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Neutrino Physics in Heaven

"What's Nu?" IFT Miniworkshop on Neutrino Physics 2005
18-20 May 2005, Madrid, Spain

Topics in Neutrino Astrophysics and Cosmology

Phenomenon	Astrophysical benefits	Particle-physics benefits
Neutrinos in ordinary stars	Important/dominant energy-loss channel	• Solar nus → mixing params • Limits on new ν properties
Neutrinos in SNe & SN 1987A	• Dominant E loss/transfer • Nucleosynthesis	Limits on new particle properties
Neutrinos from next galactic SN	Test SN theory	• Mixing parameters • Limits on new ν properties
Diffuse SN nu background	• Test SN theory • Star formation history	Limits on decays
High-E neutrinos & cosmic rays	ν astronomy	• Atm nus → mixing params • High-E nus → Θ_{13} and δ
Big-bang nucleosynthesis	Primordial light element abundances, especially ^{4}He	Limits (evidence?) on new ν properties, new states
Neutrino dark matter	Hot dark matter contribution	• m_ν limit • Future measurement?
Leptogenesis	Cosmic baryon asymmetry	Motivation for 2β experiments

Neutrinos in Ordinary Stars

Neutrinos from Thermal Plasma Processes

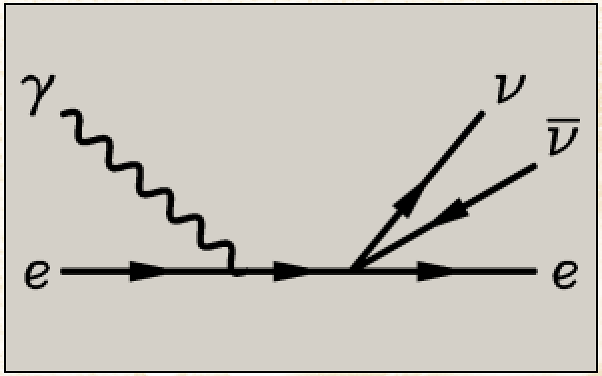
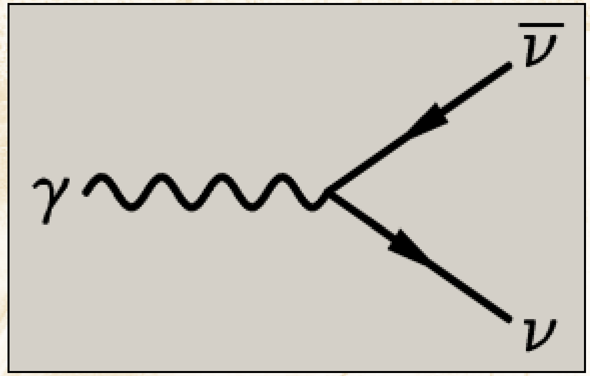
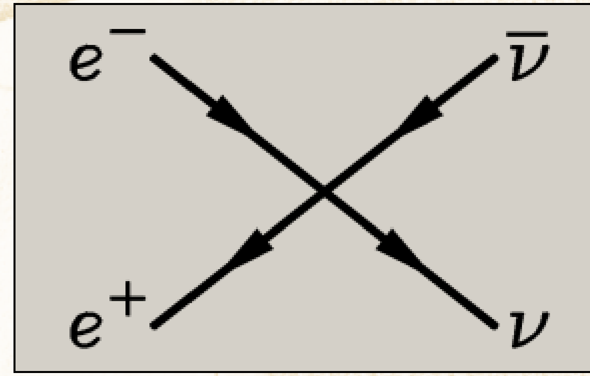


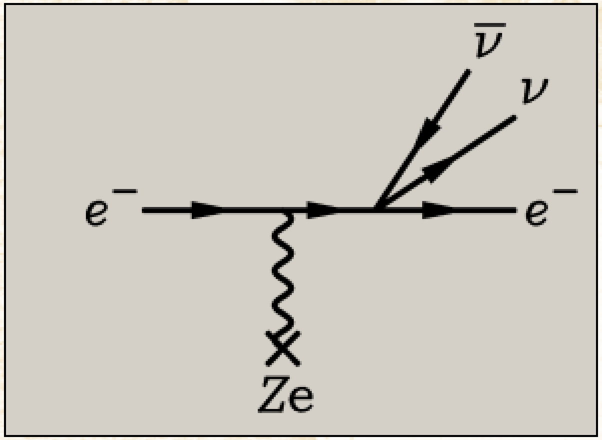
Photo (Compton)



Plasmon decay

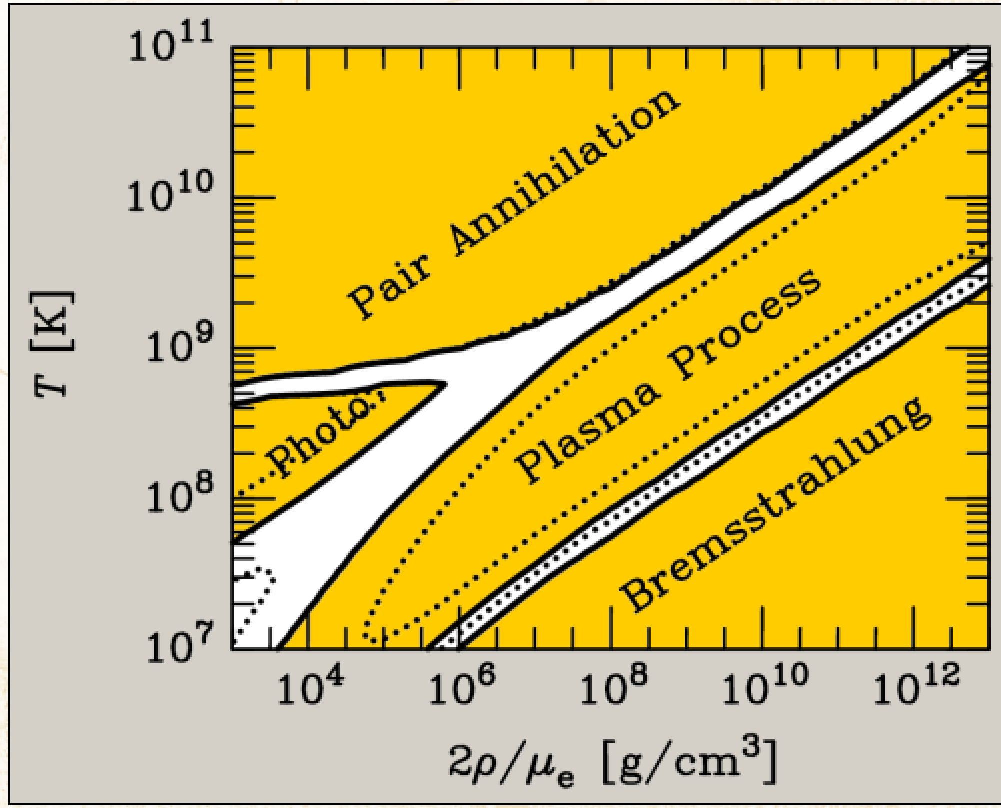


Pair annihilation



Bremsstrahlung

These processes first discussed in 1961-63 after V–A theory



Burning Phases of a 15 Solar-Mass Star

Burning Phase	Dominant Process	T_c [keV]	ρ_c [g/cm³]	L_γ [10^4 L_{sun}]	L_ν/L_γ	Duration [years]
Hydrogen	$H \to He$	3	5.9	2.1	–	1.2×10^7
Helium	$He \to C, O$	14	1.3×10^3	6.0	1.7×10^{-5}	1.3×10^6
Carbon	$C \to Ne, Mg$	53	1.7×10^5	8.6	1.0	6.3×10^3
Neon	$Ne \to O, Mg$	110	1.6×10^7	9.6	1.8×10^3	7.0
Oxygen	$O \to Si$	160	9.7×10^7	9.6	2.1×10^4	1.7
Silicon	$Si \to Fe, Ni$	270	2.3×10^8	9.6	9.2×10^5	6 days

Existence of Direct Neutrino-Electron Coupling

VOLUME 24, NUMBER 10 PHYSICAL REVIEW LETTERS 9 MARCH 1970

ASTROPHYSICAL DETERMINATION OF THE COUPLING CONSTANT FOR THE ELECTRON-NEUTRINO WEAK INTERACTION

Richard B. Stothers*
Goddard Institute for Space Studies, National Aeronautics and Space Administration, New York, New York 10025
(Received 22 December 1969)

The existence of the $(\bar{e}\nu_e)(\bar{\nu}_e e)$ weak interaction is confirmed by the results of nine astrophysical tests. The value of the coupling constant is equal to, or close to, the coupling constant of beta decay, namely, $g^2 = 10^{0\pm 2} g_\beta^2$.

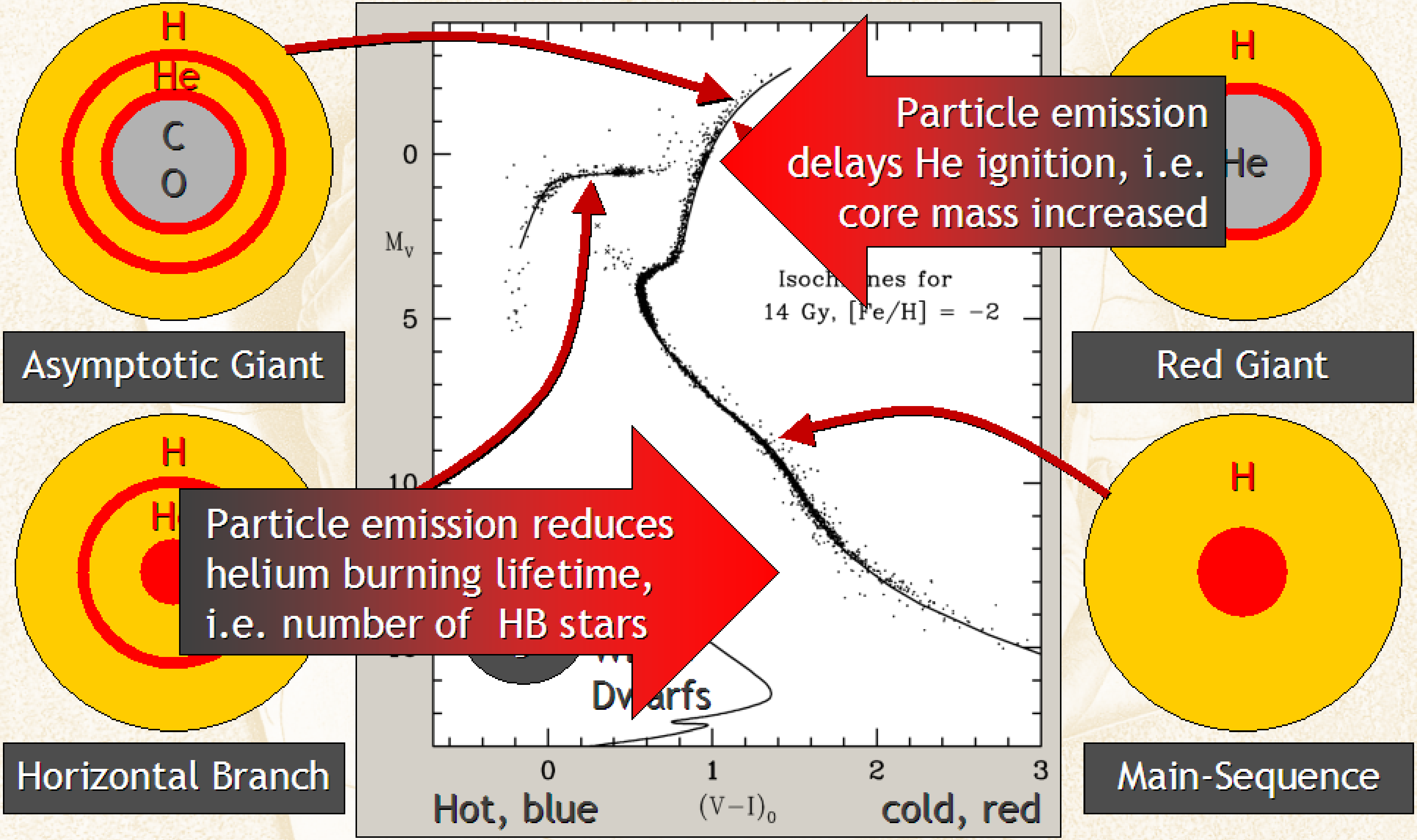
Of all the astrophysical tests applied so far for the inference of a direct electron-neutrino interaction in nature, none has unambiguously provided a useful upper limit on the coupling constant, which in the $V-A$ theory of Feynman and Gell-Mann[1] is taken to be equal to the "universal" weak-interaction coupling constant measured from beta decays (called g_β hereafter). However, it is important to point out that these tests, made by the author and his colleagues during the past eight years, do provide a nonzero lower limit, and therefore establish at least the existence of the $(\bar{e}\nu_e)(\bar{\nu}_e e)$ interaction. It should be emphasized, nonetheless, that all of these tests rely on the validity of various stellar model calculations. These models, while not subject to scrutiny in the same sense as a laboratory ex-

relative theoretical lifetimes, calculated with and without the inclusion of neutrino emission. In this Letter, the unmodified term "luminosity" will mean the photon luminosity L radiated by the star. The "neutrino luminosity" will be designated L_ν. Quantities referring to the sun are subscripted with an encircled dot.

The most accurate available data on white dwarfs are those collected by Eggen[7] for the two clusters Hyades and Pleiades and for the nearby general field. Of chief interest here are the hot white dwarfs, for which the observational data[7,8] have been reduced following the procedure of Van Horn.[9] The resulting luminosities are estimated to have a statistical accuracy of ±0.1 in $\log(L/L_\odot)$, which is adequate here.

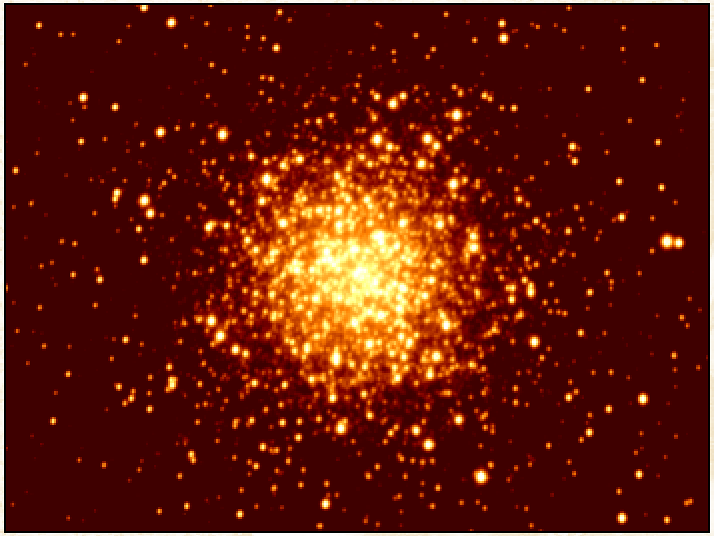
Models of cooling white dwarfs have been con-

Color-Magnitude Diagram for Globular Clusters

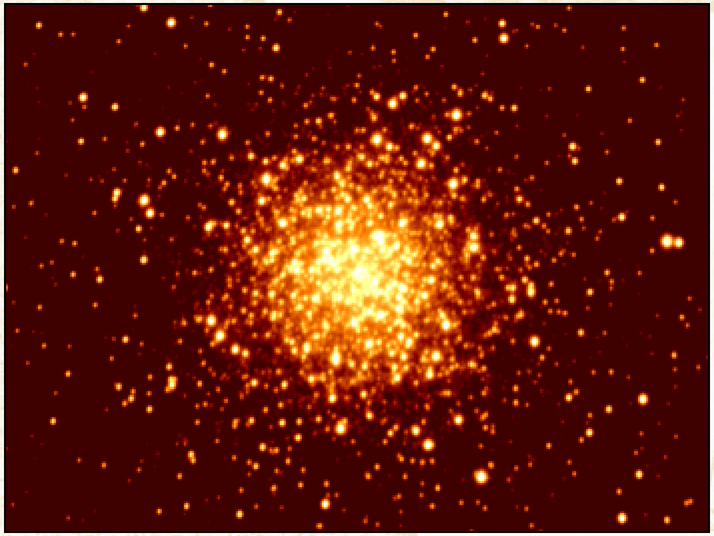


Color-magnitude diagram synthesized from several low-metallicity globular clusters and compared with theoretical isochrones (W.Harris)

Globular Clusters as Particle-Physics Laboratories



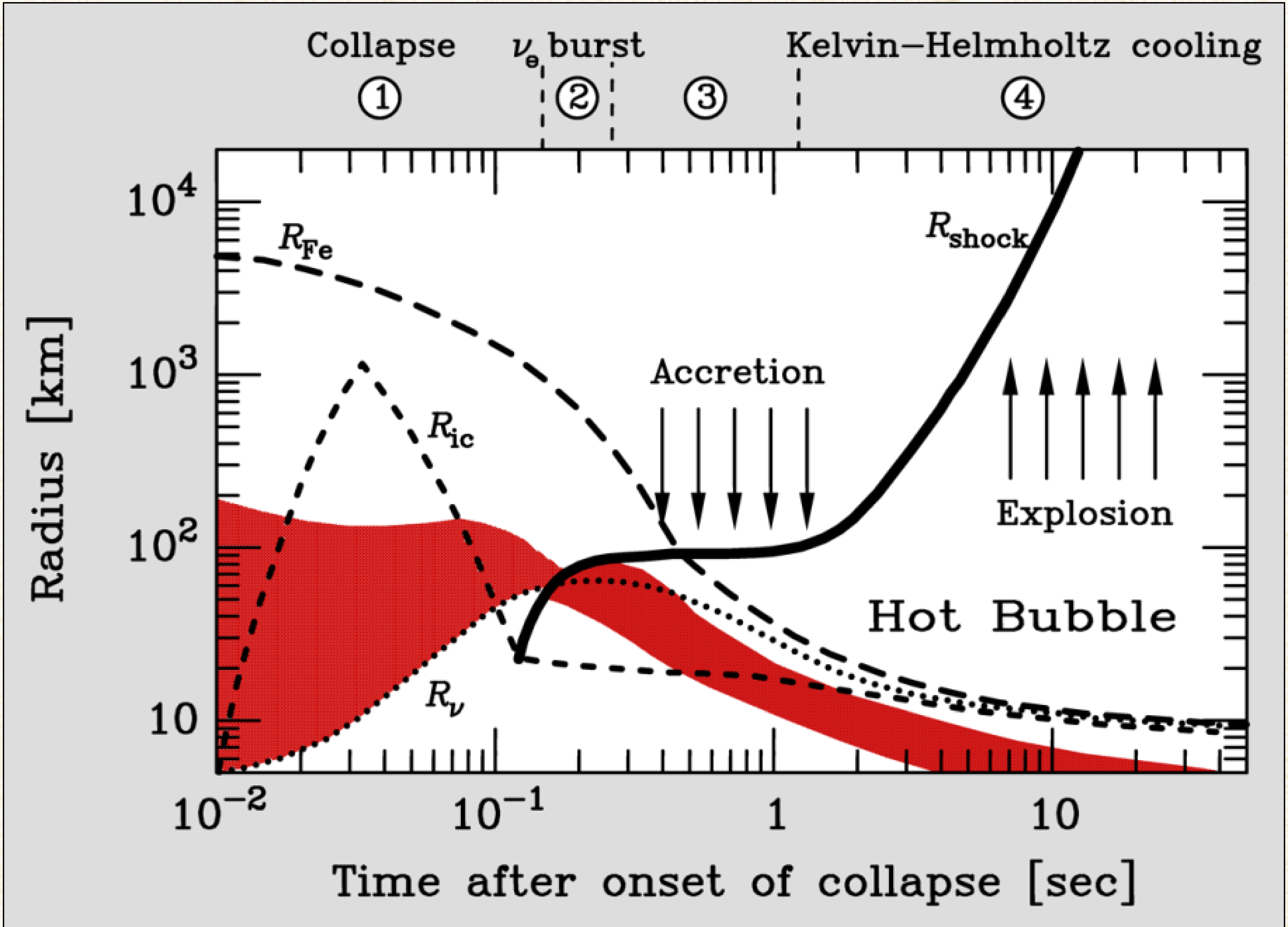
Best limits on quantities like
- Axion-photon coupling
- Axion-electron coupling
- Neutrino dipole moments
- ...



