Cosmology and Fundamental Physics Panel: laboratory astrophysics/theory connections

- Panel science priorities: four questions
- Panel recommendation of key activities
- Some comments on the evolving connections with lab-based astrophysics and theory

Wick Haxton *Gatlinburg LAW* *24 October 2010*

SCIENCE FRONTIERS PANELS

Panel on Cosmology and Fundamental Physics

DAVID N. SPERGEL, Princeton University, *Chair*,
DAVID WEINBERG, Ohio State University, *Vice Chair*
RACHEL BEAN, Cornell University
NEIL CORNISH, Montana State University
JONATHAN FENG, University of California, Irvine
ALEX V. FILIPPENKO, University of California, Berkeley
WICK C. HAXTON, University of California, Berkeley
MARC P. KAMIONKOWSKI, California Institute of Technology
LISA RANDALL, Harvard University
EUN-SUK SEO, University of Maryland
DAVID TYTLER, University of California, San Diego
CLIFFORD M. WILL, Washington University

Charge: To identify and articulate the scientific themes that will define the frontier in cosmology and fundamental physics research in the next decade

Context: A set of significant recent discoveries that strengthened the links between astrophysics/cosmology and fundamental physics conducted with ground-based or laboratory facilities

- the development of a relatively simple cosmological model fitting astronomical data, Lambda Cold Dark Matter, with parameters known to better than 10%, and with immediate implications for beyond-the-SM physics

- CMB and large-scale structure measurements that appear consistent with the predictions of inflation: a nearly flat universe with a matter distribution consistent with Gaussian and nearly scale invariant initial fluctuations

- CMB confirmation of the BBN conclusion that baryons comprise about 4% of the closure density: dark matter must be primarily nonbaryonic

- supernova data implying that the expansion of the universe is accelerating, consistent with dark energy dominance of the universe's energy density

- the astrophysical neutrino discoveries -- from the sun and from cosmic rays -- that neutrinos have mass and undergo flavor oscillations, providing the first demonstration of physics beyond the SM (and of identified dark matter)

- the identification of the cutoff in high-energy cosmic rays consistent with the expected GZK scattering off the CMB: the universe may be opaque to us at its asymptotic energies and distances

Scope: Panel considered input from communities concerned with the early universe; the CMB; probes of large-scale structure through observations of galaxies, intergalactic gas, or their associated gravitational distortions; determinations of cosmological parameters; dark matter; dark energy; tests of gravity; astrophysical measurements of physical constants; and the fundamental physics that might be derived from observations of astronomical messengers (νs, γs, UHE cosmic rays)

Among the white papers considered were ~5 primarily focused on either lab astrophysics or theory/computation

Response was organized around four questions and one discovery area: selective

How did the Universe begin? (the mechanism behind inflation)

Why is the universe accelerating? (the nature of the dark energy)

What is dark matter?

What are the properties of neutrinos?

(Discovery area: gravitational wave astronomy)

Why is the universe accelerating?

What is dark matter?

What are the properties of neutrinos?

perhaps have the more immediate connections with laboratory nuclear and particle physics/astrophysics

I. How did the Universe begin?

Inflation as a paradigm: microscopically, causally connected regions expand exponentially, driving the spatial curvature nearly to zero, and producing a homogeneous universe

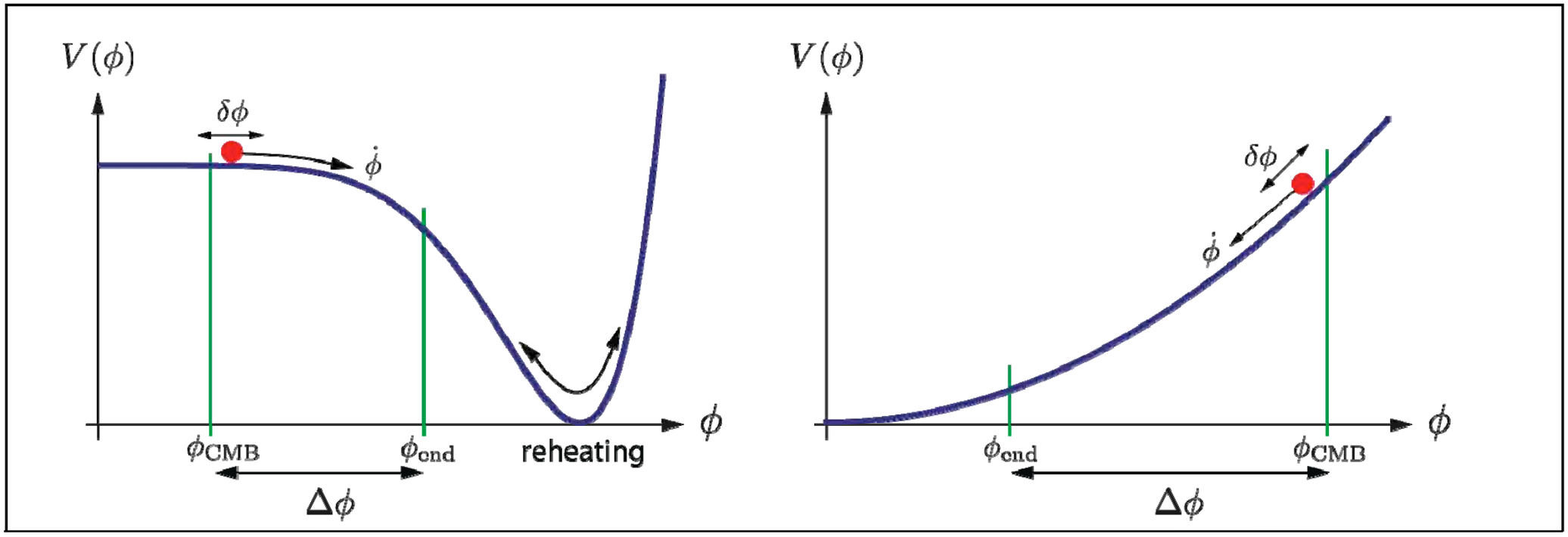
But the underlying mechanism responsible for inflation has not been identified

Operated at an energy/density not directly accessible in the laboratory

Toy-model mechanisms can be constructed in most extensions of the SM -- GUTs, string theories, phenomenologies with extra dimensions, models with relatively low-energy phase transitions (such as Peccei-Quinn), gravity theories that depart from GR at high densities, ...

Predictions of the simplest toy model -- single-field "slow roll inflation" -- establish observational benchmarks

1) a flat universe: curvature scale >> horizon scale
2) nearly scale-invariant fluctuations reflected in the matter distribution
3) fluctuations that are Gaussian, adiabatic, homogeneous, and isotropic
4) stochastic background of nearly scale-invariant inflationary GWs



Panel recommendations focused on precise astronomical measurements to look for departures from vanilla models

- measurement of the curvature of the universe to 1 part in 10^4

- as the strength of primordial gravity waves can be related to the energy scale at the time of inflation, searches for long-wavelength gravity waves through the polarization they imprint on the CMB

- extended surveys-- LSS of galaxies, CMB polarization, weak lensing of galaxies and the CMB, fluctuations in the intergalactic medium -- to determine the amplitudes of primordial fluctuations over the accessible scales

II. Why is the universe accelerating?

The panel report poses two leading questions

- is the acceleration caused by a breakdown in GR or by a new form of energy?
- if dark energy is causing the acceleration in space and time, is the energy density constant in space and time?

