# Neutrinos and Astrophysics



- Astrophysical neutrinos
- Solar and stellar neutrinos
- Supernovae
- High energy neutrinos
- Cosmology
  - Leptogenesis
  - Big bang nucleosynthesis
  - Large-scale structure and CMB
  - Relic neutrinos

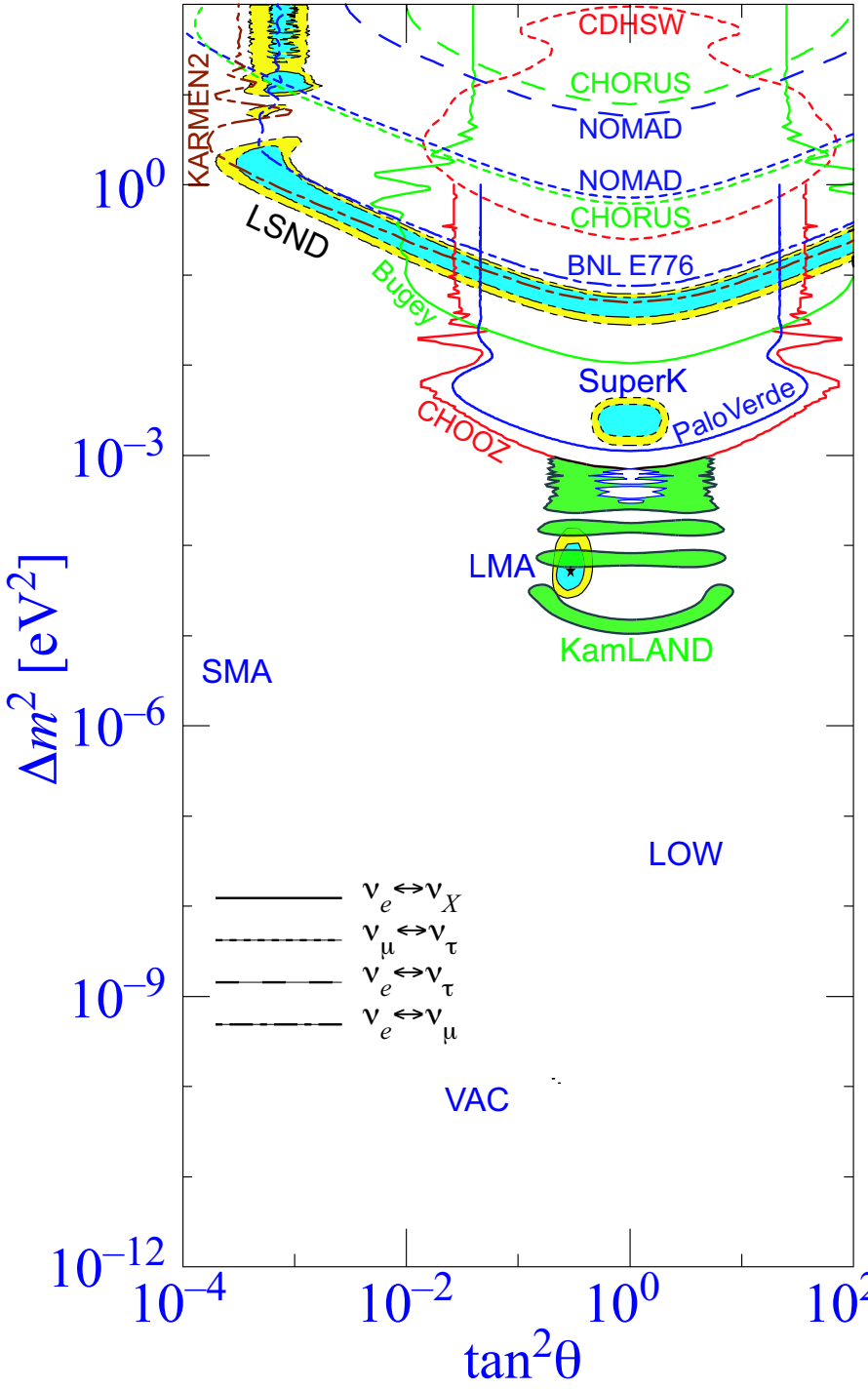
# Astrophysical Neutrinos

- Simultaneous probes of $\nu$ and astrophysics
- Big Bang neutrinos
  - 300 $\nu$'s/cm$^3$ left over from big bang
  - Leptogenesis?
  - Big bang nucleosynthesis (to $^7Li$)
  - Important for dark matter?
  - Detection?

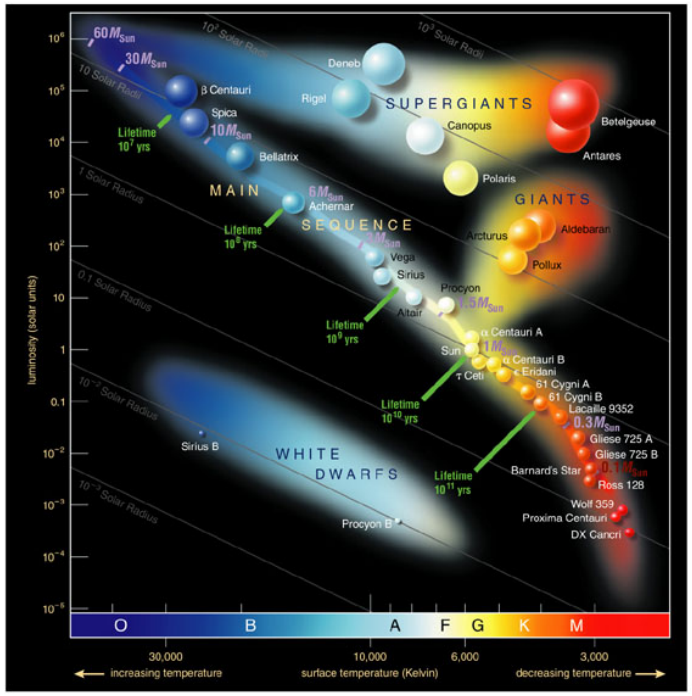
- **Solar/stellar neutrinos**
  - Nuclear reactions in core, nucleosynthesis (to $Fe$)
  - Depletion $and$ spectral distortion $\Rightarrow$neutrino mass/oscillations
  - Astrophysics vs neutrino properties
  - Bounds on magnetic moments/non-standard properties

- **Supernova neutrinos (SN1987A)**
  - Core collapse into neutron star
  - $\nu_e$ pulse from $e^- p \rightarrow \nu_e n$
  - Fireball of $\nu + \bar{\nu}$ boils off for $\sim$ 10 sec
  - $\nu$'s may revive shock, affect $r$-process (nucleosynthesis above $Fe$), pulsar kicks? (Too light?)
  - Oscillation/conversion constraints and supernova probes

- **Atmospheric neutrinos**
  - **Cosmic rays in atmosphere produce $\pi$'s**
  - **$\pi^+ \longrightarrow \mu^+\nu_\mu, \qquad \mu^+ \longrightarrow e^+\nu_e\bar{\nu}_\mu$**
  - **Expect $\mu/e \sim 2$, observe $\sim 1.2$**
  - **Zenith angle: disappearance (oscillation)**
- **High energy neutrinos**
  - **Active galactic nuclei, gamma ray bursts, supernova shocks?**
  - **$Z$ bursts (detection of relic; cosmic rays above GZK)?**



# Solar and stellar neutrinos

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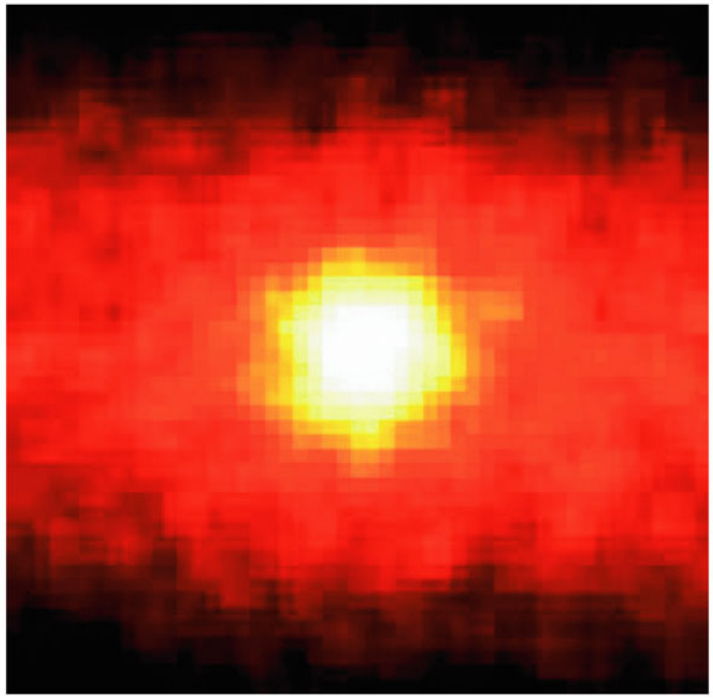