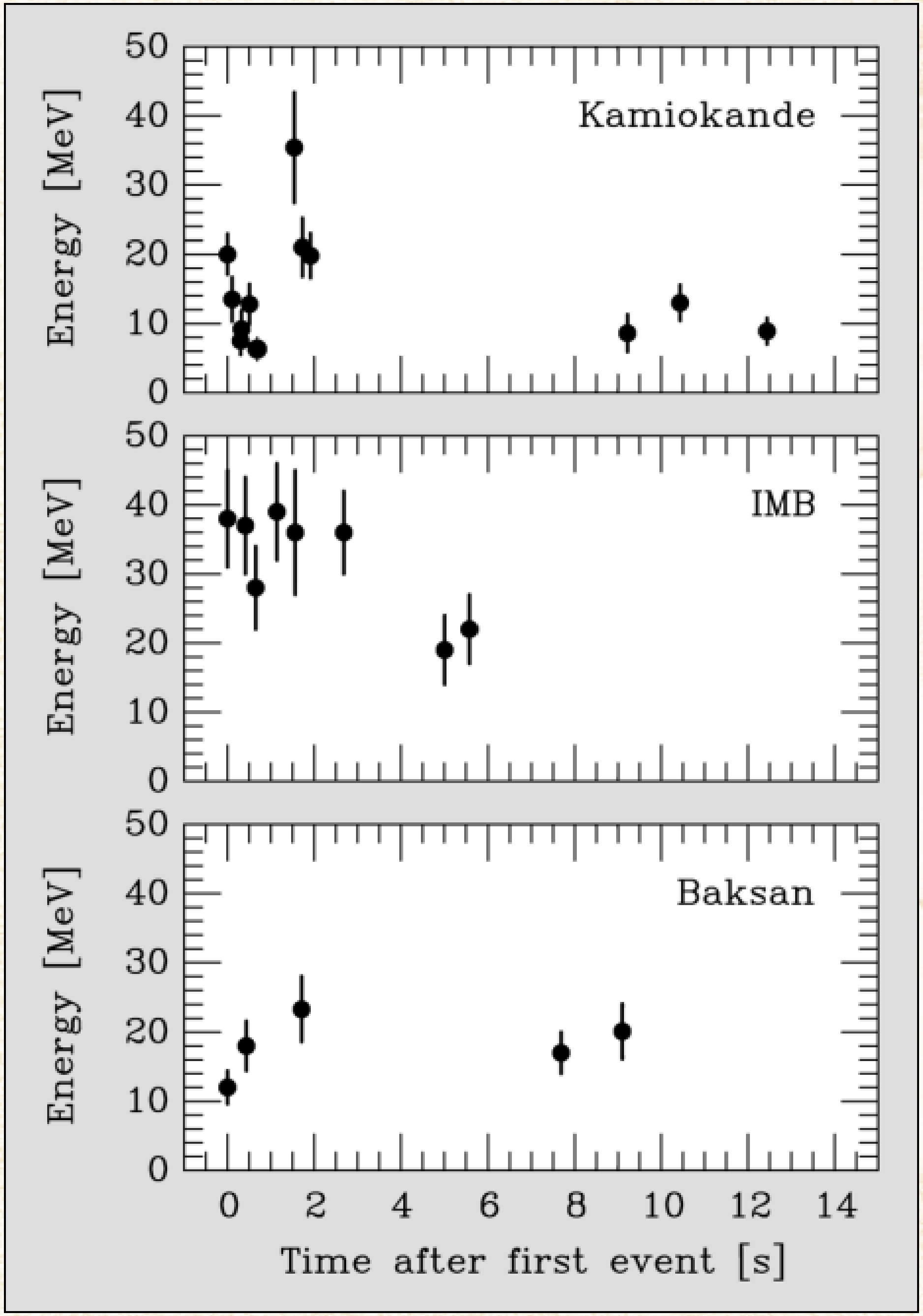
Reconsider these arguments with
- Modern photometry of
  ~ 100 galactic globular clusters
- Modern stellar evolution code
- Serious error analysis
  (statistical & systematic)

Supernova Neutrinos

Supernova Delayed Explosion Scenario



Neutrino Signal of Supernova 1987A



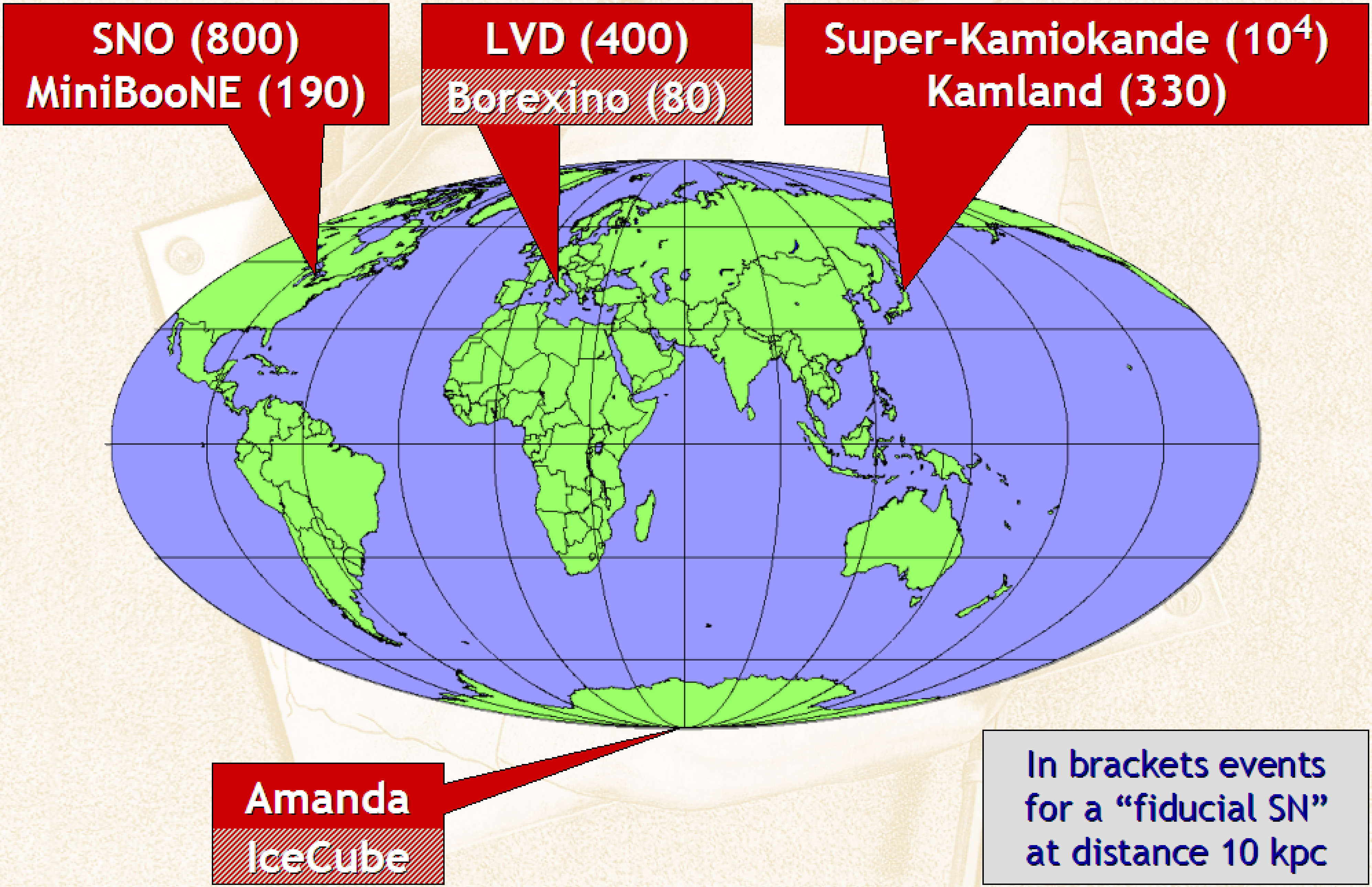
Kamiokande (Japan)
Water Cherenkov detector
Clock uncertainty ±1 min

Irvine-Michigan-Brookhaven (US)
Water Cherenkov detector
Clock uncertainty ±50 ms

Baksan Scintillator Telescope
(Soviet Union)
Clock uncertainty +2/-54 s

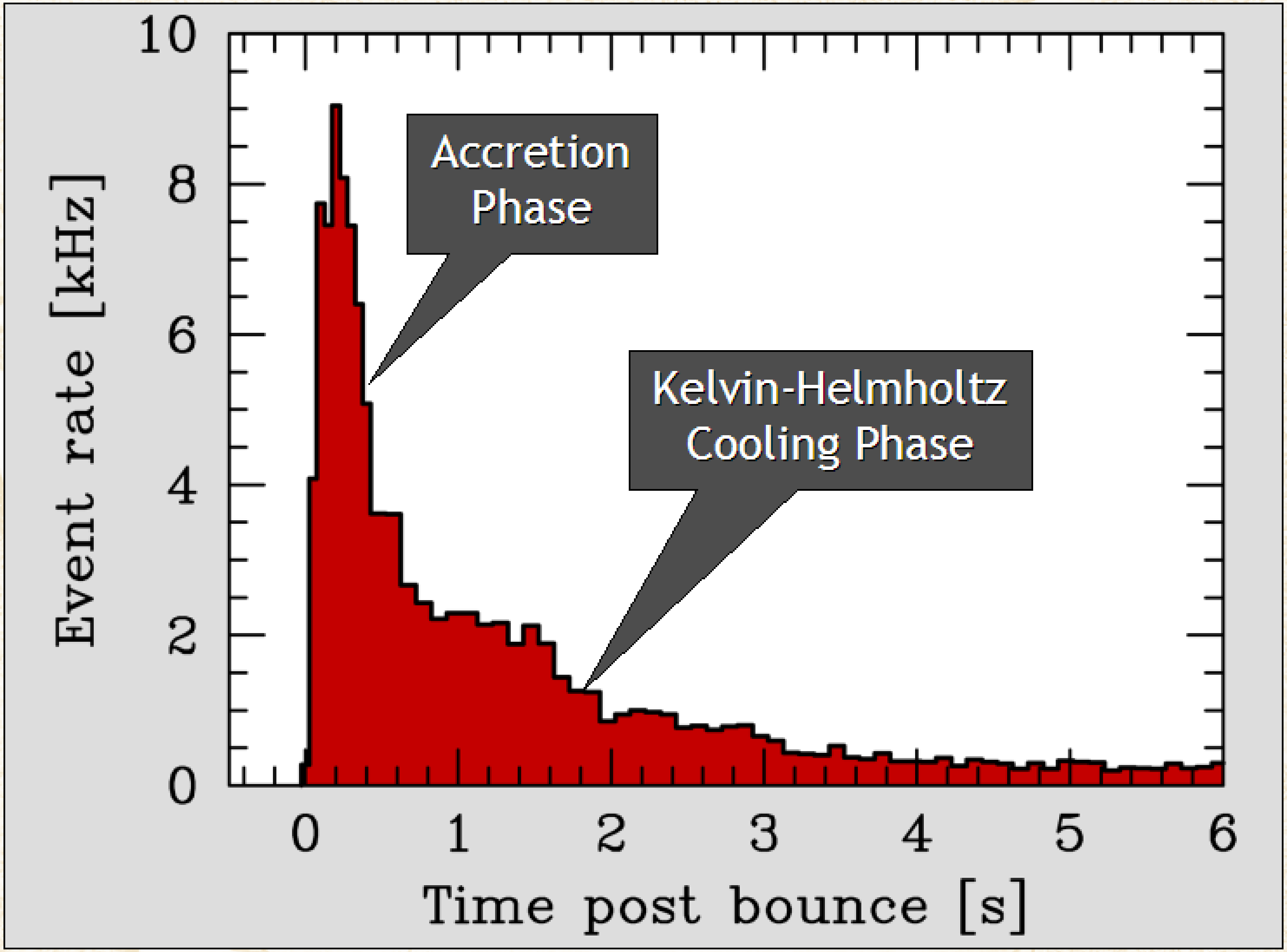
Within clock uncertainties, signals are contemporaneous

Large Detectors for Supernova Neutrinos



In brackets events for a "fiducial SN" at distance 10 kpc

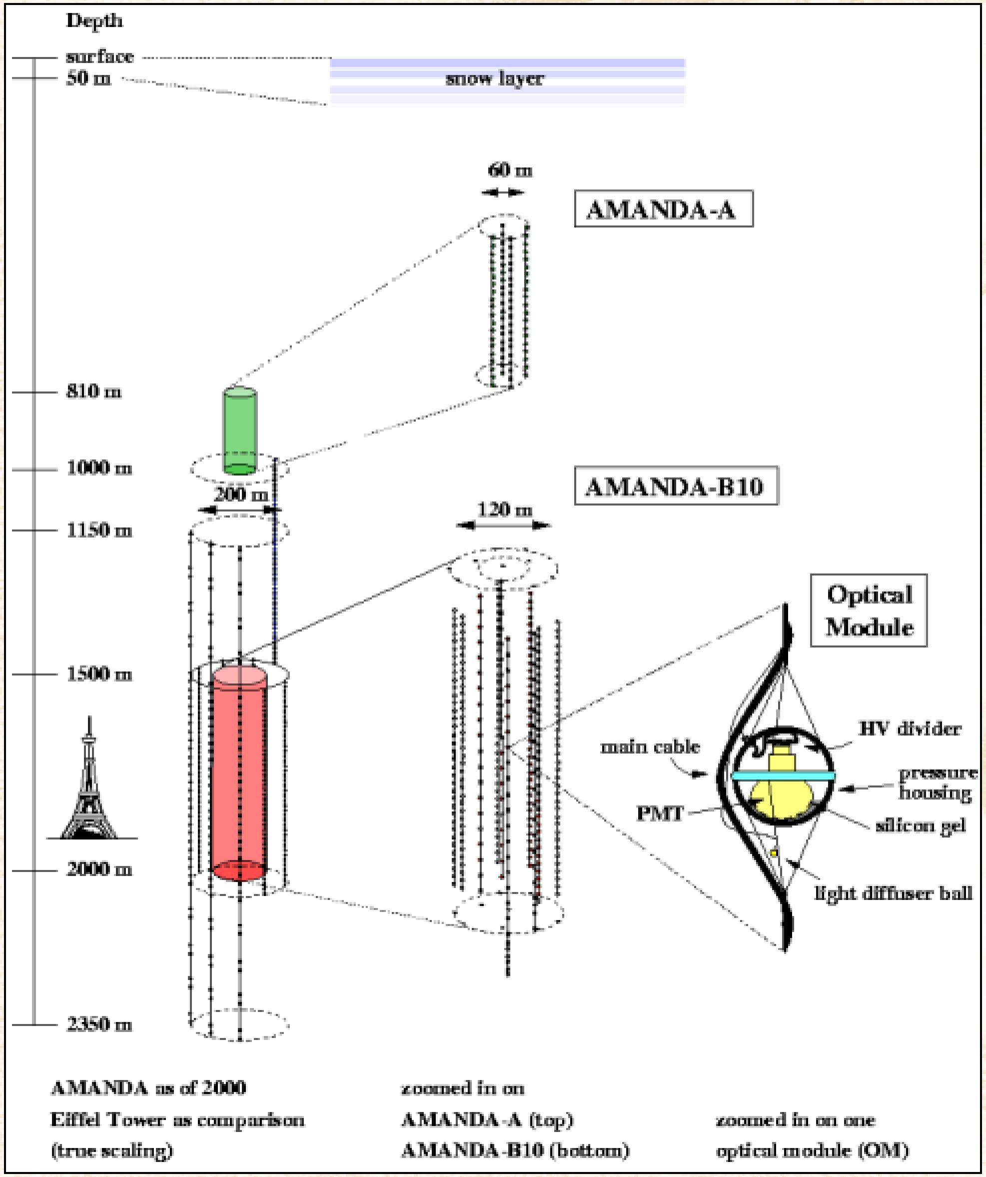
Simulated Supernova Signal at Super-Kamiokande



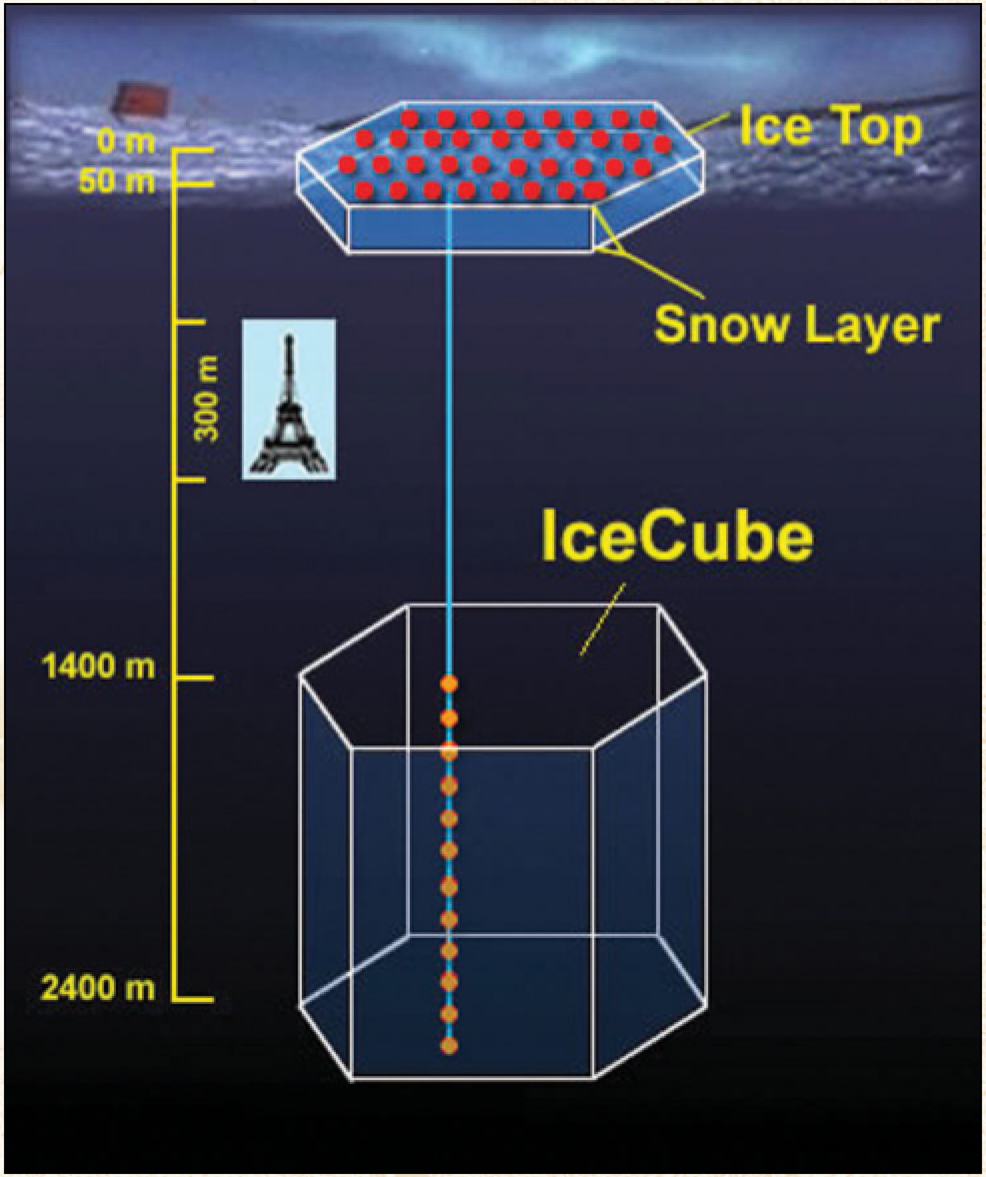
Simulation for Super-Kamiokande SN signal at 10 kpc, based on a numerical Livermore model
[Totani, Sato, Dalhed & Wilson, ApJ 496 (1998) 216]

Southpole Ice-Cherenkov Neutrino Detectors

AMANDA II (0.1 km^3, 800 PMTs)



Future IceCube (1 km^3, 4800 PMTs)

