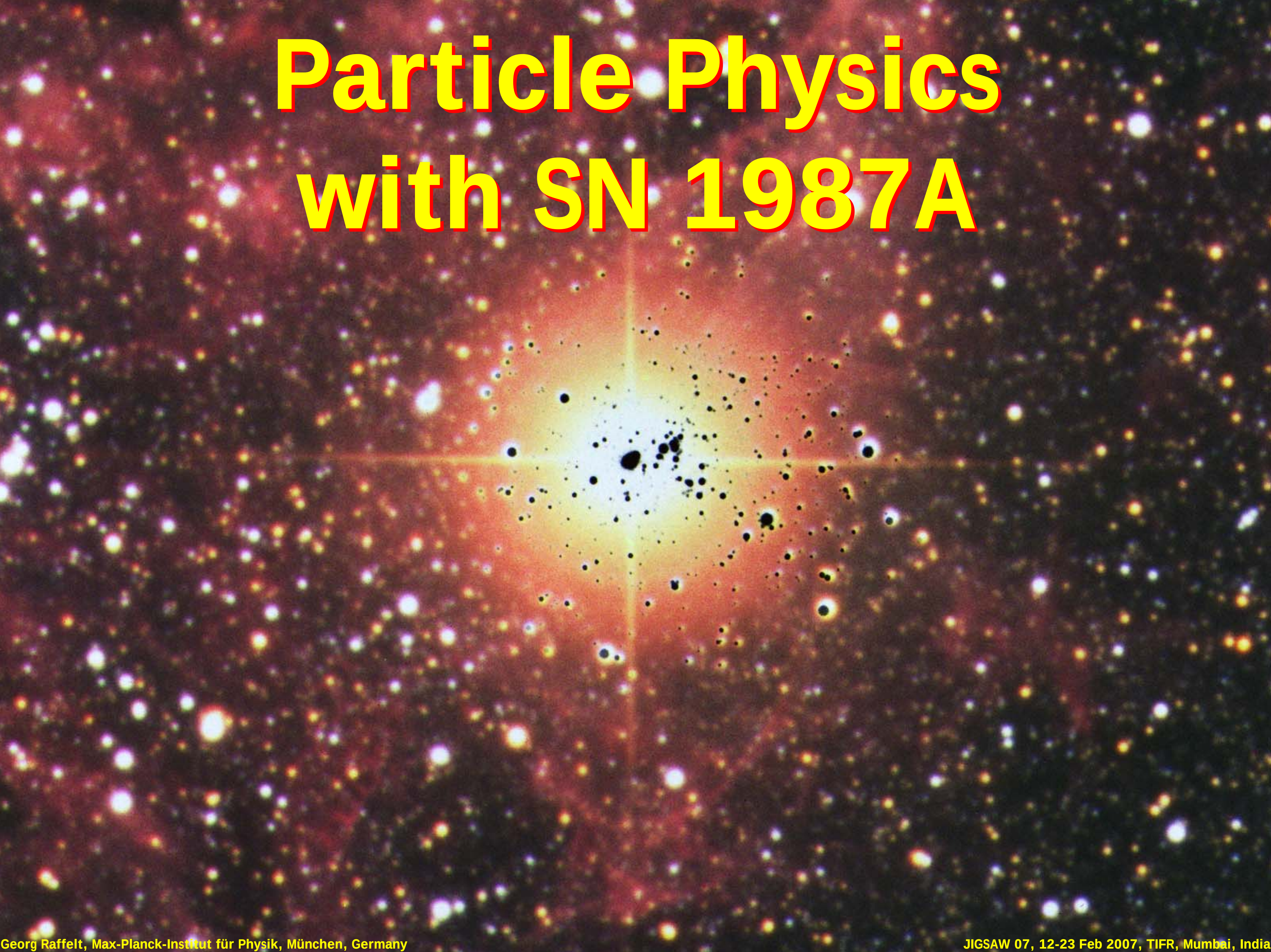
Particle Physics with SN 1987A



Neutrino Limits by Intrinsic Signal Dispersion

Time of flight delay by neutrino mass
(G. Zatsepin, JETP Lett. 8:205, 1968)

$$\Delta t = 2.57\,\mathrm{s}\left(\frac{D}{50\,\mathrm{kpc}}\right)\left(\frac{10\,\mathrm{MeV}}{E_\nu}\right)^2\left(\frac{m_\nu}{10\,\mathrm{eV}}\right)^2$$

$$m_{\nu_e} \lesssim 20\ \mathrm{eV}$$

Loredo & Lamb
Ann N.Y. Acad. Sci. 571 (1989) 601
find 23 eV (95% CL limit) from detailed maximum-likelihood analysis

- At the time of SN 1987A competitive with tritium end-point
- Today $m_\nu < 2.2$ eV from tritium
- Cosmological limit today $m_\nu \lesssim 0.2$ eV

For "milli charged" neutrinos, path bent by galactic magnetic field, inducing a time delay

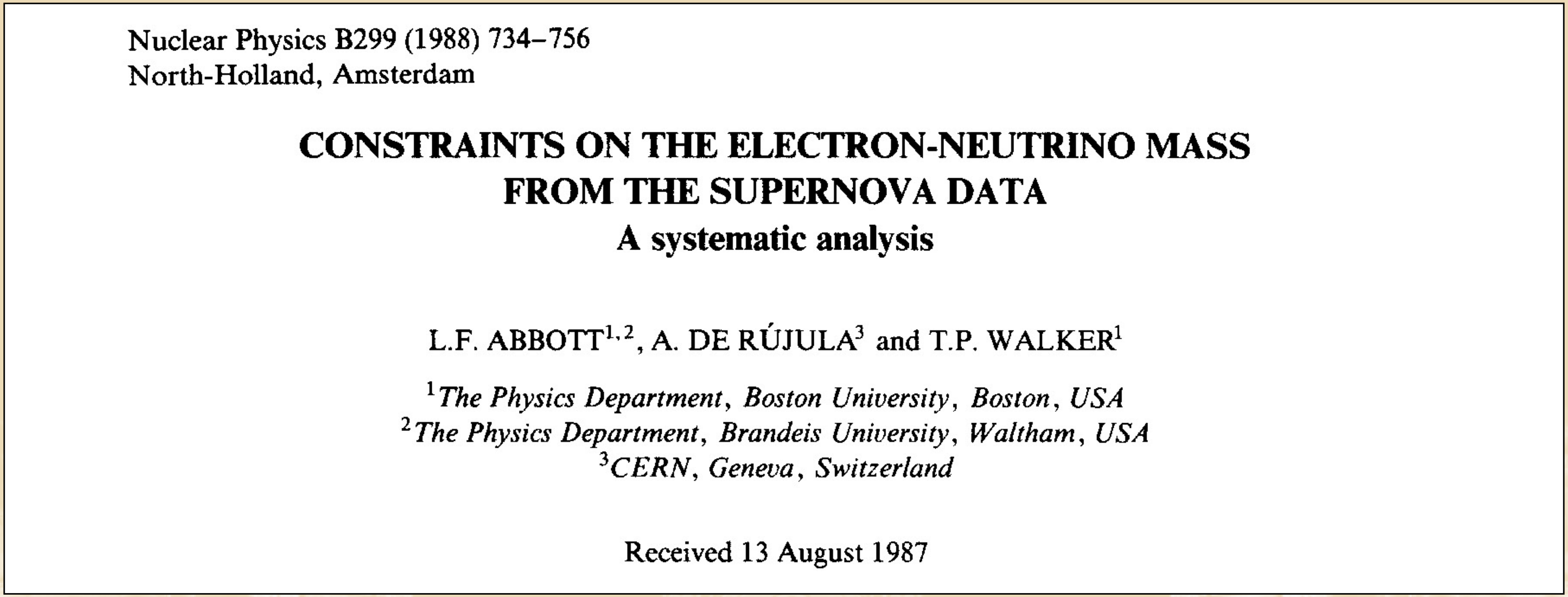
$$\frac{\Delta t}{t} = \frac{e_\nu^2 (B_\perp d_B)^2}{6 E_\nu^2} < 3\times10^{-12}$$

$$\frac{e_\nu}{e} < 3\times10^{-17}\left(\frac{1\,\mu\mathrm{G}}{B_\perp}\right)\left(\frac{1\,\mathrm{kpc}}{d_B}\right)$$

- Barbiellini & Cocconi, Nature 329 (1987) 21
- Bahcall, Neutrino Astrophysics (1989)

Assuming charge conservation in neutron decay yields a more restrictive limit of about 3×10^{-21} e

Some Papers on SN 1987A Neutrino Mass Limits



Nuclear Physics B299 (1988) 734–756
North-Holland, Amsterdam

CONSTRAINTS ON THE ELECTRON-NEUTRINO MASS FROM THE SUPERNOVA DATA

A systematic analysis

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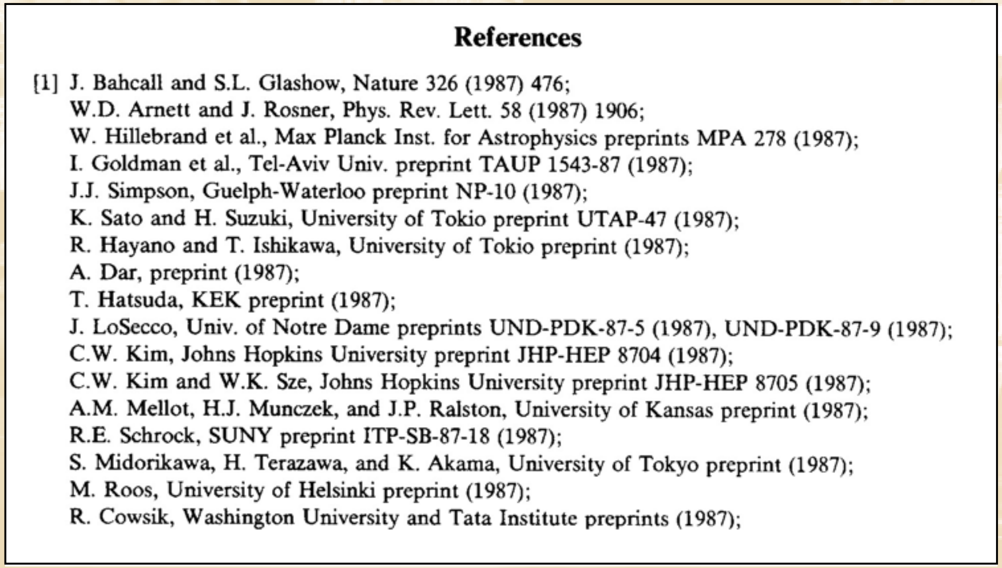
Received 13 August 1987



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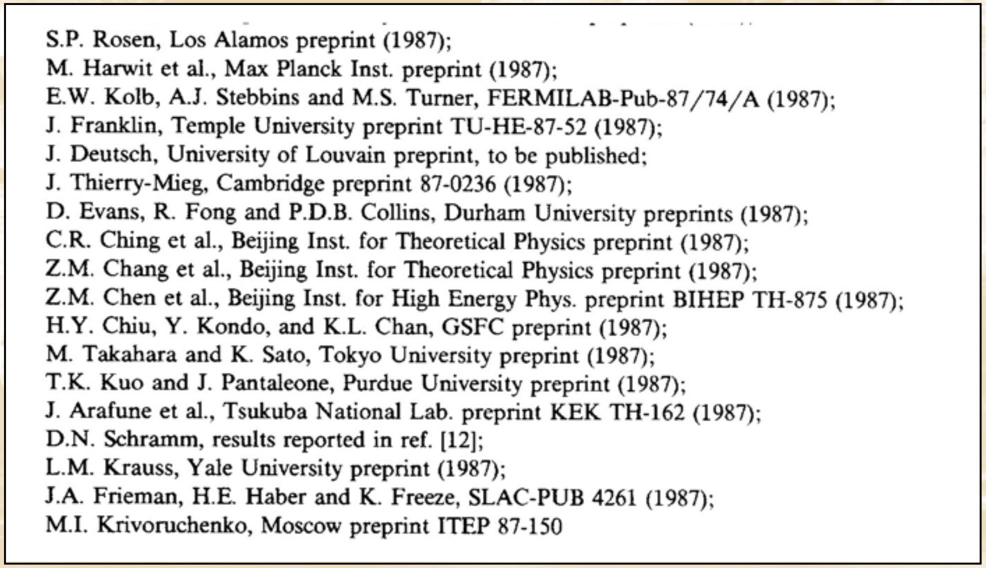

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Neutrino Mass Sensitivity by Signal Dispersion

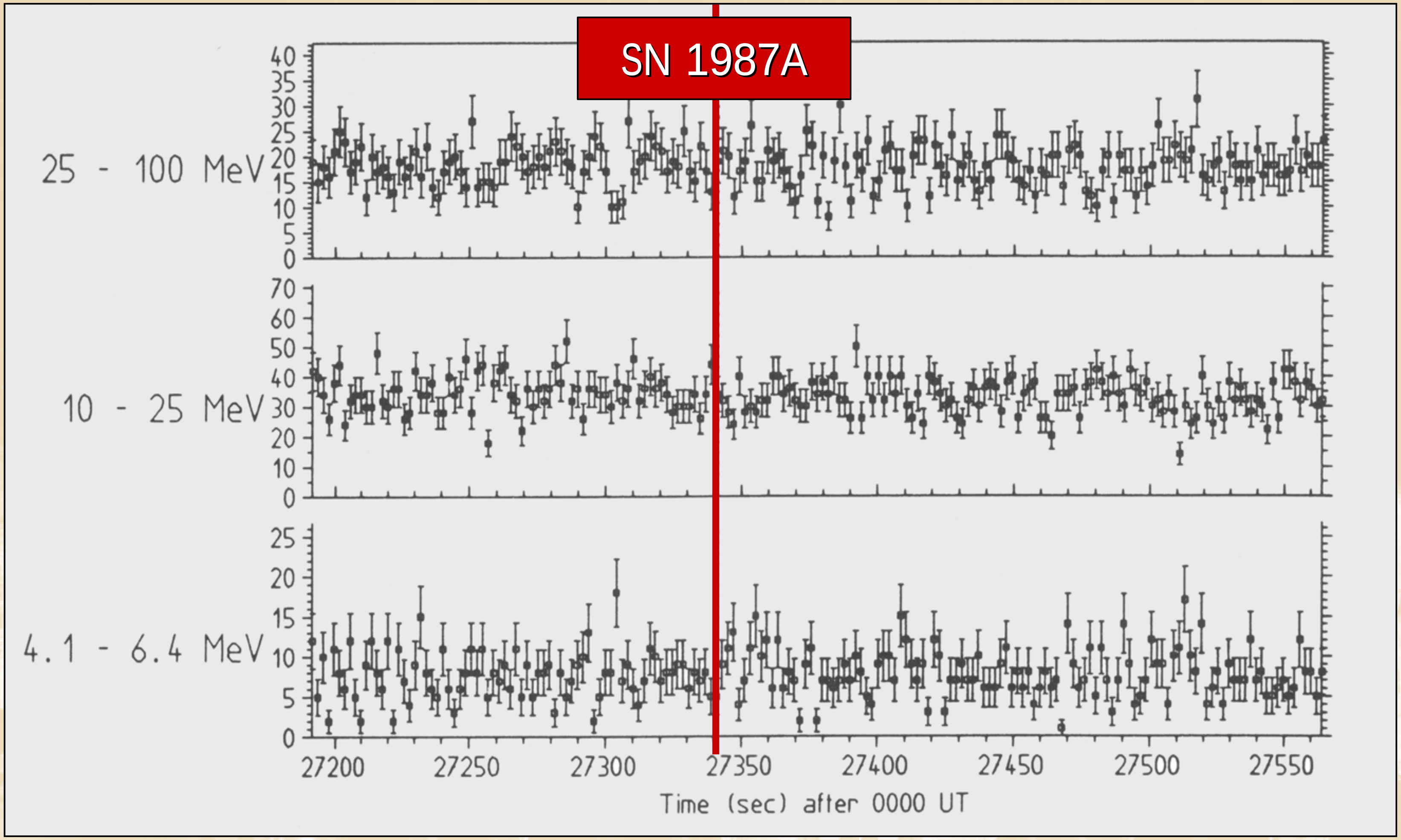
Time-of-flight delay
of massive neutrinos

$$\Delta t = 5.1\,\text{ms}\left(\frac{D}{10\,\text{kpc}}\right)\left(\frac{10\,\text{MeV}}{E_\nu}\right)^2\left(\frac{m_\nu}{1\,\text{eV}}\right)^2$$

SN 1987A (50 kpc)	$E \approx 20$ MeV, $\Delta t \approx 10$ s Simple estimate or detailed maximum likelihood analysis give similar results	$m_\nu \lesssim 20$ eV
Future Galactic SN at 10 kpc (Super-K)	Rise-time of signal ~ 10 ms (Totani, PRL 80:2040, 1998)	$m_\nu \sim 3$ eV
	Full signal (Nardi & Zuluaga, **NPB 731:140, 2005)**	$m_\nu \sim 1$ eV
With late black-hole formation	Cutoff “infinitely” fast (Beacom et al., PRD 63:073011, 2001)	$m_\nu \sim 2$ eV
Future SN in Andromeda (Megatonne)	$D \approx 750$ kpc, $\Delta t \approx 10$ s few tens of events	$m_\nu \sim 1$–2 eV

Gamma-Ray Observations of SMM Satellite

Counts in the GRS instrument on the Solar Maximum Mission Satellite



10s fluence limits

$0.9\ \mathrm{cm}^{-2}$

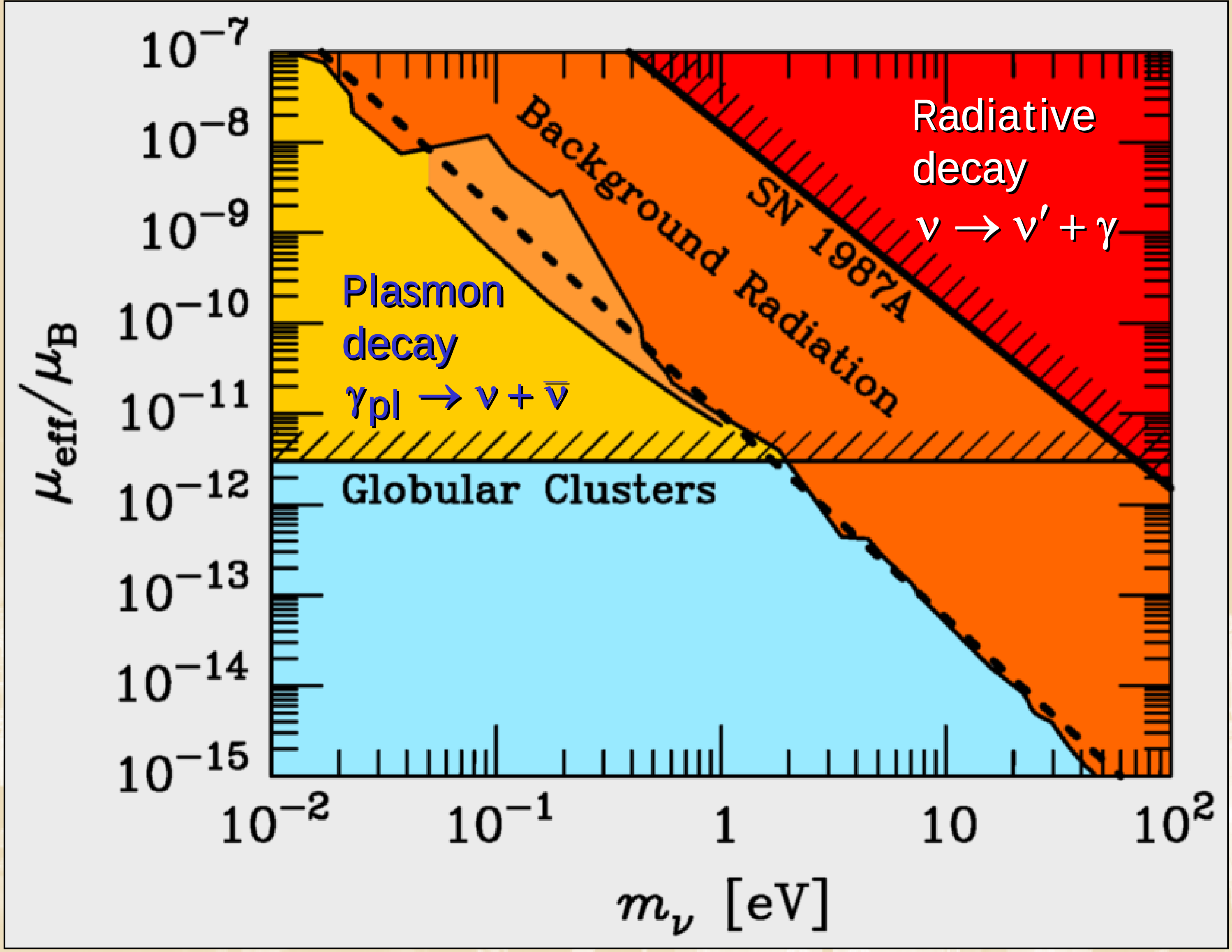
$0.4\ \mathrm{cm}^{-2}$

$0.6\ \mathrm{cm}^{-2}$

SN 1987A neutrino fluence ~ $10^{10}\ \mathrm{cm}^{-2}$

$< 10^{-10}$ of neutrinos have decayed between SN and Earth

Neutrino Radiative Lifetime Limits



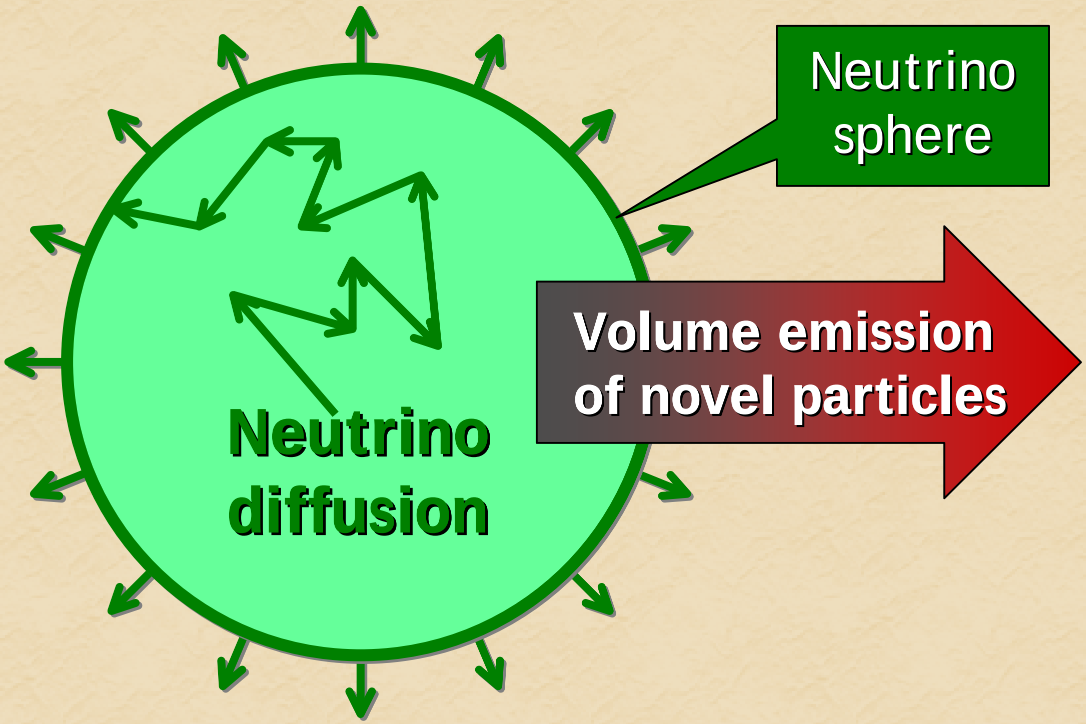
$$\Gamma_{\nu\to\nu'\gamma} = \frac{\mu_{\rm eff}^2}{8\pi} m_\nu^3$$

$$\Gamma_{\gamma\to\nu\overline{\nu}} = \frac{\mu_{\rm eff}^2}{24\pi} \omega_{\rm pl}^3$$

For low-mass neutrinos, plasmon decay in globular cluster stars yields most restrictive limits

Raffelt, PRL 81:4020,1998 [astro-ph/9808299]

The Energy-Loss Argument

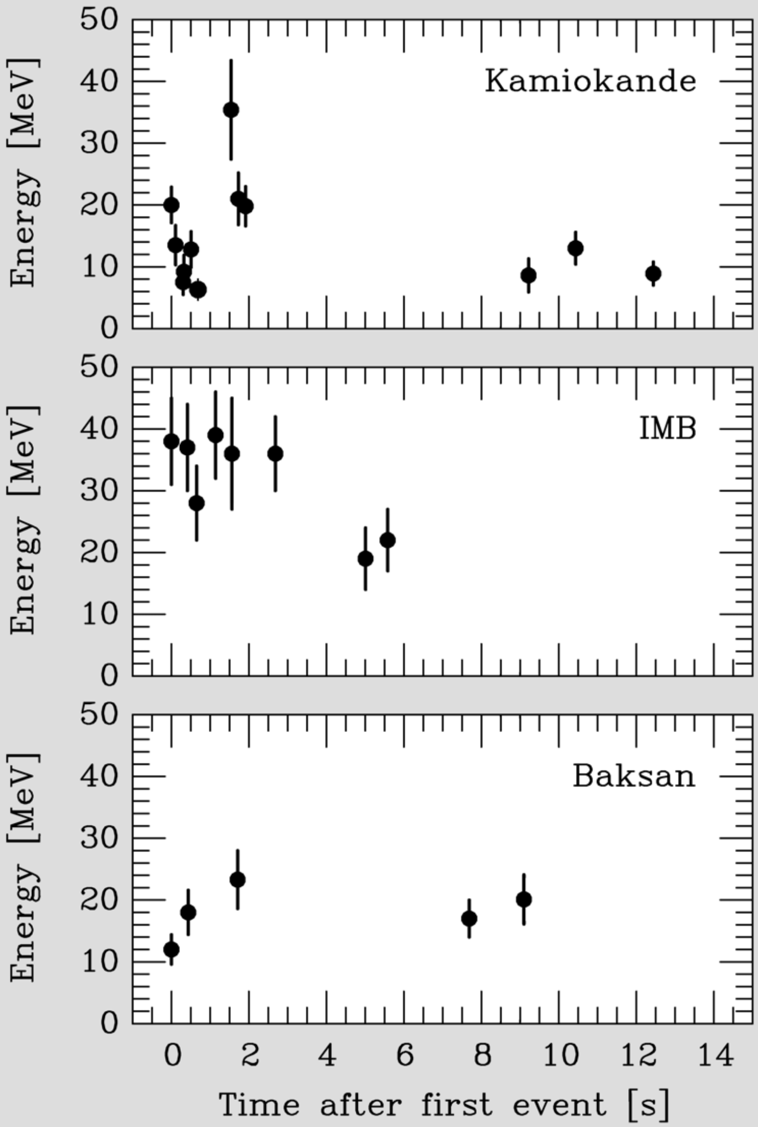


Neutrino sphere

Volume emission of novel particles

Neutrino diffusion

SN 1987A neutrino signal

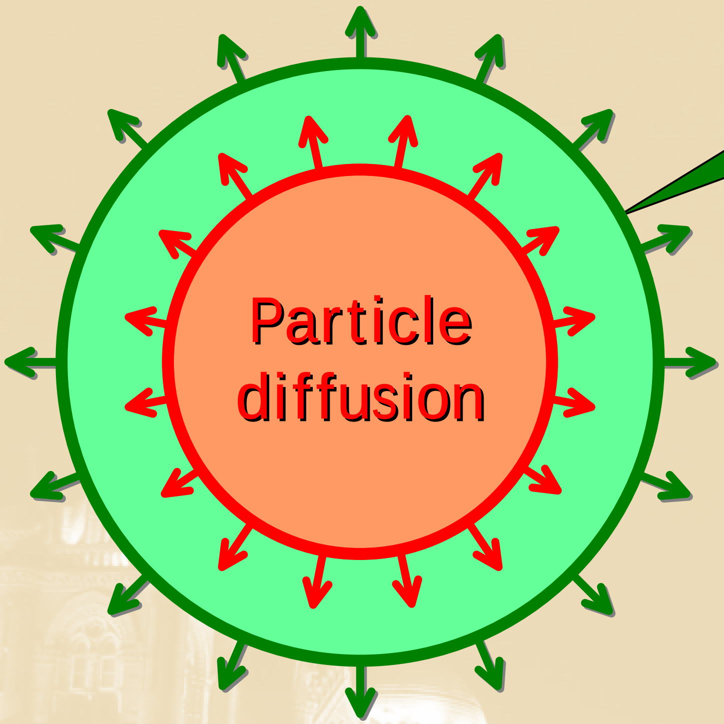


Assuming that the neutrino burst was not shortened by more than ~ ½ leads to an approximate requirement on a novel energy-loss rate of

$$\varepsilon_X < 10^{19}\ \mathrm{erg\ g^{-1}\ s^{-1}}$$

for $\rho \approx 3 \times 10^{14}\ \mathrm{g\ cm^{-3}}$ and $T \approx 30\ \mathrm{MeV}$

The Energy-Loss Argument in the Trapping Limit



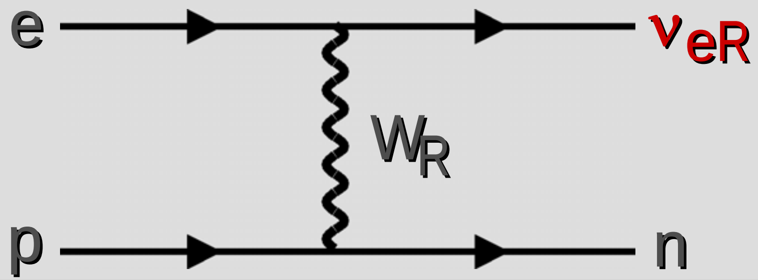
Neutrino sphere

Mean-free-path of new particles less than geometric dimension of star

- New particles are more important for energy transfer than neutrinos (Energy transfer ∝ mfp)
- Efficiency of energy transfer must be less than that of neutrinos or else speed up cooling of PNS, again shortening the observed SN 1987A signal

Right-Handed Neutrinos (Dirac Neutrinos)

Right-handed currents



Average scattering rate in SN core involving ordinary left-handed neutrinos

$$\Gamma_L \approx 10^{10}\,\mathrm{s}^{-1}$$

For right-handed neutrinos

$$\Gamma_R \approx \frac{G_R^2}{G_F^2}\,\Gamma_L$$

To avoid complete energy loss in ~ 1 s

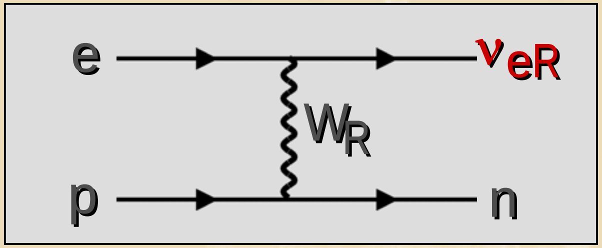
$$\frac{G_R^2}{G_F^2}10^{10}\,\mathrm{s}^{-1} < 1\mathrm{s}^{-1}$$

$$G_R < 10^{-5}\,G_F$$

Dirac Neutrinos

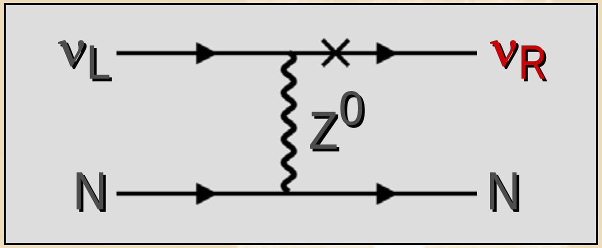
- If neutrinos are Dirac particles, right-handed states exist that do not interact by ordinary weak interactions
- Couplings are constrained by SN 1987A energy-loss argument

Right-handed currents



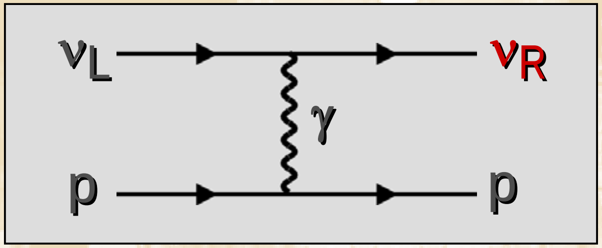
$G_R \lesssim 10^{-5}\ G_F$

Dirac mass



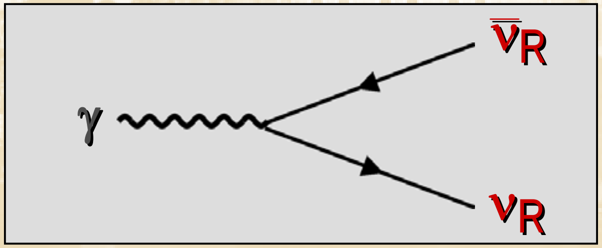
$m_D \lesssim 30$ keV

Dipole moments



$\mu_\nu \lesssim 10^{-12}\ \mu_B$

Milli charge



$e_\nu \lesssim 10^{-9}$ e

Right-Handed Neutrinos in the Early Universe

- If neutrinos are Dirac particles, will the right-handed components achieve thermal equilibrium in the early universe before big-bang nucleosynthesis?
- This would modify the light-element abundances in significant ways, notably increase the helium abundance

	Required strength	SN 1987A limit
Right-handed charged current	$G_R \sim 10^{-3}\,G_F$	$G_R \lesssim 10^{-5}\,G_F$
Dirac mass	few 100 keV	30 keV
Dipole moment	$\sim 0.5 \times 10^{-10}\ \mu_B$	$10^{-12}\ \mu_B$

Sterile Neutrinos

Sterile (right-handed) neutrinos may exist that are not Dirac partners to ordinary neutrinos

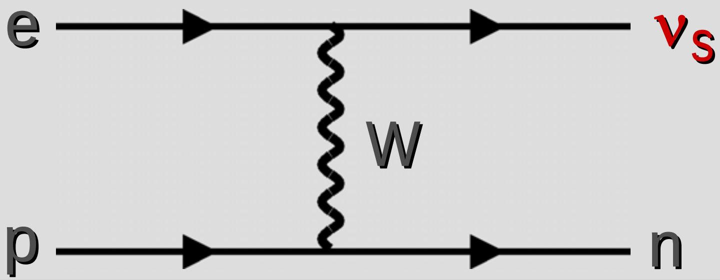
- Unknown mass m_s
- Unknown mixing angles with ordinary neutrinos Θ_{es}, $\Theta_{\mu s}$, $\Theta_{\tau s}$