The later is formulated in terms of the EOS parameter

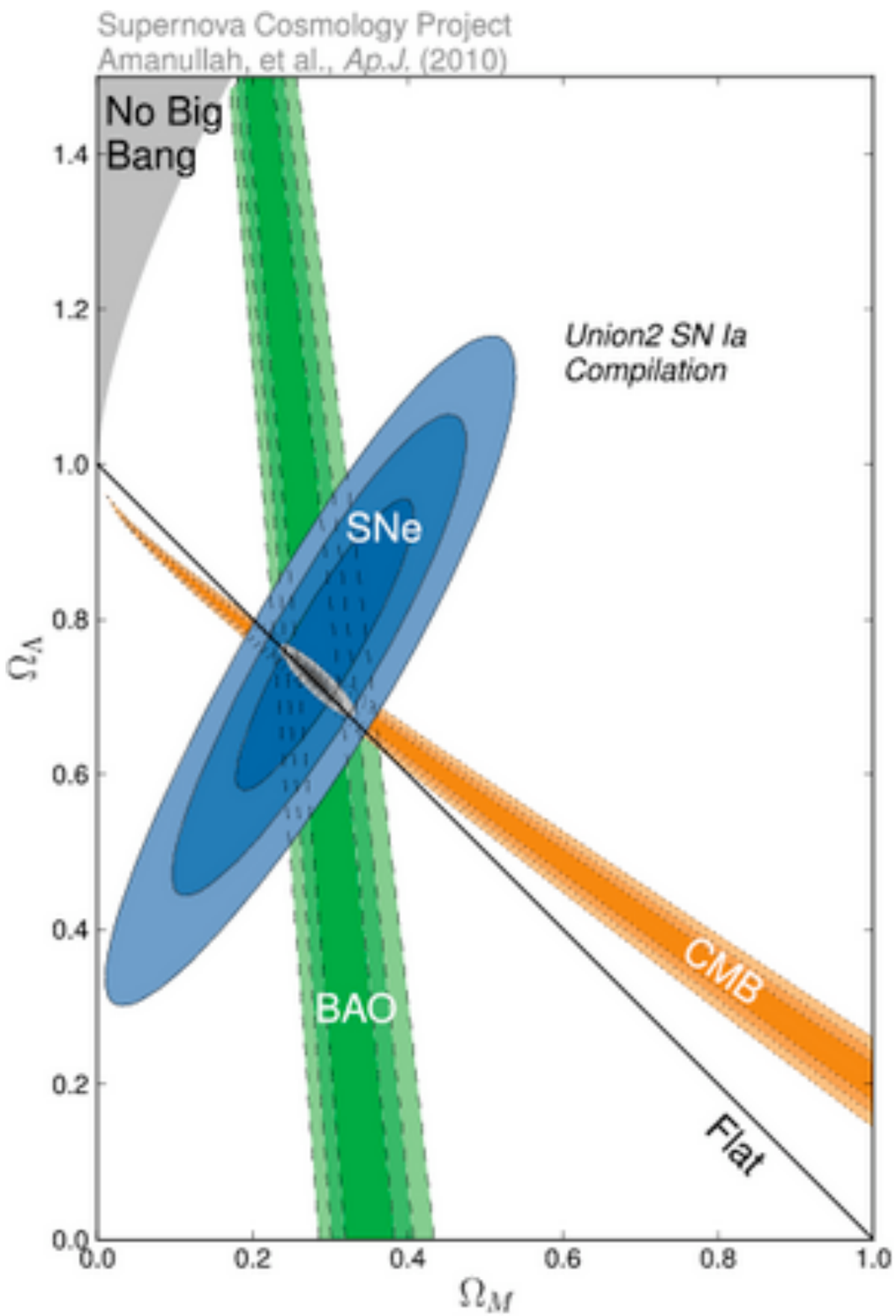
$$P = w(z)\ \rho c$$

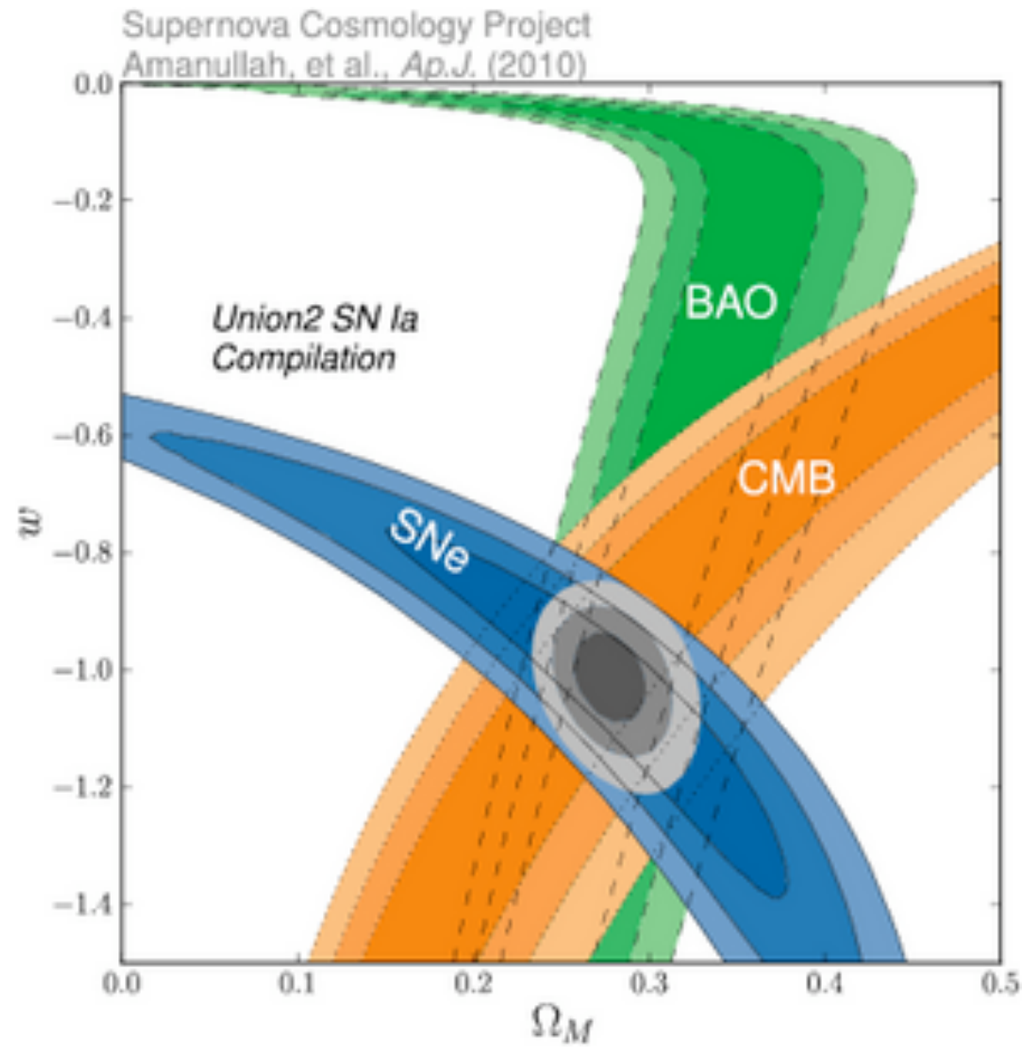
$$\rho_{ED}(z) = \rho_{ED}(0)\ \exp\left[3\int (1+w(z))\ dln(1+z)\right] \underset{w=-1}{\longrightarrow} \rho_{ED}(0)$$

Vacuum energy -- a cosmological constant -- giving $w = -1$

Lines of attack include

- measurements of the Hubble parameter $H(z)$ (the expansion rate probes total energy density -- ordinary + dark matter, radiation, dark energy)
- measurements of the distance-redshift relationship $D(z)$
- measurements of the growth function $G(z)$ describing the strength of matter clustering, which is related to $H(z)$ but probes different scales (GR test)


Supernova Cosmology Project
Amanullah, et al., Ap.J. (2010)
No Big Bang
Union2 SN Ia Compilation
SNe
BAO
CMB
Flat
Ω_Λ
Ω_M


Supernova Cosmology Project
Amanullah, et al., Ap.J. (2010)
Union2 SN Ia Compilation
BAO
CMB
SNe
w
Ω_M

$$w(z) \sim -1 \pm 0.2$$

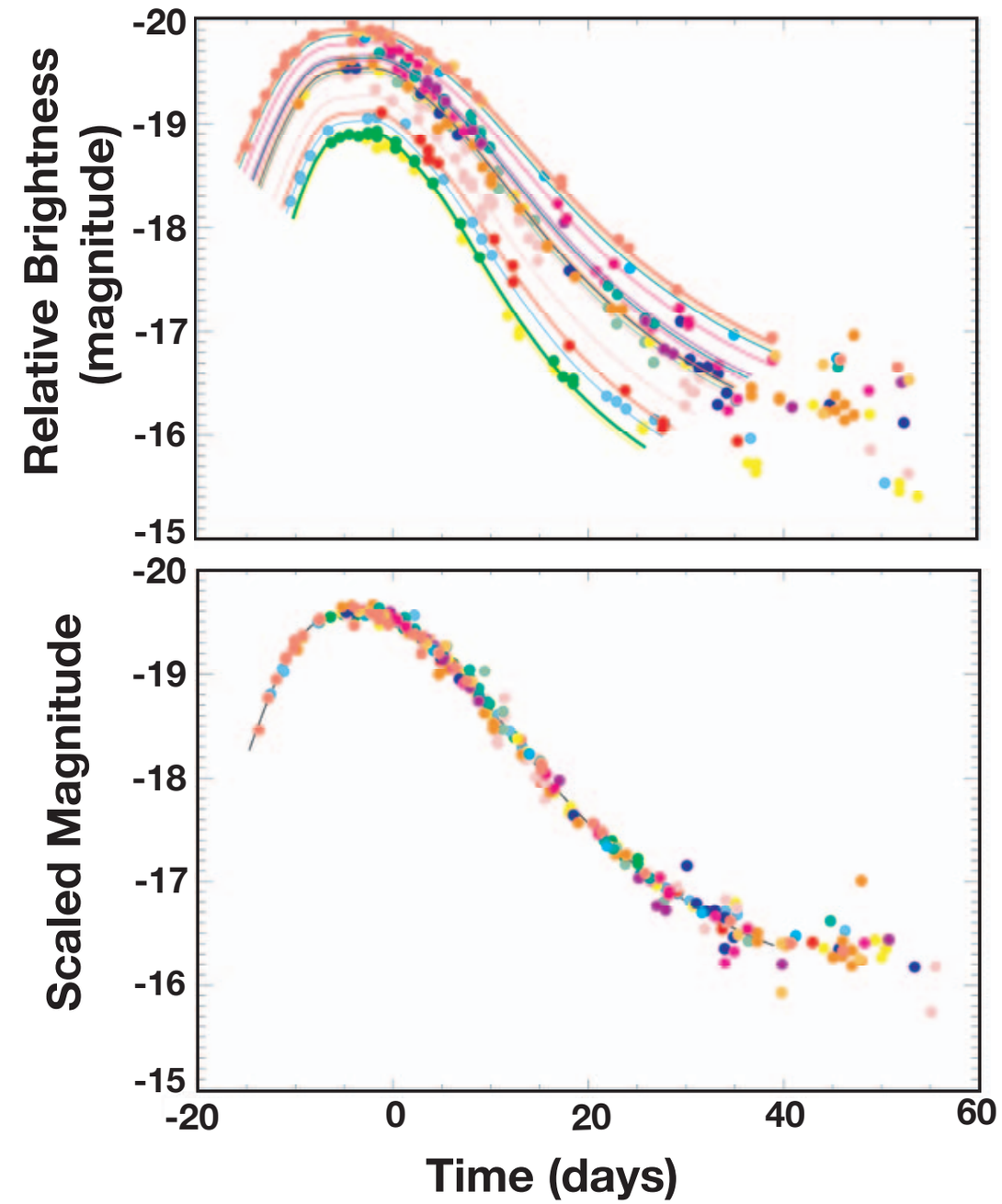
Tools include

1) SNIa as standard candle distance measurements

- good statistical power, Gpsec range

- potential systematics include corrections for dust extinction, the accuracy of photometric calibrations across a wide range of redshifts, possible evolution of the SN population with metalicity or other parameters

- method based in part on the phenomenological Phillips relation that corrects for morphological differences by scaling light curve shape according to peak luminosity, thereby correcting for the fact that bright SNIa decline more slowly than faint ones



Calan/Tololo survey

improved modeling ⇔ light curve systematics

more data ⇔ more effective Phillips parameterizations

Accounting for (or determining the exceptions to) the Phillips relationship are a key laboratory/theory challenge

The thermonuclear detonation is a computing grand challenge problem:

- how it is thermally triggered within a WD
- nuclear reaction chains from C/He to ^{56}Ni via C+C and ensuing reactions
- the heat conduction through a degenerate electron/positron plasma
- the EOS
- the propagation of very narrow flame fronts
- the embedding of the physics in 3D

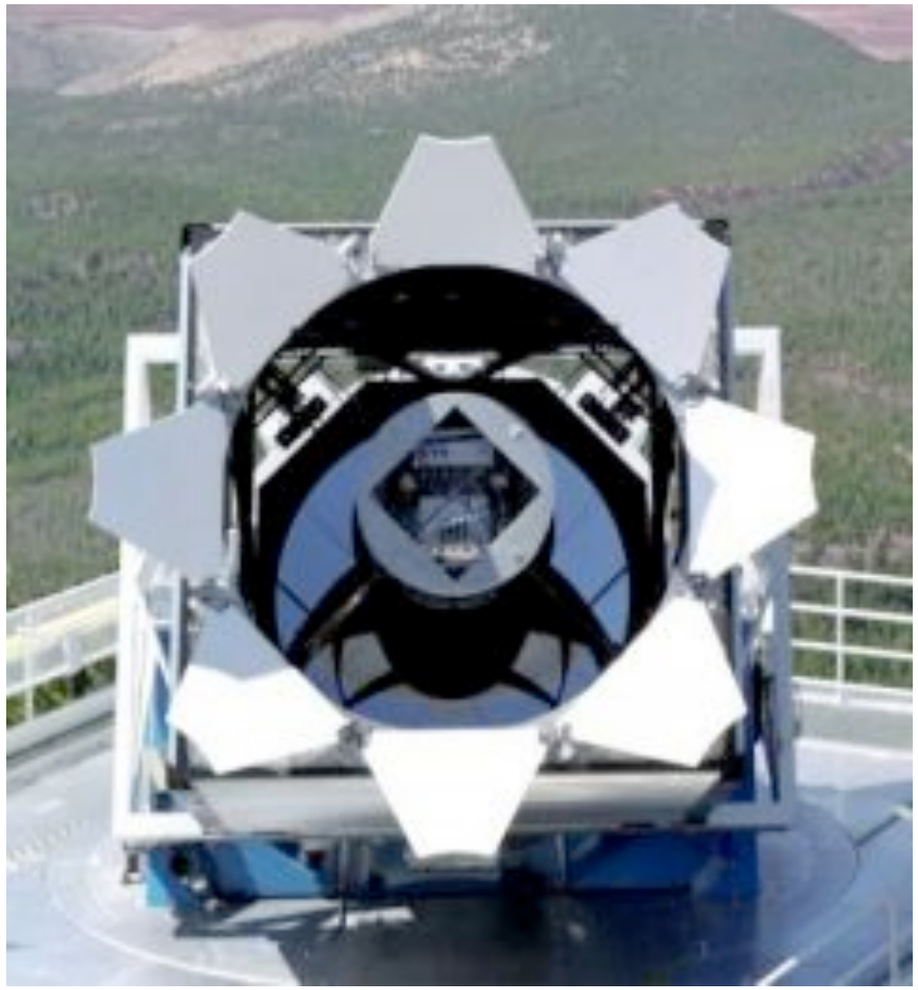
Most relevant to understanding the Phillips relation, and thus to getting better control over standard-candle systematics, is the ^{56}Ni-decay-power light curve evolution, which appears to depend on

