Nucleosynthesis at magnetorotational supernova explosion and galactic chemical evolution

Basel 2016

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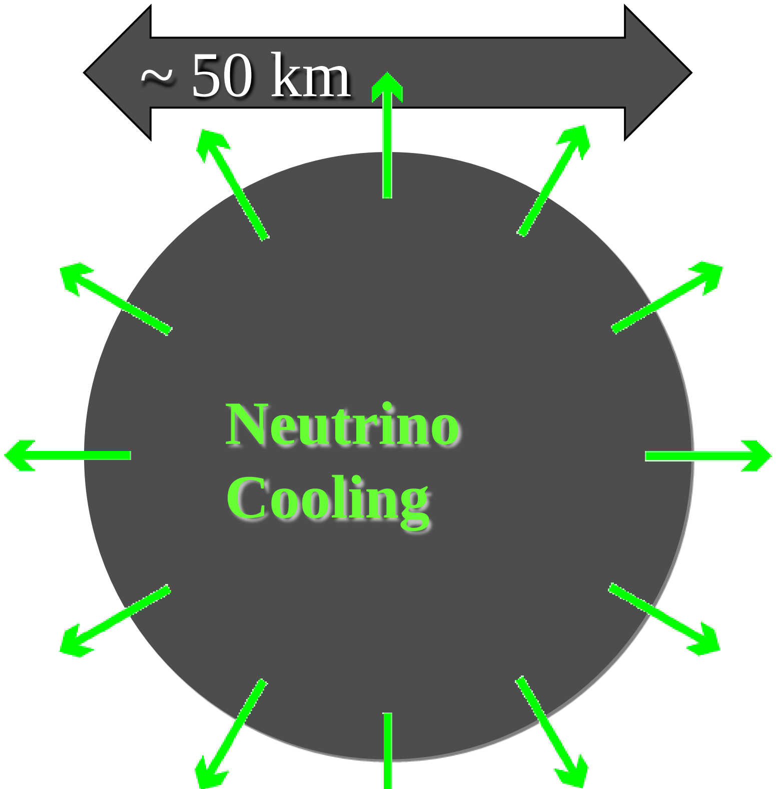
Stellar Collapse and Supernova Explosion