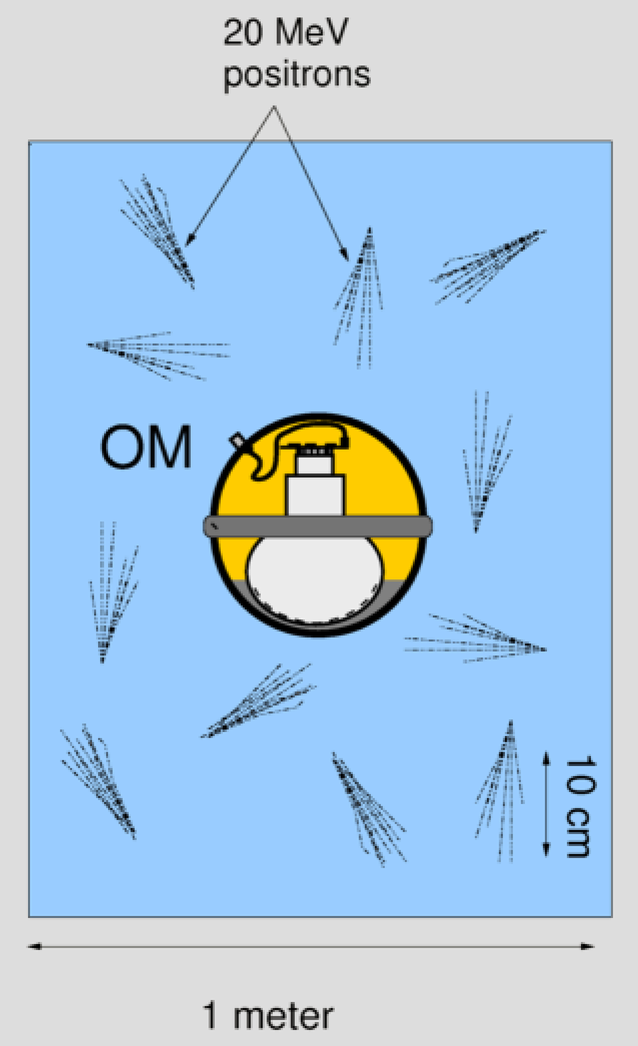


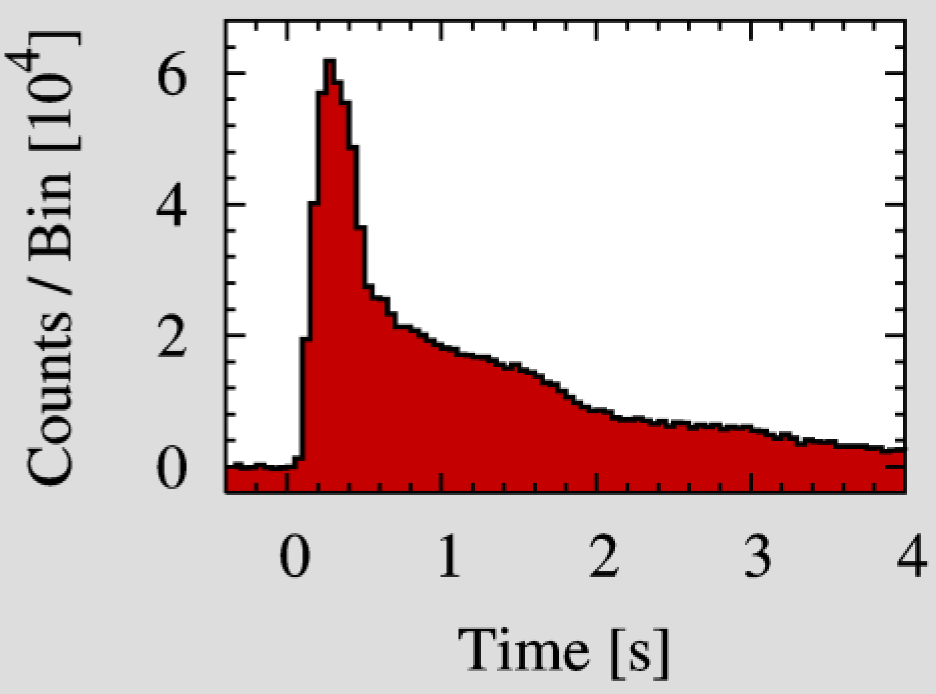
IceCube as a Supernova Neutrino Detector

Each optical module (OM) picks up Cherenkov light from its neighborhood. SN appears as "correlated noise".

~ 300 Cherenkov photons per OM from a SN at 10 kpc

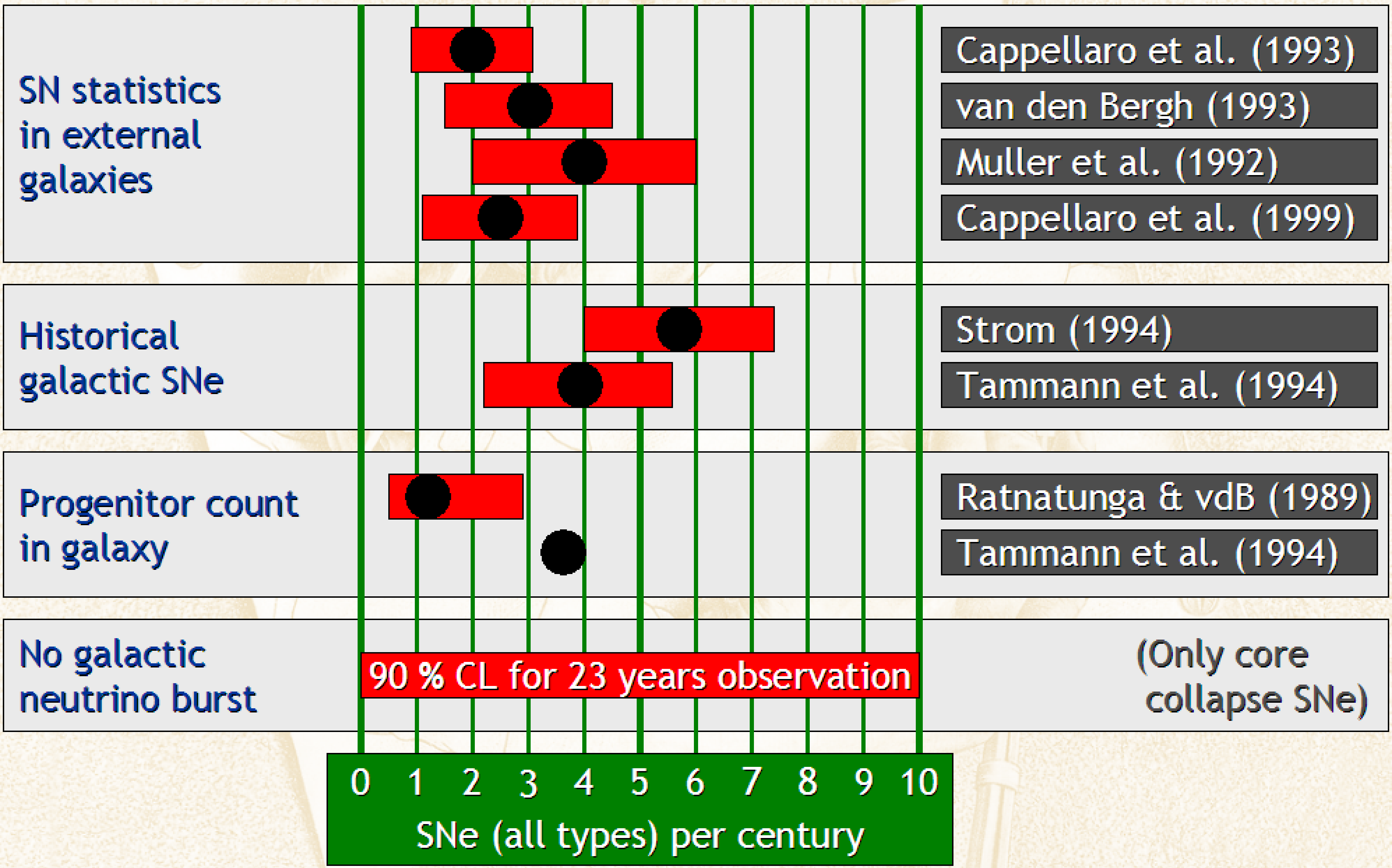
Noise per OM < 500 Hz



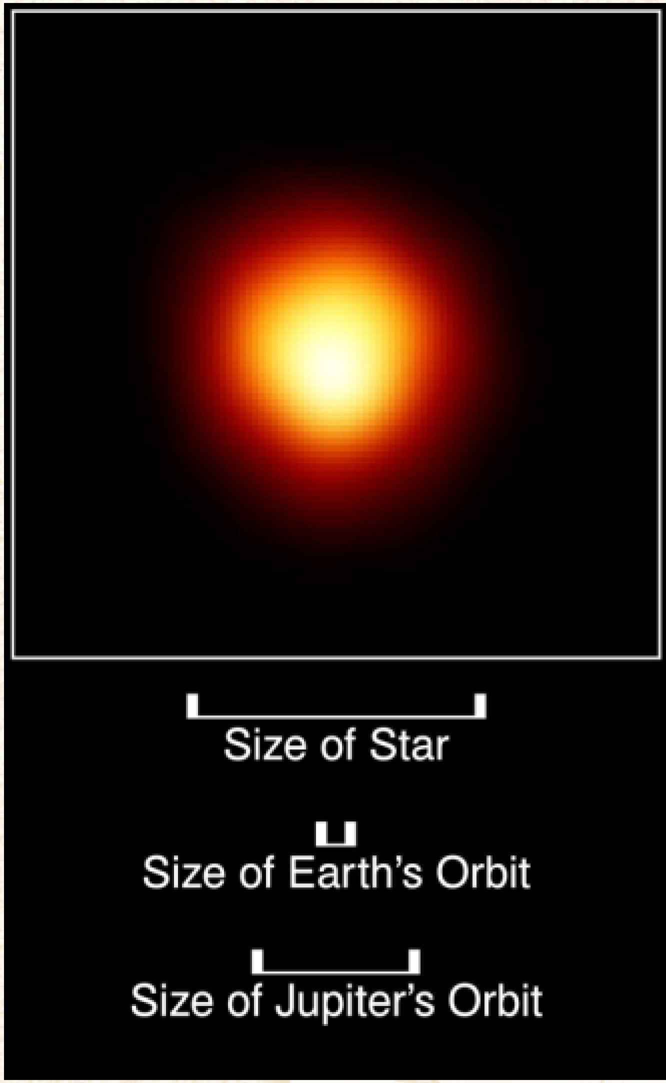


IceCube SN signal at 10 kpc, based on a numerical Livermore model [Dighe, Keil & Raffelt, hep-ph/0303210]

Estimates of the Galactic Supernova Rate



The Red Supergiant Betelgeuse (Alpha Orionis)



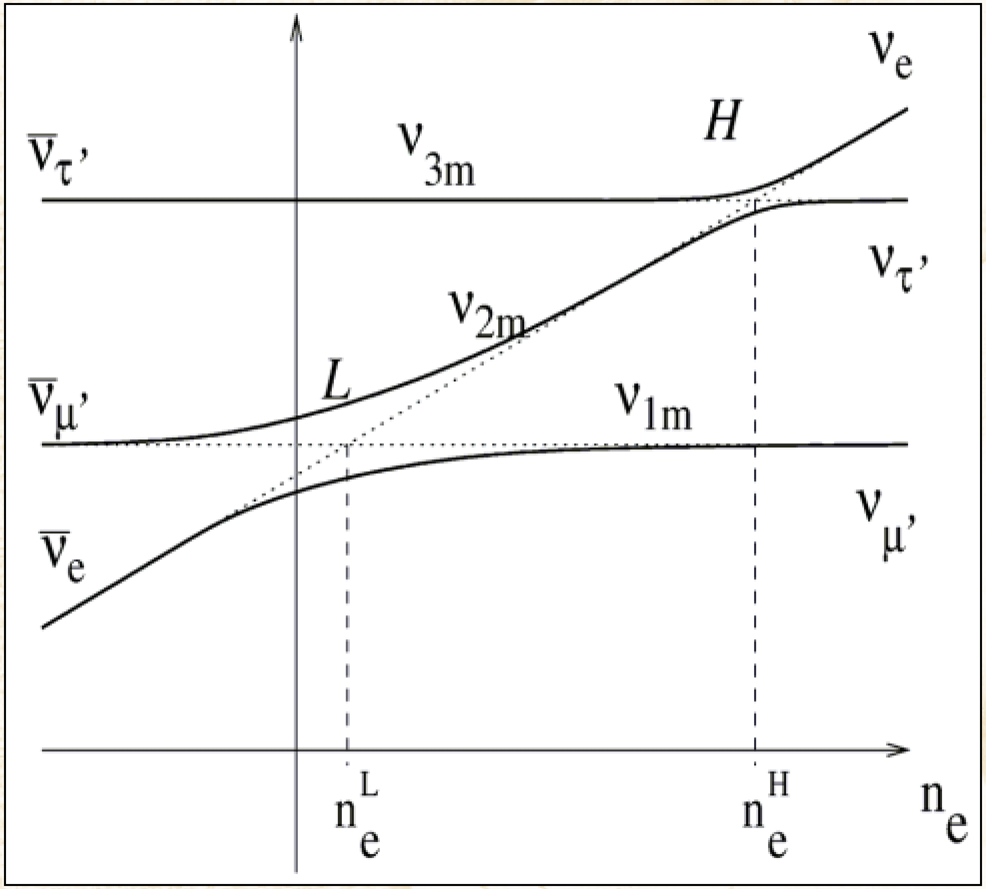
First resolved image of a star other than Sun

Distance (Hipparcos) 130 pc (425 lyr)

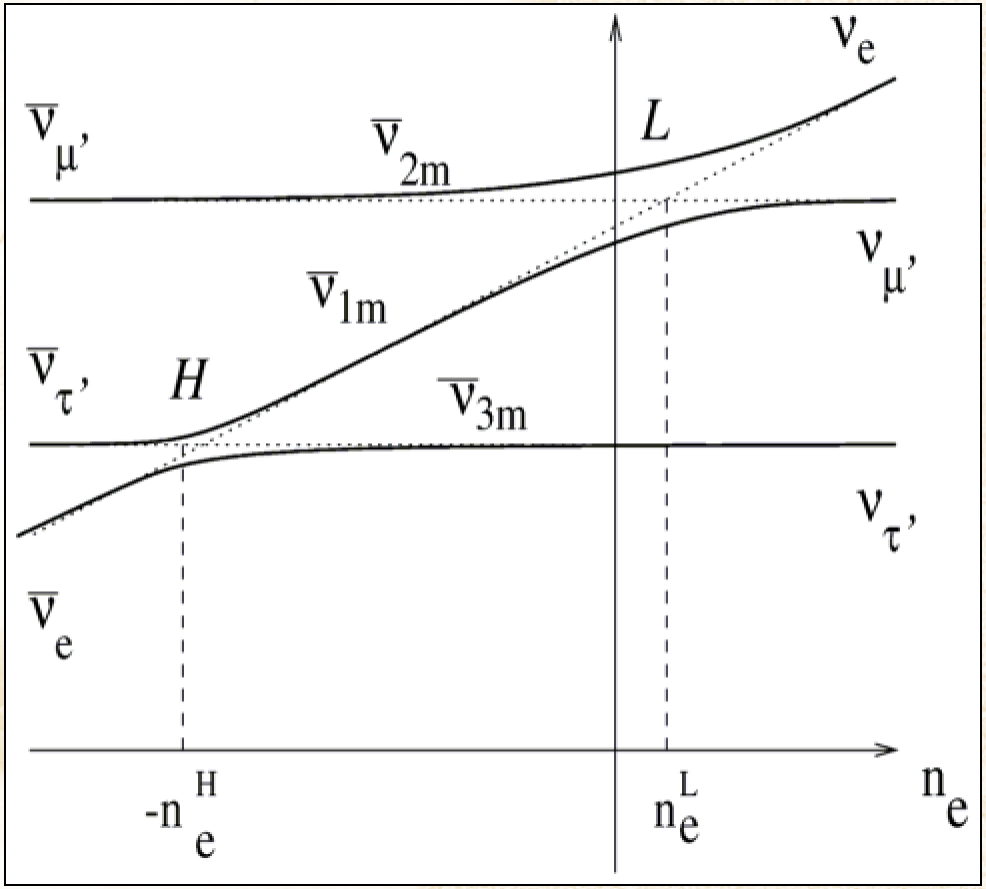
If Betelgeuse goes Supernova 6×10^7 neutrino events in Super-Kamiokande

Level-Crossing Diagram in a SN Envelope

Normal mass hierarchy



Inverted mass hierarchy



Dighe & Smirnov, Identifying the neutrino mass spectrum from a supernova neutrino burst, astro-ph/9907423

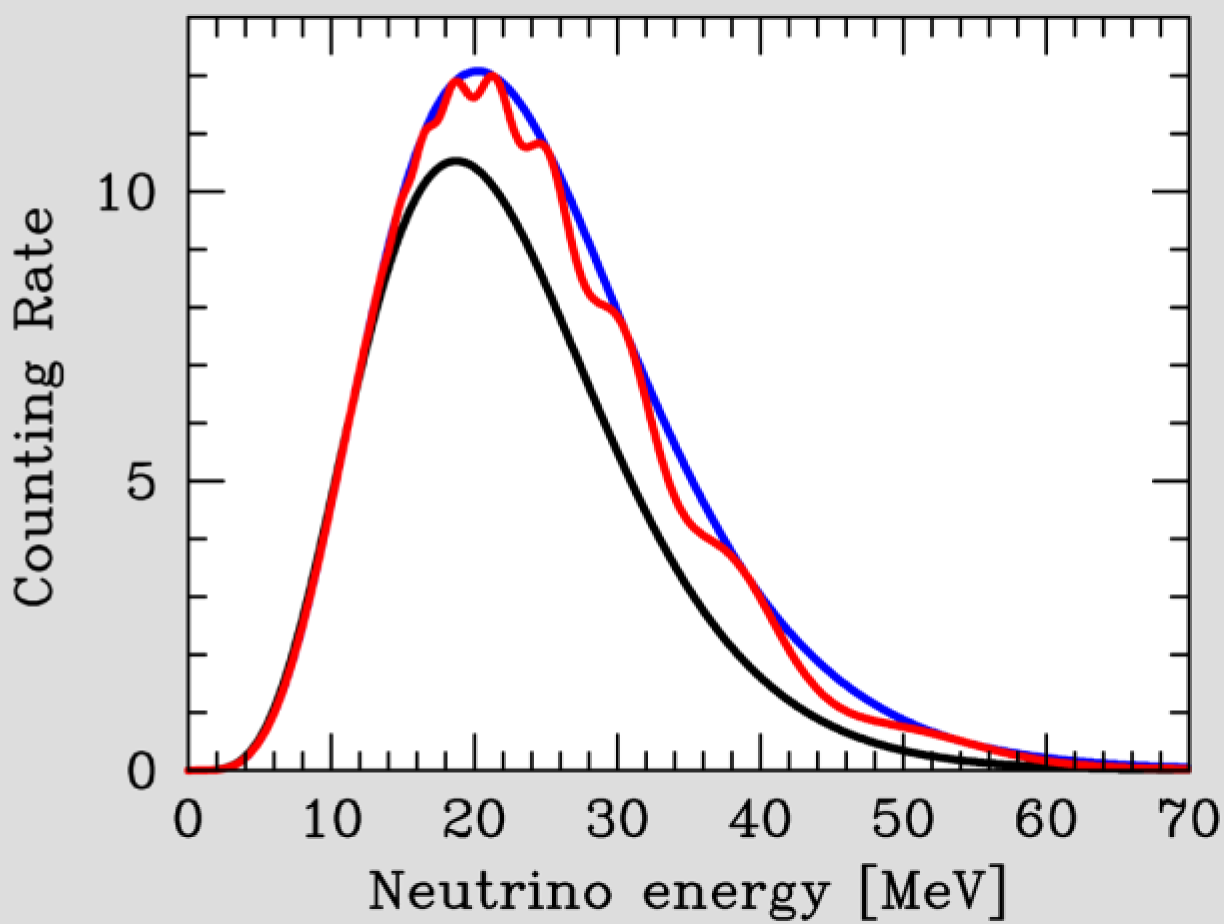
Spectra Emerging from Supernovae

Primary fluxes	F_e^0 for ν_e $F_{\bar{e}}^0$ for $\bar{\nu}_e$ F_x^0 for $\nu_\mu, \bar{\nu}_\mu, \nu_\tau, \bar{\nu}_\tau$
After leaving the supernova envelope, the fluxes are partially swapped	$F_e^0 = pF_e^0 + (1-p)F_x^0$ $F_{\bar{e}}^0 = \bar{p}F_{\bar{e}}^0 + (1-\bar{p})F_x^0$ $\frac{1}{4}\sum F_x = \frac{2+p+\bar{p}}{4}F_x^0 + \frac{1-p}{4}F_e^0 + \frac{1-\bar{p}}{4}F_{\bar{e}}^0$

