An overview of neutrino physics

A biased sampling

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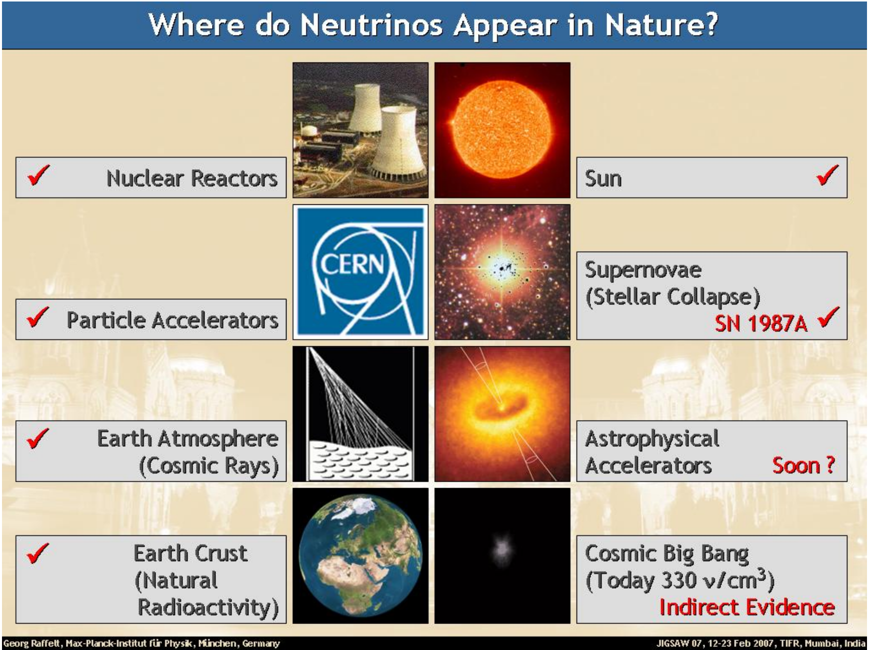
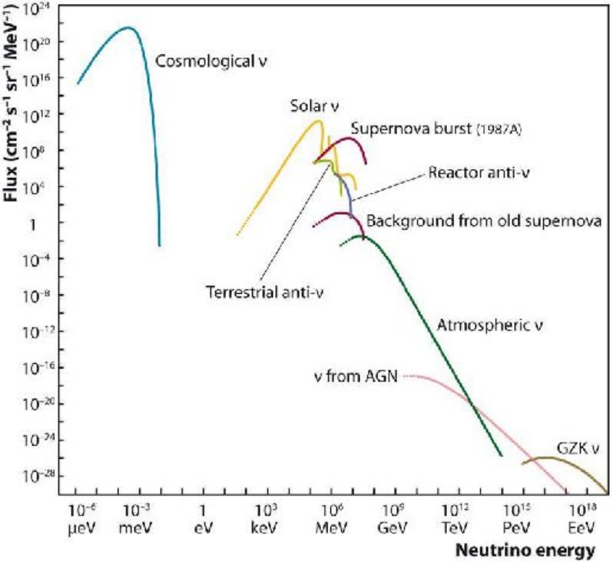
Candles of Darkness,
ICTS-TIFR, Bengaluru, Jun 8th, 2017

Omnipresent neutrinos



Energy spectra of neutrino sources



Neutrinos as candles of darkness

- Component (albeit small) of the Dark Matter.
- Masses necessarily imply physics beyond the SM
- Natural candidates for interactions with high scale physics
- Role in matter-antimatter asymmetry, supernova explosions, structure formation, ...

An overview of Neutrino Physics

1. Neutrino oscillation phenomenology
   - Three-neutrino oscillations
   - Beyond three-neutrino mixing
2. Neutrino mass generation
3. Neutrino astrophysics
   - Big–bang relic neutrinos: ($E \sim$ meV)
   - Neutrinos from a core collapse supernova (5-50 MeV)
   - High energy astrophysical neutrinos ($\gtrsim$ TeV)

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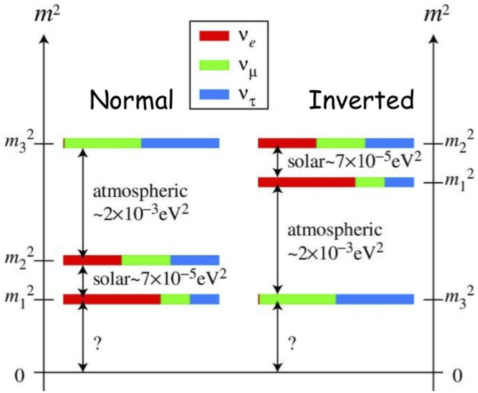
The broad picture



