Diffuse cosmic neutrino fluxes

14th December 2004

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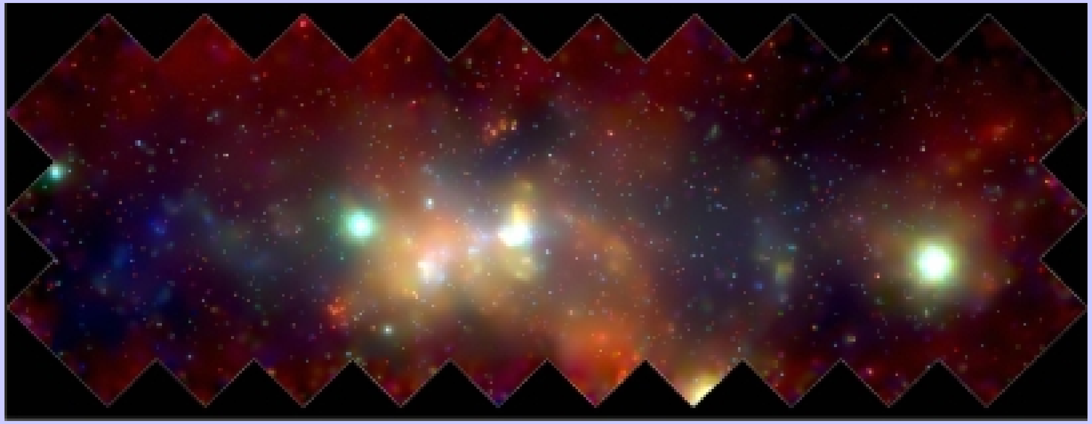
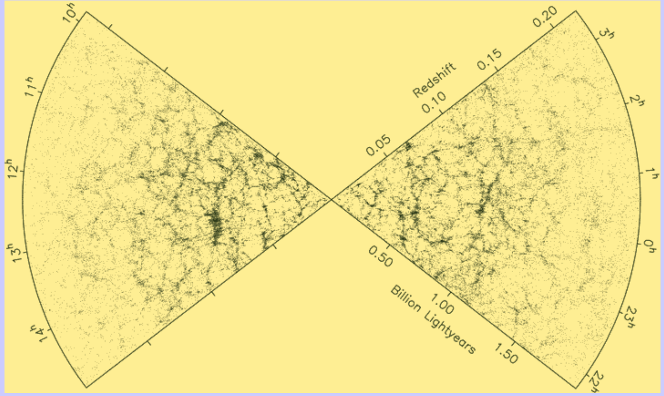
INFN Naples

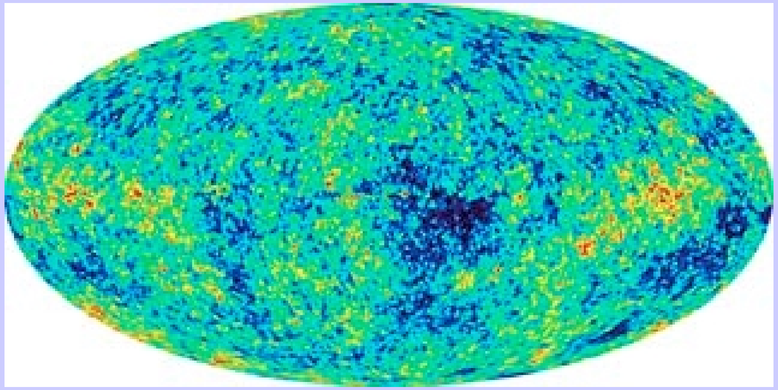
thanks to G. Raffelt and V. Pettorino for (mis)use of some plots and figures

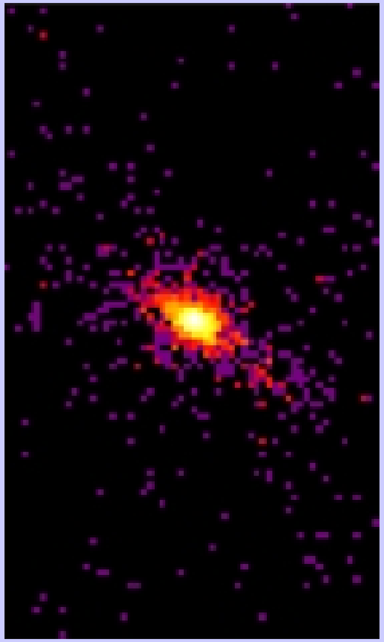
thanks to A. Cocco, A. Ereditato, G. Fiorillo, F. Iocco, G. Miele, V. Pettorino, G. Raffelt and P.D. Serpico for enjoying the subject together

Almost all our current knowledge of the universe comes from photons









However:

1. Dense regions are opaque to photons
2. Universe is optically thick on scales of few tens of Mpc for photons with energy larger than 10 TeV

GZK cut-off

$$\gamma + \gamma_{CMB} \Rightarrow e^+ + e^-$$

Charged particles:

1. Galactic magnetic fields make quite difficult to trace them back to the sources
2. GZK cut-off

$$p + \gamma_{CMB} \Rightarrow N + \pi$$

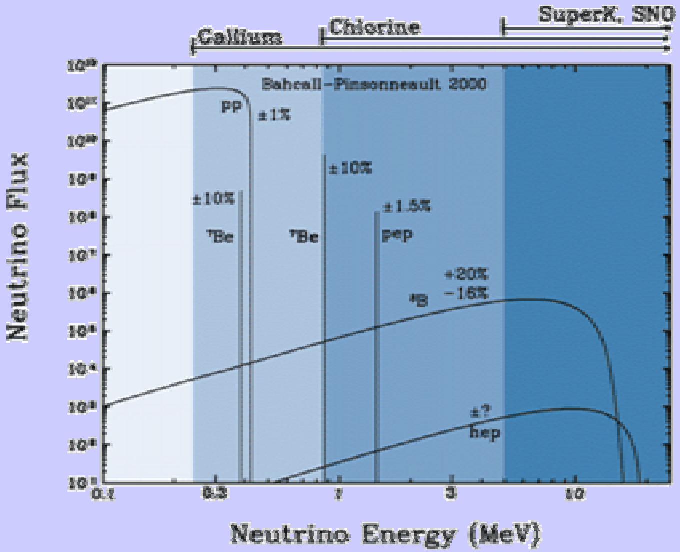
Proton mean free path is O(10) Mpc at 10^{20} eV

Neutrino astronomy

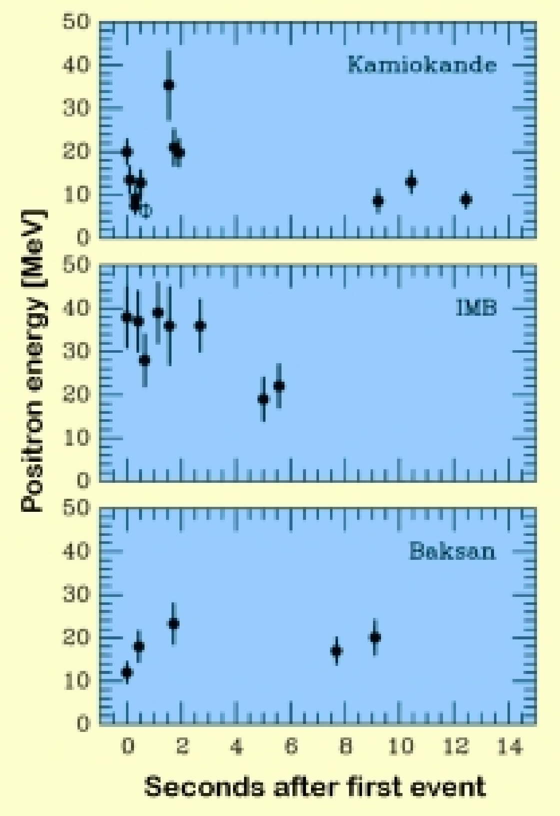
neutrinos are

- stable (or very long lived)
- electrically neutral
- weakly interacting

Only two well established observations:

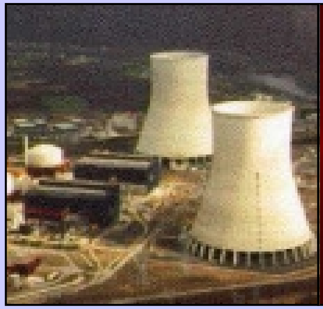


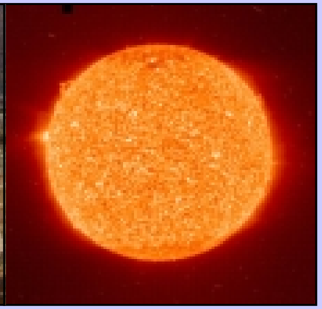
solar neutrinos



SN 1987A

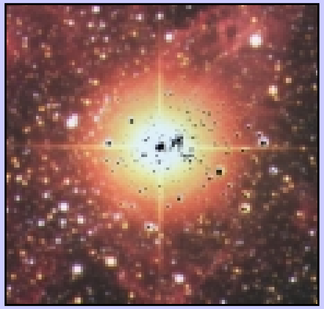
✓ Nuclear Reactors





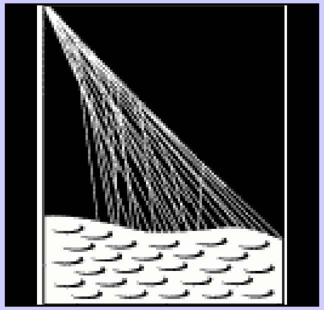
Sun ✓

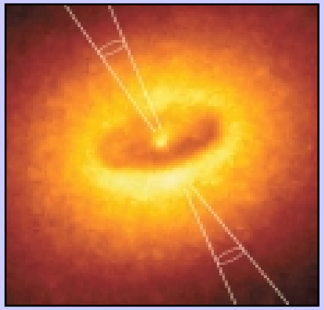
✓ Particle Accelerators



Supernovae
(Stellar Collapse)
SN 1987A ✓

✓ Earth Atmosphere
(Cosmic Rays)



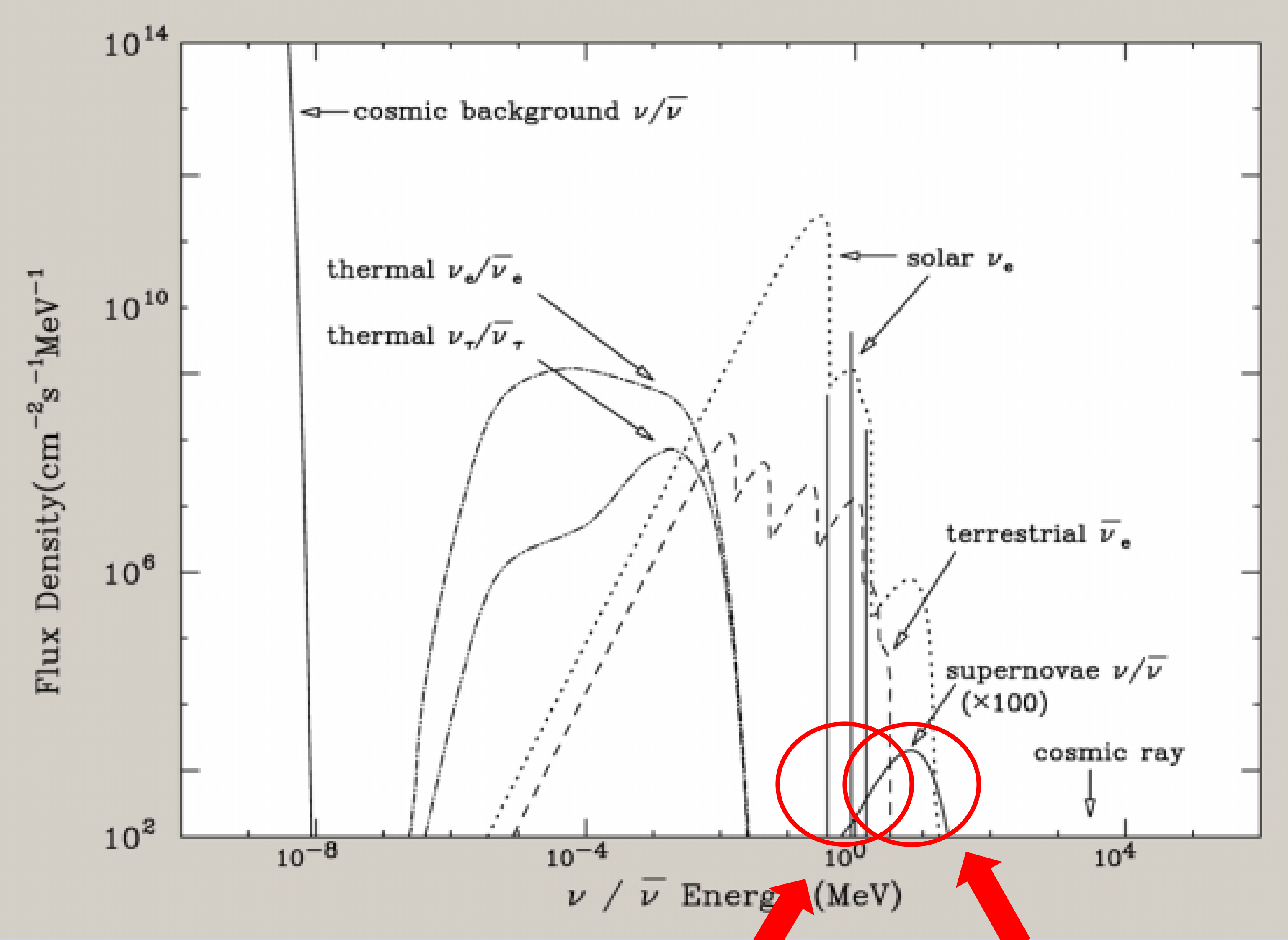


Astrophysical
Accelerators Soon ?

