Introduction: Neutrino Physics

James, Wolfgang, Enrico, Clyde, Fred, and Ray

- James Chadwick, 1914: continuous β spectrum
  - perhaps some "unobserved radiation" being emitted
- Wolfgang Pauli, 1930: postulated that a spin-1/2 "neutrino" accounted for the missing energy
  - "a terrible thing" for experimenters
  - odd notions of the neutrino as a nuclear constituent
- Fermi in 1934 postulates an effective weak theory
  - with an assist from Chadwick: $p \to n + e^{+} + \nu_e$
  - correct apart from absence of parity violation
- Cowan and Reines find the neutrino in 1956
- Davis in 1965 mounts the experiment that eventually leads us to neutrino mass

But they left a lot of unanswered questions

- absolute scale of neutrino masses
  - ◇ know mass differences but little about the scale
- why large mixing angles?: the Cabibbo angle is small
- what is θ_{13}? (CP violation, nucleosynthesis)
- is the neutrino its own antiparticle?
- is there neutrino unitarity? heavy νs?
- is the missing SM CP violation needed for baryogenesis hidden in the neutrinos?
- do neutrinos have electromagnetic moments?
- what is the ν role in large-scale structure?
- what are the astrophysical sources of neutrinos?

What have we learned recently?

I. Solar neutrinos

- Evidence for unexpected physics established in Homestake, SAGE/GALLEX/GNO, and Kamioka/Superkamiokande experiments
  - $^{37}Cl + \nu_e \rightarrow ^{37}Ar + e^-$, 0.34 $\pm$ 0.03 SSM
  - $^{71}Ga + \nu_e \rightarrow ^{71}Ge + e^-$, 0.56 $\pm$ 0.05 SSM
  - Kamioka $\nu_x + e^- \rightarrow \nu_x + e^-$, 0.54 $\pm$ 0.08 SSM
  - Superkamiokande, 0.451 $\pm$ 0.016 (ν_μ/ν_e sensitivity $\sim$ 0.15)

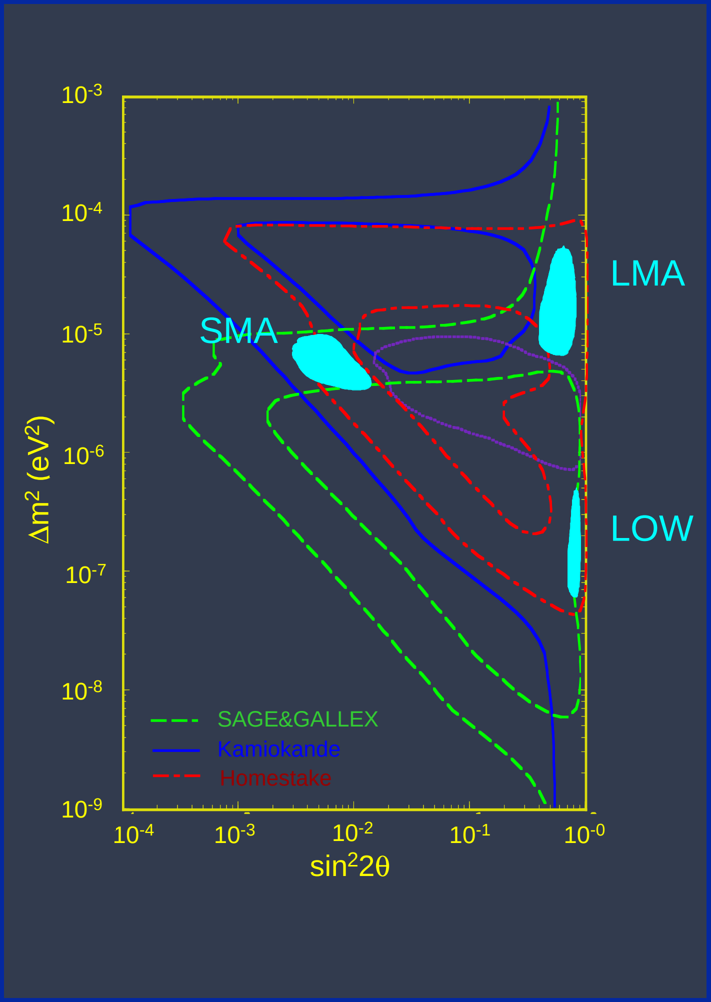
What have we learned recently?

