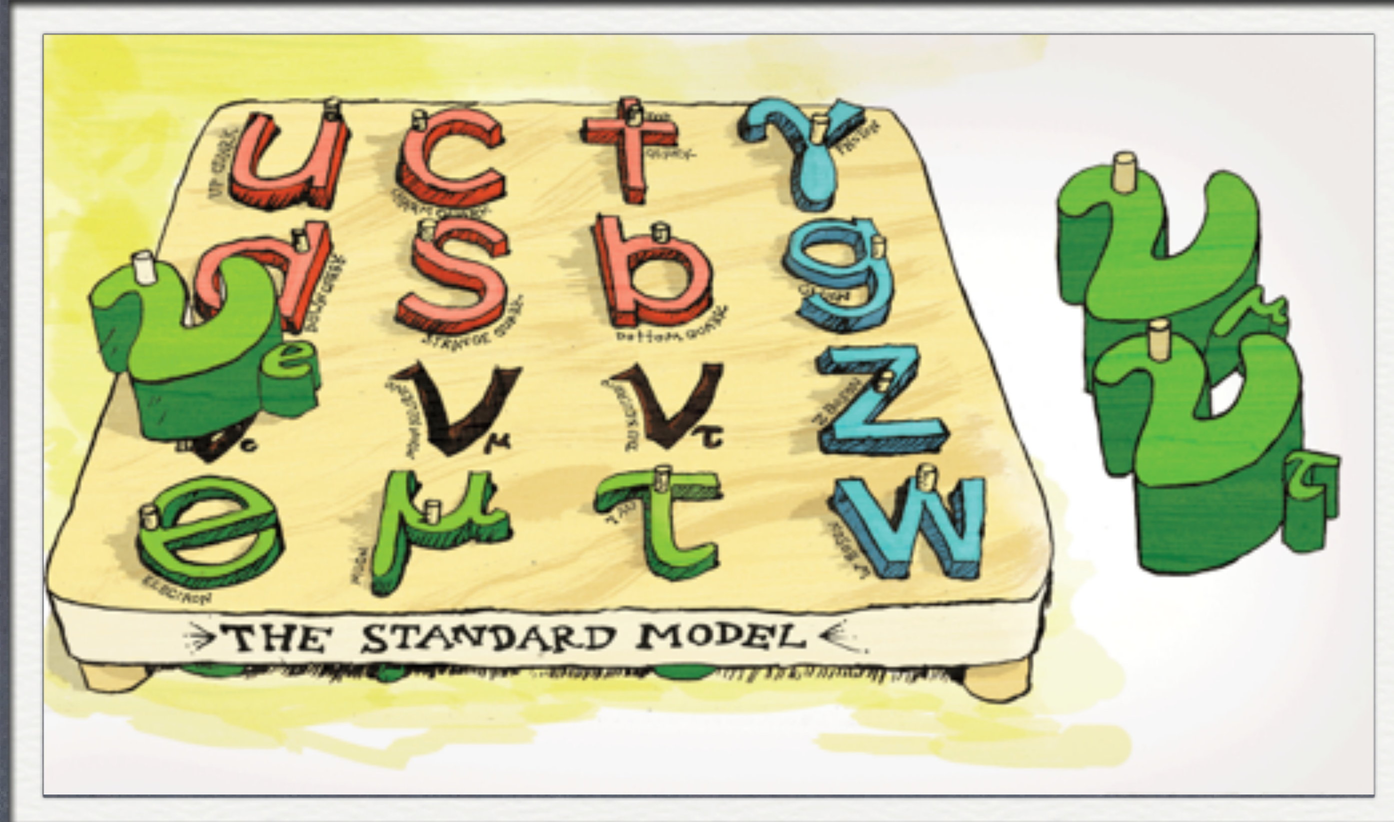



# Neutrino physics II

Alex Friedland
LANL

SLAC Summer Institute
July 2013

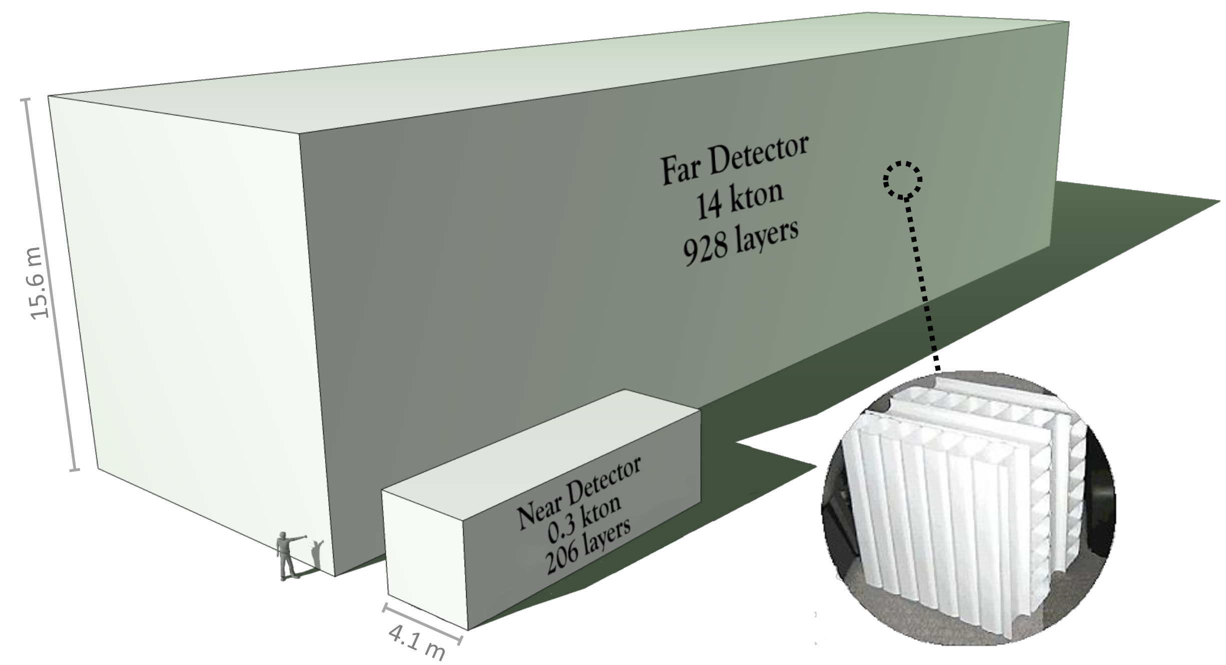
# Plan for today

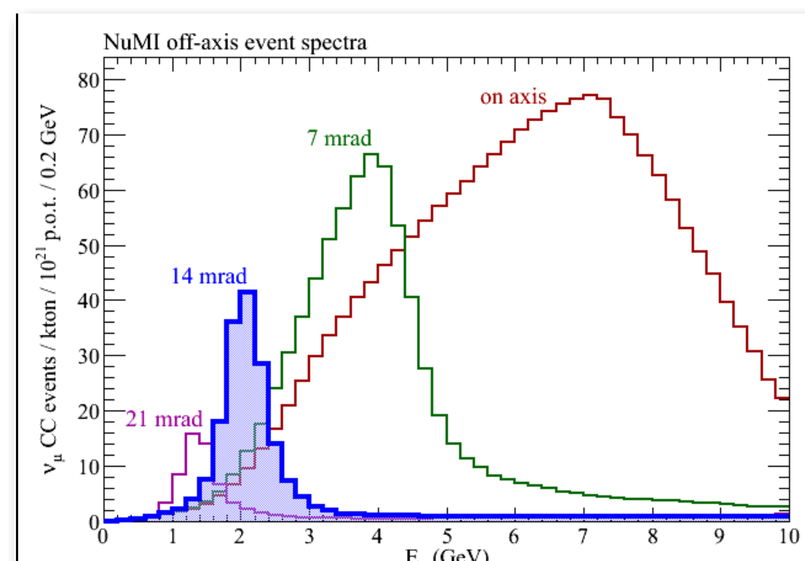
- Long-baseline oscillations
- Neutrinos in cosmology
  - Masses
  - number of species
- Stellar cooling bounds
  - Neutrino magnetic moments
  - BSM particles: Axions
- Supernova neutrino oscillations

# Long baseline oscillations

# Next long-baseline experiment in construction: NOvA

- Source: off-axis NuMI beam at Fermilab
- Far detector: 14 kton of scintillator in Ash River, MN
- Baseline: 810 km
- About an order of magnitude improvement in sensitivity for appearance $\nu_\mu \to \nu_e (\bar{\nu}_\mu \to \bar{\nu}_e)$



# Long-baseline neutrinos: 3-flavor oscillations

$$P(\nu_\mu \to \nu_e) \simeq \left| G_1 \sin\theta_{23} \frac{\exp(i\Delta_1 L) - 1}{\Delta_1} - G_2 \cos\theta_{23} \frac{\exp(i\Delta_2 L) - 1}{\Delta_2} \right|^2,$$

$$G_1 \simeq \frac{\Delta m^2_{\rm atm}}{4E_\nu} \sin 2\theta_{13} e^{i\delta}, \qquad \Delta_1 \simeq \frac{\Delta m^2_{\rm atm}}{2E_\nu} - \sqrt{2} G_F N_e$$

$$G_2 \simeq -\frac{\Delta m^2_\odot}{4E_\nu} \sin 2\theta_{12}. \qquad \Delta_2 \simeq -\sqrt{2} G_F N_e$$

- Two channels, solar and atmospheric, interfere

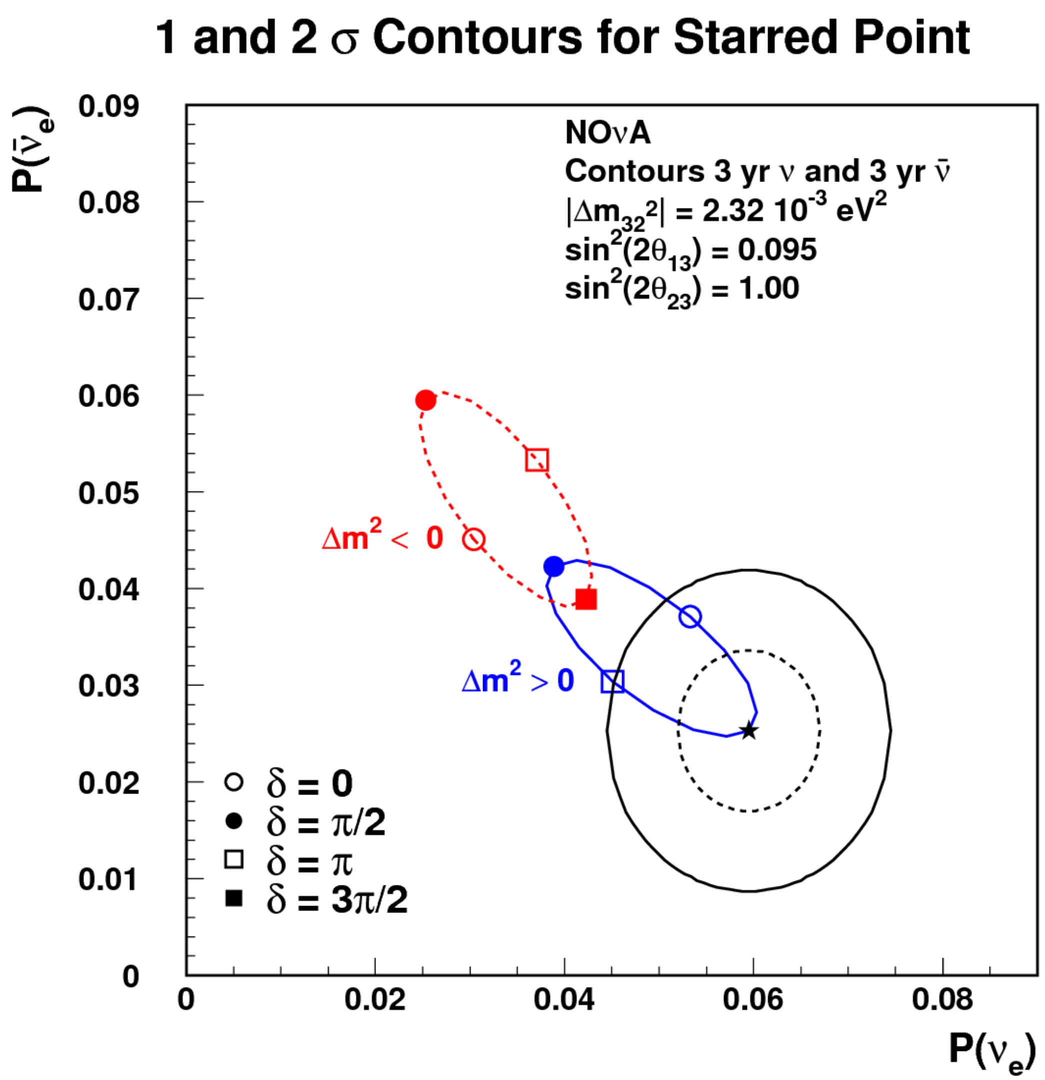
- ***Relevant scales***: assuming $E_\nu = 2$ GeV, $\theta_{23} = \pi/4$, and $\theta_{13} = 8.7^\circ$

$$\begin{aligned} \Delta m^2_{\rm atm}/4E_\nu \sin 2\theta_{13} &= 0.87 \times 10^{-13}\ \text{eV} \\ \Delta m^2_\odot/4E_\nu \sin 2\theta_{12} &= 0.09 \times 10^{-13}\ \text{eV} \end{aligned}$$

- The solar term is ~10% of atm. Upon interference, ~20% modulation (hence, search for CP requires precision)

# NOvA bi-probability plot

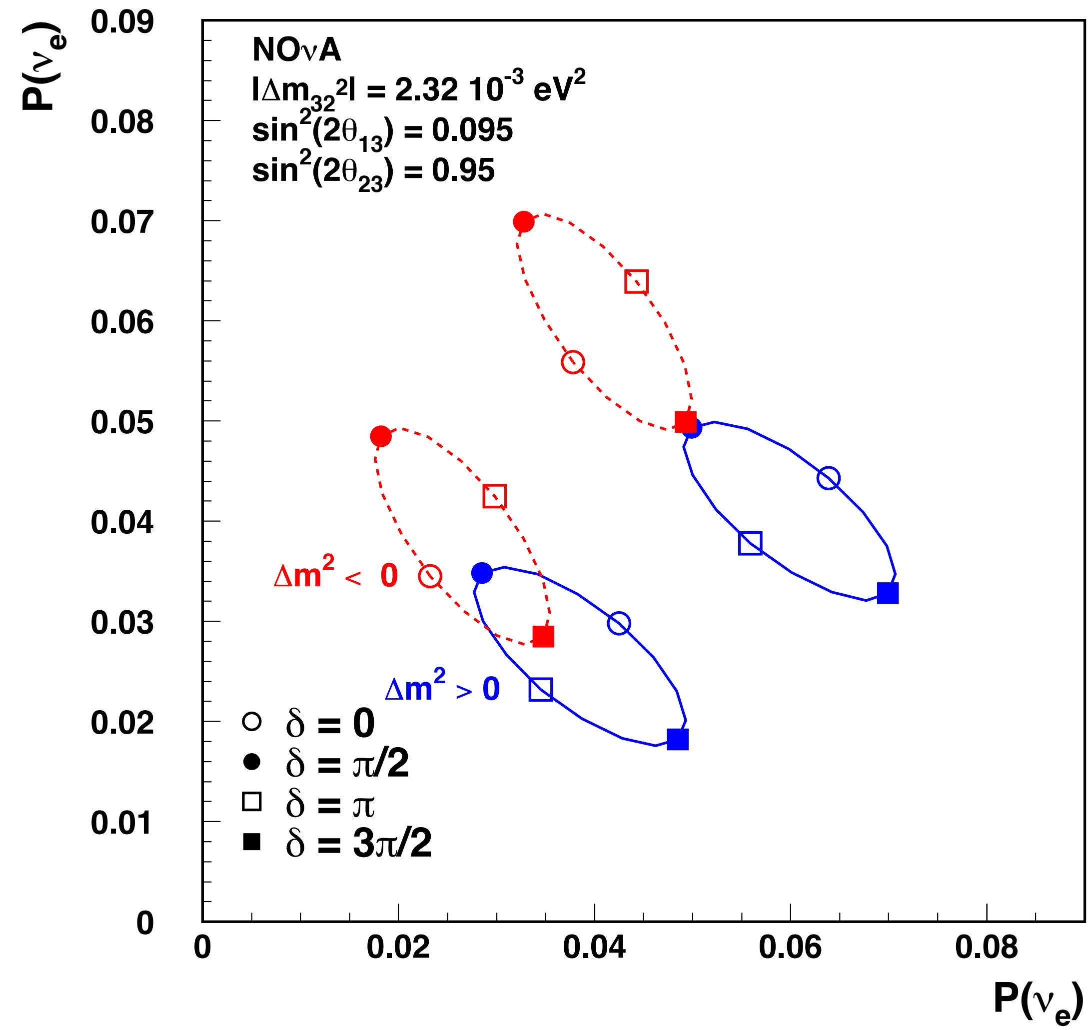
- Interference between solar and atm. terms depends on the phase, mass hierarchy
- Instead of plotting the energy spectrum people often show the "bi-probability" plot (Minakata, Nunokawa, JHEP 2001).
- Esp. useful for NOvA, since it's a narrow band off-axis beam with E ~ 2 GeV




Ryan Patterson, NU 2012

# Octant sensitivity

- It may be also possible to determine the deviation of theta23 from maximal mixing



# Now, let's add a small FC NSI, a la Wolfenstein

$$P(\nu_\mu \to \nu_e) \simeq \left| G_1 \sin\theta_{23} \frac{\exp(i\Delta_1 L) - 1}{\Delta_1} - G_2 \cos\theta_{23} \frac{\exp(i\Delta_2 L) - 1}{\Delta_2} \right|^2,$$

$$G_1 \simeq \sqrt{2} G_F N_e |\epsilon_{e\tau}| e^{i\delta_\nu} \cos\theta_{23} + \Delta \sin 2\theta_{13} e^{i\delta},$$

$$G_2 \simeq \sqrt{2} G_F N_e |\epsilon_{e\tau}| e^{i\delta_\nu} \sin\theta_{23} - \Delta_\odot \sin 2\theta_{12}.$$

- Two channels, solar and atmospheric; NSI amplitude appears in both

***Interference of the large theta13 term with the NSI term dramatically enhances the sensitivity!***

- ***NSI has its own CV-violating phase; interference depends on the relative phases!***