- the total mass of Ni produced
- the KE of the explosion
- the extent of mixing
- whether asymmetries induced by deflagration persist and have line-of-sight consequences
- the radiation transport in the Fe-rich stellar atmospheres (opacities)

see Hayden et al. (SDSSII arXiv:1001.3428) and Kasen and Woosley (Ap J 656 (2006) 661)

2) Baryon acoustic oscillations

- measurement of $D(z)$ and $H(z)$
- basic idea is that the typical scale associated with the baryon acoustic peaks and imprinted at the time of recombination can serve as a "standard ruler" in a statistical sense: this scale ~150 Mpc
- the extent by which this ruler has been stretched over some specified time z can then measured by observing any tracer of the density fluctuations: clustering of galaxies, quasars, Lyman-α forest, 21-cm emission,...
- technique thought to be relatively free of systematic bias and powerful because of its statistical nature; some systematics may remain because the observed set, e.g., the red elliptical galaxies used by BOSS, varies with z

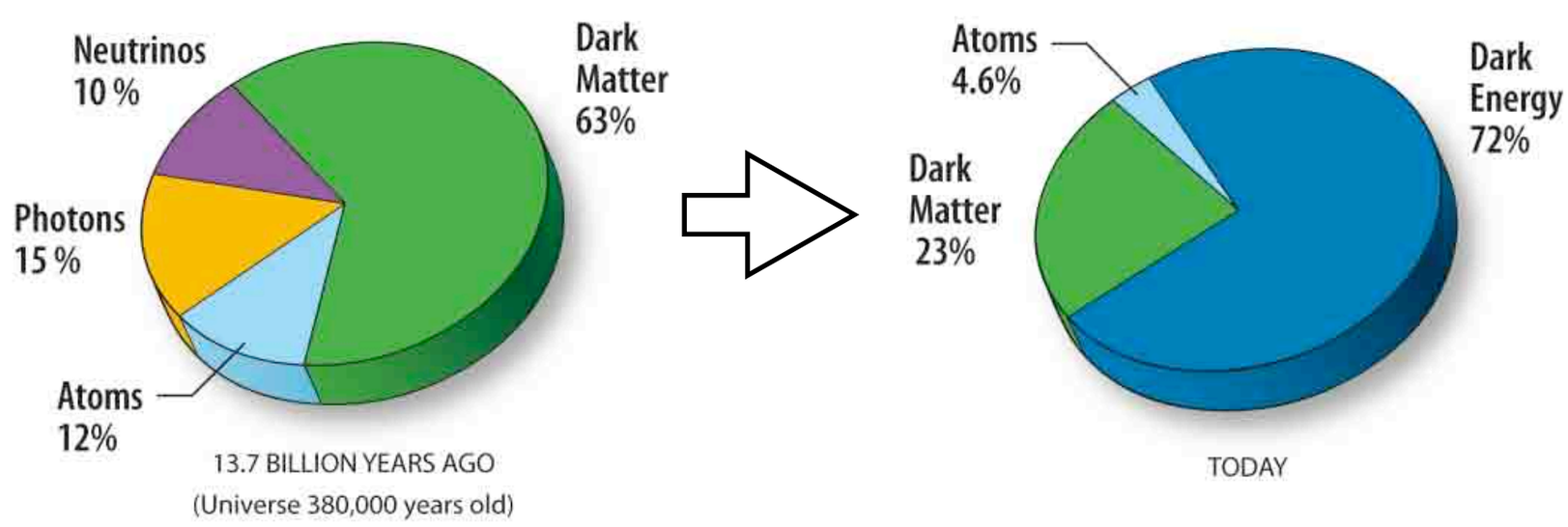


3) Matter clustering tests of $G(z)$

- abundance of galaxy clusters as a function of z
- the strength of weak lensing as a function of z

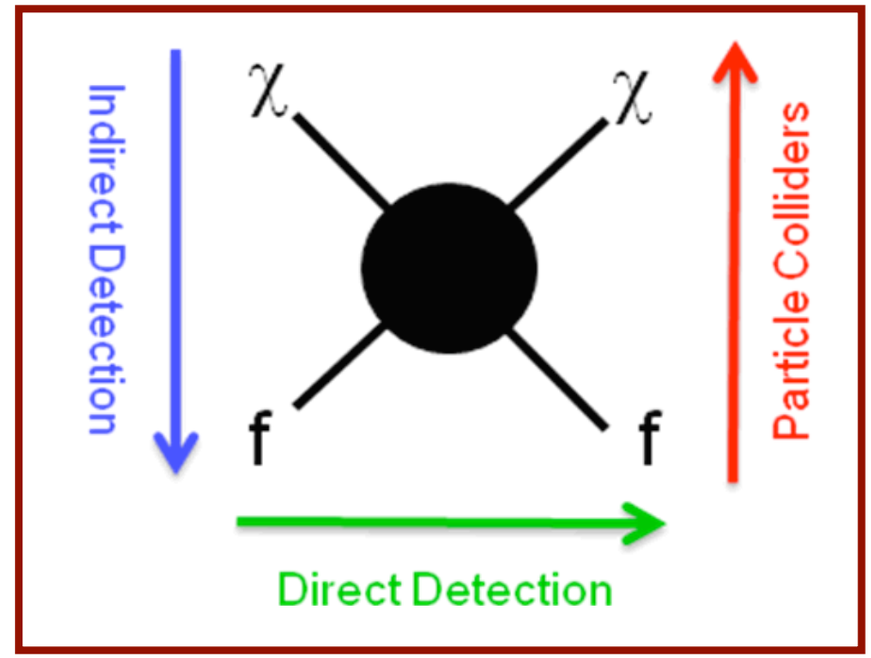
III. What is dark matter?

- perhaps the most-likely-to-be-resolved new-physics problem
- closely linked to laboratory-based accelerator and underground experiments to probe for new particles beyond the standard model
- discovered in astrophysics, from the flat velocity rotation curves of galaxies
- must be long-lived or stable, cold or warm (so that it is slow enough to seed structure formation), gravitationally active, but without strong couplings to itself or to baryons
- leading candidates are weakly interactive massive particles (WIMPs) and axions
- consistent with the generic expectation that new particles will be found at the mass generation scale of the SM of 10 GeV - 10 TeV



- "WIMP miracle" that WIMP annihilation cross sections imply $\Omega_{WIMP} \sim 0.1$

- their detection channels include
  - their role in LSS formation
  - their potential to annihilate into SM particles, an astrophysical signal
  - their direct production in the collision of SM particles at accelerators
  - their scattering off SM particles, particularly heavy nuclear targets

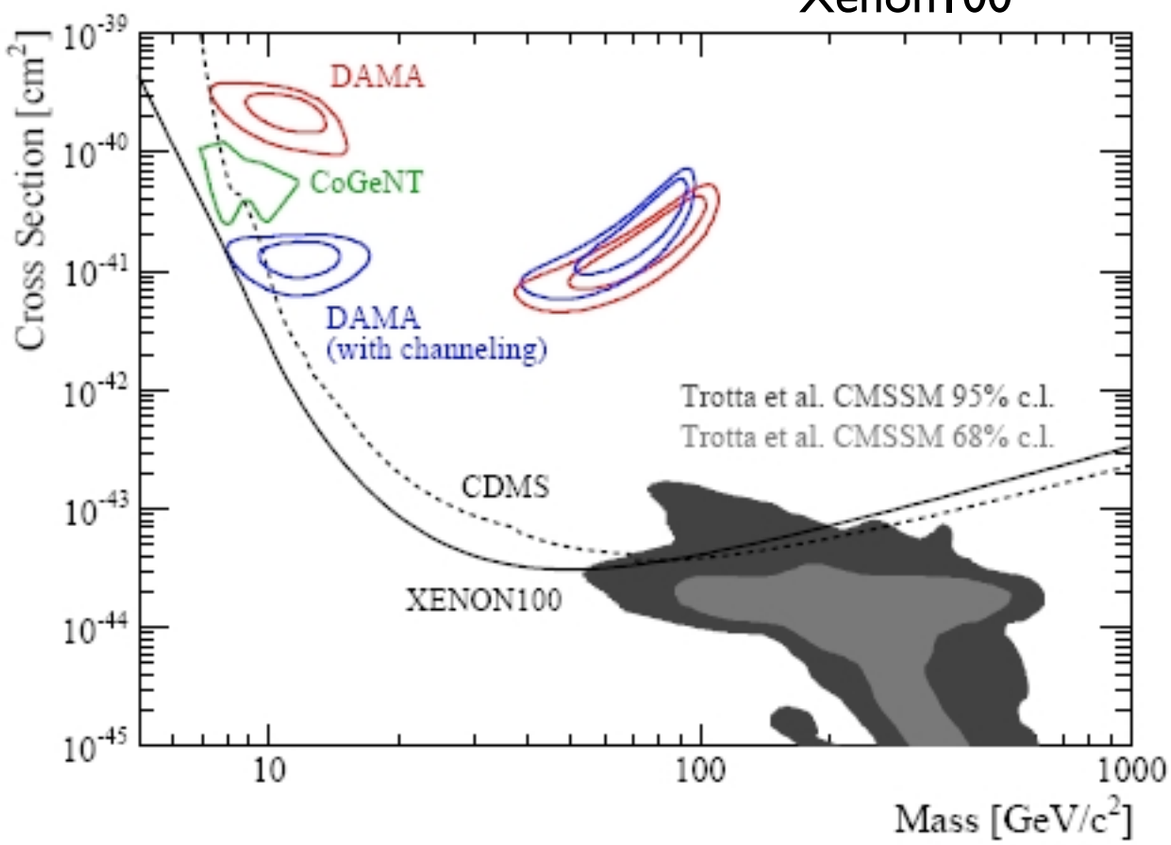


- they may have either spin-independent or spin-dependent nuclear scattering cross sections, depending on parameters

