INT National INSTITUTE FOR NUCLEAR THEORY

Some Science Motivations for DUSEL

Solar neutrinos ⇔ Nuclear astrophysics ⇔ Supernova neutrinos

- What interesting questions could a DUSEL astro-ν program answer?

- How might an underground accelerator for nuclear astrophysics advances these or other goals?

Wick Haxton Lawrence Berkeley National Laboratory 24 February 2009

Future program of HE/nuclear ν physics has been mapped out (APS study)

- constrain the absolute scale of neutrino mass: near-term ββ exps. and cosmological tests should reach 50 meV; future efforts to 10 meV

- measure the unknown mixing angle θ_{13} in reactor or LB off-axis exps.

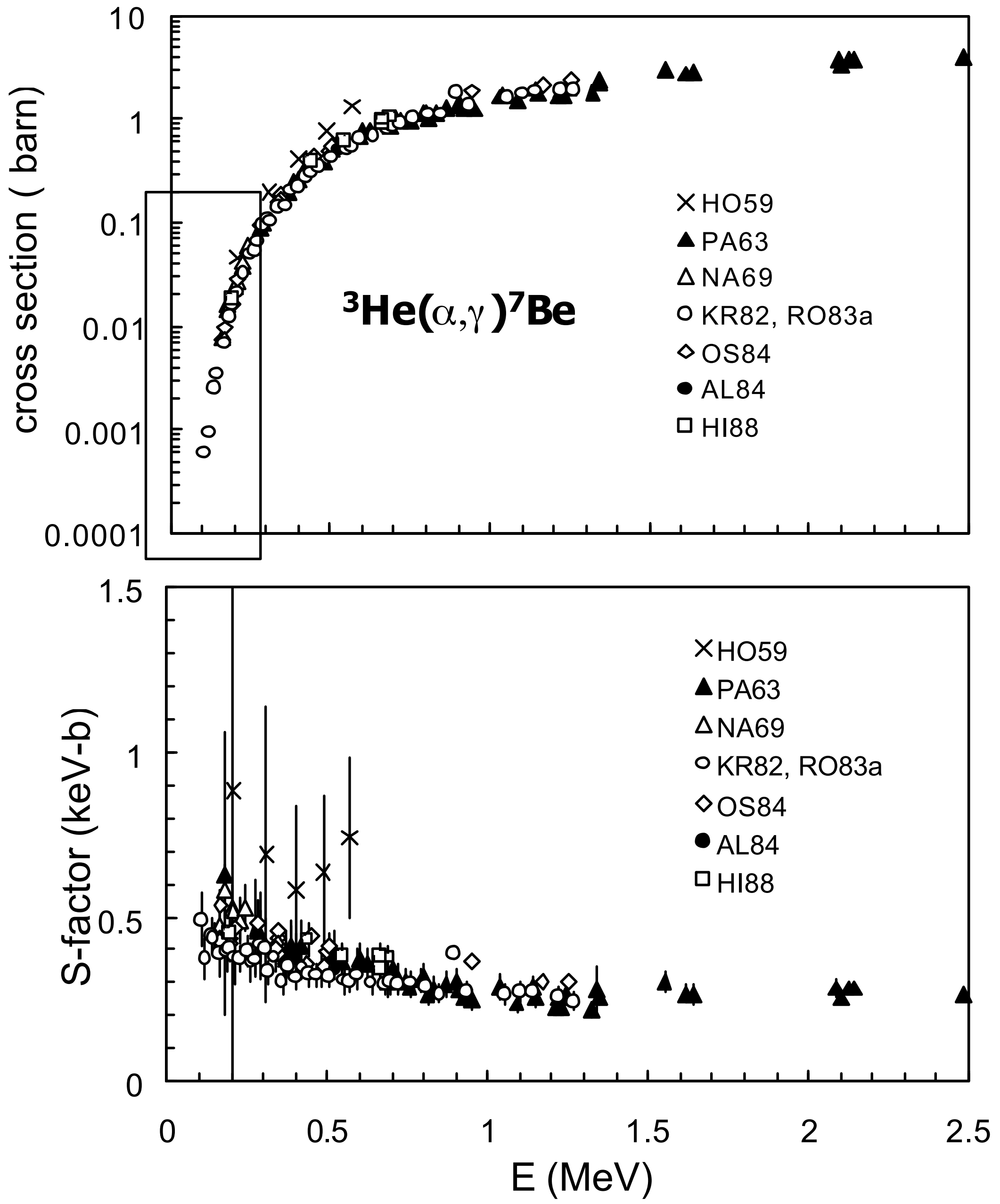
- demonstrate that Majorana masses exist in ββ decay

- distinguish between the inverted and normal hierarchies in LB or next-generation atmospheric ν studies of subdominant oscillations

- see the Dirac CP phase in LB exps: $\nu_\mu \leftrightarrow \nu_\tau$ vs. $\bar{\nu}_\mu \leftrightarrow \bar{\nu}_\tau$

- once the masses and mixing angles are known, do the nuclear physics to high precision to constrain the Majorana phases in ββ decay

- so one of the questions is the future role of neutrino astrophysics in this

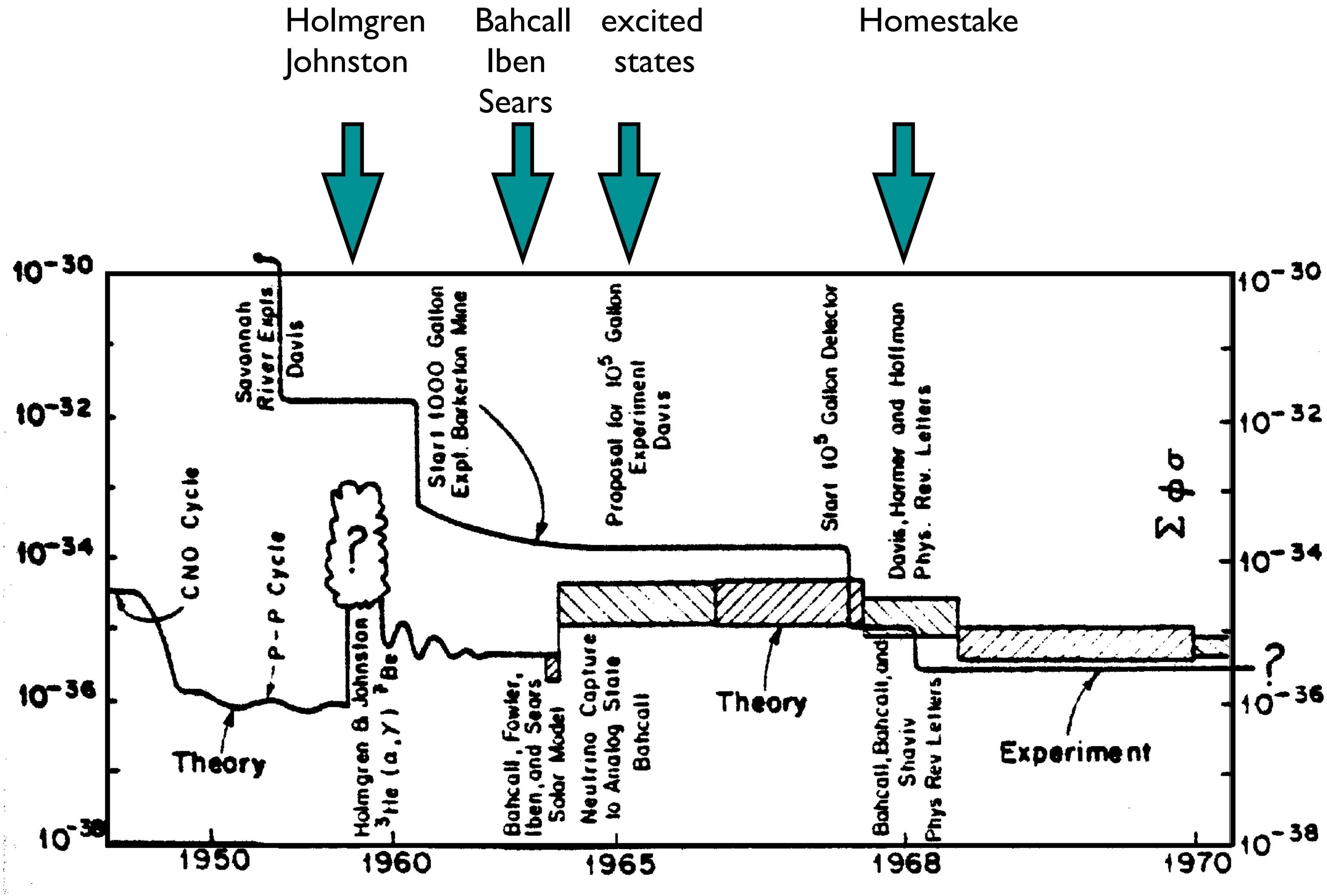


Reader's Digest solar νs

1) define nuclear microphysics governing sun
2) build a SSM by combining this NP with MS stellar stellar evolution theory
3) use neutrinos and other observables to test the SM

Lab microphysics was important from start: 1959 Holmgren/ Johnston measurement S_{34}

