«Большие нейтринные телескопы детектируют
потоки нейтрино сверхновых»
«Область знаний», Лекторий СМИ

НЕЙТРИНО МАГНОТОРОТАЦИОННЫХ СВЕРХНОВЫХ И ПОРЯДОК МАСС

2.10.2024

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«Большие нейтринные телескопы детектируют
потоки нейтрино сверхновых»
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Neutrinos from magnitorotational supernovae

2.10_2024

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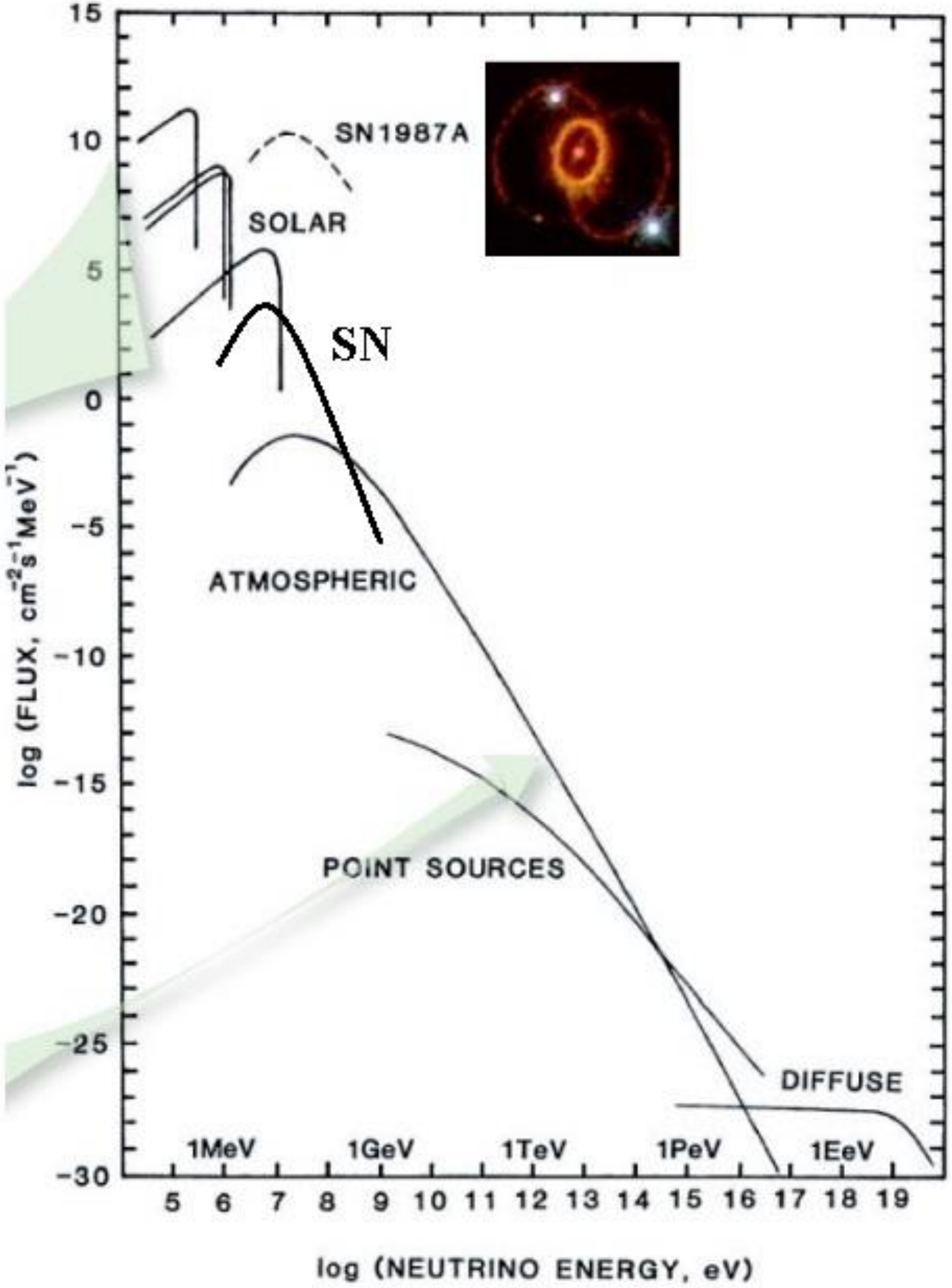
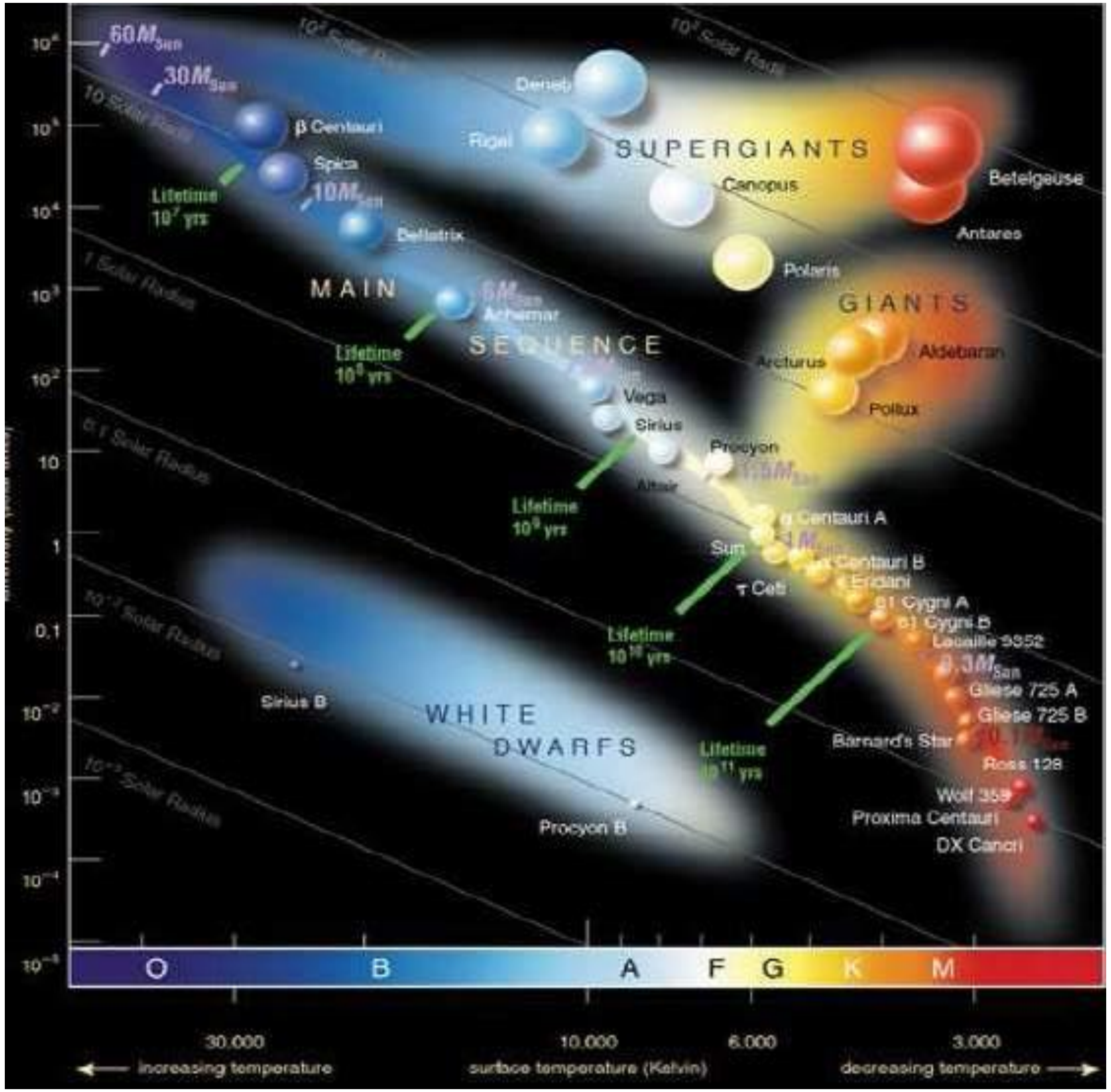
- Supernova neutrinos
- Neutrino nucleon scattering in magnetic field
- Effect of exo- and endo-energetic scattering in neutrino spectra
- Possibilities of observations by the Cherenkov Large Volume Neutrino Telescopes (IceCube, KM3NeT and Baikal-GVD detectors)



Characteristic spectra of (anti-)neutrinos from various sources.

Before and after pictures of SN1987a

Hertzsprung- Russell (H-R) diagram

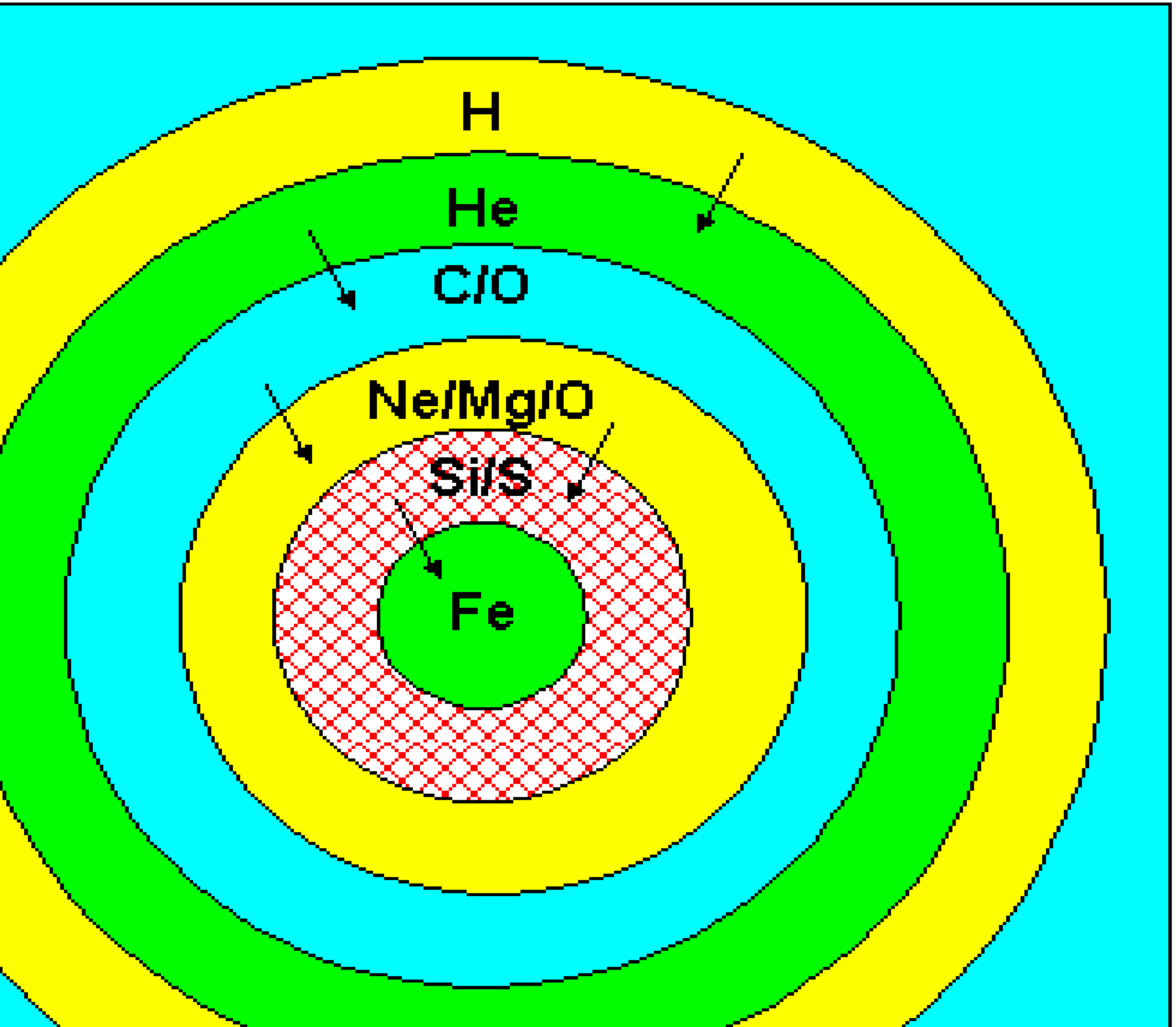


Stefan-Boltzmann
Law for flux

luminosity L
of a star with
radius R **&**
surface temperature T

$L \sim (\text{Surface}) T^4 \sim R^2 T^4$

Massive Star, $M > 8\ M_o$ *onion*



$4\mathrm{H} \rightarrow {}^{4}_{2}\mathrm{He}$

$3\ {}^{4}_{2}\mathrm{He} \rightarrow {}^{12}_{6}\mathrm{C}$

${}^{12}_{6}\mathrm{C}+{}^{12}_{6}\mathrm{C} \rightarrow {}^{20}_{10}\mathrm{Ne} + {}^{4}_{2}\mathrm{He}$

${}^{12}_{6}\mathrm{C}+{}^{12}_{6}\mathrm{C} \rightarrow {}^{24}_{12}\mathrm{Mg} + \gamma$

${}^{12}_{6}\mathrm{C}+{}^{16}_{8}\mathrm{O} \rightarrow {}^{28}_{14}\mathrm{Si} + \gamma$

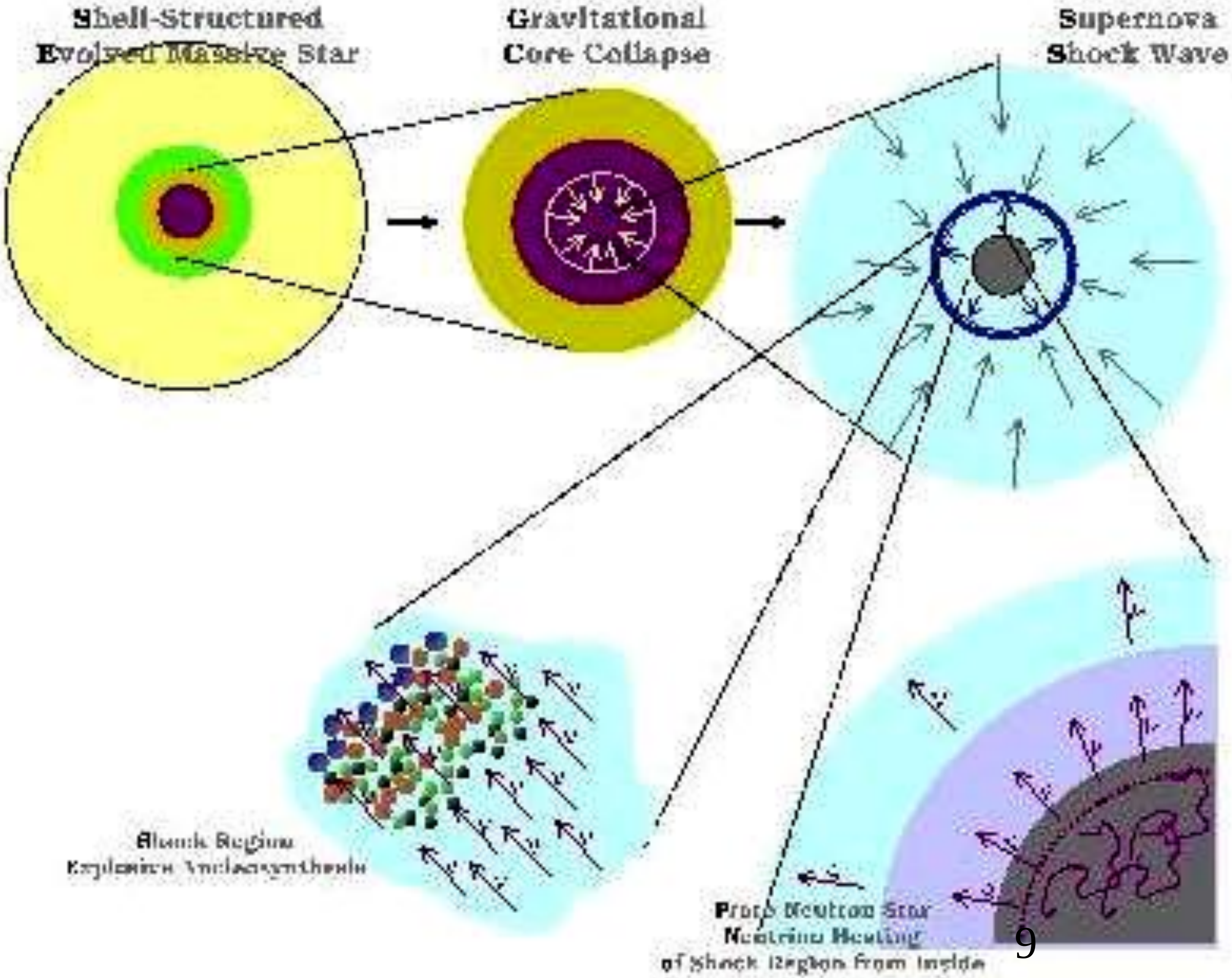
${}^{16}_{8}\mathrm{O}+{}^{16}_{8}\mathrm{O} \rightarrow {}^{32}_{16}\mathrm{S} + \gamma$

${}^{28}_{14}\mathrm{Si} + {}^{16}_{8}\mathrm{O} \rightarrow {}^{44}_{22}\mathrm{Ti}(\beta^{+})$

${}^{44}_{21}\mathrm{Sc}(\beta^{+})\ {}^{44}_{20}\mathrm{Ca}$

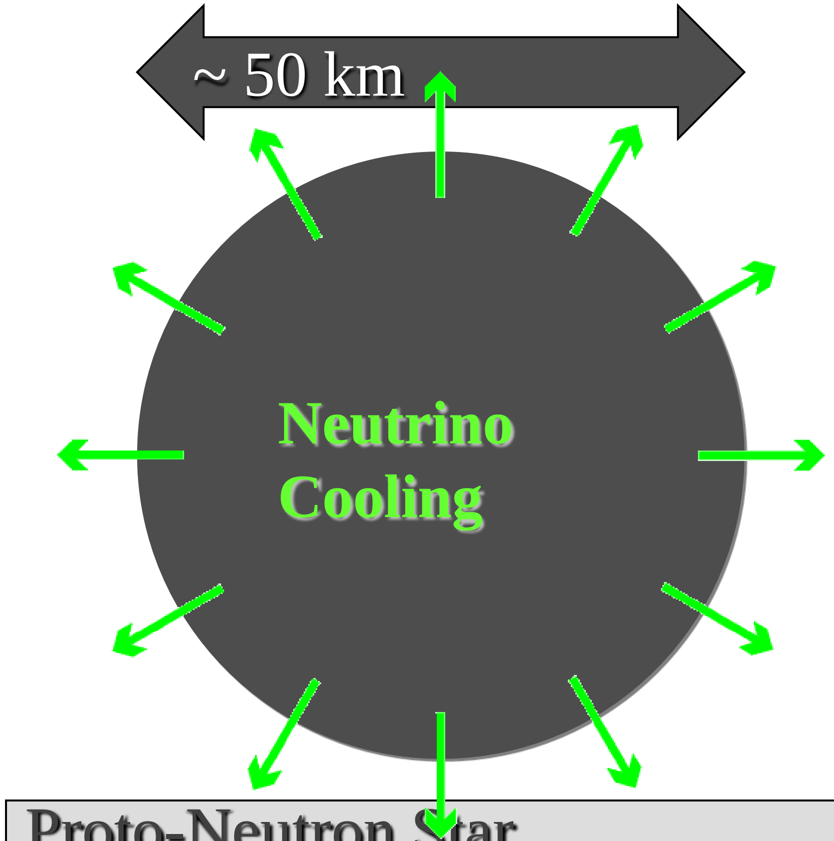
${}^{28}_{14}\mathrm{Si} + {}^{28}_{14}\mathrm{Si} \rightarrow {}^{56}_{28}\mathrm{Ni}(\beta^{+})$

${}^{56}_{27}\mathrm{Co}(\beta^{+})\ {}^{56}_{26}\mathrm{Fe}$


Shell-Structured
Evolved Massive Star
Gravitational
Core Collapse
Supernova
Shock Wave
Shock Region
Explosive Nucleosynthesis
Proto Neutron Star
Neutrino Heating
of Shock Region from Inside
ν

Stellar Collapse and Supernova Explosion

Newborn Neutron Star



Proto-Neutron Star

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

$T \approx 10\ \mathrm{MeV}$

Gravitational binding energy

$E_b \approx 10^{53,5}\ \mathrm{erg} \approx 20\%\ M_{SUN}\, c^2$

This is distributed as

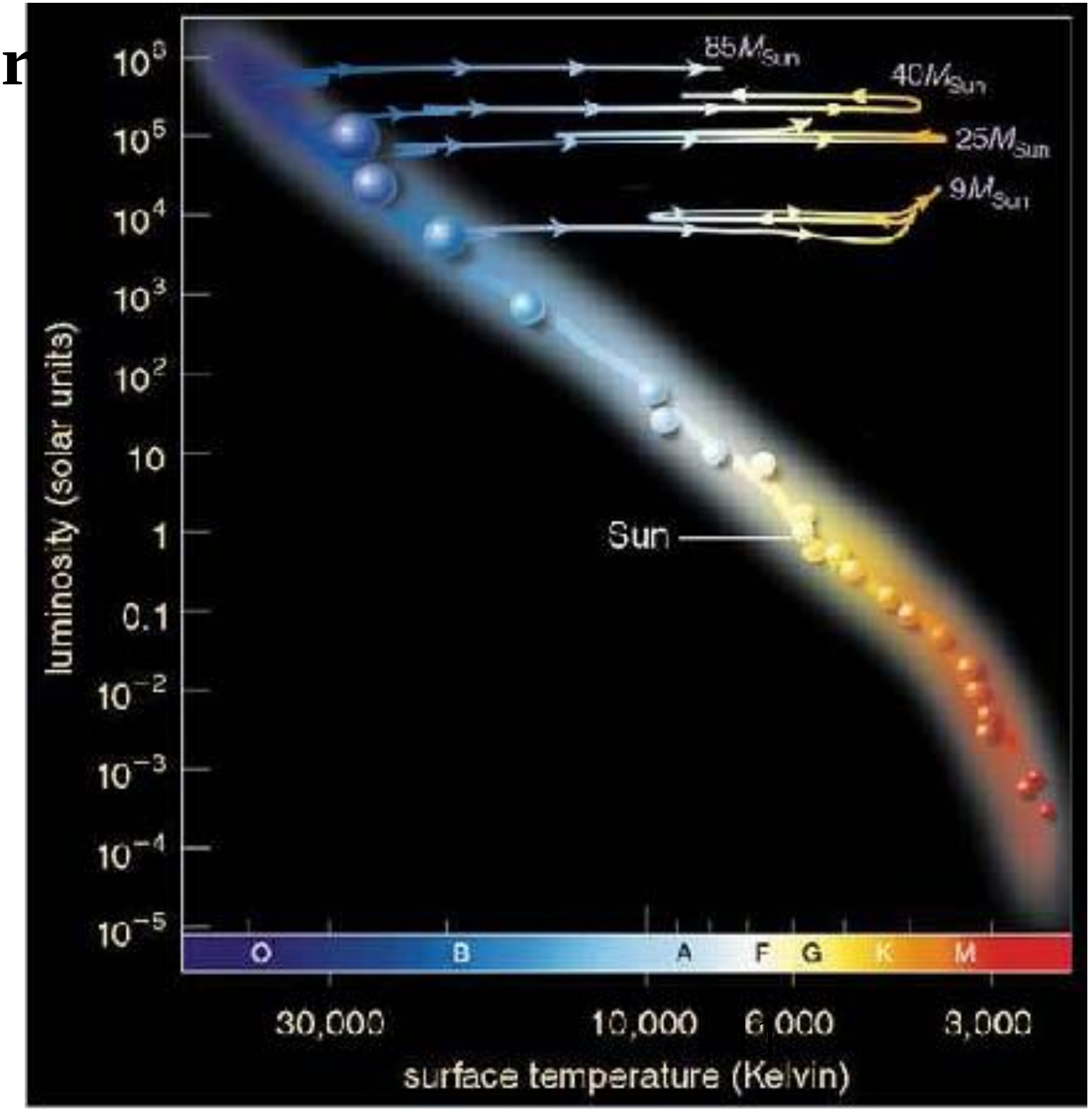
99%	Neutrinos
1%	Kinetic energy of explosion (1% of this into cosmic rays)
0.01%	Photons, outshine host galaxy

Core-collapse supernova

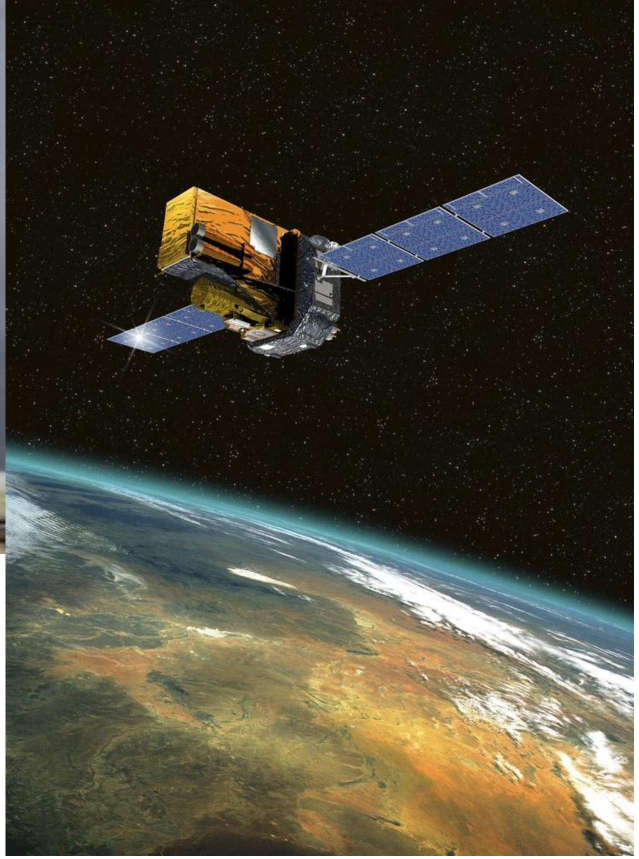
high-mass($M>10M_o$)star

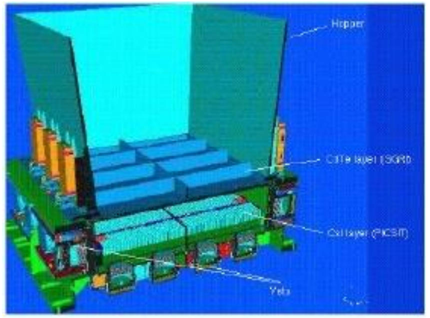
***Evolution* on HR diagram**

explosive
nucleosynthesis
origin of
Heavy Nuclides



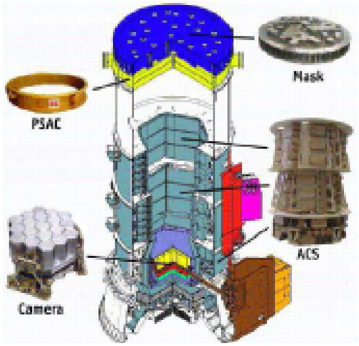
INTEGRAL
VIRGO.UA





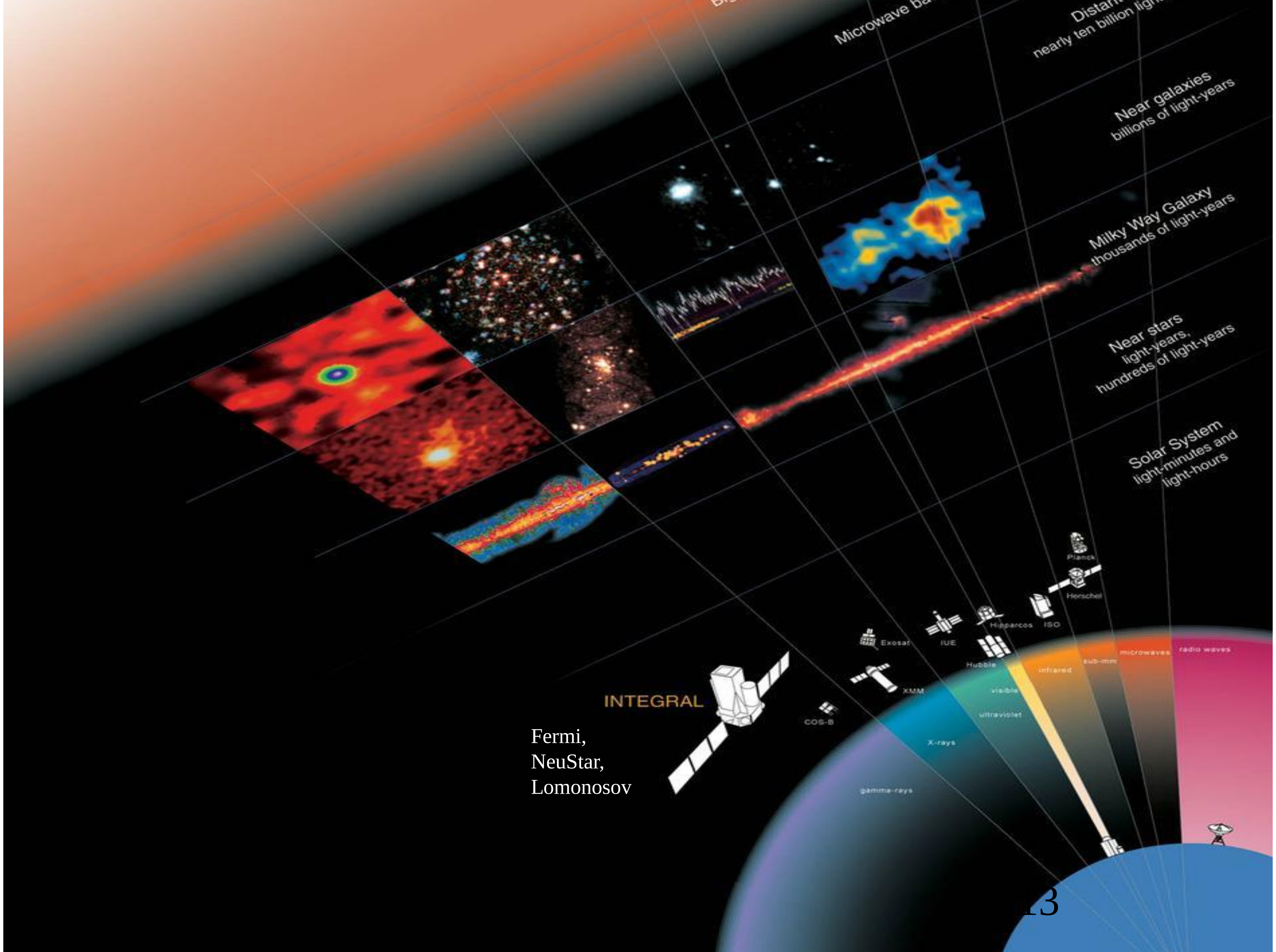
IBIS/ISGRI

Energy range	20 keV – 1 MeV
Energy resolution (FWHM)	7% at 100 keV
Detector area	960 cm2 at 50 keV



