Neutrinos and Cosmology

- ***Open questions in neutrino physics***
- ***Laboratory neutrino program***
- ***The inner space/outer space connections***

Background

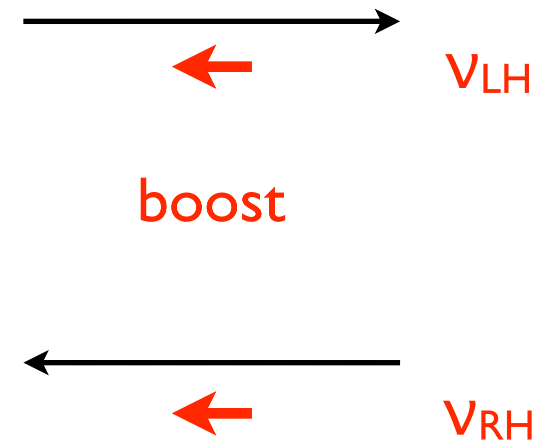
- Neutrino properties one of the four "big Questions" identified by the Astro 2010 Panel on Cosmology and Fundamental Physics
  - the mechanism responsible for inflation
  - the nature of dark energy and/or other explanations for the accelerating universe
  - the nature of the dark matter
  - ν properties: masses, mixing angles, lepton no. of the cosmos

- New ν properties are our one discovery beyond the minimal SM
  - Dirac masses require a RHed ν field, absent from the SM
  - Majorana masses correspond to the simplest "effective operator" correction to the SM, requiring a new physics scale 1/Mnew

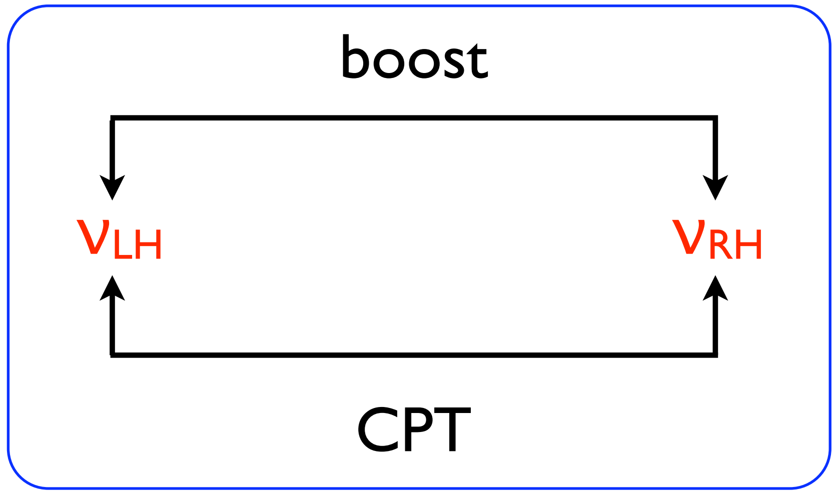
- Initial discoveries were made in astrophysics, but now an exciting interface between lab and cosmological ν physics has been established
  - there are critical ν properties issues, important to the progress of the field, that may only be answerable in cosmology

ν's richer mass structure, compared other SM fermions

Lorentz invariance

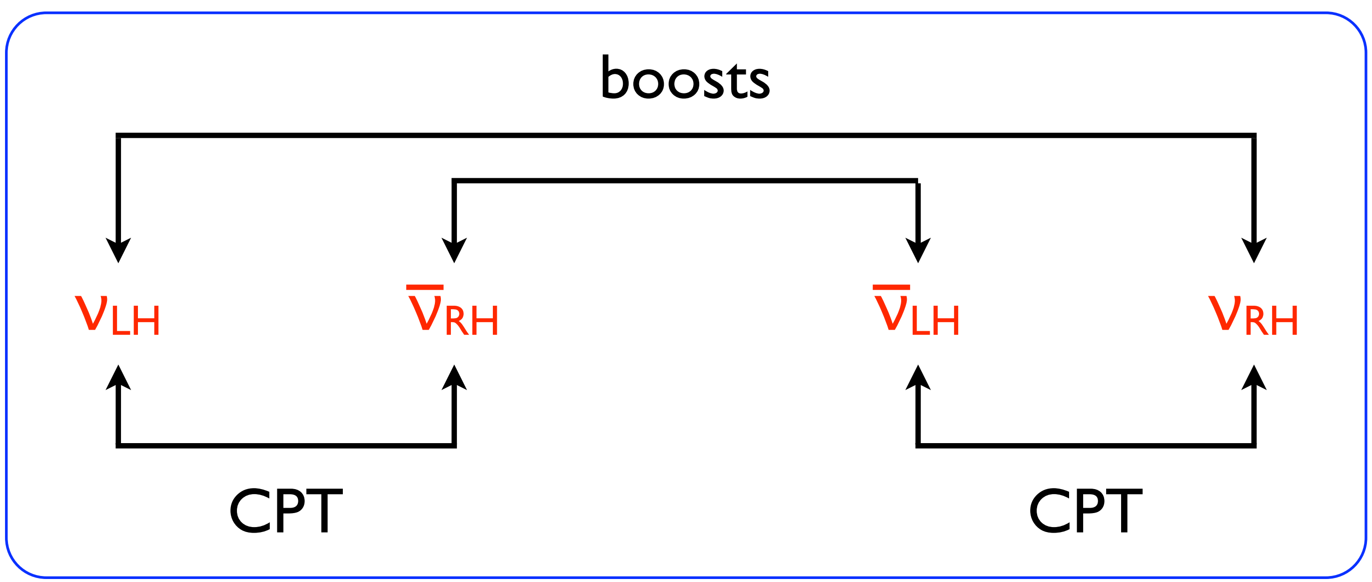


Majorana limit:



in general, linear combinations of the two

Dirac limit:



The absence of any additively conserved charge allows the addition of

$$L_m(x) \Rightarrow M_D \bar{\Psi}(x)\Psi(x) + (\bar{\Psi}^c_L(x) M_L \Psi_L(x) + \bar{\Psi}^c_R(x) M_R \Psi_R(x) + h.c.)$$

to give the more general matrix

$$(\bar{\Psi}^c_L, \bar{\Psi}_R, \bar{\Psi}_L, \bar{\Psi}^c_R) \begin{pmatrix} 0 & 0 & M_L & M_D^T \\ 0 & 0 & M_D & M_R^\dagger \\ M_L^\dagger & M_D^\dagger & 0 & 0 \\ M_D^* & M_R & 0 & 0 \end{pmatrix} \begin{pmatrix} \Psi^c_L \\ \Psi_R \\ \Psi_L \\ \Psi^c_R \end{pmatrix}$$

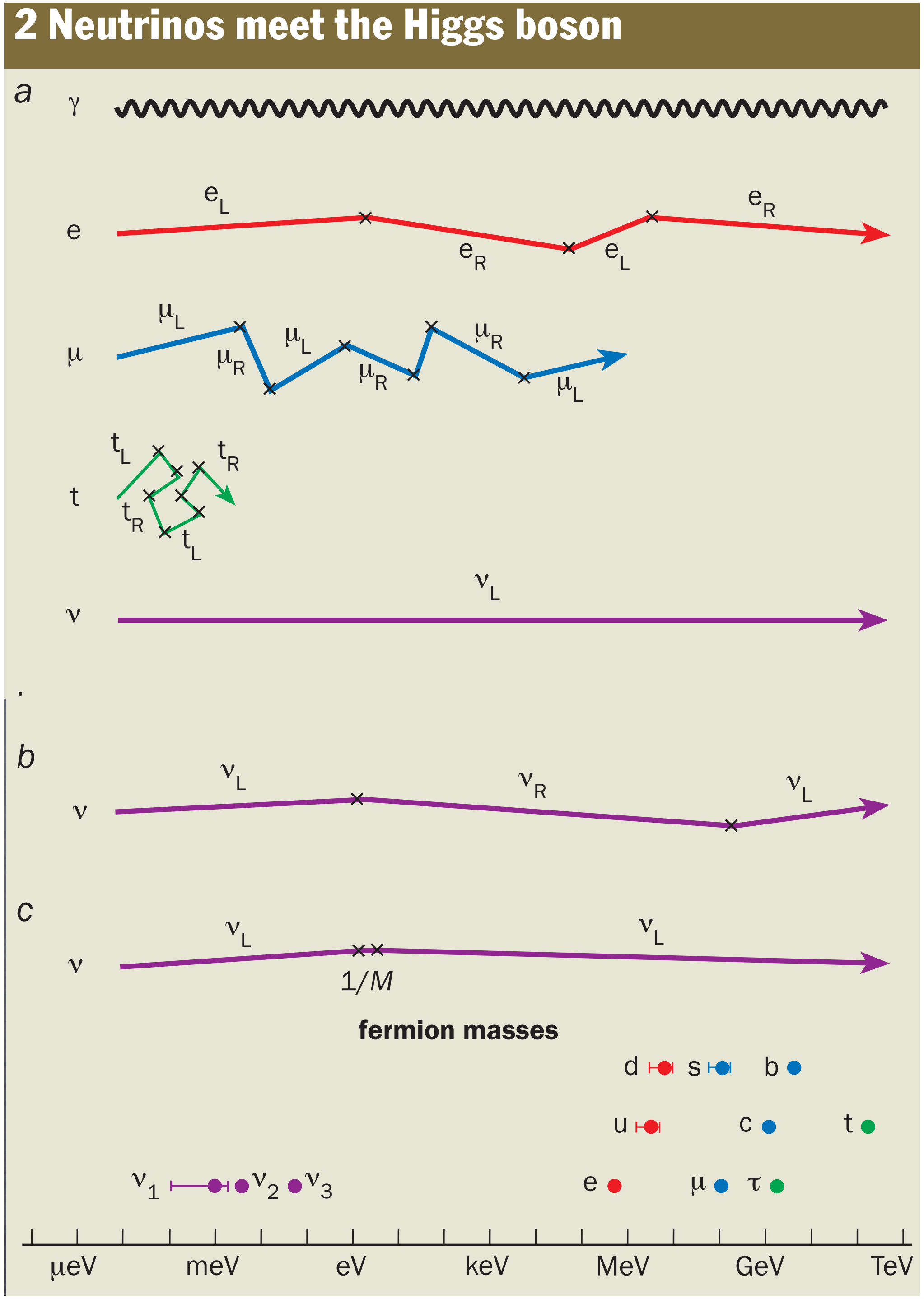
which has a number of interesting properties, including

