Neutrinos

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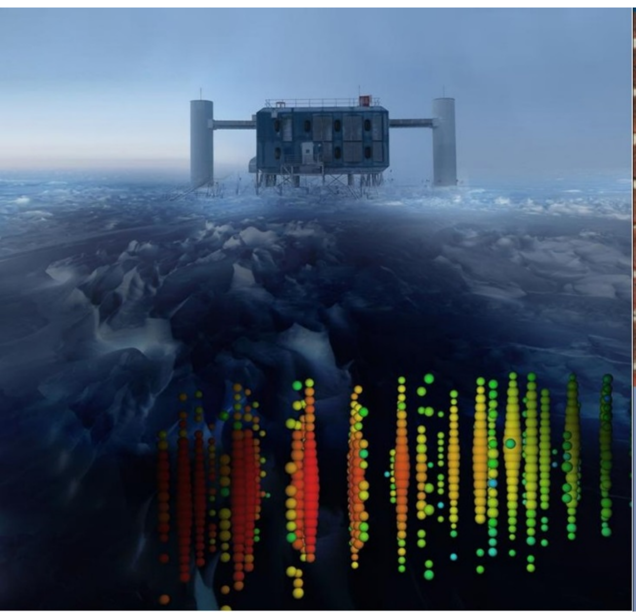
PreSusy School 2016

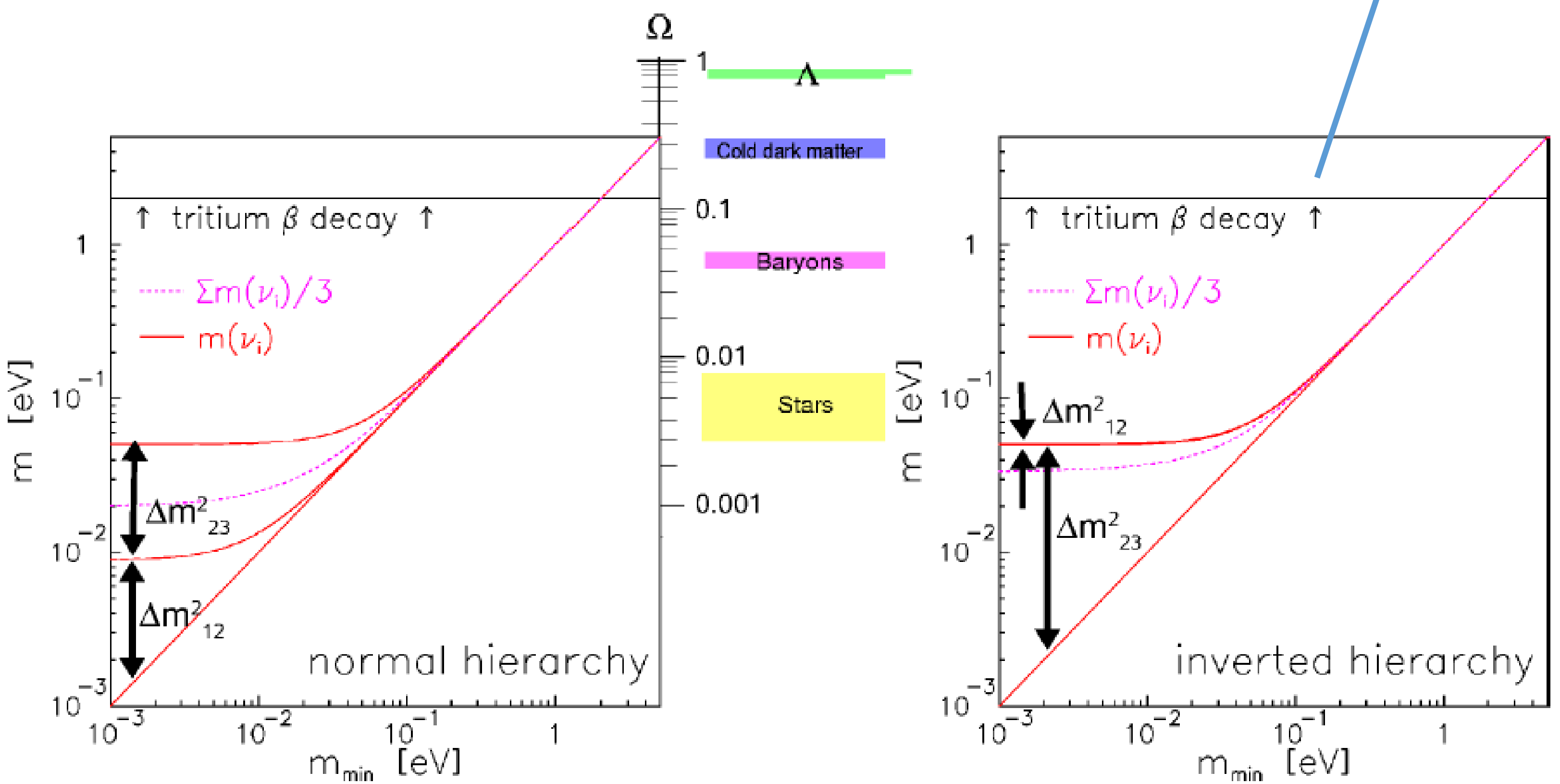


Mass differences:

Δm^2_{12}= 72–80 (meV)^2

Δm^2_{3l}= 2180–2640 (meV)^2

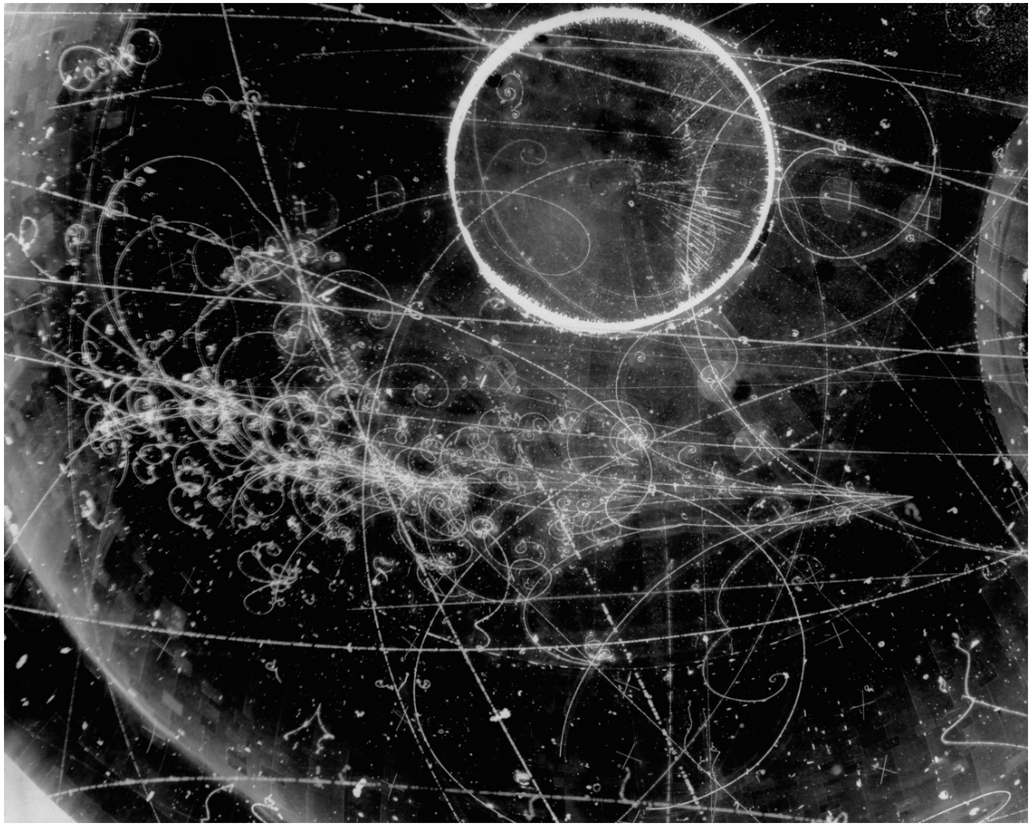
$$m_{\nu_e} = \left(\sum |U_{ei}|^2 m_i^2\right)^{1/2}$$



Weinheimer 2009

Detecting neutrinos

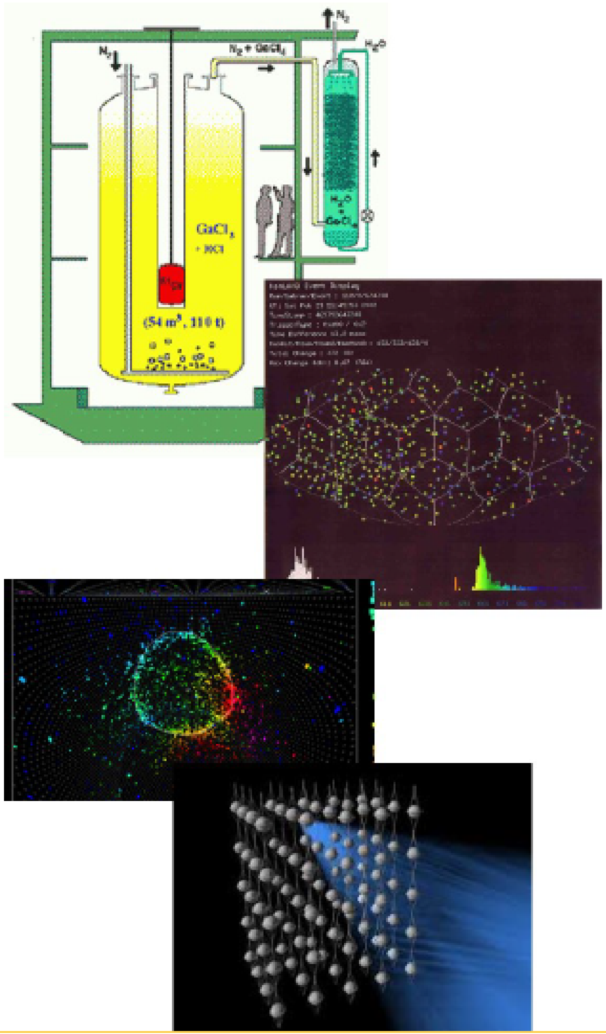
No neutrino tracks…



Basic principle is to look for evidence that neutrinos have interacted, by detecting products of the interaction

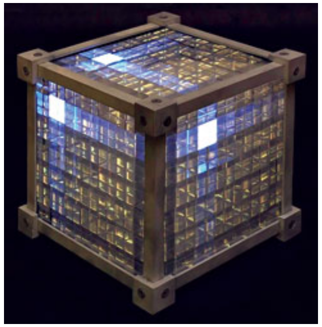
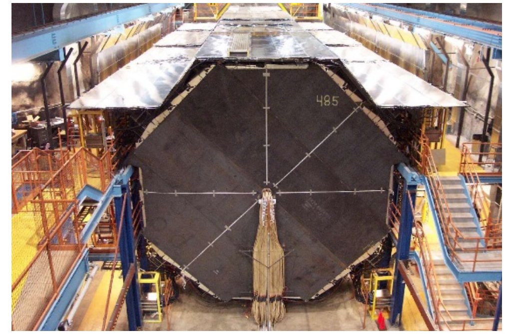
Detecting neutrinos

- Large volumes needed to combat weak interaction
- Shielding required to reduce backgrounds $\Longrightarrow$ underground
- Three main detection techniques

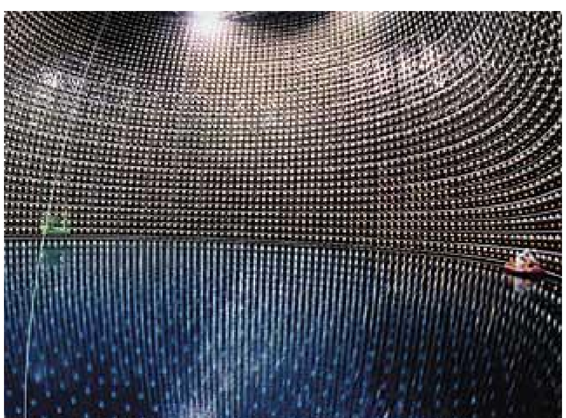
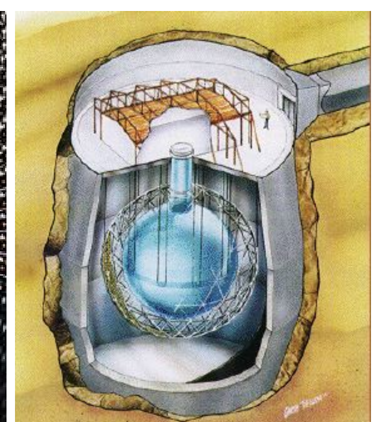
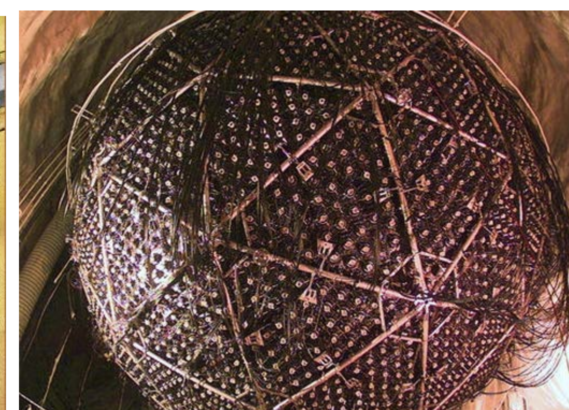


- Radio-chemical: Radioactive atoms formed by capture of neutrinos in target Eg Ray Davis's solar neutrino experiment, used the isotope ^{37}Cl, neutrino capture produces radioactive ^{37}Ar, a gas, which was removed from the target, purified, and counted.
- Scintillation Use liquid scintillator, organic liquid that gives off light, when charged particles pass through it. The scintillator is monitored by optical detectors.
- Cherenkov light detectors Cherenkov light is produced by particles moving faster than the speed of light in the medium. Optical detectors detect the Cherenkov light.