- $\Delta m^2_{\mathrm{atm}} \approx 2.4 \times 10^{-3}\ \mathrm{eV}^2$
- $\Delta m^2_{\odot} \approx 7.5 \times 10^{-5}\ \mathrm{eV}^2$
- $\theta_{\mathrm{atm}} \approx 45^\circ$
- $\theta_{\odot} \approx 32^\circ$
- $\theta_{\mathrm{reactor}} \approx 9^\circ$

What we want to find

- Mass ordering, θ_{23} octant, CP violation
- Absolute values of masses
- New physics hidden in the data

Neutrino parameter fit 2017

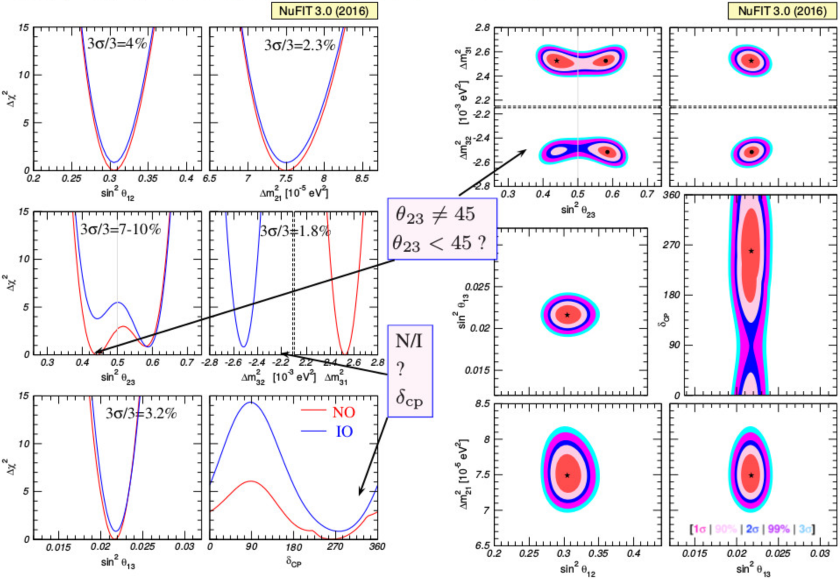
Capozzi et al., 1703.04471

Parameter	Ordering	Best fit	1σ range	2σ range	3σ range
$\delta m^2/10^{-5}$ eV^2	NO, IO, Any	7.37	7.21 – 7.54	7.07 – 7.73	6.93 – 7.96
$\sin^2\theta_{12}/10^{-1}$	NO, IO, Any	2.97	2.81 – 3.14	2.65 – 3.34	2.50 – 3.54
$\lvert\Delta m^2\rvert/10^{-3}$ eV^2	NO	2.525	2.495 – 2.567	2.454 – 2.606	2.411 – 2.646
	IO	2.505	2.473 – 2.539	2.430 – 2.582	2.390 – 2.624
	Any	2.525	2.495 – 2.567	2.454 – 2.606	2.411 – 2.646
$\sin^2\theta_{13}/10^{-2}$	NO	2.15	2.08 – 2.22	1.99 – 2.31	1.90 – 2.40
	IO	2.16	2.07 – 2.24	1.98 – 2.33	1.90 – 2.42
	Any	2.15	2.08 – 2.22	1.99 – 2.31	1.90 – 2.40
$\sin^2\theta_{23}/10^{-1}$	NO	4.25	4.10 – 4.46	3.95 – 4.70	3.81 – 6.15
	IO	5.89	4.17 – 4.48 $\oplus$ 5.67 – 6.05	3.99 – 4.83 $\oplus$ 5.33 – 6.21	3.84 – 6.36
	Any	4.25	4.10 – 4.46	3.95 – 4.70 $\oplus$ 5.75 – 6.00	3.81 – 6.26
δ/π	NO	1.38	1.18 – 1.61	1.00 – 1.90	0 – 0.17 $\oplus$ 0.76 – 2
	IO	1.31	1.12 – 1.62	0.92 – 1.88	0 – 0.15 $\oplus$ 0.69 – 2
	Any	1.38	1.18 – 1.61	1.00 – 1.90	0 – 0.17 $\oplus$ 0.76 – 2

