Astroparticle physics of neutrinos

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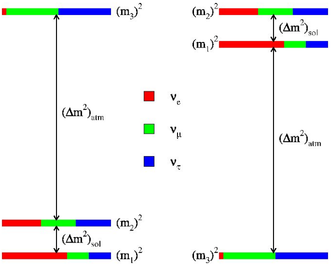
Recent Issues in Nuclear and Particle Physics (RINP2)
Visva Bharati, Feb 4th, 2019

The knowns and unknowns of neutrinos

Mixing of ν_e, ν_μ, ν_τ $\Rightarrow$ ν_1, ν_2, ν_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
- $\theta_{\rm atm} \approx 45°$
- $\theta_\odot \approx 32°$
- $\theta_{\rm reactor} \approx 9°$

- Mass ordering: Normal (N) or Inverted (I) ?
- What are the absolute neutrino masses ?
- Are there more than 3 neutrinos ?
- Is there leptonic CP violation ?
- Can neutrinos be their own antiparticles ?

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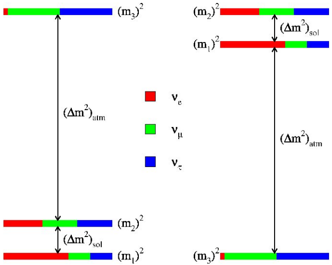

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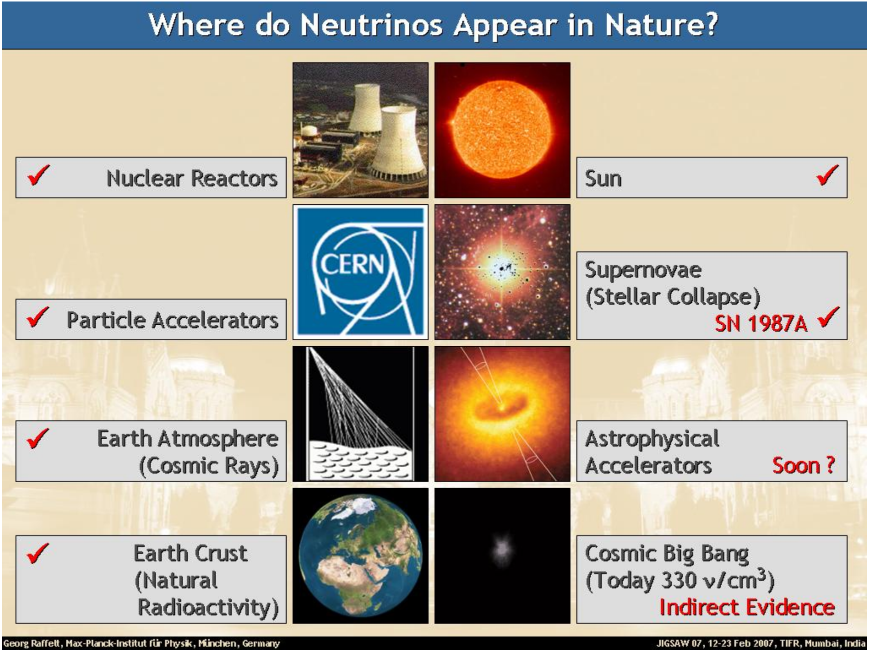
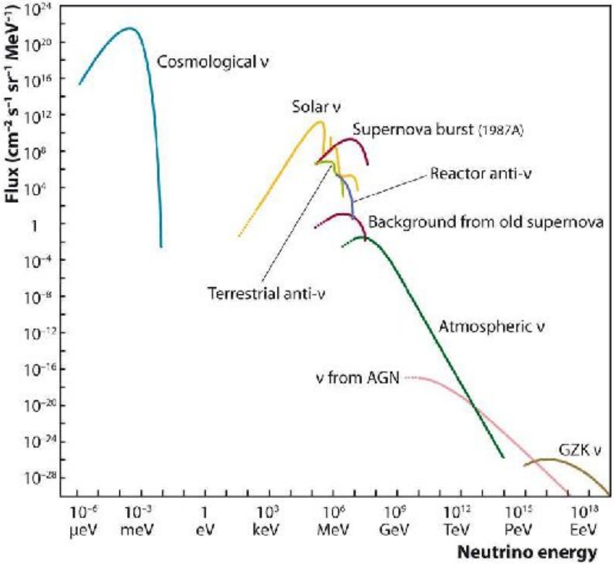
Neutrinos come from many sources...