Neutrino dectectors



ANITA ANNIE ANTARES ARIANNA BDUNT (NT-200+) BOREXINO CLEAN COBRA Daya Bay Double Chooz EXO-200 GALLEX GERDA GNO HALO HERON HOMESTAKE ICARUS IceCube INO JUNO Kamiokande KamLAND KM3NeT LAGUNA LBNE/DUNE LENS MAJORANA DEMONSTRATOR MicroBooNE MINERvA MiniBooNE MINOS MINOS+ NEMO Experiment MOON NEMO Telescope NEVOD NOvA OPERA RENO SAGE SciBooNE SNO SNO+ Super-K T2K UNO

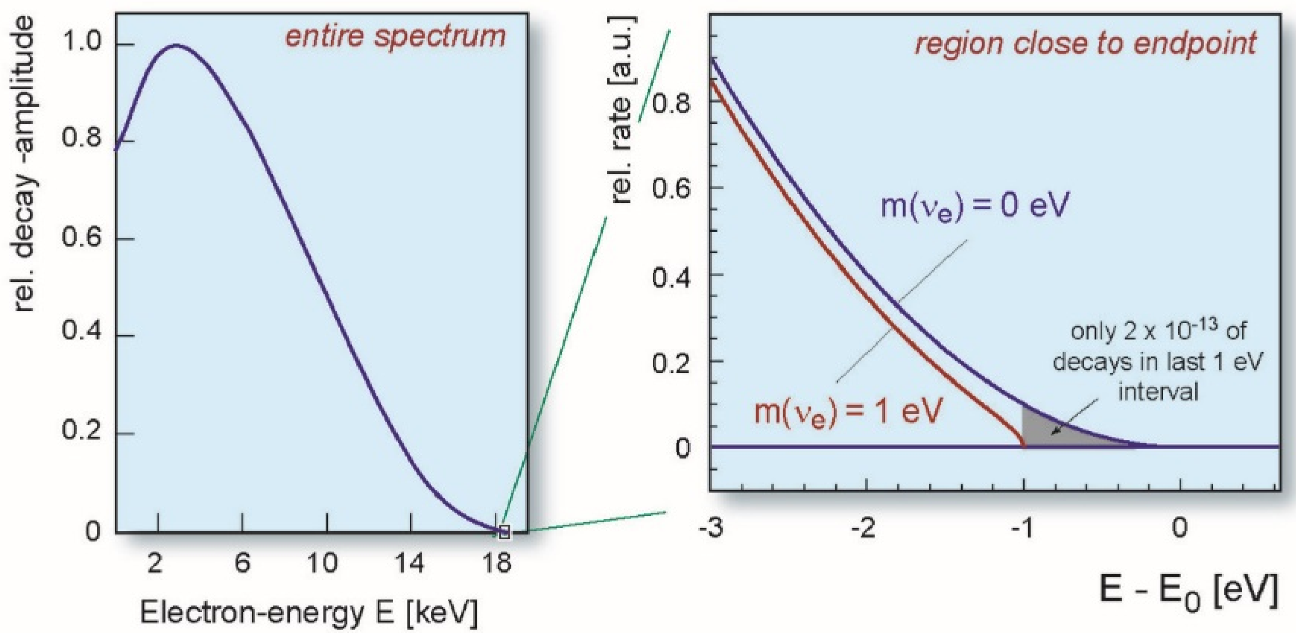


Direct neutrino mass measurement

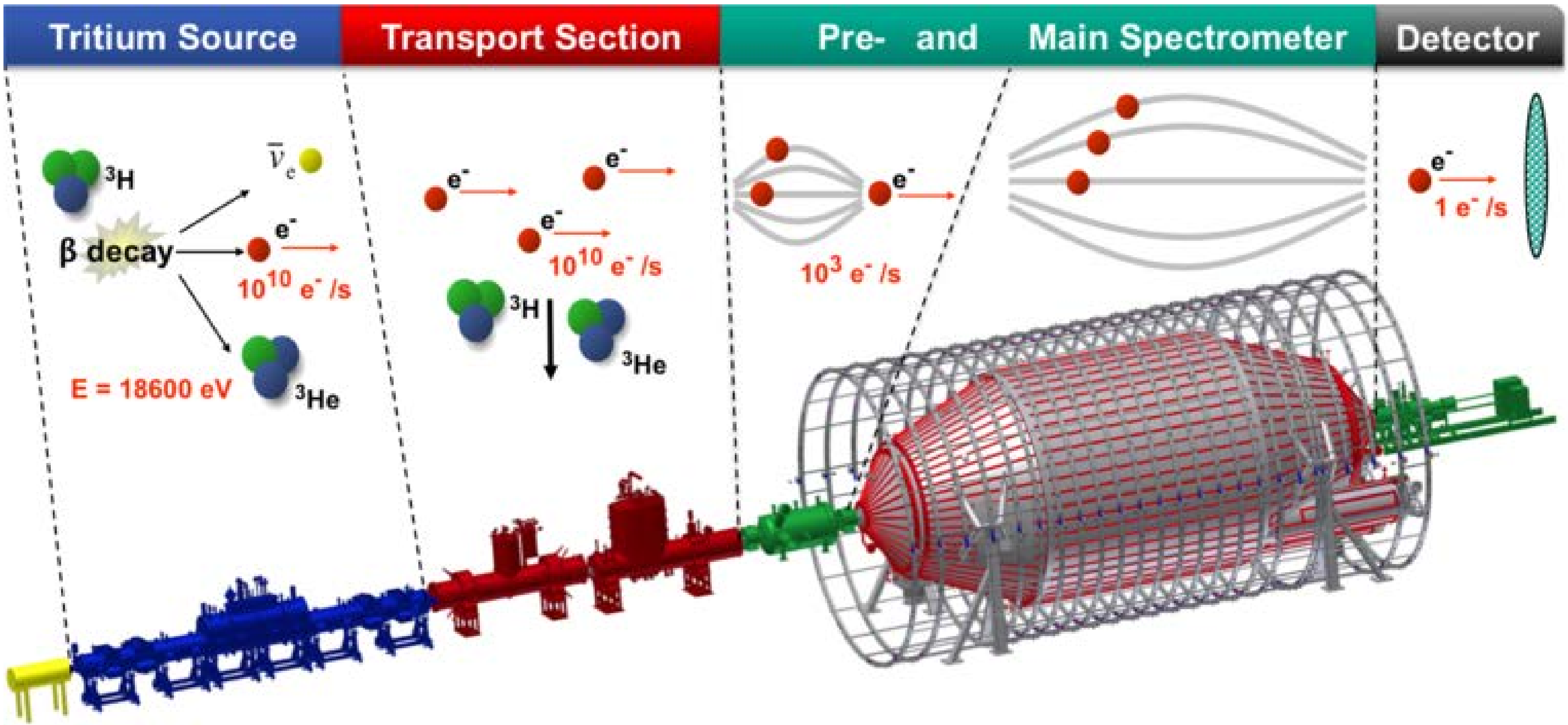
Using the end point of the beta decay spectrum

Eg Katrin experiment using tritium

$$m_{\nu_e} = \left(\sum |U_{ei}|^2 m_i^2 \right)^{1/2}$$



Direct neutrino mass measurement - Katrin



Tritium decays, releasing an electron and an anti-electron-neutrino. While the neutrino escapes undetected, the electron starts its journey to the detector.

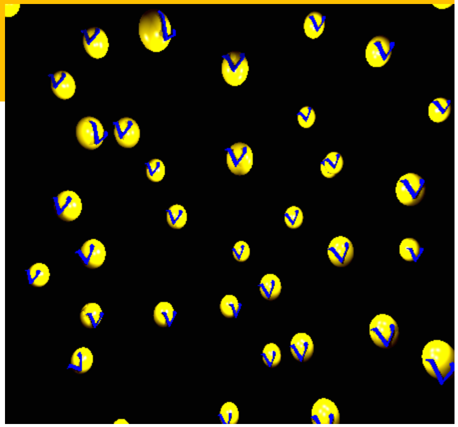
Electrons are guided towards the spectrometer by magnetic fields. Tritium has to be pumped out to provide tritium free spectrometers.

The electron energy is analyzed by applying an electrostatic retarding potential. Electrons are only transmitted if their kinetic energy is sufficiently high.

At the end of their journey, the electrons are counted at the detector. Their rate varies with the spectrometer potential and hence gives an integrated β-spectrum.

Cosmic Neutrino Background

Neutrino Cosmology



- There is a cosmic background neutrino population which is a relic from the early universe
- The neutrino background affects cosmological processes
  - Primordial nucleosynthesis
  - Cosmic microwave background
  - Large structure formation
- Observations probing these processes give us information about neutrinos
- It is important to include the neutrino background effects to be able to interpret observations and learn about other constituents of the universe

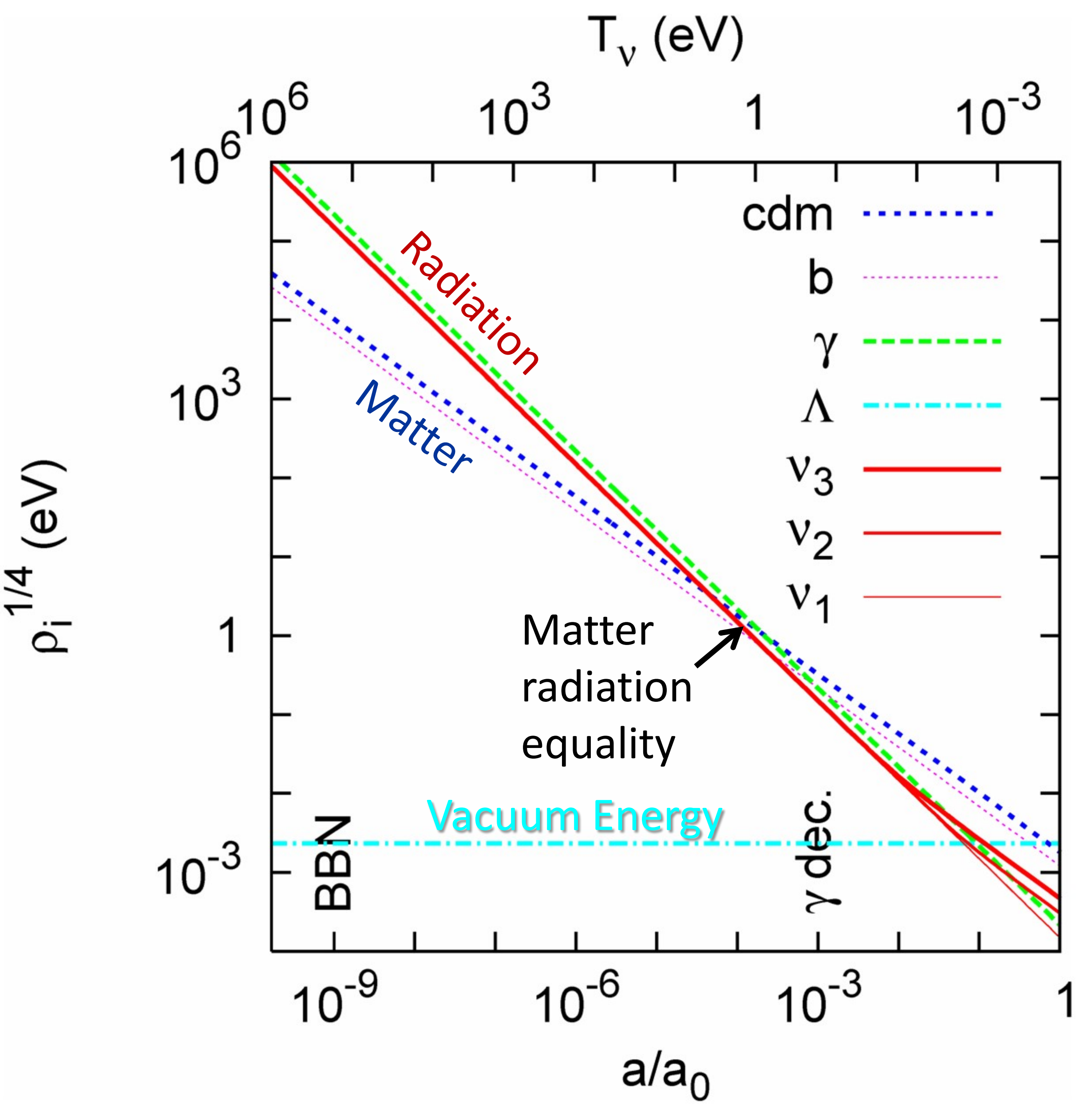
Generic Solutions of Friedman Equation

	Equation of state	Behavior of energy-density under cosmic expansion		Evolution of cosmic scale factor
Radiation	$p = \frac{\rho}{3}$	$\rho \propto a^{-4}$	Dilution of radiation and redshift of energy	$a(t) \propto t^{1/2}$
Matter	$p = 0$	$\rho \propto a^{-3}$	Dilution of matter	$a(t) \propto t^{2/3}$
Vacuum energy	$p = -\rho$	$\rho = \text{const}$	Vacuum energy not diluted by expansion	$a(t) \propto e^{\sqrt{\Lambda/3}\, t}$ $\Lambda = 8\pi G_{\rm N} \rho_{\rm vac}$

Energy-momentum tensor of a perfect fluid with density ρ and pressure p

$$T^{\mu\nu} = \begin{pmatrix} \rho & & & \\ & p & & \\ & & p & \\ & & & p \end{pmatrix} \qquad T^{\mu\nu}_{\rm vac} = \rho\, g^{\mu\nu} \begin{pmatrix} \rho & & & \\ & -\rho & & \\ & & -\rho & \\ & & & -\rho \end{pmatrix}$$