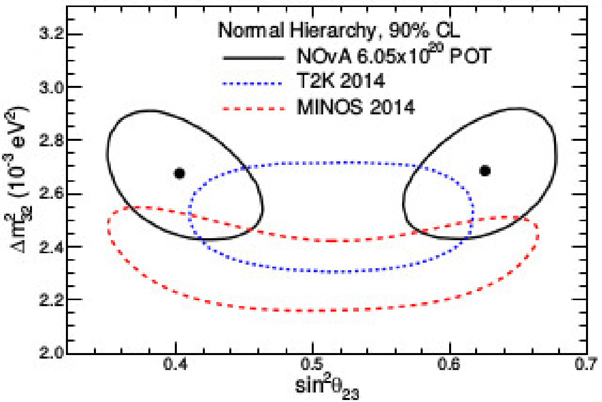
Neutrino parameter fit 2016

Global 6-parameter fit http://www.nu-fit.org

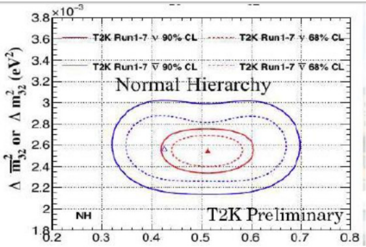
Esteban, Maltoni, Martinez-Soler, Schwetz, MCG-G ArXiv:1611:01514

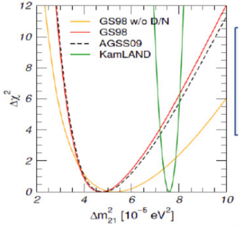


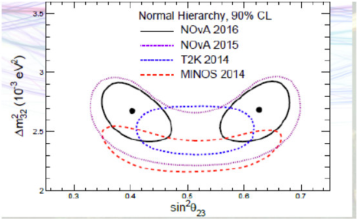
New: indication of θ_{23} non-maximality ??

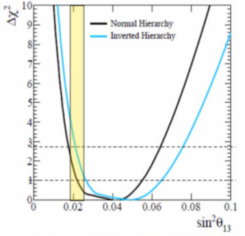


Tensions among experiments









Accelerator / reactor Experiments

- **Current Generation Superbeam Experiments**

  T2K : Tokai to Kamioka, 295 km . 0.76 GeV , 0.75 MW , Detector: SuperK

  NOvA : FNAL to Ash River , 810 km, 1.7 GeV, 0.7 MW, 14 kt TASD detector

- **Next generation Superbeam experiments**

  T2HK: JPARC to Kamioka, detector: HyperK, 1.6 Mw

  DUNE : FNAL-LEAD , 1300km, 0.7 MW ,Detector: 10 (34) kt LiqArTPC

  ESS: European Spallation source Linac , configurations under study , 540 km, 2 GeV

- **Pion decay at rest experiments**

  DAEδ DALUS : low energy, low distance (50 MeV, 20 km)

- **Reactor Experiments**

  JUNO (China), RENO50 (Korea) , reactor neutrinos, 50 km

Degeneracy issues

$$P_{\mu\mu} = 1 - \sin^2 2\theta_{23} \sin^2 \Delta + \text{ subleading terms}$$

$$\mathbf{P}_{\mu e} \simeq \sin^2\theta_{23}\sin^2 2\theta_{13}\frac{\sin^2(\hat{\mathbf{A}}-1)\boldsymbol{\Delta}}{(\hat{\mathbf{A}}-1)^2}+$$

$$\alpha\sin 2\theta_{13}\sin 2\theta_{12}\cos(\boldsymbol{\Delta}+\delta_{\mathbf{CP}})\frac{\sin(\hat{\mathbf{A}}-1)\boldsymbol{\Delta}}{(\hat{\mathbf{A}}-1)}\frac{\sin\hat{\mathbf{A}}\boldsymbol{\Delta}}{\hat{\mathbf{A}}}$$

$$\boldsymbol{\Delta} = \Delta m^2_{31}L/4E,\ \alpha = \Delta m^2_{21}/\Delta m^2_{31},\ \hat{\mathbf{A}} = \pm 2\sqrt{2}G_F n_e E/\Delta m^2_{31}$$

Intrinsic octant degeneracy

$$P_{\mu\mu}(\theta_{23}) = P_{\mu\mu}(\pi/2 - \theta_{23})$$

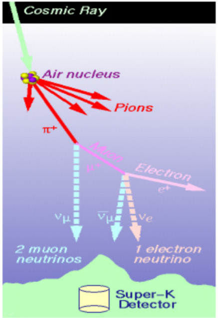
Octant – $\delta_{\rm CP}$ degeneracy

$$P_{\mu e}(\theta_{23}, \delta_{\rm CP}) = P_{\mu e}(\theta'_{23}, \delta'_{\rm CP})$$

Hierarchy (ordering) – $\delta_{\rm CP}$ degeneracy

$$P_{\mu e}(\Delta, \delta_{\rm CP}) = P_{\mu e}(-\Delta, \delta'_{\rm CP})$$

Future atmospheric neutrino experiments



Atmospheric neutrinos
Provide a broad L/E band

Magnetized iron detector

- Volume : 50 – 100 kton
- Excellent muon energy and direction reconstruction
- Charge identification
- Can determine the neutrino energy through hadron shower reconstruction
- Example : INO

Cerenkov Detectors

- Sensitive to both muon and electron events
- No charge id
- Mega ton Water detector (HyperKamiokade)
- Multi Megaton ice detector (PINGU of ICECUBE)
- Multi Megaton under water detector (ORCA)

These will be long-term workhorses !