Earth Crust
(Natural
Radioactivity)
Soon ?

Cosmic Big Bang
(Today 330 ν/cm^3)
Indirect Evidence

From G. Raffelt



from Haxton and Lin

Thermonuclear neutrinos from ordinary stars and POP III star neutrinos

SNII relic neutrinos

Why study this low energy region?

pessimistic viewpoint: background for ongoing and future experiments (geoneutrinos, low energy atmospheric fluxes)

optimistic viewpoint:

What can we gain from observations of relic SN neutrino fluxes?

Can we probe unseen POPIII stars via their neutrino fluxes?

Neutrino fluxes from core-collapse SuperNovae

A nearby (d < 10-20 kpc) future SNII would be detected by its huge neutrino flux in several ongoing (SK, Kamland, LVD) and under construction (ICARUS) experiments

Information on:

Core-collapse mechanism

Neutrino oscillation physics

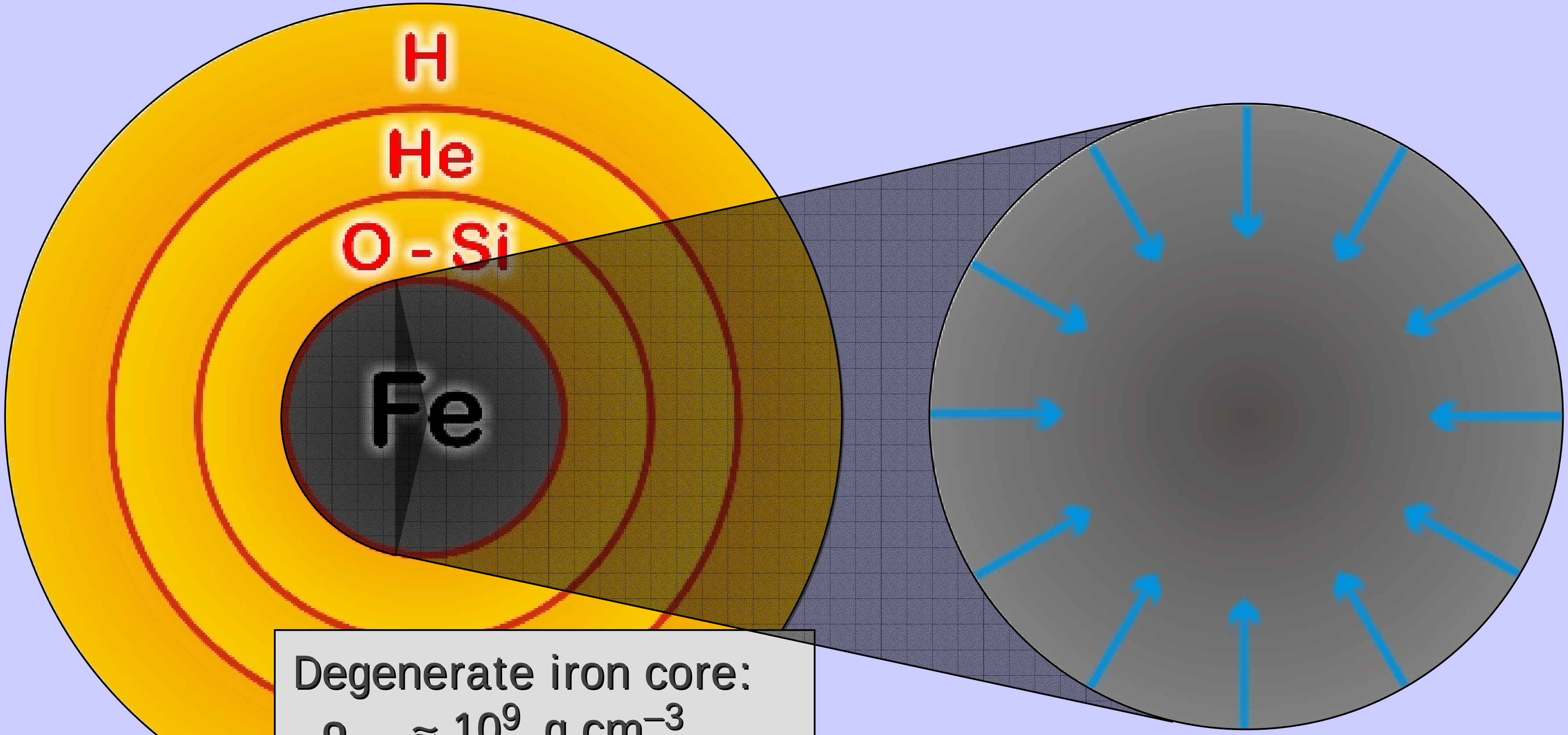
In the meantime……(rate is few in our galaxy per century)

Look at the homogeneous and isotropic neutrino flux from all past SN which have occurred in the last few redshifts

Basic picture

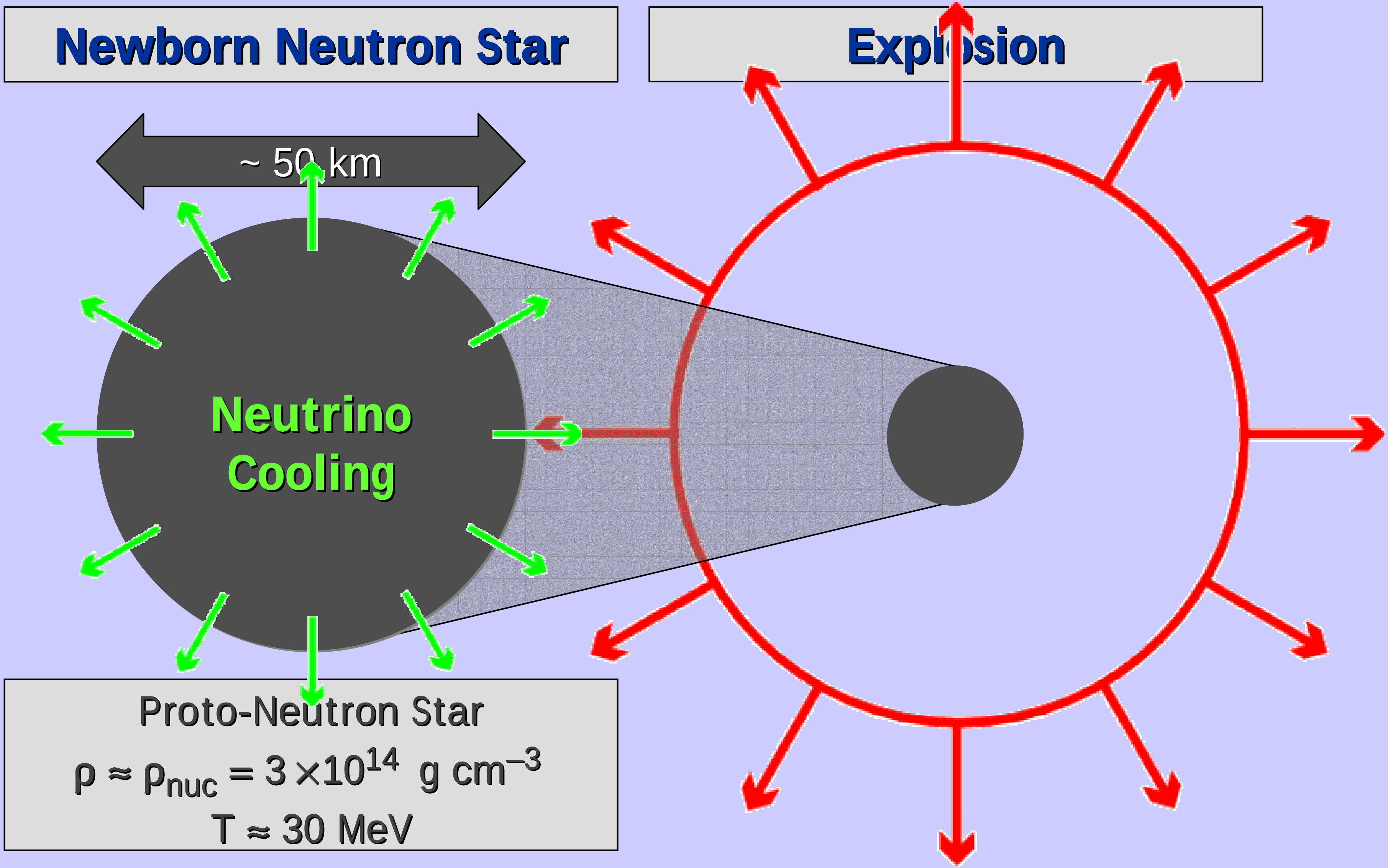
Onion structure

Collapse (implosion)



Degenerate iron core:

$\rho \approx 10^{9}\ \mathrm{g\ cm^{-3}}$
$T \approx 10^{10}\ \mathrm{K}$
$M_{Fe} \approx 1.5\ M_{sun}$
$R_{Fe} \approx 8000\ \mathrm{km}$



Newborn Neutron Star

Explosion

~ 50 km

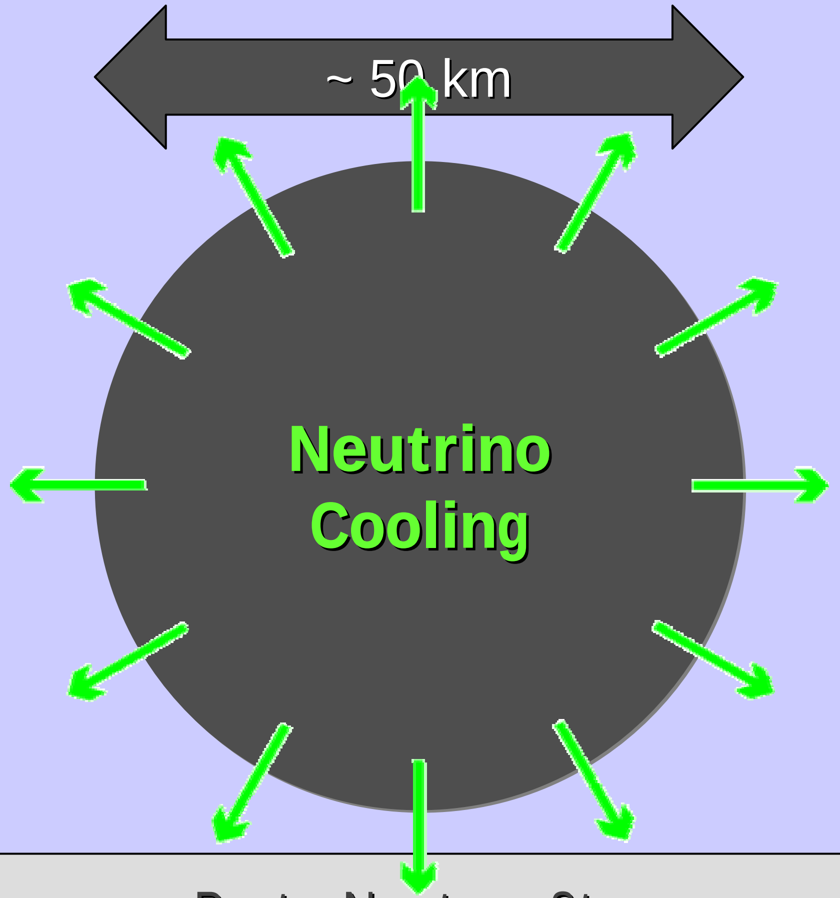
Neutrino Cooling

Proto-Neutron Star

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

$T \approx 30$ MeV

Newborn Neutron Star



Proto-Neutron Star

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

$T \approx 30\ \mathrm{MeV}$

Gravitational binding energy

$E_b \approx 3 \times 10^{53}\ \mathrm{erg} \approx 17\%\ M_{\mathrm{SUN}}\, c^2$