Evolution of Cosmic Density Components



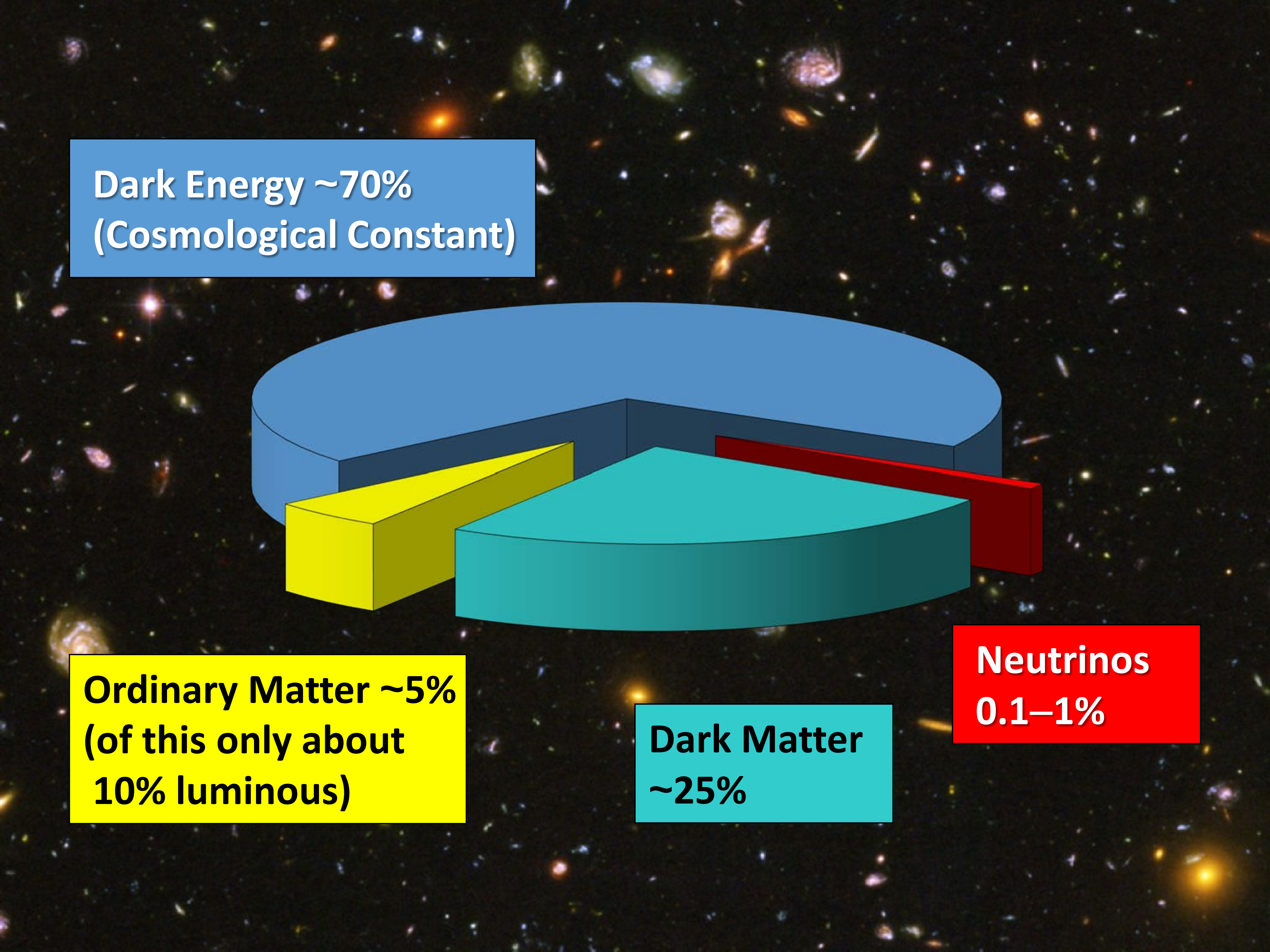
Assumed neutrino masses

m_3 = 50 meV

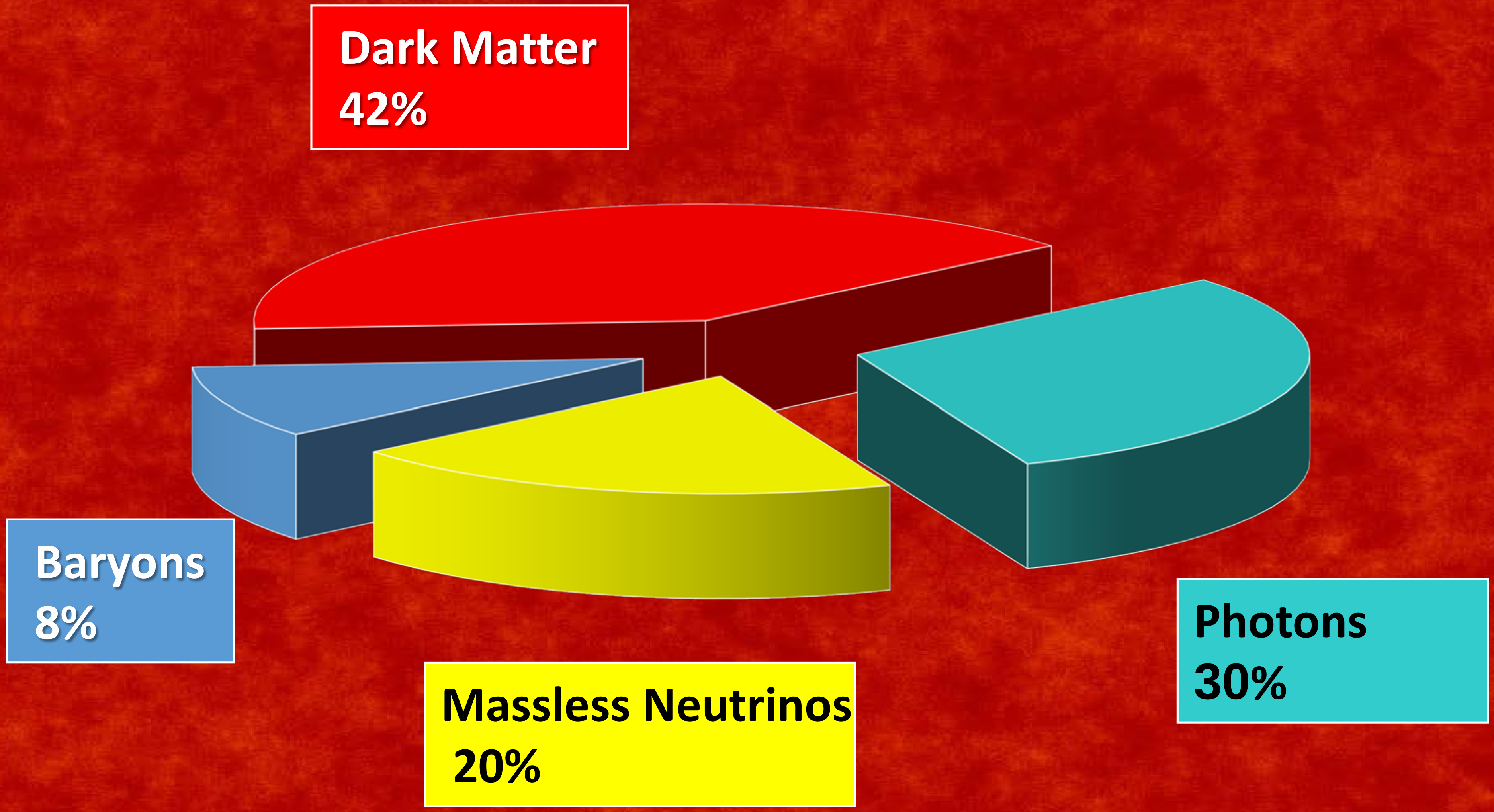
m_2 = 9 meV

m_1 = 0

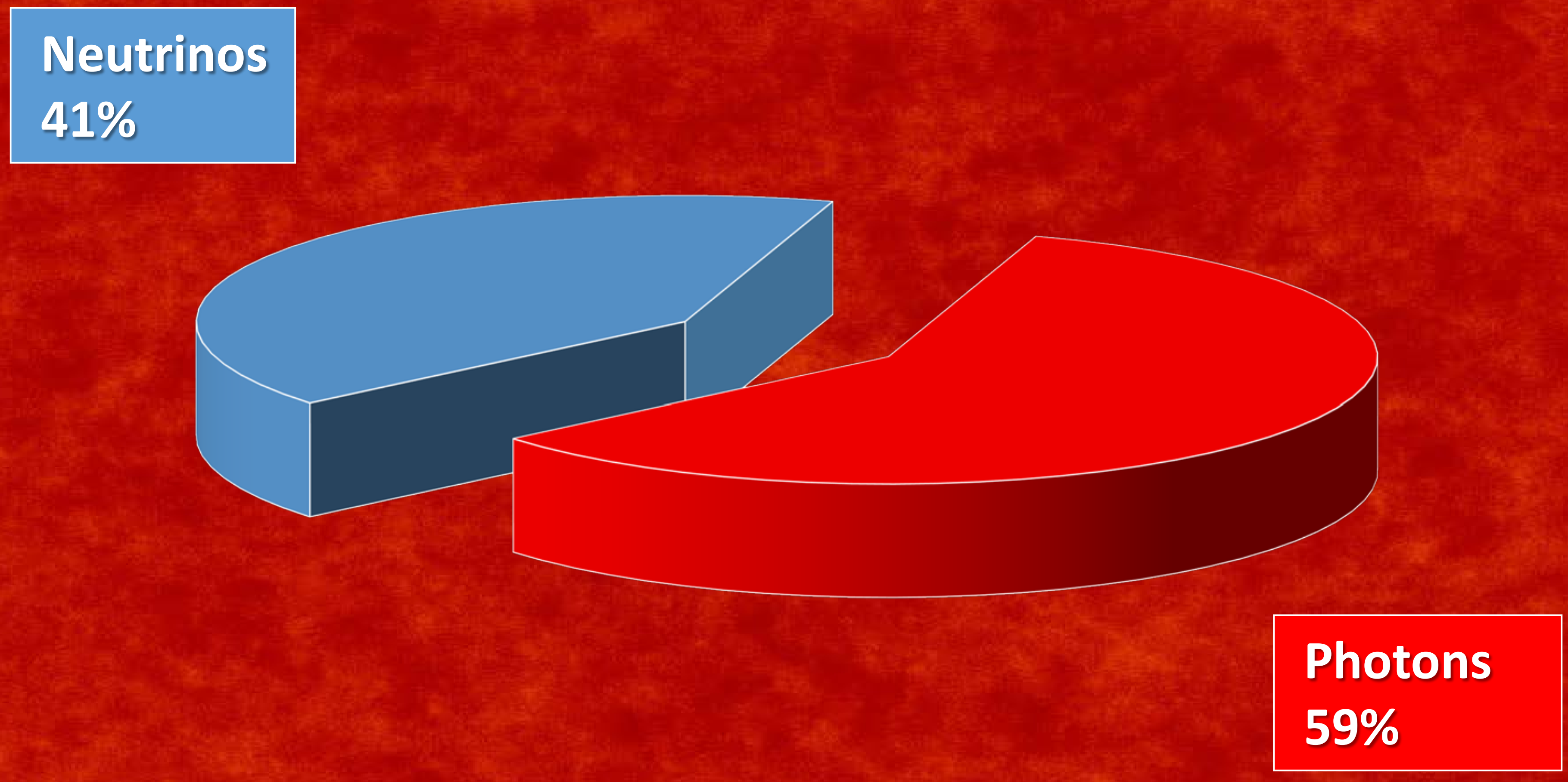
Lesgourgues & Pastor
astro-ph/0603494


Dark Energy ~70%
(Cosmological Constant)
Ordinary Matter ~5%
(of this only about
10% luminous)
Dark Matter
~25%
Neutrinos
0.1–1%

Matter-Radiation Equality (Redshift 3400)

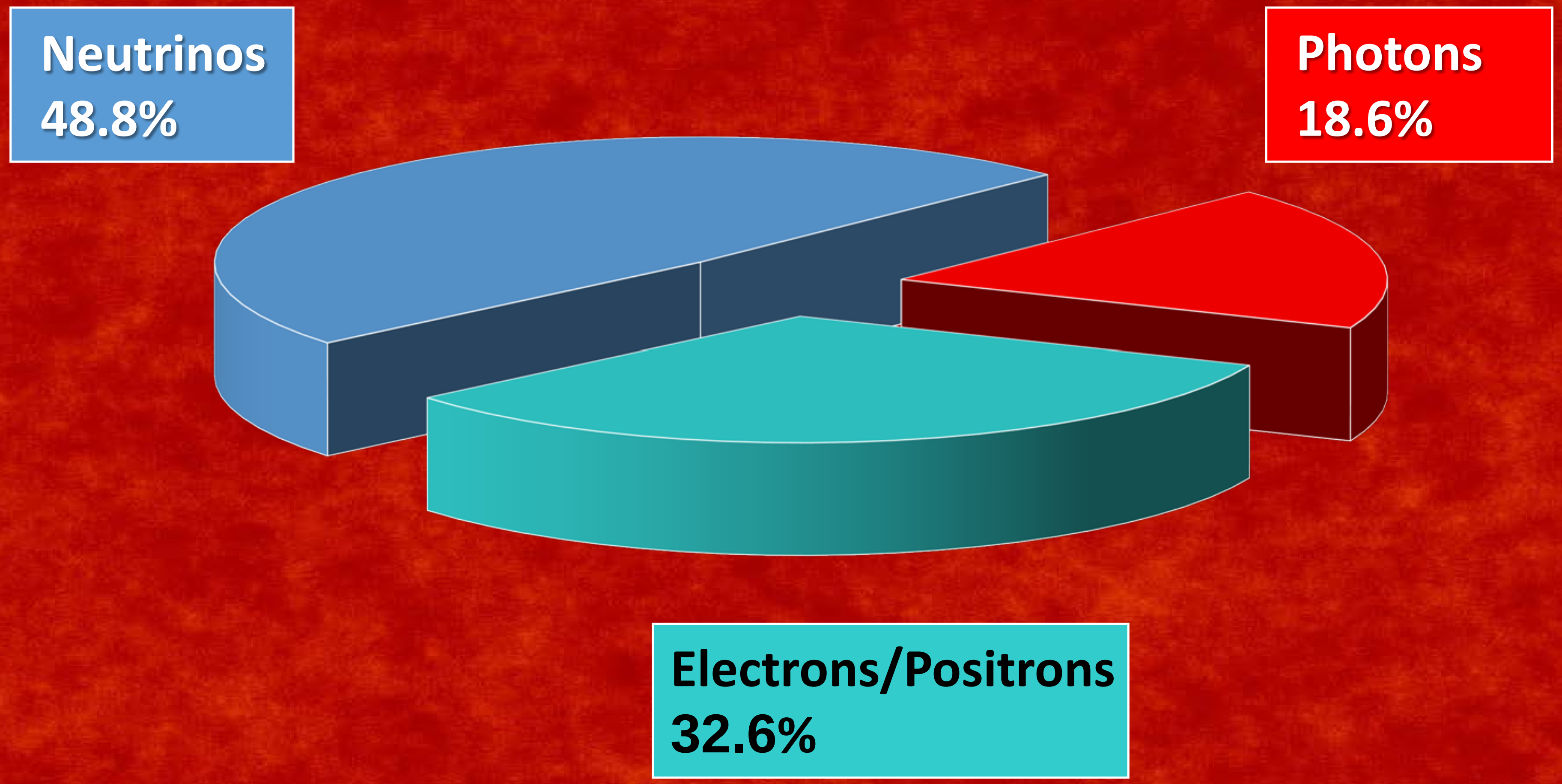


After Electron-Positron Annihilation (T = 100 keV)



