Properties of Massive Neutrinos
&
Cosmic Neutrino Background

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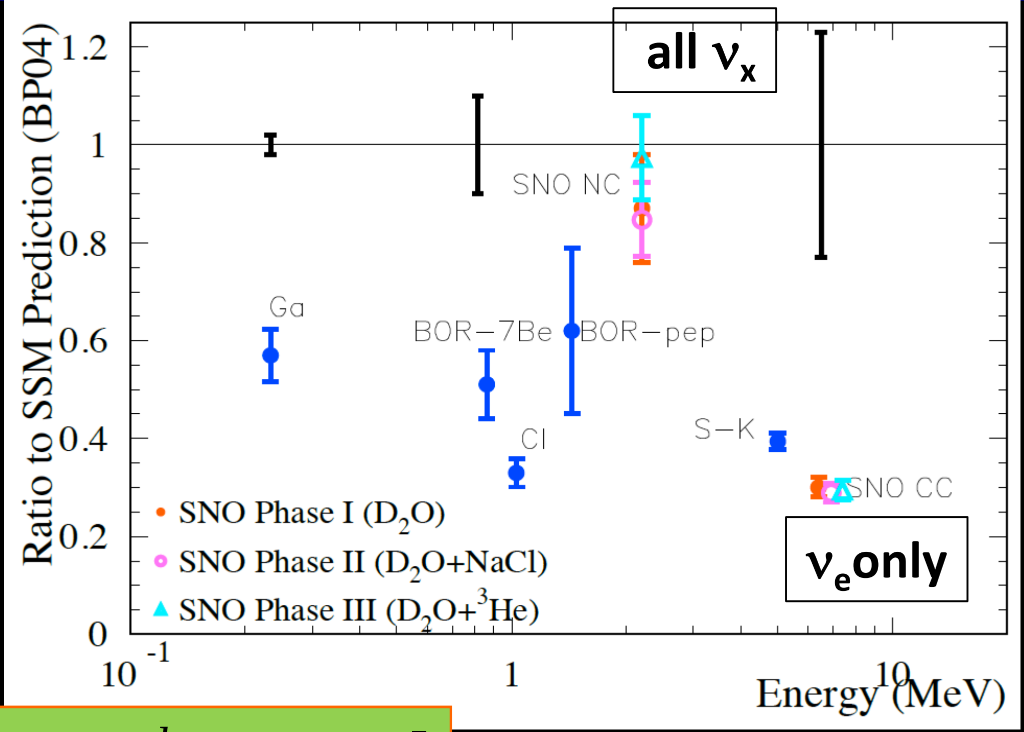
(IHEP, Beijing)

Seminar @ ICTS-USTC, Heifei, 2017-05-26

Solar Neutrino Oscillations


J. N. Bahcall **R. Davis Jr.**



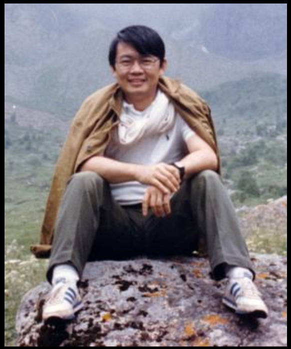
CC: $\nu_e + d \to p + p + e^-$

NC: $\nu_\alpha + d \to p + n + \nu_\alpha$

ES: $\nu_\alpha + e^- \to \nu_\alpha + e^-$

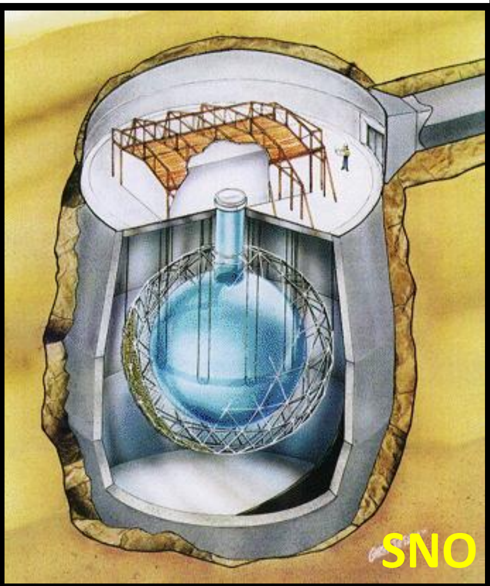
Discovery of solar neutrino oscillations

supported by KamLAND

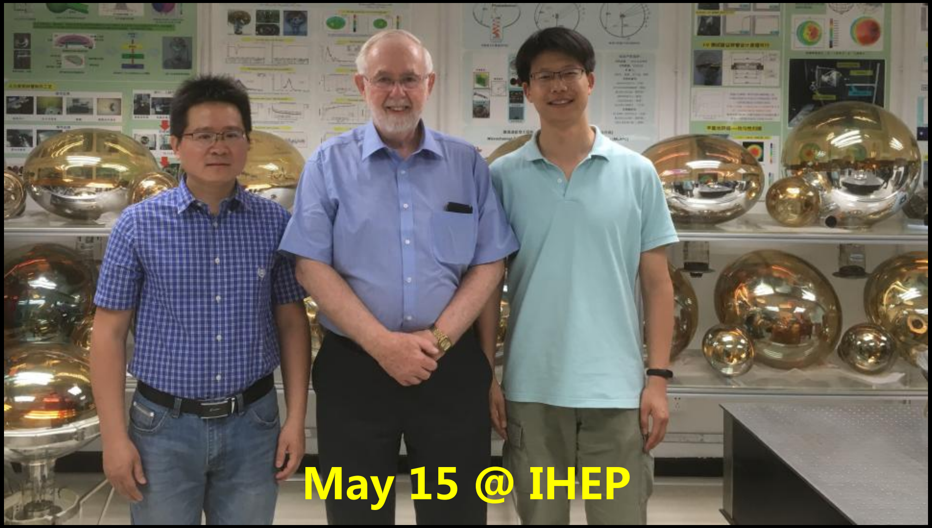
Herbert H. Chen
陈华森
(1942-1987)

Spokesperson of SNO since 1984

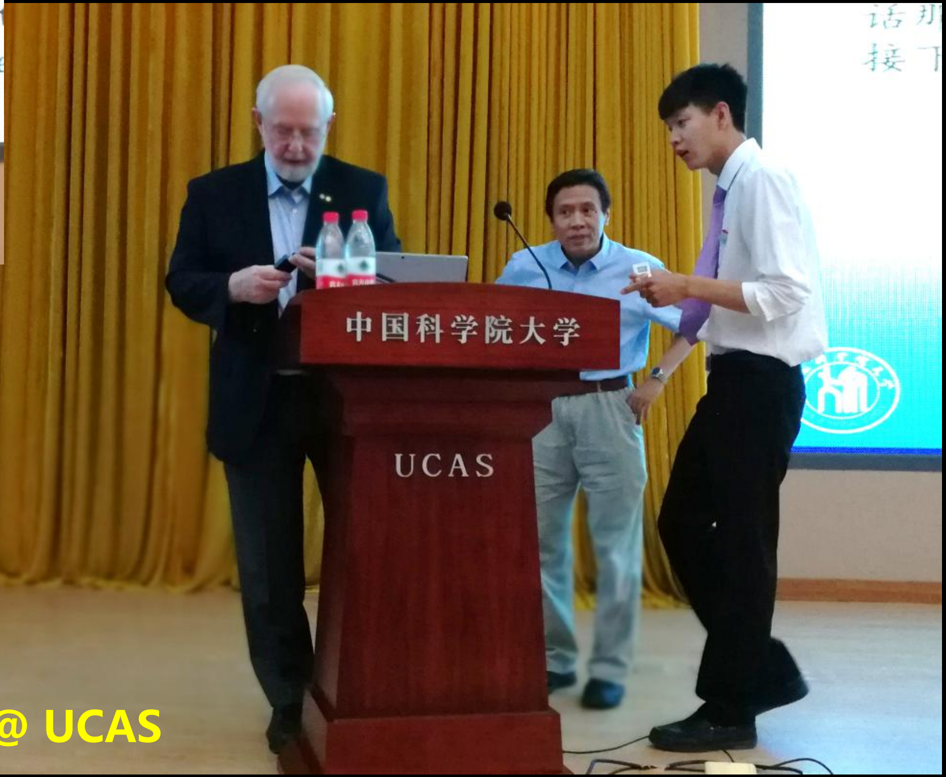


Arthur B. McDonald in Beijing

May 16 @ UCAS

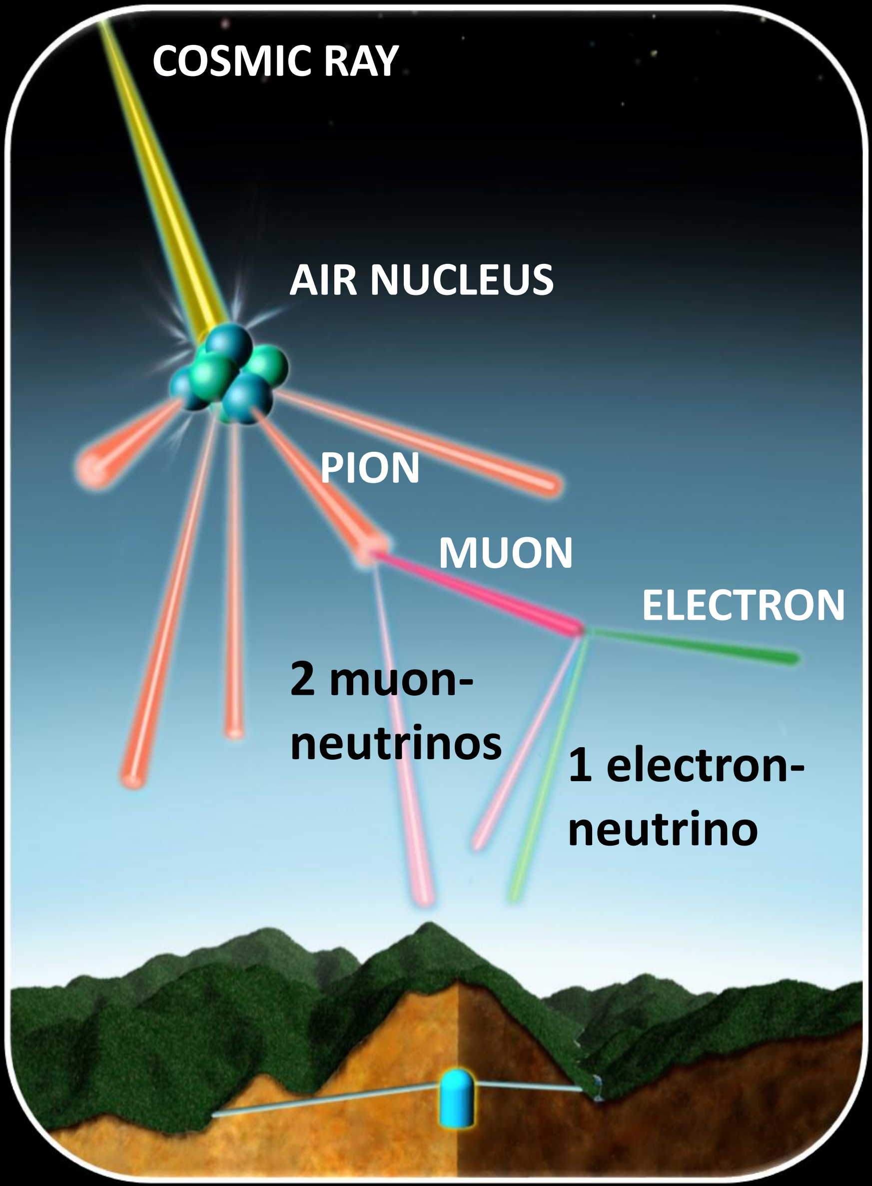


May 15 @ IHEP



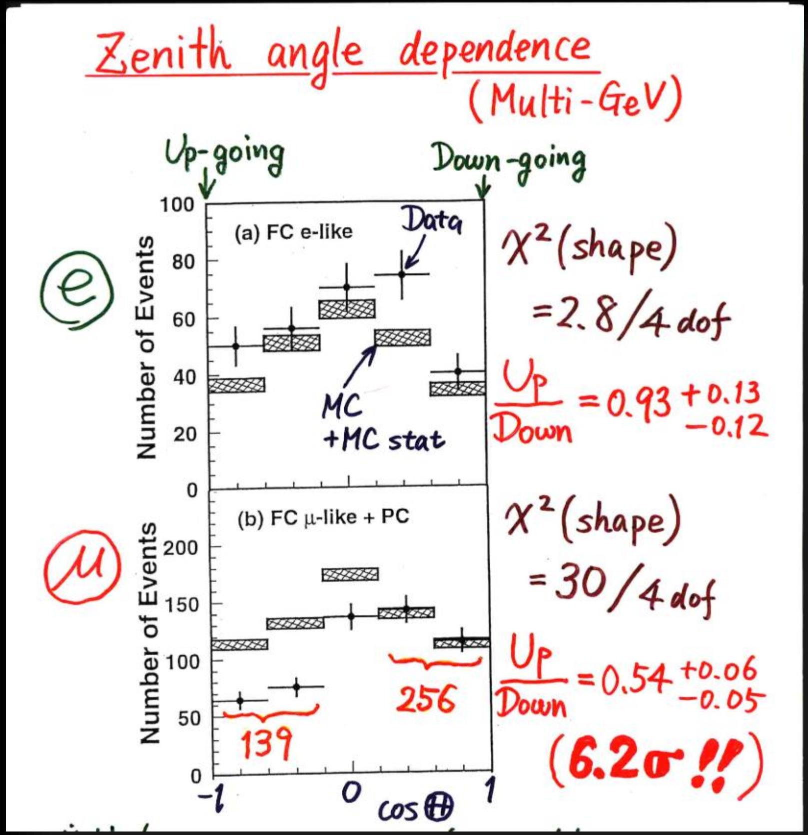
May 16 @ UCAS

Atmospheric Neutrino Oscillations



From Kajita, ICHEP 16

Super-Kamiokande @ Neutrino 98



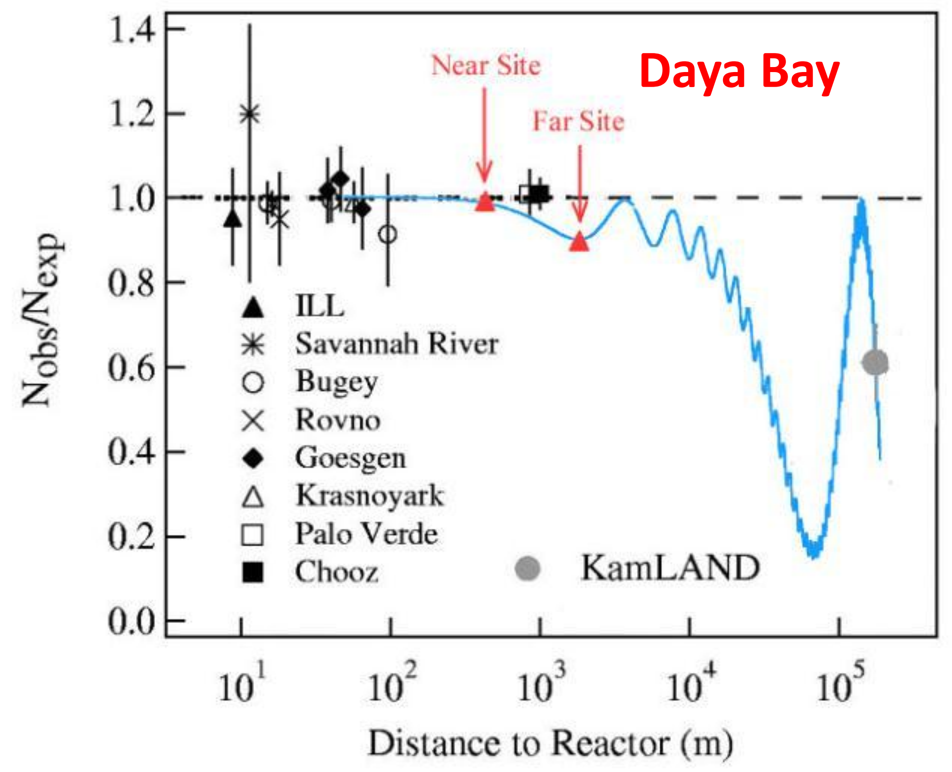
Discovery of atmospheric neutrino oscillations

supported by K2K, MINOS, T2K, NOνA

Yoji Totsuka (1942-2008)

T. Kajita

Reactor Neutrino Oscillations



Dec. 2011	$\sin^2\theta_{13} = 0.022 \pm 0.013$	1.7σ
Mar. 2012	$\sin^2\theta_{13} = 0.024 \pm 0.004$	5.2σ
Apr. 2012	$\sin^2\theta_{13} = 0.029 \pm 0.006$	4.9σ

Discovery of short-baseline reactor neutrino oscillations

A complete picture of three-flavor neutrino oscillations!

Leptonic Flavor Mixing Matrix

Standard parametrization of the PMNS matrix

$$V = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} e^{i\rho} & 0 & 0 \\ 0 & e^{i\sigma} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$\boldsymbol{\theta_{23} \sim 45^\circ}$

$\boldsymbol{|\Delta m^2_{32}| \sim 2.5 \times 10^{-3}\ \mathrm{eV}^2}$

Atmospheric,
LBL accelerator

$\boldsymbol{\theta_{13} \sim 9^\circ}$

$\boldsymbol{\delta \sim ?}$

Reactor,
LBL accelerator

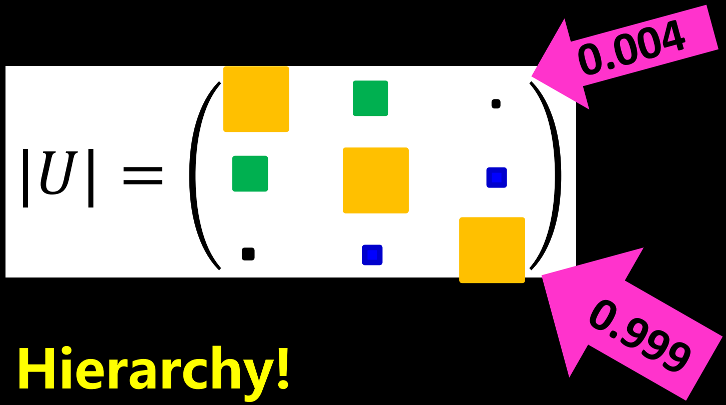
$\boldsymbol{\theta_{12} \sim 34^\circ}$

$\boldsymbol{\Delta m^2_{21} \sim 8 \times 10^{-5}\ \mathrm{eV}^2}$

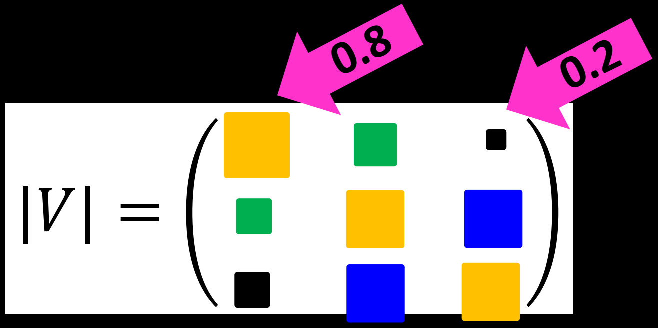
Solar,
KamLAND

0ν2β, LNV?