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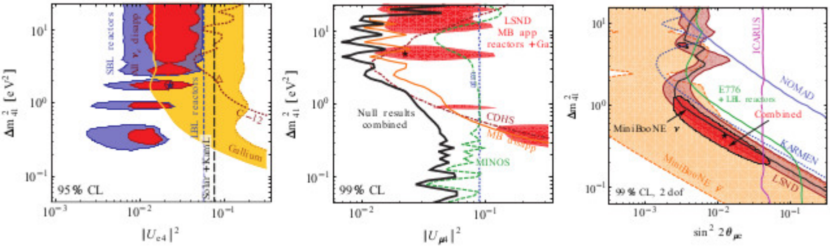
Sterile neutrinos: motivations

- $\overline{\nu}_\mu \to \overline{\nu}_e$ conversions reported at LSND and MiniBoone
- Reactor neutrinos: recalculated reactor fluxes are 3.5% more than earlier calculations
- $\sim$ 10 eV sterile neutrinos would help r-process nucleosynthesis
- keV neutrinos as warm dark matter candidates in νMSM
- Superlight sterile neutrinos ($\Delta m^2 \lesssim 10^{-4}$ eV^2) can explain the lack of upturn in solar P_{ee} at low energies

Sterile neutrinos: bounds from terrestrial expts

$[\Delta m^2_{41} - |U_{e4}|^2]$ $[\Delta m^2_{41} - |U_{\mu 4}|^2]$ $[\Delta m^2_{41} - \sin^2 2\theta_{\mu e}]$



Kopp, Schwetz et al

- Appearance $\oplus$ reactor data indicate eV sterile neutrinos
- Disappearance data (ν_μ) do not support ν_s hypothesis

Jury still out

Non-standard interactions (NSI) of neutrinos

- Help in mitigating some of the tensions among experiments

- Standard NC interaction:

$$\nu_\alpha + f \to \nu_\alpha + f$$

- Non-standard NC interaction

$$\nu_\alpha + f \to \nu_\beta + f$$

$$\mathcal{L} = -G^{\alpha\beta}\epsilon^f_{\alpha\beta}\bar{\nu}_\alpha\gamma^\mu\nu_\beta\bar{f}\gamma_\mu f$$

$$\epsilon_{\alpha\beta} = \sum_{f=e,u,d}\frac{N_f}{N_e}\epsilon^f_{\alpha\beta}$$

$$H = \frac{1}{2E}\left[U\text{diag}(0, \Delta m^2_{21}, \Delta m^2_{31})U^\dagger + V\right],$$

$V \Rightarrow$ matter potential in presence of NSI,

$$V = A\begin{pmatrix} 1+\epsilon_{ee} & \epsilon_{e\mu}e^{i\phi_{e\mu}} & \epsilon_{e\tau}e^{i\phi_{e\tau}} \\ \epsilon_{e\mu}e^{-i\phi_{e\mu}} & \epsilon_{\mu\mu} & \epsilon_{\mu\tau}e^{i\phi_{\mu\tau}} \\ \epsilon_{e\tau}e^{-i\phi_{e\tau}} & \epsilon_{\mu\tau}e^{-i\phi_{\mu\tau}} & \epsilon_{\tau\tau} \end{pmatrix}.$$

Here, $A \equiv 2\sqrt{2}G_F N_e E$ and $\epsilon_{\alpha\beta}e^{i\phi_{\alpha\beta}} \equiv \sum_{f,C}\epsilon^{fC}_{\alpha\beta}\frac{N_f}{N_e}$

$H \to -H^*$ under

$$\theta_{12} \to \pi/2 - \theta_{12},\ \delta \to \pi - \delta$$

$$\Delta m^2_{31} \to -\Delta m^2_{31} + \Delta m^2_{21}$$

$$V \to -S.V.S$$

$$S = Diag(1,-1,-1)$$

Coloma, Schwetz, 1604.05772
P. Bakhti, Y Farzan 1403.0744

Bounds on NSI parameters

Model-independent bounds (oscillation data):

$$|\epsilon_{\alpha\beta}| \sim \begin{pmatrix} |\epsilon_{ee}| < 4.2 & |\epsilon_{e\mu}| < 0.33 & |\epsilon_{e\tau}| < 3.0 \\ & |\epsilon_{\mu\mu}| < 0.068 & |\epsilon_{\mu\tau}| < 0.33 \\ & & |\epsilon_{\tau\tau}| < 21 \end{pmatrix}$$