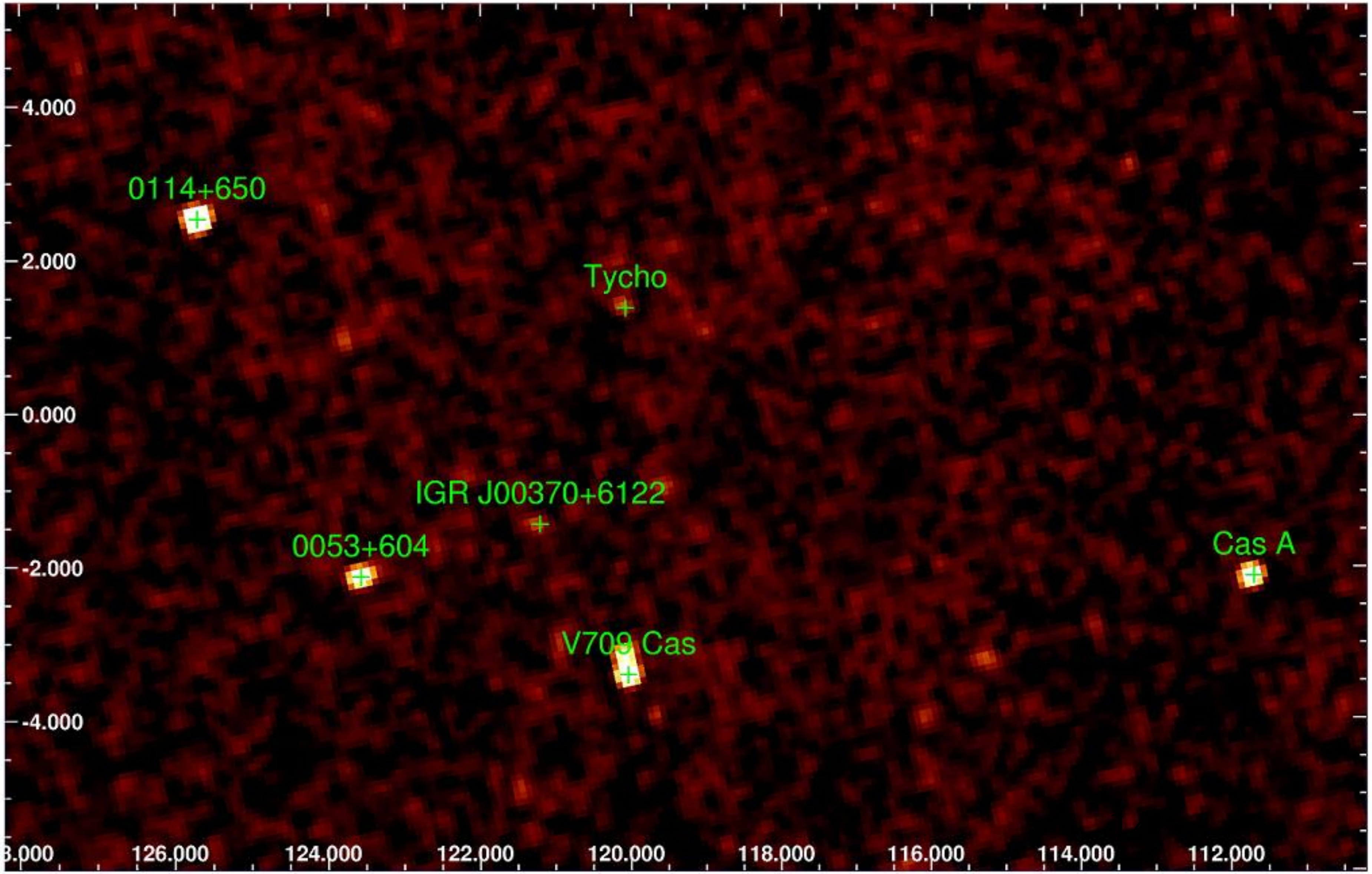
SPI

Energy range	20 keV – 8 MeV
Energy resolution (FWHM)	2.35 keV at 1.33 MeV
Detector area	~ 500 cm^2



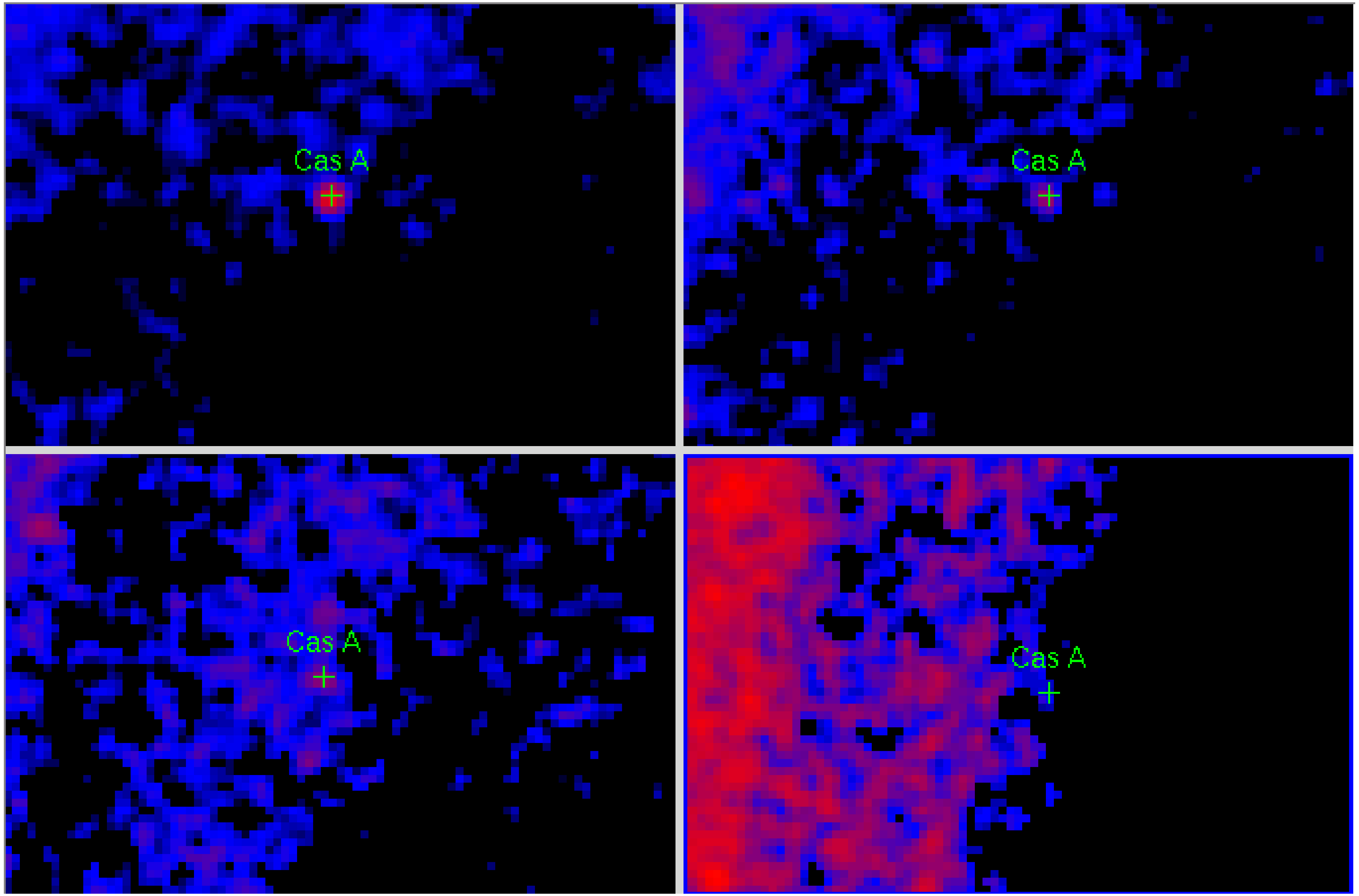
Fermi,
NeuStar,
Lomonosov

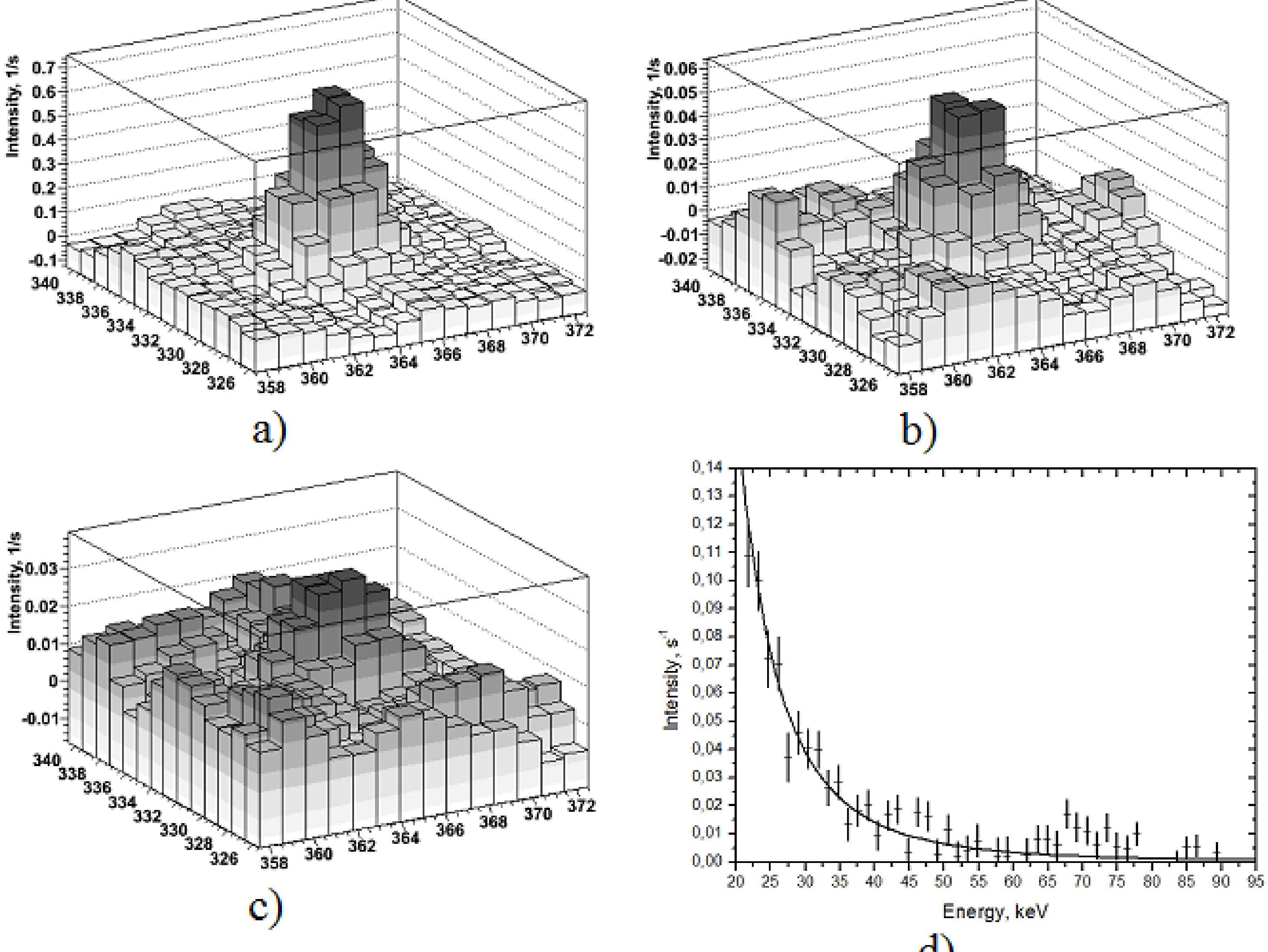
CAS A(3.4+0.3-0.1)kpc, TYCHO(2.2+/-0.3)kpc



Cassiopeia A (3.4+0.3-0.1)kpc

Energy range (keV): **20-62-72-82-100**





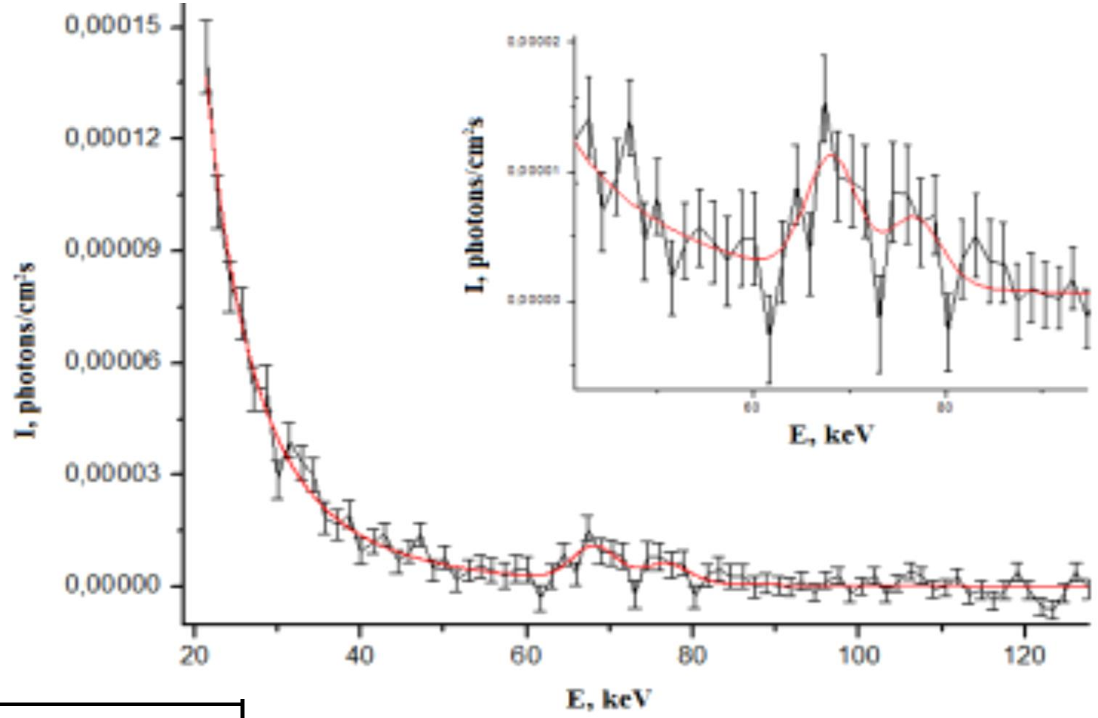
a) b) c) d)

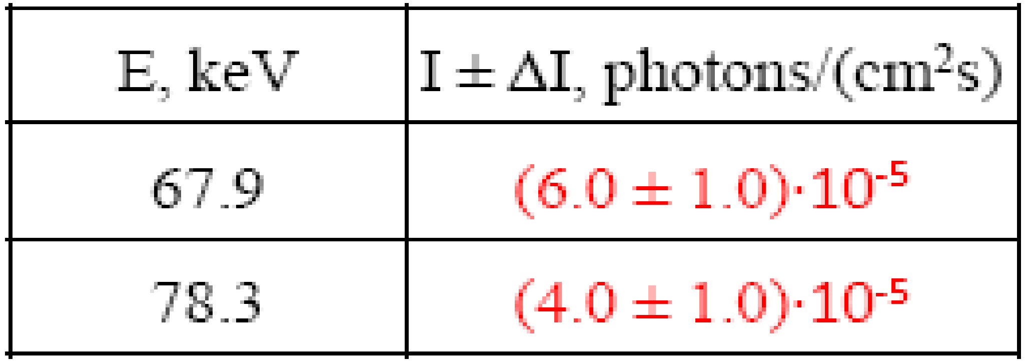
F The direction (i.e.. pixel number) dependence of the registered gamma-ray flux at different energy ranges: **20–62 keV - a, 62–72 keV - b, 72–82 keV – c**; for the angle region containing the Cassiopeia A SN remnant. The right bottom panel (d) represents the spectrum from the Cassiopeia A in the energy range 20–95 keV, the solid line shows the fit with the power law energy *E* dependence, .

Background estimate + Lines

$K \cdot E^{a}$

a=-3.64 +/- 0.09



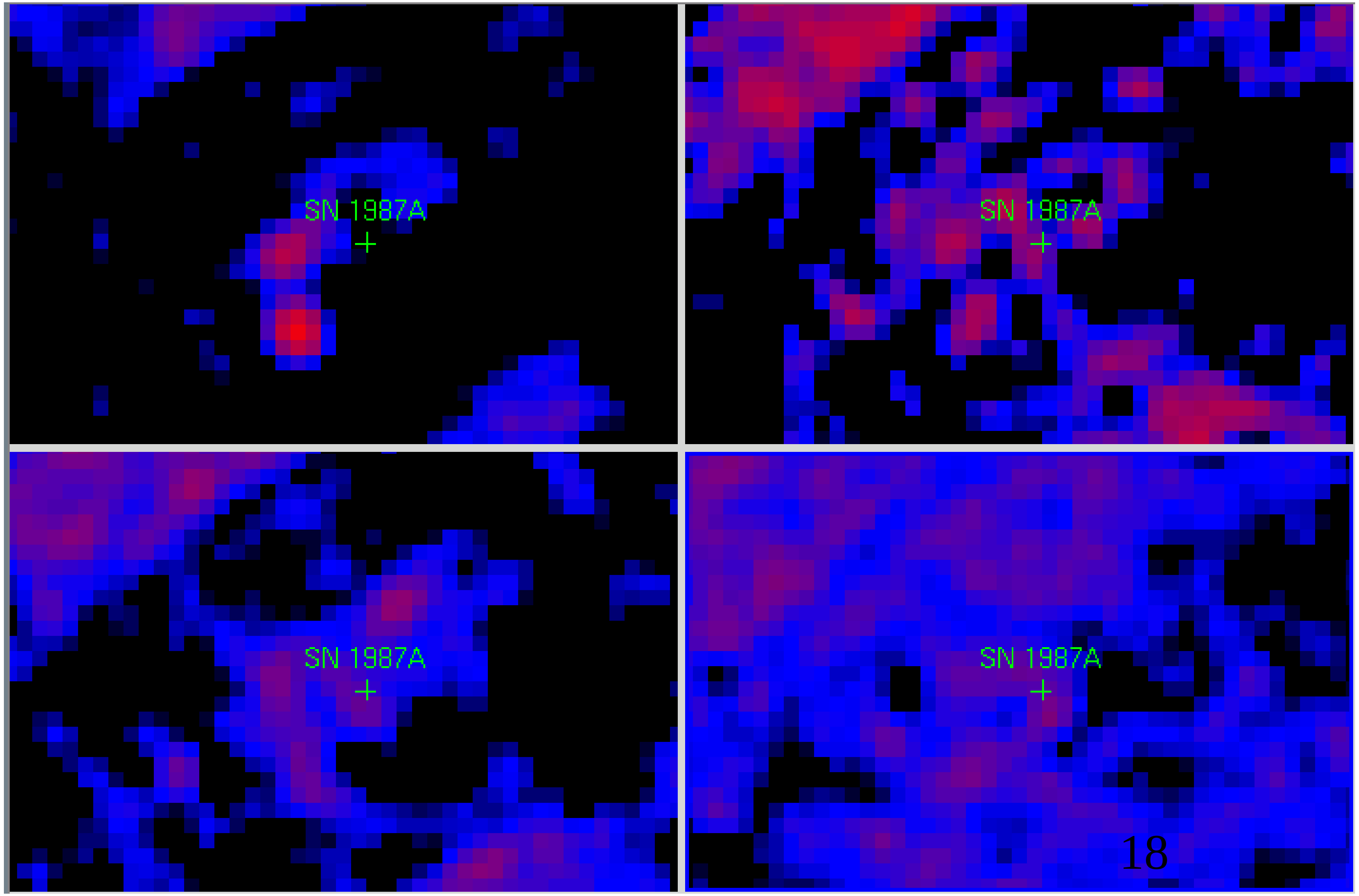


E, keV	$I \pm \Delta I$, photons/(cm²s)
67.9	$(6.0 \pm 1.0) \cdot 10^{-5}$
78.3	$(4.0 \pm 1.0) \cdot 10^{-5}$

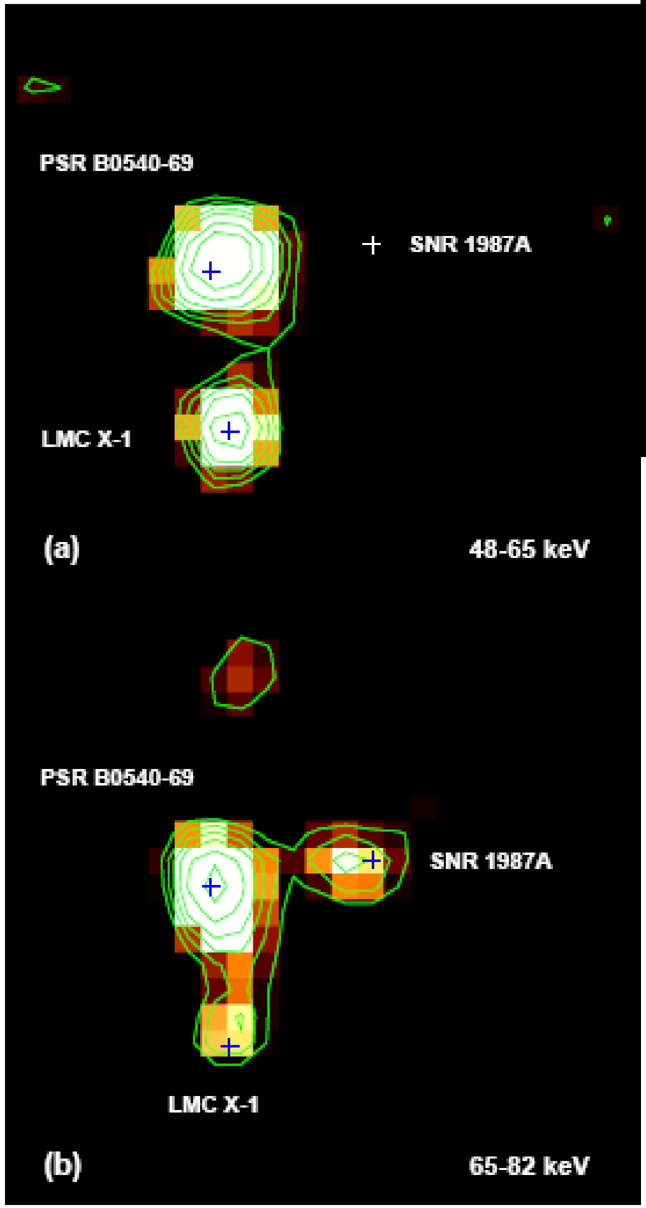
T= 1.5Ms

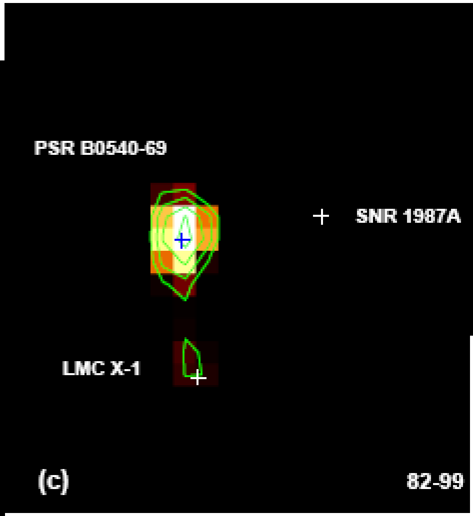
SN1987 A (50kpc)

Energy range (keV): **20-62-72-82-100**

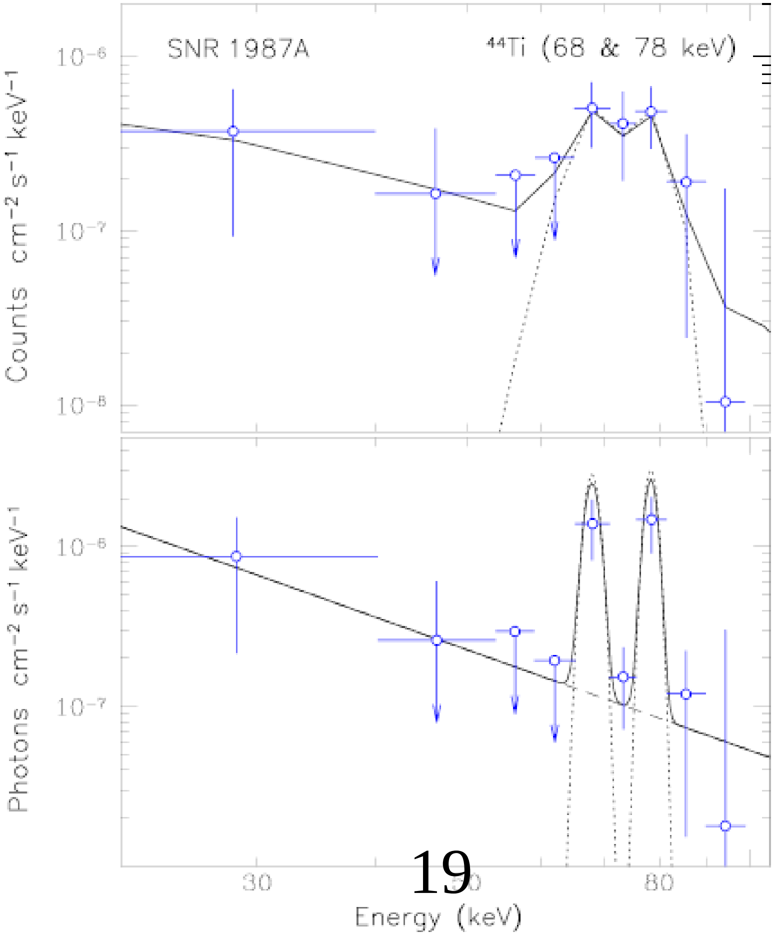


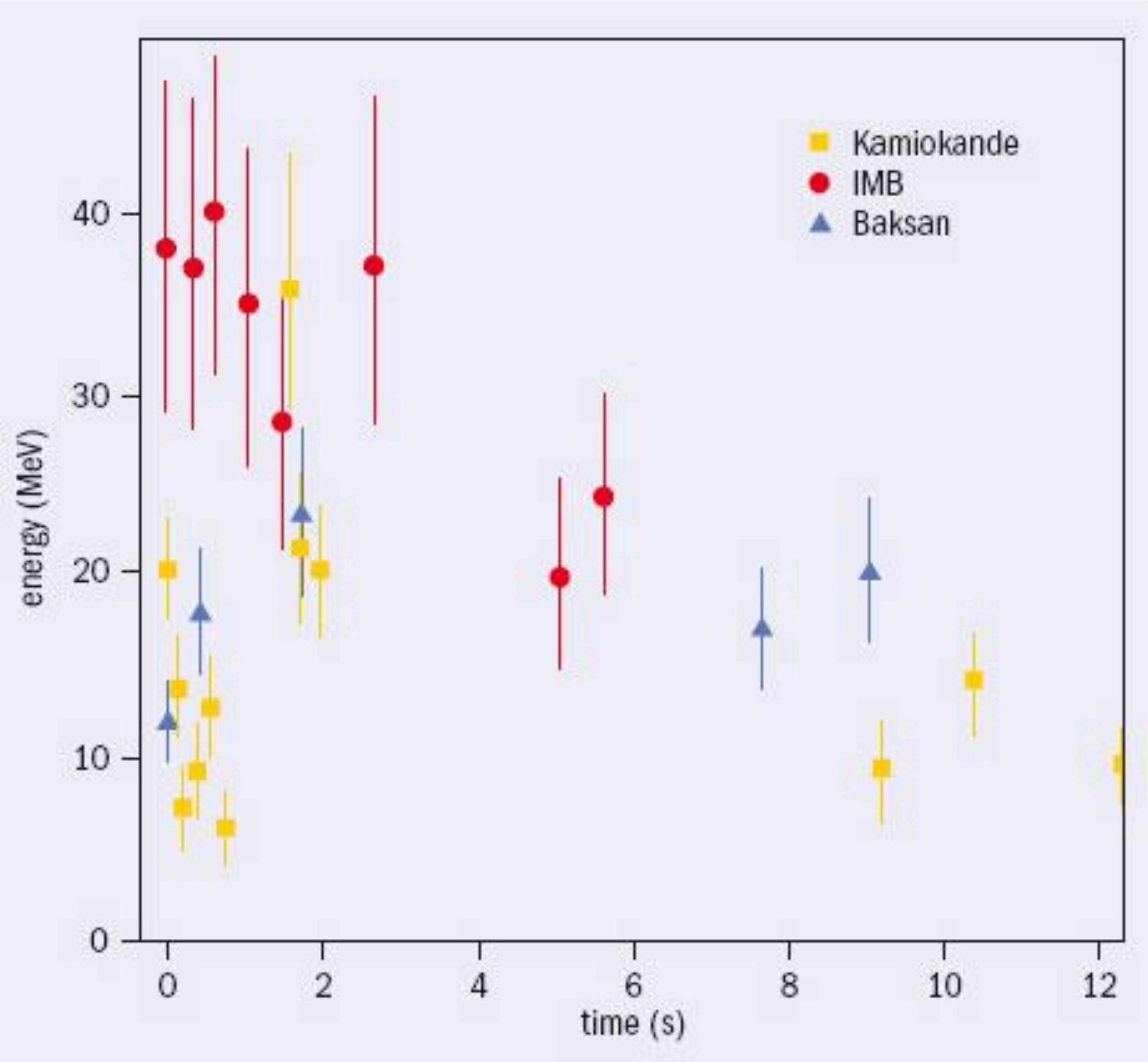
S.A.Grebenev et al *Nature*, *490*, *373-375 (2012)*.