Relevant for Big Bang Nucleosynthesis (BBN)

Before Electron-Positron Annihilation (T = 1 MeV)

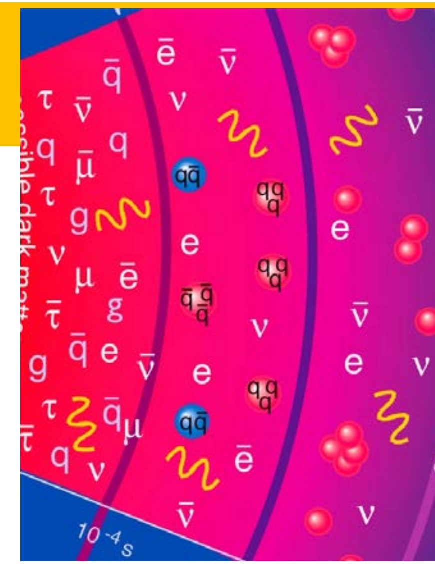


Neutrino Background

$$n_{\nu\bar{\nu}}(1\ \text{flavour}) \approx 112\ \text{cm}^{-3}$$

$$T_\nu = \left(\frac{4}{11}\right)^{1/3} T_\gamma \approx 1.95\ \text{K}$$ for massless neutrinos

Equilibrium Particle Interactions



- Boltzmann equation governs distributions

$$\frac{\mathrm{d}f_X}{\mathrm{d}t} + 3\frac{\dot{a}}{a}f_X + \langle\sigma_A v\rangle\left({f_X}^2 - {f_{Xeq}}^2\right) = 0$$

- Two regimes:

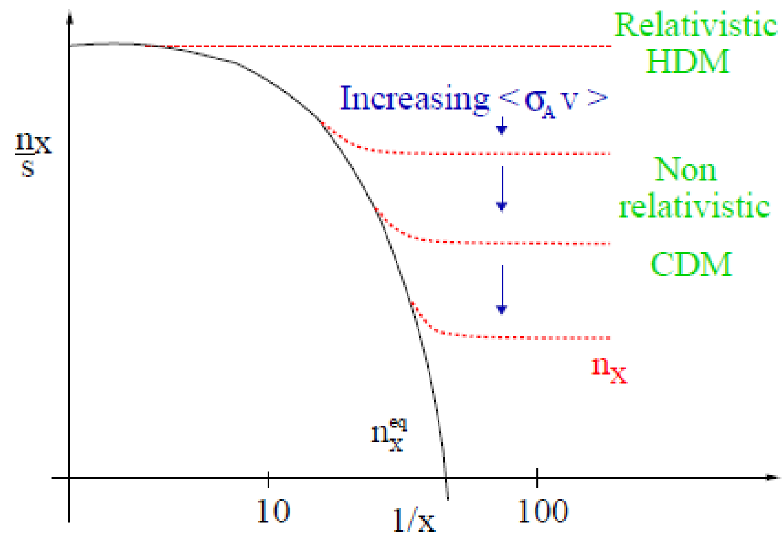
$\Gamma = \langle\sigma_A v\rangle n_X > H$ Thermal equilibrium

Interaction rate > Expansion rate

$$f_{eq}(\boldsymbol{p}) = \frac{1}{e^{E\boldsymbol{p}/T} \pm 1}$$ + Fermions, - Bosons

$\Gamma \ll H$ Freezeout

Distribution constant at freezeout level, only redshifted



Thermal Radiation

	General	Bosons	Fermions
Number density n	$g\int \frac{d^3\boldsymbol{p}}{(2\pi)^3}\frac{1}{e^{E_{\boldsymbol{p}}/T}\pm 1}$	$g_B\frac{\zeta_3}{\pi^2}T^3$	$\frac{3}{4}\,g_F\frac{\zeta_3}{\pi^2}T^3$
Energy density ρ	$g\int \frac{d^3\boldsymbol{p}}{(2\pi)^3}\frac{E_{\boldsymbol{p}}}{e^{E_{\boldsymbol{p}}/T}\pm 1}$	$g_B\frac{\pi^2}{30}T^4$	$\frac{7}{8}\,g_F\frac{\pi^2}{30}T^4$
Pressure P	$g\int \frac{d^3\boldsymbol{p}}{(2\pi)^3}\frac{\lvert\boldsymbol{p}^2\rvert}{E_p}\frac{1}{e^{E_{\boldsymbol{p}}/T}\pm 1}$	$\frac{\rho}{3}$	
Entropy density s	$\frac{\rho+P}{T}=\frac{4}{3}\frac{\rho}{T}$	$g_B\frac{2\pi^2}{45}T^3$	$\frac{7}{8}\,g_F\frac{2\pi^2}{45}T^3$

$$dE = TdS - PdV$$
$$TdS = (\rho + P)dV$$

using integrals

$$\int_0^\infty \frac{x^2dx}{\exp(x)-1} = 2\zeta(3),$$
$$\int_0^\infty \frac{x^2dx}{\exp(x)+1} = \frac{6}{8}\zeta(3),$$
$$\int_0^\infty \frac{x^3dx}{\exp(x)-1} = 6\zeta(4) = \frac{\pi^4}{15},$$
$$\int_0^\infty \frac{x^3dx}{\exp(x)+1} = \frac{7}{48}\zeta(4) = \frac{7}{8}\frac{\pi^4}{15}$$

Riemann Zeta Function

$\zeta = 1.2020569\ldots$

Thermal Degrees of Freedom

$$g_* = g_B + \frac{7}{8} g_F$$

Mass threshold		Particles	g_B	g_F	g_*
	low	γ, 3ν	2	6	(7.25)
m_e	0.5 MeV	$e^{\pm}$	2	10	10.75
m_μ	105 MeV	$\mu^{\pm}$	2	14	14.25
m_π	135 MeV	π^0, $\pi^{\pm}$	5	14	17.25
Λ_{QCD}	~170 MeV	u, d, s, gluons	18	50	61.75
$m_{c,\tau}$	2 GeV	c, τ	18	66	75.75
m_b	6 GeV	$b^{\pm}$	18	78	86.25
$m_{W,Z}$	90 GeV	Z^0, $W^{\pm}$	27	78	92.25
m_H	126 GeV	Higgs	28	78	93.25
m_t	170 GeV	t	28	90	106.75
Λ_{SUSY}	~ 1 TeV ?	SUSY particles	118	118	213.50

Neutrino Thermal Equilibrium

Neutrino reaction rate

Examples of neutrino processes

$$e^+ + e^- \leftrightarrow \bar{\nu} + \nu$$
$$\bar{\nu} + \nu \leftrightarrow \bar{\nu} + \nu$$
$$\nu + e^\pm \leftrightarrow \nu + e^\pm$$

Reaction rate in a thermal medium

for $T \ll m_{W,Z}$

$$\Gamma \sim G_F^2 T^5$$

Cosmic expansion rate

Friedmann equation (flat universe)

$$H^2 = \frac{8\pi}{3} \frac{\rho}{m_{Pl}^2} \qquad \left(G_N = \frac{1}{m_{Pl}^2} \right)$$

Radiation dominates

$$\rho \sim T^4$$

Expansion rate

$$H \sim \frac{T^2}{m_{Pl}}$$

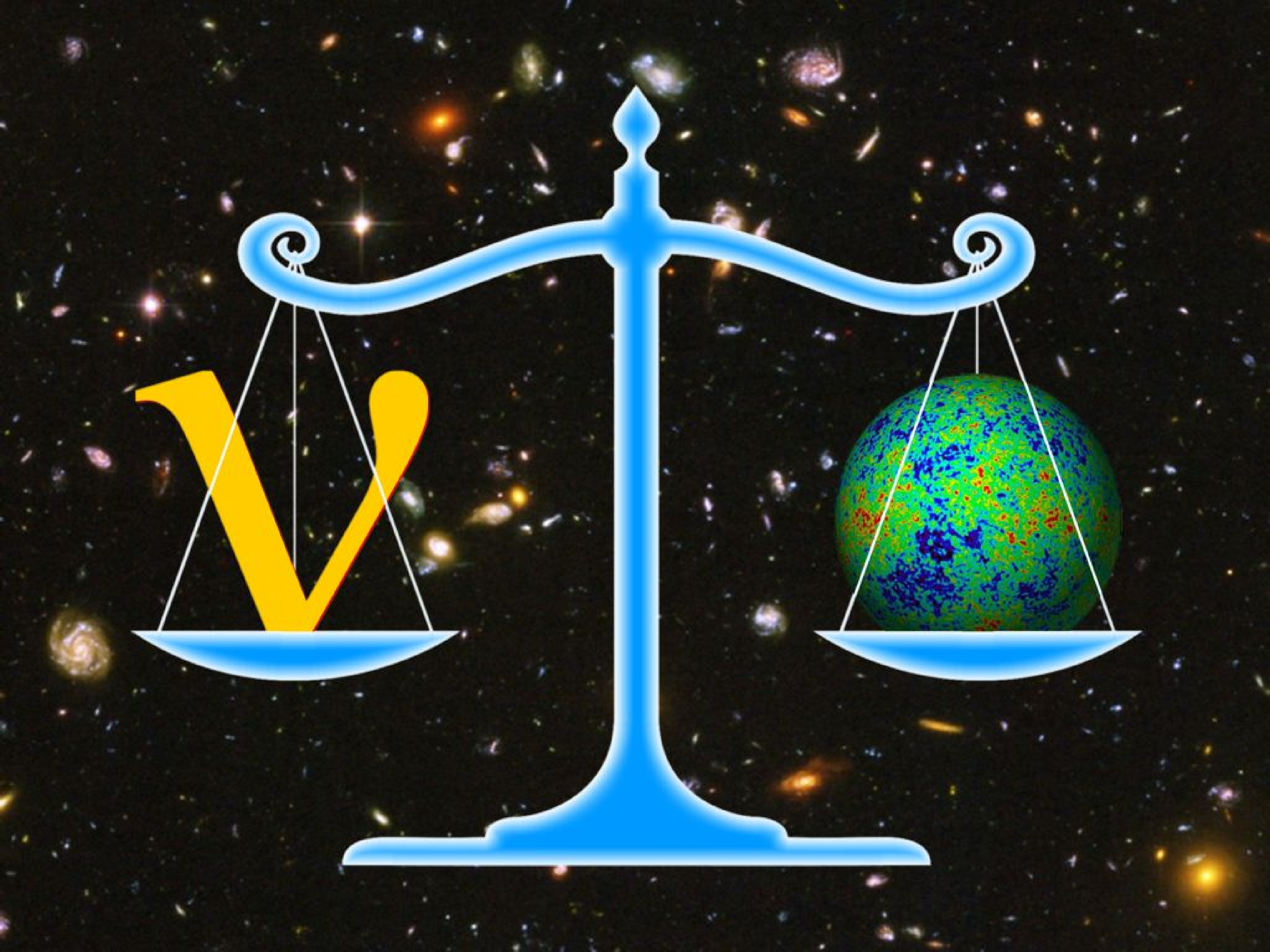
Condition for thermal equilibrium: $\Gamma > H$

$$T > \left(m_{Pl} G_F^2\right)^{-1/3} \sim [10^{19}\mathrm{GeV}\,(10^{-5}\mathrm{GeV}^{-2})^2]^{-1/3} = 1\ \mathrm{MeV}$$

Neutrinos are in thermal equilibrium for $T \gtrsim 1$ MeV
corresponding to $t \lesssim 1$ sec

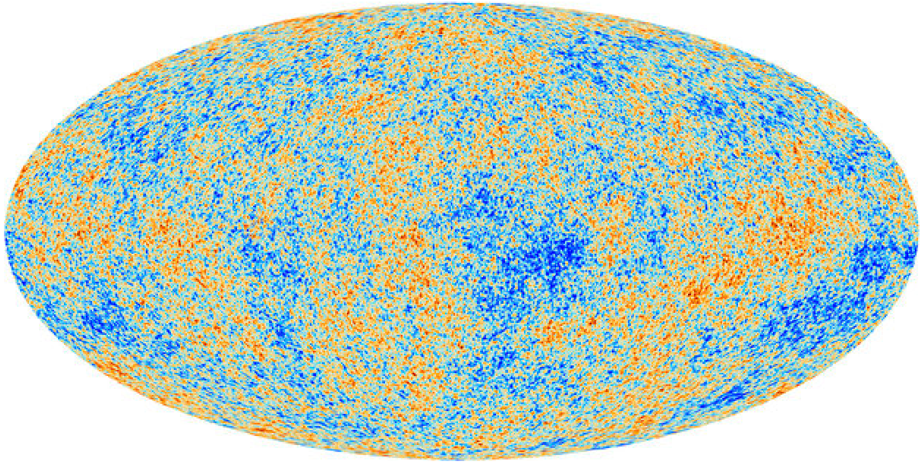
Present-Day Neutrino Density

Neutrino decoupling (freeze out)	$H \sim \Gamma$ $T \approx 2.4\ \mathrm{MeV}$ (electron flavour) $T \approx 3.7\ \mathrm{MeV}$ (other flavours)
Redshift of Fermi-Dirac distribution ("nothing changes at freeze-out")	$\frac{dn_{\nu\bar{\nu}}}{dE} = \frac{1}{\pi^2} \frac{E^2}{e^{E/T}+1}$ Temperature scales with redshift $T_\nu = T_\gamma \propto (z+1)$
Electron-positron annihilation beginning at T ≈ m_e = 0.511 MeV	• Entropy of e^+e^- transfered to photons $g_* T_\gamma^3 \Big\vert_{\text{before}} = g_* T_\gamma^3 \Big\vert_{\text{after}}$ $\overbrace{2 + \frac{7}{8} 4 = \frac{11}{2}}$ $\overbrace{2}$ $\Big\}\ T_\gamma^3 \Big\vert_{\text{before}} = \frac{\mathbf{4}}{\mathbf{11}} T_\gamma^3 \Big\vert_{\text{after}}$
Redshift of neutrino and photon thermal distributions so that today we have	$n_{\nu\bar{\nu}}(1\ \text{flavour}) = \frac{4}{11} \times \frac{3}{4} \times n_\gamma = \frac{3}{11} n_\gamma \approx 112\ \mathrm{cm}^{-3}$ $T_\nu = \left(\frac{4}{11}\right)^{1/3} T_\gamma \approx 1.95\ \mathrm{K}$ for massless neutrinos