Consequences and applications

- May (partially) account for some experimental oscillation results (LSND)
- Hot, warm, or cold dark matter contribution
- May affect big-bang nucleosynthesis
- Emission from supernova cores
- Affects r-process nucleosynthesis in the SN hot bubble
- Radiative decays → potentially detectable

Sterile Neutrinos

Active-sterile mixing



Electron neutrino appears as sterile neutrino in ½ $\sin^2(2\Theta_{es})$ of all cases

$$\Gamma_S \approx \frac{1}{2}\sin^2(2\Theta_{es})\,\Gamma_L$$

Average scattering rate in SN core involving ordinary left-handed neutrinos

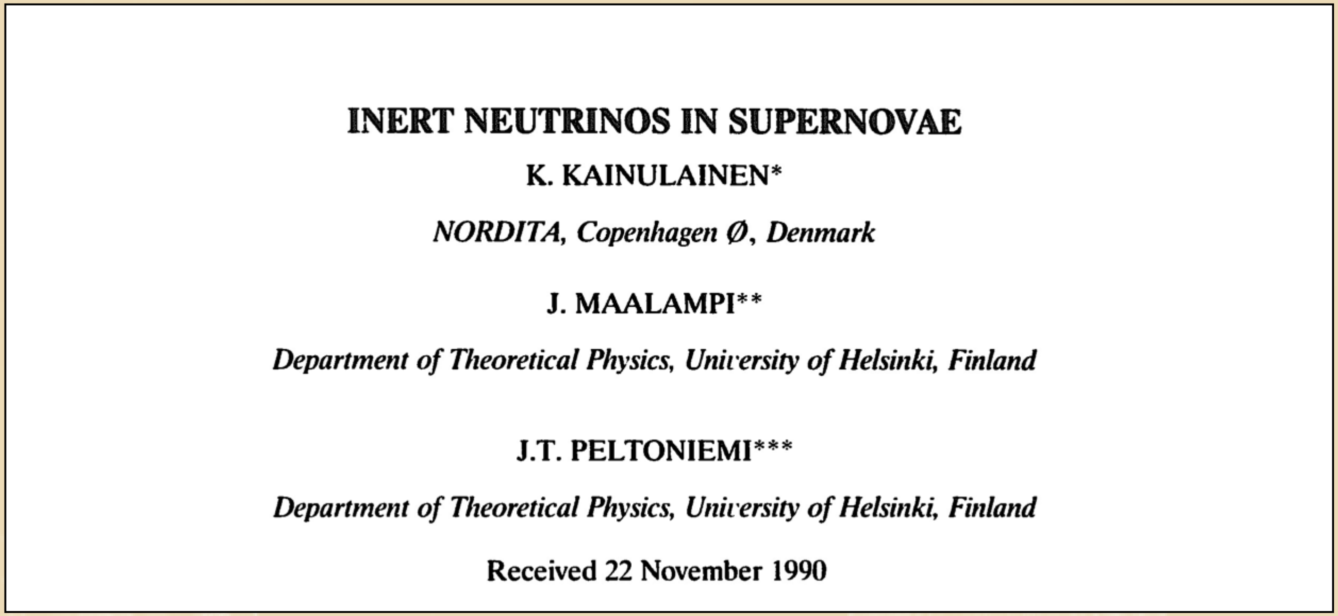
$$\Gamma_L \approx 10^{10}\,s^{-1}$$

To avoid complete energy loss in ~ 1 s

$$\frac{1}{2}\sin^2(2\Theta_{es})\,10^{10}\,s^{-1} < 1s^{-1}$$

$$\sin^2(2\Theta_{es}) \lesssim 3 \times 10^{-10}$$

Sterile Neutrino Limits



INERT NEUTRINOS IN SUPERNOVAE

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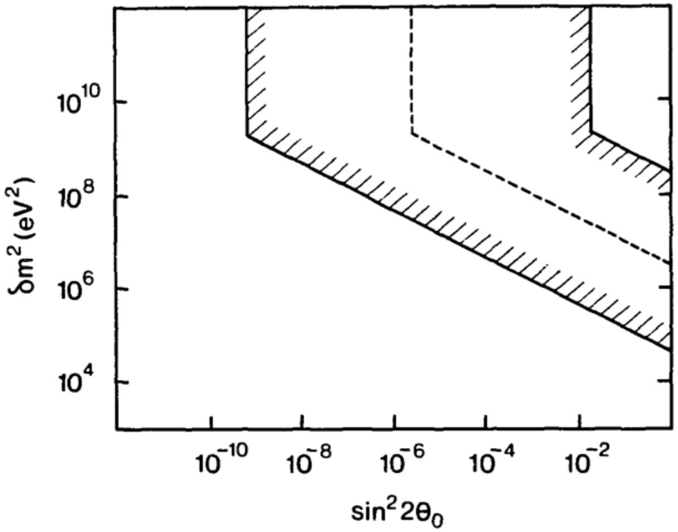


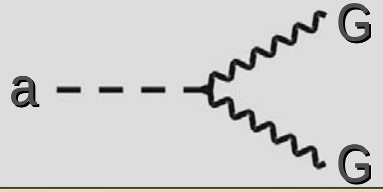
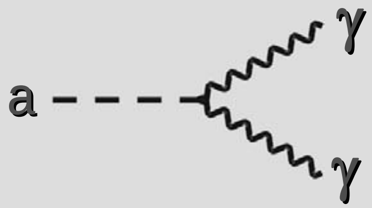
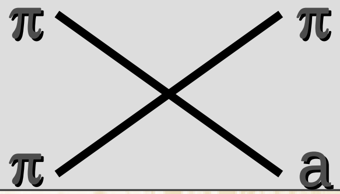
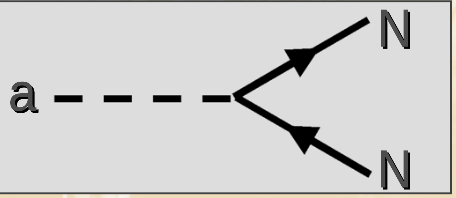
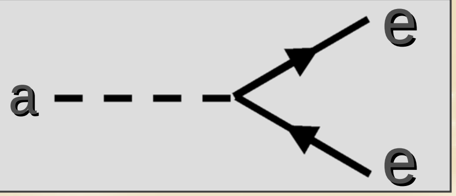
Fig. 1. Constraints from the supernova SN1987A for the squared mass difference δm^2 and the mixing angle θ_0 of the electron neutrino and an inert neutrino. The shaded region is forbidden by the observations. The dashed line shows the trapping condition (15).

See also:

Maalampi & Peltoniemi:
Effects of the 17-keV neutrino in supernovae
PLB 269:357,1991

Hidaka & Fuller:
Dark matter sterile neutrinos in stellar collapse: alteration of energy/lepton number transport and a mechanism for supernova explosion enhancement
PRD 74:125015,2006

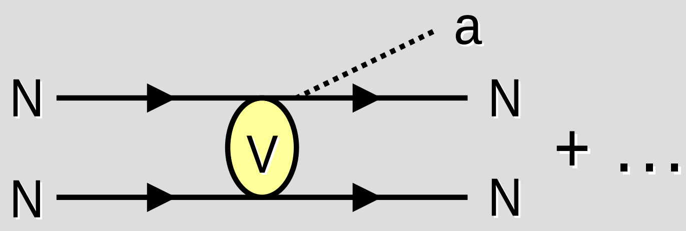
Axion Properties

Gluon coupling (Generic property)	$L_{aG}=\frac{\alpha_s}{8\pi f_a}G\tilde{G}a$ 
Mass	$m_a=\frac{0.6\,\mathrm{eV}}{f_a/10^7\,\mathrm{GeV}}\approx\frac{m_\pi f_\pi}{f_a}$
Photon coupling	$L_{a\gamma}=-\frac{g_{a\gamma}}{4}F\tilde{F}a=g_{a\gamma}\vec{E}\cdot\vec{B}\,a$ $g_{a\gamma}=\frac{\alpha}{2\pi f_a}\left(\frac{E}{N}-1.92\right)$ 
Pion coupling	$L_{a\pi}=\frac{C_{a\pi}}{f_a f_\pi}(\pi^0\pi^+\partial_\mu\pi^- + \ldots)\partial^\mu a$ 
Nucleon coupling (axial vector)	$L_{aN}=\frac{C_N}{2f_a}\overline{\Psi}_N\gamma^\mu\gamma_5\Psi_N\,\partial_\mu a$ 
Electron coupling (optional)	$L_{ae}=\frac{C_e}{2f_a}\overline{\Psi}_e\gamma^\mu\gamma_5\Psi_e\,\partial_\mu a$ 

Axion Emission from a Nuclear Medium

Axion-nucleon interaction is of current-current form:

$$L_{int} = \frac{C_N}{2f_a}\overline{\Psi}_N\gamma_\mu\gamma_5\Psi_N\partial^\mu a = \frac{C_N}{2f_a}J^A_\mu\partial^\mu a$$



Nucleon-Nucleon Bremsstrahlung

Energy loss rate (erg $\mathrm{cm}^{-3}\,\mathrm{s}^{-1}$)

$$Q = \int d\Gamma_a \int d\Gamma_{\mathrm{Nucleons}} |M|^2 \omega$$

$$= \left(\frac{C_N}{2f_a}\right)^2 \frac{n_B}{4\pi^2} \int_0^\infty d\omega\, \omega^4 S(-\omega)$$

Axion energy

Dynamical structure function

Difficulties include:

- Realistic nucleon-nucleon interaction potential (even in vacuum)
- Many-body effects (effective mass, spin-spin correlations …)
- Axion couplings in the nuclear medium
- Multiple-scattering effects:

  Frequency of NN collisions exceeds typical axion energy

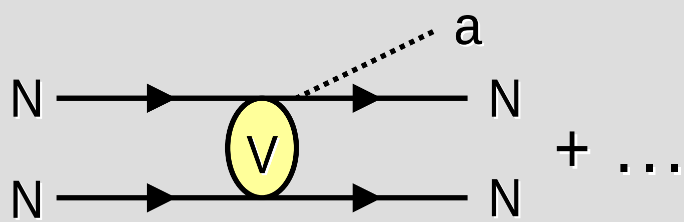
  $\tau_{\mathrm{coll}} < \omega^{-1}$

  Expect LPM-type destructive interference effects

Axion Emission from a Nuclear Medium

Axion-nucleon interaction is of current-current form:

$$L_{int} = \frac{C_N}{2f_a} \overline{\Psi}_N \gamma_\mu \gamma_5 \Psi_N \partial^\mu a = \frac{C_N}{2f_a} J_\mu^A \partial^\mu a$$



$+ \dots$

Nucleon-Nucleon Bremsstrahlung

Energy loss rate (erg $\mathrm{cm}^{-3}\,\mathrm{s}^{-1}$)

$$Q = \int d\Gamma_a \int d\Gamma_{Nucleons} |M|^2 \omega$$

$$= \left(\frac{C_N}{2f_a}\right)^2 \frac{n_B}{4\pi^2} \int_0^\infty d\omega\, \omega^4 S(-\omega)$$

Axion energy

Dynamical structure function

- Fundamentally the dynamical structure function is a correlator of the nucleon axial current
- Non-relativistic nucleons: ~ nucleon spin density operator σ

$$S(\omega,k) = \frac{4}{3n_B} \int_{-\infty}^{+\infty} dt\, e^{i\omega t} \langle \vec{\sigma}(t,k) \cdot \vec{\sigma}(0,-k) \rangle$$

- Example for the fluctuation and dissipation theorem of linear-response theory: Axion emission determined by spontaneous nucleon spin fluctuations

Properties of the Dynamical Structure Function

Nucleon spin-density autocorrelation function	$S(\omega,k) = \frac{4}{3n_B}\int_{-\infty}^{+\infty} dt\, e^{i\omega t}\langle \vec{\sigma}(t,k)\cdot\vec{\sigma}(0,-k)\rangle$
Normalization, ignoring many-body correlations	$\int_{-\infty}^{+\infty}\frac{d\omega}{2\pi}S(\omega,k) = \frac{1}{n_B}\int\frac{2d^3p}{(2\pi)^3} f_p(1-f_{p+k})$
Detailed balancing	$S(-\omega,k) = e^{-\omega/T}S(\omega,k)$ consequence of non-commuting $\sigma(t)$ at different times
Symmetric form	$\bar{S}(\omega,k) = \frac{S(-\omega,k)+S(\omega,k)}{2}$ → $S(\omega,k) = \frac{2\bar{S}(\omega,k)}{1+e^{-\omega/T}}$
Long-wavelength limit ($k \to 0$)	$\bar{S}(\omega) = \frac{4}{3}\int_{-\infty}^{+\infty} dt\, e^{i\omega t}\left\langle\frac{\vec{s}(t)\cdot\vec{s}(0)+\vec{s}(0)\cdot\vec{s}(t)}{2}\right\rangle$
Is Fourier transform of single-nucleon spin correlation function	$\bar{R}(t) = \frac{4}{3}\left\langle\frac{\vec{s}(t)\cdot\vec{s}(0)+\vec{s}(0)\cdot\vec{s}(t)}{2}\right\rangle$

Spin Relaxation Rate

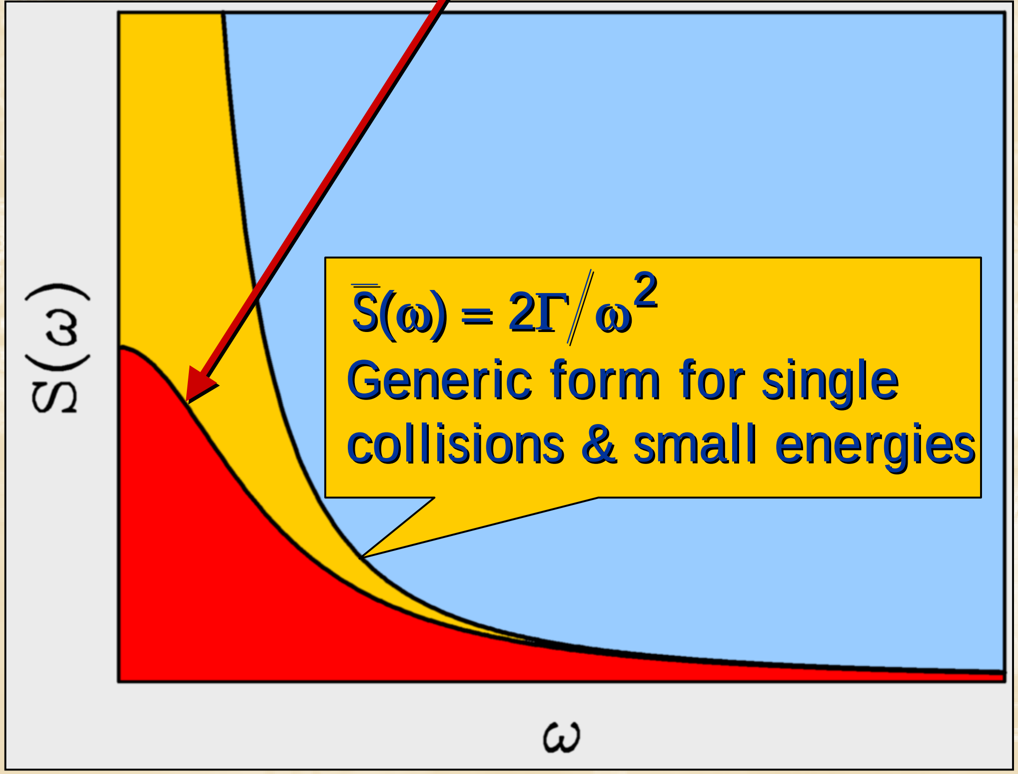
A spin immersed in a bath of scatterers with spin-dependent forces relaxes exponentially for uncorrelated kicks (Markov chain)

$$\overline{R}(t) = e^{-\Gamma t}$$

with Γ the “spin relaxation rate”, leading to the Fourier transform

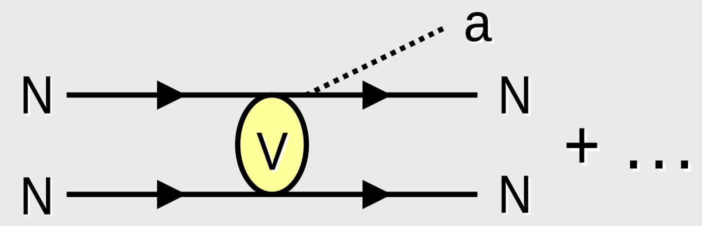
$$\overline{S}(\omega) = \frac{2\Gamma}{\omega^2 + \Gamma^2}$$

Lorentzian structure function, includes multiple scattering effects



$\overline{S}(\omega) = 2\Gamma / \omega^2$

Generic form for single collisions & small energies



Nucleon-Nucleon Bremsstrahlung

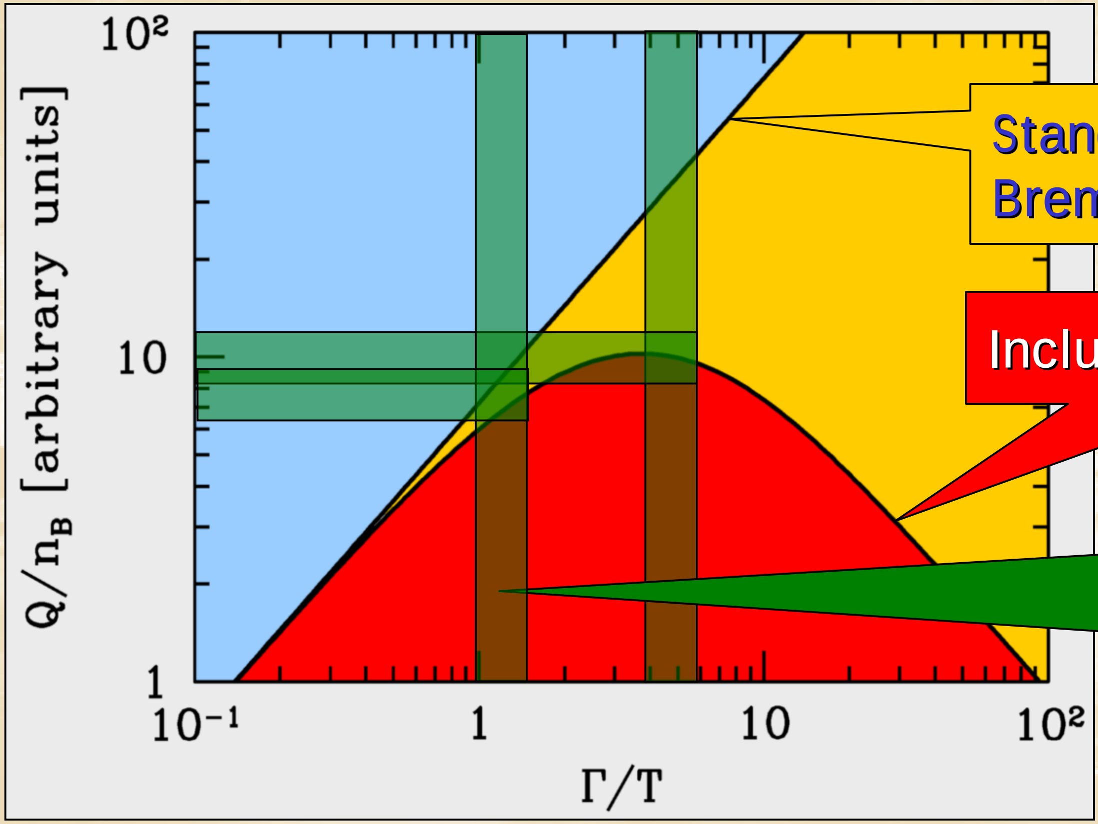
Identify coefficient Γ from bremsstrahlung calculation with spin relaxation rate

Axion Emission Rate

$$Q = \left(\frac{C_N}{2f_a}\right)^2 \frac{n_B}{4\pi^2} \int_0^\infty d\omega\, \omega^4 S(-\omega)$$

$$= \left(\frac{C_N}{2f_a}\right)^2 \frac{n_B}{4\pi^2} \int_0^\infty d\omega\, \omega^4 \frac{2\Gamma}{\omega^2+\Gamma^2} \frac{2}{1+e^{\omega/T}} \propto \begin{cases} n_B^2 & \text{for small density} \\ n_B^{-1} & \text{for large density} \end{cases}$$

Axionic volume energy loss rate of nuclear medium



Standard behavior:
Bremsstrahlung rate $\propto \rho^2$

Including LPM effect

Using phase shifts from nuclear scattering data (Hanhart, Phillips & Reddy, astro-ph/0003445)

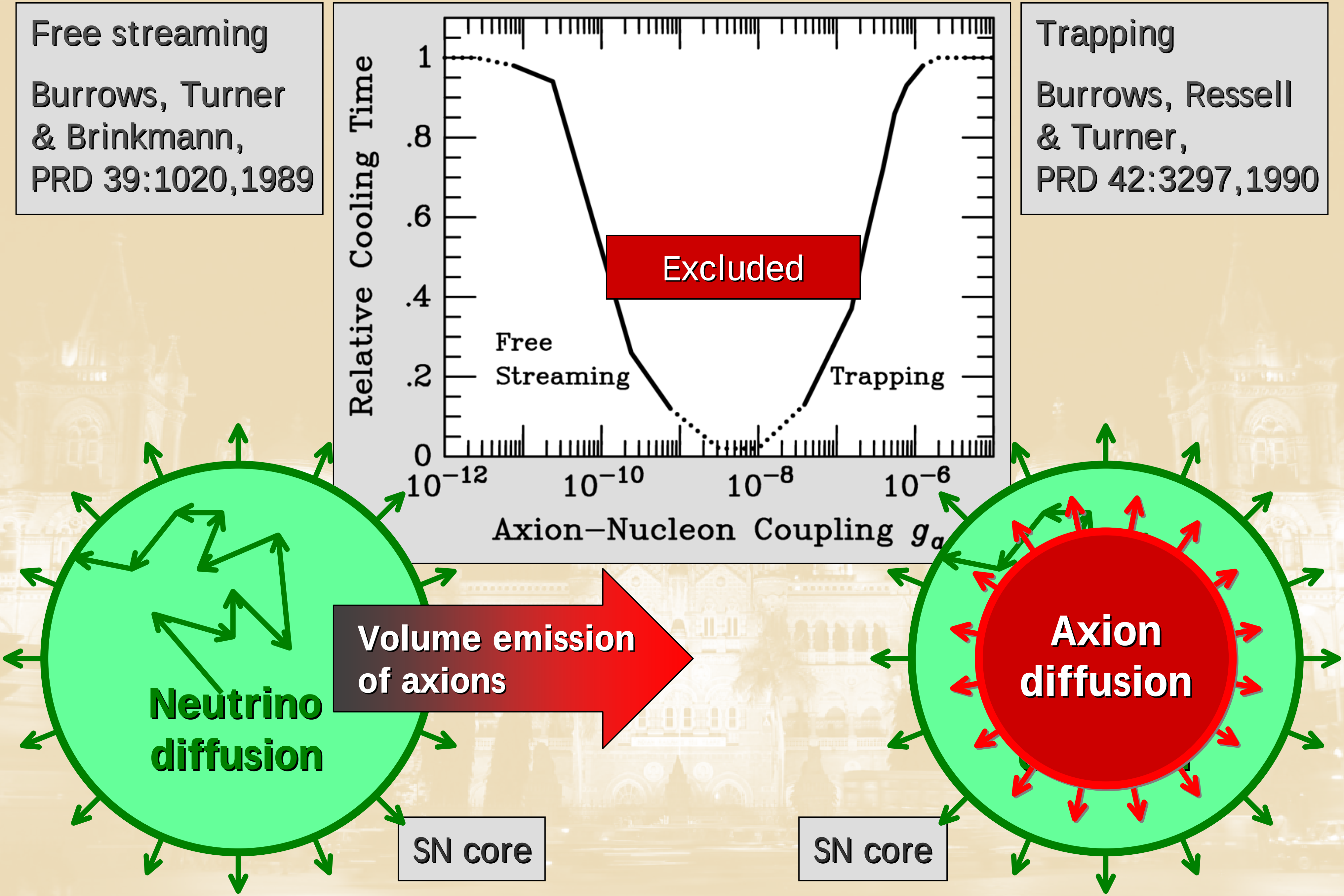
SN 1987A Axion Limits

Free streaming

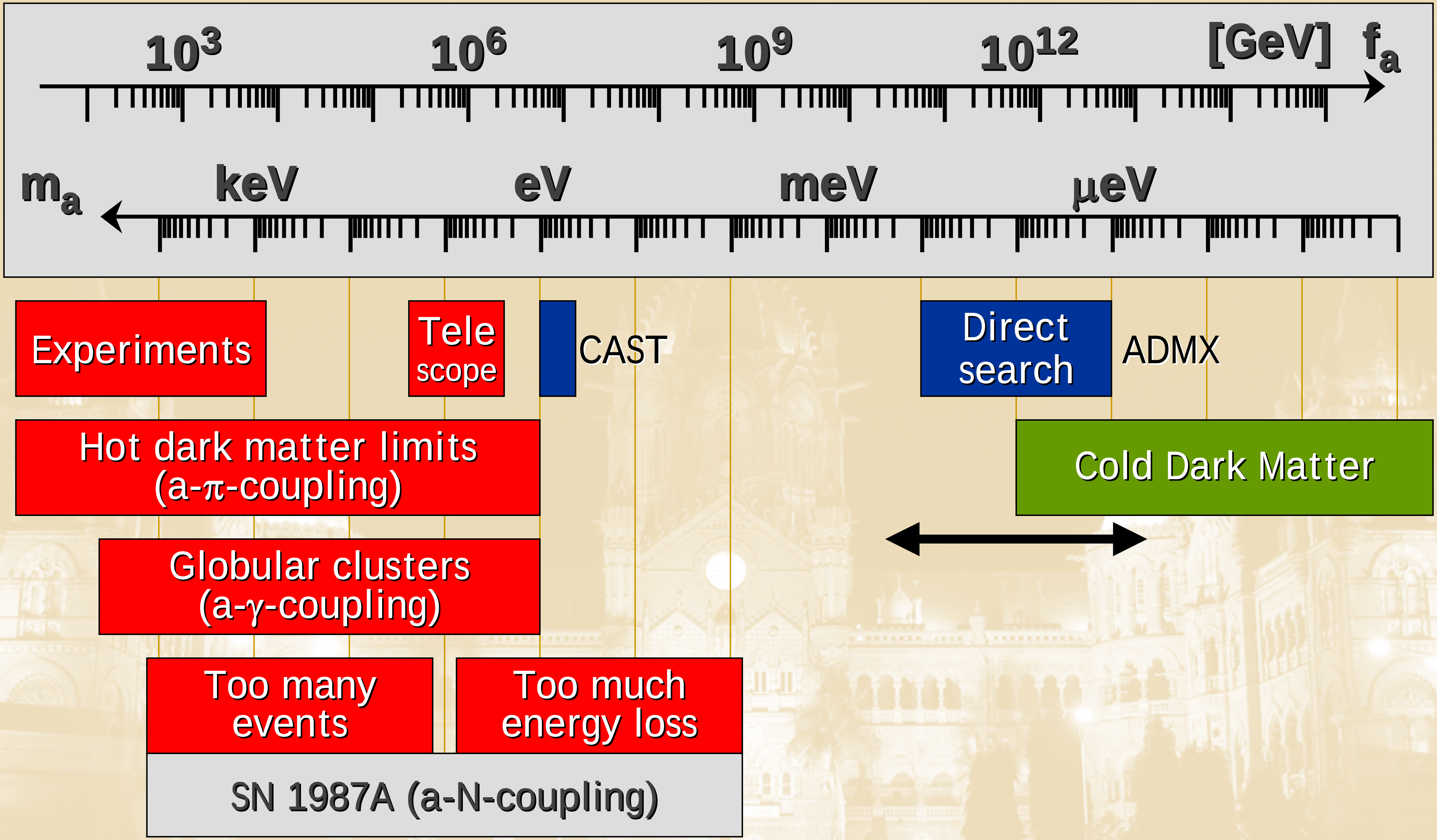
Burrows, Turner & Brinkmann,
PRD 39:1020,1989

Trapping

Burrows, Ressell & Turner,
PRD 42:3297,1990



Astrophysical Axion Bounds



Experiments

Tele scope

CAST

Direct search

ADMX

Hot dark matter limits (a-π-coupling)

Cold Dark Matter

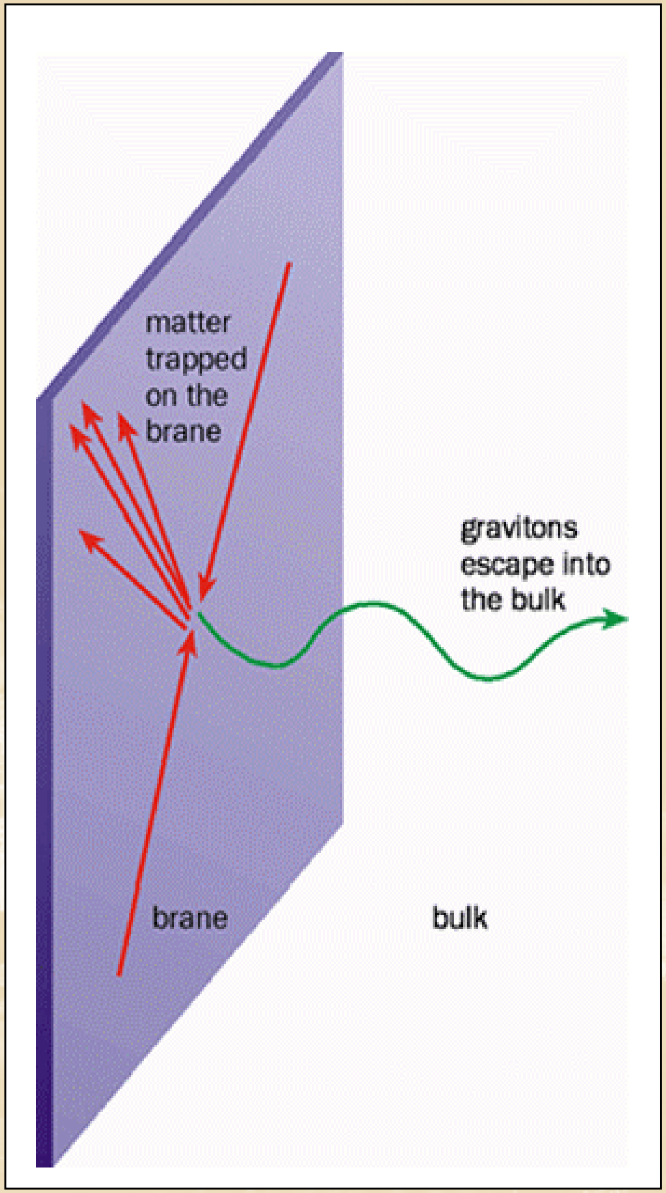
Globular clusters (a-γ-coupling)

Too many events

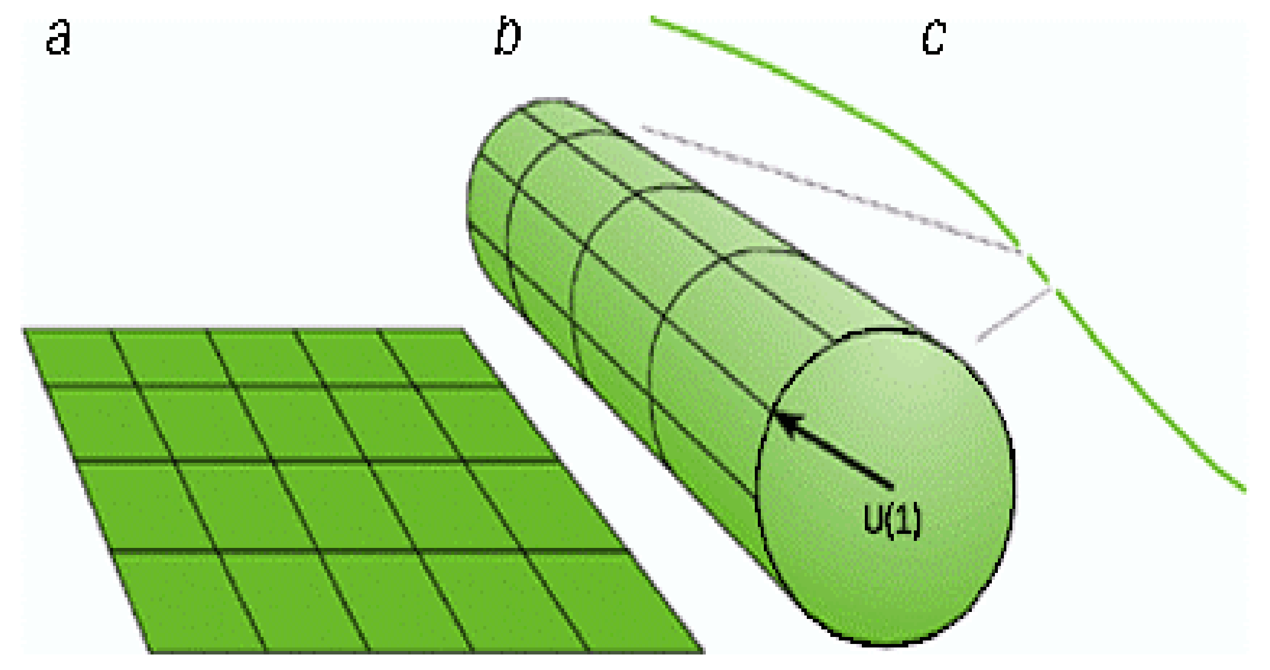
Too much energy loss

SN 1987A (a-N-coupling)

Large Extra Dimensions



- Fundamentally, space-time can have more than 4 dimensions (e.g. 10 or 11 in string theories)
- If standard model fields are confined to 4D brane in (4+n) D space-time, and only gravity propagates in the (4+n) D bulk, the compactification scale could be macroscopic



Planck Mass and Compactification Scale

Gauss' Law

$$M_{Pl}^2 = (2.4 \times 10^{18}\,\mathrm{GeV})^2 = (2\pi R)^n M^{2+n}$$

Reduced Planck mass $M_{Pl} = m_{Pl} / (8\pi)^{1/2}$

Compactification radius

Scale of fundamental physics

Gravity is strong (comparable to electroweak interaction), but looks weak because it leaks into large extra dimensions

If scale of fundamental physics ~ 1 TeV to solve the hierarchy problem, then experimentally

$n = 1$	$R_1 \sim 10^{13}$ cm	excluded
$n = 2$	$R_2 \sim 1$ mm	marginally allowed
$n = 3$	$R_3 \sim 10^{-6}$ mm	allowed

...

