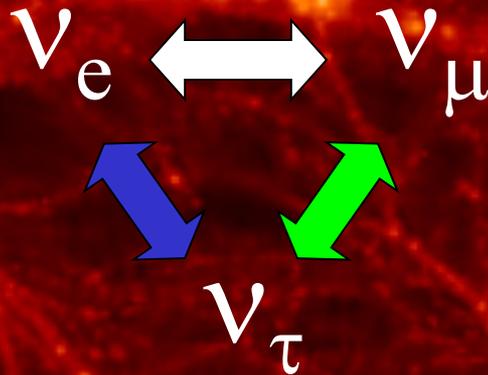


ASTROPHYSICAL NEUTRINOS



STEEN HANNESTAD, Aarhus University
GLA2011, JYVÄSKYLÄ

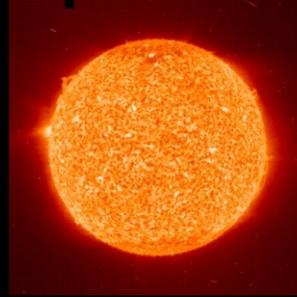
Where do Neutrinos Appear in Nature?



Nuclear Reactors



Sun



Particle Accelerators



Supernovae
(Stellar Collapse)

SN 1987A ✓

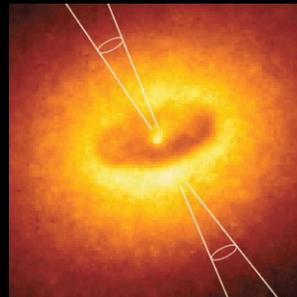


Earth Atmosphere
(Cosmic Rays)



Astrophysical
Accelerators

Soon ?



Earth Crust
(Natural
Radioactivity)

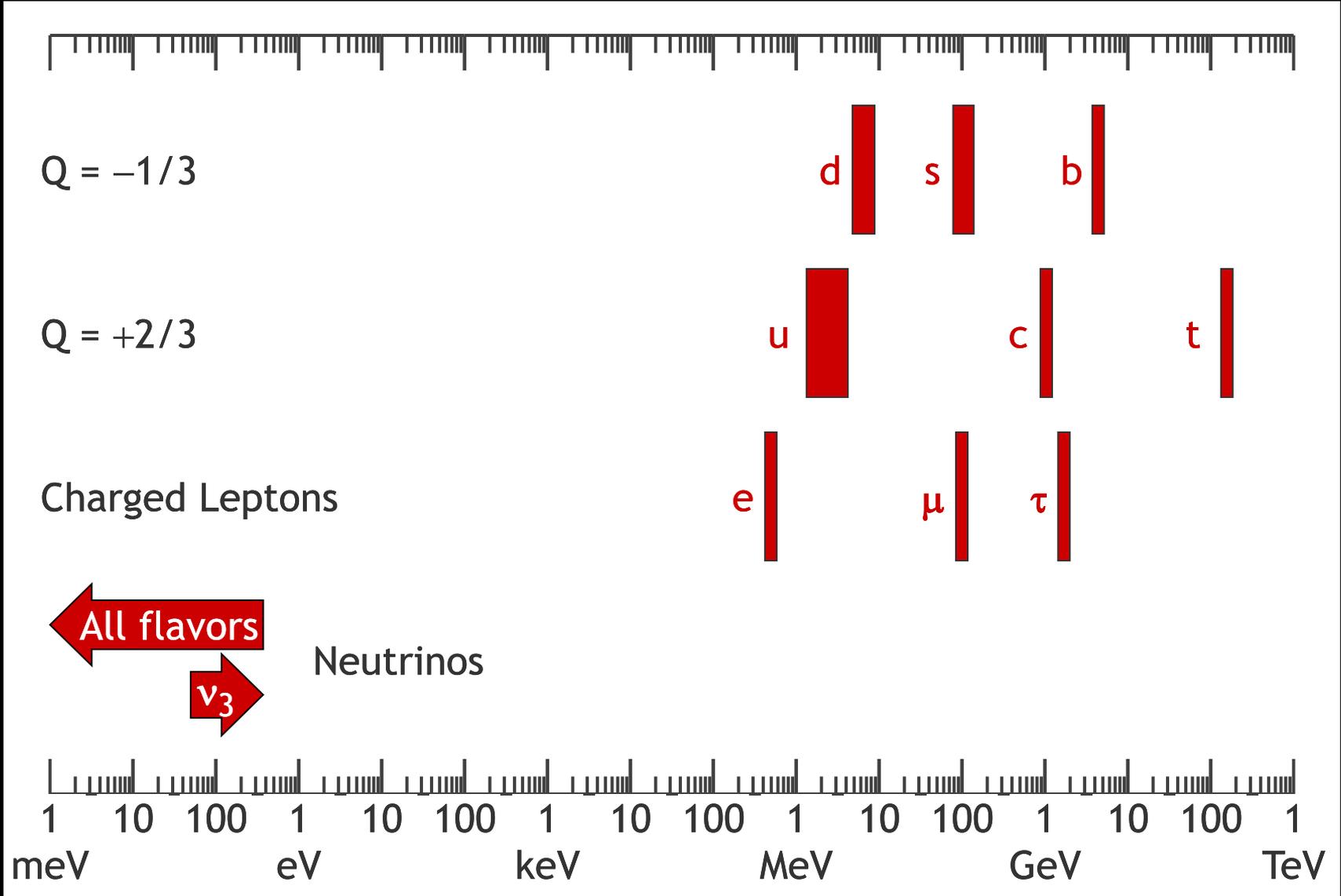


Cosmic Big Bang
(Today 330 v/cm^3)

Indirect Evidence



Fermion Mass Spectrum



FLAVOUR STATES

PROPAGATION STATES

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U \begin{pmatrix} \nu_1(m_1) \\ \nu_2(m_2) \\ \nu_3(m_3) \end{pmatrix}$$

MIXING MATRIX (UNITARY)

$$U = \begin{bmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{bmatrix} \quad \begin{matrix} c_{12} = \cos \theta_{12} \\ s_{12} = \sin \theta_{12} \end{matrix}$$

Sanduleak -69 202



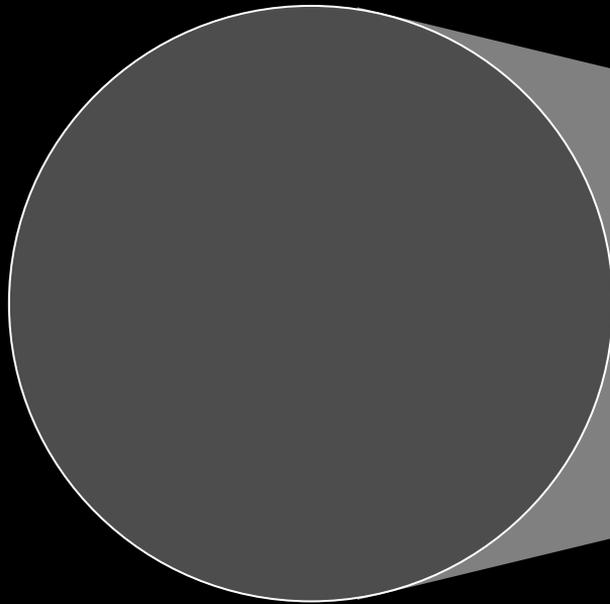
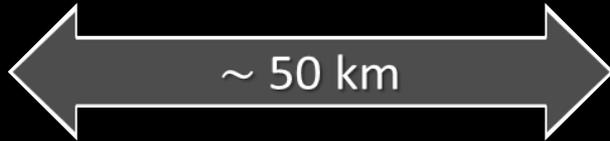
Supernova 1987A