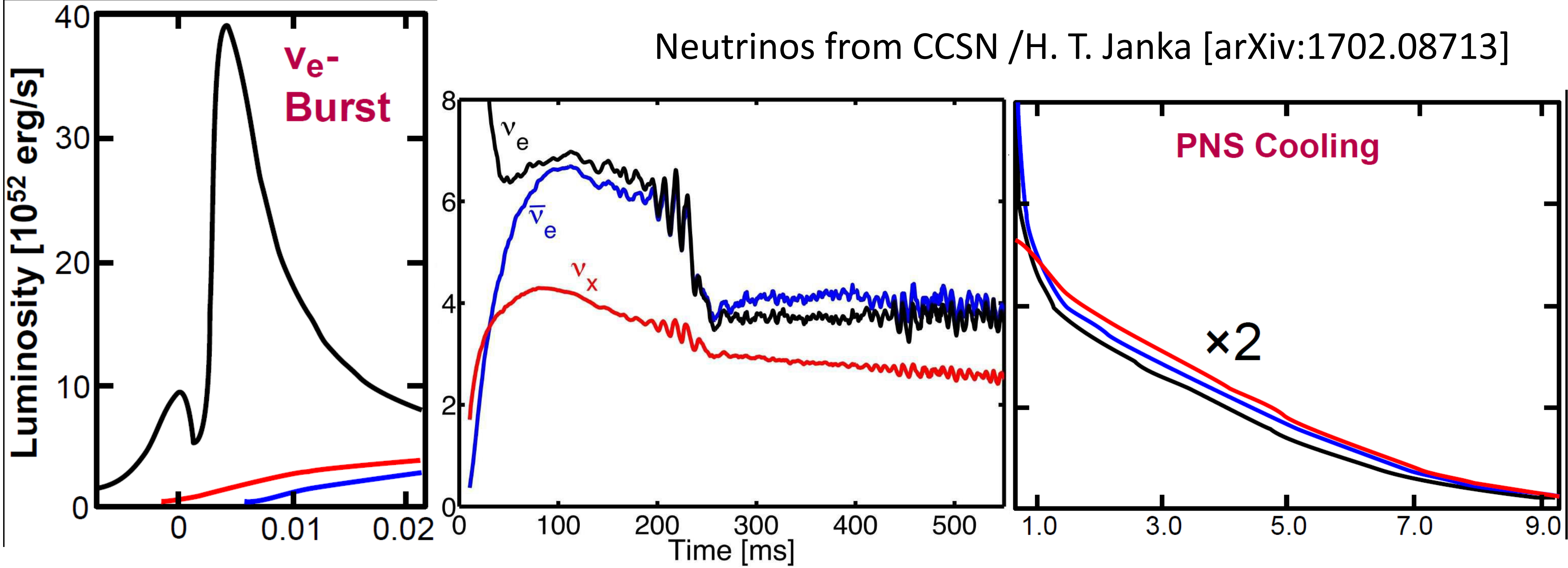
$$(3.1 \pm 0.8) \times 10^{-4} \quad M_{\odot}$$




Kamiokande
IMB
Baksan
energy (MeV)
0
10
20
30
40
time (s)
0
2
4
6
8
10
12

SN 1987A

Neutrinos from CCSN /H. T. Janka [arXiv:1702.08713]

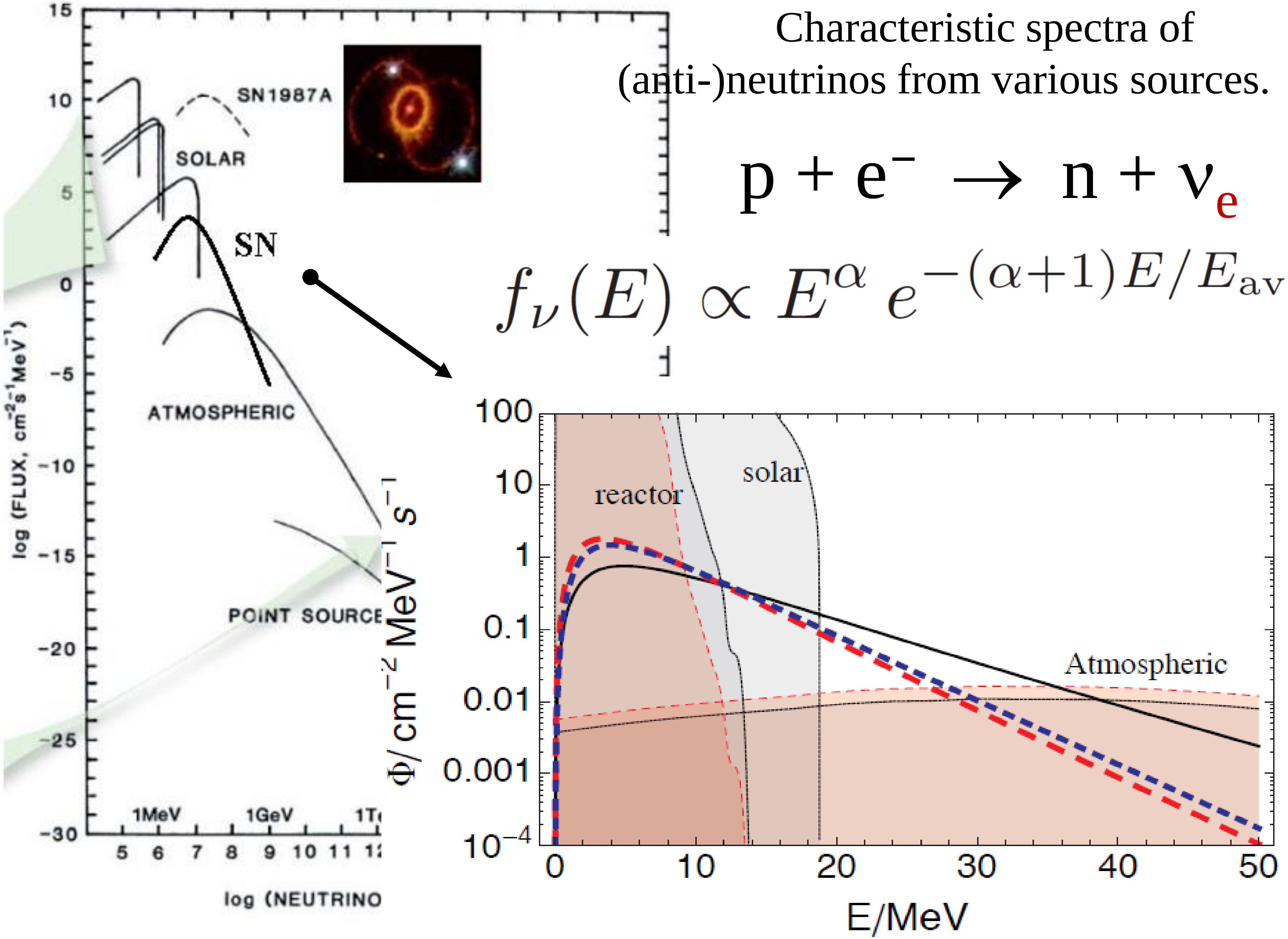


Time after core bounce (s)

Four stages: Infall (~ 10 ms); Neutronization (~50ms); Accretion (~1 s); Cooling (~9 s)

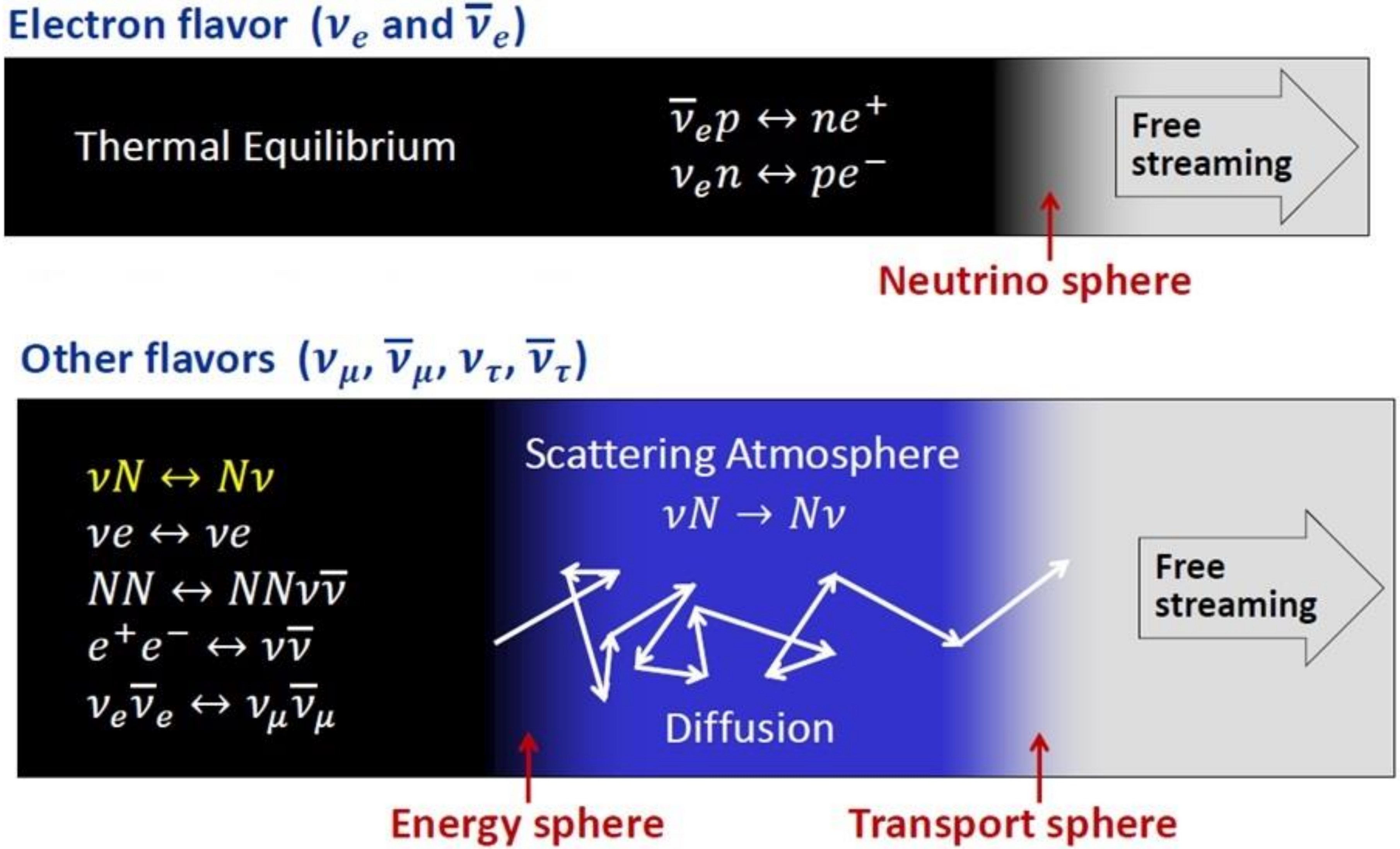
Neutrino mean energy time evolution for core-collapse SN of $27M_{sun}$
for the different neutrino species/H. T. Janka [arXiv:1702.08713]

Characteristic spectra of (anti-)neutrinos from various sources.



$$p + e^- \rightarrow n + \nu_e$$

$$f_\nu(E) \propto E^\alpha \, e^{-(\alpha+1)E/E_{\mathrm{av}}}$$



Electron flavor (ν_e and $\bar{\nu}_e$)

Thermal Equilibrium

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

$\nu_e n \leftrightarrow p e^-$

Free streaming

Neutrino sphere

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

$\nu N \leftrightarrow N\nu$

$\nu e \leftrightarrow \nu e$

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

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

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

Scattering Atmosphere

$\nu N \rightarrow N\nu$

Diffusion

Free streaming

Energy sphere

Transport sphere

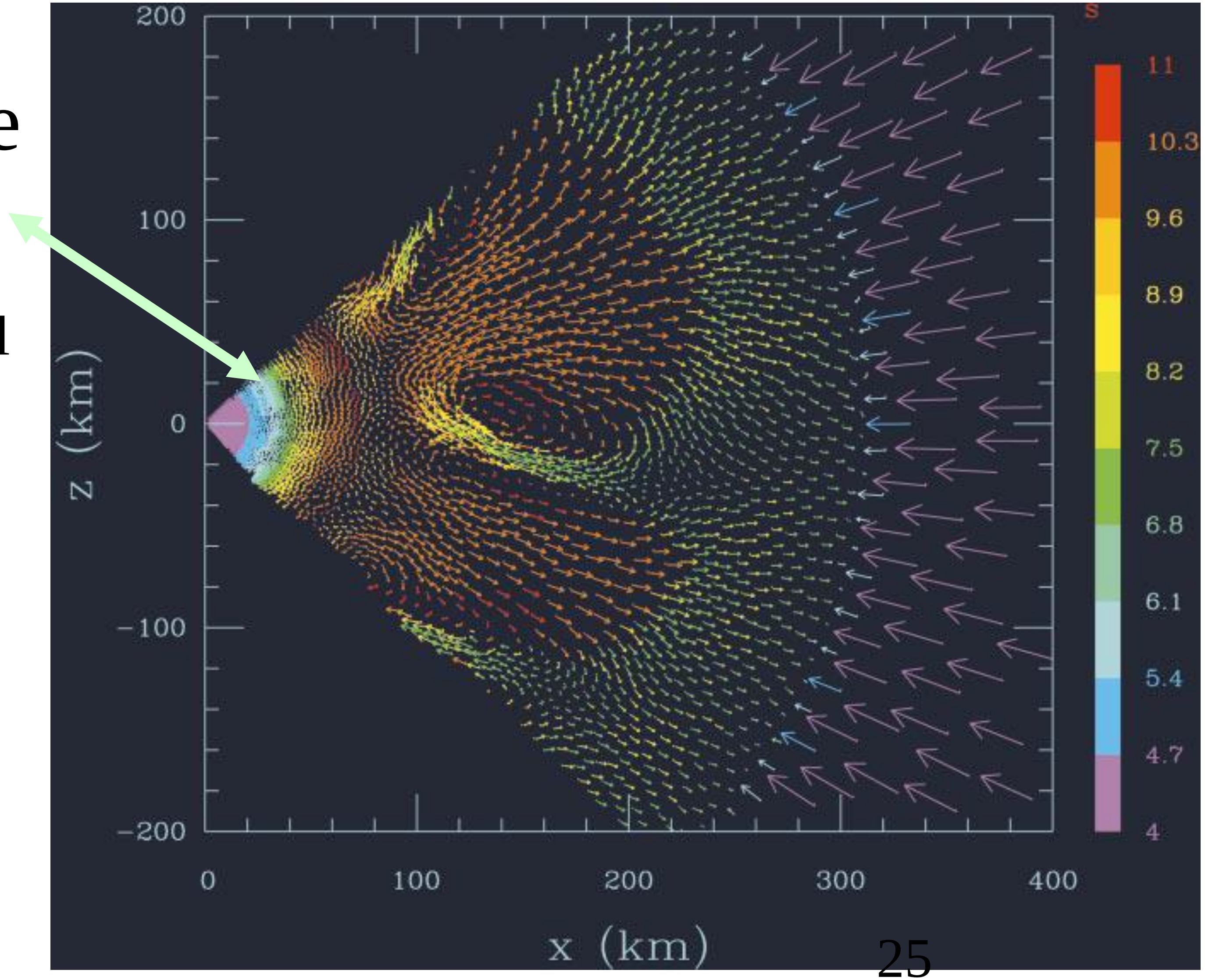
$$f_\nu(E) \propto E^\alpha \, e^{-(\alpha+1)E/E_{\rm av}}$$

explosions proceed through convection processes

ν-sphere

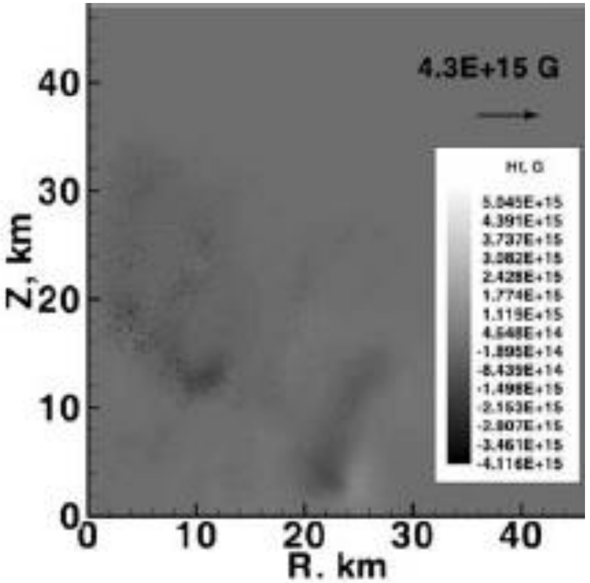
magneto-rotational
instabilities &
dynamo-action
→ amplifying

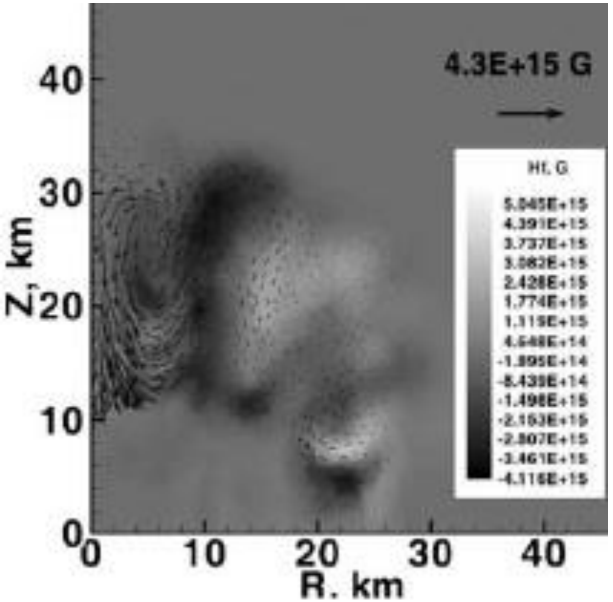
Magnetic fields
up to strengths
tens *tera-tesla*

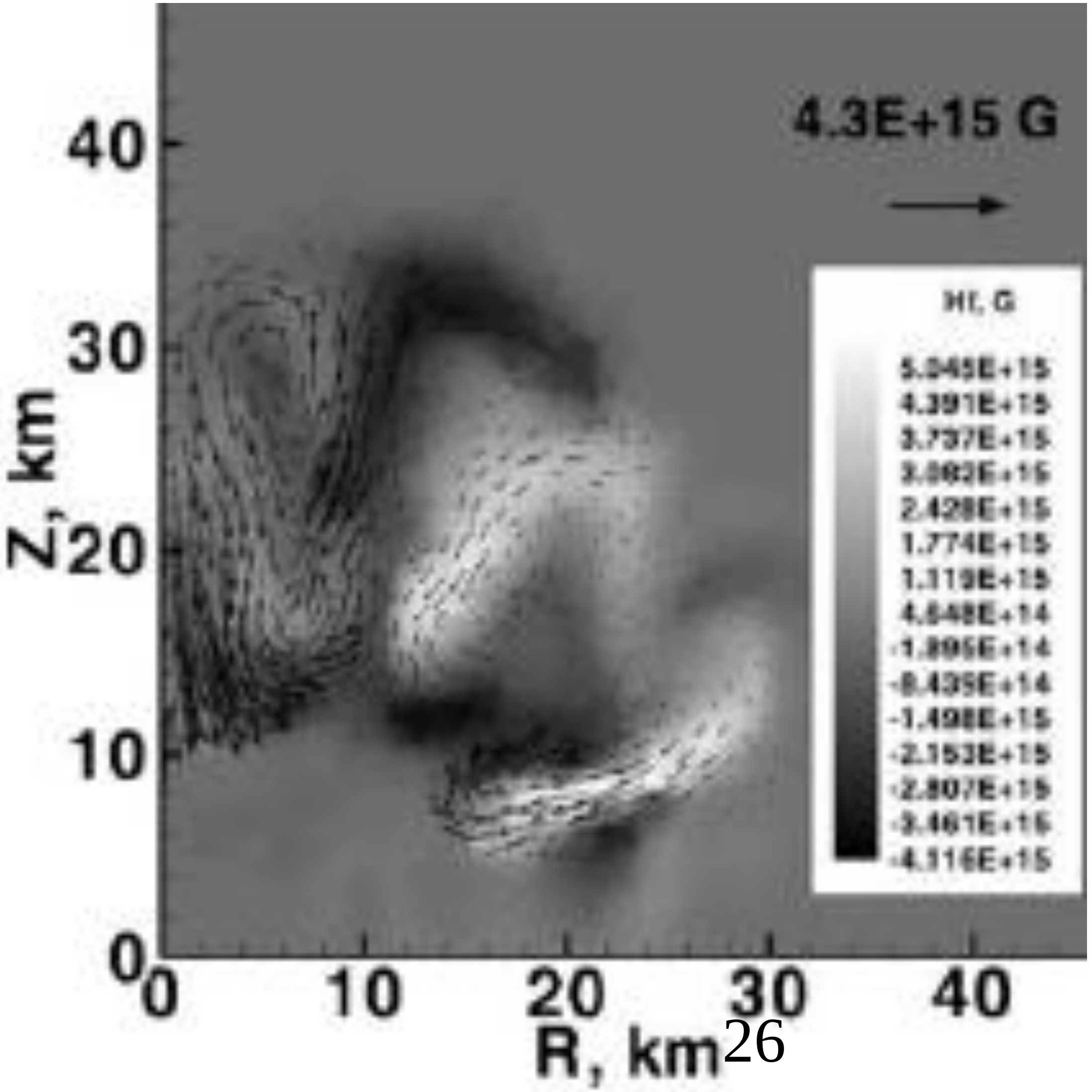


The magnetic field evaluation

(S.G.Moiseenko, G.S.Bisnovatyj-Kogan, N.V.Ardeljan, MNRAS 370 (2006) 501)







Magnetic field estimates

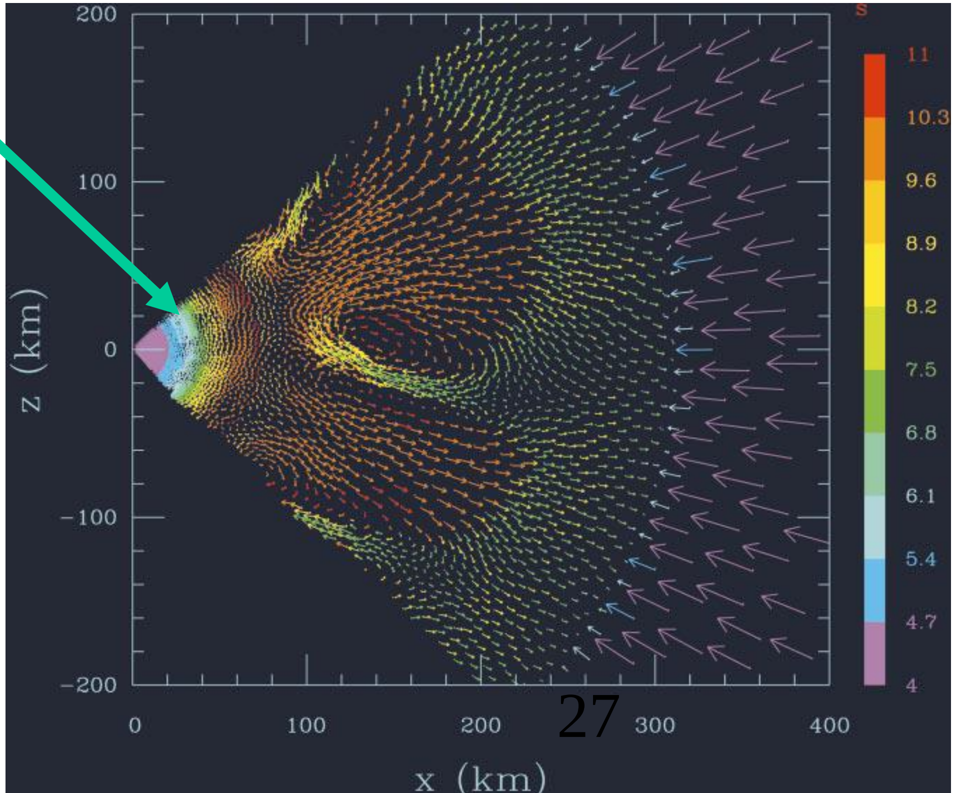
predominant energy component of shock wave E_S originates from the magnetic pressure

$$\langle B_\nu^2\rangle R_\nu^2 \Delta R \sim 2E_S \quad \sim 10^{51,5} \text{ ergs}$$