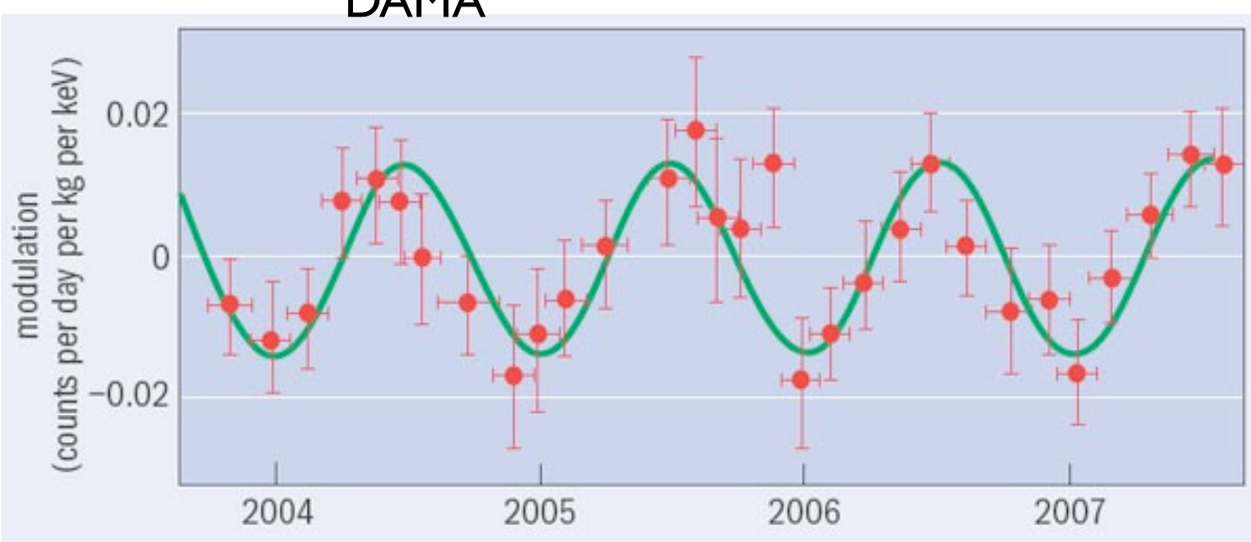
- while the range is broad, expected $\sigma_{SI} \sim 10^{-45}\ \mathrm{cm}^2$: current bounds for WIMPS in the 10 GeV - TeV are $\sim 10^{-43}\ \mathrm{cm}^2$

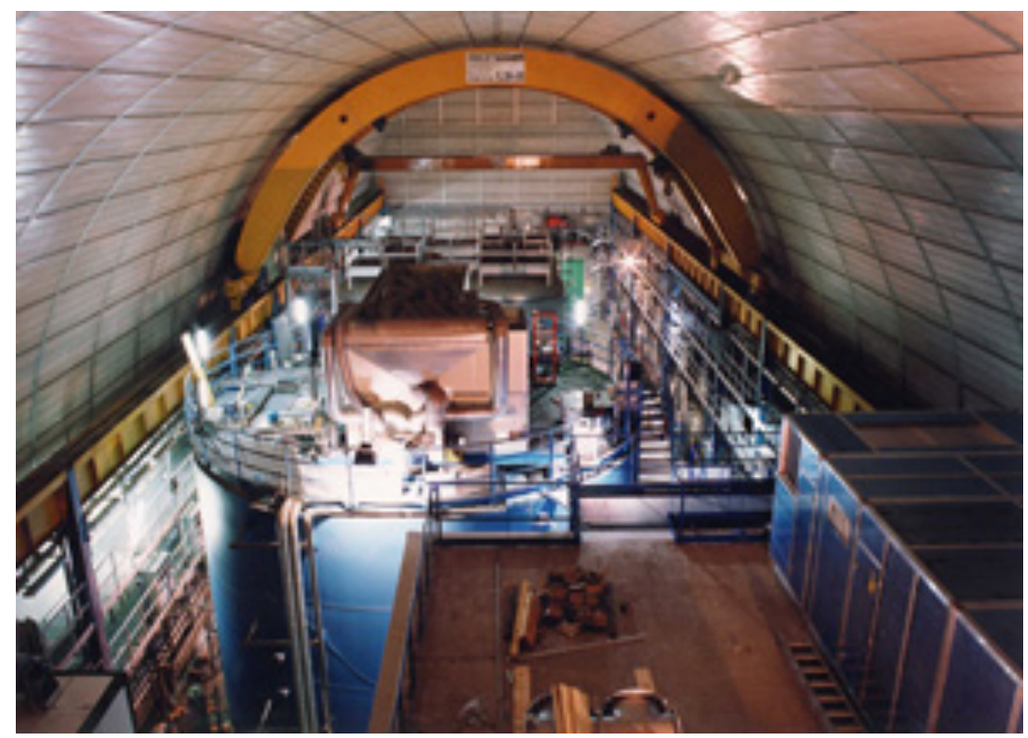
- the largest detectors are now approaching 100 kg; the international program is focused on developing new detectors in the 1-10 ton scale, based on technologies like ultra-clean noble-gas liquid, with sensitivities of a few events/y or $\sigma_{SI} \sim 10^{-47}\ \mathrm{cm}^2$

Xenon100



DAMA





controversy over DAMA, CoGeNT events at low energy vs. efficiency of Xenon100 to exclude such light-mass WIMPS - plus CDMS events

Some of the laboratory and theory needs

- support for detector R&D in both SI and SD channels
- deep locations: detectors sensitive to penetrating energetic neutrons produced by CR muons
- control of environmental activities, the limiting background source to date
- astrophysical searches for annihilation products, with attention to standard processes that might mimic possible signatures (e.g., Pamela)
- from nuclear theory, estimates of SI form factors and SD cross sections

The hope is for the kind of concordance that emerged from CMB/BBN tests of η

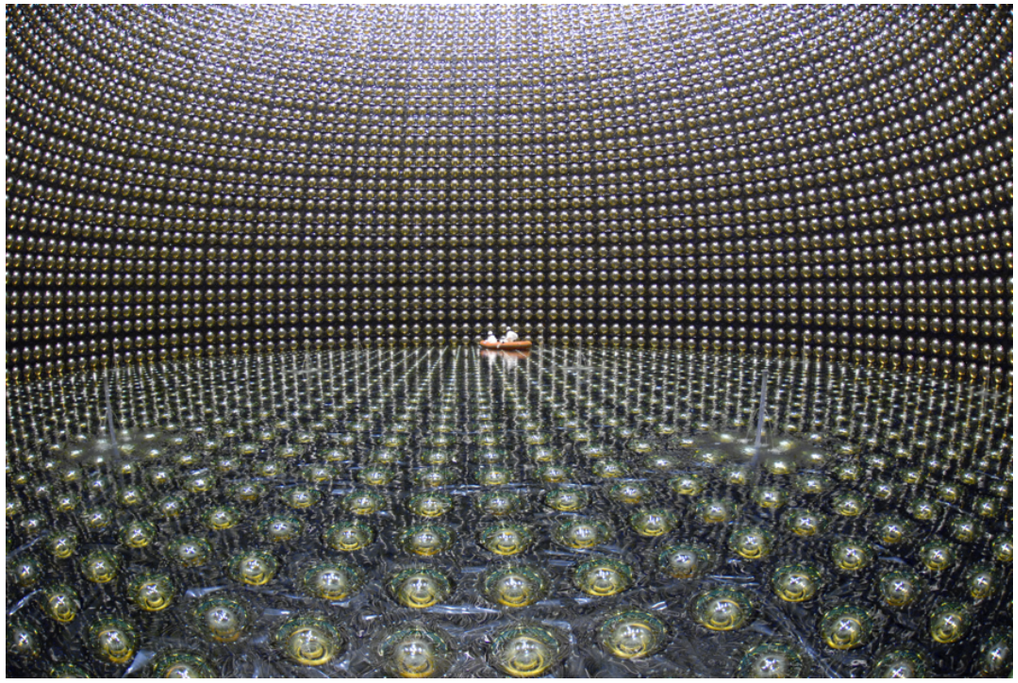
- LHC discovery of supersymmetry and a lightest stable SUSY particle
- direct detection of cosmological WIMPS with consistent properties
- improved astrophysical constraints on the local DM density and structure on subgalactic scales testing the paradigm of cold, collisionless, stable DM

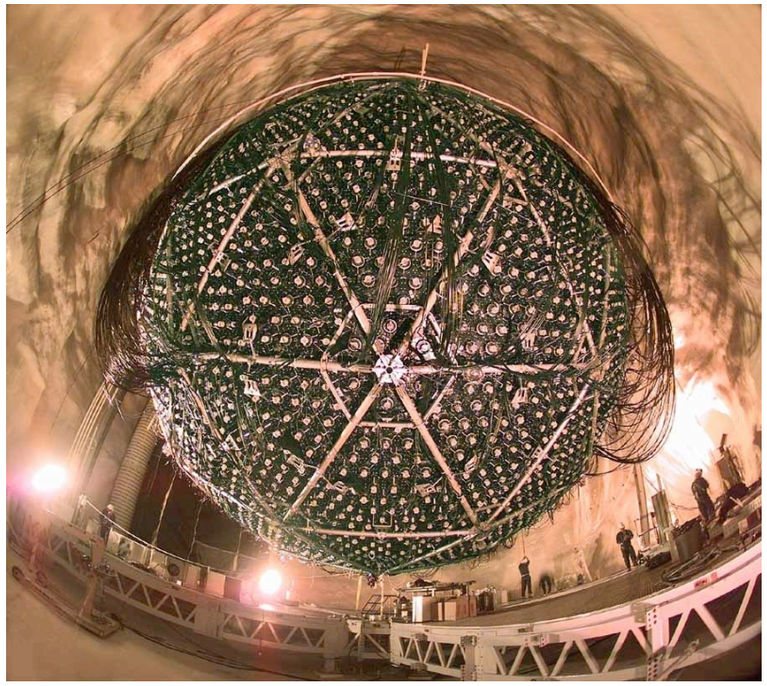
laboratory determination of DM properties $\Leftrightarrow$ removing LSS uncertainties

What are the properties of neutrinos?