I. Solar neutrinos

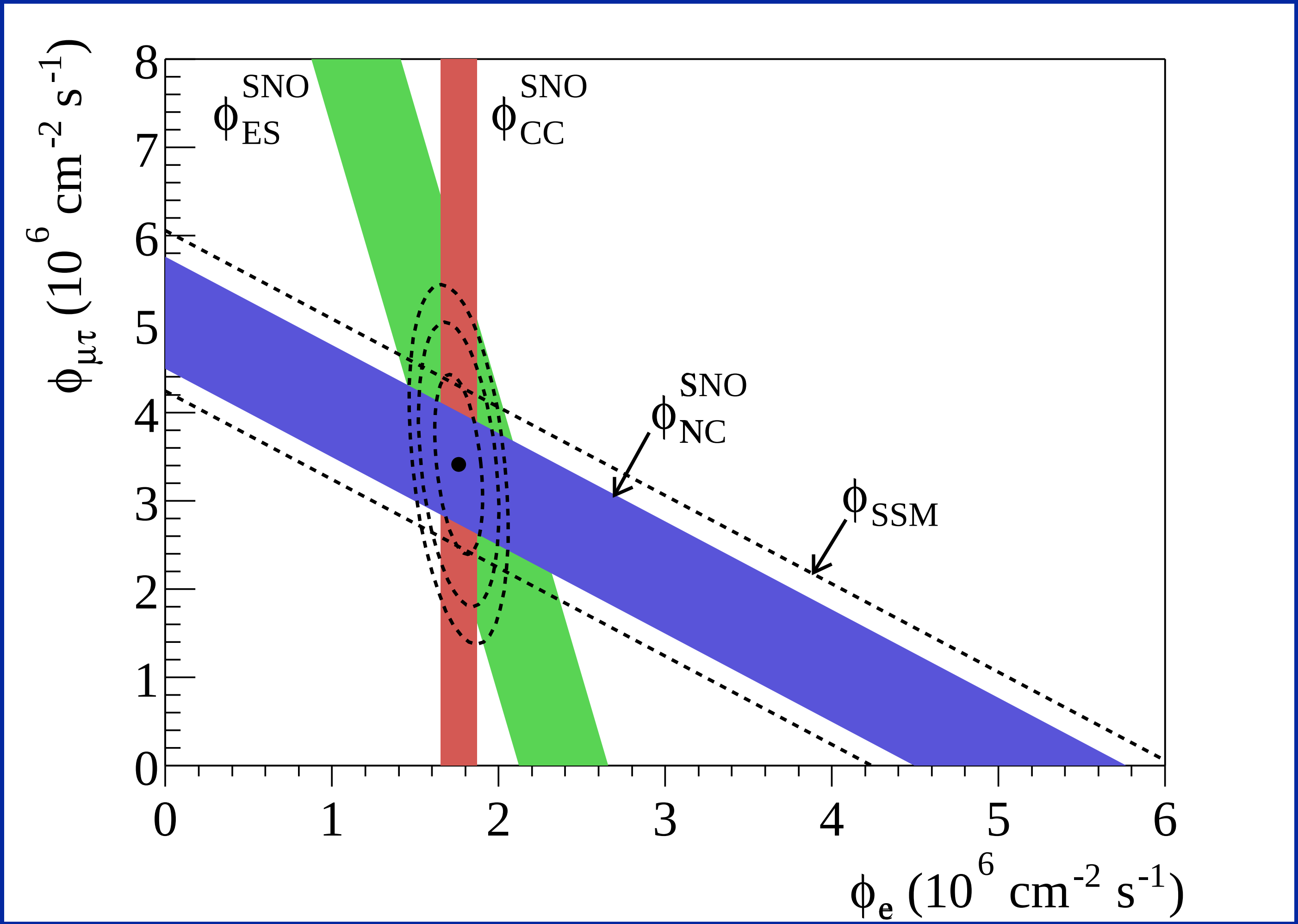
- Evidence for unexpected physics established in Homestake, SAGE/GALLEX/GNO, and Kamioka/Superkamiokande experiments
  - $^{37}Cl + \nu_e \rightarrow ^{37} Ar + e^-$, 0.34 $\pm$ 0.03 SSM
  - $^{71}Ga + \nu_e \rightarrow ^{71} Ge + e^-$, 0.56 $\pm$ 0.05 SSM
  - Kamioka $\nu_x + e^- \rightarrow \nu_x + e^-$, 0.54 $\pm$ 0.08 SSM
  - Superkamiokande, 0.451 $\pm$ 0.016 (ν_μ / ν_e sensitivity $\sim$ 0.15)
- possibility of solar ν oscillations (Pontecorvo)
  - requires massive neutrinos
  - mass eigenstates not coincident with flavor eigenstates
  - expectation of small mixing angles $\Rightarrow$ small $P(\nu_\mu)$

- discovery that matter enhances ν oscillations (MSW)
  - νs acquire an effective mass from interactions in matter
  - flavor-dependence (matter contains electrons) makes the ν_e heavier at high ρ
  - ρ_c at which the matter contribution cancels vacuum mass difference
  - adiabatic crossing of $\rho_c \Leftrightarrow \nu_e \to \nu_\mu$
  - energy-dependent $P(\nu_\mu)$

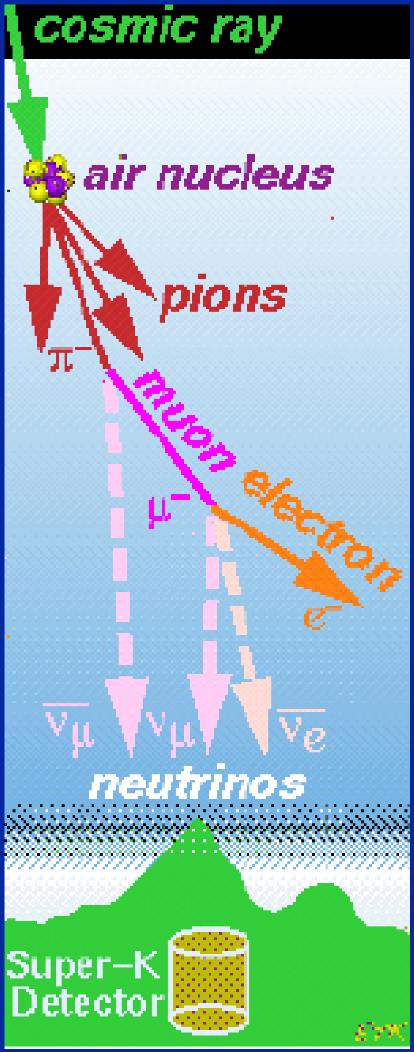
- two-flavor results: multiple solutions, great parameter range