Some model-dependent bounds (oscillation data):

$$|\epsilon_{\alpha\beta}| \sim \begin{pmatrix} -0.9 < \epsilon_{ee} < 0.75 & |\epsilon_{e\mu}| < 3.8 \times 10^{-4} & |\epsilon_{e\tau}| \lesssim 0.25 \\ & -0.05 < \epsilon_{\mu\mu} < 0.08 & |\epsilon_{\mu\tau}| \lesssim 0.25 \\ & & |\epsilon_{\tau\tau}| \lesssim 0.4 \end{pmatrix}$$

Bounds on non-standard *self-interactions:*

$|\epsilon_{\alpha\beta}| \lesssim 1$ (Invisible Z decay)

Absolute mass bounds

- Tritium beta decay:

$$\langle m_e \rangle \equiv \sqrt{c_{13}^2 c_{12}^2 m_1^2 + c_{13}^2 s_{12}^2 m_2^2 + s_{13}^2 m_3^2} \lesssim 2\ \mathrm{eV}$$

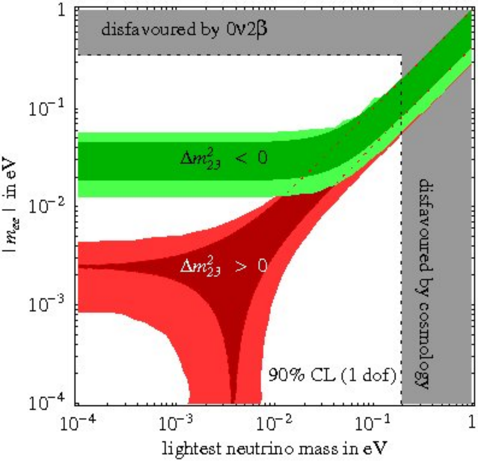
- Neutrinoless double beta decay:

$$\langle m_{ee} \rangle \equiv \left| c_{13}^2 c_{12}^2 m_1 e^{2i\alpha} + c_{13}^2 s_{12}^2 e^{2i\beta} m_2 + s_{13}^2 e^{-2i\delta} m_3 \right| \lesssim 1\ \mathrm{eV}$$

- Cosmology:

$$\sum_i m_{\nu_i} \lesssim 0.2\ \mathrm{eV}$$

Absolute mass constraints



Will hierarchy be identified here first ?

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2. **Neutrino mass generation**

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Seesaw mechanisms and testability

Type-I seesaw: singlet fermion N

- If N is heavy, cannot be produced in the lab
- If N is light, $y_D \ll 1 \Rightarrow$ cannot be produced in the lab

Type-III seesaw: $SU(2)$ triplet Σ

- Σ can be produced at LHC through gauge interactions

Type-II seesaw: $SU(2)$ triplet Higgs Δ

- $\langle \Delta_0 \rangle$ also affects M_W and M_Z
- Measurements of $\rho \equiv \frac{M_W^2}{M_Z^2 \cos^2 \theta_W} = \frac{1+2(\langle \Delta_0 \rangle / \langle \Phi_0 \rangle)^2}{1+4(\langle \Delta_0 \rangle / \langle \Phi_0 \rangle)^2}$ restricts $\langle \Delta_0 \rangle / \langle \Phi_0 \rangle < 0.07$

More possible connections to high scale physics

- Radiative mass models
- GUT-based models: SU(5), SO(10), ...
- Spontaneous B-L violation...
- Supersymmetric models (RPV)...
- Left-right symmetric models...

Talk by Sourov Roy, M. K. Parida at this meeting...

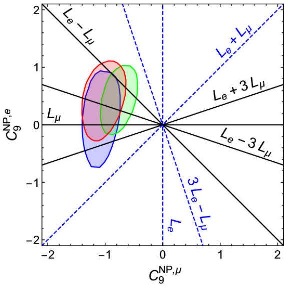
Any singlet fermion X allows $\overline{L}_L \Phi X$

Discrete symmetries for the neutrino mixing pattern

- Popular symmetries of last decade: S_4, A_4
- Texture zeroes in neutrino mass matrices
- Models with scaling symmetries

Talk by Probir Roy at this meeting...