Newborn Neutron Star



Proto-Neutron Star

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

$T \approx 1\ \mathrm{MeV}$

Gravitational binding energy

$E_b \approx 10^{53.5}\ \mathrm{erg} \approx 20\%\ M_{SUN}\, c^2$

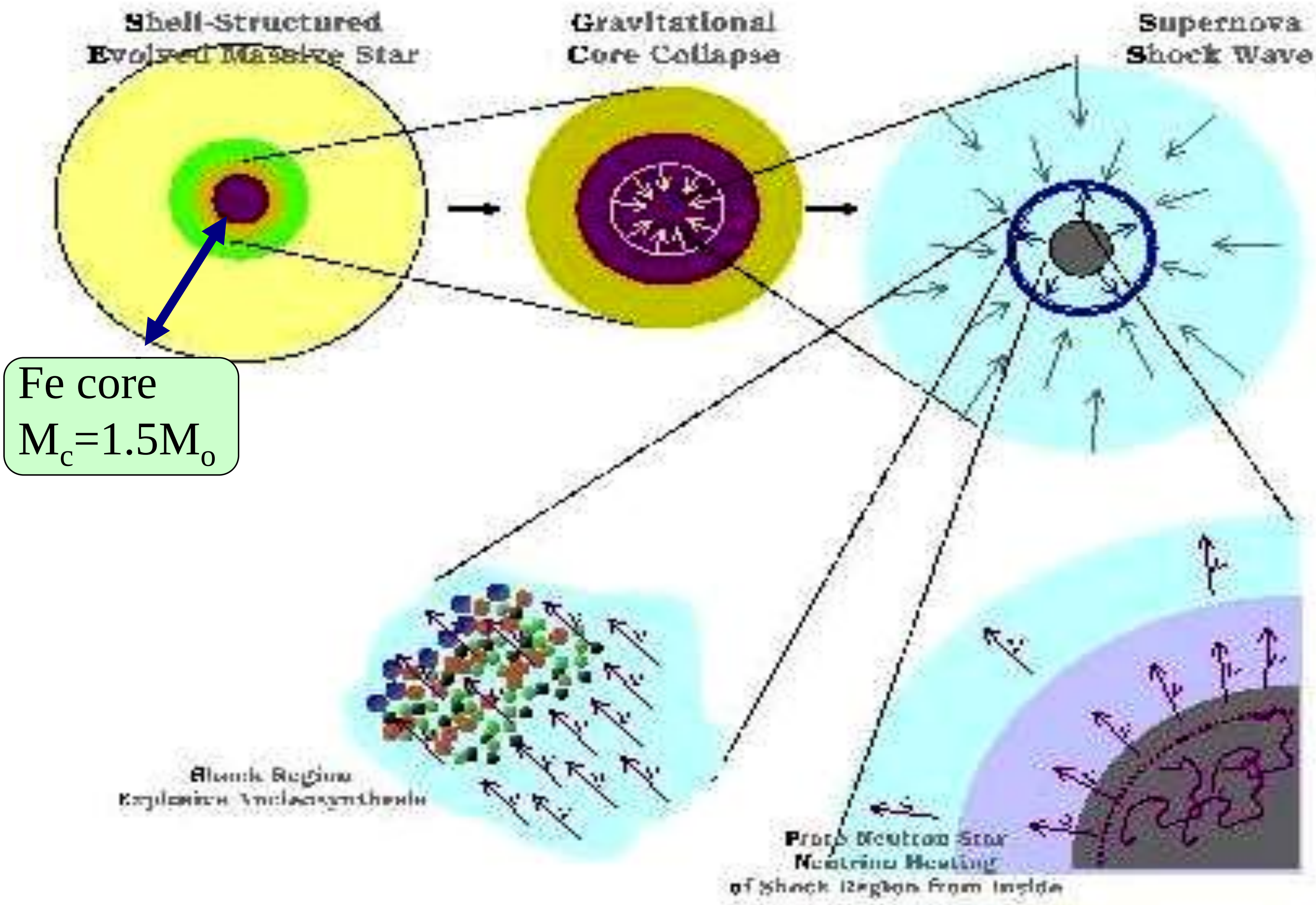
This is distributed as

99%   Neutrinos

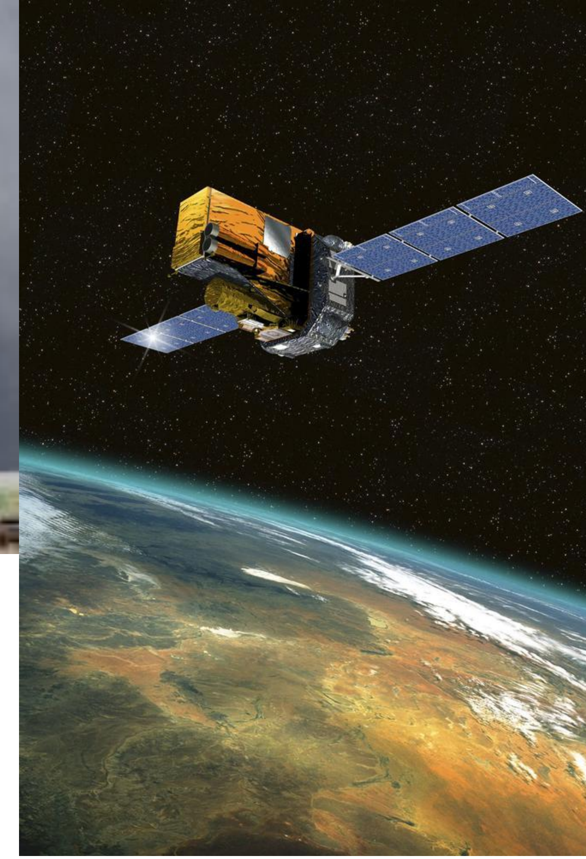
1%   Kinetic energy of explosion
(1% of this into cosmic rays)