$R_\nu \sim$ 40Km; $\Delta R \sim$ 1Km

$B_\nu \sim 10^1$ - 10^2 TeraTesla

$$B(R) \sim B_\nu \Delta R_\nu \,/\, R$$



Magnetic field estimates

Magnetic and gravitational forces

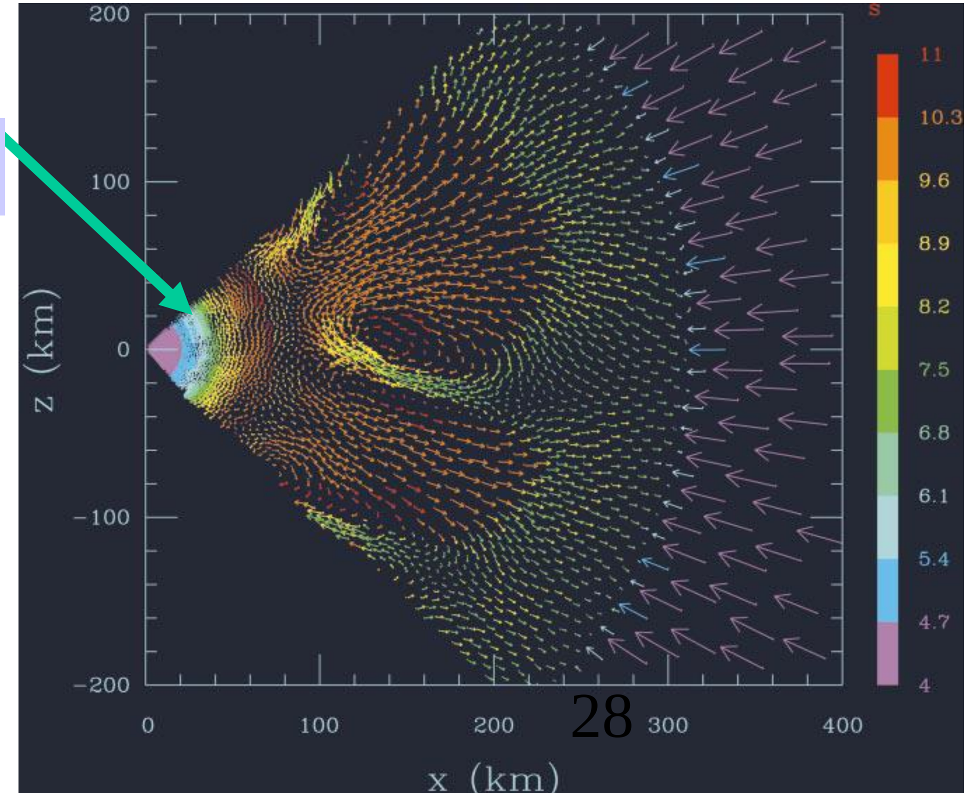
$$dB_\nu^2/dR \sim 8\pi GM\ n(R)/R^2$$

$$4\pi R^2\, n(R) = dM/dR$$

$B \sim 10^{1.5}$ TeraTesla $(M/M_o)(10\text{km}/R)^2$

$R_\nu \sim 40$ Km; $\Delta R \sim 1$ Km

$B_\nu \sim 10^1 - 10^2$ TeraTesla



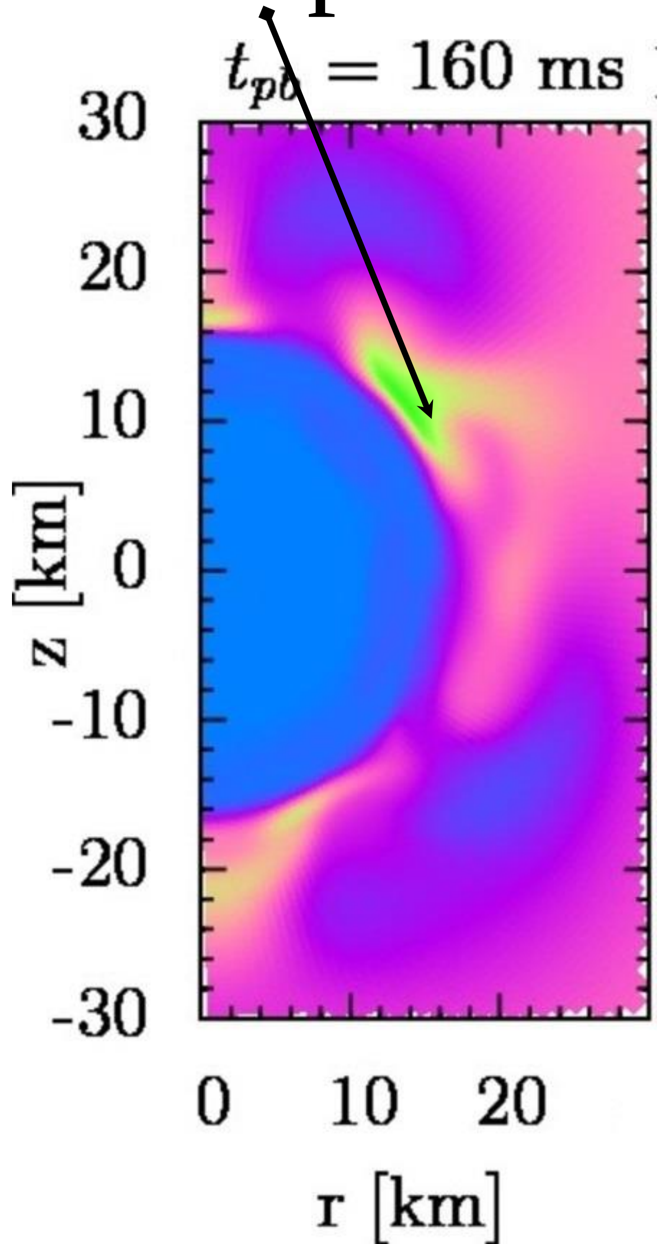
Kinetic Equation for $f(E_\nu, l)$

- $\mathrm{d}f/\mathrm{d}l = \partial f/\partial l + V\,\partial f/\partial E_\nu = \Lambda f + \mathrm{St}[f] = 0$

- $V = \mathrm{d}E_\nu/\mathrm{d}l = n_i\, S_1^{\,i}$ - energy transfer coefficient

$$S_\mathrm{n}^{\,i} = \int \mathrm{d}E\, (-E)^n\, (\mathrm{d}\sigma_i/\mathrm{d}E)$$

ν-sphere : density $n \sim 10^{12}$ g cm^{-3}



Tg cm^{-3}

$T \sim$ 5-10 MeV

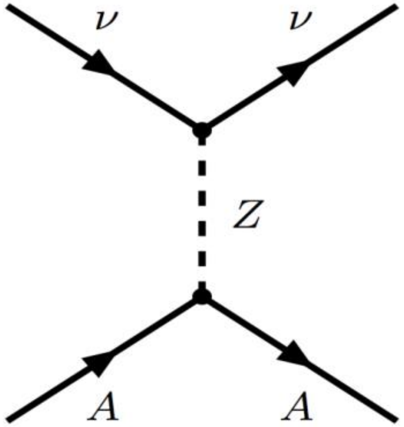
$p_{F12}^{\,i} \approx$ 40 MeV/c (n/Tg cm^{-3})$^{1/3}$

ν-sphere : neutrino-nucleons scattering

$$E_{F12}^{N} = (p_{F12}^{N}\, c)^2/2M_N\, c^2$$
$$\approx 0.88 \text{ MeV}$$

neutral current
Gamow-Teller (GT) operator

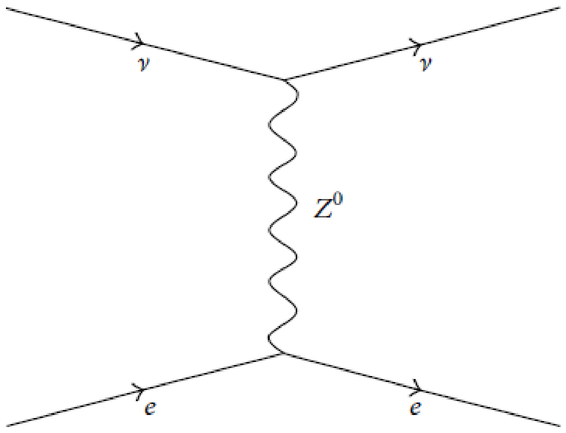
$$\mathrm{GT}_0 = \boldsymbol{\sigma} t_0$$



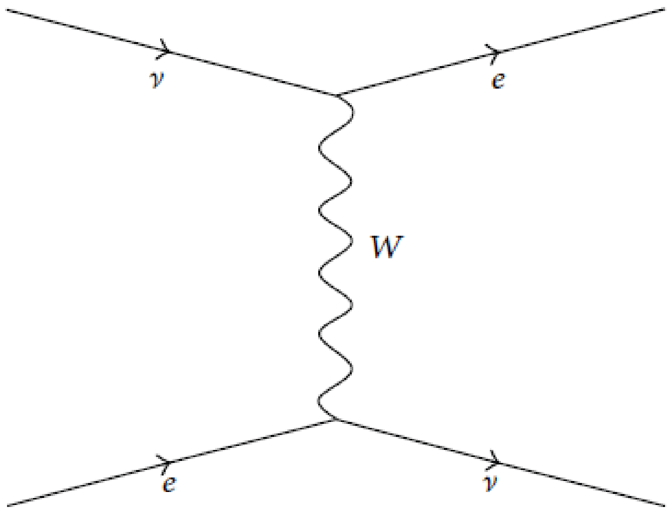
$$l_f^{N} \sim (\sigma_N\, n_N)^{-1} \sim 100 \text{ m}$$

ν-sphere : neutrino-electrons scattering

$$E_{F12}^{e} = p_{F12}^{e}\, c \approx 40 \text{ MeV}$$



$$l_f^{e} \sim (\sigma_e\, n_e)^{-1} \sim 10 \text{ km}$$



NEUTRINO NUCLEAR SCATTERING

V. N. K. et al. PRC **100**(2019)045802

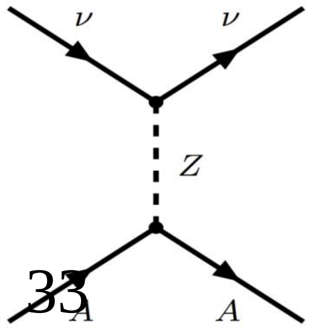
$$S_n(E_\nu,T)=\frac{G_F^2}{\pi}g_A^2\int_{-\infty}^{E_\nu}(-E)^n(E_\nu-E)^2\Sigma_{GT_0}(E,T)\,dE$$

Thermal strength function

$$\Sigma_{GT_0}(E,T)=Z^{-1}(T)\sum_{i,f}e^{-\frac{E_i}{T}}|\langle i|GT_0|f\rangle|^2\,\delta\left(E-E_f+E_i\right)$$

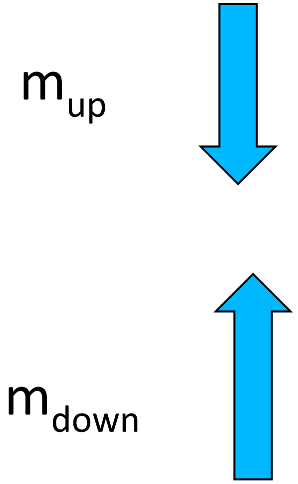
neutral Gamow-Teller (GT) operator $\mathrm{GT}_0=\boldsymbol{\sigma}t_0$

Z(T) - partition function



NEUTRINO NUCLEON SCATTERING
in Ultra-Strong Magnetic Fields

→ Splitting Energy spin-up(down)



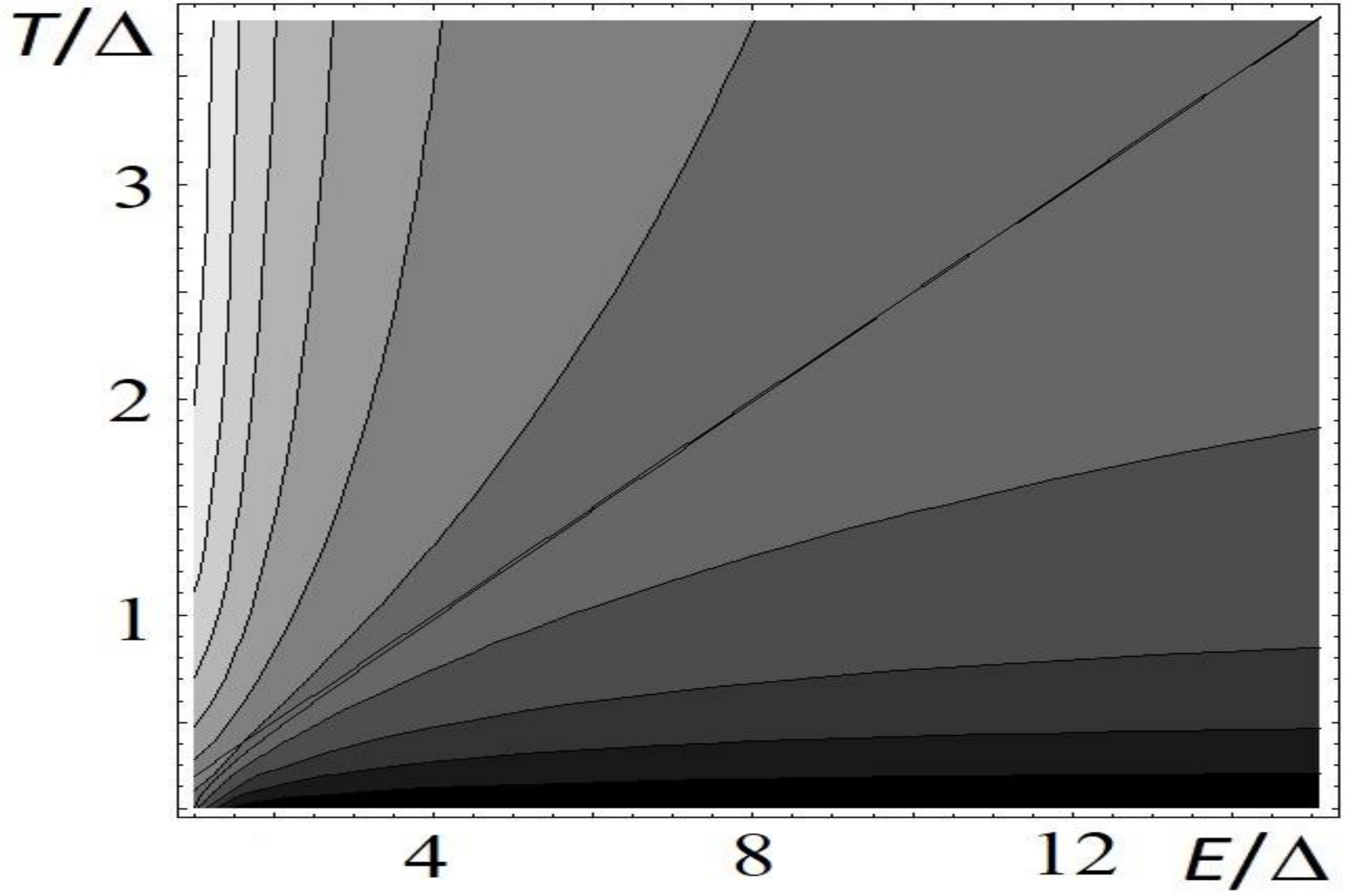
$$\Delta = |g_\alpha|\mu_{\rm N} H \equiv |g_\alpha|\omega_{\rm L}$$

$$S_n \approx \sigma_{{\rm GT}_0} \Delta^n \Phi_n$$

$$\Phi_n = \left[\exp\{-\delta_T\}(1+\delta_E)^2 + (-1)^n \right.$$
$$\left. \times \exp\{\delta_T\}(1-\delta_E)^2 \theta(1-\delta_E)\right] / \{2\cosh(\delta_T)\}$$

$$\delta_T = \Delta / 2T \qquad \delta_E = \Delta / E_\nu$$

Energy transfer cross section in units $S_0\Delta$



For a case $\Delta < T, E_\nu$

$$S_1 \approx \sigma_{\mathrm{GT}_0} \Delta \delta_E (2 - E_\nu / 2T)$$

$$S_2 \approx \sigma_{\mathrm{GT}_0} \Delta^2$$

$\sigma_{\mathrm{GT}_0} \sim 10^{-41.5}$ cm^2 $(E_\nu/10$ MeV$)^2$

Kinetic Equation $\Delta < T, E_\nu$

$$\partial f/\partial l = -l_t^{-1} E_\nu (2 - E_\nu/2T)\, \partial f/\partial E_\nu$$

$$f(E_\nu, l) = f(g_l(E_\nu))$$

$l_t \sim 100\text{m}\ (10\text{MeV}/\Delta)^2\ (10\text{Tg cm}^{-3}/n)$

A = 1 – ex

$$dE_{\nu}/dl = l_t^{-1} E_{\nu} \; (2 - E_{\nu} / 2T)$$

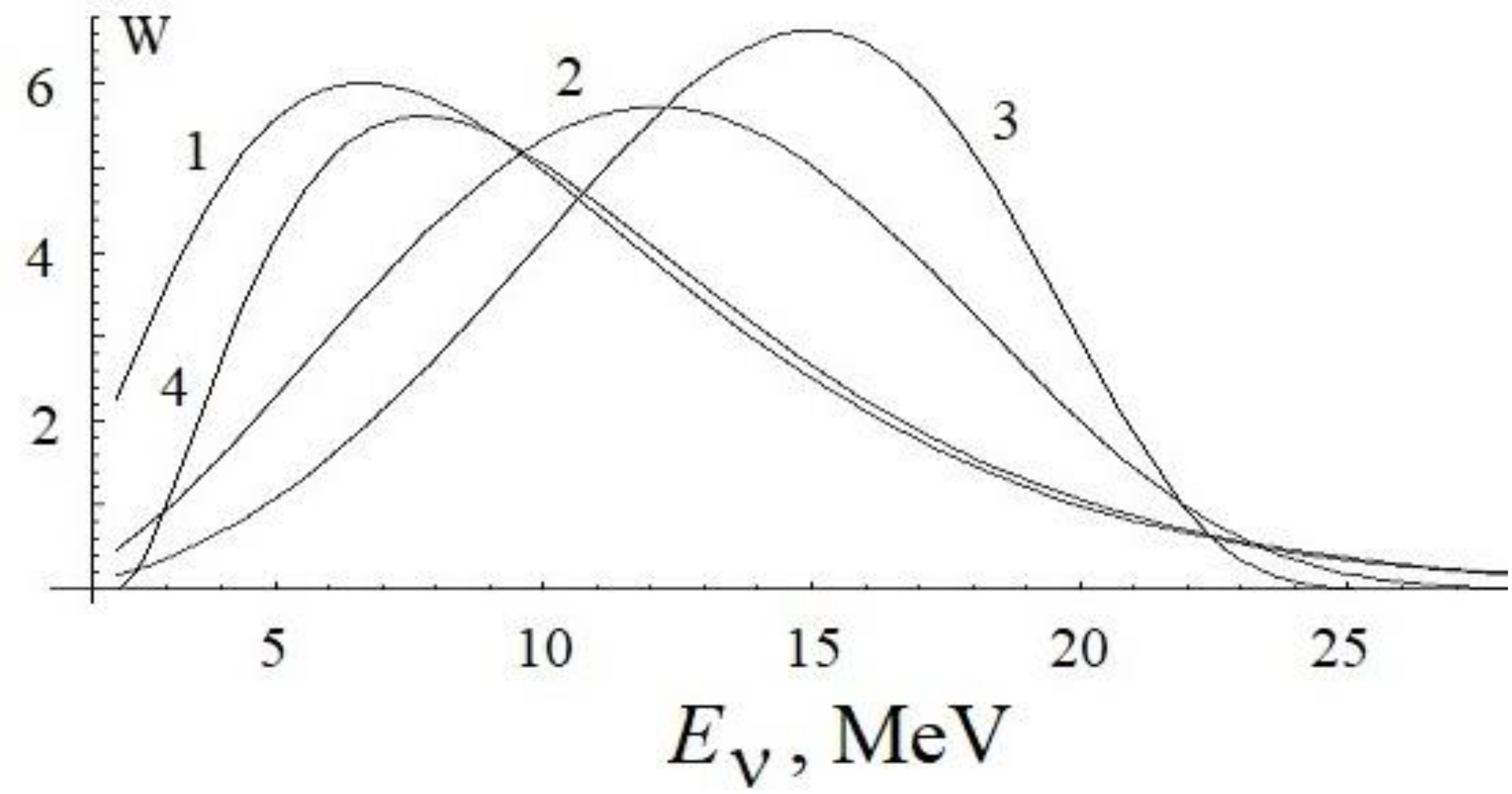
$E=g_l\,(E_l)$ E_l – energy at distance l