Arguably the richest intersection with laboratory particle/nuclear astrophysics

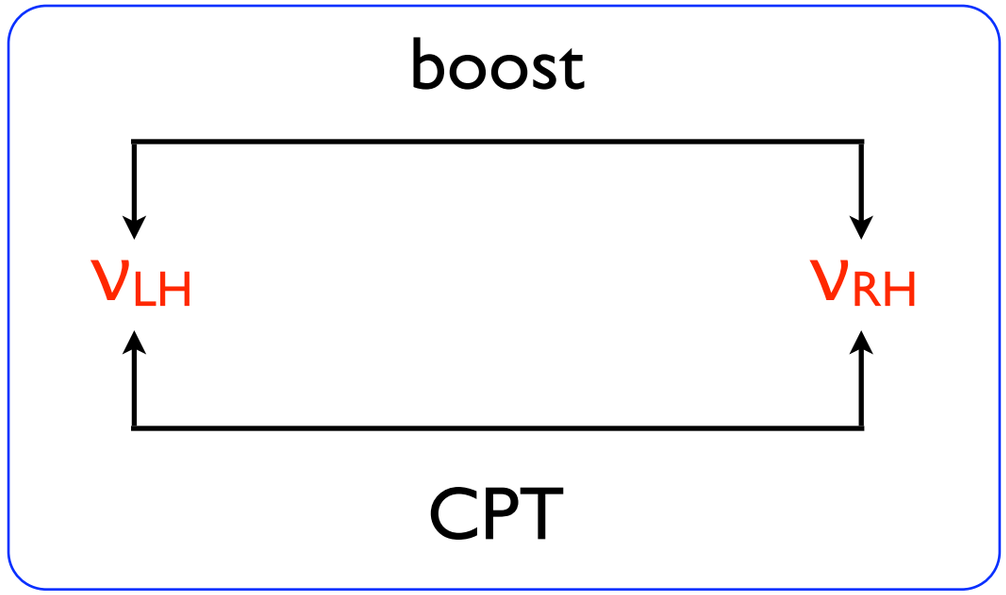
- solar and atmospheric ν programs produced new physics
- significant unknowns remain, with implications for astrophysics and cosmology
  - the origin of matter in the cosmos
  - the high-energy limits of astrophysical accelerators
  - the absolute scale of ν mass
  - energy transport, nucleosynthesis in extreme astrophysical environments
- while the lab astrophysics program has a great deal of reach, it also is embedded within and competes with major programs of particle and nuclear physics

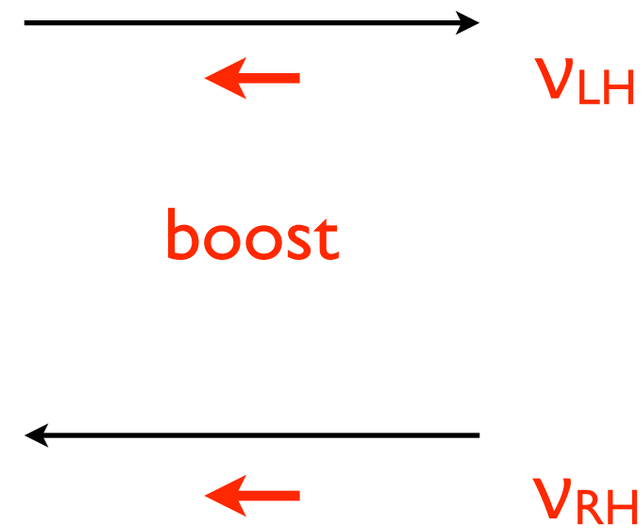




#1 measure ν mass at 0.05 eV: physics connected with unique properties of ν mass

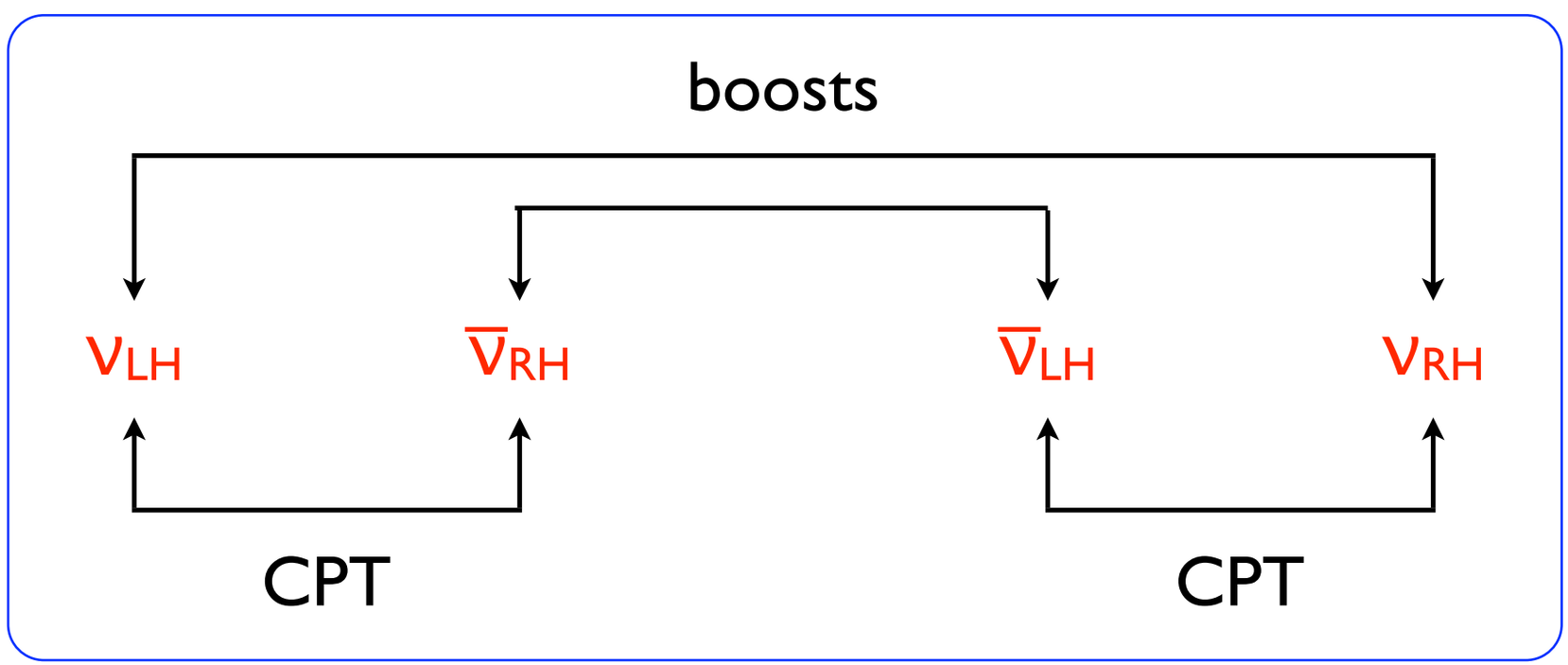
Majorana:





or some linear combinations of the two

Dirac:



SM sets both to zero

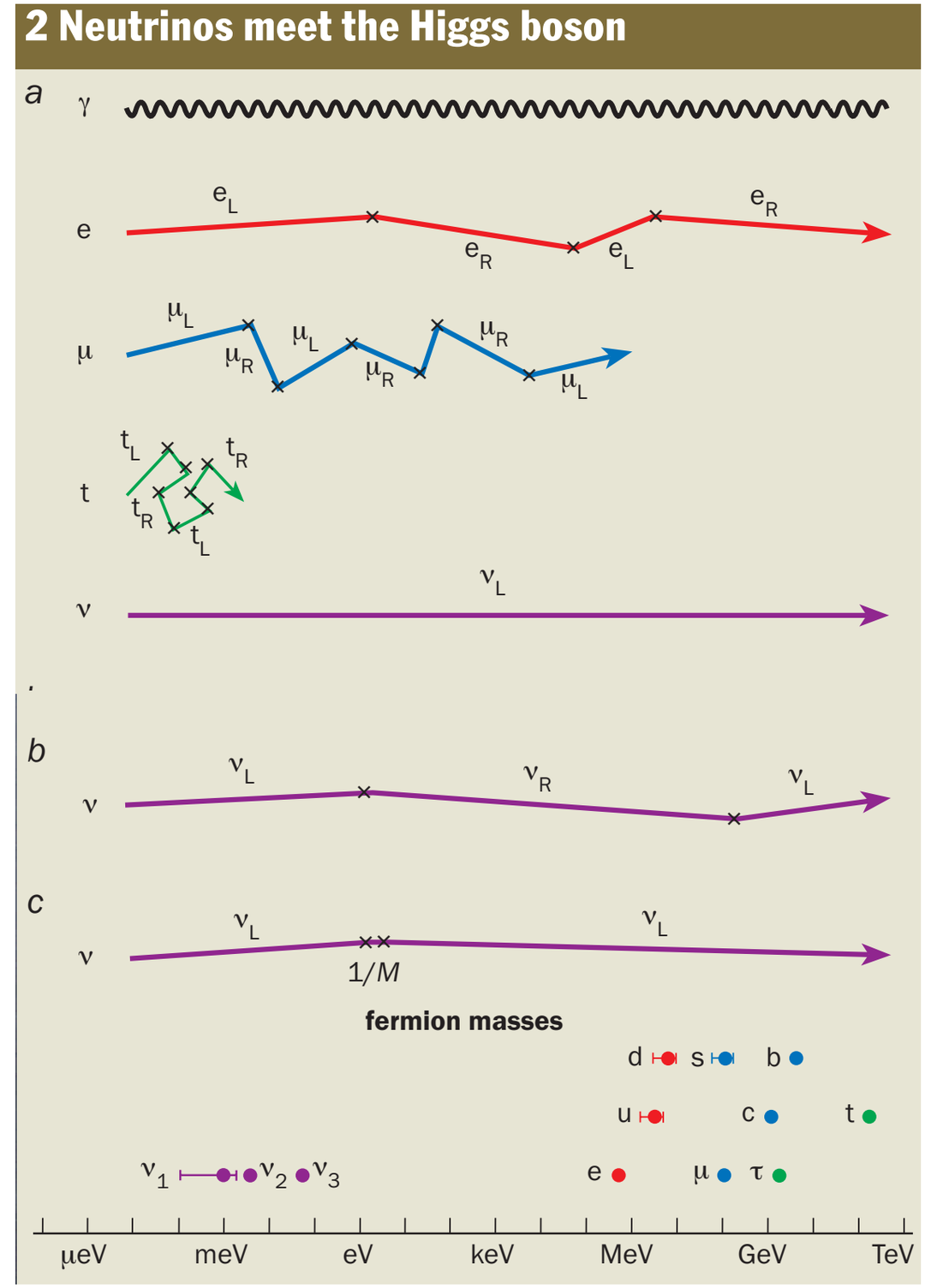
- no RHed ν field - needed for M_D^ν
- M_L^ν requires a coupling to ϕ^2, which carries dimensions, and thus requires a new scale

But the SM *is* an effective theory, and this first "correction" to that theory is expected

$$\begin{pmatrix} M_L \sim 0 & M_D \\ M_D^\dagger & M_R \end{pmatrix} \to m_\nu^{\text{light}} \sim M_D \left(\frac{M_D}{M_R}\right)$$