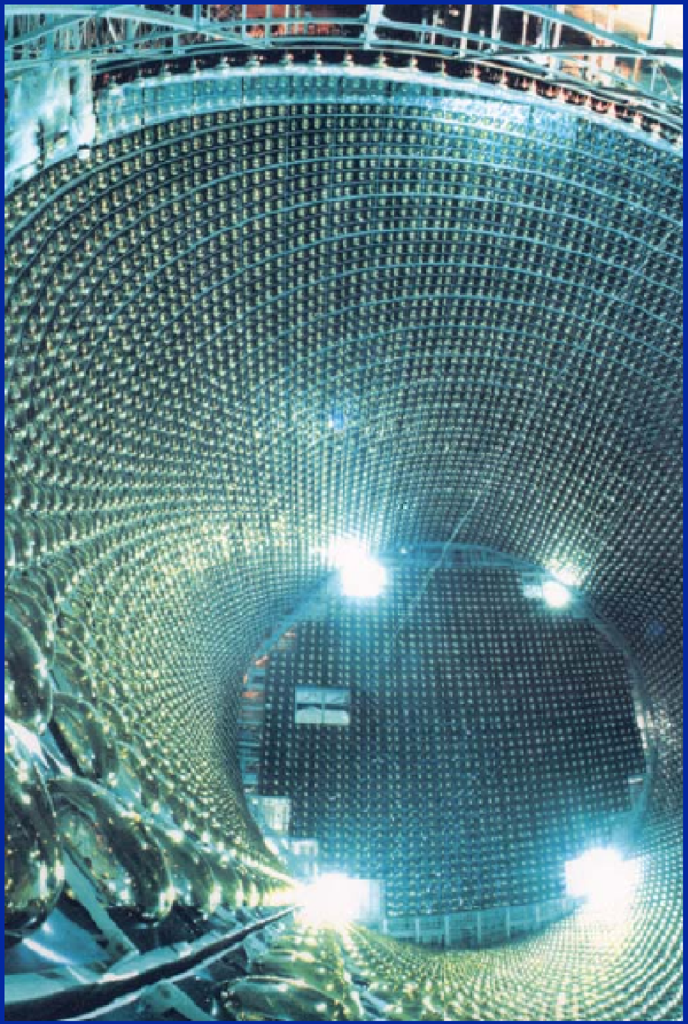


- SNO: heavy flavor νs comprise 2/3rds of solar flux
- LMA probable solution; total flux agrees with SSM



II SuperKamiokande atmospheric ν discoveries





- net result is a determination of $\delta m12^2$, θ_{12}, δm^2_{23}, θ_{23}

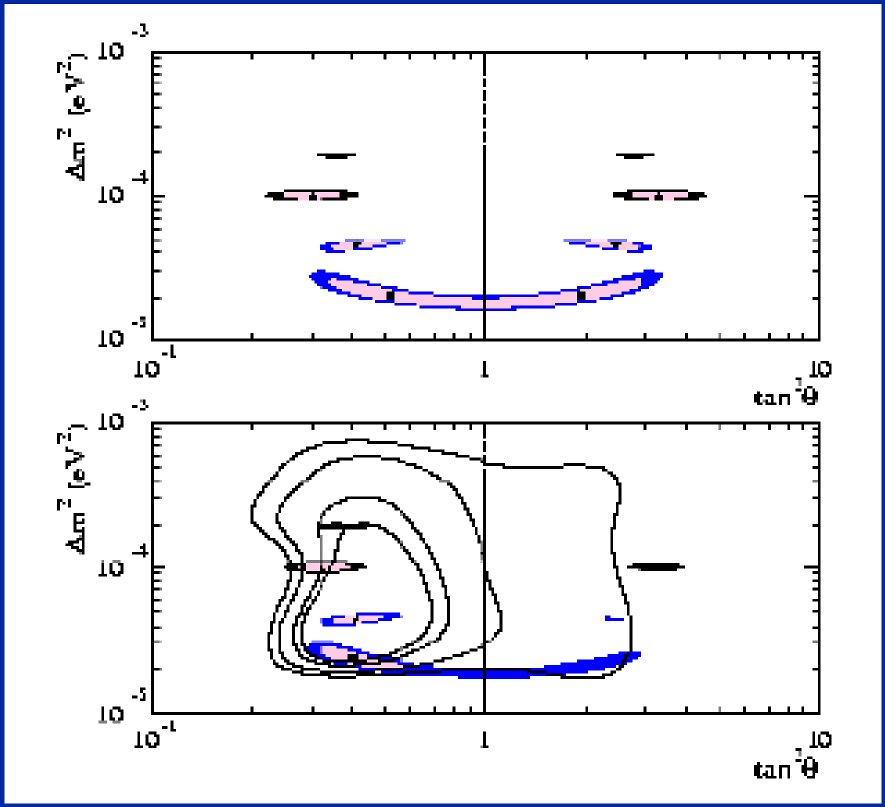
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23}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