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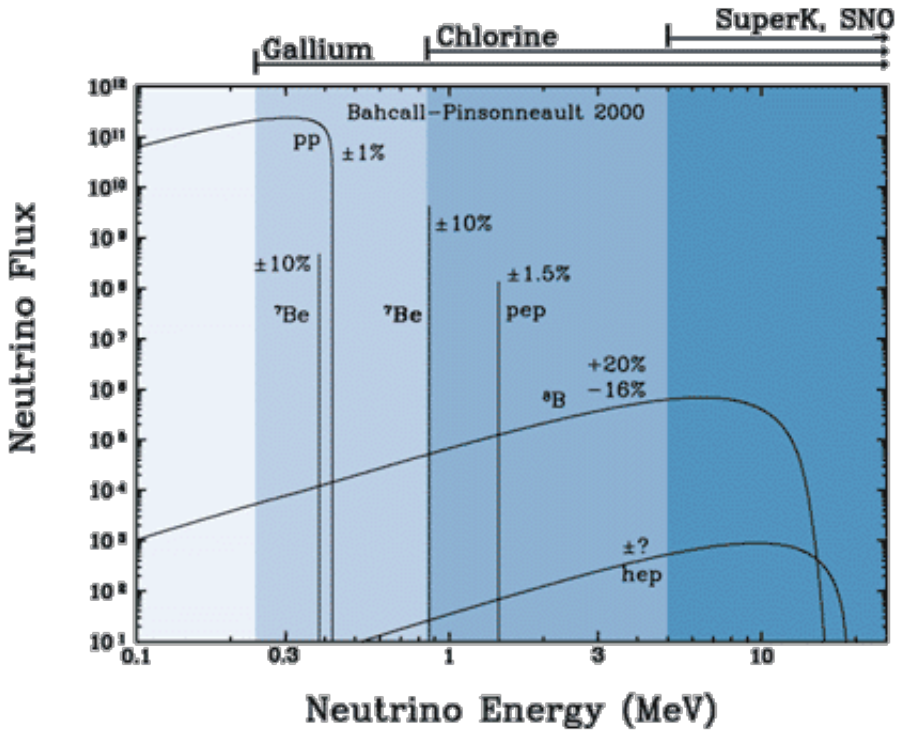
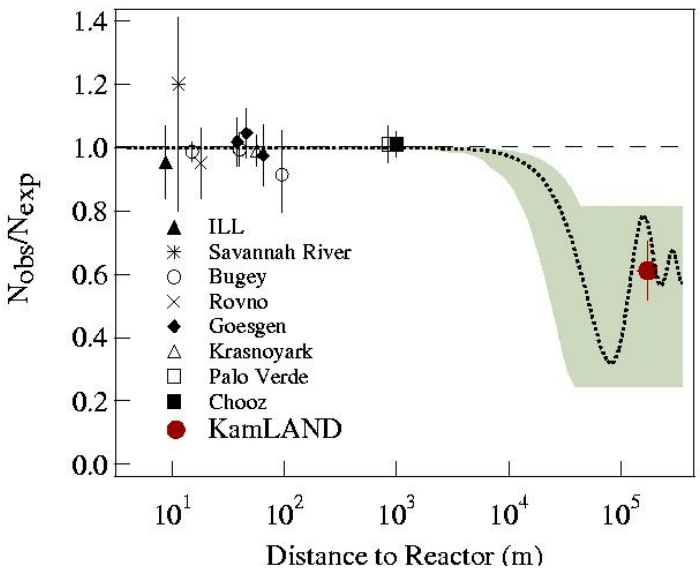
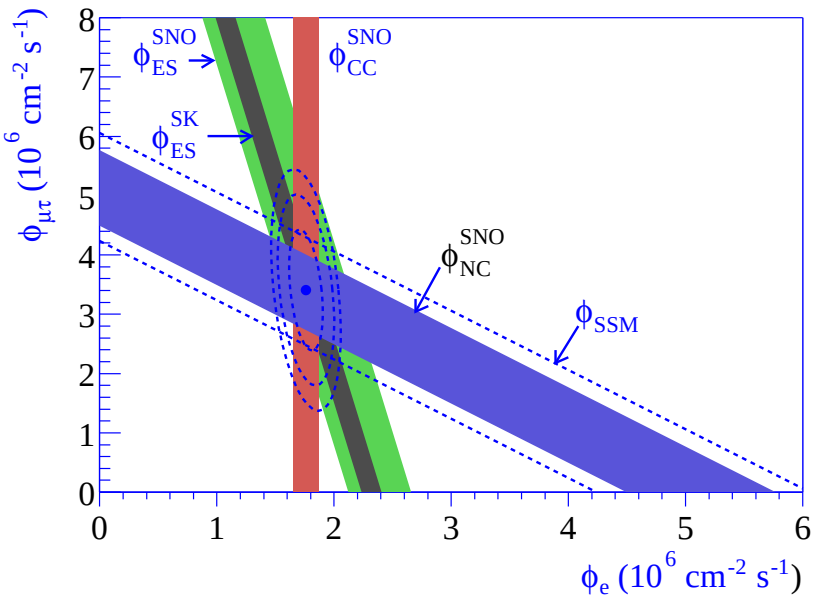
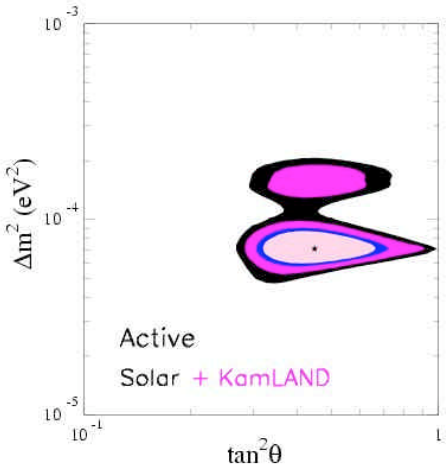
- Produced during stellar nucleosynthesis
- Energy loss constraints (globular clusters, horizontal branch, $\cdots$)
- Core collapse supernovae

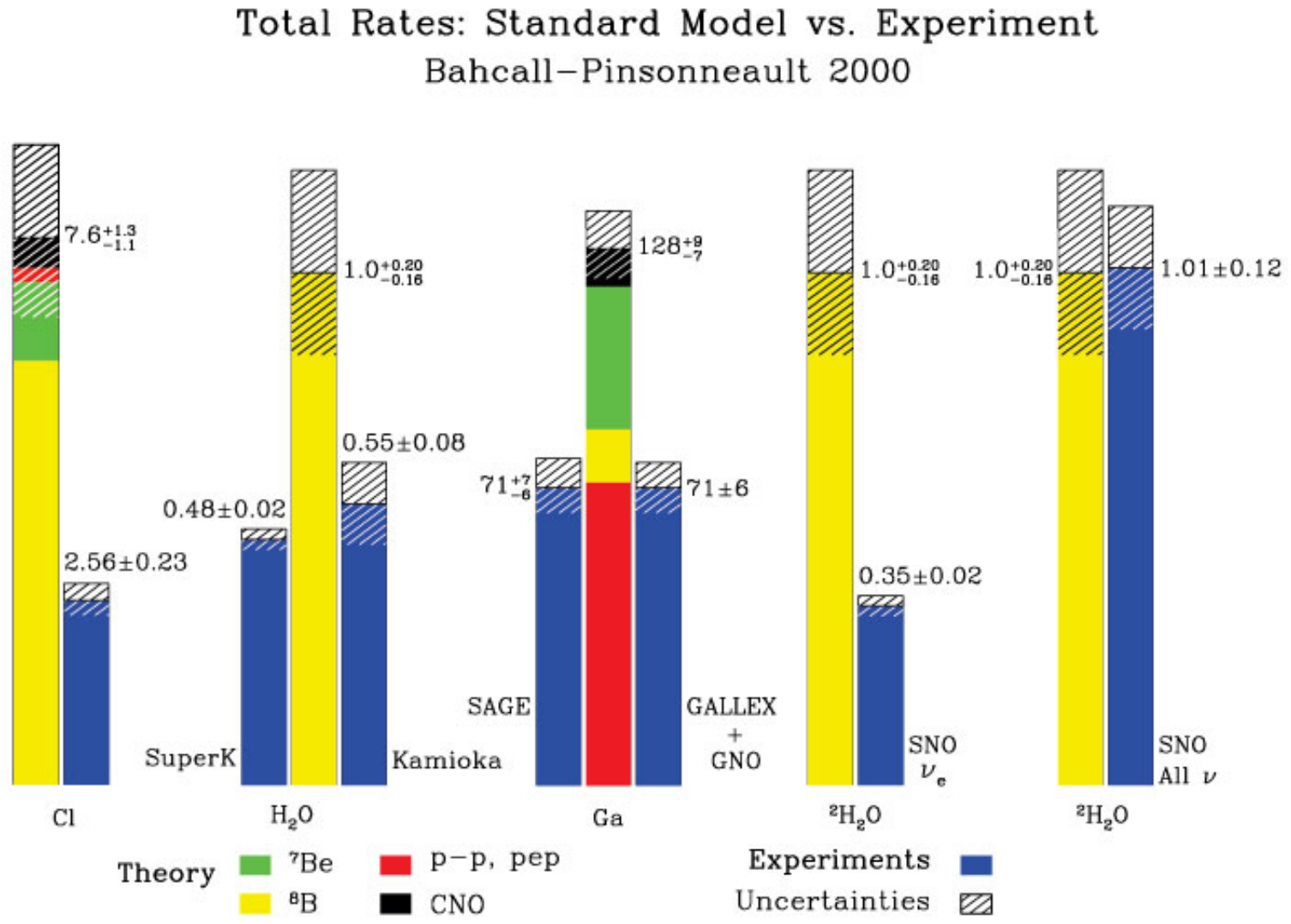
- Solar neutrinos + Kamland confirmed SSM (also helioseismology)
- Established LMA
- Excluded sterile, RSPF, new interactions as *dominant*

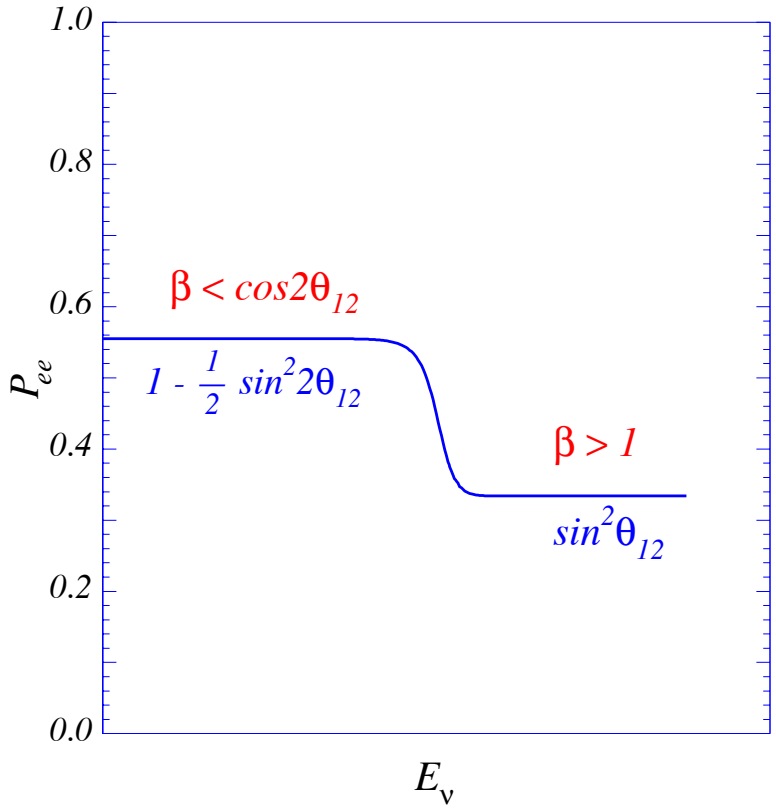



1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
$N_{obs}/N_{exp}$
ILL
Savannah River
Bugey
Rovno
Goesgen
Krasnoyark
Palo Verde
Chooz
KamLAND
$10^1$
$10^2$
$10^3$
$10^4$
$10^5$
Distance to Reactor (m)