# Again relevant scales

- Assuming $E_\nu = 2$ GeV, $\theta_{23} = \pi/4$, and $\theta_{13} = 8.7^\circ$

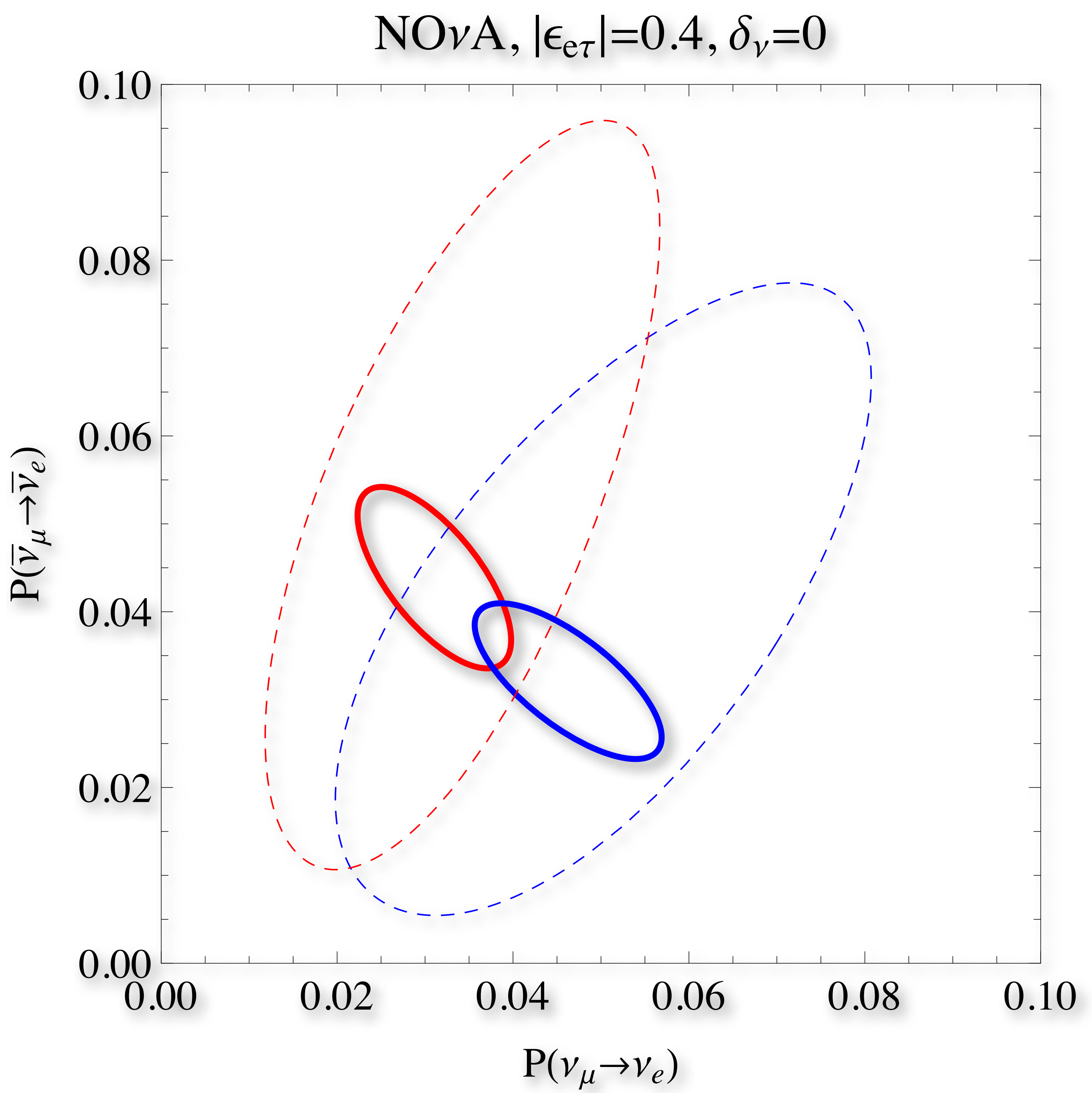
$$\begin{aligned} \Delta \sin 2\theta_{13} &= 0.87 \times 10^{-13} \text{ eV}, \\ \sqrt{2} G_F n_e \cos\theta_{23} &= 0.76 \times 10^{-13} \text{ eV}, \\ \Delta_\odot \sin 2\theta_{12} &= 0.09 \times 10^{-13} \text{ eV}. \end{aligned}$$

- Assuming NSI $\varepsilon_{e\tau}$ ~0.2-0.4, roughly motivated by the solar spectral data, we have

  - Atm > NSI > solar

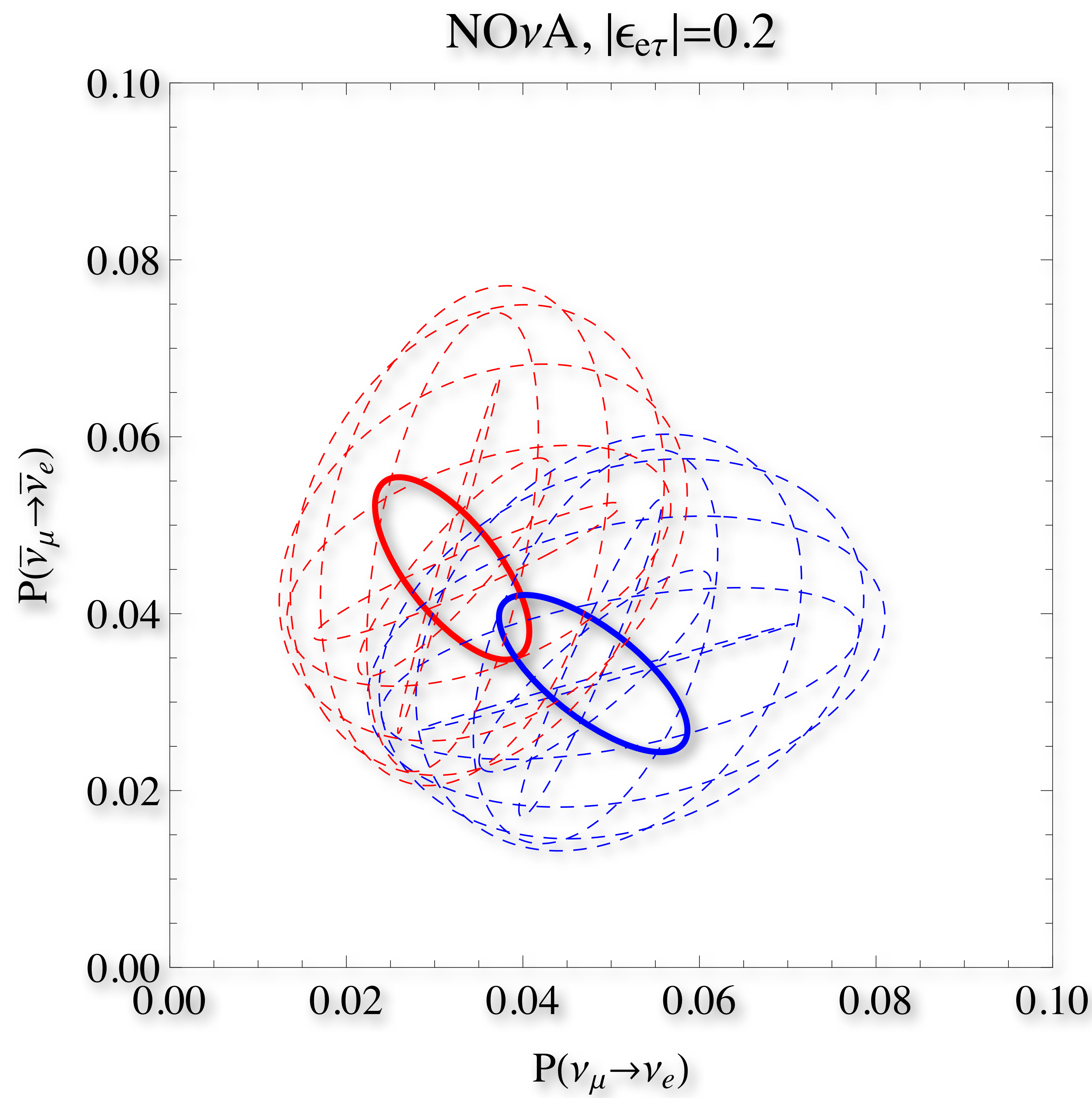
# But what what if there are also NSI?

- Let's take $\varepsilon_{e\tau}$ = +0.4, as in the earlier solar plot

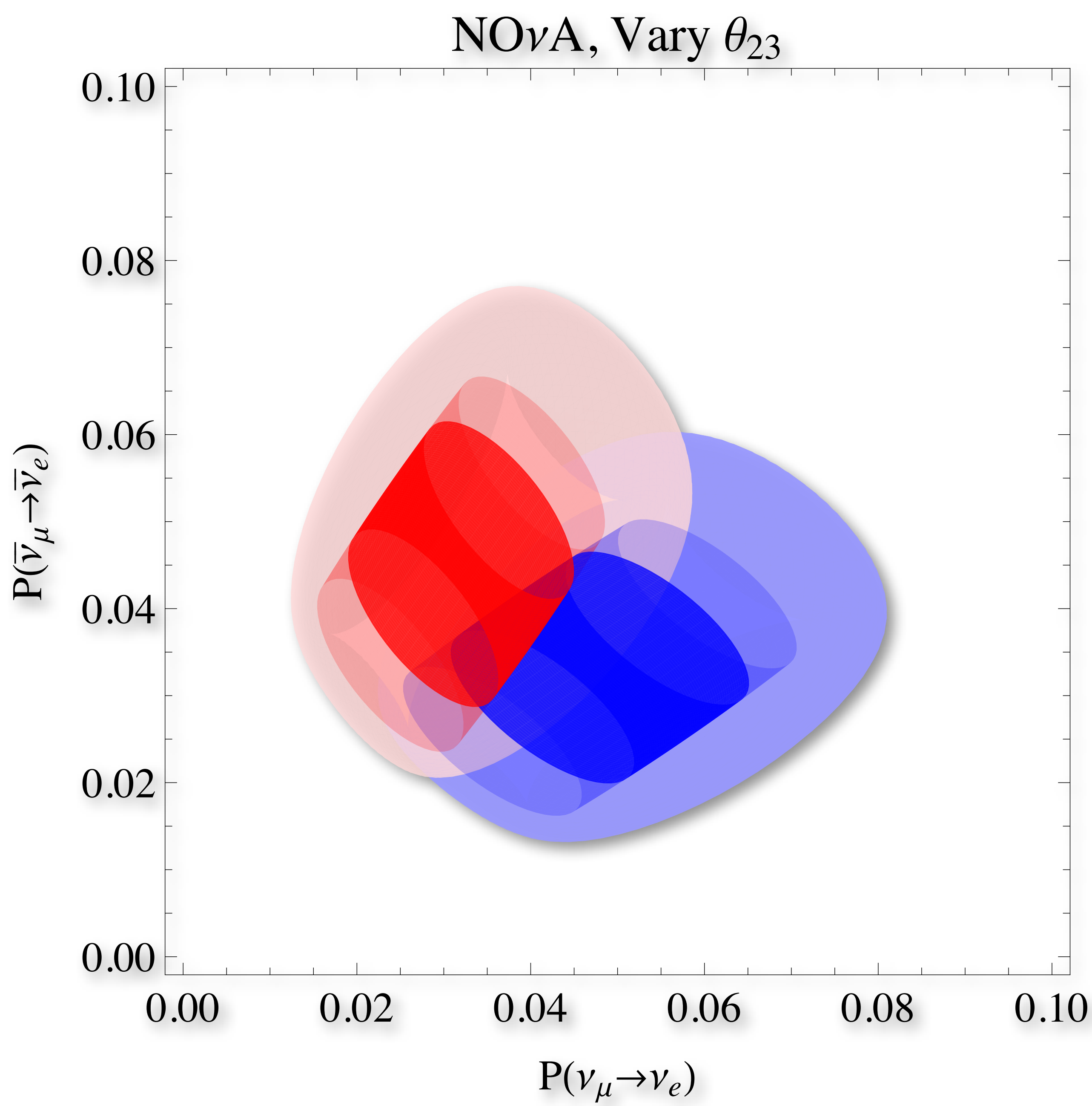


# Next step: vary the NSI phase

- Let's take a different approach: we don't care about solar data, just trying to constrain NSI.
- Take small $|\varepsilon_{e\tau}| \sim 0.2$, vary its phase freely
- The result is big regions in the bi-probability space
- How do you know what is the source of CPV you observed?

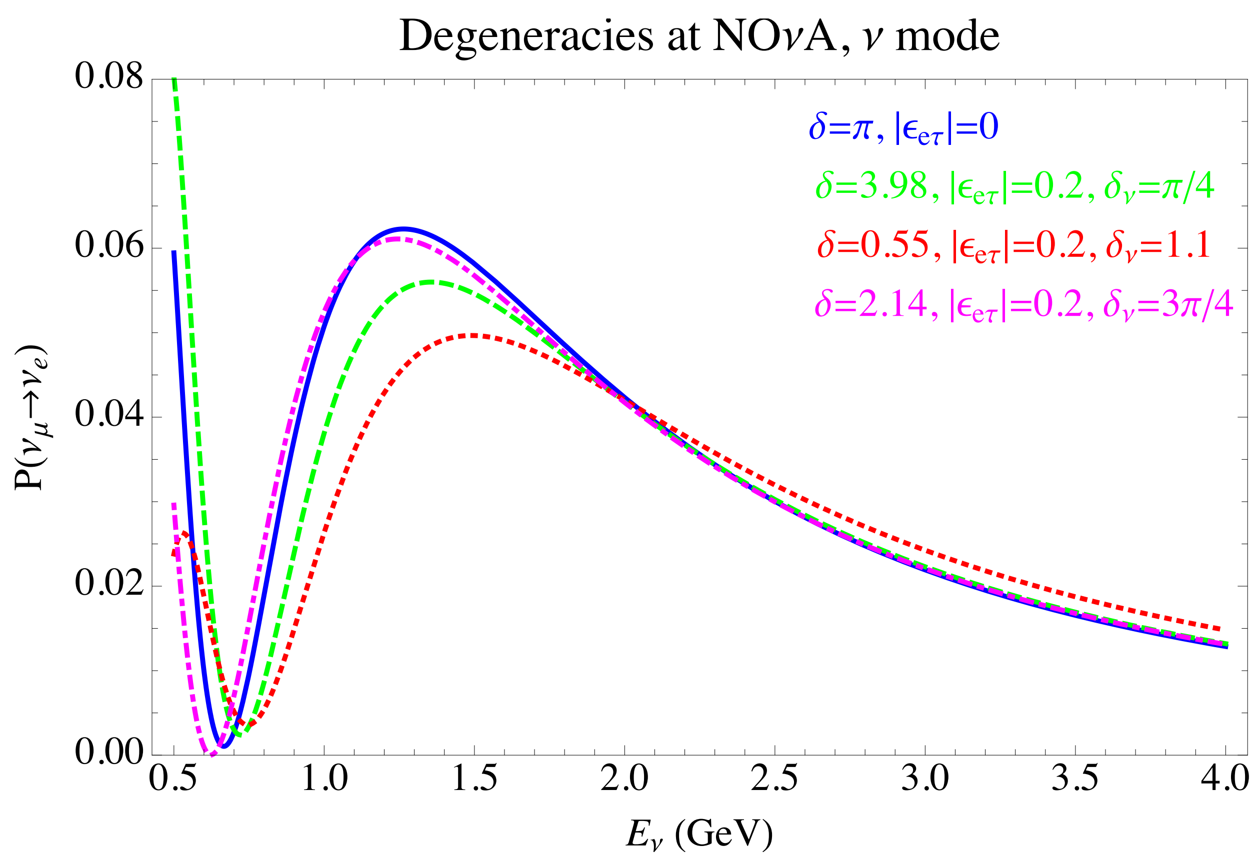


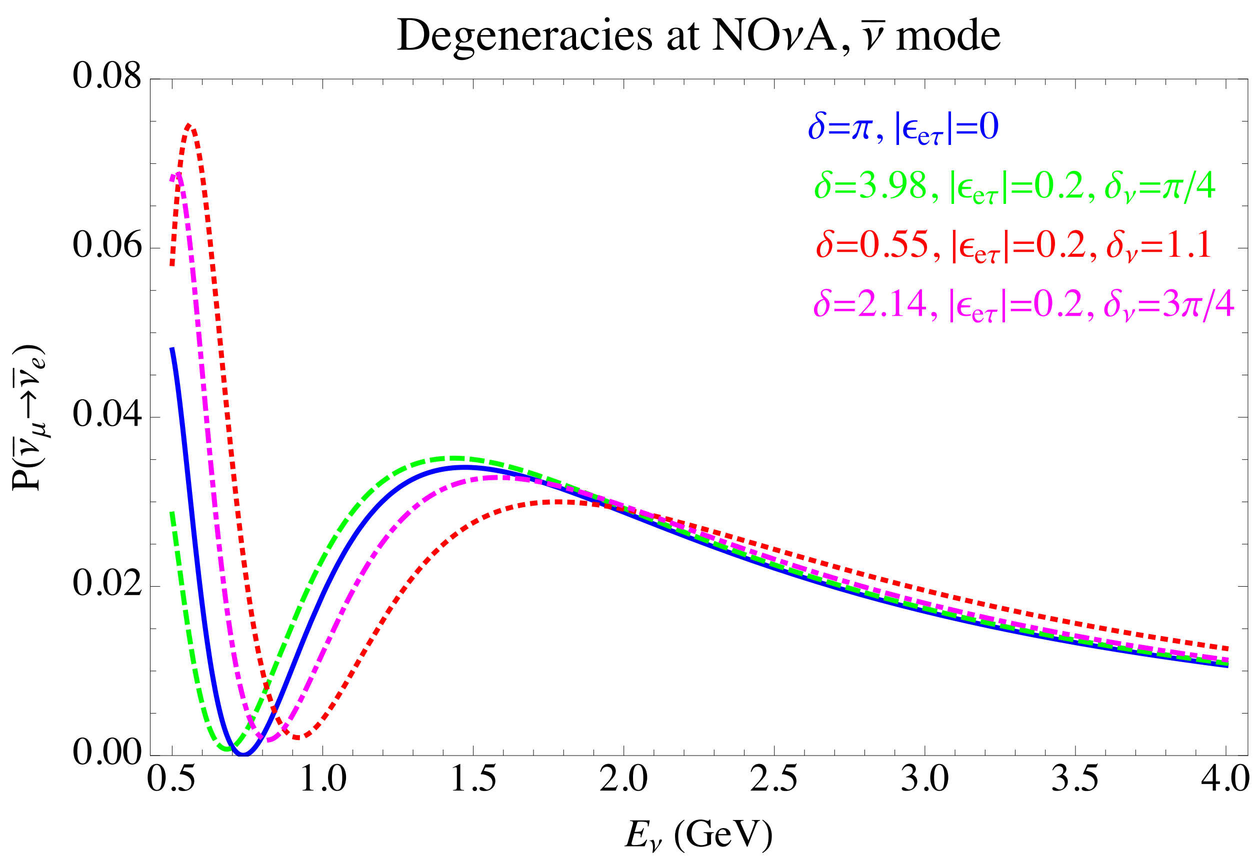
# theta23 confusion: octant measurement?