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

atmospheric ν_e disappearance   solar

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

- KamLAND to probe solar mixing parameters:
  LMA 2×10^{-5} eV$^2 \lesssim \delta m^2_{12} \lesssim$ few $\times 10^{-4}$ eV^2



- confirm LMA solution, determine δm_{12} precisely if $\lesssim 10^{-4}$ eV^2
- complemented by future pp/pep solar neutrino measurements
  - ◇ use best-known flux to better constrain θ_{12}

- confirm LMA solution, determine δm_{12} precisely if $\lesssim 10^{-4}$ eV^2
- complemented by future pp/pep solar neutrino measurements
  - use best-known flux to better constrain θ_{12}
- KEK/NuMI long baseline experiments to confirm atmospheric results, narrow uncertainty on δm^2_{23} by $\sim$ factor of 5

- confirm LMA solution, determine δm_{12} precisely if $\lesssim 10^{-4}$ eV^2
- complemented by future pp/pep solar neutrino measurements
  - ◇ use best-known flux to better constrain θ_{12}
- KEK/NuMI long baseline experiments to confirm atmospheric results, narrow uncertainty on δm^2_{23} by $\sim$ factor of 5
- θ_{13} a key parameter
  - ◇ astrophysics: governs an MSW crossing occurring near base of the carbon zone in Type II supernovae
  - ◇ governs CP violation in neutrino oscillations

$$s_{12}c_{12}s_{13}c^2_{13}s_23c_23\sin\delta \sim 0.22s_{13}\sin\delta$$

- confirm LMA solution, determine δm_{12} precisely if $\lesssim 10^{-4}$ eV^2
- complemented by future pp/pep solar neutrino measurements
  - ◇ use best-known flux to better constrain θ_{12}
- KEK/NuMI long baseline experiments to confirm atmospheric results, narrow uncertainty on δm^2_{23} by $\sim$ factor of 5
- θ_{13} a key parameter
  - ◇ astrophysics: governs an MSW crossing occurring near base of the carbon zone in Type II supernovae
  - ◇ governs CP violation in neutrino oscillations

$$s_{12}c_{12}s_{13}c^2_{13}s_23c_23\sin\delta \sim 0.22 s_{13}\sin\delta$$

- could be measured in off-axis long-baseline experiments, in new reactor experiments that improve over Chooz

- leptogenesis models for baryon number asymmetry: large neutrino mixing angles have sharpened interest
- long baseline proposals for $P(\nu_e - \nu_\mu) - P(\bar{\nu}_e \to \bar{\nu}_\mu)$

$$\sim 0.22 s_{13} \sin\delta \sin\left(\frac{\delta m_{12}^2 L}{4E}\right) \sin\left(\frac{\delta m_{13}^2 L}{4E}\right) \sin\left(\frac{\delta m_{23}^2 L}{4E}\right)$$

- must show $\sin^2\theta_{13}$ not too small ($\gtrsim 0.01$), address matter effects, sign of δm_{23}^2
- requires either a very well characterized broad-band beam or multiple baselines
- ideal for high-intensity beam, FNAL or BNL to NUSEL $\sim$ 2000-3000 km baselines, multipurpose megadetector

Absolute mass scale

- not determined by mass differences measured in oscillations
- direct tritium mass measurements now known to probe at least two mass eigenstates with good sensitivity

$$\nu_e \sim 0.8\nu_1 + 0.5\nu_2 + ??\nu_3$$

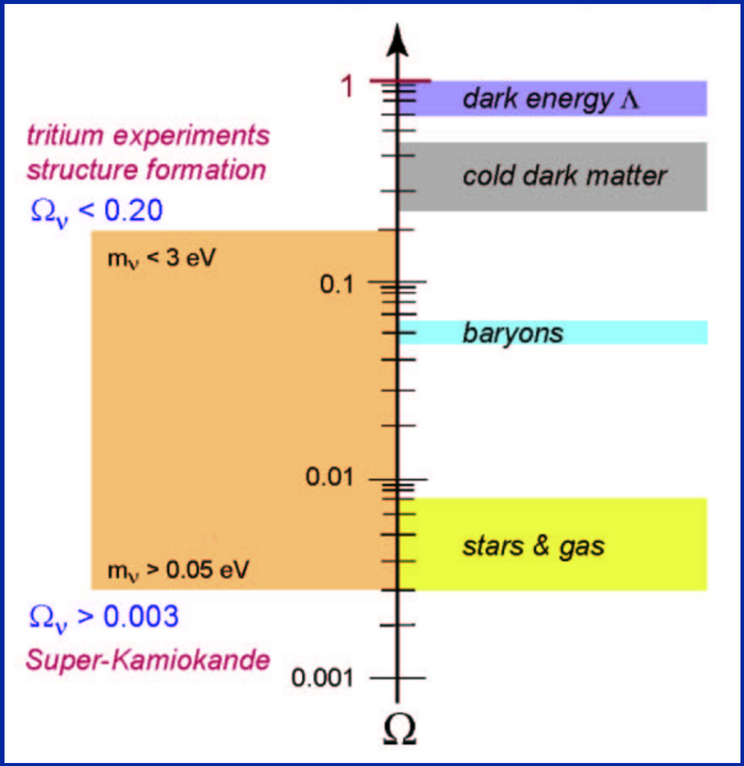
- Mainz, Troitsk experiments have established $\lesssim 2.2$ eV
  - ◇ "$-m_\nu^2$" traced to increased energy loss on roughened source surface
- order-of-magnitude improvement: planned Katrin effort
- Mainz/Troitsk limit + $\delta m^2 \Rightarrow$ bounds neutrino mass dark matter contribution
- indirect large-scale-structure limits on $\sum m_i \sim$ 2-3 eV