Case	Mass ordering	$\sin^2(2\Theta_{13})$	Survival probability	
			p (for ν_e)	$\bar{p}$ (for $\bar{\nu}_e$)
A	Normal	$\gtrsim 10^{-3}$	0	$\cos^2(\Theta_{12})$
B	Inverted		$\sin^2(\Theta_{12})$	0
C	Any	$\lesssim 10^{-5}$	$\sin^2(\Theta_{12})$	$\cos^2(\Theta_{12})$

Oscillation of Supernova Anti-Neutrinos

Measured $\bar{\nu}_e$ spectrum at a detector like Super-Kamiokande



Assumed flux parameters

Flux ratio $\bar{\nu}_e : \bar{\nu}_\mu = 0.8 : 1$

$\langle E(\bar{\nu}_e) \rangle = 15\ \text{MeV}$

$\langle E(\bar{\nu}_x) \rangle = 18\ \text{MeV}$

Mixing parameters

$\Delta m^2_{\text{sun}} = 60\ \text{meV}^2$

$\sin^2(2\theta) = 0.9$

No oscillations

Oscillations in SN envelope

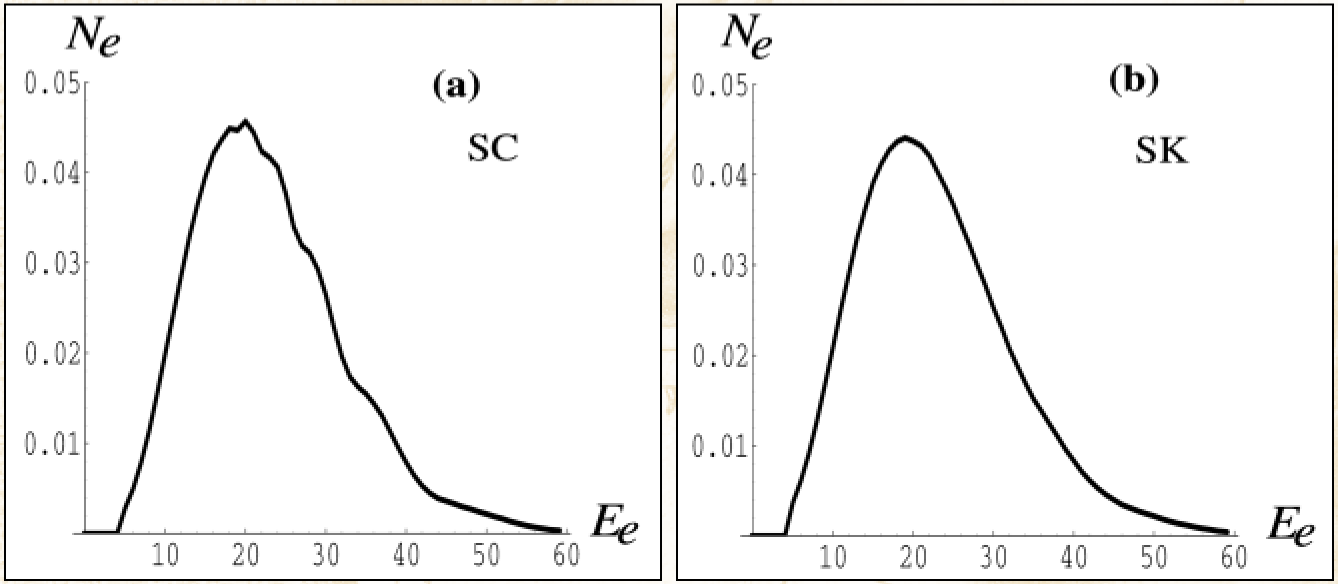
Earth effects included

Π(Dighe, Kachelriess, Keil, Raffelt, Semikoz, Tomàs),
hep-ph/0303210, hep-ph/0304150, hep-ph/0307050, hep-ph/0311172

Robust Strategies for Observing Earth Effects

One detector observes SN shadowed by Earth

Case 1: Identify "wiggles" in signal of single detector
Problem: Smearing by limited energy resolution



Scintillation detector
~ 2000 events
may be enough

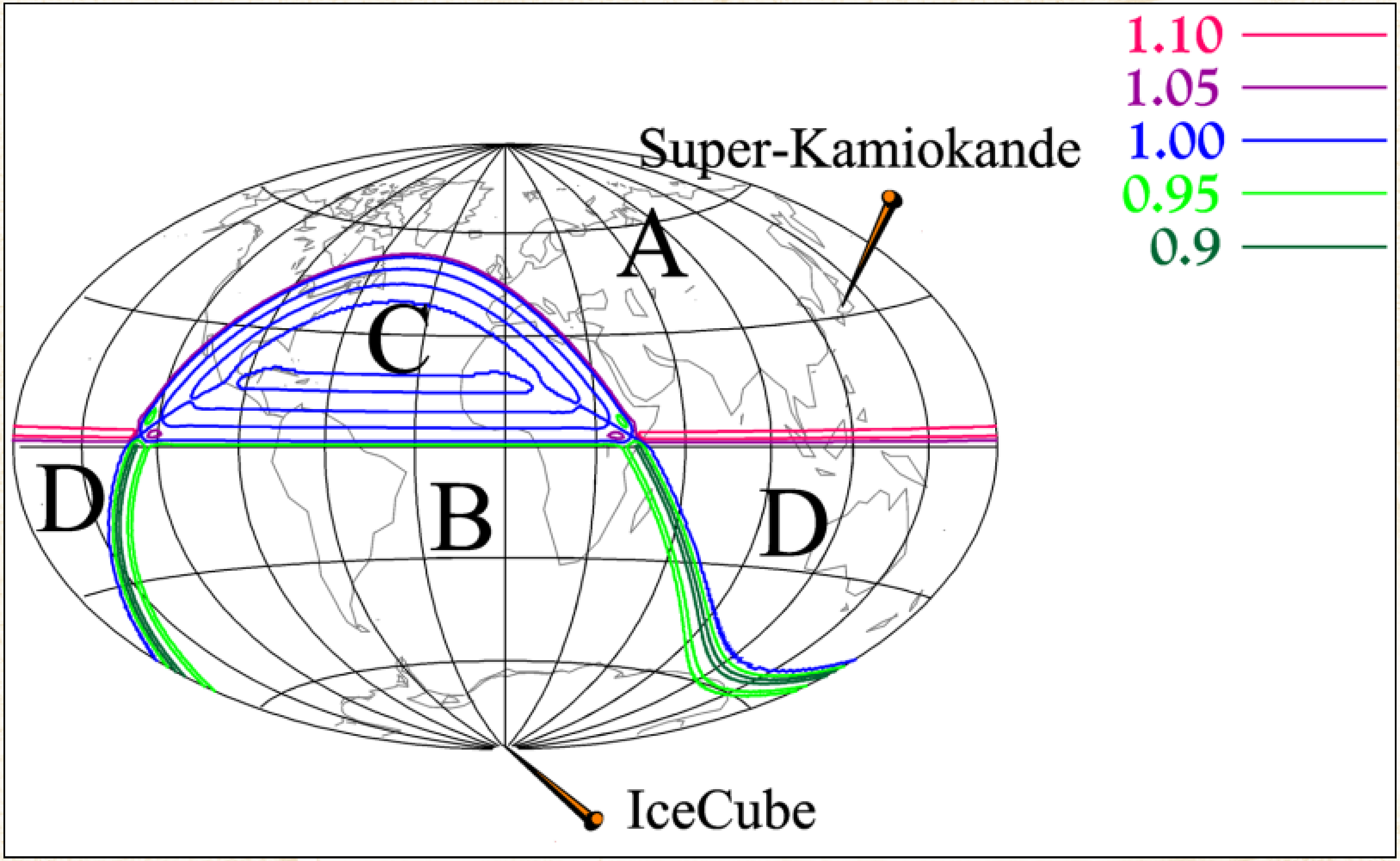
Water Cherenkov
Need megatonne
with ~ 10^5 events

Dighe, Keil & Raffelt, "Identifying Earth matter effects on supernova neutrinos at a single detector" [hep-ph/0304150]

Case 2:
- Another detector observes SN directly
- Identify Earth effects by comparing signals

Positively observing Earth effects implies normal mass ordering if $\sin^2(\Theta_{13}) \gtrsim 10^{-3}$ (e.g. established by reactor experiment)

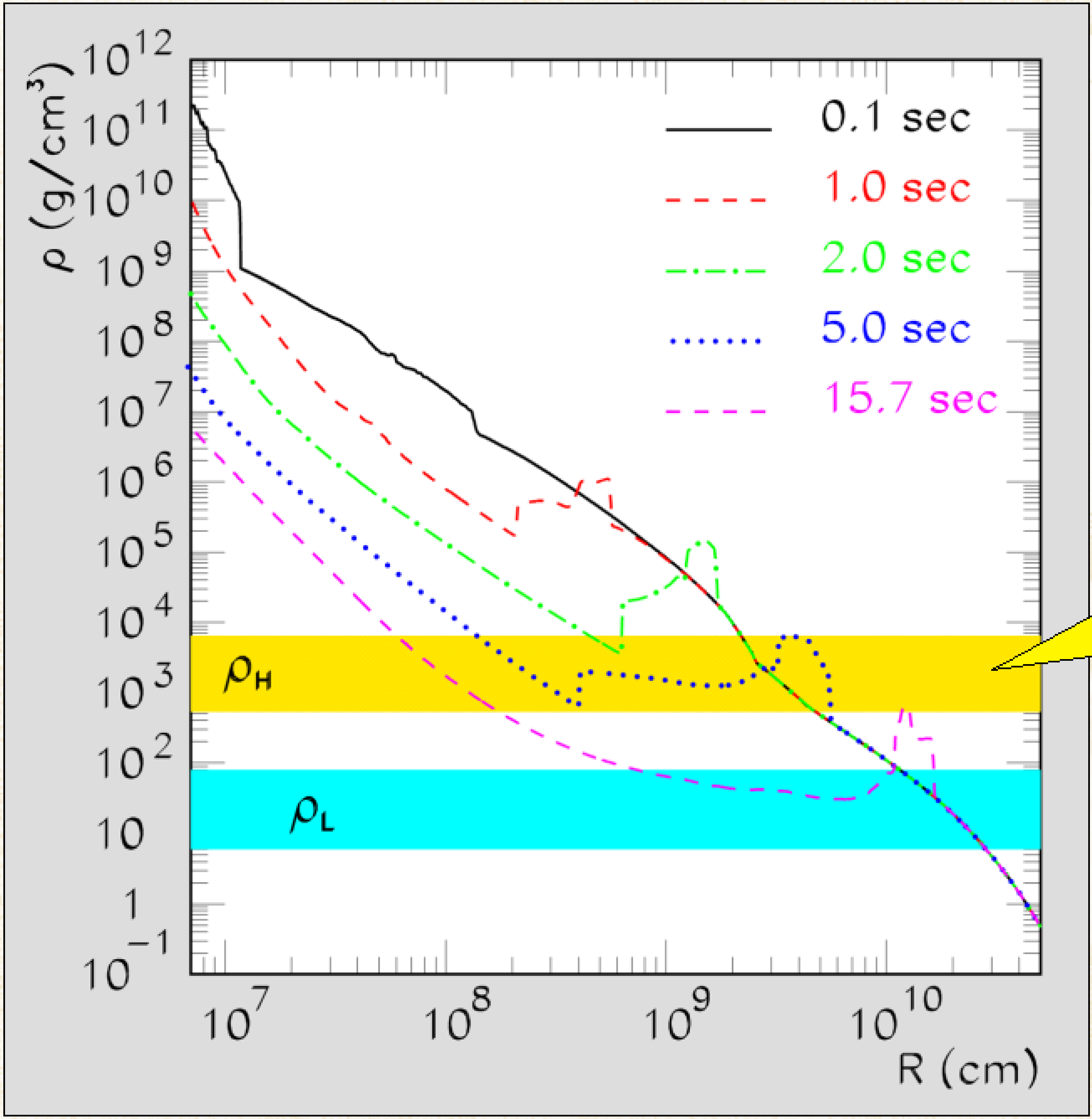
Two-Detector Sky Coverage with Super-K & IceCube



Dighe, Keil, Raffelt hep-ph/0303210

Earth effects appear in				
	IceCube	A	35%	Suitable for two-detector method
Super-K		B	35%	Suitable for two-detector method
Super-K	IceCube	C	15%	Approx. same signal in both detectors
		D	15%	Approx. same signal in both detectors

Supernova Shock Propagation and Neutrino Oscillations



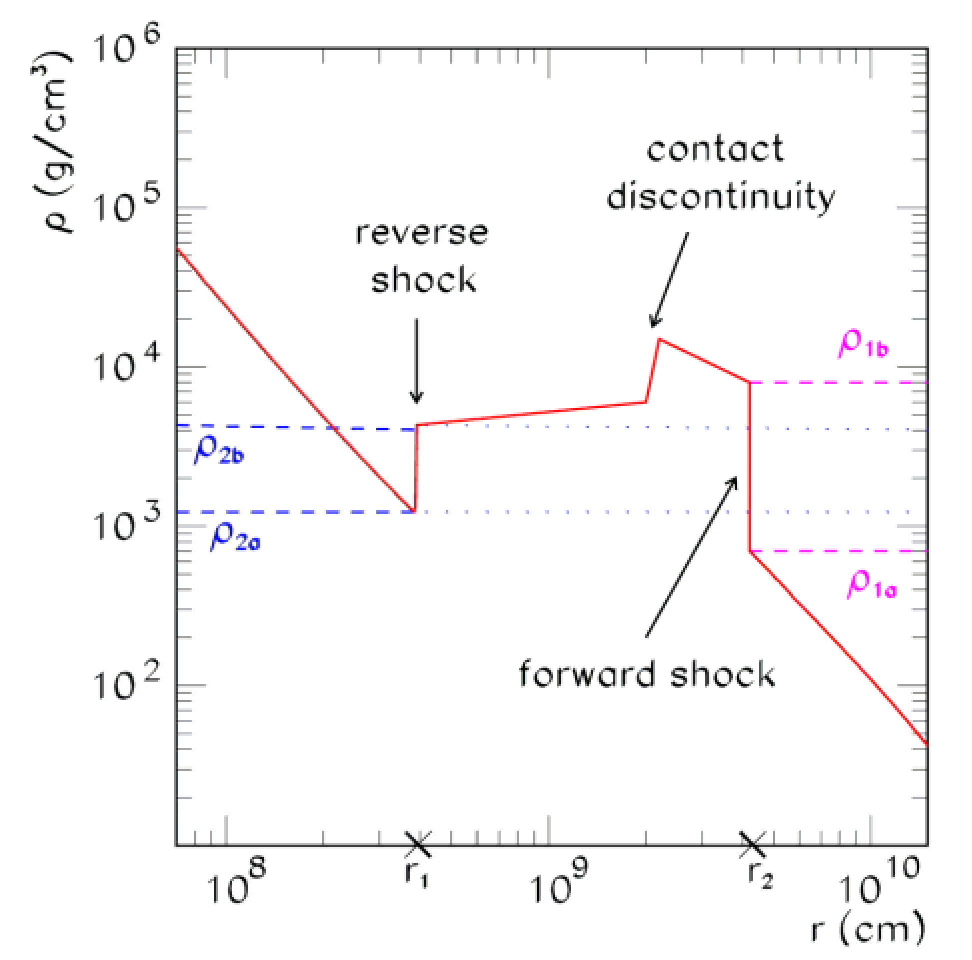
Schirato & Fuller: Connection between supernova shocks, flavor transformation, and the neutrino signal [astro-ph/0205390]

Resonance density for Δm^2_{atm}

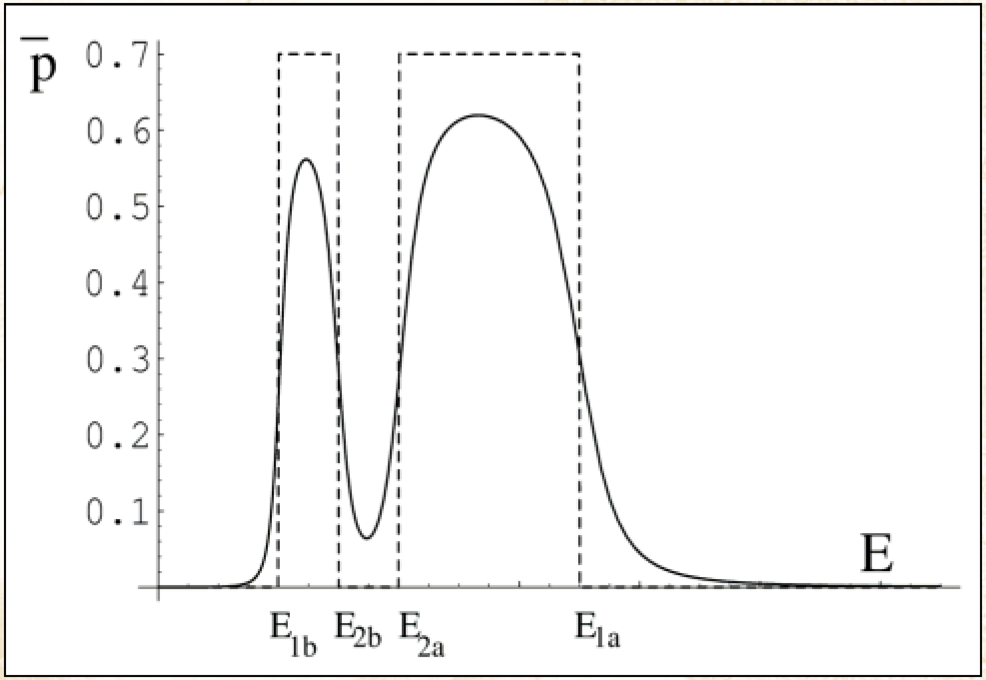
R. Tomàs, M. Kachelriess, G. Raffelt, A. Dighe, H.-T. Janka & L. Scheck: Neutrino signatures of supernova forward and reverse shock propagation [astro-ph/0407132]