Quarks vs. Leptons: A big puzzle of fermion flavor mixings

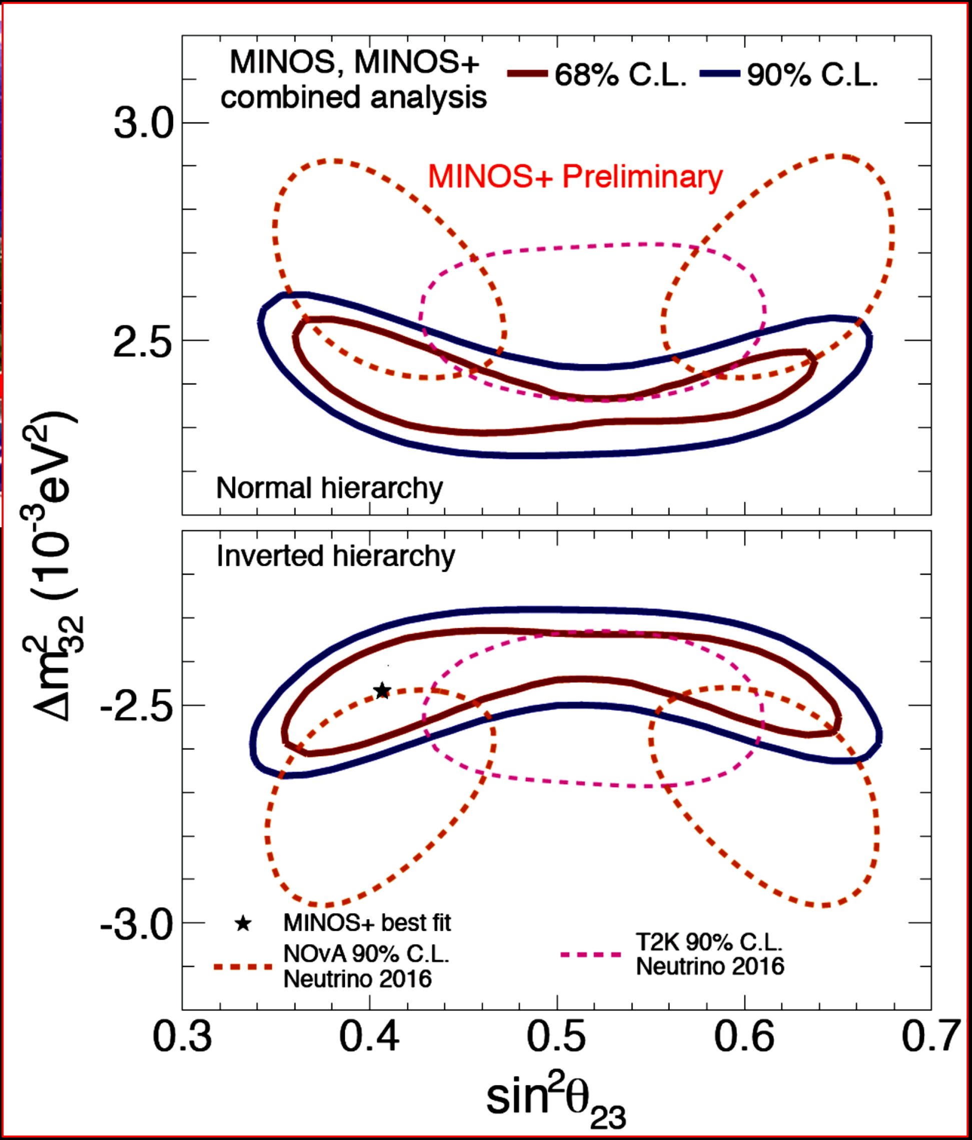


Hierarchy!



Approximate μ-τ symmetry?

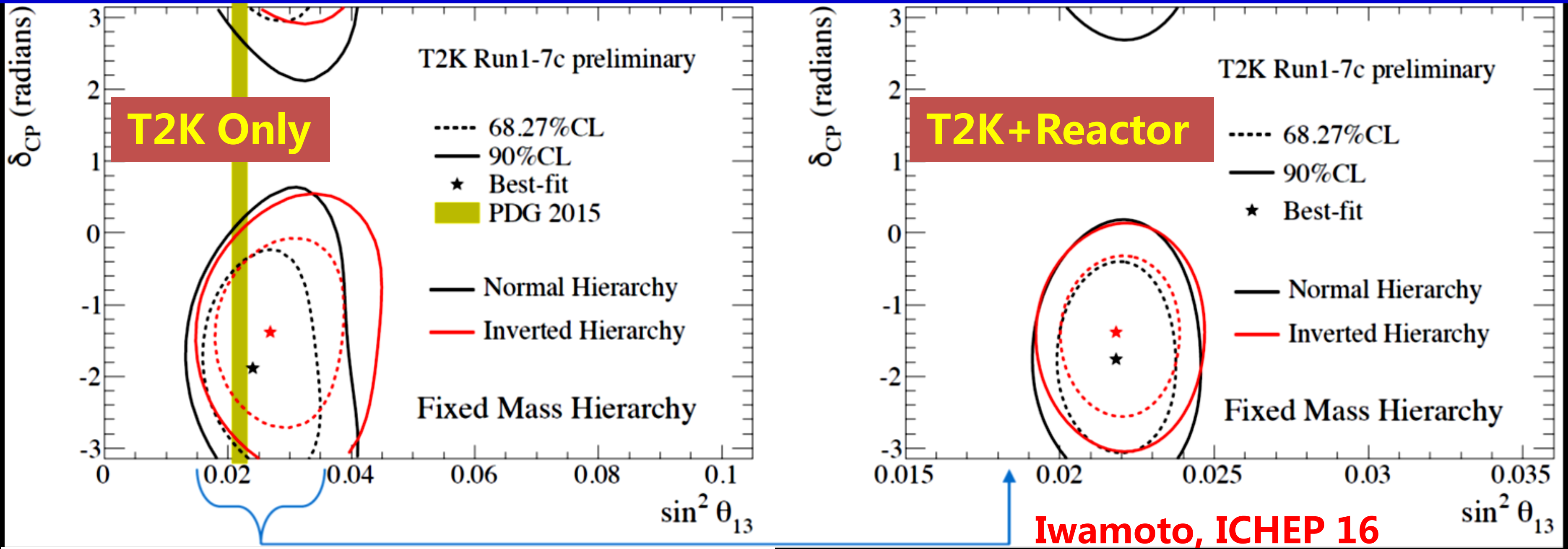
Latest Experimental Results



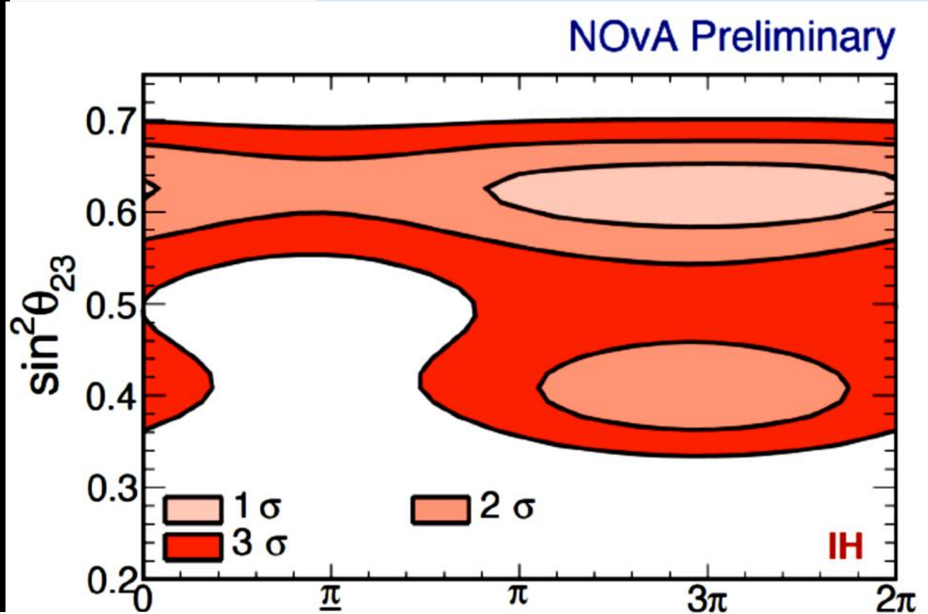
T2K favors a maximal mixing angle $\theta_{23} \sim 45^\circ$, while NOvA & MINOS not

Evans, Neutrino 16; Sanchez, ICHEP 16

Latest Experimental Results



Iwamoto, ICHEP 16



Bian, ICHEP 16

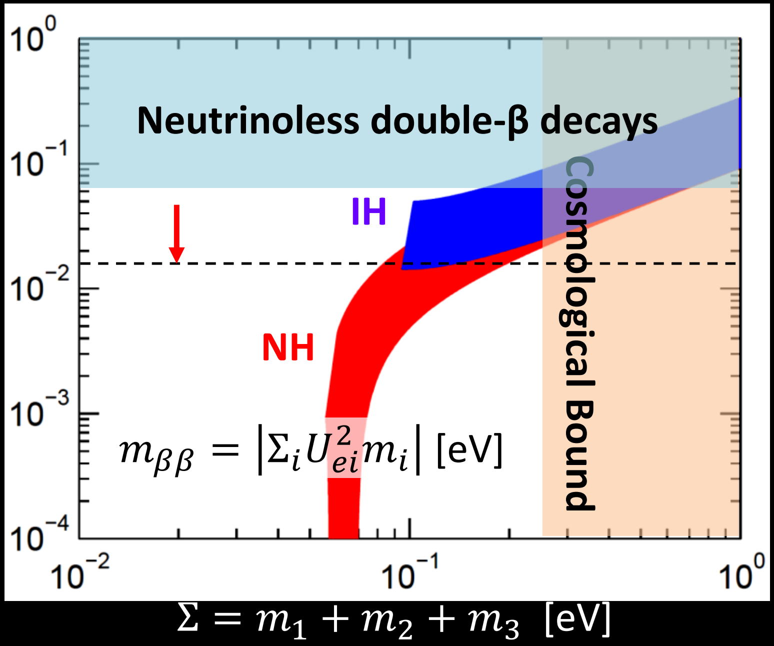
T2K Results

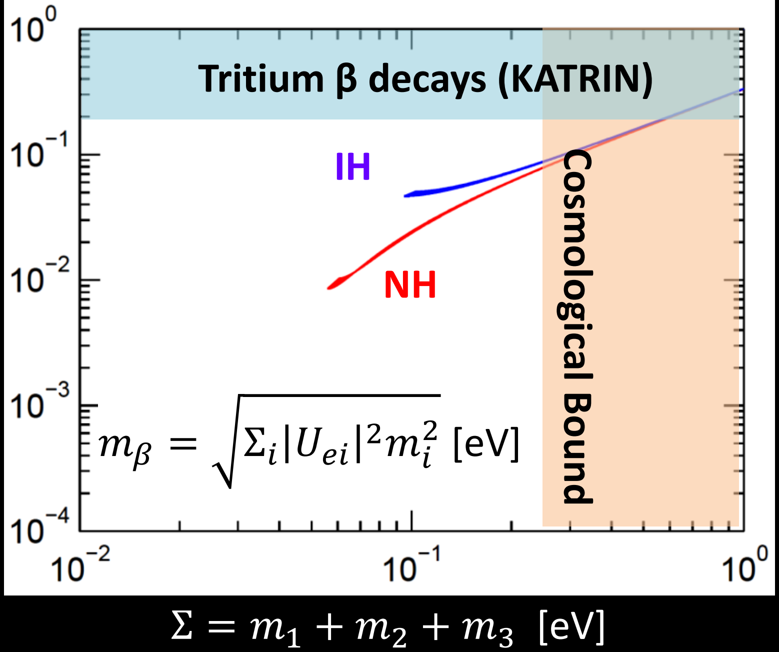
- T2K-only consistent reactor data
- maximal mixing $\theta_{23} = 45^\circ$ favored
- maximal CP phase $\delta = -90^\circ$ favored

NOνA Results

- maximal mixing $\theta_{23} = 45^\circ$ excluded @ 2.5σ
- NH, $\delta \sim -90^\circ$ and $\theta_{23} \sim 39^\circ$ favored
- IH and $\delta \sim 90^\circ$ for $\theta_{23} < 45^\circ$ excluded @ 3σ

Non-oscillation Results





$m_1 < m_2 < m_3$ NH **$m_3 < m_1 < m_2$ IH**

Constraints on absolute neutrino masses

- **Tritium β decays (95% C.L.)**

  $m_\beta < 2.3$ eV (Mainz)

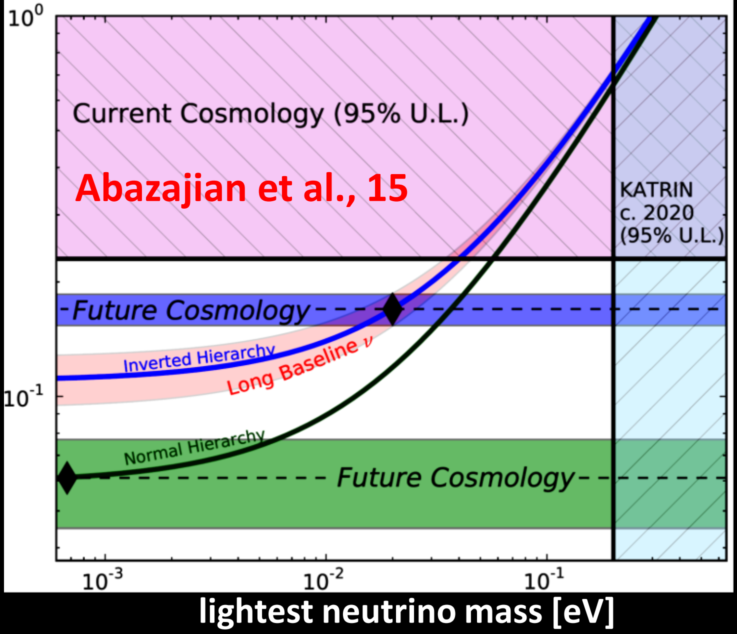
  2.1 eV (Troitzk)
- **Neutrinoless double-β decays (90% C.L.)**

  $m_{\beta\beta} < (0.06 \sim 0.16)$ eV (KamLAND-Zen)

  $(0.19 \sim 0.45)$ eV (EXO-200)

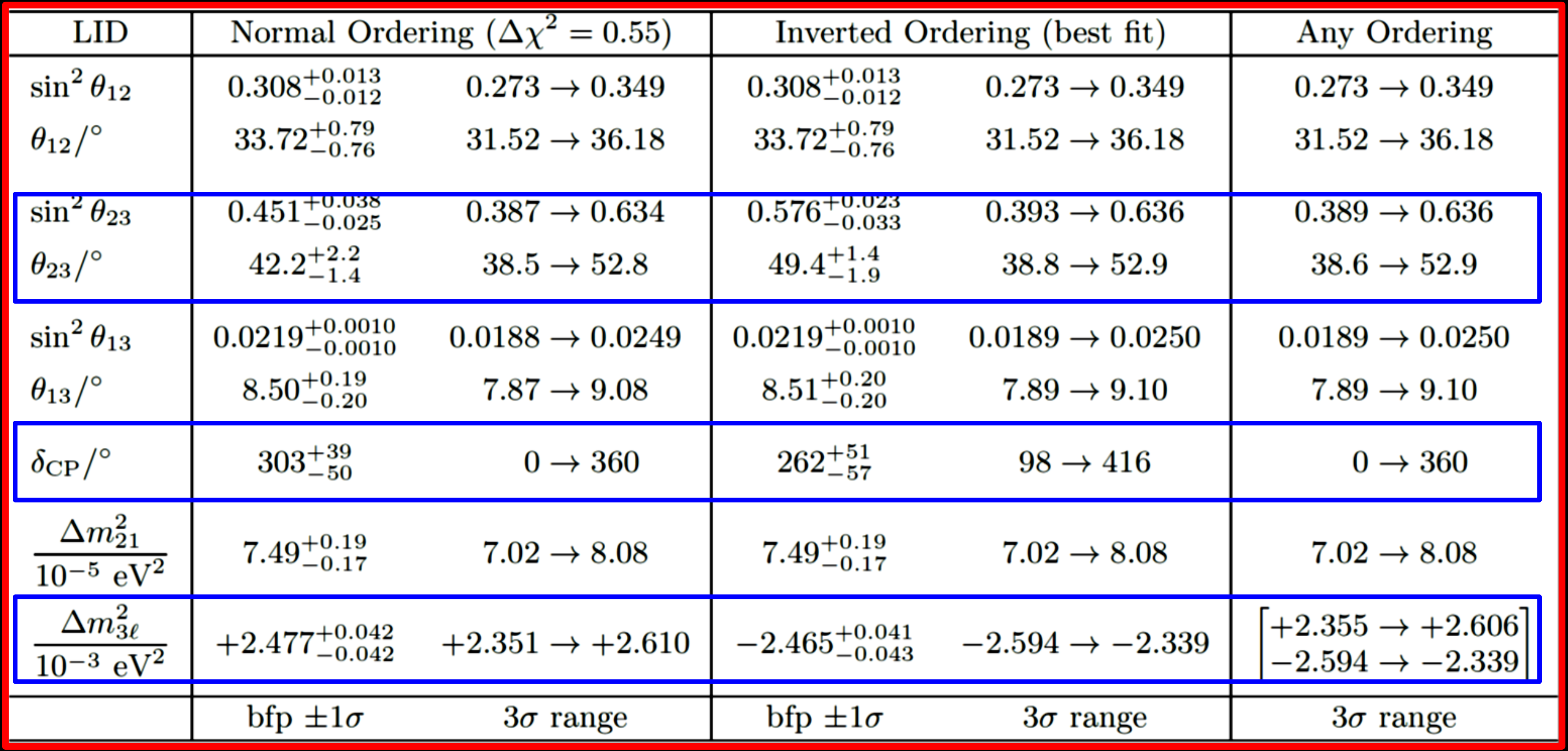
  $(0.22 \sim 0.64)$ eV (GERDA)
- **Cosmological observations (95% probability)**

  $\Sigma < 0.23$ eV (Planck)



Global-fit Analysis

Gonzalez-Garcia et al., NuFIT 2.1 (2016)