- the introduction of M_L, M_R breaks the global invariance $\Psi \rightarrow e^{i\alpha}\Psi$ associated with a conserved lepton number

- while M_L couples Ψ_L, weak isospin requires a novel mass mechanism

$$M_L \sim \frac{\langle\phi\rangle^2}{M_{new}}$$

Hitoshi Muryama’s ν mass cartoon



standard model masses

light Dirac neutrino

LHed Majorana neutrino

← the anomalous ν mass scale!

This was one reason the initial oscillation results were so exciting:

- give the ν an M_D typical of other SM fermions

- take $M_L \sim 0$, in accord with $\beta\beta$ decay

- assume $M_R >> M_D$ as we have not found new RHed physics at low E

$$\begin{pmatrix} 0 & m_D \\ m_D & m_R \end{pmatrix} \Rightarrow \; m_\nu^{\rm light} \sim m_D \left(\frac{m_D}{m_R}\right)$$

the needed small parameter!

- take $m_\nu \sim \sqrt{m^2{}_{23}} \sim 0.05$ eV and $m_D \sim m_{top} \sim 180$ GeV

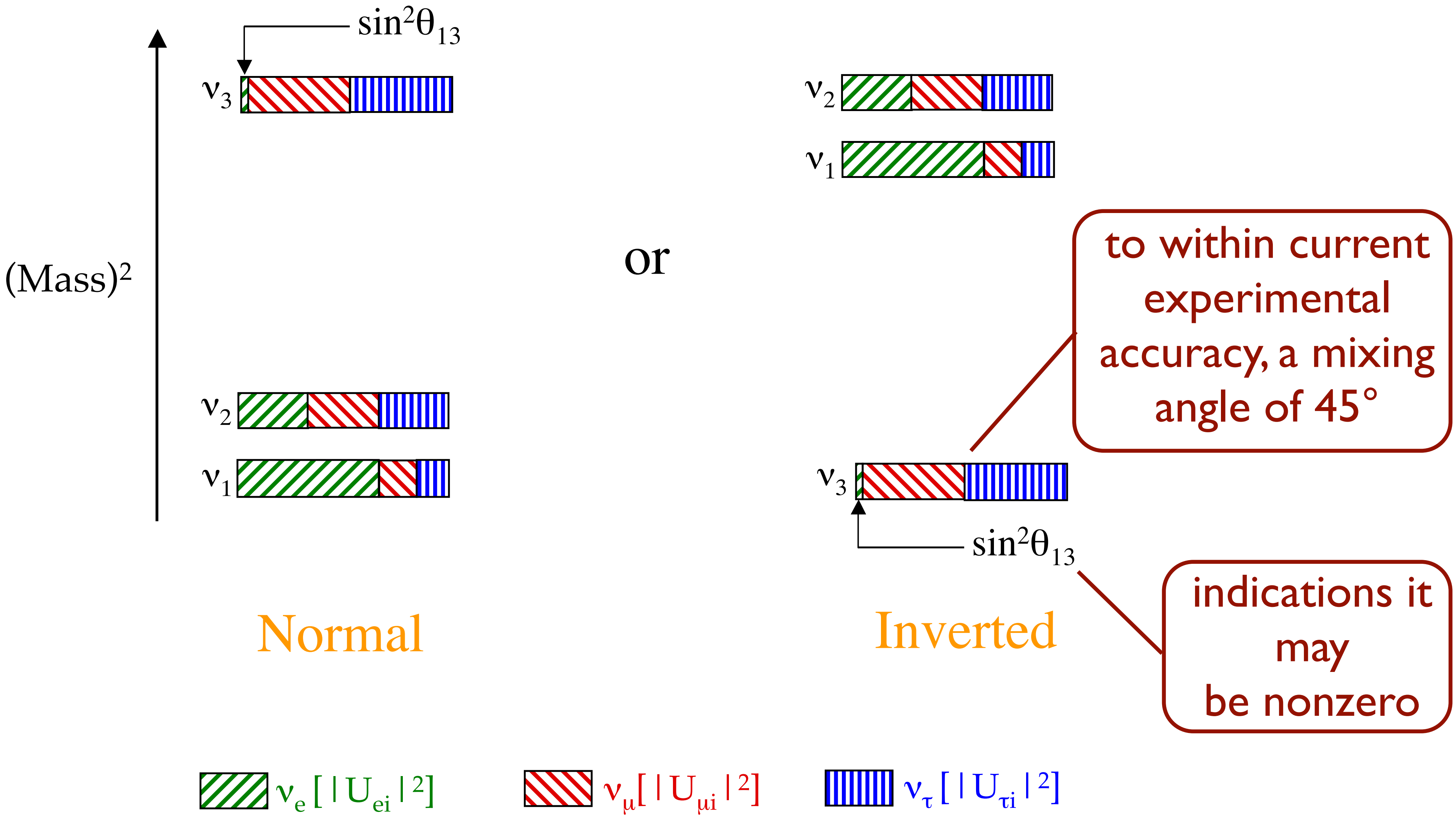
$$\Rightarrow m_R \sim 0.3 \times 10^{15} \text{ GeV}$$

The deduced ν atmospheric mass difference is consistent with a novel mass generation mechanism, not shared by other SM fermions, that the data suggest might be characteristic of the GUT scale

The Laboratory/Cosmology Program

Hierarchy

Important questions unanswered



(matter effects seen only in the solar case)

(artwork: Boris Kayser)

The mixing (where we have additional blanks to fill in)

knowns: θ_{12}, θ_{23} known unknowns: θ_{13} δ, ϕ_1, ϕ_2

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix} \begin{pmatrix} \nu_1 \\ e^{i\phi_1}\nu_2 \\ e^{i\phi_2}\nu_3 \end{pmatrix}$$

$$= \begin{pmatrix} 1 & & \\ & c_{23} & s_{23} \\ & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & & s_{13}e^{-i\delta} \\ & 1 & \\ -s_{13}e^{i\delta} & & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & \\ -s_{12} & c_{12} & \\ & & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ e^{i\phi_1}\nu_2 \\ e^{i\phi_2}\nu_3 \end{pmatrix}$$

atmospheric ν_e disappearance solar

results: $\theta_{23} \sim 45^\circ$ $\sin\theta_{13} \leq 0.17$ $\theta_{12} \sim 30^\circ$

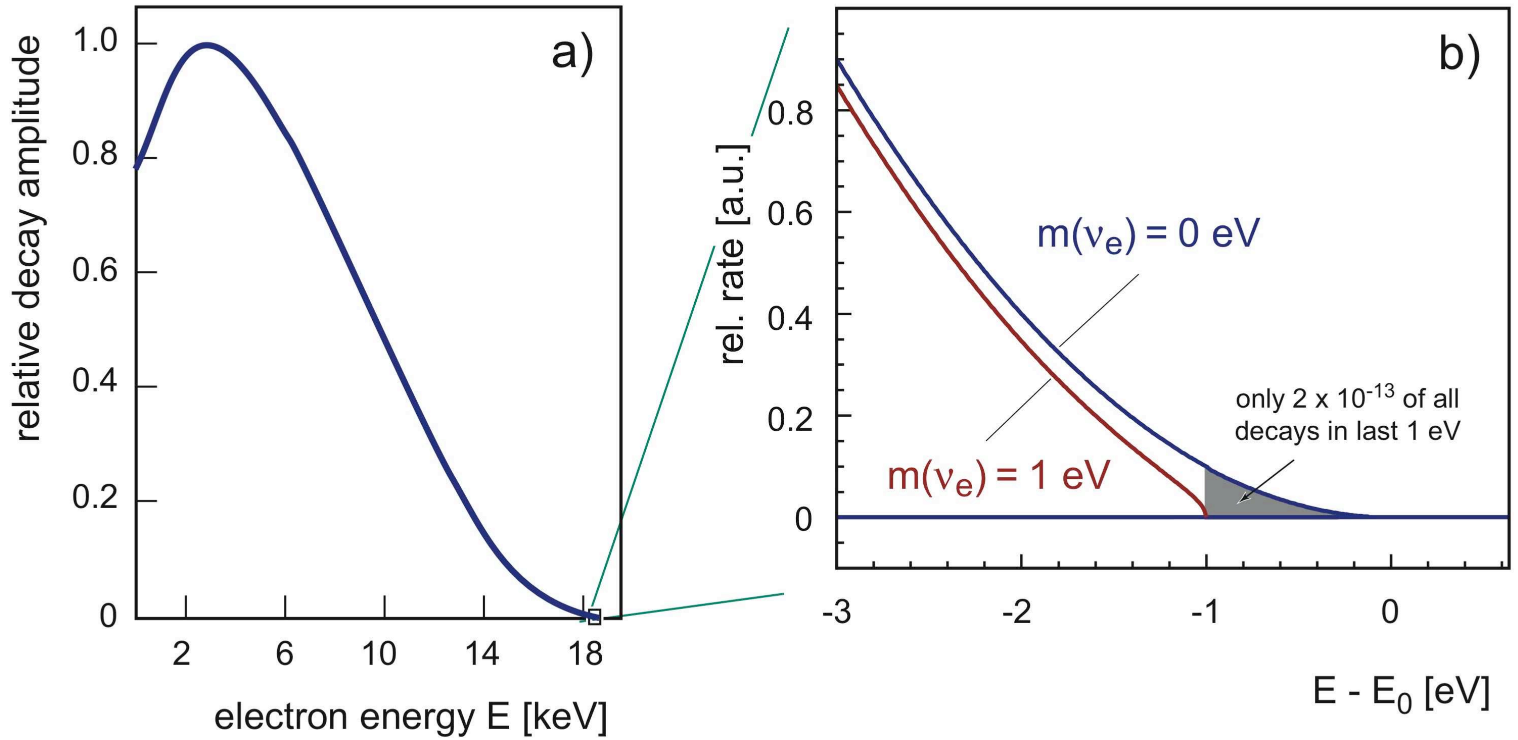
Δ_{12} $|\Delta_{23}|$ $\mathrm{sign}[\Delta_{23}]$ absolute scale