$\phi_{\mu\tau}$ ($10^6$ cm$^{-2}$ s$^{-1}$)
SNO $\phi_{ES}$
SNO $\phi_{CC}$
SK $\phi_{ES}$
SNO $\phi_{NC}$
$\phi_{SSM}$
$\phi_e$ ($10^6$ cm$^{-2}$ s$^{-1}$)


$\Delta m^2$ (eV$^2$)
Active
Solar + KamLAND
$\tan^2\theta$

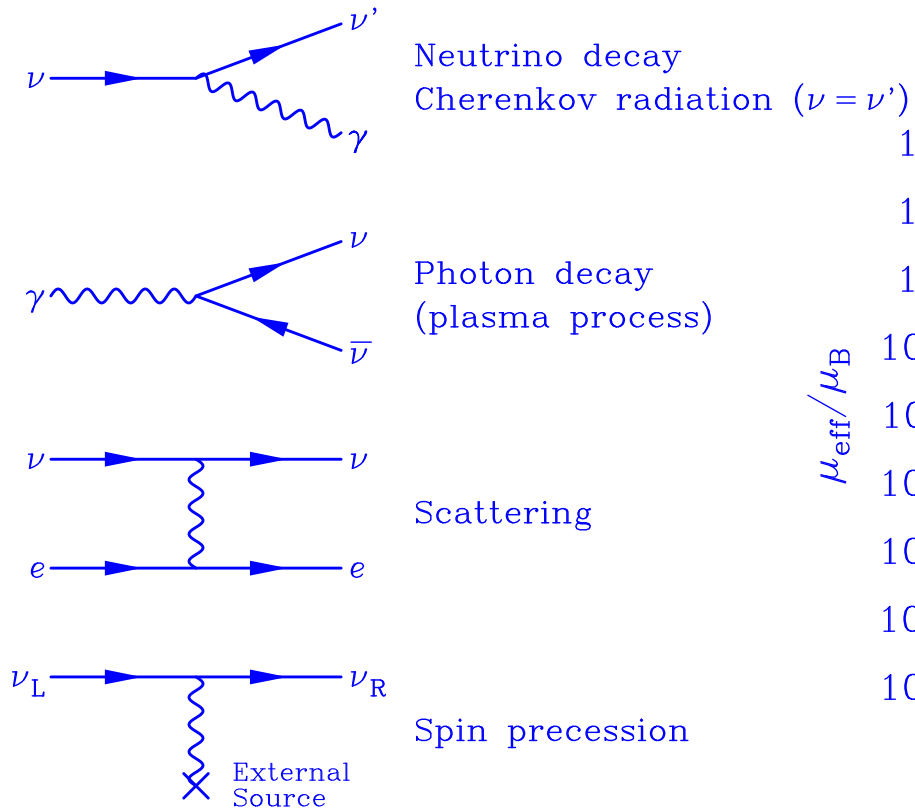

Total Rates: Standard Model vs. Experiment
Bahcall–Pinsonneault 2000
$7.6^{+1.3}_{-1.1}$
2.56±0.23
Cl
0.48±0.02
$1.0^{+0.20}_{-0.16}$
0.55±0.08
SuperK
Kamioka
$H_2O$
$71^{+7}_{-6}$
$128^{+9}_{-7}$
71±6
SAGE
GALLEX + GNO
Ga
$1.0^{+0.20}_{-0.16}$
0.35±0.02
SNO $\nu_e$
$^2H_2O$
$1.0^{+0.20}_{-0.16}$
1.01±0.12
SNO All $\nu$
$^2H_2O$
Theory
$^7$Be
$^8$B
p−p, pep
CNO
Experiments
Uncertainties

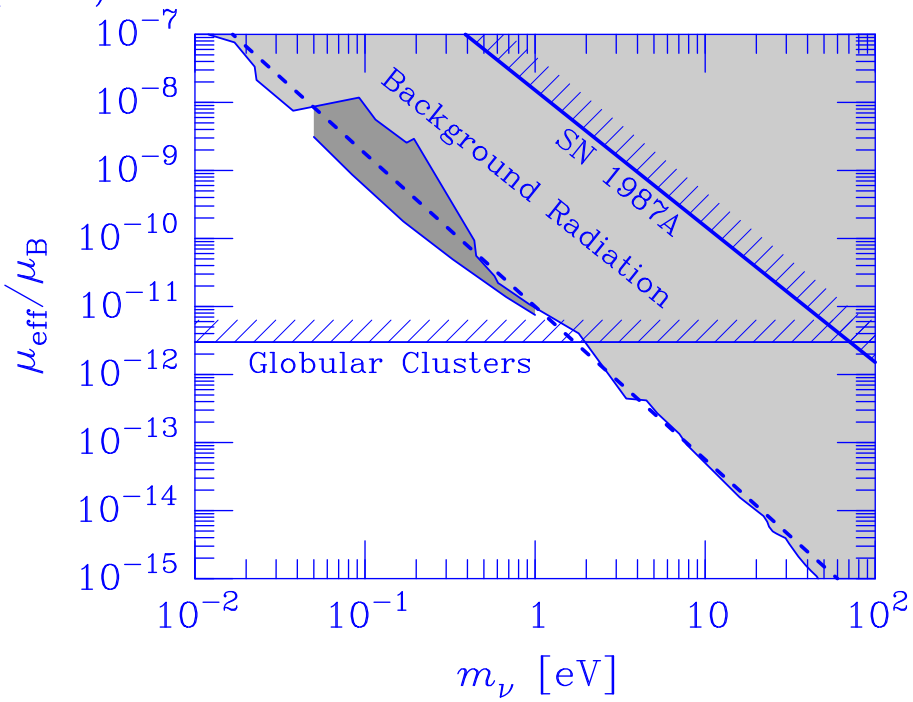



- **Future $pp$ experiment**
  - **Stellar evolution theory at 1%**
  - **$U_{e3}$ probe**
  - **MSW/vacuum transition**
  - **Constrain sterile, axions, $\cdots$**

- **Stellar energy loss severely constrains anomalous energy loss, e.g. heavy Dirac, anomalous electromagnetic moments, decays**

- **Simplest models: $\mu_\nu = 3.2\times10^{-19}\mu_B(m_\nu/eV)$**

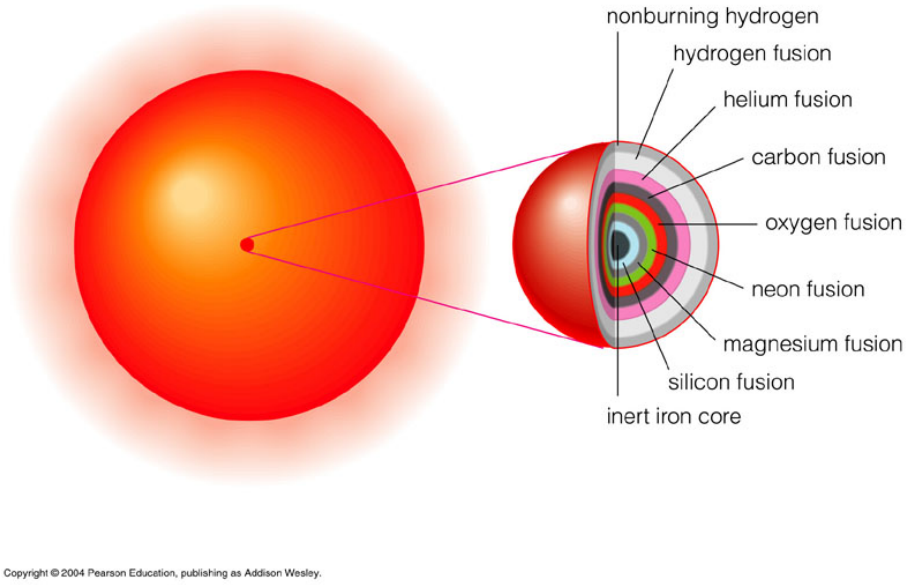


- **Magnetic or Electric Moments**
  - Motivated by alternative RSFP Solar $\nu$ solution
  - Transition (Majorana); transition or direct (Dirac)
  - $He$ ignition in globular cluster red giants (plasmon decay): $\mu_\nu \lesssim 3\times10^{-12}\mu_B$ (all types)
  - Supernova cooling: $\mu_\nu(\mathrm{Dirac}) \lesssim 3\times10^{-12}\mu_B$
  - Radiative decays

- **Neutrino Decays**
  - Radiative, $\nu_2 \to \nu_1\gamma$: diffuse background from relic $\nu$'s; SN1987A radiation
  - Invisible decays (e.g., into Majorons): matter fraction and growth of structure
  - Was mainly relevant for heavier neutrinos, now excluded by oscillations