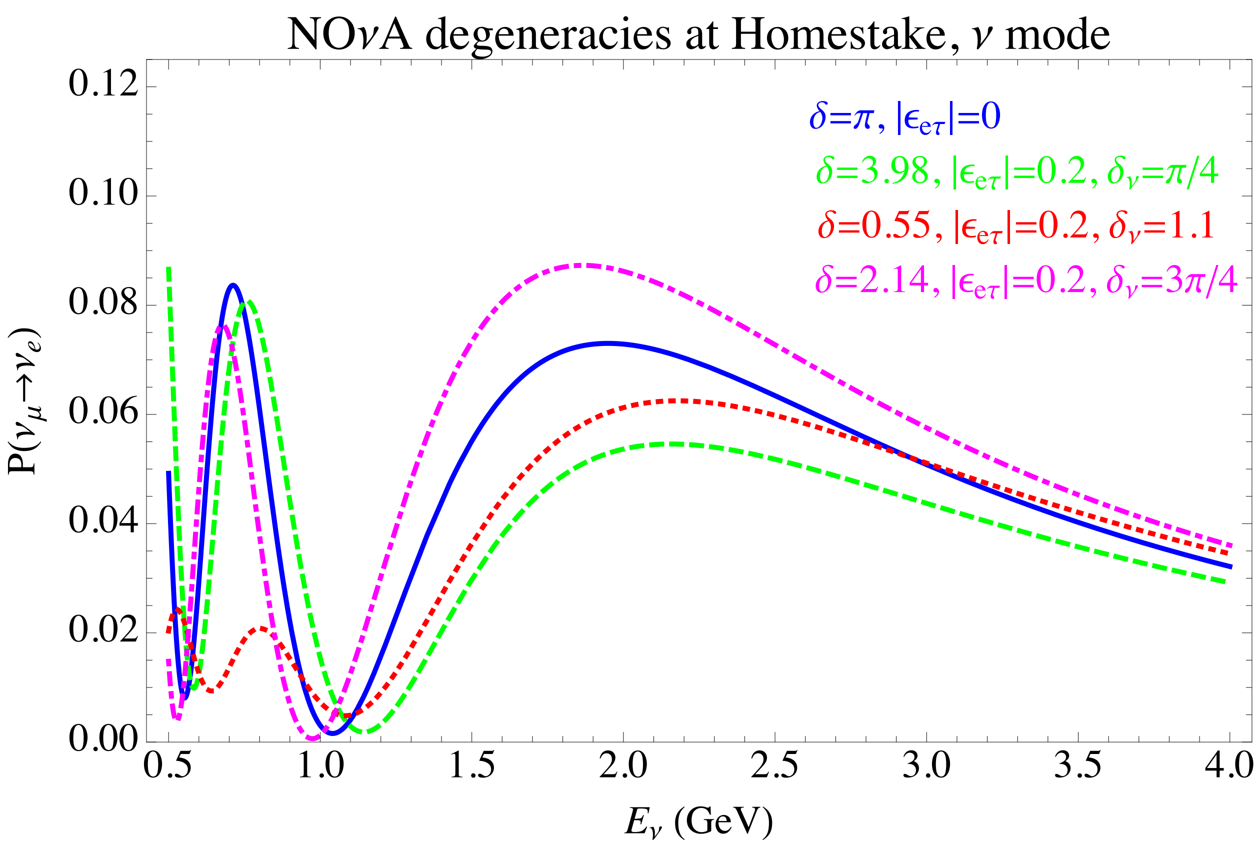

If curious, see A.F., I. Shoemaker, arXiv:1207.6642

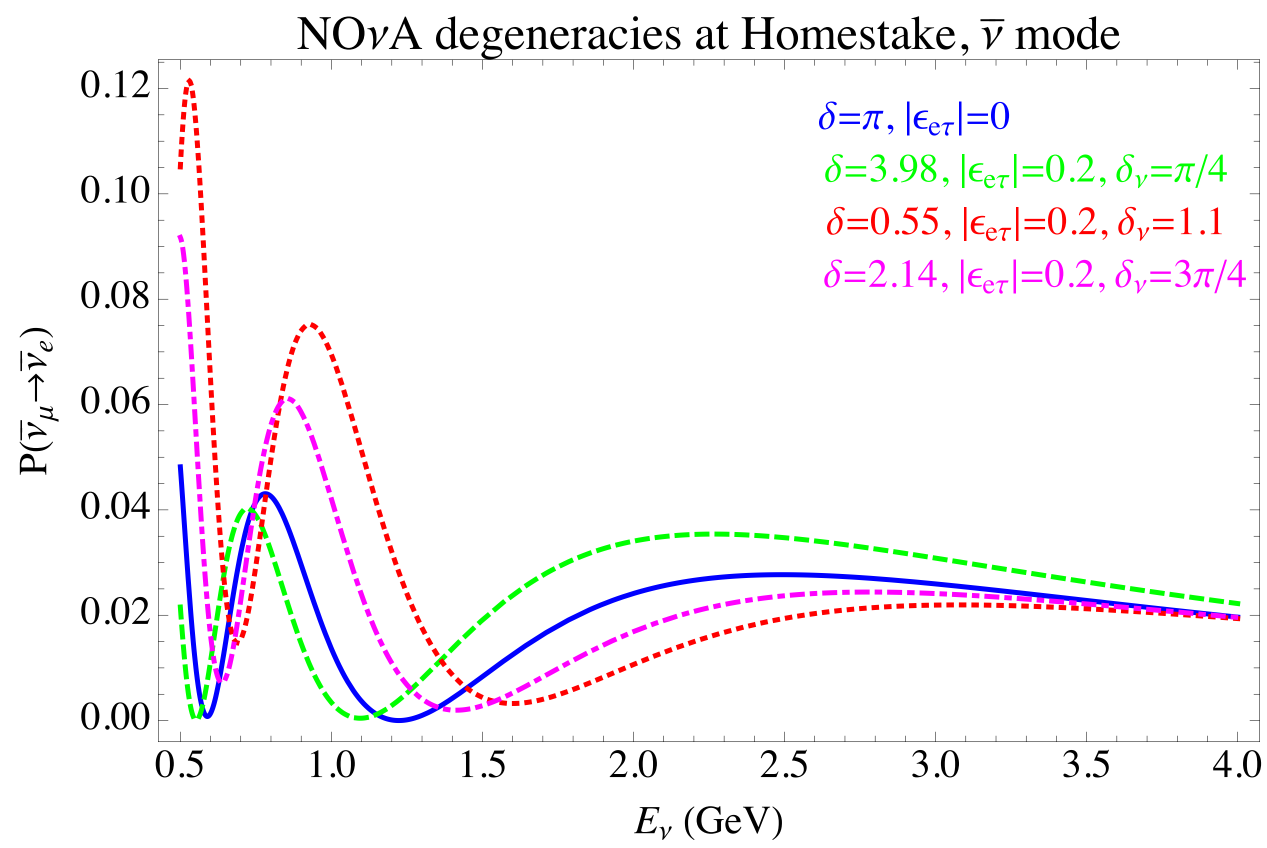
# Degeneracies for point 4



# Solution: go to longer baseline!



# The situation is analogous to the B physics

- The name of the game: do "redundant" / "overconstraining" measurements of processes sensitive to different short-distance physics — if inconsistent $\Rightarrow$ NP

Lincoln Wolfenstein: *'I do not care what the values of the Wolfenstein parameters are, so you should not either; the only question is if their independent determinations give the same results'*

From Zoltan's talk last week

Very much applies here

# Neutrino cosmology

# Cosmology and neutrino mass

Astropart.Phys. 35, 177 (2011)[arXiv:1103.5083]

| Probe | Current $\sum m_\nu$ (eV) | Forecast $\sum m_\nu$ (eV) | Key Systematics | Current Surveys | Future Surveys |
|---|---|---|---|---|---|
| CMB Primordial | 1.3 | 0.6 | Recombination | WMAP, Planck | None |
| CMB Primordial + Distance | 0.58 | 0.35 | Distance measurements | WMAP, Planck | None |
| Lensing of CMB | $\infty$ | 0.2 – 0.05 | NG of Secondary anisotropies | Planck, ACT [39], SPT [96] | EBEX [57], ACTPol, SPTPol, POLARBEAR [5], CMBPol [6] |
| Galaxy Distribution | 0.6 | 0.1 | Nonlinearities, Bias | SDSS [58, 59], BOSS [82] | DES [84], BigBOSS [81], DESpec [85], LSST [92], Subaru PFS [97], HETDEX [35] |
| Lensing of Galaxies | 0.6 | 0.07 | Baryons, NL, Photometric redshifts | CFHT-LS [23], COSMOS [50] | DES [84], Hyper SuprimeCam, LSST [92], Euclid [88], WFIRST[100] |
| Lyman $\alpha$ | 0.2 | 0.1 | Bias, Metals, QSO continuum | SDSS, BOSS, Keck | BigBOSS[81], TMT[99], GMT[89] |
| 21 cm | $\infty$ | 0.1 – 0.006 | Foregrounds, Astrophysical modeling | GBT [11], LOFAR [91], PAPER [53], GMRT [86] | MWA [93], SKA [95], FFTT [49] |
| Galaxy Clusters | 0.3 | 0.1 | Mass Function, Mass Calibration | SDSS, SPT, ACT, XMM [101] Chandra [83] | DES, eRosita [87], LSST |
| Core-Collapse Supernovae | $\infty$ | $\theta_{13} > 0.001^*$ | Emergent $\nu$ spectra | SuperK [98], ICECube[90] | Noble Liquids, Gadzooks [7] |

# Neutrino mass in cosmology 101

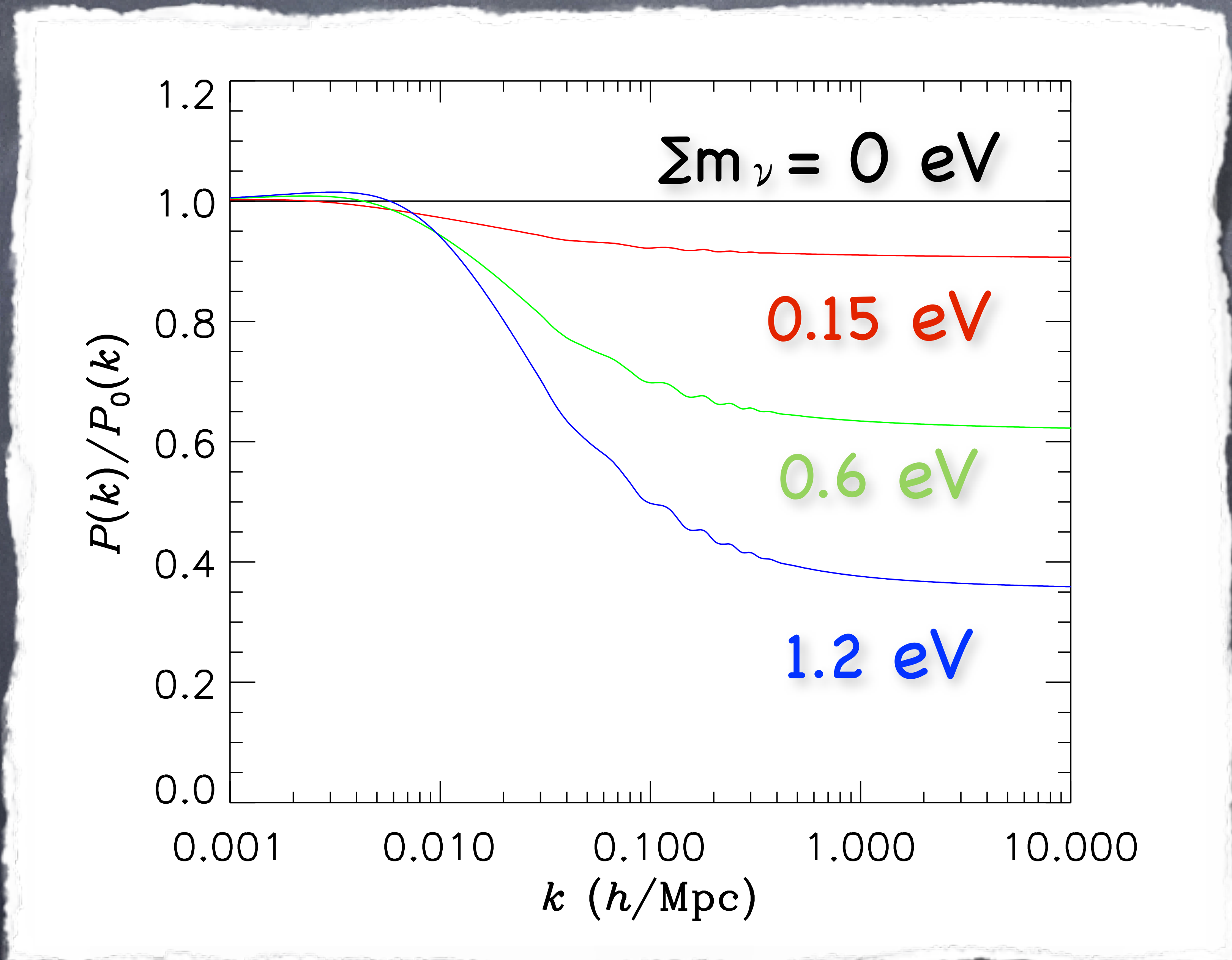
- Relativistic neutrinos stream out of density perturbations
- This stops when neutrinos become nonrelativistic, as T drops below the neutrino mass
- CMB decoupling $T_{CMB}$ ~ 1/4 eV. For $\Sigma m_\nu > T_{CMB}$ the neutrino masses can have an imprint on the primary CMB anisotropies
  - linear physics!
- For smaller masses, impact on structure growth
  - which can be observed in how structure lenses CMB

# Structure growth

- In matter dominated universe, in the linear regime, comoving density perturbations grow as the scale factor
- When some of the matter can free-stream out of overdense regions, the growth rate slows
  - Growth rate relative to expansion also slows if other components become important, e.g. cosmological constant
  - Looking for scale-dependent signature

# Neutrinos and matter power spectrum

Fig from Hannestad, arXiv: 1007.0658




Scale-dependent effect

In linear regime, $\Delta P/P \sim -8f_\nu$,

where $f_\nu = \Omega_\nu/\Omega m \simeq 0.08\,(\Sigma m_\nu/\mathrm{eV})$

# How to identify lensing effect?

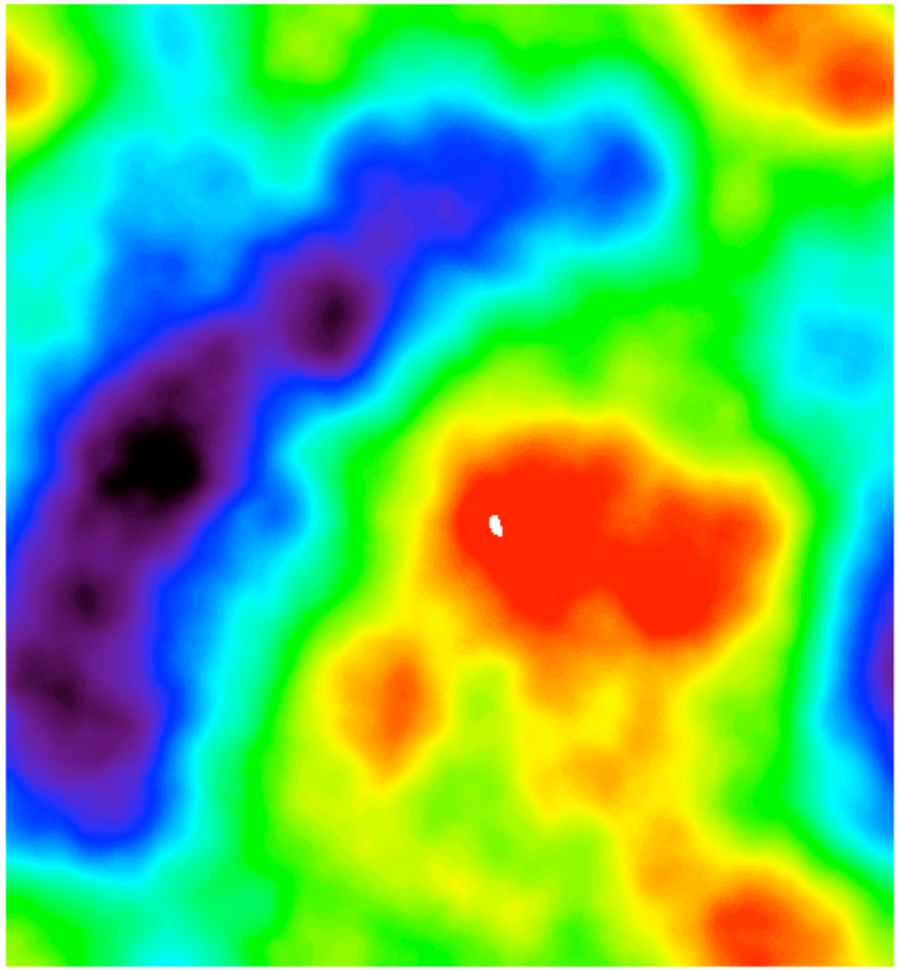
- Structures doing lensing are large, degree-size (max corresponds to $l \sim 40$)
- But the lensing deflection angles are small
- Need high angular resolution
  - search for coherent patterns of deflection