If there are no surprises, progress is needed in four areas

1) absolute mass scale
2) lepton number and the mass mechanism
3) the hierarchy: new matter effects in LBNE
4) CP violation and associated questions about the size of θ_{13}

A 15-20 year lab program is taking shape ~ \$2-3B

Absolute ν mass: the one identified component of DM



tritium β decay is running into intrinsic limits due to feasible source intensities and detector resolution

$$\langle m_\nu \rangle_{\text{tritium}} = \sum_i |U_{ei}|^2 m_\nu^2(i)$$

present limit $\langle m_\nu \rangle_{\rm tritium} < 2.2 \ {\rm eV}$ Mainz & Troitzk

KATRIN's goal is to reach 250 meV, with 5σ exclusion at 350 meV

the measurement is clean, and one could get lucky ... but cosmology may provide our best hope of reaching the 50 meV level lepton number and the mass mechanism: neutrinoless ββ decay

$$\langle m_\nu^{\rm Maj} \rangle = \sum_{i=1}^{2n} \lambda_i U_{ei}^2 m_i \quad \text{or} \quad \langle \frac{1}{m_\nu^{\rm heavy}} \rangle = U_{ei}^2 \frac{1}{m_i^{\rm heavy}}$$

analogous to the search for the Higgs

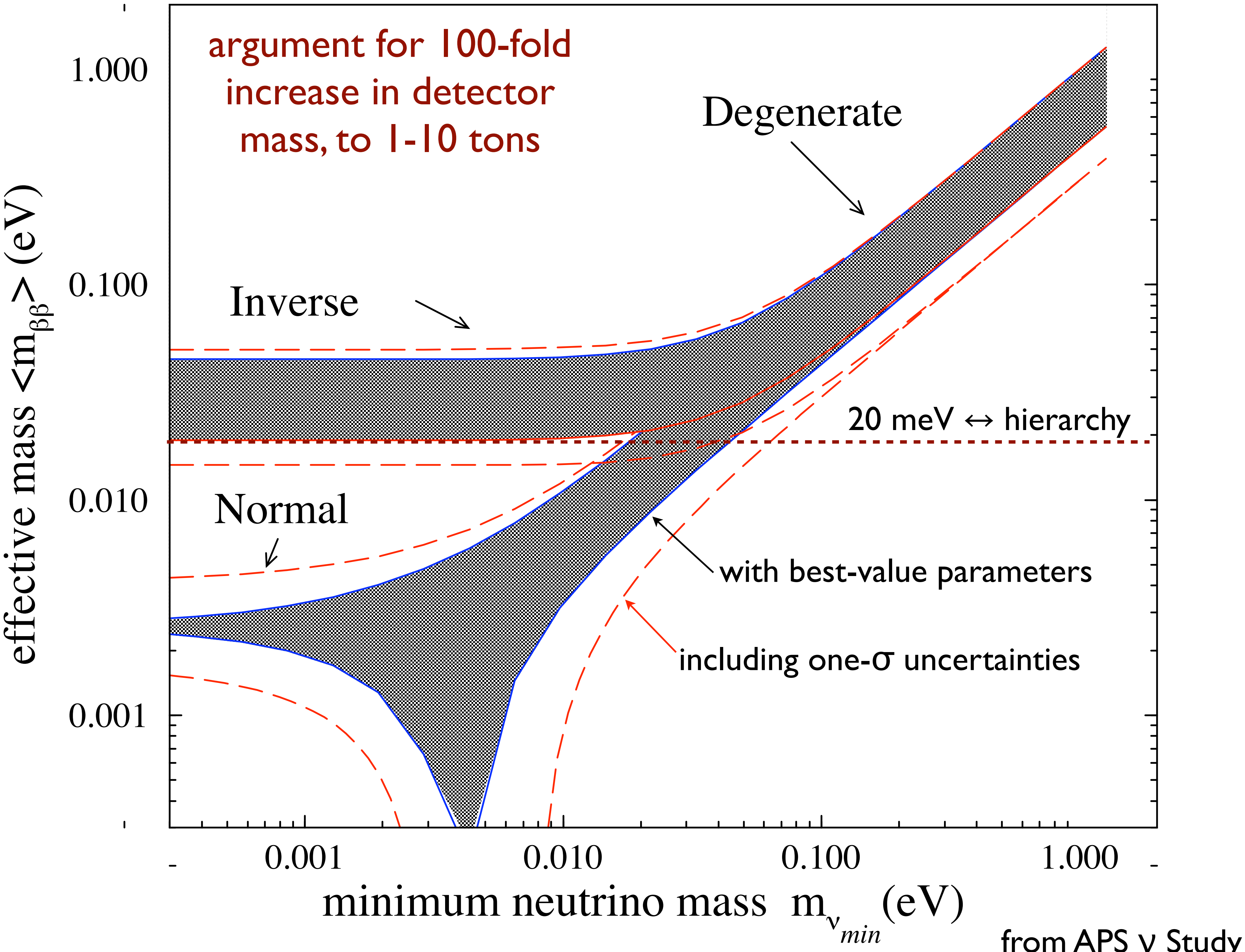
- a mass mechanism connected to the simplest effective SM operator
- indirect sensitivity to near-GUT-scale physics
- direct sensitivity to heavy-ν super-TeV physics

GERDA (^{76}Ge), CUORE (^{128}Te) currently limit

$$\langle m_\nu^{\rm Maj} \rangle < (0.3 - 1.0)\ {\rm eV} \qquad \langle \frac{1}{m^{\rm heavy}} \rangle < \frac{1}{10^4\ {\rm TeV}}$$

Should be attacked with urgency and at a more elevated scale

My view: a test of lepton number nonconservation, and possibly of the hierarchy. More ambiguity in deducing ν mass scale



argument for 100-fold increase in detector mass, to 1-10 tons
Degenerate
Inverse
Normal
20 meV ↔ hierarchy
with best-value parameters
including one-σ uncertainties
1.000
0.100
0.010
0.001
effective mass <mββ> (eV)
0.001
0.010
0.100
1.000
minimum neutrino mass mνmin (eV)
from APS ν Study