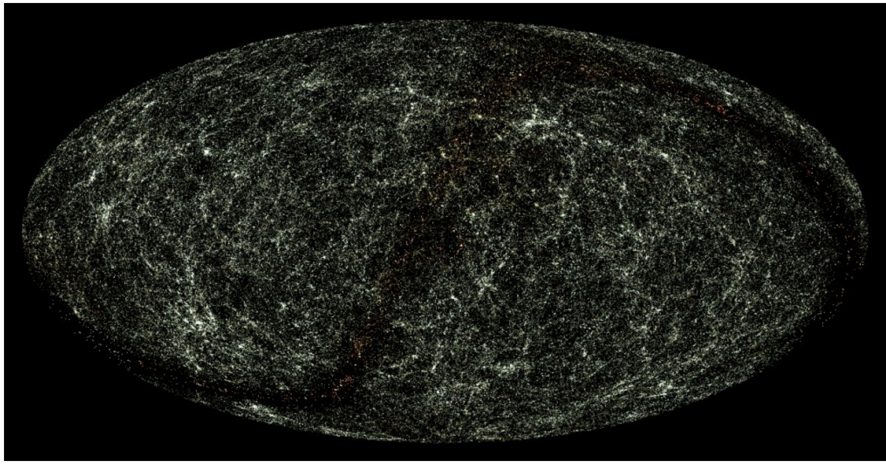


Basic Idea

Comparison of theoretical predictions with observations of the anisotropy
(temperature (and polarisation) differences from isotropy)
of the cosmic microwave background and correlations in the large scale structure

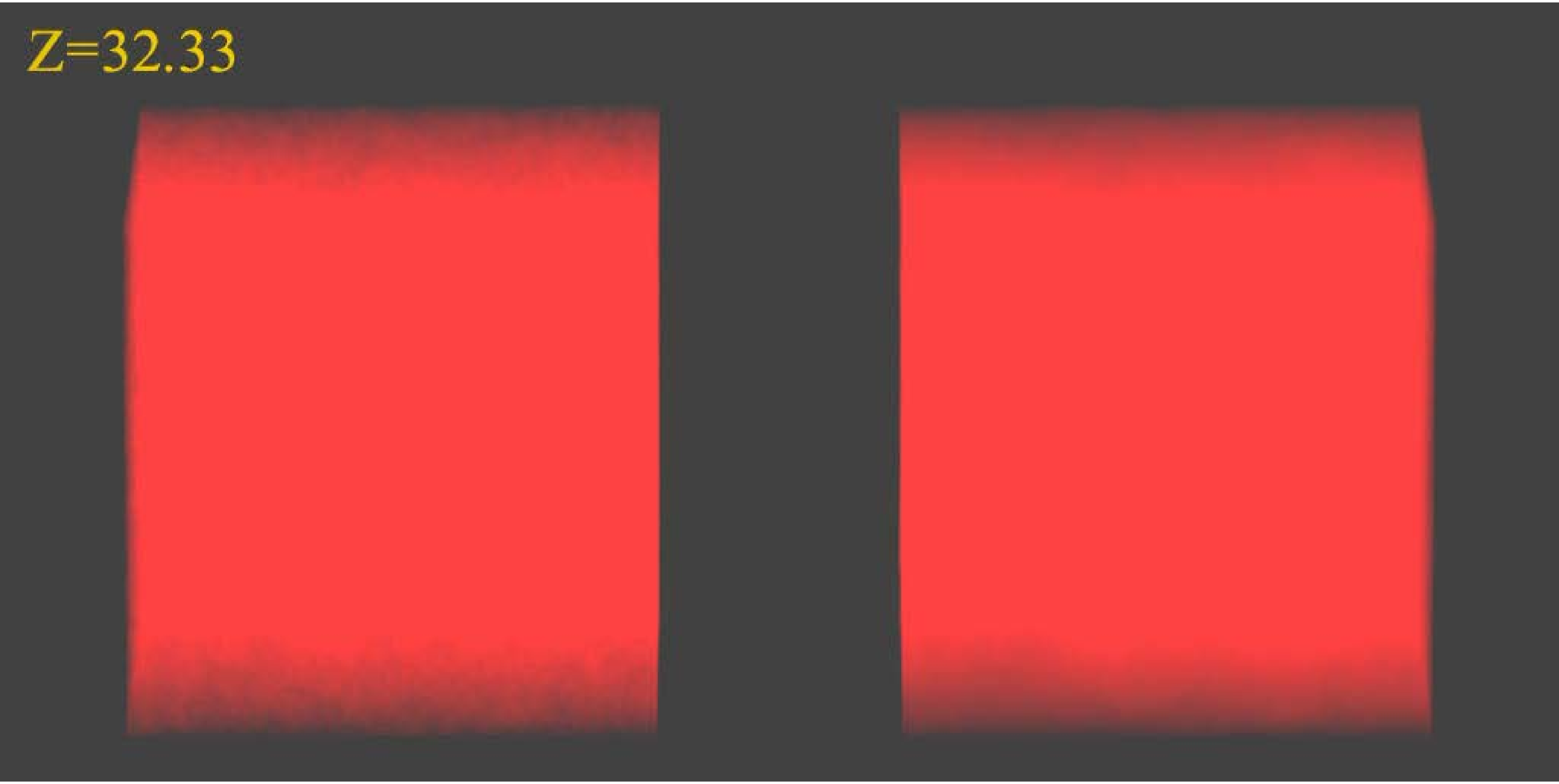


Wmap9 CMB
http://wmap.gsfc.nasa.gov/resources/cmbimages.html



Sky Map of Galaxies (2MASS XSC)
http://spider.ipac.caltech.edu/staff/jarrett/2mass/XSC/jarrett_allsky.html

Neutrino effect on large scale structure growth



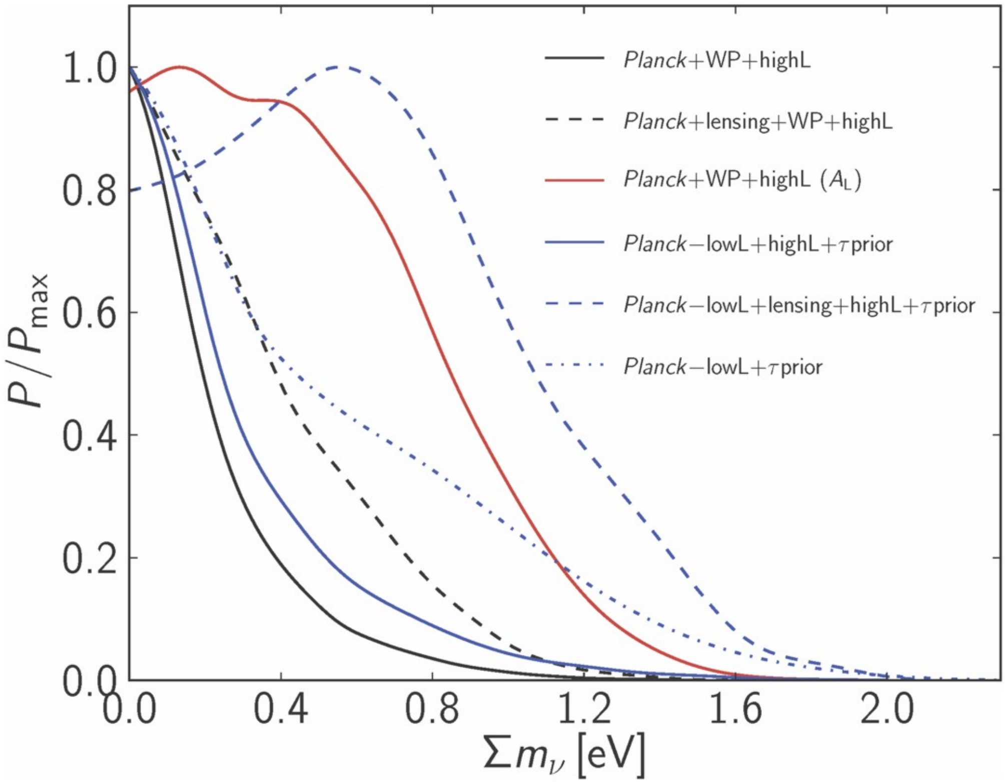
Standard ΛCDM Model

Neutrinos with Σm_ν = 6.9 eV

Troels Haugbølle, http://users-phys.au.dk/haugboel

Neutrino Mass Limits Post Planck (2013)

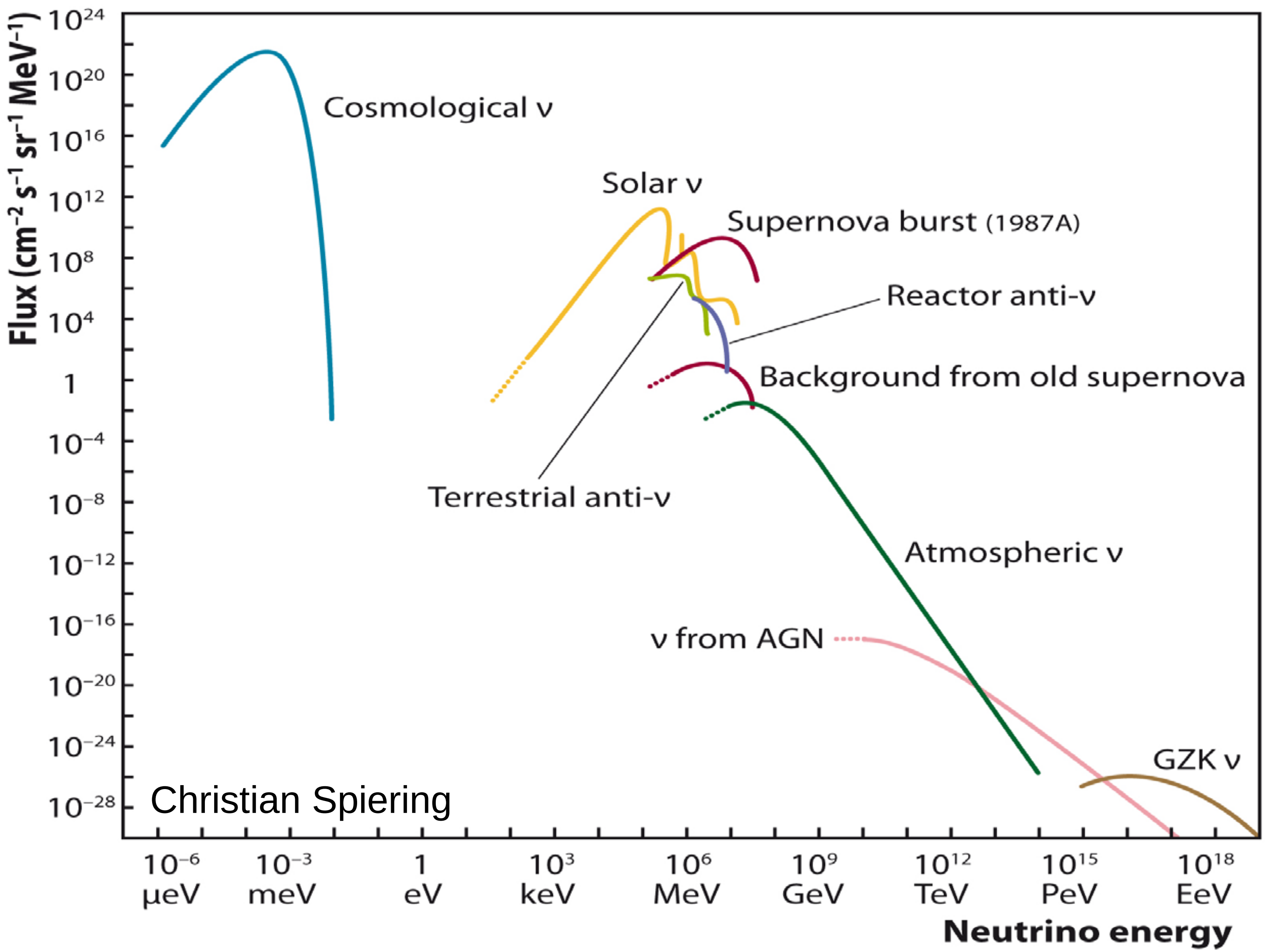
Depends on the data sets used
Many different analyses in the literature



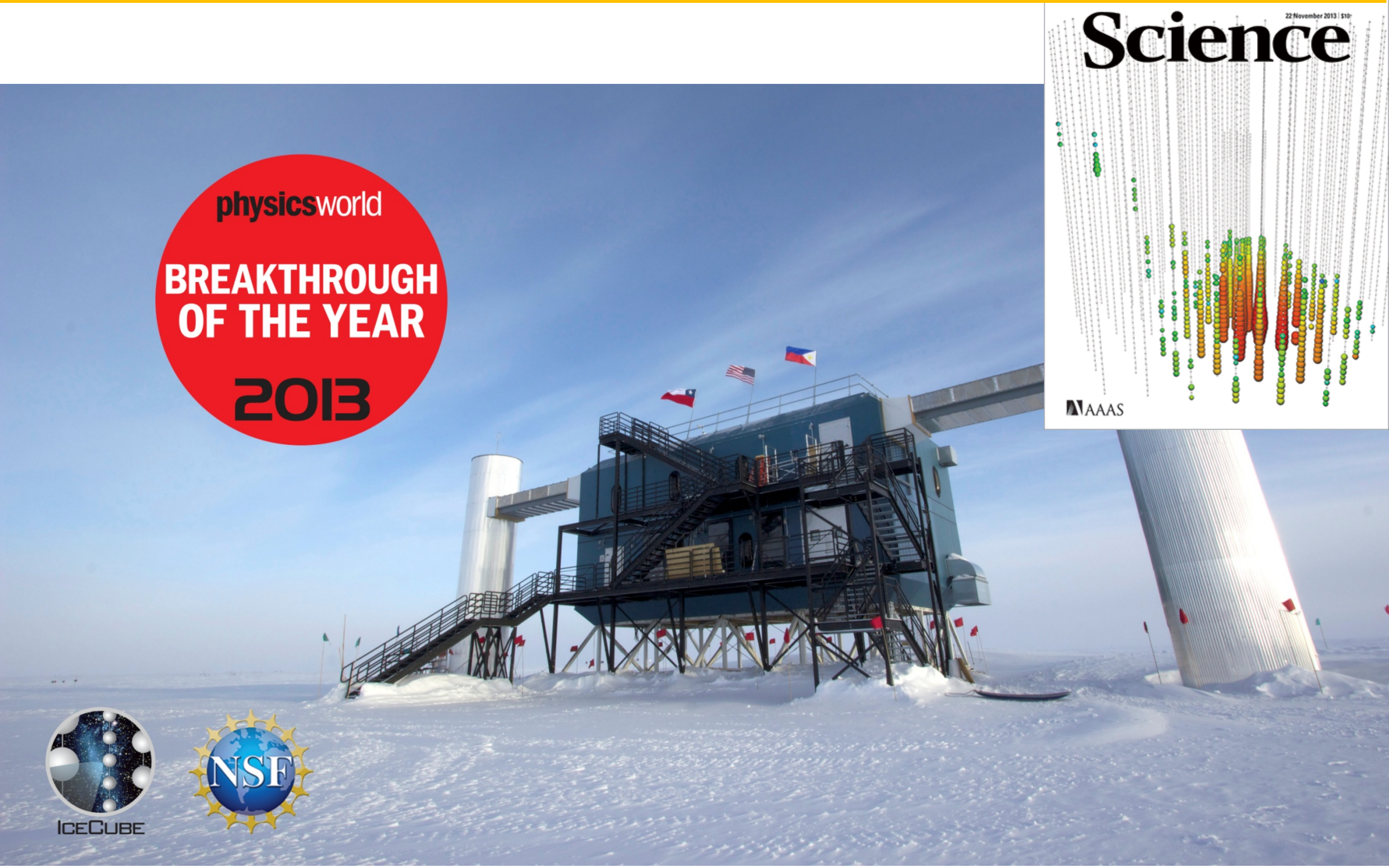
Planck alone: $\Sigma m_\nu < 1.08$ eV (95% CL)
CMB + BAO limit: $\Sigma m_\nu < 0.23$ eV (95% CL)