# Sensing in action

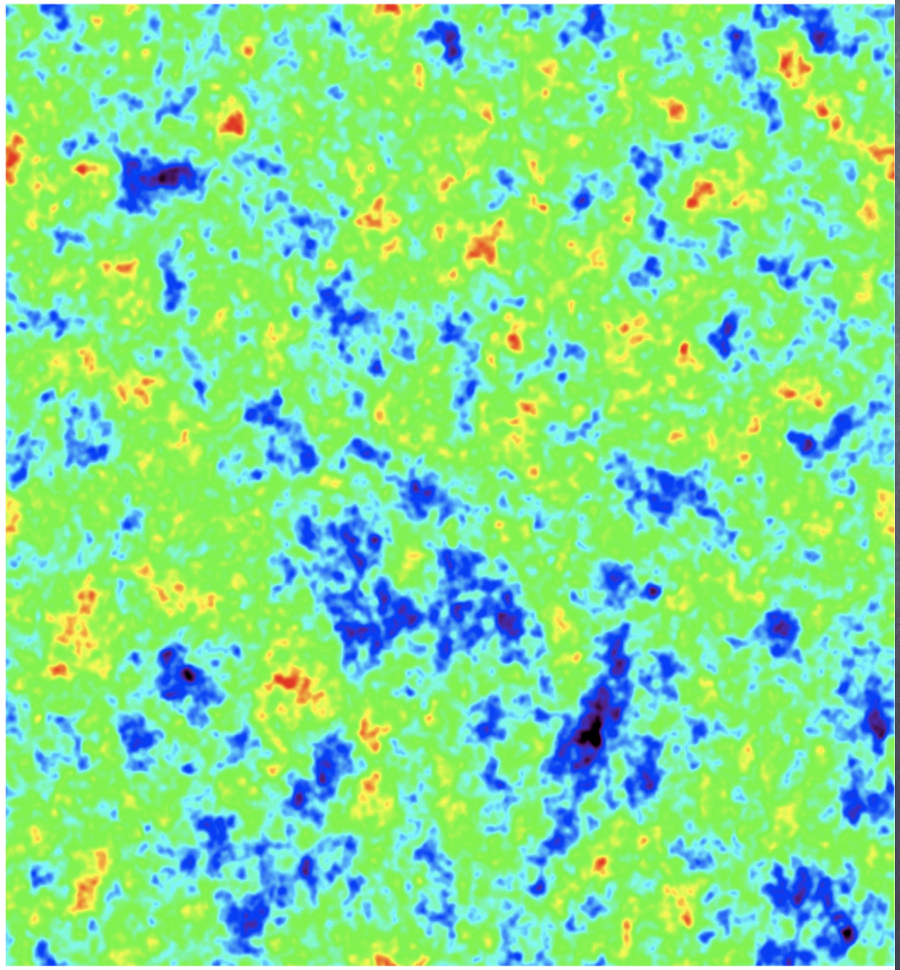
Thanks to Gil Holder

## Lensing of the CMB

17°x17°



lensing potential



unlensed cmb

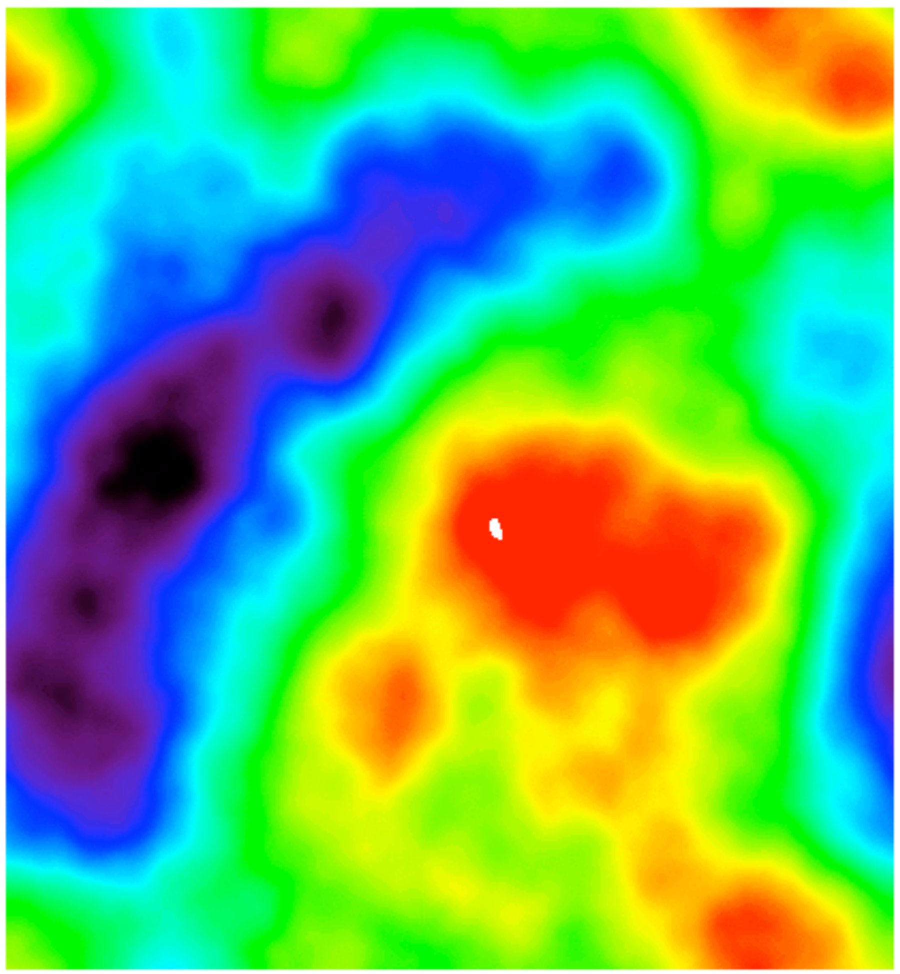
*from Alex van Engelen*

# Sensing in action

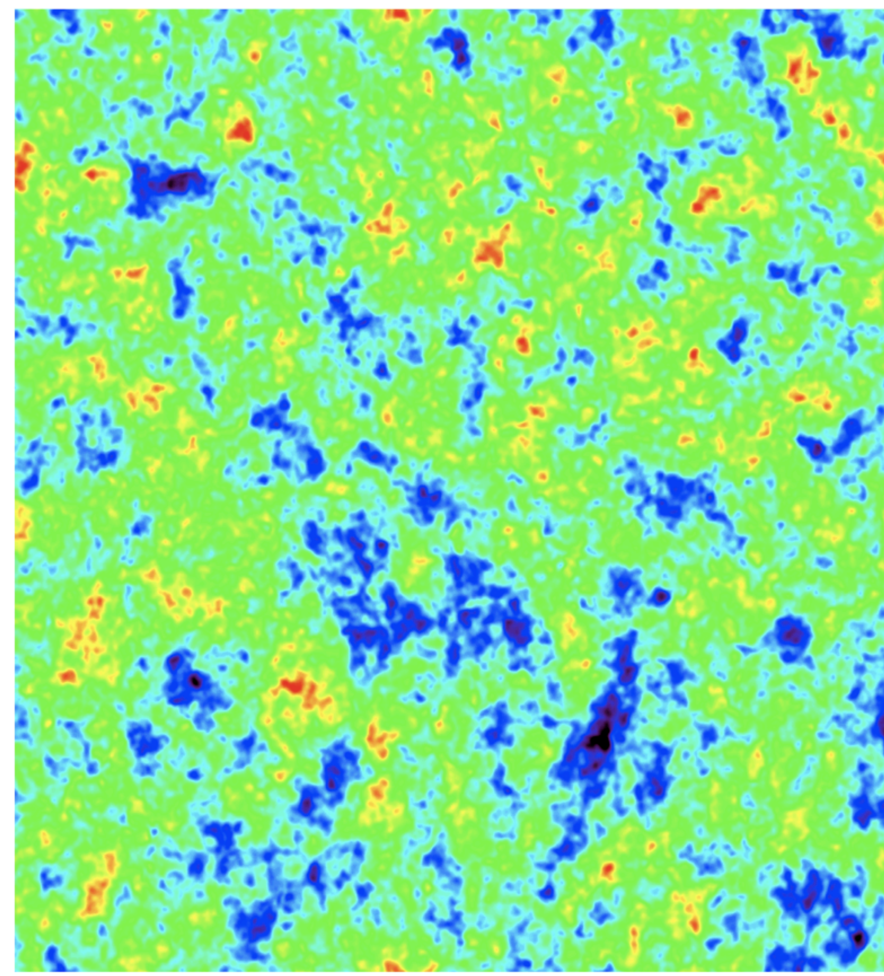
Thanks to Gil Holder

## Lensing of the CMB

17°x17°



lensing potential



lensed cmb

*from Alex van Engelen*

# Polarization

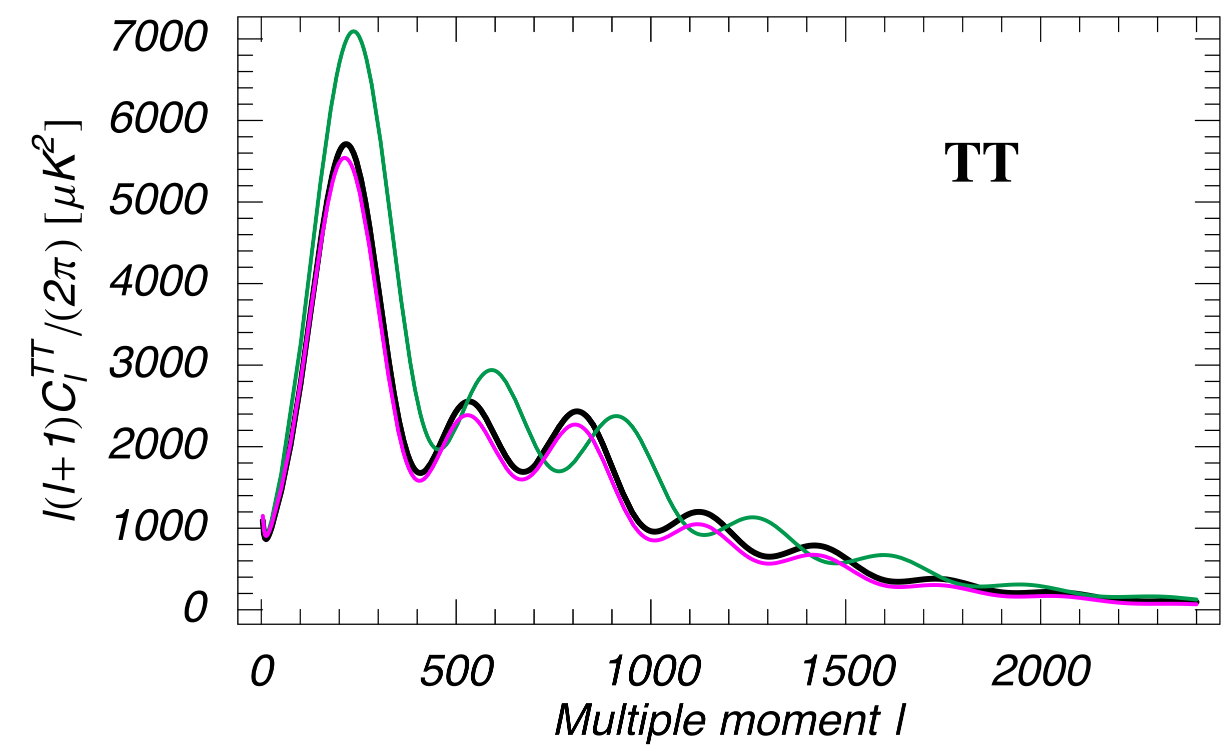
- Polarization is expected to provide a dramatic signature of lensing
  - Polarization field can be decomposed into E and B modes
  - B modes are not expected in the primary CMB (not generated by scalar perturbations) $\rightarrow$ added by lensing
- I expect this to be addressed in the cosmology talks later this week

# $N_{eff}$

- Another important development is counting of neutrino-like species in the early universe by modern CMB experiments
- Both free-streaming and coupled d.o.f. can be constrained
- Very valuable for looking for new neutrino-like particles

# Name of the game: degeneracies

- In addition to the numbers of neutrino-like species, there are numerous other cosmological parameters
- Example here: readjusting the Hubble constant to keep $z_{eq}$ constant cancels most of the effect of having 7 streaming neutrinos



# Effect on perturbations

- Streaming of neutrinos out of density perturbations dumps their amplitude

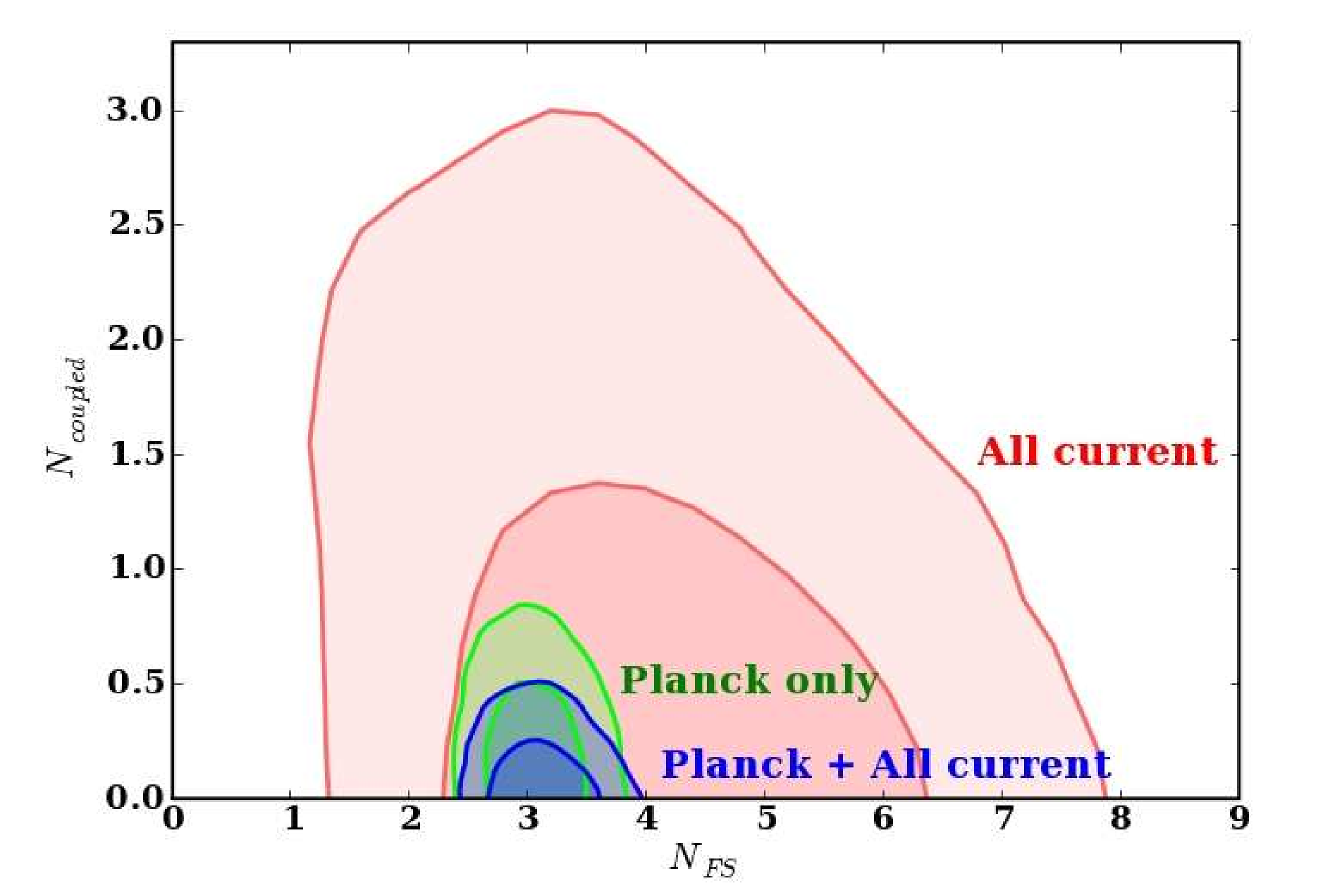
$$\boxed{\delta C_\ell / C_\ell \approx -0.53\, \rho_{FS}/\rho_{rad},}$$

- And shifts their phase

$$\boxed{\delta \ell \approx -57\, \rho_{FS}/\rho_{rad}.}$$

# $N_{eff}$

- The analysis is numerical, MCMC maps out the 10 dim parameter space, catching the degeneracies

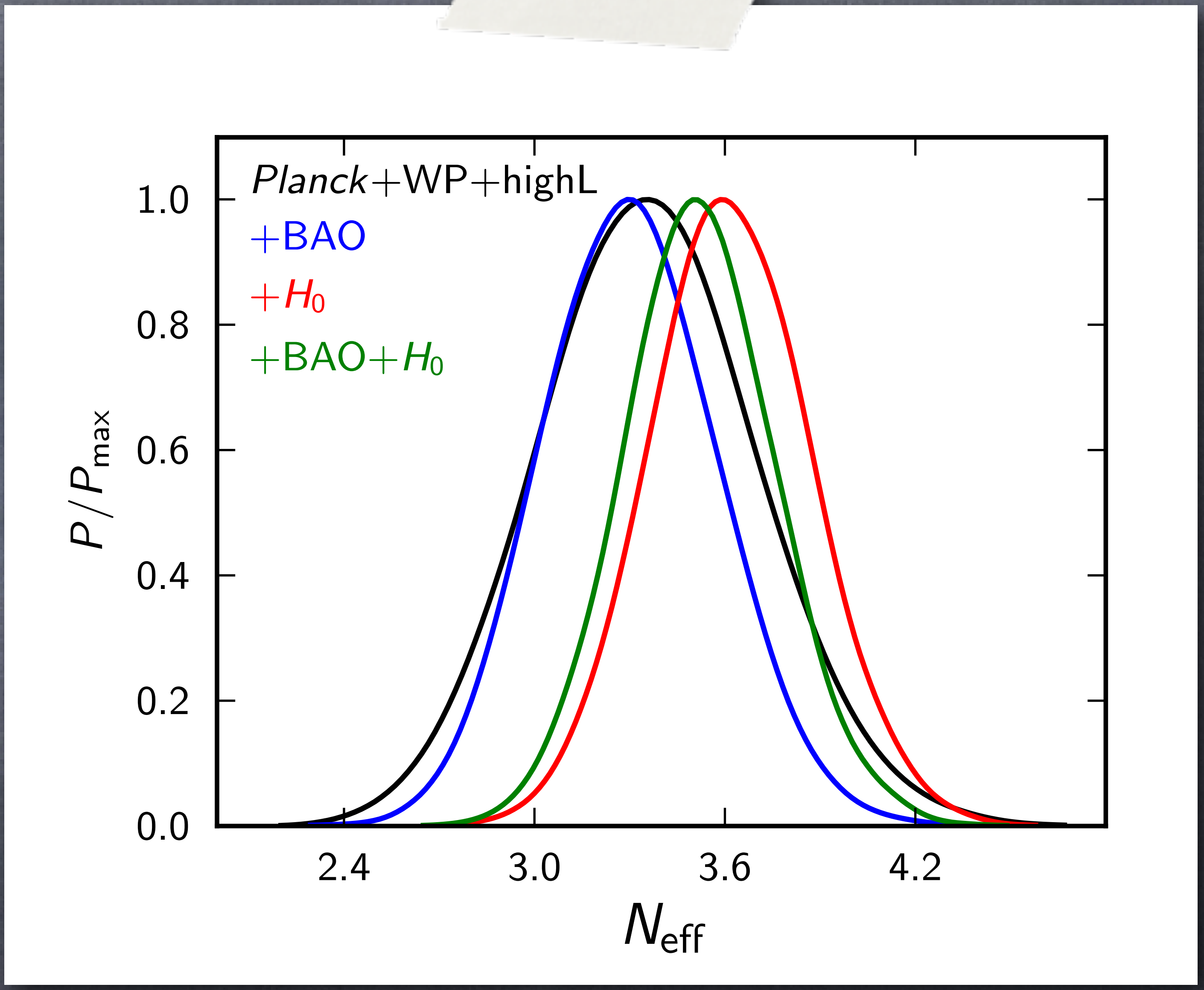



forecast, circa 2007

A.F., K. Zurek, S. Bashinsky, arXiv:0704.3271

# Planck, March 2013

- Using CMB + BAO:
  - Neff=3.3±0.27
  - $\sum m_\nu$<0.23 eV



# Commercial break

Los Alamos
NATIONAL LABORATORY

**Santa Fe Summer Workshop**

**Implications of Neutrino Flavor Oscillations**

**INFO 13**

**August 26 - 30, 2013**

Neutrinos, dark matter, etc

Students and postdocs are generously subsidized

http://public.lanl.gov/friedland/info13/info13.html

# Stellar cooling

# Stars 101

- Stars are blobs of gas held together by gravity
- The gravity must be counteracted by pressure, thermal and/or electron degeneracy
  - If degeneracy, the object can just sit there ...
    - ... unless the mass of the degenerate core reaches a certain threshold, ~ 1.4 $M_{\odot}$ (see later)

# Energy generation and escape

- If pressure is thermal, the interior must be hot

$$\frac{3}{2}kT \sim \frac{1}{2}\frac{GM_* m_p}{R_*} \rightarrow T_\odot \sim 10^7 K$$

- Energy escapes through the surface as photons or through the volume as neutrinos; without sources of energy the Sun would cool

Kelvin, Helmholtz, 19th century

$$U_\odot \sim \frac{1}{2}\frac{GM_\odot^2}{R_\odot} \sim 10^{48}\mathrm{erg} \rightarrow \frac{U_\odot}{L_\odot} \sim \frac{10^{48}\mathrm{erg}}{10^{33}\mathrm{erg/s}} \sim 10^7\mathrm{yr}$$

- Need internal sources of energy, to compensate for energy lost

Eddington, Gamow, Bethe ...