# Supernovae



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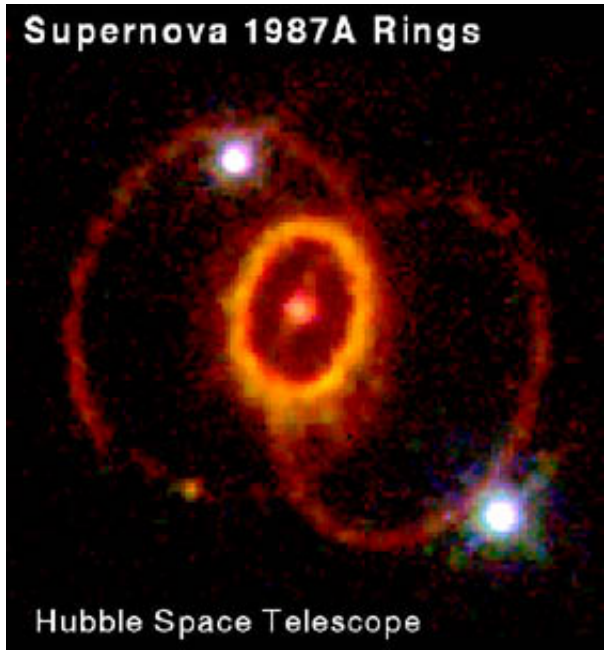
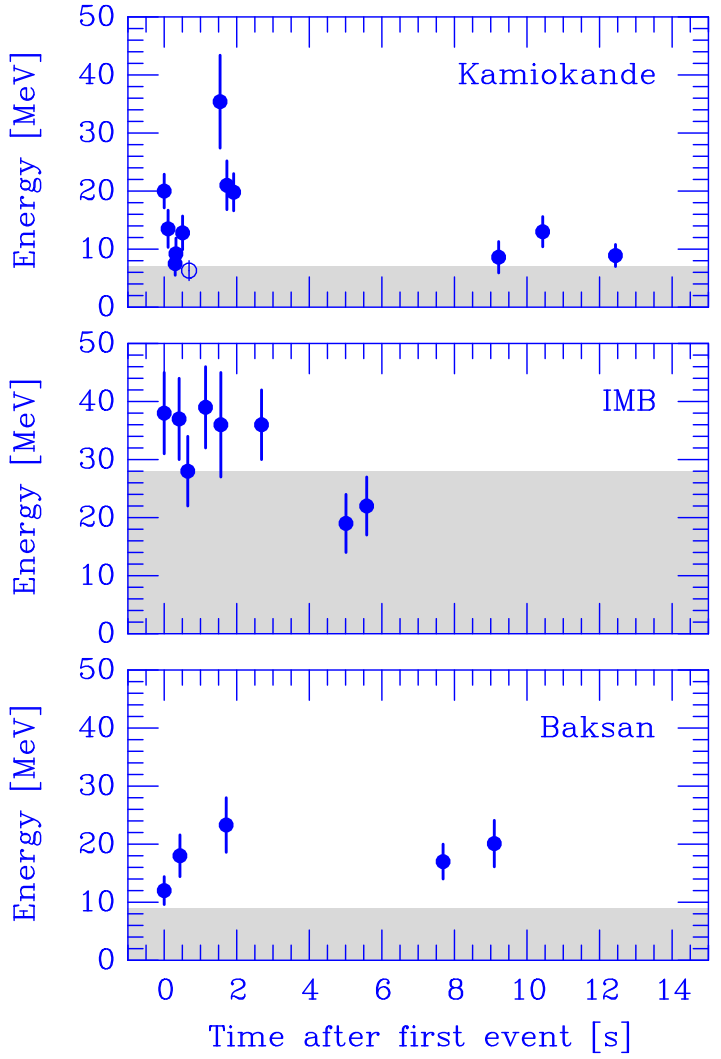



- **Collapse of iron core of $M \gtrsim 8M_\odot$ star**
- **99% of energy ($\gtrsim 3\times10^{53}$ ergs) radiated in neutrinos**

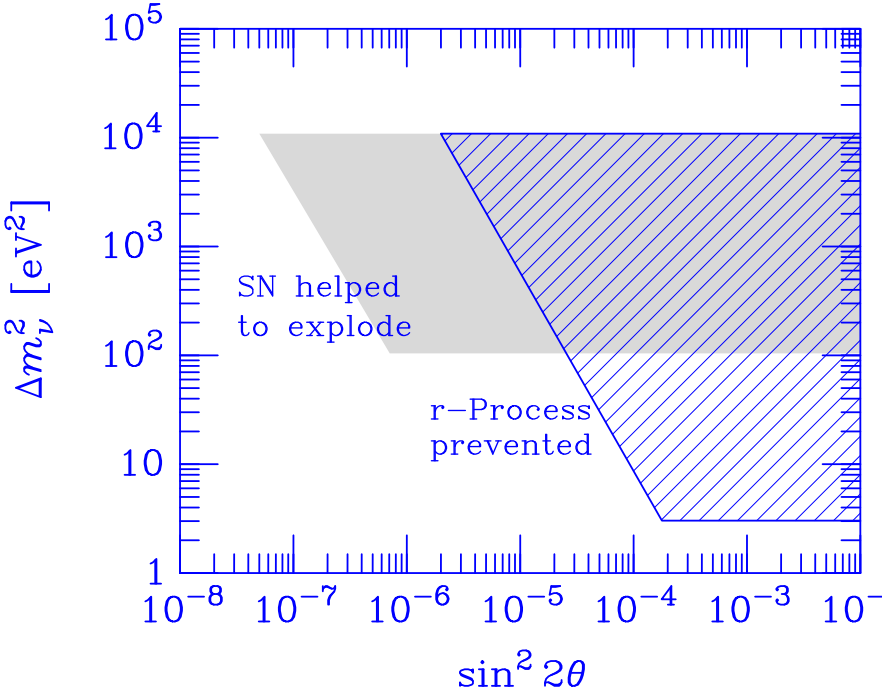
- Neutronization pulse: $e^- p \rightarrow \nu_e n$ (ms)
- Bounce and expanding shock. Stalls in simulations.
- Neutrinosphere radiates $\nu_i + \bar{\nu}_i$ for $\sim$ 10 s
- $\bar{\nu}_e$ observed for SN1987A



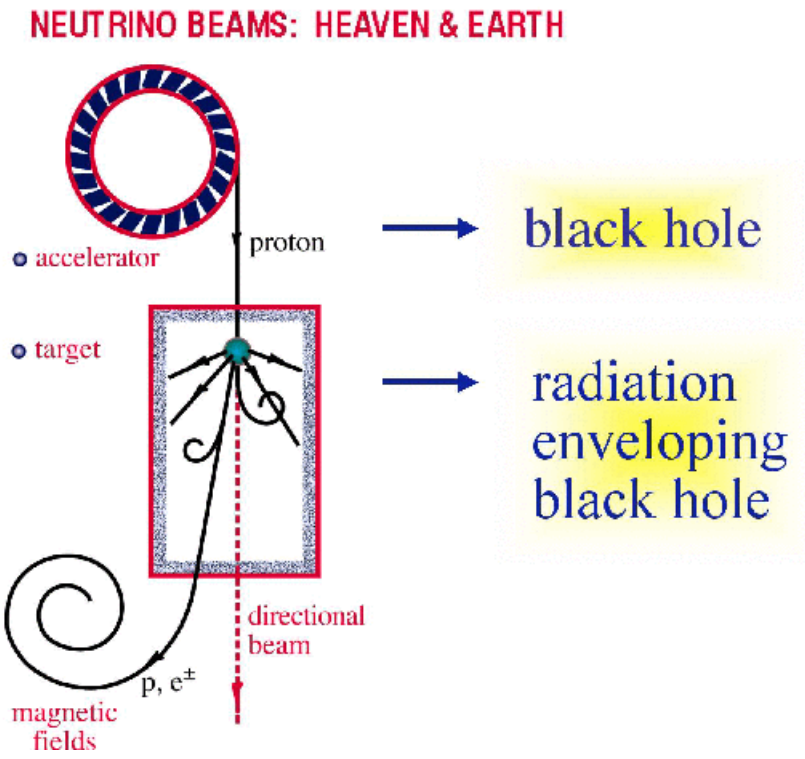
- **Neutrinos probe supernova dynamics**
  - **Basic picture verified by 1987A**
  - **Expect thousands of events for galactic SN (30-100 yr)**
    - **Keep detectors running for 50 yr!**
    - **SNEWS: The SuperNova Early Warning System**
    - **Sensitive to obscured or failed supernovae!**
  - **Experiments becoming sensitive to diffuse SN $\nu$'s from other galaxies**

- **Probe of neutrino properties**
  - $m_{\bar{\nu}_e} \lesssim$ 20 eV from 1987A
  - $m_i \lesssim$ 10's eV (future), but now irrelevant
  - SN1987A energetics may disfavor inverted if $U_{e3} \neq 0$ (hardened $\bar{\nu}_e$ spectrum)
  - Limits on energy loss, e.g. for LED, $Z' \rightarrow N_R \bar{N}_R$, large Dirac masses, millicharge, $\mu_\nu(\mathrm{Dirac})$
  - New interactions (e.g. Majoron models)
  - Future (including Earth effect): sensitive to oscillation patterns

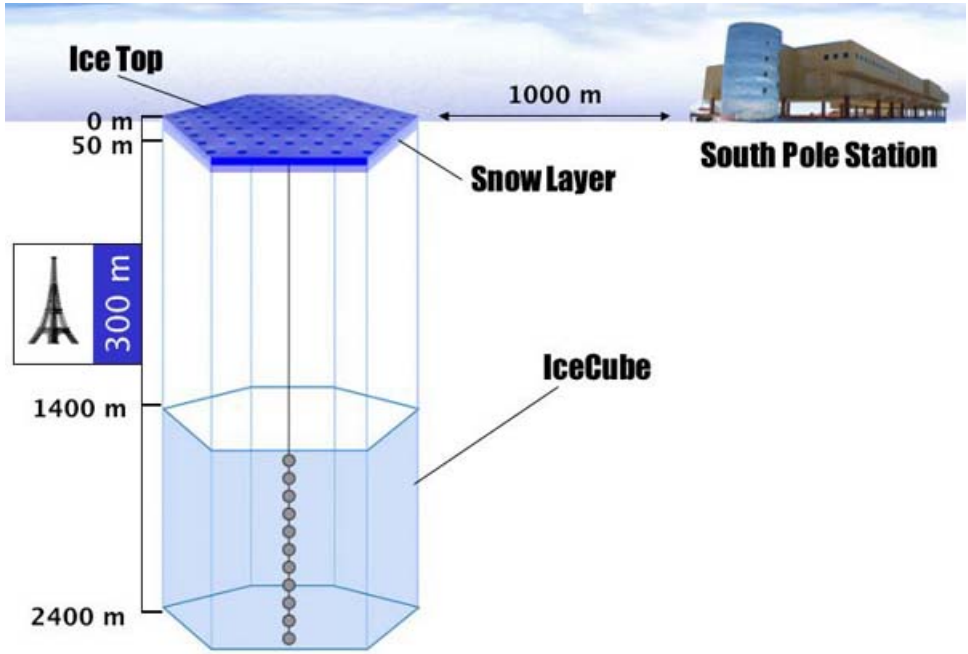
- **Neutrinos may affect supernova dynamics**
  - **Massive neutrinos could revive stalled shock, but not for standard 3 $\nu$ scheme**
  - **$r$-process not prevented by $\nu_\mu \leftrightarrow \nu_e$ and $\nu_e n \rightarrow e^- p$ for standard 3$\nu$**
  - **Heavy sterile conversion could help $r$-process by removing active $\nu$'s to prevent $\nu_e n \rightarrow e^- p$**
  - **Pulsar kick mechanism for 1-20 KeV sterile**