LID	Normal Ordering ($\Delta\chi^2 = 0.55$)		Inverted Ordering (best fit)		Any Ordering
$\sin^2\theta_{12}$	$0.308^{+0.013}_{-0.012}$	$0.273 \to 0.349$	$0.308^{+0.013}_{-0.012}$	$0.273 \to 0.349$	$0.273 \to 0.349$
$\theta_{12}/^\circ$	$33.72^{+0.79}_{-0.76}$	$31.52 \to 36.18$	$33.72^{+0.79}_{-0.76}$	$31.52 \to 36.18$	$31.52 \to 36.18$
$\sin^2\theta_{23}$	$0.451^{+0.038}_{-0.025}$	$0.387 \to 0.634$	$0.576^{+0.023}_{-0.033}$	$0.393 \to 0.636$	$0.389 \to 0.636$
$\theta_{23}/^\circ$	$42.2^{+2.2}_{-1.4}$	$38.5 \to 52.8$	$49.4^{+1.4}_{-1.9}$	$38.8 \to 52.9$	$38.6 \to 52.9$
$\sin^2\theta_{13}$	$0.0219^{+0.0010}_{-0.0010}$	$0.0188 \to 0.0249$	$0.0219^{+0.0010}_{-0.0010}$	$0.0189 \to 0.0250$	$0.0189 \to 0.0250$
$\theta_{13}/^\circ$	$8.50^{+0.19}_{-0.20}$	$7.87 \to 9.08$	$8.51^{+0.20}_{-0.20}$	$7.89 \to 9.10$	$7.89 \to 9.10$
$\delta_{\rm CP}/^\circ$	303^{+39}_{-50}	$0 \to 360$	262^{+51}_{-57}	$98 \to 416$	$0 \to 360$
$\frac{\Delta m^2_{21}}{10^{-5}\ \rm eV^2}$	$7.49^{+0.19}_{-0.17}$	$7.02 \to 8.08$	$7.49^{+0.19}_{-0.17}$	$7.02 \to 8.08$	$7.02 \to 8.08$
$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \rm eV^2}$	$+2.477^{+0.042}_{-0.042}$	$+2.351 \to +2.610$	$-2.465^{+0.041}_{-0.043}$	$-2.594 \to -2.339$	$\begin{bmatrix} +2.355 \to +2.606 \\ -2.594 \to -2.339 \end{bmatrix}$
	bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range	3σ range

Neutrino Mass Hierarchy

- Reactor: JUNO, RENO-50
- LBL Acc.: T2K, NOνA, LBNF/DUNE
- Atm: PINGU, ORCA, Hyper-K, INO

Leptonic CP Violation

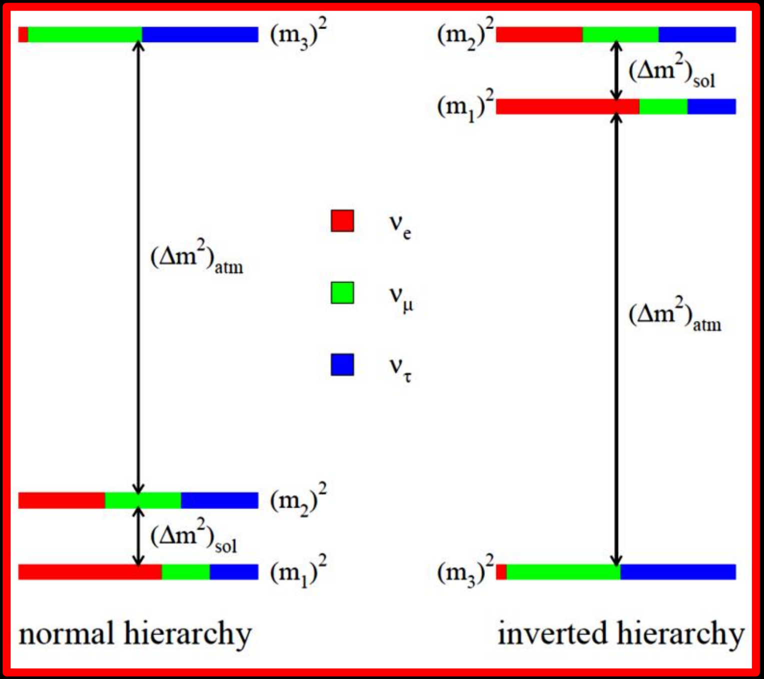
- LBL Acc.: LBNF/DUNE
- Super-B: ESSνSB, MOMENT
- NF & Beta-Beams

Absolute Masses: KATRIN, 0ν2β (e.g., ^{136}Xe & ^{76}Ge), cosmology, …

Future Prospects

Open Questions

- Normal or Inverted (sign of Δm^2_{32}?)
- Leptonic CP Violation ($\delta = ?$)
- Octant of θ_{23} (> or < 45°?)
- Absolute Neutrino Masses ($m_{\mathrm{lightest}} = 0$?)
- Majorana or Dirac Nature ($\nu \neq \nu^{C}$?)
- Majorana CP-Violating Phases (how?)



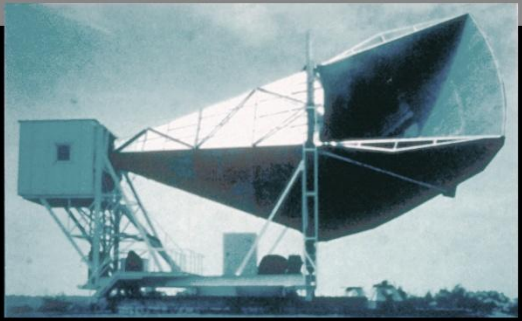
- Extra Neutrino Species
- Exotic Neutrino Interactions
- Other LNV & LFV Processes
- Leptonic Unitarity Violation

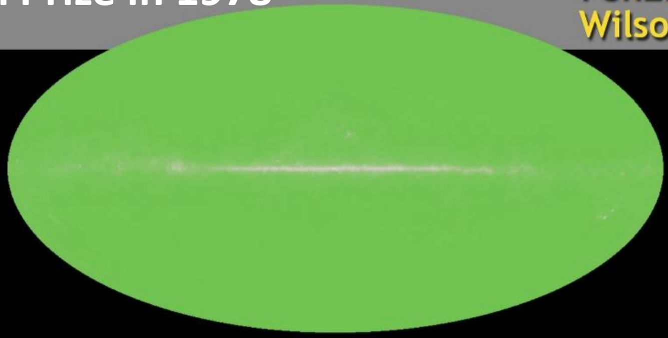
- Origin of Neutrino Masses
- Flavor Structure (Symmetry?)
- Quark-Lepton Connection
- Relations to DM, BAU, or NP

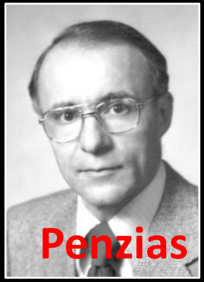
Progress in Observational Cosmology

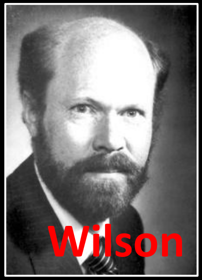
1965 Discovery of CMB, Nobel Prize in 1978

Penzias and Wilson



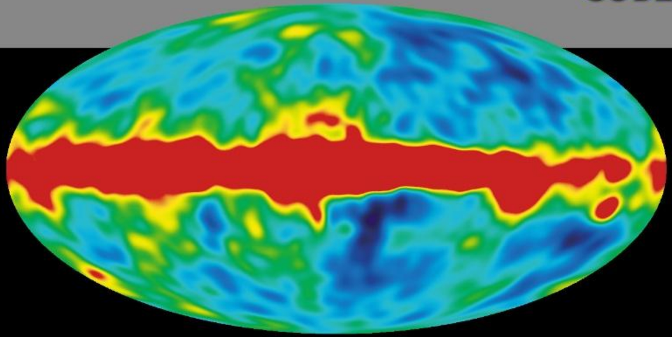


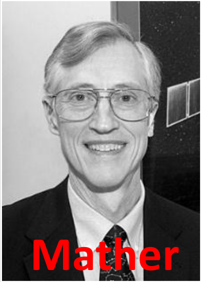


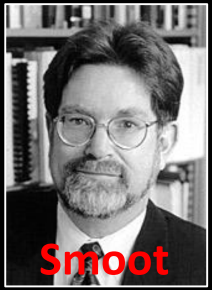


1992 Anisotropy in CMB, Nobel Prize in 2006

COBE

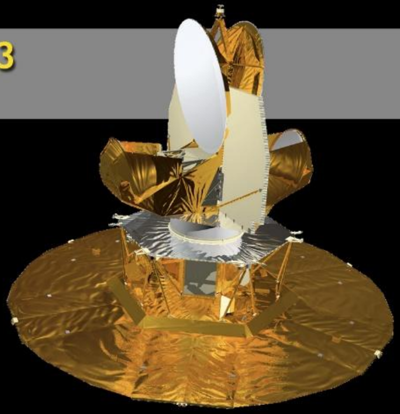


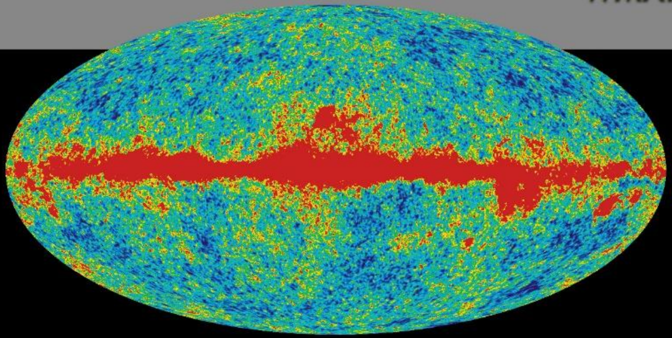




2003

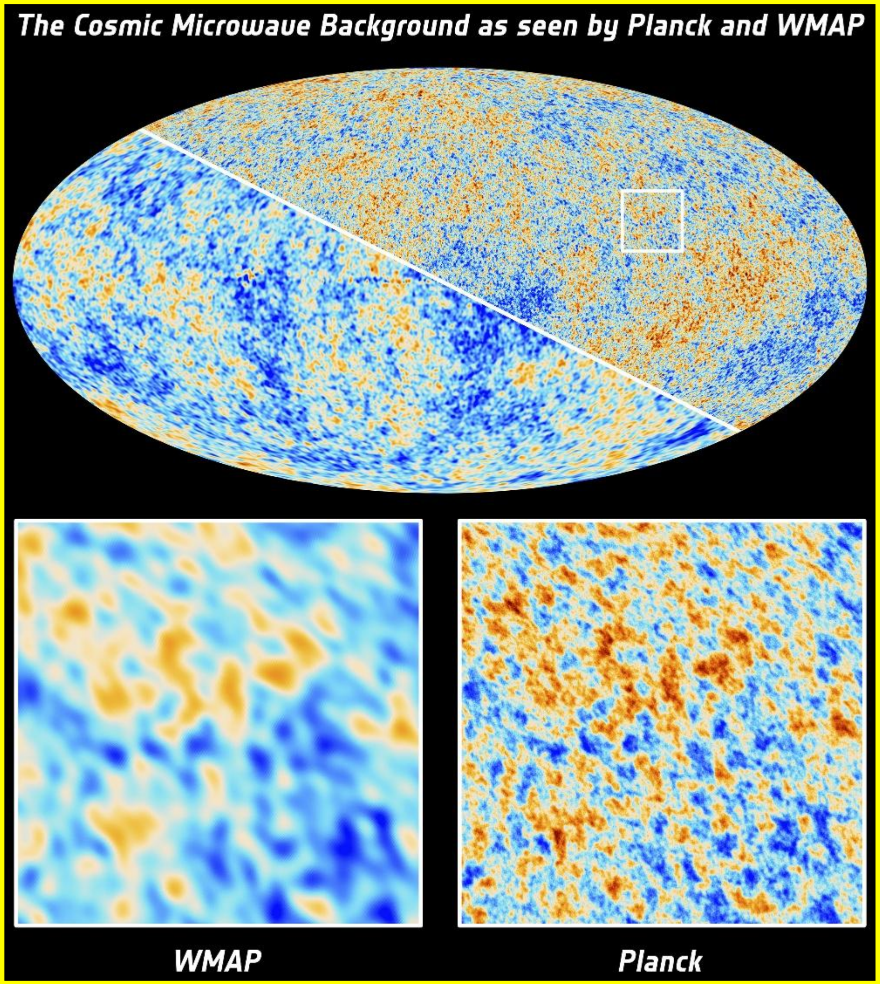
WMAP

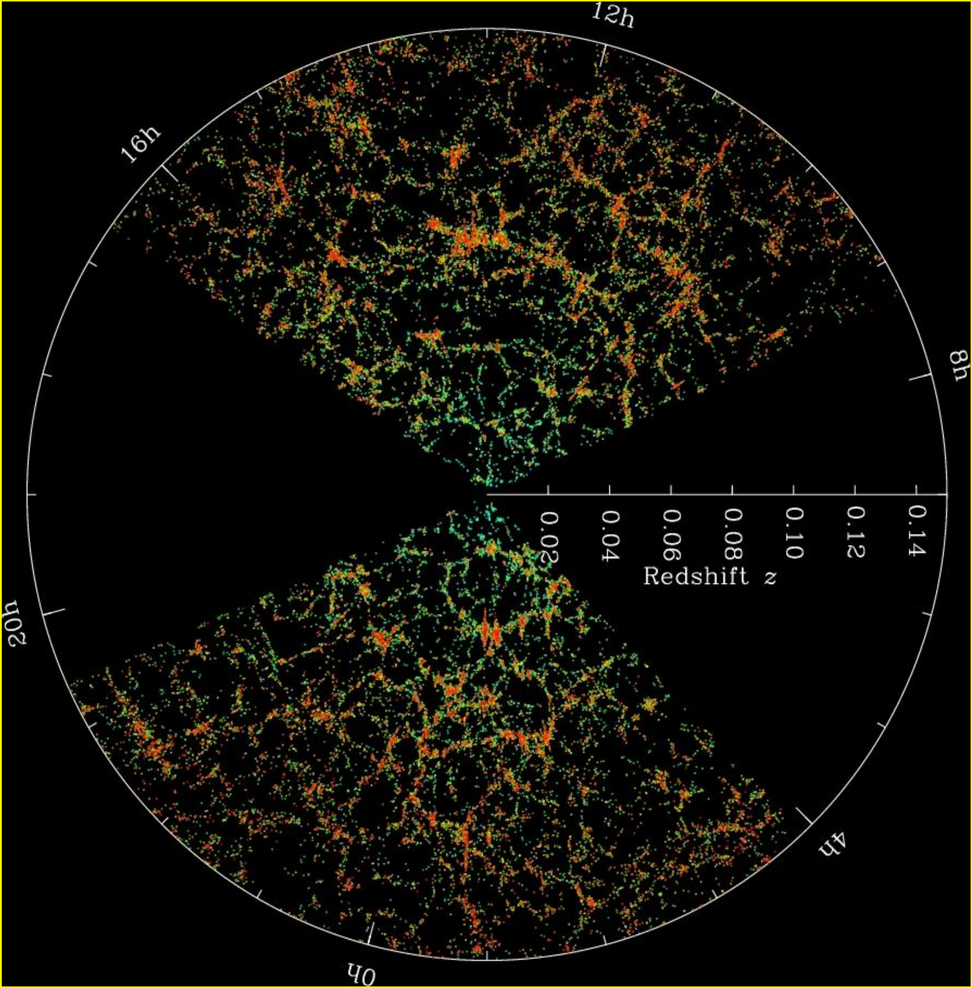




Cosmic Microwave Background (CMB)