Double-Dip Survival Probability

Schematic forward and reverse shock profile

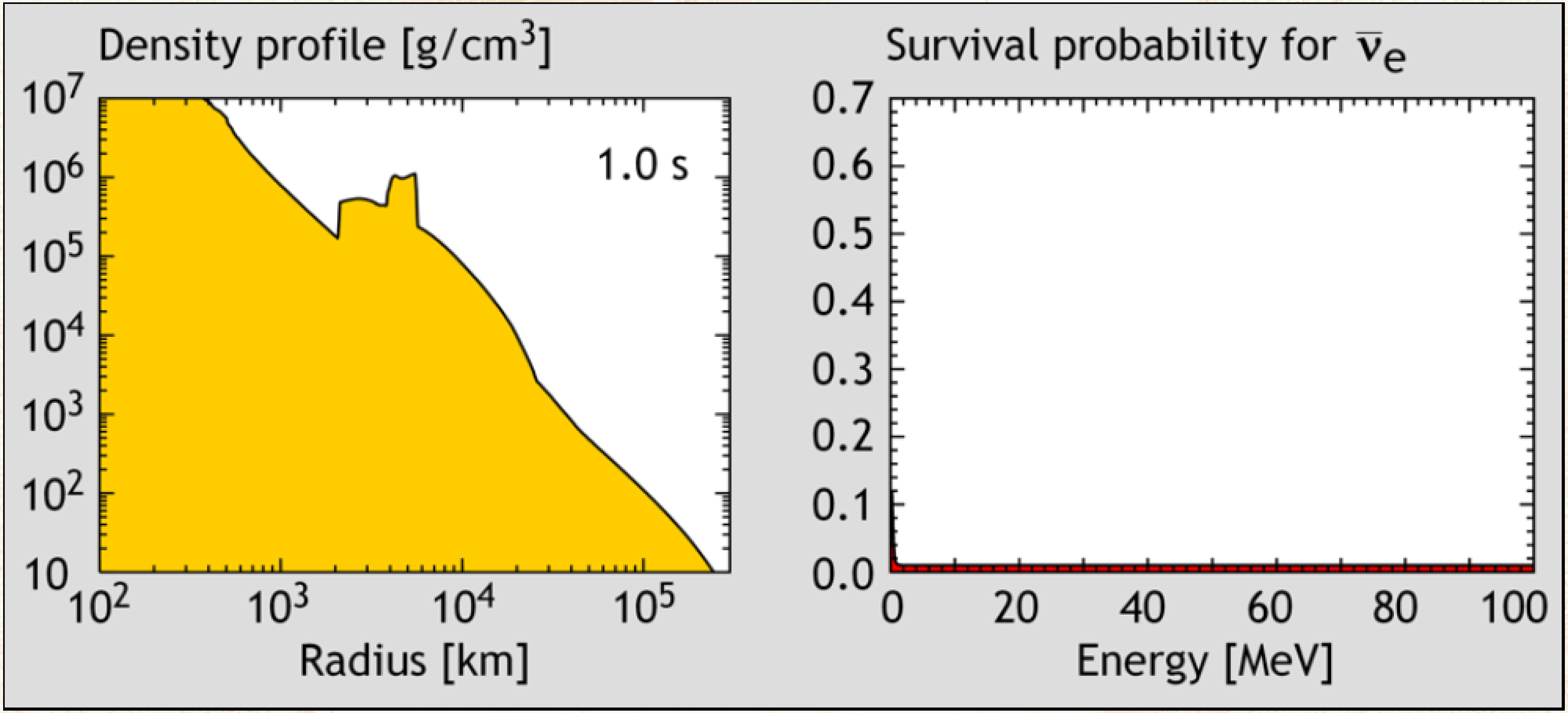


Survival probability for $\bar{\nu}_e$

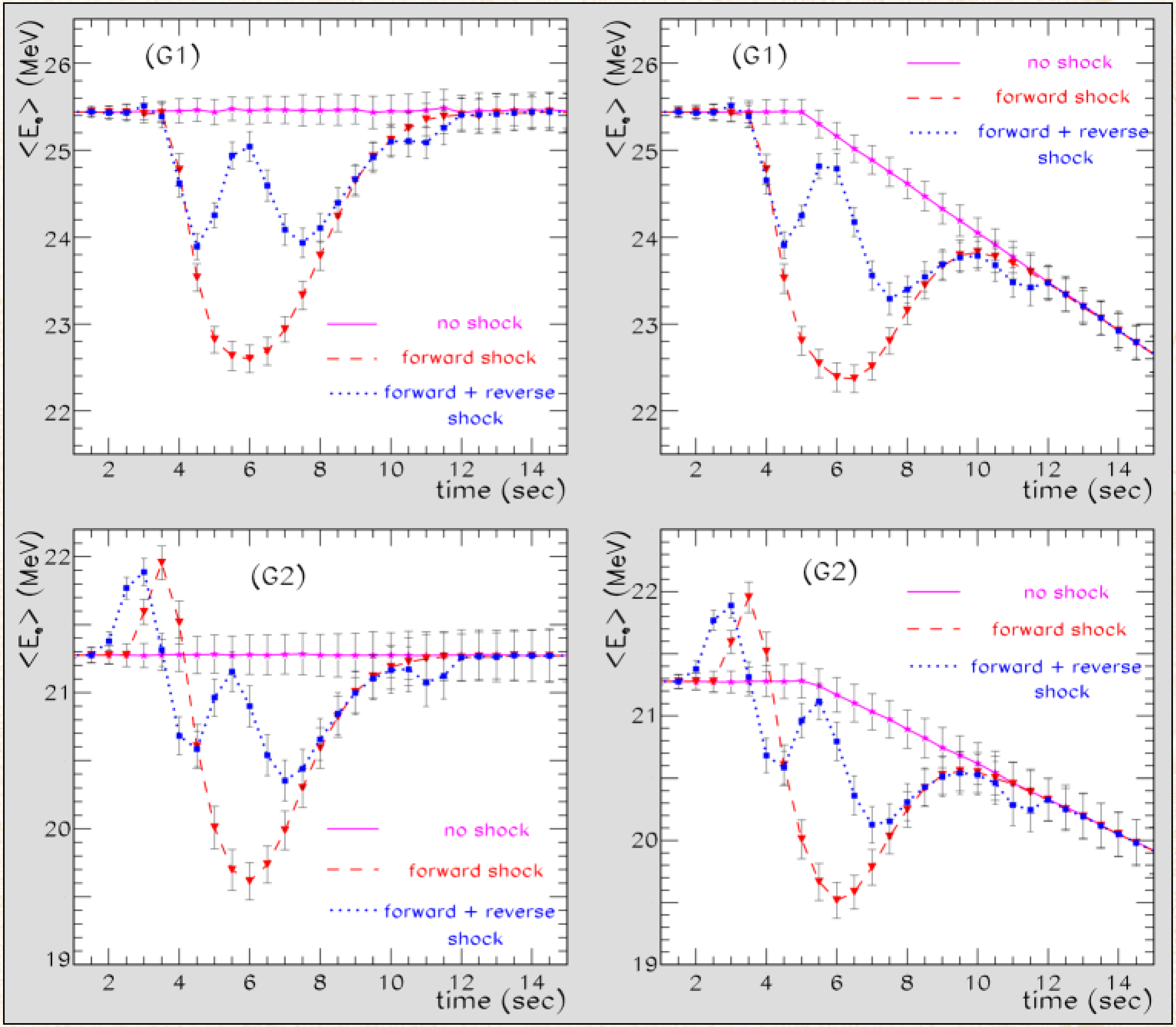


Adiabaticity is broken twice, leading to a characteristic double-dip $\bar{\nu}_e$ survival probability as a function of energy

Shock-Wave Propagation and Survival Probability



Signature in a Megatonne Cherenkov Detector



$$\frac{\mathrm{Flux}(\bar{\nu}_e)}{\mathrm{Flux}(\bar{\nu}_x)} = 0.8$$

$E_0(\bar{\nu}_e) = 15\,\mathrm{MeV}$

$E_0(\bar{\nu}_x) = 18\,\mathrm{MeV}$

$$\frac{\mathrm{Flux}(\bar{\nu}_e)}{\mathrm{Flux}(\bar{\nu}_x)} = 0.5$$

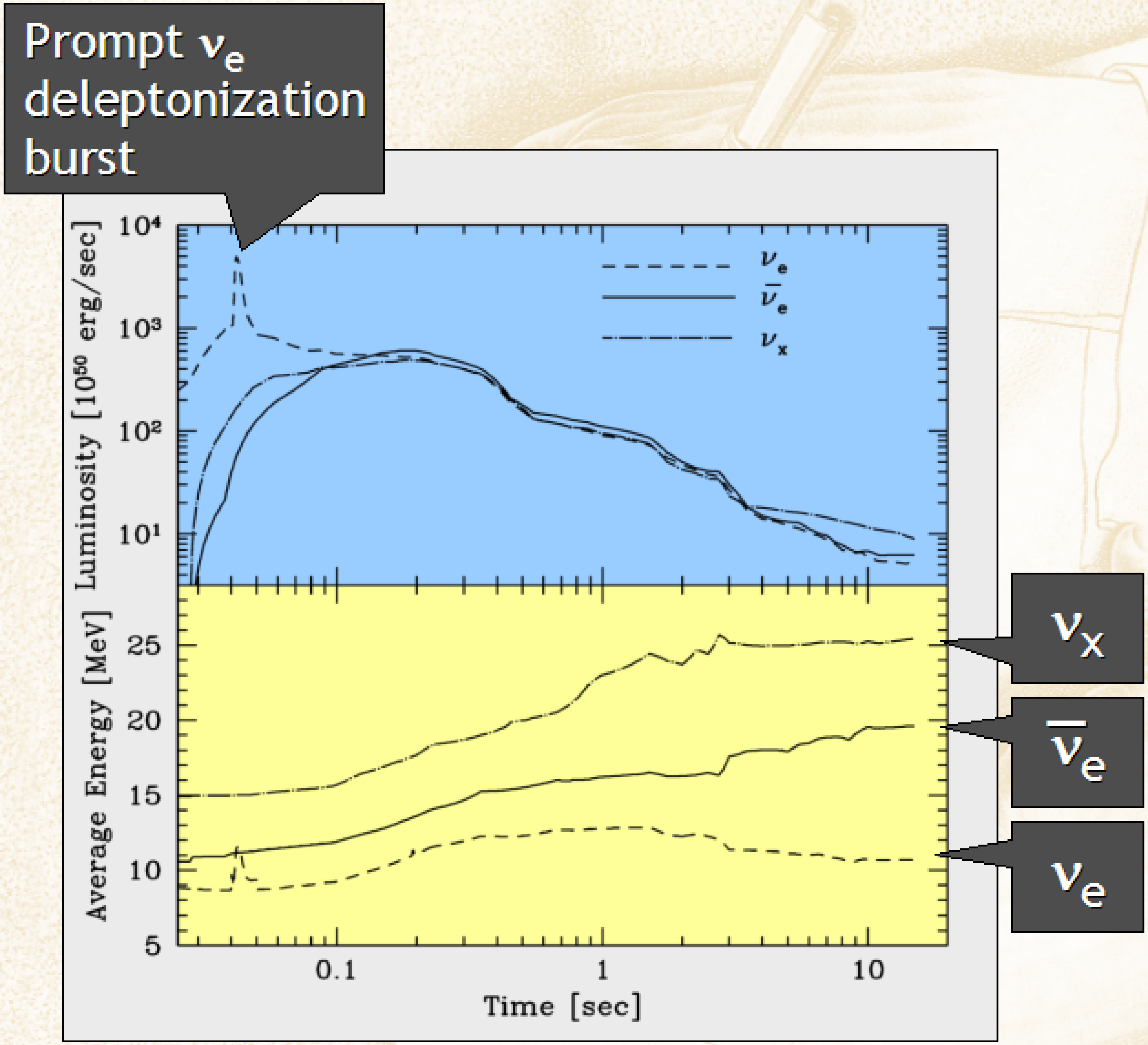
$E_0(\bar{\nu}_e) = 15\,\mathrm{MeV}$

$E_0(\bar{\nu}_x) = 15\,\mathrm{MeV}$

Observable Features in a Water Cherenkov Detector

Case	Mass ordering	$\sin^2(2\Theta_{13})$	p	$\bar{p}$	Observable effects in $\bar{\nu}_e$ channel
A	Normal	$\gtrsim 10^{-3}$	0	$\cos^2(\Theta_{12})$	Earth effects
B	Inverted		$\sin^2(\Theta_{12})$	0	Shock-wave propagation
C	Any	$\lesssim 10^{-5}$	$\sin^2(\Theta_{12})$	$\cos^2(\Theta_{12})$	Earth effects

Flavor-Dependent Fluxes and Spectra



Livermore numerical model
ApJ 496 (1998) 216

Broad characteristics

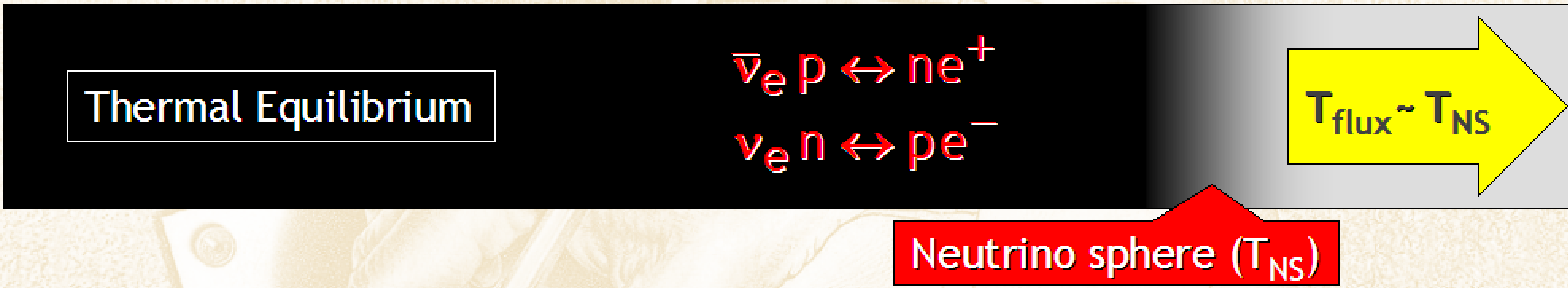
- Duration a few seconds
- $\langle E_\nu \rangle$ ~ 10–20 MeV
- $\langle E_\nu \rangle$ increases with time
- Hierarchy of energies

$$\langle E_{\nu_e} \rangle < \langle E_{\bar{\nu}_e} \rangle < \langle E_{\nu_x} \rangle$$

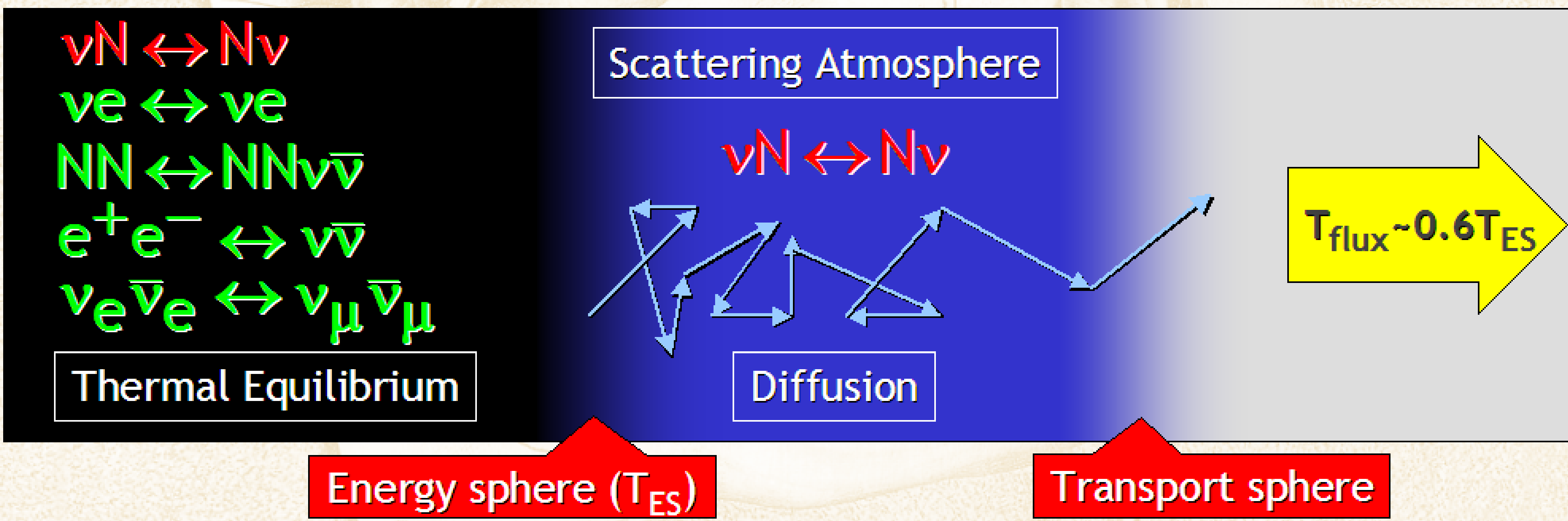
- Approximate equipartition of energy between flavors

Supernova Neutrino Spectra Formation

Electron flavor $(\nu_e, \bar{\nu}_e)$



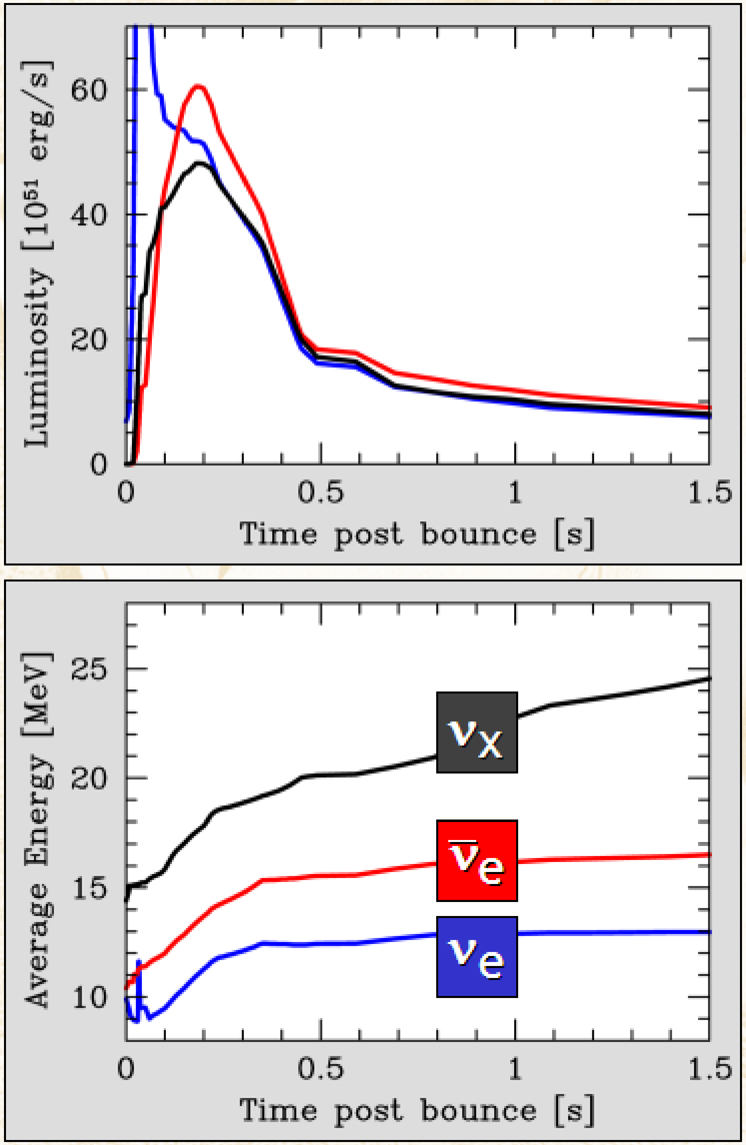
Other flavors $(\nu_\mu, \nu_\tau, \bar{\nu}_\mu, \bar{\nu}_\tau)$



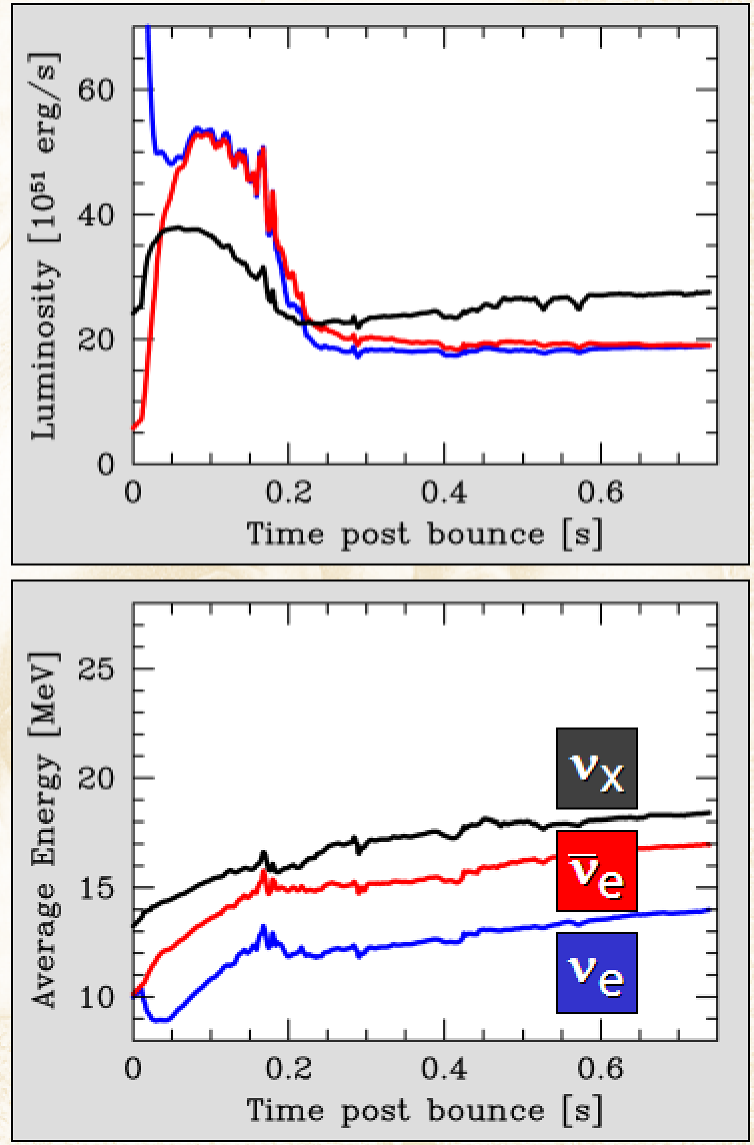
Raffelt (astro-ph/0105250), Keil, Raffelt & Janka (astro-ph/0208035)