23 February 1987



Stellar Collapse and Supernova Explosion

Newborn Neutron Star

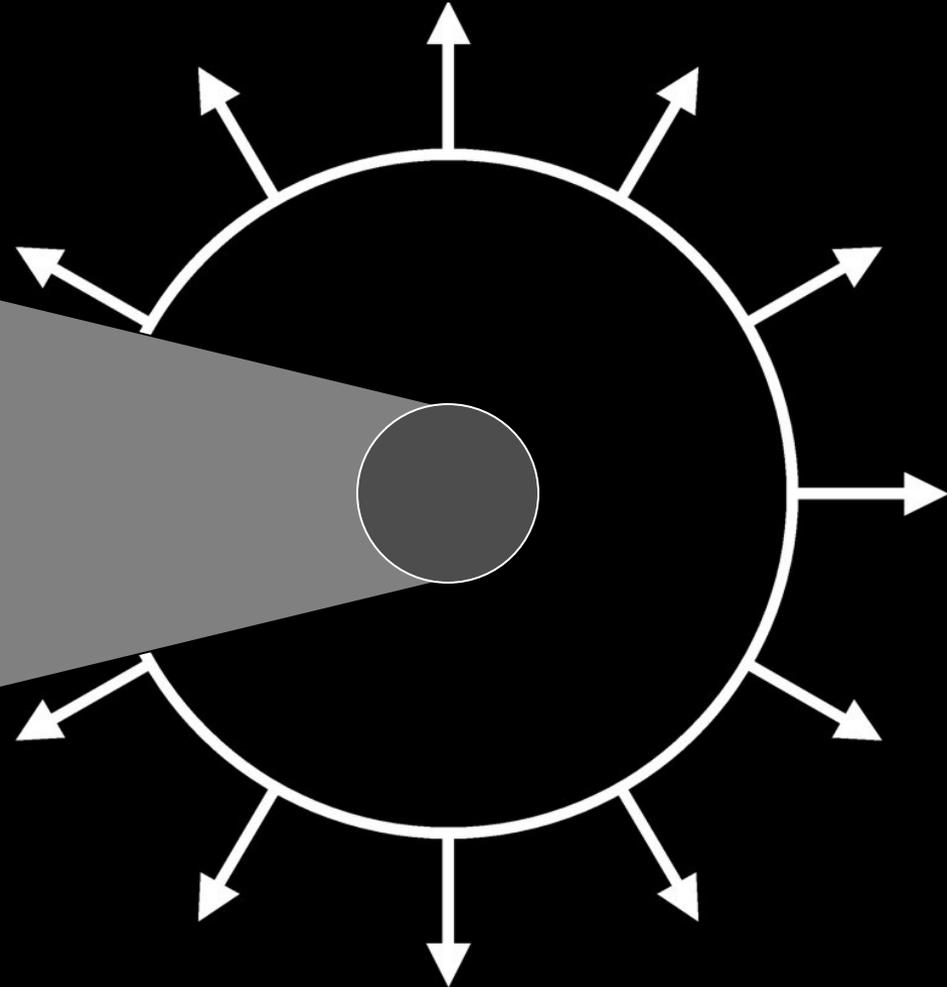


Proto-Neutron Star

$$\rho \sim \rho_{\text{nuc}} = 3 \times 10^{14} \text{ g cm}^{-3}$$

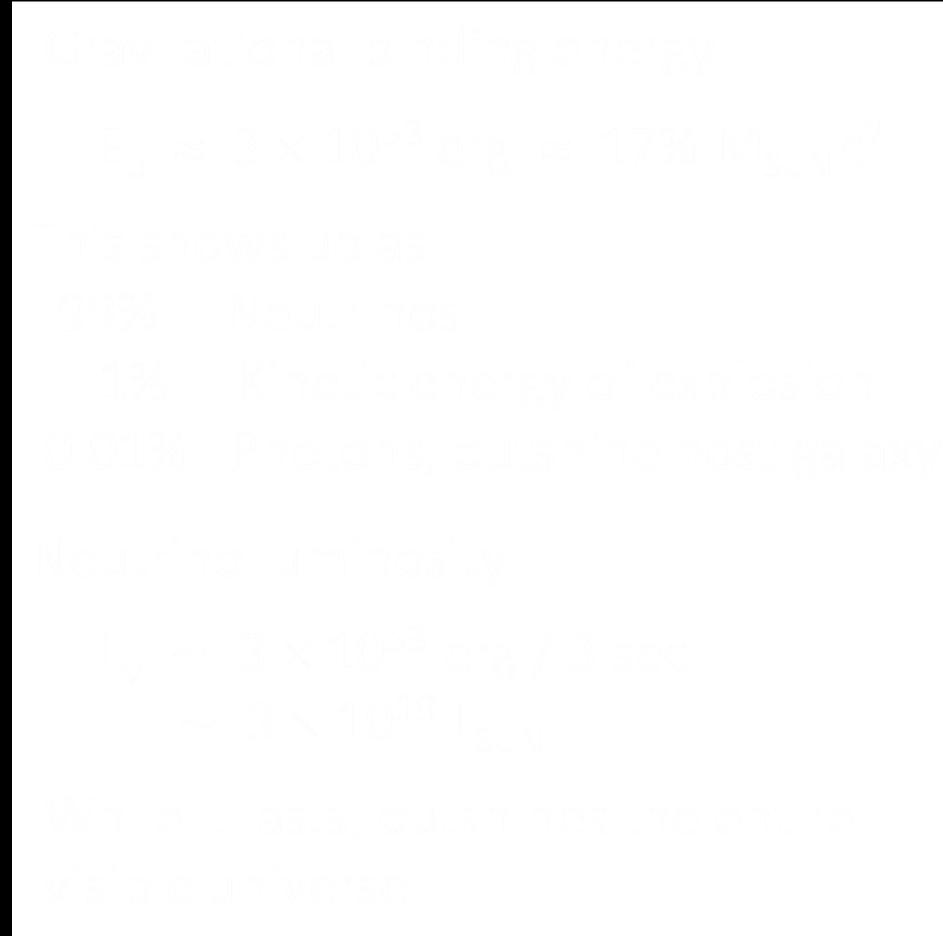
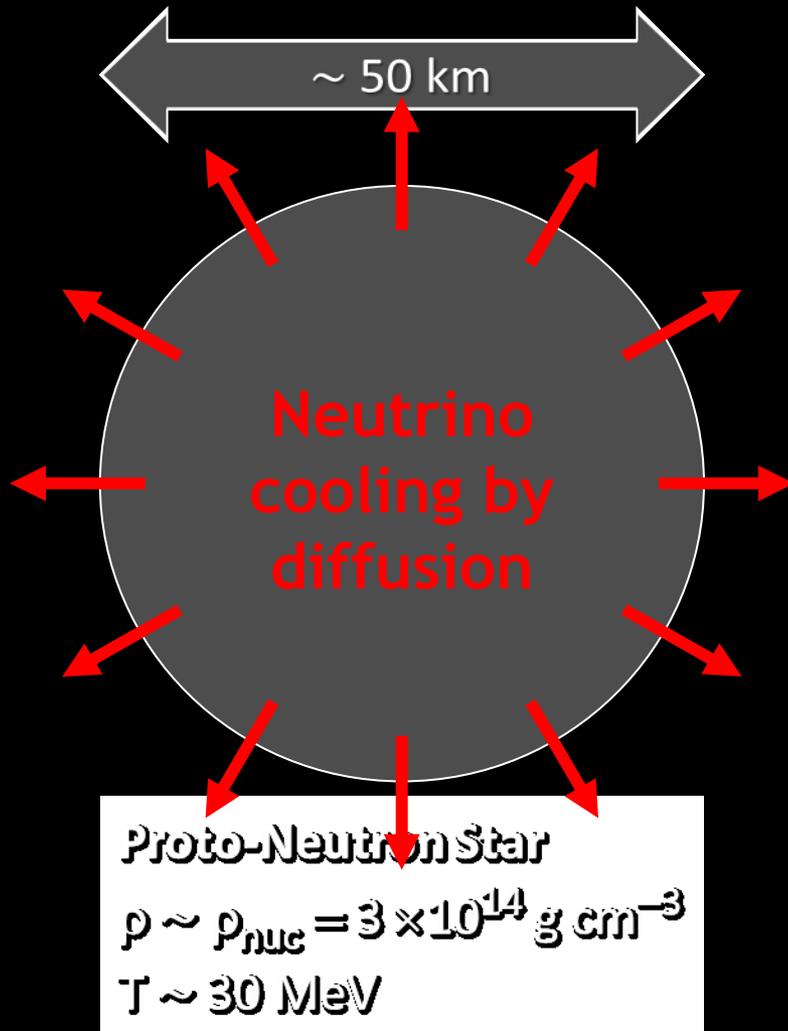
$$T \sim 30 \text{ MeV}$$

Explosion

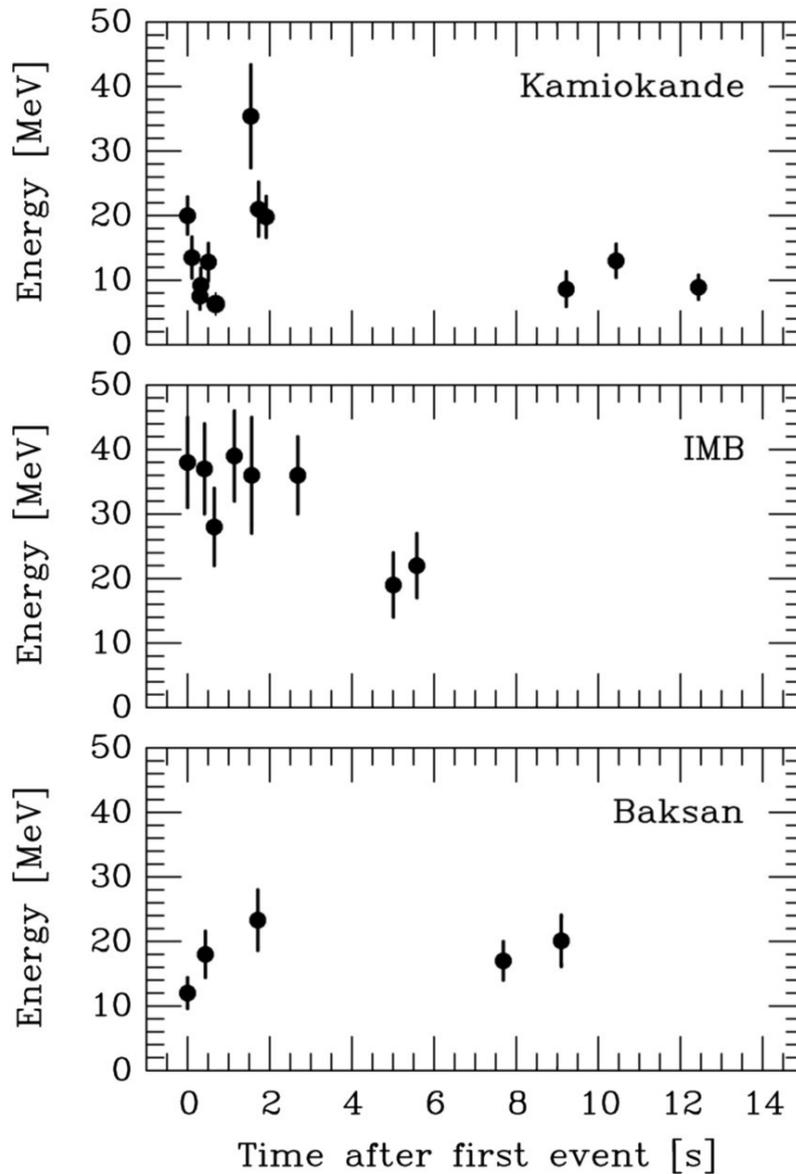


Stellar Collapse and Supernova Explosion

Newborn Neutron Star



Neutrino Signal of Supernova 1987A



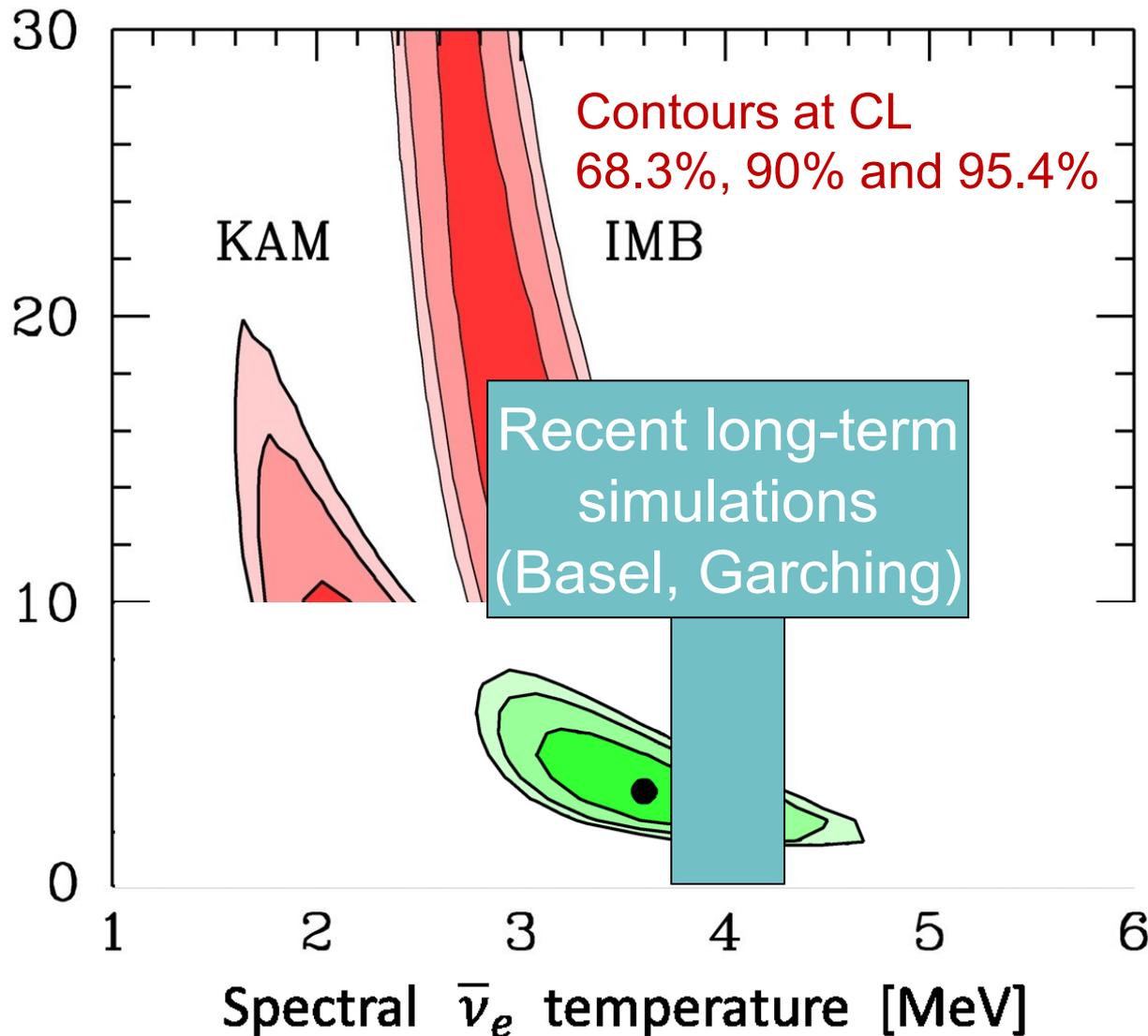
Kamiokande-II (Japan)
Water Cherenkov detector
2140 tons
Clock uncertainty ± 1 min

Irvine-Michigan-Brookhaven (US)
Water Cherenkov detector
6800 tons
Clock uncertainty ± 50 ms

Baksan Scintillator Telescope
(Soviet Union), 200 tons
Random event cluster $\sim 0.7/\text{day}$
Clock uncertainty $+2/-54$ s

**Within clock uncertainties,
all signals are contemporaneous**

Interpreting SN 1987A Neutrinos



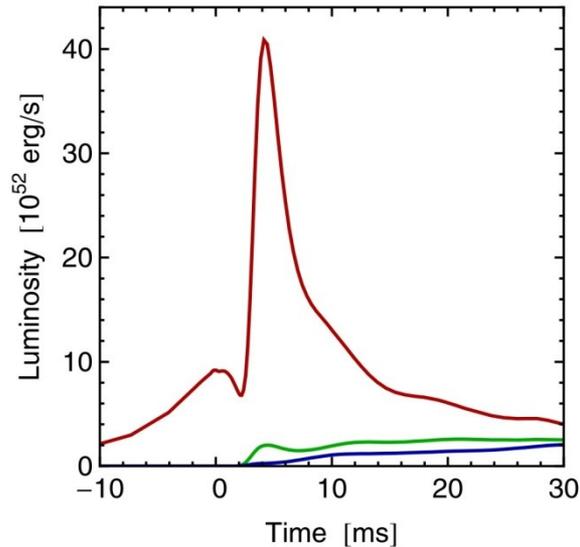
Assume

- Thermal spectra
- Equipartition of energy between $\nu_e, \bar{\nu}_e, \nu_\mu, \bar{\nu}_\mu, \nu_\tau$ and $\bar{\nu}_\tau$

Jegerlehner,
Neubig & Raffelt,
PRD 54 (1996) 1194

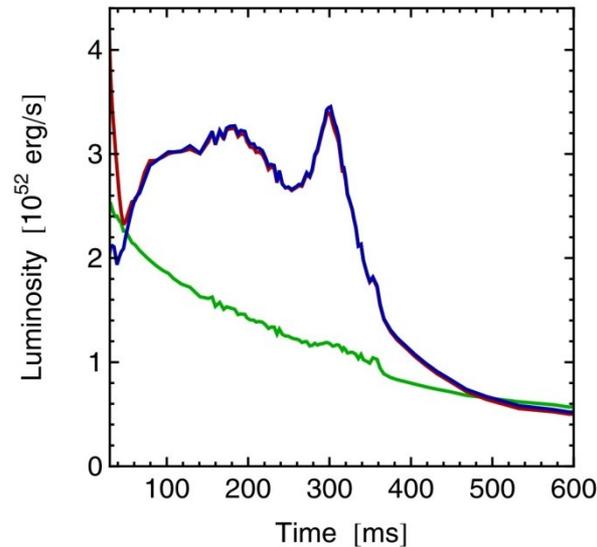
Three Phases of Neutrino Emission

Prompt ν_e burst



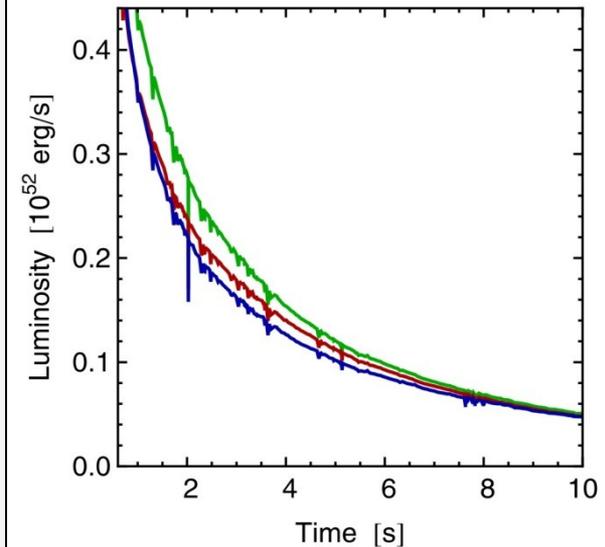
- Shock breakout
- De-leptonization of outer core layers