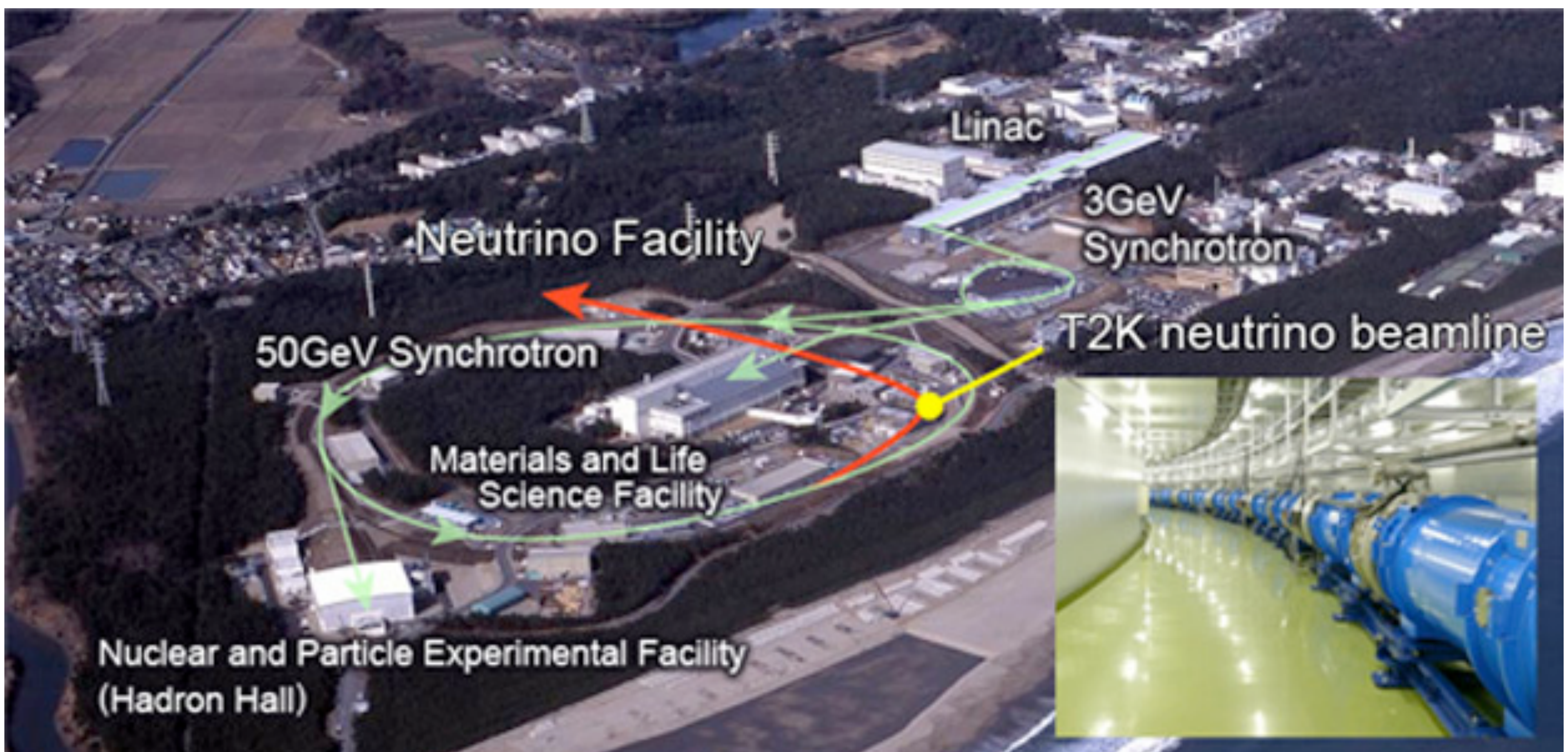
CP violation, θ_{13}, leptogenesis

From modeling the early universe

- baryon number violation
- out of equilibrium interactions
- C and CP violation: known SM $\not{C}P$ sources appear insufficient

$$\text{but} \quad J^{\nu}_{CP} = \sin\theta_{12}\sin\theta_{23}\sin\theta_{13}\cos\theta_{12}\cos\theta_{23}\cos\theta_{13}{}^{2}\sin\delta$$
$$\sim 0.2 \sin\theta_{13}\sin\delta$$

T2K $\nu_\mu \to \nu_e$ search



Experimental parameters

- 2.5° off-axis relatively narrow ν beam, yielding $E_\nu^{\rm peak} \sim$ 0.6 GeV
- the J-PARC : SuperK baseline, which then places the detector at the Δm_{23} first oscillation maximum
- $\nu_\mu \to \nu_e$ appearance at a baseline much shorter than that optimizing appearance via θ_{12}, so the effects of θ_{13} can be seen

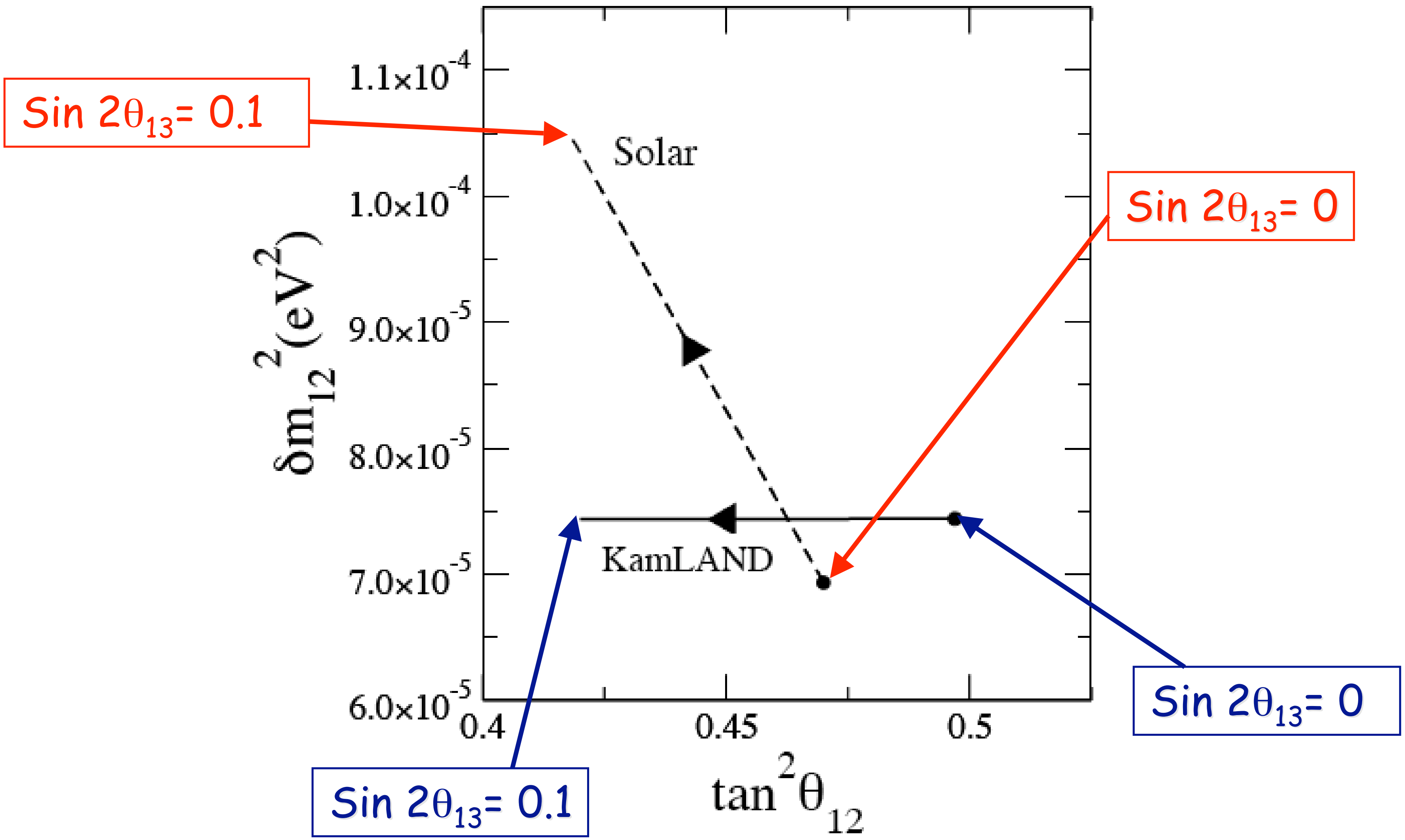
find 6 events when 1.5 ± 0.3 would be expected were $\theta_{12} = 0$ (2.5 σ)

deduce $0.03(0.04) \lesssim \sin^2 2\theta_{13} \lesssim 0.28(0.34)$ normal(inverted), $\delta_{CP} = 0$

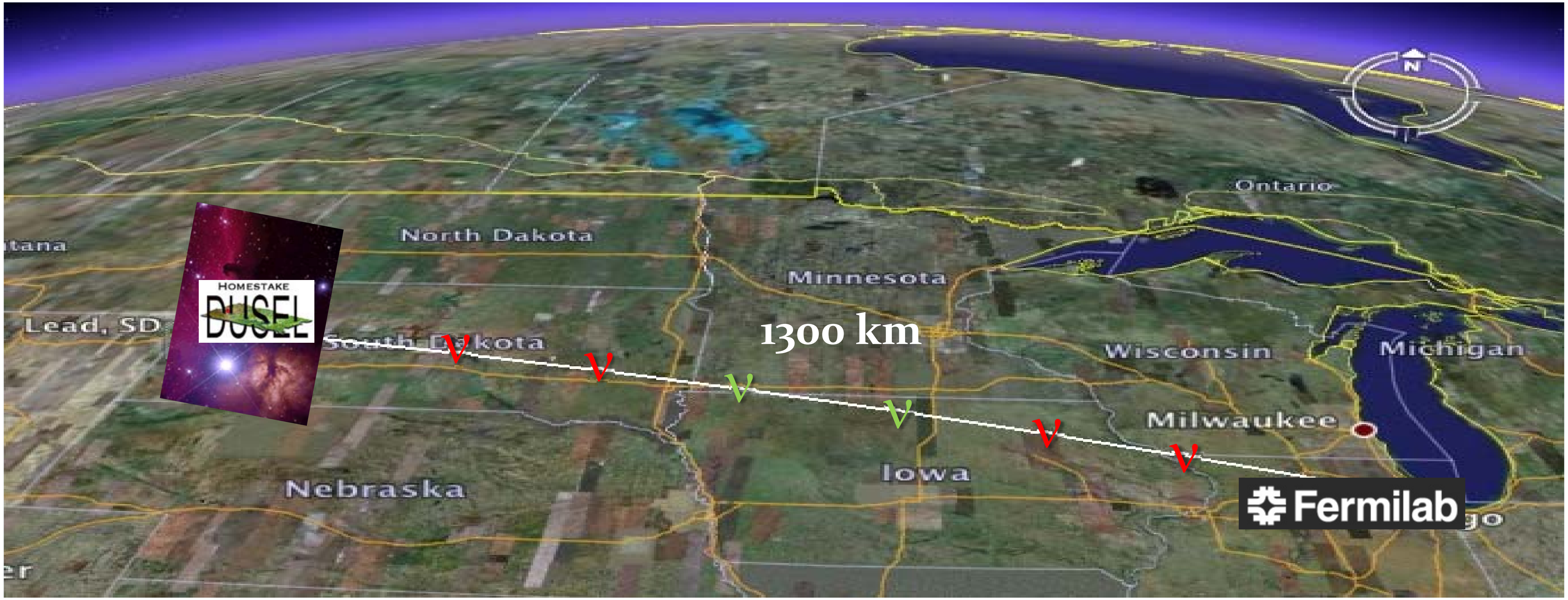
best value, normal hierarchy ~ 0.11

compares to CHOOZ, MINOS $\sin^2 2\theta_{13} \lesssim 0.15$ and potentially indicates significant future LBNE sensitivity to $\delta_{CP} = 0$