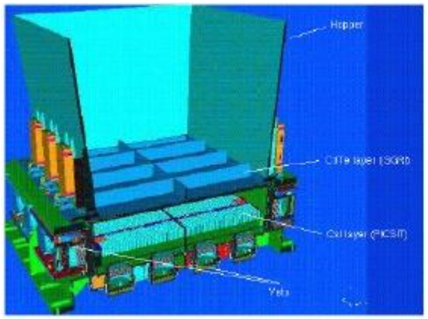
0.01% Photons, outshine host galaxy

Explosive nucleosynthesis



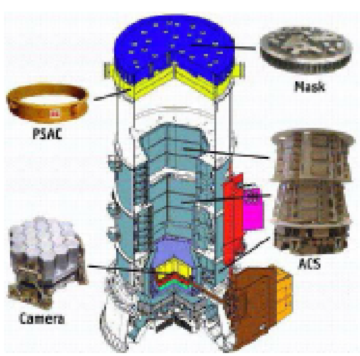
INTEGRAL
VIRGO.UA





IBIS/ISGRI

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



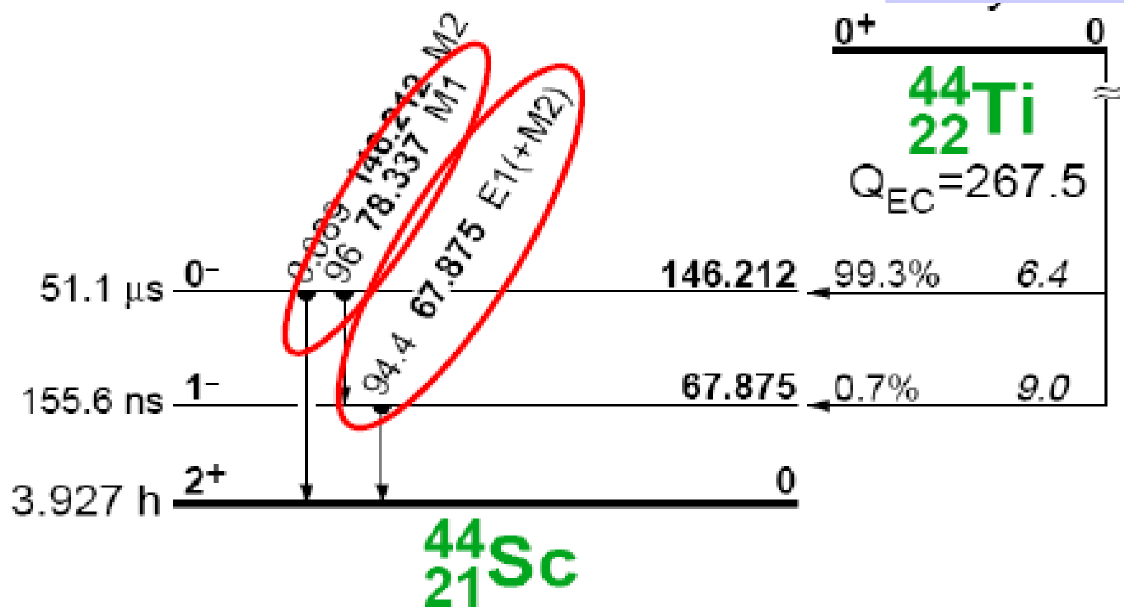
SPI

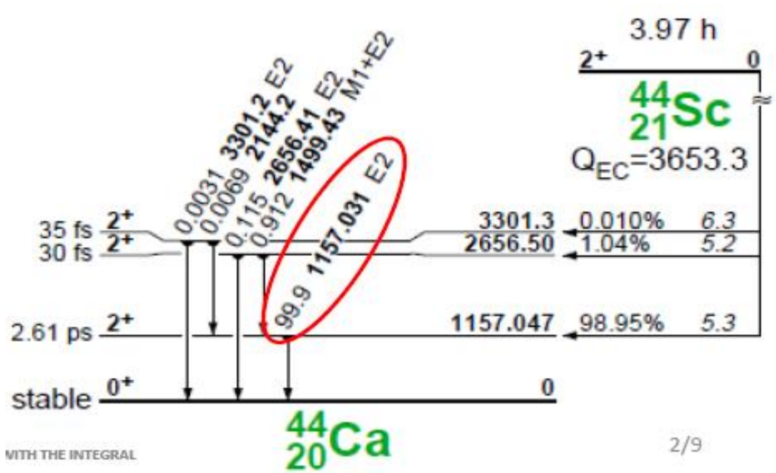
Energy range	20 keV – 8 MeV
Energy resolution (FWHM)	2.35 keV at 1.33 MeV
Detector area	$\sim 500\ cm^2$