Accretion



- Shock stalls ~ 150 km
- Neutrinos powered by infalling matter

Cooling

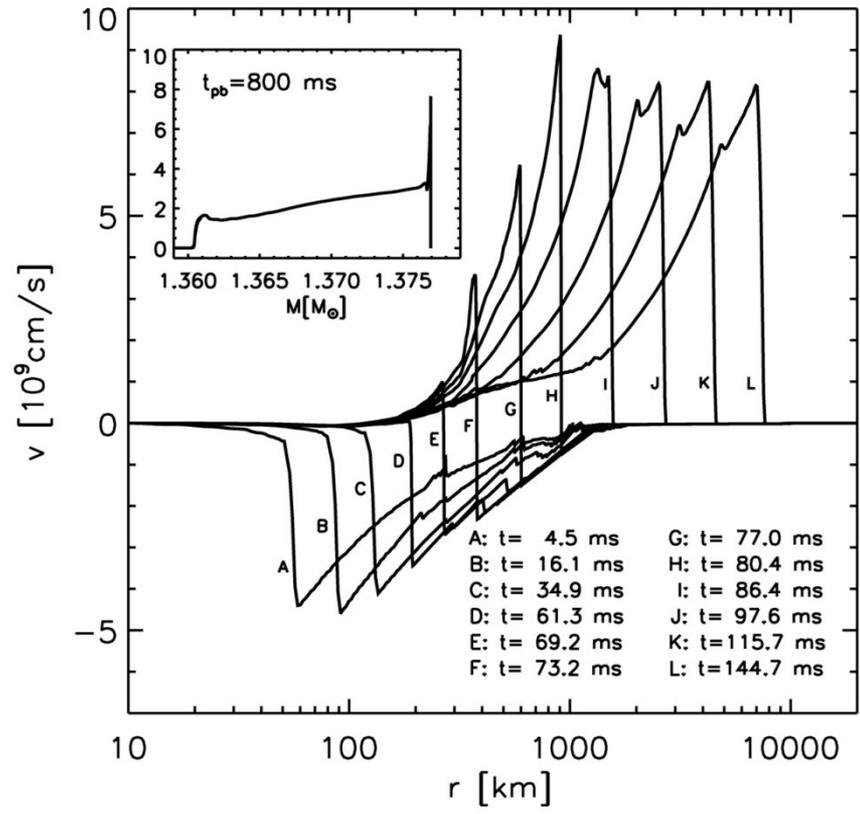
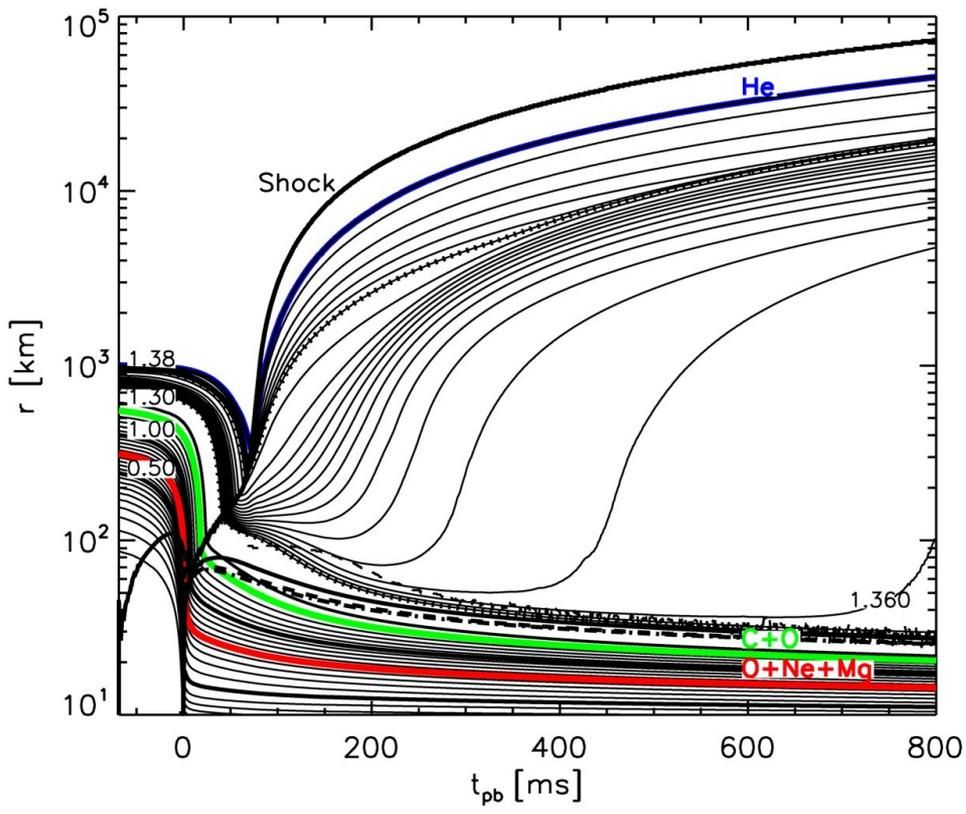


Cooling on neutrino diffusion time scale

- Spherically symmetric model ($10.8 M_{\odot}$) with Boltzmann neutrino transport
- Explosion manually triggered by enhanced CC interaction rate

Fischer et al. (Basel group), A&A 517:A80, 2010 [arxiv:0908.1871]

Exploding Models (8–10 Solar Masses) with O-Ne-Mg-Cores



Kitaura, Janka & Hillebrandt: “Explosions of O-Ne-Mg cores, the Crab supernova, and subluminous type II-P supernovae”, astro-ph/0512065



Neutrinos from Next Nearby SN

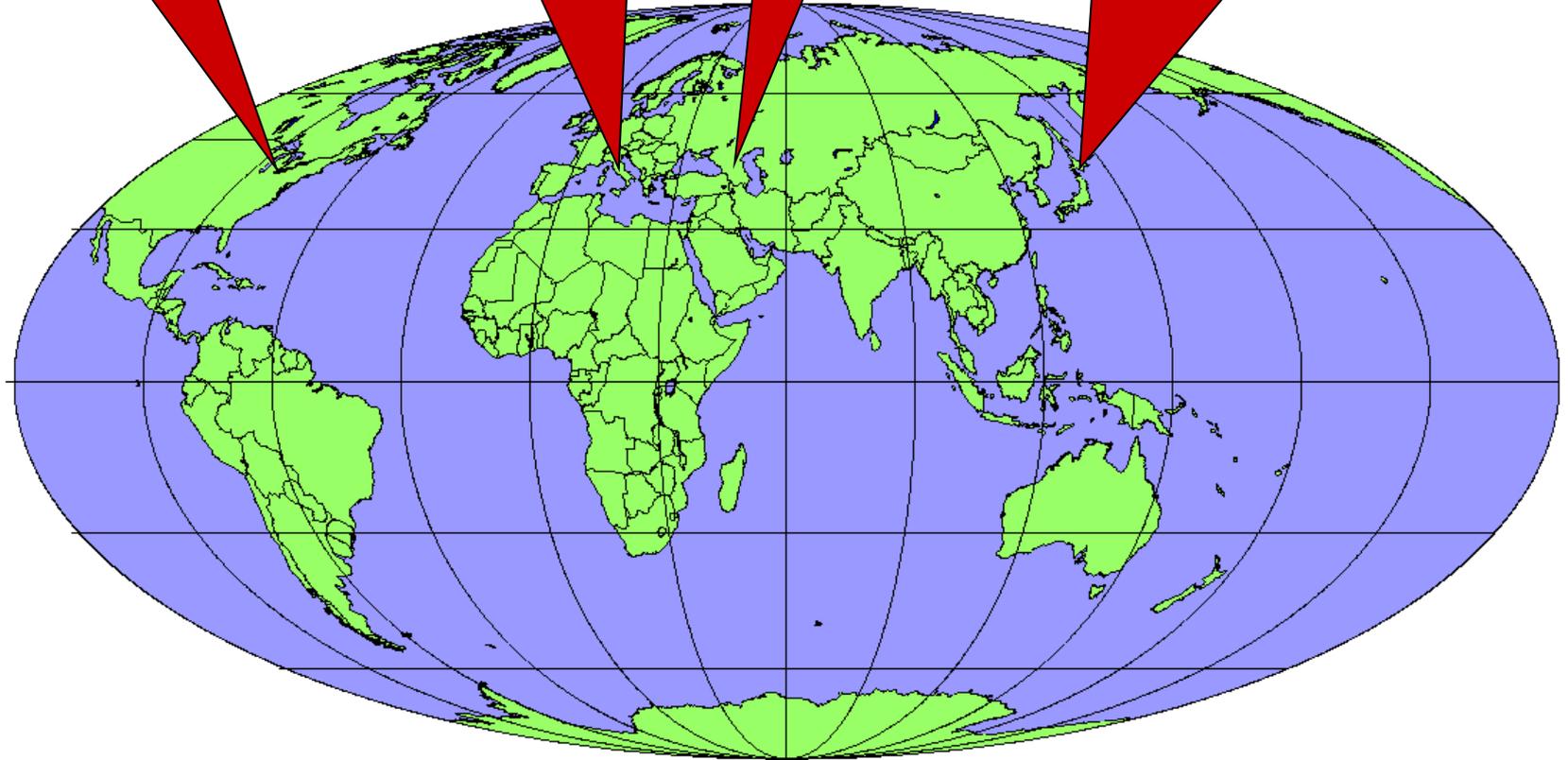
Operational Detectors for Supernova Neutrinos

**MiniBooNE
(200)**

**LVD (400)
Borexino (100)**

**Baksan
(100)**

**Super-Kamiokande (10^4)
KamLAND (400)**



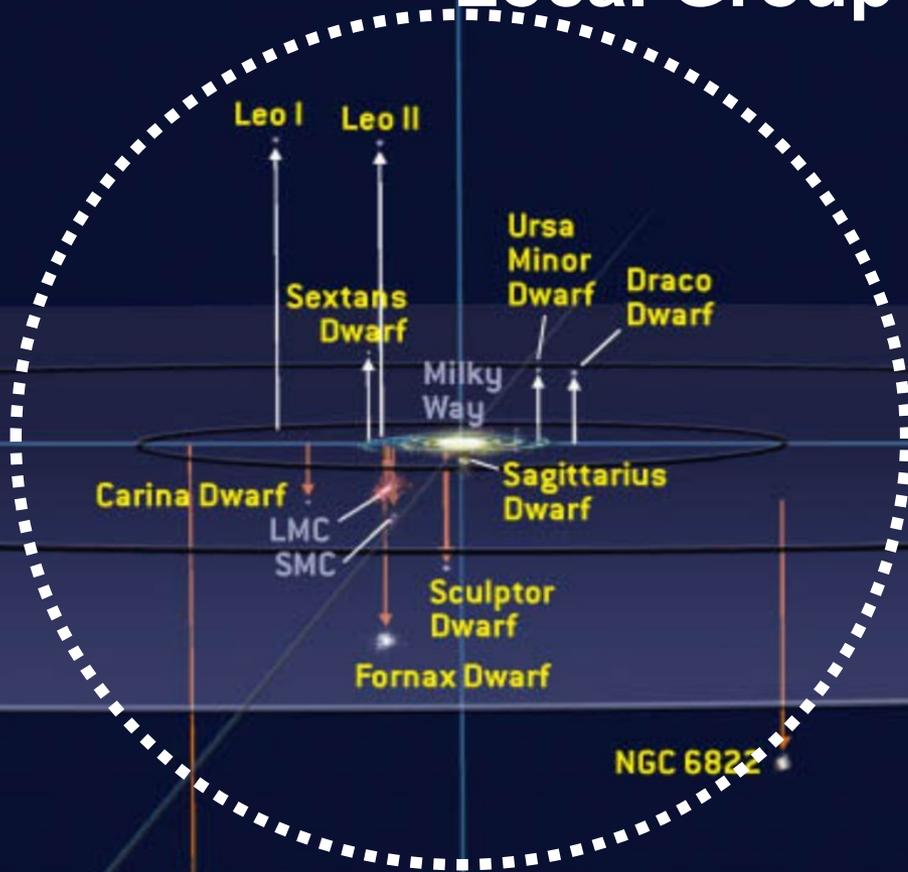
IceCube (10^6)