Progress in Observational Cosmology

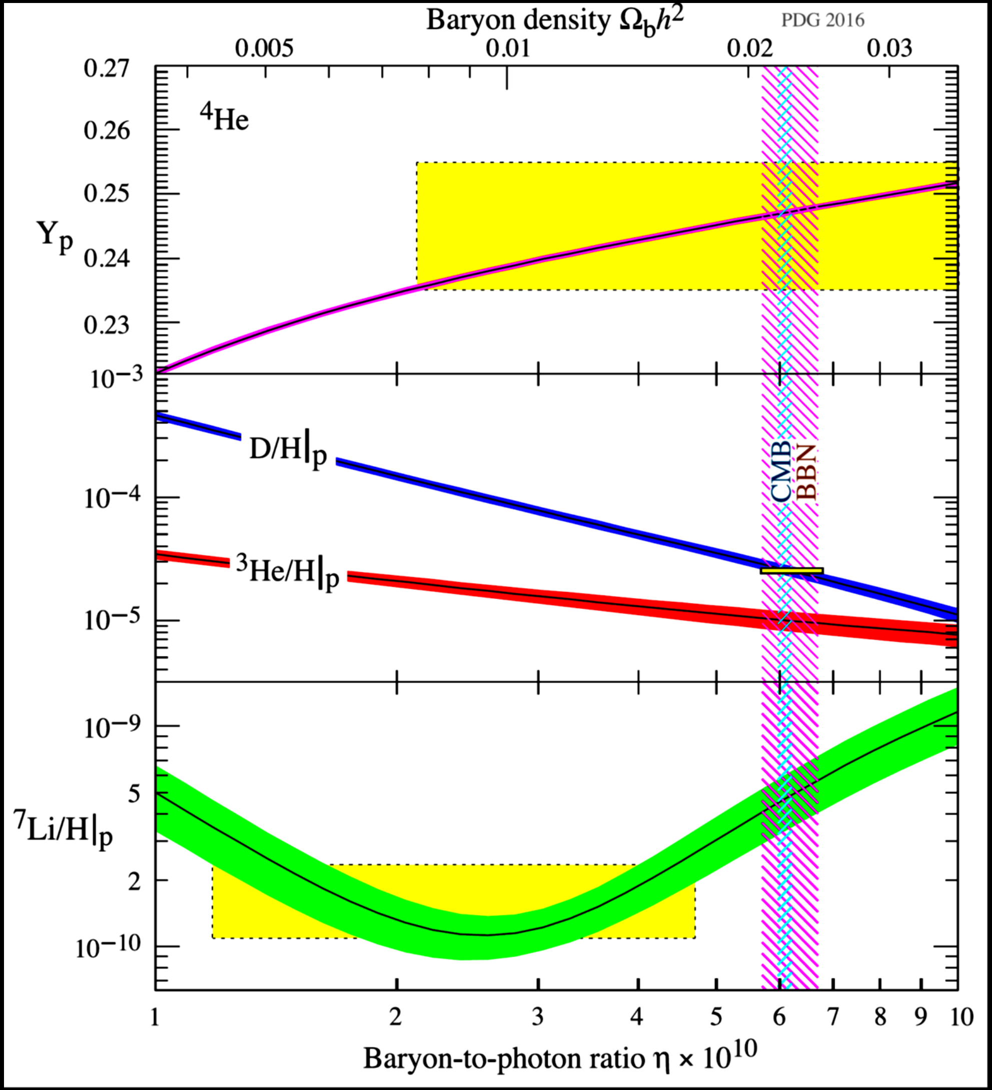


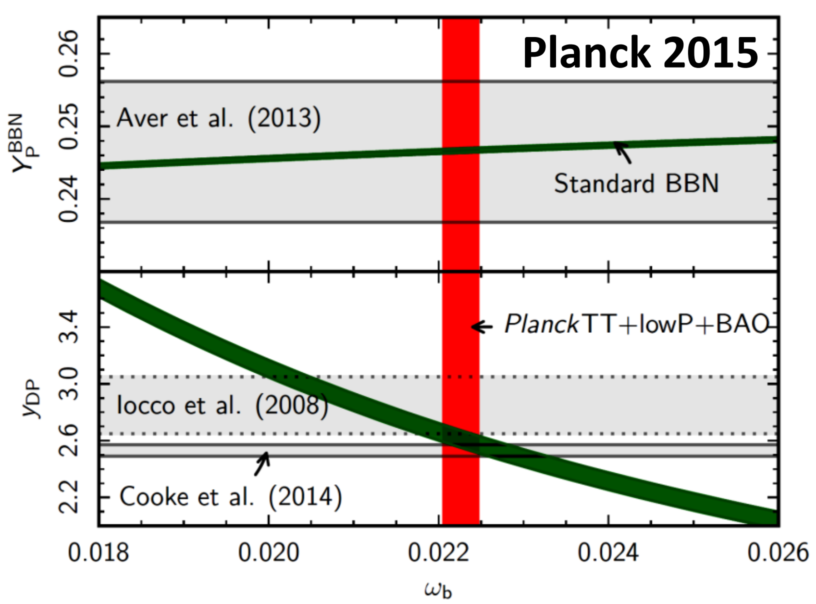


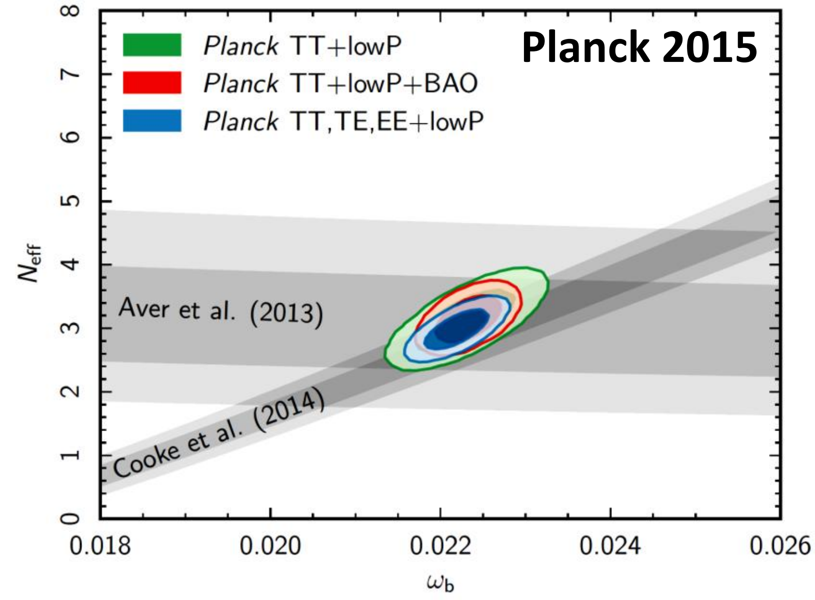
Cosmic **M**icrowave **B**ackground (**CMB**)

Large **S**cale **S**tructure (**LSS**) from Sloan Digital Sky Survey (SDSS)

Progress in Observational Cosmology

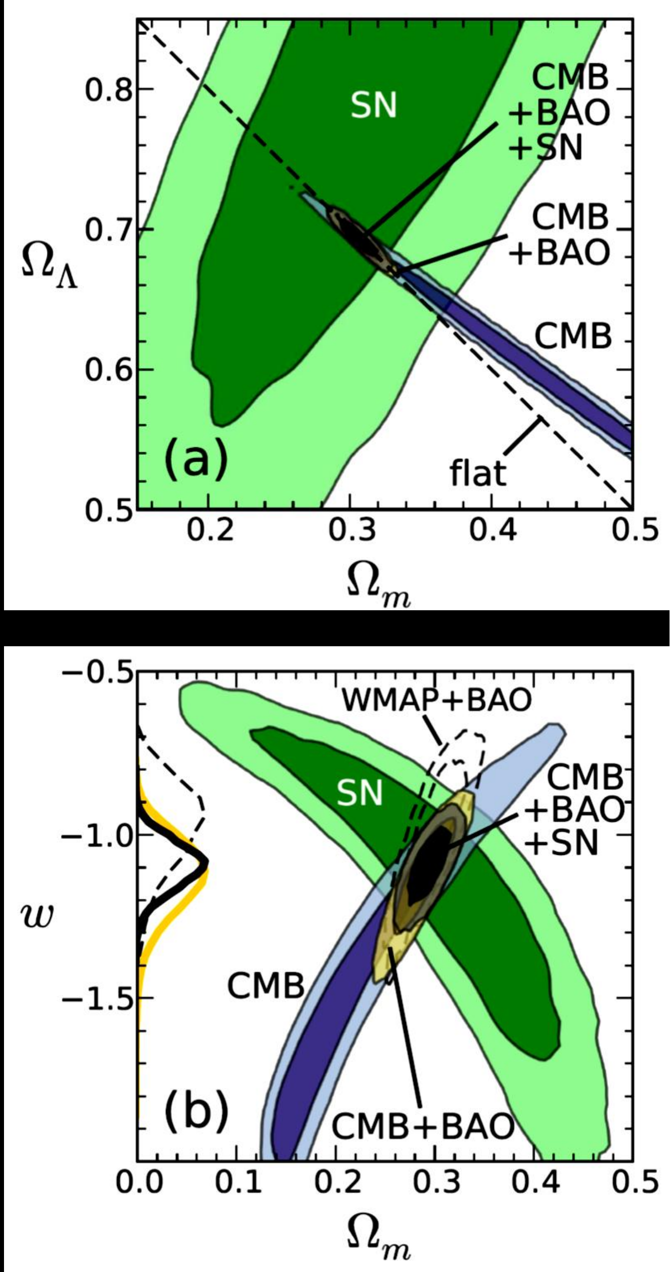


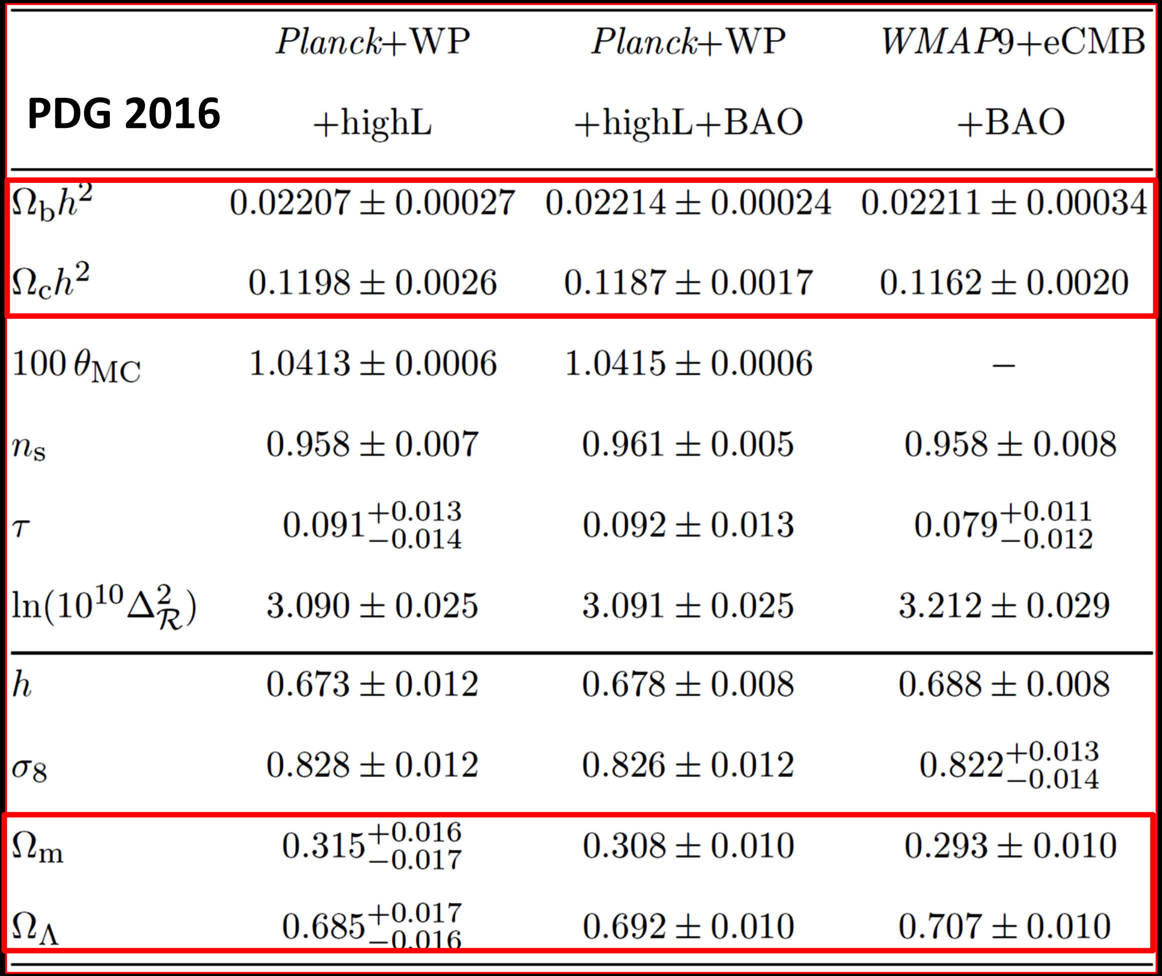




Big Bang Nucleosynthesis (BBN) and CMB

Standard Model of Cosmology



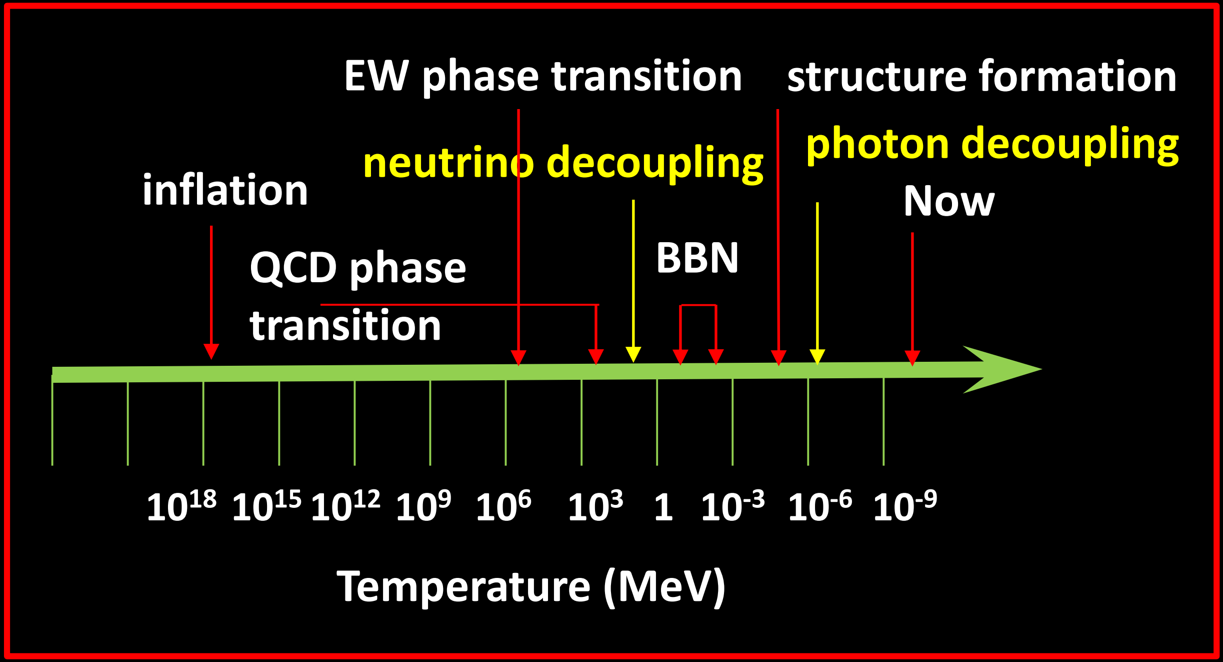


PDG 2016	*Planck*+WP +highL	*Planck*+WP +highL+BAO	*WMAP*9+eCMB +BAO
$\Omega_b h^2$	0.02207 ± 0.00027	0.02214 ± 0.00024	0.02211 ± 0.00034
$\Omega_c h^2$	0.1198 ± 0.0026	0.1187 ± 0.0017	0.1162 ± 0.0020
$100\,\theta_{MC}$	1.0413 ± 0.0006	1.0415 ± 0.0006	–
n_s	0.958 ± 0.007	0.961 ± 0.005	0.958 ± 0.008
τ	$0.091^{+0.013}_{-0.014}$	0.092 ± 0.013	$0.079^{+0.011}_{-0.012}$
$\ln(10^{10}\Delta^2_{\mathcal{R}})$	3.090 ± 0.025	3.091 ± 0.025	3.212 ± 0.029
h	0.673 ± 0.012	0.678 ± 0.008	0.688 ± 0.008
σ_8	0.828 ± 0.012	0.826 ± 0.012	$0.822^{+0.013}_{-0.014}$
Ω_m	$0.315^{+0.016}_{-0.017}$	0.308 ± 0.010	0.293 ± 0.010
Ω_Λ	$0.685^{+0.017}_{-0.016}$	0.692 ± 0.010	0.707 ± 0.010

Cosmic Neutrino Background (CvB)

- Indirect evidence from BBN, CMB and LSS
- How to detect **CvB** in terrestrial experiments?

Formation of CνB



EW phase transition

structure formation

neutrino decoupling

photon decoupling

inflation

Now

BBN

QCD phase transition

10^{18} 10^{15} 10^{12} 10^{9} 10^{6} 10^{3} 1 10^{-3} 10^{-6} 10^{-9}

Temperature (MeV)

☐ ν in thermal equilibrium

@ high temperature

$$\boxed{\begin{aligned} &\nu_\alpha \nu_\beta \leftrightarrow \nu_\alpha \nu_\beta \\ &\nu_\alpha \bar{\nu}_\beta \leftrightarrow \nu_\alpha \bar{\nu}_\beta \\ &\nu_\alpha e^- \leftrightarrow \nu_\alpha e^- \\ &\nu_\alpha \bar{\nu}_\alpha \leftrightarrow e^+ e^- \\ &e^+ e^- \leftrightarrow \gamma\gamma \end{aligned}}$$

$$T_\nu = T_e = T_\gamma$$

☐ neutrino decoupling

$\Gamma < H$ @ $T \sim 1$ MeV

Weak interactions $\boxed{\Gamma \approx G_F^2 T^5}$

Hubble expansion $\boxed{H \approx \frac{\sqrt{g_*}\,T^2}{M_{pl}}}$

Fermi-Dirac spectrum

☐ photon reheating

@ $T < m_e$

$$\boxed{e^+ e^- \leftrightarrow \gamma\gamma} \qquad \boxed{T_\nu = \left(\frac{4}{11}\right)^{1/3} T_\gamma}$$

☐ Basic properties of CνB

- ➢ $T_0 = 1.95$ K and $\langle p \rangle = 3T_0 = 5 \times 10^{-4}$ eV
- ➢ number density $n = 56\ \text{cm}^{-3}$ per species

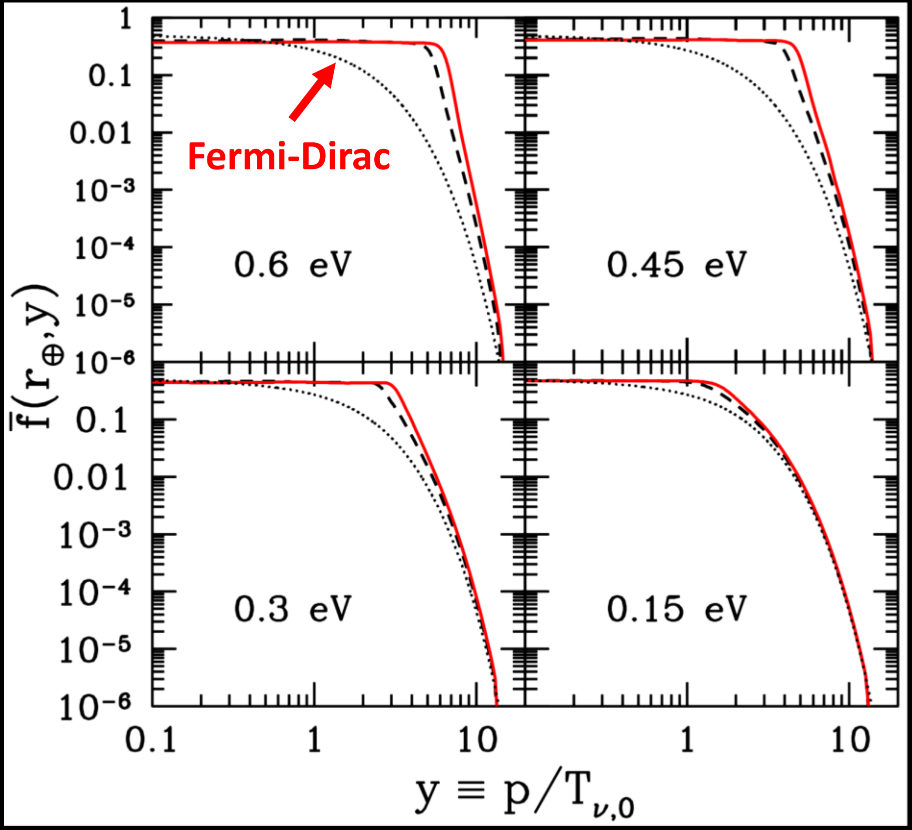
Neutrino Clustering

Neutrinos in the gravitational potential of CDM halos

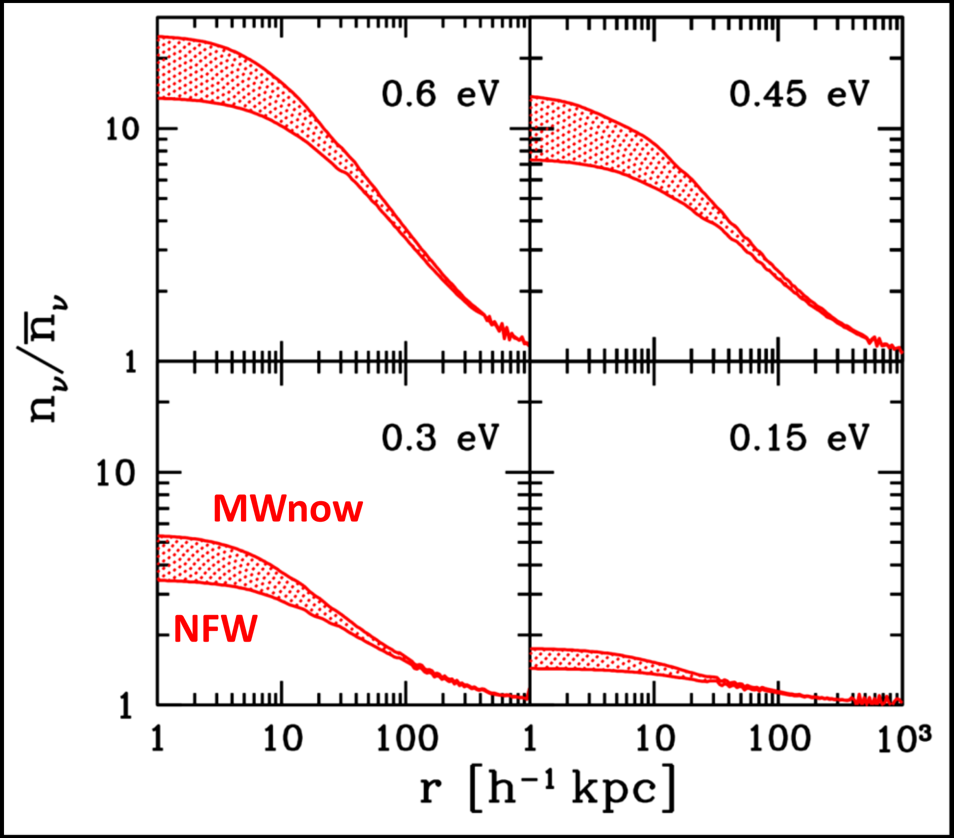
- Input CDM halo profiles (Navarro-Frenk-White)
- Neutrinos are treated as perturbations