Probably need to wait: values this large may be problematic elsewhere



LBNE: hierarchy and CP violation

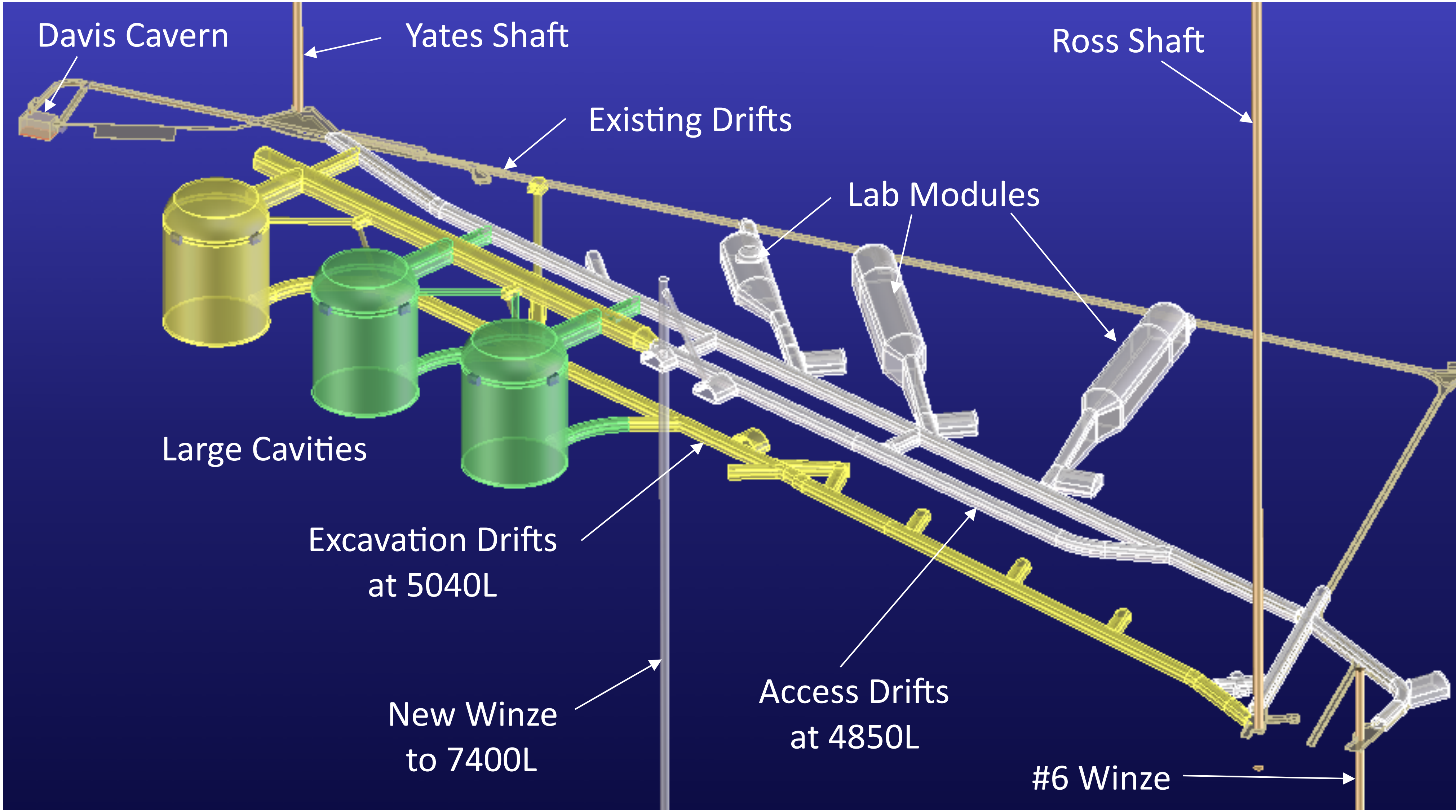


700 kW beam, on axis, water/argon megadetector, beamline to "DUSEL"

1300 km of matter: sign of matter effects ⇔ normal/inverted;

5 years of ν_μs, $\bar{\nu}_\mu$s running $\nu_\mu \to \nu_e$ vs $\bar{\nu}_\mu \to \bar{\nu}_e$ for $\not{C}$P

sounds like a good plan...

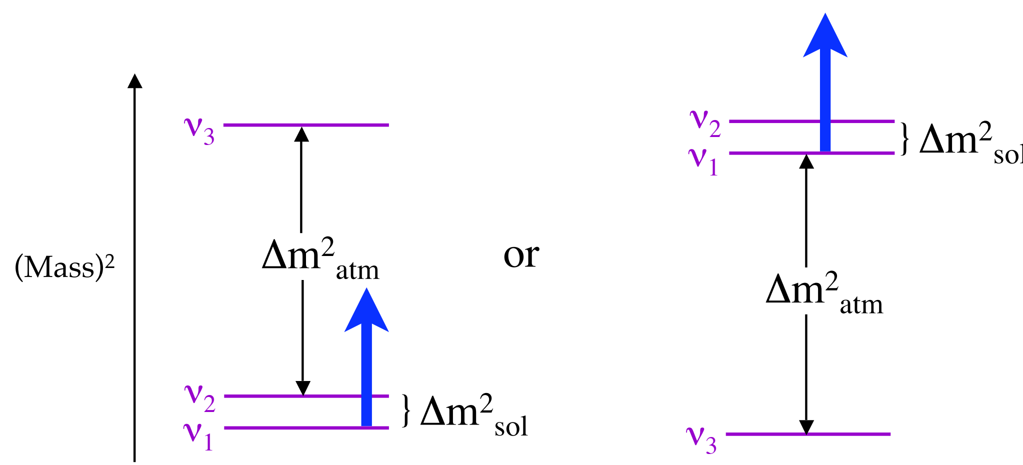

Davis Cavern
Yates Shaft
Ross Shaft
Existing Drifts
Lab Modules
Large Cavities
Excavation Drifts
at 5040L
Access Drifts
at 4850L
New Winze
to 7400L
#6 Winze

Vacuum formula

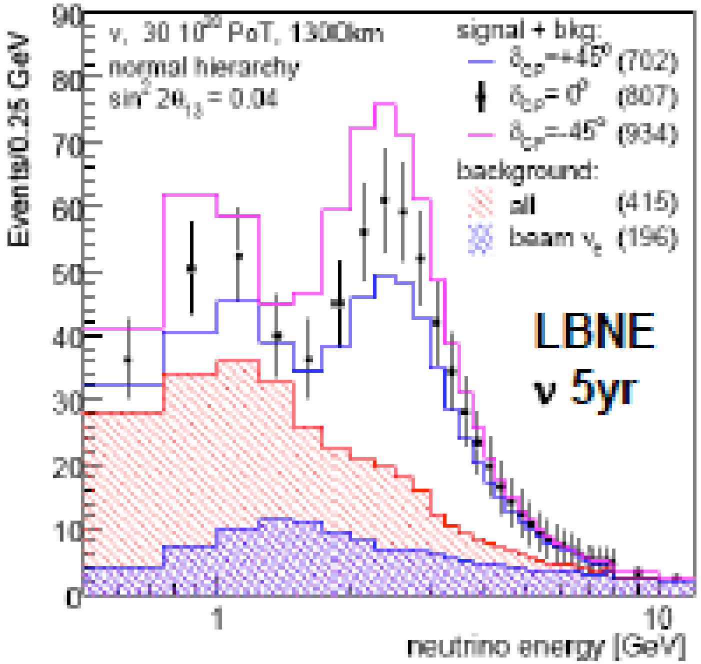
$$P\begin{pmatrix} \nu_\mu \rightarrow \nu_e \\ \bar{\nu}_\mu \rightarrow \bar{\nu}_e \end{pmatrix} = \begin{array}{c} (\sin^2 2\theta_{23} \sin^2 2\theta_{13})(\sin^2 \Delta_{31}) \\ \pm \sin\delta \; (\sin 2\theta_{13} \sin 2\theta_{23} \sin 2\theta_{12})(\sin^2 \Delta_{31} \sin \Delta_{21}) \\ + \cos\delta \; (\sin 2\theta_{13} \sin 2\theta_{23} \sin 2\theta_{12})(\sin \Delta_{31} \cos \Delta_{31} \sin \Delta_{21}) \\ +(\cos^2 \theta_{23} \sin^2 2\theta_{12})(\sin^2 \Delta_{21}) \end{array}$$