  - Nuclear reactions, H -> He ->C,O ->...
  - **Loss rate determines the burning (evolution!) rate**

# Stellar evolution: opacity and lifetime

- If energy is lost through photons, the luminosity is given by

$$\mathcal{L}_r = -\frac{4\pi r^2}{3\kappa\rho}\frac{d(aT^4)}{dr}$$ where the opacity $$\kappa^{-1} = \kappa_\gamma^{-1} + \kappa_e^{-1} + \kappa_x^{-1}$$

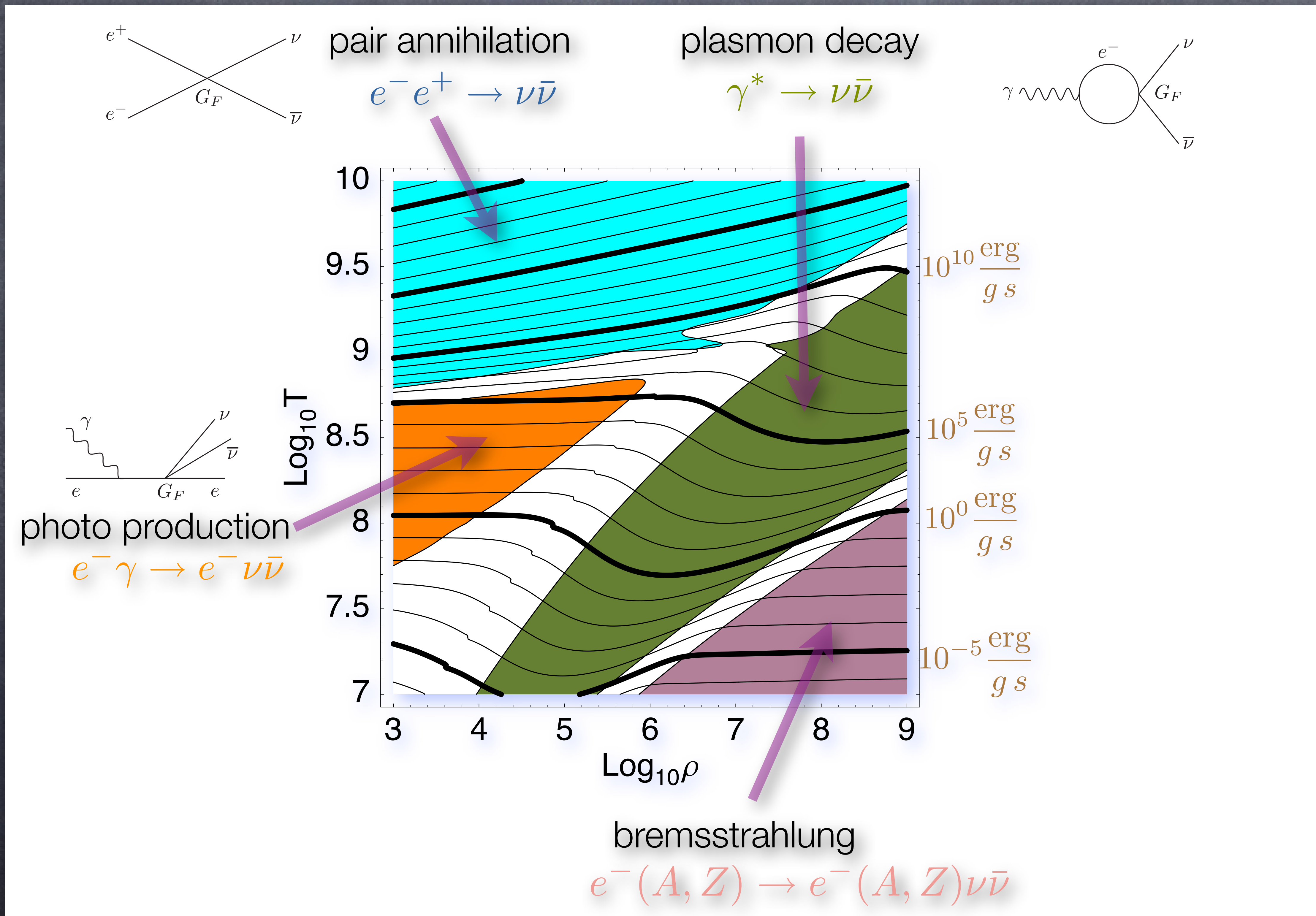
  - More massive stars are hotter inside, burn faster, have shorter lives

$$\mathcal{L}_* \sim \frac{R_*^2}{\kappa M_*/R_*^3}\frac{a(GM_* m_p/R_* k)^4}{R_*} \propto M_*^3$$

  - If a novel particle x is trapped in a star, the smaller the opacity $k_x$, the more important it is for cooling

  - If x is free-streaming, compute production through the volume (e.g., neutrinos, except in SN)

# Standard neutrino cooling



# Hermetic detector!

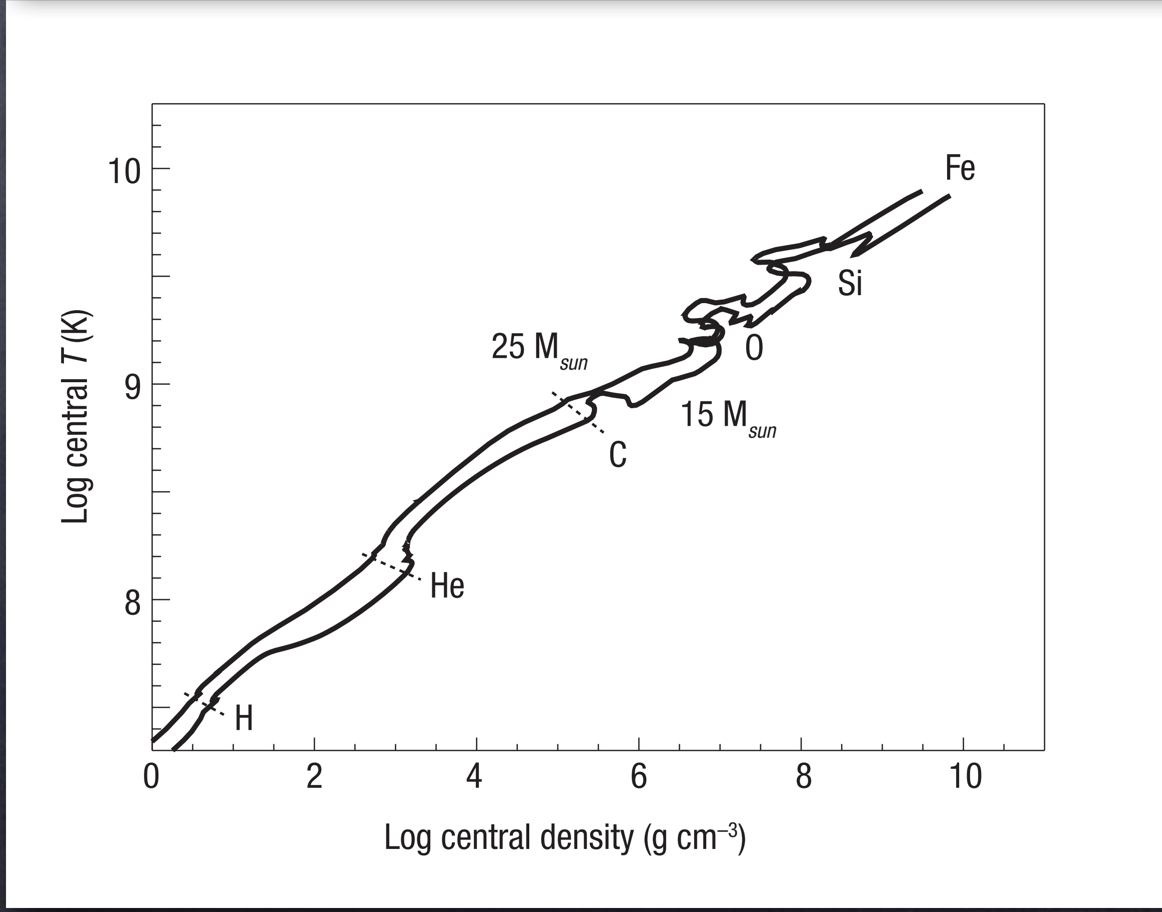
- The branching ratio for $e^+e^-$ -> neutrino pair is
  - ~ $10^{-18}$ for ~ 1 MeV energies
  - The main annihilation mode is $e^+e^- \to \gamma\ \gamma$
- Plasmon decay $\gamma$ -> neutrino pair probability between collisions is ~ $10^{-26}$
- Yet, neutrino energy losses are known to be crucial for stellar evolution

# Example: Massive stars

**Table 1 Evolution of a 15-solar-mass star.**

| Stage | Timescale | Fuel or product | Ash or product | Temperature ($10^9$ K) | Density (gm cm$^{-3}$) | Luminosity (solar units) | Neutrino losses (solar units) |
|---|---|---|---|---|---|---|---|
| Hydrogen | 11 Myr | H | He | 0.035 | 5.8 | 28,000 | 1,800 |
| Helium | 2.0 Myr | He | C, O | 0.18 | 1,390 | 44,000 | 1,900 |
| Carbon | 2000 yr | C | Ne, Mg | 0.81 | $2.8 \times 10^5$ | 72,000 | $3.7 \times 10^5$ |
| Neon | 0.7 yr | Ne | O, Mg | 1.6 | $1.2 \times 10^7$ | 75,000 | $1.4 \times 10^8$ |
| Oxygen | 2.6 yr | O, Mg | Si, S, Ar, Ca | 1.9 | $8.8 \times 10^6$ | 75,000 | $9.1 \times 10^8$ |
| Silicon | 18 d | Si, S, Ar, Ca | Fe, Ni, Cr, Ti, . . . | 3.3 | $4.8 \times 10^7$ | 75,000 | $1.3 \times 10^{11}$ |
| Iron core collapse* | $\sim$1 s | Fe, Ni, Cr, Ti, . . . | Neutron star | $>7.1$ | $>7.3 \times 10^9$ | 75,000 | $>3.6 \times 10^{15}$ |

* The pre-supernova star is defined by the time at which the contraction speed anywhere in the iron core reaches 1,000 km s$^{-1}$.



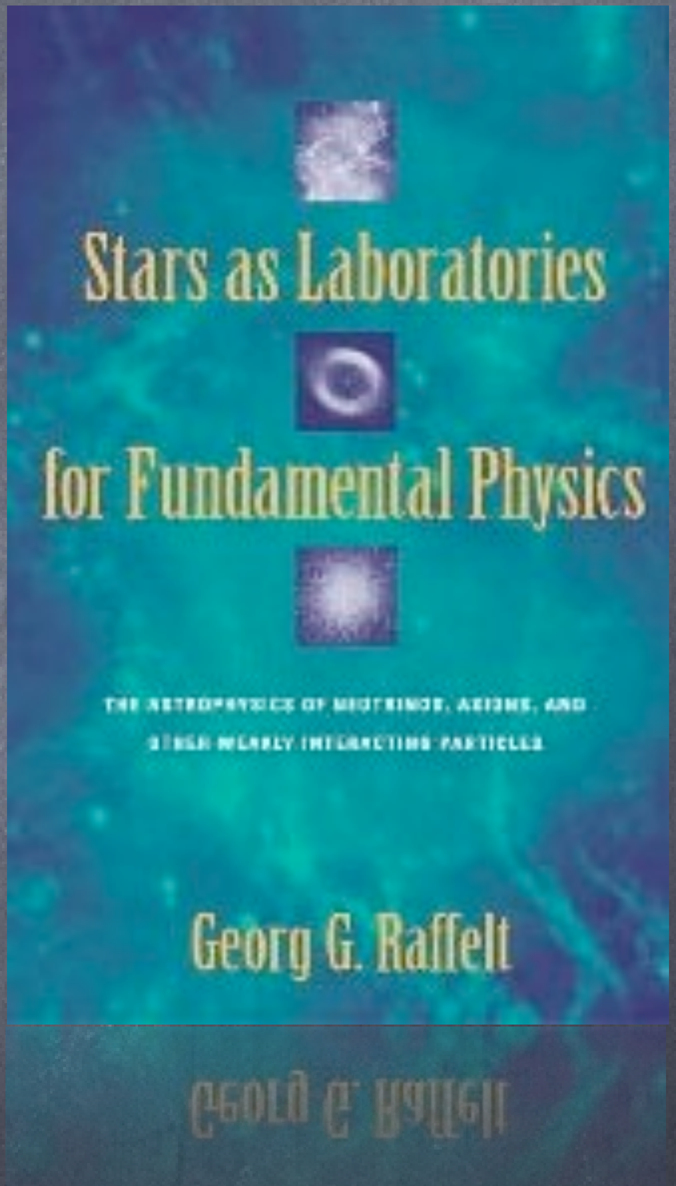

Woosley, Janka, Nature Physics V. 1, p. 147 (2005)

New physics losses cannot drastically exceed standard rates

# Old subject!

- Neutrino properties:
  - Bernstein, Ruderman, and Feinberg, Phys.Rev. 132, 1227 (1963).
  - Sutherland, Ng, Flowers, Ruderman, and Inman, Phys.Rev. D13, 2700 (1976).
  - Dicus and Kolb, Phys.Rev. D15, 977 (1977).
  - ...
- New physics
  - K. Sato and H. Sato, Prog.Theor.Phys. 54, 1564 (1975)
  - Dicus, Kolb, Teplitz, and Wagoner, Phys.Rev. D18, 1829 (1978).
  - Georgi, Glashow, and Nussinov, Nucl.Phys. B193, 297 (1981).
  - Fukugita and Sakai, Phys.Lett. B114, 23 (1982).
  - ....

A great reference is a book by Georg Raffelt




See also, Phys.Rept. 198, 1 (1990)

and

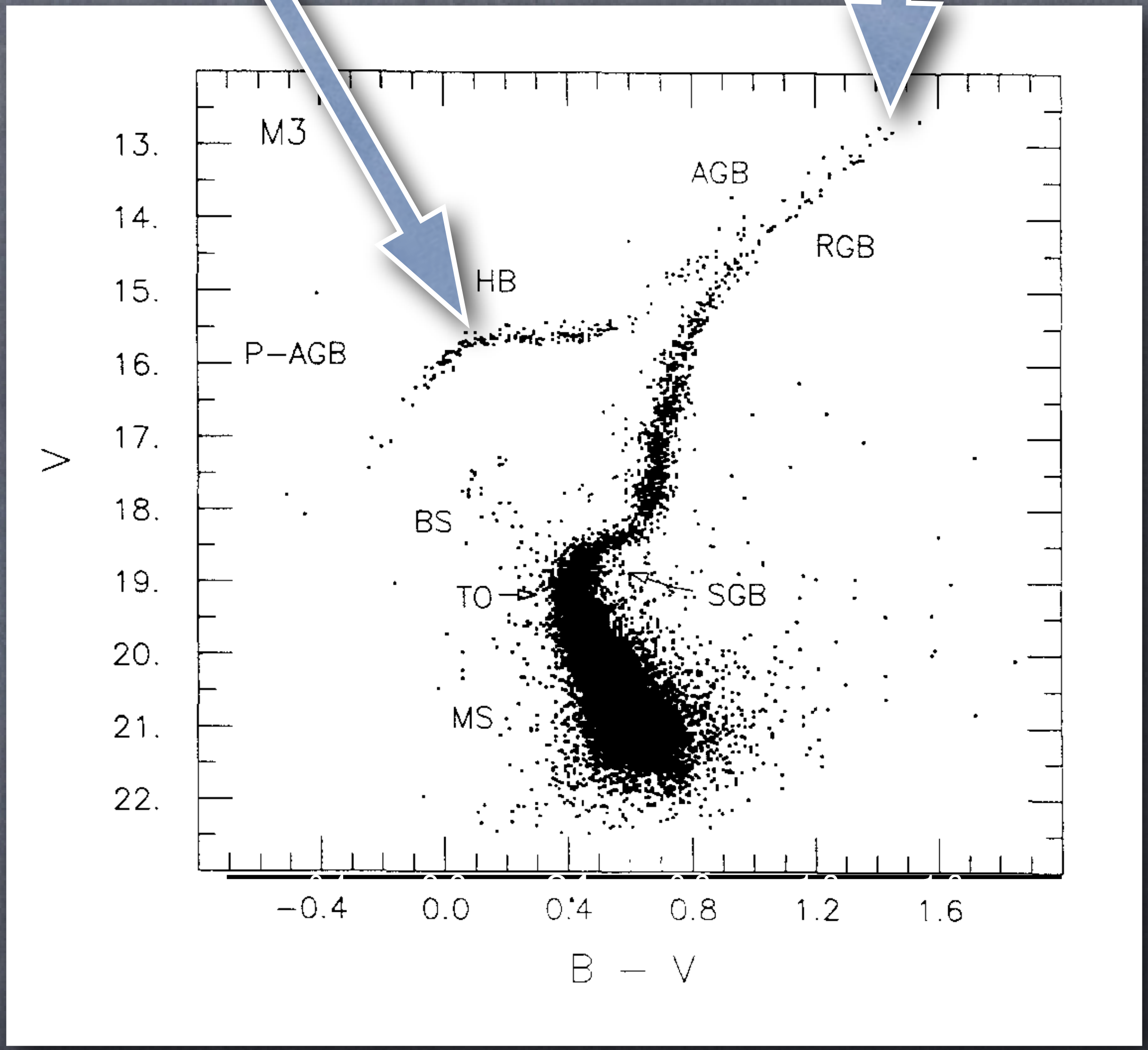
PDG (2012)

$\nu$ magnetic moment

Axion-photon

Known bounds come from low-mass stars:

- Red Giants before He flash
- ✓ New cooling cannot exceed standard neutrino cooling
- Horizontal branch stars




Larger losses (due to emission of novel weakly interacting particles) require more burning (shorter HB stage) or else greater core size before He flash

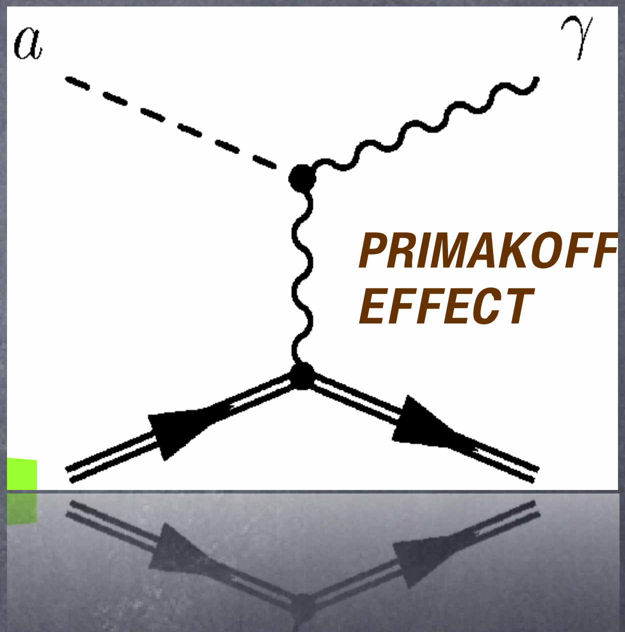
In stellar cooling, axions are also neutrinos!

