm{Pb} + 2n$

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



Vanishing neutronization (ν_e) burst

- Flux during the neutronization burst well-predicted ("standard candle")

M. Kachelriess et al, PRD 2005

Mass hierarchy identification (now that θ_{13} is large)

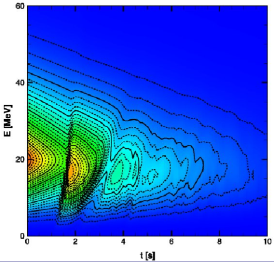
- Burst in CC suppressed by $\sim \sin^2\theta_{13} \approx 0.025$ for NH, only by $\sim \sin^2\theta_{12} \approx 0.3$ for IH
- Liquid Ar detector with good time resolution (for separating ν_e burst from the accretion phase signal) crucial

O-Ne-Mg supernova

- MSW resonances take place within the collective region
- Distinctive spectral modulations in the neutronization burst spectrum (even more due to Halo effect)

Duan et al 2008, Dasgupta et al 2008, Cherry et al 2011, 2013

Shock wave effects and turbulence



2D simulation
Positron spectrum
(inverse beta reaction)

Kneller et al., PRD 2008

Observable shock signals

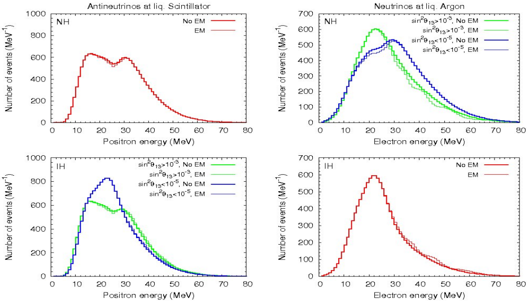
- Time-dependent dip/peak features in $N_{\nu_e,\bar{\nu}_e}(E)$, $\langle E_{\nu_e,\bar{\nu}_e}\rangle$, ...
- Can track the shock wave while still inside the mantle

R.Tomas et al., JCAP 2004, Gava et al., PRL 2009

Identifying mixing scenario: independent of collective effects

- Shock effects present in ν_e only for NH
- Shock effects present in $\bar{\nu}_e$ only for IH
- Absence of shock effects gives no concrete signal.
  primary spectra too close ? turbulence ?

Earth matter effects



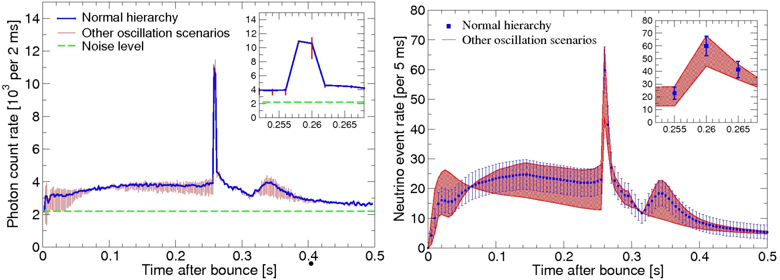
Choubey et al, 2010

- Spectral split may be visible as "shoulders"
- Earth effects possibly visible, more prominent in ν_e
- Detection through spectral modulation, or comparison between time-dependent luminosities at large detectors.
- Recent simulations do not paint such a rosy picture.

Borriello et al, 2012

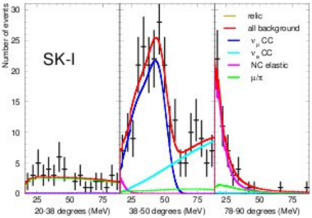
QCD phase transition (if it takes place)

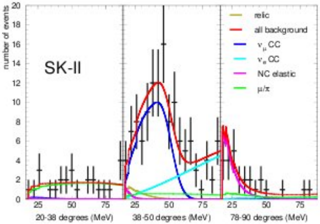
- Sudden compactification of the progenitor core during the QCD phase transition
- Prominent burst of $\bar{\nu}_e$, visible at IceCube and SK

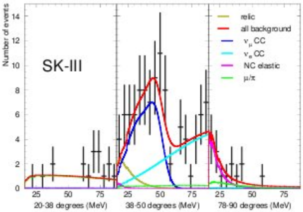


Dasgupta et al, PRD 2010

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

Neutrinos and SN astrophysics

1. High / ultra-high energy neutrinos ($E \gtrsim$ TeV)
2. Neutrinos from a core-collapse SN ($E \sim MeV$)
3. Big–bang relic neutrinos: ($E \sim$ meV)

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:

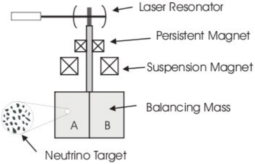
$$\Omega_\nu/\Omega_{\rm baryon} = 0.5 \left(\sum m_\nu/{\rm eV}\right)$$

- 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

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.

The inverse beta reaction

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

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

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, so not feasible.

Lazauskas, Vogel, Volpe 2009, Hodak et al 2011

Summary

HE / UHE neutrinos

- Cerenkov ν telescopes, large cosmic ray detector arrays
- We are on the threshold of detection
- Flavor identification holds clues on sources and ν properties

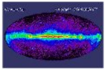
Supernova neutrinos

- Rich SN astrophysics and ν oscillation phenomenology
- Instant identification of mass hierarchy possible
- Unique way of extracting information on SN dynamics
- Wanted: large underground liquid Ar detector with good Δt

Big bang relic neutrinos

- Inverse beta processes on beta-decaying nuclei: only feasible idea ?

Mapping the universe

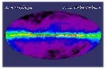

Gamma ray

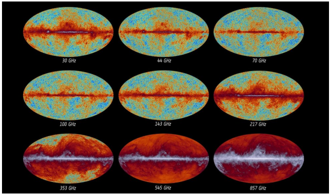

X-ray


Visible

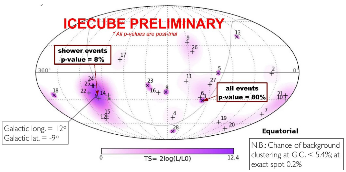

Near infrared


Infrared

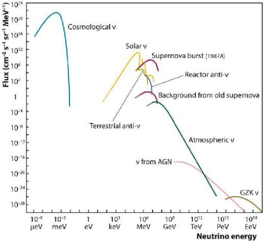

Radio waves



Neutrinos entering this domain, slowly but surely...



Talk by Darren Grant



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