- Symmetries that connect quarks and leptons



Discrete symmetries that give rise to the required *lepton flavour non-universality* to explain R_K and R_{K^*} (low q^2)

Bhatia, Chakraborty, AD, JHEP 2017

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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:

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

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 needed 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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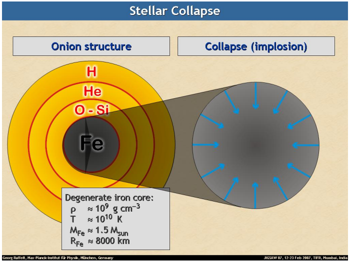
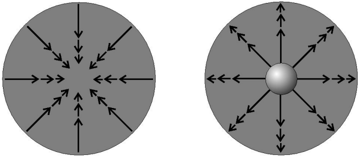
The death of a star: role of different forces

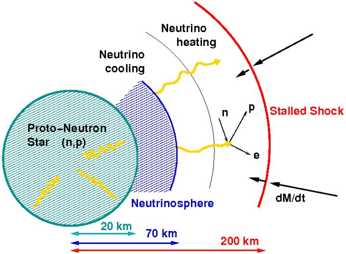
Gravity ⇒



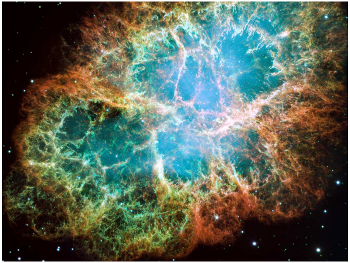
Nuclear forces ⇒



Neutrino push ⇒

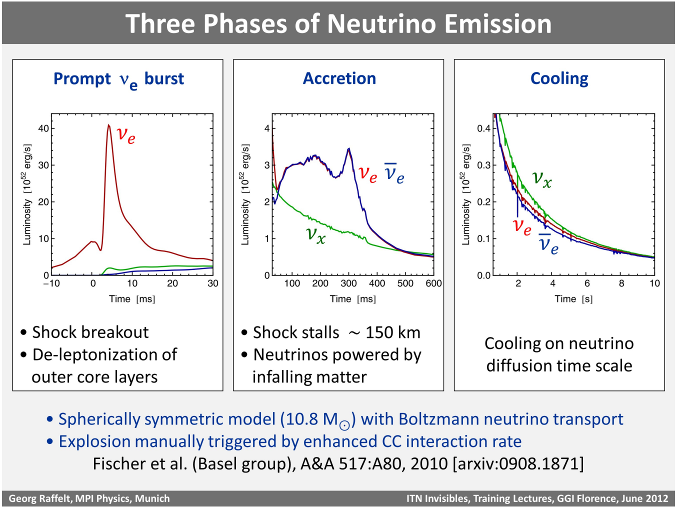


Hydrodynamics ⇒



(Crab nebula, SN seen in 1054)

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

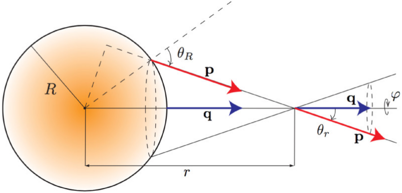


- Escaping neutrinos: $\langle E_{\nu_e} \rangle < \langle E_{\bar{\nu}_e} \rangle < \langle E_{\nu_x} \rangle$

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:

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

- Dimension of ρ matrix: $(3 \times N_{E-bins} \times N_{\theta-bins})$

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$$
\begin{aligned}
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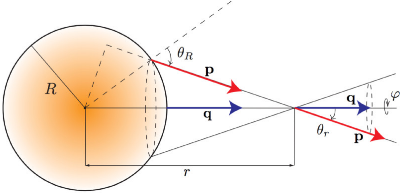
\end{aligned}
$$



Duan, Fuller, Carlson, Qian, PRD 2006

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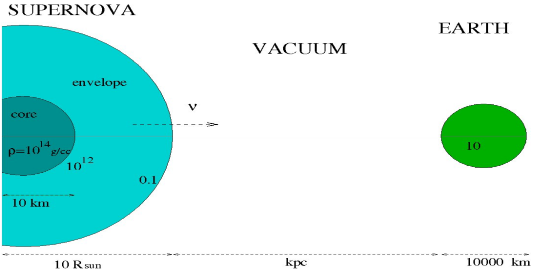
Neutrino oscillations in matter of varying density



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*)

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: 1000 km, Neutrino-neutrino collective effects: 100 km
- "Fast conversions": 10 km [Angular anisotropies needed, but quite naturally possible]