$=e_t\, E_l\,/(1 - (1 - e_t)\, E_l/4T)$

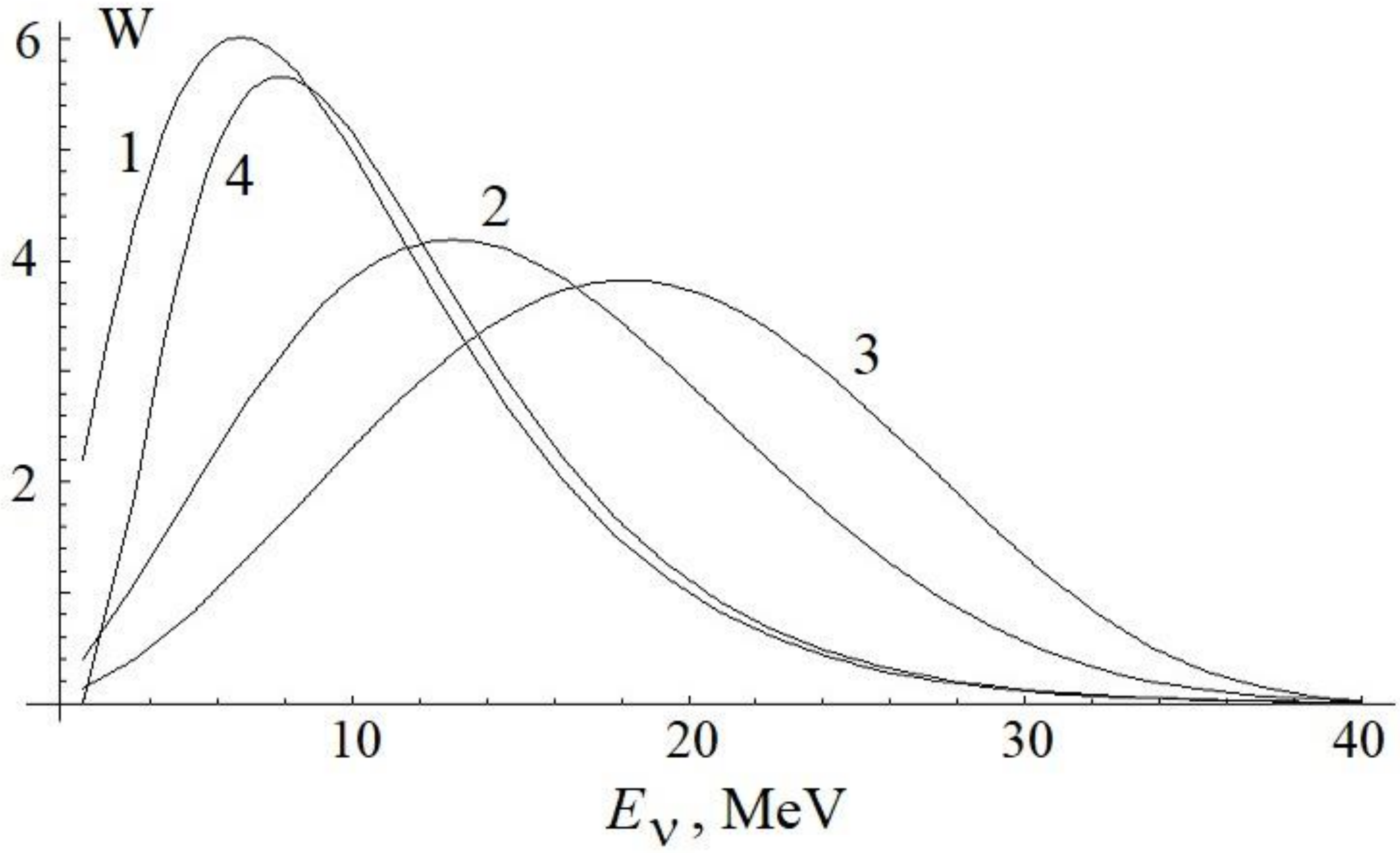
$e_t = \exp\{l/\, l_t\}$

$l_t \sim 100\text{m}\, (10\text{MeV}/\Delta)^2\;\; (10\text{Tg cm}^{-3}/n)$

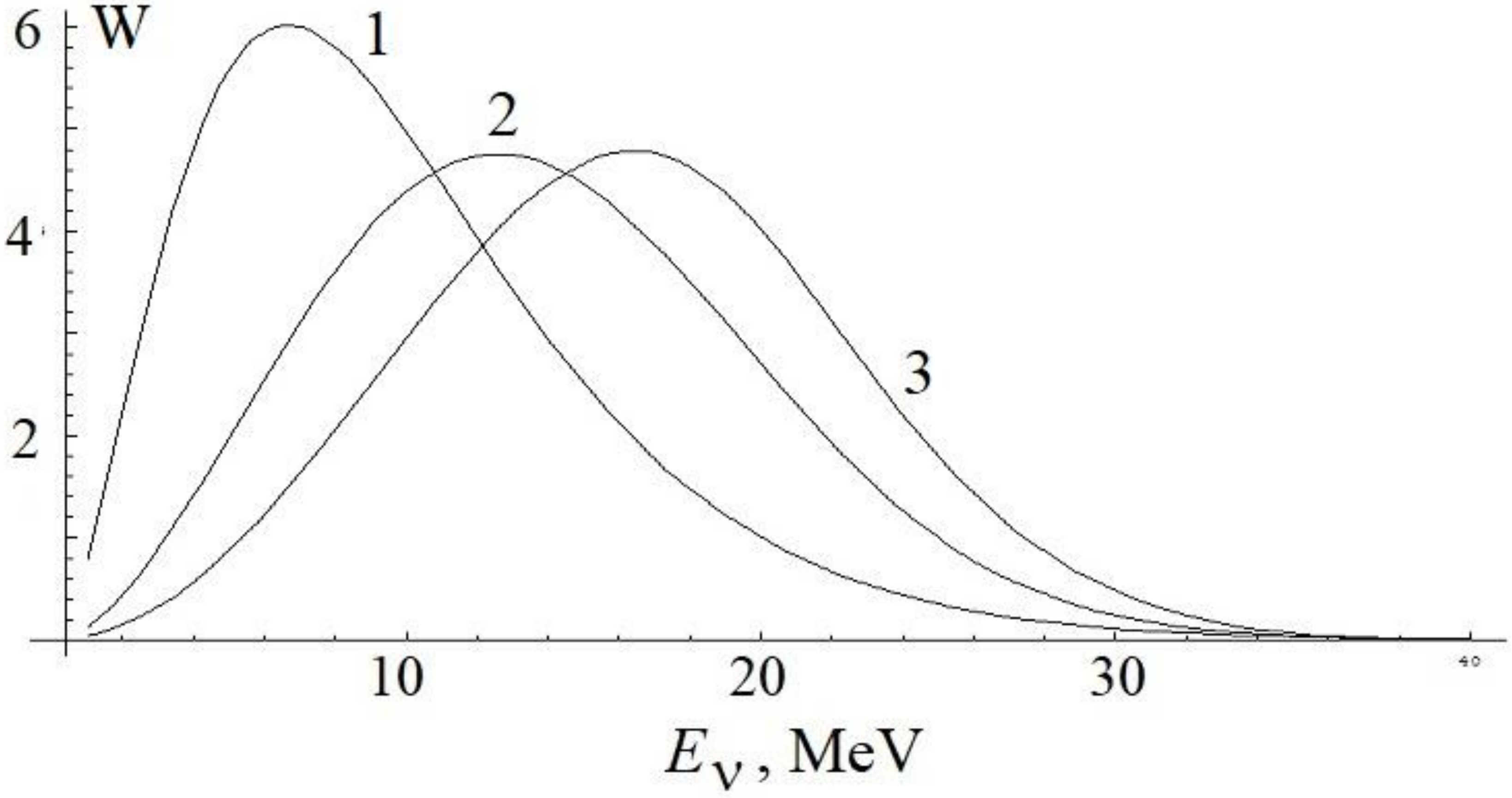
T = 5 MeV, e_t = 1, 2, 3



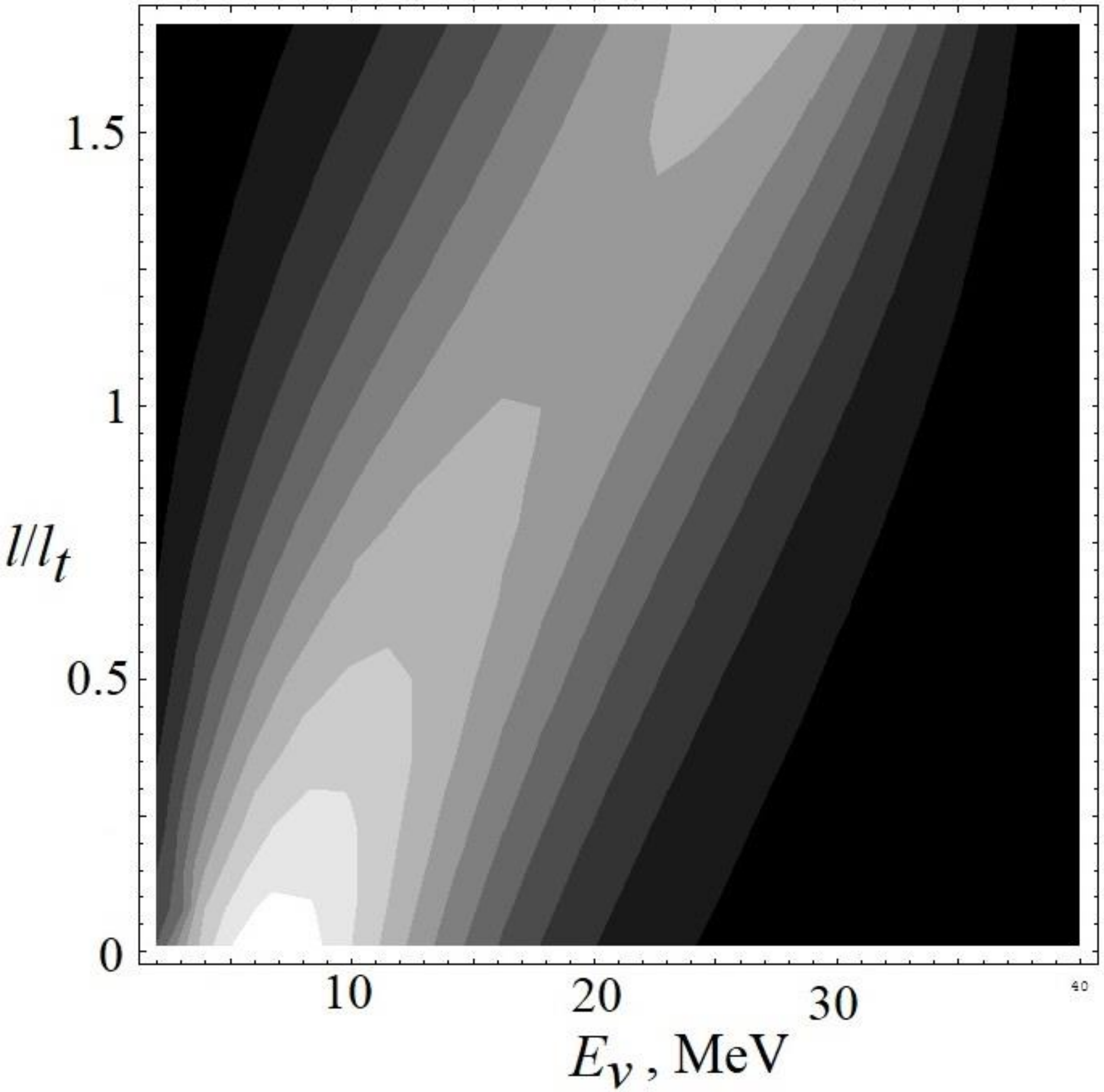
$T = 10$ MeV, $e_t = 1, 2, 3$



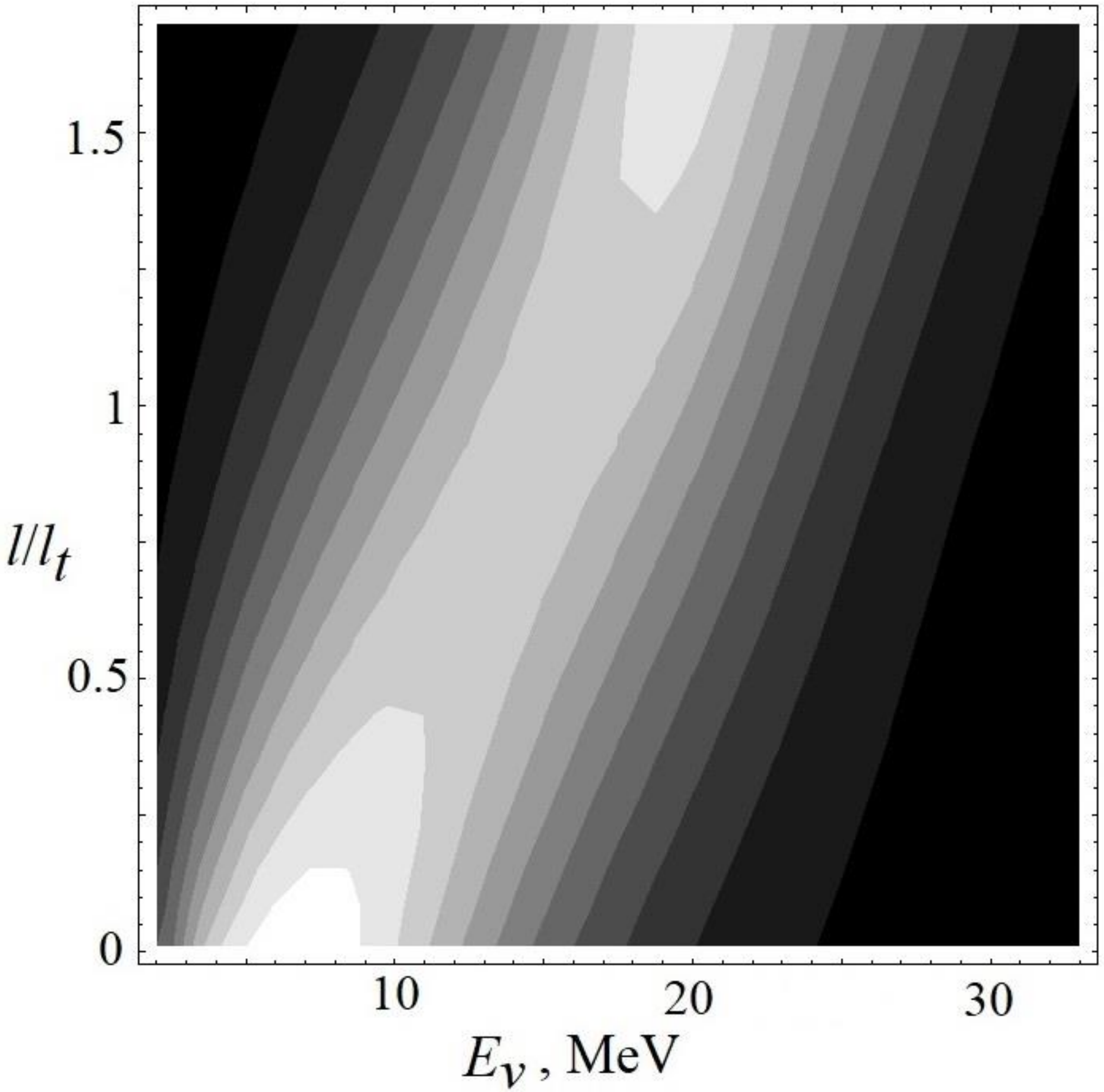
$T = 5 – 10$ MeV, $e_t = 1, 2, 3$

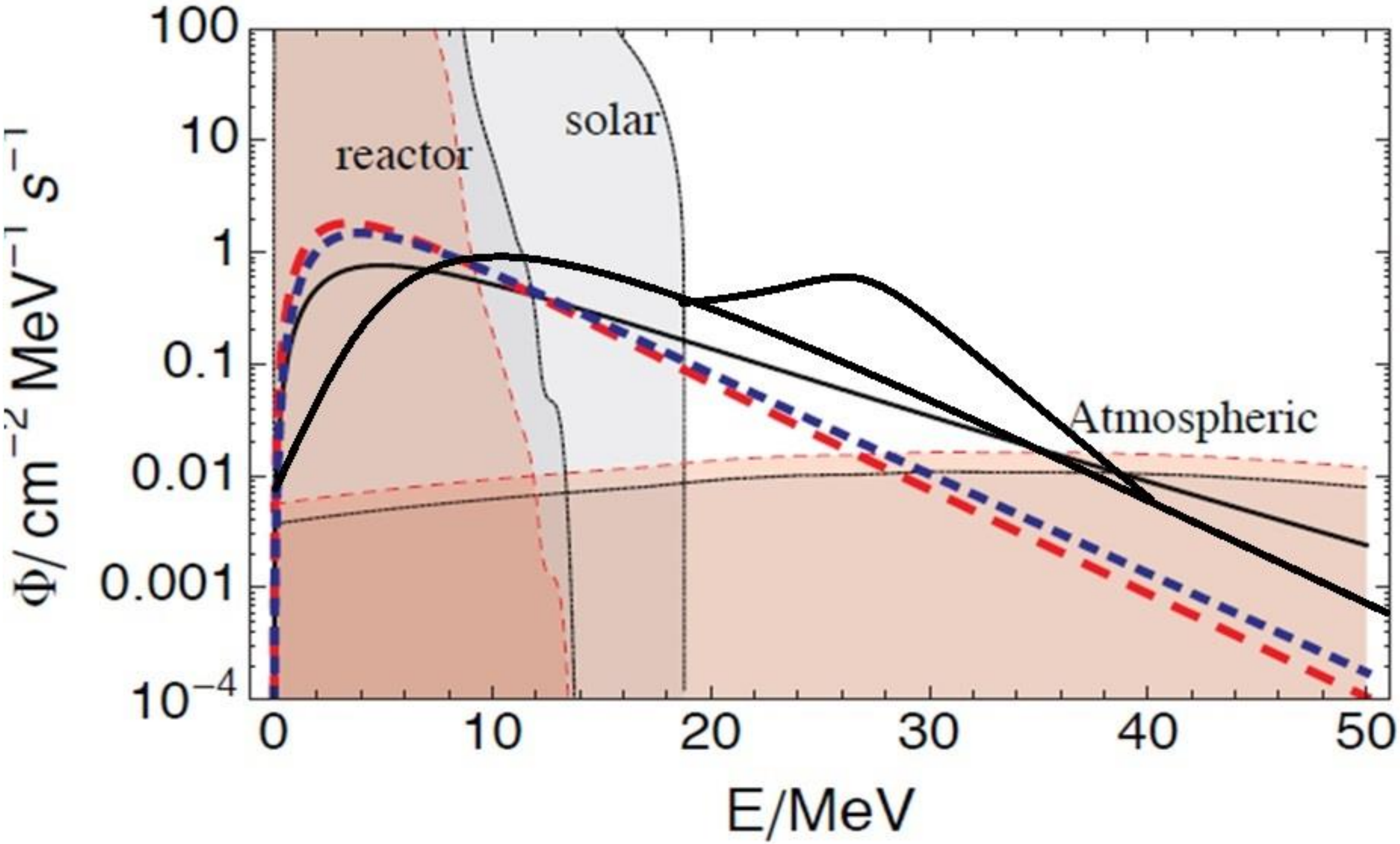


$T = 10$ MeV

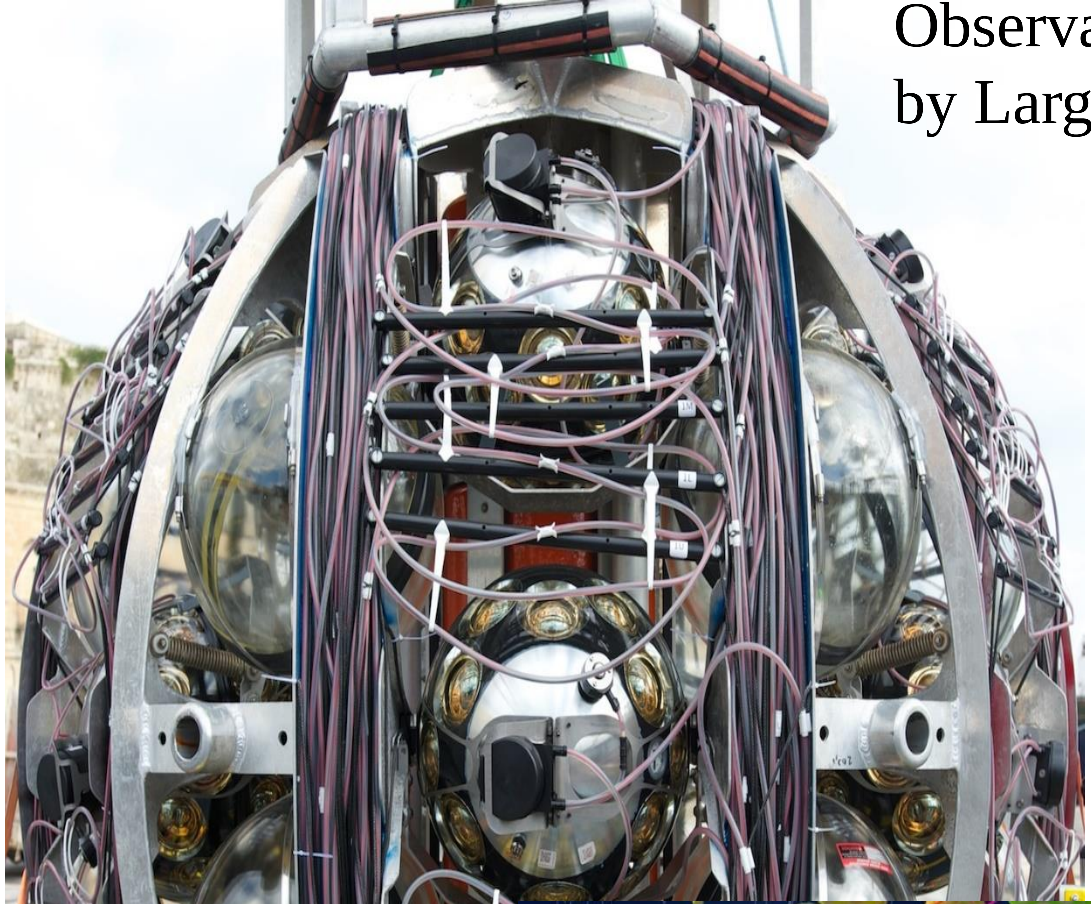


$T = 5 - 10$ MeV





$$f_\nu(E) \propto E^\alpha\, e^{-(\alpha+1)E/E_{\mathrm{av}}}$$



Observation of supernova neutrino flux by Large Volume Neutrino Telescopes

KM3NeT & **Baikal-GVD**

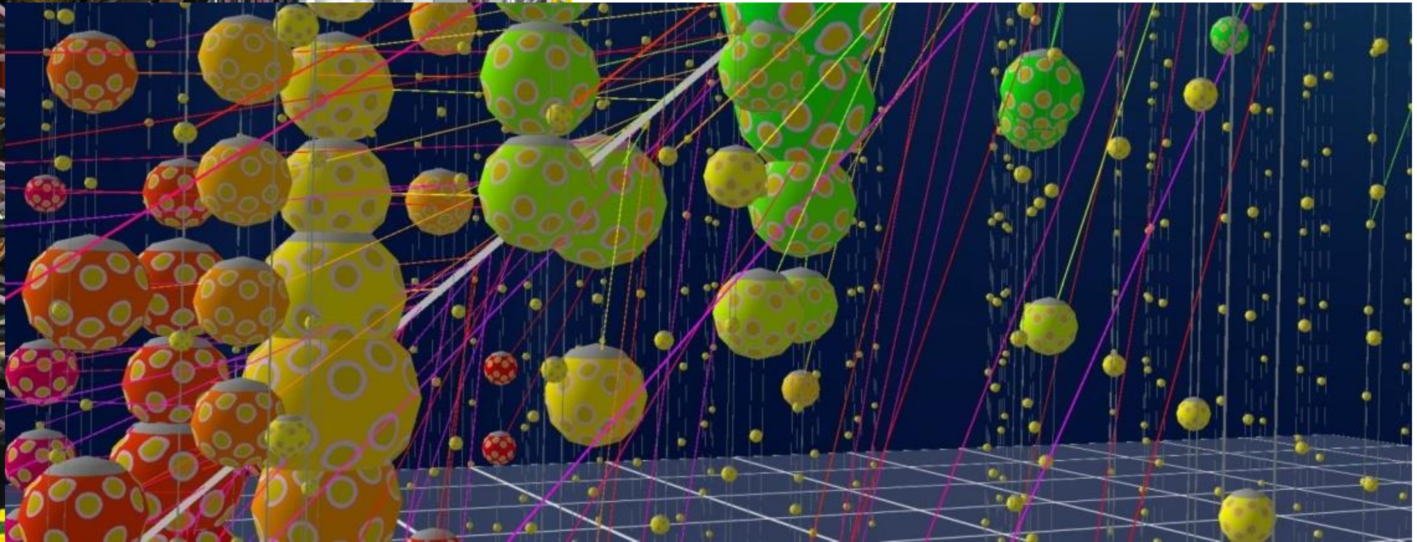
Digital Optical Module (DOE)

$$\overline{\nu}_e + p \rightarrow e^+ + n$$

$$\nu + e^- \rightarrow \nu + e^-$$

$$\nu_e + {}^{16}\mathrm{O} \rightarrow e^- + {}^{16}\mathrm{F},$$

$$\bar{\nu}_e + {}^{16}\mathrm{O} \rightarrow e^+ + {}^{16}\mathrm{N}$$



Neutrino fluence

$$\Phi(t) = \frac{L}{4\pi d^2} = \frac{L}{10^{57} \nu \ /s} \times \left(\frac{3\text{кпк}}{d}\right)^2 \times 10^{12} \ \nu \ sec^{-1} \ cm^{-2}$$

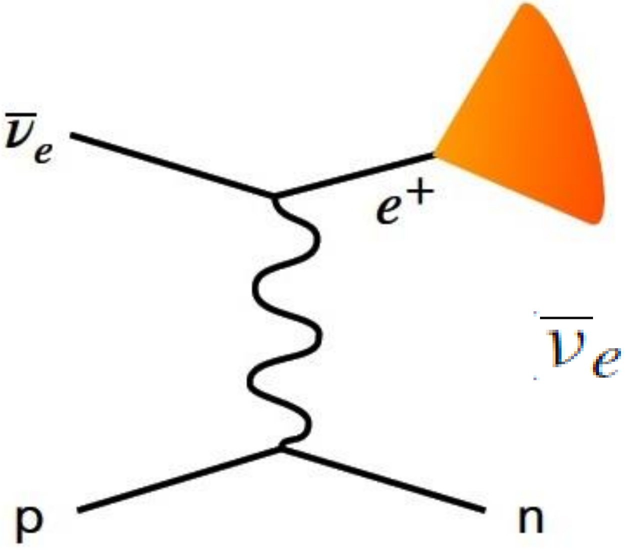
L & *d* – luminosity & *distance* to SN

Count rate

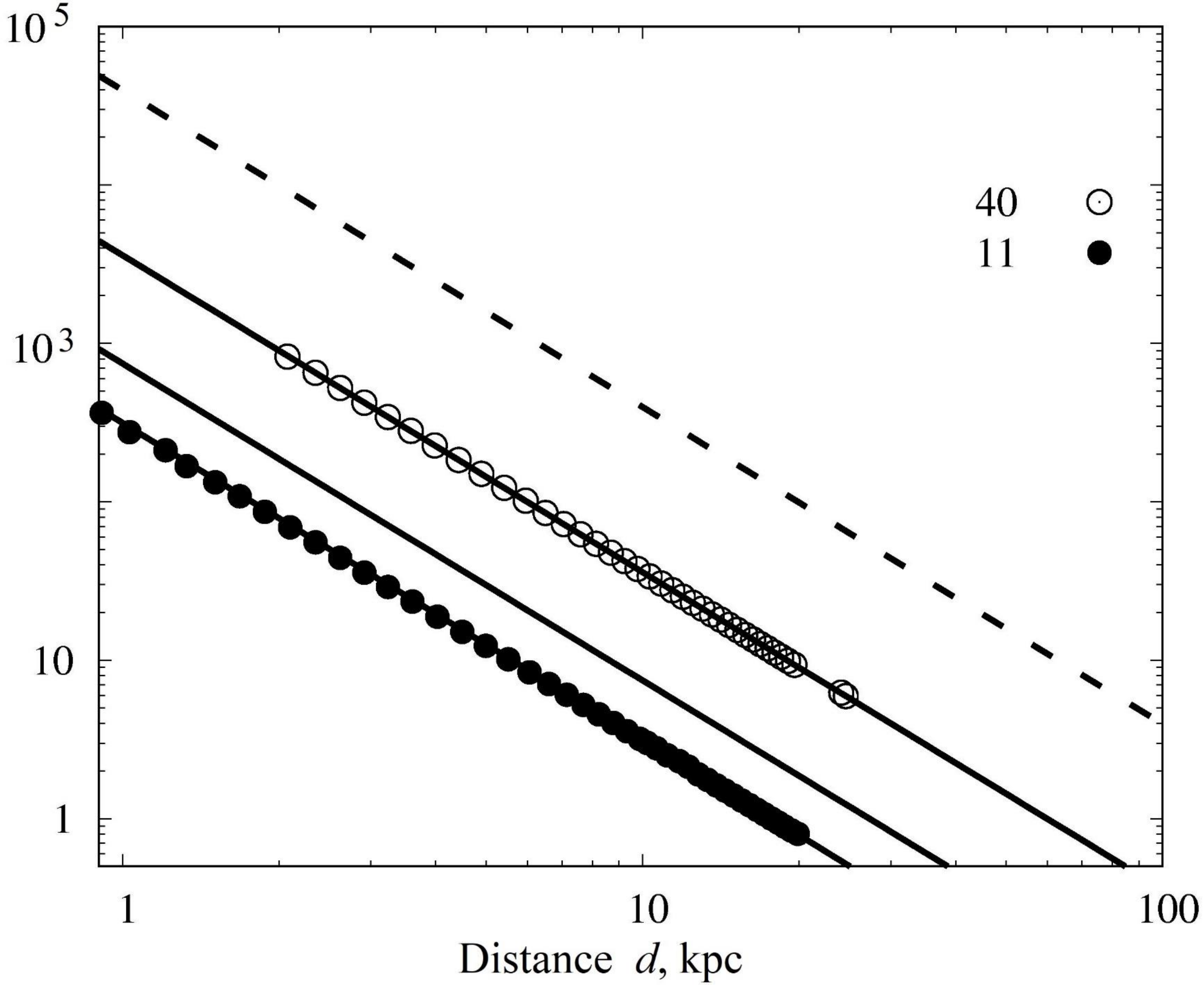
SN signal

$$r_{SN}(t) = \Phi(t) \, \Sigma_i \, n_i < \sigma^i \varphi > \sim L < \varepsilon^{3.5} > /d^2$$

$$< \sigma^i \varphi > = \int d\varepsilon \, W(\varepsilon) \, \sigma^i(\varepsilon) \, \varphi(\varepsilon) \sim < \varepsilon^{3.5} >$$



$$\overline{\nu}_e + p \rightarrow e^+ + n$$

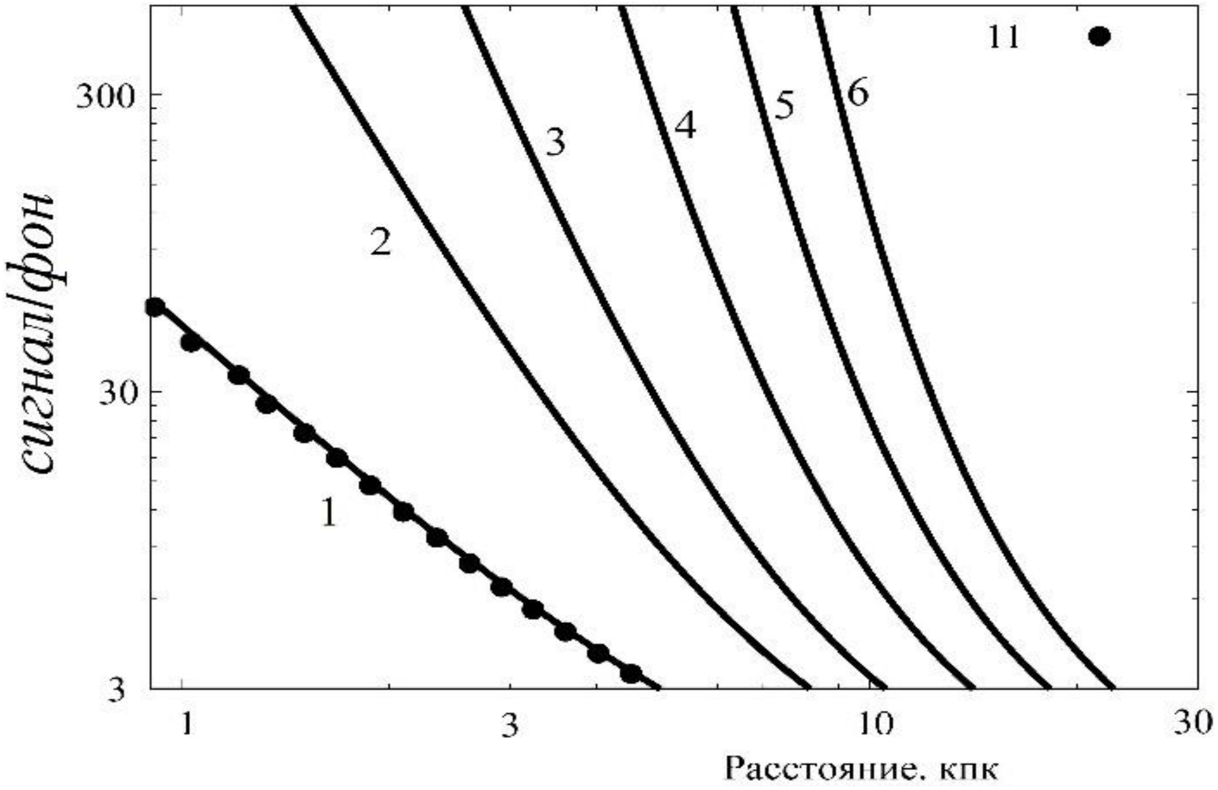


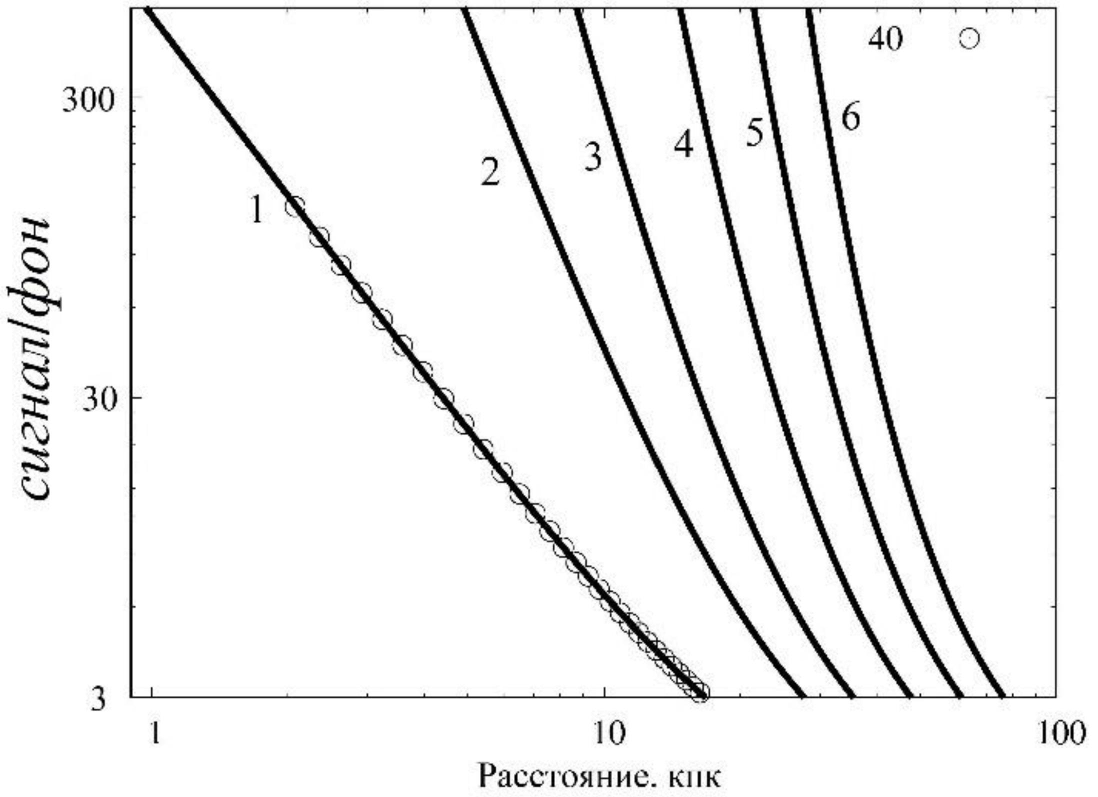
10^5
10^3
10
1
1
10
100
Distance *d*, kpc
40 ○
11 ●