Fluxes and Spectra from Numerical Simulations

Livermore (traditional)
[ApJ 496 (1998) 216]

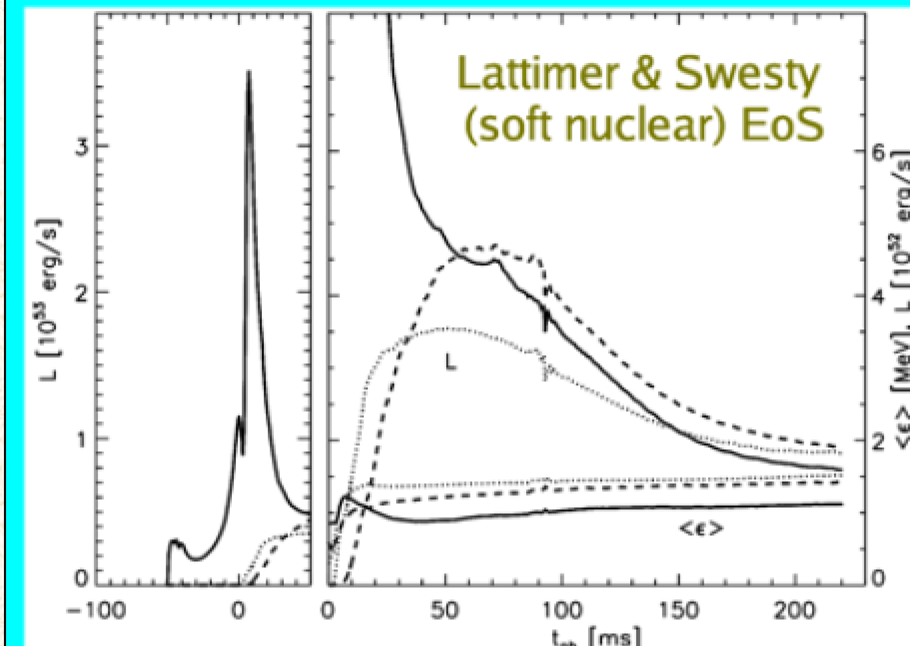


Garching (new microphyiscs)
[astro-ph/0303226]

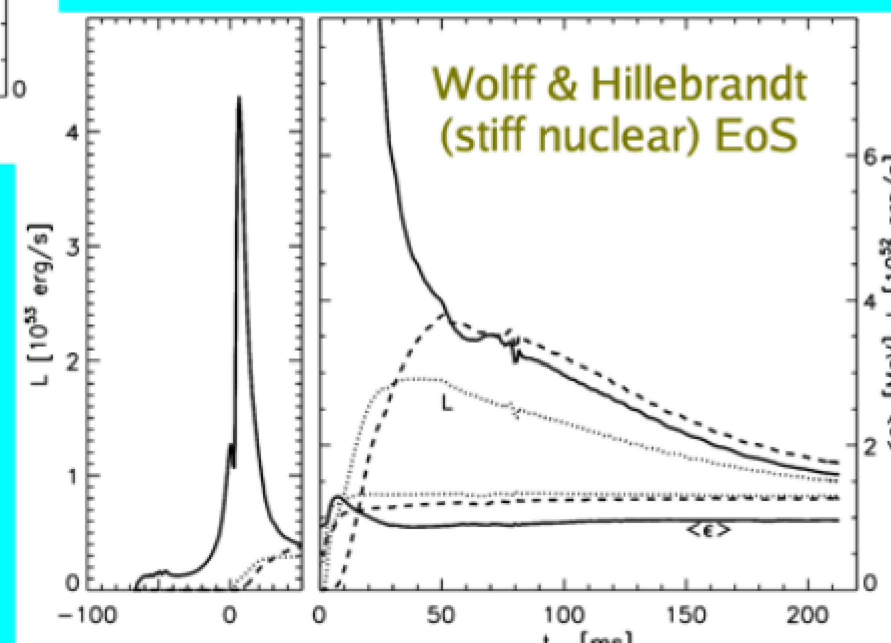


Exploding Models with O-Ne-Mg Cores (Janka et al. 2005)

1D Simulations: ONeMg Core



Neutrino luminosities
and
mean energies

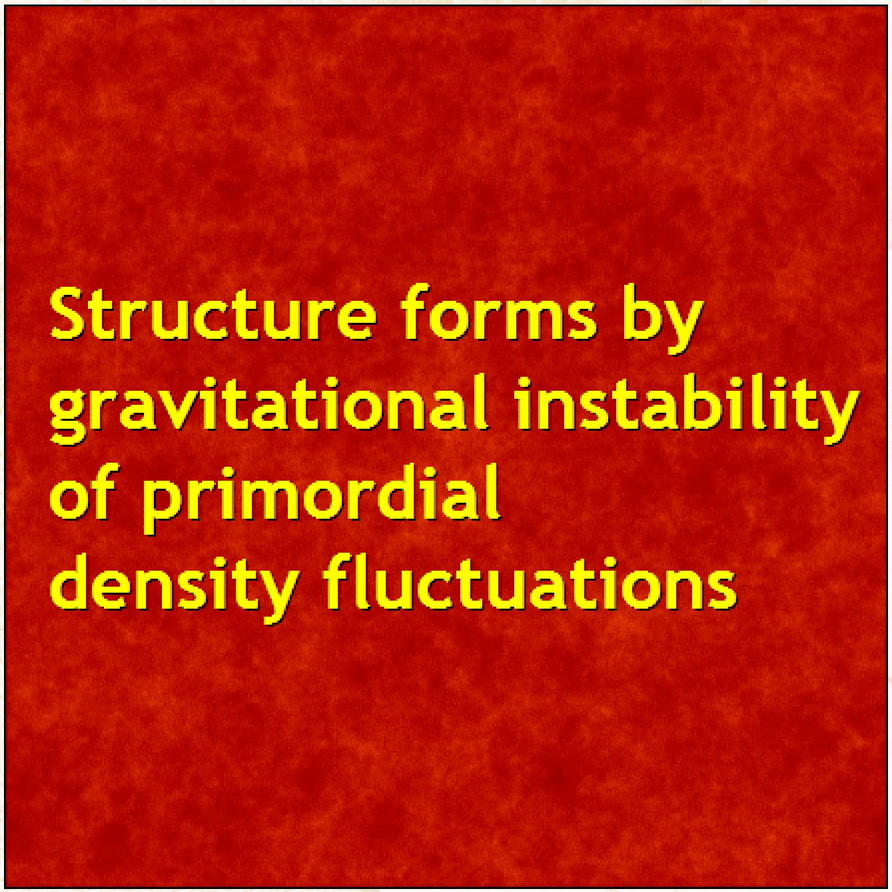


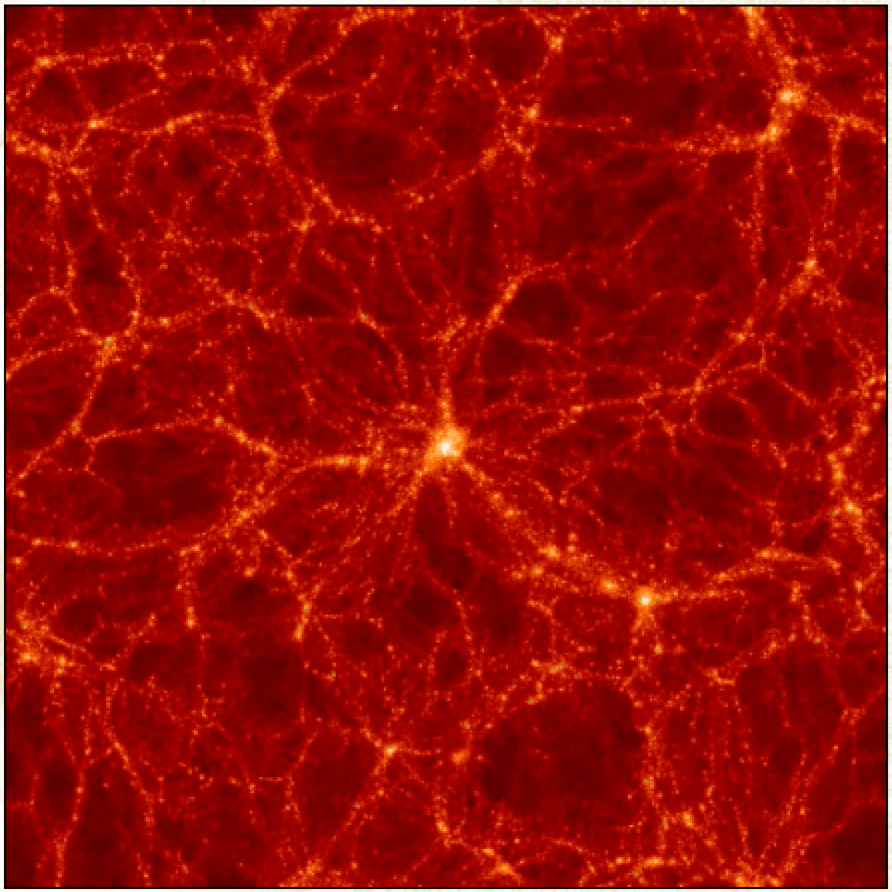
- solid: electron neutrinos
- dashed: electron antineutrinos
- dotted: heavy-lepton neutrinos

Neutrino Dark Matter

Formation of Structure

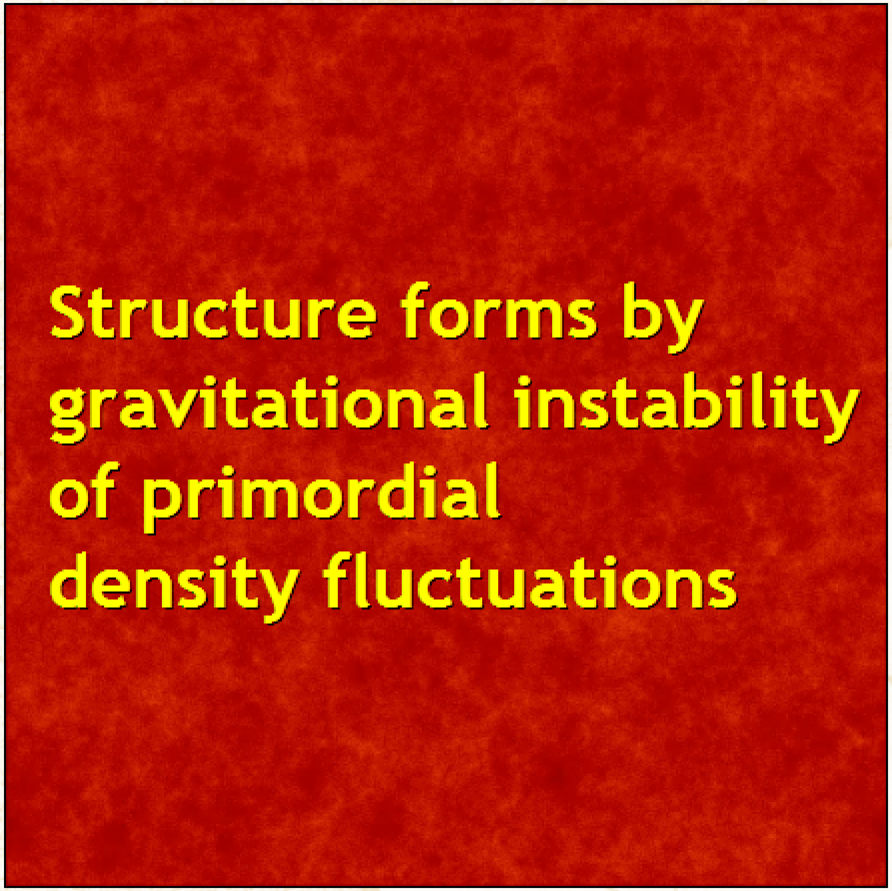
Smooth	→	Structured

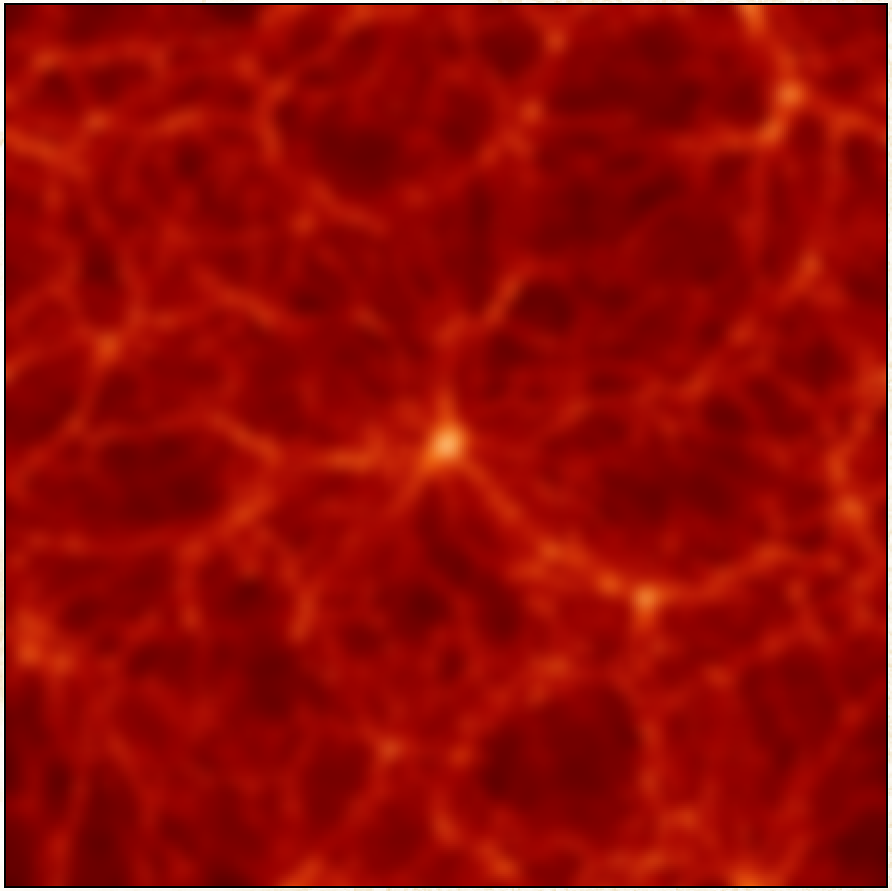




Formation of Structure

Smooth	→	Structured





A fraction of hot dark matter suppresses small-scale structure

Processed Power Spectrum in Cold Dark Matter Scenario

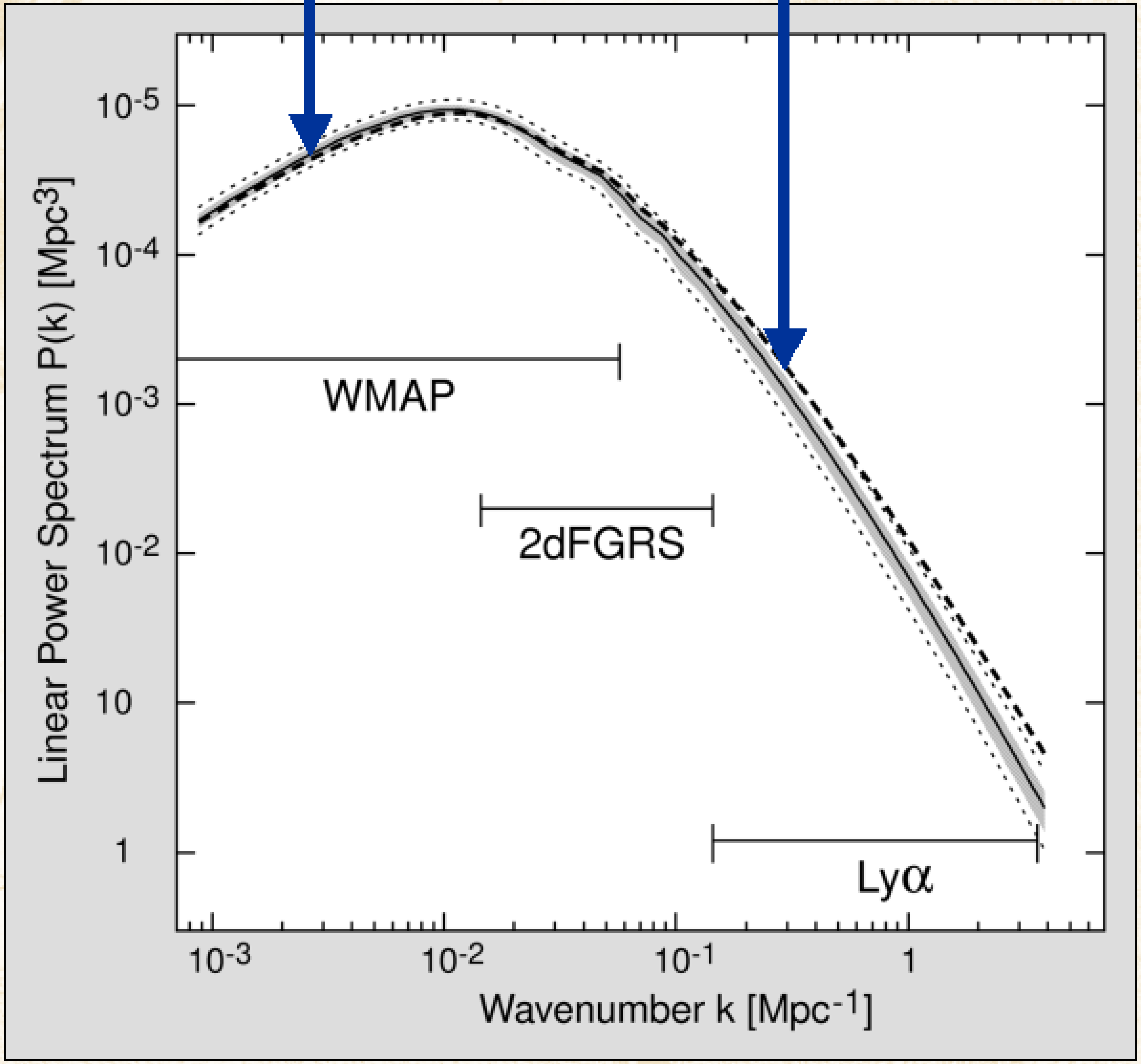
Primordial spectrum usually assumed to be of power-law form