In brackets events
for a “fiducial SN”
at distance 10 kpc

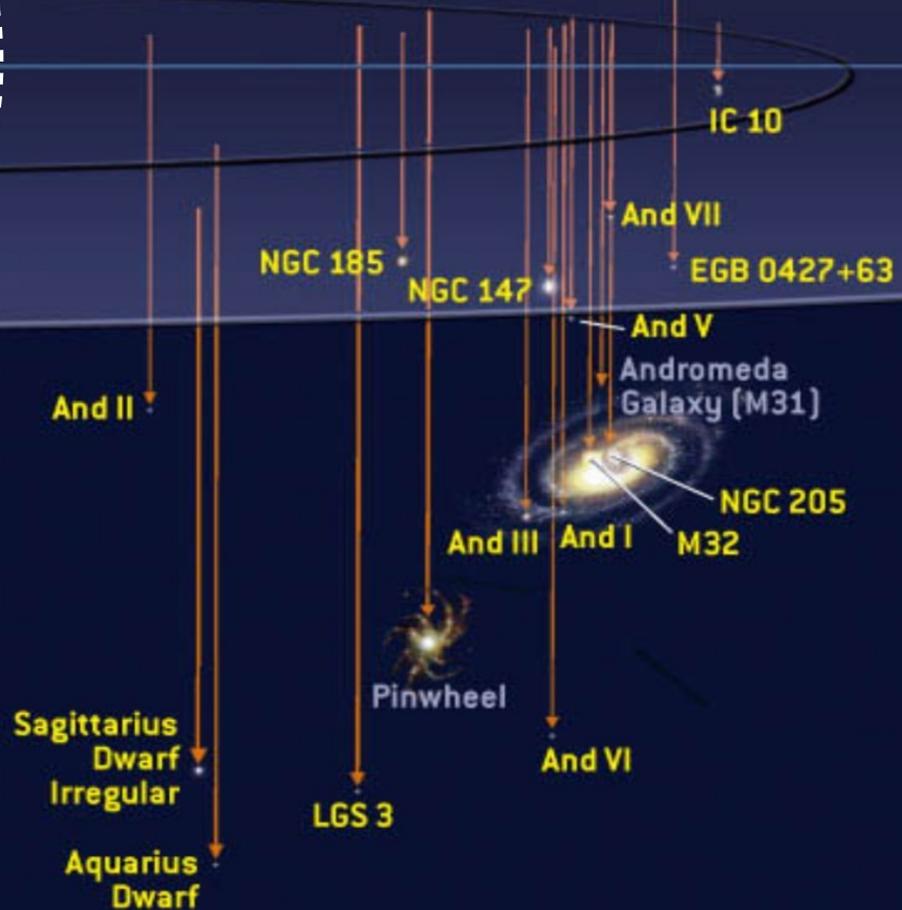


Supernova Rate

Local Group of Galaxies

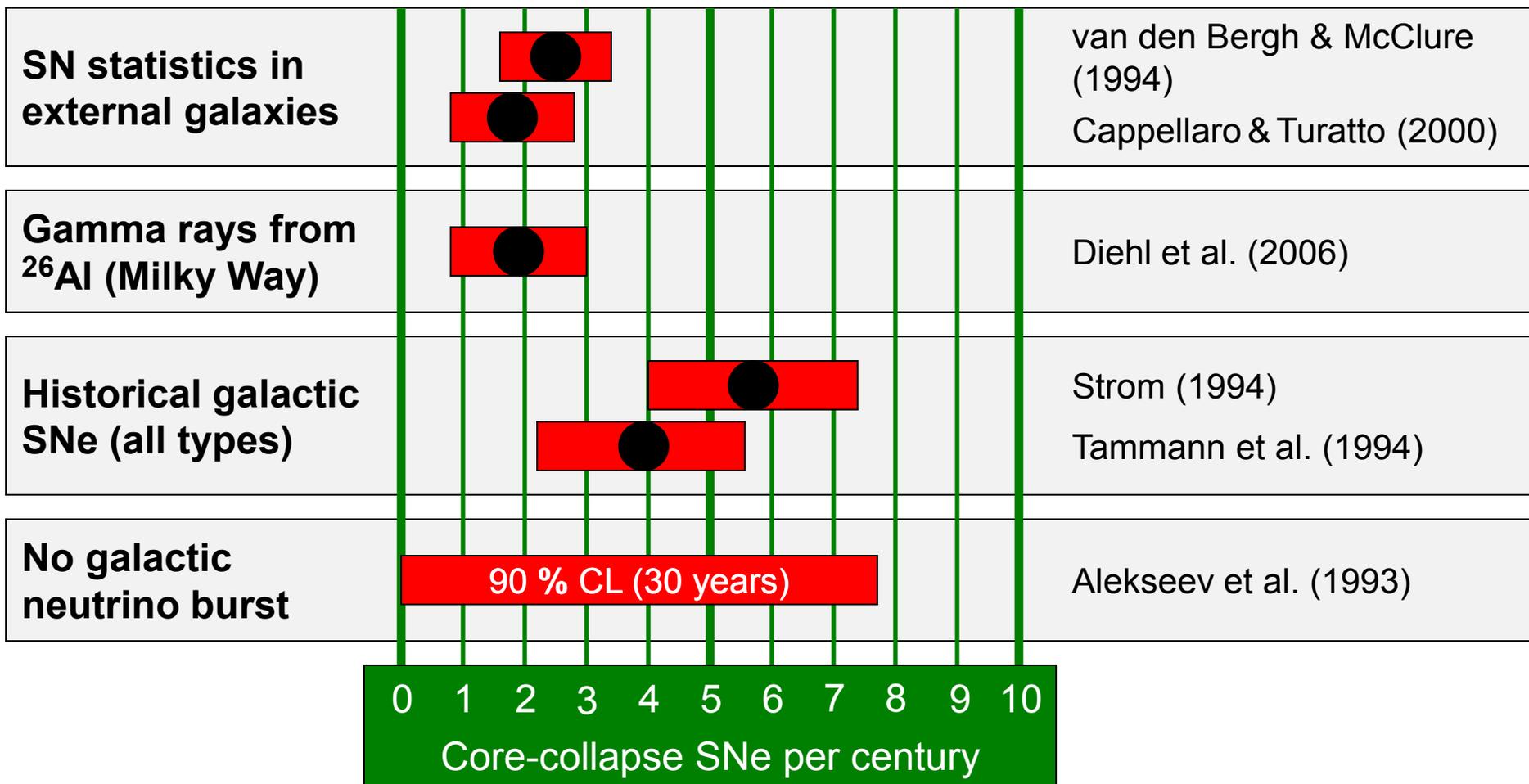


With megatonne class (30 x SK)
60 events from Andromeda



Current best neutrino detectors
sensitive out to few 100 kpc

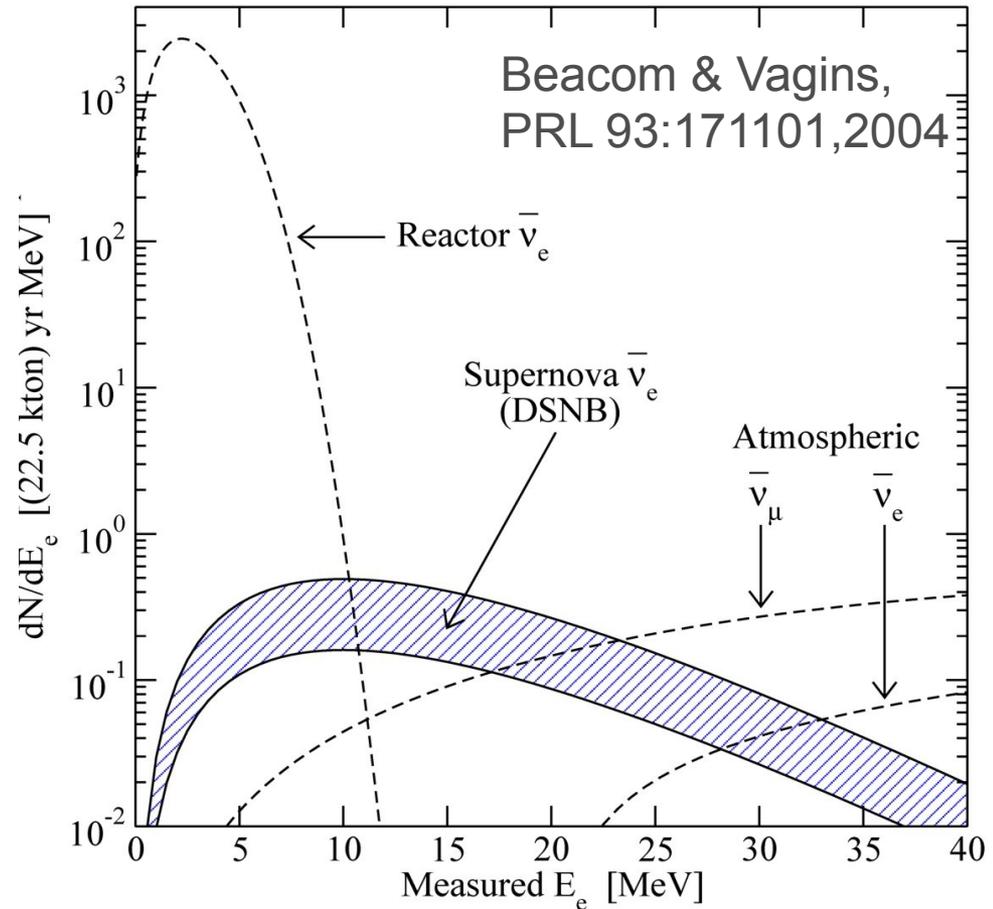
Core-Collapse SN Rate in the Milky Way



References: van den Bergh & McClure, *ApJ* 425 (1994) 205. Cappellaro & Turatto, *astro-ph/0012455*. Diehl et al., *Nature* 439 (2006) 45. Strom, *Astron. Astrophys.* 288 (1994) L1. Tammann et al., *ApJ* 92 (1994) 487. Alekseev et al., *JETP* 77 (1993) 339 and my update.

Diffuse Supernova Neutrino Background (DSNB)

- Approx. 10 core collapses/sec in the visible universe
- Emitted ν energy density
~ extra galactic background light
~ 10% of CMB density
- Detectable $\bar{\nu}_e$ flux at Earth
 $\sim 10 \text{ cm}^{-2} \text{ s}^{-1}$
mostly from redshift $z \sim 1$
- Confirm star-formation rate
- Nu emission from average core collapse & black-hole formation
- Pushing frontiers of neutrino astronomy to cosmic distances!



Window of opportunity between reactor $\bar{\nu}_e$ and atmospheric ν bkg

Neutrino Oscillations in Matter

2-flavor neutrino evolution as an effective 2-level problem

$$i \frac{\partial}{\partial z} \begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = H \begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix}$$

With a 2x2 Hamiltonian matrix

$$H = \frac{1}{2E} \begin{pmatrix} \cos \theta & \sin \theta \\ -\sin \theta & \cos \theta \end{pmatrix} \begin{pmatrix} m_1^2 & 0 \\ 0 & m_2^2 \end{pmatrix} \begin{pmatrix} \cos \theta \\ \sin \theta \end{pmatrix}$$

Mass-squared matrix, rotated by mixing angle θ relative to interaction basis, drives oscillations

$$\frac{\Delta m^2}{2E} \sim \begin{cases} 4 \text{ peV} & \text{for } 12 \text{ mass splitting} \\ 120 \text{ peV} & \text{for } 13 \text{ mass splitting} \end{cases}$$

Solar, reactor and supernova neutrinos:

$$E \sim 10 \text{ MeV}$$

Negative
for $\bar{\nu}$

$$\begin{pmatrix} -\sin \theta \\ \cos \theta \end{pmatrix} \pm \sqrt{2} G_F \begin{pmatrix} N_e - \frac{N_n}{2} & 0 \\ 0 & -\frac{N_n}{2} \end{pmatrix}$$

Weak potential difference

$$\Delta V_{\text{weak}} = \sqrt{2} G_F N_e \sim 0.2 \text{ peV}$$

for normal Earth matter, but large effect in SN core (nuclear density $3 \times 10^{14} \text{ g/cm}^3$)

$$\Delta V_{\text{weak}} \sim 10 \text{ eV}$$

Suppression of Oscillations in Supernova Core

Effective mixing angle in matter

$$\tan 2\theta_m = \frac{\sin 2\theta}{\cos 2\theta - N_e 2E\sqrt{2}G_F/\Delta m^2}$$

Supernova core

$$\rho = 3 \times 10^{14} \text{ g cm}^{-3}$$

$$Y_e = 0.35$$

$$N_e = 6 \times 10^{37} \text{ cm}^{-3}$$

$$E \sim 100 \text{ MeV}$$

Solar mixing

$$\Delta m^2 \sim 75 \text{ meV}^2$$

$$\sin 2\theta \sim 0.94$$

Matter suppression effect

$$N_e 2E\sqrt{2}G_F/\Delta m^2 \sim 2 \times 10^{13}$$

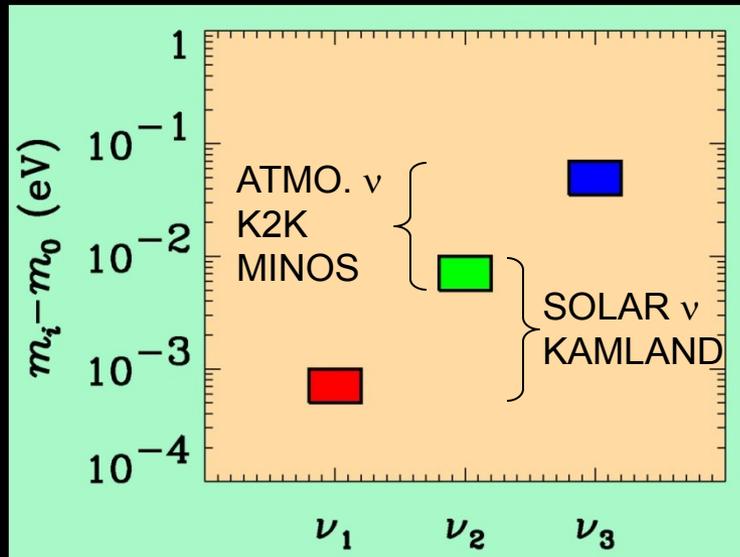
- Inside a SN core, flavors are “de-mixed”
- Very small oscillation amplitude
- Trapped e-lepton number can only escape by diffusion