Singh, Ma, 03;
Ringwald, Wong, 04

Distribution function at the Earth



Clustering in the Milky Way



At the Earth, enhanced by about 1 to 20

Prospects for CνB Detection

- ☐ **Acceleration in the neutrino wind**

  Shvartsman et al., 82; Smith, Lewin, 83; Duda et al., 01

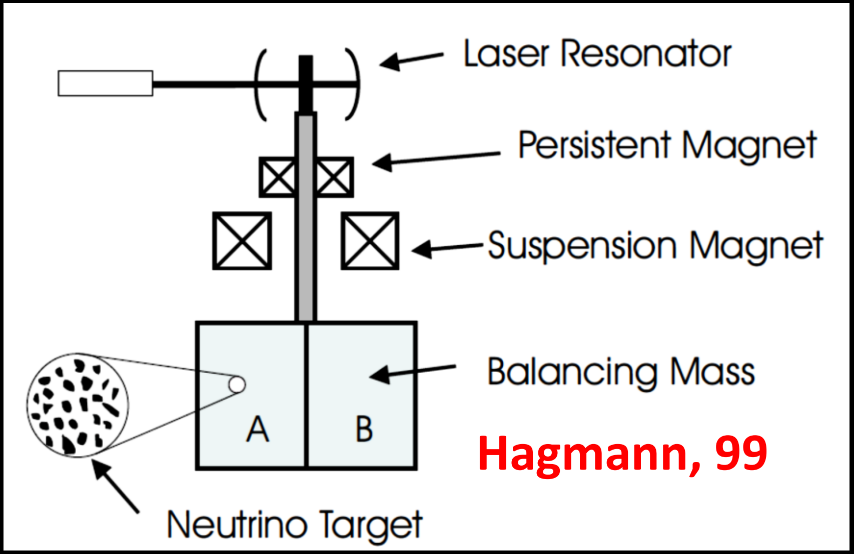
Target mass

$$2 \times 10^{-28} \frac{n_\nu}{\bar{n}_\nu} \frac{10^{-3}\,c}{v_{\rm rel}} \boxed{\frac{\rho_{\rm t}}{{\rm g/cm^3}} \left(\frac{r_{\rm t}}{\lambdabar}\right)^3} \frac{\rm cm}{\rm s^2}$$

de Broglie wavelength

Current Sensitivity
10^{-13} cm s^{-2}

Ringwald, 05



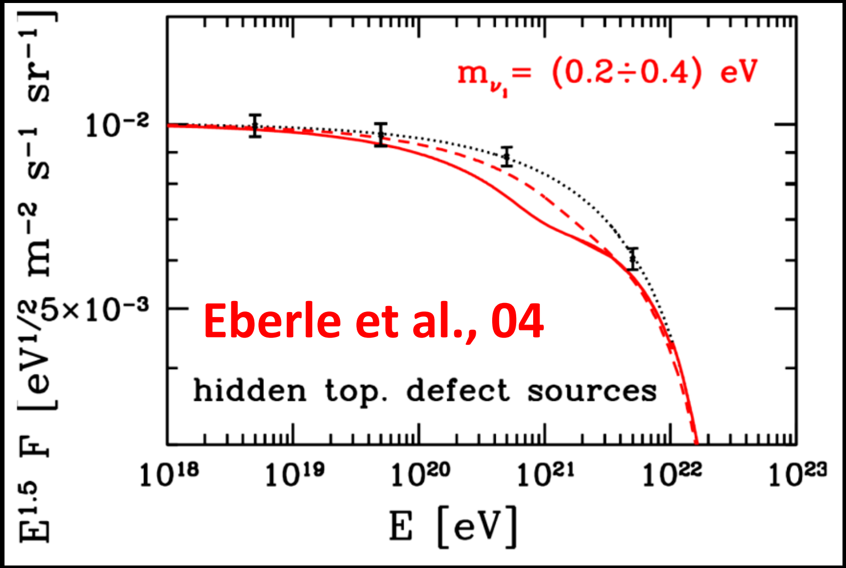
Hagmann, 99

- ☐ **Resonant absorption of EHE neutrinos**

  Weiler, 82; Eberle et al., 04; Ringwald, 09

$$E^{\rm res}_{0,i} = \frac{m_Z^2}{2 m_{\nu_{0,i}}} = 4.2 \times 10^{12} \left(\frac{\rm eV}{m_{\nu_i}}\right) {\rm GeV}$$

Sources of EHE neutrinos
Nearly-degenerate masses
Z-burst for EHE CR events



Eberle et al., 04

Prospects for CνB Detection

- Direct evidence for **CνB**, trace back to the early Universe at 1s while CMB tells us the story at 380 000 yrs
- Probe intrinsic properties of neutrinos, the only chance to get non-relativistic neutrinos (e.g., Majorana vs. Dirac)

Temperature today

$$T_\nu = \left(\frac{4}{11}\right)^{1/3} T_\gamma \simeq 1.945\ \mathrm{K}$$

Mean momentum today

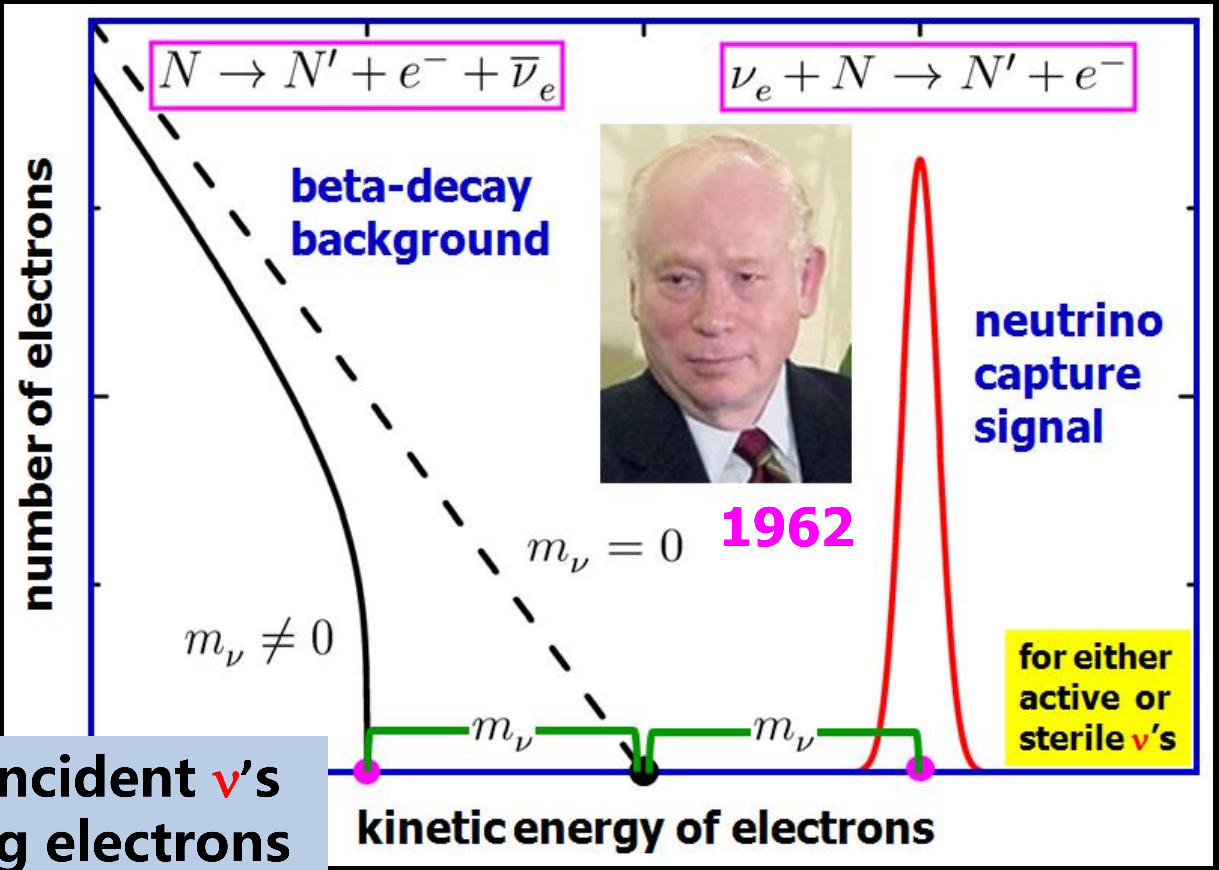
$$\begin{aligned}\langle p_\nu \rangle &\simeq 3.151 T_\nu \\ &\simeq 5.281 \times 10^{-4}\ \mathrm{eV}\end{aligned}$$

At least 2 ν's cold today

NON-relativistic ν's!

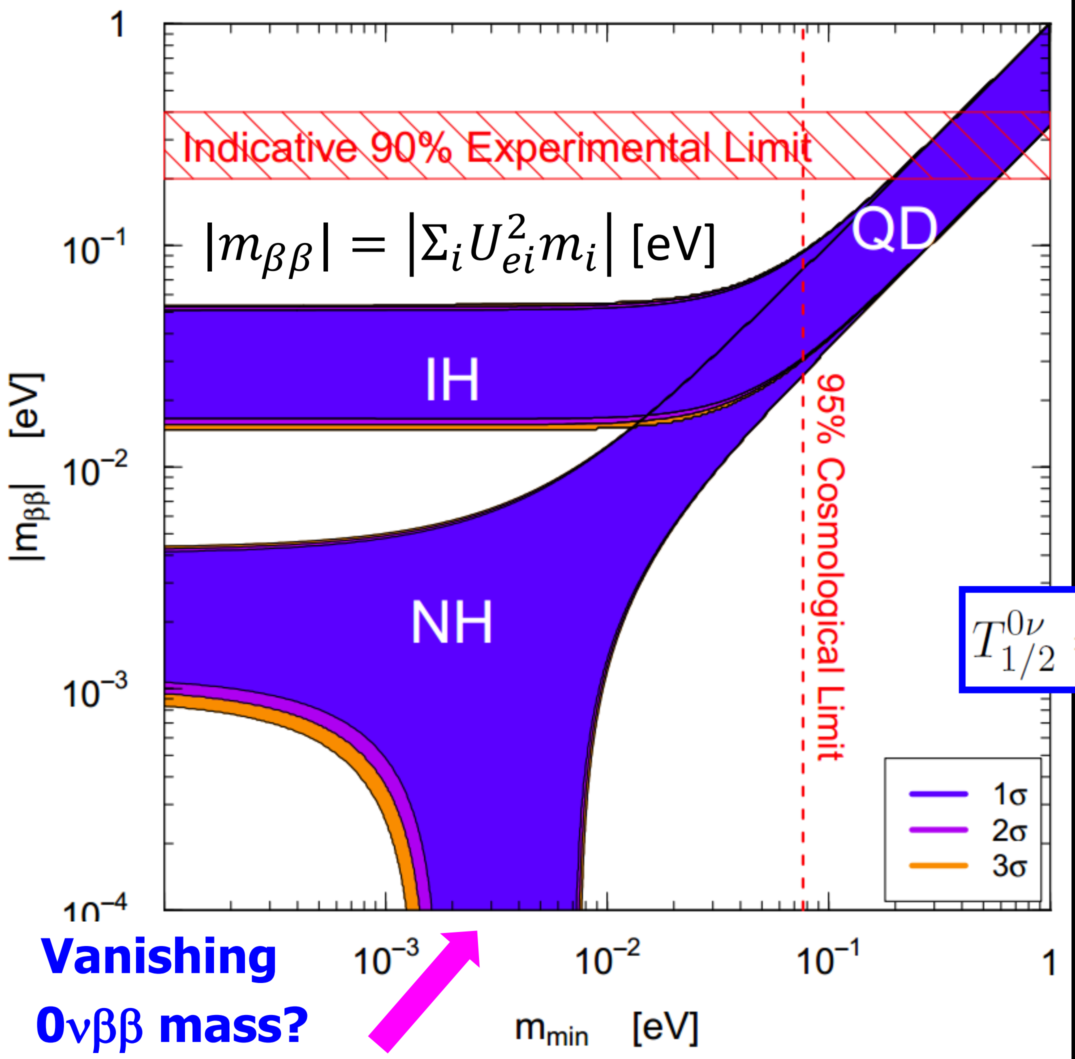
(Irvine & Humphreys, 83)

Relic neutrino capture on β-decaying nuclei



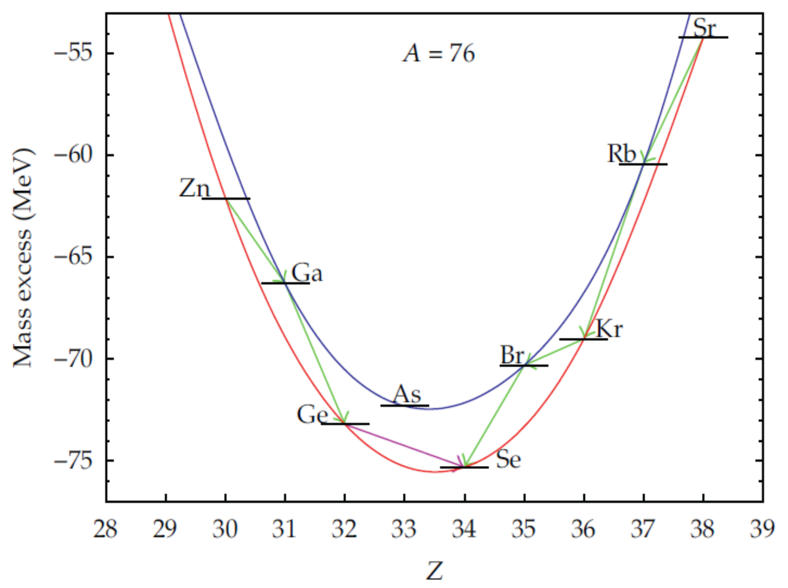
no energy threshold on incident ν's
mono-energetic outgoing electrons

Neutrinoless Double Beta Decays

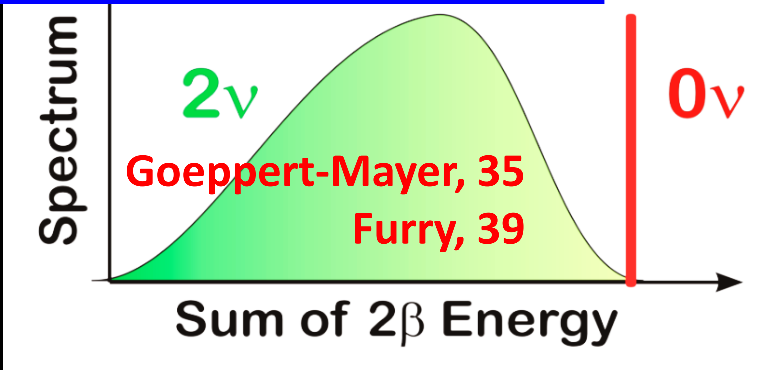


$$|m_{\beta\beta}| = \left|\Sigma_i U_{ei}^2 m_i\right| \text{ [eV]}$$

Vanishing 0νββ mass?



$$T_{1/2}^{0\nu} = \left(G^{0\nu}\right)^{-1} \left|M^{0\nu}\right|^{-2} \left|m_{\beta\beta}\right|^{-2}$$



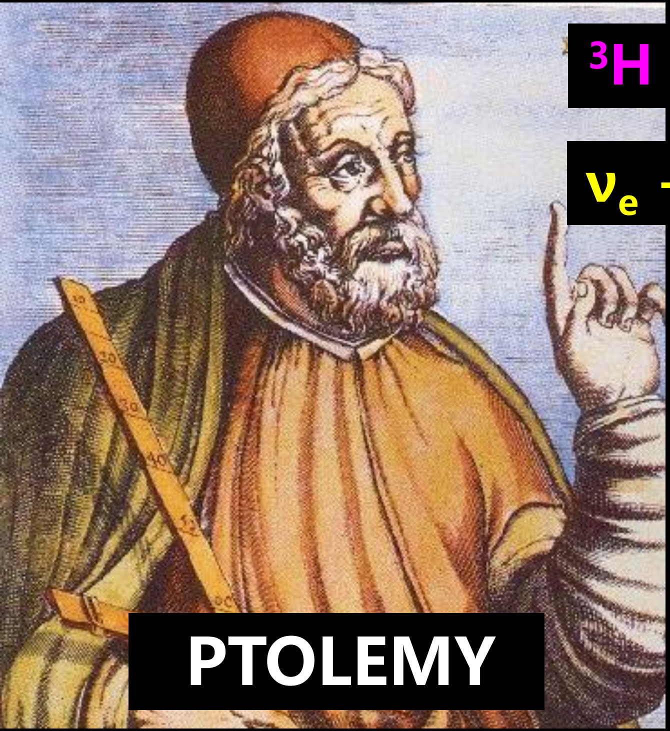
Goeppert-Mayer, 35
Furry, 39

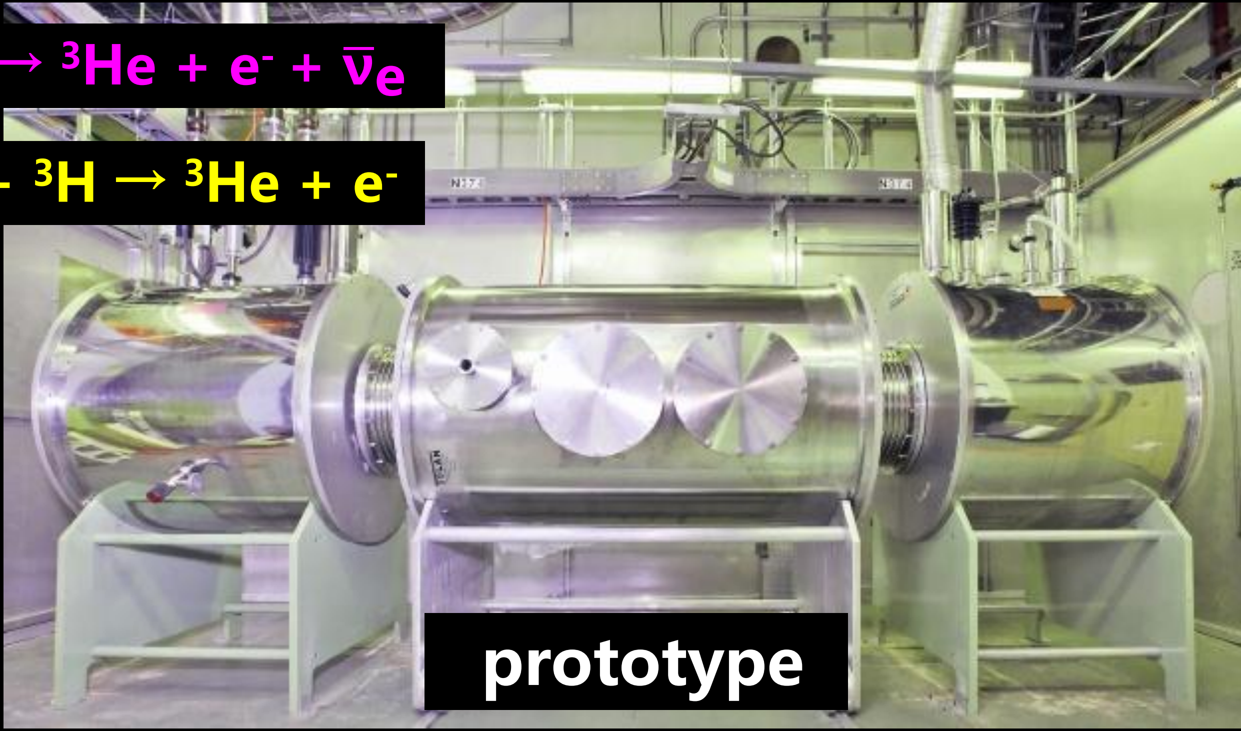
Three possible ways to distinguish between Majorana and Dirac ν's:
(a) 0νββ decays (b) EM dipole moments (c) Nonrelativistic behaviors

Towards a real experiment?