Significant high E ν flux possible. depending on SSM core T



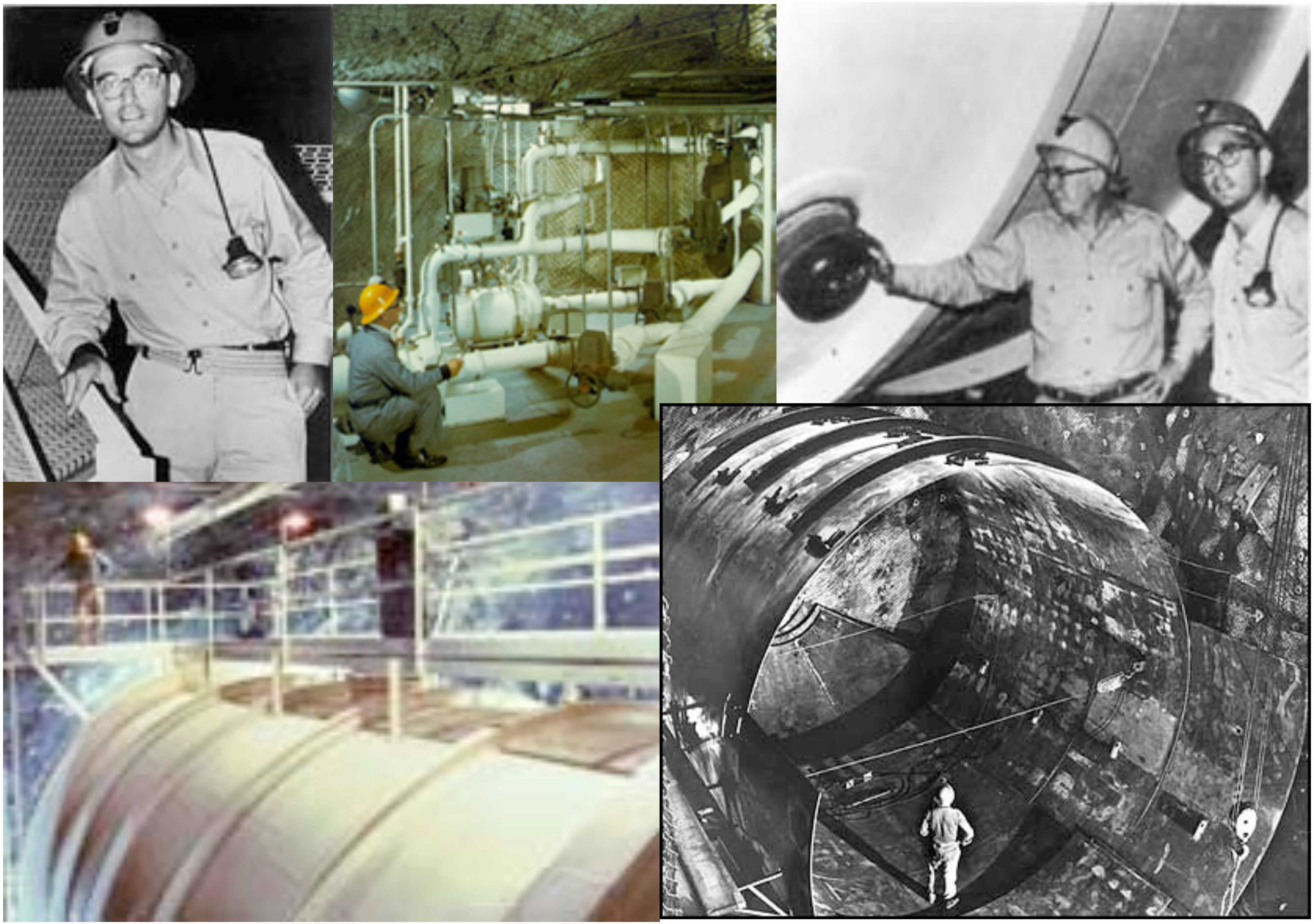
Holmgren
Johnston

Bahcall
Iben
Sears

excited
states

Homestake

Davis's sketch: the Cl experiment's "reach" vs solar model predictions



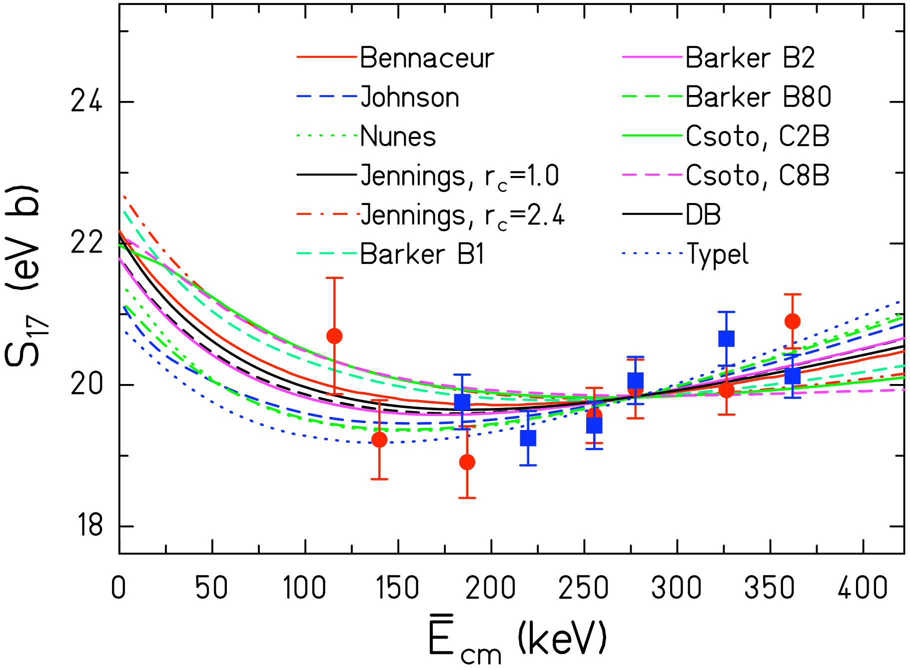
Standard Solar Model

- Based on a simple model of low-mass, main-sequence stellar evolution
  - ◇ local hydrostatic equilibrium: gas pressure gradient counteracting gravitational force
  - ◇ hydrogen burning, dominated by the pp chain
  - ◇ energy transport by radiation (interior) and convection (envelope)
  - ◇ boundary conditions: today's mass, radius, luminosity; the ZAMS abundance ratios H:He:Z needed

- The implementation of this physics requires
  - ◇ electron gas EOS, which under solar conditions is quite close to that of an ideal gas
  - ◇ low-energy S-factors for the pp chain and CN-cycle
  - ◇ an understanding of solar metalicity: the opacity is dominated by free-bound transitions
  - ◇ some means of fixing the composition at ZAMS: SSM assumes a homogeneous proto-sun, formed from the nebular gas cloud: this fixes Z, with H/He then adjusted to reproduce luminosity

19 parameters: uncertainties dominated (until recently) by S-factors

S_{17} has been a key uncertainty affecting the high-energy neutrino flux



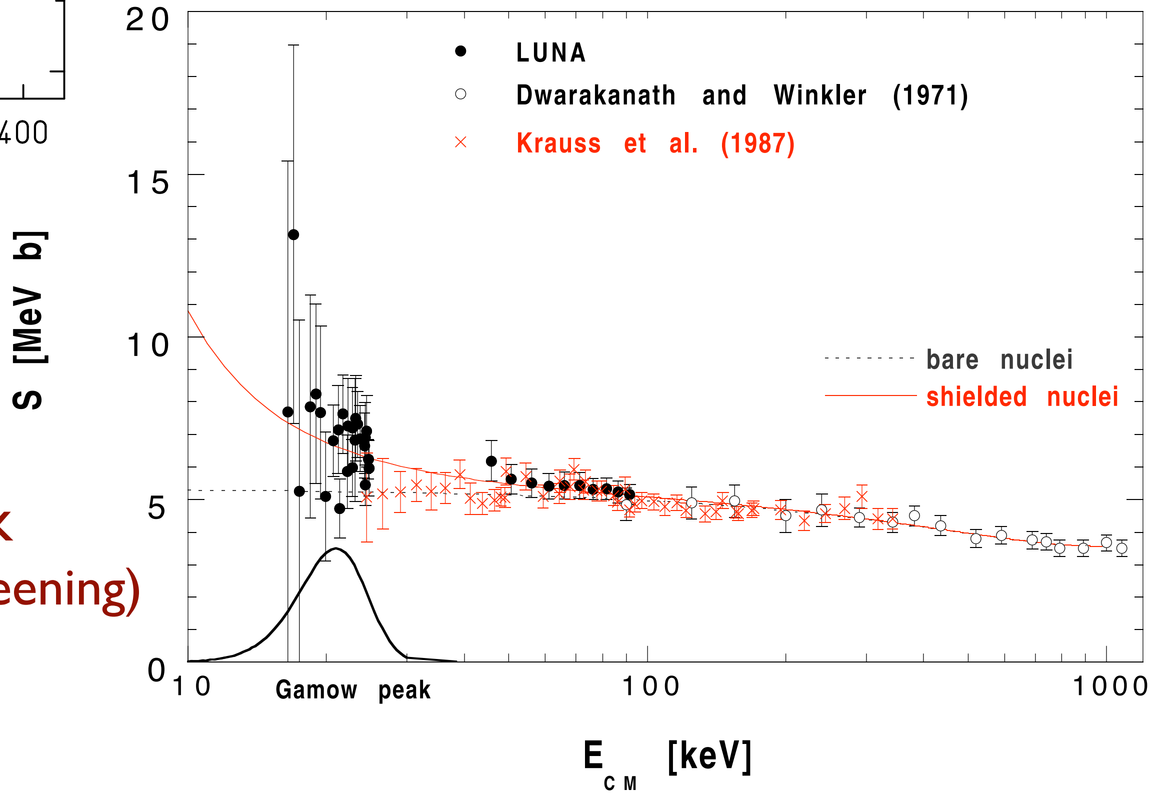
S_{17}(20 keV)~ 20.6±0.5±0.6 eV-b

(average over 6 direct measurements)
Junghans et al. PRC6 (2003) 065803

(surface)

$S_{33}(0)$ measurements by
LUNA in the solar Gamow peak
Bonetti et al. PRL 82 (1999) 5205 (screening)

(underground)



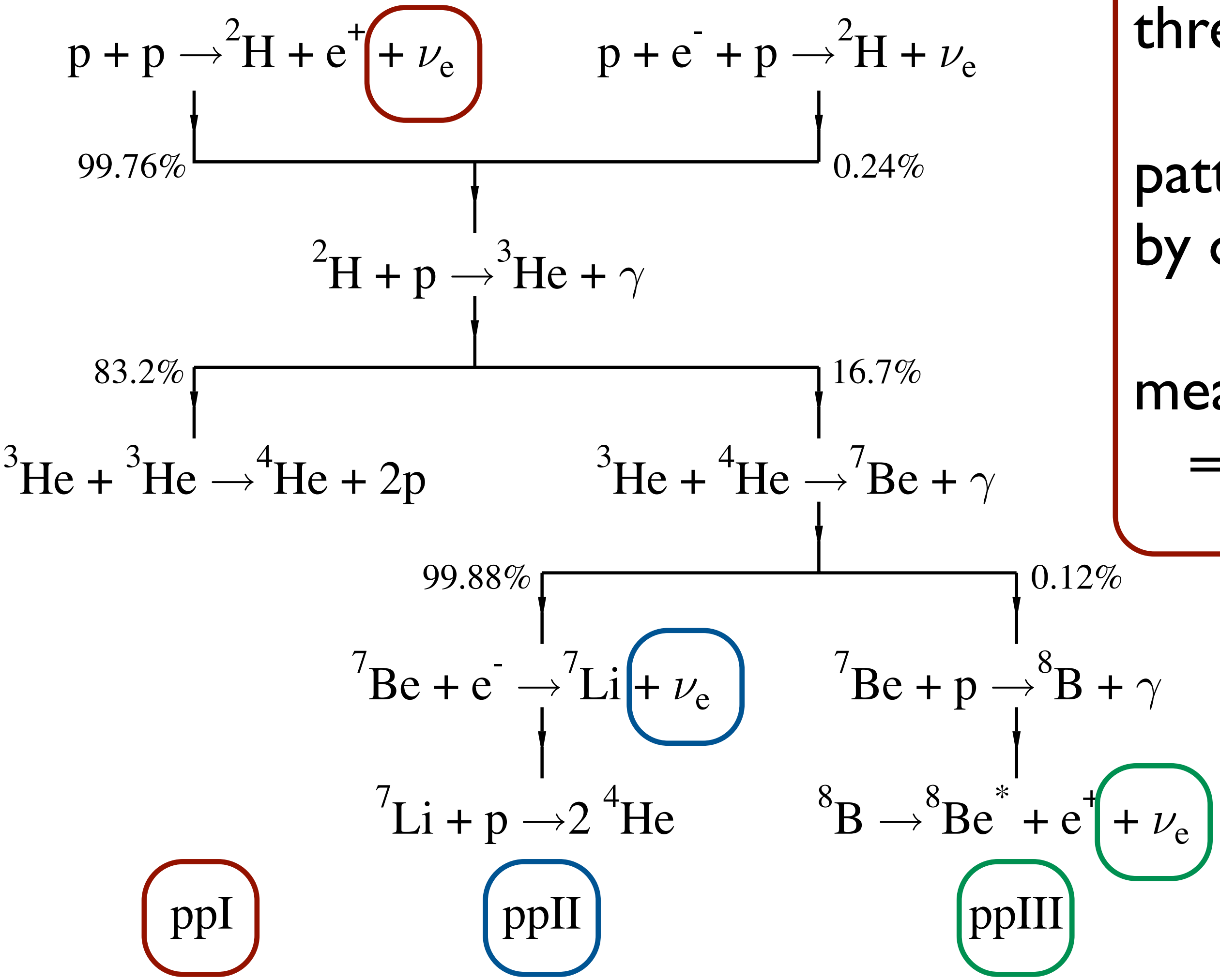
Model tests:

- Solar neutrinos: direct measure of core temperature to ~ 1%
- Helioseismology: inversions map out the local sound speed
  - ◇ provides c(r) to better than 0.5% through most of sun
  - ◇ sensitive to convective zone depth and surface He abundance

Things we know we don’t know in SSM:

- Assumed initial conditions
- No multi-D physics
  - ◇ Li depletion
  - ◇ early convective core
  - ◇ description of the radiative/convective zone boundary
  - ◇ most convective zone physics

Solar neutrino tests: core temperature sensitivity comes from the nuclear microphysics, the ^{8}B branch varies as ~ T^{22} while the pp varies as ~ T^4