This shows up as

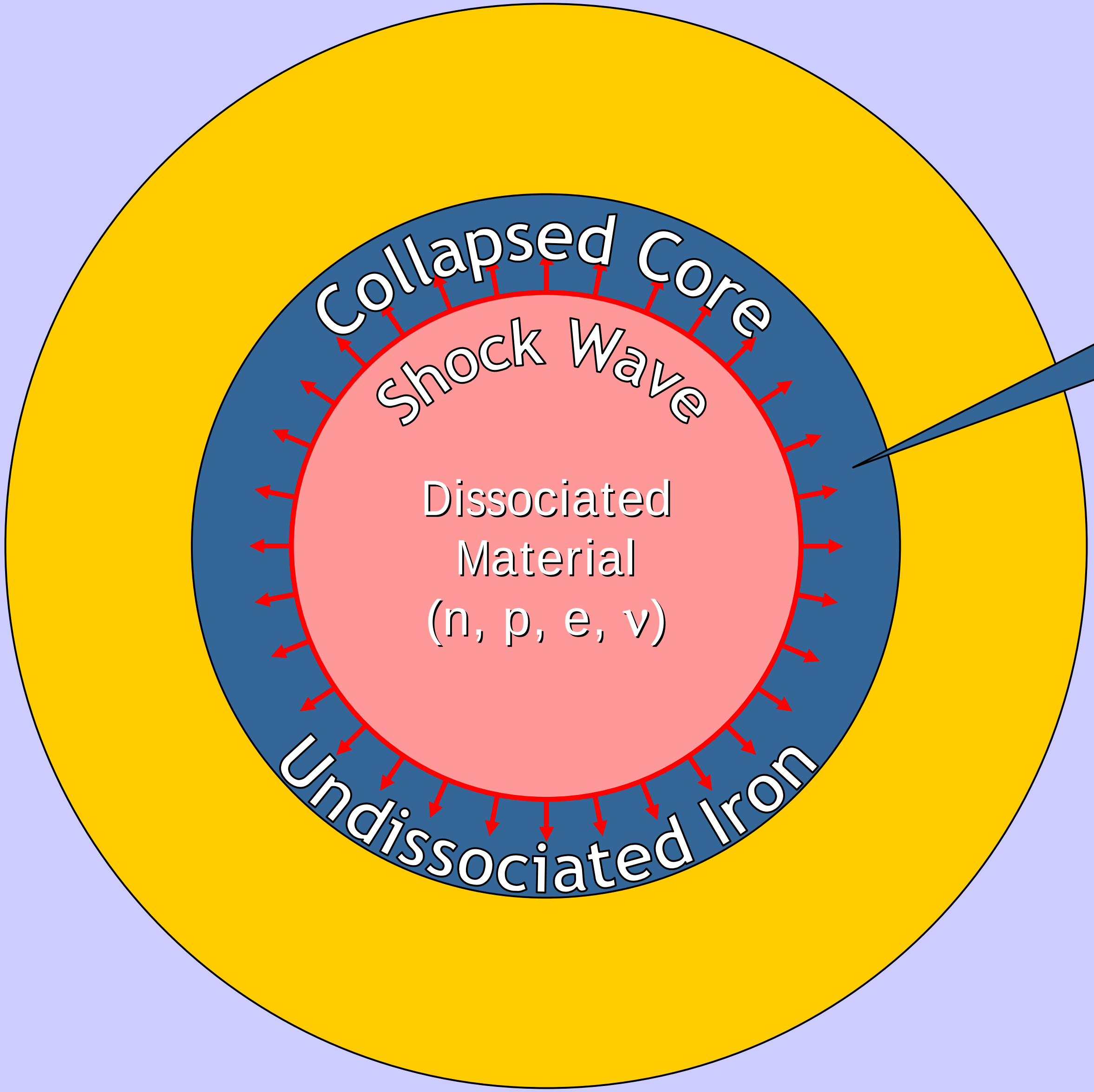
99%	Neutrinos
1%	Kinetic energy of explosion (1% of this into cosmic rays)
0.01%	Photons, outshine host galaxy

Neutrino luminosity

$$L_\nu \approx 3 \times 10^{53}\ \mathrm{erg}\ /\ 3\ \mathrm{sec}$$
$$\approx 3 \times 10^{19}\ L_{\mathrm{SUN}}$$

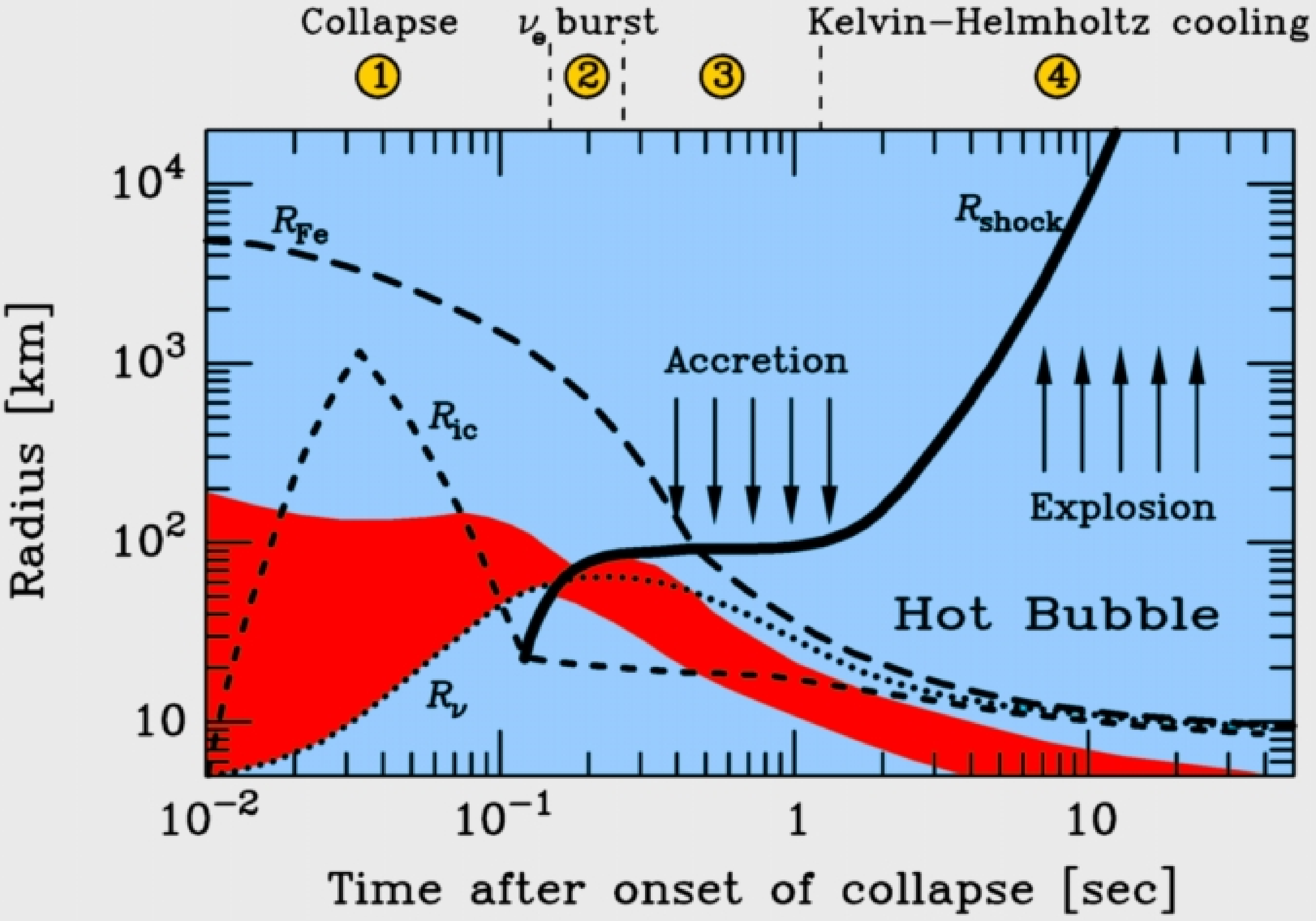
While it lasts, outshines the entire visible universe

PROMPT EXPLOSION DOES NOT WORK

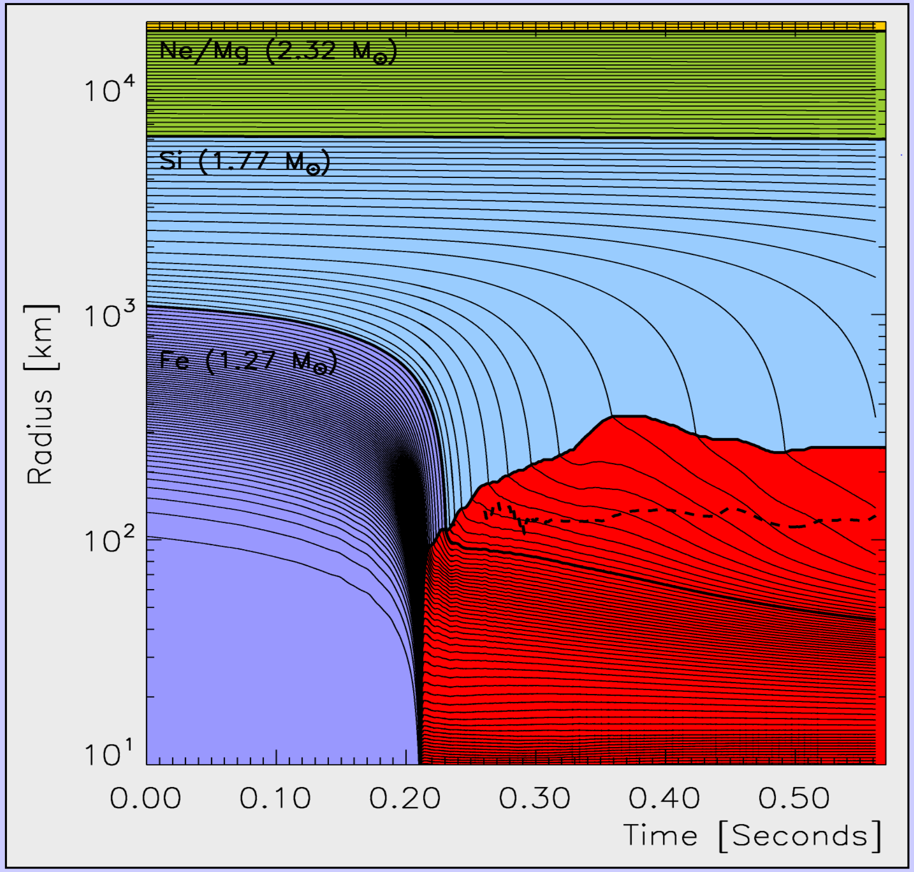


- 0.1 M_{sun} of iron has a nuclear binding energy $\approx 1.7 \times 10^{51}$ erg
- Comparable to explosion energy

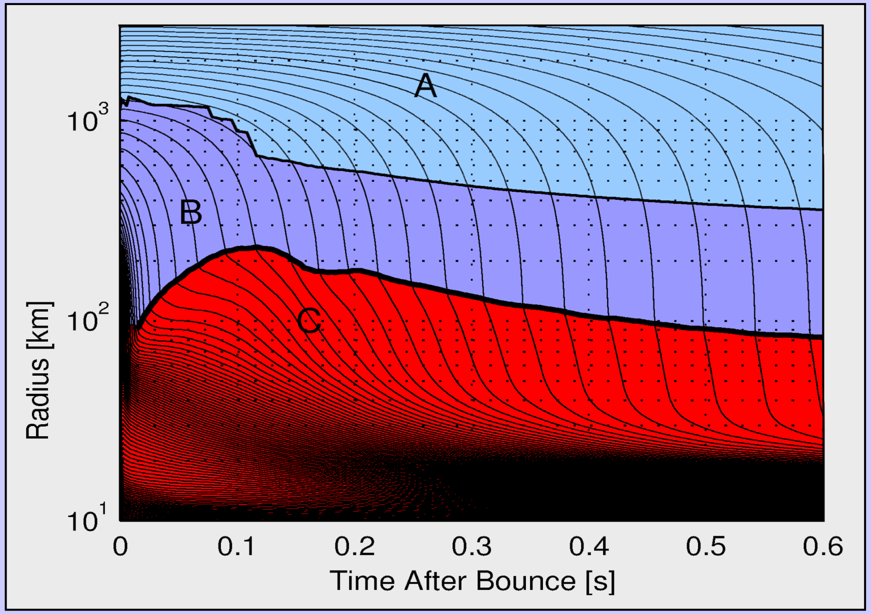
- Shock wave forms within the iron core
- Dissipates its energy by dissociating the remaining layer of iron


Collapse
ν_e burst
Kelvin–Helmholtz cooling
①
②
③
④
Radius [km]
10^4
10^3
10^2
10
10^{-2}
10^{-1}
1
10
Time after onset of collapse [sec]
$R_{\rm Fe}$
$R_{\rm ic}$
R_ν
$R_{\rm shock}$
Accretion
Explosion
Hot Bubble