$$P(k) = |\delta_k|^2 \propto k^n$$

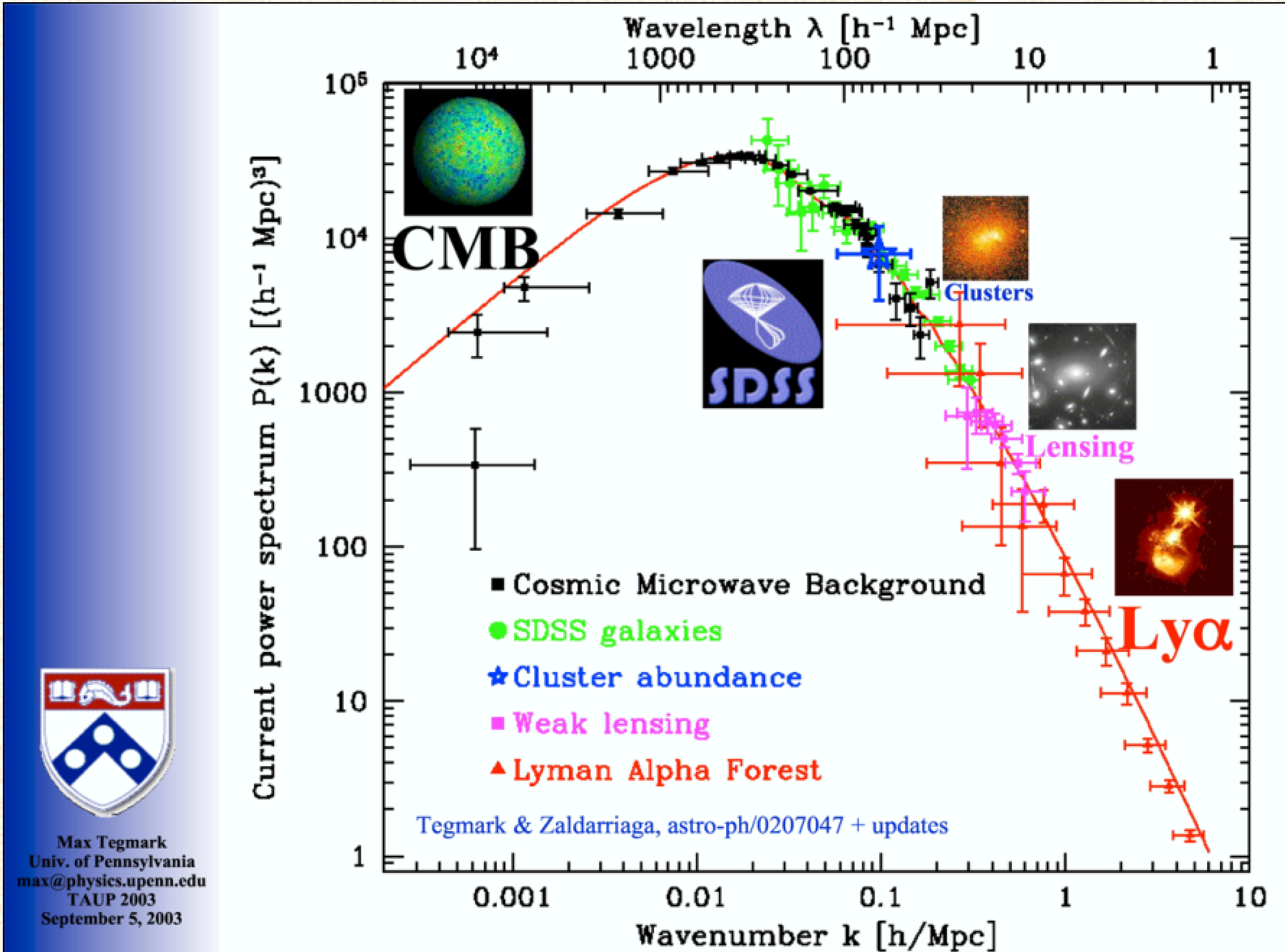
Harrison-Zeldovich ("flat") spectrum
$n = 1$
expected from inflation (may be slightly less than 1, depending on details of inflationary phase)

Primordial spectrum

Suppressed by stagnation during radiation phase

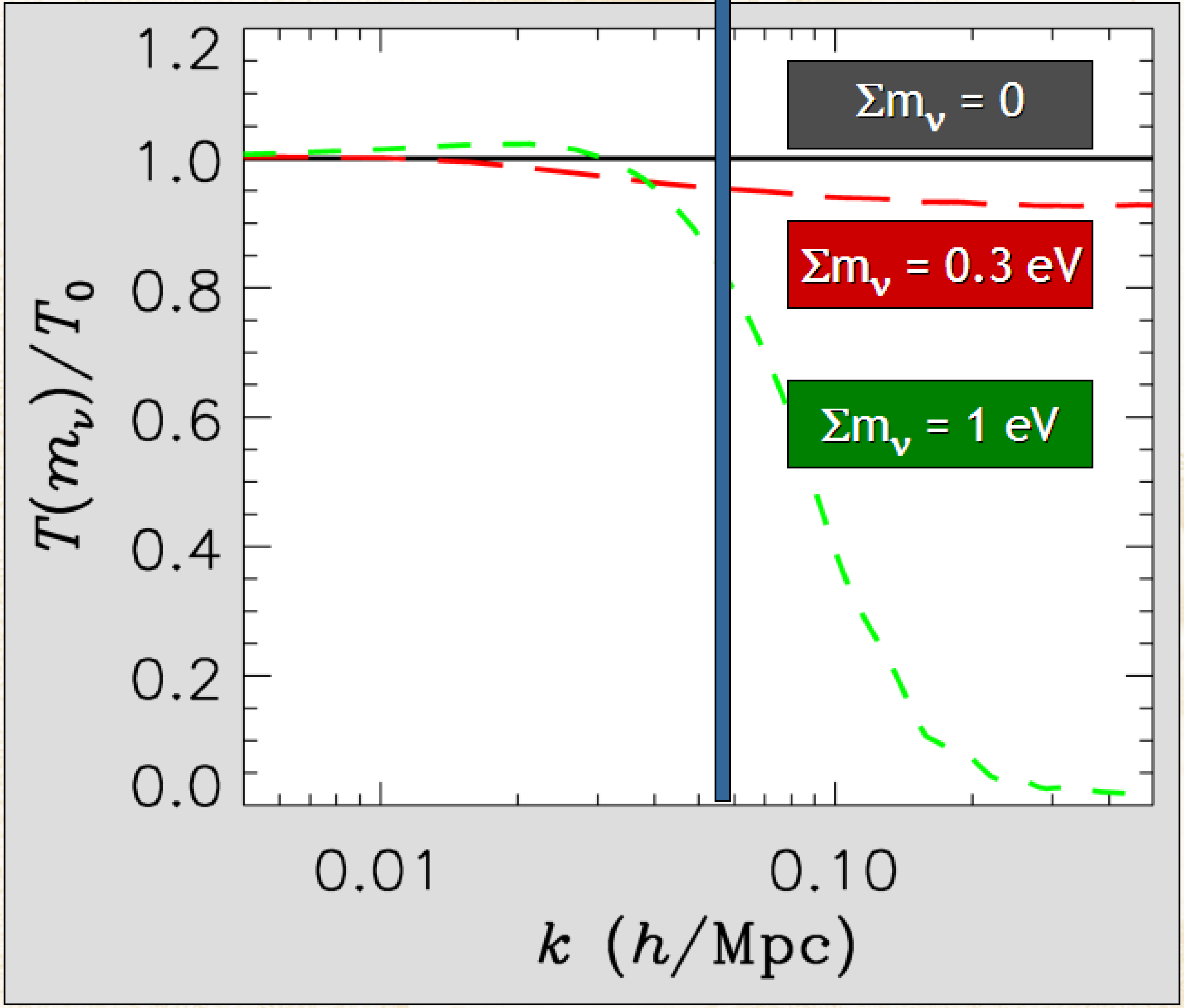


Power Spectrum of Cosmic Density Fluctuations



Neutrino Free Streaming - Transfer Function

Power suppression for $\lambda_{FS} \lesssim 100$ Mpc/h



Transfer function

$P(k) = T(k)\, P_0(k)$

Effect of neutrino free streaming on small scales

$T(k) = 1 - 8\Omega_\nu/\Omega_M$

valid for

$8\Omega_\nu/\Omega_M \ll 1$

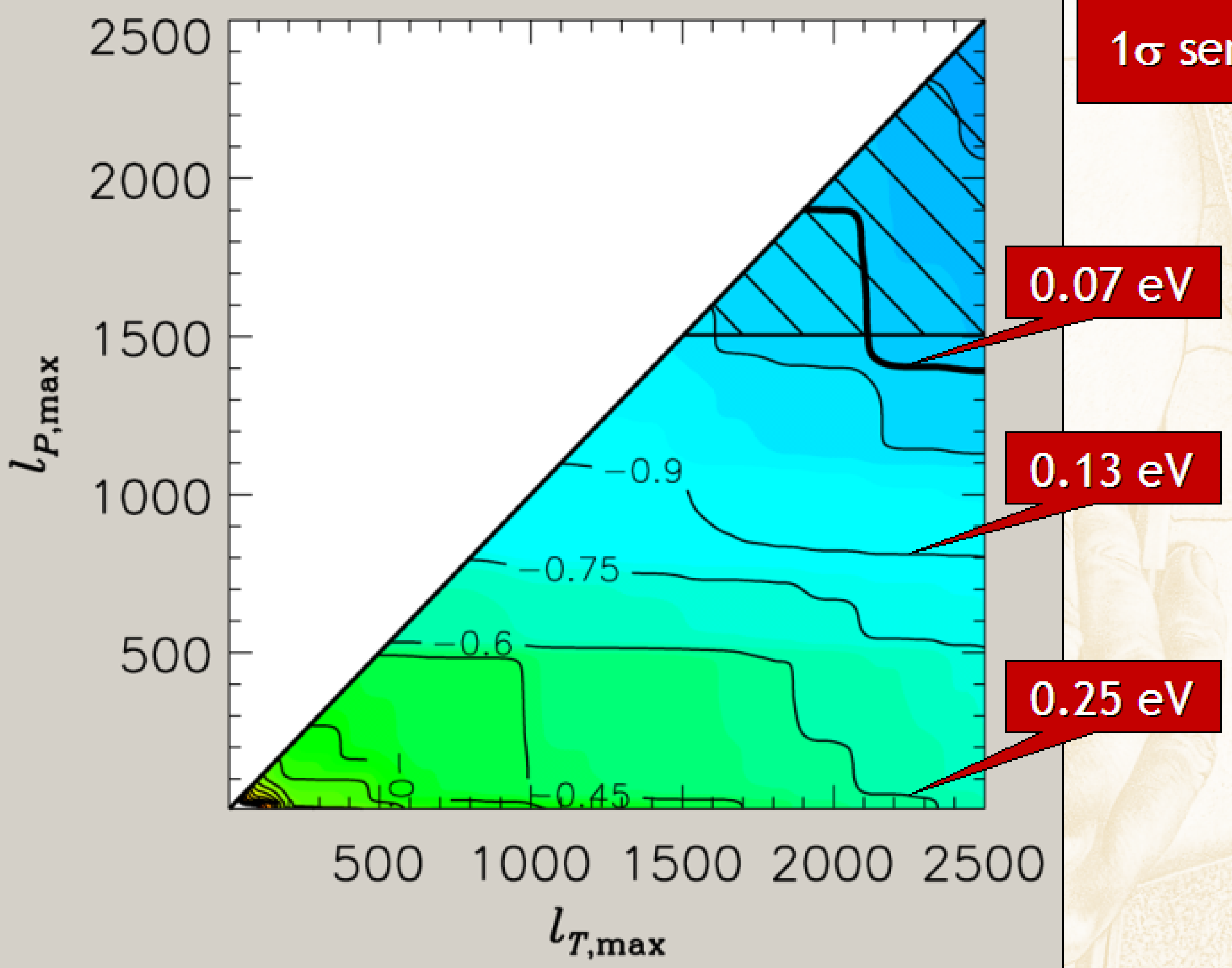
Hannestad, Neutrinos in Cosmology, hep-ph/0404239

Recent Cosmological Limits on Neutrino Masses

Authors	Σm_ν/eV (limit 95%CL)	Data / Priors
Spergel et al. (WMAP) 2003 [astro-ph/0302209]	0.69	WMAP, CMB, 2dF, σ_8, HST
Hannestad 2003 [astro-ph/0303076]	1.01	WMAP, CMB, 2dF, HST
Tegmark et al. 2003 [astro-ph/0310723]	1.8	WMAP, SDSS
Barger et al. 2003 [hep-ph/0312065]	0.75	WMAP, CMB, 2dF, SDSS, HST
Crotty et al. 2004 [hep-ph/0402049]	1.0 0.6	WMAP, CMB, 2dF, SDSS & HST, SN
Hannestad 2004 [hep-ph/0409108]	0.65	WMAP, SDSS, SN Ia gold sample, Ly-α data from Keck sample
Seljak et al. 2004 [astro-ph/0407372]	0.42	WMAP, SDSS, Bias, Ly-α data from SDSS sample

PLANCK Sensitivity to Neutrino Mass

Maximum polarization multipole that can be measured to cosmic-variance precision



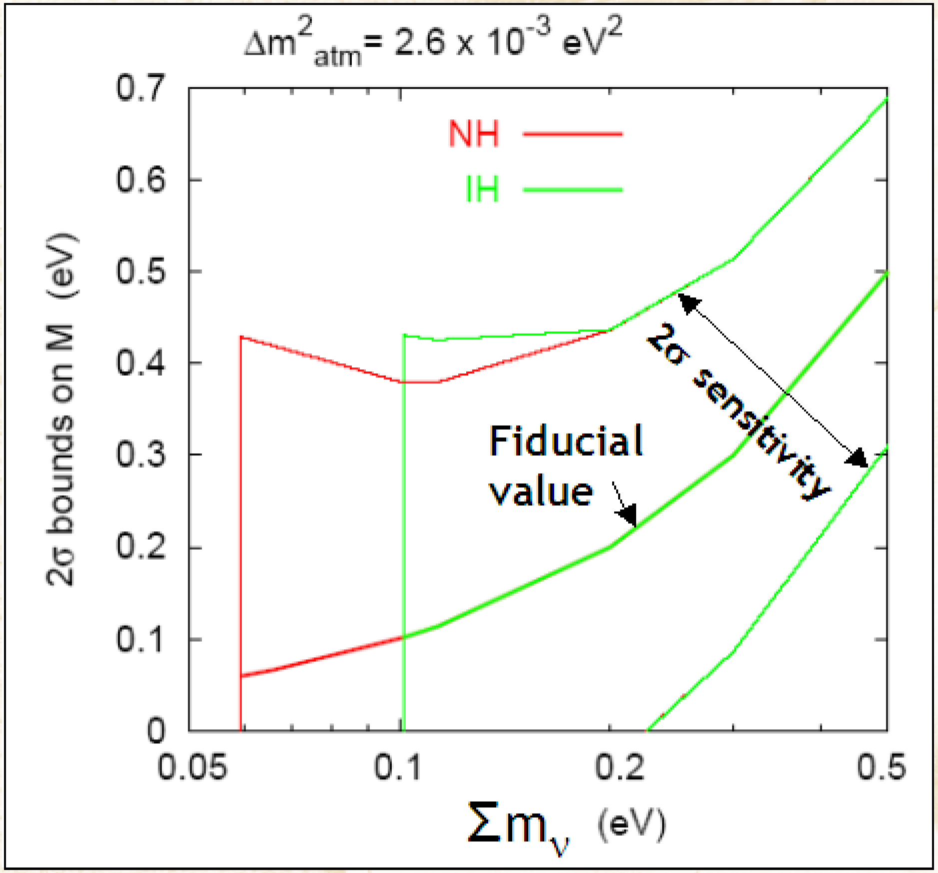
1σ sensitivity to Σm_ν

Maximum temperature multipole that can be measured to cosmic-variance precision

Steen Hannestad
astro-ph/0211106

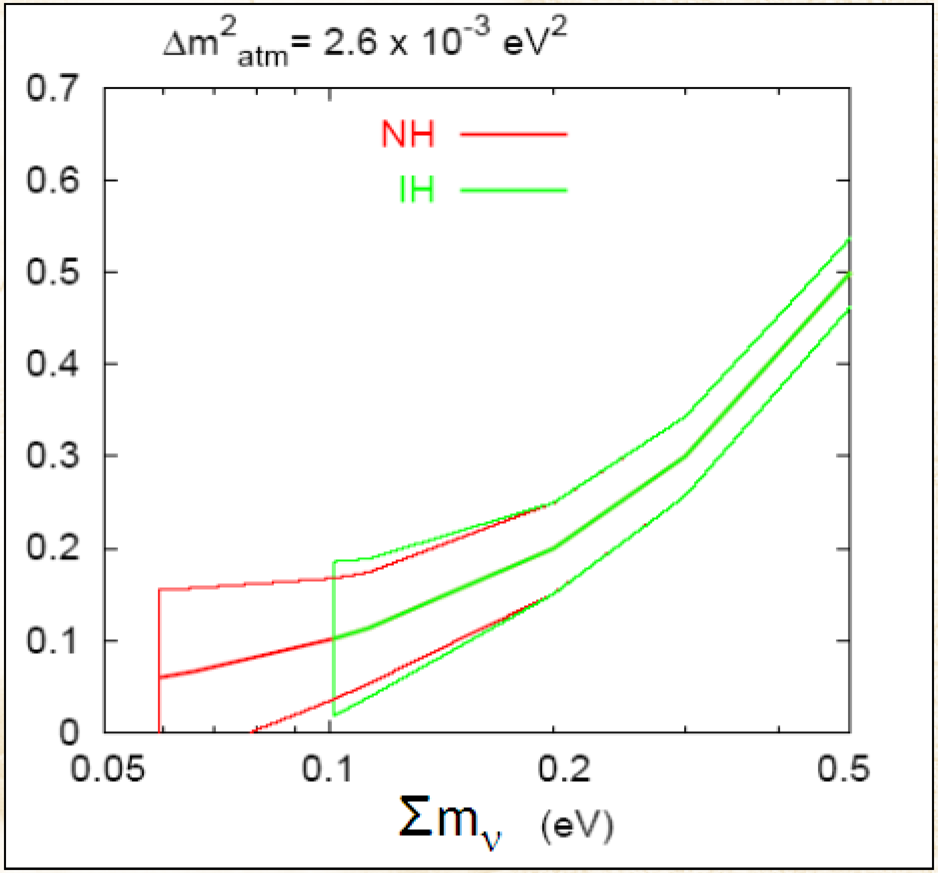
Probing Neutrino Masses with Future Redshift Surveys

Planck & SDSS



$\Sigma m_\nu > 0.21$ eV detectable at 2σ

Ideal CMB & 40 × SDSS



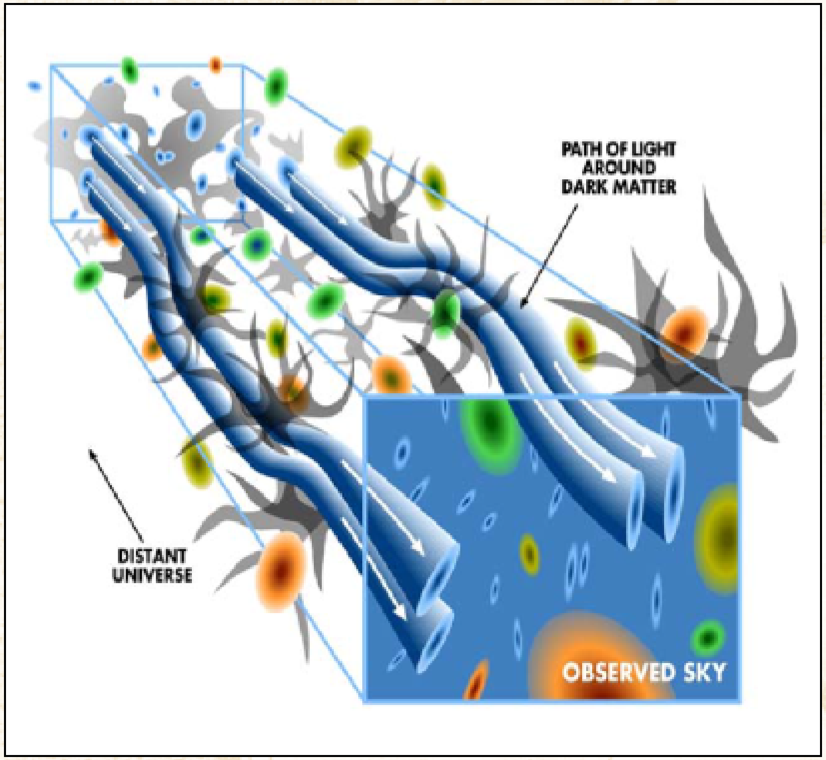
$\Sigma m_\nu > 0.13$ eV detectable at 2σ