$^{3}H \rightarrow {}^{3}He + e^{-} + \bar{\nu}_e$

$\nu_e + {}^{3}H \rightarrow {}^{3}He + e^{-}$





- ★ first experiment
- ★ 100 g of tritium
- ★ graphene target
- ★ planned energy resolution 0.15 eV

★ CνB capture rate

$$\Gamma^{D}_{C\nu B} \sim 4\ \mathrm{yr}^{-1}$$

$$\Gamma^{M}_{C\nu B} \sim 8\ \mathrm{yr}^{-1}$$

D = Dirac

M = Majorana

PTOLEMY

Princeton **T**ritium **O**bservatory for **L**ight, **E**arly-Universe, **M**assive-Neutrino **Y**ield (Betts et al, arXiv:1307.4738)

Detection of CνB

Capture rate of a polarized neutrino state $\nu_j(s_\nu)$ on a free neutron

$$\sigma_j(s_\nu)v_{\nu_j} = \frac{G_F^2}{2\pi}|V_{ud}|^2\left|U_{ej}\right|^2 F(Z,E_e)\frac{m_p}{m_n}E_e p_e A(s_\nu)(f^2+3g^2)$$

Note: Spin-dependent Factor

$$A(s_\nu) \equiv 1 - 2s_\nu v_{\nu_j} = \begin{cases} 1 - v_{\nu_j}\,, & s_\nu = +1/2 \\ 1 + v_{\nu_j}, & s_\nu = -1/2 \end{cases}$$

RH Helicity

LH Helicity

In the limit $v_{\nu_j} \longrightarrow 1$, the state of $s_\nu = +1/2$ cannot be captured

In the limit $v_{\nu_j} \longrightarrow 0$, both RH and LH helical states do contribute

Total Rate

Long et al., 14;
Lisanti et al., 14

$$\boxed{\Gamma_{\mathrm{C\nu B}} = \sum_j \left[\sigma_j\left(+\frac{1}{2}\right)v_{\nu_j}n_j(\nu_{\mathrm{hR}}) + \sigma_j\left(-\frac{1}{2}\right)v_{\nu_j}n_j(\nu_{\mathrm{hL}})\right]N_T}$$

Number Densities of Helical States

Conservation of Helicity: $[\hat{H}, \hat{h}] = 0$ for free particles after decoupling

$$\hat{H} \equiv \gamma^0 m + \gamma^0 \vec{\gamma} \cdot \vec{p} = \begin{pmatrix} m & \vec{\sigma} \cdot \vec{p} \\ \vec{\sigma} \cdot \vec{p} & -m \end{pmatrix} \qquad \hat{h} \equiv \frac{\vec{\Sigma} \cdot \vec{p}}{|\vec{p}|} = \frac{1}{|\vec{p}|} \begin{pmatrix} \vec{\sigma} \cdot \vec{p} & 0 \\ 0 & \vec{\sigma} \cdot \vec{p} \end{pmatrix}$$

In the rest frame of CνB, the background neutrinos are isotropic

Long et al., 14	Dirac Neutrinos		Majorana Neutrinos
Decoupling	$n(\nu_\mathrm{L}) = n(z)$, $n(\bar{\nu}_\mathrm{R}) = n(z)$,	$n(\nu_\mathrm{R}) \approx 0$ $n(\bar{\nu}_\mathrm{L}) \approx 0$	$n(\nu_\mathrm{L}) = n(z)$ $n(\nu_\mathrm{R}) = n(z)$
Nowadays	$n(\nu_\mathrm{hL}) = n_0$, $n(\bar{\nu}_\mathrm{hR}) = n_0$,	$n(\nu_\mathrm{hR}) \approx 0$ $n(\bar{\nu}_\mathrm{hL}) \approx 0$	$n(\nu_\mathrm{hL}) = n_0$ $n(\nu_\mathrm{hR}) = n_0$
Total Rates	$\boxed{\Gamma^\mathrm{D}_\mathrm{C\nu B} = \bar{\sigma} n_0 N_\mathrm{T}}$	$\bar{\sigma} \approx 3.8 \times 10^{-45}\ \mathrm{cm}^2$	$\boxed{\Gamma^\mathrm{M}_\mathrm{C\nu B} = 2\bar{\sigma} n_0 N_\mathrm{T}}$

Negligible RH Dirac Neutrinos?

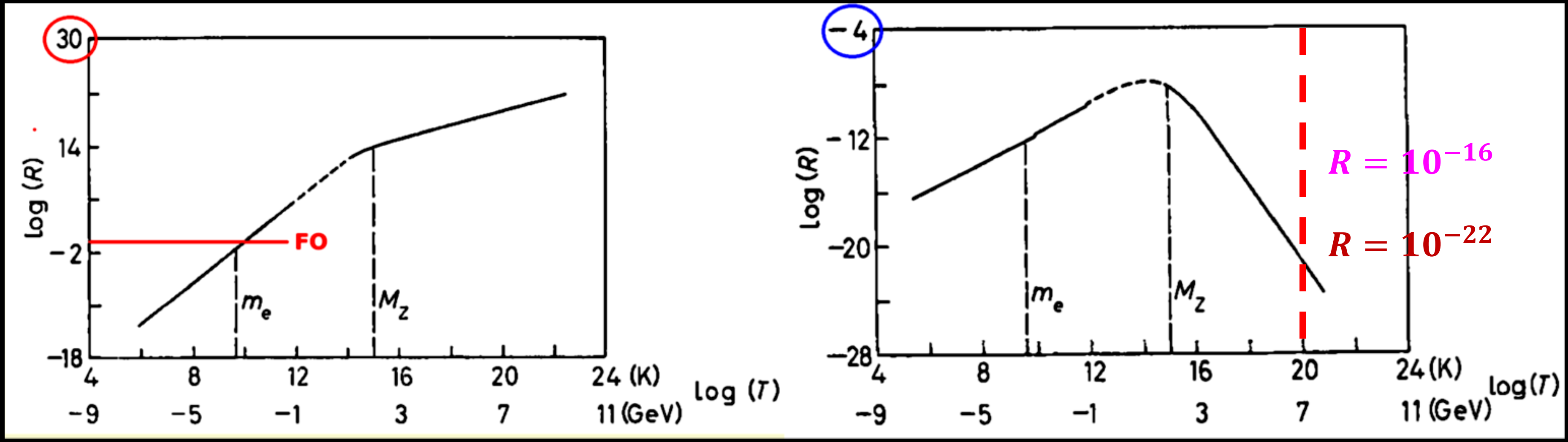
Zhang, S.Z., arXiv:1509.02274

Extension of SM with RH ν's

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \overline{\nu_{\alpha\rm R}}\, i\partial\!\!\!/\, \nu_{\alpha\rm R} - \left[\overline{\ell_{\alpha\rm L}}\, (Y_\nu)_{\alpha\beta}\, \tilde{H} \nu_{\beta\rm R} + \text{h.c.}\right]$$

$$m_i = O(0.1\ \text{eV}) \quad \Longrightarrow \quad y_i = O\left(10^{-12}\right) \ll 1$$

$$\frac{\mathrm{d}n_{\nu_{i\rm R}}}{\mathrm{d}t} + 3Hn_{\nu_{i\rm R}} = \left(1 - \frac{n_{\nu_{i\rm R}}}{n^{\rm eq}_{\nu_{i\rm R}}}\right)\gamma_{\rm D} \qquad \boxed{R = \frac{\Gamma_{\nu_R}}{H}} \qquad \gamma(H \to \overline{\nu_{i\rm L}}\nu_{i\rm R}) = \frac{M_H \Gamma_H T^2}{2\pi^2} K_1(M_H/T) \equiv \gamma_{\rm D}$$

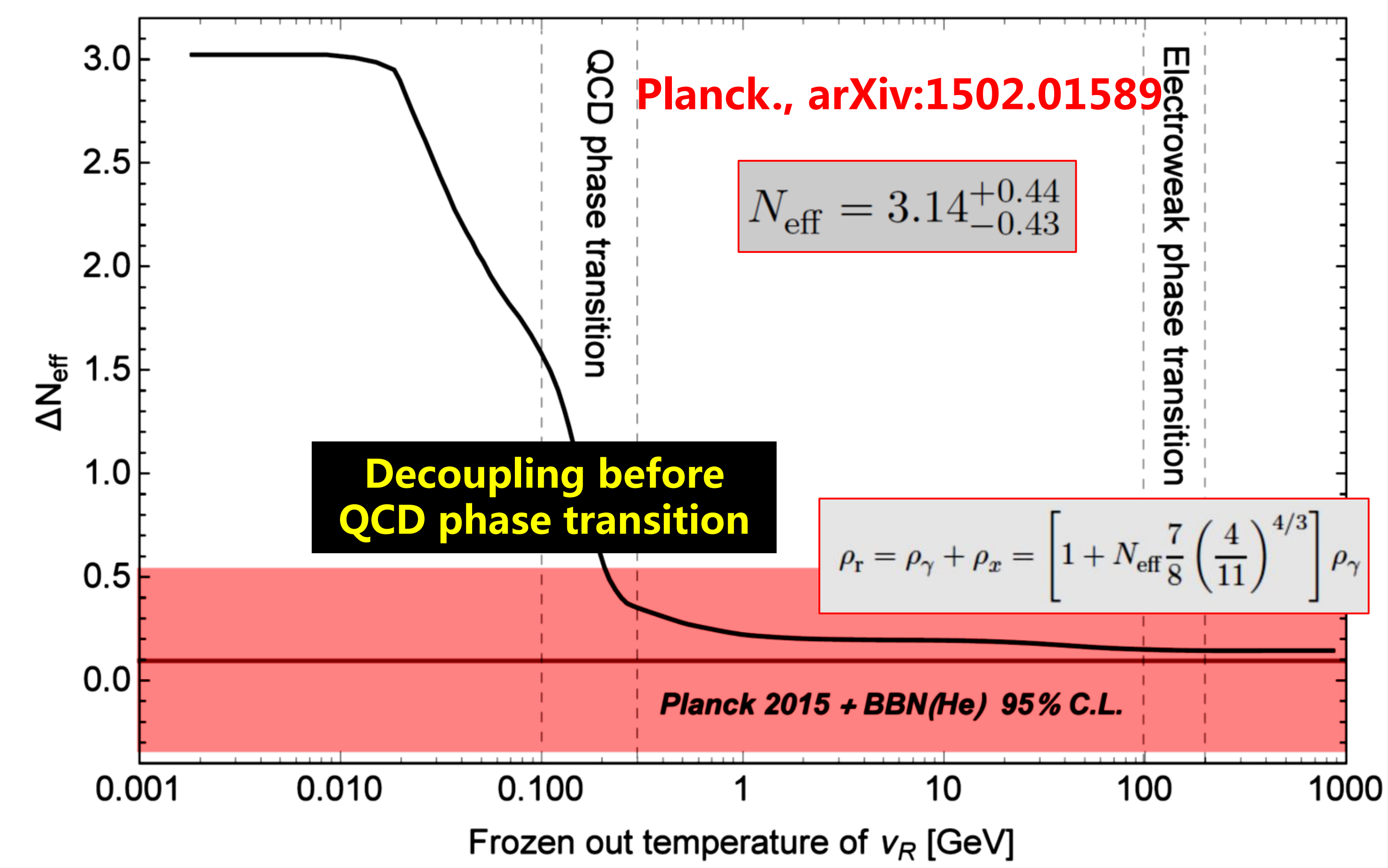


(Antonelli, Fargion & Konoplich, 81)

The production rate found to be much larger, but not large enough

Cosmological Constraints

Zhang, S.Z., arXiv:1509.02274



Planck., arXiv:1502.01589

$$N_{\rm eff} = 3.14^{+0.44}_{-0.43}$$

Decoupling before QCD phase transition

$$\rho_{\rm r} = \rho_\gamma + \rho_x = \left[1 + N_{\rm eff}\frac{7}{8}\left(\frac{4}{11}\right)^{4/3}\right]\rho_\gamma$$

Anchordoqui, Goldberg, 12;

Anchordoqui, Goldberg, Steigman, 13

$$\frac{n_{\nu_{\rm R}}(T^{\rm L}_{\rm fo})}{n_{\nu_{\rm L}}(T^{\rm L}_{\rm fo})} = \frac{g_{*s}(T^{\rm L}_{\rm fo})}{g_{*s}(T^{\rm R}_{\rm fo})}$$

$$\Delta N_{\rm eff} = \left[\frac{g_{*s}(T^{\rm L}_{\rm fo})}{g_{*s}(T^{R}_{\rm fo})}\right]^{4/3} N^{\nu}$$

$$\Delta N_{\rm eff} = 0.53$$

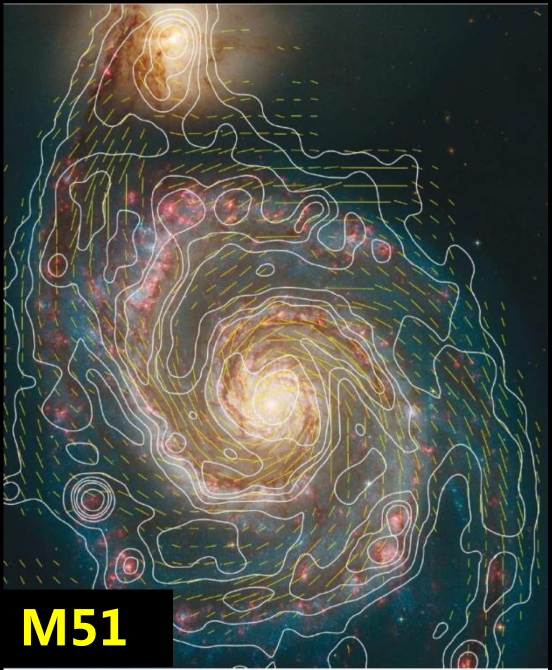
$$\frac{n(\nu_{\rm R})}{n(\nu_{\rm L})} = 0.28$$

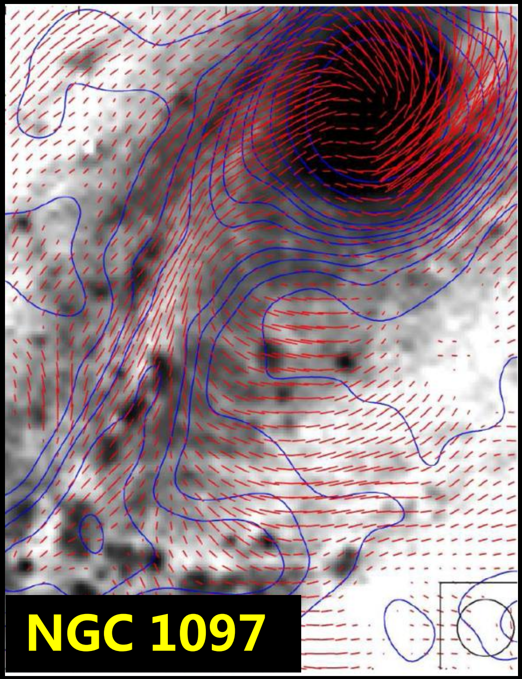
★ Assume that RH ν's can be in thermal equilibrium with matter

★ RH ν's will be counted as extra radiation during BBN and CMB

★ QCD phase transition releases a large entropy to dilute RH ν's

Primordial Magnetic Fields


M51


NGC 1097

The galactic magnetic fields **B ~ O(1) μG** are observed

★ seed B fields ~ 10^{-21} G

★ amplified during the galaxy formation

★ phase transitions may generate seed B fields

Enqvist, astro-ph/9803196

Evolution of primordial B fields (a phenomenological model)

$$B(t,L) = B_0 \left[\frac{a_0}{a(t)}\right]^2 \left(\frac{L_0}{L}\right)^p$$

$$\Gamma_{\mathrm{L}\to\mathrm{R}} = \frac{4}{3}\mu_{\nu_i}^2 B^2 L_0 H^{-1} L_{\mathrm{W}}^{-1}$$

$\mu_{\nu_i} \sim 3\times 10^{-20}\,\mu_{\mathrm{B}}$

Decoupling before QCD phase transition (for p=1/2 and $L_0=5\mathrm{x}10^{-5}$cm)

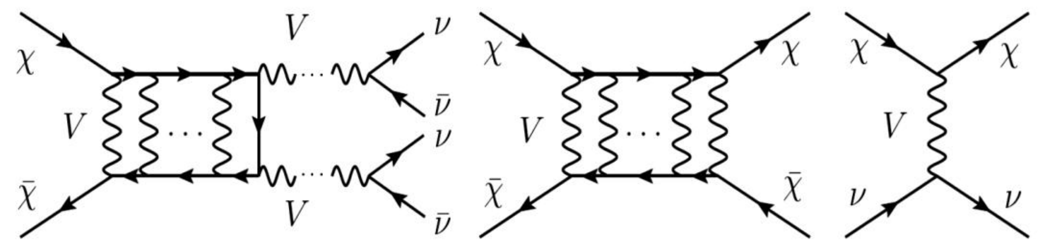
$$B_0 \lesssim 10^{26}\ \mathrm{G}\left(\frac{3\times 10^{-20}\mu_{\mathrm{B}}}{\mu_{\nu_i}}\right)$$