Kaluza-Klein (KK) Gravitons

Bulk particles have discrete momenta in extra dimensions

$$\phi = \exp(ip \cdot x) \exp\left(i \sum_{j=1}^{n} \frac{n_j y_j}{R} \right)$$

p	4D energy-momentum
x	4D coordinate
y_j	extra dimensional coordinate
n_j	whole number

Assuming toroidal compactification with dimenion $2\pi R$

Klein-Gordon Equation for massless bulk particle in 4+nD

$$\left(\frac{\partial^2}{\partial t^2} - \sum_{j=1}^{3+n} \frac{\partial^2}{\partial x_j^2} \right) \phi = \left(p^2 - \sum_{j=1}^{n} \frac{n_j^2}{R^2} \right) \phi = 0$$

- There are many massless modes, appearing in 4D as massive particles, e.g. a “tower of Kaluza-Klein gravitons”
- Are weakly coupled like normal gravitons, but may be astrophysically important because of huge number of modes

Supernova 1987A Limit on Large Extra Dimensions

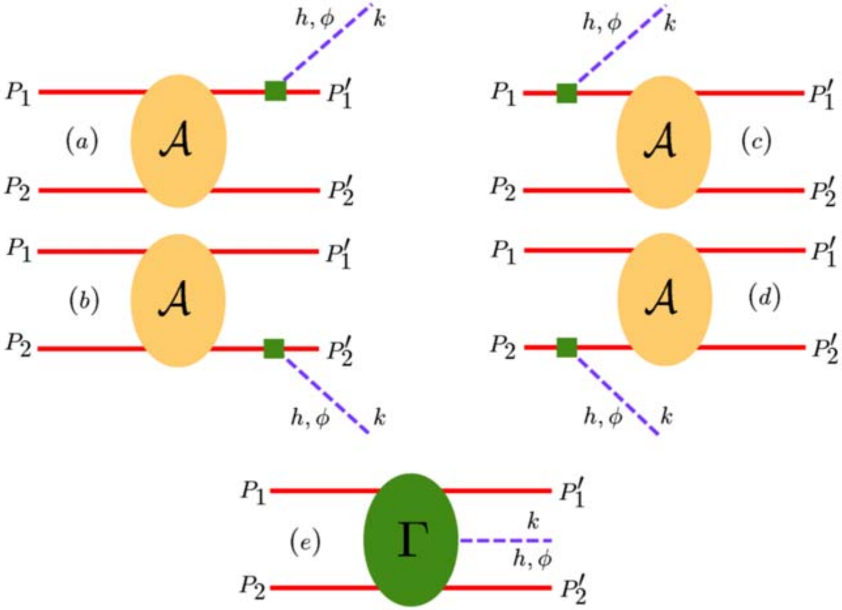


FIG. 1. *The leading diagrams contributing to processes $NN \to NNh$ and $NN \to NN\phi$. Nucleons are denoted by solid lines and the KK-modes h or ϕ are denoted by dashed lines. Solid squares denote an insertion of the single-nucleon energy-momentum tensor, while solid ovals containing $\mathcal{A}$ denote an insertion of the full NN scattering amplitude. The solid oval containing Γ denotes the non-pole vertex required for the sum of diagrams to satisfy $\partial_\mu M^{\mu\nu} = 0$.*

SN core emits large flux of KK gravity modes by nucleon-nucleon bremsstrahlung

Rate $\propto M_{Pl}^{-2}$

Large multiplicity of modes

RT ~ 10^{11}

for R ~ 1 mm, T ~ 30 MeV

$$\text{Rate} \propto \frac{(RT)^n}{M_{Pl}^2} \propto \frac{T^n}{M_{Pl}^{2+n}}$$

Cullen & Perelstein, hep-ph/9904422
Hanhart et al., nucl-th/0007016

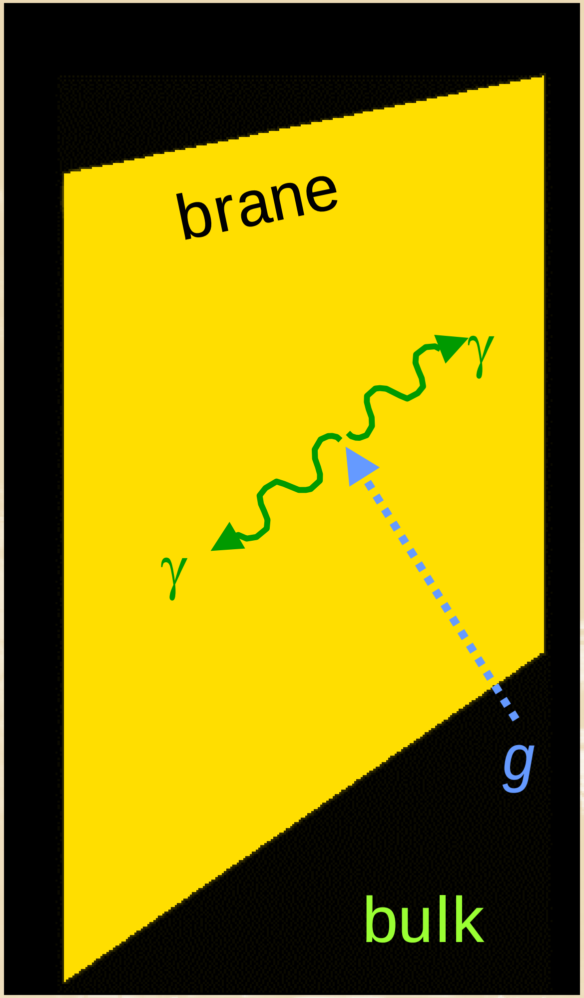
SN 1987A energy-loss argument:

R < 1 mm,	M > 9 TeV	(n = 2)
R < 1 nm,	M > 0.7 TeV	(n = 3)

Originally the most restrictive limit on such theories, except for cosmological arguments

Kaluza-Klein Graviton Decays

Gravitons are stable in the bulk, but can decay when they are within a Compton wavelength of the brane



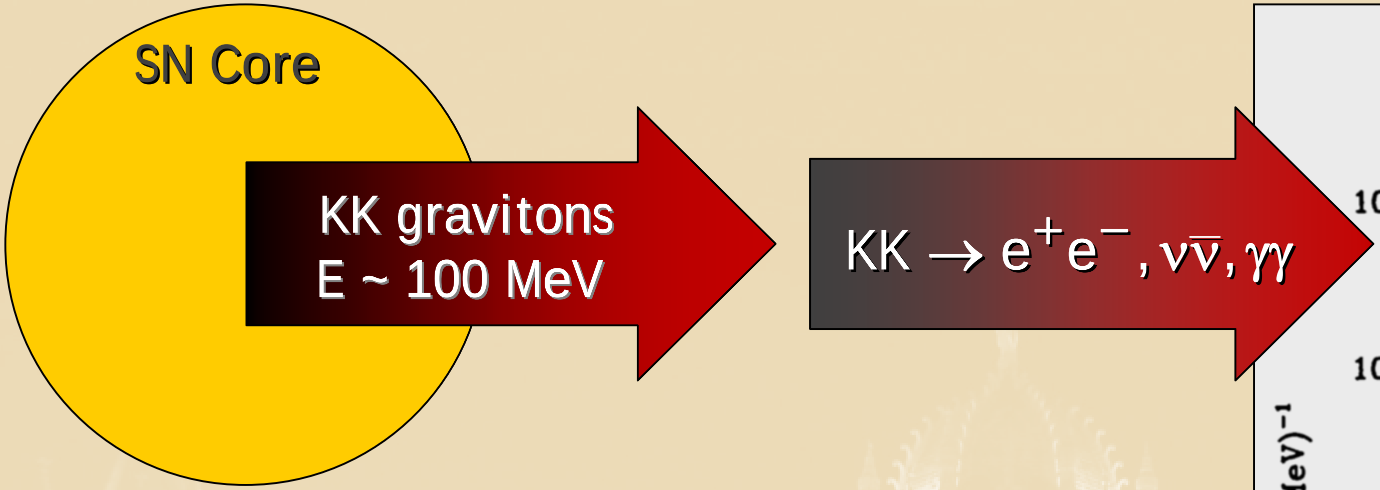
$$\Gamma_{\text{tot}} \sim P_{\text{wall}} \Gamma_{\text{brane}}$$

$$\sim (mR)^{-n} \times \frac{m^{n+3}}{M_{nD}^{n+2}} \sim \frac{m^3}{M_{Pl}^2}$$

$$\tau_{2\gamma} \sim 6 \times 10^9 \text{ yr } (m/100 \text{ MeV})^{-3}$$

Most gravitons produced by cosmological supernovae have decayed and produced γ rays

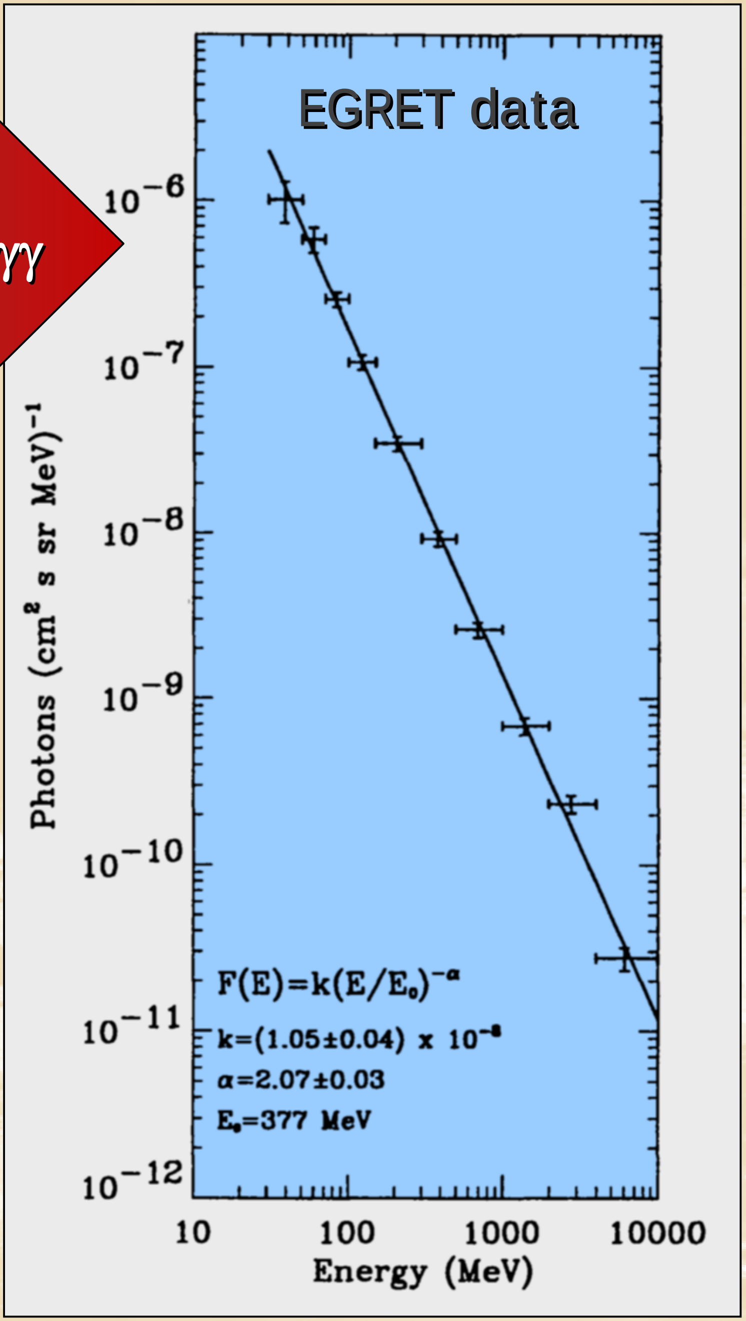
Improved Limits on Large Extra Dimensions



SN Core

KK gravitons
E ~ 100 MeV

$\mathrm{KK} \to e^+e^-, \nu\bar{\nu}, \gamma\gamma$



- From all SNe in the universe, KK decay contributes to diffuse cosmic γ-rays in 100 MeV range
- EGRET data & conservative estimate of SN rate:
  < 1 % of SN energy into KK gravitons
  i.e. 0.01 of SN 1987A cooling limit

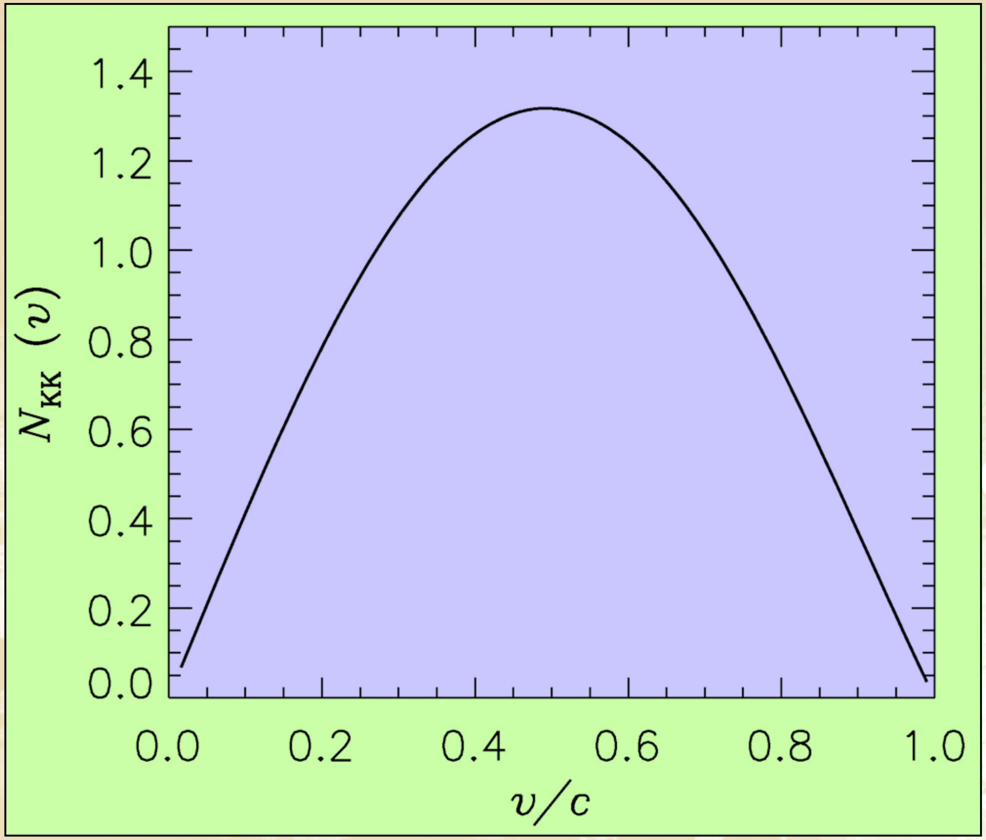
Our new limits R < 0.1 μm, M > 28 TeV (n = 2)
R < 0.2 nm, M > 1.7 TeV (n = 3)

Hannestad & Raffelt, hep-ph/0103201

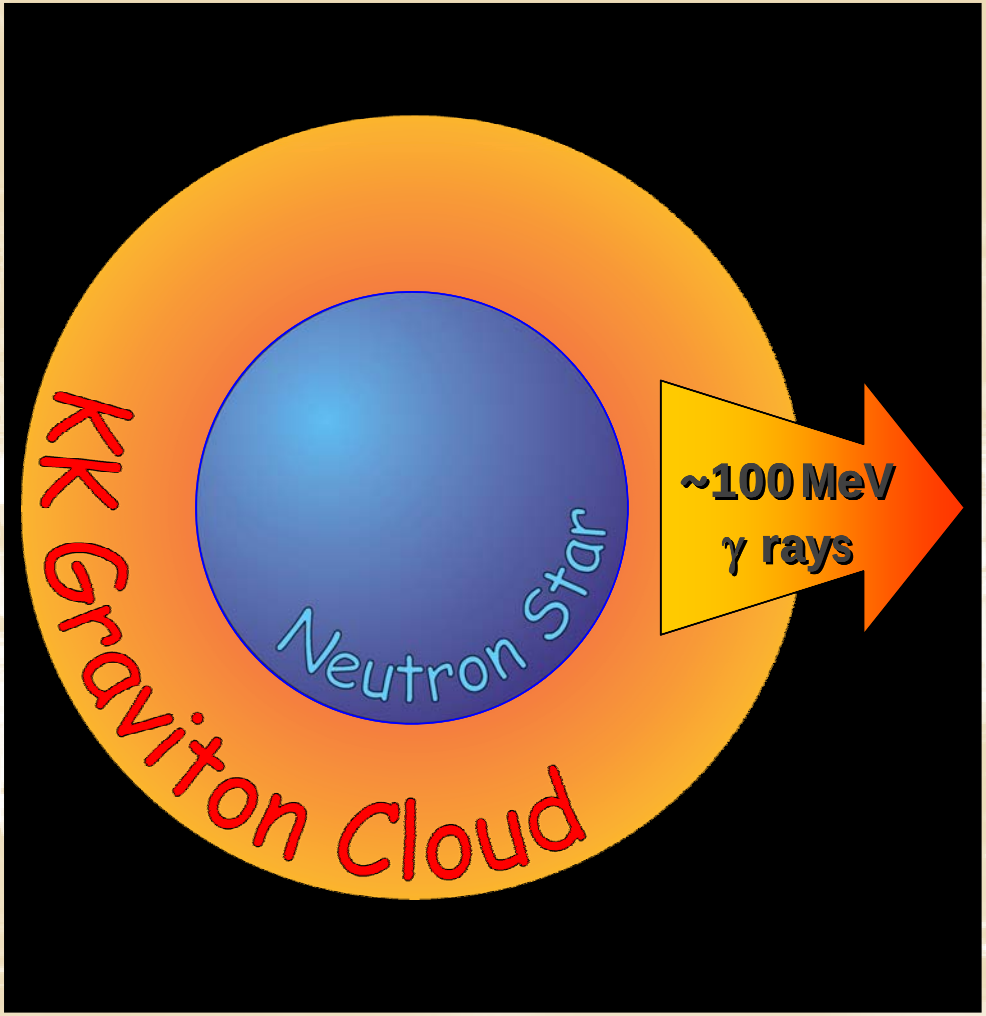
KK Graviton Retention by Neutron Star

$$v_{\text{escape}} = \sqrt{\frac{2GM}{R}} \approx 0.6c$$

- Neutron stars retain 50-60% of KK gravitons in a halo
- Emits γ rays by KK decays

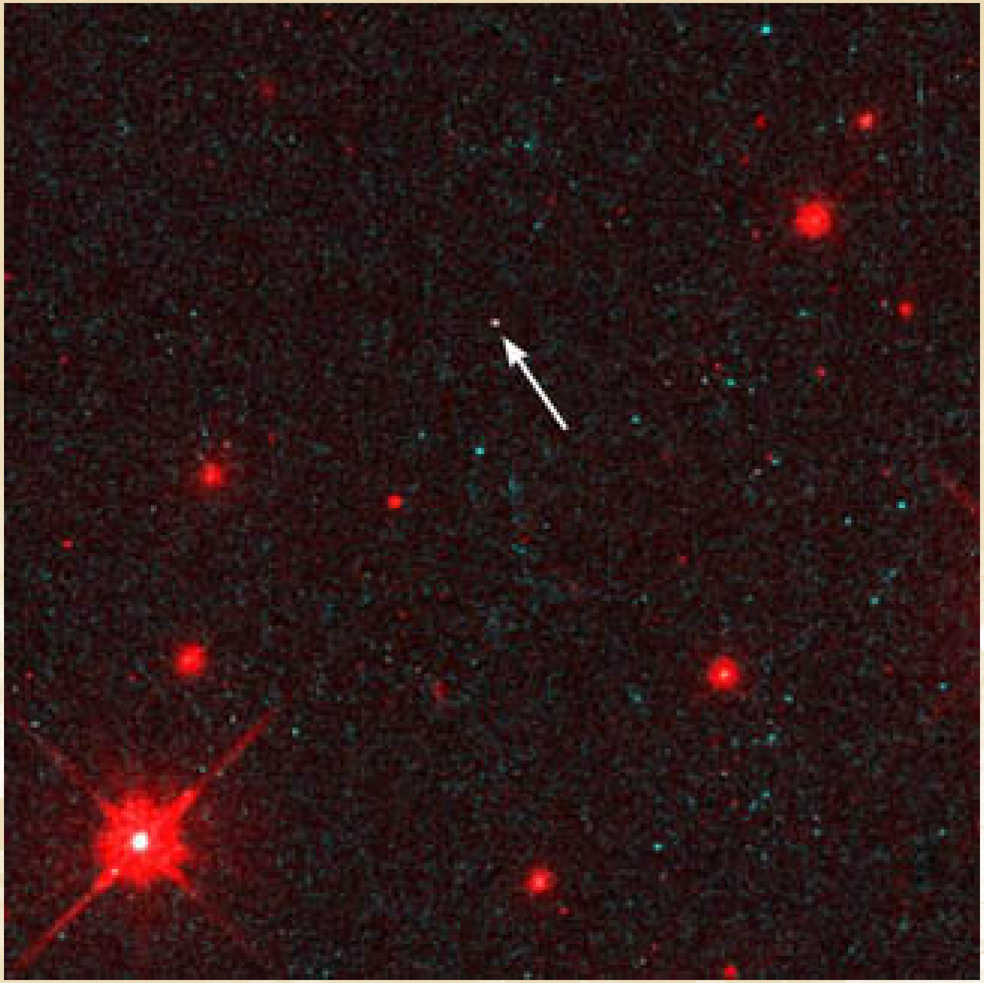


Velocity distribution of KK-gravitons emitted by supernova

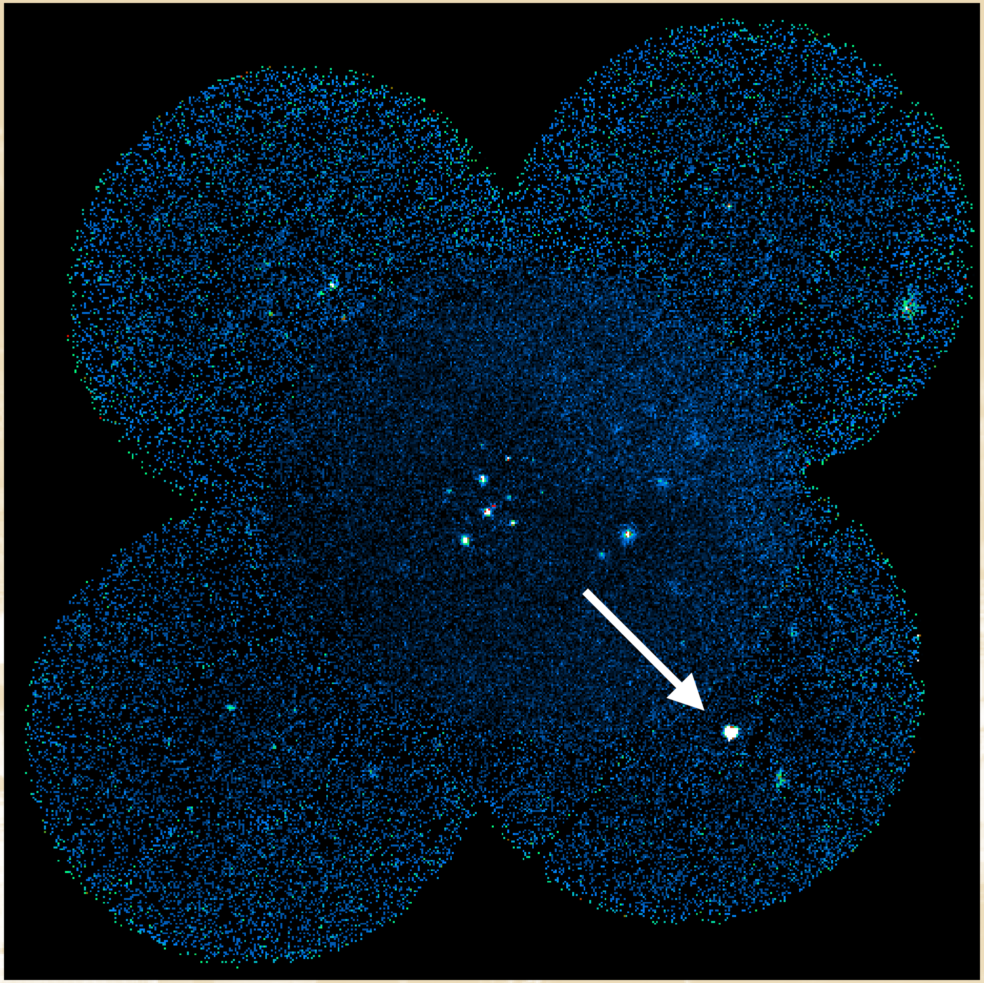


Nearby Neutron Star RX J185635-3754

D = 120 pc (closest known neutron star), Age ~ 1.2 × 10^6 yr

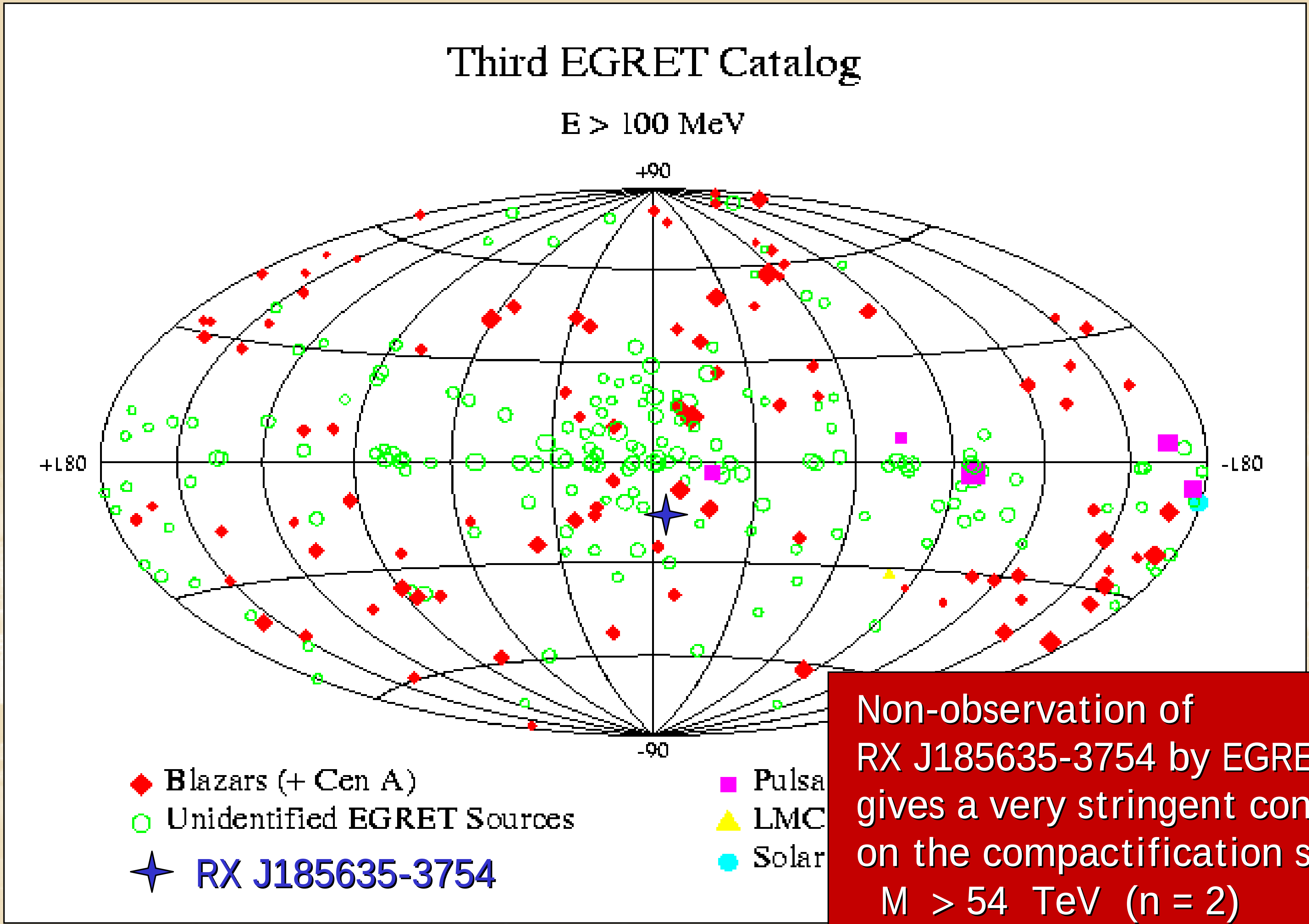


HST Image
(Walter & Matthews 1997)



ROSAT Image
(Walter, Wolk & Neuhauser 1996)

Third EGRET Catalog (Hartmann et al. 1999)

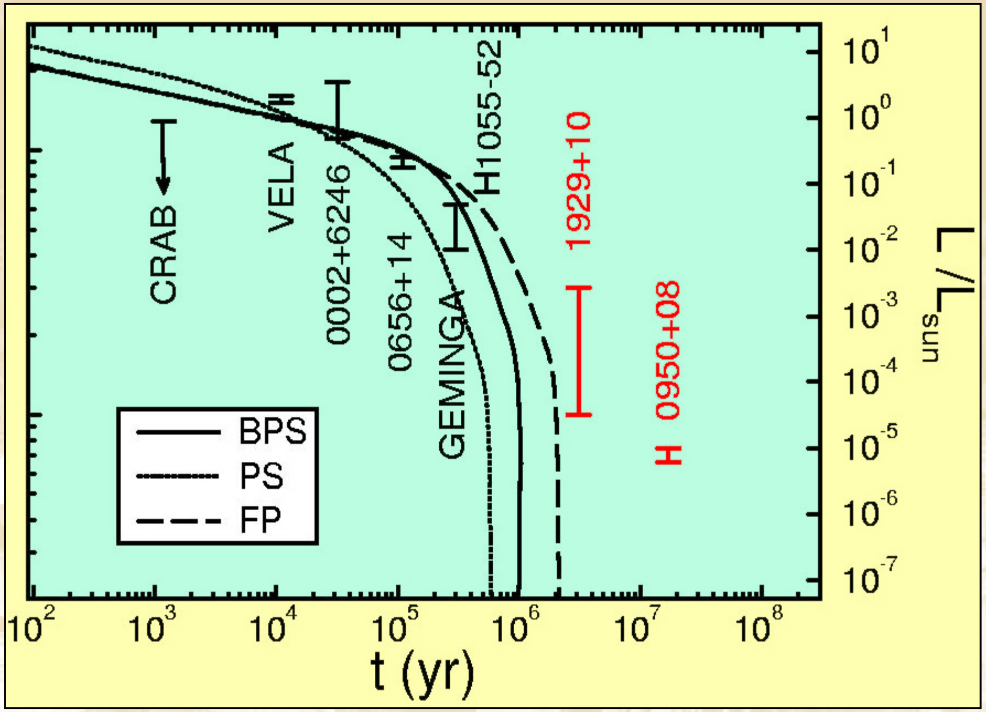


Non-observation of
RX J185635-3754 by EGRET
gives a very stringent constraint
on the compactification scale:
M > 54 TeV (n = 2)
M > 3.5 TeV (n = 3)

Neutron Star Excess Heat

- Neutron stars retain 50-60% of KK gravitons in a halo
- Emits γ rays by KK decays

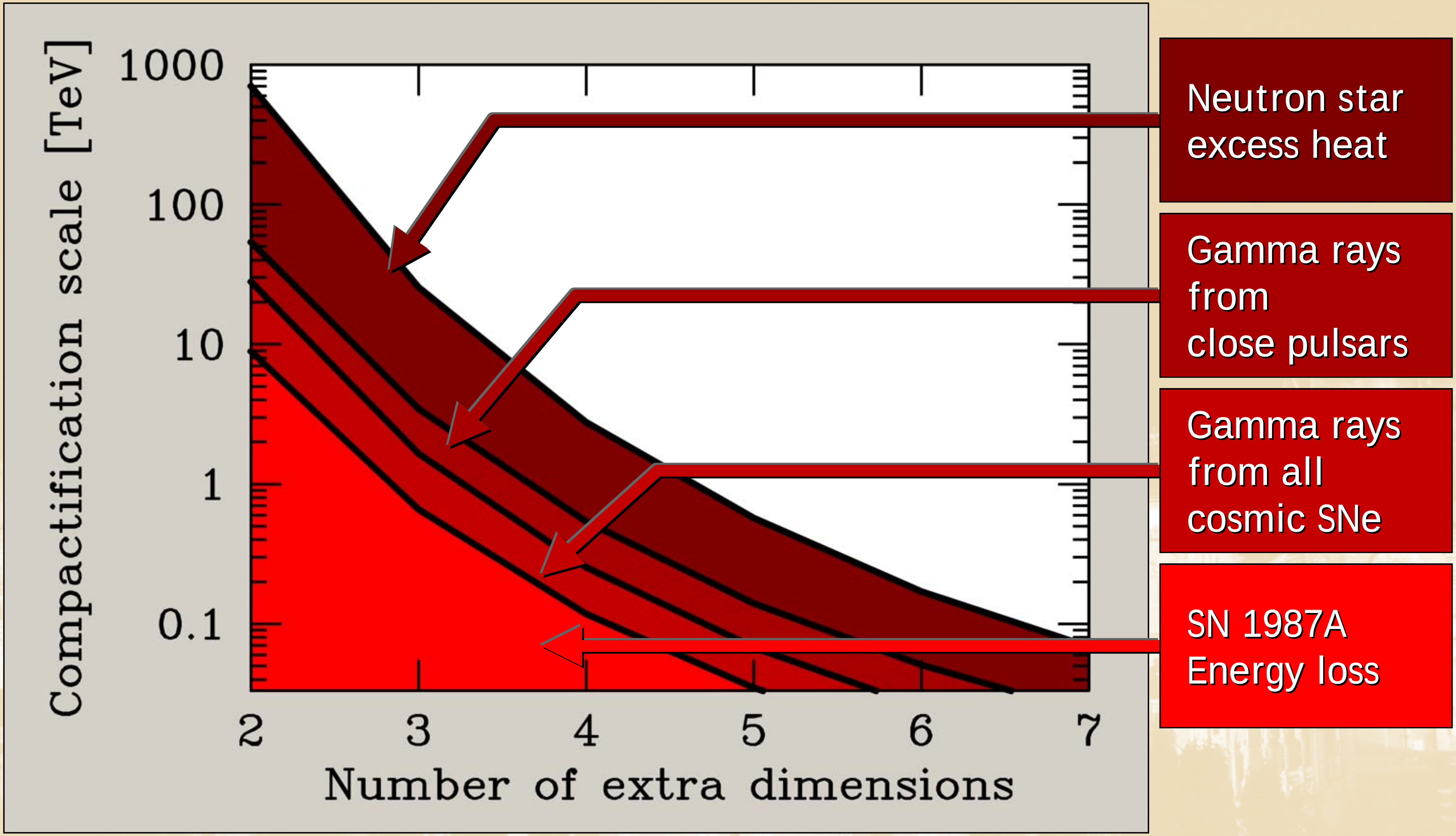
Neutron star cooling calculations vs. observations (Pavlov, Stringfellow & Cordova 1996, Larson & Link 1999)