$p + p \rightarrow {}^2H + e^+ \boxed{+ \nu_e}$

$p + e^- + p \rightarrow {}^2H + \nu_e$

99.76%

0.24%

${}^2H + p \rightarrow {}^3He + \gamma$

83.2%

16.7%

${}^3He + {}^3He \rightarrow {}^4He + 2p$

${}^3He + {}^4He \rightarrow {}^7Be + \gamma$

99.88%

0.12%

${}^7Be + e^- \rightarrow {}^7Li \boxed{+ \nu_e}$

${}^7Be + p \rightarrow {}^8B + \gamma$

${}^7Li + p \rightarrow 2\,{}^4He$

${}^8B \rightarrow {}^8Be^* + e^+ \boxed{+ \nu_e}$

ppI

ppII

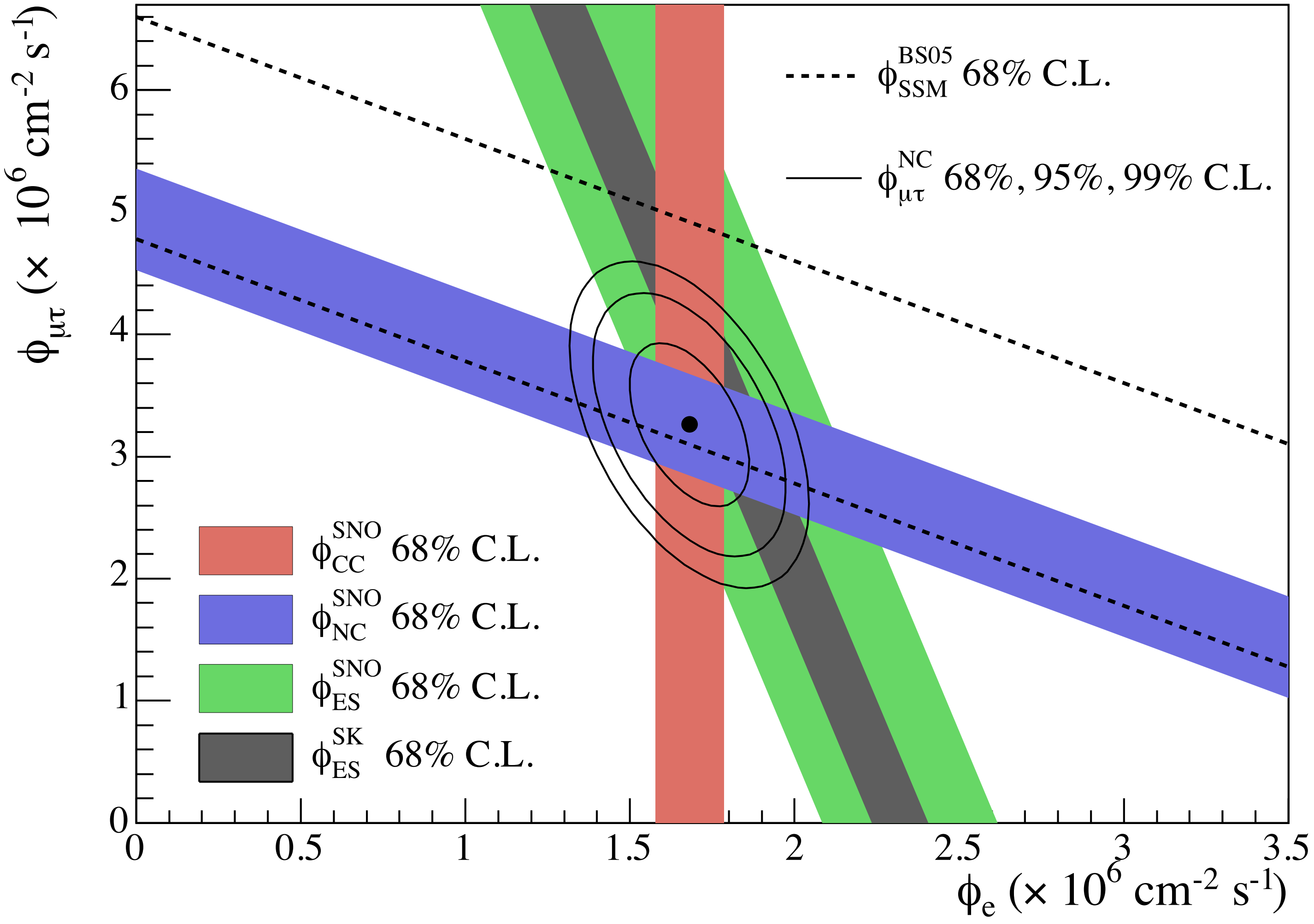
ppIII

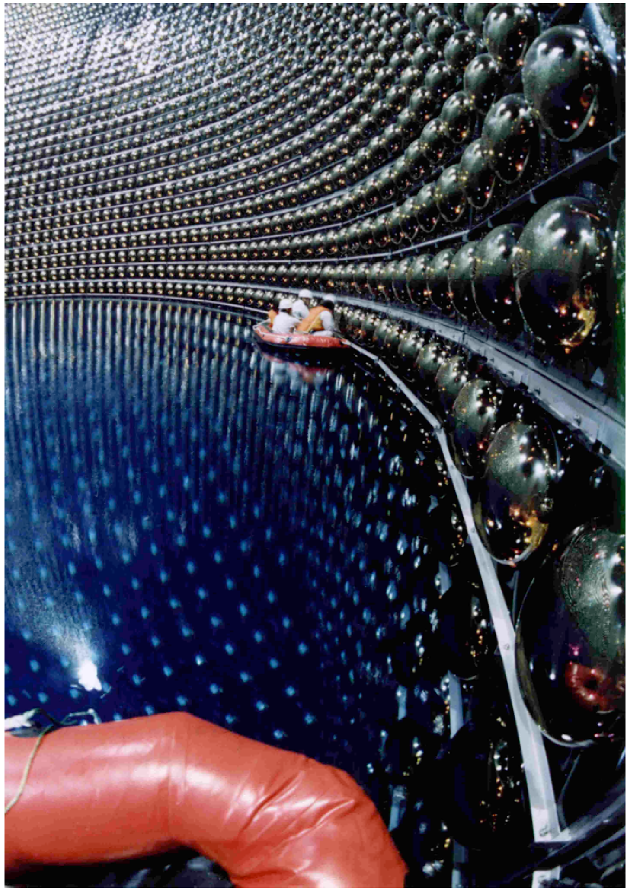
three cycles, three νs

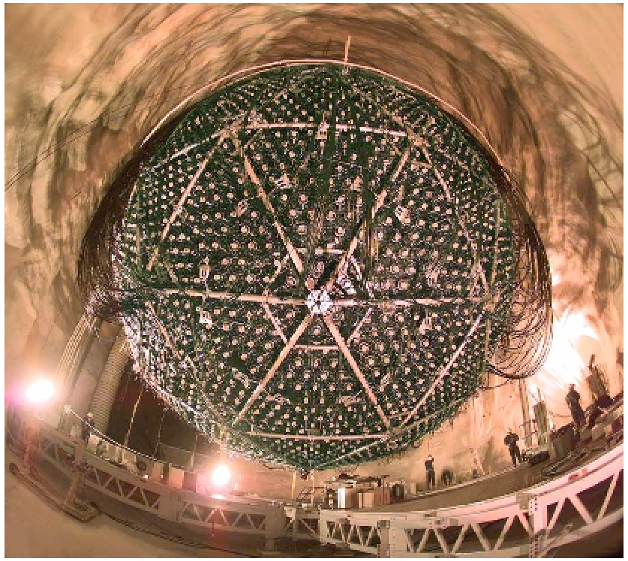
pattern of fluxes governed by one SSM parameter, T

measured pattern differed
⇒ new physics

And that issue was resolved: $\nu_e \rightarrow \nu_{heavy}$







With the flavor physics issues resolved, one can go back to the original game plan, testing the SSM through its ^{8}B flux predictions

SNO 391-day NCD-phase result:
5.54 ± 0.32 (stat) ± 0.35 (sys)$\times 10^6$/cm^{2}s

SSM (Opacity project opacities, 1998 GS abundances with Z=0.0169):
BPS08(GS): 5.95×10^6/cm^{2}s

SSM (Opacity project opacities, 2005 AGS abundances with Z=0.0122):
BPS08(AGS): 4.72×10^6/cm^{2}s

So a DUSEL question might be, are we done now? If not, there are two possible directions, using neutrinos to further probe

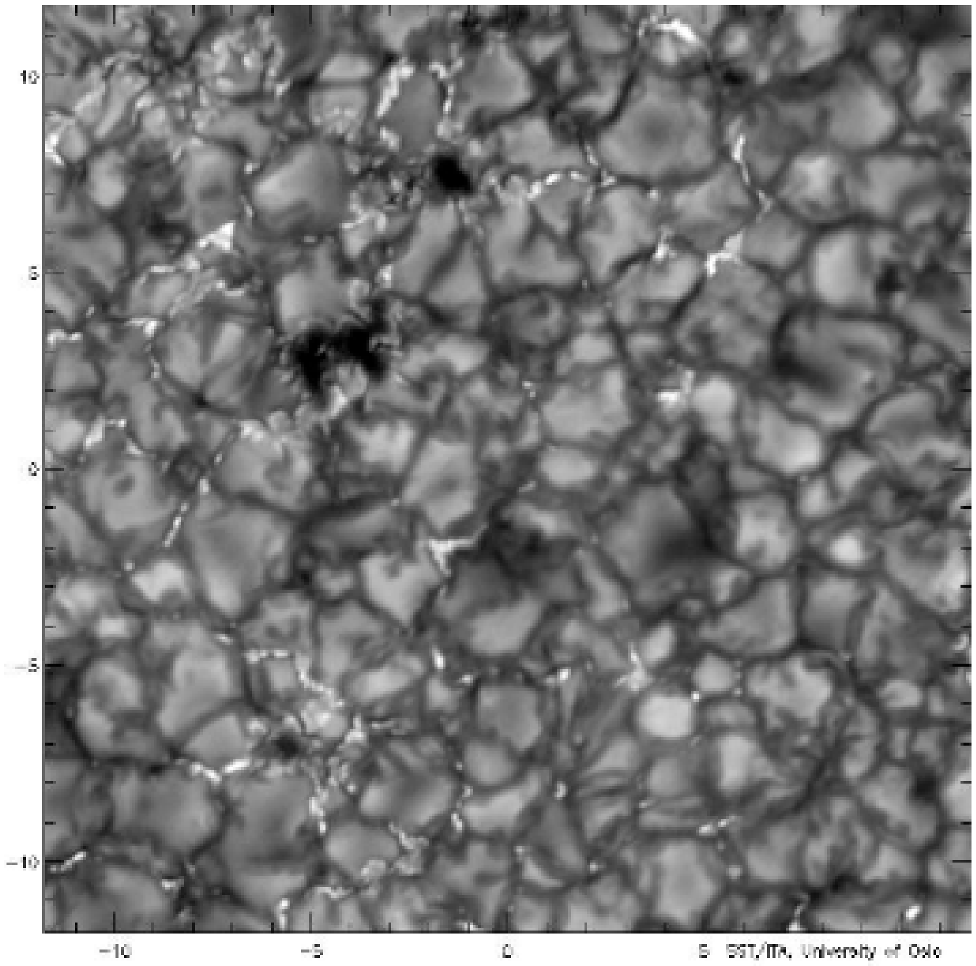
1) flavor physics
2) solar astrophysics

Are there measurement opportunities?

One SSM issue: the abundances of certain volatile metals must be taken from photospheric absorption lines

The analysis recently improved: new 3D, parameter-free methods were introduced, incorporating a lot of physics previously ignored in 1D

Dynamic and 3D due to convection



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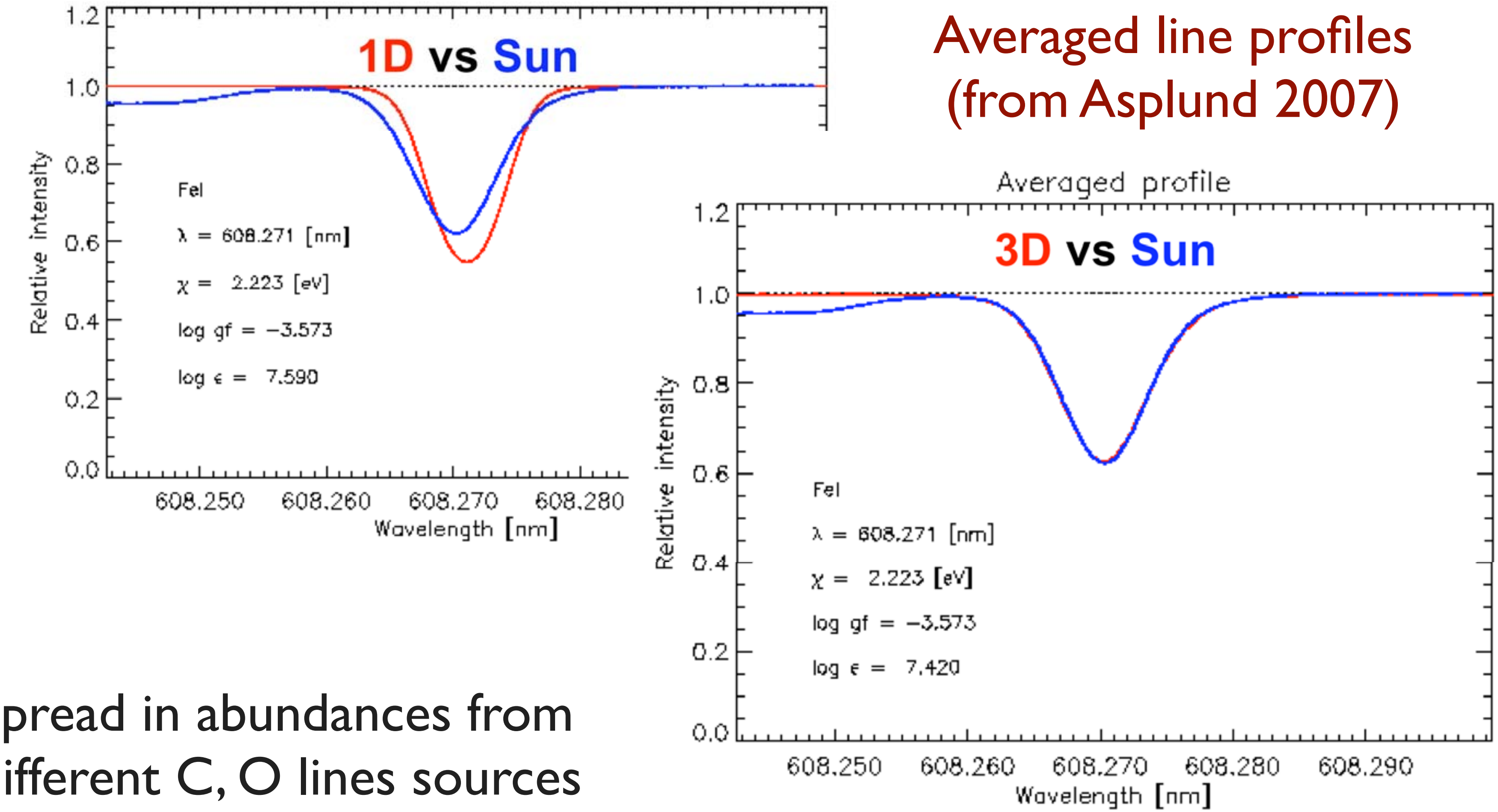
Mats Carlsson (Oslo)