$B_0=10^{24}$ G in EW phase transition

Vachaspati, 91; Enqvist, Rez & Semikoz, 95

Secret Interactions of RH ν's

van den Aarssen et al., arXiv:1205.5809



Small-scale structure problems: CDM

- ★ missing satellites problem
- ★ a cored or cusp profile
- ★ too-big-to-fail problem

Late-time kinetic decoupling of CDM

$$\mathcal{L} \supset -g_\nu \overline{\nu_{i\mathrm{R}}} \gamma^\mu \nu_{i\mathrm{R}} V_\mu - g_\chi \overline{\chi} \gamma^\mu \chi V_\mu$$

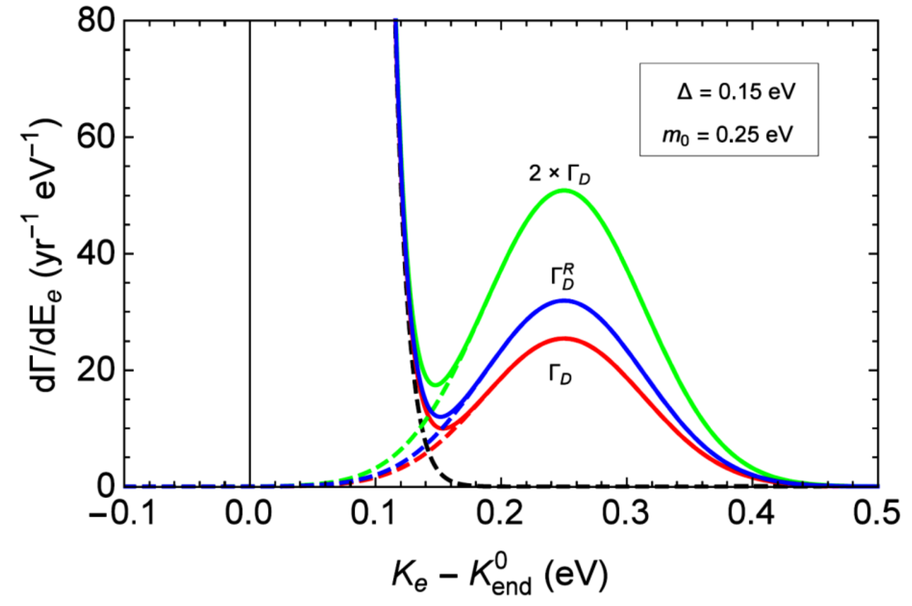
- ☐ SM particles interacting with CDM particle χ (of a mass ~ 2 TeV) to thermalize the later, and chemical decoupling at $T_d > 10$ TeV
- ☐ Secret interactions between χ and RH ν's will also lead to a thermal production of RH ν's before chemical decoupling of χ
- ☐ The kinematical decoupling between χ and RH ν's happens at a late time around T = 1 keV

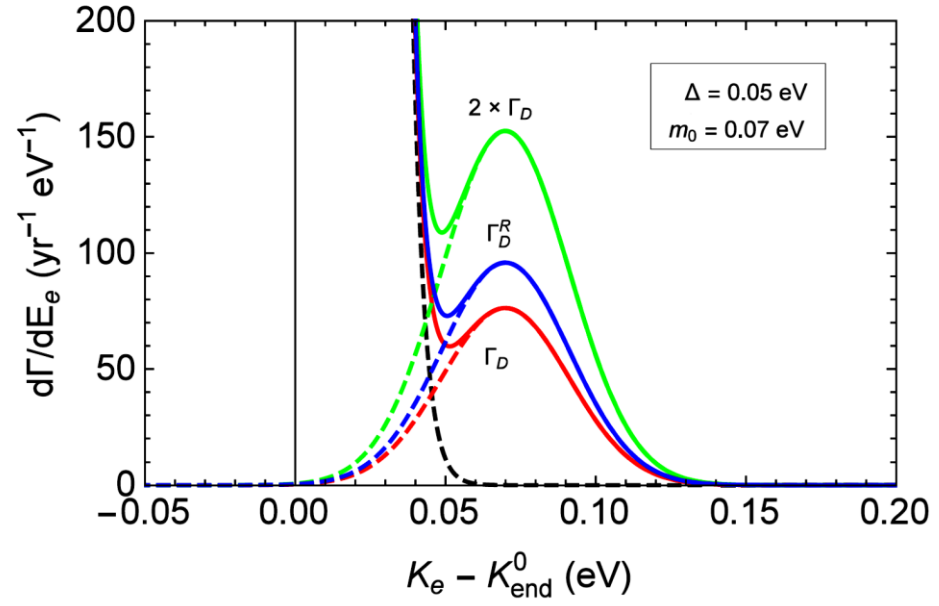
$$\Delta N_{\mathrm{eff}} = \frac{\rho_{\nu_\mathrm{R}}}{(\rho_{\nu_\mathrm{L}}/3)} \approx 3 \times \left[\frac{g_{*s}(T_{\mathrm{CMB}})}{g_{*s}(T_\mathrm{d})}\right]^{4/3} \times \left(\frac{11}{7}\right)^{4/3} \times \left(\frac{11}{4}\right)^{4/3} \approx 0.26$$

$$\frac{n(\nu_\mathrm{R})}{n(\nu_\mathrm{L})} = 0.16$$

Impact on Detection of CνB

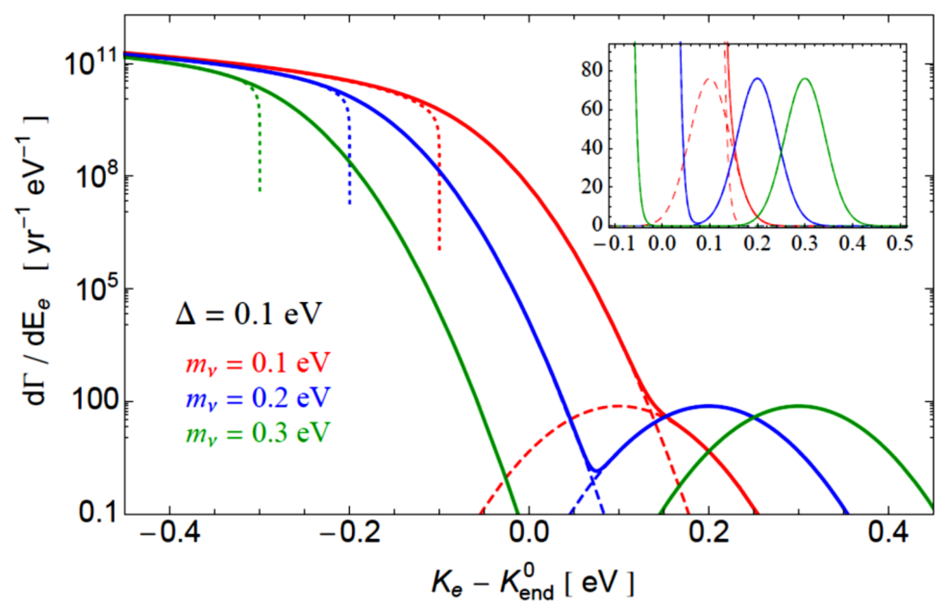
J. Zhang, S.Z., arXiv:1509.02274

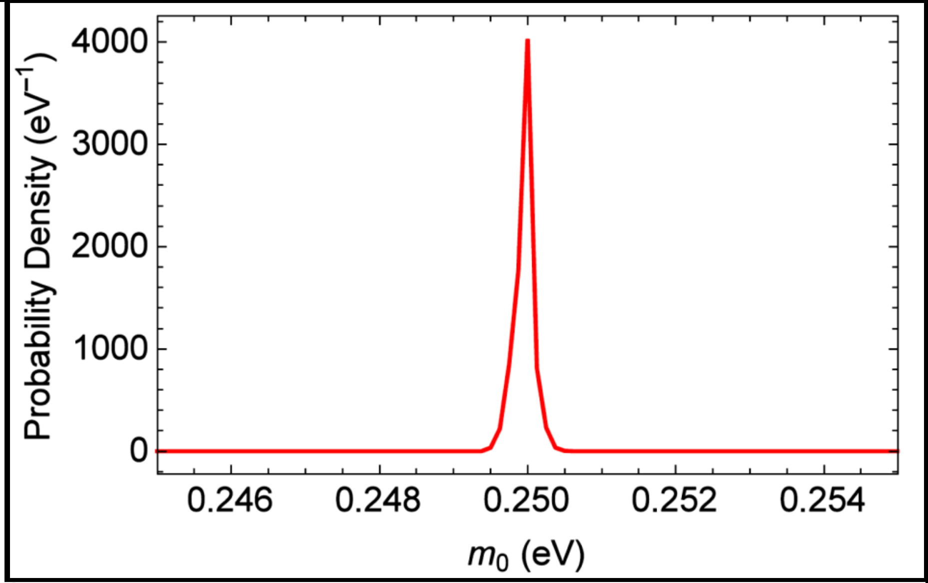




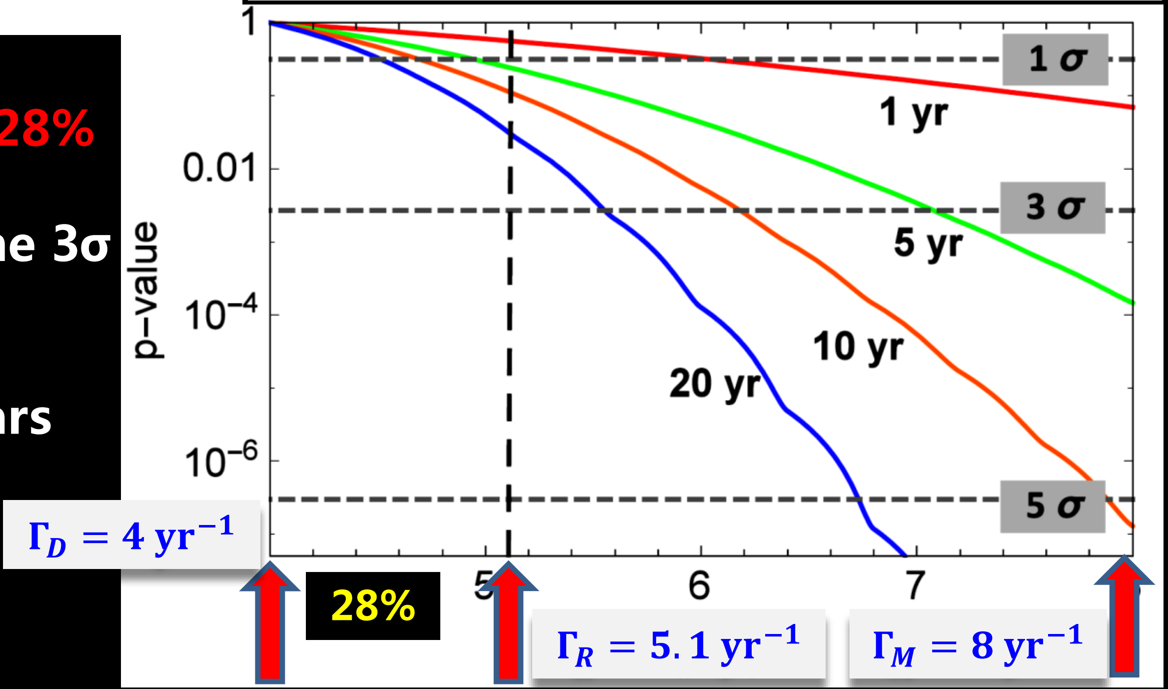
- ★ Main background comes from the intrinsic β-decay events of ^{3}H
- ★ Energy resolution **Δ < 0.7 m_i** for signal-to-background ratio > 1
- ★ For the nominal setup of PTOLEMY **Δ = 0.15 eV**, only sensitive to large ν masses, which are in contradiction with the Planck bound
- ★ The presence of RH ν's changes the capture rate from 4.0 yr^{-1} to 5.1 yr^{-1} in the Dirac case (enhanced by 28%)

Impact on Detection of CνB

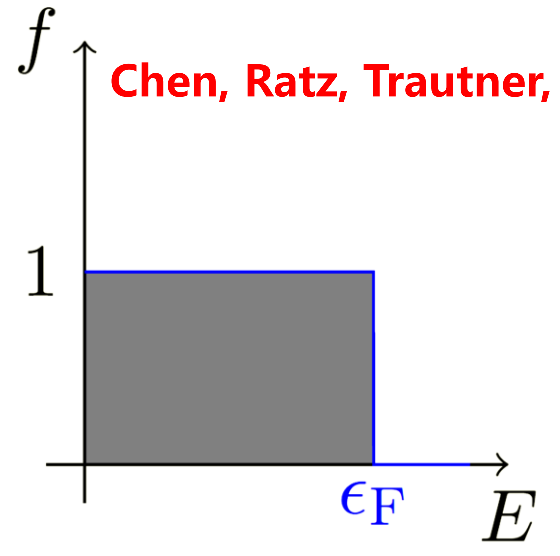




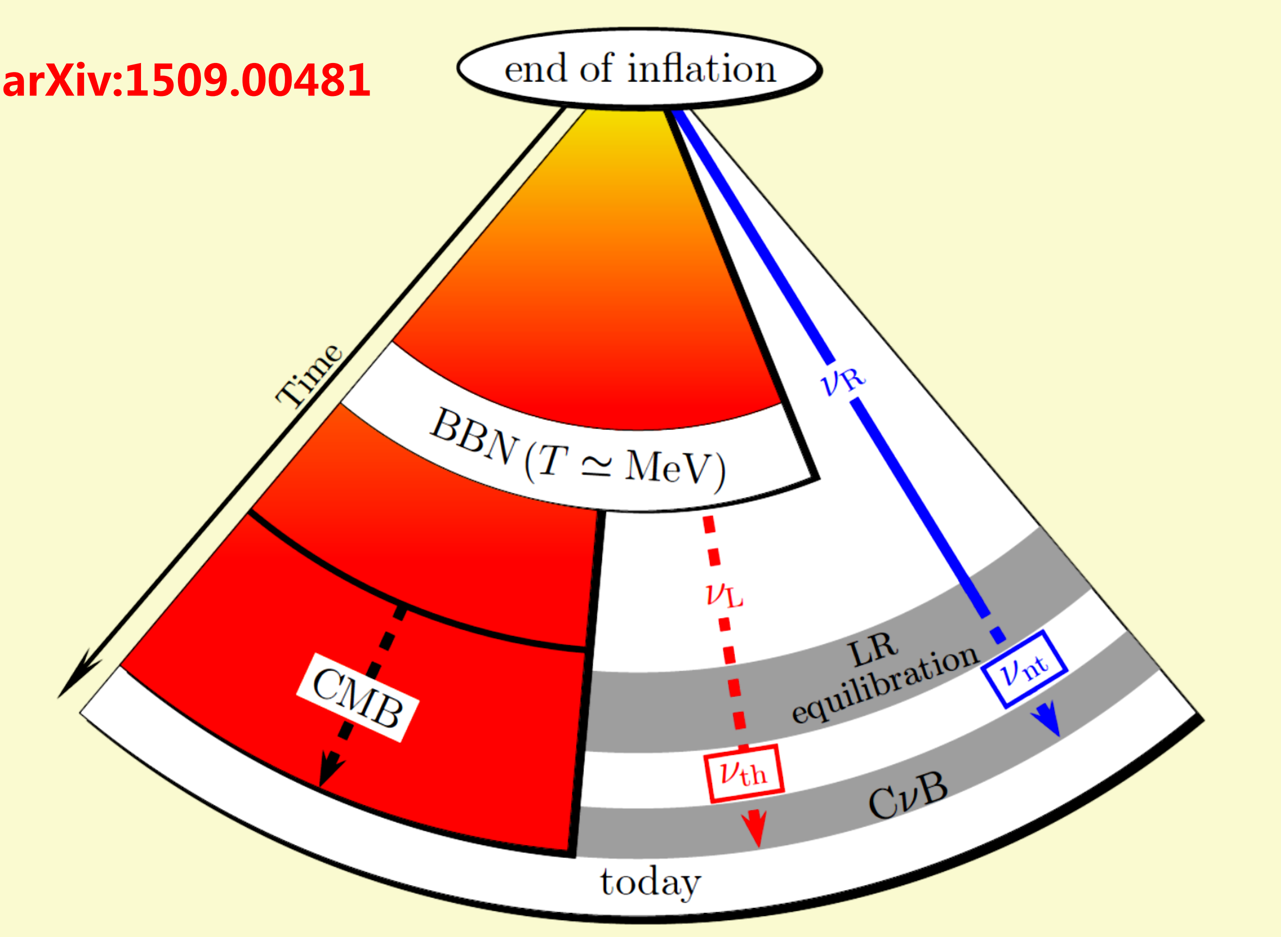
- Capture rate enhanced by **28%**
- Probing RH neutrinos at the 3σ needs more than 20 years
- Majorana vs. Dirac, 3-5 years
- Precise measurement of absolute neutrino masses



Nonthermal Background of RH ν's



Chen, Ratz, Trautner, arXiv:1509.00481

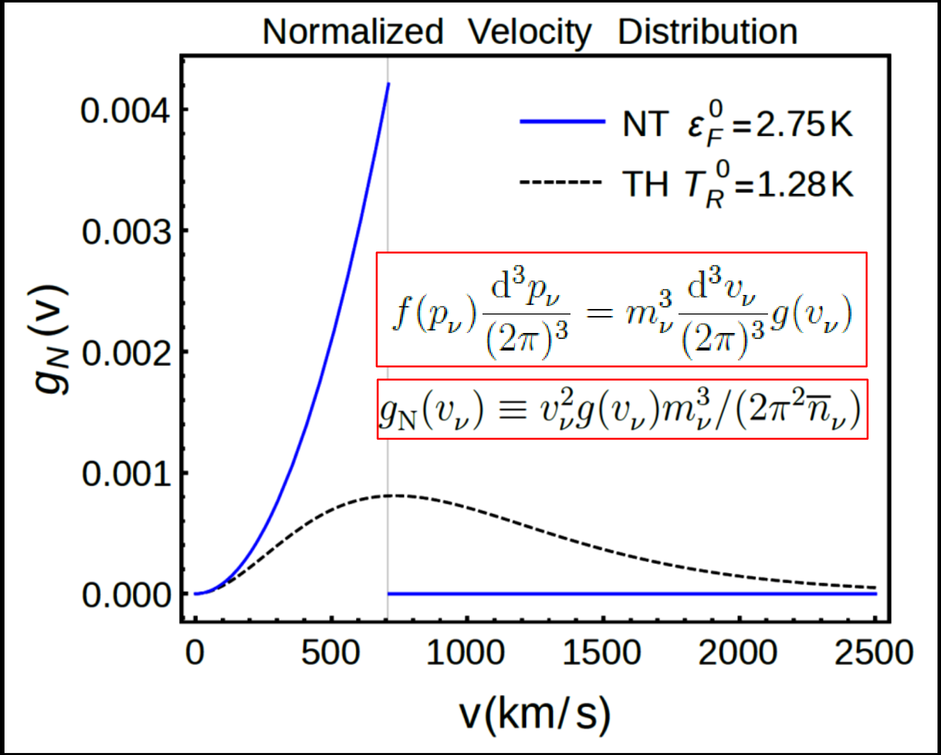


- ★ Degenerate RH ν's from inflaton decays
- ★ Concentrated on low energies, so high number density (64%)

- ★ Further reduce the difference between Dirac and Majorana cases
- ★ Gravitational clustering of massive neutrinos increases the rate & the uncertainties of CDM profiles are large, worsening the situation

Nonthermal or Thermal RH ν's: how to test them?