To avoid excess heating by KK decay

M > 700 TeV (n = 2)
M > 26 TeV (n = 3)

Summary of Limits on Large Extra Dimensions



Neutron star excess heat

Gamma rays from close pulsars

Gamma rays from all cosmic SNe

SN 1987A Energy loss

Hannestad & Raffelt, PRD (2003) [hep-ph/0304029]

Loop Holes

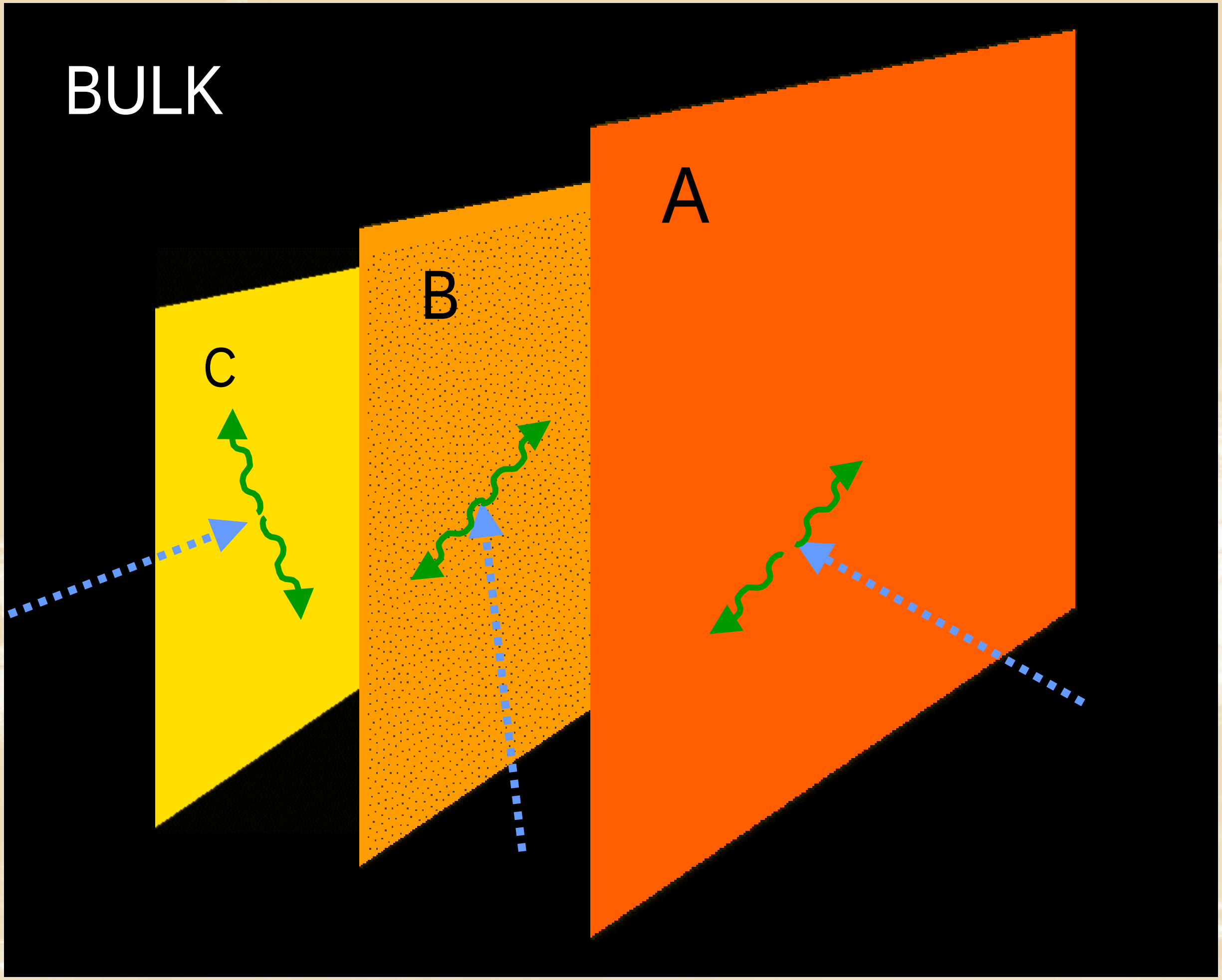
In other than toroidal compactifications, processes such as

$G(m_1) \rightarrow G(m_2) + G(m_3)$

can be much faster than radiative decays so that all KK states cascade to lower-mass KK states.

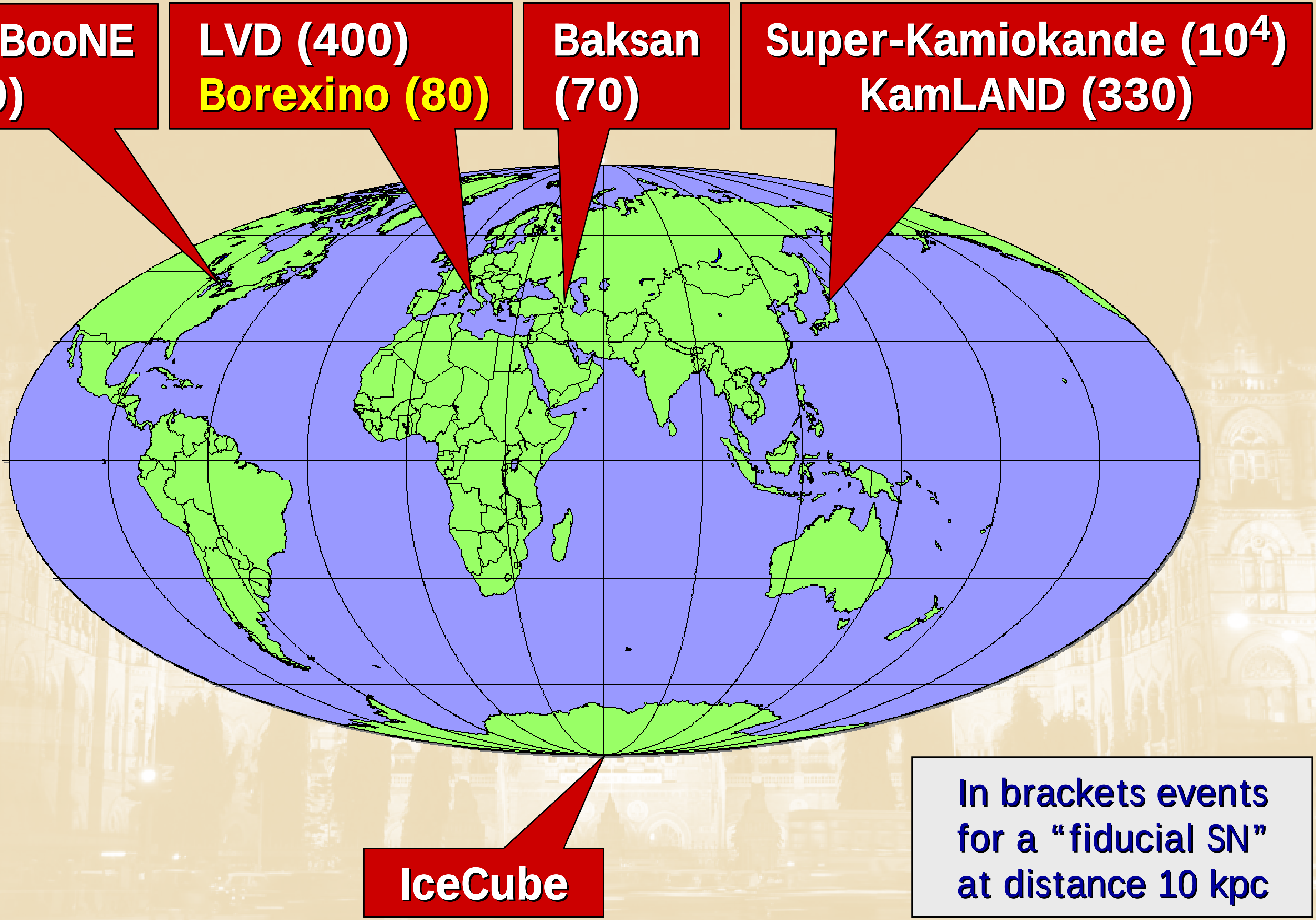
In non-toroidal geometries, the mode spacing can be much larger
→ KK gravitons are not produced astrophysically

If there are more branes, photons can be produced on all of them, leaving fewer in our world, weakening the limits



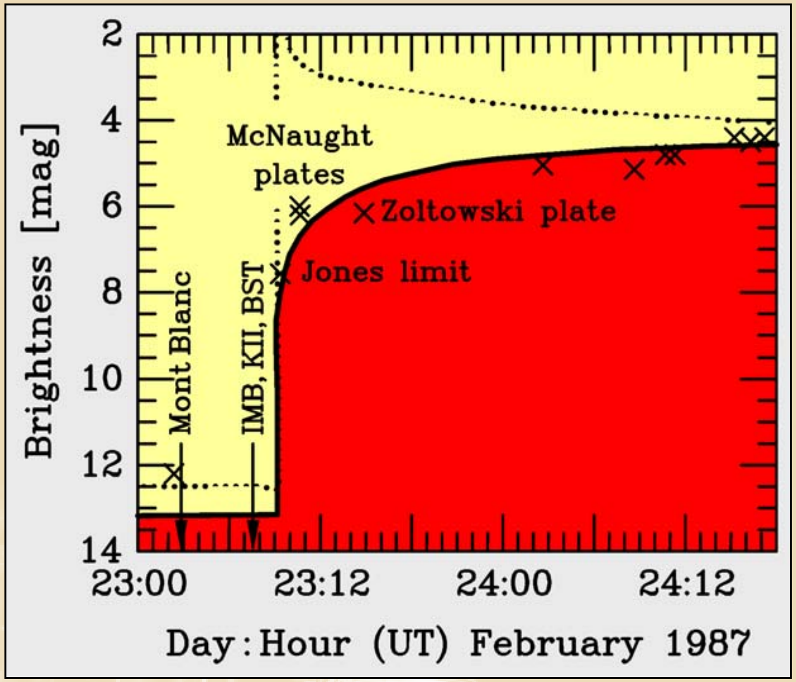
Neutrinos from the Next Galactic Supernova

Large Detectors for Supernova Neutrinos



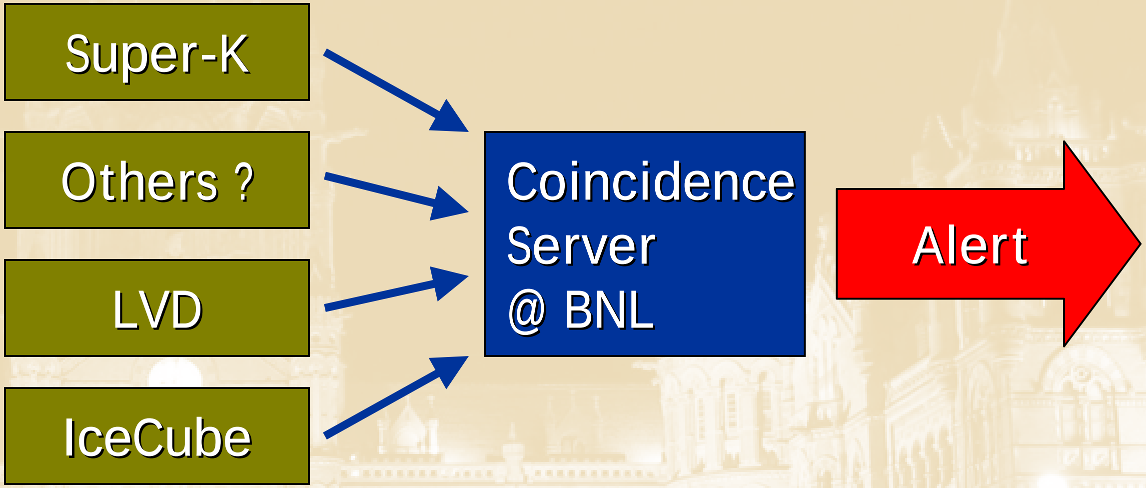
In brackets events for a "fiducial SN" at distance 10 kpc

SuperNova Early Warning System (SNEWS)



Supernova 1987A
Early Light Curve

Neutrino observation can alert astronomers several hours in advance to a supernova.
To avoid false alarms, require alarm from at least two experiments.



Super-K

Others ?

LVD

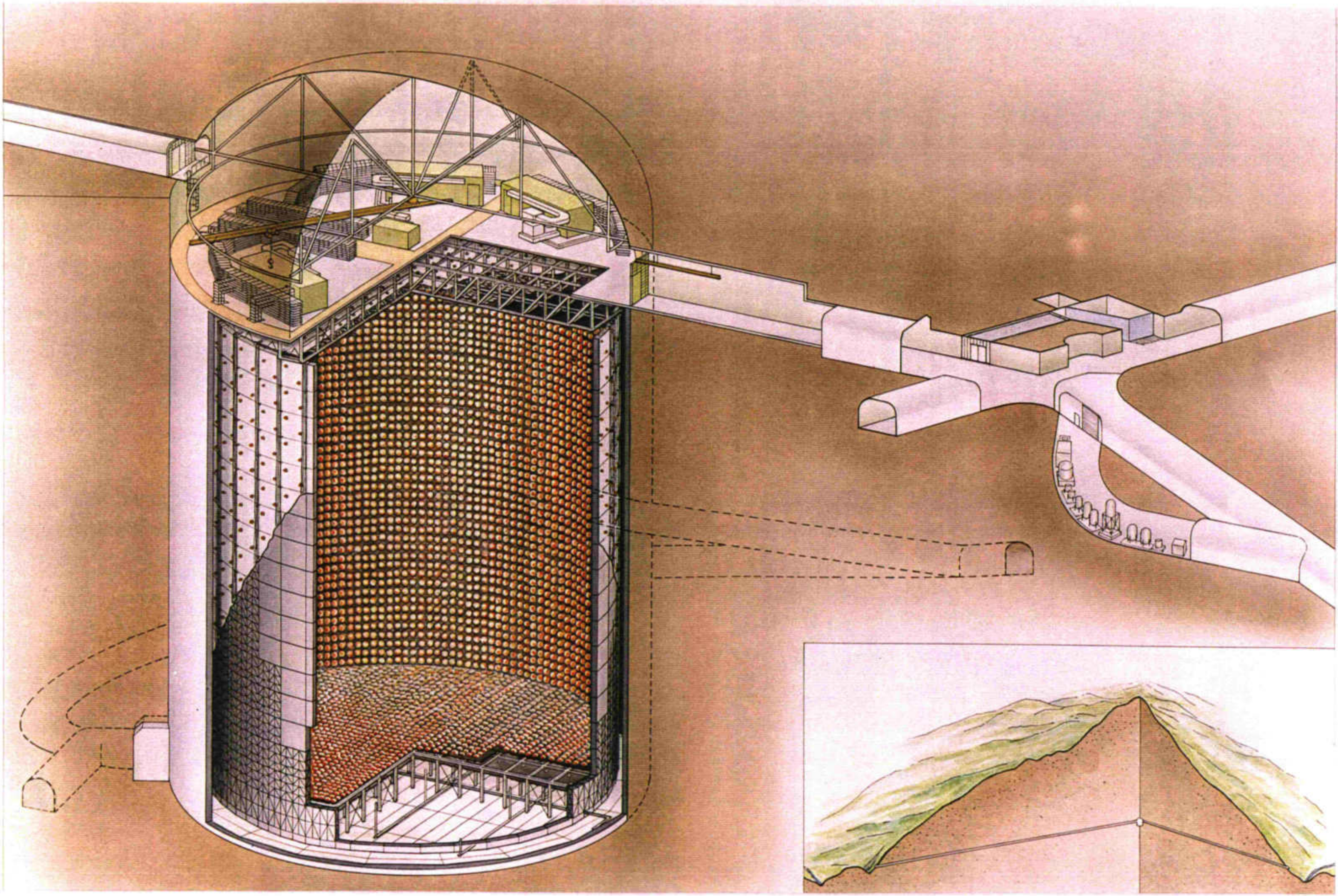
IceCube

Coincidence Server @ BNL

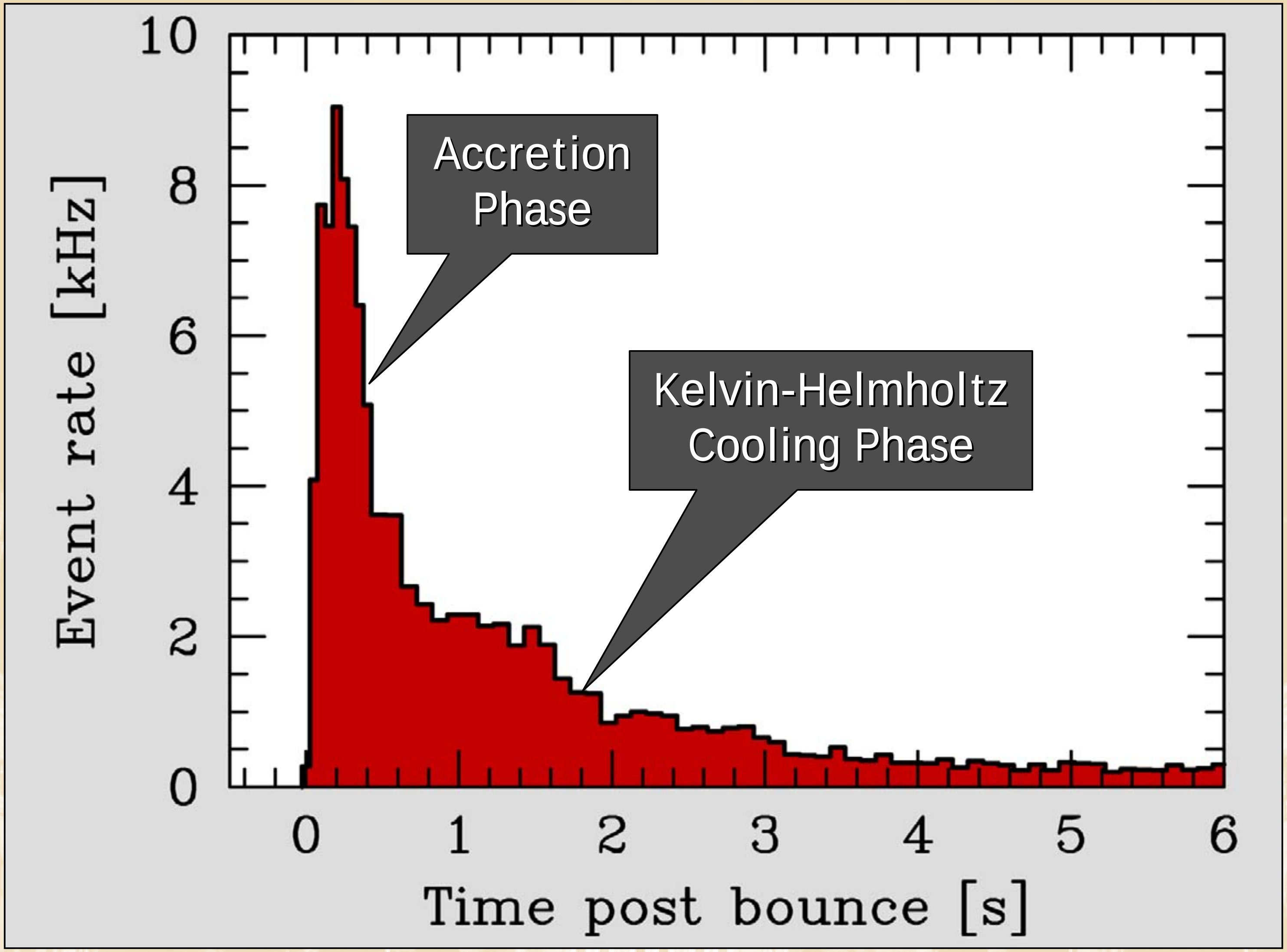
Alert

http://snews.bnl.gov
astro-ph/0406214

Super-Kamiokande Neutrino Detector



Simulated Supernova Signal at Super-Kamiokande

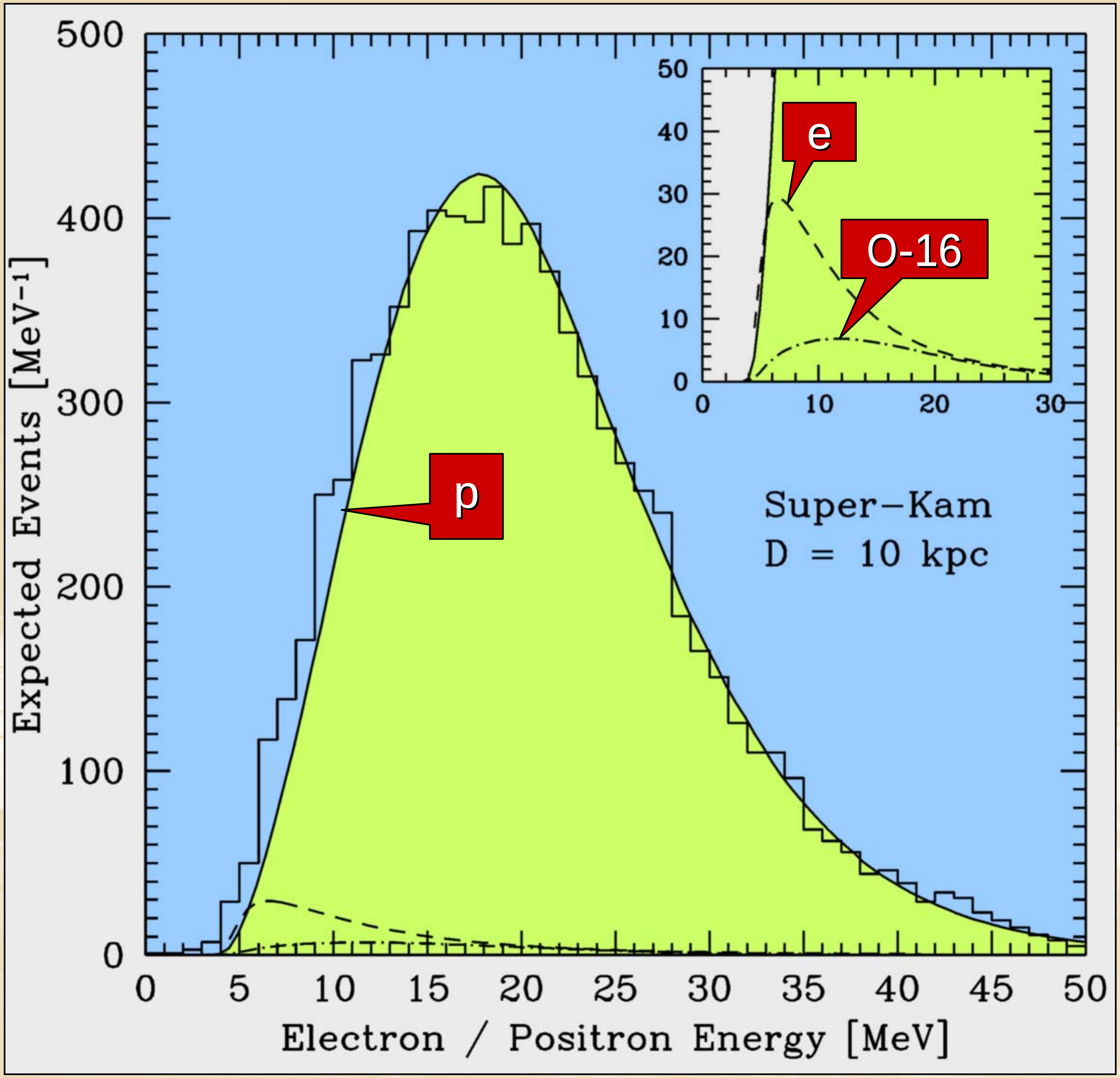


Accretion Phase

Kelvin-Helmholtz Cooling Phase

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

Galactic Supernova Signal in Super-Kamiokande



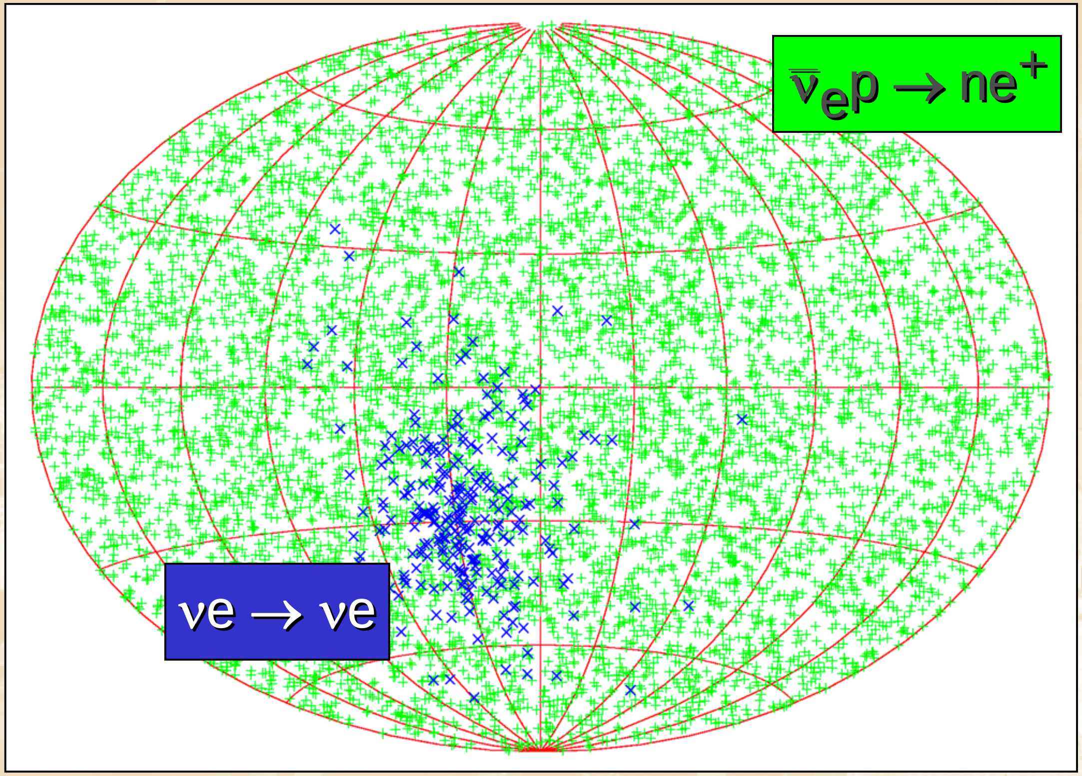
Monte-Carlo simulation for Super-Kamiokande signal of SN at 10 kpc, based on a numerical model with Livermore code

Total of about 8300 events for t < 18 s

Totani, Sato, Dalhed & Wilson, ApJ 496 (1998) 216

Supernova Pointing with Neutrinos

- Beacom & Vogel: Can a supernova be located by its neutrinos? [astro-ph/9811350]
- Tomàs, Semikoz, Raffelt, Kachelriess & Dighe: Supernova pointing with low- and high-energy neutrino detectors [hep-ph/0307050]

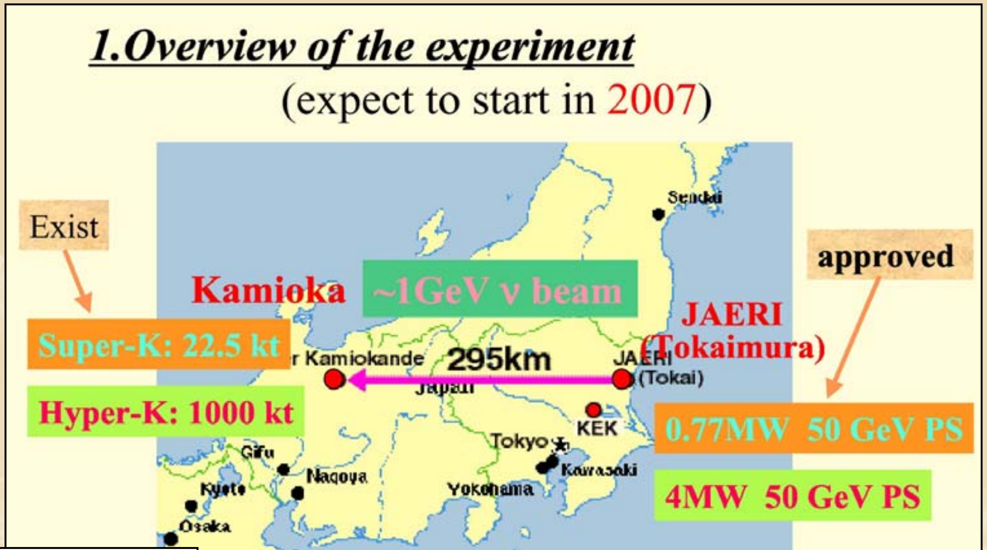


95% CL half-cone opening angle

	Neutron tagging efficiency	
	None	90 %
SK	7.8º	3.2º
SK × 30	1.4º	0.6º

The Future: A Megatonne Detector?