Ade et al. (Planck Collaboration), arXiv:1303.5076

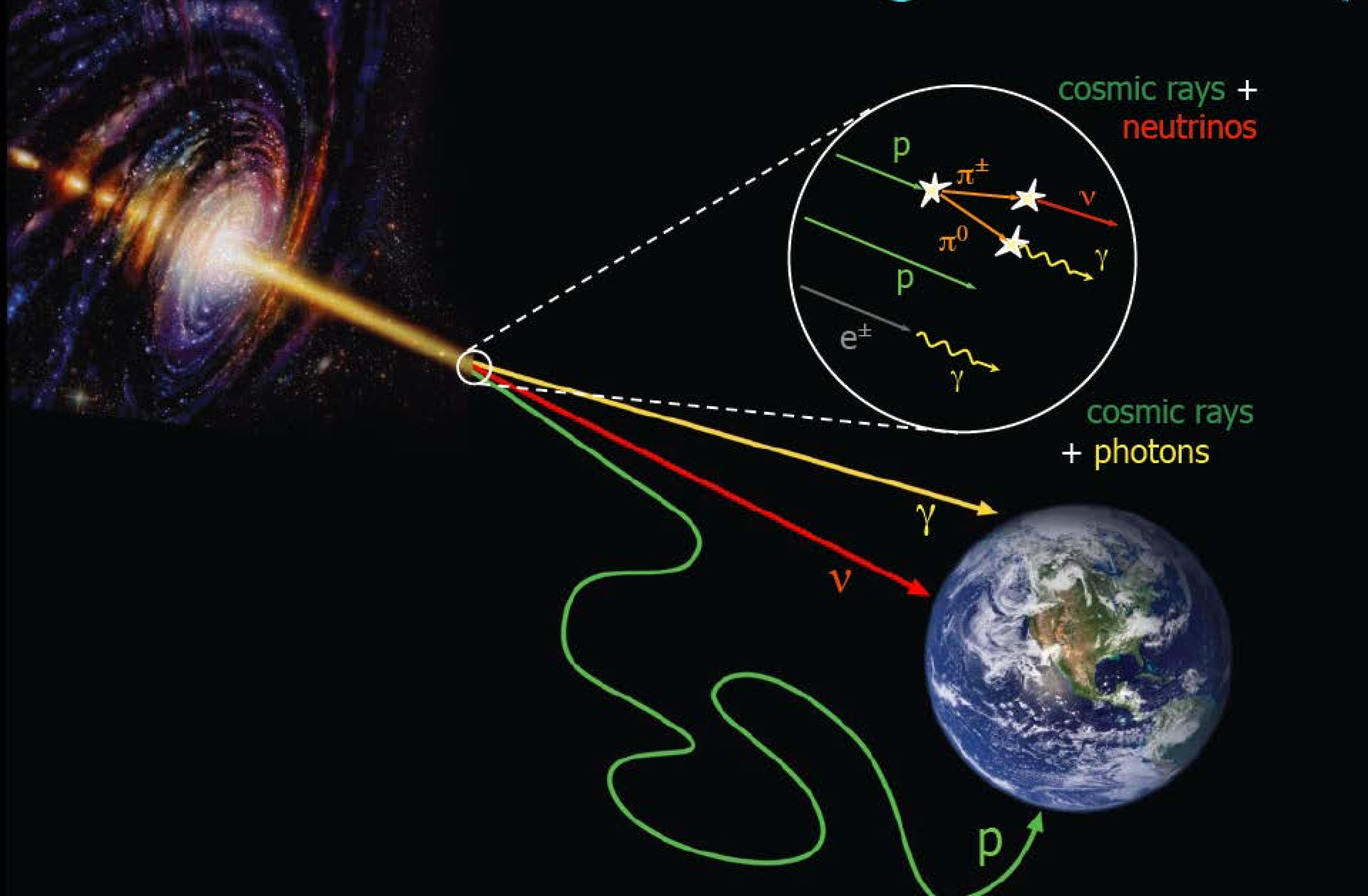
Neutrino source fluxes



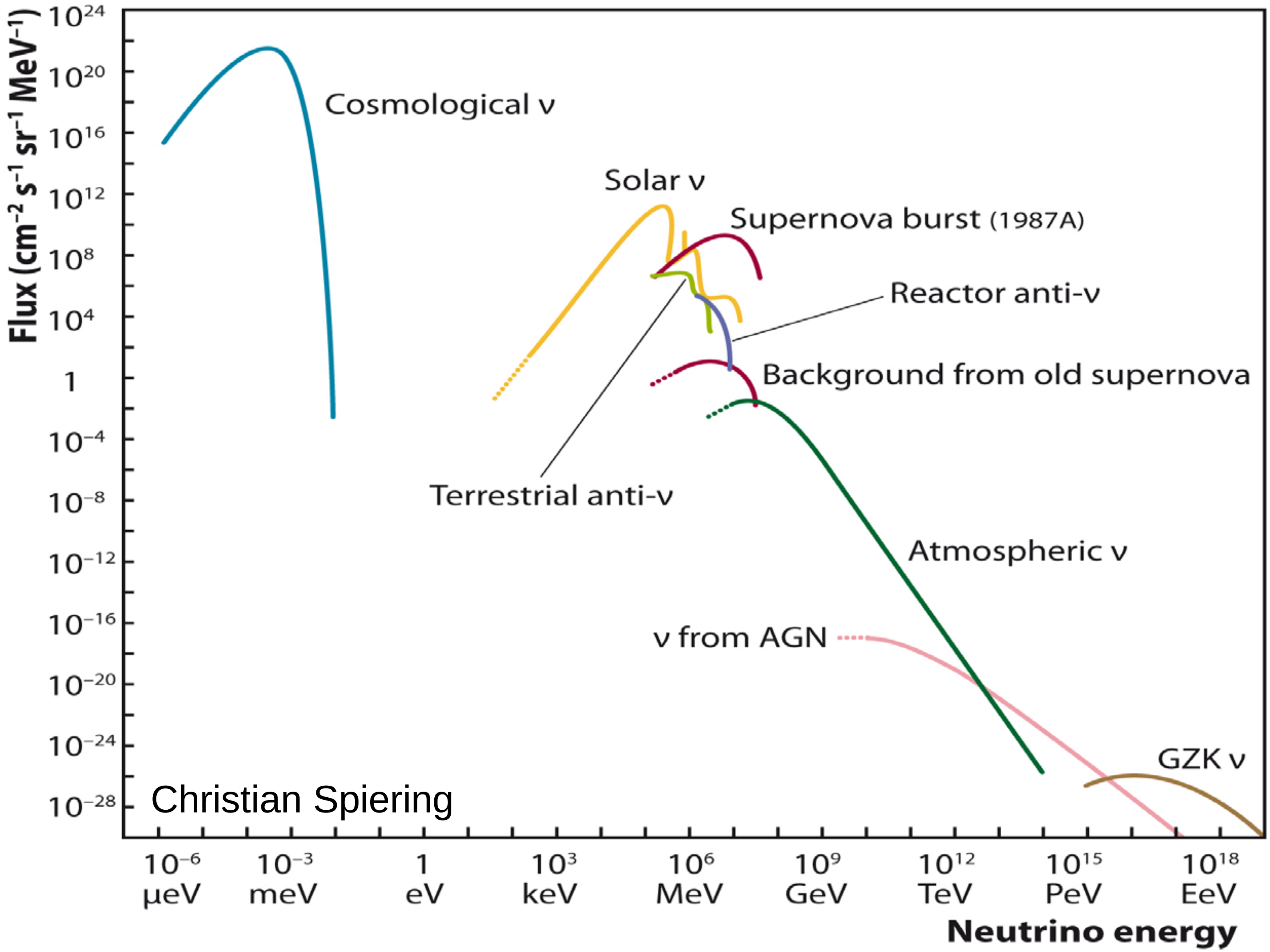
IceCube high energy astrophysical neutrino discovery



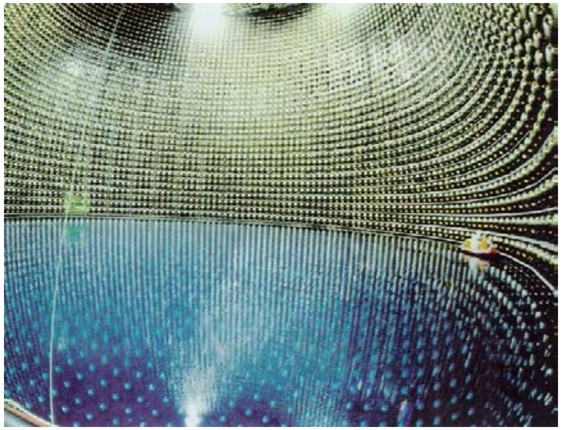
Multimessenger Astronomy



Neutrino source fluxes

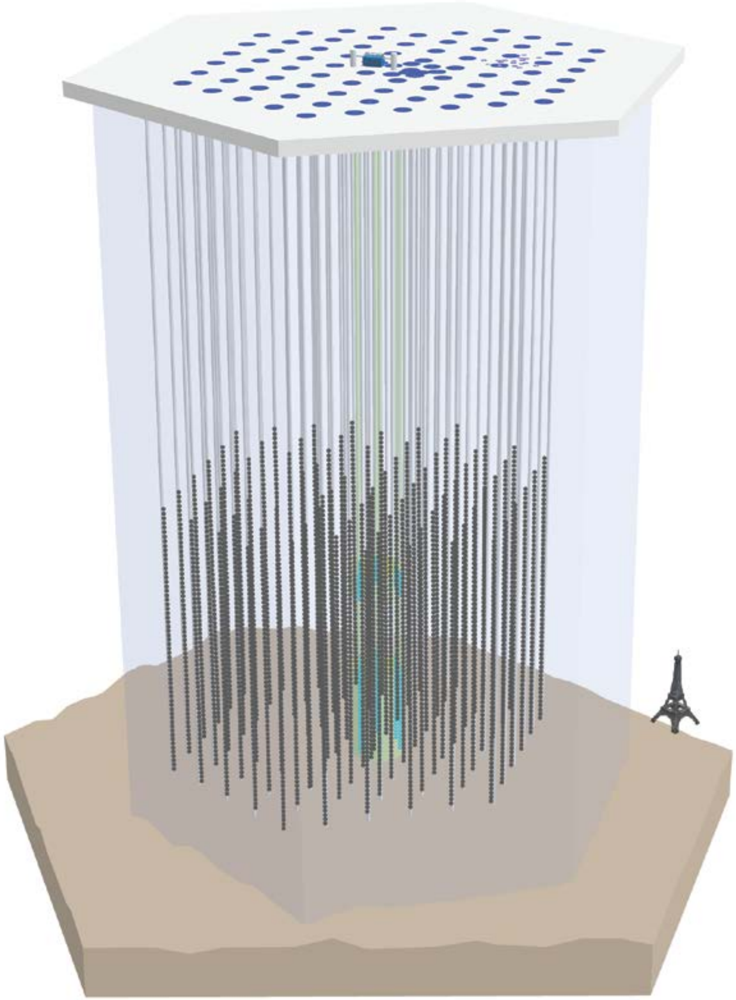


IceCube is a LARGE neutrino detector...