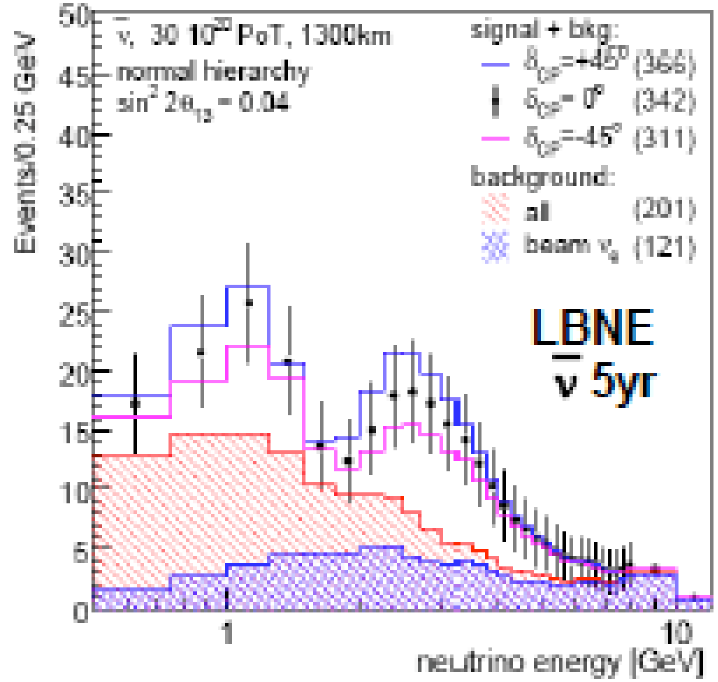
altered by matter

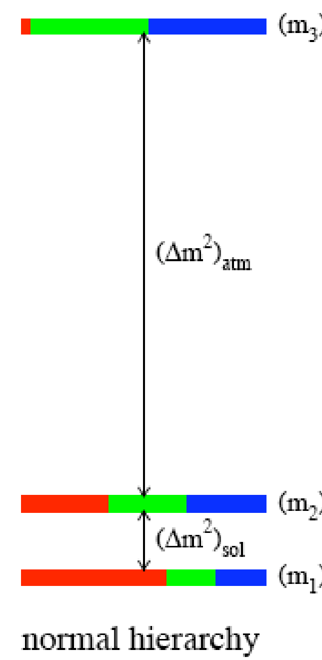
nonzero?



Effects intertwined, as two channels are not CP conjugate when in matter





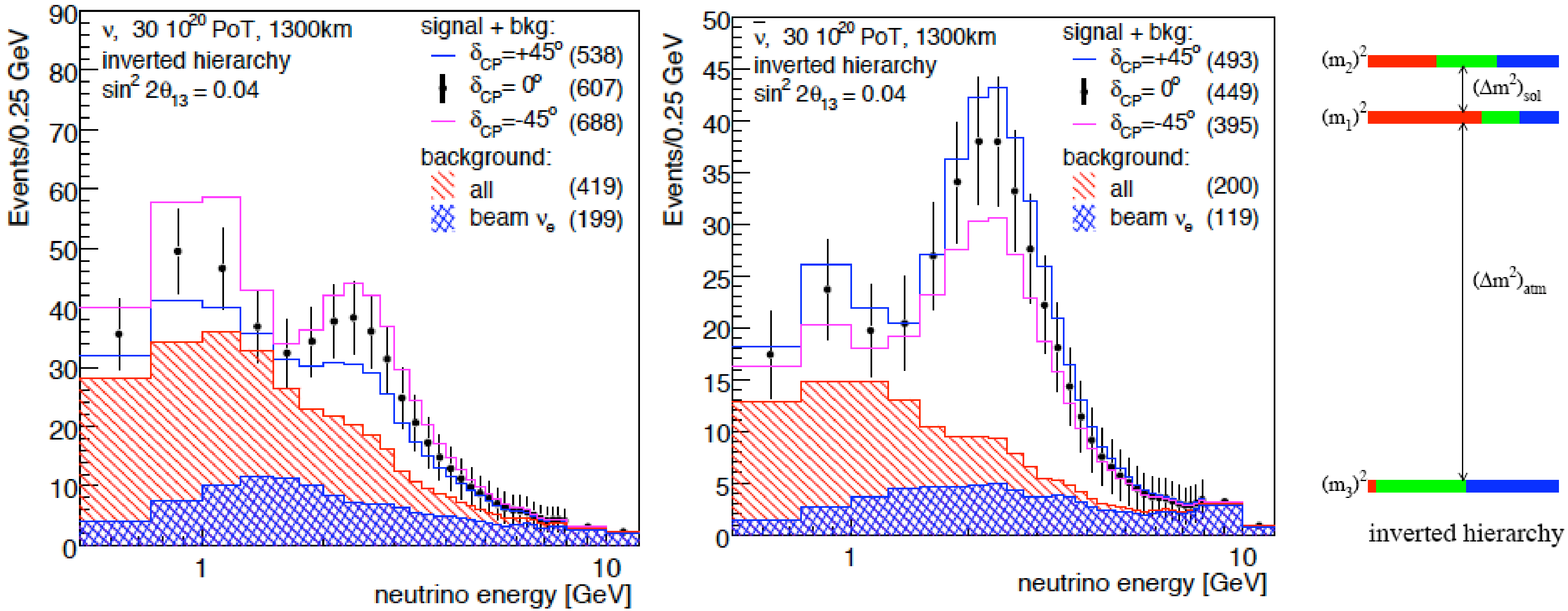


challenging:

broad band beam; baseline requires a spectrum centered at about 2 GeV

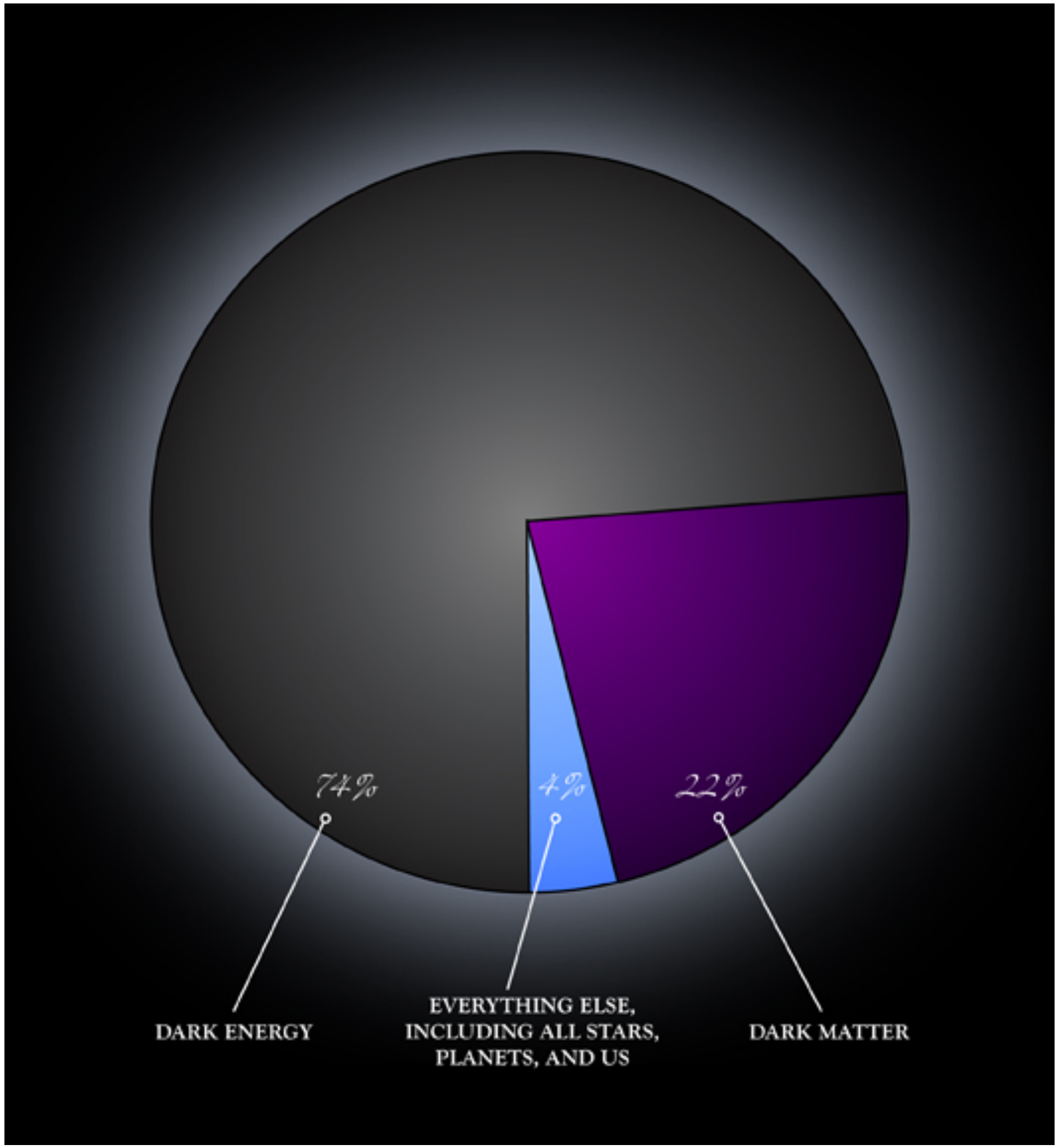
low statistics, some beam contamination, backgrounds from π^0 production

must be able to identify events (quasielastic kinematics) for which one can reconstruct the initial beam energy