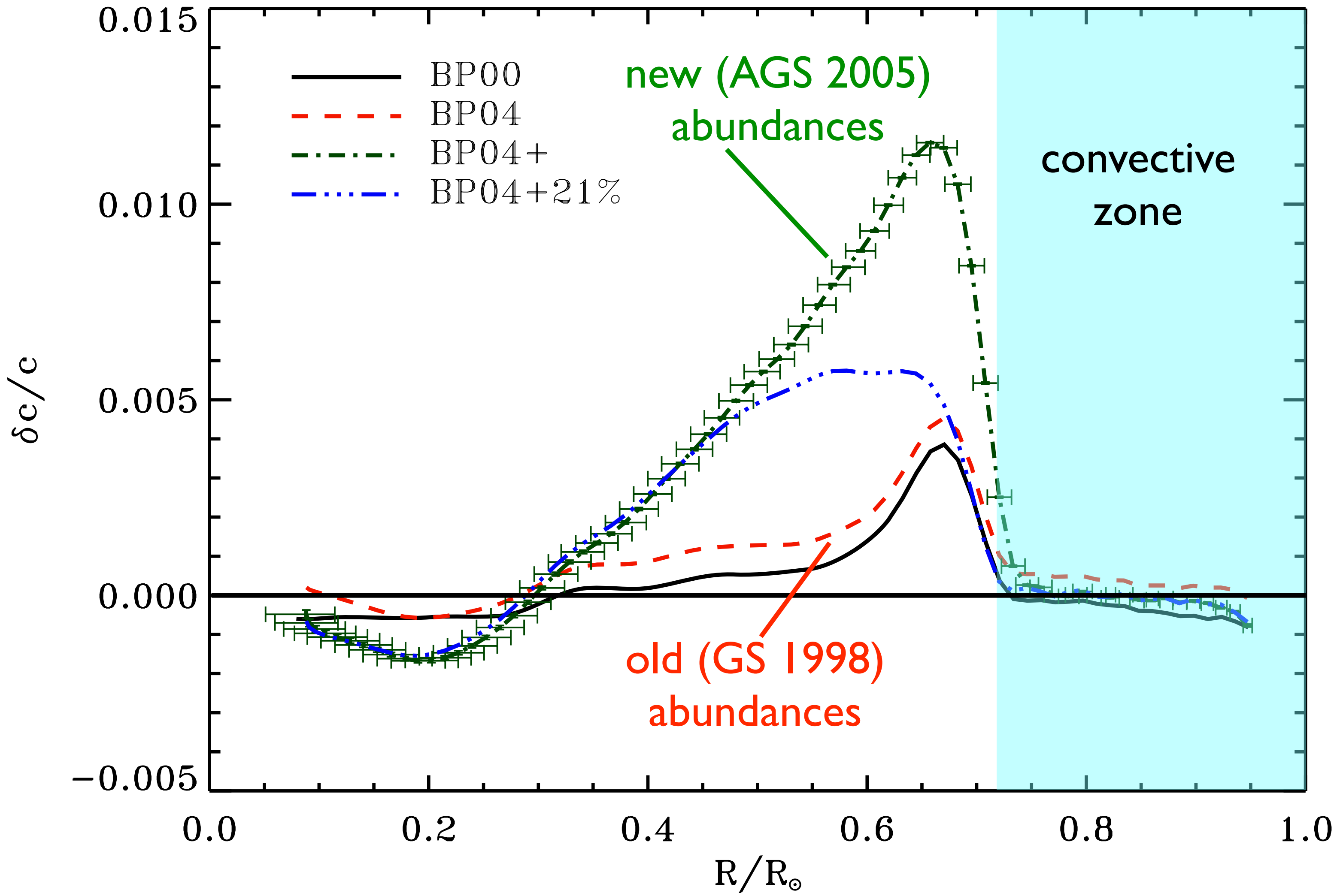
Sun

Averaged line profiles (from Asplund 2007)



- Spread in abundances from different C, O lines sources reduced from ~ 40% to 10%
- But abundances significantly reduced Z: 0.0169 ⇒ 0.0122
- Makes sun more consistent with similar stars in local neighborhood
- Lowers SSM ^{8}B flux by 20% -- large compared to SuperK uncertainties

But the consequences for helioseismology are not good

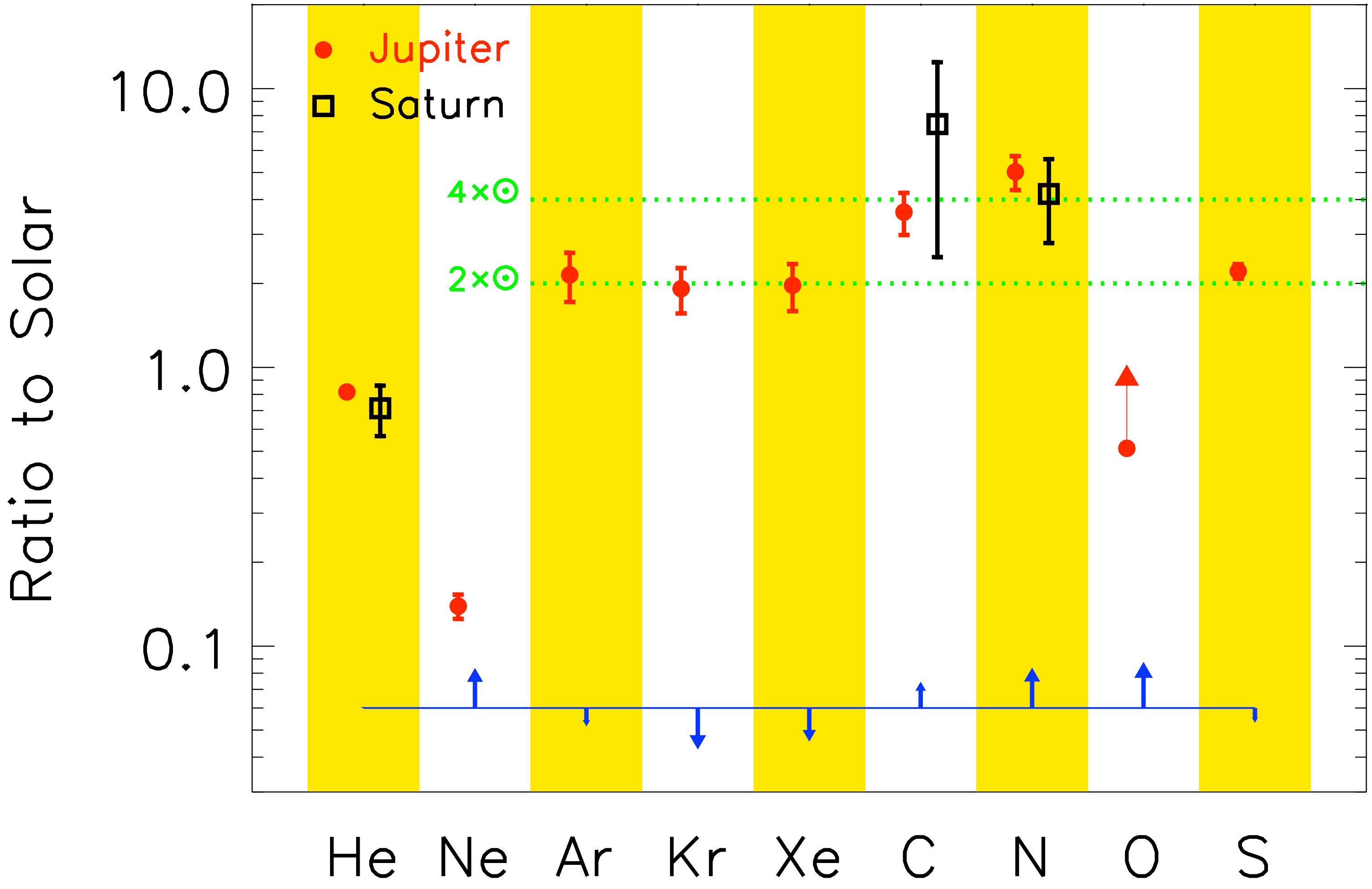


Bahcall, Basu, Pinsonneault, Serenelli 2004

- Doing a ν experiment to measure core metalicity would
    - remove a SSM assumption that has little observational support
    - provide a comparison to surface abundances

- The equivalence of surface, interior metals is an interesting question: planetary formation, late in the evolution of the solar disk, extracted a great deal of metal from the remaining nebular gas (50 $M_\oplus$)

- This program requires
    - an neutrino experiment that responds to metalicity
    - improved laboratory astrophysics to reduce S-factor uncertainties
    - improved laboratory experiments to reduce flavor uncertainties

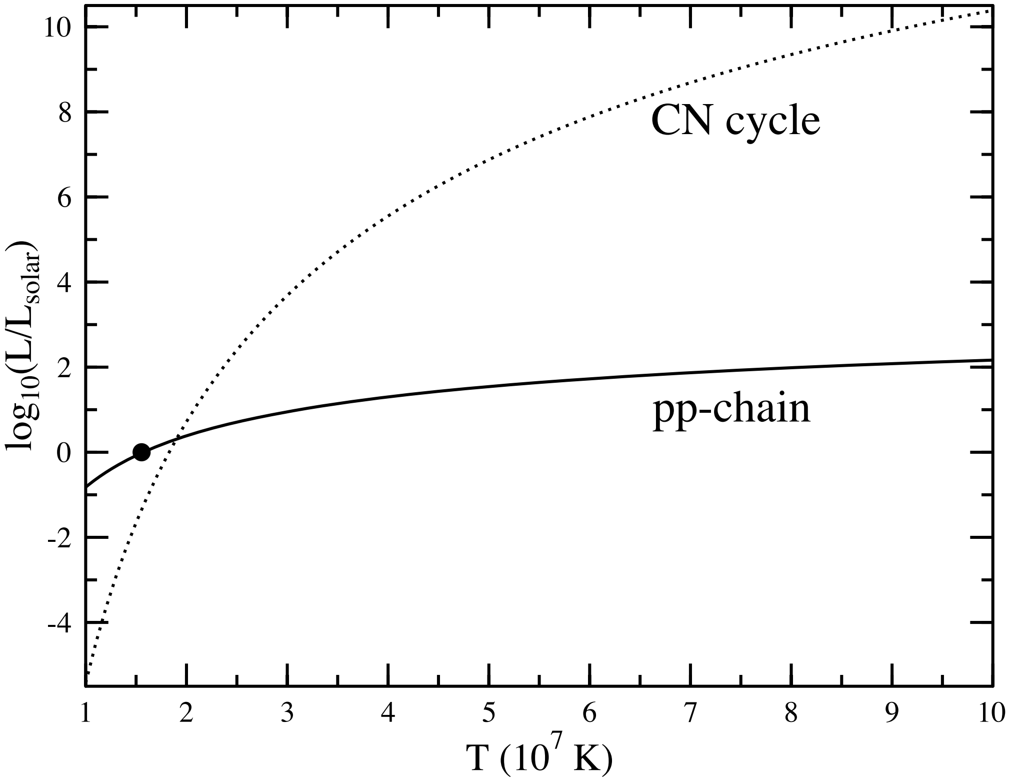


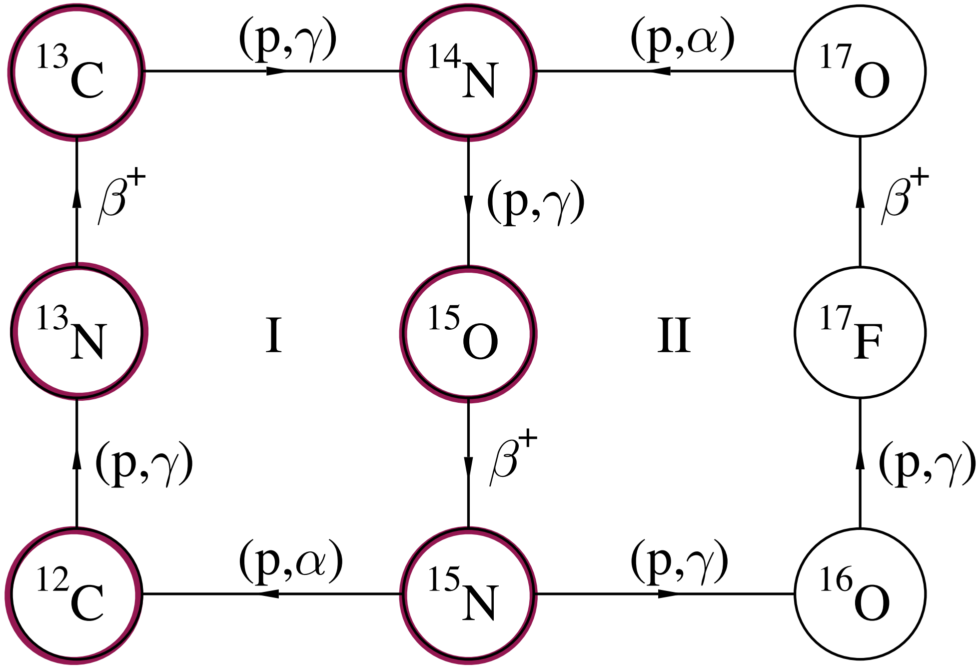
Galileo data, from Guillot AREPS 2005

Standard interpretation of Galileo, Cassini data: late-stage planetary formation in a chemically evolved disk over ~ 1 m.y. time scale