Neutrinos as messengers from astrophysical sources

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

Spectra of neutrino sources



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Astroparticle Physics of Neutrinos

1. Neutrinos from a core collapse supernova
2. Astrophysical neutrinos with ultra-high energies
3. Cosmological Neutrinos with ultra-small energies
4. Multi-messenger astronomy

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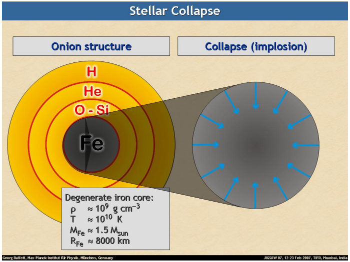
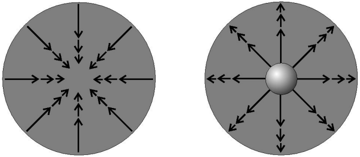
The death of a star: role of different forces

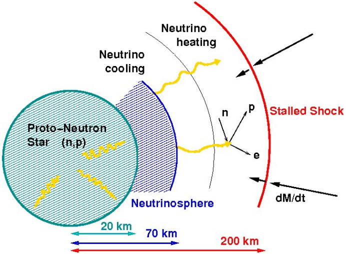
Gravity ⇒



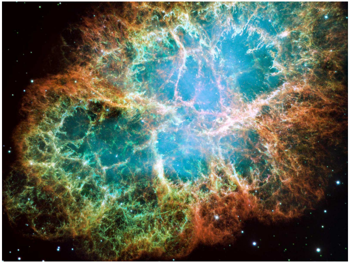
Nuclear forces ⇒



Neutrino push ⇒

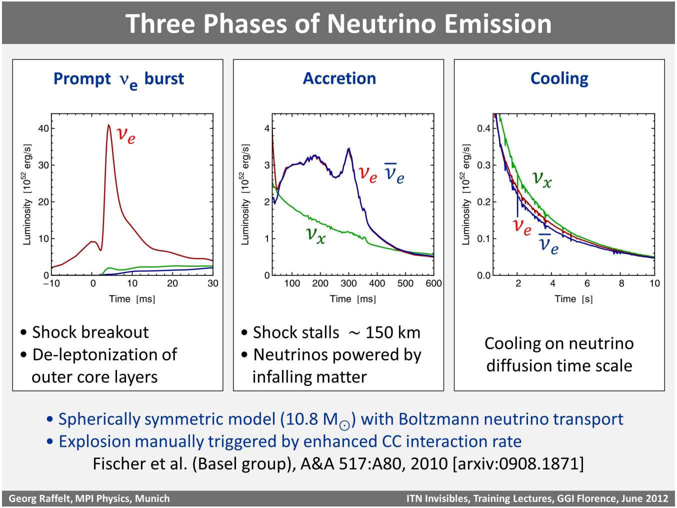


Hydrodynamics ⇒



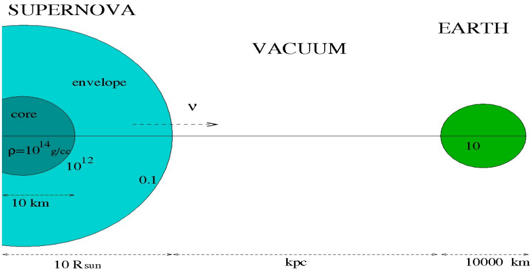
(Crab nebula, SN seen in 1054)

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***

Mass eigenstates travel independently

Inside the Earth: ***flavour oscillations***

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

Can neutrino conversions affect SN explosions ?