G.Huang, S.Z., arXiv: 1610.01347



$$f(p_\nu)\frac{\mathrm{d}^3 p_\nu}{(2\pi)^3} = m_\nu^3 \frac{\mathrm{d}^3 v_\nu}{(2\pi)^3} g(v_\nu)$$

$$g_{\mathrm{N}}(v_\nu) \equiv v_\nu^2 g(v_\nu) m_\nu^3/(2\pi^2 \overline{n}_\nu)$$

- ★ **Thermal spectrum**

$$f_{\mathrm{TH}}(p_\nu) = \frac{1}{\exp(p_\nu/T_{\mathrm{R}}^0)+1}$$

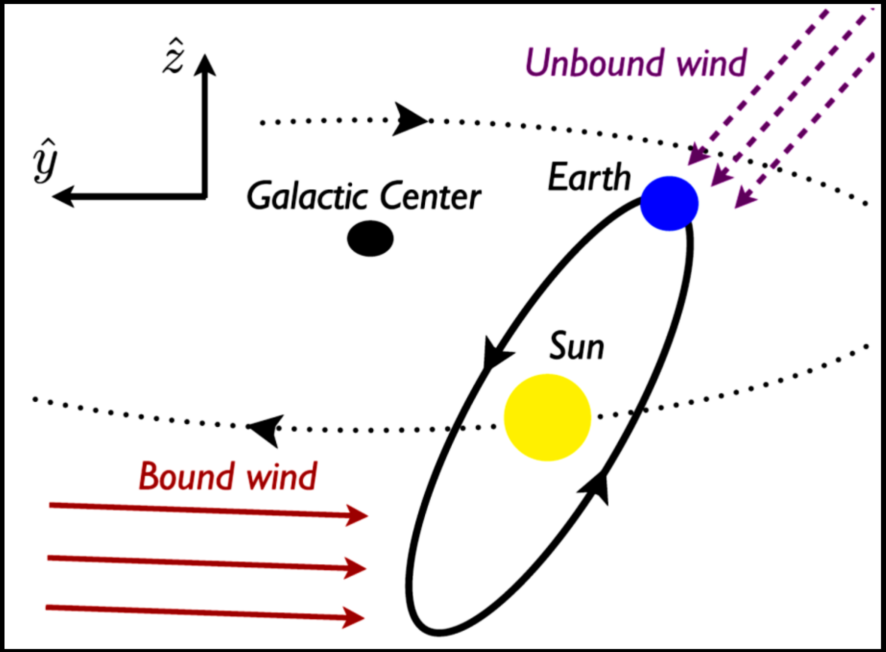
- ★ **Nonthermal spectrum**

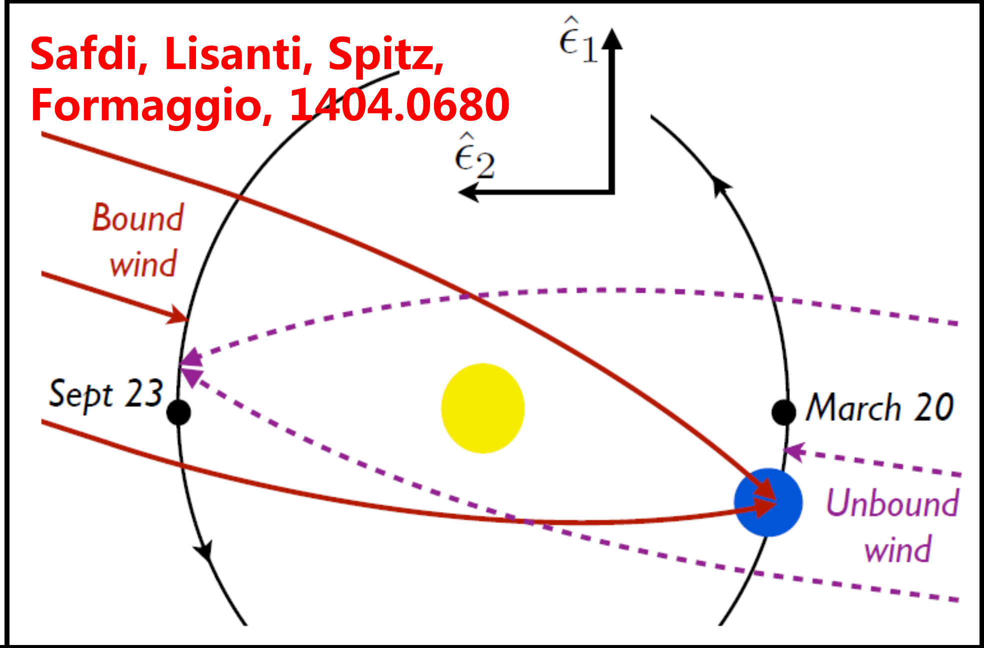
$$f_{\mathrm{NT}}(p_\nu) = \begin{cases} \eta & , p_\nu \leq \varepsilon_{\mathrm{F}}^0 \\ 0 & , p_\nu > \varepsilon_{\mathrm{F}}^0 \end{cases}$$

with η an occupation fraction

- ★ **Both scenarios consistent with the BBN bound on extra radiation**
- ★ **The main difference: NT concentrates more on low velocities**
- ★ **A similar feature exists in other thermal and nonthermal relics**

Nonthermal or Thermal RH ν's: Annual Modulation




Safdi, Lisanti, Spitz, Formaggio, 1404.0680

- **Velocity of the Earth relative to the Sun** $V_\oplus = 29.79 \text{ km s}^{-1}$ and $\omega = 2\pi \text{ yr}^{-1}$

$$\mathbf{V}_\oplus = V_\oplus \left[\hat{\mathbf{e}}_1 \cos\omega(t - t_{\text{ve}}) + \hat{\mathbf{e}}_2 \sin\omega(t - t_{\text{ve}})\right]$$ where $t_{\text{ve}} \approx$ March 20

- **Velocity of the Sun relative to the CMB**

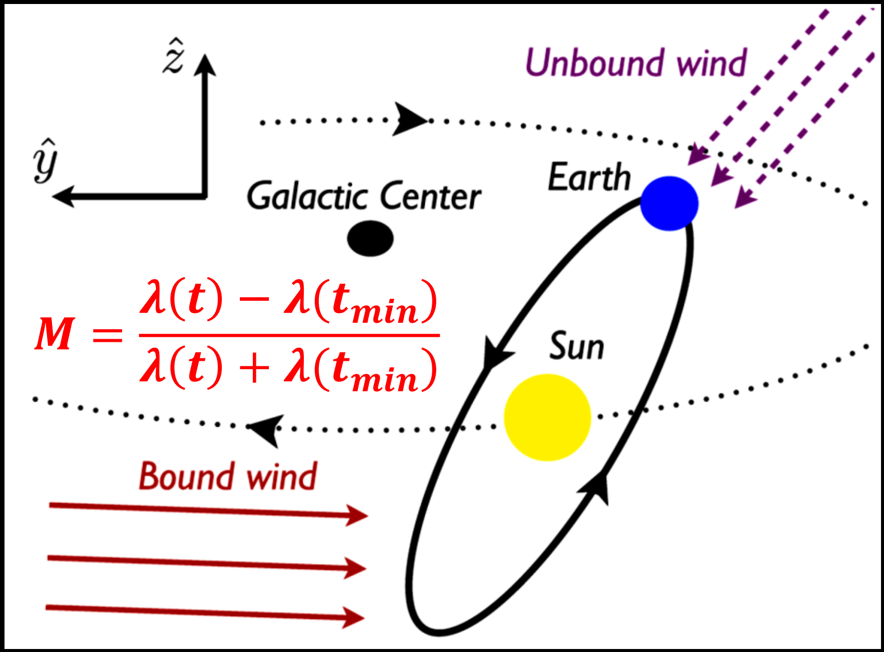
$$\mathbf{V}_\odot = V_\odot(-0.0695, -0.662, 0.747) \text{ with } V_\odot = 369 \text{ km s}^{-1}$$

- **Distribution at the Earth**

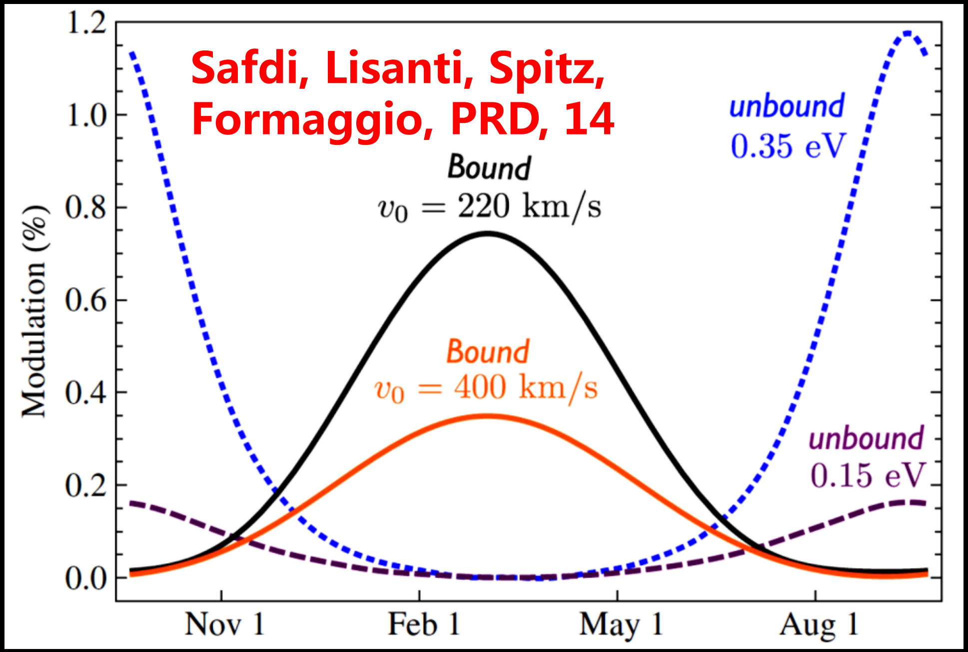
$$\boxed{g_\oplus(\mathbf{v}_\nu) = g\left[\mathbf{V}_\odot + \mathbf{v}_\infty(\mathbf{V}_\oplus + \mathbf{v}_\nu)\right]}$$

$$\mathbf{v}_\infty(\mathbf{v}_\nu) = \frac{v_\infty^2 \mathbf{v}_\nu + v_\infty(G_N M_\odot/|\mathbf{r}|)\hat{\mathbf{r}} - v_\infty(\mathbf{v}_\nu \cdot \hat{\mathbf{r}})\mathbf{v}_\nu}{v_\infty^2 + G_N M_\odot/|\mathbf{r}| - v_\infty(\mathbf{v}_\nu \cdot \hat{\mathbf{r}})}$$

Nonthermal or Thermal RH ν's: Annual Modulation



$$M = \frac{\lambda(t) - \lambda(t_{min})}{\lambda(t) + \lambda(t_{min})}$$

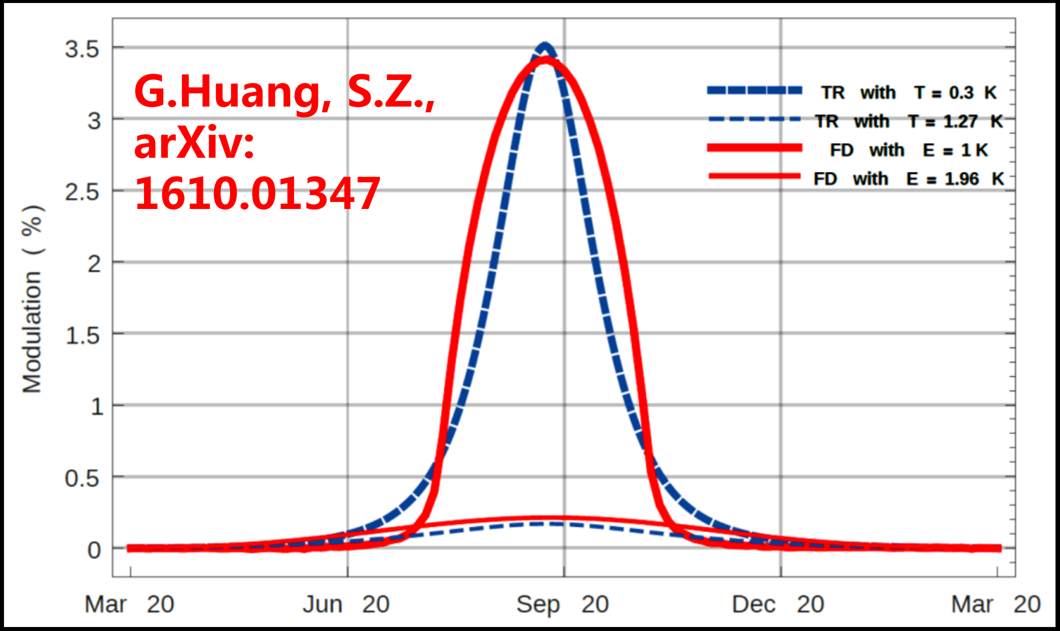


Safdi, Lisanti, Spitz, Formaggio, PRD, 14

- Gravity focus by the Sun
- Assume neutrinos unbound to the Milky Way
- Large modulations for slow neutrino velocities
- Visible difference between TH and NT RH neutrinos

Capture rate at the Earth:

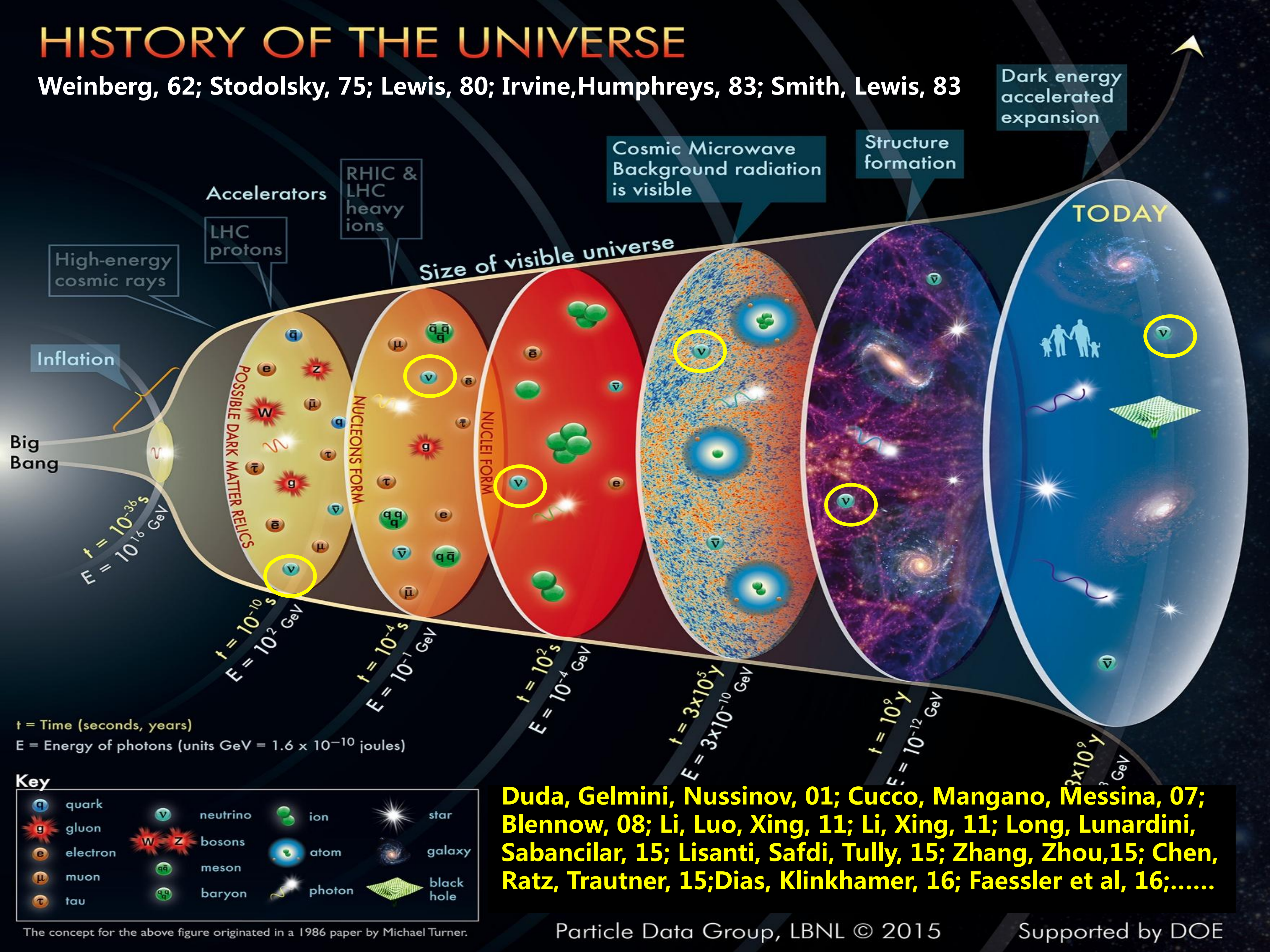
$$\Gamma_{\rm D} = N_{\rm T} \sum_{i=1}^{3} \int \frac{{\rm d}^3 p_{\nu_i}}{(2\pi)^3} \left[\sigma_i(-\frac{1}{2}) v_{\nu_i} f_{\nu_{\rm hL}}(p_{\nu_i}) + \sigma_i(+\frac{1}{2}) v_{\nu_i} f_{\nu_{\rm hR}}(p_{\nu_i}) \right]$$



G.Huang, S.Z., arXiv: 1610.01347

HISTORY OF THE UNIVERSE

Weinberg, 62; Stodolsky, 75; Lewis, 80; Irvine,Humphreys, 83; Smith, Lewis, 83



The concept for the above figure originated in a 1986 paper by Michael Turner.

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Supported by DOE

Duda, Gelmini, Nussinov, 01; Cucco, Mangano, Messina, 07; Blennow, 08; Li, Luo, Xing, 11; Li, Xing, 11; Long, Lunardini, Sabancilar, 15; Lisanti, Safdi, Tully, 15; Zhang, Zhou,15; Chen, Ratz, Trautner, 15;Dias, Klinkhamer, 16; Faessler et al, 16;……