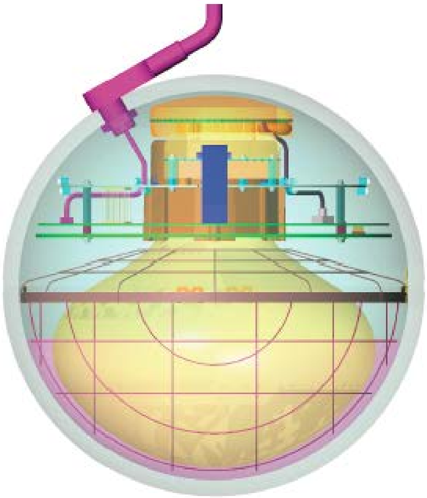


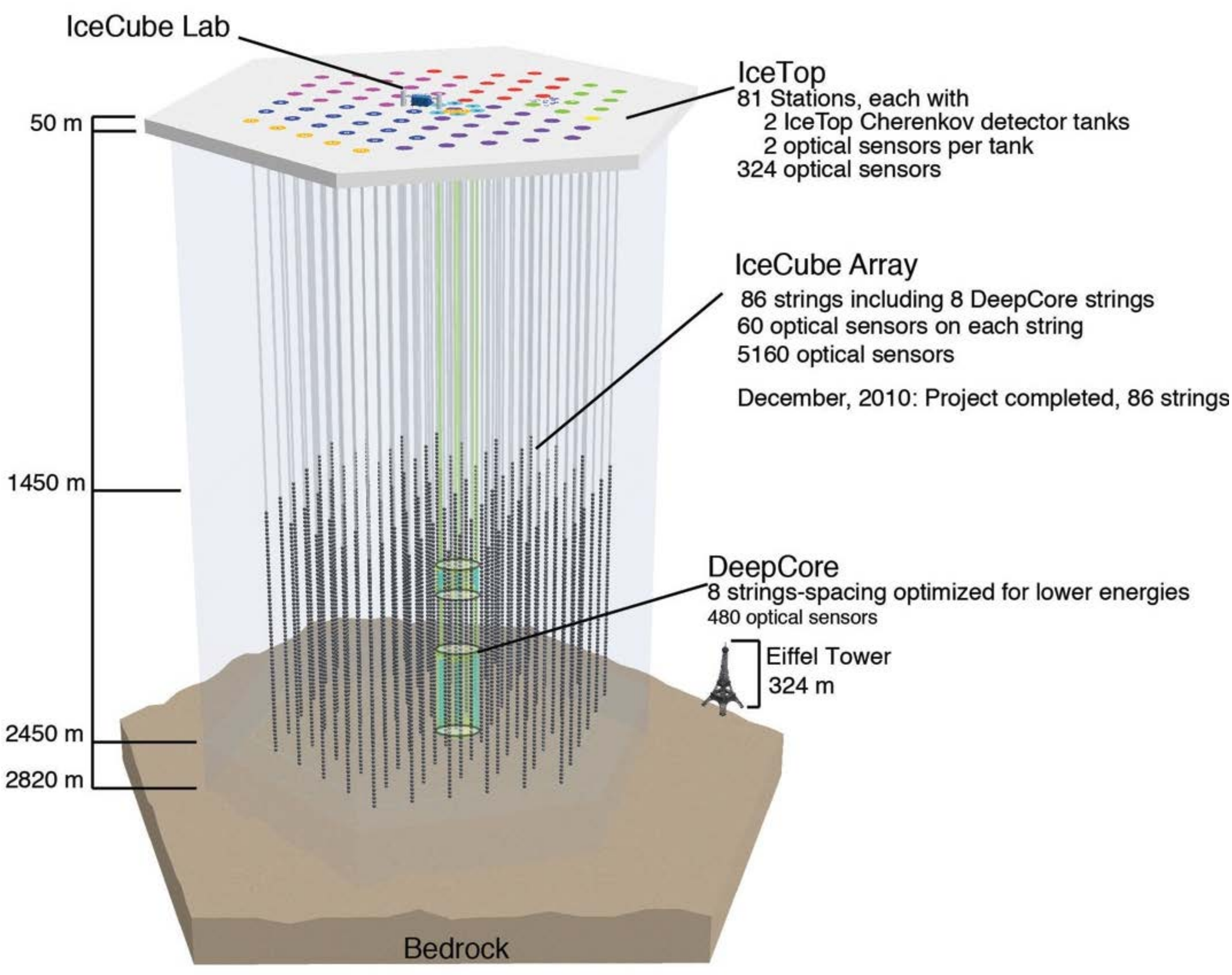
Super Kamiokande

SNO

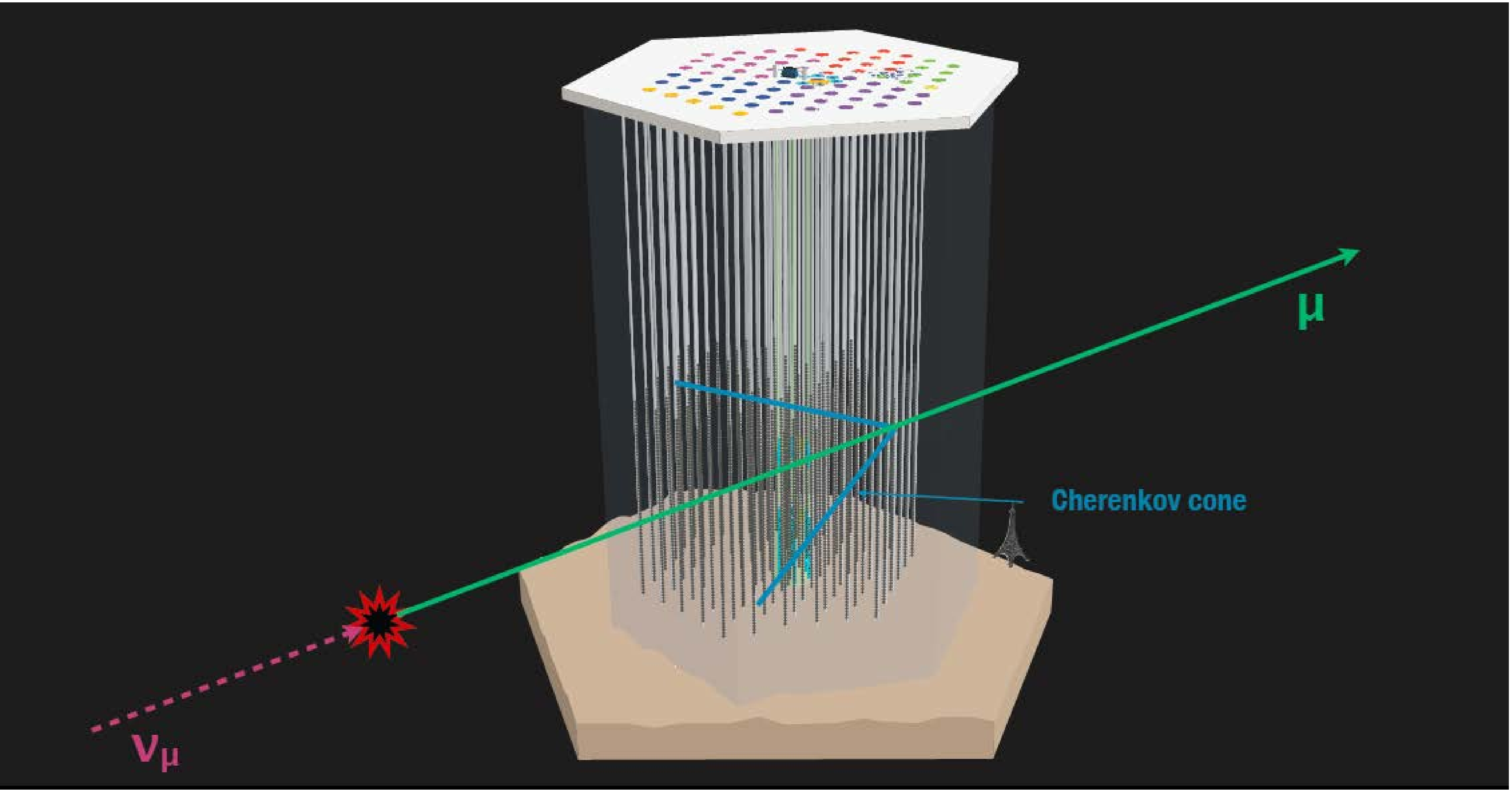


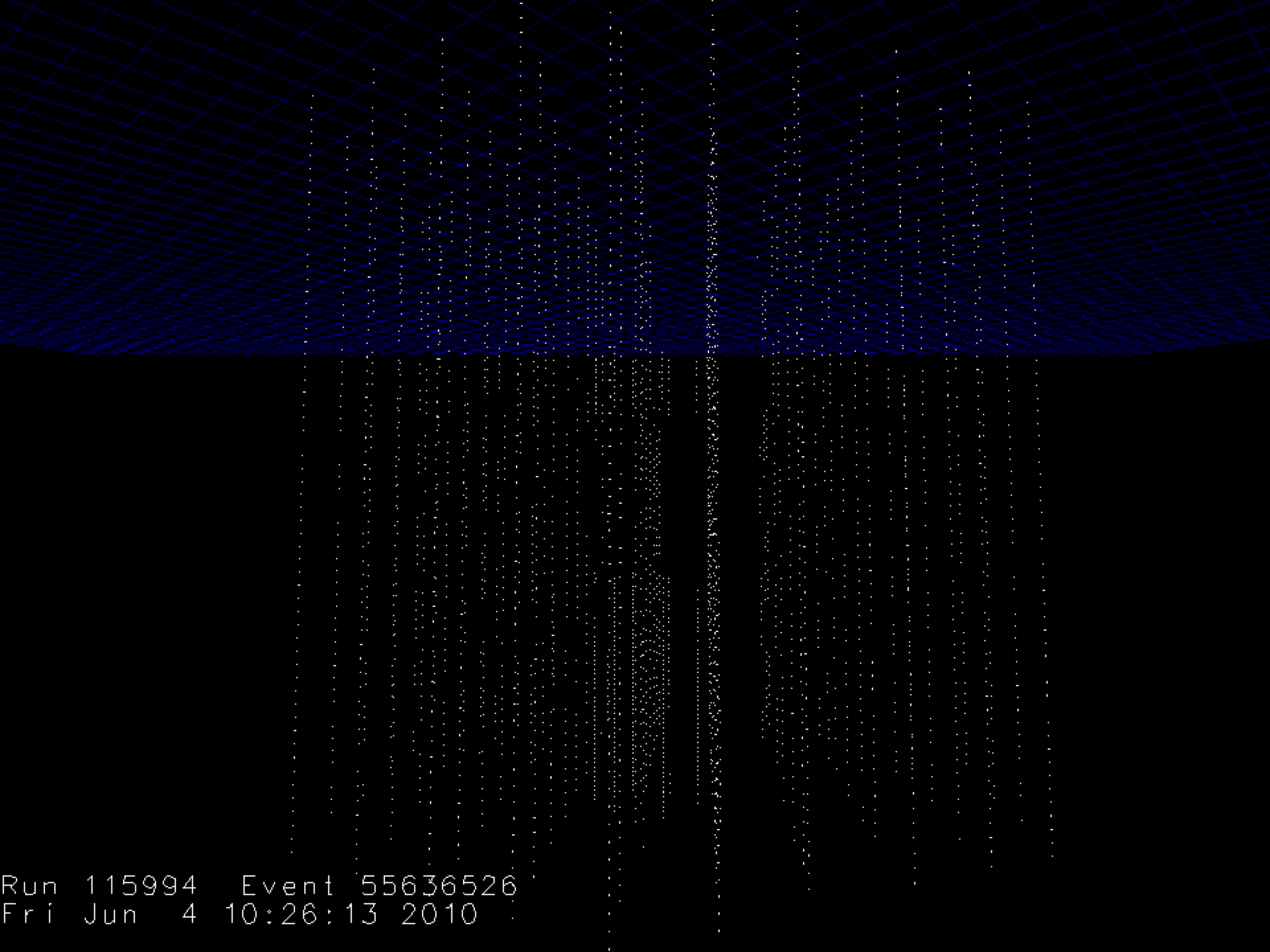
IceCube detector





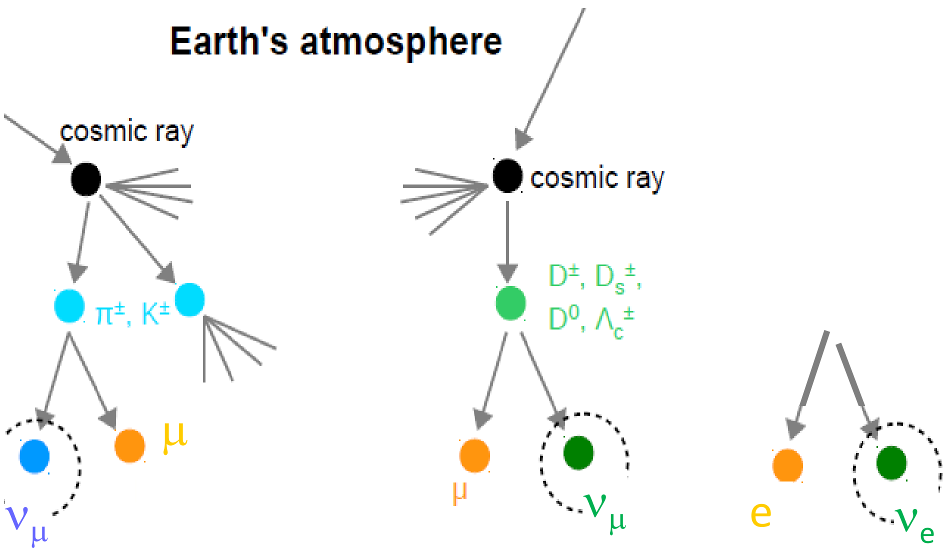
Detection principle




Run 115994 Event 55636526
Fri Jun 4 10:26:13 2010

Backgrounds

Cosmic rays – interacting in the Earth's atmosphere
– source of atmospheric neutrinos and muon background



- **"Conventional"**
- From π / K decay
- $\Phi \sim E^{-3.7}$

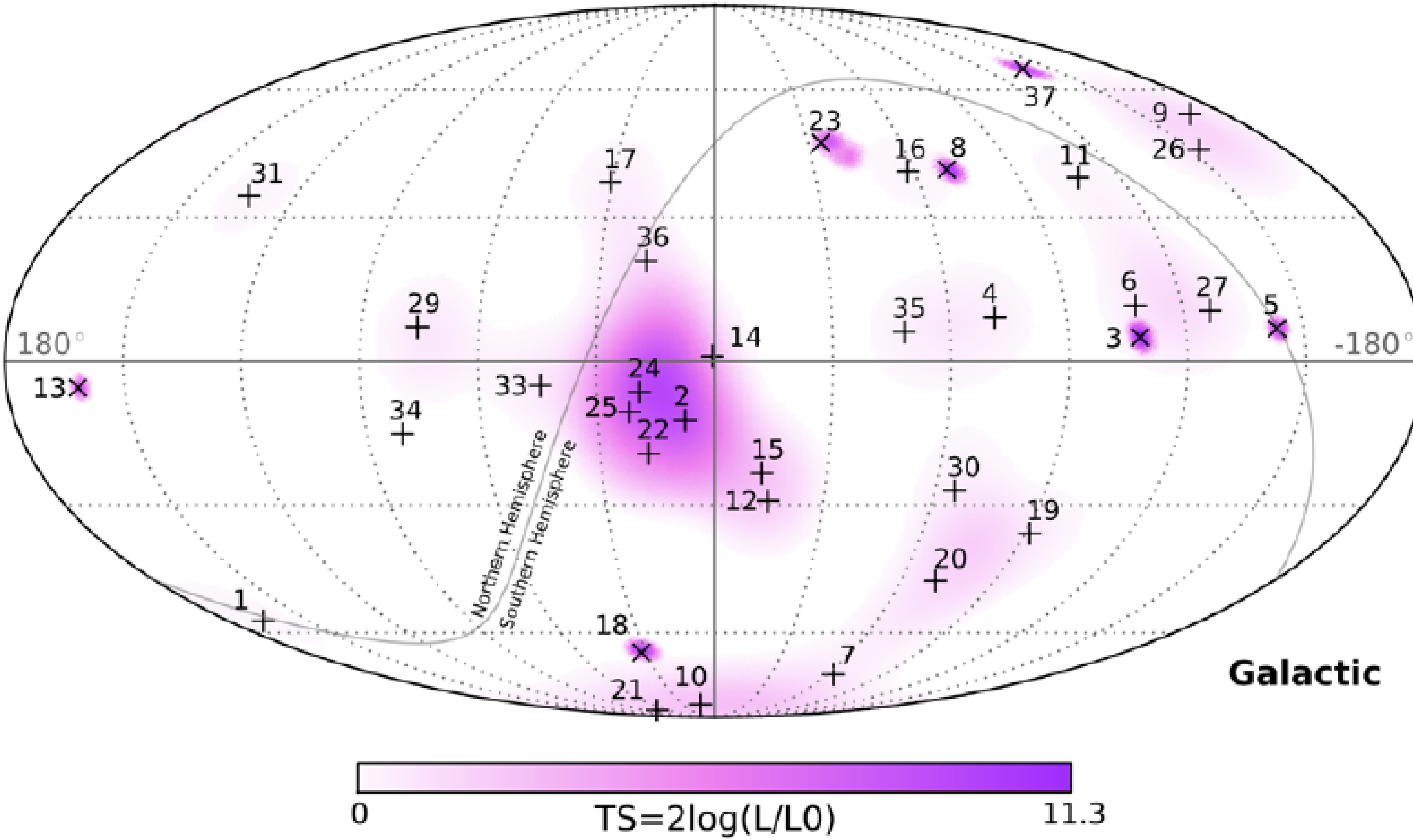
- **"Prompt"**
- From charmed meson decay
- $\Phi \sim E^{-2.7}$
- Undetected so far