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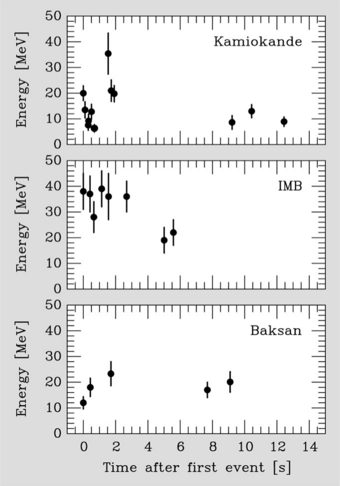
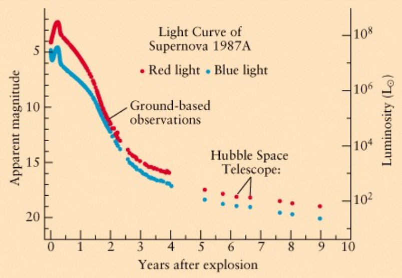
SN1987A: neutrinos and light

Neutrinos: Feb 23, 1987



Light curve: 1987-1997

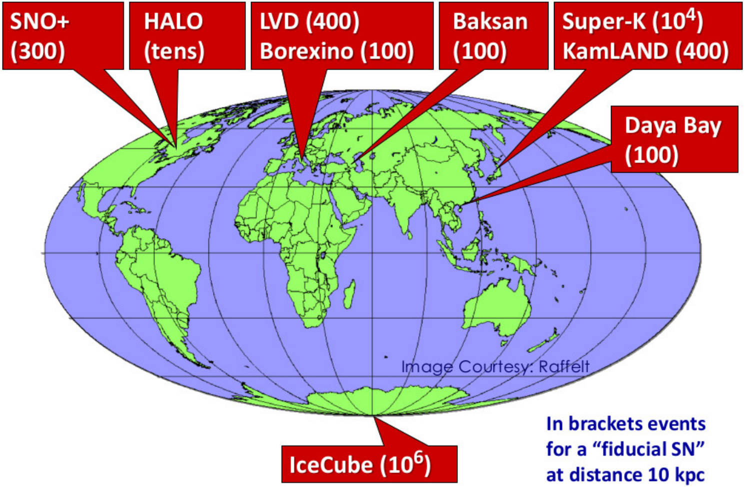


SN1987A: what did we learn ?

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



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
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Neutrino physics: a biased sampling

1. Neutrino oscillation phenomenology
   - Three-neutrino oscillations
   - Beyond three-neutrino mixing
2. Neutrino mass generation
3. Neutrino astrophysics
   - Big–bang relic neutrinos: ($E \sim$ meV)
   - Neutrinos from a core collapse supernova (5-50 MeV)
   - High energy astrophysical neutrinos ($\gtrsim$ TeV)

Sources of HE/UHE neutrinos

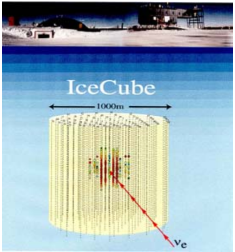
Secondaries of cosmic rays

Primary protons interacting within the source or with CMB photons $\Rightarrow \pi^{\pm} \Rightarrow$ Decay to ν

Theoretical bounds on fluxes

- 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 ~ 100 GeV $\Rightarrow$ $E^2 dN/dE \lesssim 100\ \mathrm{eV\ cm^{-2}\ sr^{-1}\ s^{-1}}$

Detection of HE neutrinos: water/ice Cherenkov



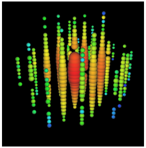
- Thresholds of $\sim$ 100 GeV, controlled by the distance between optical modules
- Track for ν_μ
- Cascade for ν_e, hadrons, ν_τ
- Double-bang for ν_τ ?

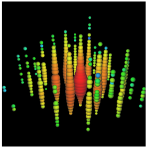
Up-going / down-going thresholds

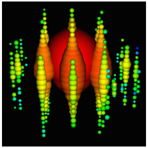
- $E \lesssim 10^{16}$ eV: only up-going ν useful since prohibitive background from atmospheric muons
- $E \gtrsim 10^{16-17}$ eV: only down-going neutrinos available since more energetic neutrinos get absorbed in the Earth

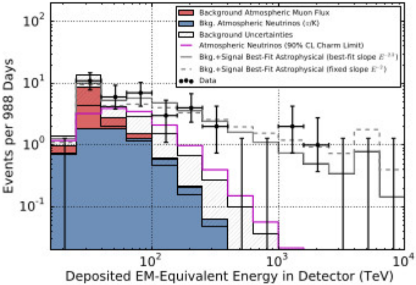
G. Sigl, 1202.0466

The three PeV events at Icecube


Bert


Ernie


Big Bird



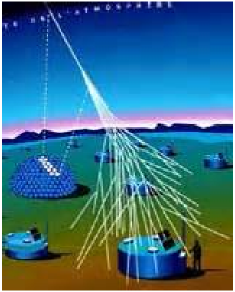
- Three events at $\sim 1, 1.1, 2.2$ PeV energies found
- Cosmogenic ? X Glashow resonance? X atmospheric ?