The scheme of the ^{44}Ti decay

Earth environment

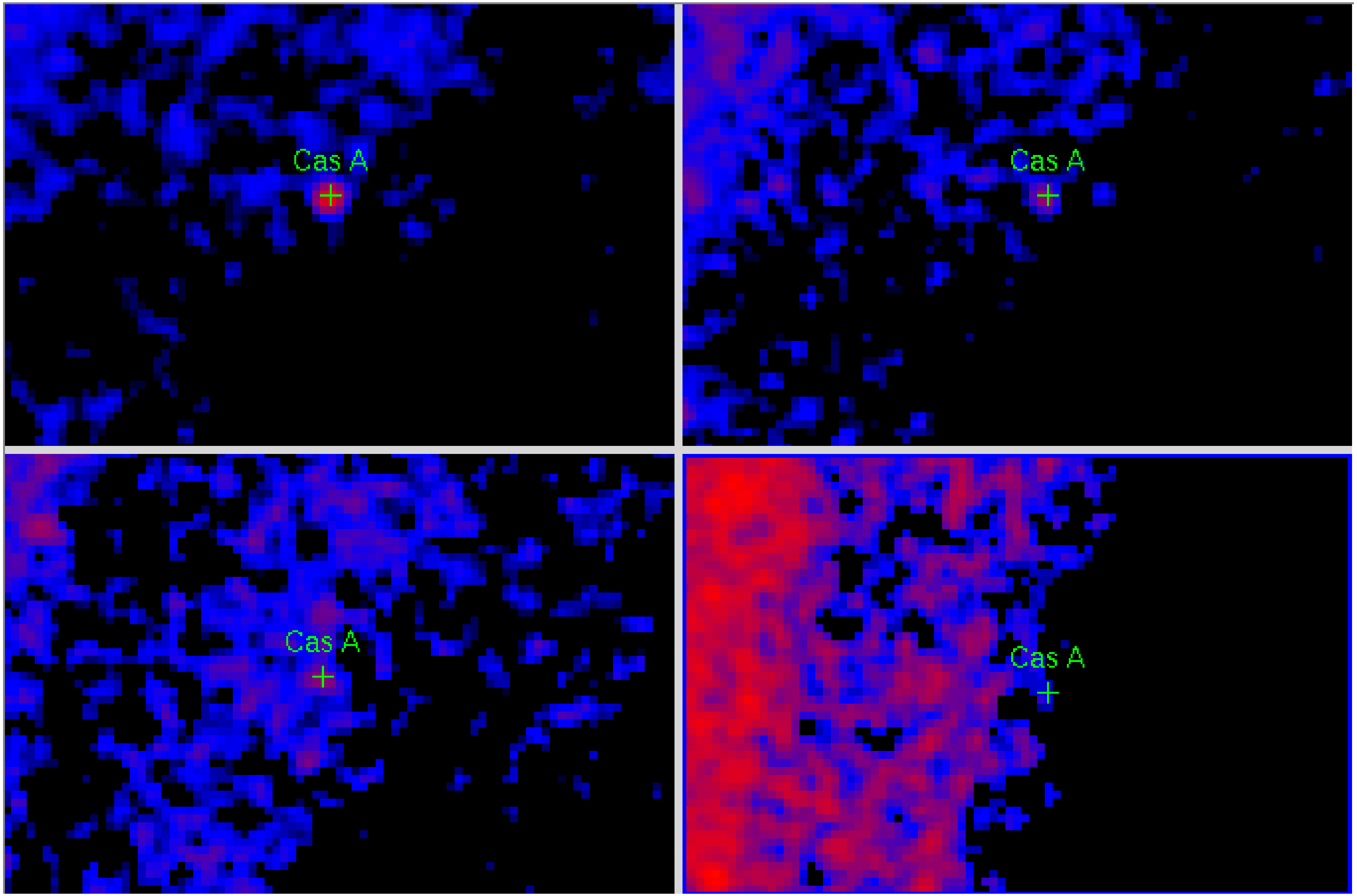
59 y

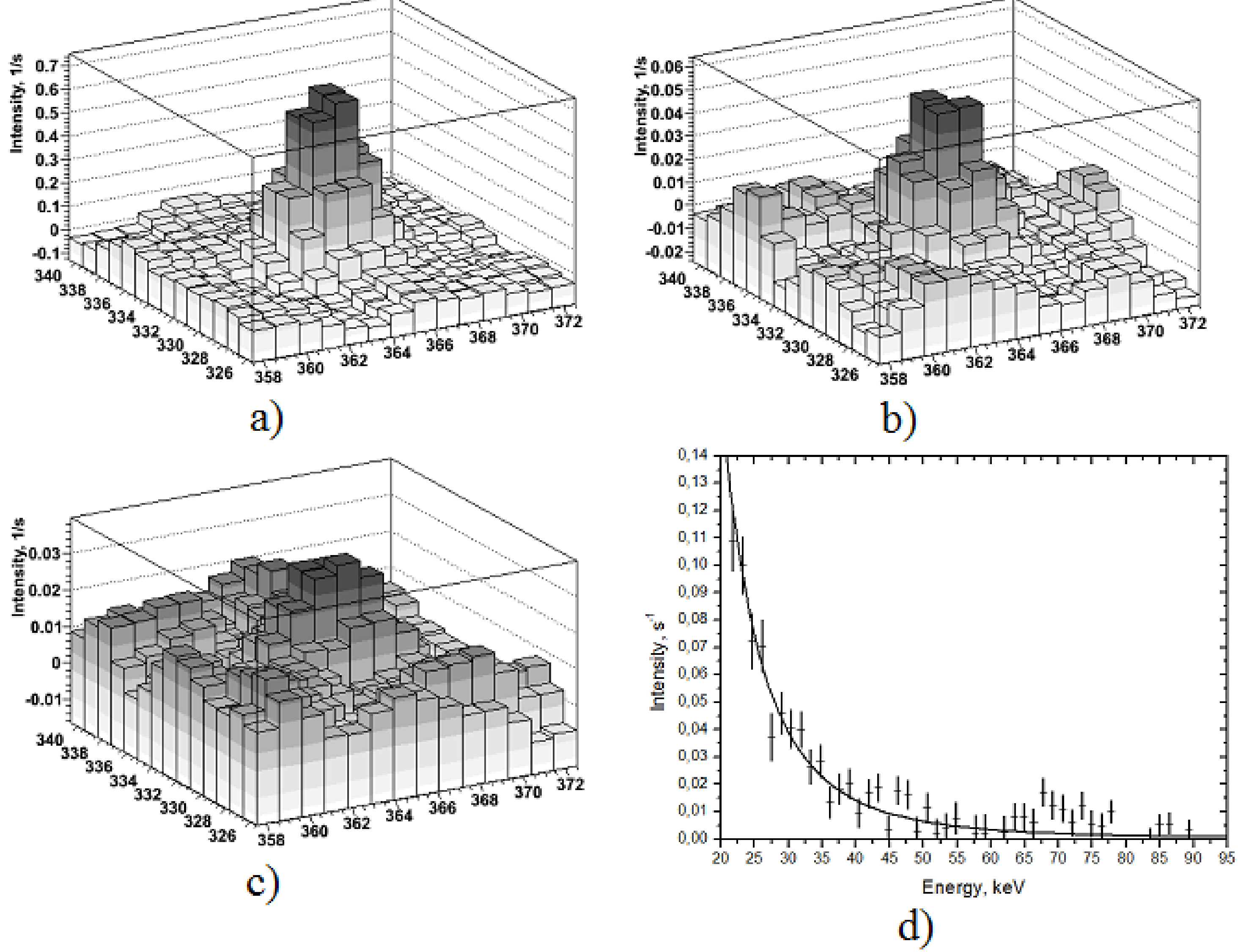




Cassiopeia A (3.4+0.3-0.1)kpc

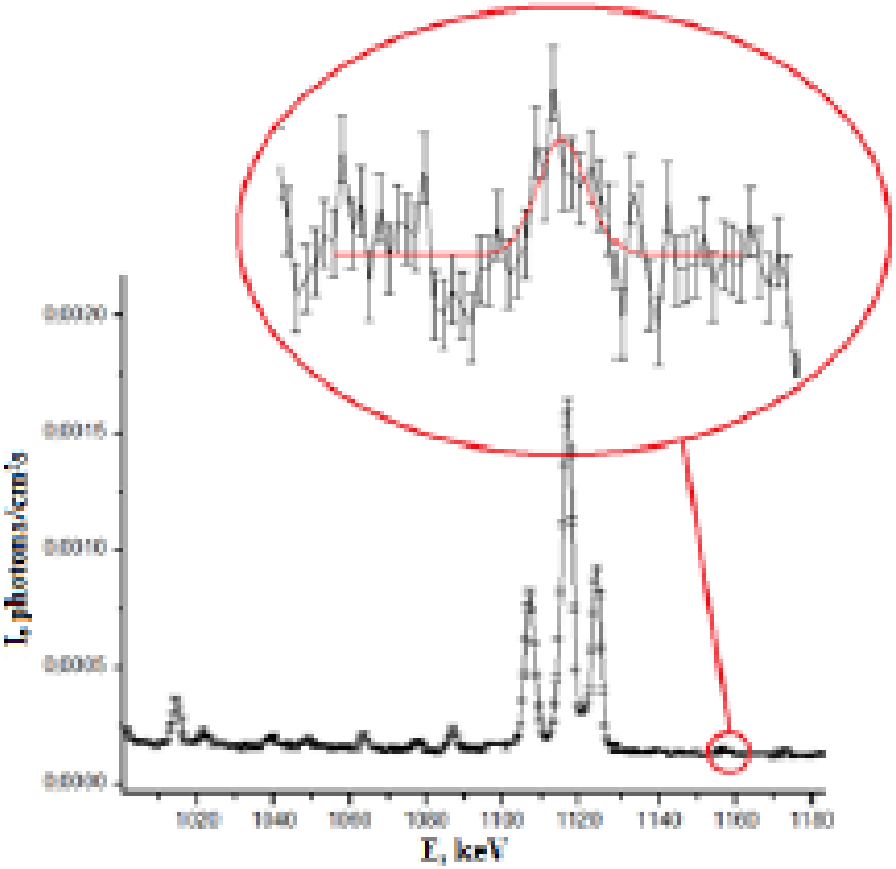
Energy range (keV): **20-62-72-82-100**





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, .

SPI detector data



Fit results

$$E = 1157.20 \pm 0.26\ keV$$

$$FWHM = 3.1 \pm 0.7\ keV$$

Flux=(5.1+/-1.0) 10^{-5}ph/cm^2 s

T=1.5 Ms

mass of ^{44}Ti synthesized at Cassiopeia A explosion [VNK et al *'Nucleus2004'; PhAN (2009)*]

$$m = \frac{4\pi R^2 \cdot T_{1/2} \cdot M \cdot I}{\ln 2 \cdot N_a \cdot p} \cdot 2^{-\frac{t}{T_{1/2}}}$$

R–distance to the object,$T_{1/2}$–the element half-life, N_a–theAvogadro constant,M–mola rmass,I–γ-quanta flux,p-quantum yield, t–remnant age.