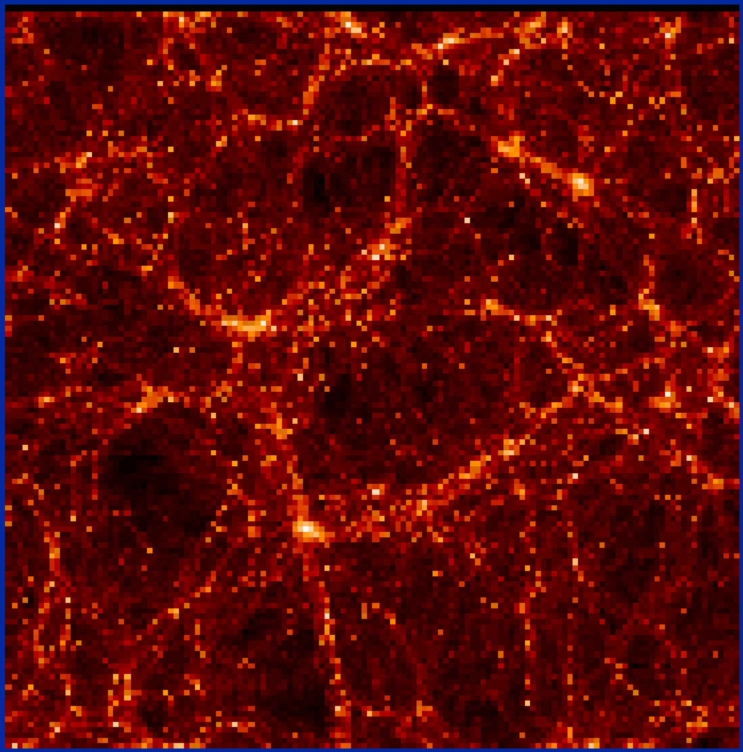
Current mass/energy budget in standard cosmology

primordial neutrinos as dark matter

Ω=1 flat universe (inflation)

evolution of largescale structure





- Many mass pattern issues remain to be resolved
  - δm_{23} sign: both normal (m_3 heavy, separated from light m_1, m_2 solar neutrino pair) and inverted (m_3 the lightest neutrino) patterns allowed
  - both hierarchical ($m_1 \ll m_2 \ll m_3$) and quasidegenerate ($m_1 \sim m_2 \sim m_3$) schemes possible
  - absolute scale: future CMB + Sloan DSS analysis will be sensitive to $m_\nu \sim 0.3$ eV

m_ν may become a cosmological uncertainty soon

- crucial issue of LSND and MiniBoone: $\delta m^2_{LSND} \sim 1\ \mathrm{eV}^2$
  - ◇ various 4-neutrino schemes, sterile/active mixing
  - ◇ strong astrophysical consequences because MSW conversion occurs at high density: r-process
  - ◇ possibility of 3-ν schemes with CPT violation
- MiniBoone confirmation would make matters even more interesting

Next-generation $\beta\beta$ Decay

Next-generation $\beta\beta$ Decay

- very rare opportunity provided by nuclear physics to study second-order weak interactions

$$
\begin{aligned}
(A,Z) &\rightarrow (A,Z+2)+e^-+e^-+\bar{\nu}_e+\bar{\nu}_e \quad \text{Standard Model} \\
(A,Z) &\rightarrow (A,Z+2)+e^-+e^- \quad \text{lepton}-\text{number}-\text{violating}
\end{aligned}
$$

- connected with $\nu - \bar{\nu}$ nature of neutrino

$$
\bar{\psi}_R M_D \psi_L \Rightarrow \bar{\psi}_L^c M_L \psi_L, \quad \bar{\psi}_R^c M_R \psi_R
$$

$$
m_\nu \sim M_D \frac{M_D}{M_R} \Rightarrow M_R \sim 0.3 \times 10^{15}\text{GeV}
$$

- directly probes a variety of beyond-the-SM mechanism for lepton number violation, including Majorana masses
- light ν masses sampled according to U_{ei}^2

$$\langle m_\nu^{Maj} \rangle = \sum_{i=1}^{2n} \lambda_i U_{ei}^2 m_i$$

- λ_i is relative CP eigenvalue: quasidegenerate νs can interfere destructively
- current $\langle m_\nu^{Maj} \rangle$ bound $\sim$ 0.3-1.3 eV

- sensitive to very heavy neutrinos

$$m_i^{Maj} = U_{ei}^2 \frac{1}{m_i}$$

- heavy Majorana mass limit $m_i \gtrsim U_{ei}^2\ 2 \times 10^4$ TeV

- sensitive to very heavy neutrinos

$$m_i^{Maj} = U_{ei}^2 \frac{1}{m_i}$$

- heavy Majorana mass limit $m_i \gtrsim U_{ei}^2 \; 2 \times 10^4$ TeV
- sensitive to new CP-violation phases