Signature of Flavor Oscillations

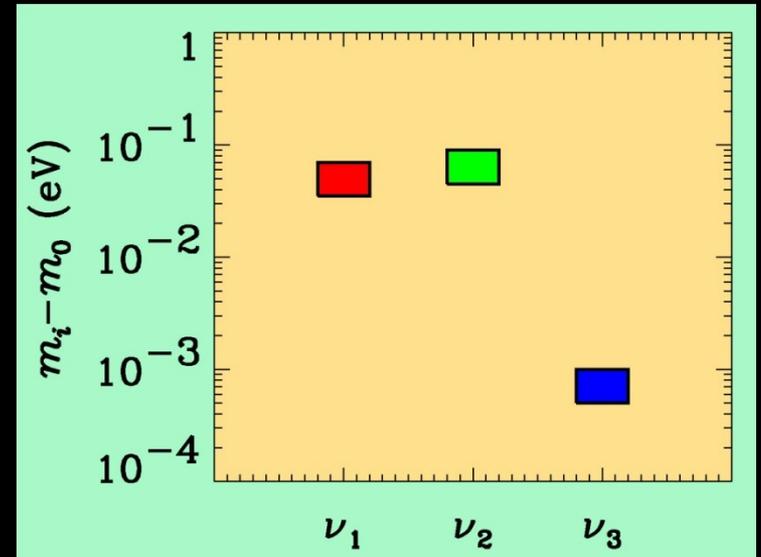
	1-3-mixing scenarios		
	A	B	C
Mass ordering	Normal (NH)	Inverted (IH)	Any (NH/IH)
$\sin^2 \theta_{13}$	$\gtrsim 10^{-3}$		$\lesssim 10^{-5}$
MSW conversion	adiabatic		non-adiabatic
ν_e survival prob.	0	$\sin^2 \theta_{12} \approx 0.3$	$\sin^2 \theta_{12} \approx 0.3$
$\bar{\nu}_e$ survival prob.	$\cos^2 \theta_{12} \approx 0.7$	0	$\cos^2 \theta_{12} \approx 0.7$
$\bar{\nu}_e$ Earth effects	Yes	No	Yes
May distinguish mass ordering			

Assuming collective effects are not important during accretion phase
(Chakraborty et al., arXiv:1105.1130v1)

If neutrino masses are hierarchical then oscillation experiments do not give information on the absolute value of neutrino masses



Normal hierarchy



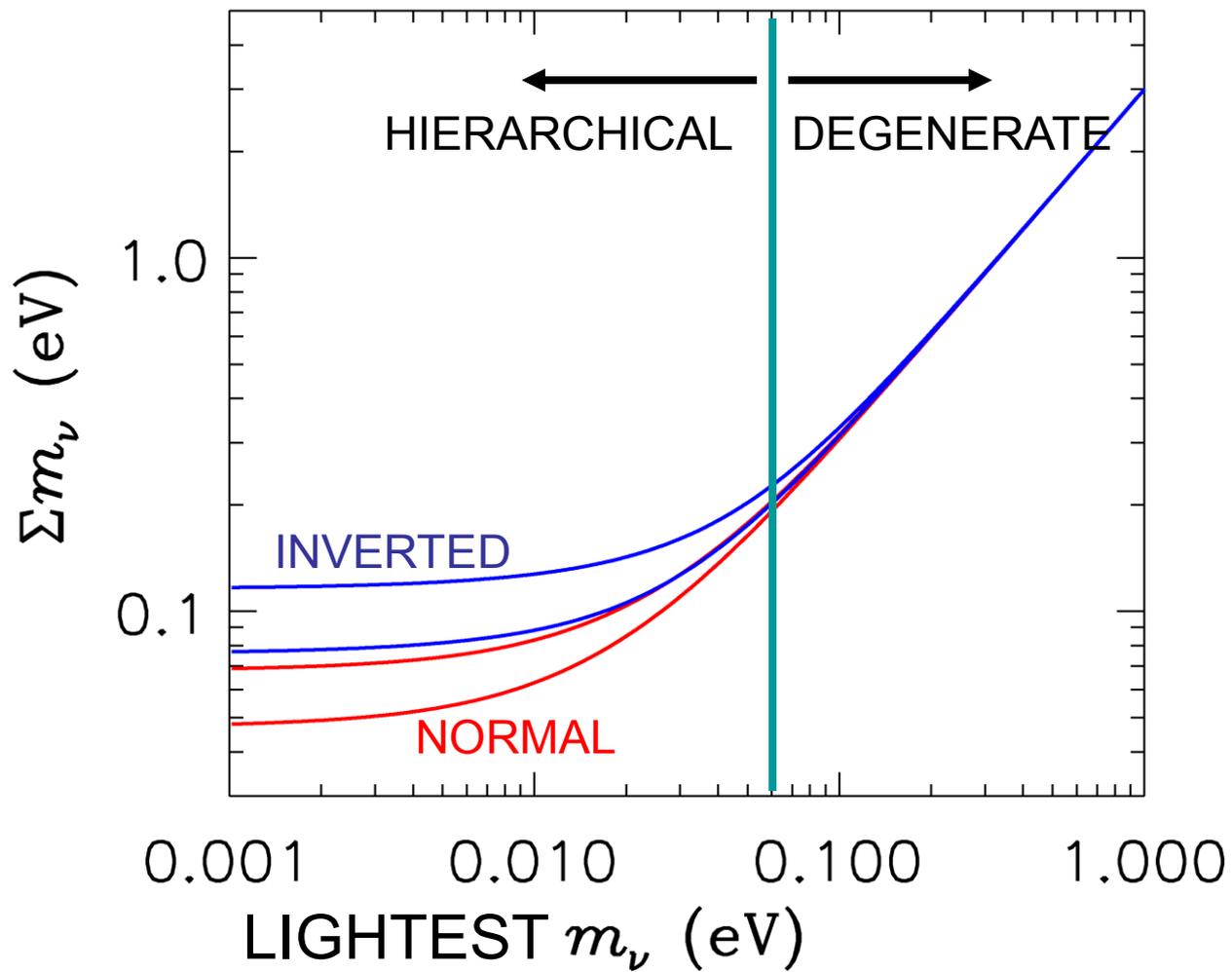
Inverted hierarchy

If neutrino masses are degenerate

$$m_0 \gg \delta m_{\text{atmospheric}}$$

no information can be gained from such experiments.

Experiments which rely on either the kinematics of neutrino mass or the spin-flip in neutrinoless double beta decay are the most efficient for measuring m_0



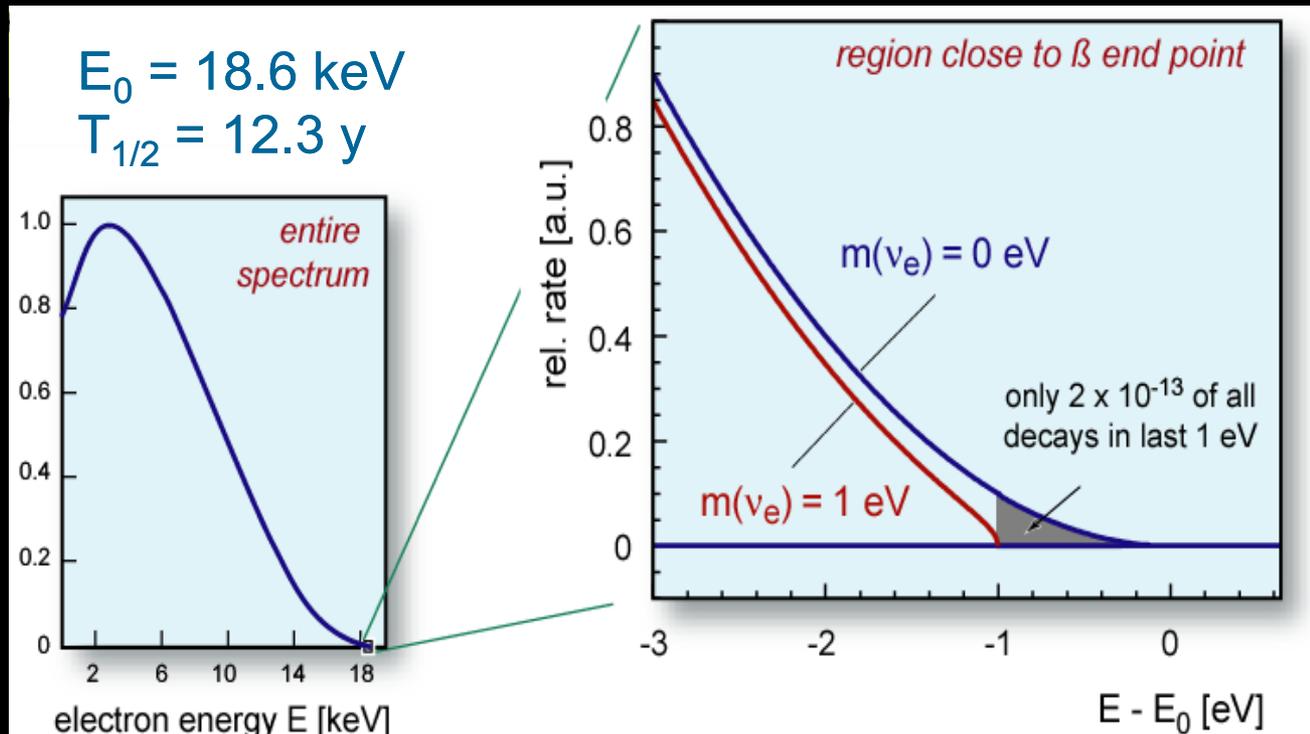
β -decay and neutrino mass

model independent neutrino mass from β -decay kinematics

only assumption: relativistic energy-momentum relation

$$\frac{d\Gamma_i}{dE} = C p (E + m_e) (E_0 - E) \sqrt{(E_0 - E)^2 - m_i^2} F(E) \theta(E_0 - E - m_i)$$

experimental \downarrow observable is m_ν^2



Tritium decay endpoint measurements have provided limits on the electron neutrino mass

$$m_{\nu_e} = \left(\sum |U_{ei}|^2 m_i^2 \right)^{1/2} \leq 2.3 \text{ eV} \quad (95\%)$$

Mainz experiment, final analysis (Kraus et al.)

This translates into a limit on the sum of the three mass eigenstates

$$\sum m_i \leq 7 \text{ eV}$$

NEUTRINO MASS AND ENERGY DENSITY FROM COSMOLOGY

NEUTRINOS AFFECT STRUCTURE FORMATION
BECAUSE THEY ARE A SOURCE OF DARK MATTER
($n \sim 100 \text{ cm}^{-3}$)

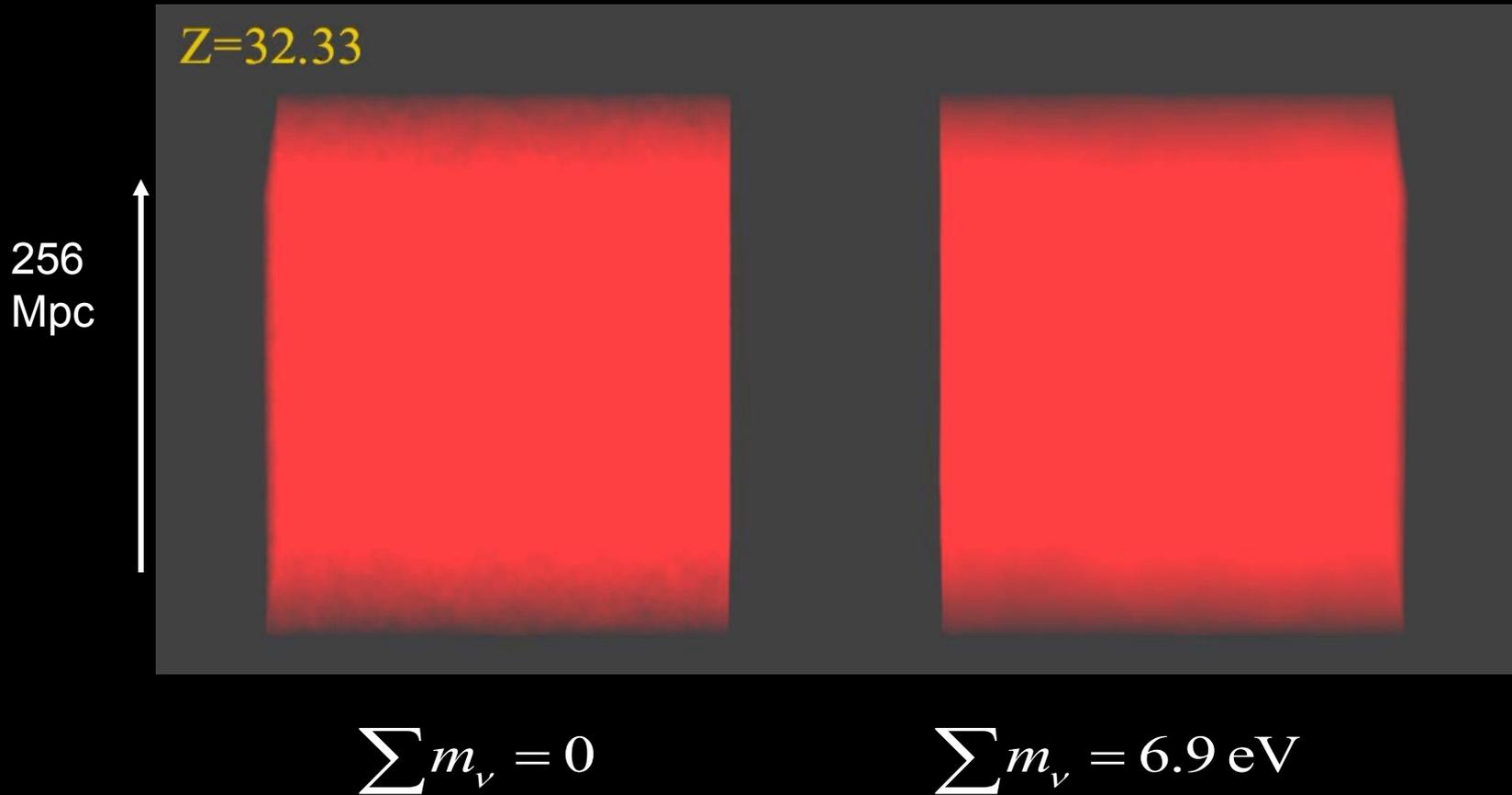
$$\Omega_\nu h^2 = \frac{\sum m_\nu}{93 \text{ eV}} \quad \text{FROM} \quad T_\nu = T_\gamma \left(\frac{4}{11} \right)^{1/3} \approx 2 \text{ K}$$