- Simulations of light SN have started giving explosions with the inclusions of 2D/3D large scale convections and hydrodynamic instabilities
- More push to the shock wave is still desirable.
- Non-electron neutrino primary spectra harder
  $\oplus$ electron neutrino cross section higher
  $\Rightarrow$ After conversion, greater push to the shock wave
- Deeper the conversions, greater the neutrino push
- MSW resonances: $\sim$ 1000 km,
  Neutrino-neutrino collective effects: $\sim$ 100 km
- "Fast conversions": $\sim$ 10 km
  (Angular anisotropies needed, but quite naturally possible)

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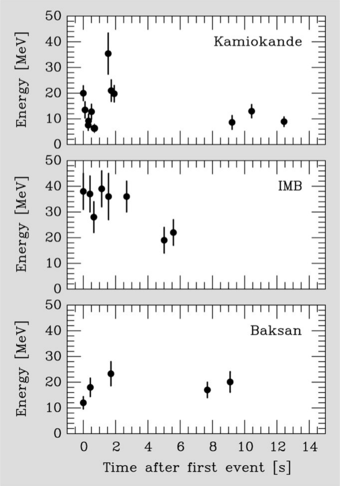
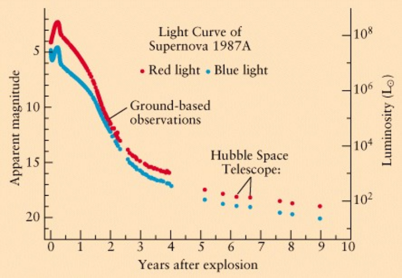
SN1987A: neutrinos and light

Neutrinos: Feb 23, 1987



Light curve: 1987-1997

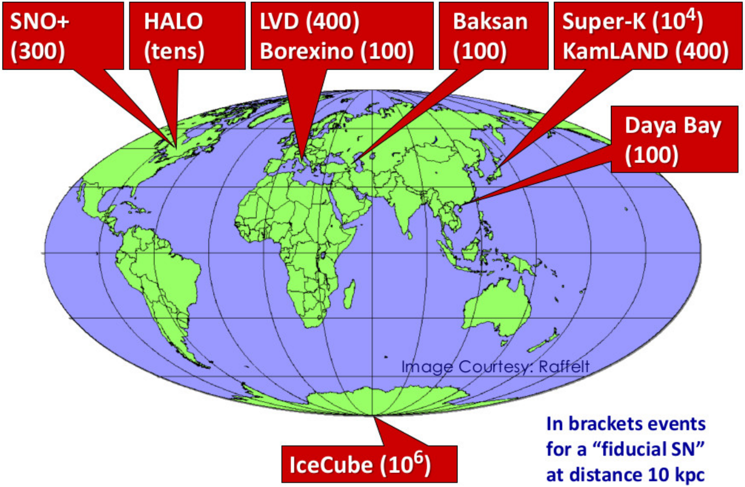


SN1987A: what did we learn ?

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, ...)

Supernova neutrino detectors



In brackets events for a “fiducial SN” at distance 10 kpc

Slide by Georg Raffelt

What a galactic SN can tell us

On neutrino masses and mixing

- Instant identification of neutrino mass ordering (N or I), through
  - Neutronization burst: (almost) disappears if N
  - 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
- Hints on heavy element nucleosynthesis (r-process)