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} e^{-i\delta} \\ & & \\ & & \end{pmatrix} \begin{pmatrix} \nu_1 \\ e^{i\phi_2} \nu_2 \\ e^{i\phi_3} \nu_3 \end{pmatrix}$$

- light νs contribute $\lambda_1 U_{e1}^2 m_1 + \lambda_2 U_{e2}^2 m_2 e^{2i\phi_2} + \lambda_3 U_{e3}^2 m_3 e^{2i(\phi_3 - \delta)}$

- sensitive to very heavy neutrinos

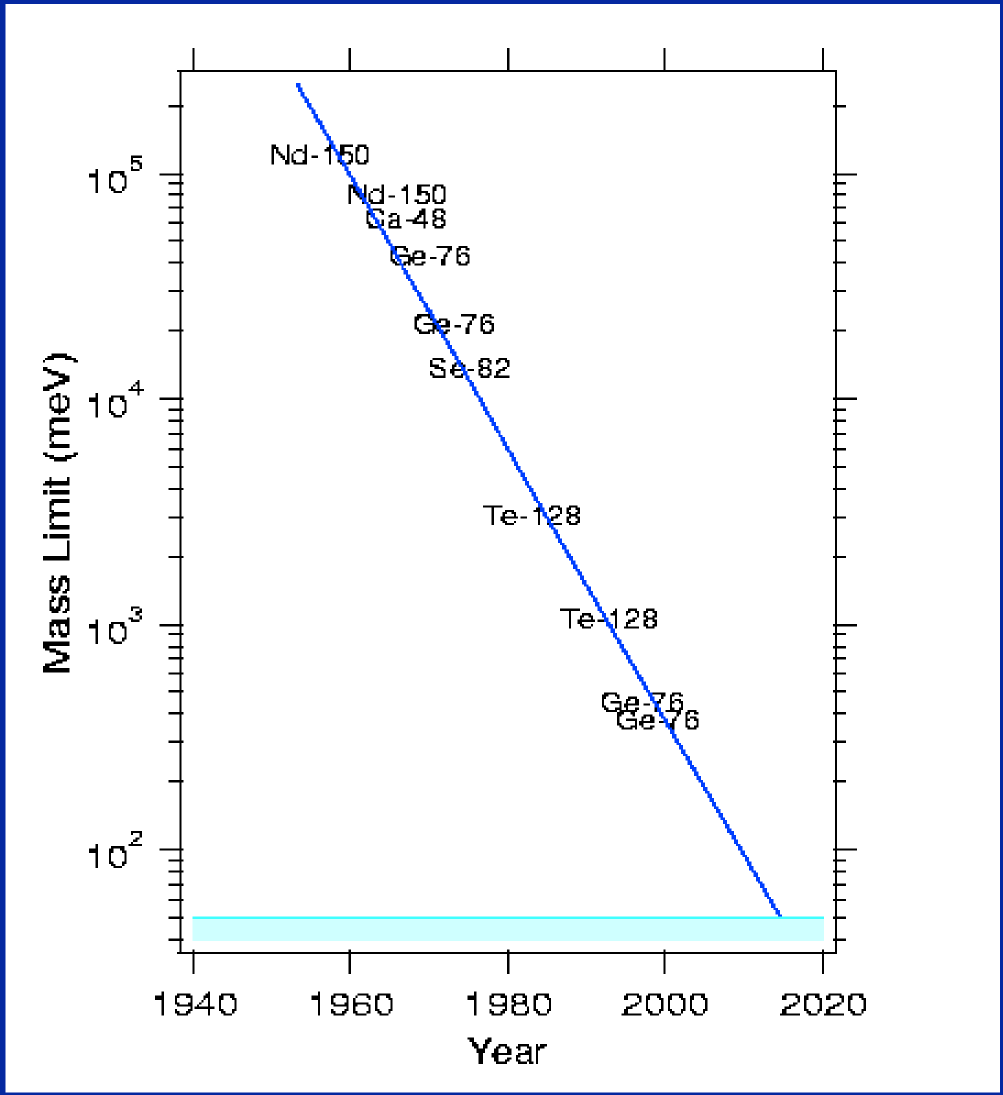
$$m_i^{Maj} = U_{ei}^2 \frac{1}{m_i}$$

- heavy Majorana mass limit $m_i \gtrsim U_{ei}^2\ 2 \times 10^4$ TeV
- sensitive to new CP-violation phases

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3}e^{-i\delta} \\ & & \\ & & \end{pmatrix} \begin{pmatrix} \nu_1 \\ e^{i\phi_2}\nu_2 \\ e^{i\phi_3}\nu_3 \end{pmatrix}$$

- light νs contribute $\lambda_1 U_{e1}^2 m_1 + \lambda_2 U_{e2}^2 m_2 e^{2i\phi_2} + \lambda_3 U_{e3}^2 m_3 e^{2i(\phi_3 - \delta)}$
- nuclear physics uncertainties complicates extraction of CP violation