Muon rate:
In ice: ~3000 Hz

Atmospheric neutrinos:
~1 neutrino/10 minutes

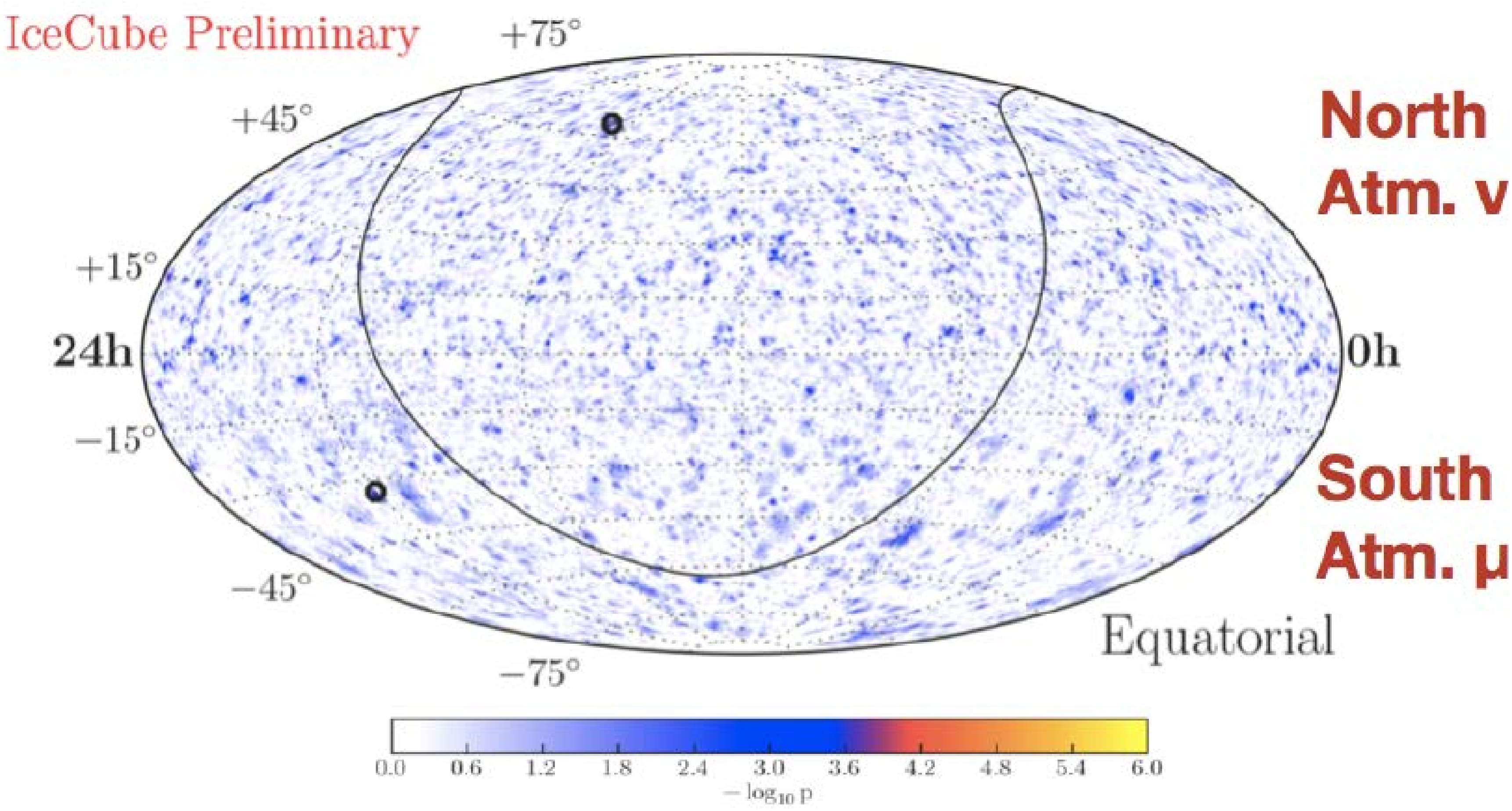
Neutrino Detection:
Requires 10^6 background rejection

Sky map of high-energy, starting events

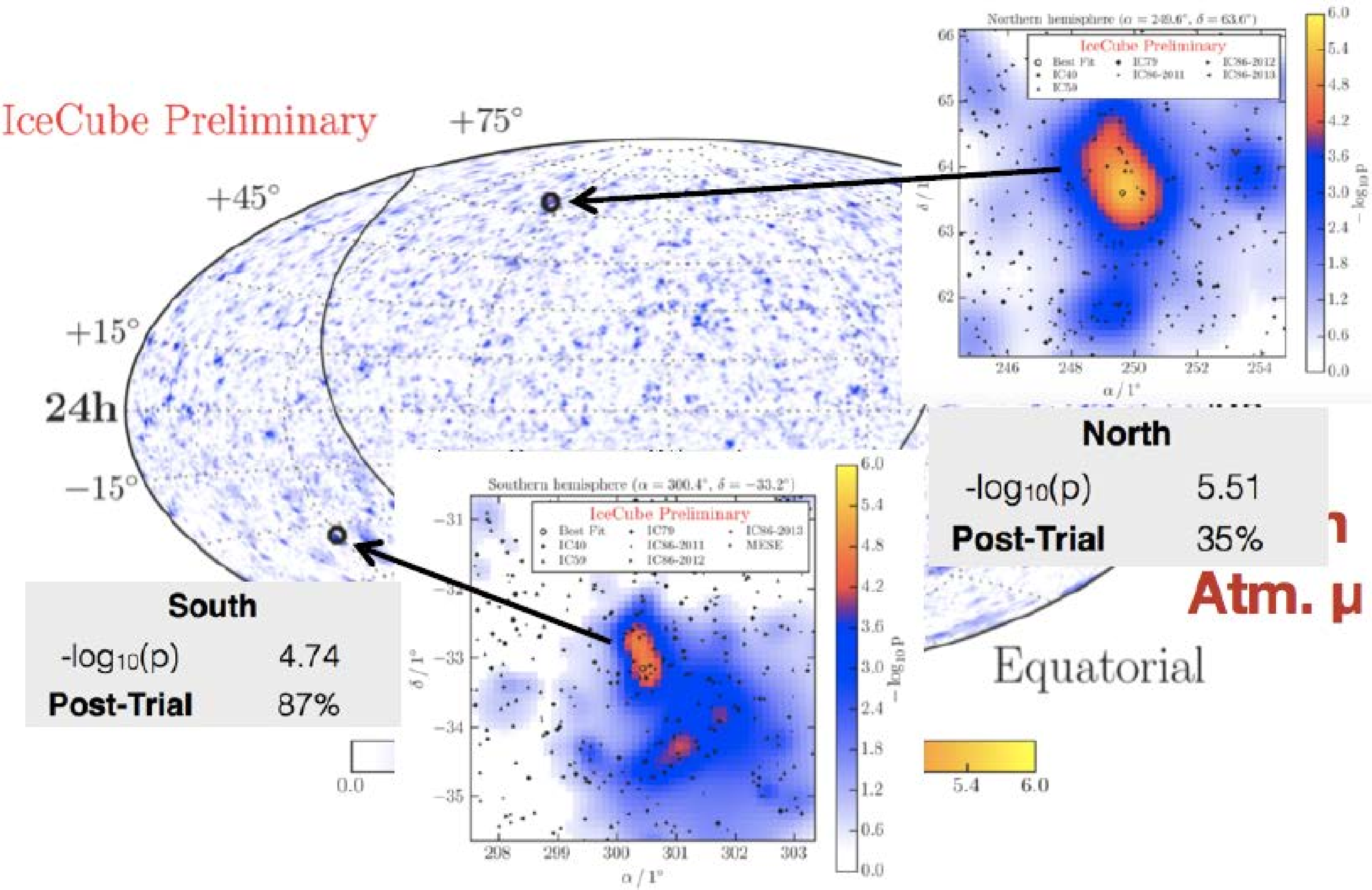


Largely isotropic ⇒ extragalatic origin!

Point source search in six years of data



Point source search in six years of data



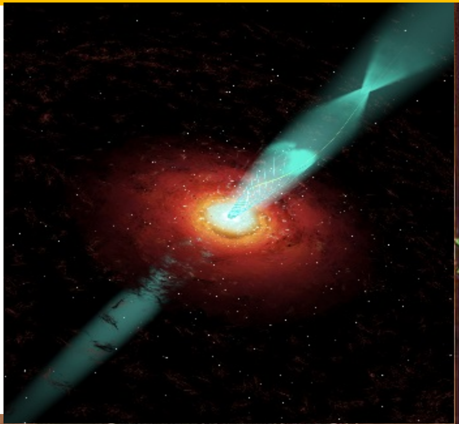
Neutrinos

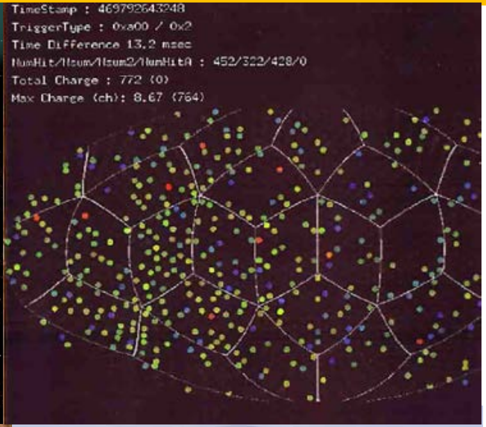
Neutrinos

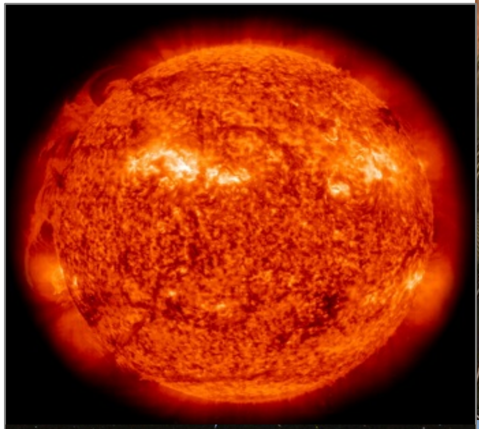
$$\begin{pmatrix} \nu_{eL} \\ \nu_{\mu L} \\ \nu_{\tau L} \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_{1L} \\ \nu_{2L} \\ \nu_{3L} \end{pmatrix}$$

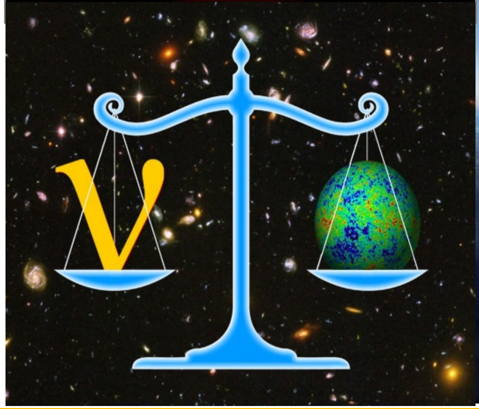
$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{13}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{13}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

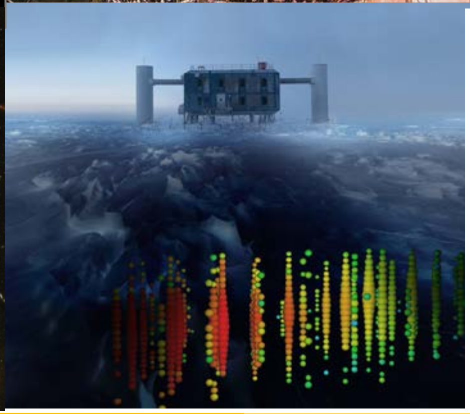
$$= \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{13}} \\ -s_{12}c_{23}-c_{12}s_{23}s_{13}e^{i\delta_{13}} & c_{12}c_{23}-s_{12}s_{23}s_{13}e^{i\delta_{13}} & s_{23}c_{13} \\ s_{12}s_{23}-c_{12}c_{23}s_{13}e^{i\delta_{13}} & -c_{12}s_{23}-s_{12}c_{23}s_{13}e^{i\delta_{13}} & c_{23}c_{13} \end{pmatrix}$$

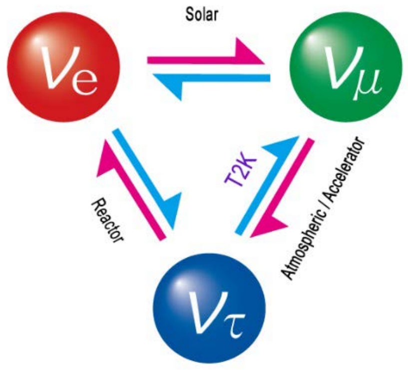












Earth attenuation E>TeV