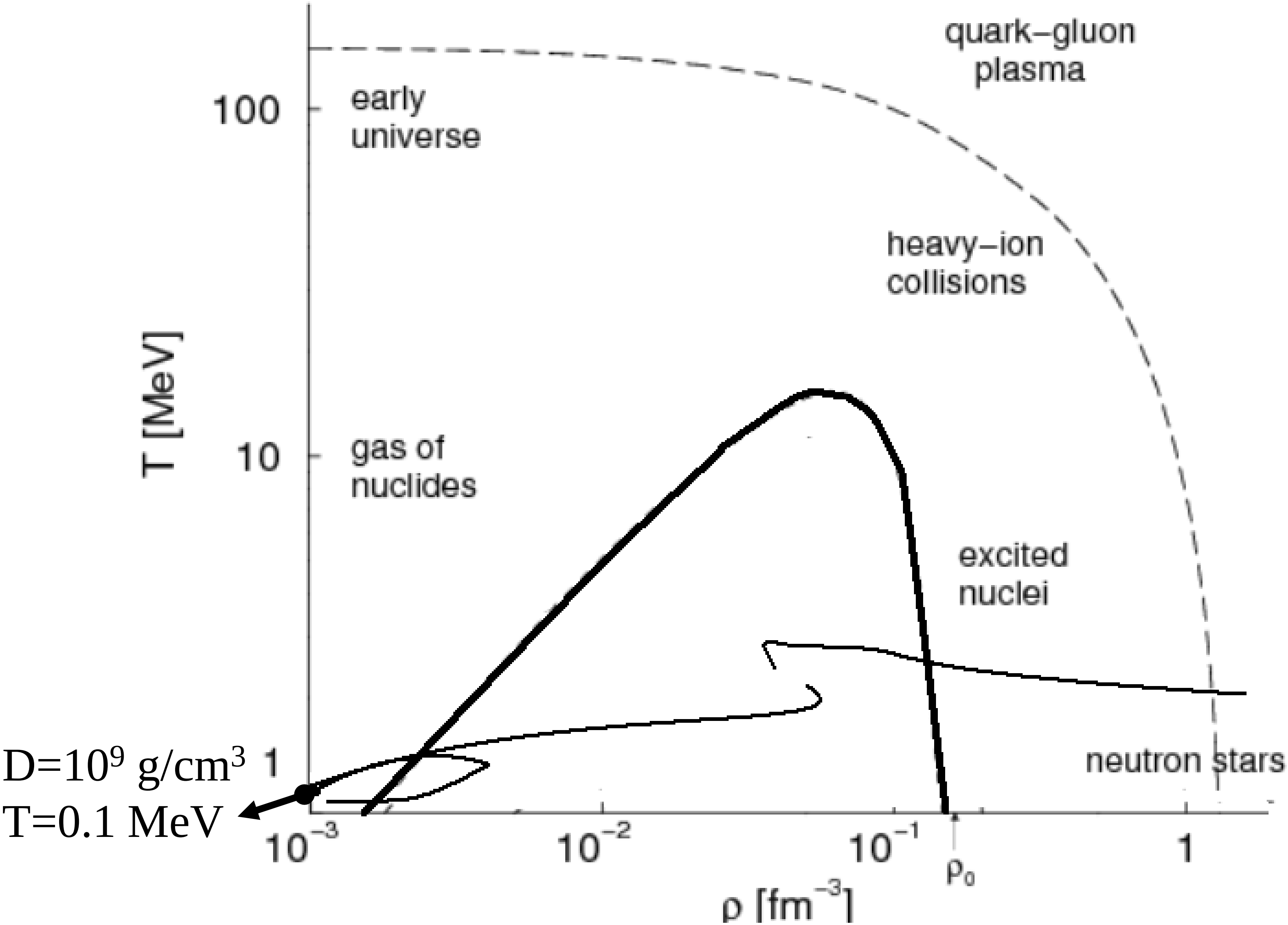
E, keV	$I \pm \Delta I$, 10^{-5} photons/cm^{2}s	$m \pm \Delta m$, 10^{-4} $M_{\odot}$
67.9 keV	6.0 ± 1.0	4.0 ± 0.7
78.3 keV	4.0 ± 1.0	2.6 ± 0.7
1157.1 keV	5.1 ± 1.1	3.3 ± 0.7