- experimental capabilities have improved rapidly



- current motivation: large θs and atmos. ν mass scale
- requirements for reaching $\langle m_\nu^{Maj} \rangle \sim \sqrt{\delta m^2_{atmos}} \sim (0.01 - 0.05)$ eV
  - ◇ 100-fold increase in detector mass, fixed absolute background rate
  - ◇ ton quantities of isotopically enriched materials
  - ◇ excellent energy resolution (2ν tail background!)
  - ◇ ultralow activity materials
  - ◇ underground depths of $\sim$ (2000-6000) mwe

- current motivation: large θs and atmos. ν mass scale
- requirements for reaching $\langle m_\nu^{Maj} \rangle \sim \sqrt{\delta m^2_{atmos}} \sim (0.01 - 0.05)$ eV
  - ◇ 100-fold increase in detector mass, fixed absolute background rate
  - ◇ ton quantities of isotopically enriched materials
  - ◇ excellent energy resolution (2ν tail background!)
  - ◇ ultralow activity materials
  - ◇ underground depths of $\sim$ (2000-6000) mwe
- excellent discovery potential in the next decade

$\beta\beta$ Exps.	Isotope	Technique	Mass(kg)	Enriched	$\langle m_\nu \rangle$ eV	m.w.e.	Location
Heid/Moscow	^{76}Ge	Ge crystal	9.9	86%	$\leq$0.40	2700	Gran Sasso
IGEX	^{76}Ge	Ge crystal	$\sim$ 9	86%	$\leq$0.44	2450	Canfranc, Sp.
UCI	^{82}Se	TPC with foils	0.014	97%	$\leq$7.7	290	Hoover Dam
ELEGANT	^{100}Mo	drift chamber-scintillators	0.20	94.5%	$\leq$2.7	1800	Oto, Japan
Kiev	^{116}Cd	$CdWO_4$ crystals	0.09	83%	$\leq$3.3	1000	Ukraine
Missouri	^{128}Te	geochemical	Te ore	no	$\leq$1.5	N/A	N/A
Milano	^{130}Te	cryogenic TeO_2 crystals	2.3	no	$\leq$2.6	2700	Gran Sasso
Cal-UN-PSI	^{136}Xe	high pres. TPC	2.1	62.5%	$\leq$3.5	3000	Switzerland
UCI	^{150}Nd	TPC foils	0.015	91%	$\leq$7.1	290	Hoover Dam
NEMO3	^{82}Se,^{100}Mo, ^{116}Cd,^{150}Nd	drift chamber-scintillator	1-10	yes	$\sim$0.1	4800	Frejus, France
CUORICINO	^{130}Te	cryogenic TeO_2 crystals	11.5	no	$\sim$0.1	2700	Gran Sasso
GENIUS	^{76}Ge	400 Ge cystals	1000	yes	0.01	2700	Gran Sasso
MAJORANA	^{76}Ge	400 Ge crystals	500	yes	0.02	$\geq$4000	
CAMEO	^{82}Se,...	Borexino CTF	$\sim$1	yes	$\sim$1		Gran Sasso
MOON	^{100}Mo	scintillator+foils	3400	no	0.03	$\geq$2500	
CUORE	^{130}Te	1020 cryogenic TeO_2 crystals	210	no	0.02		Gran Sasso
EXO	^{136}Xe	high pres. TPC	10000	yes	0.01	$\geq$2000	
DBCA-II(2)	^{150}Nd	drift chamber	18	yes	$\sim$0.05		Oto, Japan

Electromagnetic moments

- Dirac νs may have magnetic, electric dipole, and anapole moments, and a nonzero charge radius
- Majorana νs can have anapole moments and transition moments
  - ◇ spin-flavor transition much discussed in connection with solar magnetic field effects
  - ◇ red giant cooling limit of $\lesssim 3 \times 10^{-12} \mu_B$ would appear to make this improbable
  - ◇ but much larger fields in protoneutron star
- some promising experimental efforts
  - ◇ ITEP's GEMMA effort focused on (2-3) $\times 10^{11} \mu_B$