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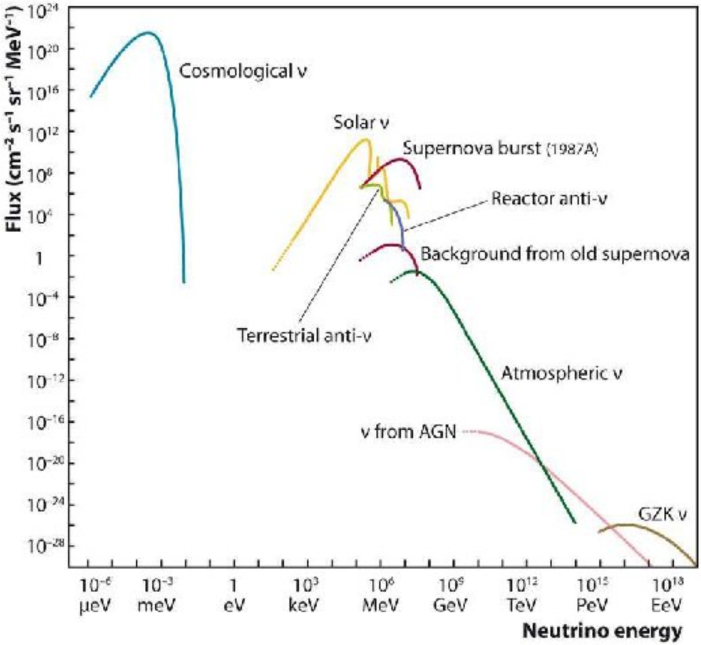
Flux (cm⁻² s⁻¹ sr⁻¹ MeV⁻¹)
Cosmological ν
Solar ν
Supernova burst (1987A)
Reactor anti-ν
Background from old supernova
Terrestrial anti-ν
Atmospheric ν
ν from AGN
GZK ν
10⁻⁶ μeV
10⁻³ meV
1 eV
10³ keV
10⁶ MeV
10⁹ GeV
10¹² TeV
10¹⁵ PeV
10¹⁸ EeV
Neutrino energy

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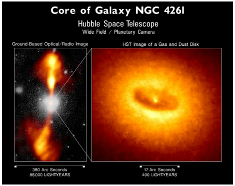
High / Ultrahigh energy neutrinos ($E \gtrsim$ TeV)



Sources of UHE neutrinos

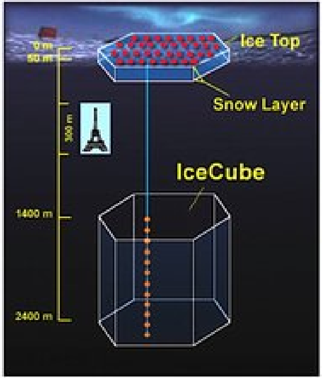
- Primary protons interacting within the source $\Rightarrow \pi^{\pm} \Rightarrow$ Decay to ν
- Primary protons interacting with CMB photons $\Rightarrow \pi^{\pm} \Rightarrow$ Decay to ν (GZK)
- Individual sources like AGNs and GRBs
- Diffused flux accumulated over the lifetime of universe

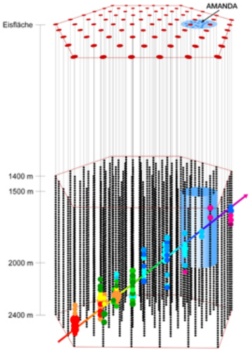
What we will learn

- Mechanisms of astrophysical phenomena
- Limits on neutrino decay, Lorentz violation, etc

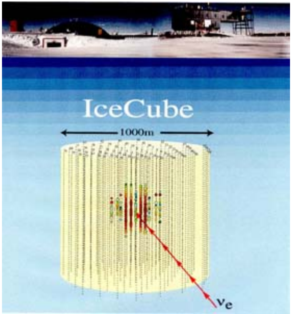
Below the antarctic ice: Gigaton IceCube

1 000 000 000 000 litres of ice





Detection of HE neutrinos: water/ice Cherenkov



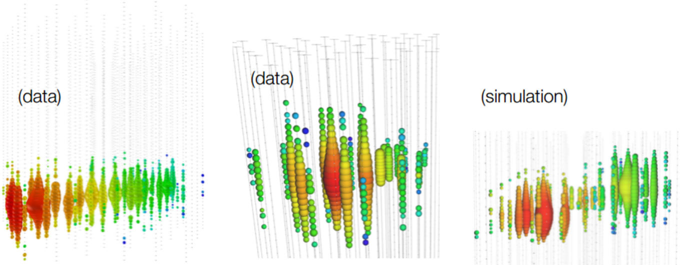
- Thresholds of $\sim$ 100 GeV, controlled by the distance between optical modules