Megatonne detector motivated by
- Long baseline neutrino oscillations
- Proton decay
- Atmospheric neutrinos
- Solar neutrinos
- Supernova neutrinos
  (~10^5 events for SN at 10 kpc)



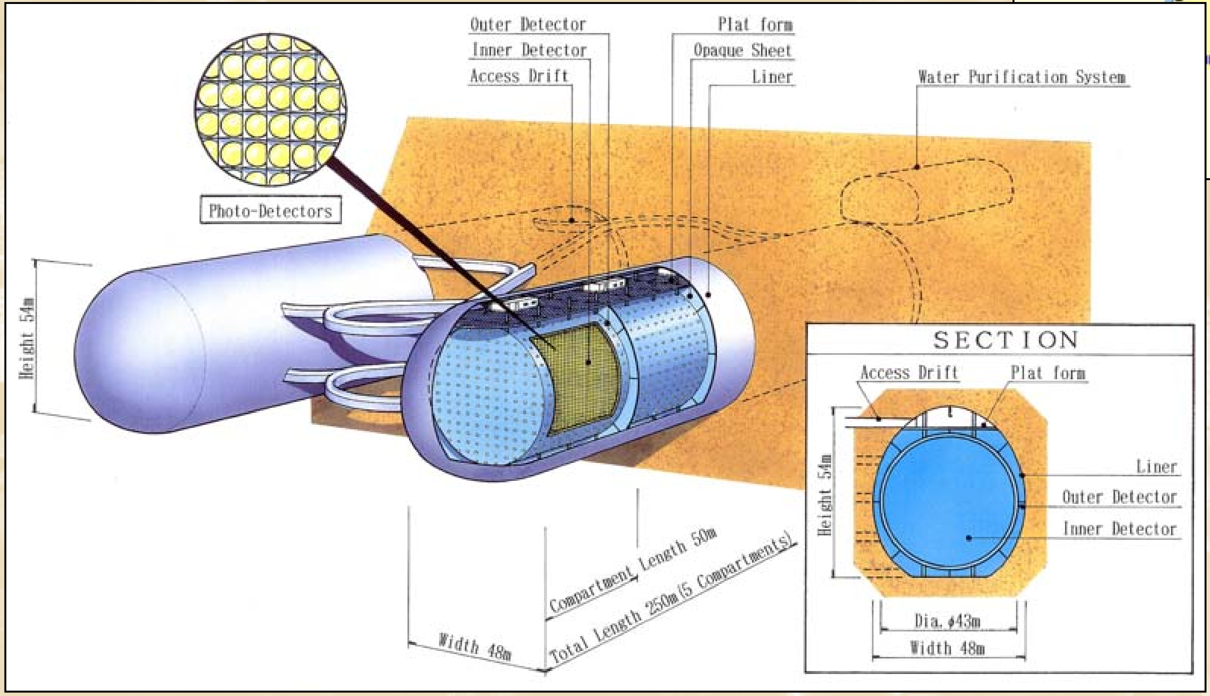
1.Overview of the experiment

(expect to start in 2007)

Phase-I (0.77MW + Super-K)

Phase-II (4MW+Hyper-K) ~ Phase-I × 200

3

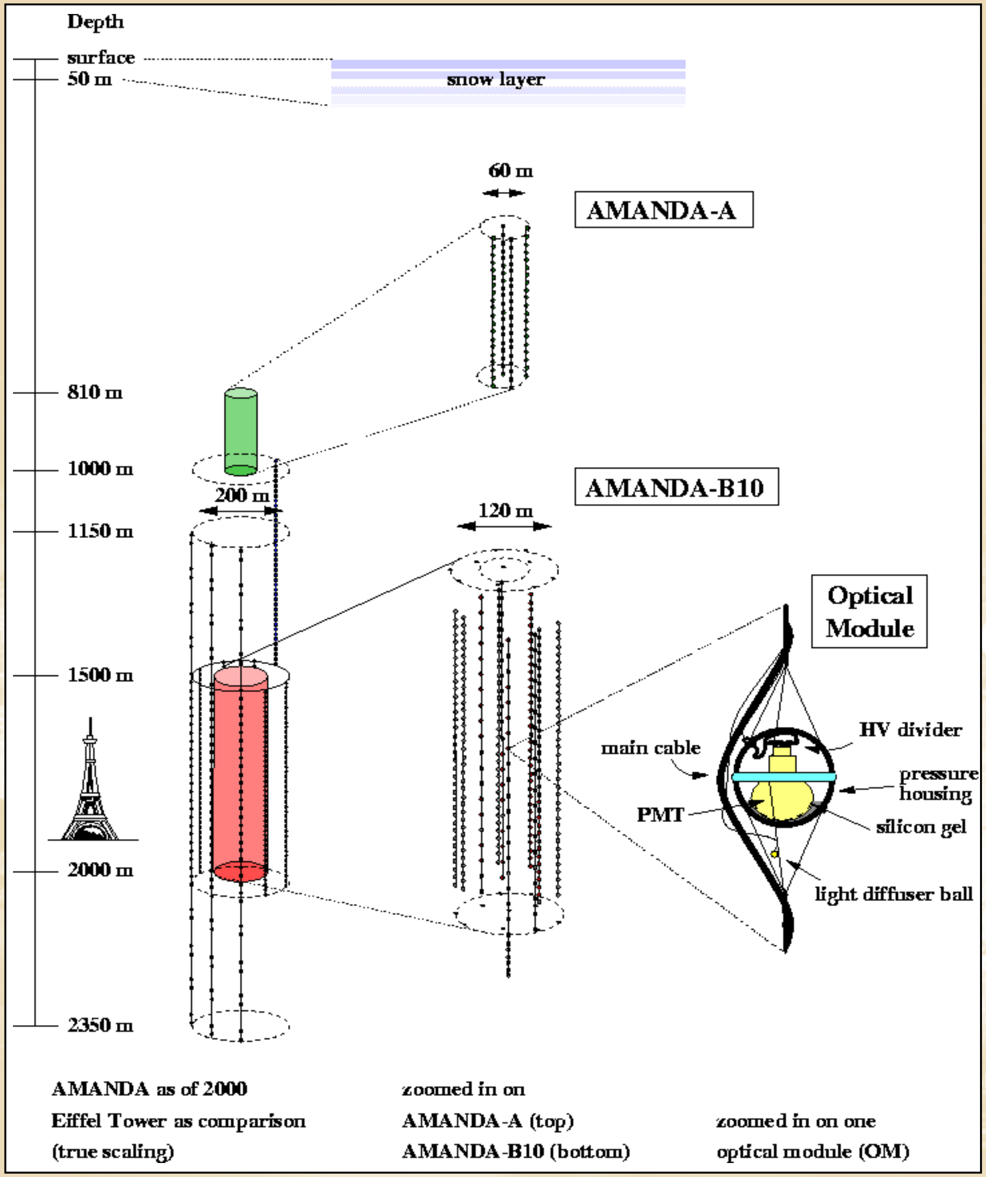


Similar discussions in
- US (UNO project)
- Europe (MEMPHYS project)

Southpole Ice-Cherenkov Neutrino Detectors

AMANDA II (0.1 km^3, 800 PMTs)

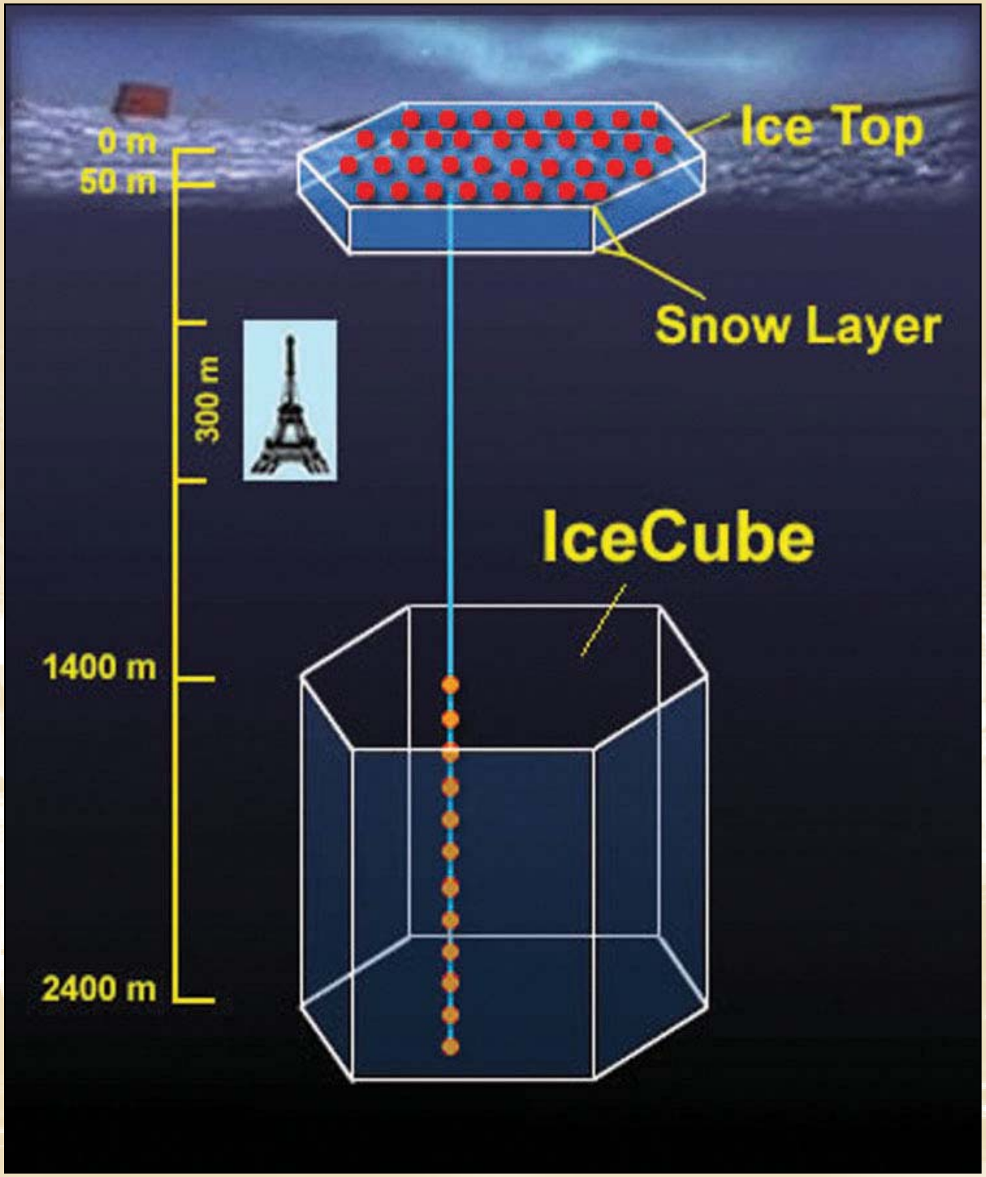
Future IceCube (1 km^3, 4800 PMTs)



AMANDA as of 2000
Eiffel Tower as comparison
(true scaling)

zoomed in on
AMANDA-A (top)
AMANDA-B10 (bottom)

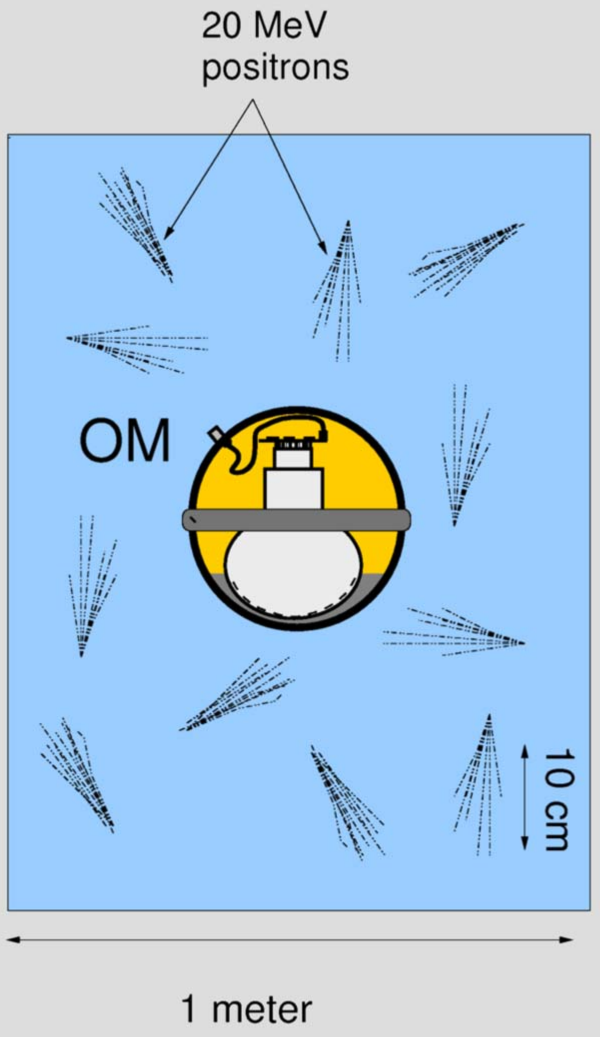
zoomed in on one
optical module (OM)

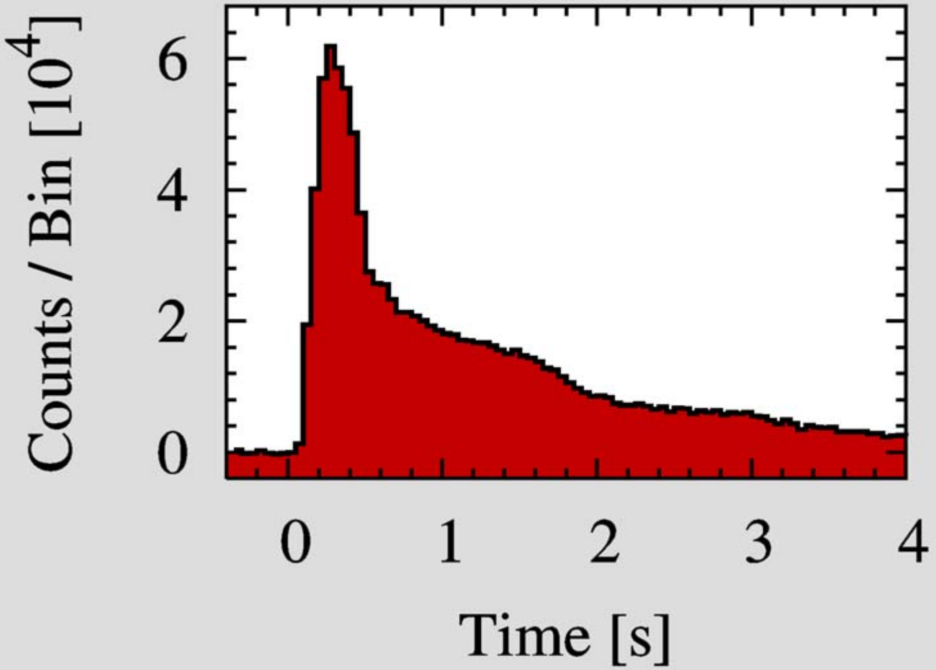


IceCube as a Supernova Neutrino Detector

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

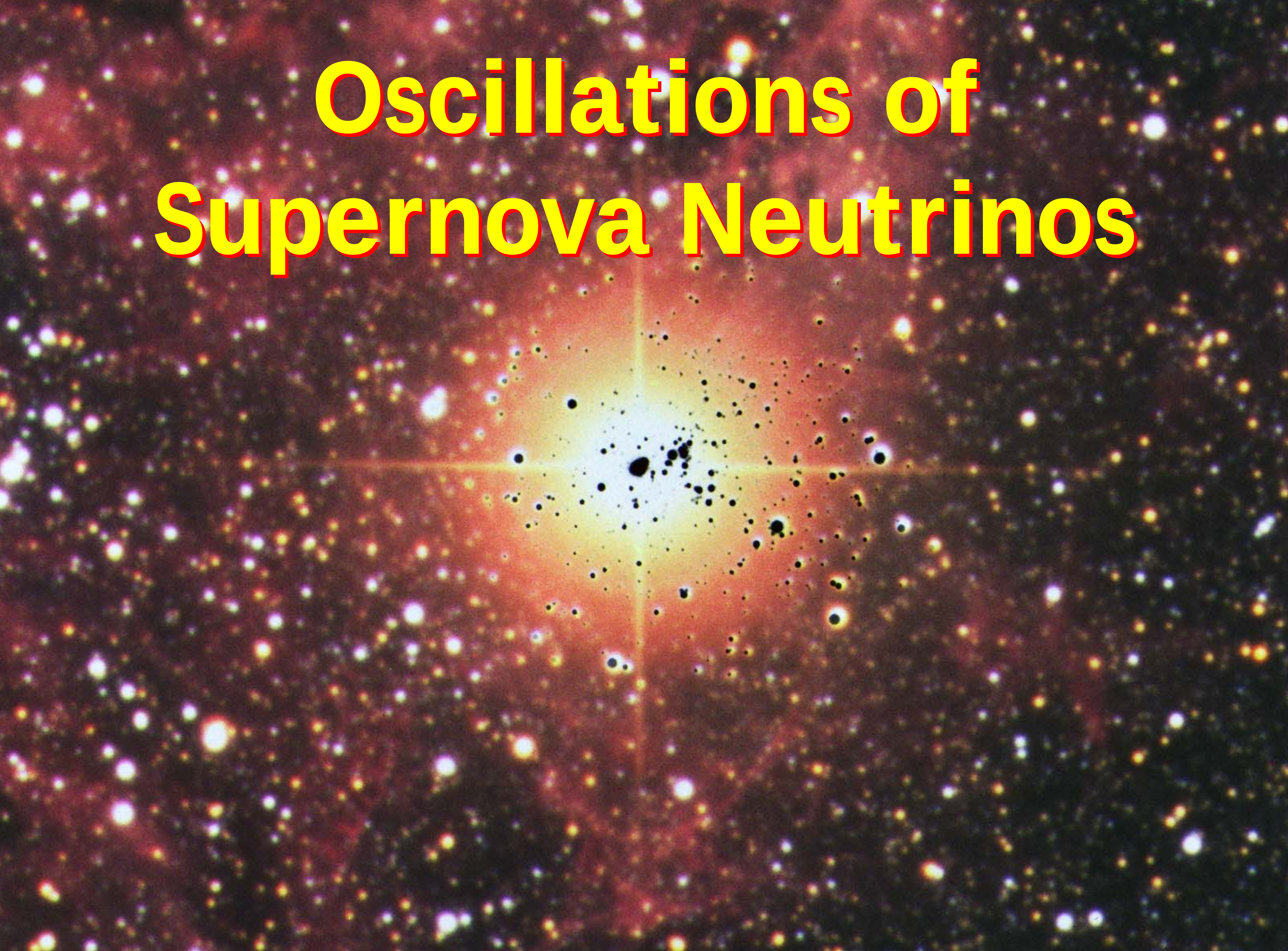
- About 300 Cherenkov photons per OM from a SN at 10 kpc
- Noise per OM < 500 Hz
- Total of 4800 OMs in IceCube





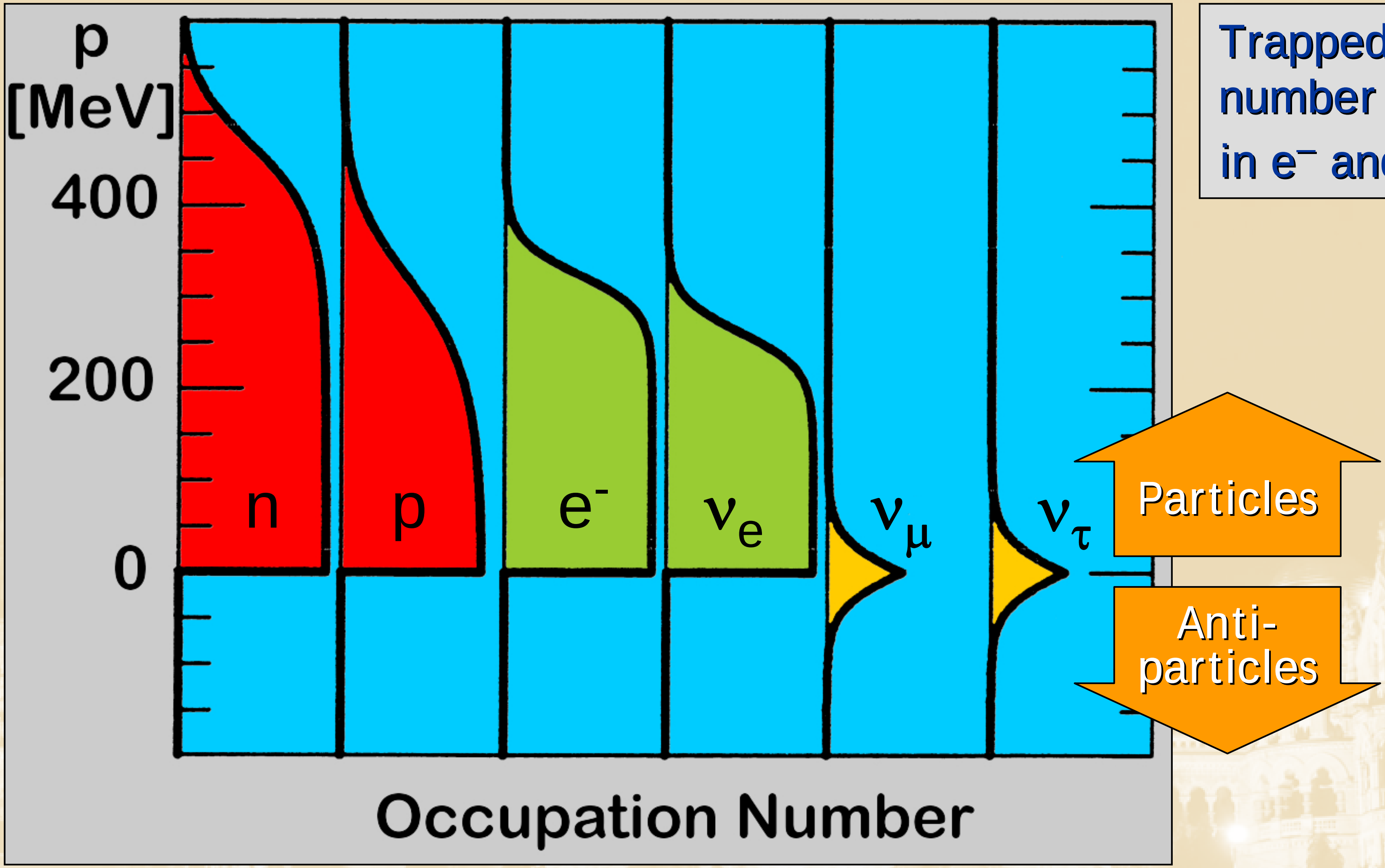
IceCube SN signal at 10 kpc, based on a numerical Livermore model
[Dighe, Keil & Raffelt, hep-ph/0303210]

Method first discussed by Halzen, Jacobsen & Zas astro-ph/9512080



Oscillations of Supernova Neutrinos

Degenerate Fermi Seas in a Supernova Core



Trapped lepton number is stored in e^- and ν_e

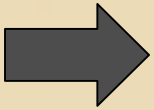
In true thermal equilibrium with flavor mixing, only *one* chemical potential for charged leptons and *one* for neutrinos

Time scale to achieve flavor equilibrium?

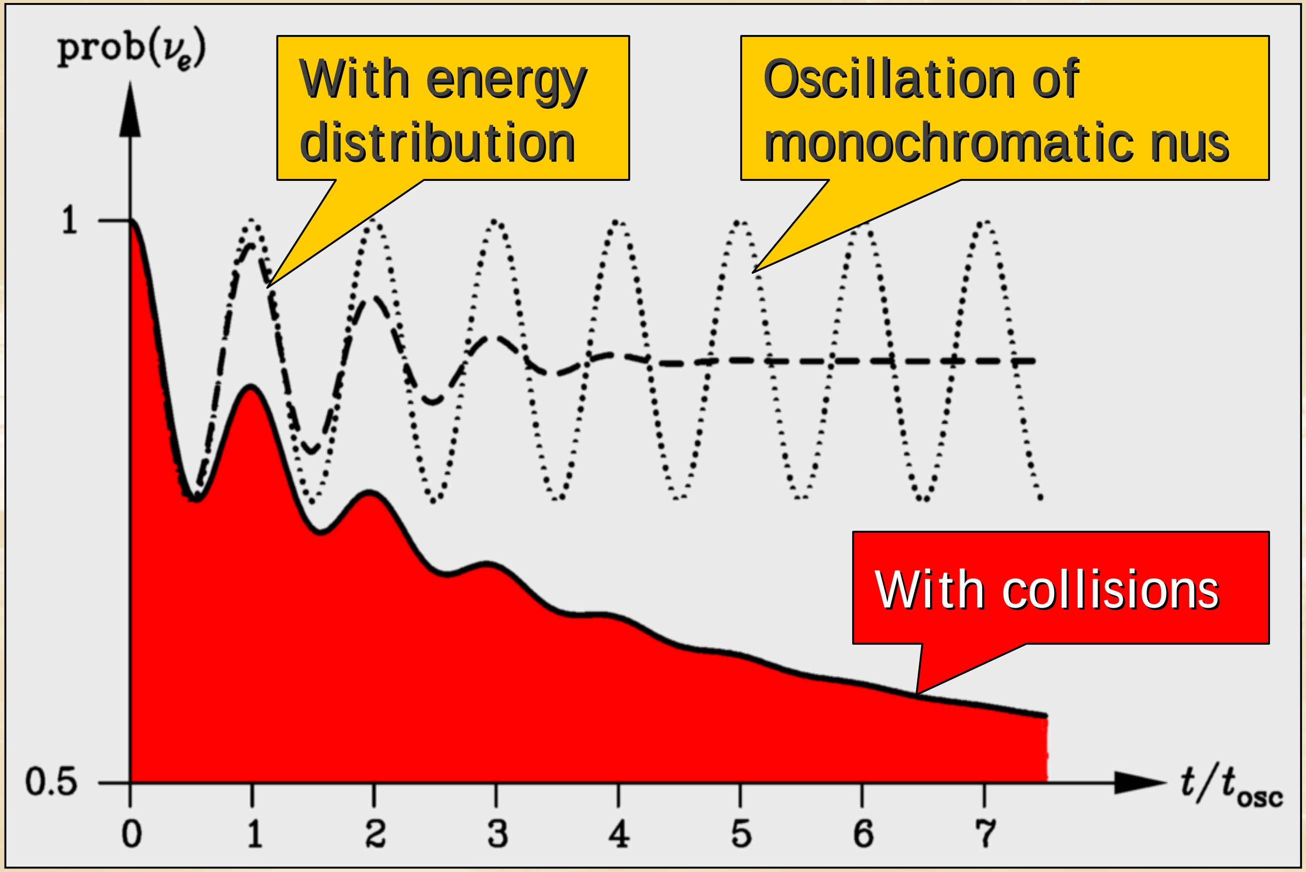
Flavor Relaxation in a Supernova Core

Neutrinos suffer collisions in a medium that can interrupt the coherence of flavor oscillations: The flavor content is "measured" and oscillations start from scratch from the "collapsed state".

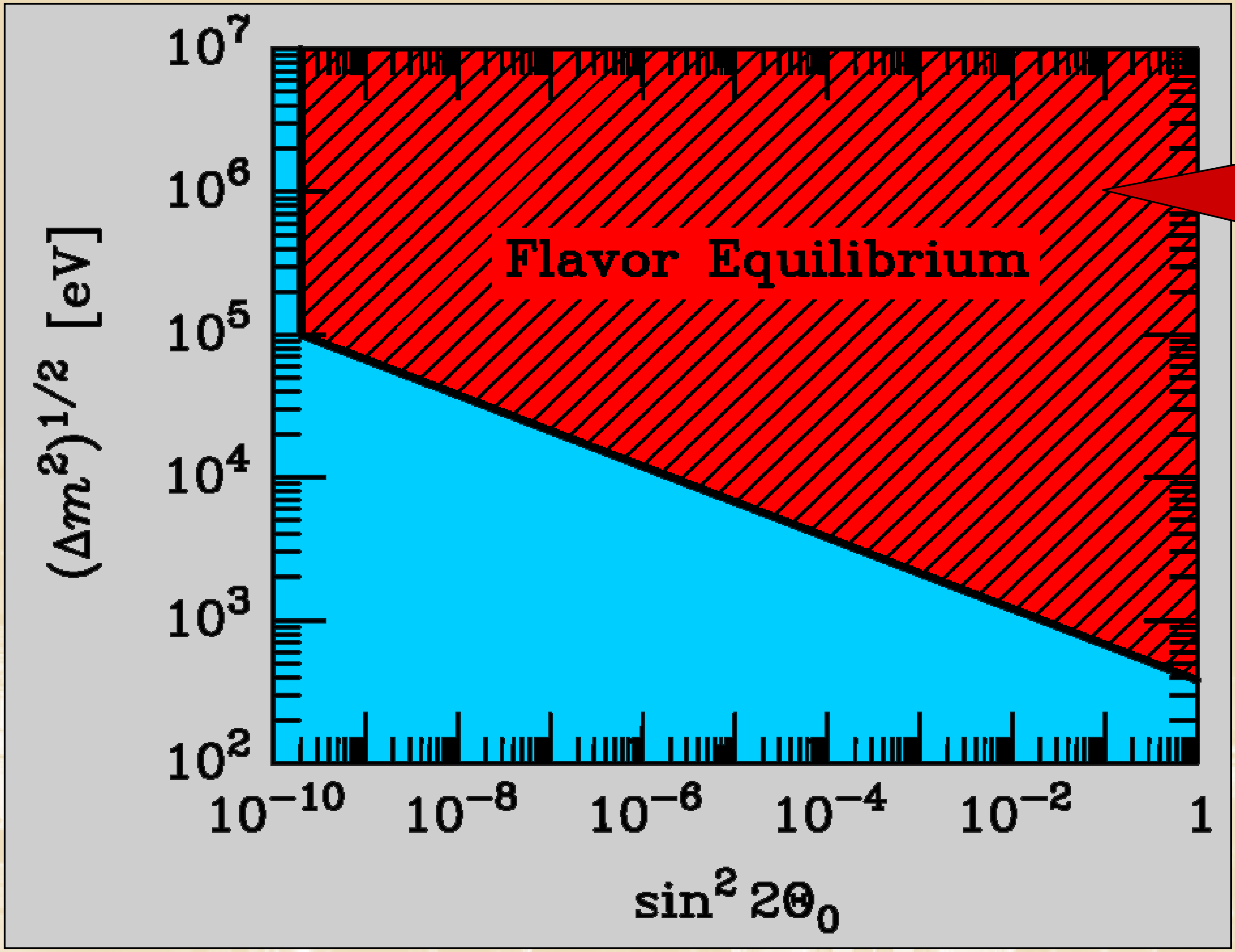
Average oscillation probability ½ $\sin^2(2\Theta)$
Collision rate ~ damping rate Γ



Conversion rate ½ $\sin^2(2\Theta)\ \Gamma$



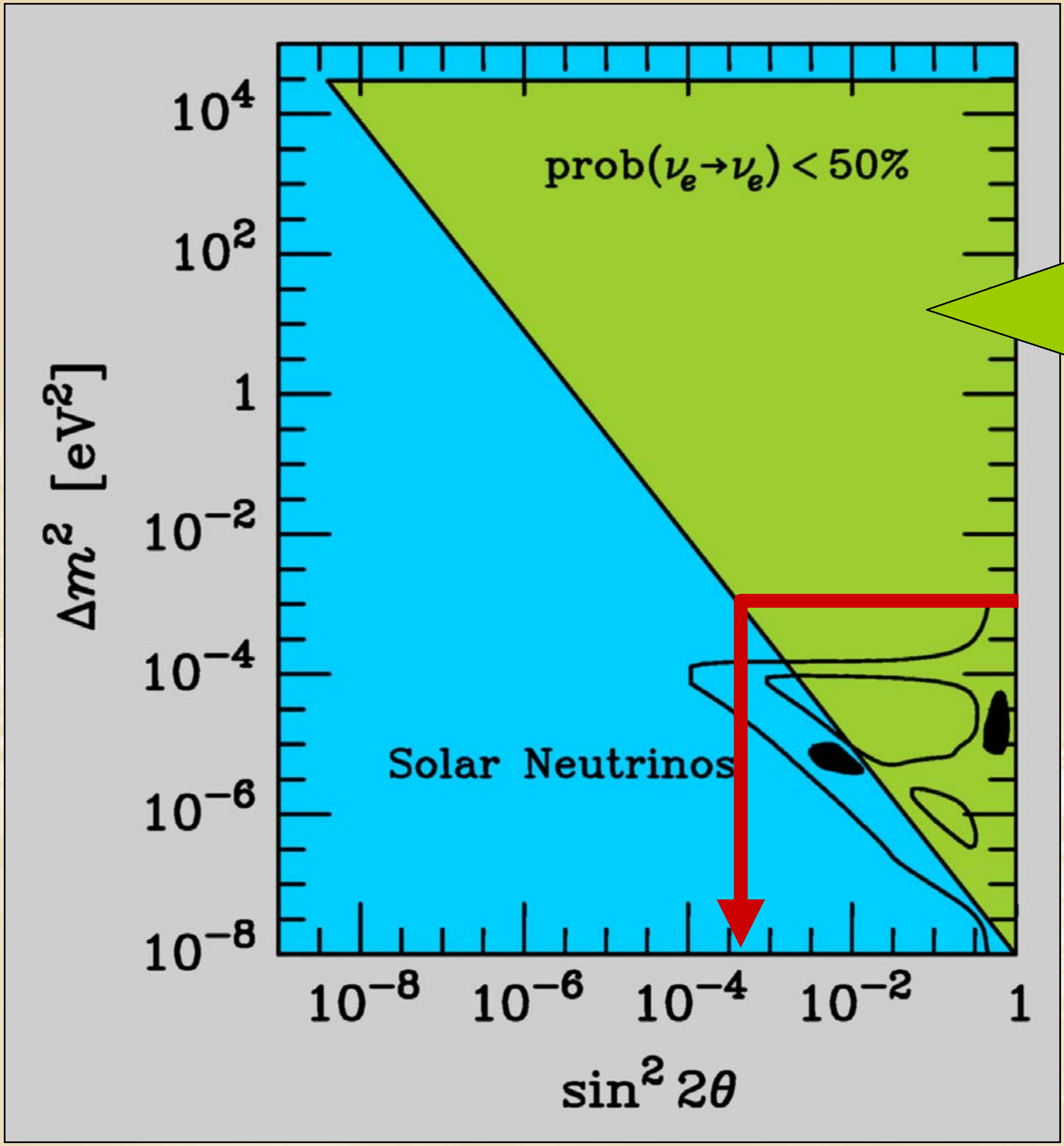
Flavor Conversion in a Supernova Core



Within ~ 1 sec flavor equilibrium is achieved between ν_e and ν_μ or ν_τ

Suppression of mixing angle by medium effects responsible for flavor-lepton number conservation in a supernova core

Resonant Oscillations in a Supernova Envelope



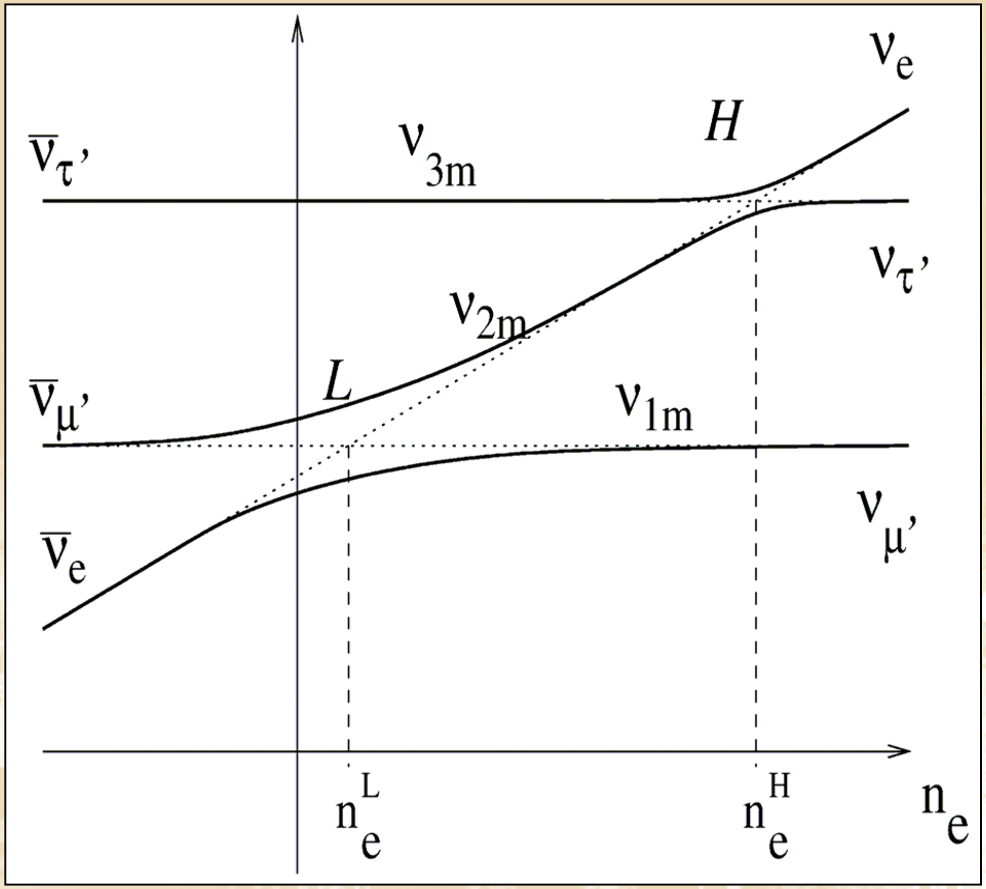
Adiabatic oscillations for a large range of mixing parameters