ν, 30 10^20 PoT, 1300km
inverted hierarchy
sin^2 2θ13 = 0.04
signal + bkg:
δCP=+45° (538)
δCP= 0° (607)
δCP=-45° (688)
background:
all (419)
beam νe (199)
Events/0.25 GeV
neutrino energy [GeV]
ν̄, 30 10^20 PoT, 1300km
inverted hierarchy
sin^2 2θ13 = 0.04
signal + bkg:
δCP=+45° (493)
δCP= 0° (449)
δCP=-45° (395)
background:
all (200)
beam νe (119)
Events/0.25 GeV
neutrino energy [GeV]
(m2)^2
(Δm^2)sol
(m1)^2
(Δm^2)atm
(m3)^2
inverted hierarchy

The Inner Space ⇔ Outer Space Connection



To date, the major discoveries have come from astro/cosmo

uncertain properties of SM νs known/suspected to infuence

- baryon asymmetry
- BBN: the number of relativistic degrees of freedom, net lepton number
- DM density, DM effects on expansion
- unique astrophysical oscillation environments
  - novel MSW effects
  - new level crossings

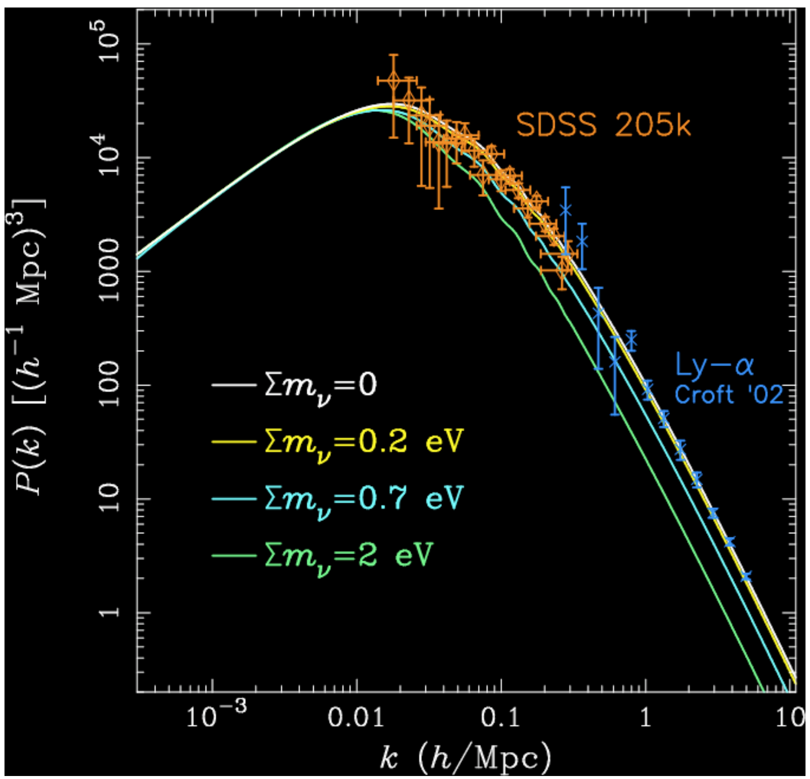
Plus incomparable sensitivity to new (sterile) νs

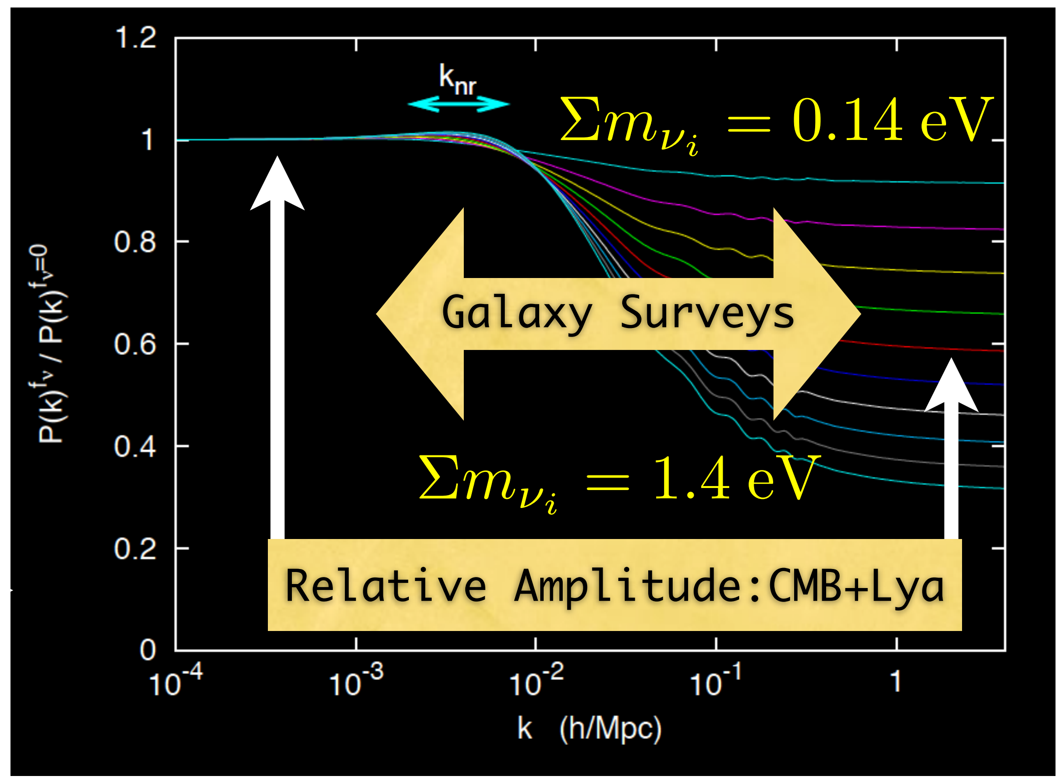
Absolute ν mass scale: the one "known" component of DM is the ν

Standard BBN: $n_\nu = N_\nu \left(\frac{3}{11}\right) n_\gamma \sim 340/\mathrm{cm}^3$

$$\rho_\nu = \sum m_i n_{\nu_i} \qquad \Omega_\nu \sim \sum \frac{m_{\nu_i}}{h^2\ 93\ \mathrm{eV}} \qquad E_i^2 = p^2 + m_i^2$$

smaller mass νs ⇒ relativistic longer, travel further ⇒ suppress growth of structure on larger scales $k_{\rm free\ streaming} \sim 0.004\sqrt{m_\nu/0.05\mathrm{eV}}\ \mathrm{Mpc}^{-1}$





from Kev Abazajian

Thus ν influences on structure evolve with both redshift Z and spatial scale in a characteristic way:

$$\sum m_\nu \sim 0.05 \text{ eV}, \; z = \begin{pmatrix} 3.5 \\ 3.5 \\ 1.5 \\ 0.0 \end{pmatrix} \Rightarrow \text{ power decrease} \sim \begin{pmatrix} 1.9\% \\ 1.0\% \\ 2.1\% \\ 3.5\% \end{pmatrix} \text{ for } k > \begin{pmatrix} 0.6 \\ 0.03 \\ 0.6 \\ 0.6 \end{pmatrix} \frac{1}{\text{Mpc}}$$

leverage: alter baryons + CDM at the ~ % level, when $\Omega_\nu \sim 0.1\%$

typical combined analysis using existing data

$$\sum m_{\nu_i} < 0.58 \text{ eV}$$

Komatsu et al. 2010, WMAP7 + SDSS LRG BAO + Ho

$$\left(\frac{\Delta P}{P}\right)_{\text{future}} \sim 1\% \sim -12 \frac{\Omega_\nu}{\Omega_m} \Rightarrow \sum m_{\nu_i} \sim 11 \text{ meV}$$

Hu, Eisenstein, & Tegmark 1998; Abazajian & Dodelson 2003

A series of Astro2010 white papers were submitted that examined consequences of anticipated surveys, typically ~ ×100 increase in statistics

- high redshift galaxy surveys, SDSS-III BOSS 10^5 QSO survey, Planck CMB data, 21-cm radio telescopes with 0.1 km^2 collection, weak lensing
- the statistical power for discovery at 50 meV were variously estimated at 1-7σ, depending on the assumptions made on combining data sets

may be the field's only nearterm strategy for determining $\sum m_\nu(i)$ for many scenarios, e.g., normal hierarchy with $m_\nu(1) \sim 0$

this is also an example of a scenario where one could be sensitive to the hierarchy: inverted hierarchy requires $\sum m_\nu(i) \gtrsim 10\ \mathrm{meV}$

Systematic contributions to the error? Harder to assess

The leverage one gains from combining different types of measurements to increase the range in scale and Z, has the downside of increasing the chances of systematic conflicts

One of the reasons that the kind of unified computational program discussed here could be helpful: a team with the capacity to build, then continue to develop, a standard cosmological model, to fully vary that model, to apply it in a consistent way to disparate data sets, then to come to consensus when discrepancies among data sets emerge