1-D SPHERICAL SIMULATIONS DO NOT WORK

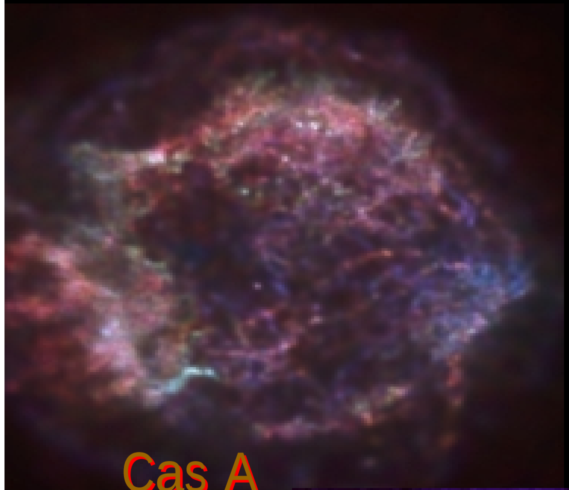


Rampp and Janka ApJ 2000



Mezzacappa et al PRL 2001

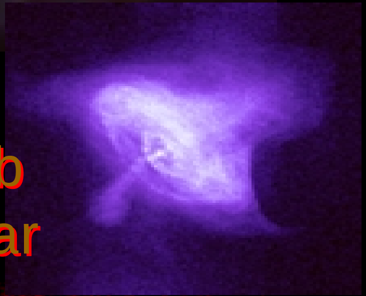
Spherical Symmetry in Astrophysics



Cas A

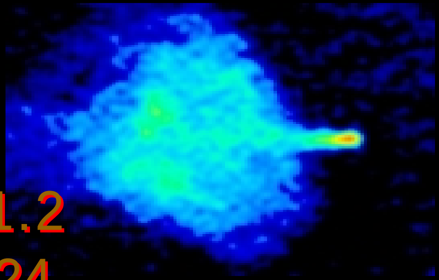
Eta Carinae

Crab Nebula

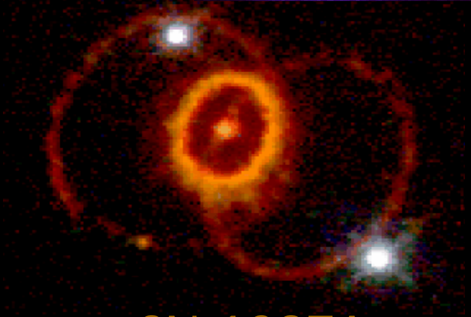


Crab Pulsar

Convection in SN simulations

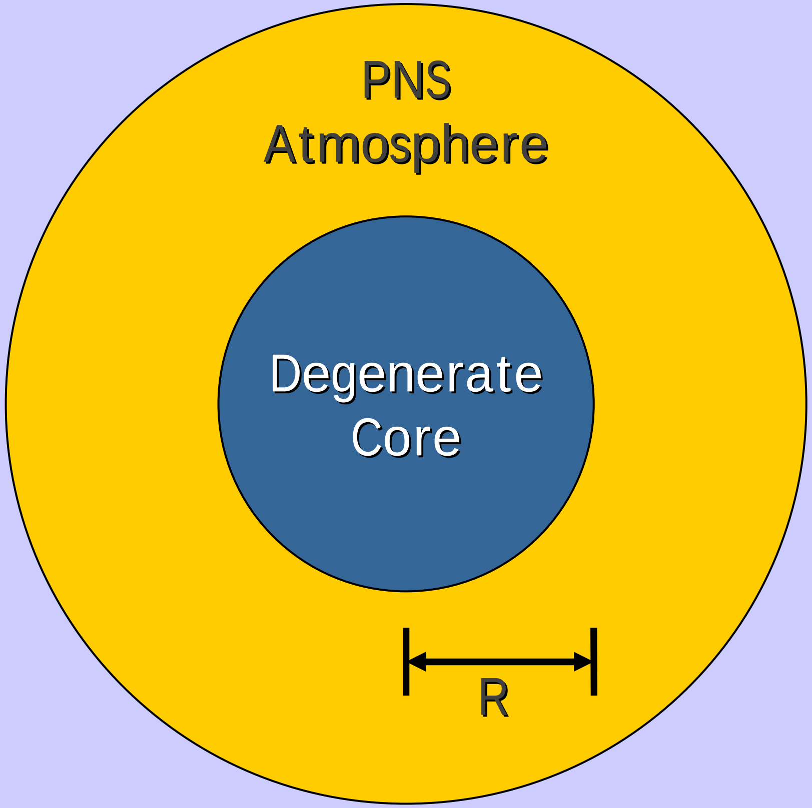


SNR G5.4-1.2
PSR 1757-24



SN 1987A

Neutrino flux from SNII



Gravitational potential of a given nucleon

$\Phi = -G_N M_{PNS} m_N R^{-1}$

With $M_{PNS} \approx 1.5\, M_{sun}$ and $R \approx 30$ km

$\Phi \approx -27$ MeV

Virial theorem (hydrostatic equilibrium) assuming nondegenerate conditions,

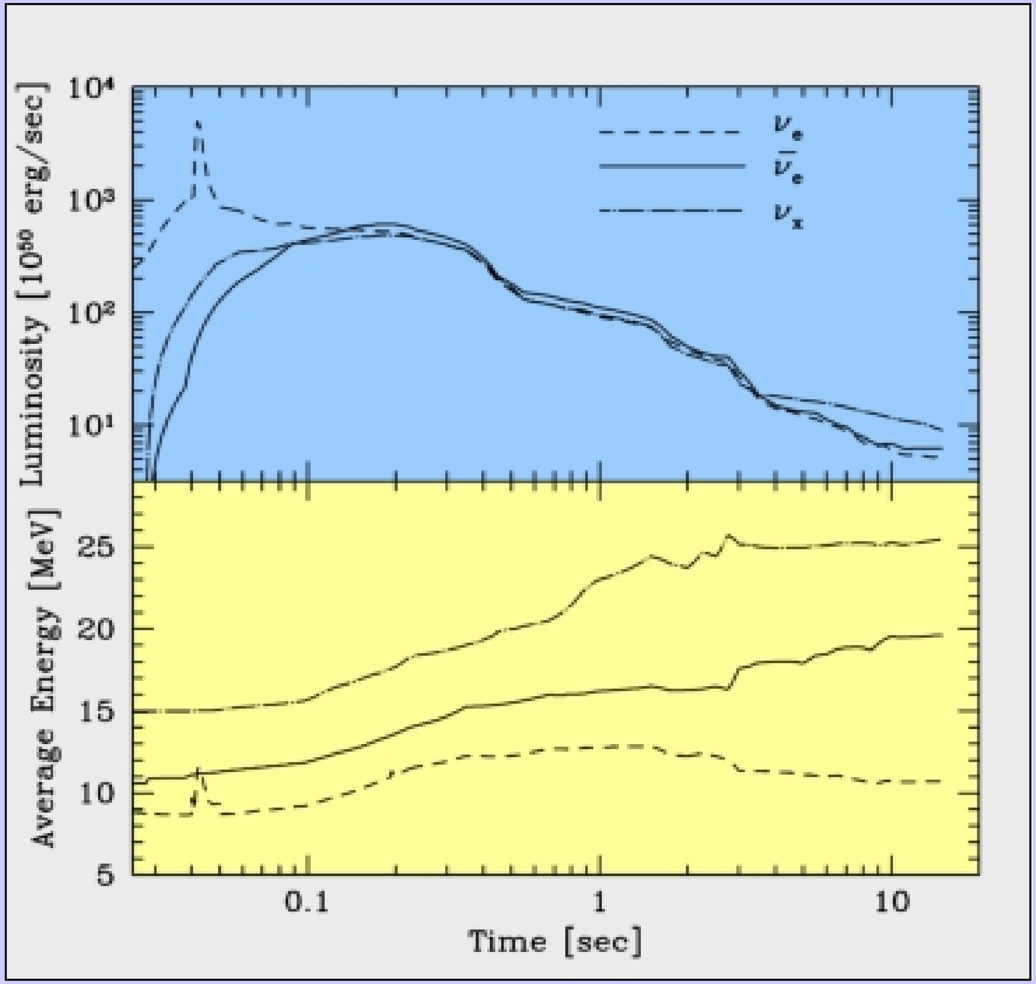
$\langle E_{kin} \rangle = -\frac{1}{2} \langle \Phi \rangle \approx 13$ MeV

Thermal equilibrium

$T = (2/3) \langle E_{kin} \rangle \approx 9$ MeV

Main neutrino reactions	**Electron flavor** $\nu_e + n \to p + e^-$ $\bar{\nu}_e + p \to n + e^+$ **Other flavors** $\nu_e + N \to N + \nu$
Neutral-current scattering cross section	$\sigma(\nu N \to N\nu) = \frac{C_V^2 + 3C_A^2}{\pi} G_F^2 E_\nu^2 \approx 2\times 10^{-40}\,\mathrm{cm}^2 \left(\frac{E_\nu}{100\ \mathrm{MeV}}\right)^2$
Nucleon density	$n_B = \frac{\rho_{\mathrm{nuc}}}{m_N} \approx 1.8\times 10^{38}\,\mathrm{cm}^{-3}$
Scattering rate	$\Gamma = \sigma n_B \approx 1.1\times 10^9\,\mathrm{s}^{-1} \left(\frac{E_\nu}{100\ \mathrm{MeV}}\right)^2$
Mean free path	$\lambda = (\sigma n_B)^{-1} \approx 28\,\mathrm{cm} \left(\frac{100\ \mathrm{MeV}}{E_\nu}\right)^2$
Diffusion time	$t_{\mathrm{diff}} \approx \frac{R^2}{\lambda} \approx 1.2\,\mathrm{sec} \left(\frac{R}{10\,\mathrm{km}}\right)^2 \left(\frac{E_\nu}{100\ \mathrm{MeV}}\right)^2$

Neutrino luminosities



Livermore group
ApJ 496, 1998

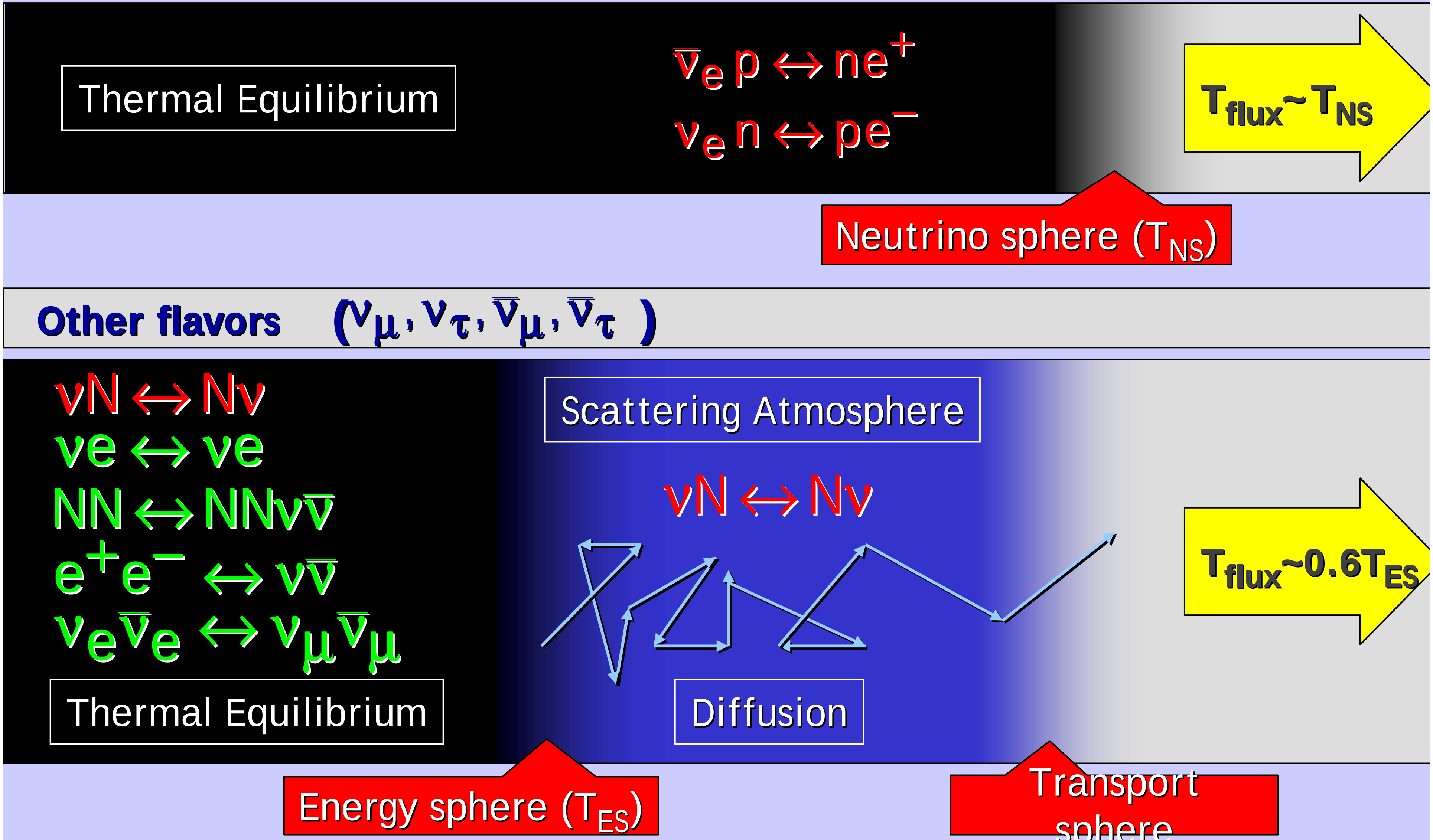
$\boldsymbol{\nu}_{\mu,\tau}$, $\bar{\boldsymbol{\nu}}_{\mu,\tau}$

$\bar{\boldsymbol{\nu}}_{\mathbf{e}}$

$\boldsymbol{\nu}_{\mathbf{e}}$

$\langle E_{\mu,\tau} \rangle > \langle E_{\bar{e}} \rangle > \langle E_e \rangle$

How neutrino spectra form



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

Thermal Equilibrium

$\bar{\nu}_e p \leftrightarrow n e^+$

$\nu_e n \leftrightarrow p e^-$

$T_{flux} \sim T_{NS}$

Neutrino sphere (T_{NS})

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

$\nu N \leftrightarrow N \nu$

$\nu e \leftrightarrow \nu e$

$NN \leftrightarrow NN\nu\bar{\nu}$

$e^+e^- \leftrightarrow \nu\bar{\nu}$

$\nu_e \bar{\nu}_e \leftrightarrow \nu_\mu \bar{\nu}_\mu$

Thermal Equilibrium

Scattering Atmosphere

$\nu N \leftrightarrow N \nu$

Diffusion

$T_{flux} \sim 0.6 T_{ES}$

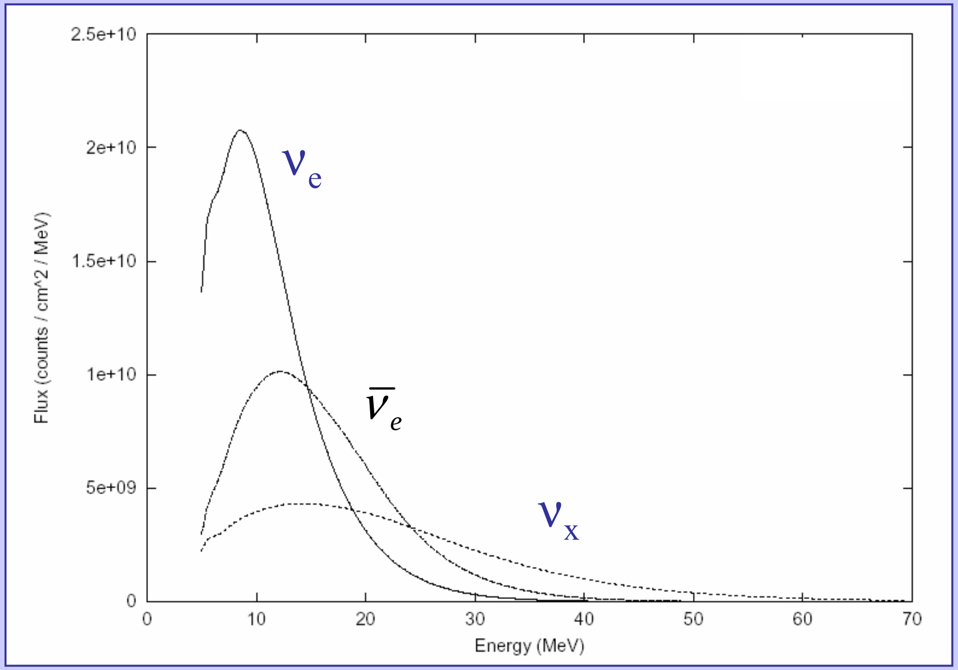
Energy sphere (T_{ES})

Transport sphere

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

Neutrino spectra

Well approximated by a black-body spectrum



$N_{tot} \sim 10^{57}$

$$N_x = \frac{E_{tot}}{6 < E_x >}$$

Supernova Relic Neutrinos

SNs II (3±1 SN/century)

But… explosions started shortly after star formation.
What about neutrinos emitted in the past explosions?