HOWEVER, eV NEUTRINOS ARE DIFFERENT FROM CDM
BECAUSE THEY FREE STREAM

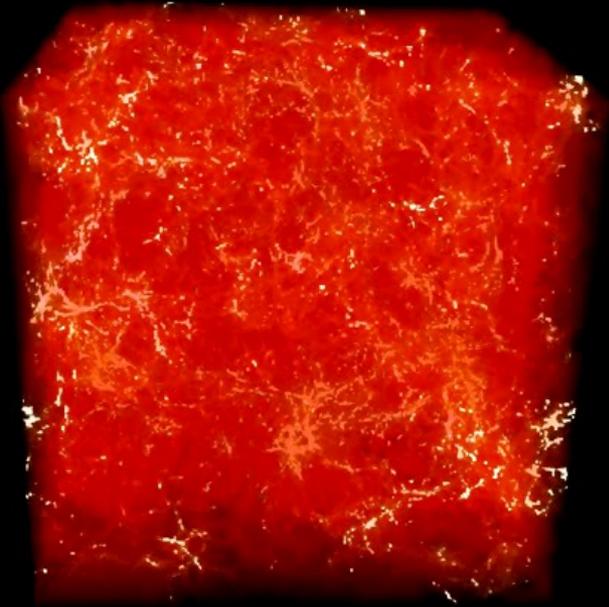
$$d_{\text{FS}} \sim 1 \text{ Gpc } m_{\text{eV}}^{-1}$$

SCALES SMALLER THAN d_{FS} DAMPED AWAY, LEADS TO
SUPPRESSION OF POWER ON SMALL SCALES

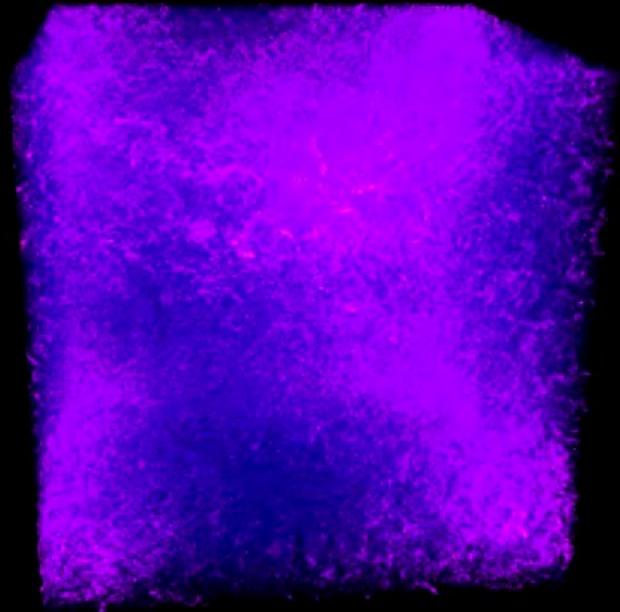
N-BODY SIMULATIONS OF Λ CDM WITH AND WITHOUT NEUTRINO MASS (768 Mpc³) – GADGET 2



SIMULATION WITH $\sum m_\nu = 1.2 \text{ eV}$



DARK MATTER

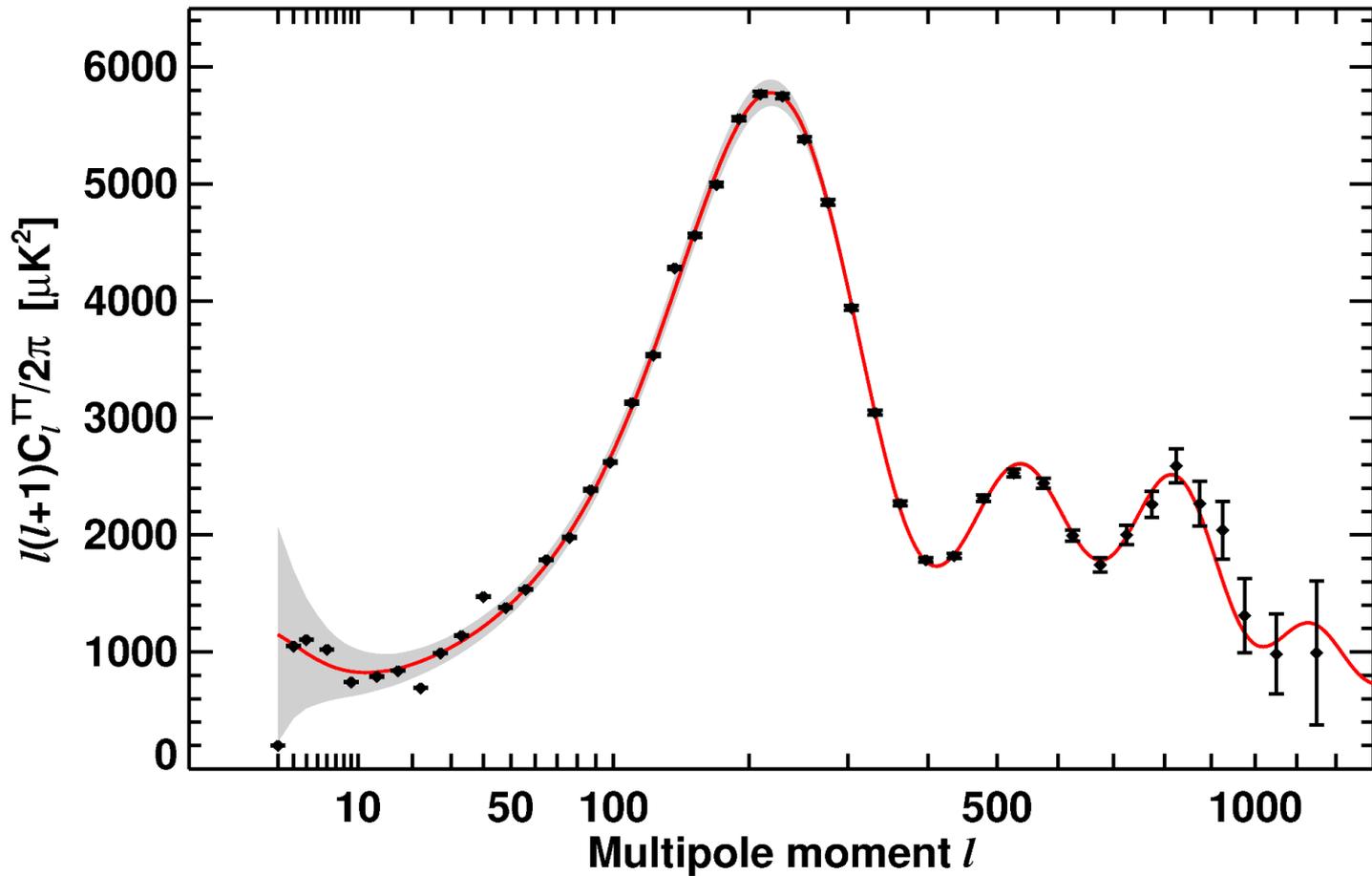


NEUTRINOS

STH, HAUGBØLLE, RIIS & SCHULTZ (IN PREPARATION)