- M_D/M_R is the needed small parameter is explain ν mass scale
- atmospheric ν mass scale ⇒

$$M_R \sim 0.3 \times 10^{15}\ \text{GeV} \sim M_{GUT}$$



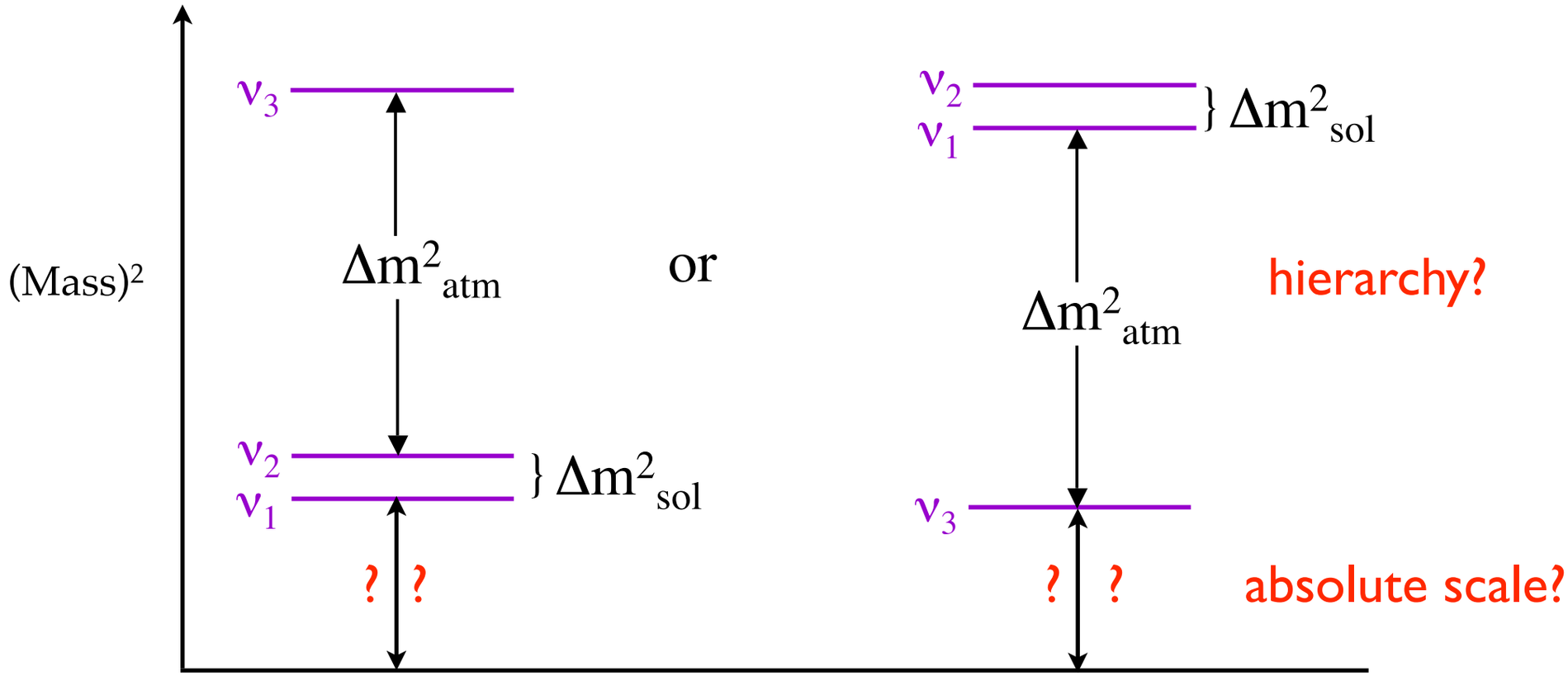
SM masses

M_D^ν

M_L^ν

anomaly

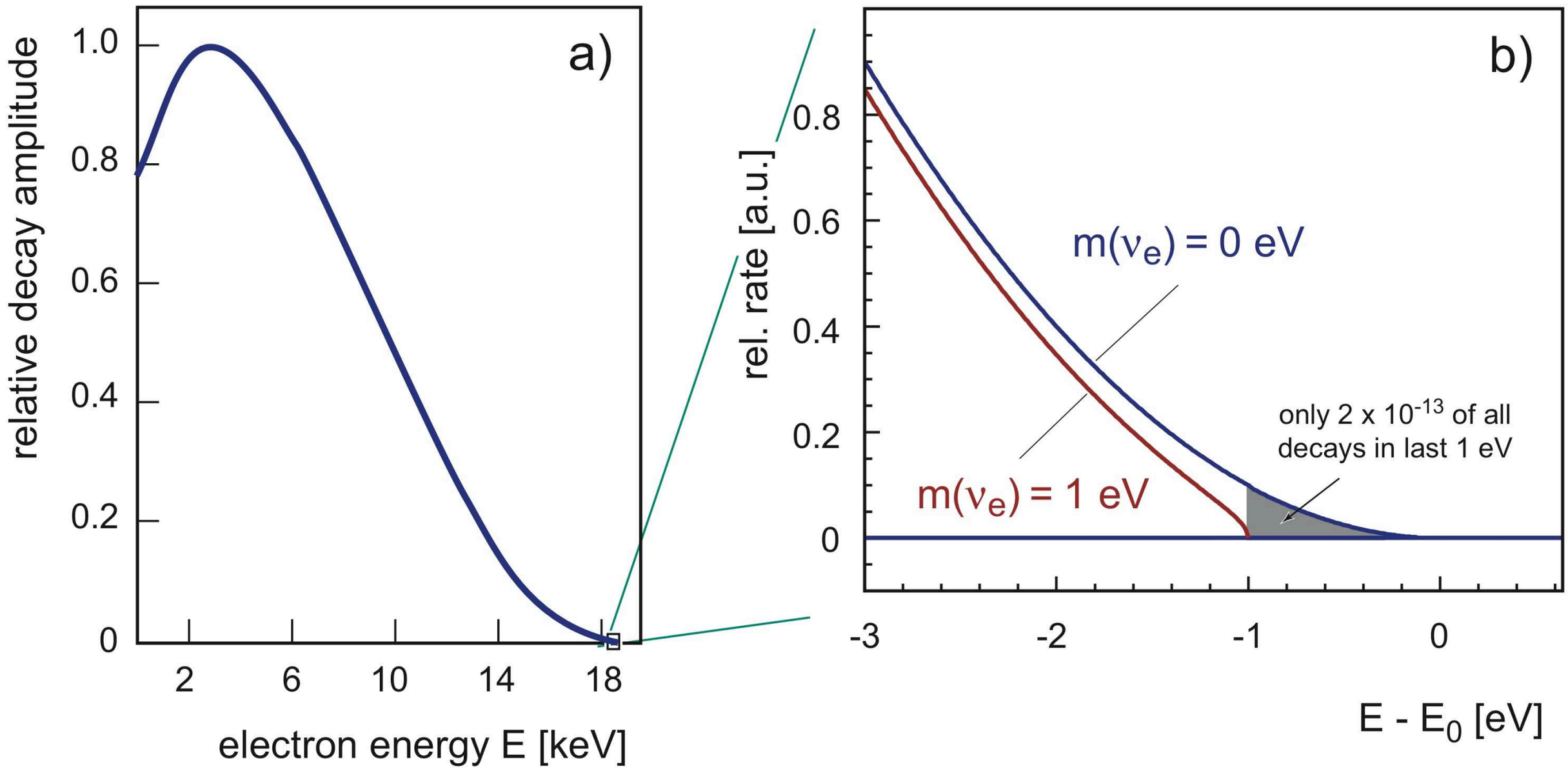
from Muryama



$$\sum_i m_i \geq \sqrt{\Delta m^2_{\rm atm}} \sim 50 \text{ meV}$$

$$\sum_i m_i \geq 2\sqrt{\Delta m^2_{\rm atm}} \sim 100 \text{ meV}$$

while in principle one can measure the absolute mass in the lab



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

in practice there are limitations

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

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

structure surveys may reach the needed sensitivity, probing m_ν and the hierarchy

- νs with a smaller mass remain relativistic longer, travel further, and suppress growth of structure on larger scales

$$k_{\text{free streaming}} \sim 0.004\sqrt{m_\nu/0.05\text{eV}}\ \text{Mpc}^{-1}$$

- νs are a unique DM component because they transition from relativistic to nonrelativistic matter with expansion: thus effects are both scale- and Z-dependent

- 50 meV requires sensitivity hot DM at ~ .001 ρ_{crit} : current sensitivity ~ .013 ρ_{crit}

- scale-dependent effects at fixed Z that evolve characteristically with Z, depending on the value m_ν, naturally leads to analyses that combine data sets sensitive to different scale and Z sensitivities

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

νs are effective in altering the evolution of matter+CDM at the few % level, though they comprise only 0.1% of today's energy density

#1 measure ν mass at 0.05 eV: reach of LSS surveys typically scale $\propto 1/\sqrt{N}$, so a factor of 100 needed

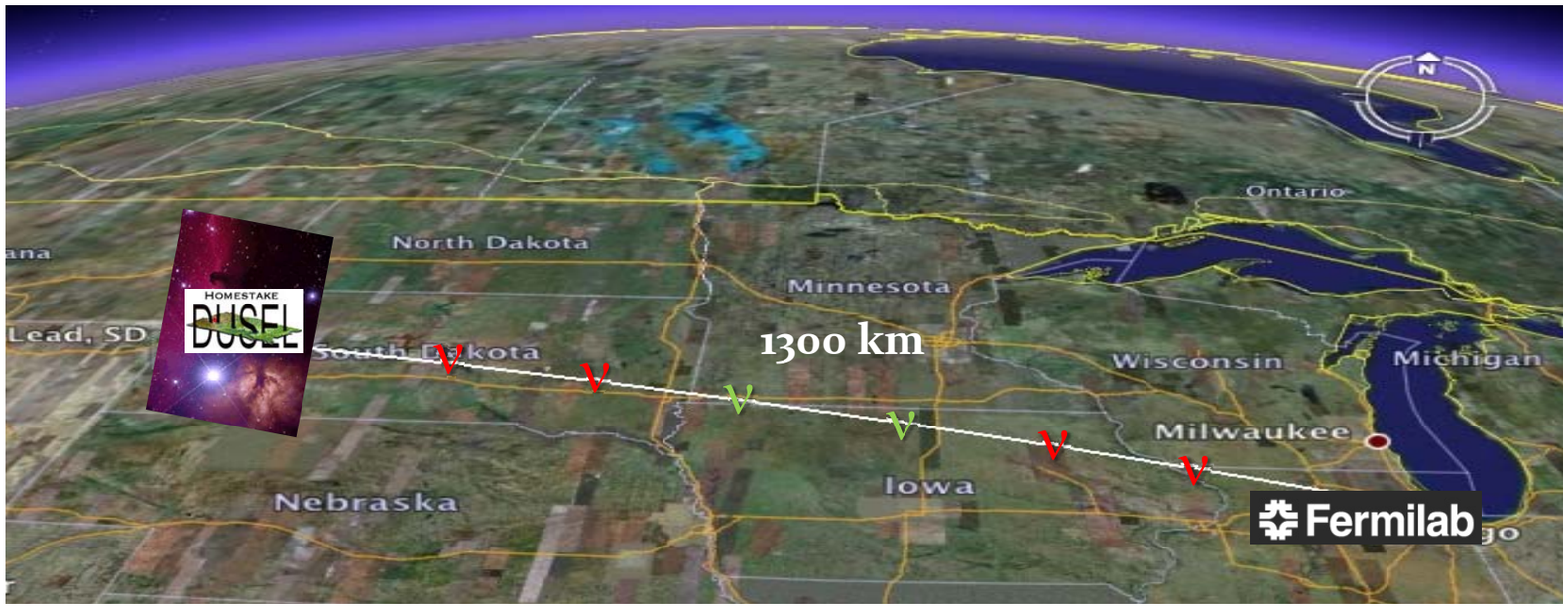
- such improvements in surveys with sensitivity to (1-100) Mps scales could come from
  - high-redshift galaxy surveys
  - SDSS-III BOSS 10^5 QSO survey
  - Planck CMB
  - 21cm radio telescopes with 0.1 km^2 collection
  - weak lensing ...