# CAST axion telescope

- LHC dipole magnet, mounted to point at the Sun

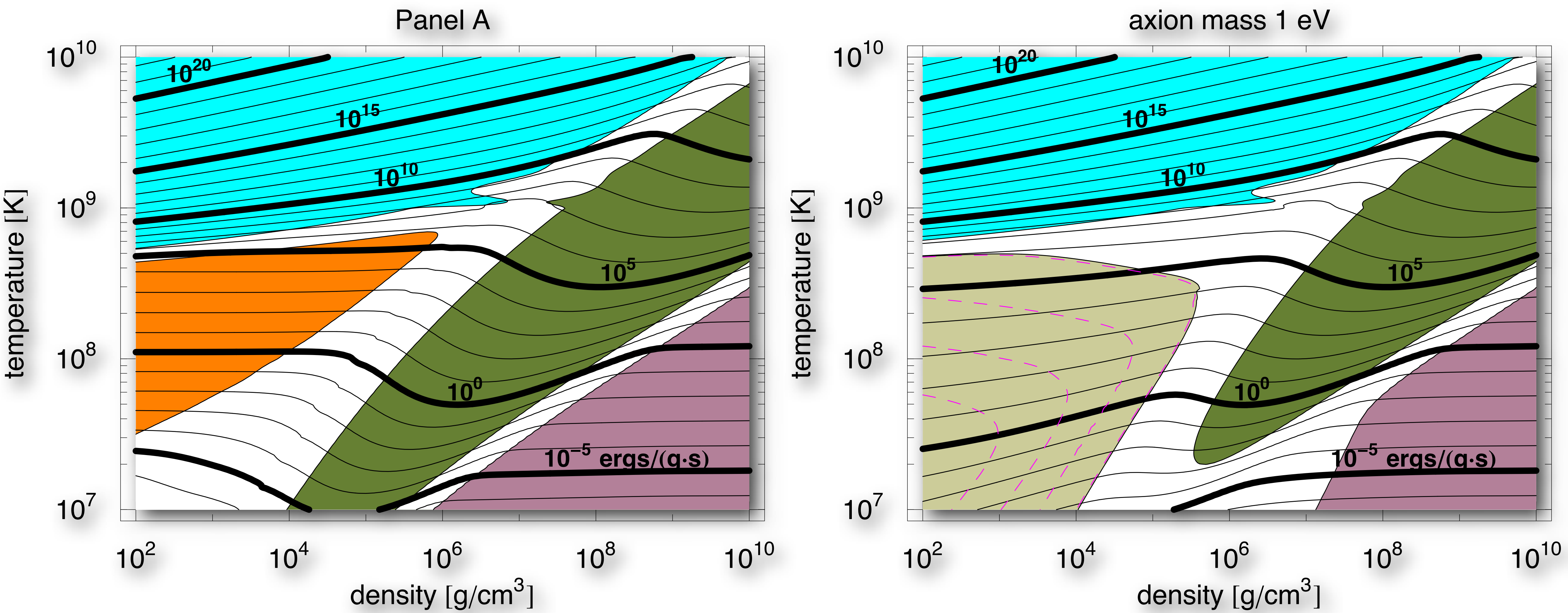
# Primakoff process

- In stars, photons would convert into axions in the background fields of nuclei
- Soft process, regulated by plasma screening (Raffelt 1986)



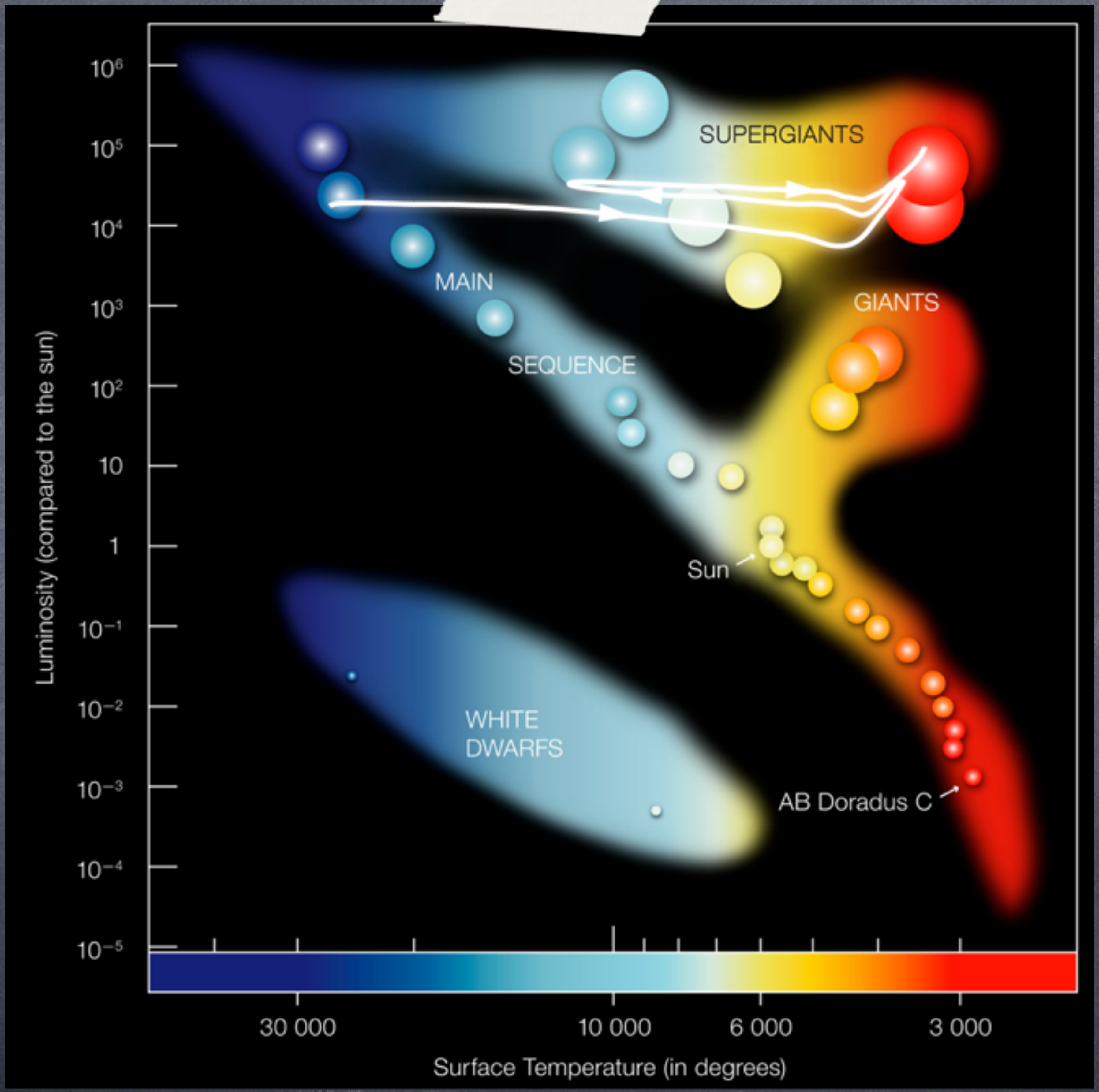

$$\epsilon_A = Z(\xi^2)\frac{G^2_{A\gamma\gamma}}{4\pi^2}\frac{T^7}{\rho} = 27.2\frac{\mathrm{erg}}{\mathrm{g}\cdot\mathrm{s}}Z(\xi^2)g^2_{10}T^7_8\rho_3^{-1},$$

# Add axion-photon coupling



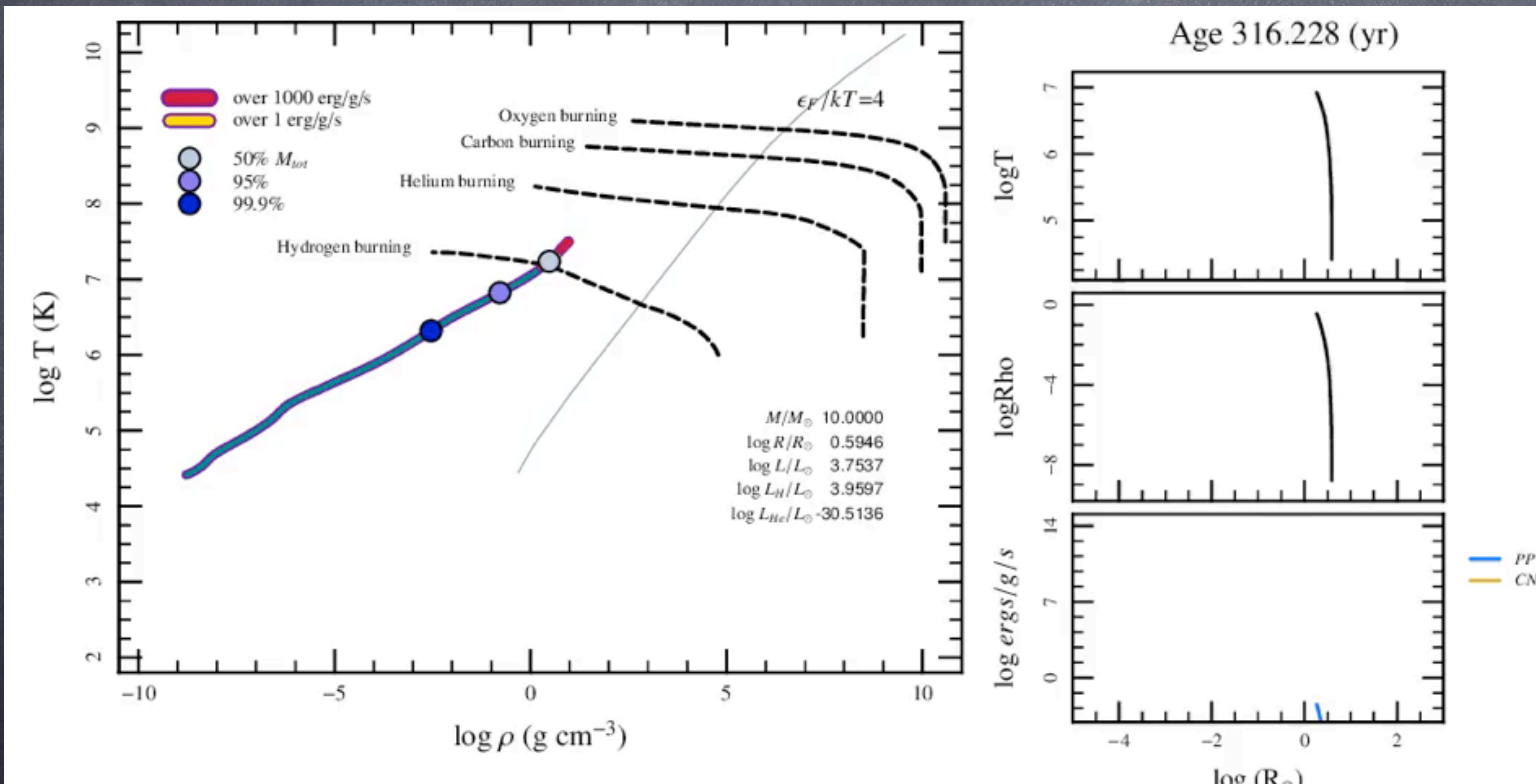

Standard cooling

Good stage to probe is He burning




http://physics.aps.org/articles/large_image/f1/10.1103/Physics.6.14

# Evolution through blue loop

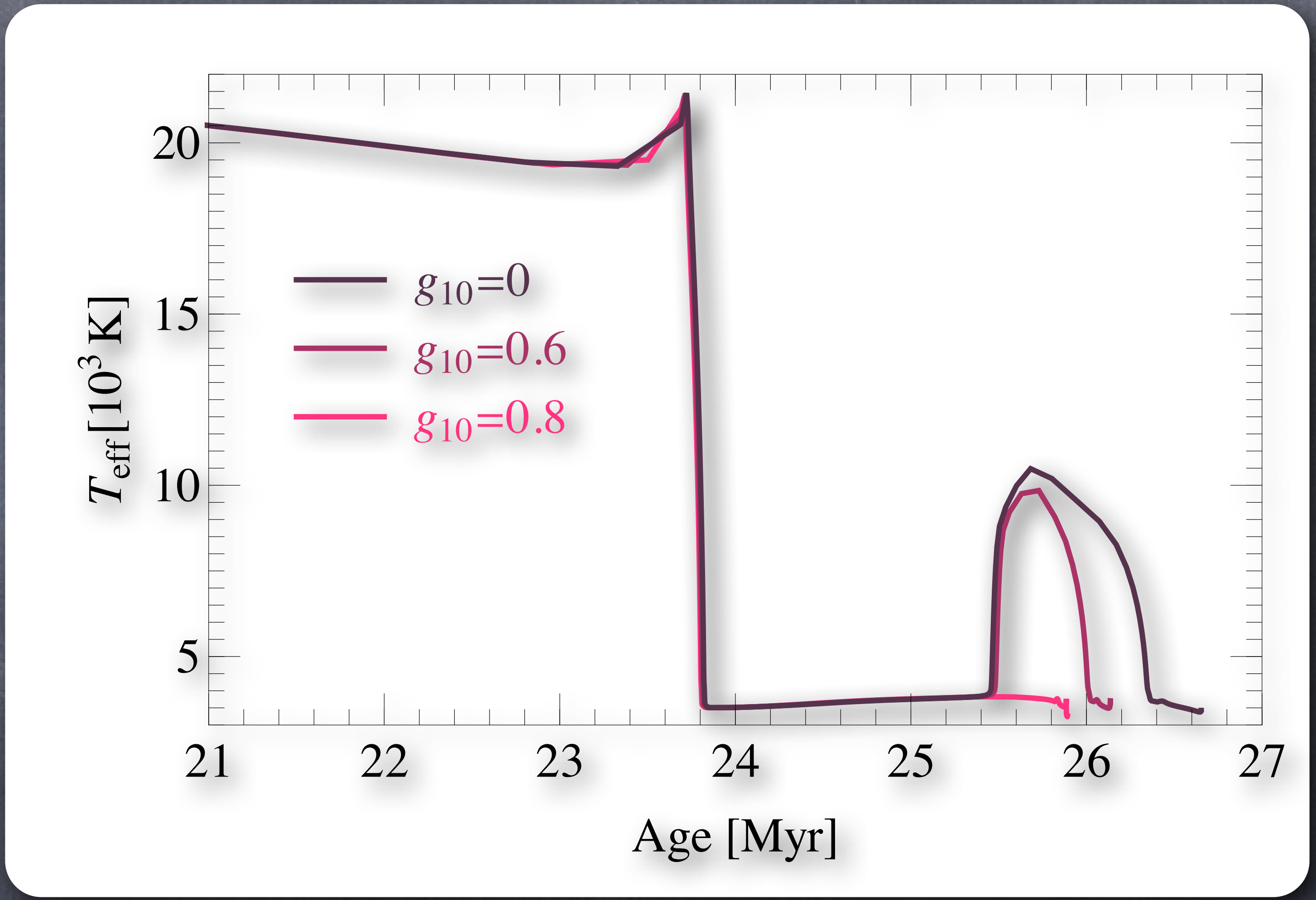


# MESA code

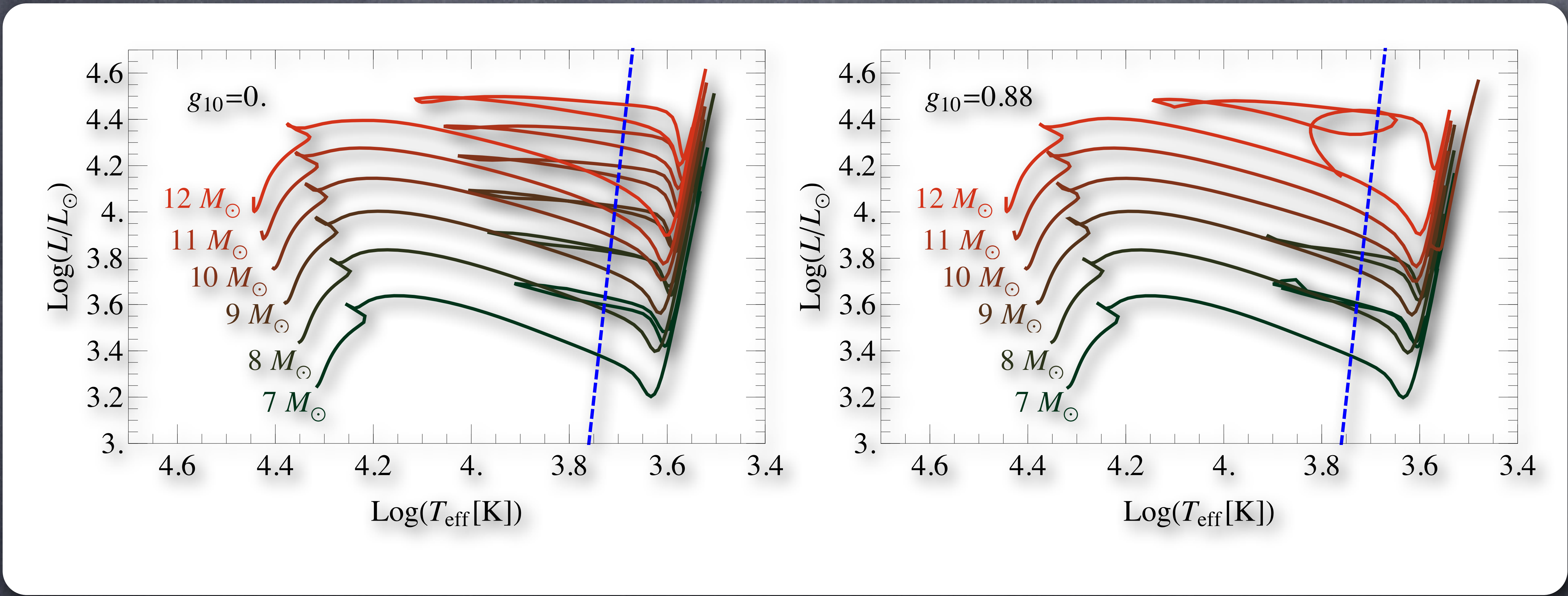
- Excellent stellar evolution code
- Publicly available
  - http://mesa.sourceforge.net
- We added axion cooling and looked at the evolution of massive stars
- Only 4 years later, we have a paper out ;-)

# Surface temperature, with axion cooling

- Axion cooling accelerates He burning in the center, so that the time for the blue loop never comes