Sensitive energy ranges

- 10^{11} eV $\lesssim E \lesssim 10^{16}$ eV: up-going neutrinos
  - No background from cosmic rays
- $E \gtrsim 10^{16-17}$ eV: down-going neutrinos
  - Atmospheric neutrino background insignificant
  - Up-going neutrinos get absorbed in the Earth

Flavour sensitivity of IceCube

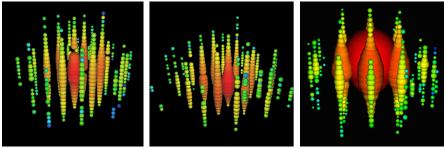
Charged-current ν_μ	Neutral-current / ν_e	Charged-current ν_τ



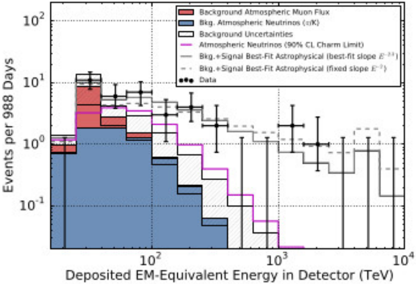
Up-going track	Isolated energy deposition (cascade) with no track	"Double-bang"
Factor of ~2 energy resolution < 1 degree angular resolution	15% deposited energy resolution 10 degree angular resolution (above 100 TeV)	(none observed yet: τ decay length is 50 m/PeV)

Early  Late

The three PeV events at Icecube



Bert Ernie Big Bird

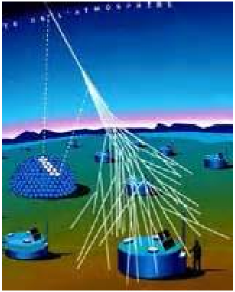


- Three events at $\sim 1, 1.1, 2.2$ PeV energies found
- Cosmogenic ? X Glashow resonance? X atmospheric ?

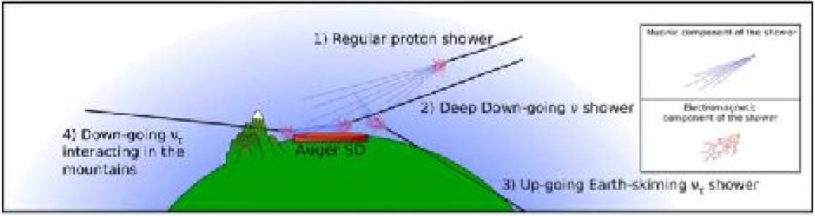
  Roulet et al 2013 ++ many
- IceCube analyzing 54 events from 30 TeV to 10 PeV
- Constraints on Lorentz violation: $\delta(v^2 - 1) \lesssim \mathcal{O}(10^{-18})$

  Borriello, Chakraborty, Mirizzi, 2013

Detection of UHE neutrinos: cosmic ray showers



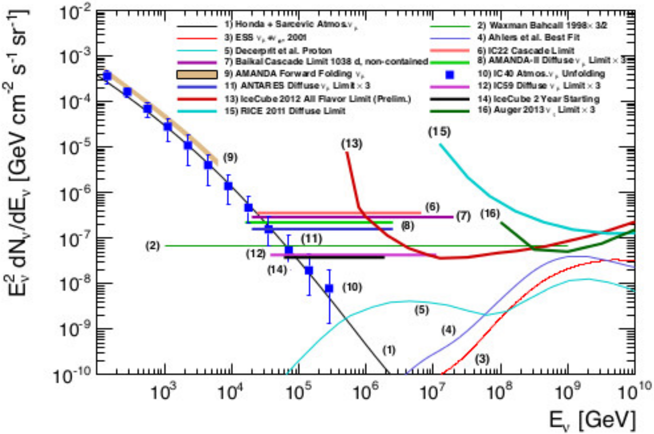
- Neutrinos with $E \gtrsim 10^{17}$ eV can induce giant air showers (probability $\lesssim 10^{-4}$)
- Deep down-going muon showers
- Deep-going ν_τ interacting in the mountains
- Up-going Earth-skimming ν_τ shower