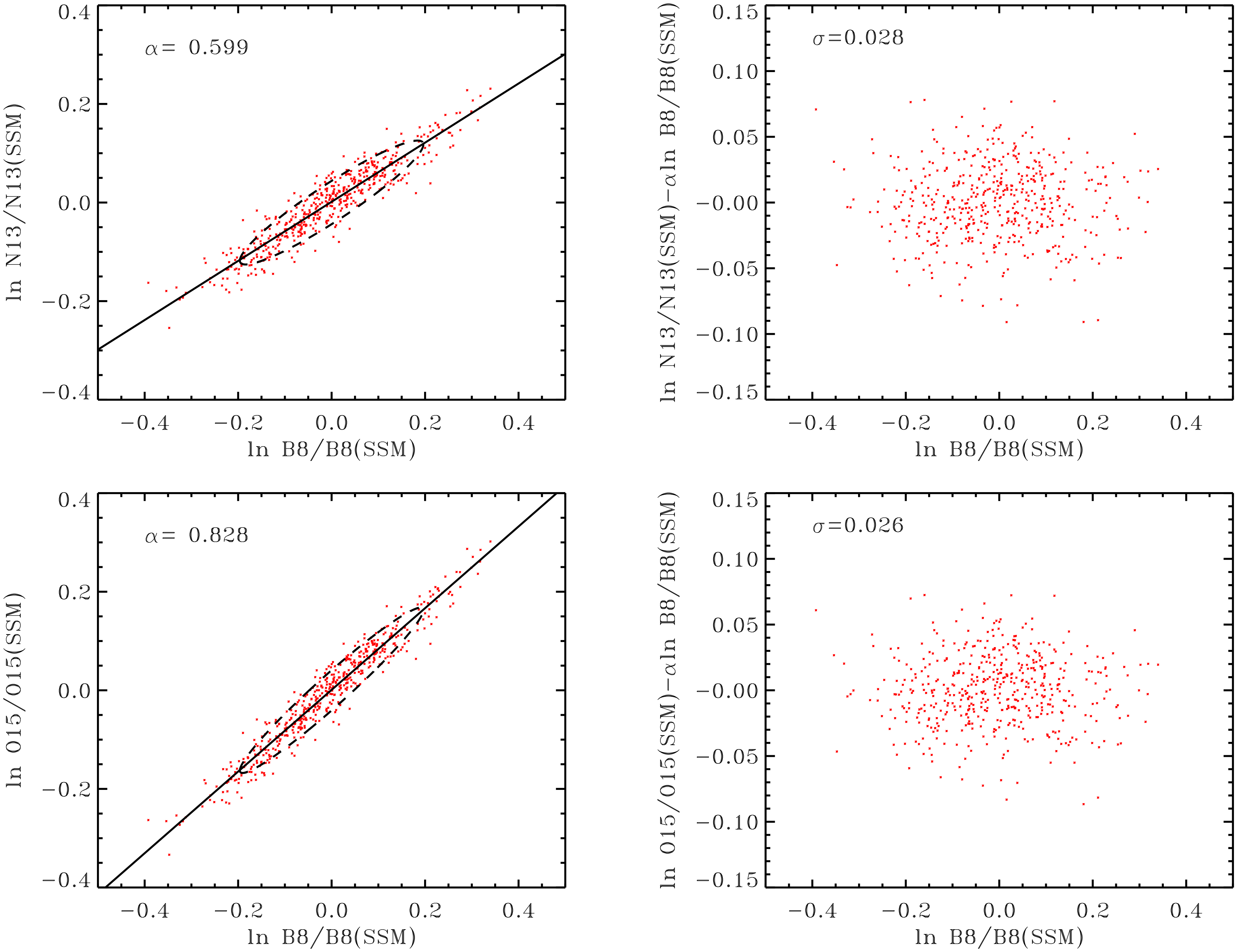
The CN neutrino flux is highly sensitive to metalicity

- CN cycle sustains massive MS stars, but generates just 1% of solar energy
- Low-energy νs, <1.72 MeV   total SSM C+N flux ~ 5.1× 10^8/cm^{2}s
- Production governed by two parameters: linear dependence on CN core metalicity, ~T^{18} dependence on core temperature





Remove T-dependent effects by using SuperK as a solar thermometer

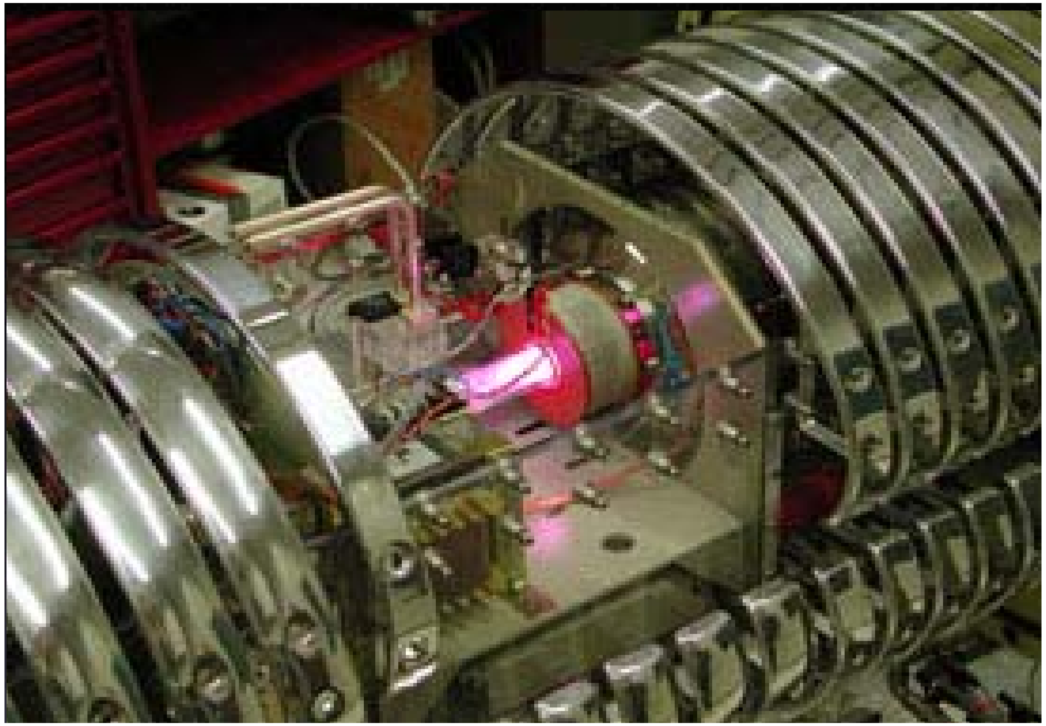


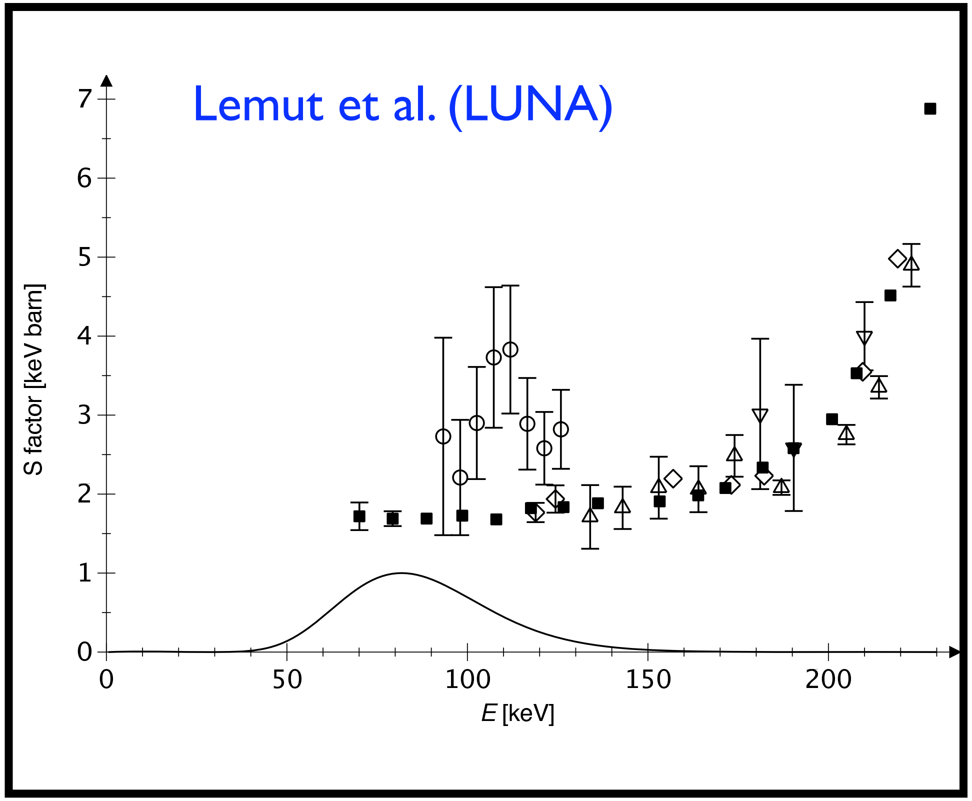
The experiment would not be worth doing, except for underground nuclear astrophysics

LUNA (and LENA) measurements of $^{14}N(p,\gamma)$

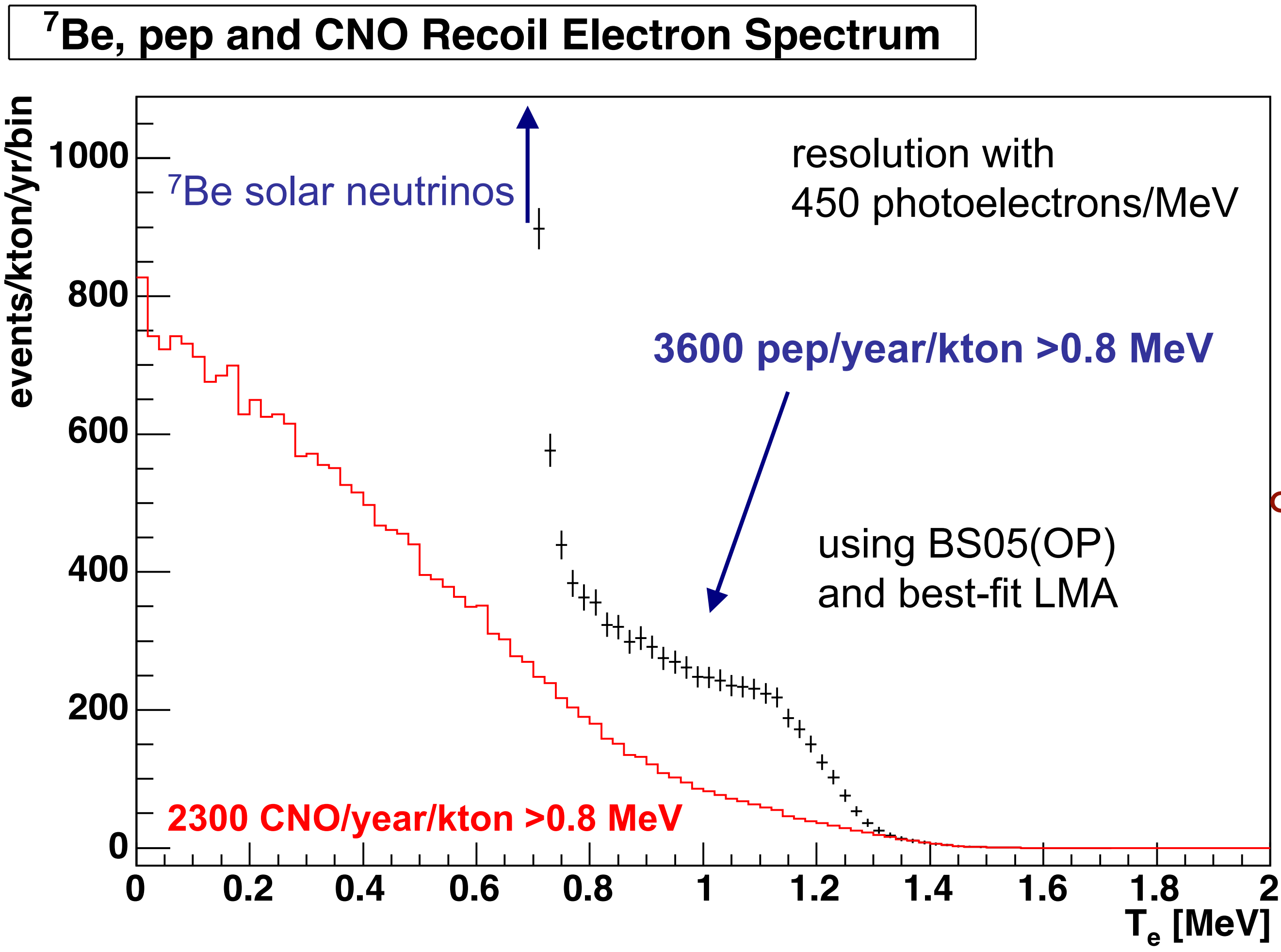
Formicola (LUNA) et al. (2004); Imbriani et al. (2005);
Bemmerer et al (2006); Lemut et al. (2006);
Trautvetter et al. (2008); Runkle (TUNL) et al. (2005)