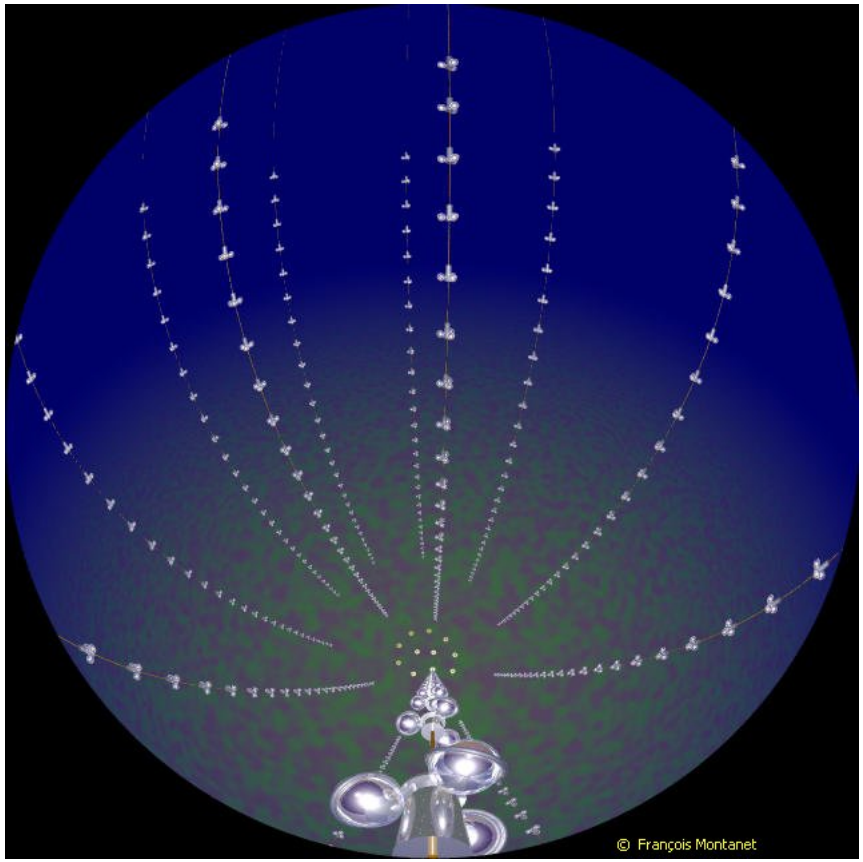


# High energy neutrinos



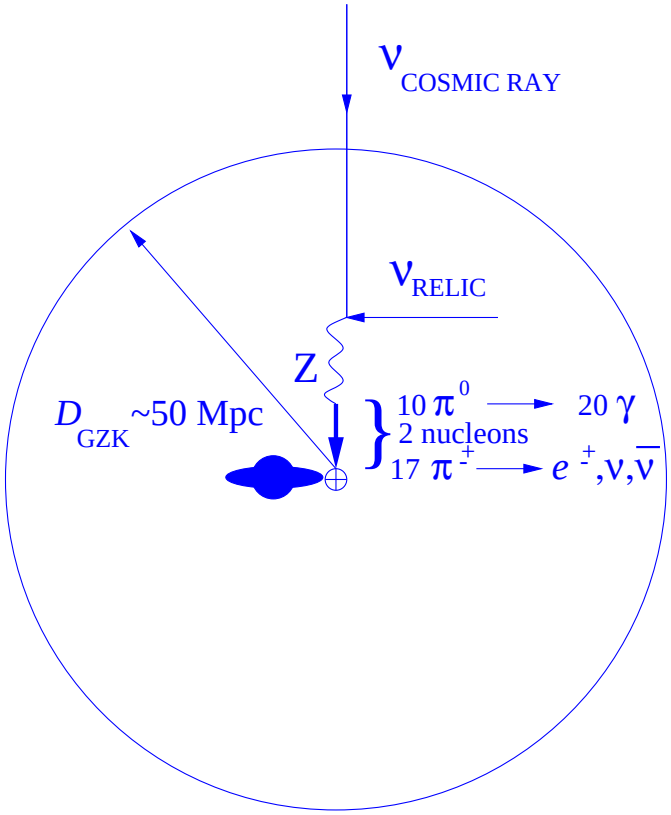

- Probe of ultra high energy sources (GRB, AGN, BH, SN)
- Probe of ultra high energy $\nu N$ interactions (e.g., anomalous in LED)
- Probe of neutrino properties (oscillations into $\nu_\tau$), mass hierarchy, decays, moments
- Earth tomography?

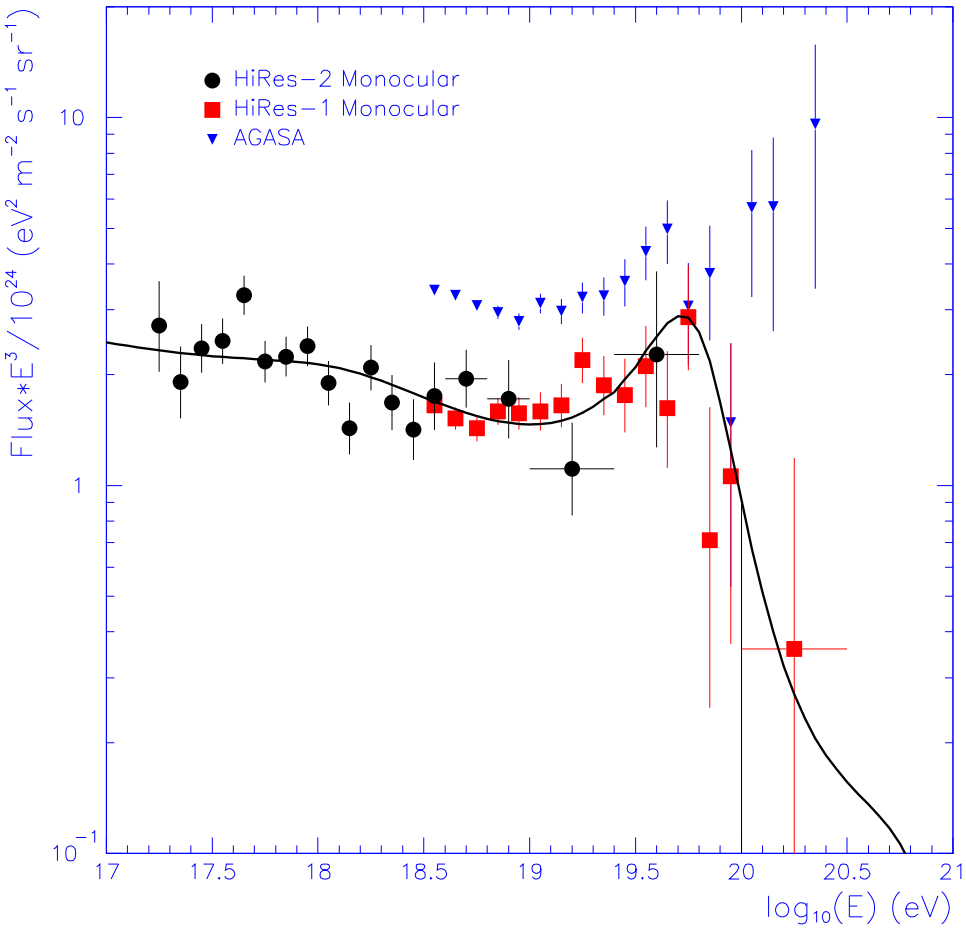



**IceCube** **Antares**

- The $Z$ burst scenario: possible probe of relic $\nu$ for $m_\nu \lesssim$ eV: $\nu(\mathrm{UHE})\bar{\nu}(\mathrm{relic}) \rightarrow Z \rightarrow$ hadrons
  - Depends on (unknown) large flux of ultra HE $\nu$'s

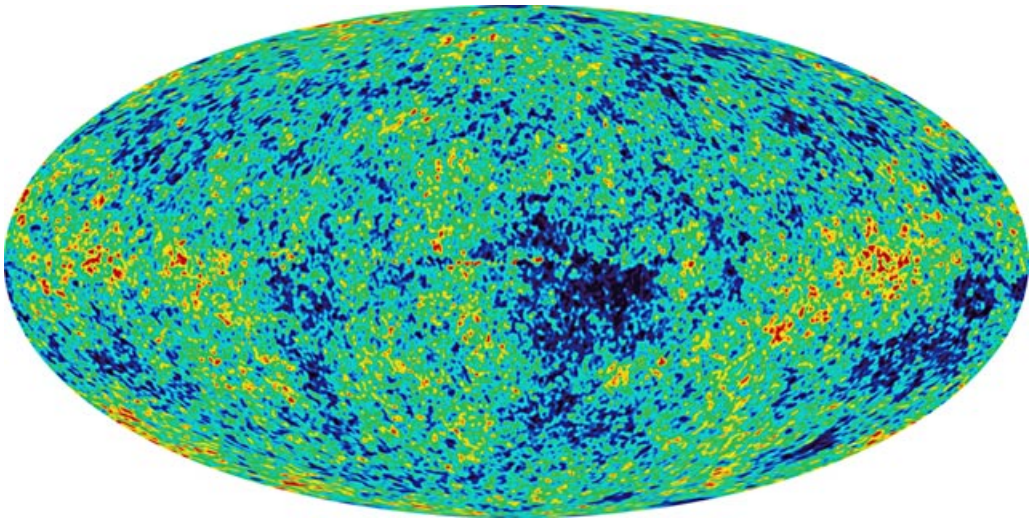





- **Cosmic ray events with $E_p >$ GZK cutoff? (or energy calibration?)**
  **(Best fit $m_\nu = 0.26^{+0.20}_{-0.14}\ eV$, Fodor, Katz, Ringwald)**
- **Future: Auger project**