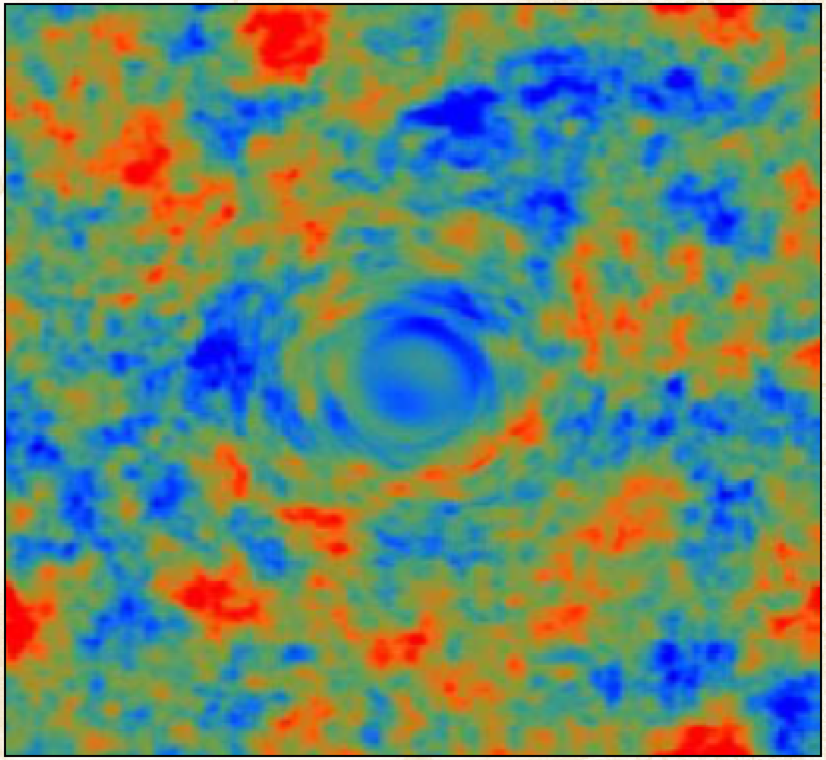
Lesgourgues, Pastor & Perotto, hep-ph/0403296

Possible Sensitivity from Weak Lensing

Weak galaxy lensing
- No bias uncertainty
- Small scales in linear regime

CMB lensing
Sensitive to much smaller masses

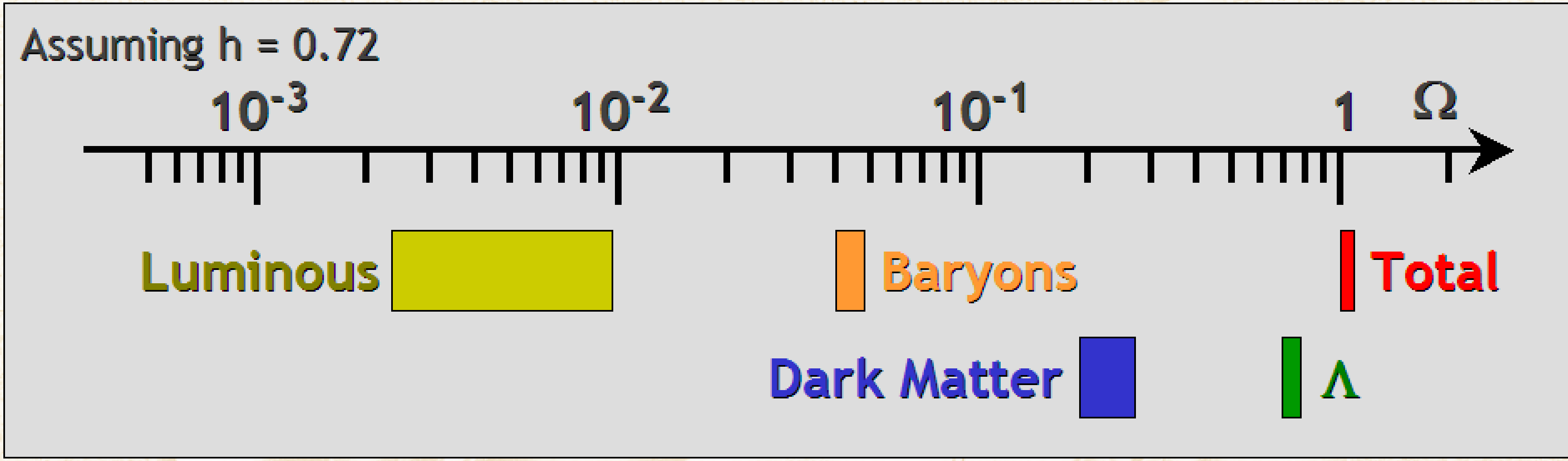


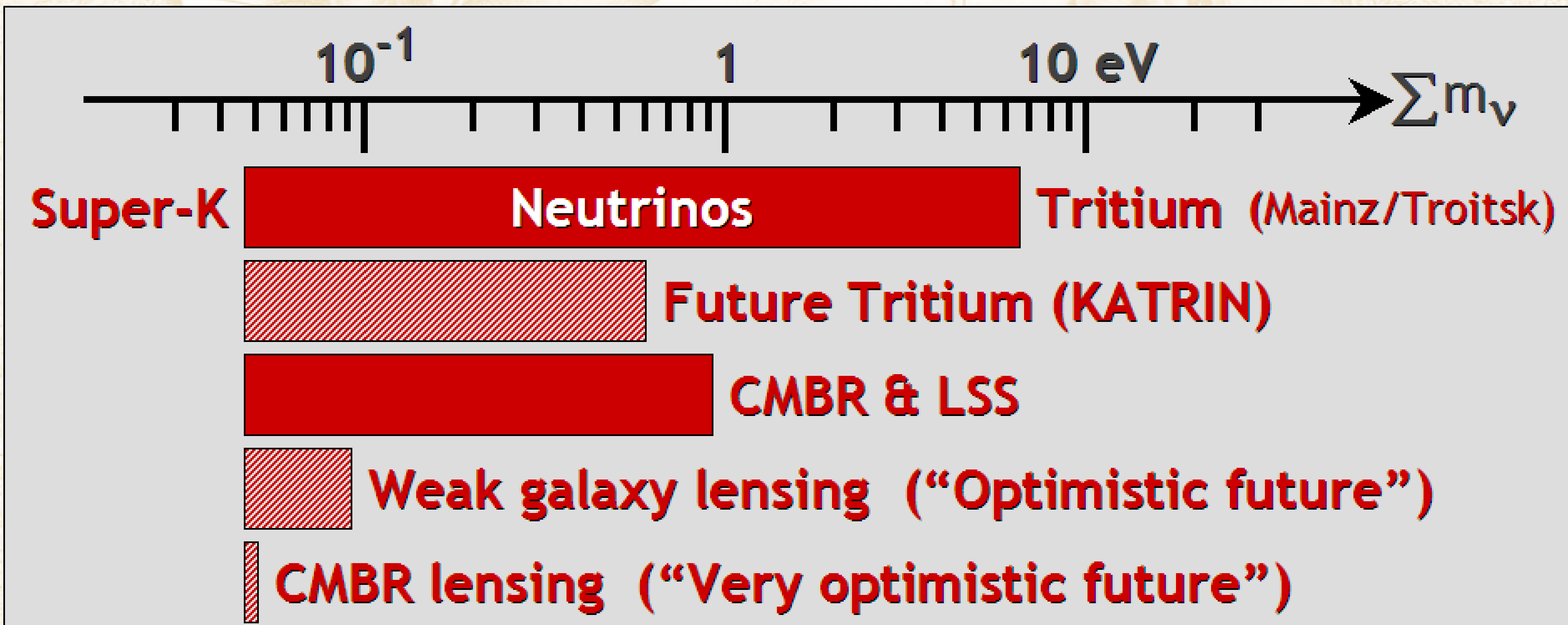


Future weak lensing survey
4000 deg^2
$\sigma(m_\nu) \sim 0.1$ eV
Abazajian & Dodelson
astro-ph/0212216

Primary and lensing
$\sigma(m_\nu) \sim 0.15$ eV (Planck)
$\sigma(m_\nu) \sim 0.044$ eV (CMBpol)
Kaplinghat, Knox & Song,
astro-ph/0303344

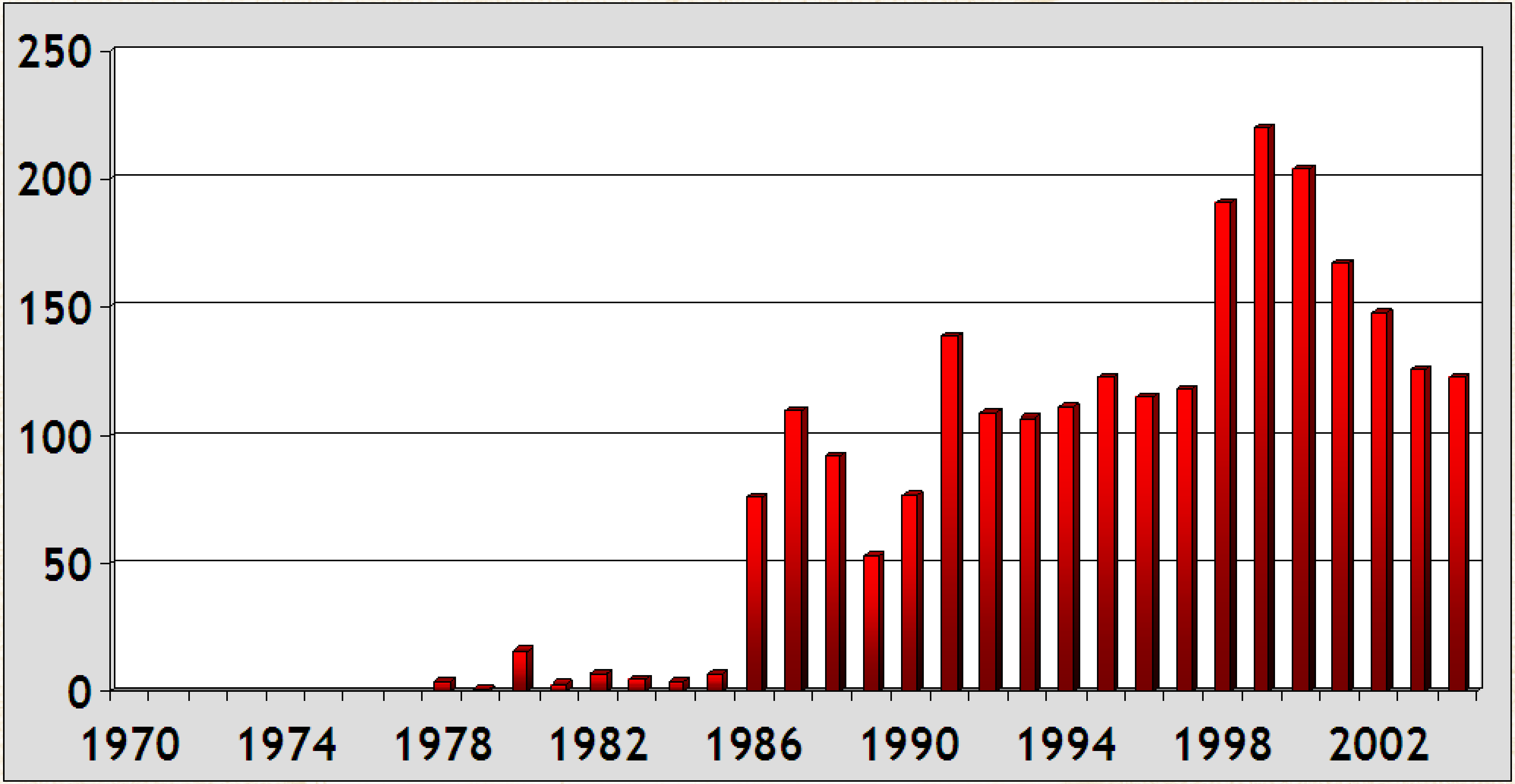
Mass-Energy-Inventory of the Universe





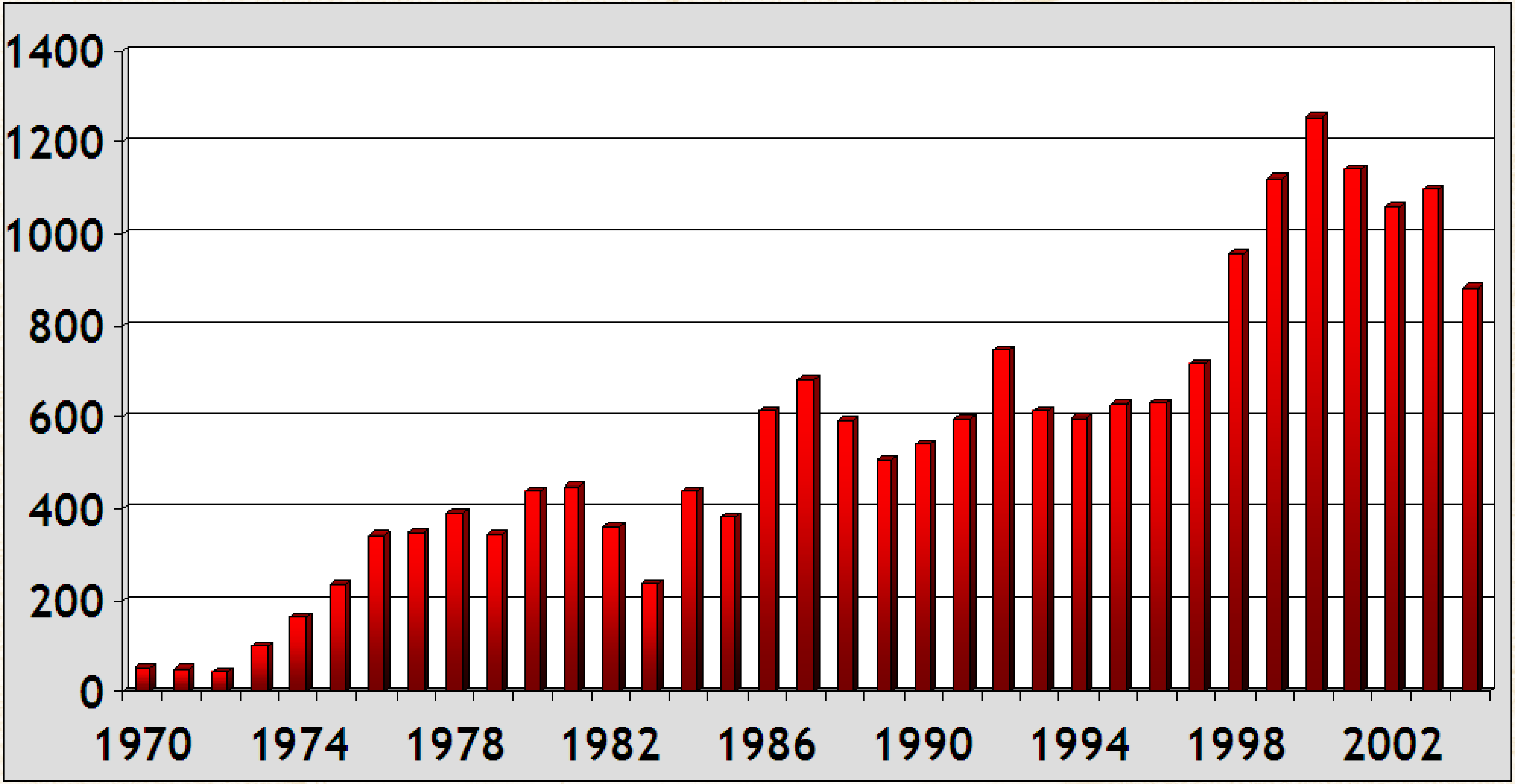
Neutrinos in the Next Decade - Bull or Bear?

Citations of Wolfenstein's Paper on Matter Effects



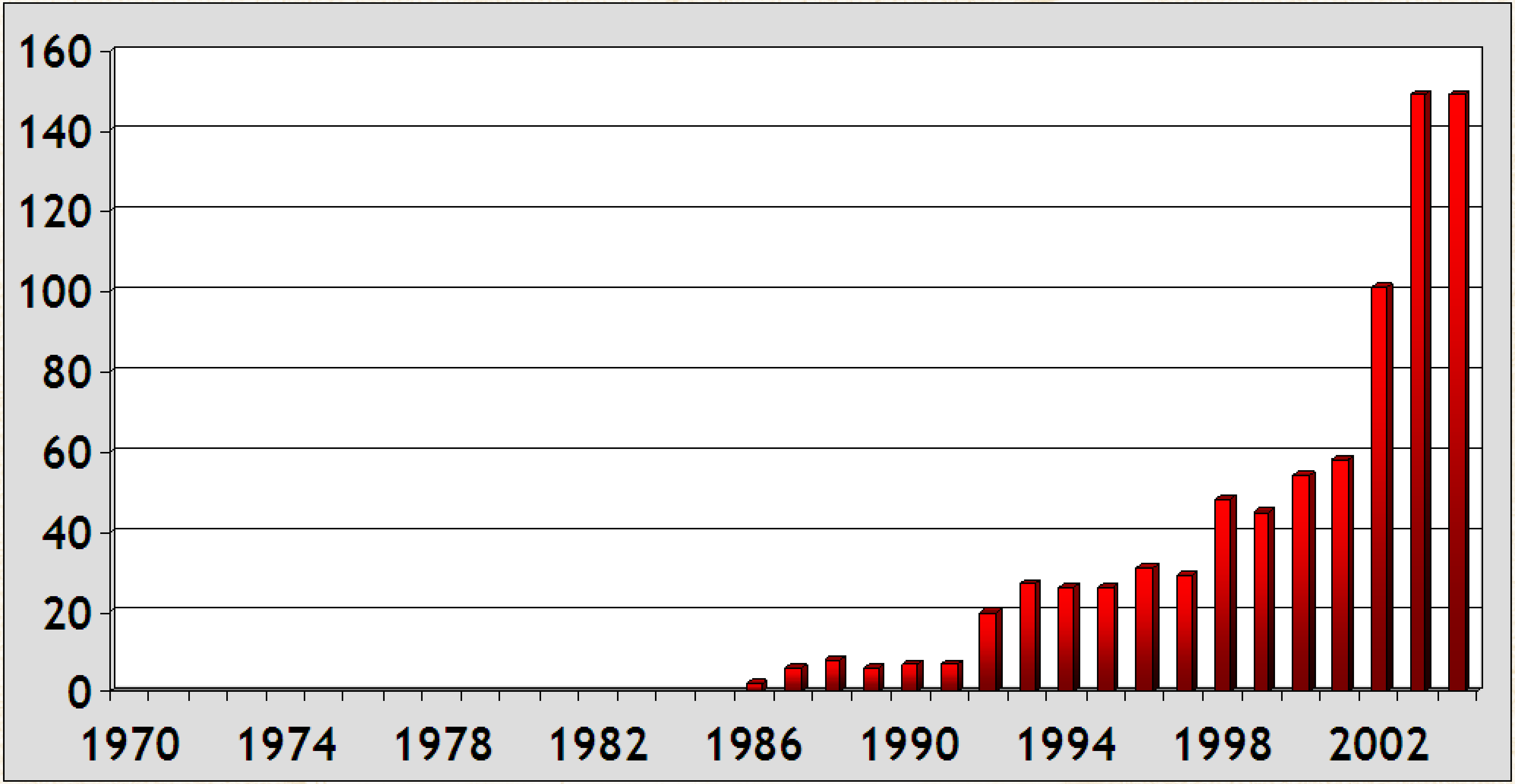
Annual citations of Wolfenstein, PRD 17:2369, 1978
in the SPIRES data base (total of 2456 citations 1978-2004)

Community Interest in Neutrinos



Papers with "Neutrino" in title
(SPIRES data base, 19486 "neutrino" papers 1970-2004)

Leptogenesis as a Research Topic



Citation of Fukugita & Yanagida, PLB 174 (1986) 45 or "leptogenesis" in title (SPIRES data base)

Wish List of "Bull Events" from Astro/Cosmo

Clear evidence for neutrino mass in 2β experiments, KATRIN, and cosmology
or conflicting signatures between these channels

High-statistics neutrino signal from a galactic supernova

Clear evidence for high-energy neutrino sources

First realistic idea for a direct detection of the cosmic neutrino background

Or a bull in unexpected guise ...