Supernova Relic Neutrinos (SRN)

A diffuse background of neutrinos emitted from all past supernovae. Contribution from each SN is minimal, so SRN are thought to be an isotropic background.

SRN energy scales with the redshift of the Supernova

$$\frac{E_{detect}}{E_{emit}} = \frac{1}{1+z}$$

SRN flux

SRN (N/E/L^2/t)

$$\frac{dF(E)}{dE} = c\int_0^{z_{\max}} R_{SN}(z)\left.\frac{dN(E')}{dE'}\right|_{E'=E(1+z)}(1+z)\left|\frac{dt}{dz}\right|dz$$

Supernova rate (N/t/L^3)

Neutrinos flux N/E (with oscillations)

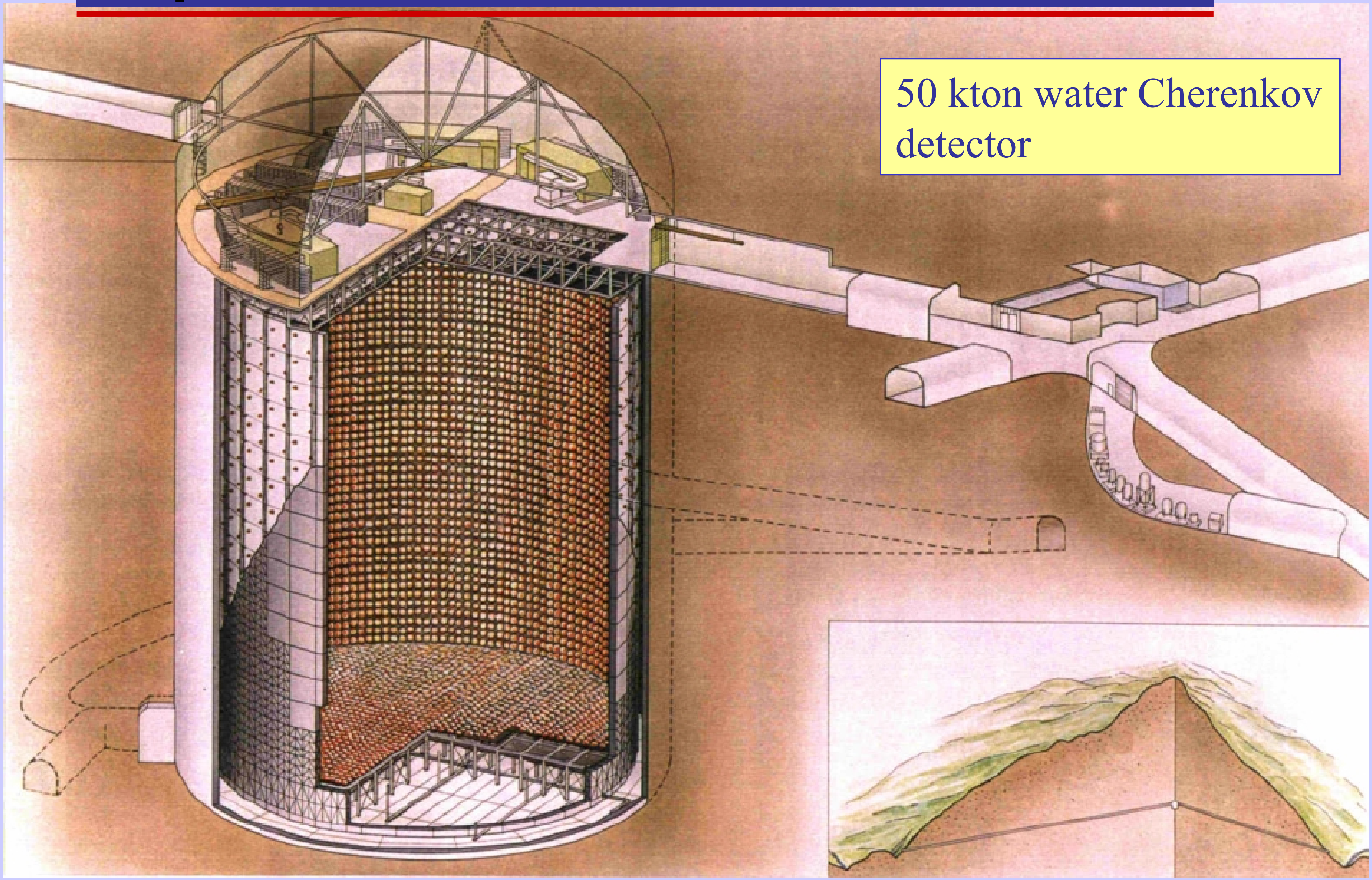
1/H(z)

SRN rate (N/t)

$$R(E_1 < E < E_2) = N_b \int_{E_1}^{E_2} \sigma(E)\frac{dF(E)}{dE}dE$$

Look for an energy window not hidden by background

Super-Kamiokande



50 kton water Cherenkov detector

Super-Kamiokande: background for SRN

Sk looks for SRN (via inv. β: $\overline{\nu}_e + p \rightarrow e^+ + n$)

Matthew S. Malek
February 10th , 2003

Spallation μ from cosmic rays:
cut for E < 18 MeV $\mu + O \rightarrow \mu + X^*$

SK coll. hep-ph/02126067; Phys.Rev.Letts 90-6

β, γ decay, as high as 20.8 MeV (600/day) indistinguishable from a SRN $\overline{\nu}_e$ event

Cut all events for t < 0.15 s after a cosmic ray

Atmospheric ν_e $\overline{\nu}_e$
(low energy)

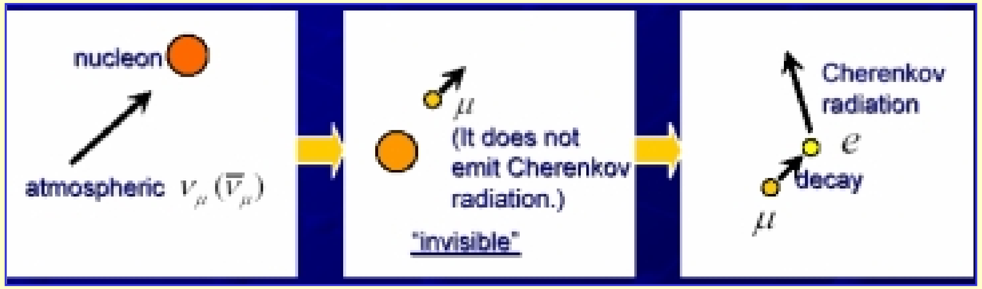
Subtracted (Fukuda 1998, Barr 1989)

Atmospheric ν_μ

$\nu_\mu + X \rightarrow \mu^- + X'$

High energy muons

Removed either from decay e^{+-} reconstruction (sub-event cut) or by Cherenkov angle cut (reject events with $\theta_C < 38^o$)



Super-Kamiokande: background (2)

Solar events

4.9±2.7 events.

Detected from Sk via elastic scattering

$\nu_e + e \rightarrow \nu_e + e$

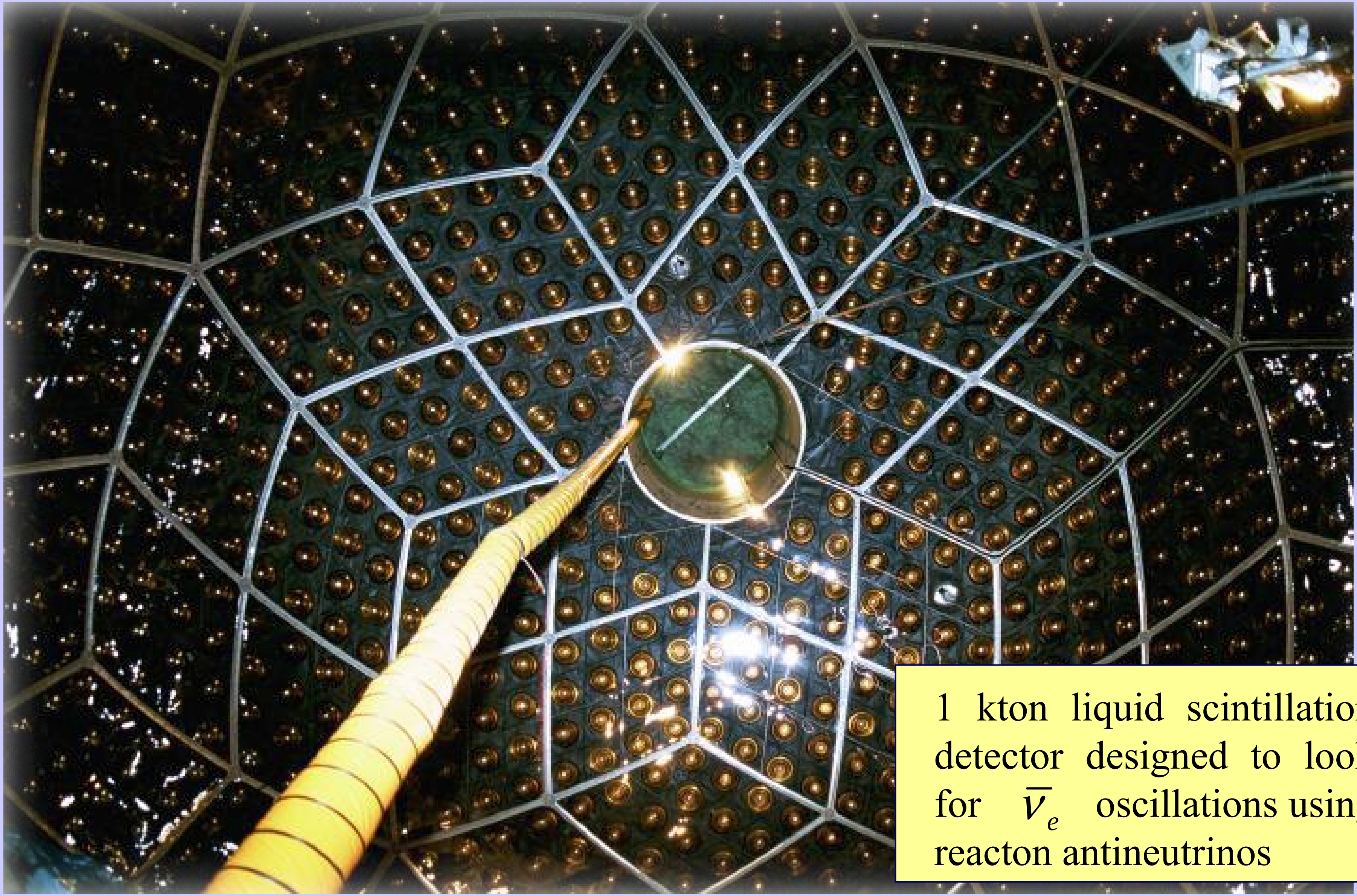
Subtracted by directionality

Rate = $(1.1 < R < 3.6)\bar{\nu}_e yr^{-1}$

$R < 1.2 cm^{-2} s^{-1}$ at 90% C.L. for E > 19.3 MeV

The limit is about 3-6 times larger than typical theoretical expected SRN fluxes. 9 years for 1 sigma!

Kamland



1 kton liquid scintillation detector designed to look for $\bar{\nu}_e$ oscillations using reacton antineutrinos

Kamland

SRN search through $\bar{\nu}_e + p \to n + e^+$ $(10 < E < 25) MeV$

Rate: $(0.1 < R < 0.4) \bar{\nu}_e yr^{-1}$ E > 6 MeV

$\bar{\nu}_e$ from Earth	(cut for E < 2.6 MeV)
atmospheric $\bar{\nu}_e$ (low energy)	E > 6 MeV Compete with SRN for E > 25MeV
$\bar{\nu}_e$ from reactors	Negligible for E > 6 MeV
$\nu_{\mu(atm)} \to \mu ... \to e^{\pm} ...$	Kamland rejects e^+, e^- that are not followed by neutron capture (unlike SRN $\bar{\nu}_e + p \to n + e^+$)

few years for 1 sigma!