#2 enable precision measurements of the multi-flavor ν spectrum from a galactic SN

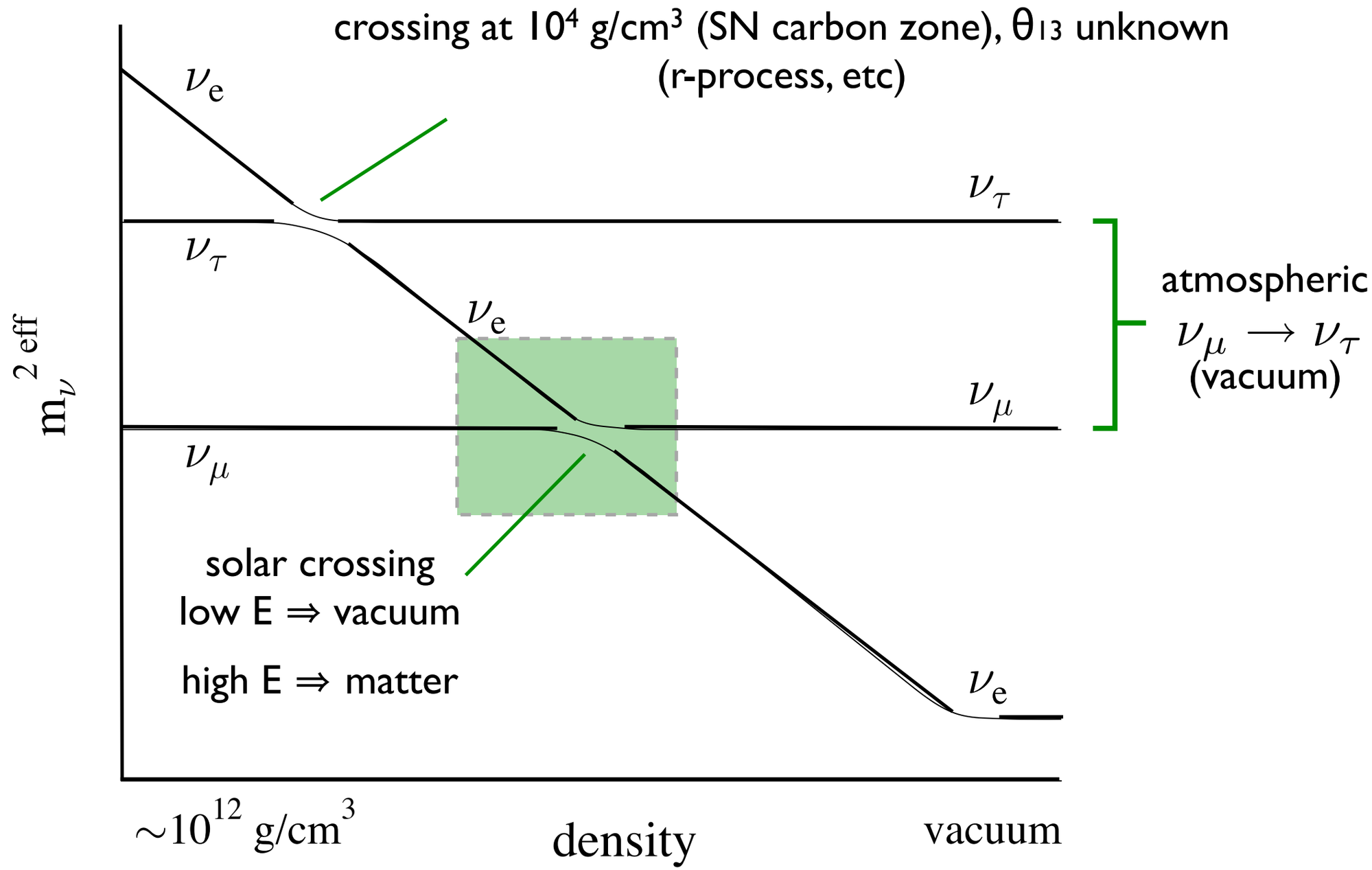
- key issue: third mixing angle θ_{13} unknown, but critical in determining the strength of ν CP violation -- with leptogenesis being a leading theory for explaining the baryon number asymmetry

- the next decade's lab experiments may reach sensitivities

$$\sin^2 2\theta_{13} \sim 0.01$$



Physics issues: 1) SN ν transport, nucleosynthesis changed if $\theta_{13} > 10^{-4}$



second crossing is standard MSW, a consequence of higher progenitor densities

- SNII emit $\sim 3 \times 10^{53}$ ergs in νs of all flavors, cooling as e^{-t/t_0} with $t_0 \sim 3$ sec

- we are not doing well in keeping an array of capable detectors operating

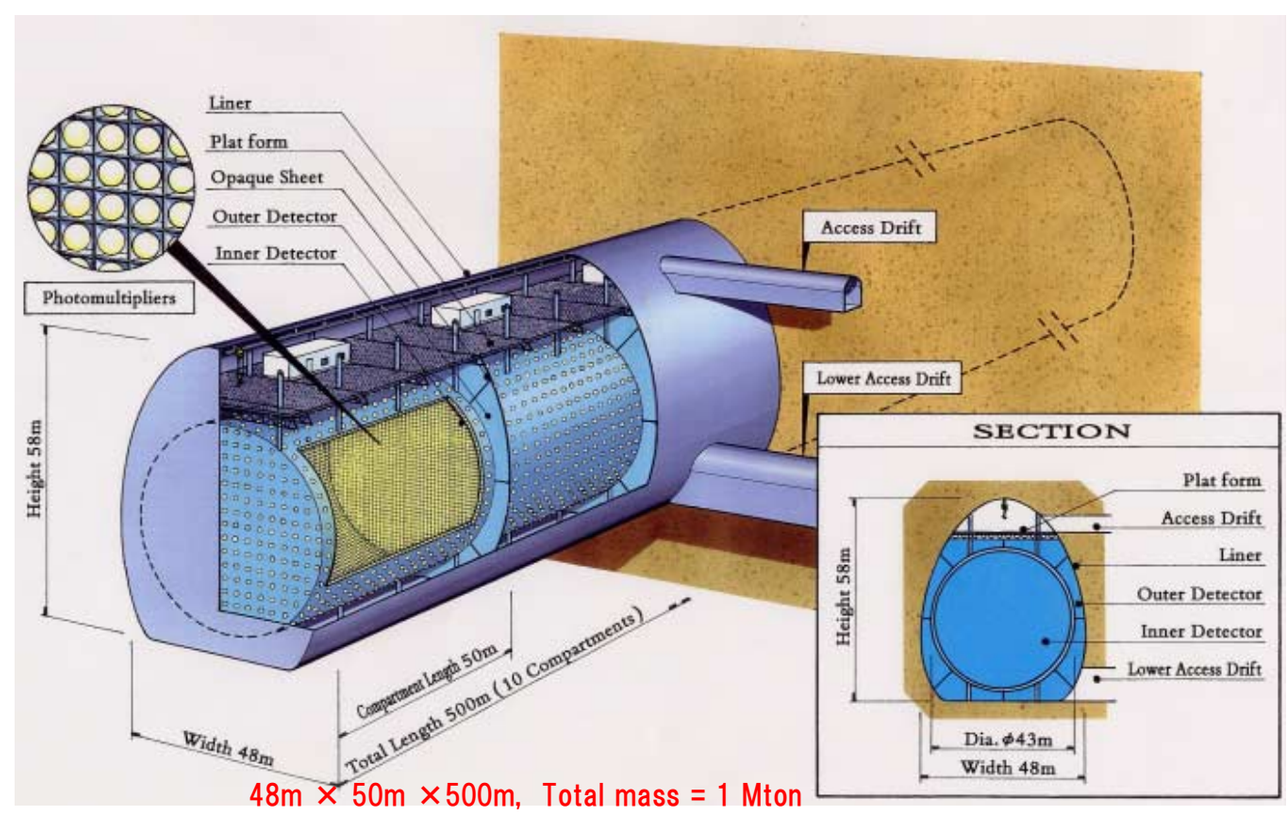
- but next-generation detectors for LB ν experiments and proton decay, at the 300 kt - 500 kt scale, could measure the SN ν light curve out to ~ 20 s, background-free, for moderately deep detectors

Physics issues: 2) test neutrino phenomena unique to extreme environments

- startling oscillation effects -- flavor swaps -- predicted to occur from a new contribution to the MSW potential unique to SN, ν scattering off trapped νs

- phase transitions in the cooling nuclear matter that alter the shape of the ν light curve

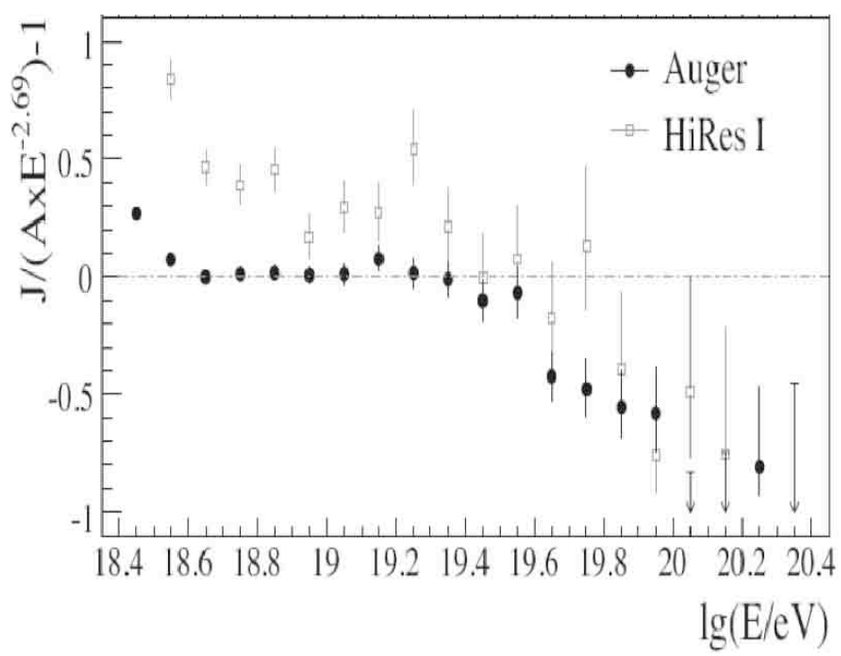
- the ν burst as a clock, signaling BH formation, or correlated with GWs