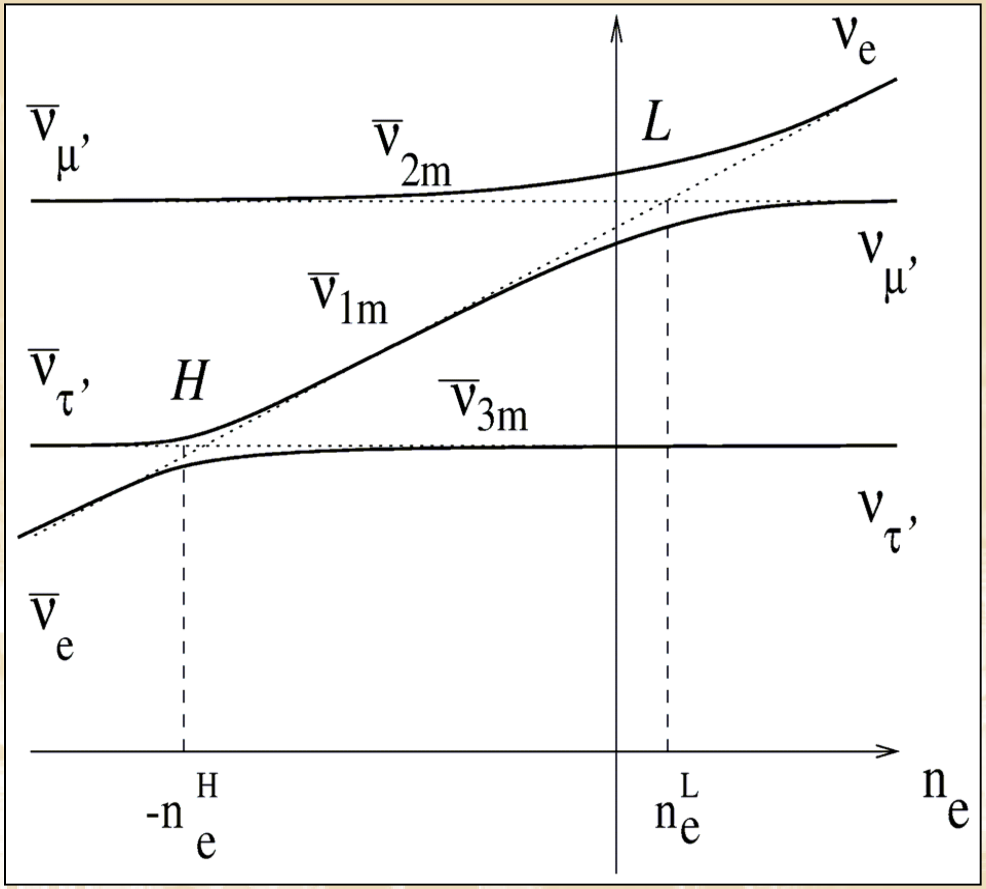
- 13-oscillations involve atmospheric mass difference
- Adiabatic for $\sin^2(2\Theta_{13}) > 10^{-3}$

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

$$F_e^0 = pF_e^0 + (1-p)F_x^0$$

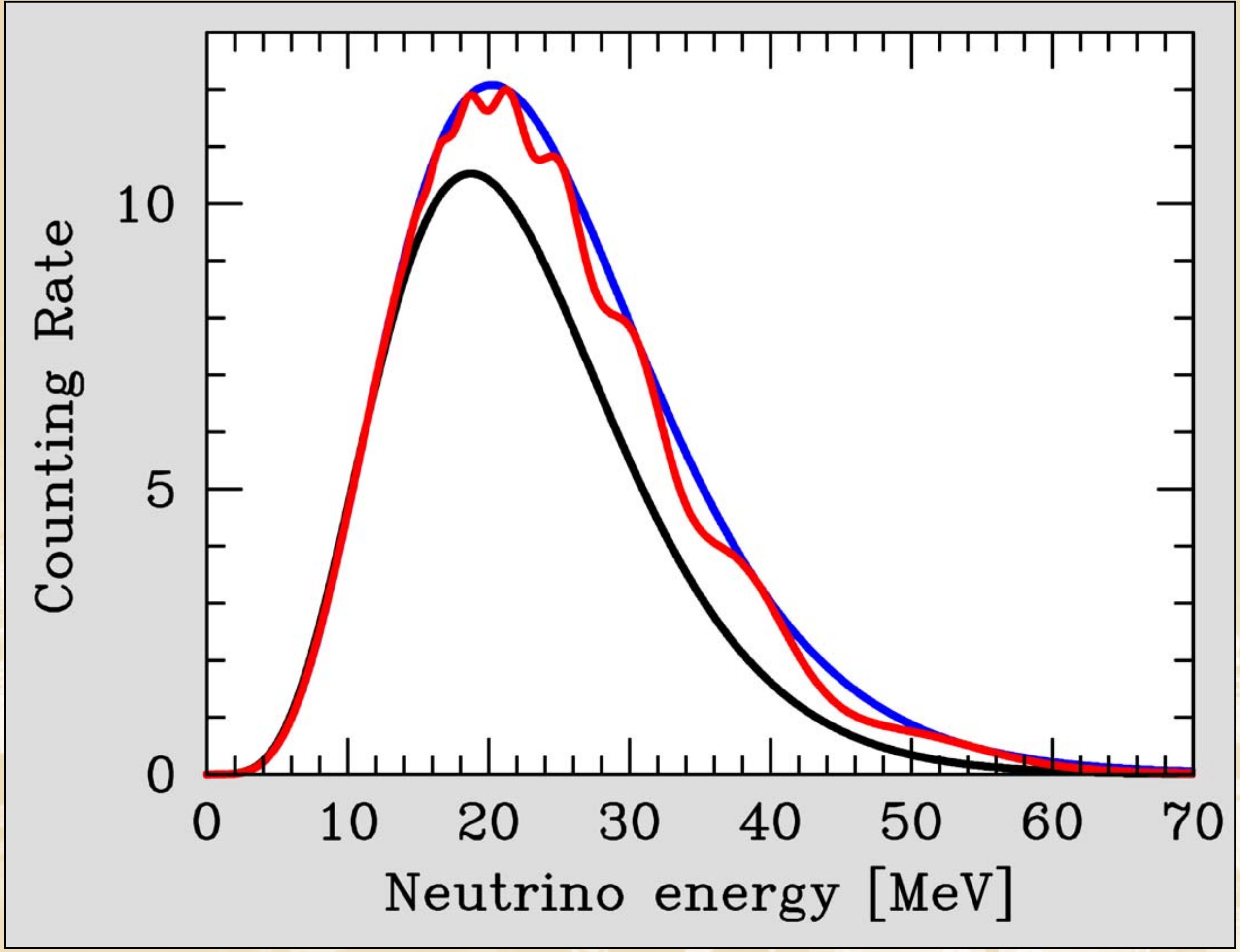
$$F_{\bar{e}}^0 = \bar{p}F_{\bar{e}}^0 + (1-\bar{p})F_x^0$$

$$\tfrac{1}{4}\sum F_x = \frac{2+p+\bar{p}}{4}F_x^0 + \frac{1-p}{4}F_e^0 + \frac{1-\bar{p}}{4}F_{\bar{e}}^0$$

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	$\cos^2(\Theta_{12}) \approx 0.7$
B	Inverted		$\sin^2(\Theta_{12}) \approx 0.3$	0
C	Any	$\lesssim 10^{-5}$	$\sin^2(\Theta_{12}) \approx 0.3$	$\cos^2(\Theta_{12}) \approx 0.7$

Oscillation of Supernova Anti-Neutrinos

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



Assumed flux parameters

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

$\langle E(\overline{\nu}_e) \rangle = 15\,\mathrm{MeV}$

$\langle E(\overline{\nu}_x) \rangle = 18\,\mathrm{MeV}$

Mixing parameters

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

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

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

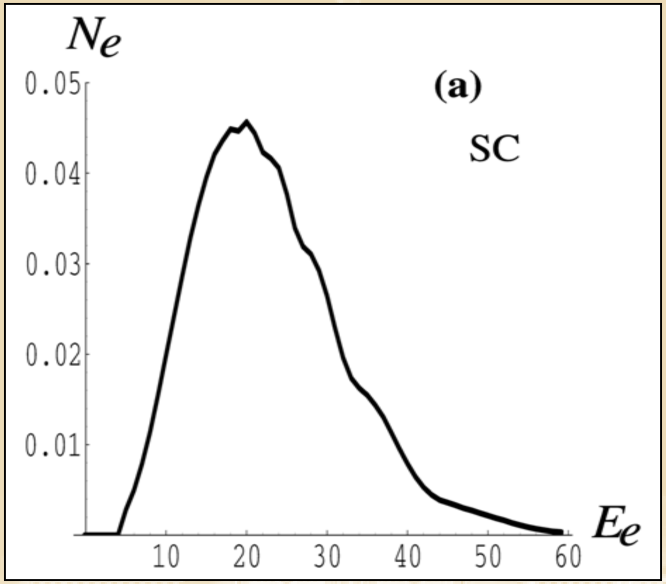
Model-Independent Strategies for Observing Earth Effects

One detector observes SN shadowed by Earth

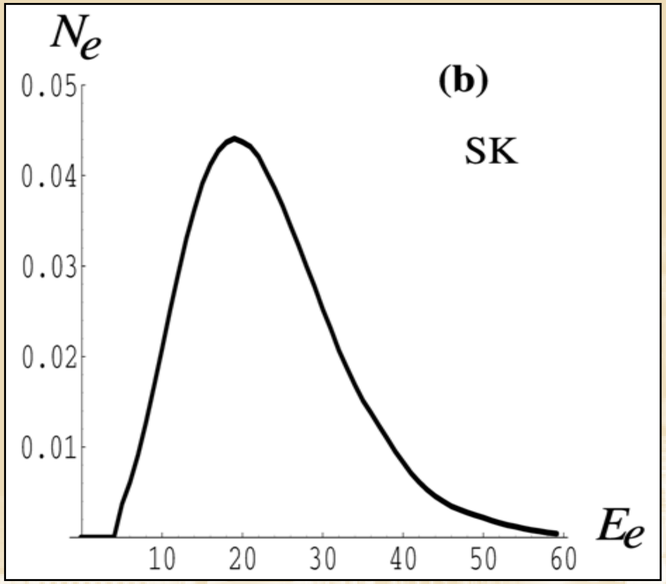
Case 1:

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

Case2: Identify “wiggles” in signal of single detector
Problem: Smearing by limited energy resolution



Scintillator detector
~ 2000 events
may be enough

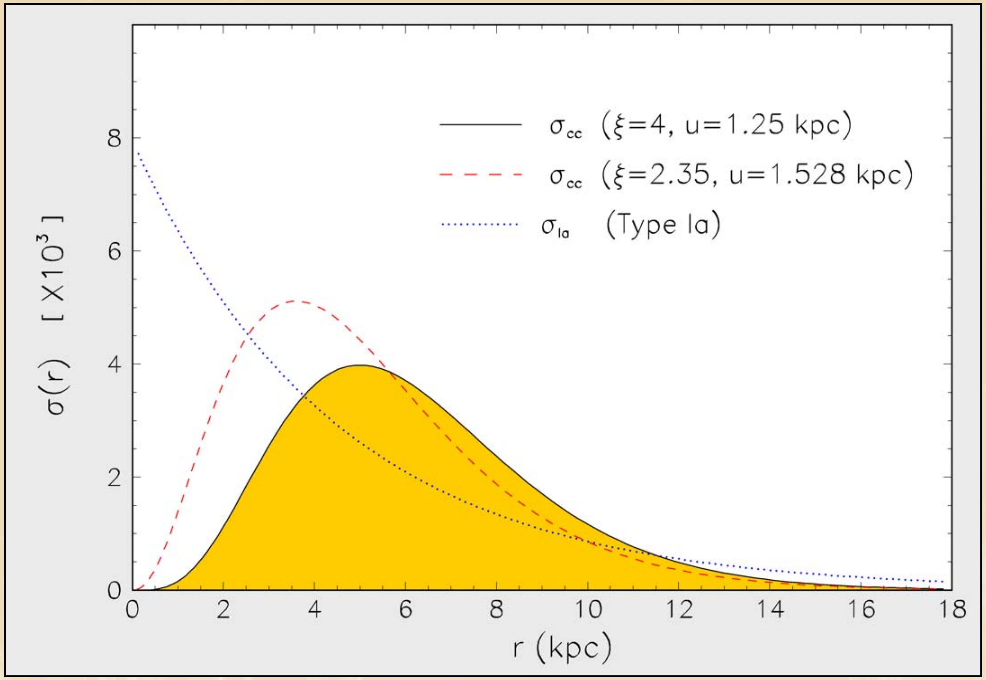


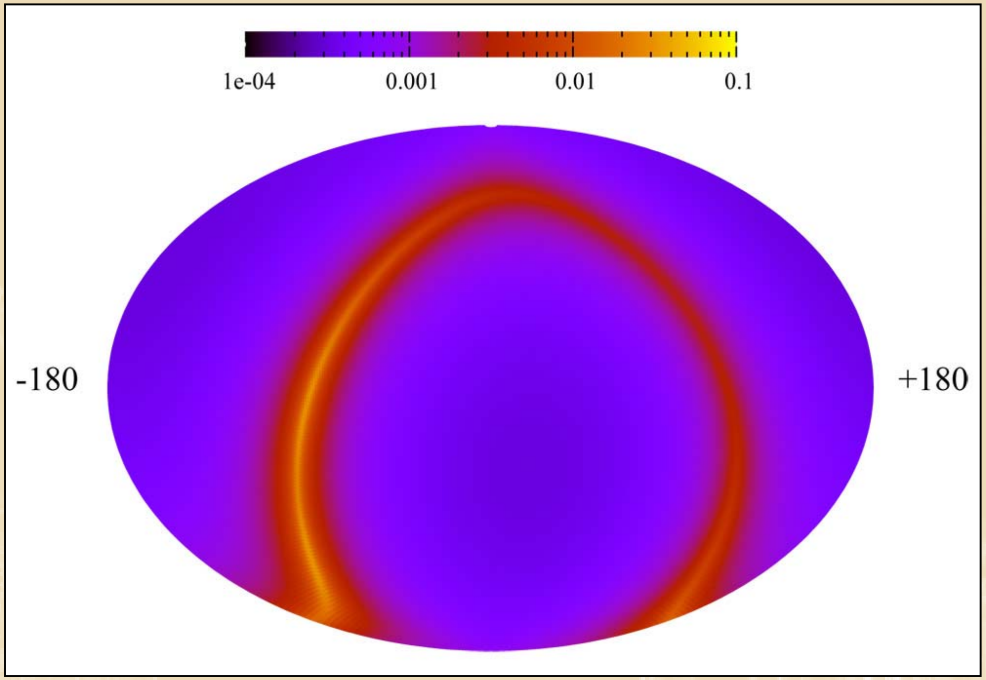
Water Cherenkov
Need megaton detector
with ~ 10^5 events

If 13-mixing angle is known to be “large”, e.g. from Double Chooz, observed “wiggles” in energy spectrum signify normal mass hierarchy

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

Galactic Distribution of Core-Collapse Supernovae





"Surface density" depleted near center
(from pulsar distribution and other indicators)

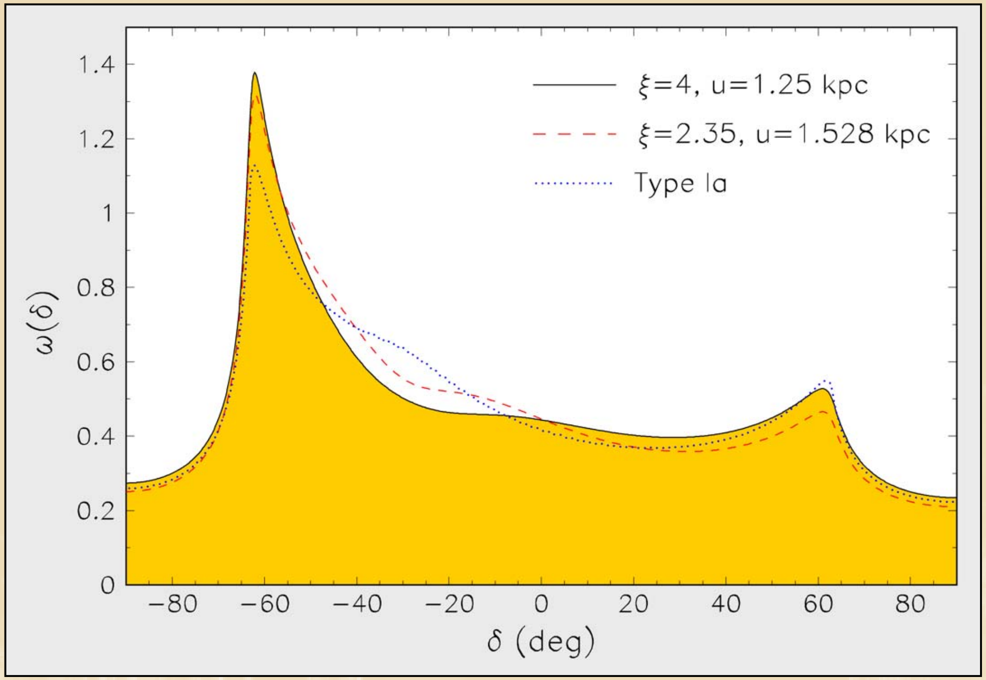
$$\sigma \propto r^{\xi} \exp\left(-\frac{r}{u}\right)$$

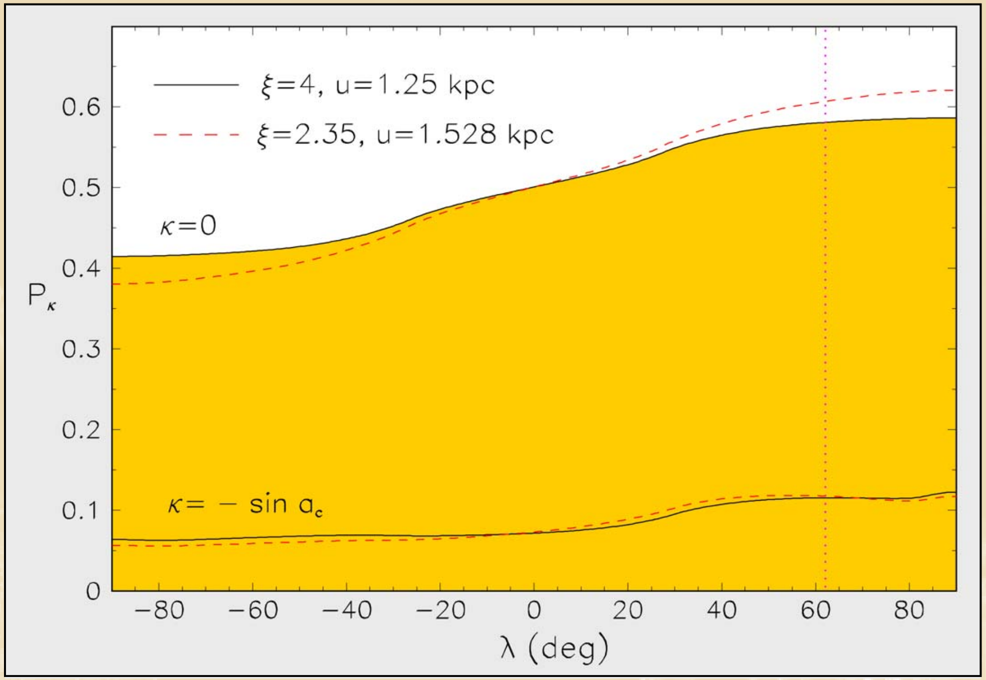
Assumed vertical distribution in the galactic disk

$$R(z) \propto 0.79 \exp\left[-\left(\frac{z}{212\ \mathrm{pc}}\right)^2\right] + 0.21 \exp\left[-\left(\frac{z}{636\ \mathrm{pc}}\right)^2\right]$$

Mirizzi, Raffelt & Serpico, "Earth matter effects in supernova neutrinos: Optimal detector locations", astro-ph/0604300

Average over Right Ascension (Earth Rotation)





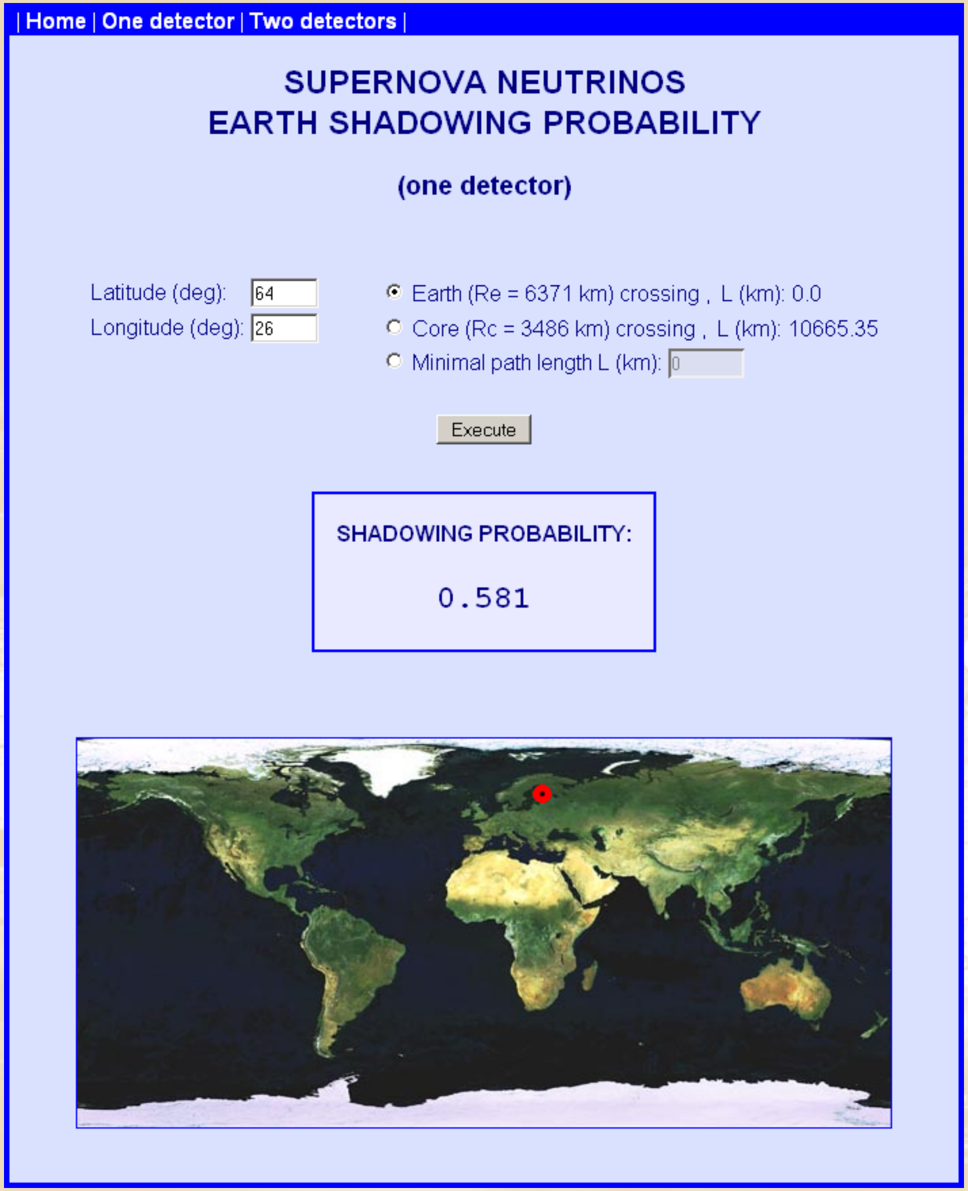
Dependence on geographic latitude quite robust relative to details of assumed galactic distribution

Probability of Earth and core shadowing as a function of geographic latitude

Mirizzi, Raffelt & Serpico, “Earth matter effects in supernova neutrinos: Optimal detector locations”, astro-ph/0604300

http://www.mppmu.mpg.de/supernova/shadowing

Mirizzi, Raffelt & Serpico
astro-ph/0604300



| Home | One detector | Two detectors |

SUPERNOVA NEUTRINOS
EARTH SHADOWING PROBABILITY

(one detector)

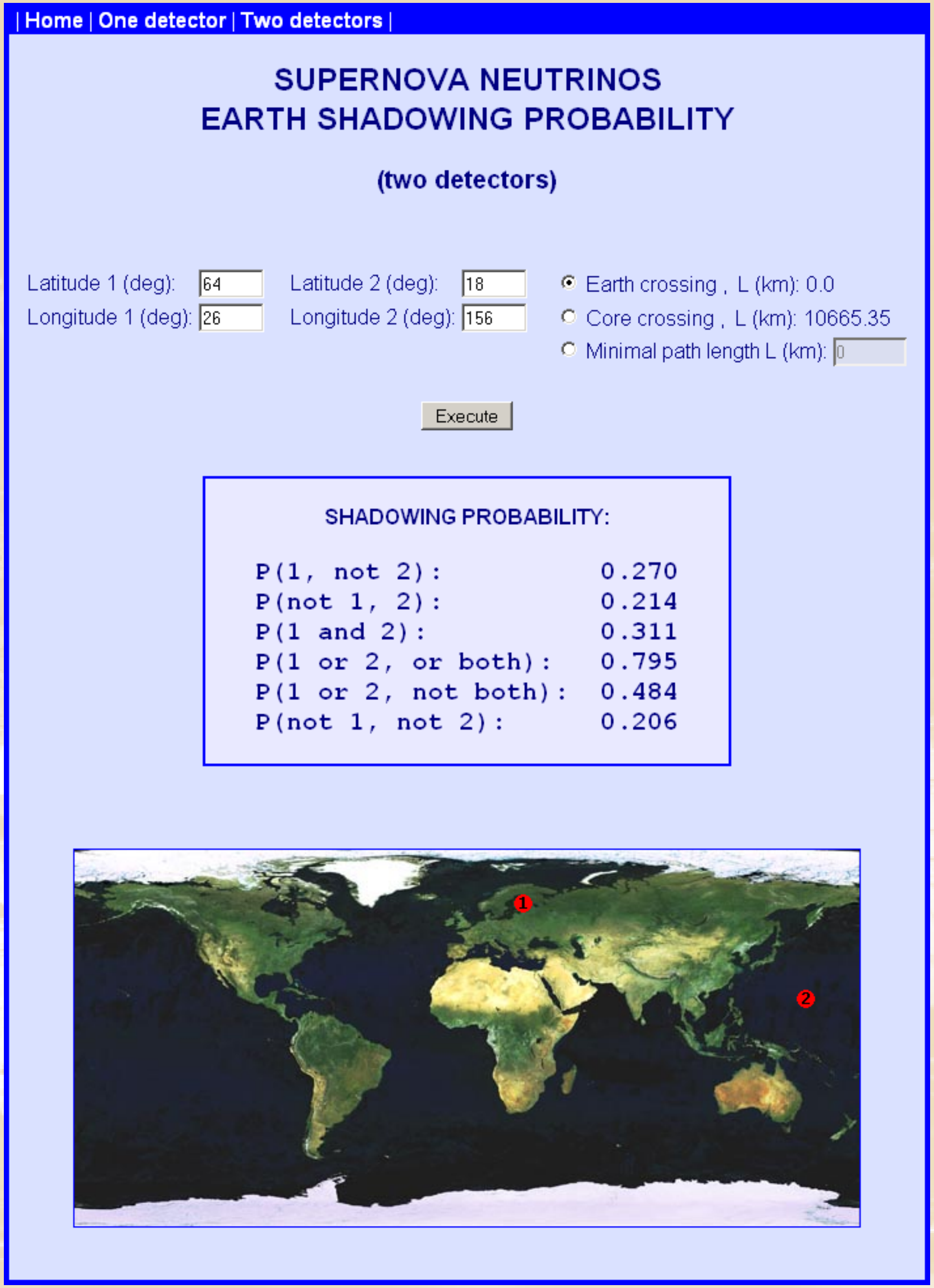
Latitude (deg): 64
Longitude (deg): 26

● Earth (Re = 6371 km) crossing , L (km): 0.0
○ Core (Rc = 3486 km) crossing , L (km): 10665.35
○ Minimal path length L (km): 0

Execute

```
SHADOWING PROBABILITY:

0.581
```



| Home | One detector | Two detectors |

SUPERNOVA NEUTRINOS
EARTH SHADOWING PROBABILITY

(two detectors)

Latitude 1 (deg): 64
Longitude 1 (deg): 26
Latitude 2 (deg): 18
Longitude 2 (deg): 156

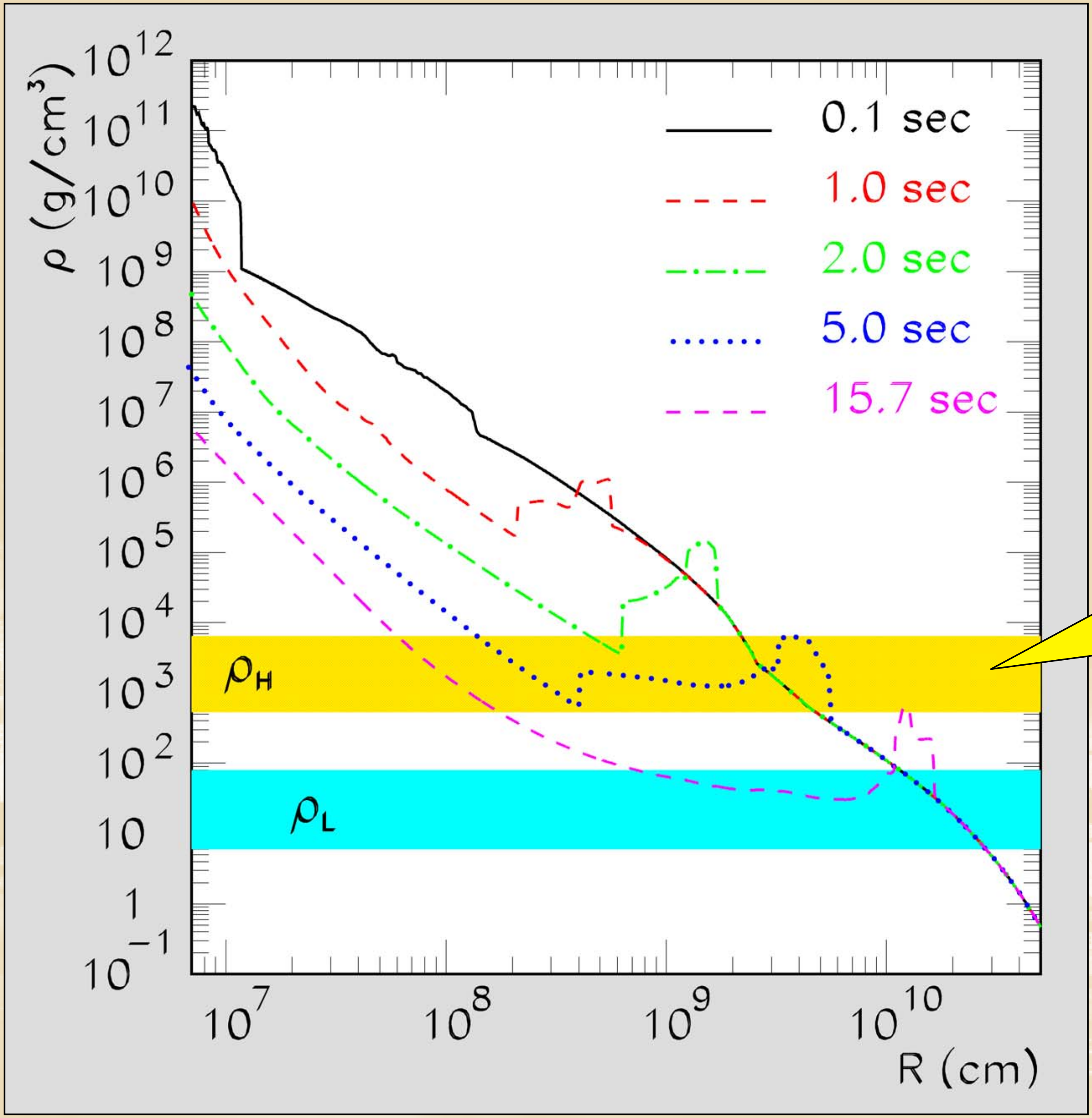
● Earth crossing , L (km): 0.0
○ Core crossing , L (km): 10665.35
○ Minimal path length L (km): 0

Execute

```
SHADOWING PROBABILITY:

P(1, not 2):            0.270
P(not 1, 2):            0.214
P(1 and 2):             0.311
P(1 or 2, or both):     0.795
P(1 or 2, not both):    0.484
P(not 1, not 2):        0.206
```