S-factor mapped down to 70 keV





The candidate experiment is a key one for DUSEL/SNOLab ⇔ depth!



(from Mark Chen)

A similar detector -- Borexino -- now operating at Gran Sasso, with exceptionally low environmental radioativity rates

DUSEL, SNOlab provide an essential factor-of-70+ reduction in long-lived cosmogenic ^{11}C, to 0.1 c/d/100 tons, relative to Gran Sasso

10% CN flux measurement possible, SNO+ collaboration estimates

The limiting uncertainties in relating observation to core metals are

- the flavor physics (4.9%): error bar on θ_{12}
- the nuclear physics, $S_{1\,14}$ (7.1%)

Need to reduce each of these errors by ~2 to get the maximum benefit from the SK thermometer

Without improvements, one can determine core C+N to 15%, a very interesting result

From this perspective, both underground accelerators and LB oscillation experiments become part of the “laboratory infrastructure” that will make neutrinos more precise probes of astrophysics

This is a piece of a broader program...

Neutrinos as probe of the interiors of solar system bodies

- Geoneutrinos also require very large, deep scintillation detectors
  - ◇ complements seismology, a probe of densities
  - ◇ KamLAND has made a first measurement
  - ◇ earth's initial composition, energy budget influenced by ^{40}K/U/Th
  - ◇ envisioned program would determine ^{238}U and ^{232}Th continental crust and mantle concentrations to ~20%
  - ◇ standard geophysical models predict current radiogenic heat production of ~19 TW, compared to current heat flux of 30-44 TW
  - ◇ effects on early earth and subsequent evolution

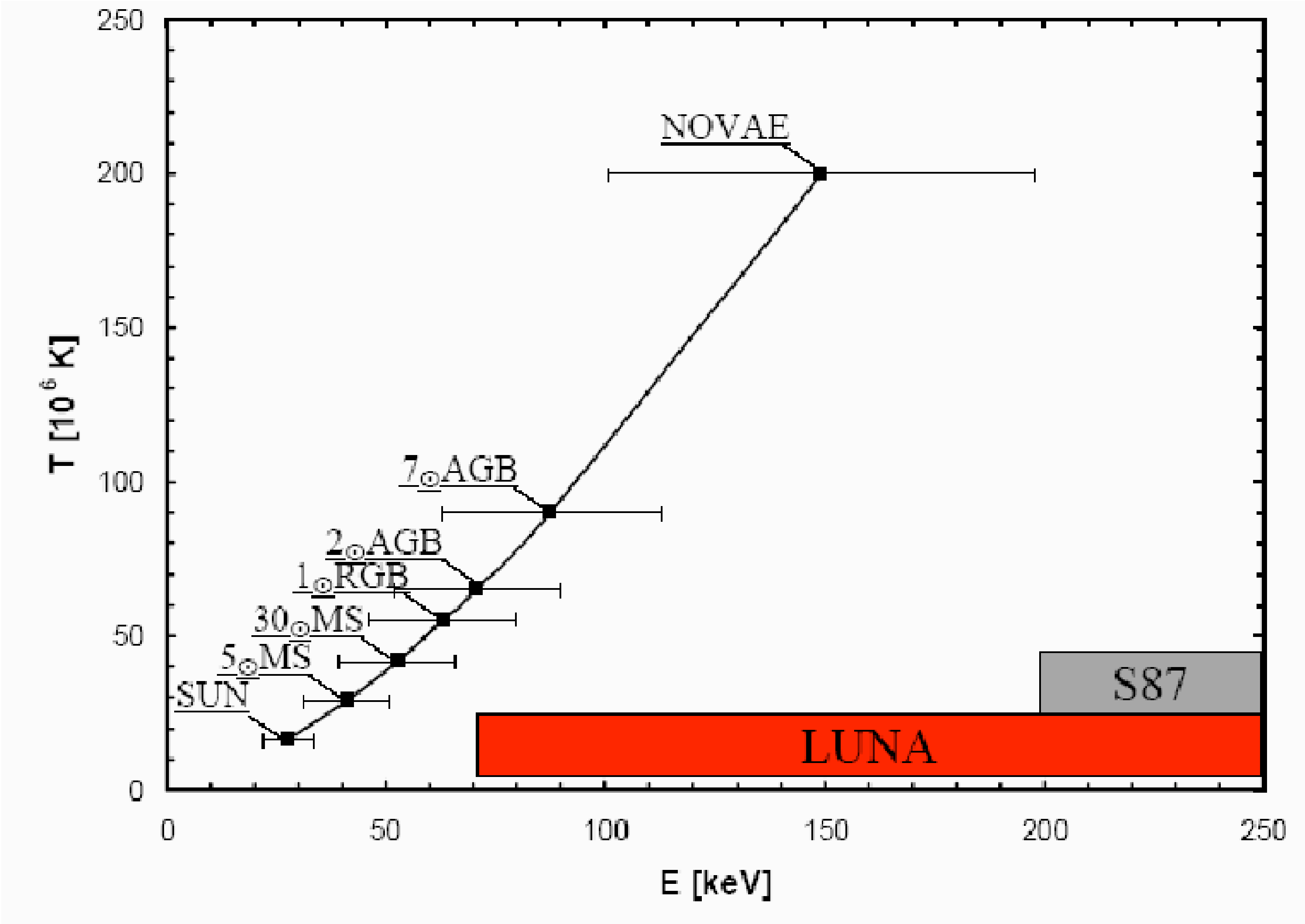
Radiogenic Heat

Source	4.5 b.y. (TW)	0 b.y. (TW)
40K	1	11.5
238U	8	16.1
232 Th	8	10.2

Impact of underground laboratory astrophysics on other stellar evolution

- e.g., LUNA $^{14}N(p,\gamma)$ effect on globular cluster age determinations
  - ◇ controlling rate for the low-energy CN cycle
  - ◇ LUNA results are a factor of two lower than older NACRE values
  - ◇ globular clusters are believed to be the oldest stellar populations
  - ◇ CN rate influences evolutionary track of red giants
    - - lower luminosity prior to He core ignition, due to reduced CN cycle H burning in the burning shell
    - - increased core mass at the point of He core ignition
    - - alters later evolution along HB branch
  - ◇ net effect is an increase in globular cluster age estimates of 0.5-1.0 b.y., depending on cluster metalicity (12b.y.)

- underground experiments can succeed with very low counting rates, providing data at or close to the Gamow peak



from Junker

50-150 keV: target for low-Z reactions with underground accelerators - massive main-sequence burning, RGs and AGB stars, to white dwarfs

⇒ s-process, novae

DUSEL-inspired compilations of key reactions have been made

- hydrogen burning: $^{7}Be(p,\gamma)^{8}B$, $^{14}N(p,\gamma)^{15}O$

- helium burning: $^{12}C(\alpha,\gamma)^{16}O$, $^{16}O(\alpha,\gamma)^{20}Ne$
  - ◇ C-burning the key uncertainty in evolving SNII progenitors
  - ◇ Gamow peak ~ 300 keV, data limited to > 1 MeV
  - ◇ extrapolations complicated by subthreshold resonances
  - ◇ experimental problems include CR backgrounds in detectors, beam-induced backgrounds (larger at higher E), low currents
  - ◇ DUSEL proponents:
    - ^{12}C beams on He gas targets, with a recoil separator
    - conventional approach with a high-intensity α beam
  - ◇ large-solid-angle arrays for γ detection

- s process neutron sources
  - ◇ $^{13}C(\alpha,n)^{16}O$ thought to be main RG source, operates at $T_8 \sim 1$
  - ◇ $^{22}Ne(\alpha,n)^{25}Mg$ operates at $T_8 \sim 2$-3, important in more massive stars

- ◇ rates determine the ambient stellar n fluences
- ◇ $^{13}C(\alpha,n)^{16}O$ measured to 300 keV, needed in the range (150-200) keV
  - extrapolations hampered by poorly constrained subthreshold resonances
- ◇ $^{22}Ne(\alpha,n)^{25}Mg$ dominated by narrow resonances near threshold
- ◇ NACRE uncertainties ~ order of magnitude or more
- ◇ past experiments also had CR background issues
- ◇ underground measurements would be cleaner and extend to lower energies, reducing uncertainties

- hydrogen burning in both MS and more evolved stars
  - ◇ CNO, NeNa, MgAl cycles: (p,γ) and (p,α) reactions on isotopes of N, O, Ne, Na, Mg, Al
  - ◇ important to isotopic abundance anomalies (^{17}O, ^{22}Ne, ^{26}Al) in primordial nebular gas

Oscillation physics potential of future solar neutrino experiments

- sun is the only intense source of electron neutrinos
- direct evidence of matter effects (day-night differences, spectral distortions) has not emerged from SK, SNO
- one of the Borexino motivations:

high-E ^{8}B (SNO, SuperK) νs are in the near-adiabatic MSW region where

$$P_{\nu_e}(E_\nu) \rightarrow \frac{1}{2}(1 - \cos 2\theta_{12})$$

P increases as θ_{12} increases

pp/pep, 7Be, CN νs are in the near-vacuum region where

$$P_{\nu_e}(E_\nu) \rightarrow 1 - \frac{1}{2}\sin 2\theta_{12}$$

P decreases as θ_{12} increases

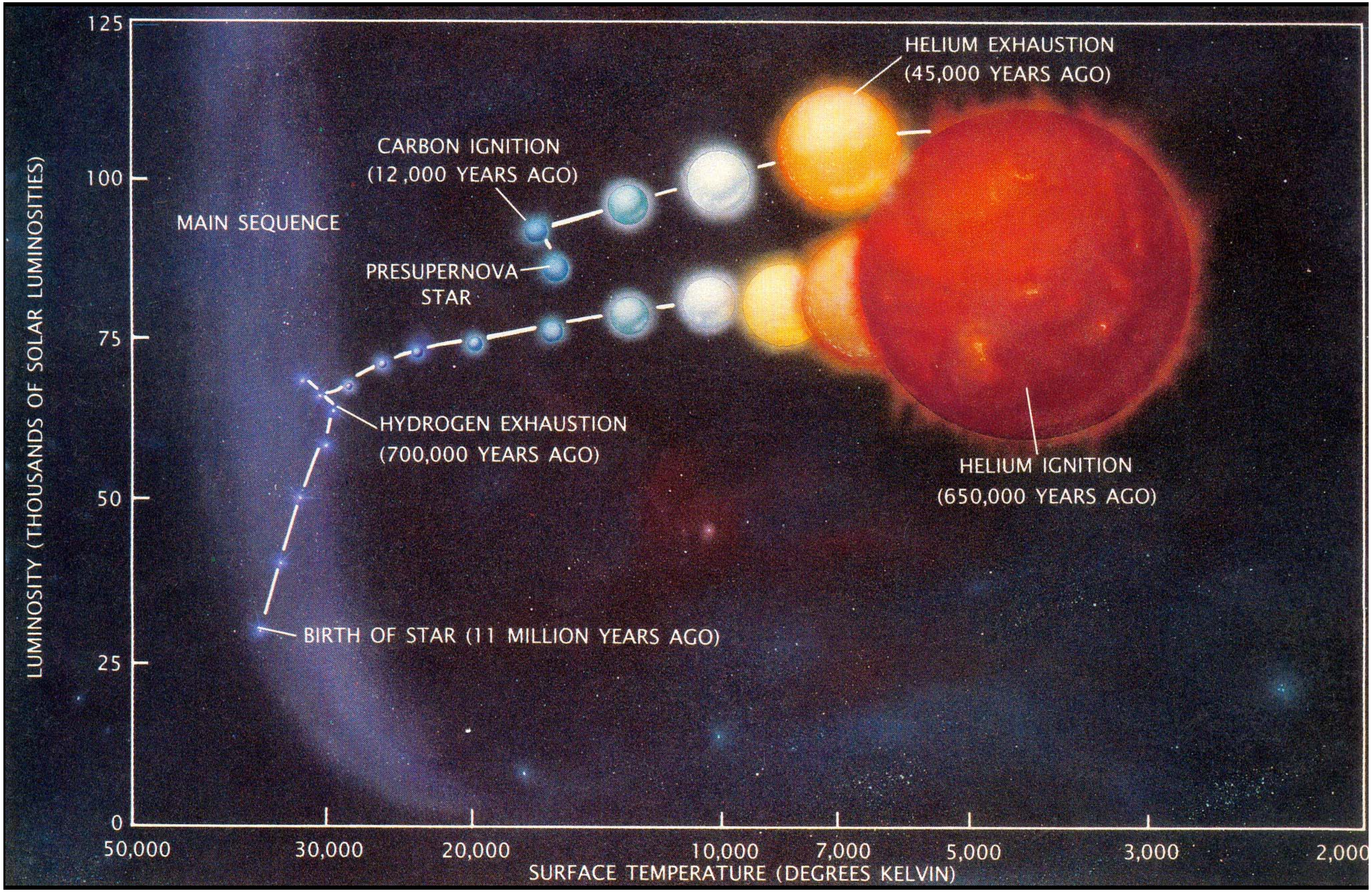
in principle one can constrain θ_{12}, though in practice SSM uncertainties in the 7Be/8B ratio limit what one can do

- this leads to proposals to using pp or pep flux
  - ◇ S-factor uncertainty is 0.4%, governed by g_A
  - ◇ flux is tightly constrained by observed solar luminosity
    - a 1% measurement would not be limited by theory
    - a factor-of-three reduction in the error on θ_{12}

- there are additional flavor physics motivations
  - ◇ NC and CC measurements of pp or 7Be neutrinos could place limits on couplings to sterile neutrinos at ~ 2%
  - ◇ CPT tests by comparing reactor and solar neutrino mass splittings derived from oscillations
  - ◇ ES pp experiment to limit the ν magnetic moment at 10^{-11} μ_B

most proposed pp neutrino experiments are expensive, and there are terrestrial experiments that compete on some issues

SNII progenitor evolution to collapse instability



Woosley and Weaver, 1987

Qualitative picture of collapse

- evolve the progenitor: all of the nuclear physics just described

- iron core collapse proceeds at about 0.6 of free fall
  - rising density drives $p + e^- \rightarrow \nu_e + n$: loss of gas pressure
  - additional energy into nuclear excited states

- ν_es escape, carrying of energy, lepton number: this sets conditions for size of the homologous core, strength of shock wave

- at $\sim 10^{12}$ g/cm^3 neutrinos trapped $\Rightarrow$ $\tau_{diffusion} > \tau_{collapse}$

$$\sigma \sim E_\nu^2 Z_{weak}^2$$

downscattering allows low-E neutrinos to escape

- halts losses $\Rightarrow$ initial conditions of core collapse fixed

- the SN mechanism is all about energy transfer: some matter must become deeply bound so other matter can be free

- shock wave formation: $v_{sound} > v_{infall}$ at high nuclear density
    - pressure wave forms when innermost ring of matter hits super-nuclear densities, rebounds
    - next ring repeats process, pressure wave chases first
    - waves concentrate at edge of homologous core
    - shock wave breaks out when that point reaches nuclear density

- shock propagates out through outer iron core
    - boils iron to nucleon soup at the cost of 8 MeV/nucleon
    - trapped ν_es released -- luminosity peak $\sim$ few milliseconds
    - losses stall shock at a radius of 250-300 km
    - subsequently revived by neutrino heating of the nucleon gas left in the shock's wake

- major uncertainties include the nuclear EOS and 3D radiative hydro, beyond our present capacity to model realistically

- Final (third phase) is the hot-bubble: hot, puffy neutron star cools with time scale of 2-3 secs -- long neutrino cooling tail
  - neutron-rich nucleon gas heated, blown off star -- neutrino winds
  - high entropy per baryon ~ 60-300

- Neutrinos dominate SN energetics: $E_{grav} \sim \frac{GM_{NS}^2}{R_{NS}} \sim 3 \times 10^{53} ergs$
  - optical + explosion ~ 1 Bethe
  - 99% of the energy emitted in 10-20 seconds in neutrinos

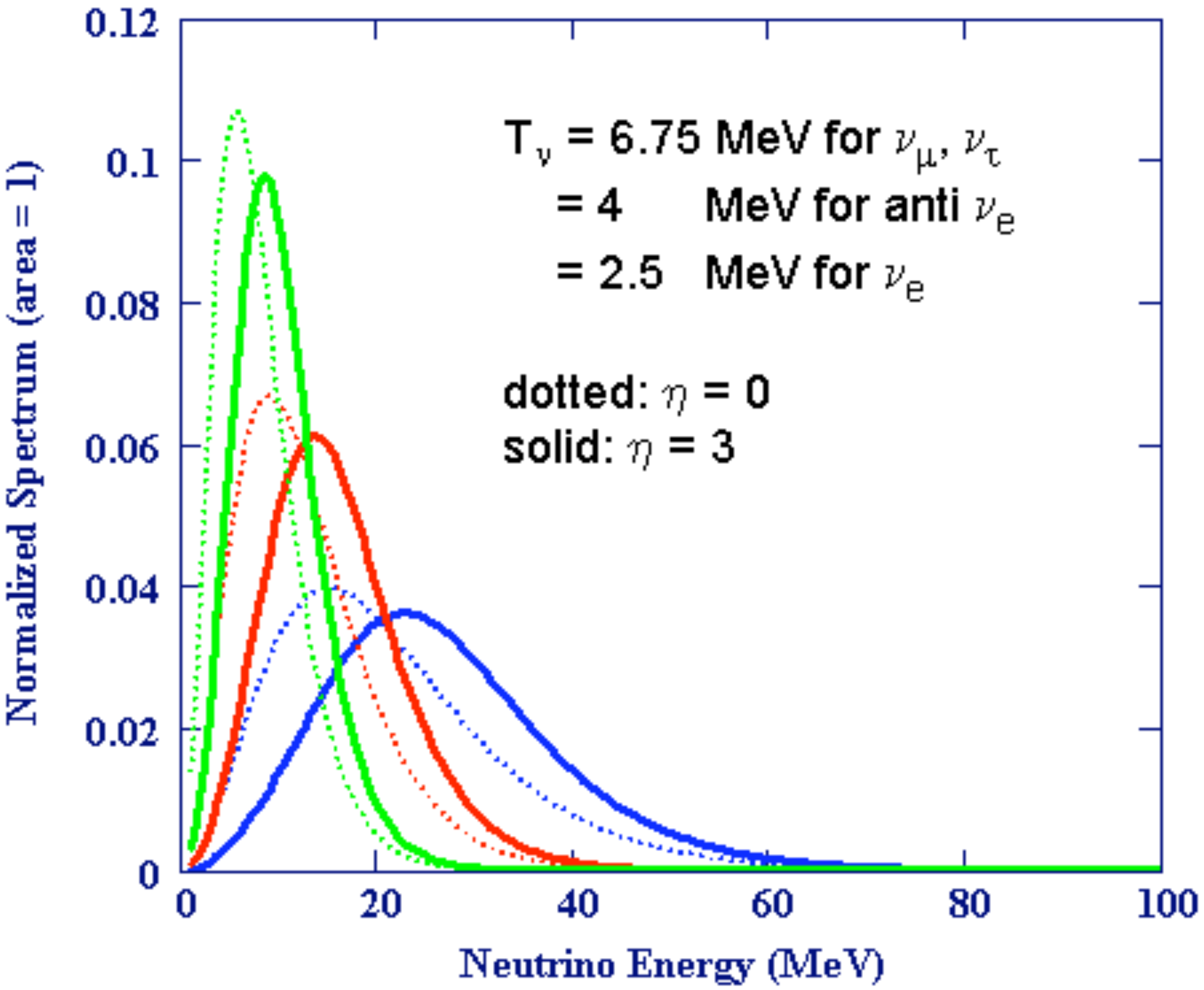
- Weak decoupling at neutrinosphere, flavor dependent

- Rough equipartition of energy, e.g., $\nu_e + \bar{\nu}_e \leftrightarrow \nu_\mu + \bar{\nu}_\mu$

- So an interesting neutrino spectrum irradiates a high-entropy neutron-rich gas that expands off the star

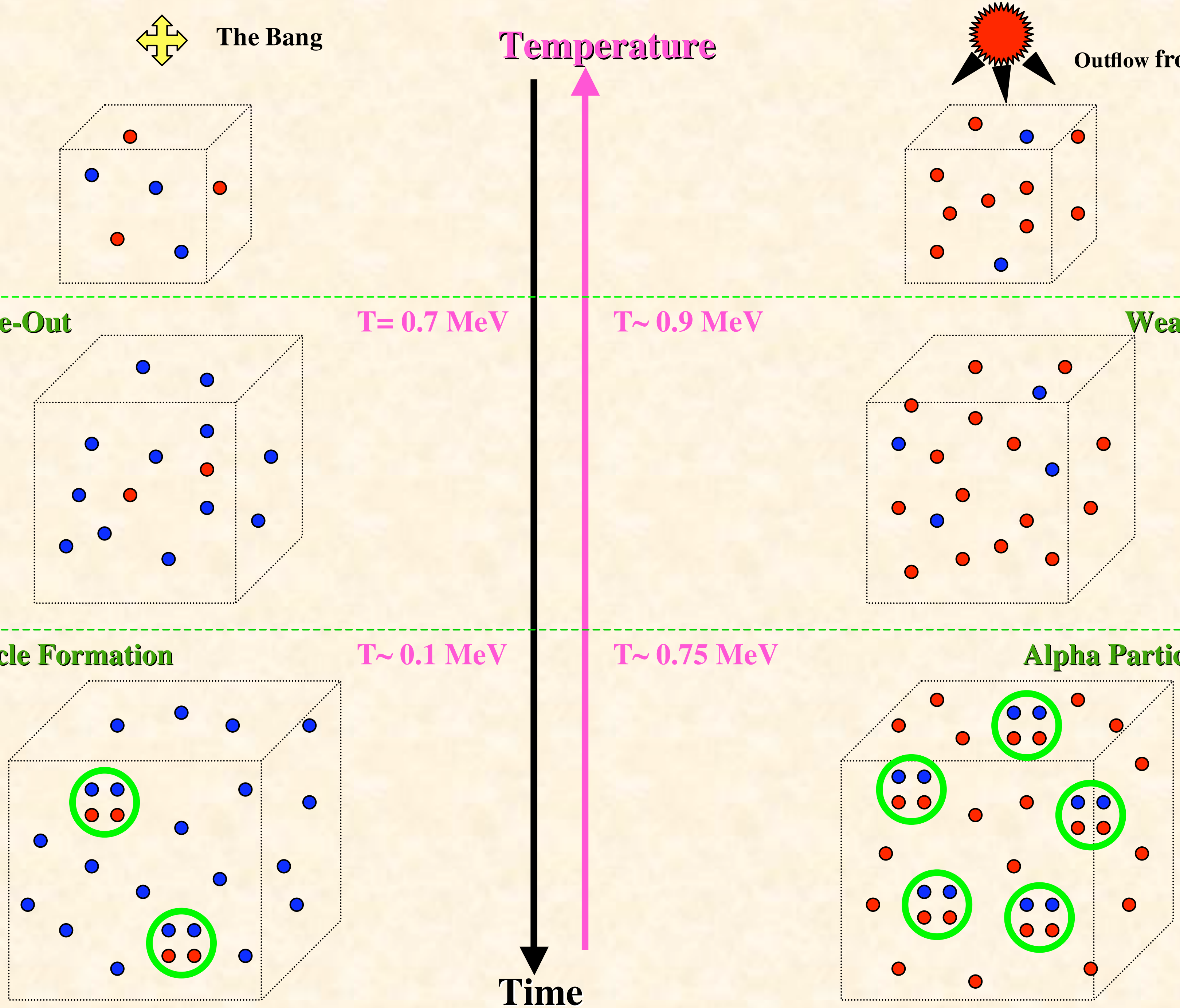
Spectrum determined by weak decoupling at neutrinosphere