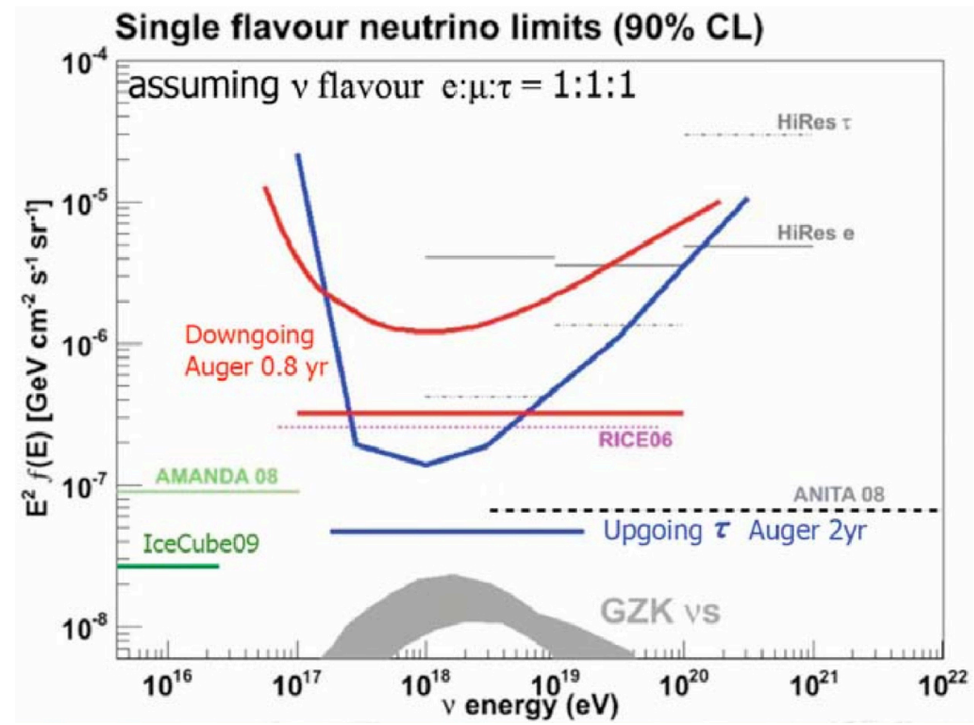


Hyper-Kamiokande

#3 develop techniques to detect and study UHE νs

- apparent observation of the GZK cutoff in hadronic CRs leaves open the question of the ultimate limits of cosmic acceleration





- the is a curious trend -- based on extrapolated theory -- that the CR composition trends away from protons at ~ 10^{16} eV to "Fe" at GZK energies
  - measurement of the associated GZK neutrinos (products of the CR primary interactions with the CMB) could test primary composition

- but an exciting long-term goal is the observation of still higher energy νs above CR proton energies by the Askaryan effect - coherent radio emission by electrons swept along UHE neutrino shower front

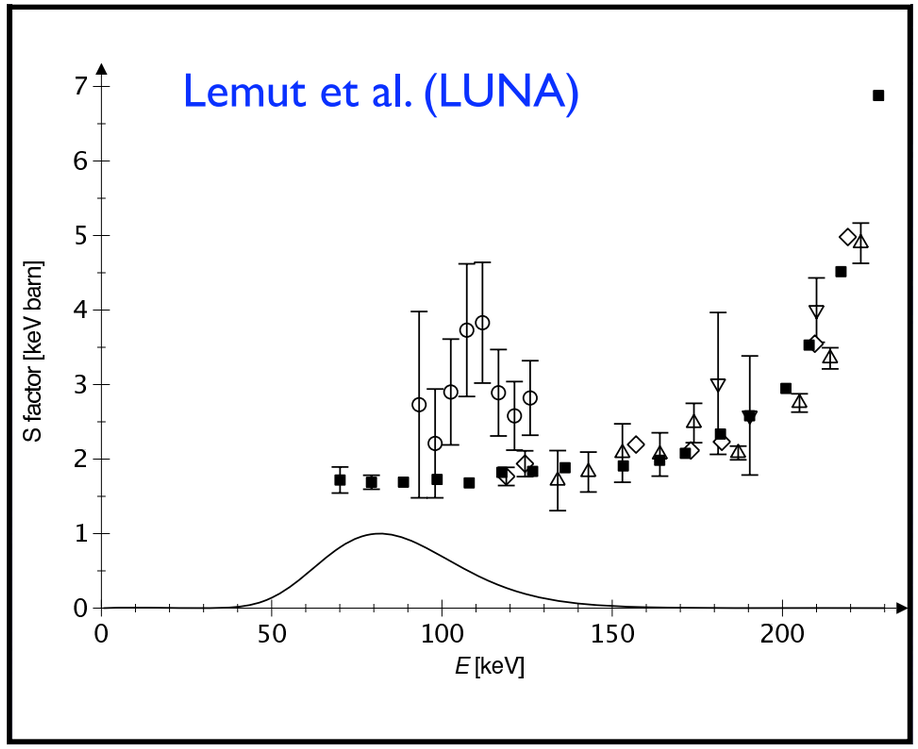
#4 improve measurements of BBN abundances and supporting theory

- despite qualitative agreement between CMB and BBN determinations of η, in detail discrepancies exist
  - ^{7}Li is a factor of four below BBN prediction, though observed abundances in old halo nuclei are stable to ~ 5%
  - observed ^{4}He typically below predictions

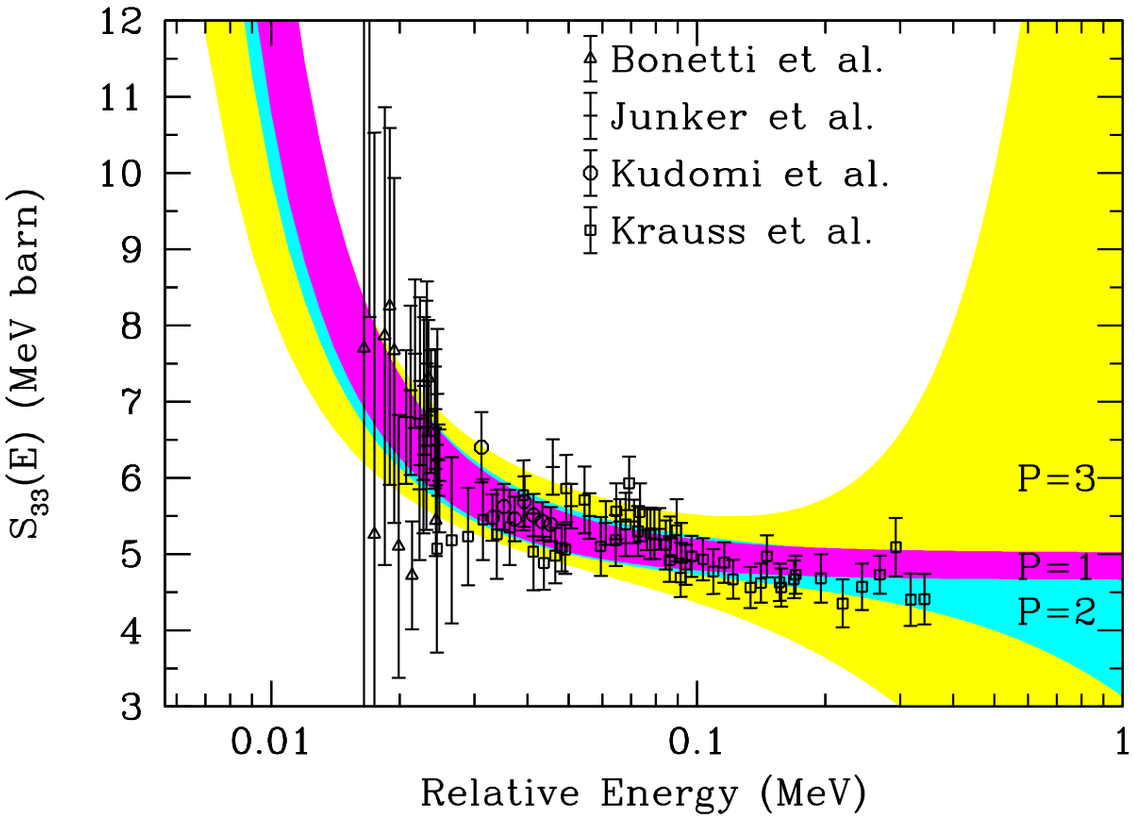
- such discrepancies could arise from sterile neutrino species with superweak interactions, a primordial net lepton number, dark matter decays that alter abundances after the BBN -- or more mundane issues, including the nuclear physics

- panel reports the potential for improving abundance determinations with 30m-class telescope with a high resolution stable spectrograph; corresponding improvements in nuclear cross section measurements; improved 3D stellar atmosphere models

The nuclear physics recommendations fit into a continuing program to more precisely determine cross sections for solar and red giant burning, with accelerators build underground to permit nearly background-free measurements


Lemut et al. (LUNA)
S factor [keV barn]
E [keV]
0
1
2
3
4
5
6
7
0
50
100
150
200

$^{14}N(p\gamma,)$


Bonetti et al.
Junker et al.
Kudomi et al.
Krauss et al.
P=3
P=1
P=2
S33(E) (MeV barn)
Relative Energy (MeV)
3
4
5
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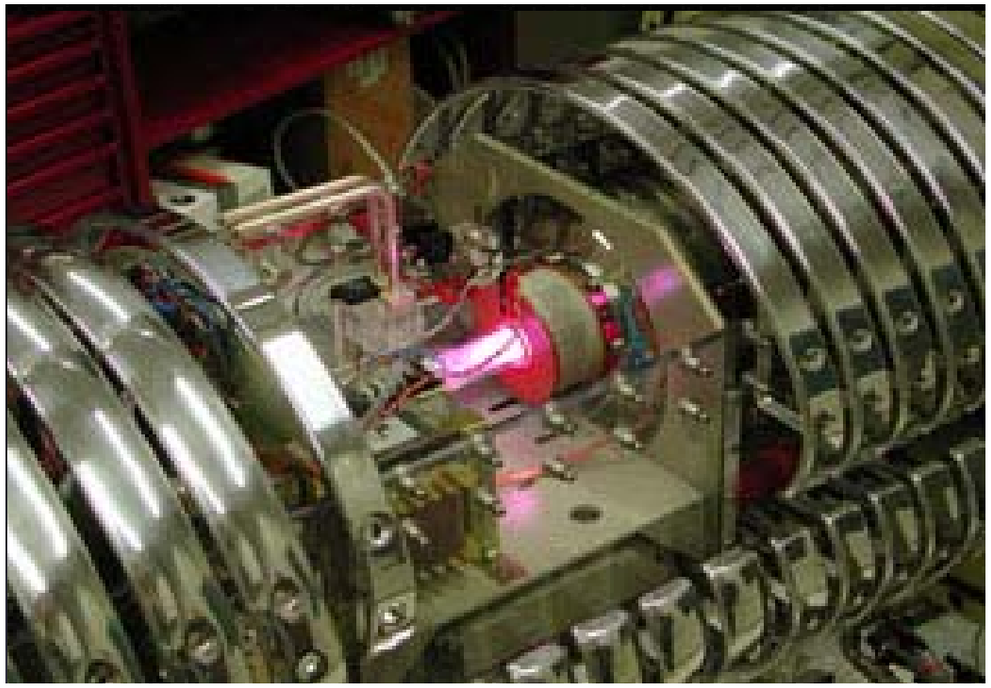

Summary

- the laboratory astrophysics interface with particle/nuclear physics has changed remarkably over 20 years

- not too many years ago most of the focus was on supporting nuclear reaction studies for problems like BBN and solar νs, with solar and atmospheric ν anomalies generally attributed to limitations in astrophysics models

- the resolution of these problems through new neutrino properties, and the growing appreciation of the DM problem, changed the culture

- the theme exposed in "from quarks to the cosmos" now is broadly embraced: cosmological, astrophysical, accelerator, and underground experiments attacking the same problems, with the potential of complementary discoveries

- the inclusion in Astro2010 of a panel addressing cosmology and fundamental physics reflects this new collaborative mode