Supernova Shock Propagation and Neutrino Oscillations

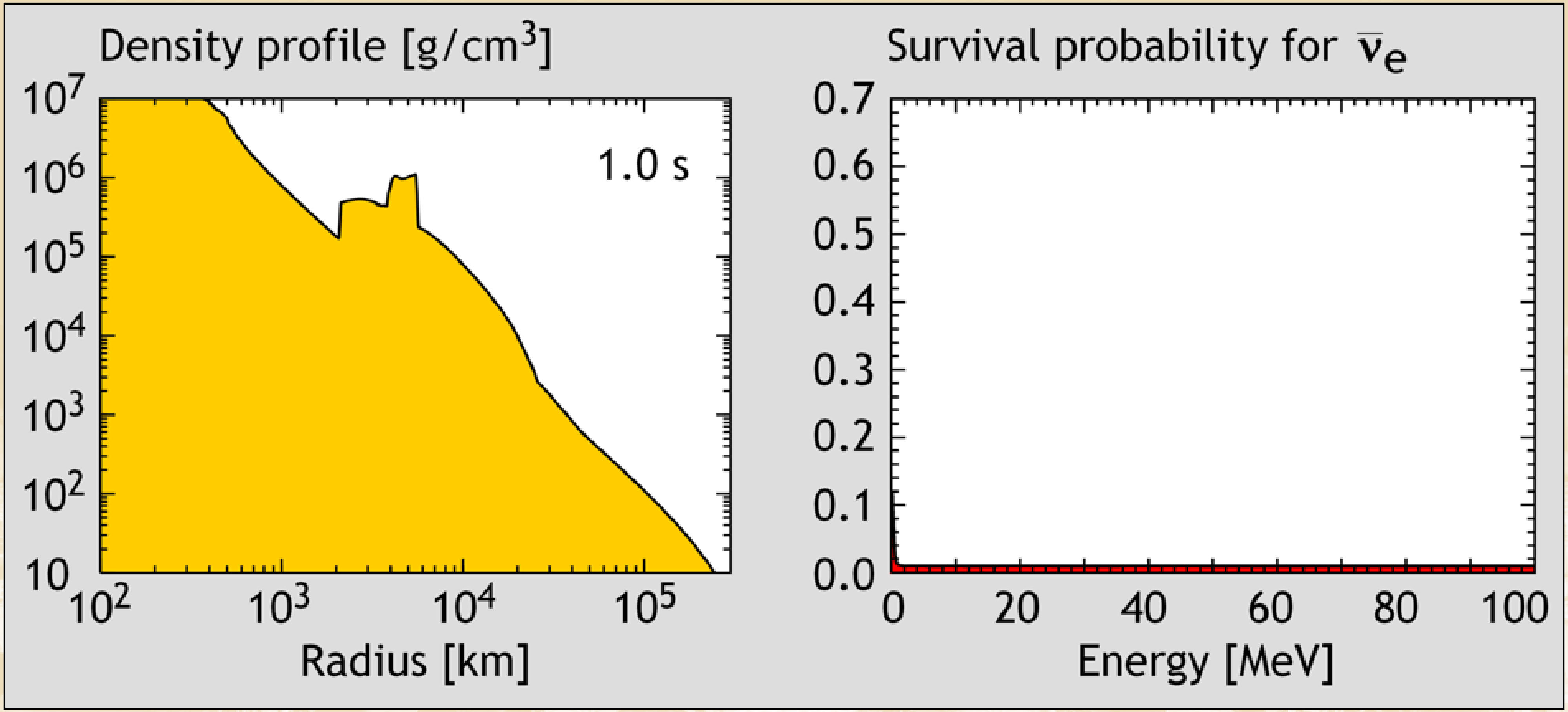


Resonance density for Δm^2_{atm}

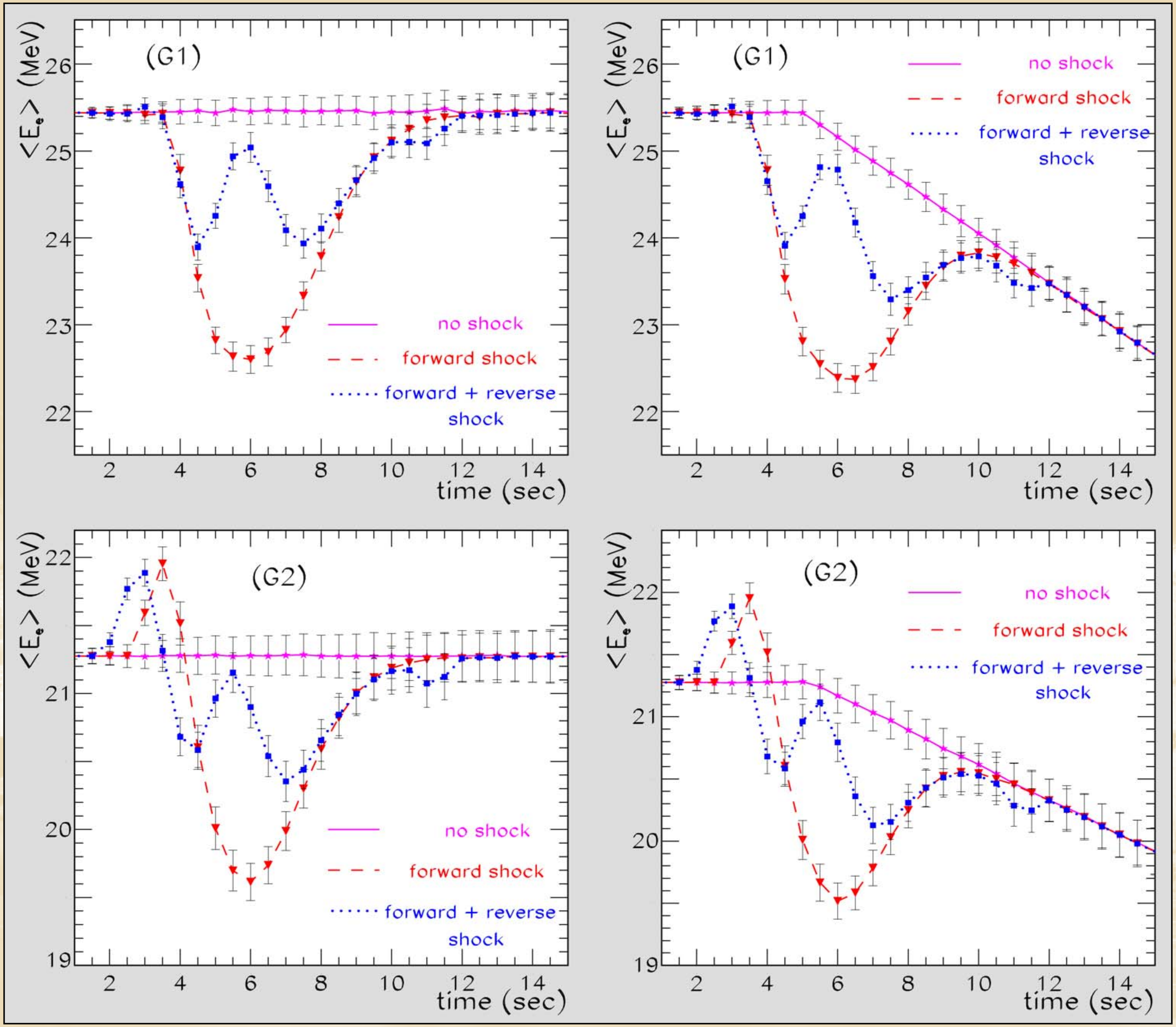
Schirato & Fuller: Connection between supernova shocks, flavor transformation, and the neutrino signal [astro-ph/0205390]

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]

Shock-Wave Propagation and Survival Probability



Megatonne Cherenkov Detector (Inverted Hierarchy)



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

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

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

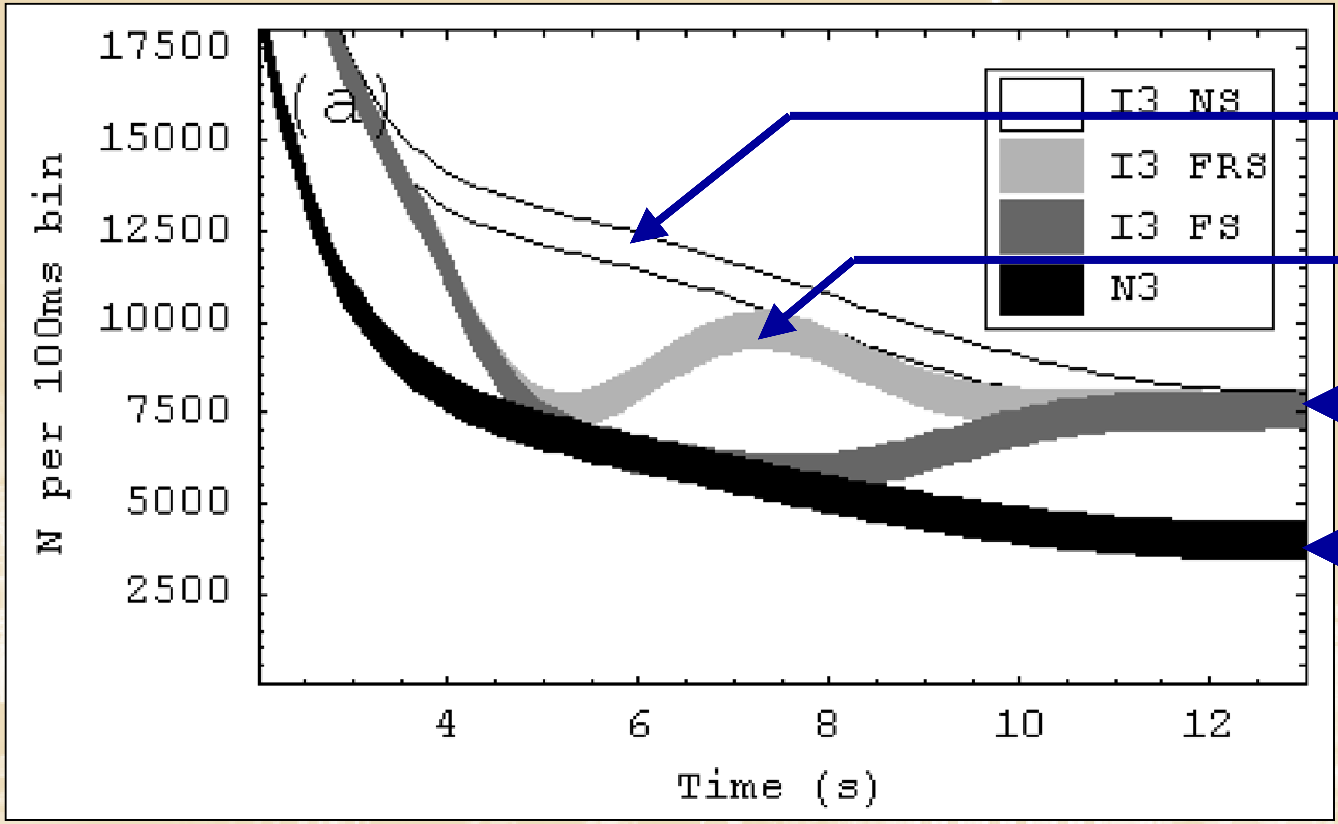
$$\frac{\text{Flux}(\bar{\nu}_e)}{\text{Flux}(\bar{\nu}_x)} = 0.5$$

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

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

Shock-Wave Propagation in IceCube

$$\frac{\mathrm{Flux}(\overline{\nu}_e)}{\mathrm{Flux}(\overline{\nu}_x)} = 0.8, \qquad \left\langle E_{\overline{\nu}_e} \right\rangle = 15\,\mathrm{MeV}, \qquad \left\langle E_{\overline{\nu}_x} \right\rangle = 18\,\mathrm{MeV}$$



Inverted Hierarchy
No shockwave

Inverted Hierarchy
Forward & reverse shock

Inverted Hierarchy
Forward shock

Normal Hierarchy

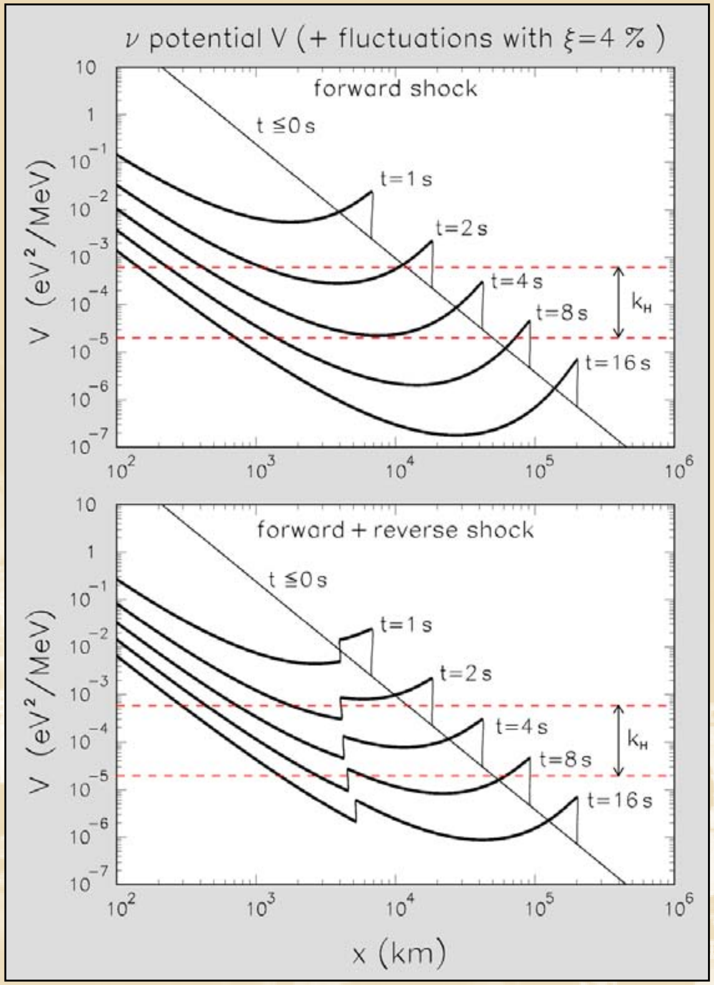
Choubey, Harries & Ross, “Probing neutrino oscillations from supernovae shock waves via the IceCube detector”, astro-ph/0604300

Observable Features in a Water Cherenkov Detector

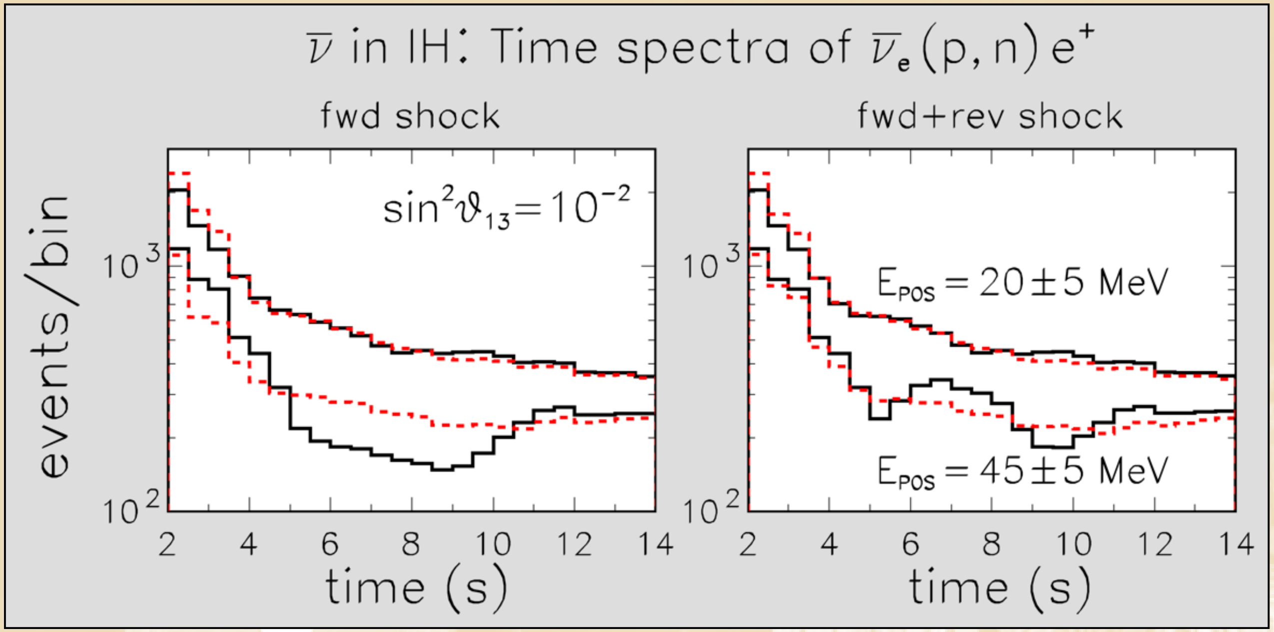
Case	Mass ordering	$\sin^2(2\Theta_{13})$	p	$\bar{p}$	Observable effects in $\bar{\nu}_e$ channel
A	Normal	$\gtrsim 10^{-3}$	0	$\cos^2(\Theta_{12})$	Earth effects
B	Inverted		$\sin^2(\Theta_{12})$	0	Shock-wave propagation
C	Any	$\lesssim 10^{-5}$	$\sin^2(\Theta_{12})$	$\cos^2(\Theta_{12})$	Earth effects

Stochastic Density Fluctuations

Schematic time-dependent shock-wave profile



Events in a 0.4 Mt water Cherenkov detector
Black: no noise. Red: with noise.



Assume δ-correlated noise, length-scale of order the oscillation length (10 km), amplitude 4% (line-width on plot)

Fogli, Lisi, Mirizzi & Montanino, "Damping of supernova neutrino transitions in stochastic shock-wave density profiles", hep-ph/0603033

Self-Induced Flavor Oscillations of SN Neutrinos

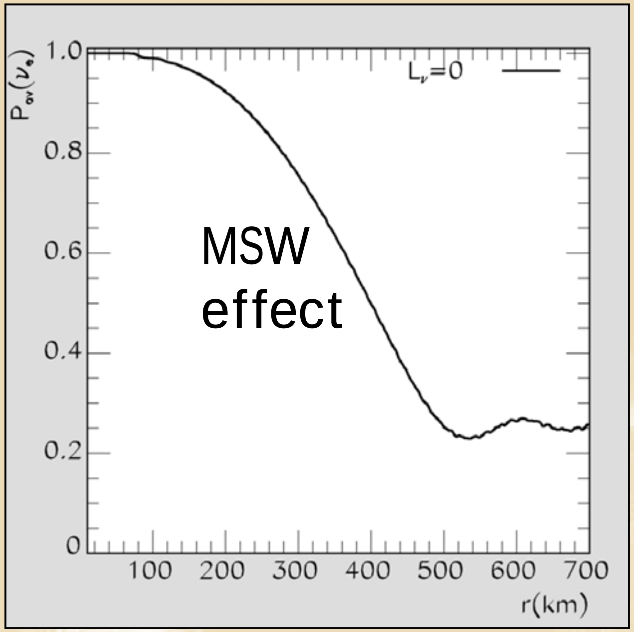
Survival probability ν_e

Survival probability $\overline{\nu}_e$

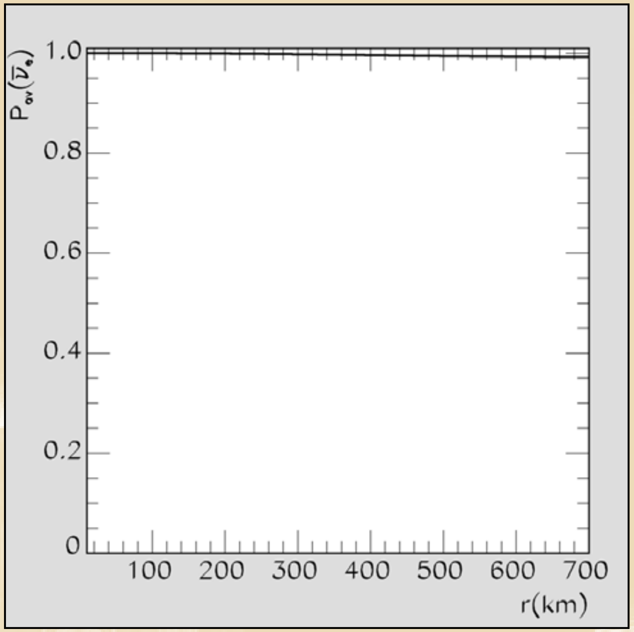
Normal Hierarchy

atm Δm^2

Θ_{13} close to Chooz limit

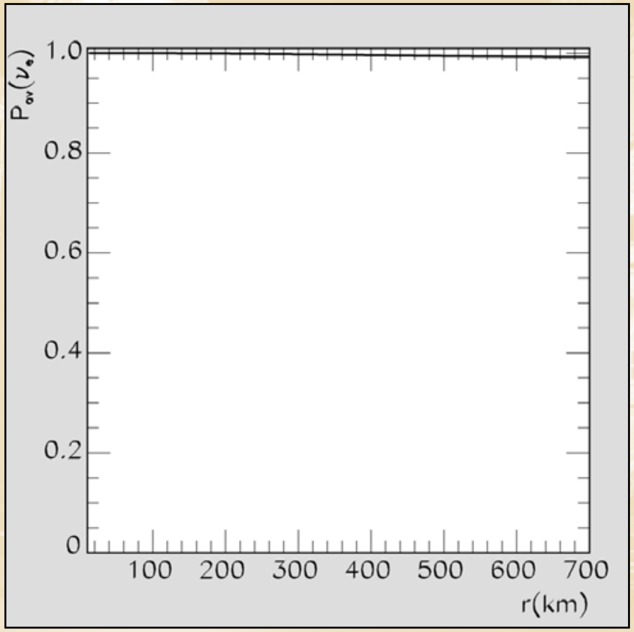


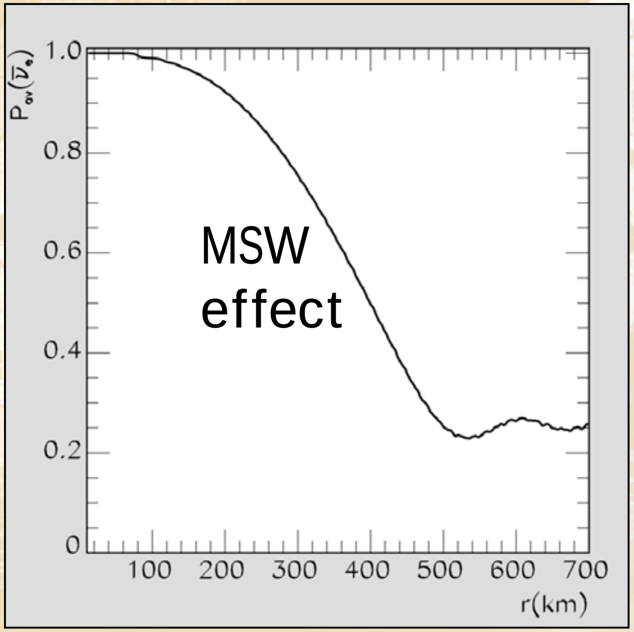
MSW effect



No nu-nu effect

Inverted Hierarchy





MSW effect

No nu-nu effect

Self-Induced Flavor Oscillations of SN Neutrinos

Survival probability ν_e

Survival probability $\overline{\nu}_e$

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atm Δm^2

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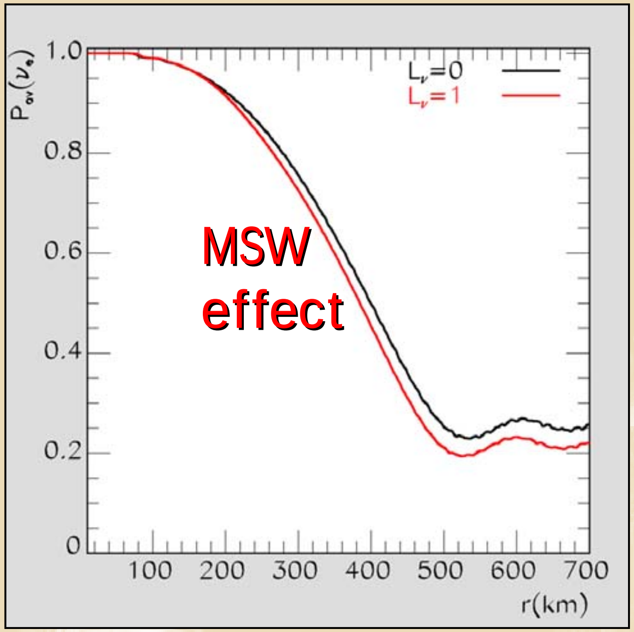
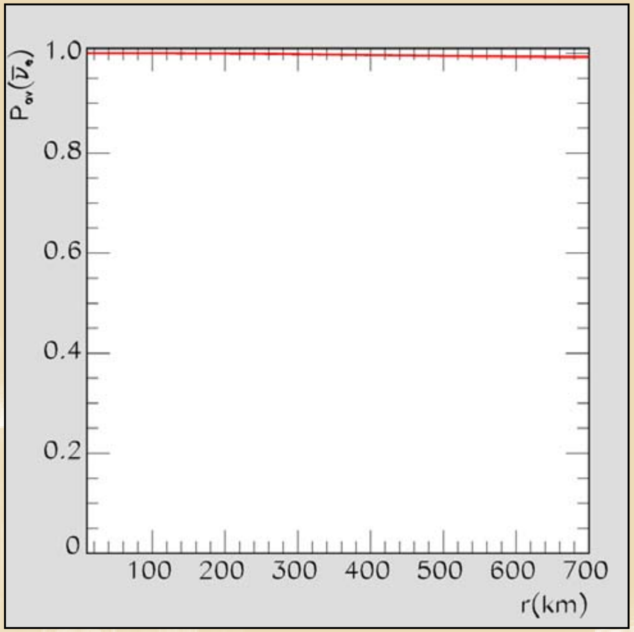
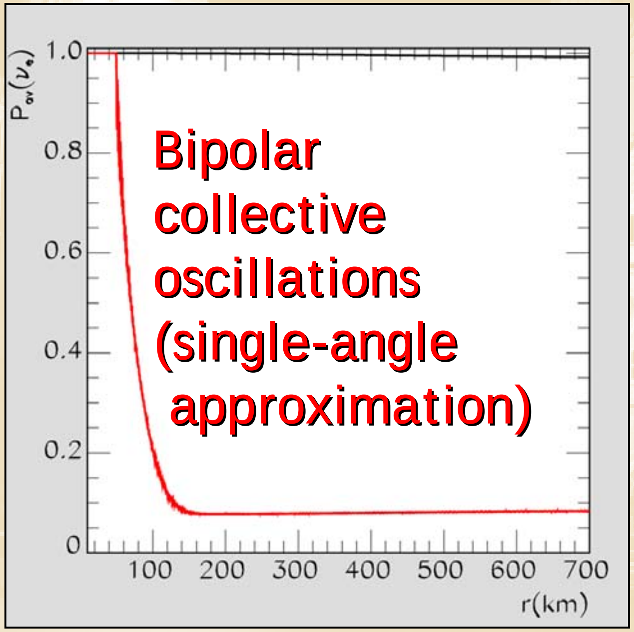


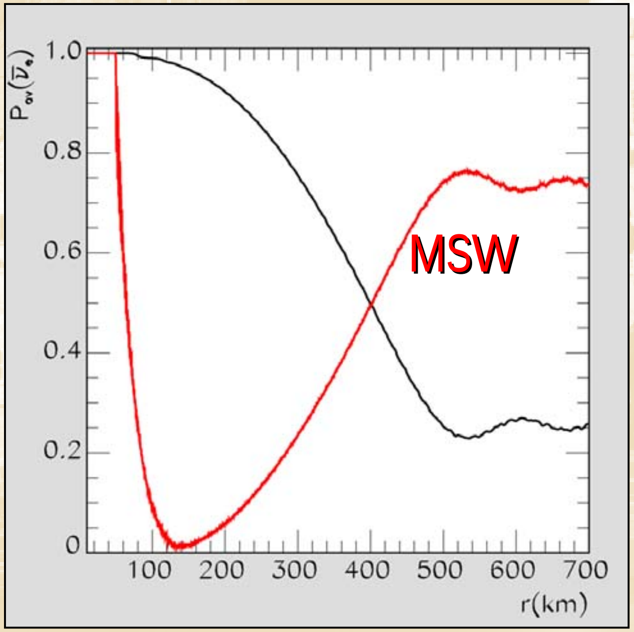


Realistic nu-nu effect

No nu-nu effect

Inverted Hierarchy

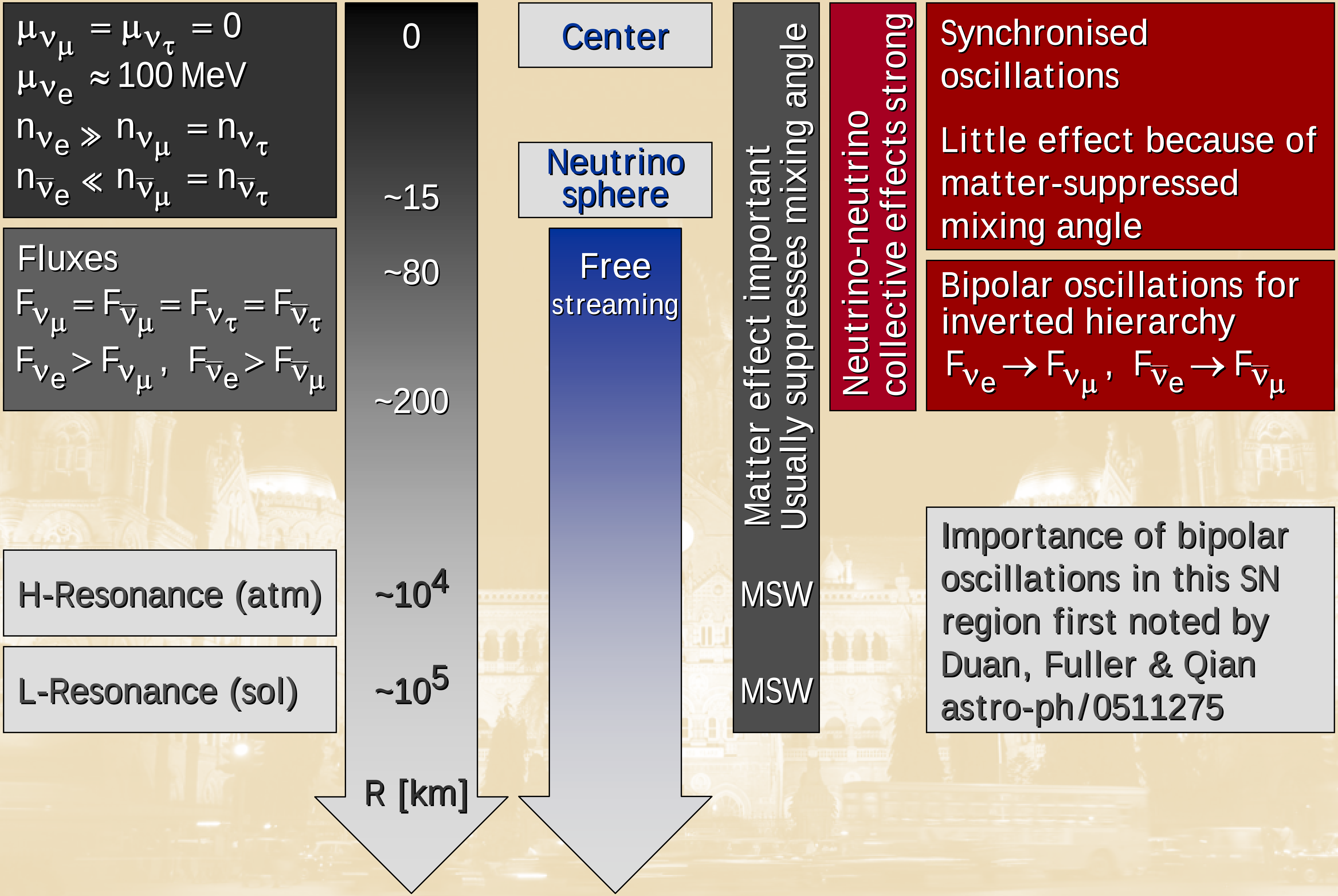




Realistic nu-nu effect

No nu-nu effect

Different Oscillation Modes in Supernovae



$\mu_{\nu_\mu} = \mu_{\nu_\tau} = 0$

$\mu_{\nu_e} \approx 100$ MeV

$n_{\nu_e} \gg n_{\nu_\mu} = n_{\nu_\tau}$

$n_{\overline{\nu}_e} \ll n_{\overline{\nu}_\mu} = n_{\overline{\nu}_\tau}$

Fluxes

$F_{\nu_\mu} = F_{\overline{\nu}_\mu} = F_{\nu_\tau} = F_{\overline{\nu}_\tau}$

$F_{\nu_e} > F_{\nu_\mu}, \quad F_{\overline{\nu}_e} > F_{\overline{\nu}_\mu}$

H-Resonance (atm)

L-Resonance (sol)

Center

Neutrino sphere

Free streaming

Matter effect important
Usually suppresses mixing angle

MSW

MSW

Neutrino-neutrino collective effects strong

Synchronised oscillations

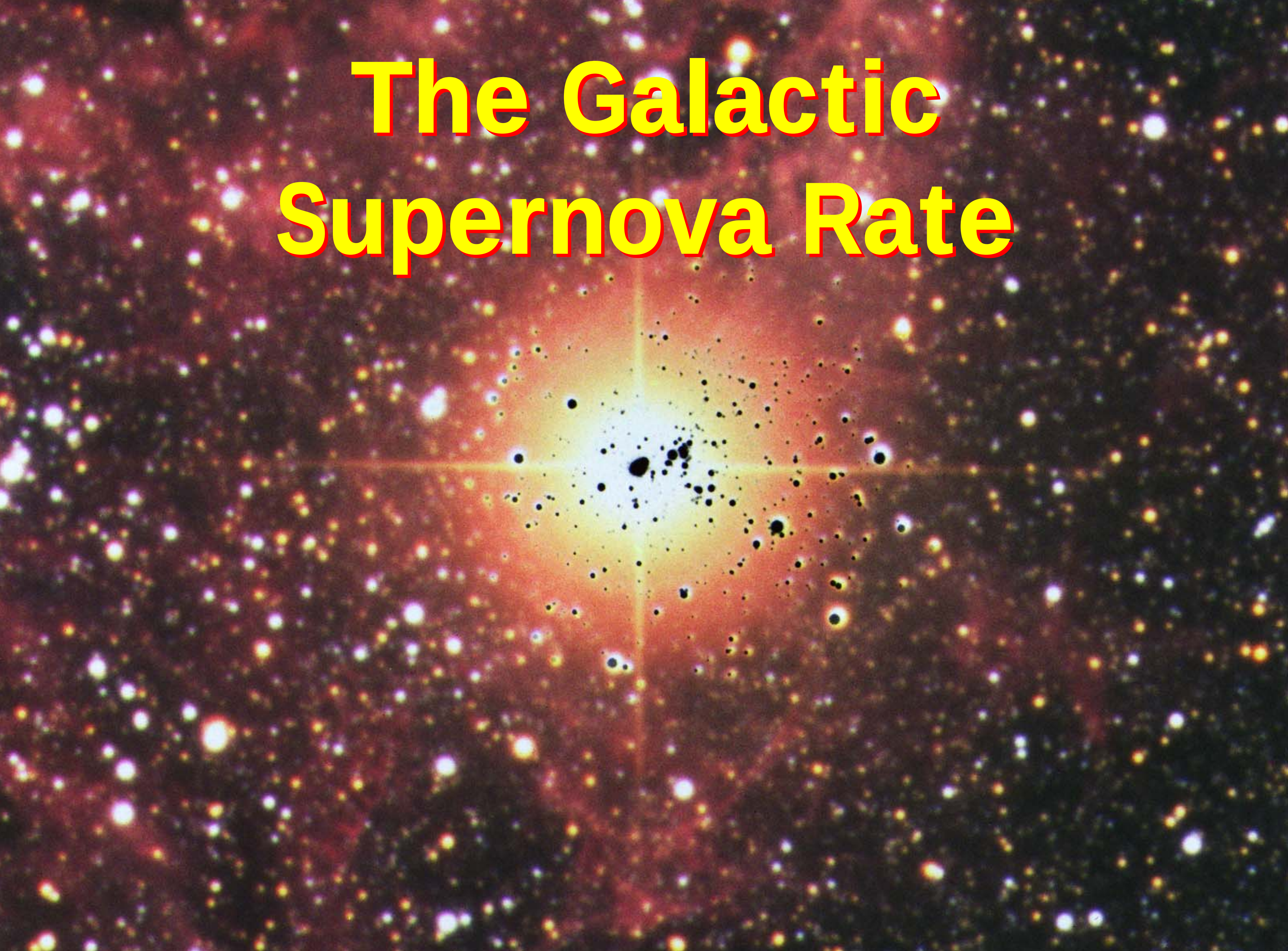
Little effect because of matter-suppressed mixing angle