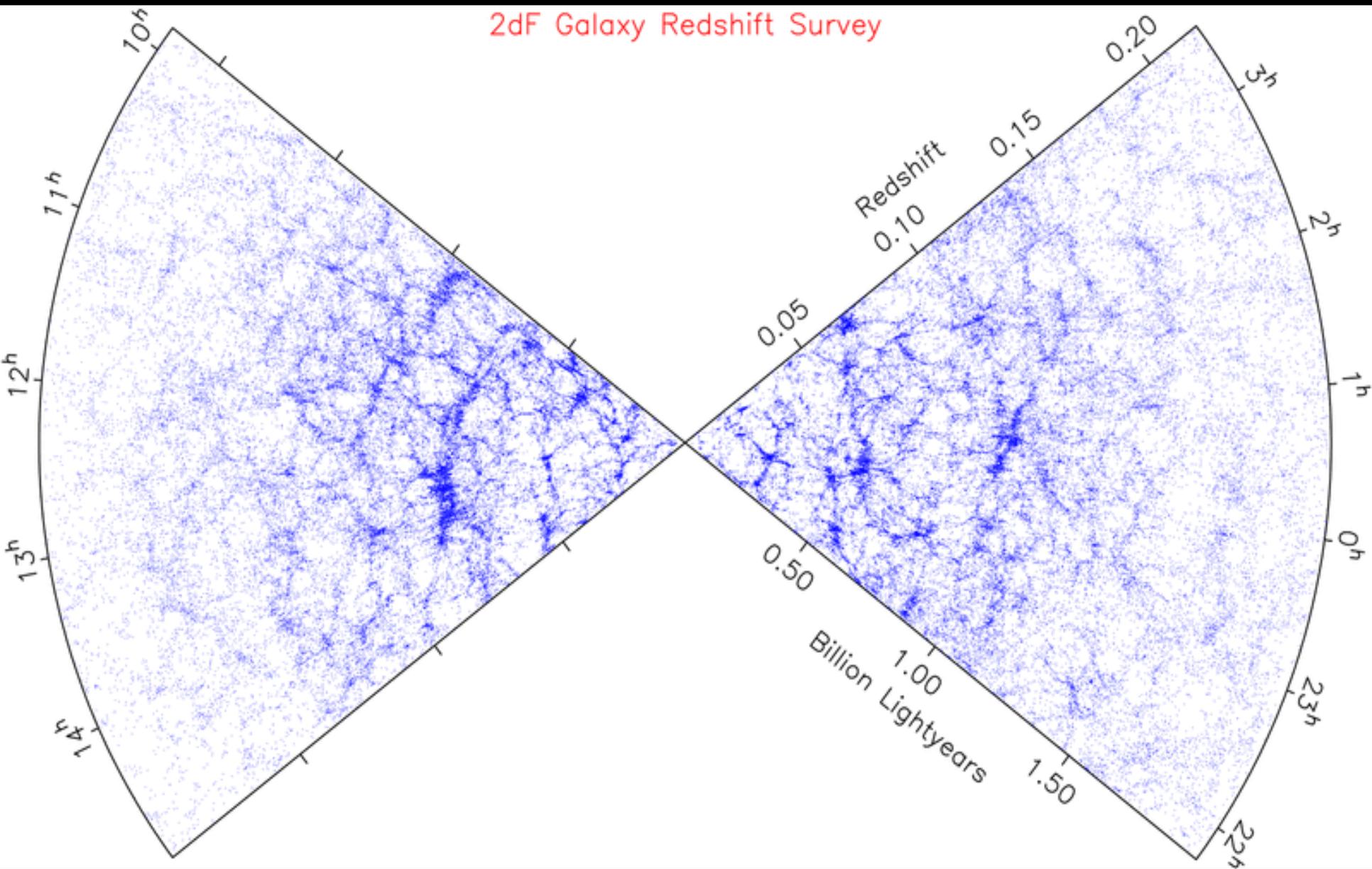
AVAILABLE COSMOLOGICAL DATA

WMAP-7 TEMPERATURE POWER SPECTRUM

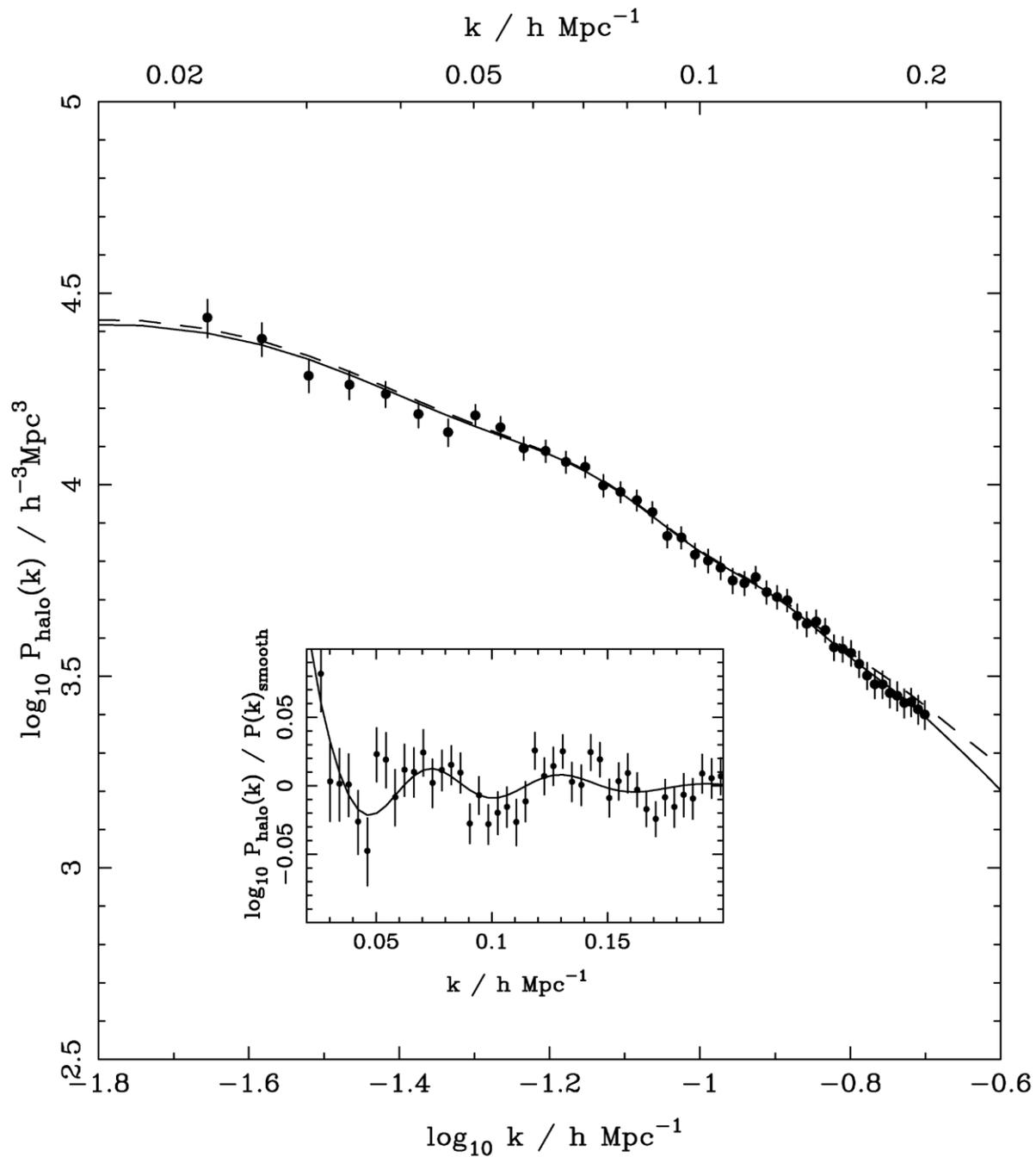


LARSON ET AL, ARXIV 1001.4635

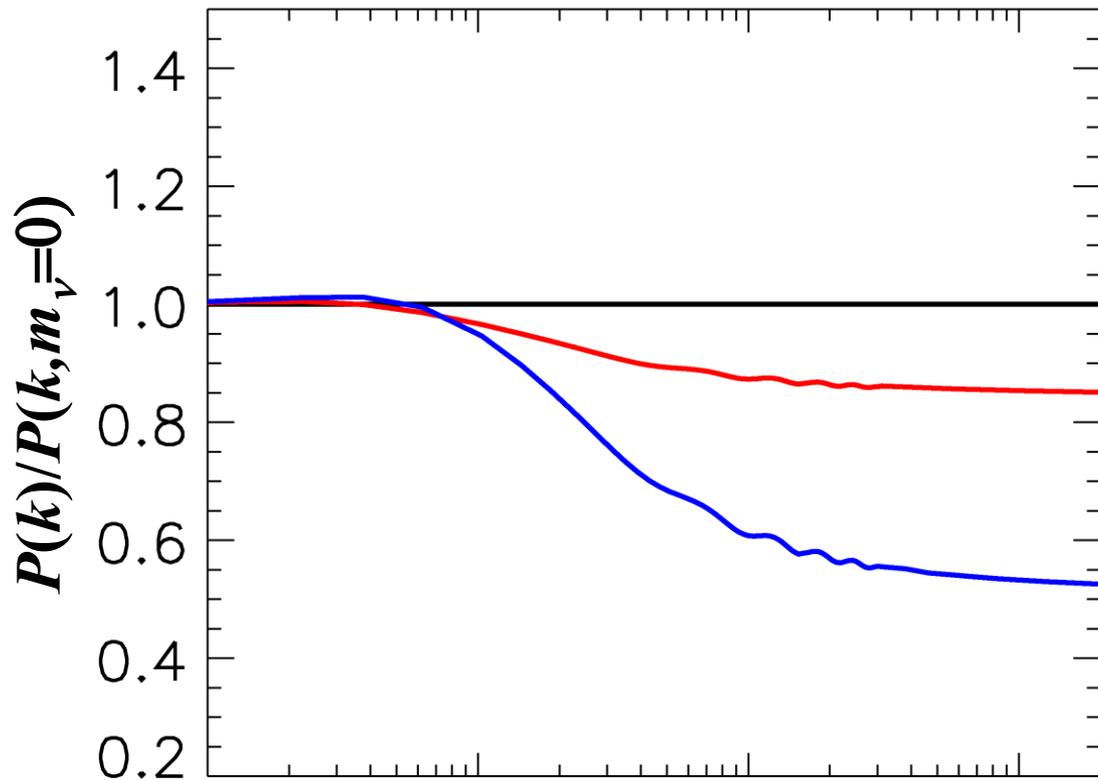
LARGE SCALE STRUCTURE SURVEYS - 2dF AND SDSS



SDSS DR-7
LRG SPECTRUM
(Reid et al '09)



FINITE NEUTRINO MASSES SUPPRESS THE MATTER POWER SPECTRUM ON SCALES SMALLER THAN THE FREE-STREAMING LENGTH



$\Sigma m = 0 \text{ eV}$

$\Sigma m = 0.3 \text{ eV}$

$\Sigma m = 1 \text{ eV}$

$$\frac{\Delta P}{P_{m=0}} (k \gg k_{FS}) \sim -8 \frac{\rho_\nu}{\rho_{TOT}} \frac{1}{k \text{ (h/Mpc)}}$$

NOW, WHAT ABOUT NEUTRINO
PHYSICS?

WHAT IS THE PRESENT BOUND ON THE NEUTRINO MASS?

DEPENDS ON DATA SETS USED AND ALLOWED PARAMETERS

THERE ARE MANY ANALYSES IN THE LITERATURE

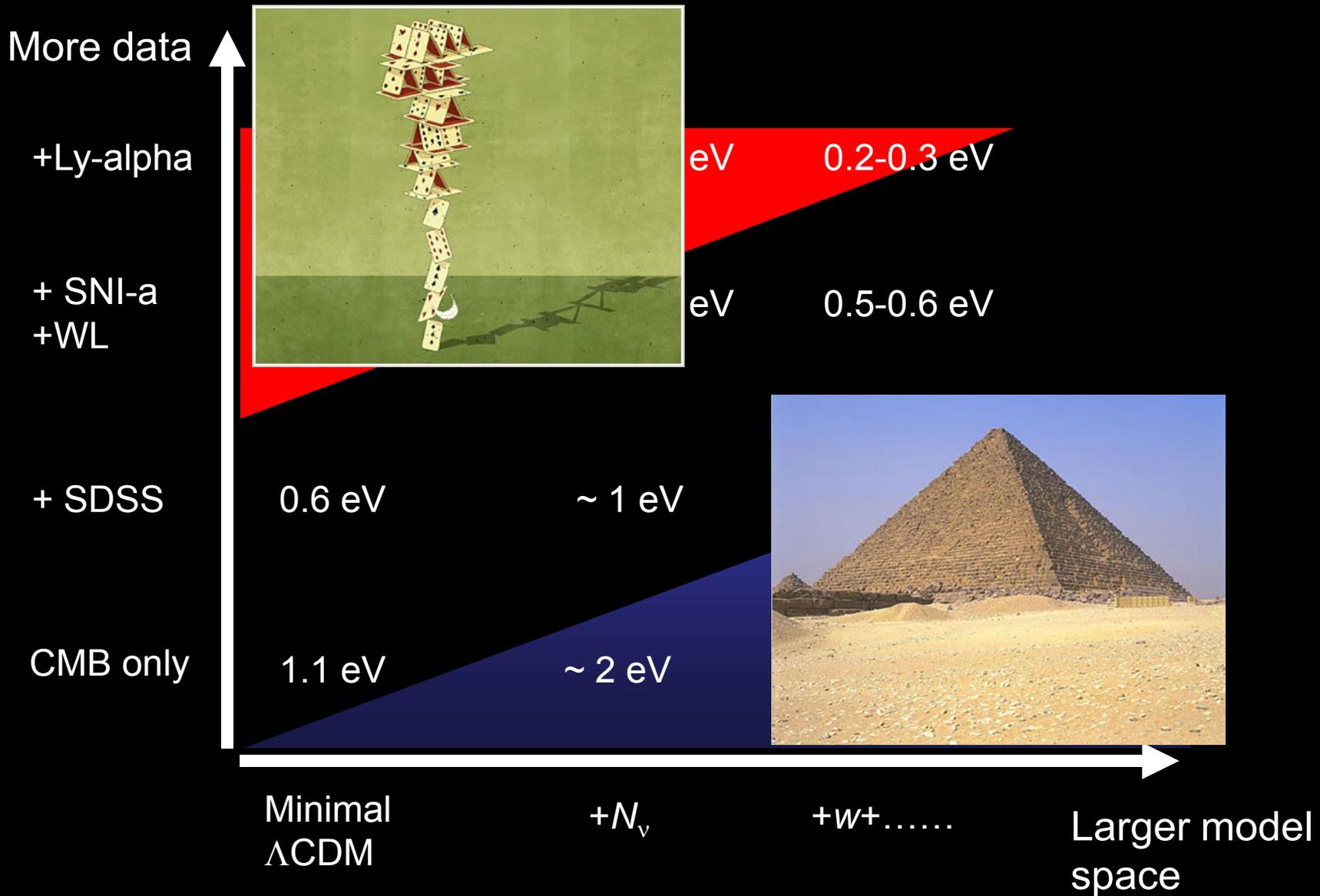
$$\sum m_\nu \leq 0.44 \text{ eV @ 95 C.L.} \quad \text{USING THE MINIMAL COSMOLOGICAL MODEL}$$

STH, MIRIZZI, RAFFELT, WONG (arxiv:1004:0695)

HAMANN, STH, LESGOURGUES, RAMPF & WONG (arxiv:1003.3999)

JUST ONE EXAMPLE

THE NEUTRINO MASS FROM COSMOLOGY PLOT



Model	Observables	Σm_ν (eV) 95% Bound
$\omega\text{CDM} + \Delta N_{\text{rel}} + m_\nu$	CMB+H0+SN+BAO	≤ 1.5
$\omega\text{CDM} + \Delta N_{\text{rel}} + m_\nu$	CMB+H0+SN+LSSPS	≤ 0.76
$\Lambda\text{CDM} + m_\nu$	CMB+H0+SN+BAO	≤ 0.61
$\Lambda\text{CDM} + m_\nu$	CMB+H0+SN+LSSPS	≤ 0.36
$\Lambda\text{CDM} + m_\nu$	CMB (+SN)	≤ 1.2
$\Lambda\text{CDM} + m_\nu$	CMB+BAO	≤ 0.75
$\Lambda\text{CDM} + m_\nu$	CMB+LSSPS	≤ 0.55
$\Lambda\text{CDM} + m_\nu$	CMB+H0	≤ 0.45

WHAT IS N_ν ?