пуассоновские потоки –
сигнал (SN) + фон (B)

$$\frac{P(X_1+X_2=k)}{P(X_1=k)} = \left(1+\frac{r_{SN}}{r_B}\right)^k e^{-p_{SN}} \approx 1+k\frac{r_{SN}}{r_B}.$$

Отношение   сигнал (SN) / фон (B)



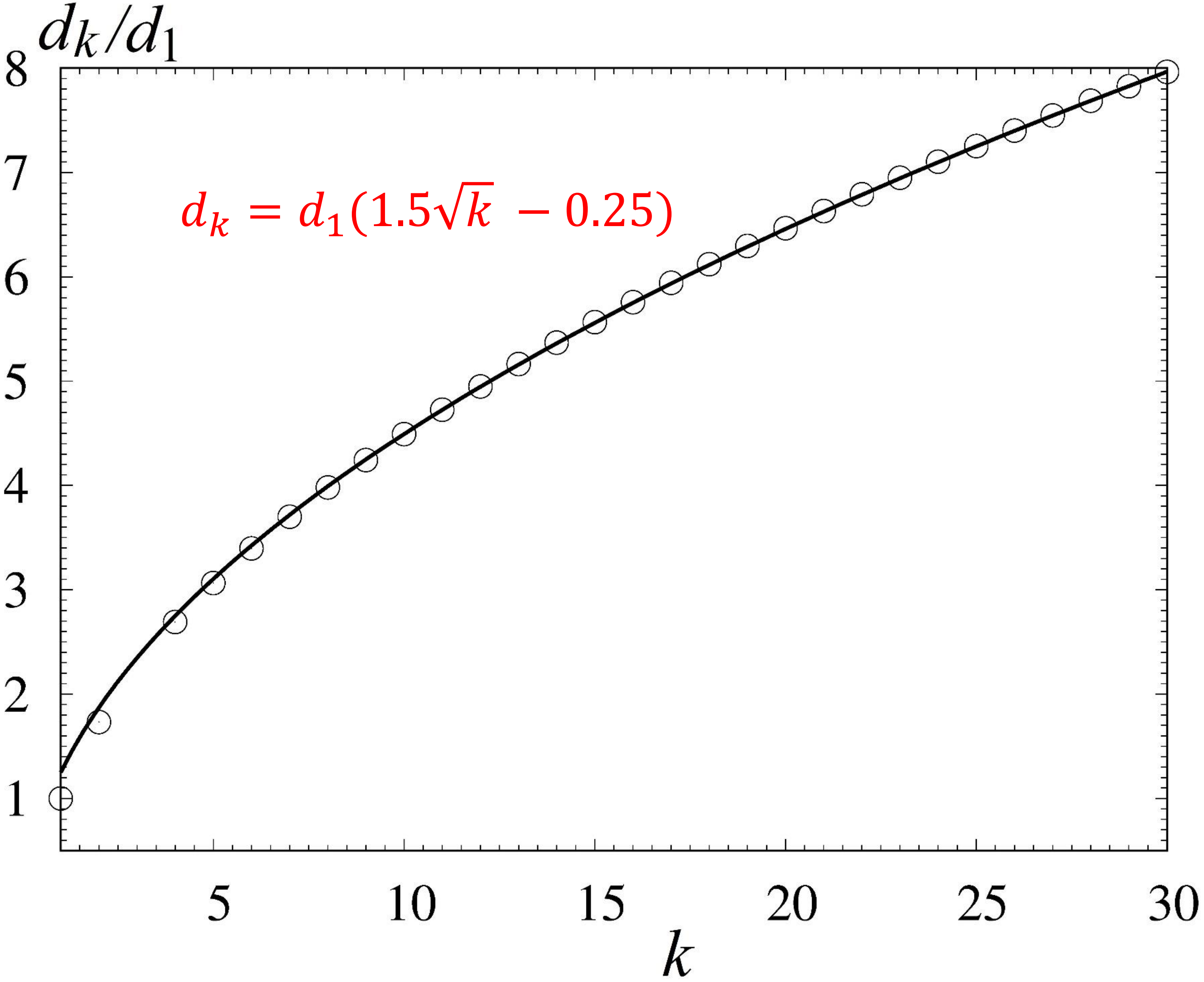


Расстояния

: кривые 1, 2, 3, 4, 5 и 6 --- 1, 2, 3, 5, 8 и 12 совпадений

$$d_k = d_1\sqrt{3/(4^{\frac{1}{k}}-1)}$$

Distance



$$d_k = d_1(1.5\sqrt{k} - 0.25)$$

Расстояния

$$d_k = d_1\sqrt{3/(4^{\frac{1}{k}}-1)}$$

Neutrino masses &
vacuum neutrino oscillations

weak interaction eigenstates

NEUTRINO $\nu_e \leftrightarrow$ positron

$\nu_\mu \leftrightarrow$ muon

MASS eigenstates $|\upsilon_1\rangle$ & $|\upsilon_2\rangle$ with masses

m$_1$ & m$_2$

$$|\upsilon_e\rangle = \cos\theta_\upsilon\ |\upsilon_1\rangle + \sin\theta_\upsilon\ |\upsilon_2\rangle$$

$$|\upsilon_\mu\rangle = \sin\theta_\upsilon\ |\upsilon_1\rangle + \cos\theta_\upsilon\ |\upsilon_2\rangle$$

(vacuum) mixing angle θ_υ .

time t=0 → $\left|\upsilon(\mathrm{t=0})\right\rangle = \left|\upsilon_{\mathrm{e}}\right\rangle = \cos\theta_{\upsilon}\left|\upsilon_1\right\rangle + \sin\theta_{\upsilon}\left|\upsilon_2\right\rangle$

Each eigenstate propagates with a phase ↘

$$\exp\left\{i\left(\vec{k}\vec{x}-\omega t\right)\right\} = \exp\left\{i\left(\vec{k}\vec{x}-t\sqrt{m_i^2+k^2}\right)\right\}$$

$$\sqrt{m_i^2+k^2} \approx k\left(1+\frac{m_i^2}{2k^2}\right)$$

neutrino mass<<momentum ↙

$$\left|\upsilon(\mathrm{t})\right\rangle = \exp\left\{i\left(\vec{k}\vec{x}-kt-\frac{m_1^2+m_2^2}{2k}t\right)\right\}$$

$$\left[\cos\theta_{\upsilon}\left|\upsilon_1\right\rangle\exp\left\{i\delta m^2 t/4k\right\}+\sin\theta_{\upsilon}\left|\upsilon_2\right\rangle\exp\left\{-i\delta m^2 t/4k\right\}\right]$$

BEAT PHASE $\delta m^2 = m_2^2 - m_1^2$

PROBABILITY for neutrino state

to remain $|\upsilon_e\rangle$ at time ***t***

$$P_{\upsilon_e}(t) = \left|\langle \upsilon_e | \upsilon(t)\rangle\right|^2$$

$$= 1 - \sin^2 2\theta_\upsilon \sin^2\left(\frac{\delta m^2 t}{4k}\right) \rightarrow \quad 1 - \sin^2 2\theta_\upsilon$$

m<< E ~ k → $P_\upsilon(x) = 1 - \sin^2 2\theta_\upsilon \sin^2\left(\frac{\delta m^2 c^4 x}{4\hbar c E}\right)$

oscillation length $L_o = \frac{4\pi\hbar c E}{\delta m^2 c^4}$

E~ 1 MeV: sensitivity to $\delta m_\upsilon^2 \geq 10^{-12}\ \text{eV}^2$

initial muon neutrino ($\left|\upsilon(t=0)\right\rangle = \left|\upsilon_\mu\right\rangle$) is

$$\left|\upsilon(\mathrm{t})\right\rangle = \exp\left\{ i\left(\vec{k}\vec{x} - kt - \frac{m_1^2 + m_2^2}{2k} t \right) \right\}$$

(eq.B)

$$\left[\text{-}\sin\theta_\upsilon \; \left|\upsilon_1\right\rangle \exp\left\{ i\delta m^2 t/4k \right\} + \cos\theta_\upsilon \; \left|\upsilon_2\right\rangle \exp\left\{ -i\delta m^2 t/4k \right\} \right]$$

`more general form`

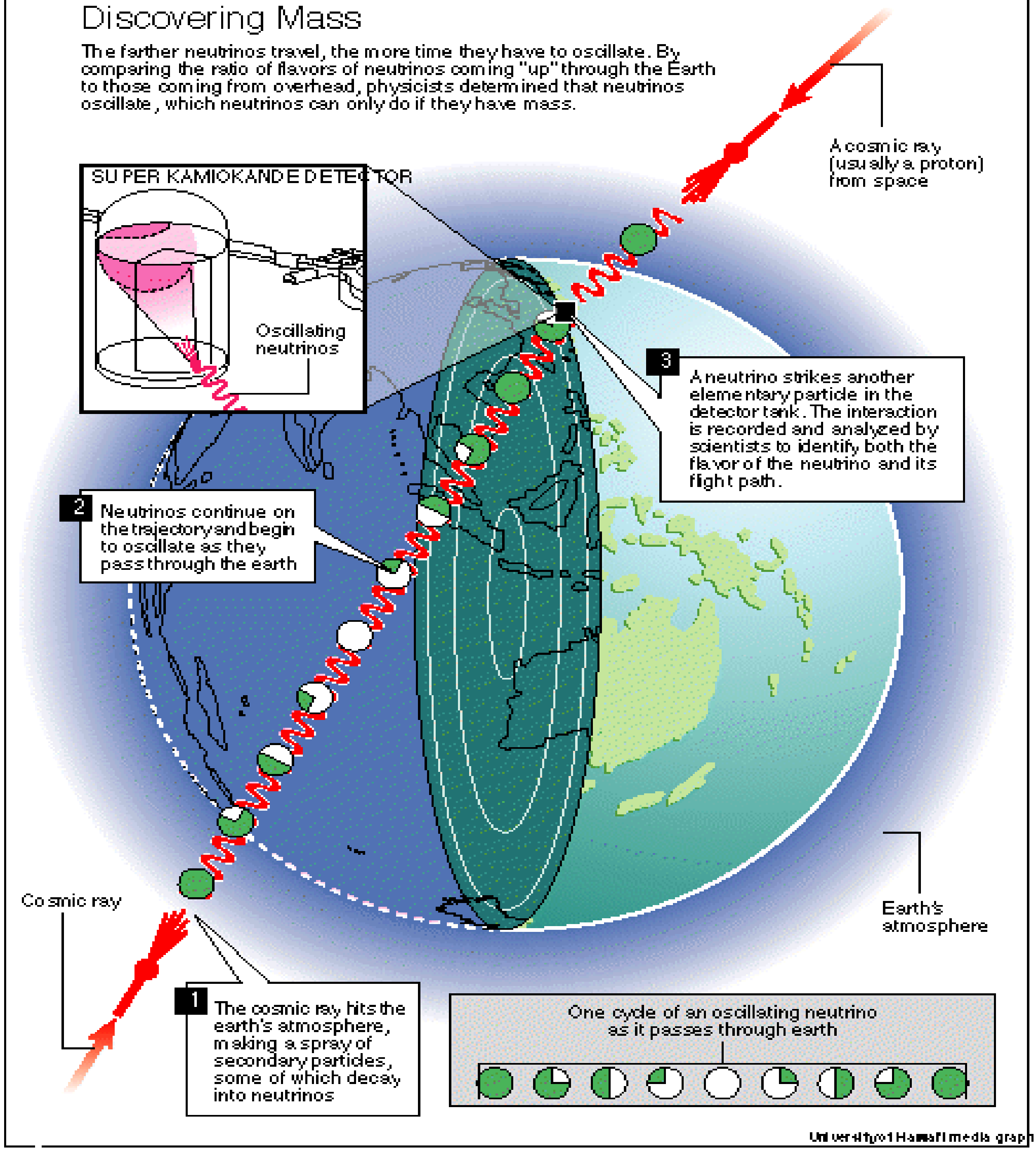
$$\left|\upsilon(t=0)\right\rangle = a_e(t=0)\left|\upsilon_e\right\rangle + a_\mu(t=0)\left|\upsilon_\mu\right\rangle$$

From eqs. (A) and (B) → propagation is described by changes in ***$a_e(x)$ & $a_\mu(x)$*** according to

$$i\frac{d}{dx}\begin{pmatrix} a_e \\ a_\mu \end{pmatrix} = \frac{1}{4E}\begin{pmatrix} -\delta m^2 \cos 2\theta_\upsilon & \delta m^2 \sin 2\theta_\upsilon \\ \delta m^2 \sin 2\theta_\upsilon & \delta m^2 \cos 2\theta_\upsilon \end{pmatrix}\begin{pmatrix} a_e \\ a_\mu \end{pmatrix}$$

Discovering Mass

The farther neutrinos travel, the more time they have to oscillate. By comparing the ratio of flavors of neutrinos coming "up" through the Earth to those coming from overhead, physicists determined that neutrinos oscillate, which neutrinos can only do if they have mass.



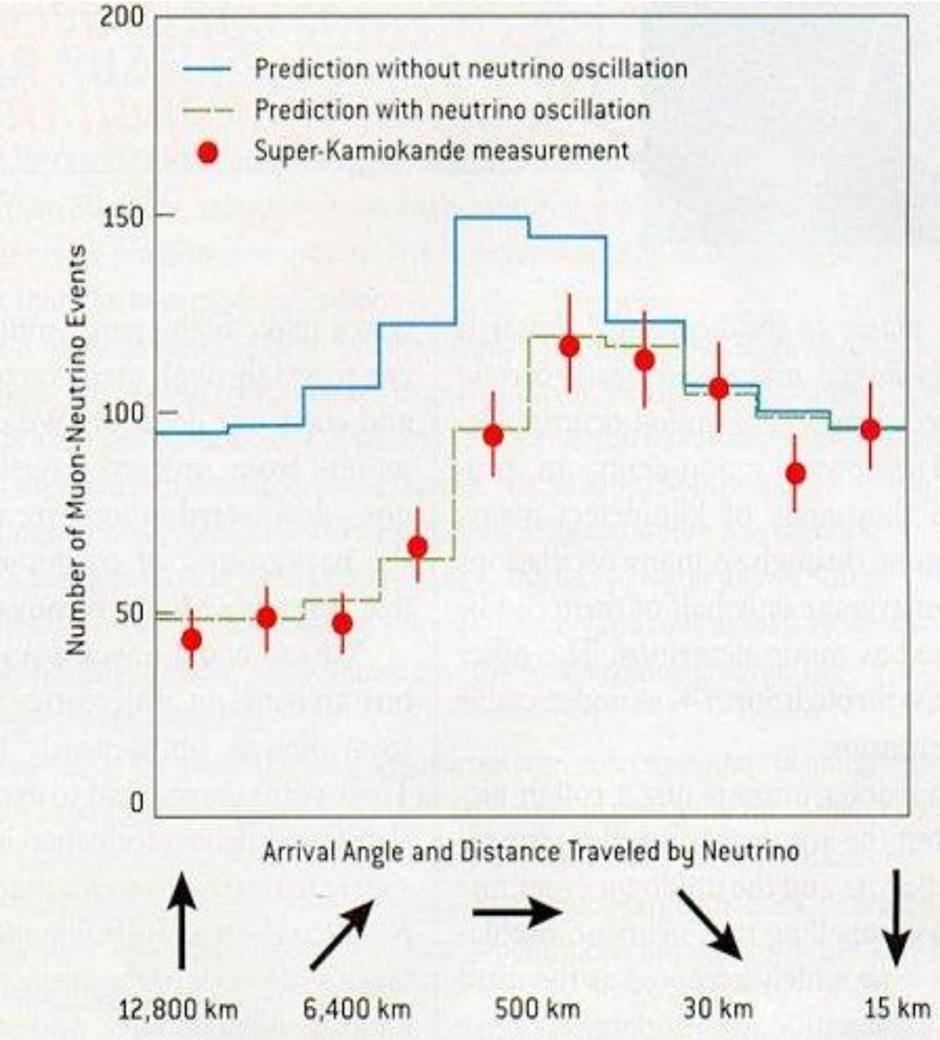
1 The cosmic ray hits the earth's atmosphere, making a spray of secondary particles, some of which decay into neutrinos

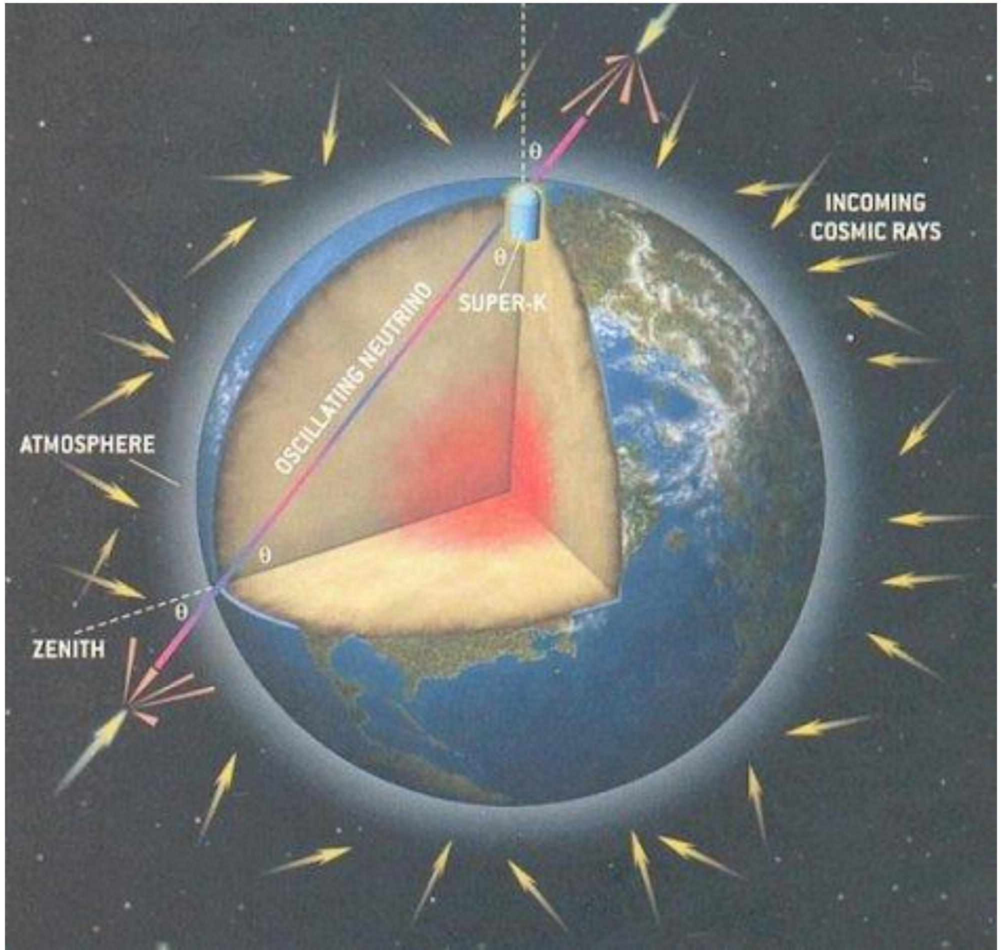
2 Neutrinos continue on the trajectory and begin to oscillate as they pass through the earth

3 A neutrino strikes another elementary particle in the detector tank. The interaction is recorded and analyzed by scientists to identify both the flavor of the neutrino and its flight path.

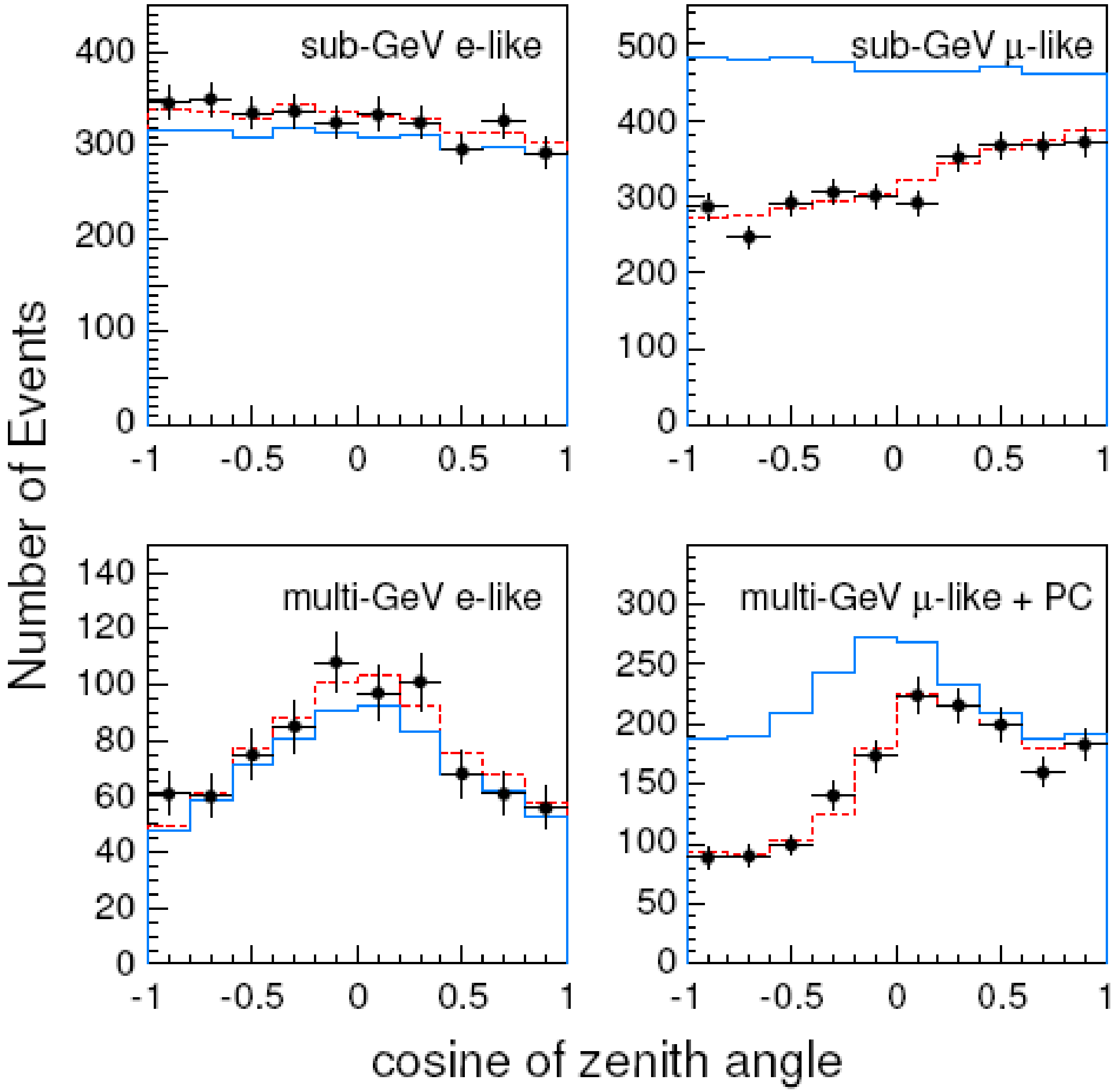
University of Hawaii media graphic

SuperKamiokande

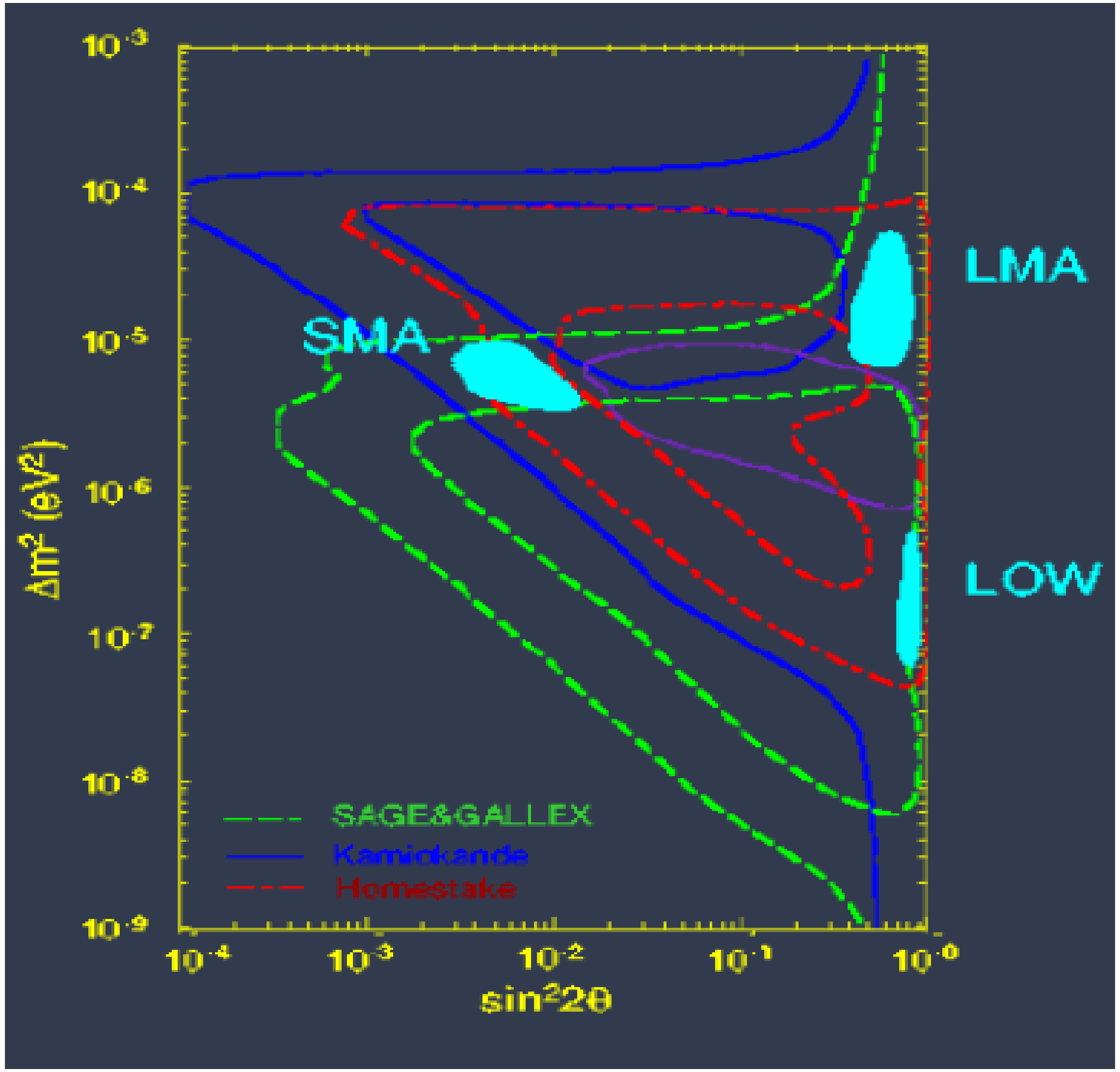




SuperKamiokande



solution for Cl/Ga/Kamiokande/Super-Kamiokande solar neutrino puzzle



Mikheyev-Smirnov-Wolfenstein effect

NEUTRINO WAVE FUNCTION in matter

$$\left|\upsilon(x)\right\rangle = a_e(x)\left|\upsilon_e\right\rangle + a_\mu(x)\left|\upsilon_\mu\right\rangle$$

coordinate along neutrino’s path ↗↘***x***↗↘

Amplitudes *$a_e(x)$& $a_\mu(x)$*

$$i\frac{d}{dx}\begin{pmatrix} a_e \\ a_\mu \end{pmatrix} = \frac{1}{4E}\begin{pmatrix} 2E\sqrt{2}\mathrm{G_F}\rho(\mathrm{x}) - \delta m^2\cos 2\theta_\upsilon & \delta m^2\sin 2\theta_\upsilon \\ \delta m^2\sin 2\theta_\upsilon & 2E\sqrt{2}\mathrm{G_F}\rho(\mathrm{x}) + \delta m^2\cos 2\theta_\upsilon \end{pmatrix}\begin{pmatrix} a_e \\ a_\mu \end{pmatrix}$$

contribution $2E\sqrt{2}G_F\rho(x)$ ➚ diagonal parts,

neutrino-electron scattering.