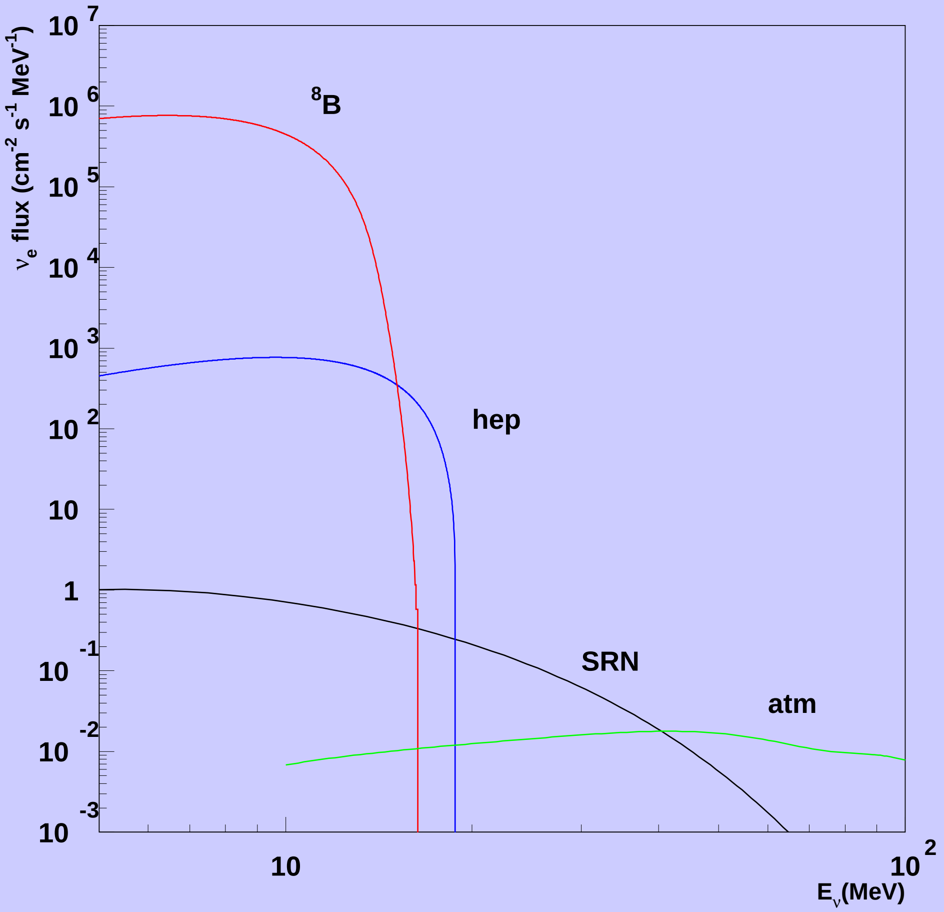
ICARUS

3 kton liquid Argon detector

Background

Solar neutrinos

Atmospheric neutrinos



Reactions and cross sections

- Elastic scattering

$$\nu_{e,x} e^- \rightarrow \nu_{e,x} e^-$$

$$\overline{\nu}_{e,x} e^- \rightarrow \overline{\nu}_{e,x} e^-$$

$$\sigma_{\nu_e e^- \rightarrow \nu_e e^-}(E_{\nu_e}) = 0.92\times10^{-44} E_{\nu_e}(MeV) cm^2$$

$$\sigma_{\overline{\nu}_e e^- \rightarrow \overline{\nu}_e e^-}(E_{\overline{\nu}_e}) = 0.383\times10^{-44} E_{\overline{\nu}_e}(MeV) cm^2$$

$$\sigma_{\nu_x e^- \rightarrow \nu_x e^-}(E_{\nu_x}) = 0.157\times10^{-44} E_{\nu_x}(MeV) cm^2$$

$$\sigma_{\overline{\nu}_x e^- \rightarrow \overline{\nu}_x e^-}(E_{\overline{\nu}_x}) = 0.129\times10^{-44} E_{\overline{\nu}_x}(MeV) cm^2$$

- Neutral current on Argon

$$\nu_{e,x}\, {}^{40}Ar \rightarrow \nu_{e,x}\, {}^{40}Ar^* \rightsquigarrow \gamma$$

- Charged current on Argon

$$\nu_e\, {}^{40}\mathrm{Ar} \rightarrow e^-\, {}^{40}\mathrm{K}^*$$

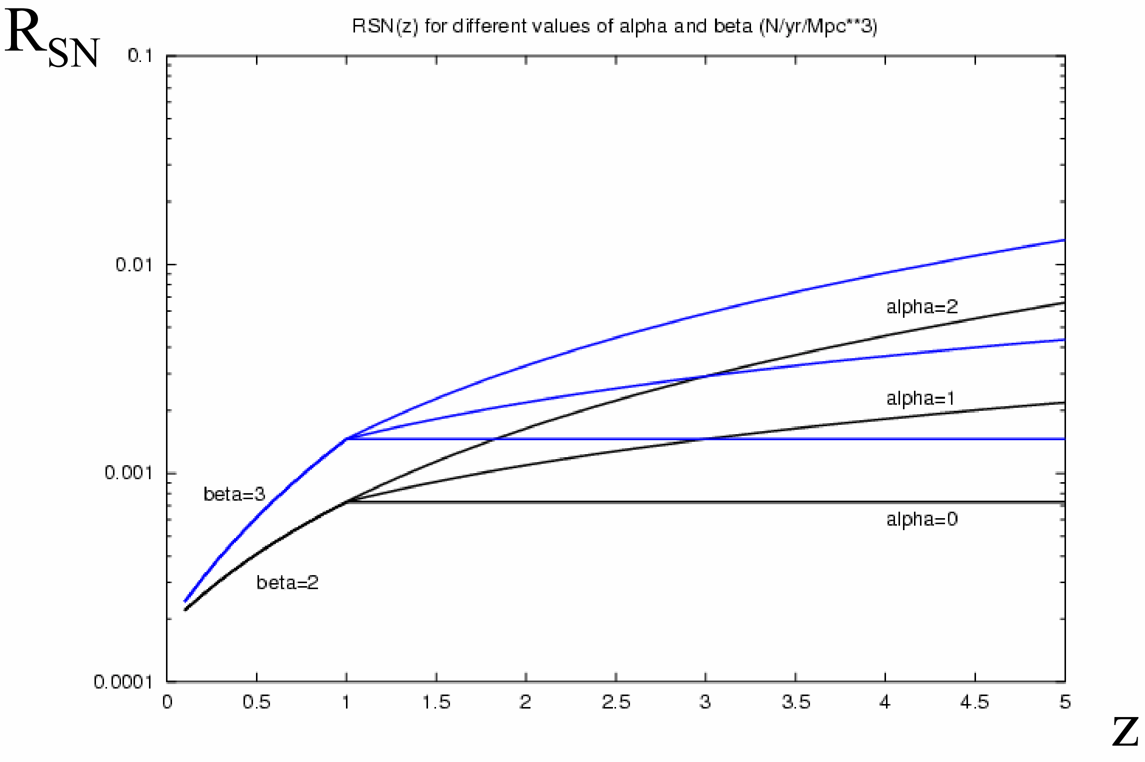
$$\overline{\nu}_e\, {}^{40}\mathrm{Ar} \rightarrow e^+\, {}^{40}\mathrm{Cl}^*$$

$$\rightsquigarrow \gamma$$

What SRN detection can do for astrophysicist: star formation rate at moderately high redshifts

$$R_{SN} = \begin{cases} \rho_0 (1+z)^{\beta} & z<1 \\ \rho_0 2^{\beta-\alpha} (1+z)^{\alpha} & z>1 \end{cases}$$

RSN parametrization from Strigari et al. ‘03



The behaviour at high z is not well established; it gives contribution to low energy neutrinos

Correction for neutrinos oscillations

The flux we observe is different from the original emitted flux due to oscillations inside the supernova

Corrected using analytical expression of p

$$\phi_{\nu_e} = p\phi^0{}_{\nu_e} + (1-p)\phi^0{}_{\nu_x}$$

$$\phi_{\nu_x} = (1-p)\phi^0{}_{\nu_e} + p\phi^0{}_{\nu_x}$$

$$\phi_{\overline{\nu}_e} = \overline{p}\phi^0{}_{\overline{\nu}_e} + (1-\overline{p})\phi^0{}_{\overline{\nu}_x}$$

$$\phi_{\overline{\nu}_x} = (1-\overline{p})\phi^0{}_{\overline{\nu}_e} + \overline{p}\phi^0{}_{\overline{\nu}_x}$$

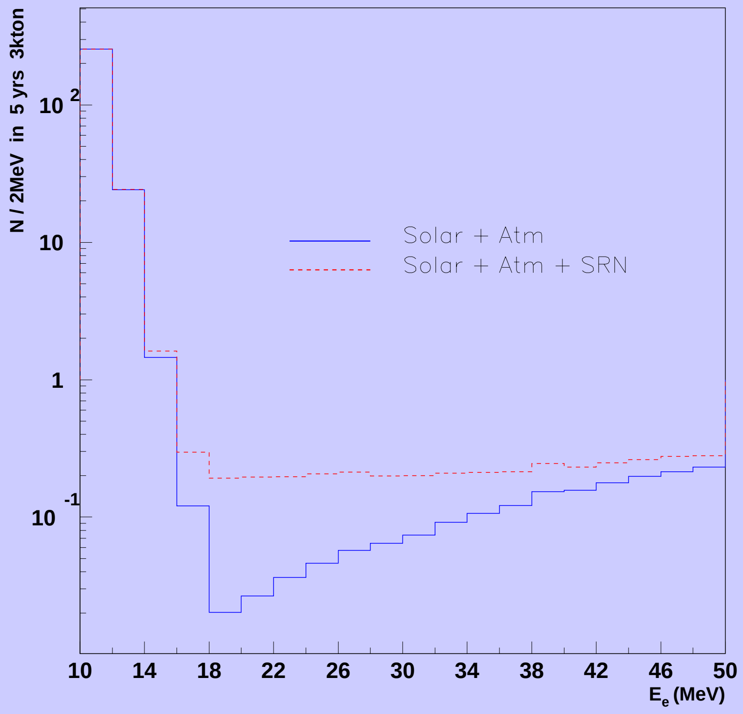
	p	$\overline{\text{p}}$
normal v mass hierarchy $\theta_{13} > 10^{-3}$	0	$\cos^2\theta_{12}$
inverted v mass hierarchy $\theta_{13} > 10^{-3}$	$\sin^2\theta_{12}$	0
any v mass hierachy $\theta_{13} < 10^{-3}$	$\sin^2\theta_{12}$	$\cos^2\theta_{12}$

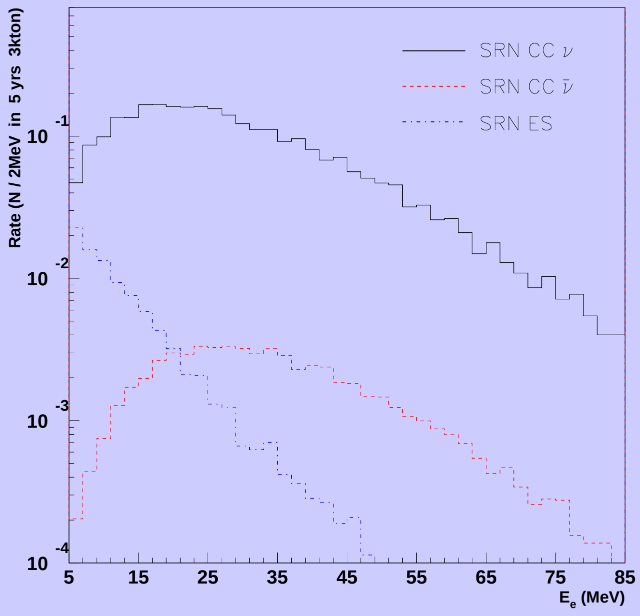
Hardly distinguishable by SRN detection!

Results for ICARUS T3000

A. Cocco et al JCAP 2004

Almost completely due to electron neutrinos





Complementary with respect to SK!

Present bound from Mont Blanc experiment:

$\Phi_{\nu e} < 6.8\ 10^{3}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$ (25 < E/MeV<50)

Expected rate:

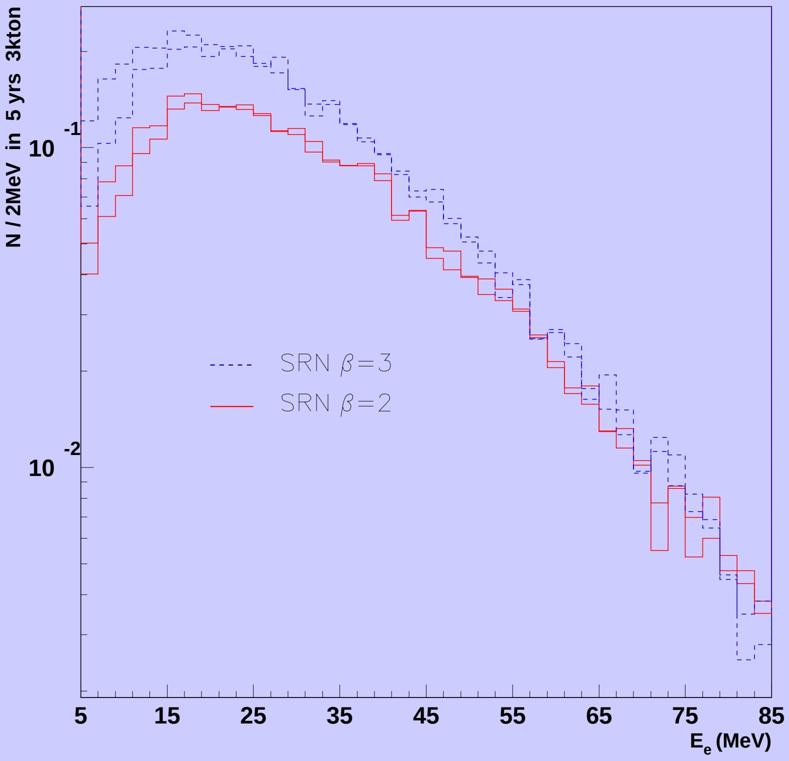
T3000: 1.7 signal vs 0.9 background (16 <E/MeV< 40)

or $\Phi_{ve} < 1.6$ cm^{-2} s^{-1} (16 < E/MeV<40) for no detection

More than 3 orders of magnitude better than Mont Blanc result

100kton: 57 signal vs 12 background (16 <E/MeV< 40)

Using SK, Kamland and ICARUS SRN detection: possible improved bound on star formation rate



Apart from relic neutrinos ($z = 10^9$), other cosmological (i.e. isotropic and homogeneous) neutrino sources at higher redshifts?