A MEASURE OF THE ENERGY DENSITY IN NON-INTERACTING RADIATION IN THE EARLY UNIVERSE

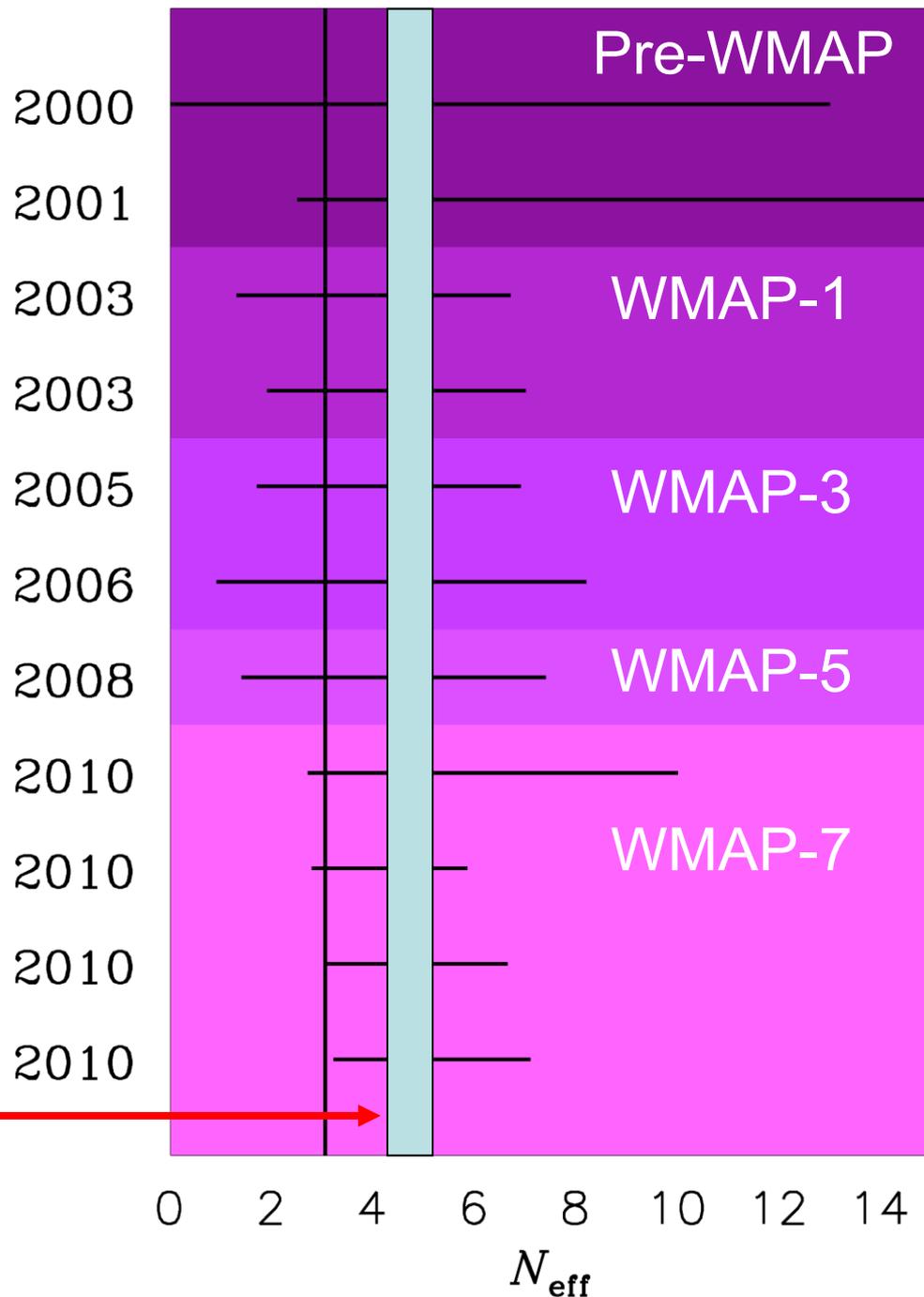
THE STANDARD MODEL PREDICTION IS

$$N_\nu \equiv \frac{\rho}{\rho_{\nu,0}} = 3.046 \quad , \quad \rho_{\nu,0} \equiv \frac{7}{8} \left(\frac{4}{11} \right)^{4/3} \rho_\gamma$$

Mangano et al., hep-ph/0506164

BUT ADDITIONAL LIGHT PARTICLES (STERILE NEUTRINOS, AXIONS, MAJORONS,.....) COULD MAKE IT HIGHER

TIME EVOLUTION OF
THE 95% BOUND ON
 N_{ν}



ESTIMATED PLANCK
SENSITIVITY



N_{eff}

A STERILE NEUTRINO IS PERHAPS THE MOST OBVIOUS CANDIDATE FOR AN EXPLANATION OF THE EXTRA ENERGY DENSITY
Hamann, STH, Raffelt, Tamborra, Wong, arxiv:1006.5276 (PRL)

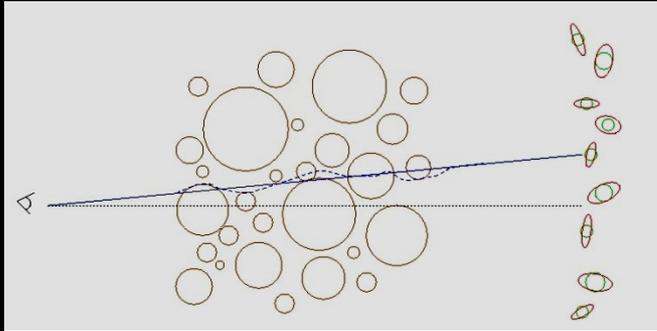
ASSUMING A NUMBER OF ADDITIONAL STERILE STATES OF APPROXIMATELY EQUAL MASS, TWO QUALITATIVELY DIFFERENT HIERARCHIES EMERGE



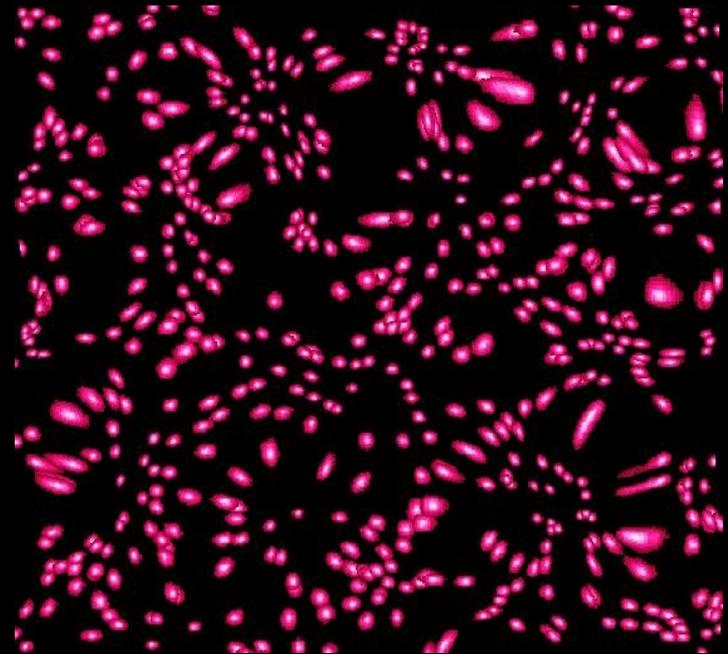
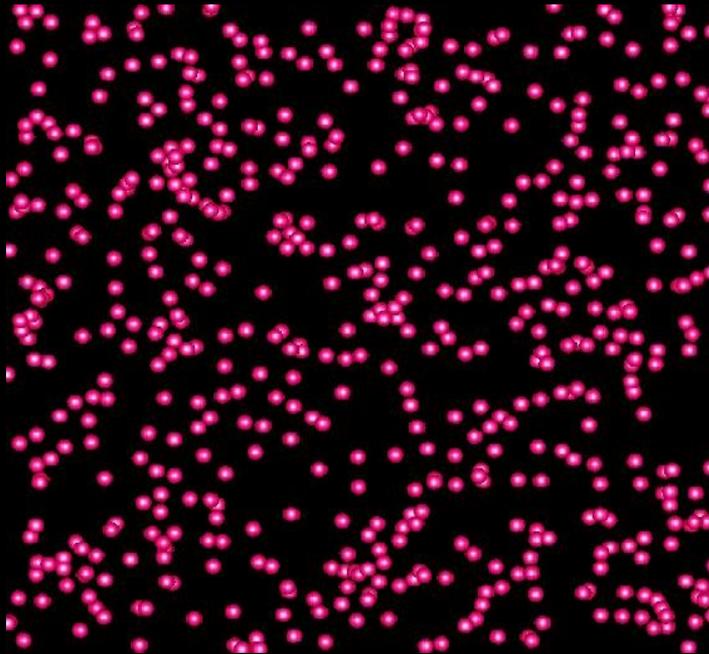
WHAT IS IN STORE FOR THE FUTURE?

- BETTER CMB TEMPERATURE AND POLARIZATION MEASUREMENTS (PLANCK)
- LARGE SCALE STRUCTURE SURVEYS AT HIGH REDSHIFT
- MEASUREMENTS OF WEAK GRAVITATIONAL LENSING ON LARGE SCALES

WEAK LENSING – A POWERFUL PROBE FOR THE FUTURE

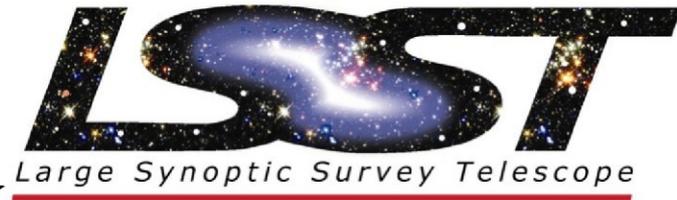
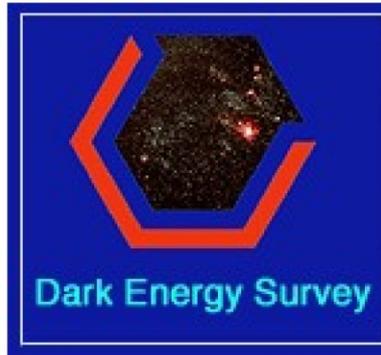


Distortion of background images by foreground matter



Unlensed

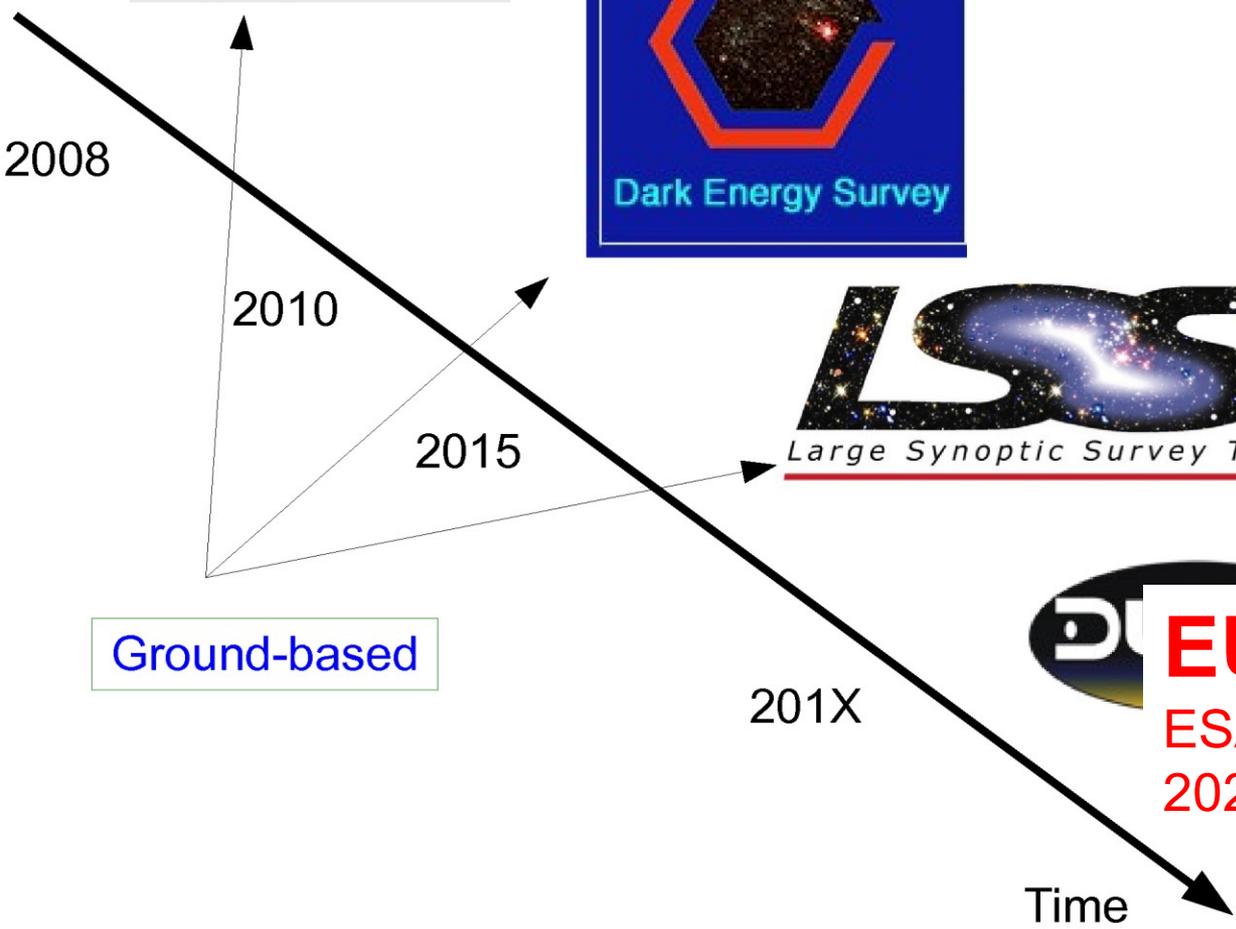
Lensed



Future surveys with lensing capacity

Space-based

Ground-based



	Planck	+Wide-1	+Wide-5	+Deep-1	+Deep-5
$\sigma(\sum m_\nu)$ (eV)	0.48	0.15	0.043	0.39	0.047
$\sigma(\Omega_{de})$	0.08	0.020	0.0068	0.036	0.0099
$\sigma(\Omega_b h^2)$	0.00028	0.00016	0.00013	0.00024	0.00014
$\sigma(\Omega_c h^2)$	0.0026	0.0017	0.0015	0.0019	0.0015
$\sigma(w_0)$	0.83	0.093	0.034	0.35	0.045
$\sigma(w_a)$	4.0	0.39	0.081	1.7	0.063
$\sigma(\tau)$	0.0046	0.0043	0.0042	0.0045	0.0043
$\sigma(n_s)$	0.0089	0.0056	0.0028	0.0074	0.0047
$\sigma(\alpha_s)$	0.024	0.013	0.0061	0.020	0.012
$\sigma(\sigma_8)$	0.084	0.019	0.0076	0.030	0.0092
$\sigma(N_{\text{eff}})$	0.19	0.11	0.067	0.14	0.093