G_F -- the weak coupling constant &

$\rho(x)$ solar electron density

LIGHT & HEAVY local mass *eigenstates*

$$\left|\upsilon_{\mathrm{L}}\right\rangle = \cos\theta(x)\ \left|\upsilon_e\right\rangle - \sin\theta(x)\ \left|\upsilon_\mu\right\rangle$$

$$\left|\upsilon_{\mathrm{H}}\right\rangle = \sin\theta(x)\ \left|\upsilon_e\right\rangle + \cos\theta(x)\ \left|\upsilon_\mu\right\rangle$$

local mixing angle

$$\sin 2\theta(x) = \frac{\sin 2\theta_\upsilon}{\sqrt{X^2(x) + \sin^2 2\theta_\upsilon}}$$

$$\cos 2\theta(x) = \frac{-X(x)}{\sqrt{X^2(x) + \sin^2 2\theta_\upsilon}}$$

$$X(x) = 2E\sqrt{2}G_F\,\rho(x)E/\delta m^2 - \cos 2\theta_\upsilon \ :$$

$\theta(x) \in\ \theta_\upsilon \rightarrow {}^{\pi/2}$ as density $\rho(x)$ $0 \rightarrow \infty$.

neutrino

$$\left|\upsilon(x)\right\rangle = a_H(x)\left|\upsilon_H(x)\right\rangle + a_L(x)\left|\upsilon_L(x)\right\rangle$$

propagation in terms of the LOCAL MASS EIGENSTATES

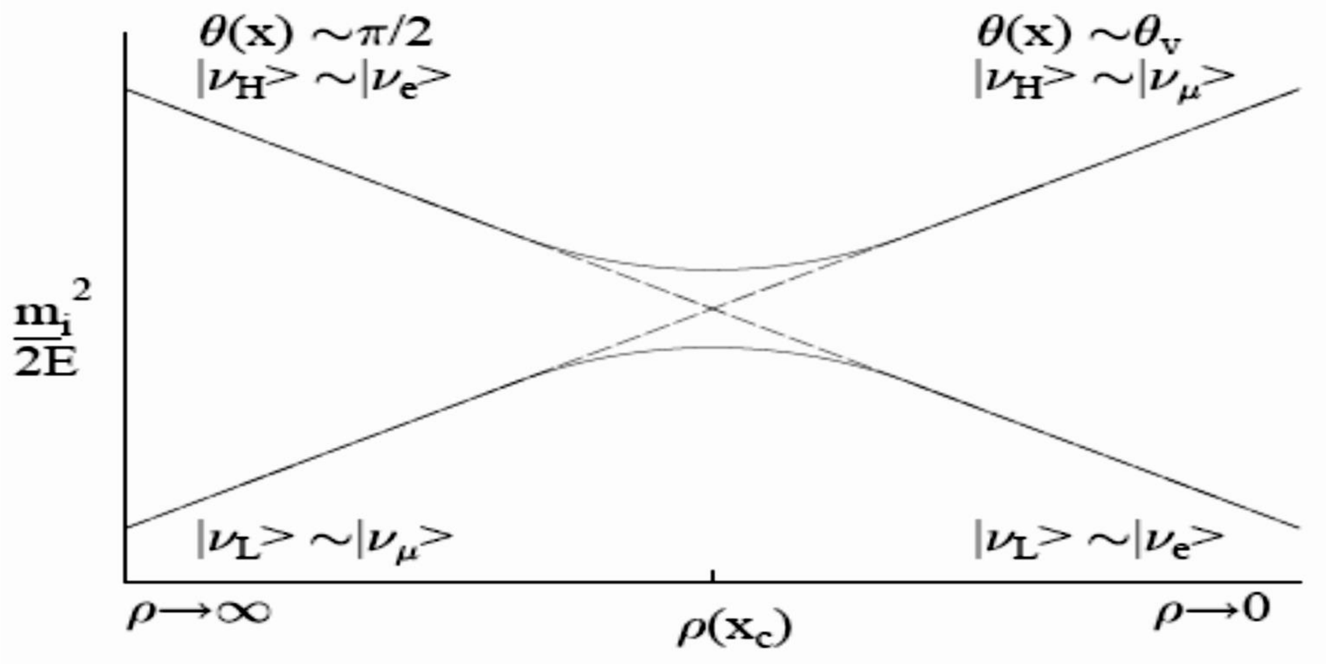
$$i\frac{d}{dx}\begin{pmatrix} a_H \\ a_L \end{pmatrix} = \frac{1}{4E}\begin{pmatrix} \lambda(\mathrm{x}) & i\alpha(x) \\ -i\alpha(x) & -\lambda(\mathrm{x}) \end{pmatrix}\begin{pmatrix} a_H \\ a_L \end{pmatrix}$$

local mass eigenstates **splitting** $2\lambda(x) = \frac{\delta m^2}{2E}\sqrt{X^2(x) + \sin^2 2\theta_\upsilon}$

& mixing $\alpha(x) = \left(\frac{E}{\delta m^2}\right)\frac{\sqrt{2}G_F \partial_x \rho(x) \sin 2\theta_\upsilon}{X^2(x) + \sin\ 2\theta_\upsilon}$

Mikheyev-Smirnov-Wolfenstein

avoided level crossing



splitting minimum value: -- $\sin 2\theta_\upsilon \delta m^2 / 2E$,

at ***critical density*** $\rho_c = \rho(x_c) \leftarrow 2\sqrt{2}EG_F\rho_c = \delta m^2 \cos 2\theta_\upsilon$

cross point for diagonal elements of original flavor matrix

diagonal >> off-diagonal elements

$$\gamma(x)=\left|\frac{\lambda(x)}{\alpha(x)}\right|=\frac{\sin^2 2\theta_\upsilon}{\cos 2\theta_\upsilon}\left(\frac{\delta m^2}{2E}\right)\frac{1}{\left|\rho_c^{-1}\partial_x\rho(x)\right|}\frac{X^2(x)+\sin^2 2\theta_\upsilon}{\sin^2 2\theta_\upsilon}\gg 1$$

stringent to ***crossing point***

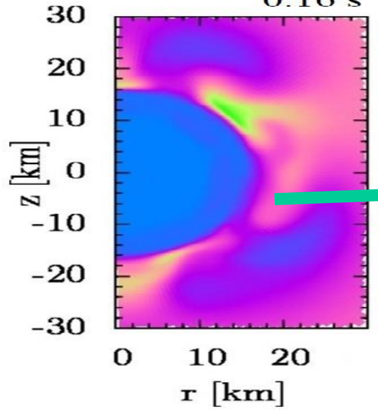
$$\gamma_c=\gamma(x_c)=\frac{\sin^2 2\theta_\upsilon}{\cos 2\theta_\upsilon}\left(\frac{\delta m^2}{2E}\right)\frac{1}{\left|\rho_c^{-1}\partial_x\rho(x)\right|_{x=x_c}}\gg 1$$

ELECTRON NEUTRINO SURVIVAL PROBABILITY

(adiabatic $\gamma_c \gg 1$)

$$P_{\upsilon_e}^{\text{adiab}}=\frac{1}{2}+\frac{1}{2}\cos 2\theta_\upsilon\cos 2\theta_i$$

local mixing angle $\theta_i=\theta(x_i)$ at point(density) **X↗↘** of neutrino creation.



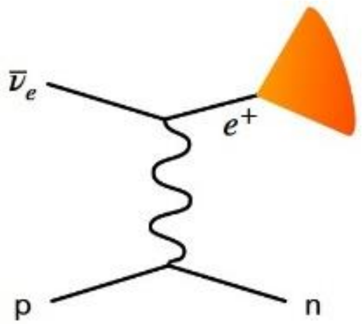
1–10 kg/cc

L

H

10–10^2 g/cc

$\overline{\nu}_e + p \rightarrow e^+ + n$ *SN ν signal* **Cou**

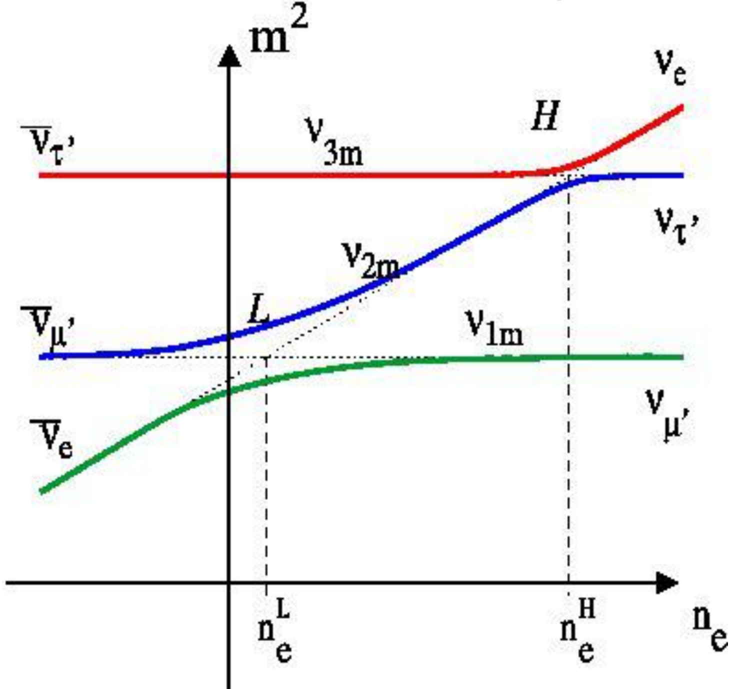


$r_{\mathrm{SN}}(t) \sim L < \varepsilon^{3.5} > /d^2$

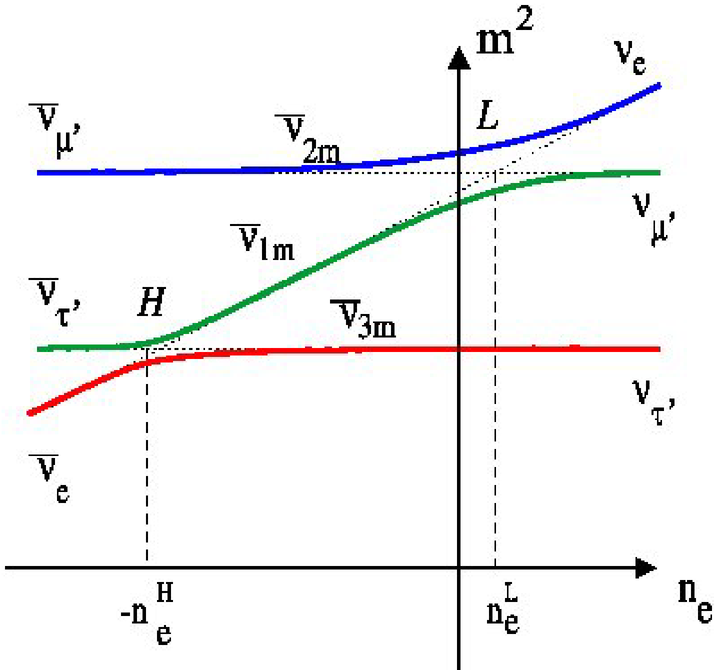
MSW Resonances inside a SN

$$\Phi^{E}_{\overline{\nu}_e} = g\,\Phi^{0}_{\overline{\nu}_e} + (1-g)\Phi^{0}_{\nu x}$$

Normal mass ordering



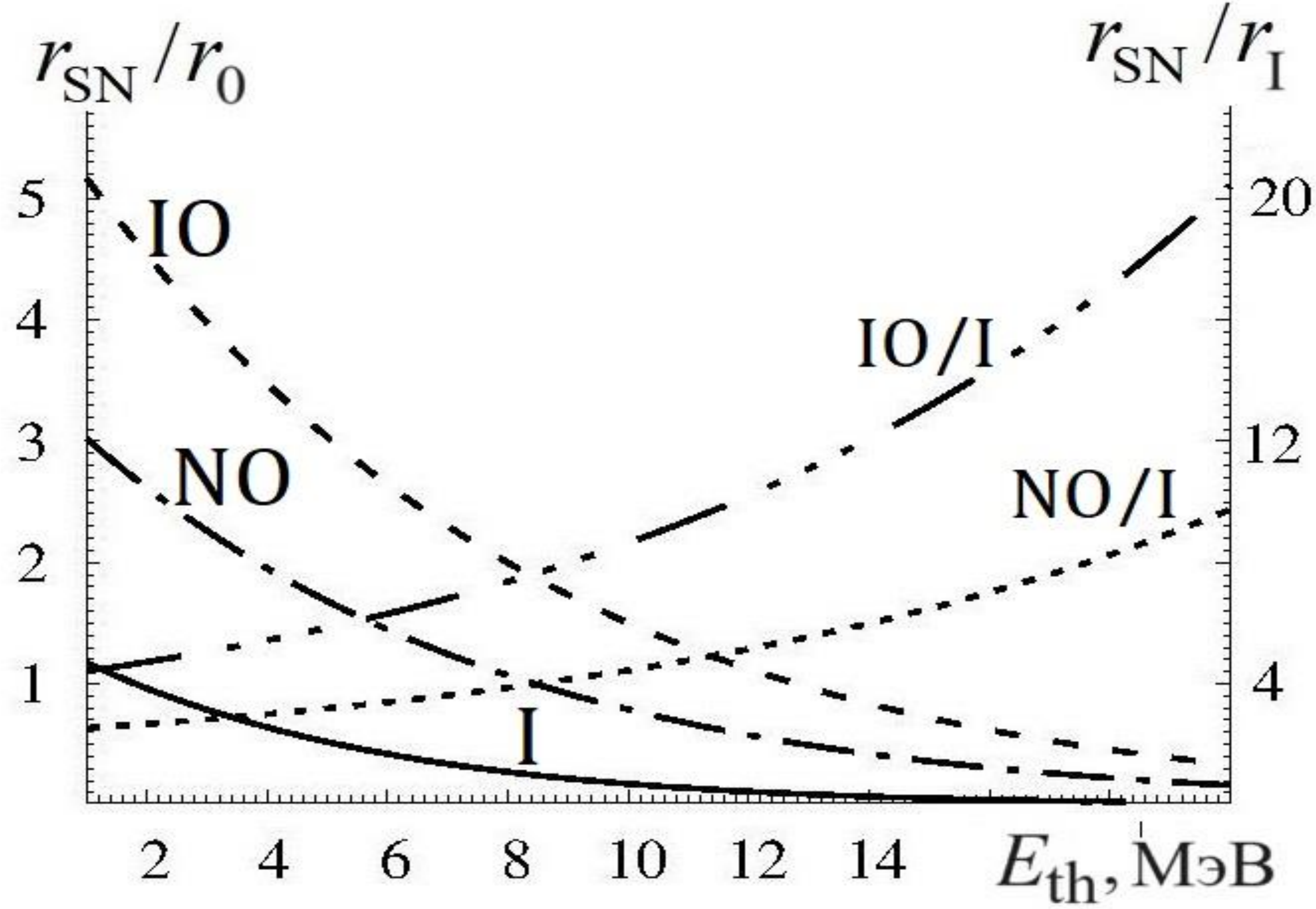
Inverted mass ordering



NO -> $g \approx 0.55$

IO -> $g \approx 0$

Rate *vs* mass ordering



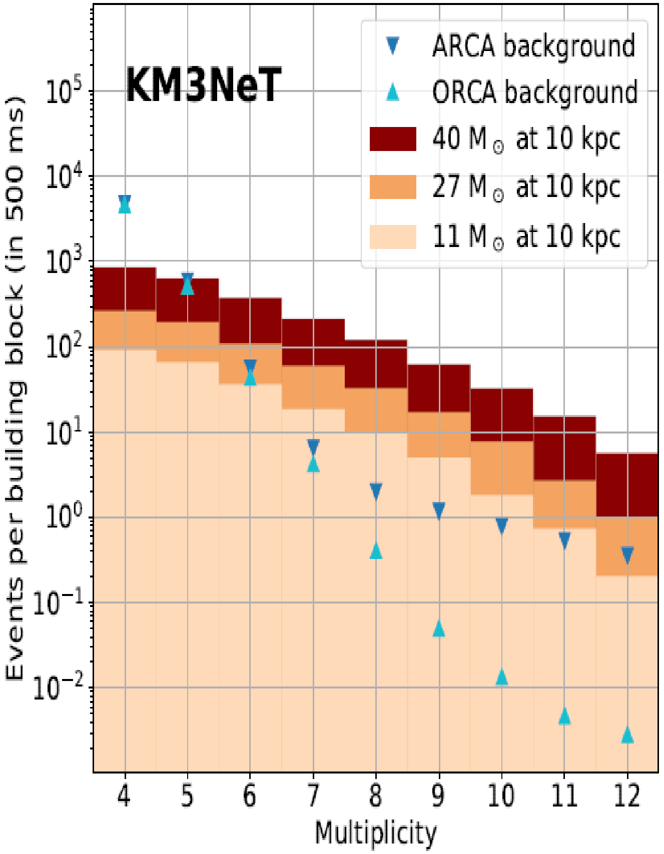
SUMMARY

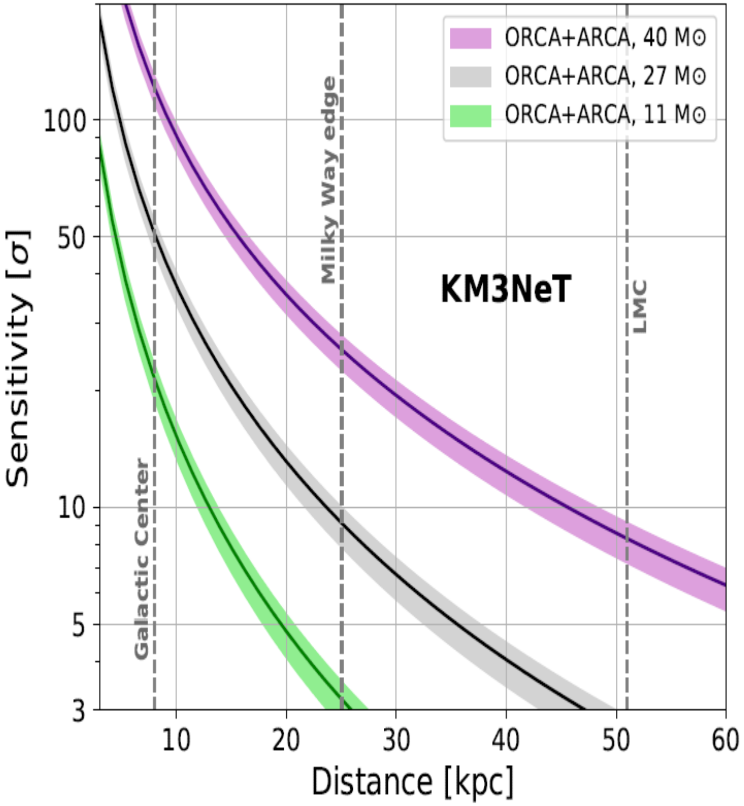
- We analyze the neutrino dynamics in hot & dense matter, SNe
- At finite temperature neutrinos undergo exo- and endo-energetic scattering on nuclei due to the Gamow-Teller component of neutral current.

SUMMARY

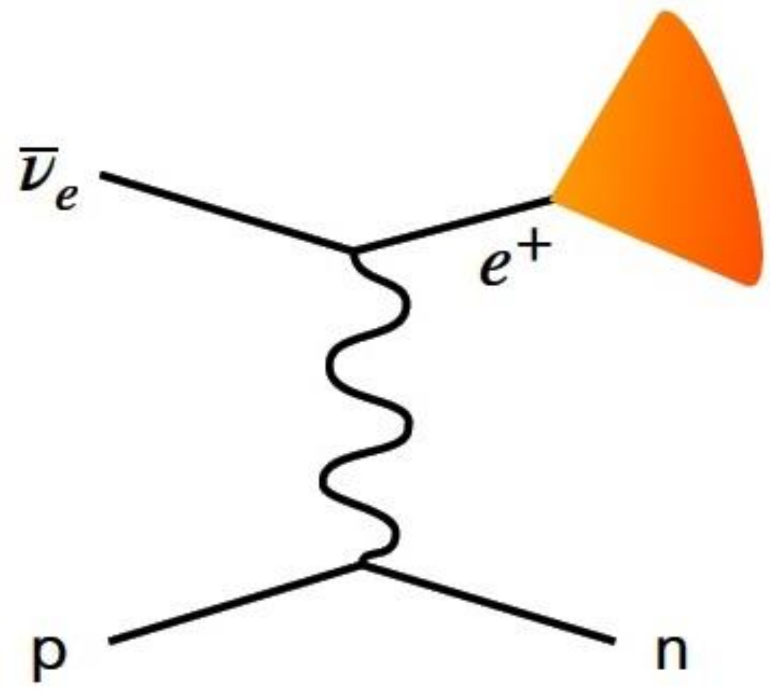
- kinetic equation for a neutrino phase-space distribution function
- energy transfer coefficient changes from positive to negative values when the neutrino energy exceeds four times the temperature.
- Overall increase neutrino energy
- Favorable for observation supernova neutrino flux by Large Volume Neutrino Telescopes

(MeV) Supernova neutrinos





SN WG (EPJC’21)

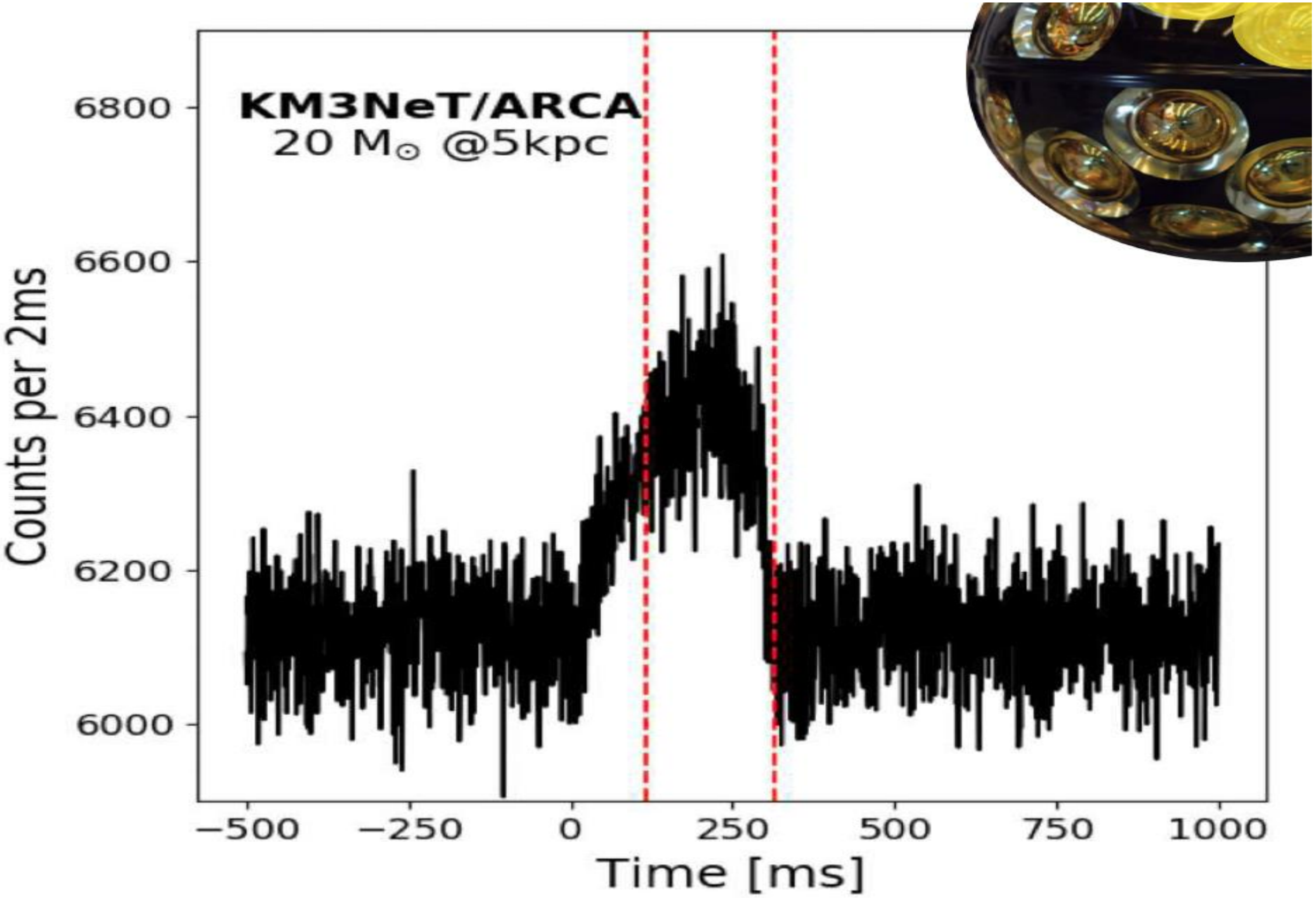


Single OM activation
No reconstruction

Inverse Beta Decay
$\mathcal{O}$(10 MeV) electron antineutrinos

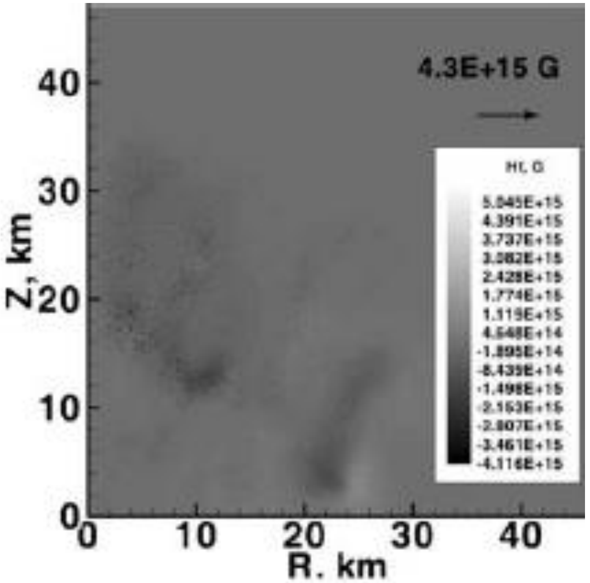
Buffer 10 min of data — Time evolution of supernova signal

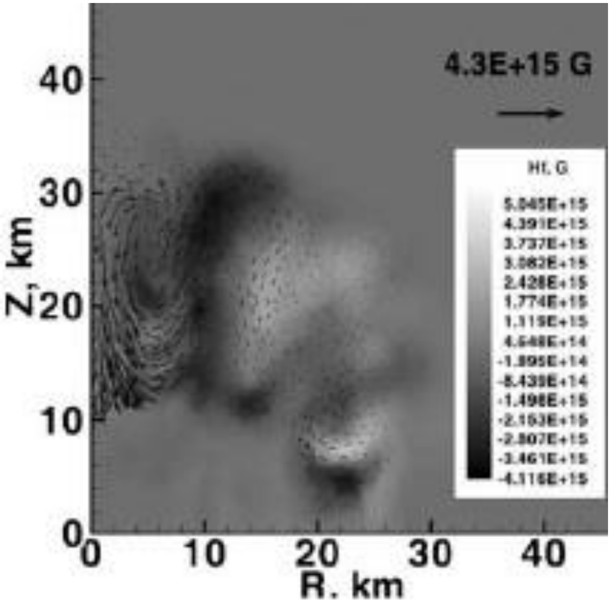
≥ 2 hits in 5 ns KM3NeT collaboration, *Eur. Phys. J. C* 81 (2021)