Higher z ⟺ lower energy range !

Neutrino fluxes from POPIII stars

POP III stars:

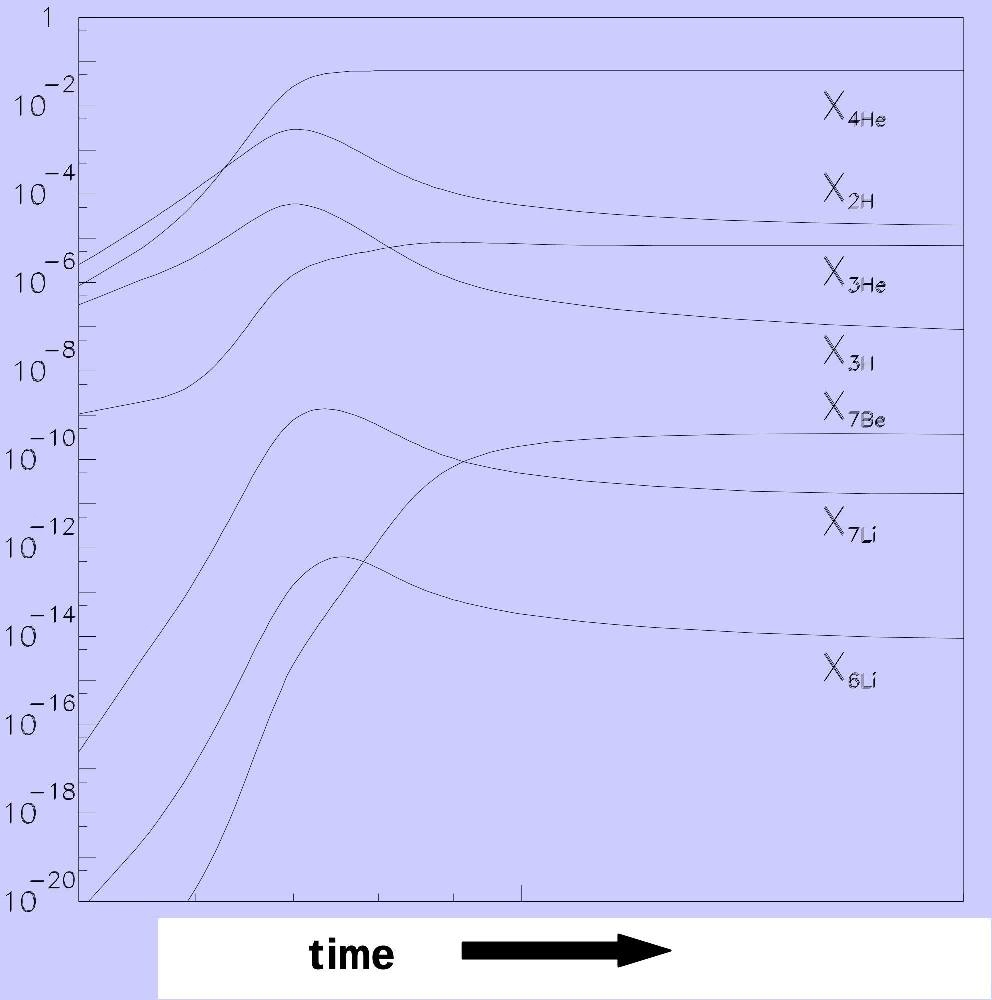
first generation of stars which formed from the pristine material left by Big Bang Nucleosynthesis

75% Hydrogen, 25% ^{4}He in mass

Why POPIII stars:

1) no evidence of stars with zero “metallicity”
2) source of reionization from WMAP data on polarization of Cosmic Microwave Background (CMB)
3) Lyman alpha carbon abundances of $10^{-3.7}$ solar metallicity observed at z=5

At early stages of evolution light nuclei formed via fusion processes (three “minutes” after the Bang)



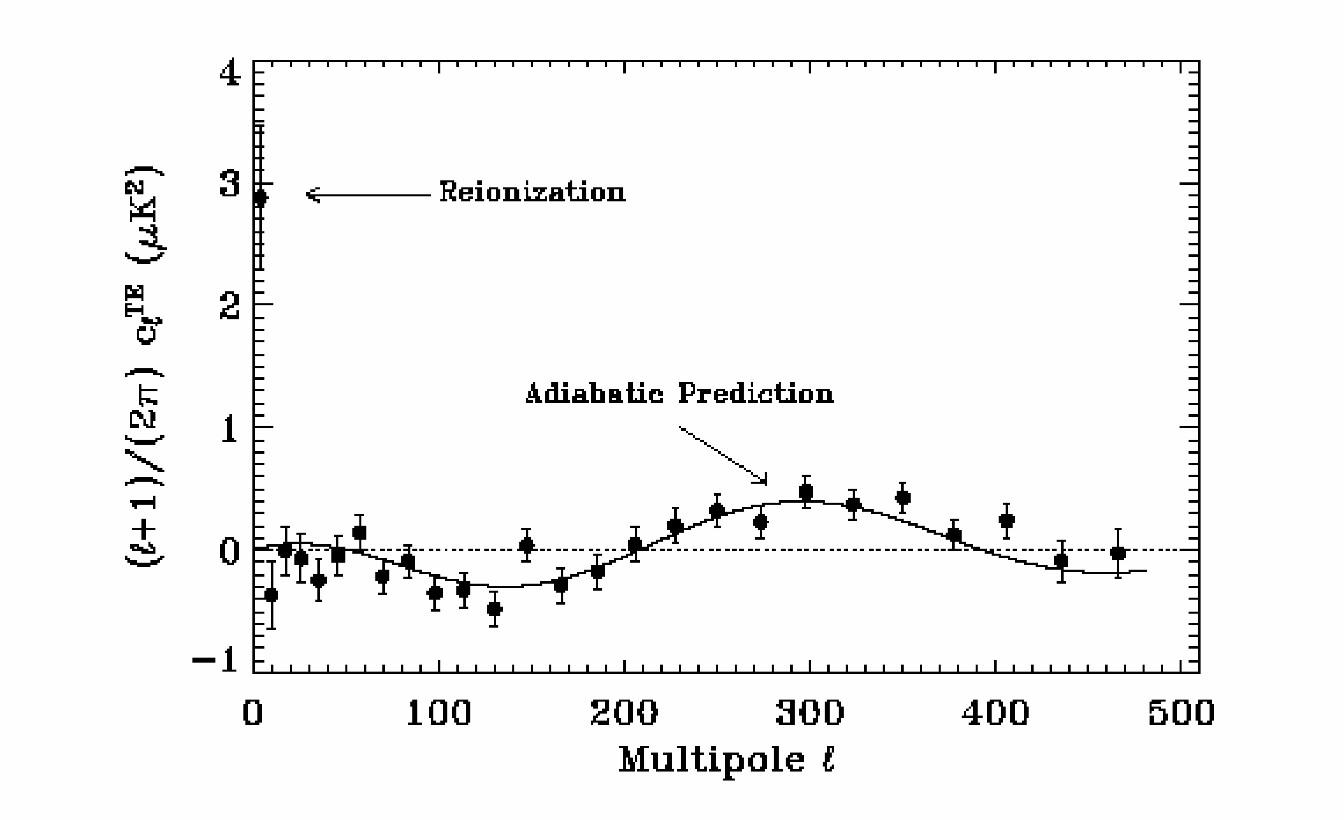
25 % mass

Tiny percentage

NO C,N,O

Why we don’t see stars with primordial mass composition?

Hint from polarization measurements in CMB spectrum of early re-ionizing sources at very high redshit, z =20 ±10



What is responsible for the early ionizing event? A first pregalactic generation of stars?

POPIII star modelling:

Gravitational instability after recombination

$$M_J = 6\times10^4 \left(\frac{1+z}{30}\right)^{-3/2} \left(\frac{T}{500K}\right)^{3/2} \Omega_b M_\Theta$$

Collapse provided cooling time is shorter than expansion time

First objects with 10^6 solar masses can form at high redshifts ($z \approx 20 - 30$) (Tegmark et al 1997)

Metal free molecular clouds collapse and loose energy via deexcitation of vibrational and rotational levels of H_2 molecules ($T_{gas} < 8000$ K)

Fragmentation leads to very massive (100-300 $M_\odot$) stars but the initial mass function (IMF) very uncertain.

Very short lived (10^6 yrs) due to very efficient burning

up to 1% of the total baryonic mass can form these massive objects

CNO material produced via nuclear burning and then released to the environment via mass losses or “hypernova” explosions

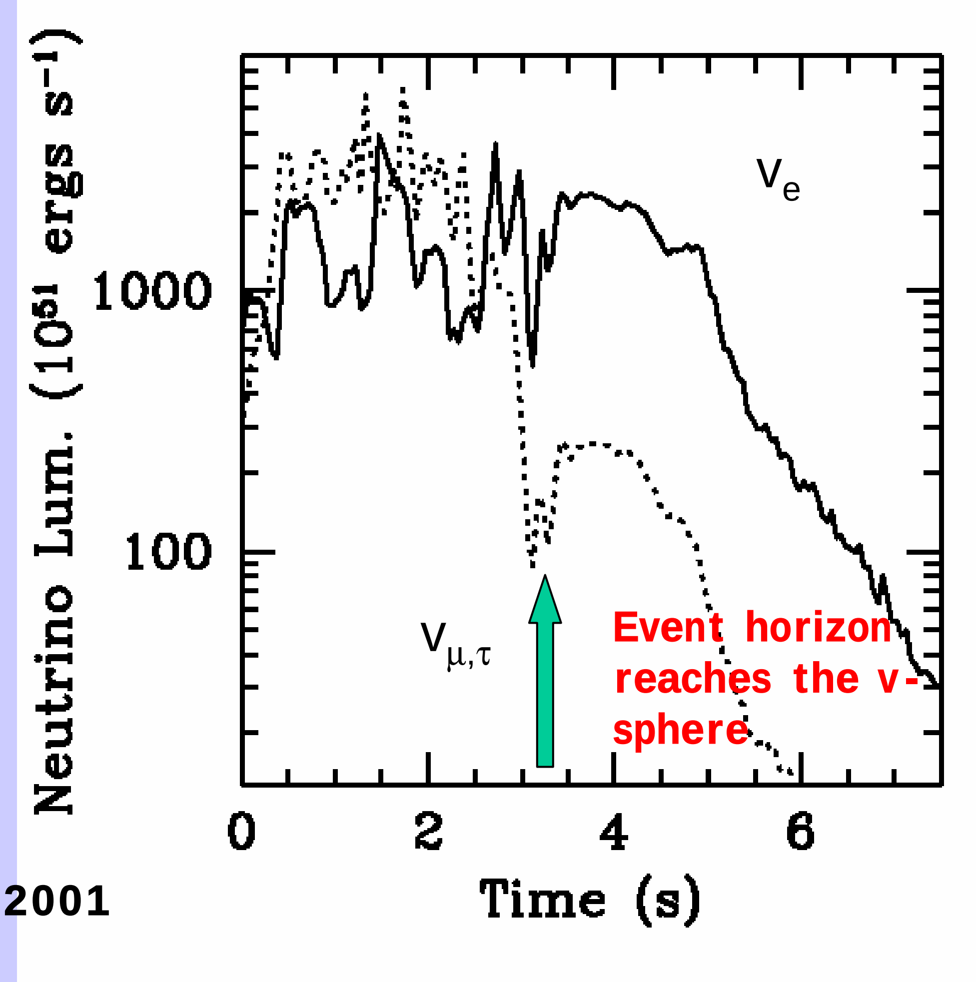
Can we probe POPIII stars via their neutrino emissions?