# Cosmology

- Leptogenesis
- Big bang nucleosynthesis
- Large-scale structure and CMB
- Relic neutrinos



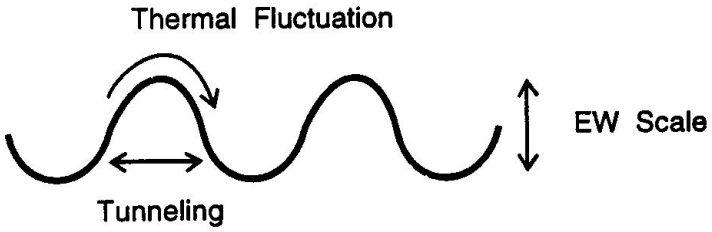
# Leptogenesis

- **Baryon asymmetry $n_B/n_\gamma \sim 6 \times 10^{-10}$**
- **Basic ideas worked out by Sakharov in 1967, but no concrete model**



1. **Baryon number violation**
2. **CP violation: to distinguish baryons from antibaryons**
3. **Nonequilibrium of $B$-violating processes**

- **Possible mechanisms**
  - **GUT baryogenesis (wiped out by sphalerons for $B-L$=0)**
  - **Electroweak baryogenesis (easier with $U(1)'$)**
  - **Leptogenesis (heavy Majorana $N$ decays)** (involves new CP phases)




- **Out of equilibrium decays created *lepton* asymmetry**
  $N_{heavy} \to l +$ Higgs $\neq N_{heavy} \to \bar{l} +$ Higgs

- **Electroweak tunneling** (actually thermal fluctucation) **then converts some of the lepton asymmetry into a baryon asymmetry!**

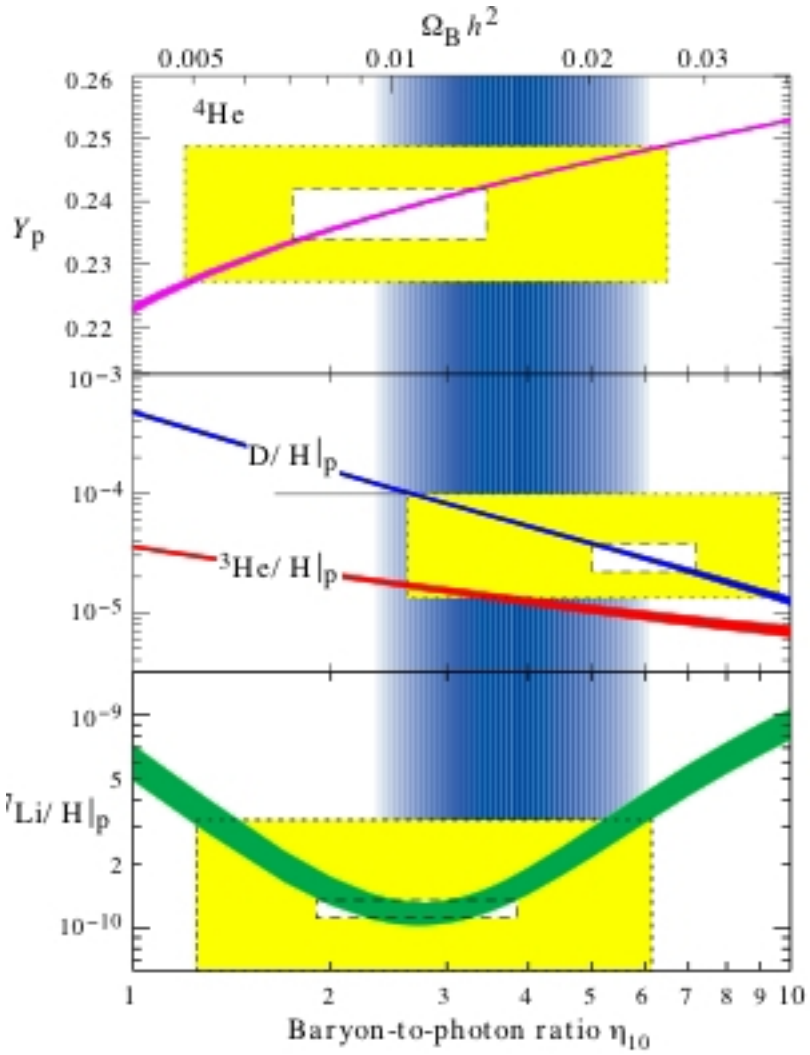
- **Difficulties in supersymmetric version: gravitino problem suggests reheating temperature too low** (unless $N_{heavy}$ produced nonthermally)

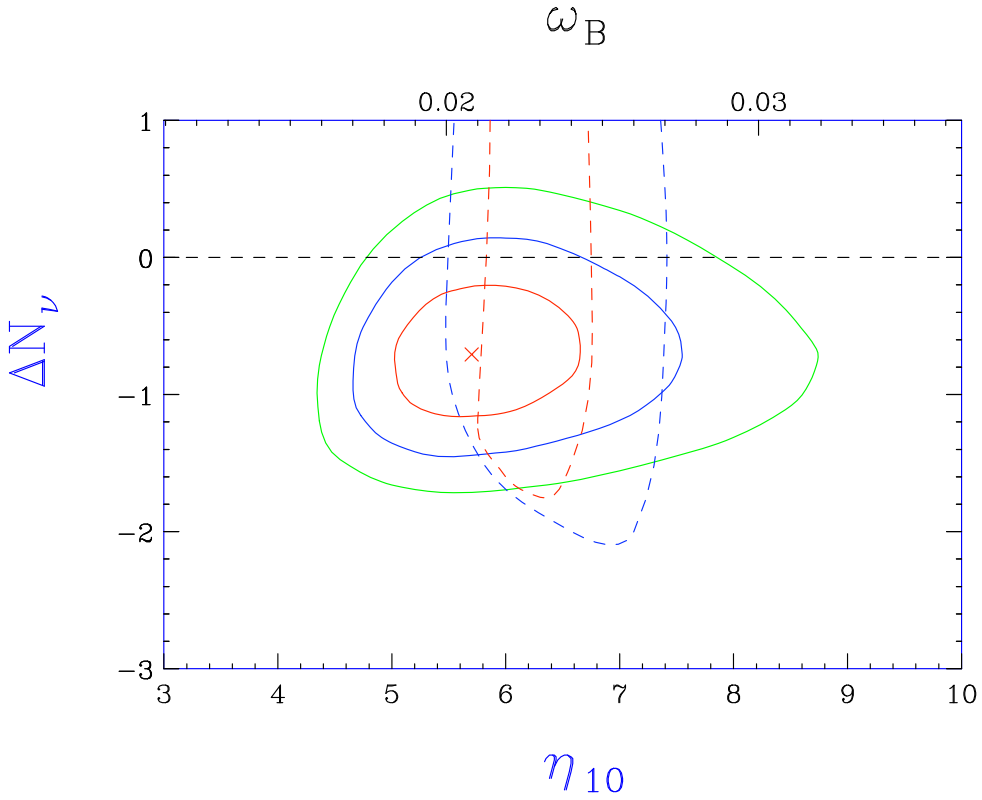
# Big bang nucleosynthesis

- Production of light nuclei ($^4He,\ D,\ ^3He,\ ^7Li$) in early Universe
- Parameters
  - $\eta = n_B/n_\gamma$ ($\eta_{10} \sim 274\ \Omega_b h^2$)
  - $\Delta N_\nu$ (any new source of energy density, relative to one active $\nu$ flavor)
  - $\xi_e = \mu_{\nu_e}/T$, related to $(n_{\nu_e} - n_{\bar{\nu}_e})/n_\gamma$
- SBBN: $\Delta N_\nu = \xi_e = 0$

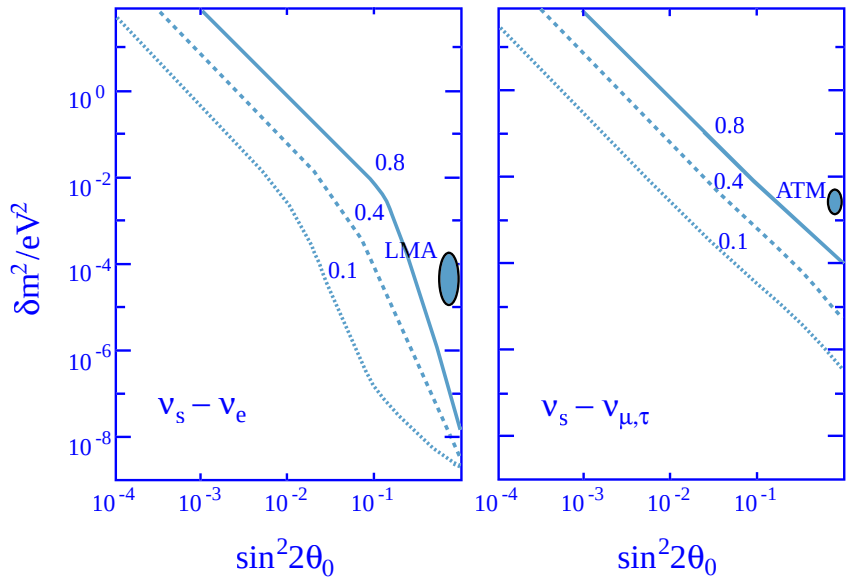
- $\nu_e n \leftrightarrow e^- p$ and $e^+ n \leftrightarrow \bar{\nu}_e p$ keep $n_n/n_p$ in equilibrium as long as it is rapid enough