Bipolar oscillations for inverted hierarchy

$F_{\nu_e} \to F_{\nu_\mu}, \quad F_{\overline{\nu}_e} \to F_{\overline{\nu}_\mu}$

Importance of bipolar oscillations in this SN region first noted by Duan, Fuller & Qian astro-ph/0511275

The Galactic Supernova Rate



Supernova Rates

Multiply rates with h^2

		Supernova Type			
		Thermonuclear	Core Collapse		All
		Ia	Ib/c	II	
Galaxy Type	E-S0	0.32 ± .11	< 0.02	< 0.04	0.32 ± .11
	S0a-Sb	0.32 ± .12	0.20 ± .11	0.75 ± .34	1.28 ± .37
	SBc-Sd	0.37 ± .14	0.25 ± .12	1.53 ± .62	2.15 ± .66
	All	0.36 ± .11	0.14 ± .07	0.71 ± .34	1.21 ± .36

Measured in SuperNova unit: 1 SNu = 1 SN / 10^{10} $L_{\mathrm{sun,B}}$ / 100 years

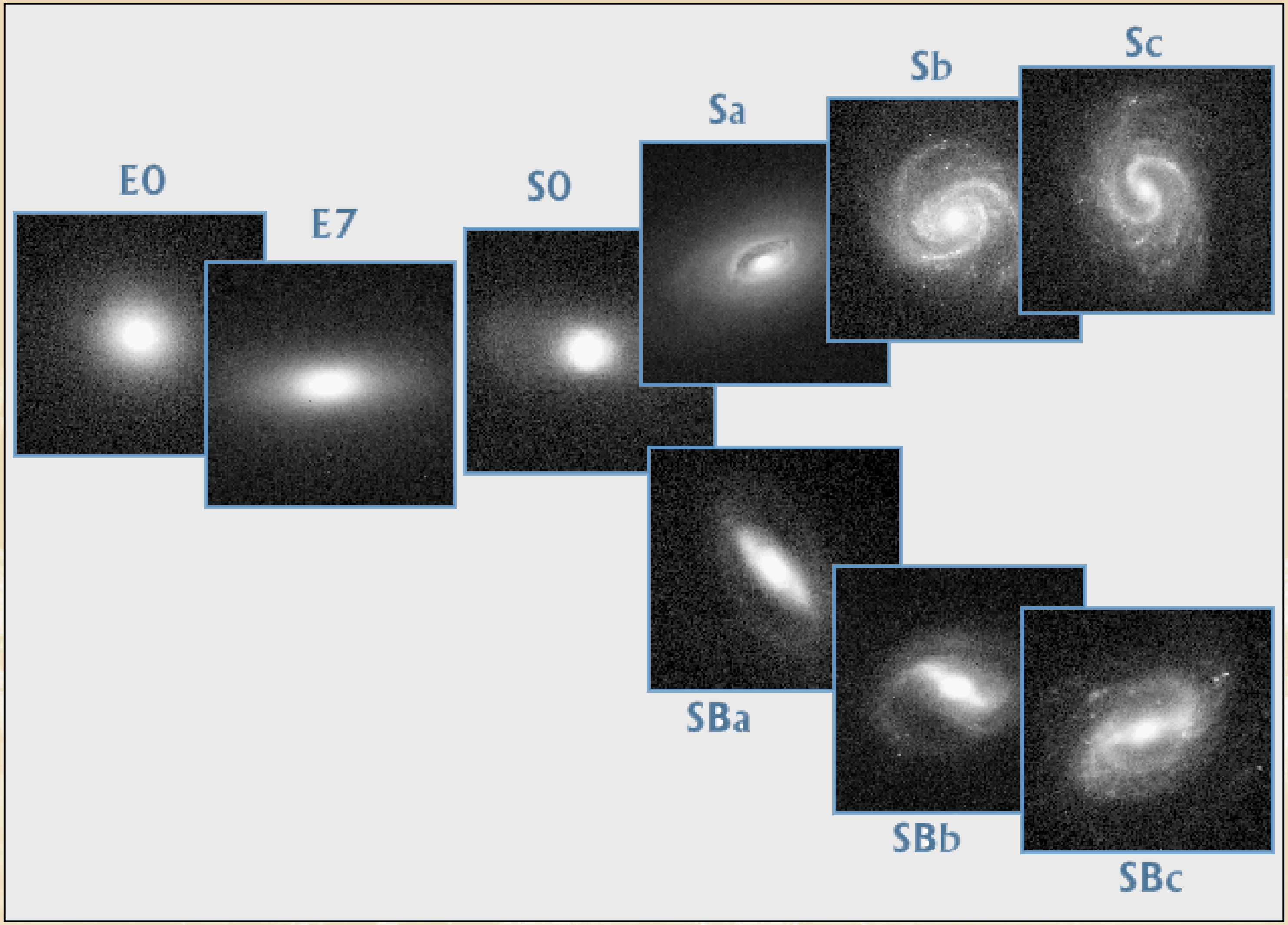
Milky Way Galaxy:
Type Sb–Sbc, $L_B = 2.3 \times 10^{10}\ L_{\mathrm{sun,B}}$, $h = 0.72$
About 2.0 ± 1.0 core-collapse SNe per century

Cappellaro & Turatto, Supernova Types and Rates, astro-ph/0012455

Hubble Sequence of Galaxy Types

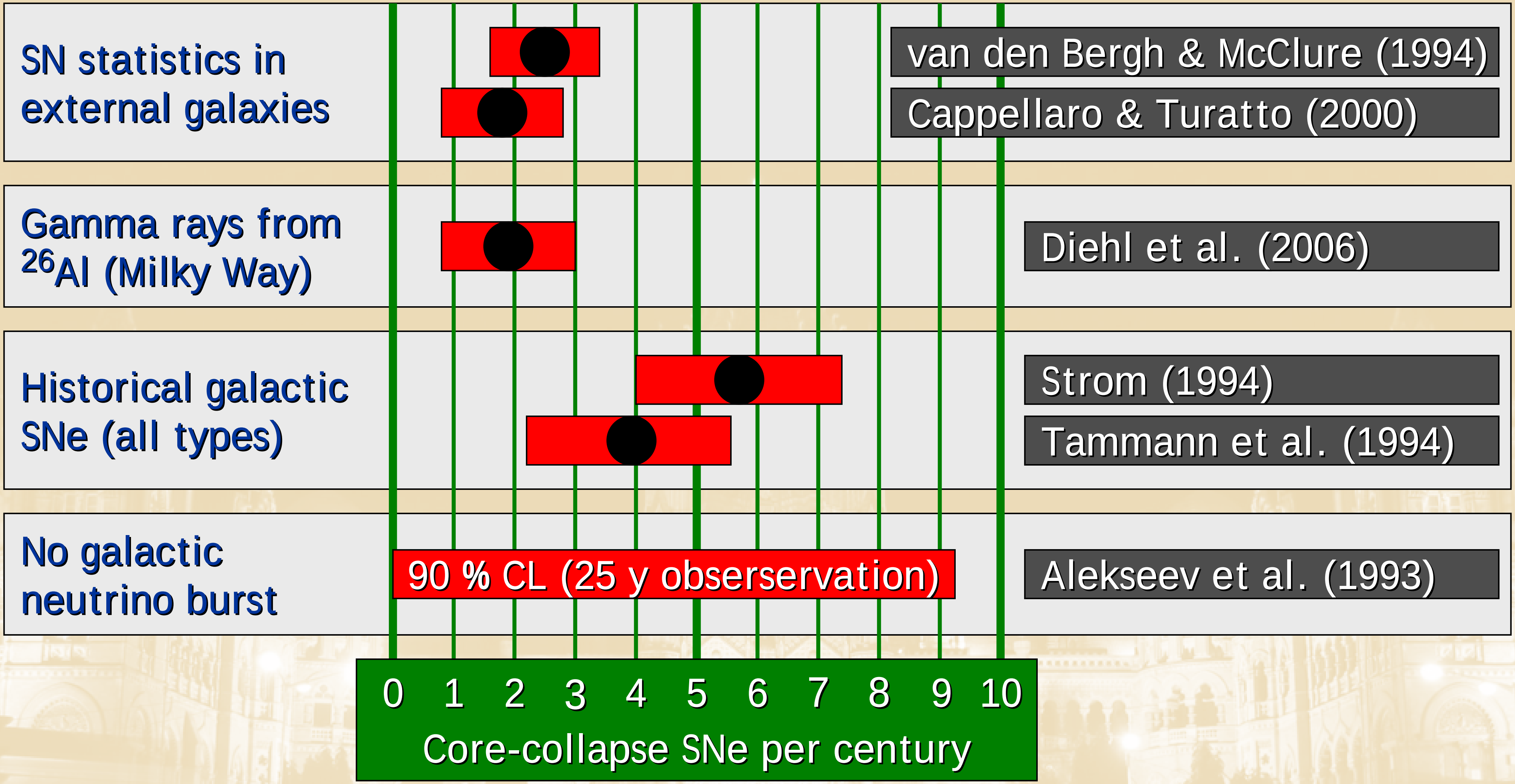
Ellipticals

Normal Spirals



Barred Spirals

Core-Collapse SN Rate in the Milky Way



SN statistics in external galaxies

- van den Bergh & McClure (1994)
- Cappellaro & Turatto (2000)

Gamma rays from ^{26}Al (Milky Way)

- Diehl et al. (2006)

Historical galactic SNe (all types)

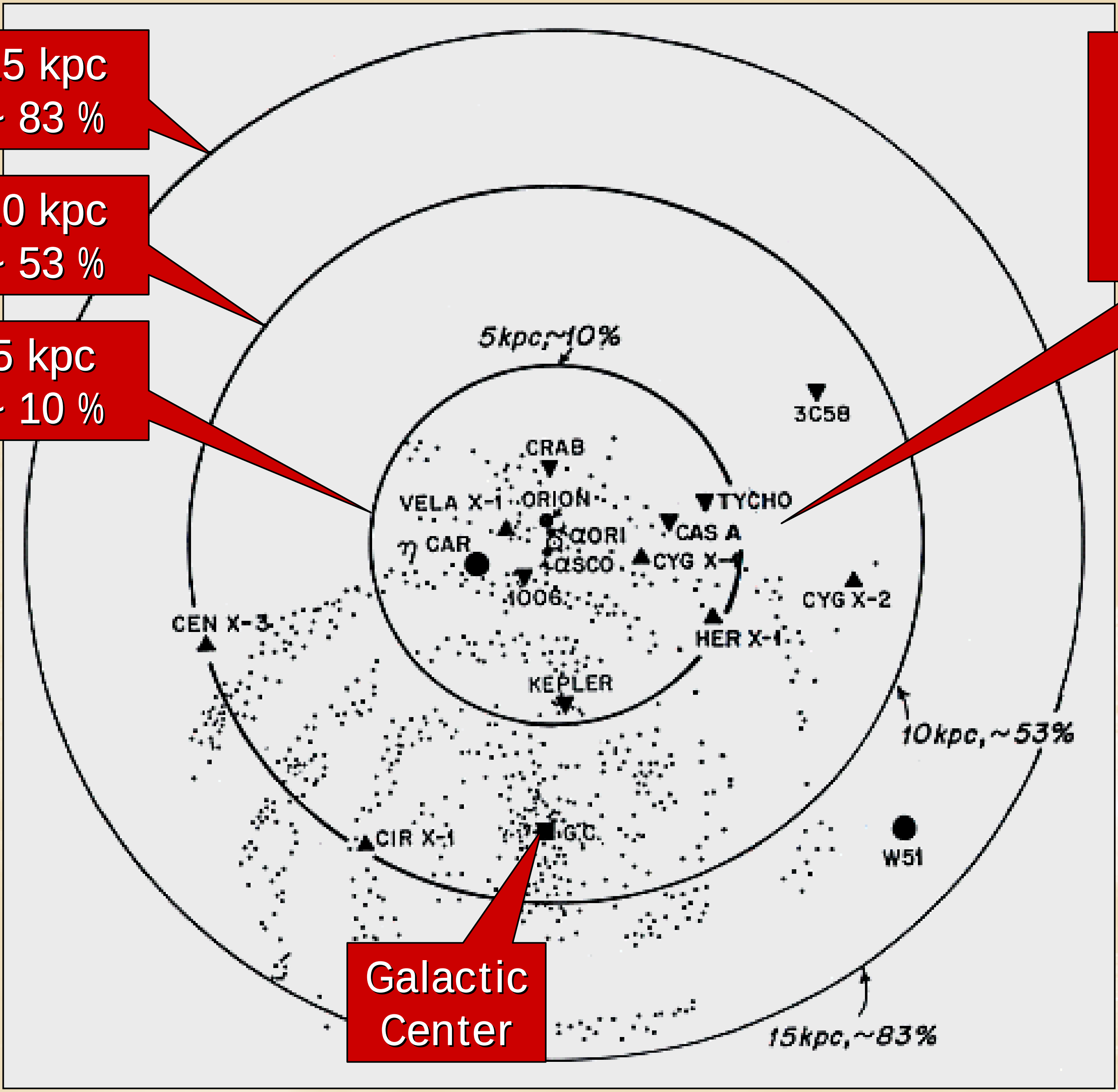
- Strom (1994)
- Tammann et al. (1994)

No galactic neutrino burst

- Alekseev et al. (1993)

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. Alekeseev et al., JETP 77 (1993) 339 and my update.

Galactic Supernova Events



15 kpc
~ 83 %

10 kpc
~ 53 %

5 kpc
~ 10 %

Galactic Center

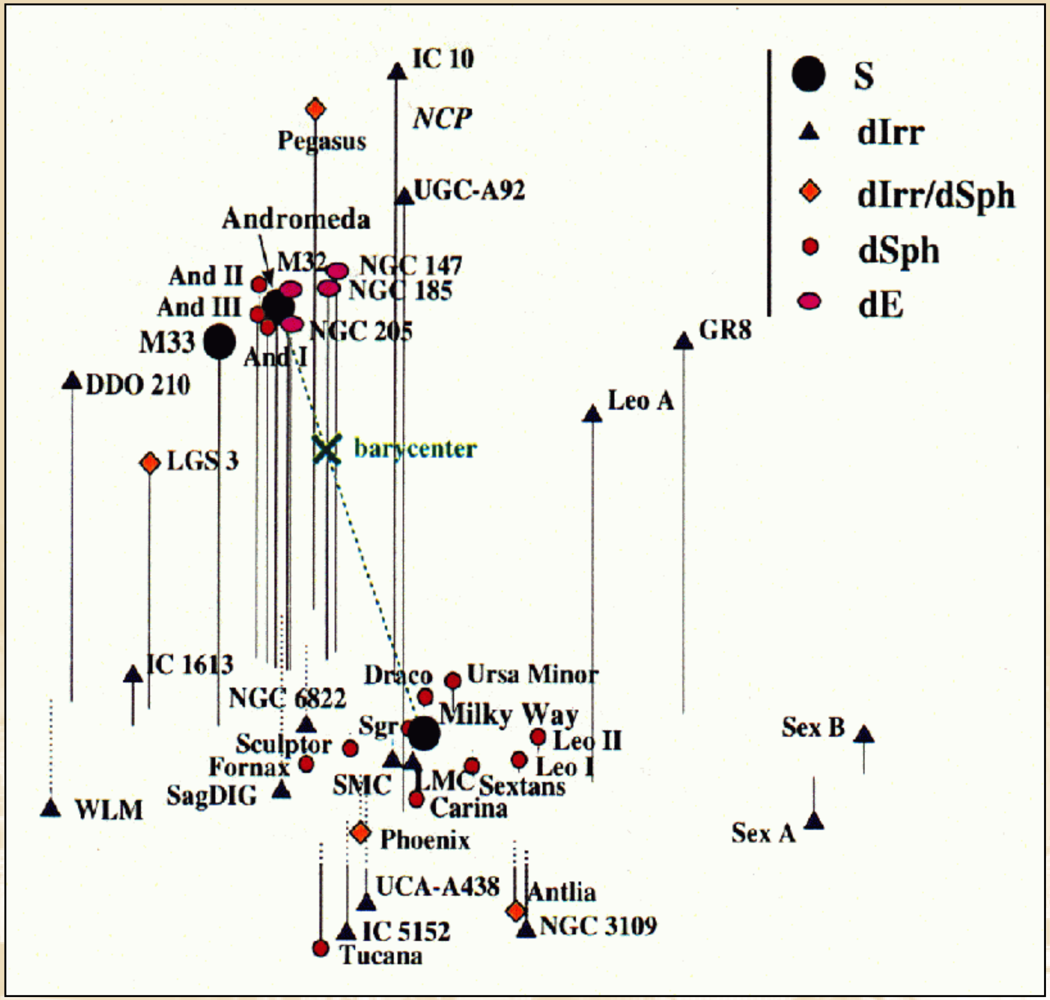
Most historical supernovae in ~ 10% of the galaxy

Anomalously large rate in our galaxy?

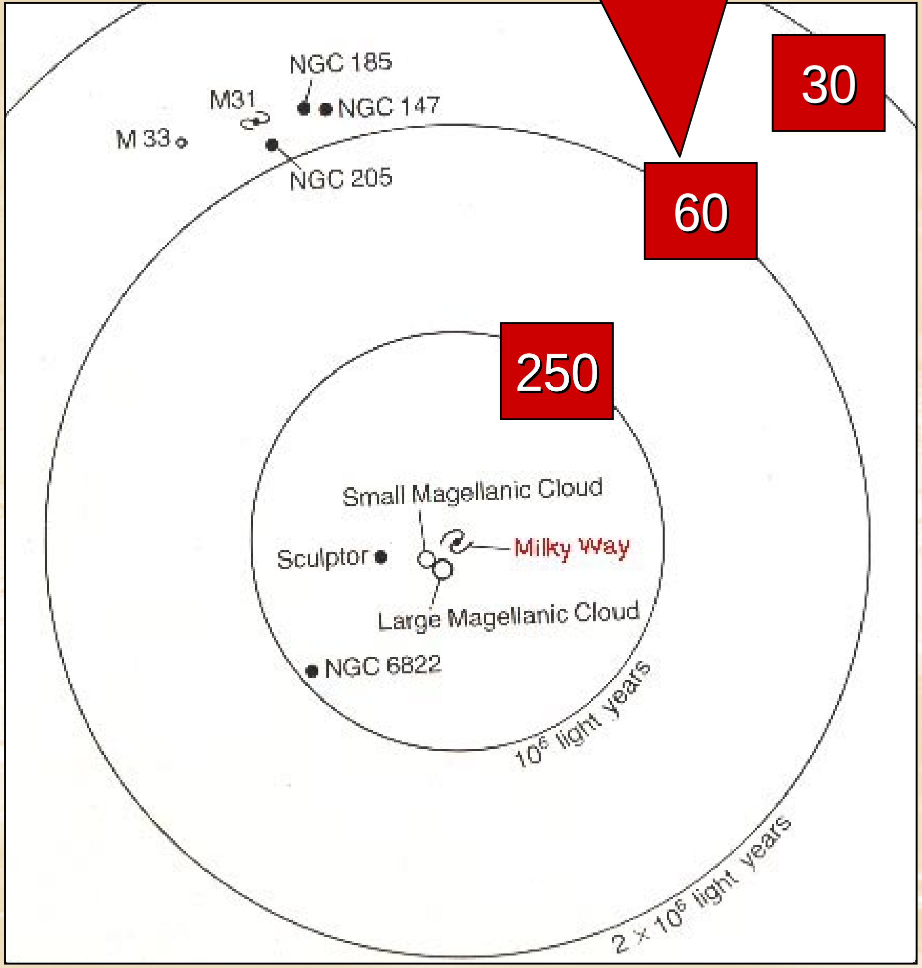
Small-number statistics?

Adam Burrows

Local Group of Galaxies



Events in a detector with
30 x Super-K fiducial volume,
e.g. Hyper-Kamiokande



Brightest Members of Local Group

	Type	Lumin	D [kpc]	Neutrino events	SNe (all types) per century
Milky Way	S(B)bc	1	8.5	330,000	1-6
LMC	Ir	0.11	50	9,600	0.1 / 0.23 / 0.49
SMC	Ir	0.030	60	6,600	0.065 / 0.12
NGC 6822	Ir	0.011	500	96	0.04
IC 10 (UGC 192)	Ir	0.015	660	55	0.082-0.11
NGC 205	Sph	0.016	760	42	
M32 (NGC 221)	E2	0.017	760	42	
Andromeda (M31)	Sb	1.3	760	42	0.9 / 1.21 / 1.25
Triangulum (M33)	Sc	0.16	790	38	0.28 / 0.35 / 0.68

- Luminosity: Visual in units of the Milky Way
- Neutrino events in 30 x SK fiducial volume (8000 events in SK for SN at 10 kpc)
- Refs. for SN rates in Pavlidou & Fields, Ap. J. 558 (2001) 63.

Nearby Galaxies with Many Observed Supernovae

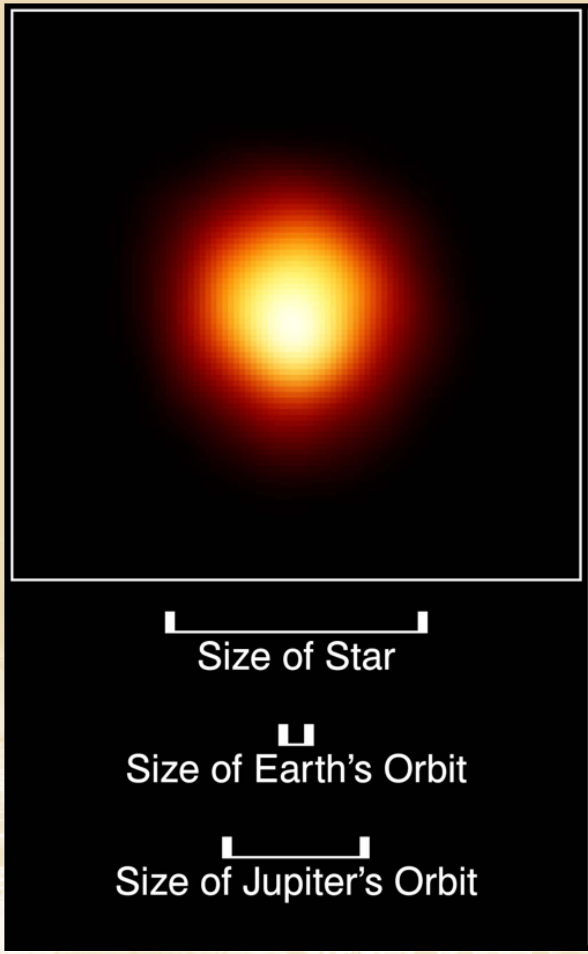
M83 (NGC 5236, Southern Pinwheel)
D = 4.5 Mpc

Observed Supernovae:
1923A, 1945B, 1950B,
1957D, 1968L, 1983N

NGC 6946
D = (5.5 ± 1) Mpc

Observed Supernovae:
1917A, 1939C, 1948B, 1968D,
1969P, 1980K, 2002hh, 2004et

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
- 2.4×10^3 neutron events per day from Silicon-burning phase (few days warning!), need neutron tagging [Odrzywolek, Misiaszek & Kutschera, astro-ph/0311012]

Neutrinos From All Cosmic Supernovae

Diffuse Background Flux of SN Neutrinos

1 SNu = 1 SN / 10^{10} $L_{\mathrm{sun,B}}$ / 100 years

$L_{\mathrm{sun,B}} = 0.54\ L_{\mathrm{sun}} = 2 \times 10^{33}$ erg/s

$E_\nu \sim 3 \times 10^{53}$ erg per core-collapse SN

→

1 SNu ~ 4 L_ν / $L_{\gamma,\mathrm{B}}$
Average neutrino luminosity of galaxies ~ photon luminosity

- Photons come from nuclear energy
- Neutrinos from gravitational energy

→

For galaxies, average nuclear & gravitational energy release comparable

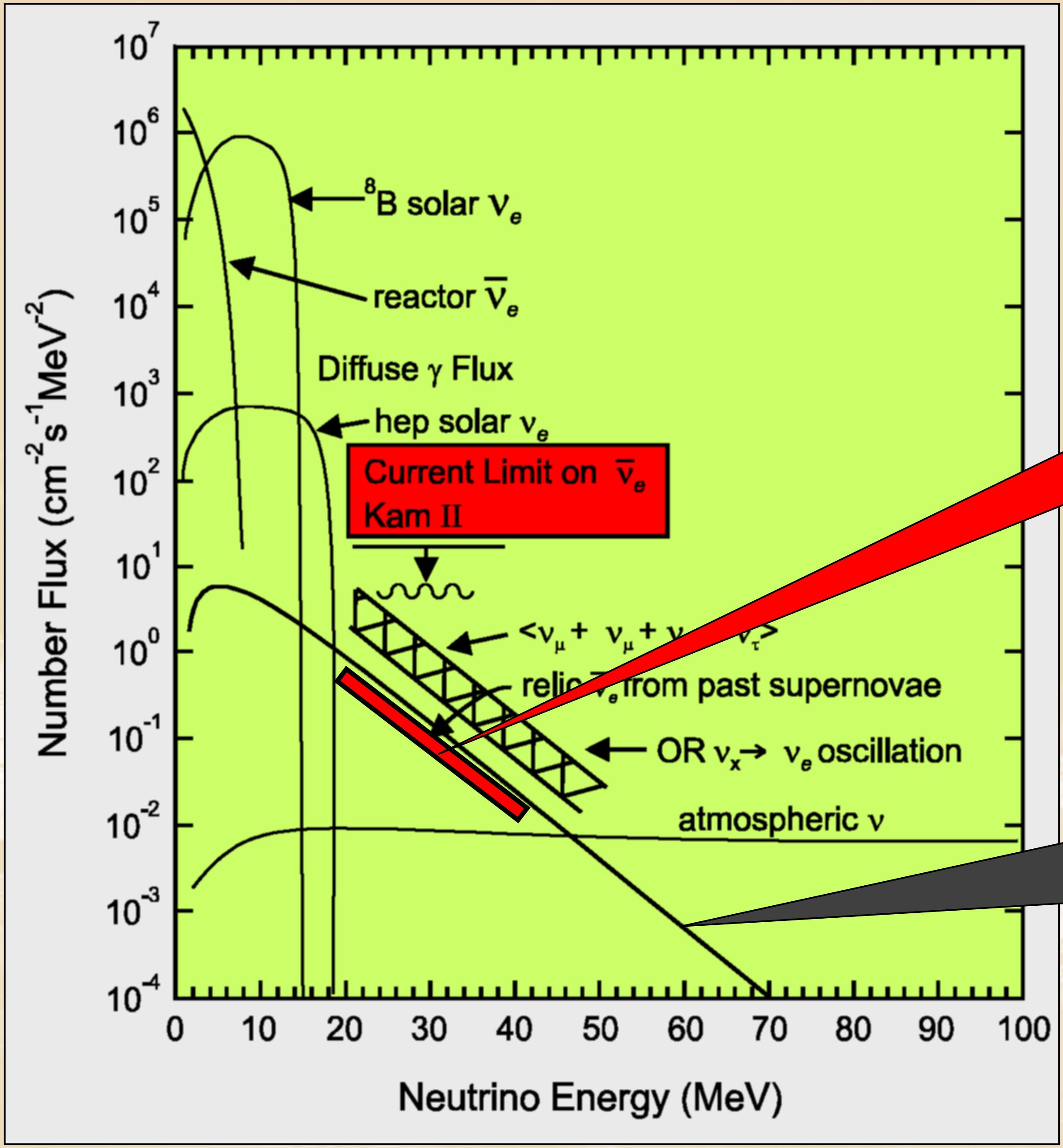
Present-day SN rate of ~ 1 SNu, extrapolated to the entire universe, corresponds to ν_e flux of ~ 1 $\mathrm{cm}^{-2}\ \mathrm{s}^{-1}$

Realistic flux is dominated by much larger early star-formation rate

- Upper limit ~ 54 $\mathrm{cm}^{-2}\ \mathrm{s}^{-1}$
  [Kaplinghat et al., astro-ph/9912391]
- "Realistic estimate" ~ 10 $\mathrm{cm}^{-2}\ \mathrm{s}^{-1}$
  [Hartmann & Woosley, Astropart. Phys. 7 (1997) 137]

Measurement would tell us about early history of star formation

Experimental Limits on Relic Supernova Neutrinos



Super-K upper limit
29 cm^{-2} s^{-1} for
Kaplinghat et al. spectrum
[hep-ex/0209028]

Upper-limit flux of
Kaplinghat et al.,
astro-ph/9912391
Integrated 54 cm^{-2} s^{-1}

Cline, astro-ph/0103138

Improved Sensitivity with Neutron Tagging

Beacom & Vagins, hep-ph/0309300
[Phys. Rev. Lett., 93 (2004) 171101]

Detection of DSNB limited by

- Solar neutrinos for $E_\nu \lesssim 18$ MeV
- Sub-Cherenkov muons from atm nus $\mu \to e + \nu_e + \overline{\nu}_\mu$
- Solution: neutron tagging from $\overline{\nu}_e + p \to e^+ + n$
- 2.2 MeV gamma from $n + p \to d$ invisible in water Cherenkov detector

Add gadolinium to Super-Kamiokande

- Efficient neutron capture on Gd
- 8 MeV gamma cascade easily visible
- 0.1% (100 tons of Gd Cl_3) achieves $>$ 90% tagging efficiency
- Diffuse SN nu background (DSNB): a few events per year in Super-K with no background at all

Status of R & D (04/2006)
[Mark Vagins, private communication]

Nov 05: Gd Cl_3 added to K2K test tank (kiloton or KT detector)

- Gd Cl_3 is easy to dissolve
- Gd Cl_3 does not significantly affect the light collection
- Choice of detector materials critical (old rust in KT with Gd Cl_3 badly affected transparency)
- The 20 inch Super-K PMT's operate well in conductive water
- Gd filtration works as designed at 3.6 tons/h, can easily be scaled up

- Looks promising for Super-K, conceivable within next few years
- Capital cost negligible for future megatonne-class detectors

DSNB Measurement with Neutron Tagging

Beacom & Vagins, hep-ph/0309300
[Phys. Rev. Lett., 93:171101, 2004]

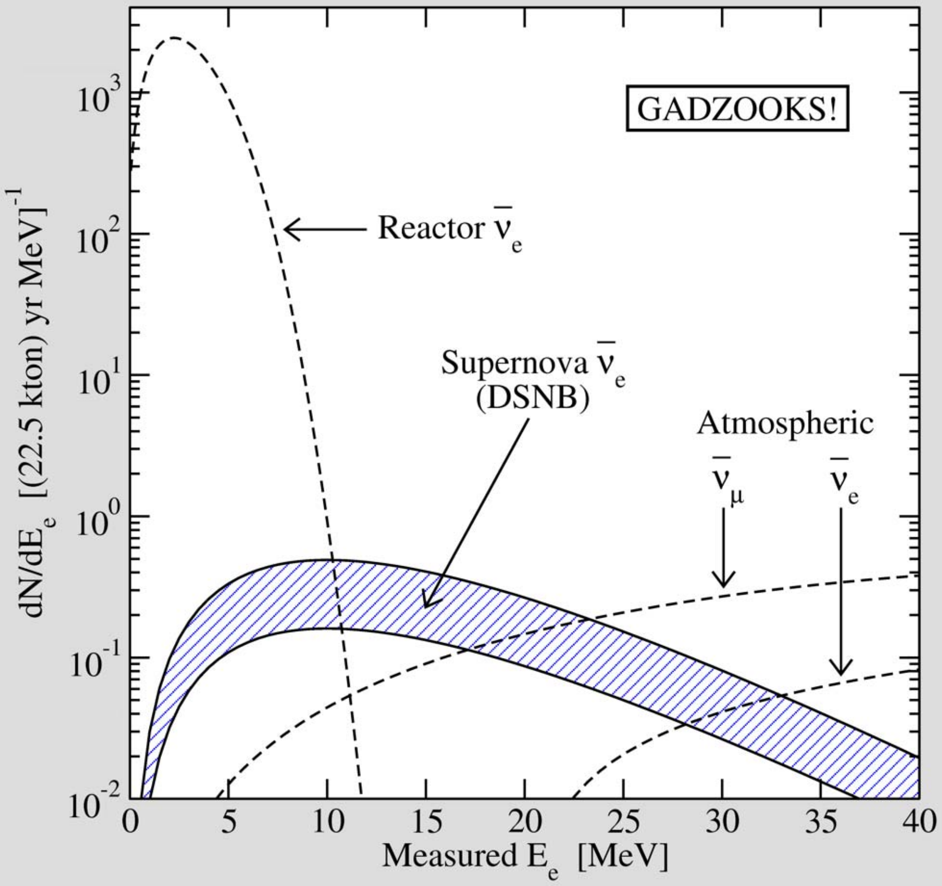


FIG. 1: Spectra of low-energy $\bar{\nu}_e + p \rightarrow e^+ + n$ coincidence events and the sub-Čerenkov muon background. We assume full efficiencies, and include energy resolution and neutrino oscillations. Singles rates (not shown) are efficiently suppressed.

Future large-scale scintillator detectors (e.g. LENA with 50 kt)

- Inverse beta decay reaction tagged
- Location with smaller reactor flux (e.g. Pyhäsalmi in Finland) could allow for lower threshold

Pushing the boundaries of neutrino astronomy to cosmological distances

Looking forward to the next galactic supernova!

http://antwrp.gsfc.nasa.gov/apod/ap060430.html