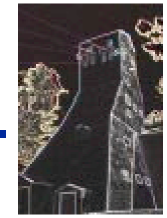
Location, location, location

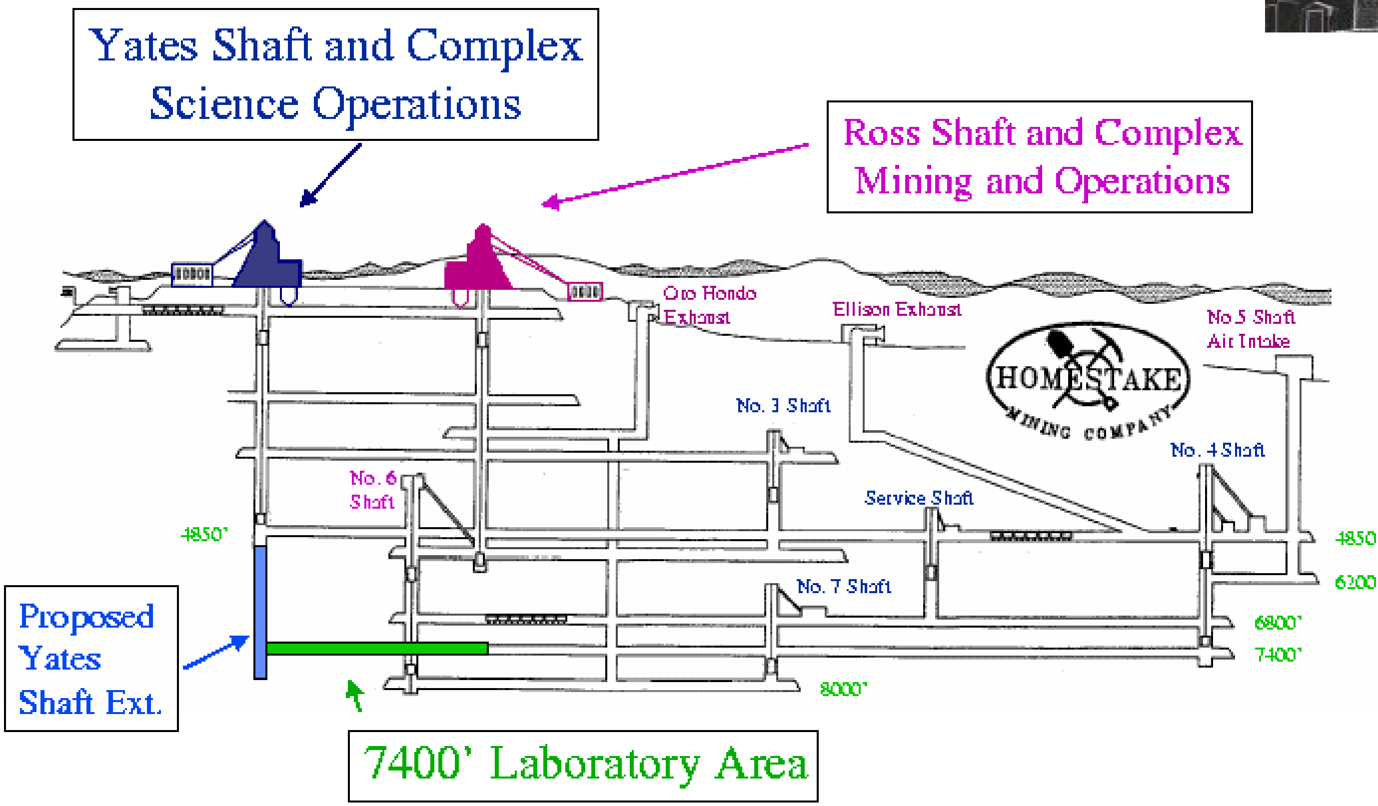
- the US needs a place to do next-generation very-low-background $\beta\beta$ decay, solar ν, ... experiments
- a community is forming that would grow with and benefit from a central facility
  - ◇ accelerator $\leftrightarrow$ nonaccelerator intersection
    - ⋆ remarkable luck that astrophyical δm^2 are accessible in terrestrial experiments
  - ◇ low-background $\leftrightarrow$ large detector intersection
  - ◇ physics $\leftrightarrow$ rock mechanics, earth science, geomicrobiology $\leftrightarrow$ applications
- Homestake

- Homestake attributes
  - existing access to the proposed main level at 7400 ft: coring studies before construction
  - permitted for construction, waste rock disposal, safety
  - all levels have multiple access routes, vented for safe egress
  - capacity to isolate risky experiments
  - site is operating; experienced engineering staff; infrastructure includes sophisticated hoist, HVAC, sensor and safety, communications systems and office buildings, hydroelectric plants
  - established mining costs
  - remarkable mining, pumping capacities
  - great depth, choice of depths

Laboratory depths

NUSL Overview (cross-section)





Envisioned National Underground Science Laboratory at Homestake

Conference on Underground Science
October 4, 2001
Lead, South Dakota

- Physical attributes and the megadetector
  - rock may be unique in US in terms of its strength: rock bursts very rare even at depth
  - easiest megacavity location 4850 ft (1/10 SK CR flux)
  - decades of *in situ* rock deformation measurements $\Rightarrow$ UNO-like cavities stable to $\sim$ 7000 ft

- Physical attributes and the megadetector
  - rock may be unique in US in terms of its strength: rock bursts very rare even at depth
  - easiest megacavity location 4850 ft (1/10 SK CR flux)
  - decades of *in situ* rock deformation measurements $\Rightarrow$ UNO-like cavities stable to $\sim$ 7000 ft
- present excavation capacity $\sim$ 1 mton/y
  - rock hoisted to 600 ft level, by conveyor underground to open cut $\Rightarrow$ minimal surface disturbance
  - detector drainage to surface by Ross 12-inch pump column, at 11.5 ktons/day
  - excavation $\sim$ \$34.50/ton (based on HMC costs)

Conclusion

- νs have opened a door to physics beyond the standard model
- additional new physics appears to be within reach: the mass scale, the charge conjugation properties, the CP properties
- likelihood that the new physics affects astrophysical phenomena: baryogenesis, large-scale structure, supernova properties
- the scale of the physics - manpower and cost – is well within our reach

Conclusion

- νs have opened a door to physics beyond the standard model
- additional new physics appears to be within reach: the mass scale, the charge conjugation properties, the CP properties
- likelihood that the new physics affects astrophysical phenomena: baryogenesis, large-scale structure, supernova properties
- the scale of the physics - manpower and cost – is well within our reach
- Just do it!