$(weakly\ coupled)\quad T_{heavy flavor} > T_{\bar{\nu}_e} > T_{\nu_e}\quad (neutron\ rich)$



FLRW Universe (S/k~10^{10})

Neutrino-Driven Wind (S/k~10^{2})



The Bang

Temperature

Outflow from Neutron Star

Weak Freeze-Out

T= 0.7 MeV

T~ 0.9 MeV

Weak Freeze-Out

n/p<1

n/p>1

Alpha Particle Formation

T~ 0.1 MeV

T~ 0.75 MeV

Alpha Particle Formation

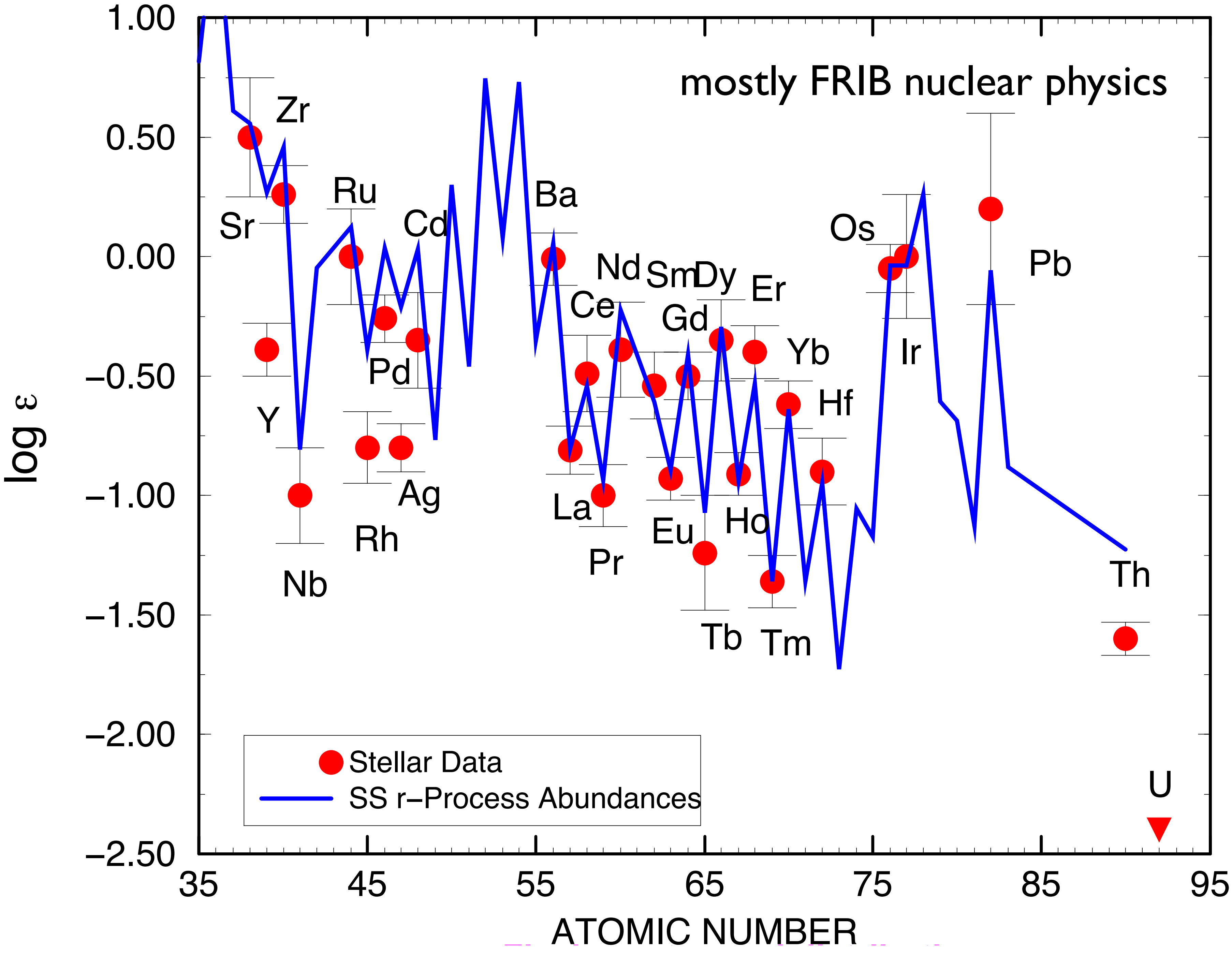
Time

● PROTON

a neutron rich big bang: figure by George Fuller

● NEUTRON

From Cowan et al.



SN neutrino detection at DUSEL

- we do not have an adequate set of SN ν detectors in operation

- neutrino flux measurements can help constrain models
  - ◇ the total energy released in gravitational collapse (assuming an independent measurement of distance)
  - ◇ the total lepton number radiated by the star
  - ◇ the end state of the collapse: truncation of the neutrino light curve by black hole formation
  - ◇ early ν_es to test shock wave propagation through the iron core
  - ◇ shock propagation time, by correlating neutrino burst with surface response to shock breakout: related to progenitor mass
  - ◇ galactic frequency of SN, by detecting optically obscured sources
  - ◇ possibly, constraints on nuclear matter phase changes, as the proto-neutron star cools, from slope of ν light curve
  - ◇ correlations with GW signals, confirming latter

- detectors do not need to be deep: at 20 kpc, a detector at 1.9 kmwe can map the ν light curve to 20 s with a signal/noise of > 10
  - ◇ so compatible with most LB, proton decay programs

- detectors do need to be capable: large volume, flavor specificity, directionality

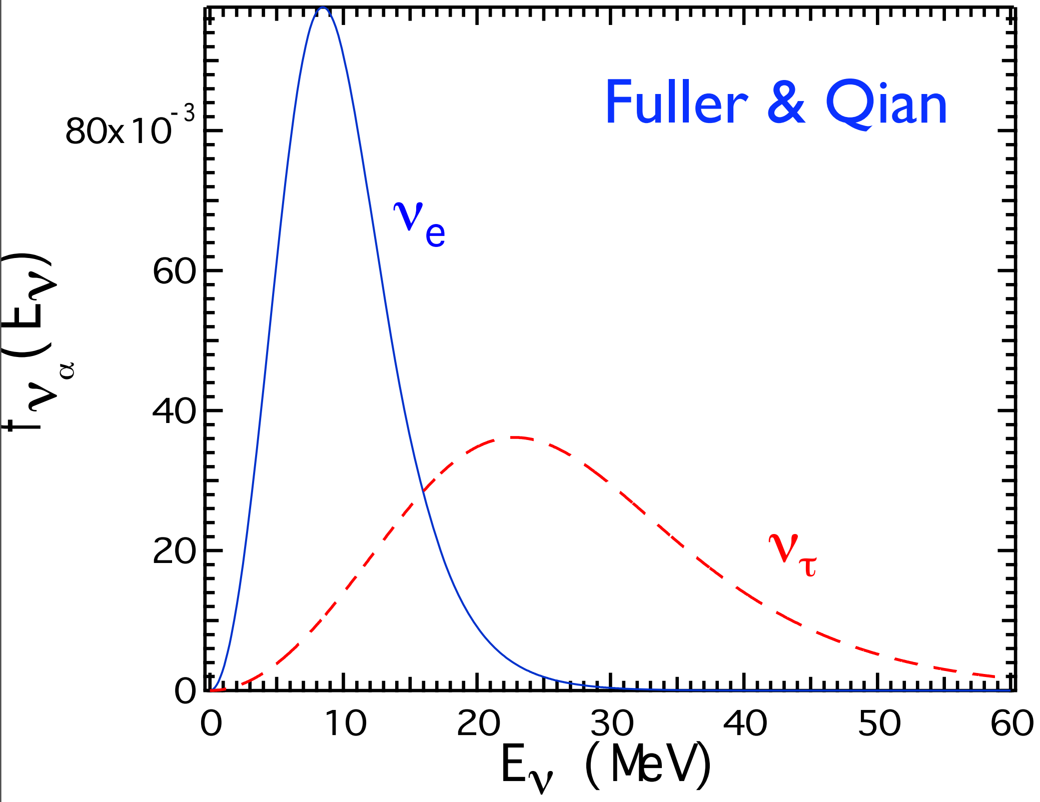
- no single-purpose supernova neutrino detector has yet been built, and one expects this trend to continue
  - ◇ parasitic use of water Cerenkov detectors: electron antineutrinos, early forward-scattered electron neutrinos
  - ◇ large-volume scintillation detectors (geoneutrinos ~10 kt)

SN flavor physics is interesting

- signature: flavor oscillations exchange spectra with different temperatures

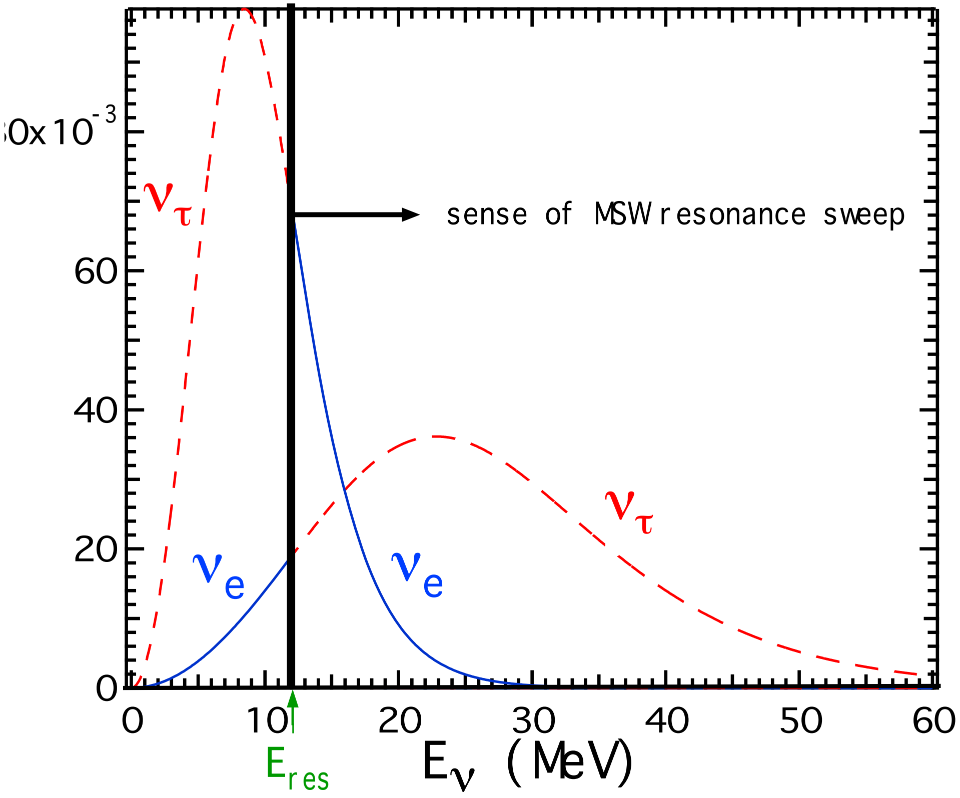
- in principle, there is exceptional sensitivity to θ_{13}
  - ◇ naively, this is the deepest MSW crossing in the star, occurring in the carbon shell, after neutrinos have thermally decoupled
  - ◇ would exchange ν_e and ν_τ spectra
  - ◇ oscillation remains adiabatic for $\theta_{13} > 10^{-4}$
  - ◇ this mixing angle sensitivity on earth requires a neutrino factory

- in practice, this physics will be combined with an entirely new phenomenon, an MSW potential dominated by ν-ν scattering
  - ◇ very complex: depends on the energy, angle, and flavor of scattering
  - ◇ affects flux deep within the star
  - ◇ as yet has not been incorporated into any realistic SN model
  - ◇ a high density effect -- not restricted to mantle



Oscillations are a dynamic effect in supernova, due to its energy dependence:
can influence energy deposition, even the nucleosynthesis

Sweep by the 1-3 resonance: most of the spectrum now heavy flavor -- and soon to have hot ν_e's



Summary

Solar neutrino tests of solar structure seem timely

- surprising that a 1D model has done so well
- interesting photospheric abundance/helioseismology tension
- progress on nuclear and flavor physics
- solar neutrinos/ββ decay/geoneutrinos in one detector
- unique depth requirements nice match to DUSEL

The pp/pep flux is the primary opportunity for precision flavor physics

Supernova neutrino detection could impose an important set of constraints on models of core collapse

The flux will be affected by flavor physics we cannot otherwise test: small mixing angles, new MSW effects: good and bad

Underground nuclear astrophysics supports much of this work, limiting uncertainties in underlying microphysics