Three mechanisms:

1. Thermonuclear neutrinos, produced during H and advanced burning stages
2. Pair annihilation

$$e^{+}e^{-} \rightarrow \nu\bar{\nu}$$

3. Core collapse leading to black hole formation. Numerical simulations suggest a huge ν luminosity



300 solar mass

Fryer, Woosley, Heger; ApJ 550, 2001

Order of magnitude estimate (Iocco et al 2004):

A fraction $f=10^{-3}$ of the total baryonic matter forms POPIII stars with $M_* \sim 300\ M_\odot$

Flux:

$$\frac{dF}{dE} = c\ f\ n_\gamma \frac{m_N}{M_*} \int_{zf}^{zi} dz \rho(z)(1+z) \frac{dN(E(1+z))}{dE}$$

$n_\gamma = 410\ \mathrm{cm}^{-3}$ present photon density

$\rho(z)$ normalized star formation rate per unit redshift

dN/dE = neutrino spectrum at emission

Thermonuclear neutrinos

Initial mass composition 75% H and 25% ^{4}He

From the value of ^{4}He core mass after numerical simulation we read that almost 20-30% of the initial stellar mass is converted into helium

$N_\nu \sim 0.1\ M_*/M_N = 10^{56}\ M_*/\ M_\odot$

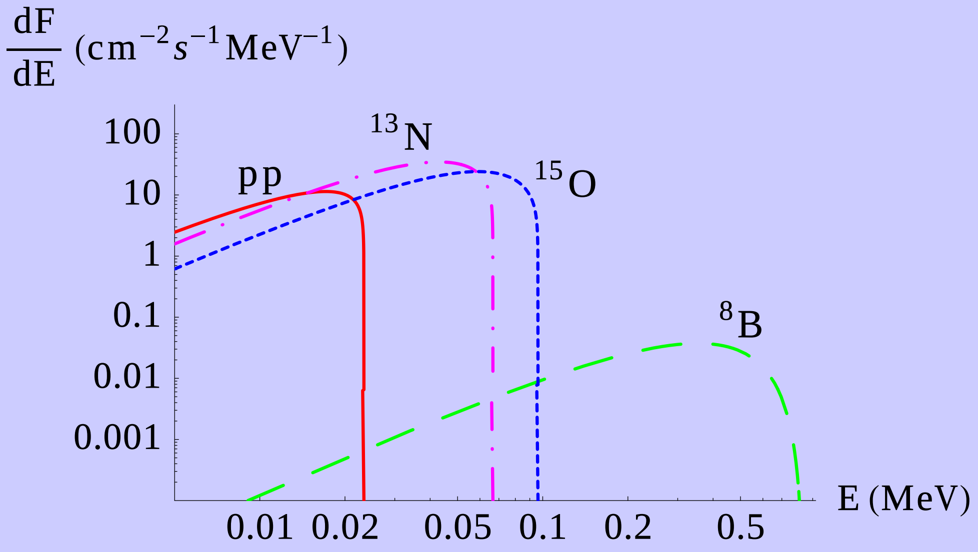
Leading ν channels

$p\ p \to {}^2H\ e^+\ \nu_e$

${}^8B \to {}^4He\ {}^4He\ e^+\ \nu_e$

${}^{13}N \to {}^{13}C\ e^+\ \nu_e$

${}^{15}O \to {}^{15}N\ e^+\ \nu_e$



Thermal neutrinos

For temperatures and densities reached in the inner layers of the star the leading process is pair production

$$e^+e^- \to \nu\bar{\nu}$$

Luminosity depends crucially on:
Details of late burning phases (C,Si,Ne...)
Temperature-density profile and burning times

Order of magnitude: neutrino carry away ALL energy produced by C burning on; 10-20 % of the total mass involved (Heger and Woosley ApJ 567 2001)

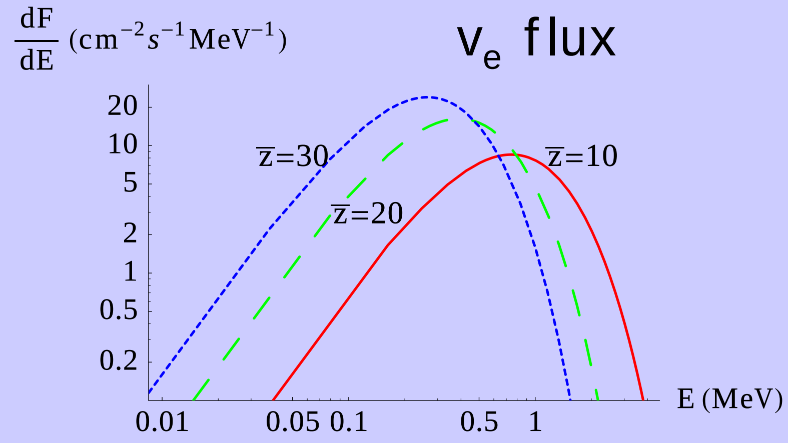
$$N_{thermal} \leq 0.1 - 0.2 \, \frac{\mathrm{M}_*}{\mathrm{M}_N} \frac{B_{Fe} - B_C}{< E_\nu >} \approx 10^{56} \frac{\mathrm{M}_*}{\mathrm{M}_\Theta}$$

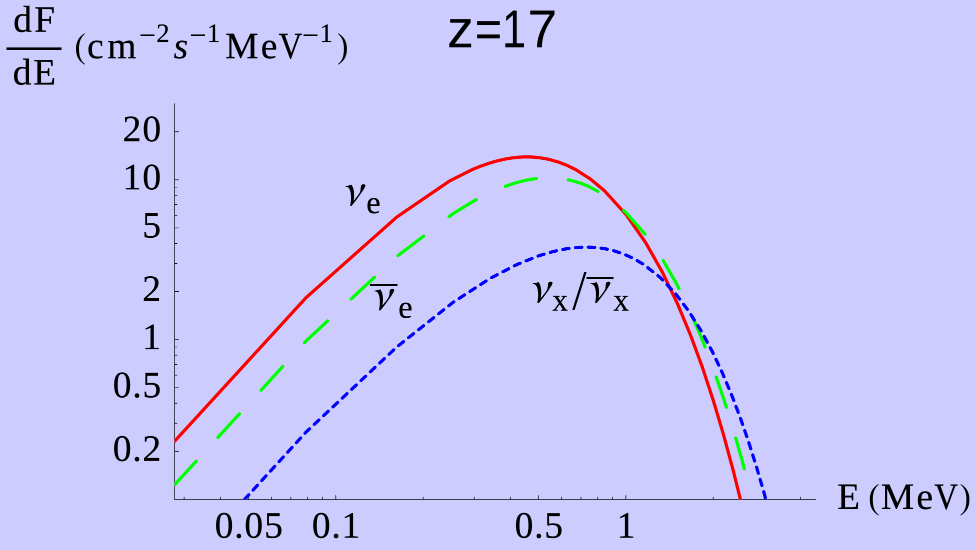
Core collapse neutrinos

Huge luminosity 10^{55}erg in about 10 seconds

Two different behaviour:

- Luminosity peak: neutrinos produced from inner core with an almost thermal behavior
- After neutrino-sphere disappears inside the event horizon emittivity is due to outer layers, with lower v mean energy





SUMMARY

Expected spectra in the 100 KeV- MeV range:

Background:

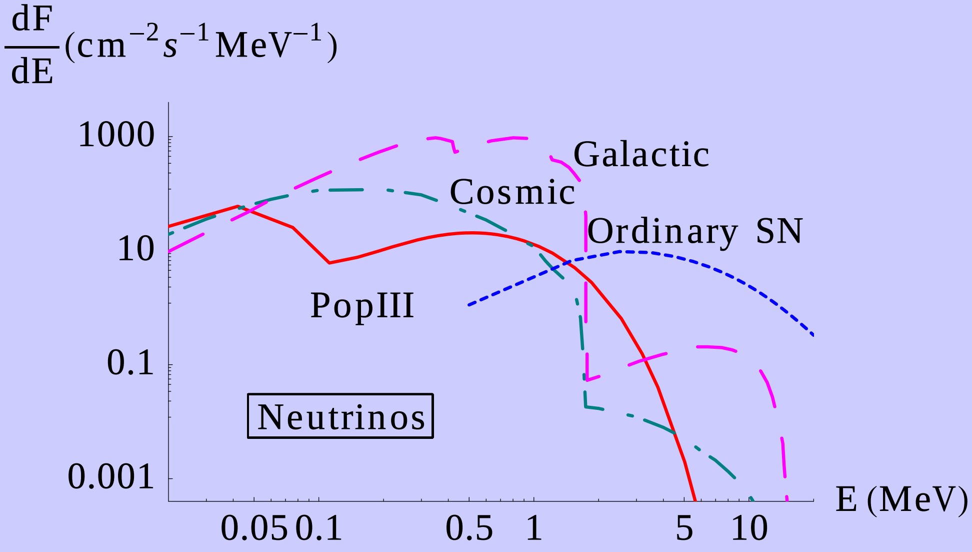
ν_e solar neutrinos

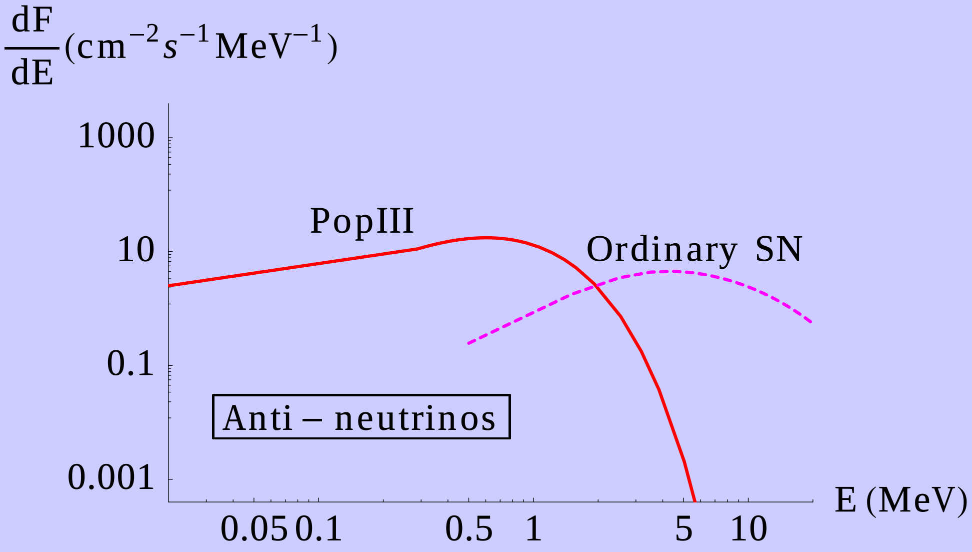
diffuse thermonuclear flux from low redshift stars (Porciani et al 2003)

geoneutrinos

Quite a challenging task!

Antineutrino direction at low energy should be reconstructed!





Outlooks I

Neutrino diffuse flux spans several order of magnitude in energy:

cosmological relic neutrinos

POPIII ν’s (if any)

relic supernovas

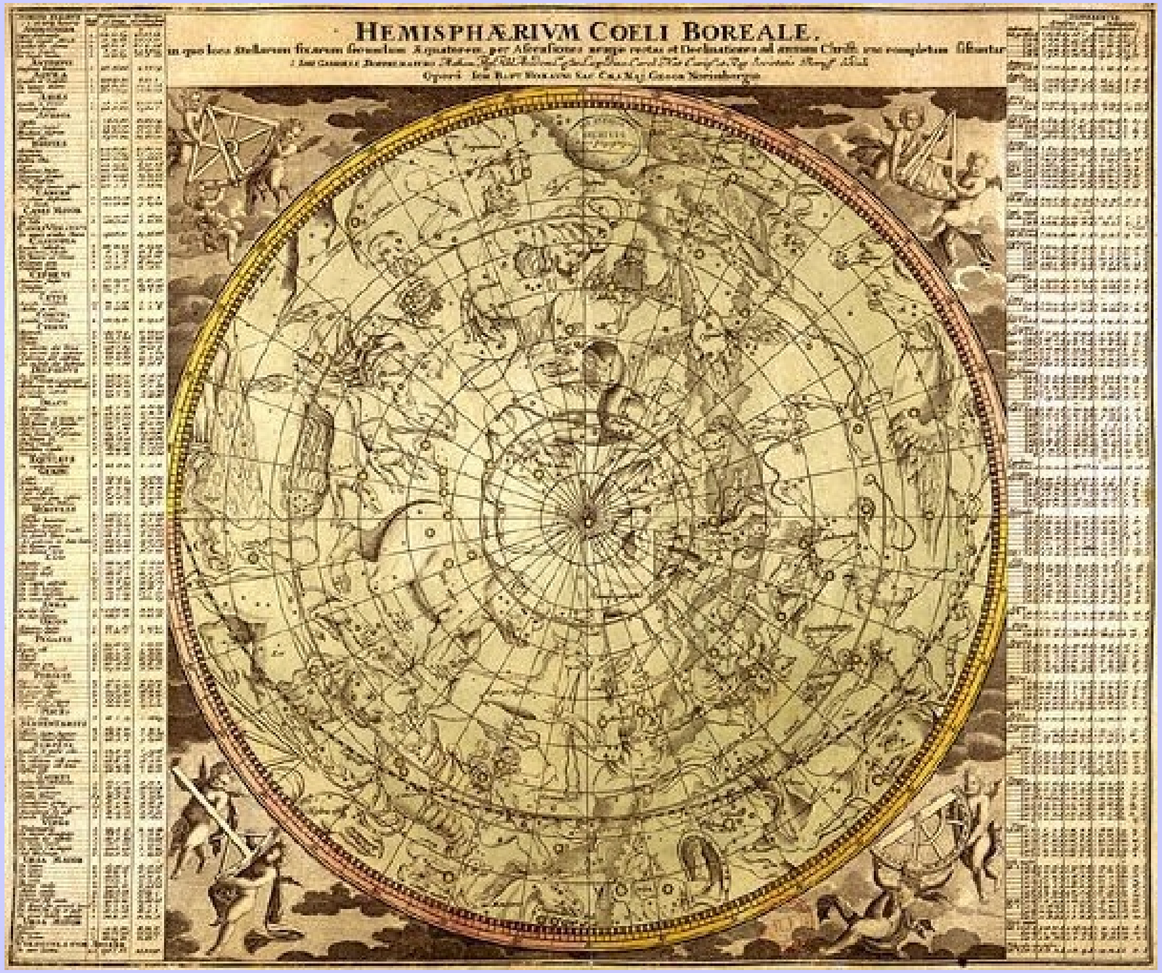
diffuse thermonuclear neutrinos from stars at low redshift

Two leading research projects:

NEUTRINO Telescopes looking at point sources: very energetic phenomena (up to GZK cutoff, Auger, Amanda, Icecube, Antares, Baikal, Nestor, Nemo, …)

NEUTRINO Telescopes looking at diffuse fluxes: key information on the cosmological model and the path to structure formation

Outlooks II



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