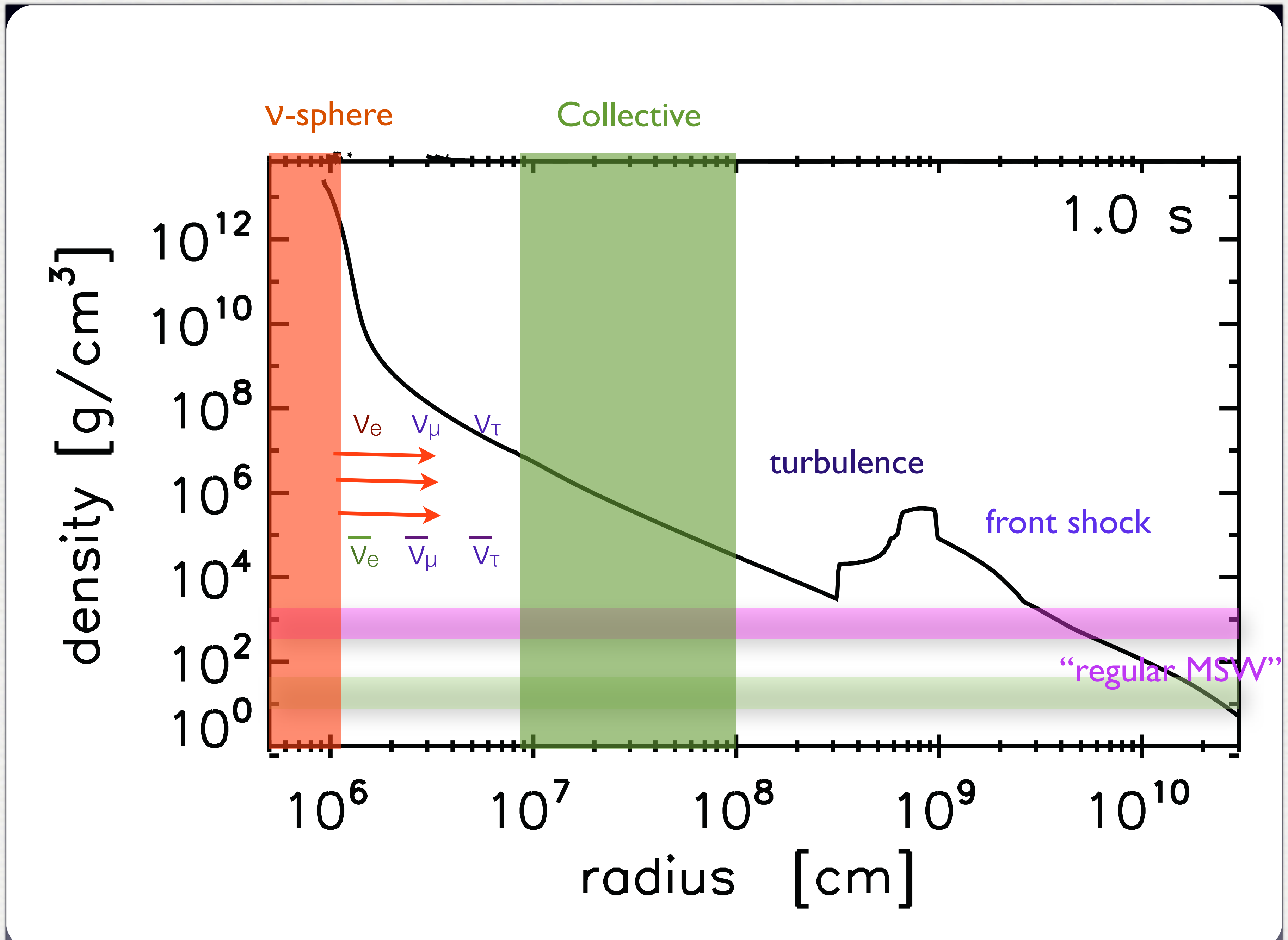
# H-R diagrams with and without axion cooling




- No blue loop stars
- **No Cepheid variables in a broad range of periods**

# Supernova neutrinos

# SN ν: the most complicated known oscillation problem



# Neutrino self-refraction

- 10% of the rest mass of the collapsed core (~ 1.4 $M_\odot$) is emitted in $10^{58}$ neutrinos in a burst lasting $\delta t$ ~ seconds
- At ~ 100 km, the number density of streaming neutrinos is
  - ~ $10^{58}/4\pi r^2 c\delta t \sim 10^{32}$ cm$^{-3}$
  - Comparable to the number density of matter

# Neutrino "self-refraction"

Fuller et al, 1988;
Pantaleone 1992;
Duan, Fuller, Qian, Carlson, 2006;
+ hundreds more

- Above the neutrino-sphere, streaming neutrinos are so dense that their flavor evolutions become coupled
- A given neutrino scatters on an ensemble of the "background" neutrinos
- One has to evolve an ensemble of neutrinos as a whole
- Rich many-body physics, with many regimes

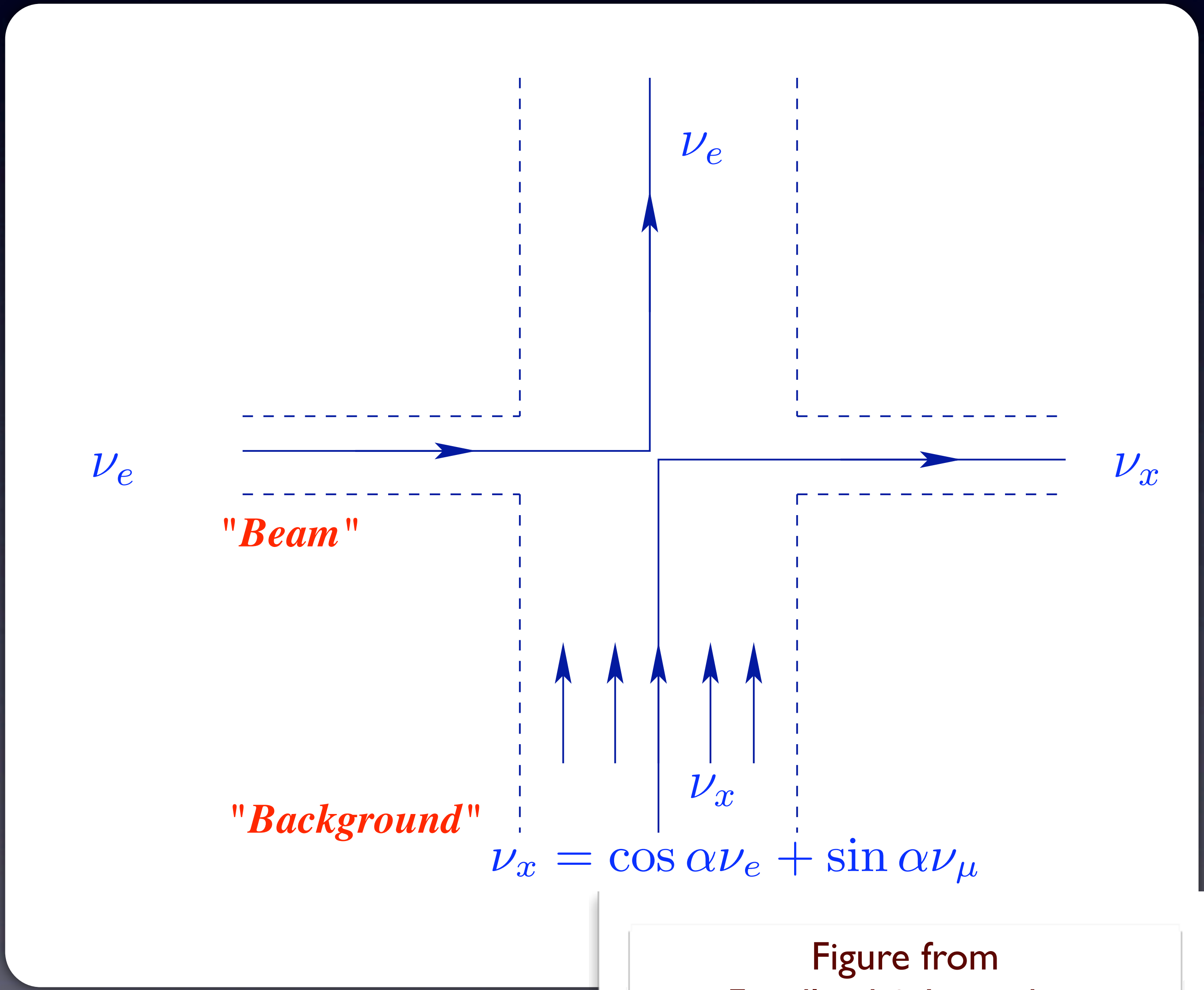
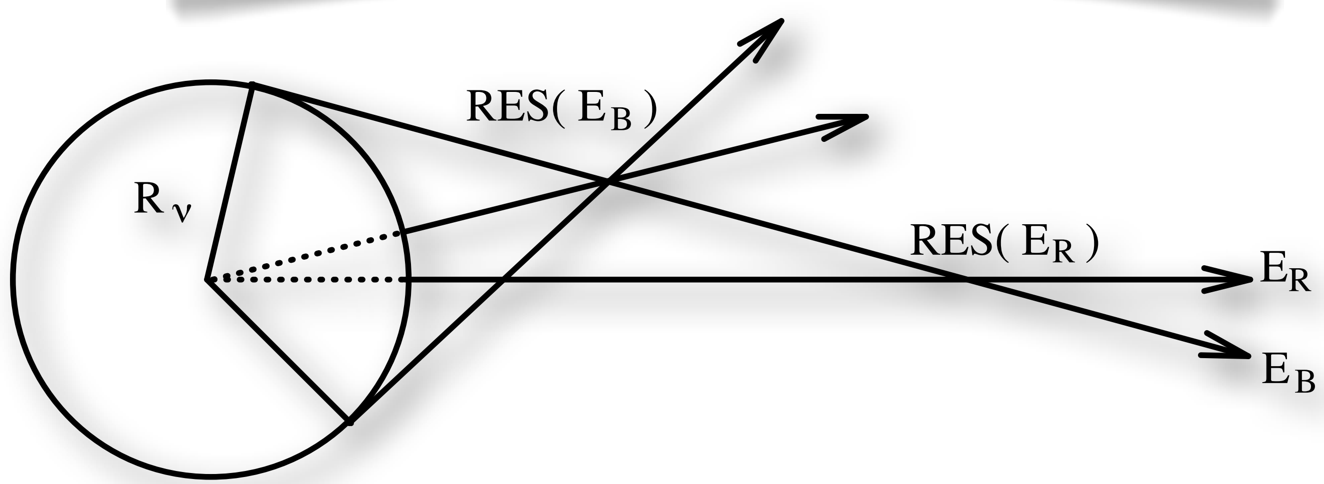



Figure from
Friedland & Lunardini,
Phys. Rev. D 68, 013007 (2003)

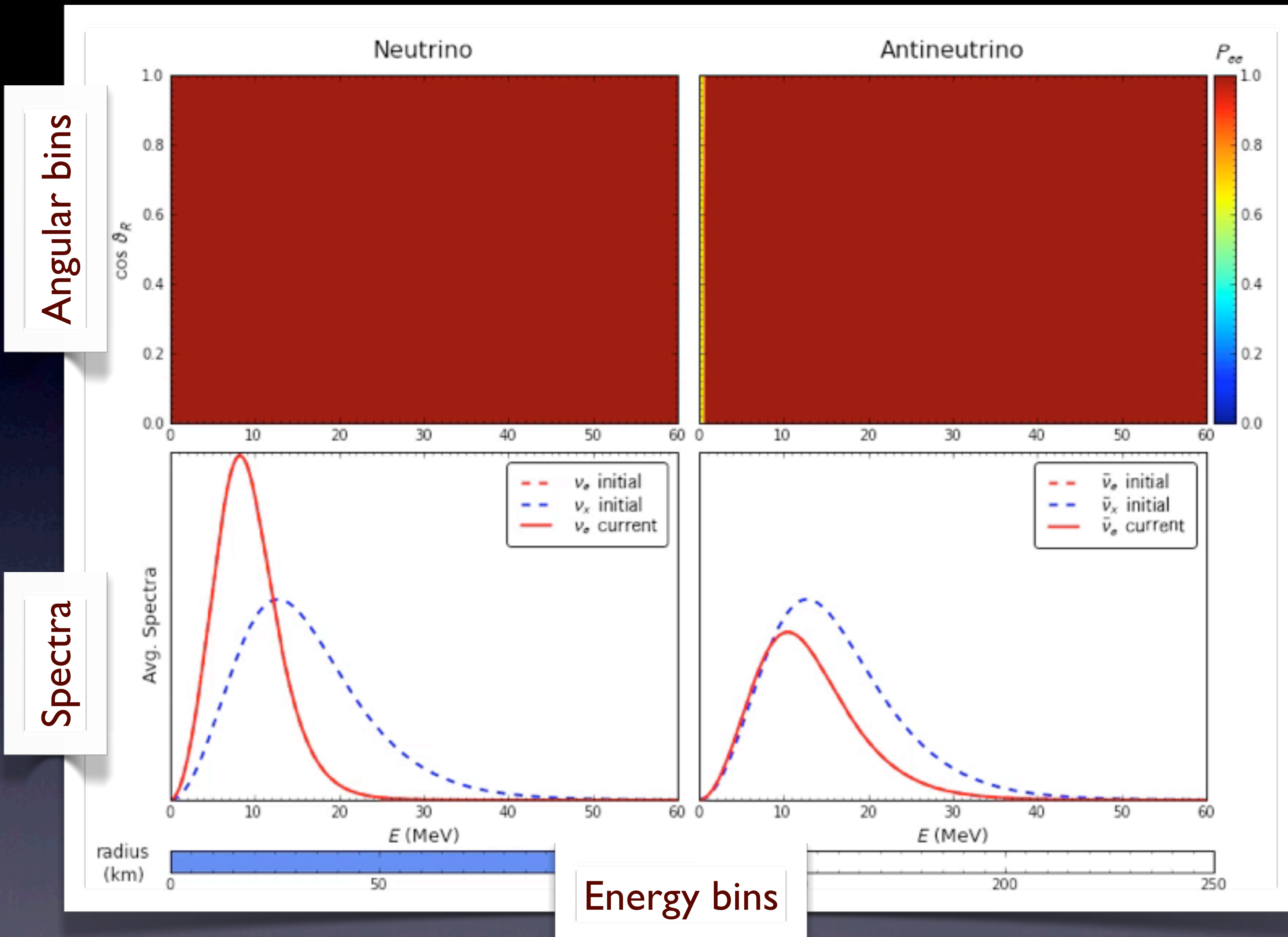
- Known physics: Z-mediated coherent neutrino scattering
  - Not optional!

# Multiangle, multienergy problem

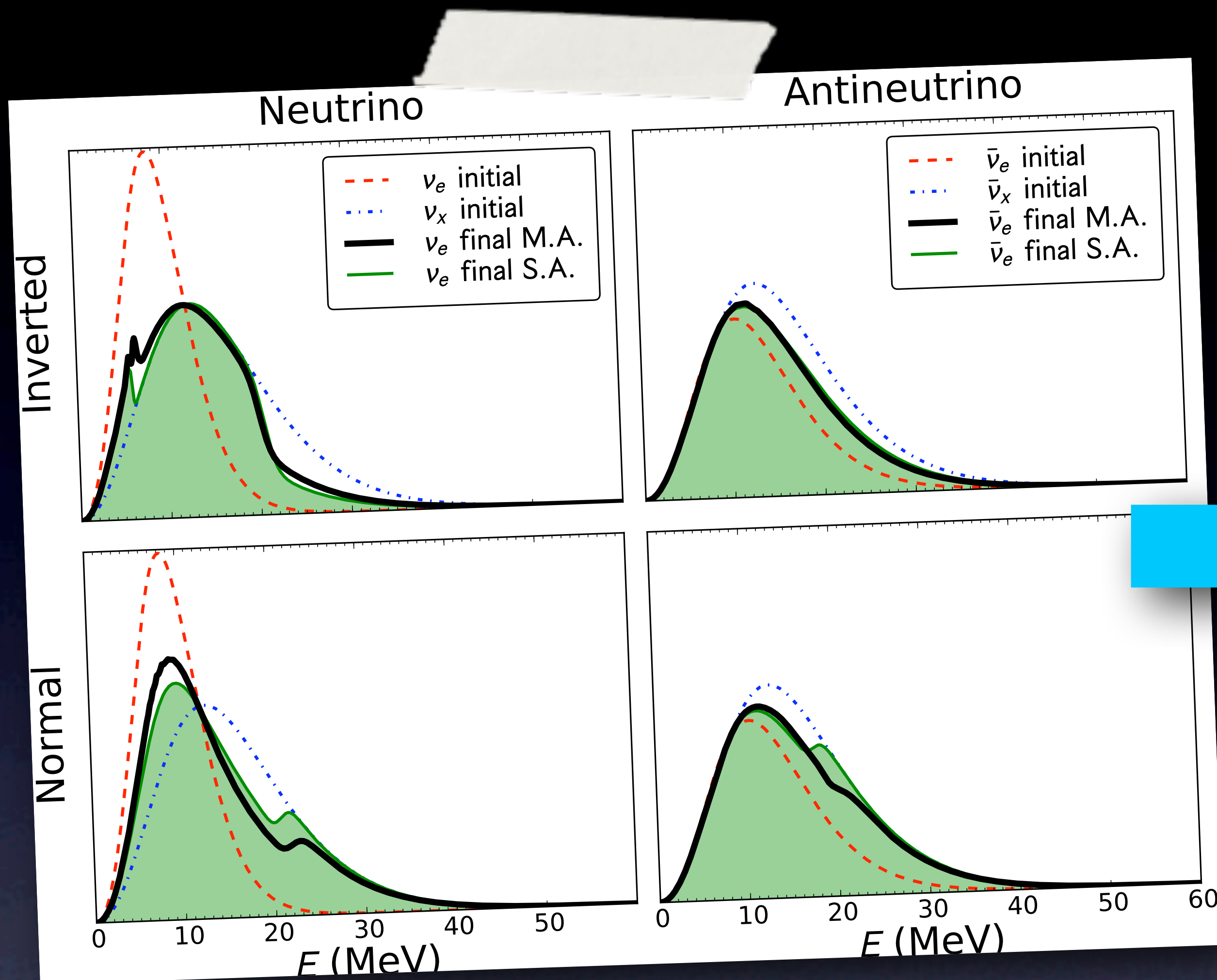
Figure from Qian & Fuller, astro-ph/9406073

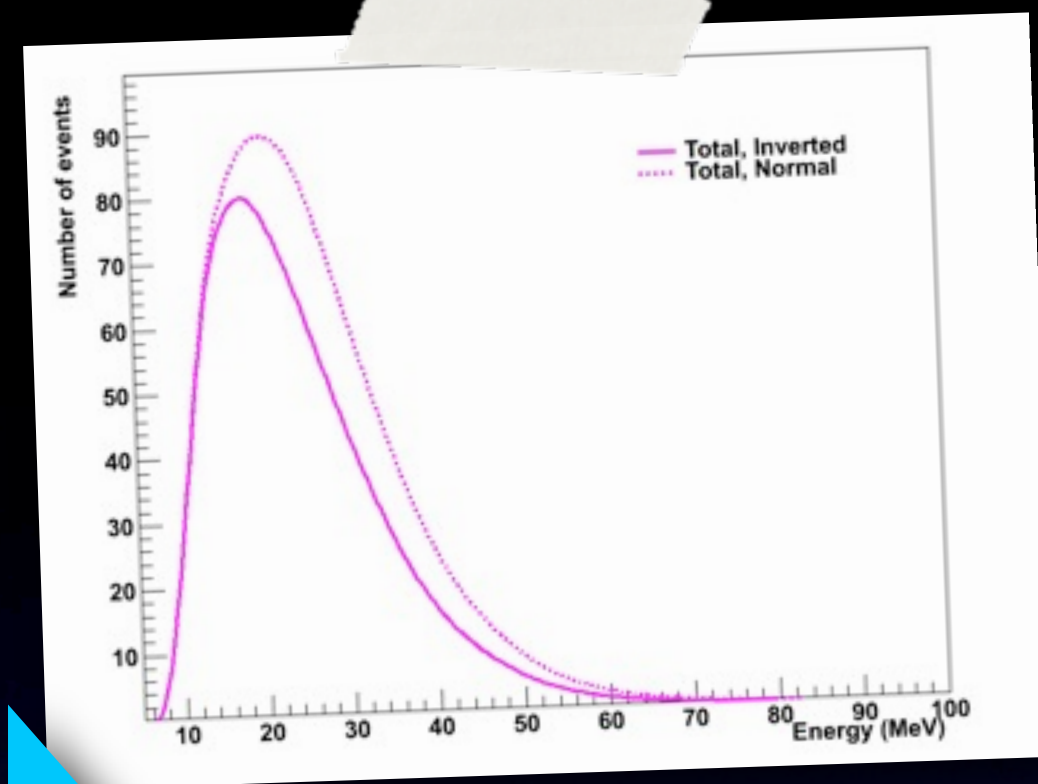



- Typical calculations: $10^3$ energy bins and $10^4$ angle bins
  - Rapid oscillations in all bins
  - Computer intensive
  - Moore's Law caught up with this problem in 2005