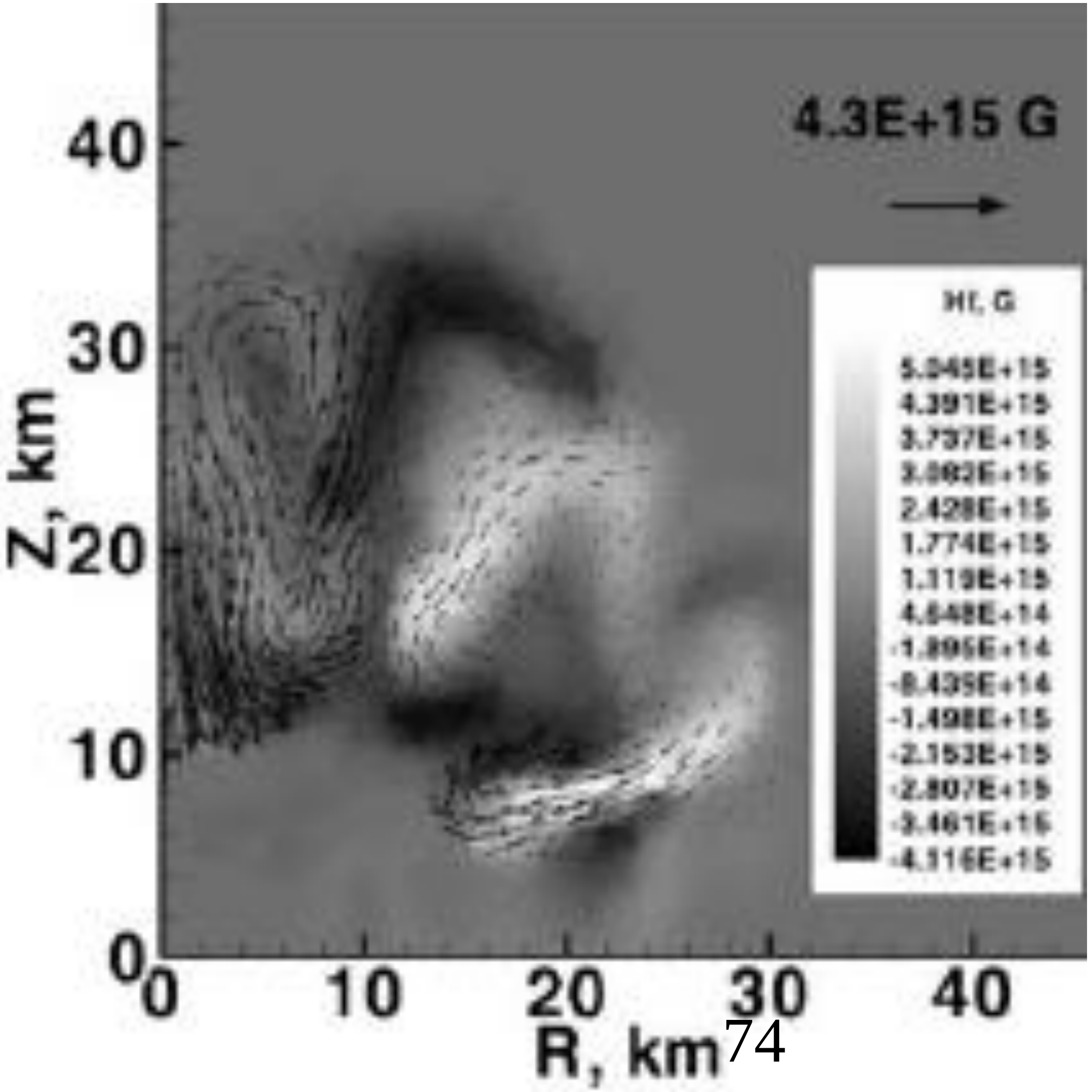


The magnetic field evaluation

(S.G.Moiseenko, G.S.Bisnovatyj-Kogan, N.V.Ardeljan, MNRAS 370 (2006) 501)







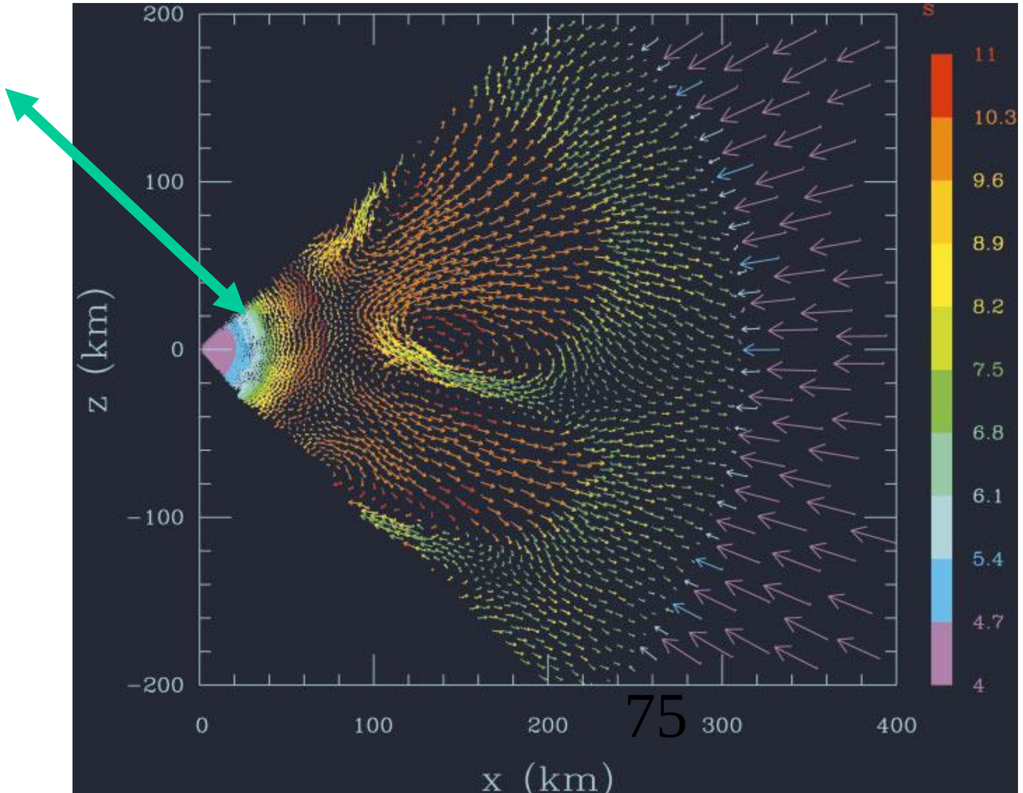
Magnetic field estimates

predominant energy component of shock wave E_S originates from the magnetic pressure

$$\langle B_\nu^2\rangle R_\nu^2 \Delta R \sim 2E_S \quad \sim 10^{51,5} \text{ ergs}$$

$R_\nu \sim 40$Km; $\Delta R \sim 1$Km

$B_\nu \sim 10^1 - 10^2$ TeraTesla



$$B(R) \sim B_\nu \quad R_\nu / R$$

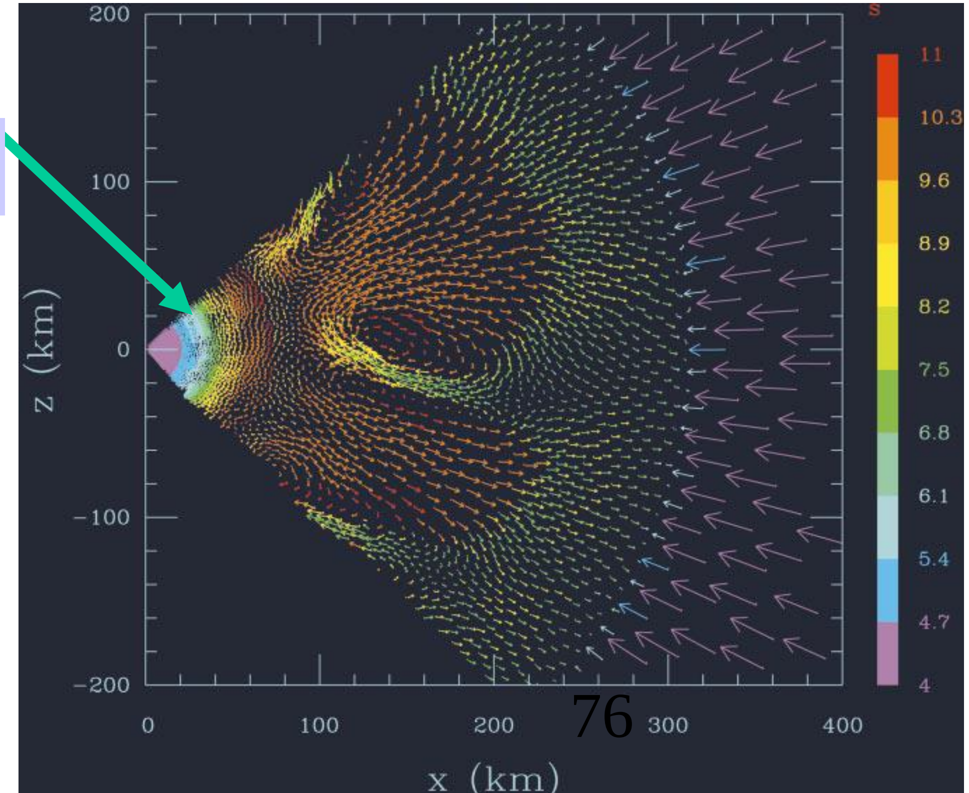
Magnetic field estimates

Magnetic and gravitational forces

$$dB_\nu^2/dR \sim 8\pi GM\, n(R)/R^2$$

$$4\pi R^2\, n(R) = dM/dR$$

$B \sim 10^{1.5}$ TeraTesla $(M/M_o)(10\text{km}/R)^2$



$R_\nu \sim 40$Km; 👎$R \sim 1$Km

$B_\nu \sim 10^1 - 10^2$ TeraTesla

Кинетическое уравнение для $f(E_\nu, l)$: Фоккера-Планка

$$\frac{d\hat{f}}{dt} = \frac{\partial \hat{f}}{\partial t} + p\frac{\partial \hat{f}}{\partial r} + \frac{\partial \hat{p}}{\partial t}\frac{\partial \hat{f}}{\partial p} = \Lambda[f] + \mathrm{St}[f] = 0_{p\hat{}}$$

Флуктуирующие величины: $\hat{p} = p + \delta p$

$$\hat{f} = f + \delta f \quad : \quad \delta f = -\left(f - \hat{f}\right) = -\frac{\partial f}{\partial p}\delta p$$

Успедняя Кинетическое уравнение для $f(E_\nu, l)$: Фоккера-Планка

$$\frac{\partial f}{\partial t} = -\frac{\partial p}{\partial t}\frac{\partial f}{\partial p} + \frac{1}{2}\frac{\partial < \delta p^2 >}{\partial t}\frac{\partial^2 f}{\partial p^2}$$

$$S_n^{\ i} = \int dE\,(-E)^n\,(d\sigma_i/dE)$$

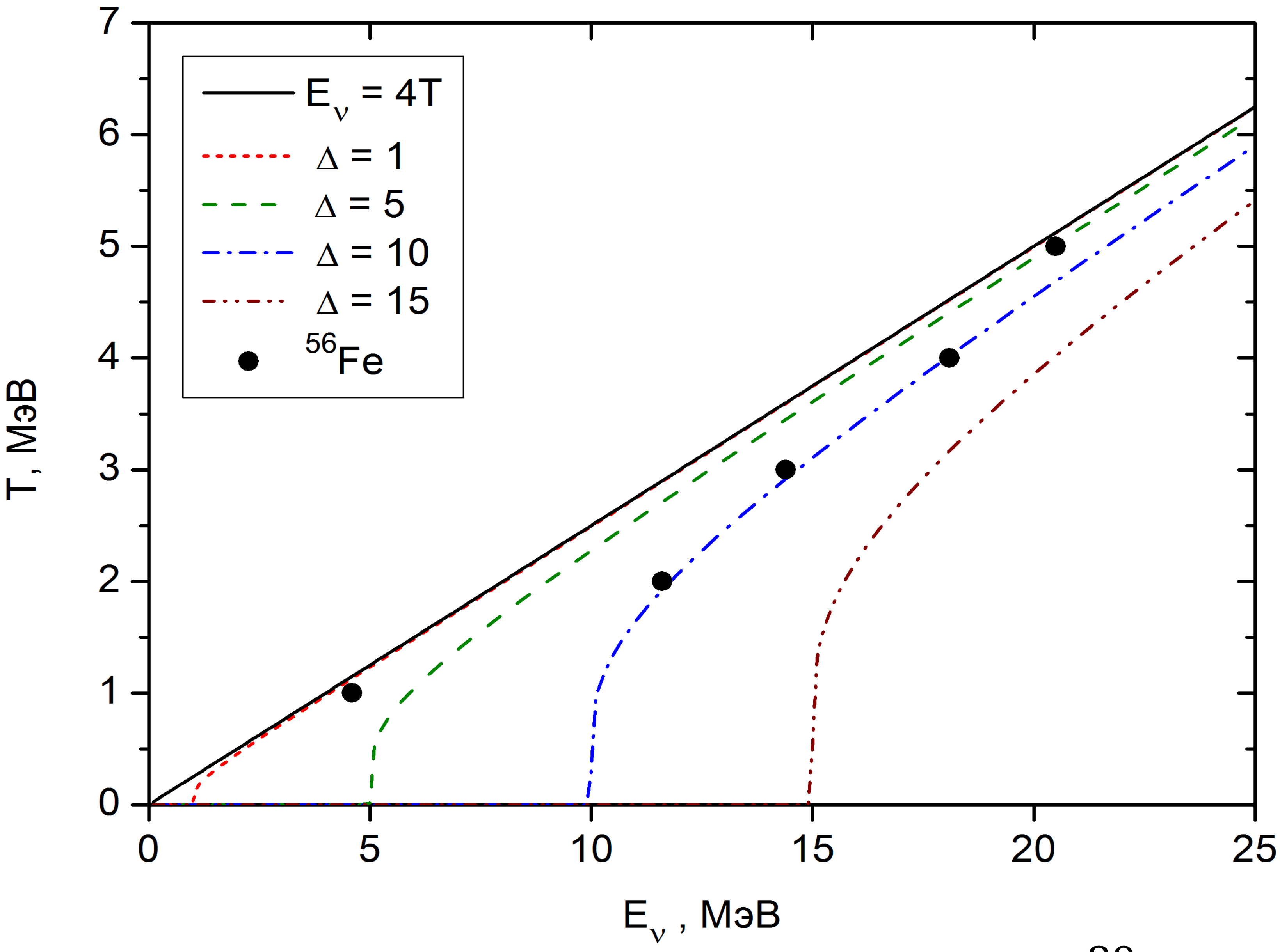
- $\frac{\partial p}{\partial t} = dE_\nu/dl = n_i S_1^{\ i}$ - коэф. переноса
- $\frac{\partial <\delta p^2>}{\partial t} = n_i S_2^{\ i}$ -- ***страглинг***

Kinetic Equation for $f(E_\nu,l)$

- $\mathrm{d}f/\mathrm{d}l = \partial f/\partial l + V\,\partial f/\partial E_\nu = \Lambda f + \mathrm{St}[f]$

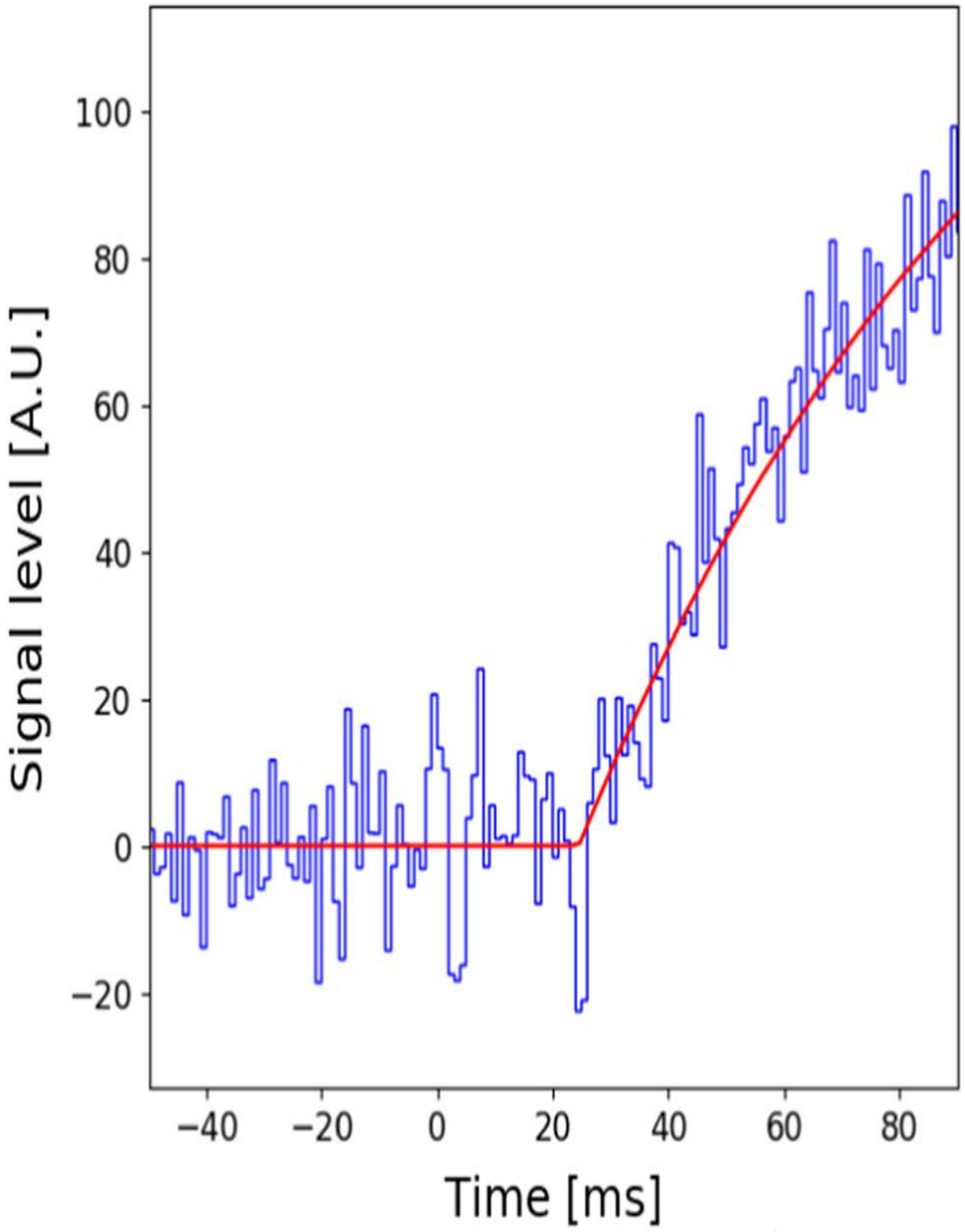
- $V = \mathrm{d}E_\nu/\mathrm{d}l = n_i S_1^{\,i}$ - energy transfer coefficient

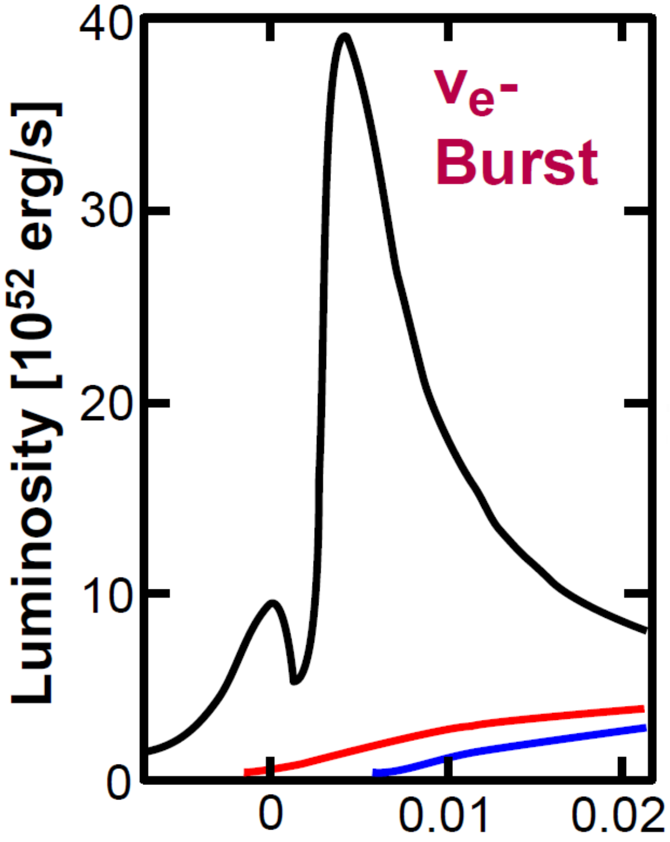
$$S_\mathrm{n}^{\,i} = \int \mathrm{d}E\,(-E)^n\,(\mathrm{d}\sigma_i/\mathrm{d}E)$$



7
6
5
4
3
2
1
0
T, МэВ
0
5
10
15
20
25
E_ν , МэВ
E_ν = 4T
Δ = 1
Δ = 5
Δ = 10
Δ = 15
56Fe

Time profile of neutrino burst



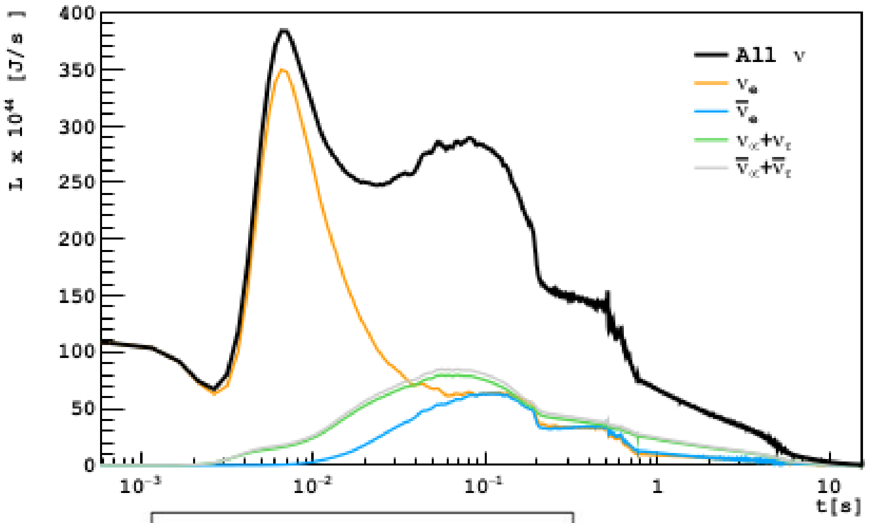


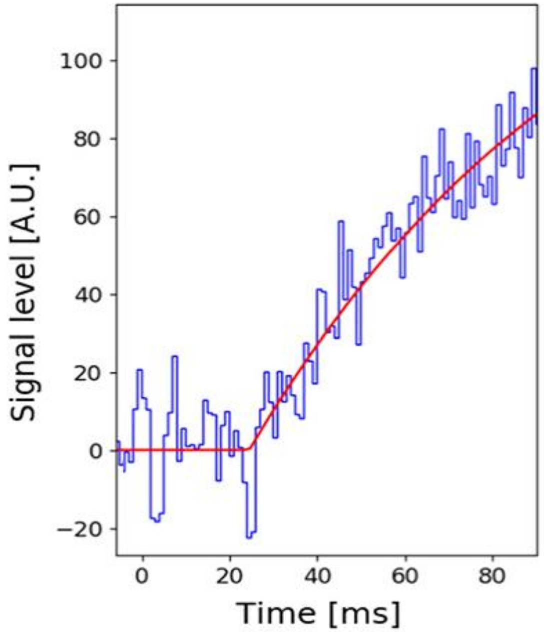
1kpc = 3.08567758 × 10^19 метра

core-collapse SN of $27M_{sun}$ / Garching group simulations

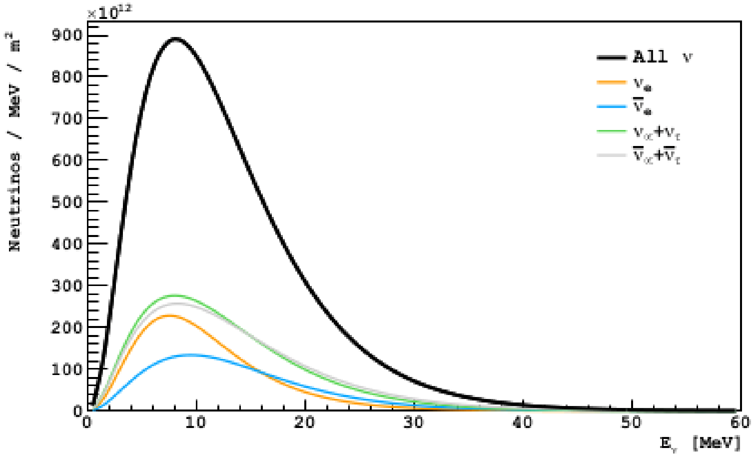
Various neutrino species

Neutrino luminosity time evolution



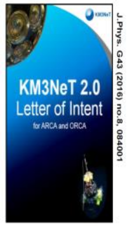


Energy spectra



KM3NeT

Multi-site, deep-sea infrastructure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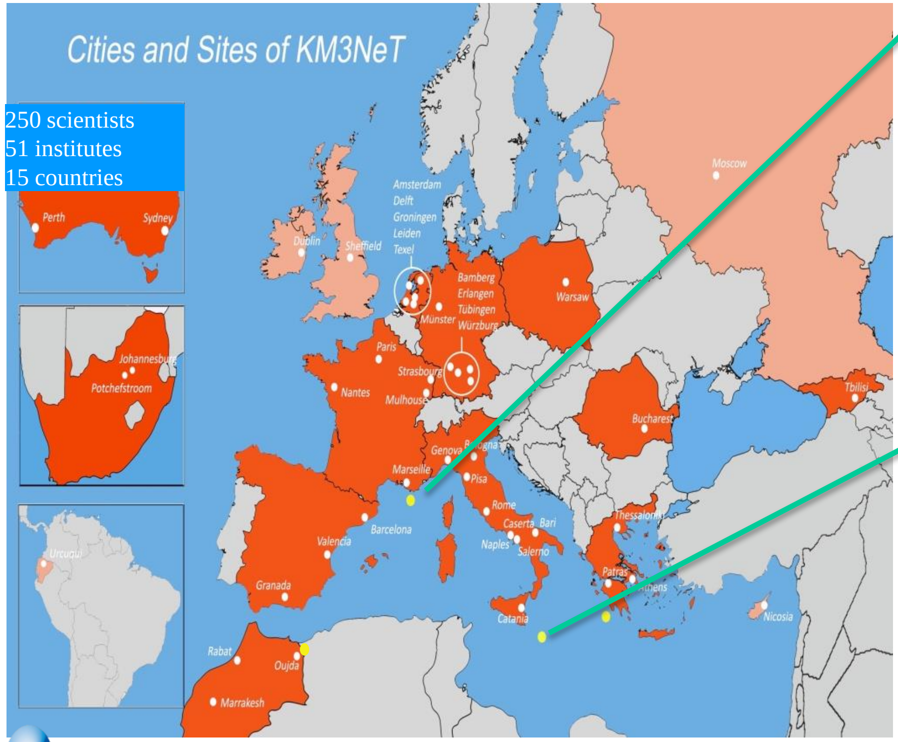
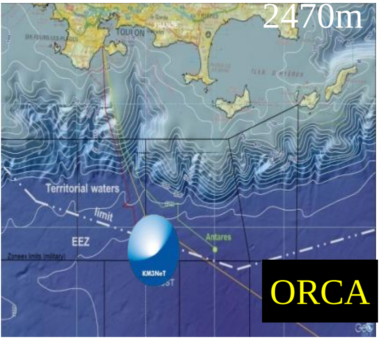
Letter of Intent
for ARCA and ORCA
J. Phys. G43 (2016) no.8, 084001



250 scientists
51 institutes
15 countries



Oscillation **R**esearch
with **C**osmics In the **A**byss

Astroparticle **R**esearch
with **C**osmics In the
Abyss

Connection nodes of
european
multidisciplinary
seafloor & water column
observatory
emso

[KM3NeT 2.0: Letter of Intent](http://dx.doi.org/10.1088/0954-3899/43/8/084001)
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