Detection through radio waves: ANITA

- Charged particle shower $\Rightarrow$ Radio Askaryan: charged clouds emit coherent radio waves through interactions with $\mathbf{B}_{\mathrm{Earth}}$ 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 (with neutrino mixing)

- 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

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Beacom et al, PRL 2003

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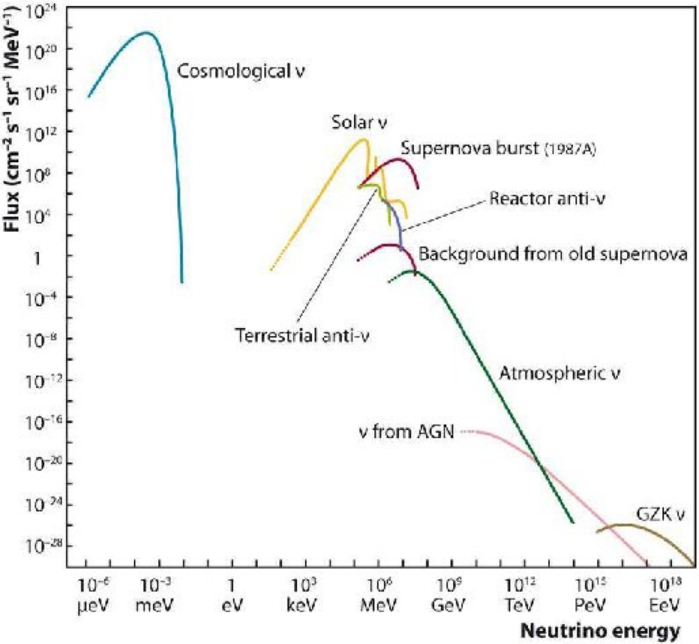
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10^{24}
10^{20}
10^{16}
10^{12}
10^{8}
10^{4}
1
10^{-4}
10^{-8}
10^{-12}
10^{-16}
10^{-20}
10^{-24}
10^{-28}
Cosmological ν
Solar ν
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10^{15} PeV
10^{18} EeV
Neutrino energy

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The big-bang relic neutrinos ($\sim$ 0.1 meV)

- Relic density: $\sim$ 110 neutrinos /flavor /cm^3
- Temperature: $T_\nu = (4/11)^{1/3} T_{\rm CMB} \approx 1.95\ {\rm K} = 0.17\ {\rm meV}$
- 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
CMB photons	$\sim$ 400,000 years	0.26 eV	1100
Relic neutrinos	0.18 s	$\sim$ 2 MeV	$\sim 10^{10}$

Lazauskas, Vogel, Volpe, 2008

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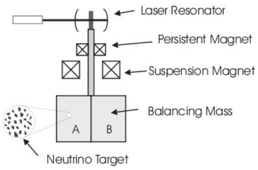
Detection of relic neutrinos: the torsion balance idea



- 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 rather impractical at the moment.

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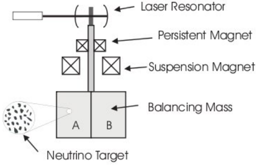

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The inverse beta reaction

- 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
- Search for ways of detection still on ...

Lazauskas, Vogel, Volpe 2009, Hodak et al 2011

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

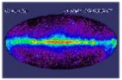
- Possible at ^{3}H experiments with 100 g of pure tritium but atomic tritium is neeed to avoid molecular energy levels
- ^{187}Re at MARE also suggested, but a lot more material will be needed
- Search for ways of detection still on ...