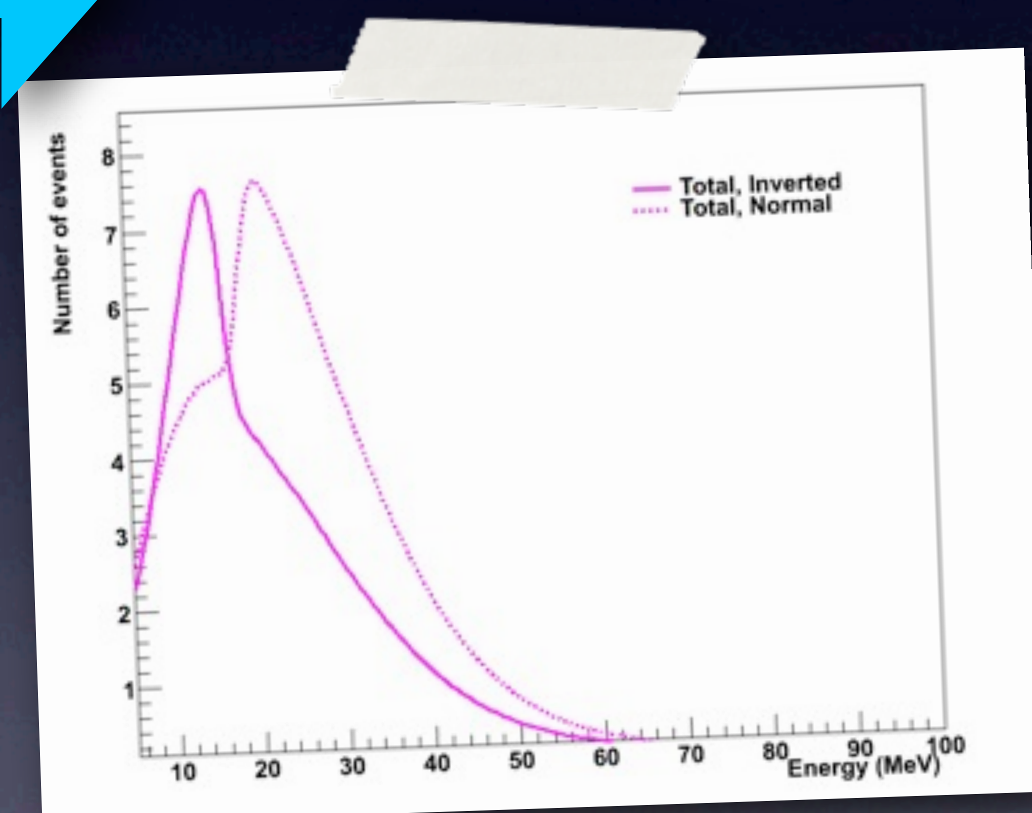



# Sample calculation




WC




LAr

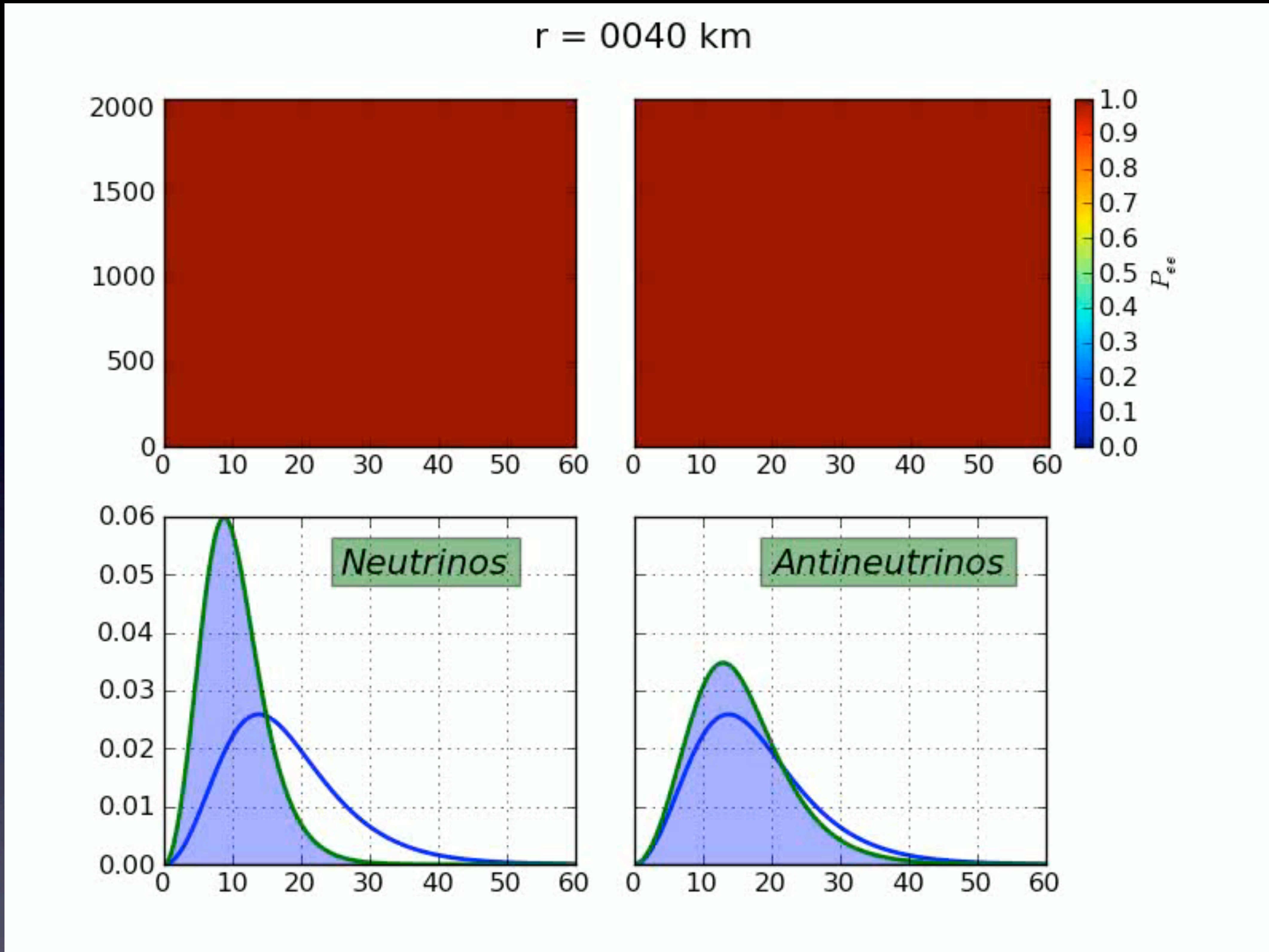
LBNE physics report: SN working group (arXiv:1110.6249)

* spectra by Duan & Friedland

* detector modeling by Kate Scholberg & co

# Next goal

- Qualitatively different regimes possible, depending on physical conditions in the explosion
- Map out these regimes



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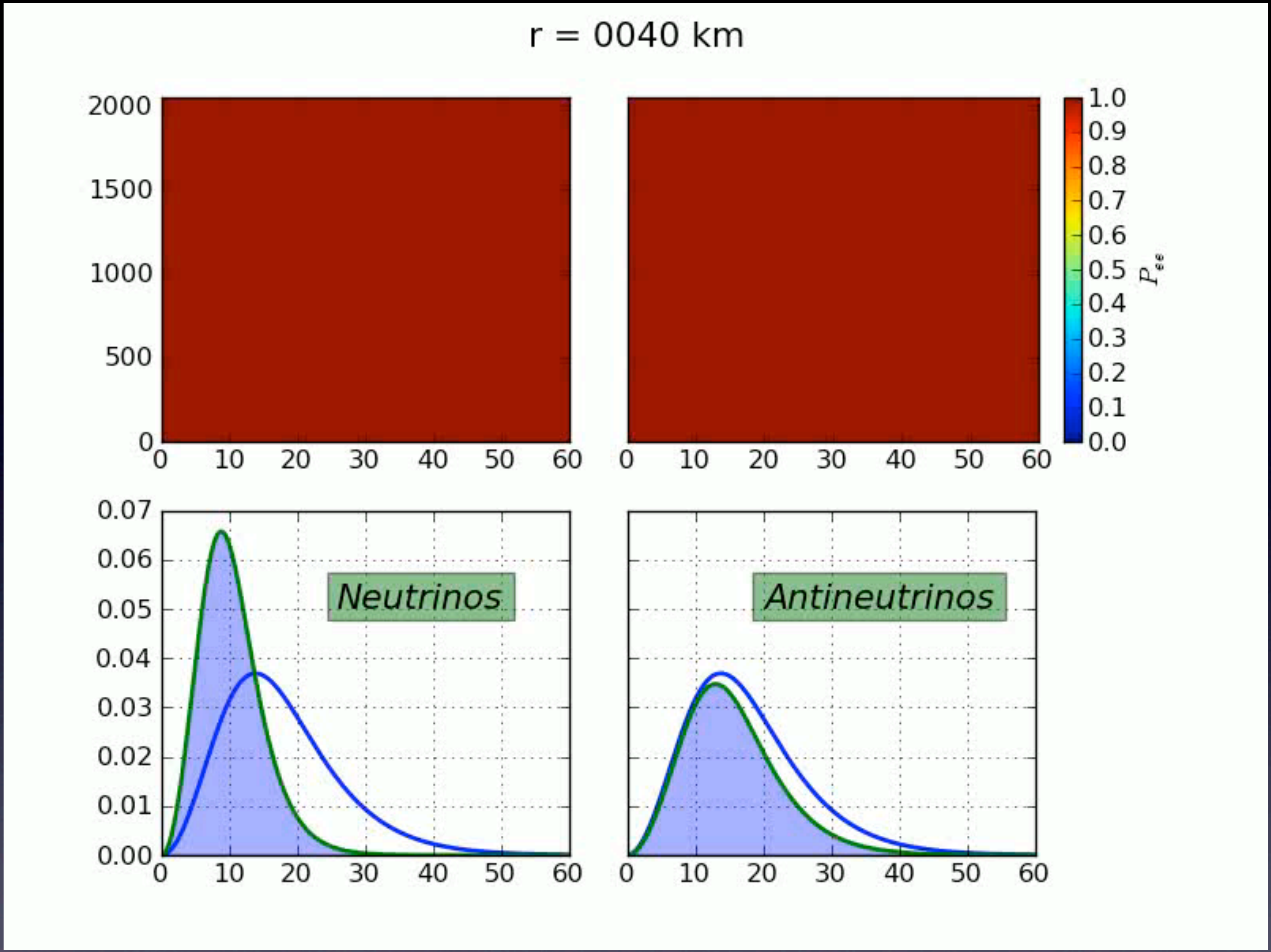
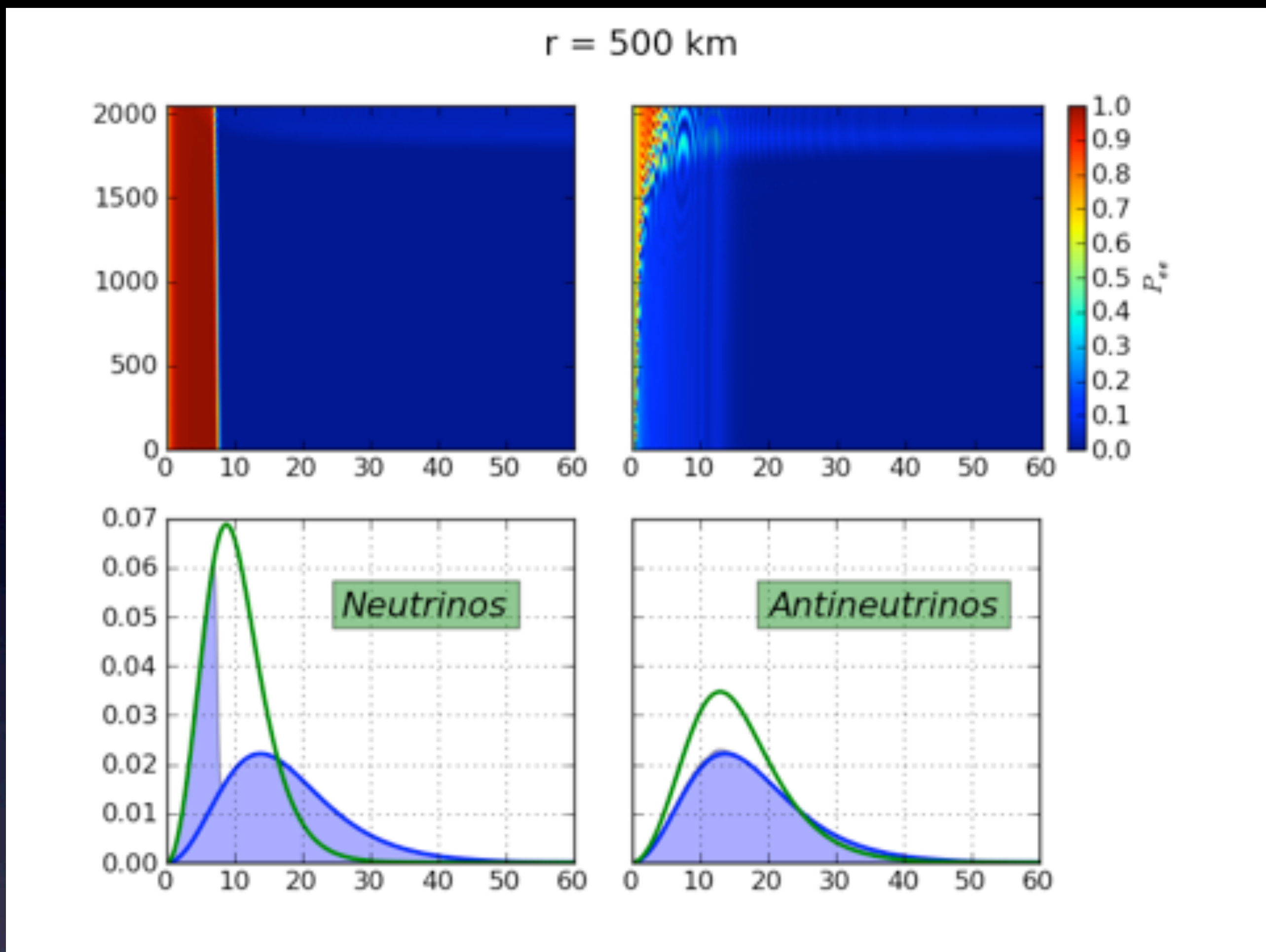
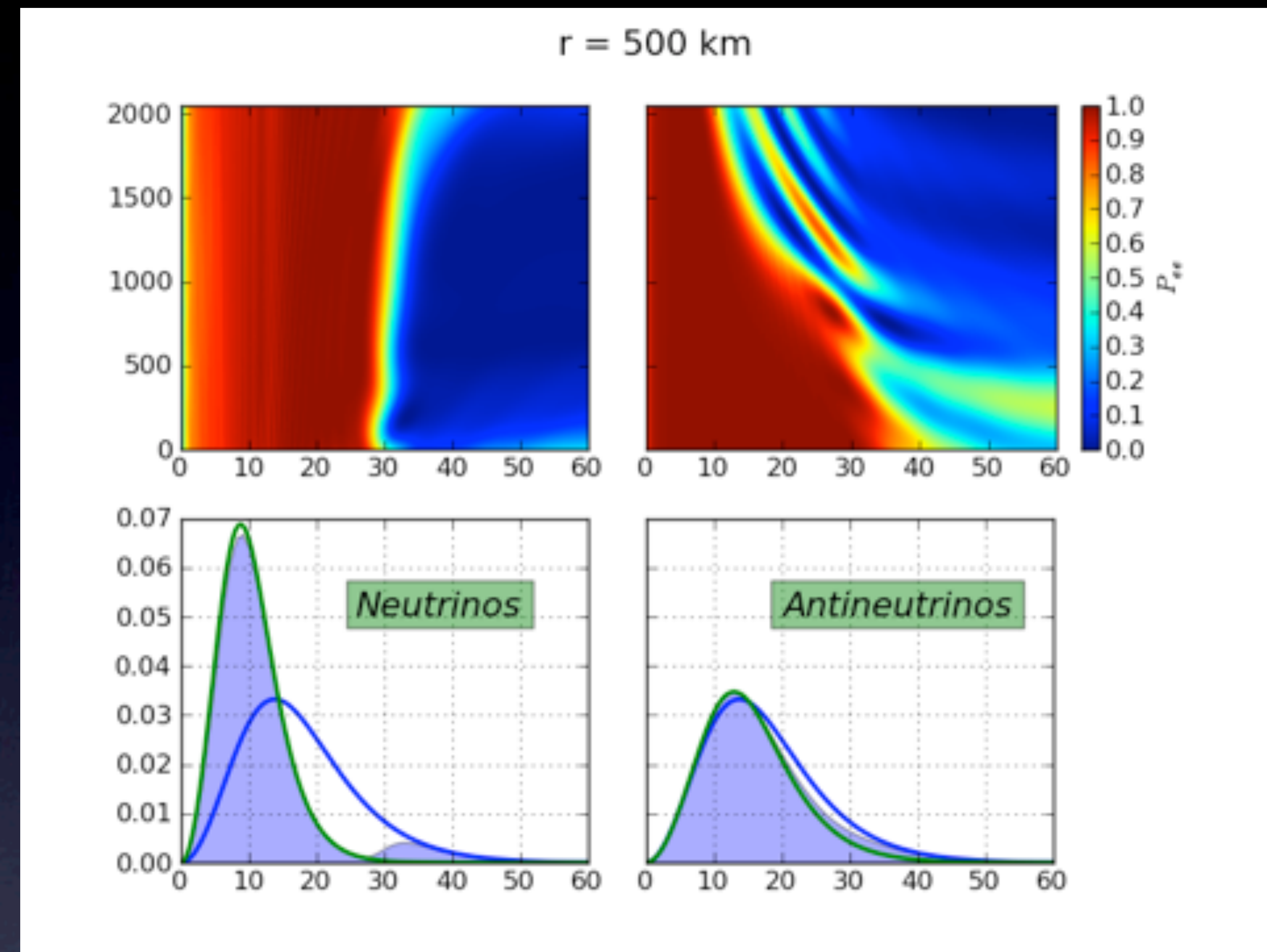
2000
1500
1000
500
0
0 10 20 30 40 50 60
1.0 0.9 0.8 0.7 0.6 0.5 0.4 0.3 0.2 0.1 0.0
$P_{ee}$
0.06 0.05 0.04 0.03 0.02 0.01 0.00
Neutrinos
Antineutrinos



r = 0040 km
2000
1500
1000
500
0
0 10 20 30 40 50 60
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
$P_{ee}$
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0.00
Neutrinos
Antineutrinos




# Qualitatively different patterns for normal and inverted mass hierarchies

# Conclusions

- Neutrino masses could be all there is
  - or the neutrino sector could contain more BSM surprises
- We have seen how neutrino properties could be probed in oscillations
  - solar, atmospheric, long baseline beams
- at the LHC
- with cosmological observations
- with stellar evolution
- We have also seen the oscillations in a supernova are unlike anything that can be produced on Earth

Los Alamos
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**Implications of Neutrino Flavor Oscillations**

**INFO 13**

**August 26 - 30, 2013**

Neutrinos, dark matter, etc

Students and postdocs are generously subsidized

http://public.lanl.gov/friedland/info13/info13.html