  - Freezeout at $T_\star \sim 1$ MeV, when $\Gamma_{\rm weak} \sim H$
  - $\Gamma_{\rm weak} = c G_F^2 T^5$
  - $H = \left[\frac{8\pi}{3} G_N \rho\right]^{1/2} \sim 1.66 g_\star^{1/2} T^2/M_{Pl}$
  - $g_\star = g_B + \frac{7}{8} g_F$, with $g_F = 10 + 2\Delta N_\nu$
  - $T_\star \sim \left(\frac{g_\star^{1/2}}{G_F^2 M_{Pl}}\right)^{1/3}$
  - $\frac{n_n}{n_p} = e^{-(m_n - m_p + \mu_{\nu_e})/T_\star} \longrightarrow {}^4He$
  - ${}^4He$ mass fraction: $Y_p = \frac{4 n_{^4He}}{n_H}$ depends strongly on $\Delta N_\nu$ ($\Delta Y_p \sim 0.013 \Delta N_\nu$) and $\xi_e$, weakly on $\eta$
  - $Y_2 = \frac{D}{H}$ depends on $\eta$ (baryometer)
  - Independent determination of $\eta$ from CMB


$\Omega_B h^2$
0.005
0.01
0.02
0.03
$^4$He
$Y_p$
0.26
0.25
0.24
0.23
0.22
$10^{-3}$
D/ H|$_p$
$10^{-4}$
$^3$He/ H|$_p$
$10^{-5}$
$10^{-9}$
5
$^7$Li/ H|$_p$
2
$10^{-10}$
1
2
3
4
5
6
7
8
9
10
Baryon-to-photon ratio $\eta_{10}$

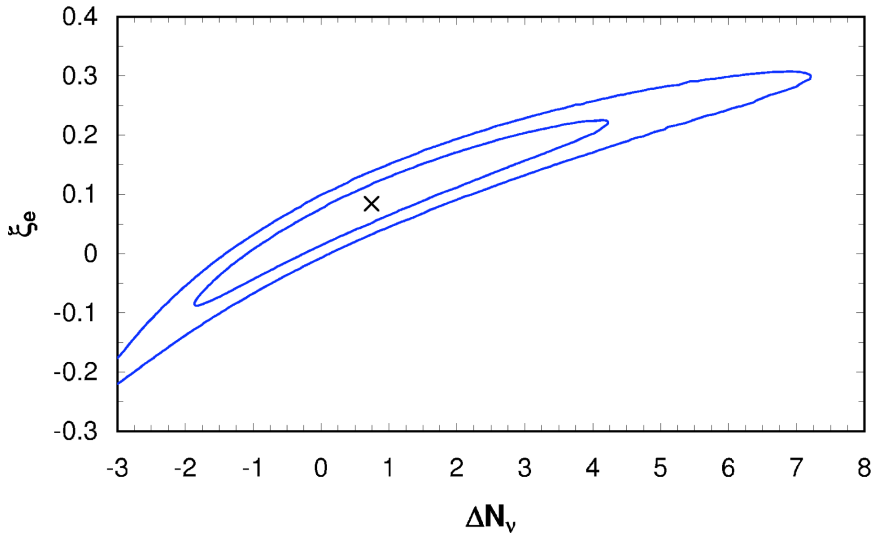



- Central $^4He$ somewhat low
- Best fit for $\Delta N_\nu < 0$, but consistent with zero
- Most new physics yields $\Delta N_\nu > 0 \Rightarrow$ strongly constrained
- $Z' \to \nu_R\ \bar{\nu}_R$; sterile neutrinos (LSND); $\xi_{\mu,\tau}$
- Can compensate by $\xi_e \sim 0.1$; naively expect $\sim 10^{-10}$




## Exclusion on sterile for $\Delta N_\nu < 1$

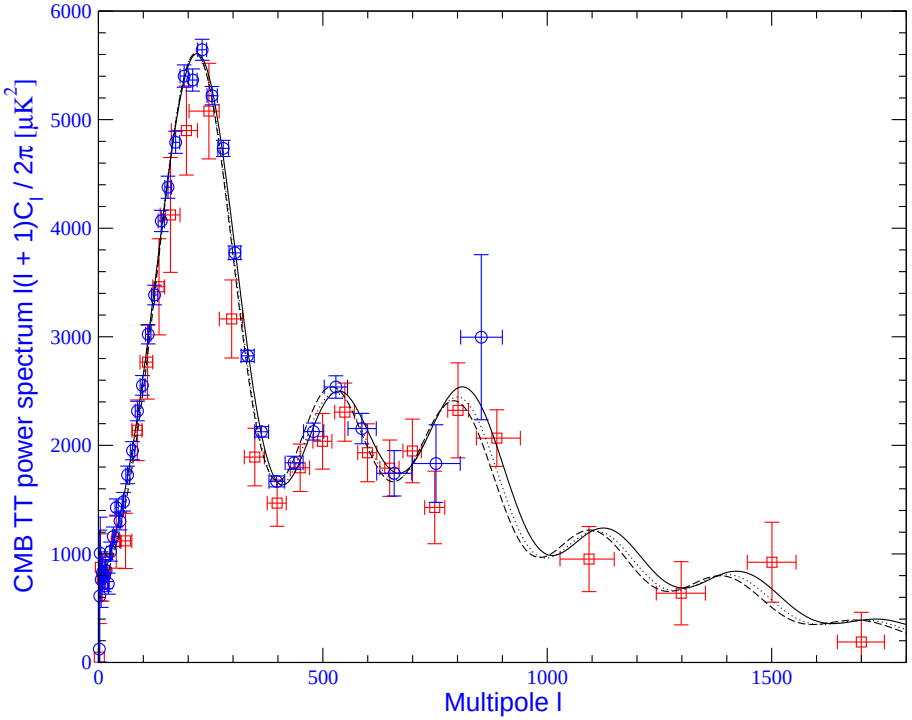
## Compensation of $\xi_e$ and $\Delta N_\nu$

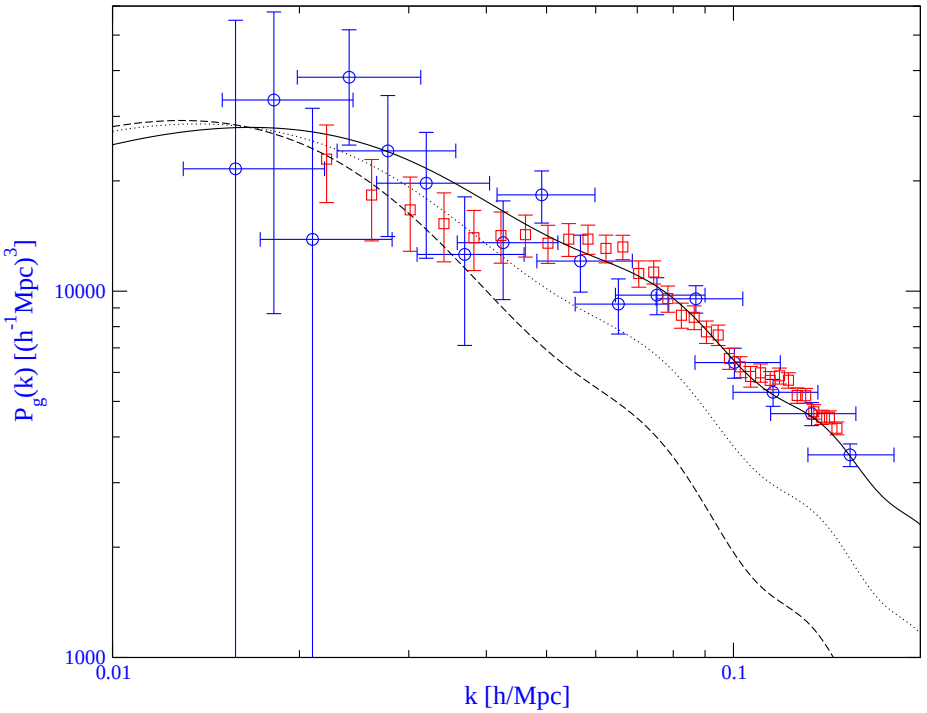


# Large-scale structure (LSS) and CMB

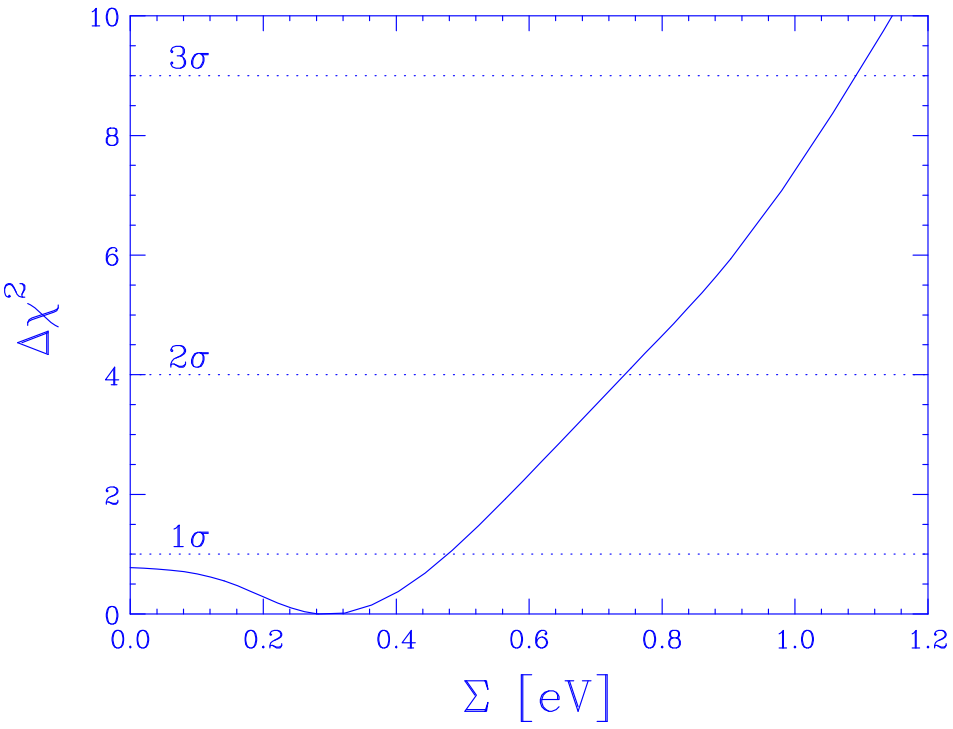
- **Hot Dark Matter (HDM)**
  - $\Omega_\nu h^2 = \sum_l m_{\nu_i}/92.5$ eV
  - HDM excluded by free-streaming: not enough time for large structures to fragment
  - Mixed CHDM models, typically $\Omega_{\rm matter} \sim 1$ and $\sum_i m_{\nu_i} \sim$ few eV $\longrightarrow$ motivated degenerate $\nu$ spectra
  - Now excluded by (a) $\Omega_{\rm matter} \sim 0.3$ (clusters, etc); (b) $\Omega_{\rm total} = \Omega_{\rm DE} + \Omega_{\rm matter} \sim 1$, DE = dark energy (1st CMB peak, WMAP); (c) $\Omega_{\rm DE} \neq 0$ (Type Ia supernovae)