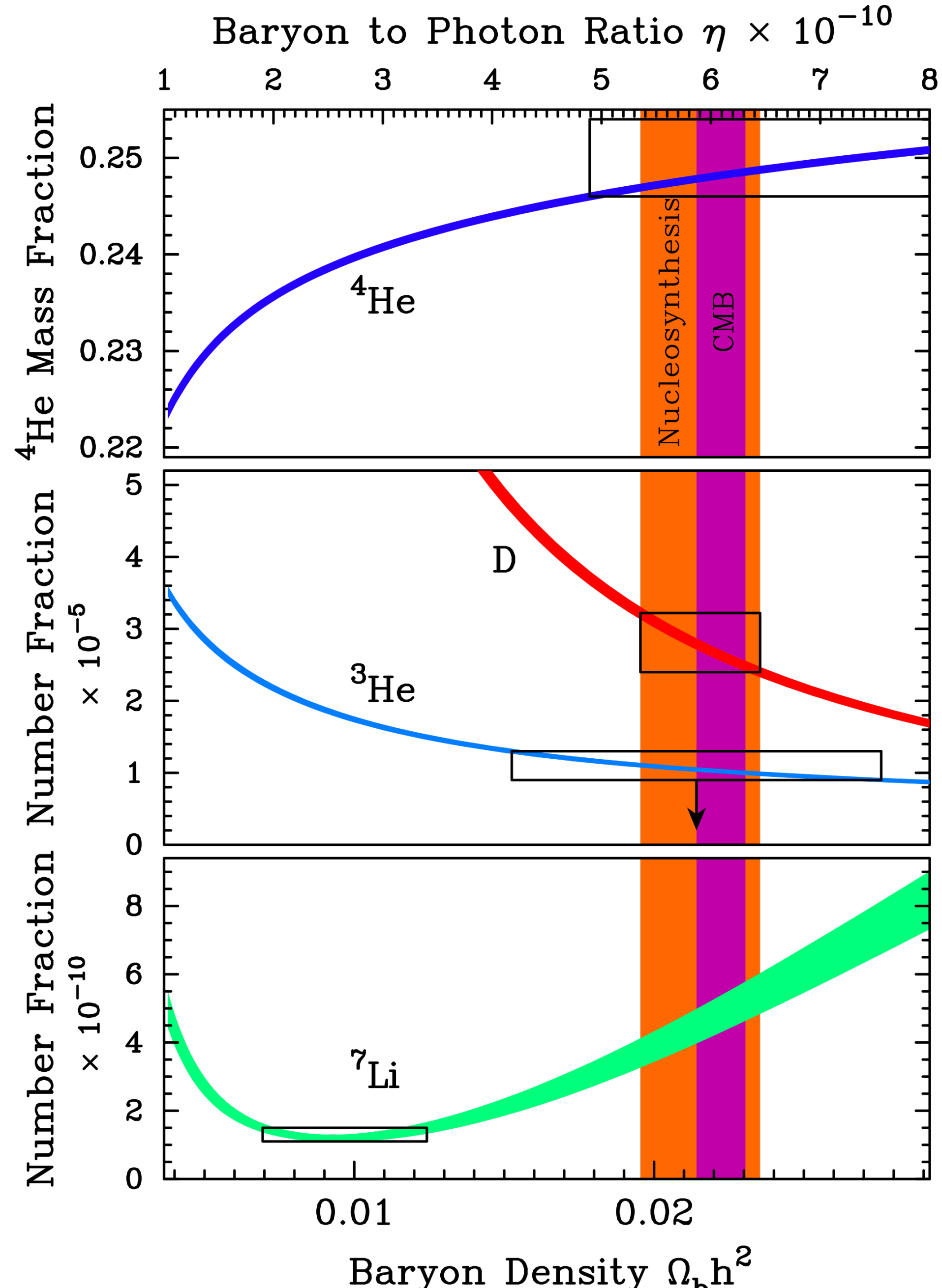
(reminiscent of the SSM, with its 19 free parameters)

m_ν could be a inner space/outer space "home run," impacting lab ν physics interpretations: $\beta\beta$ decay and LBNE (hierarchy)

<u>BBN</u>: issues include $\eta = n_B/n_\gamma$ consistency, the number of relativistic species (e.g., sterile neutrinos), the lepton number asymmetry, and alternatives to conventional abundance determinations

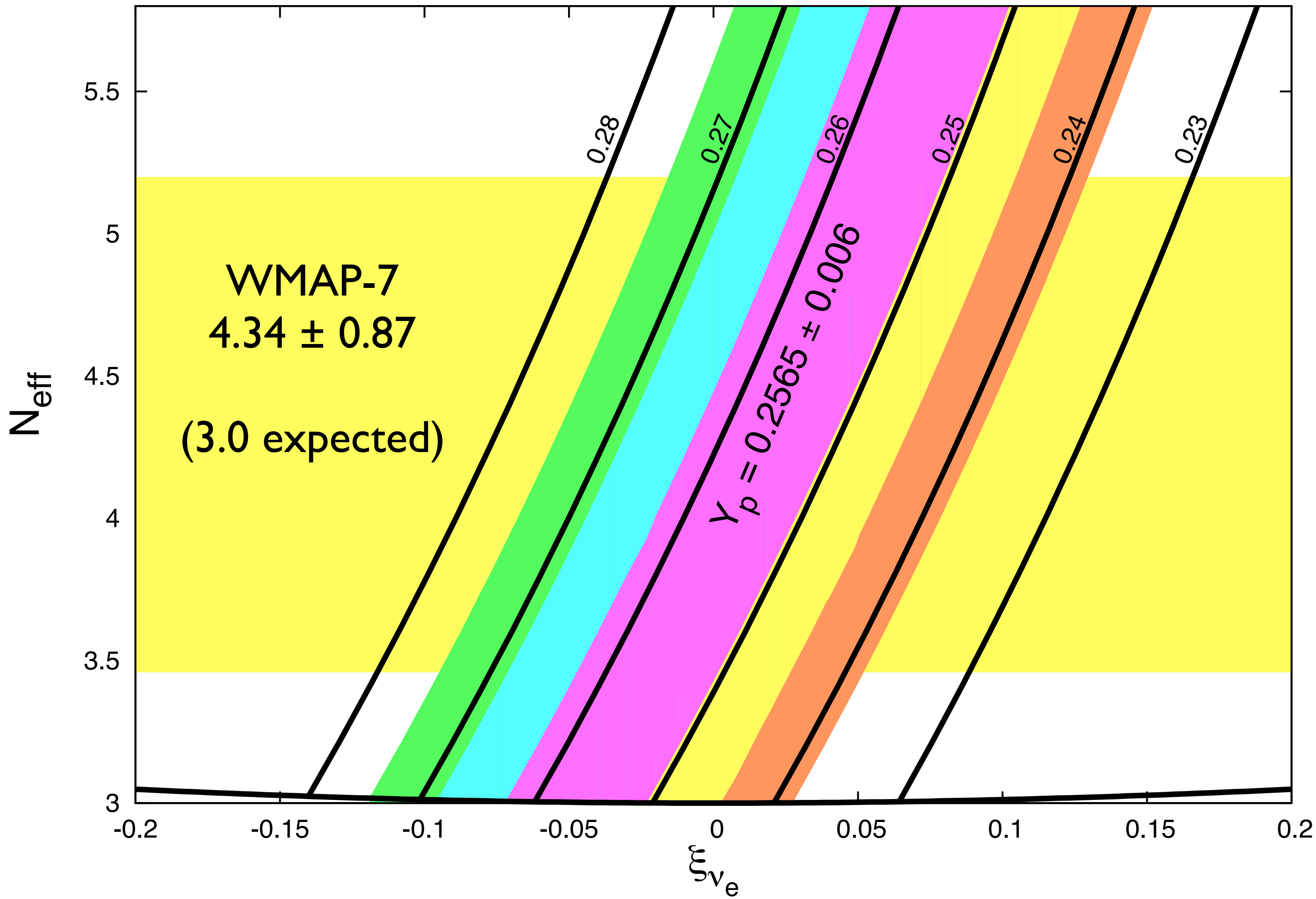
An issue exists with ^{7}Li, which has a well-defined primordial abundance plateau, corresponding to an $\eta \sim \eta_{CMB}$

The tension is ^{7}Li - d, with cosmology indicating that ^{7}Li is the outlier



Nao Suzuki (Tytler group) 2006

Competing clocks of expansion driven by the relativistic species and weak interactions driving n densities downward



Krauss, Lunardini, Smith

BBN and CMB studies constrain the ν number and asymmetry
weak hints that all is not right (but best to wait for Planck...)

Abundances: Potential to cross-check conventional low-Z abundance determinations with high-Z, pre-stellar determinations

^{4}He at recombination provides an earlier sink for electrons, altering the electron density and thus the radiation scattering, and thus spectrum

(and ^{7}Li provides a tiny amount of reheating)

$Y_P = 0.326 \pm 0.075$ (Komatsu et al. 2010: WMAP7 + BAO + Ho)

Deuterium abundance deduced from QSO absorption line systems ⇒

η_{BBN} ⇒ assuming $N_\nu = 3$ ⇒ $Y_P = 0.2482 \pm 0.0007$

Direct stellar determinations 0.25 ± 0.004

Comments

The analogy between the proposal to better organize computational cosmology, in response to rapidly advancing observations, is reminiscent to the Fowler/Bahcall/Iben/Sears initiative in 1962, to develop the standard solar model in anticipating of future neutrino experiments

Provided a very important way to correlate data, to feed in steadily improving microphysics (opacities, nuclear cross sections), to improve the physics when new measurements (e.g. helioseismology) required this

Led to major discoveries

The scales of physics are different today, the computers more complex, the computational teams much larger ... but the essential role of modeling in data-driven fields remains