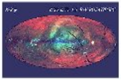
Lazauskas, Vogel, Volpe 2009, Hodak et al 2011

Astroparticle Physics of Neutrinos

1. Neutrinos from a core collapse supernova
2. Astrophysical neutrinos with ultra-high energies
3. Cosmological Neutrinos with ultra-small energies
4. Multi-messenger astronomy

Light, neutrinos, and gravitational waves

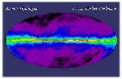

Gamma ray

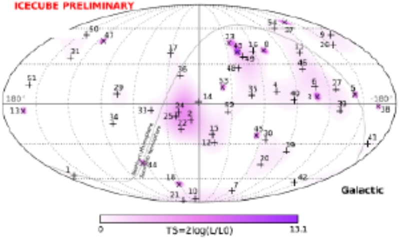

X-ray

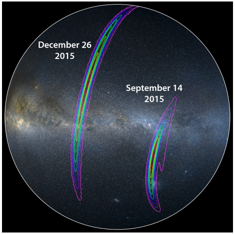

Visible


Near infrared

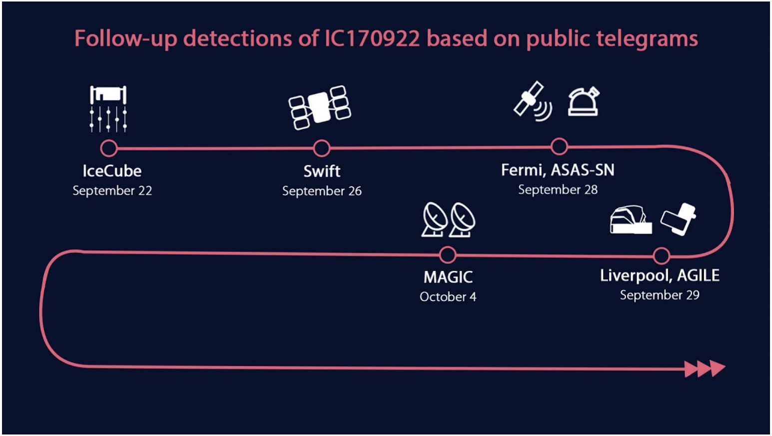

Infrared


Radio waves

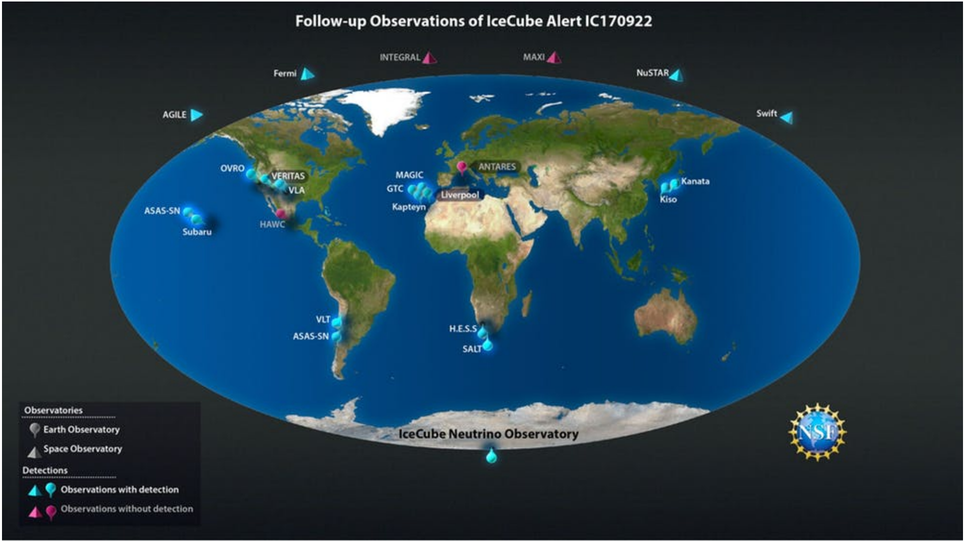




Blazar at IceCube



Blazar at IceCube



Final Remarks

- Astrophysical observations have played a crucial role in unravelling neutrino properties.

- The knowledge of neutrino properties can now be used to learn about astrophysical phenomena.