- **Small admixture of HDM still possible**
  - **LSS (2dF, SDSS) sensitive to $\Sigma_\nu \equiv \sum_i m_{\nu_i}$**
  - **CMB (WMAP) fixes other (degenerate) parameters**
  - **Current: $\Sigma_\nu \lesssim 0.75 - 1$ eV $\Rightarrow m_{\nu_i} \lesssim 0.3$ eV**



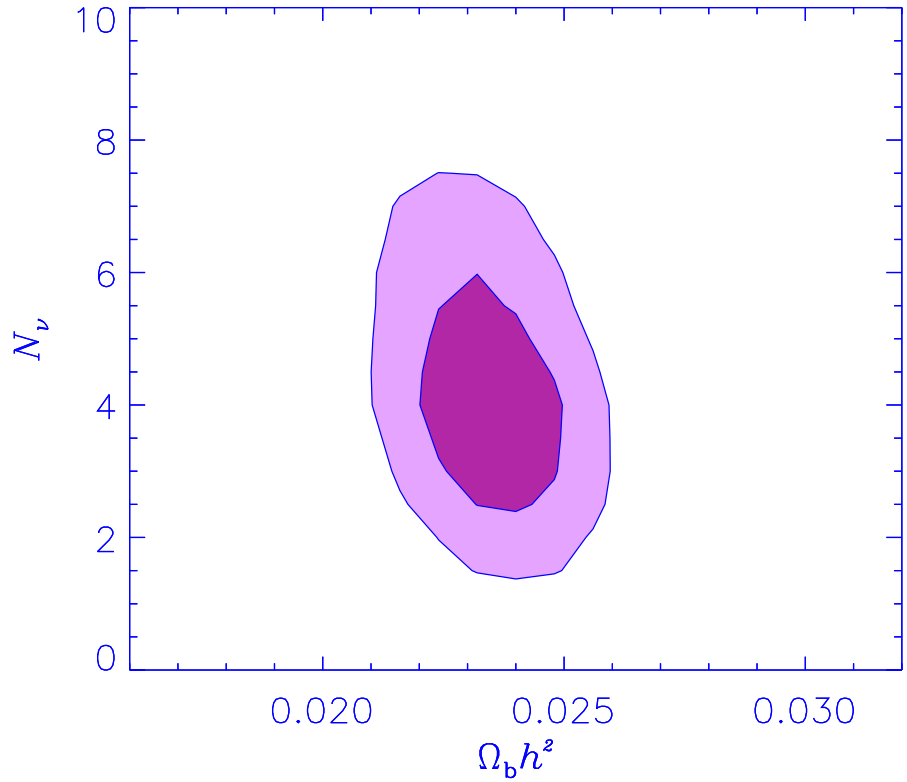

**$\Sigma_\nu = 0.28$ eV (solid), 1.5 eV (dotted), 3.0 eV (dashed)**




- **Current:** $\Sigma_\nu \lesssim 0.75 - 1$ **eV** $\Rightarrow$ $m_{\nu_i} \lesssim 0.3$ **eV**
- **Future: sensitive to** $\sim 0.1$ **eV, weak lensing, LSS, CMB**
- **cf. tritium** $\beta$ **decay:** $m_\nu < 2.4$ **eV (future: KATRIN,** $\sim 0.3$ **eV)**
- **cf.** $\beta\beta_{0\nu} \lesssim$ **few** $\times 10^{-1}$ **eV (future:** $\sim 0.02$ **eV)**

- **CMB has some sensitivity to $\Delta N_\nu$ (matter-radiation transition)**

- **Warm dark matter (e.g. 10 keV decaying $\nu$) may still be viable**



# Relic neutrinos

- $\nu_i, \bar{\nu}_i$ decoupled at $T_D \sim$ few MeV, while still relativistic
- Subsequently, $p'$ redshifted to $p = p'/\eta$, where $\eta \equiv R(t)/R(t_D)$
- Now have *form* of relativistic thermal distribution, with

$T_\nu \equiv \frac{T_D}{\eta} = \left(\frac{4}{11}\right)^{1/3} T_\gamma \sim 1.9K$, and $m_{eff_i} \equiv \frac{m_i}{\eta} \ll m_i$

- **For hierarchical pattern**

  $m_3 \sim 0.05\ eV, \quad m_2 \sim 0.005\ eV, \quad m_1 \ll m_2$

  $(\langle v_3 \rangle \sim 10^{-2}, \quad \langle v_2 \rangle \sim 10^{-1})$

- **For degenerate pattern,** $m_1 \sim m_2 \sim m_3 \lesssim 0.23\ eV$ **(WMAP),**

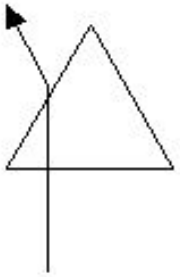
  $\langle v_i \rangle \sim 2 \times 10^{-3} \left( \frac{0.23\ eV}{m_i} \right)$

- **Clustering?**

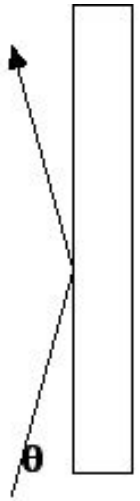
  $v_{\rm esc} \sim 10^{-4}\ (\rm Sun),\ 2 \times 10^{-3}\ (\rm Galaxy),\ 3 \times 10^{-3}\ (\rm Large\ Cluster)$

  - Little effect on velocities except degenerate case
  - Little clustering unless $m_i \gtrsim 0.3\ eV$, and then on supercluster scale

- **Indirect detection: effects of BBN, LSS**
- **Direct detection?**
  - **Incoherent scattering? Impossible**
  - **Coherent effects (forces, torques)? Impossible**
  - **$Z$-burst: only known plausible mechanism, but only if flux of ultra high energy $\nu$**

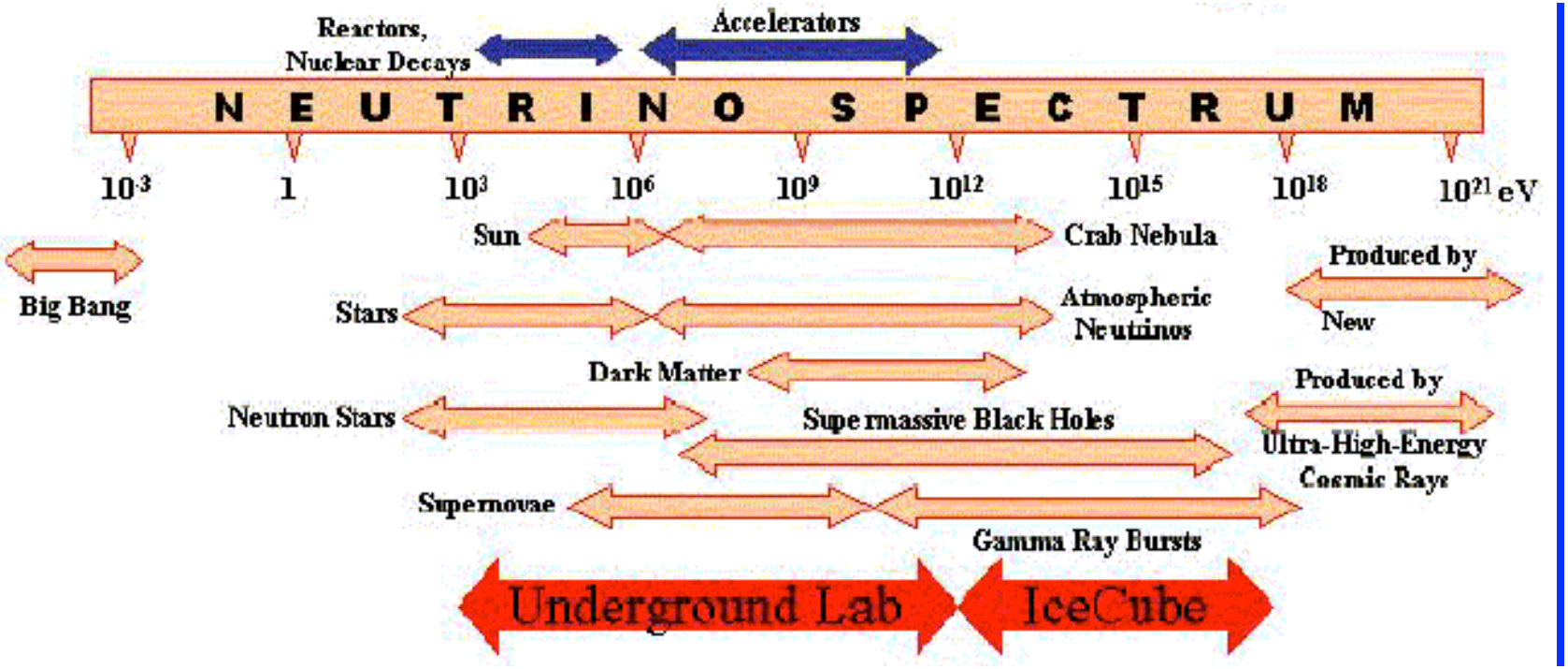


**Refraction**




**Total External Reflection**

# Conclusions




**(From Neutrino Facilities Assessment Committee report (NAS 2002))**