Roulet et al 2013 ++ many

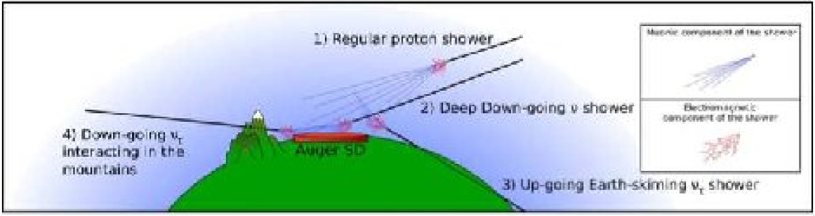
- IceCube analyzing 54 events from 30 TeV to 10 PeV
- Constraints on Lorentz violation: $\delta(v^2 - 1) \lesssim \mathcal{O}(10^{-18})$

Borriello, Chakraborty, Mirizzi, 2013

Detection of UHE neutrinos: cosmic ray showers



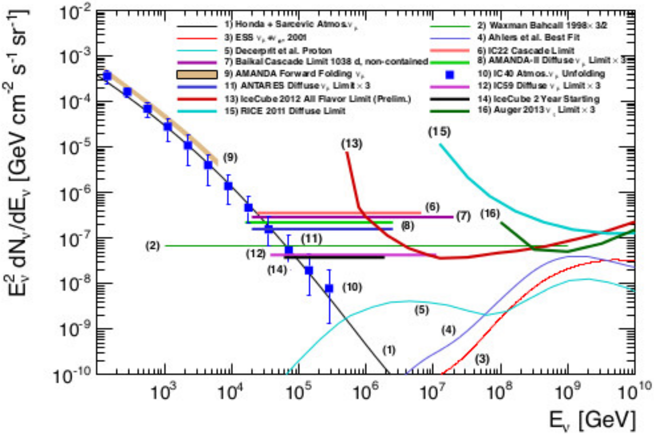
- Neutrinos with $E \gtrsim 10^{17}$ eV can induce giant air showers (probability $\lesssim 10^{-4}$)
- Deep down-going muon showers
- Deep-going ν_τ interacting in the mountains
- Up-going Earth-skimming ν_τ shower



Detection through radio waves: ANITA

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

- Neutron source: $\approx 5 : 2 : 2$
- Pion source: $\approx 1 : 1 : 1$
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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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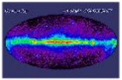
Beacom et al, PRL 2003

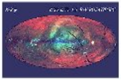
Astrophysical neutrinos as messengers

- No bending in magnetic fields $\Rightarrow$ point back to the source
- Minimal obstruction / scattering $\Rightarrow$ can arrive directly from regions from where light cannot reach us.
- Early warning of a galactic SN (SNEWS network)
- Signals of shock propagation, QCD phase transition, SASI instabilities, BH formation...
- Simultaneous neutrino detection with EM-observed events

Multi-messenger astronomy



Gamma ray

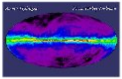


X-ray

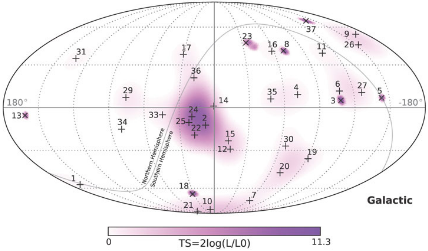
Visible

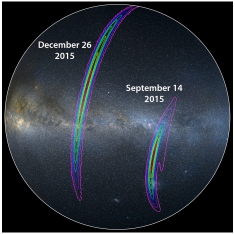
Near infrared

Infrared



Radio waves





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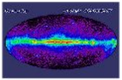
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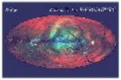
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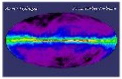
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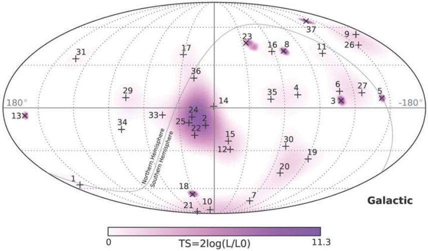

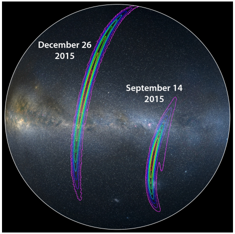

... candles that will keep on probing darkness...