Investigated Supernovae

Name	Age	M_{ti} (10^{-4} $M_\odot$)
SN 1987A	**29 y**	**3.1±0.8**
Cas A	**330 y**	$3.3^{+0.9}_{-0.5}$
TYCHO	**440 y**	**<0.8**
Vela Junior	**?**	
Theory		**~ 0.1**

3.1±0.8

Symmetric nuclear matter: Phase diagram



Magnetic field estimates

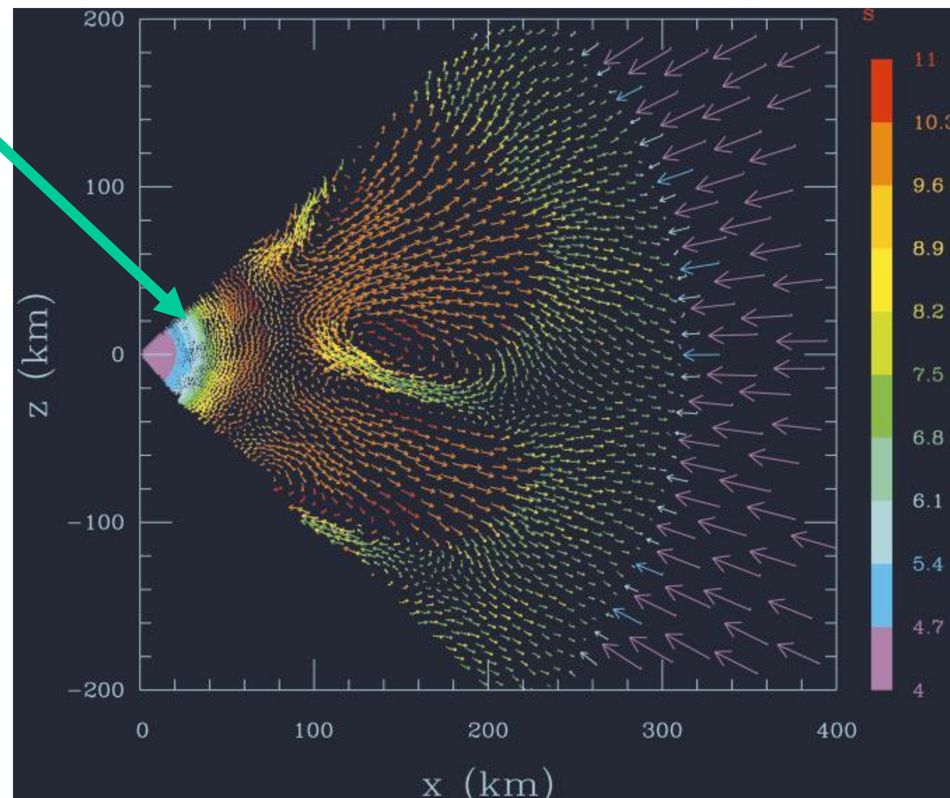
predominant energy component of shock wave E_S originates from the magnetic pressure

$$<H_\nu^2> R_\nu^2 \Delta R \sim 2E_S \quad \sim 10^{51,5} \text{ ergs}$$

$R_\nu \sim$ 40Km; ☟$R \sim$ 1Km

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

$$H(R) \sim H_\nu \quad R_\nu / R$$



Magnetic field estimates

Magnetic and gravitational forces

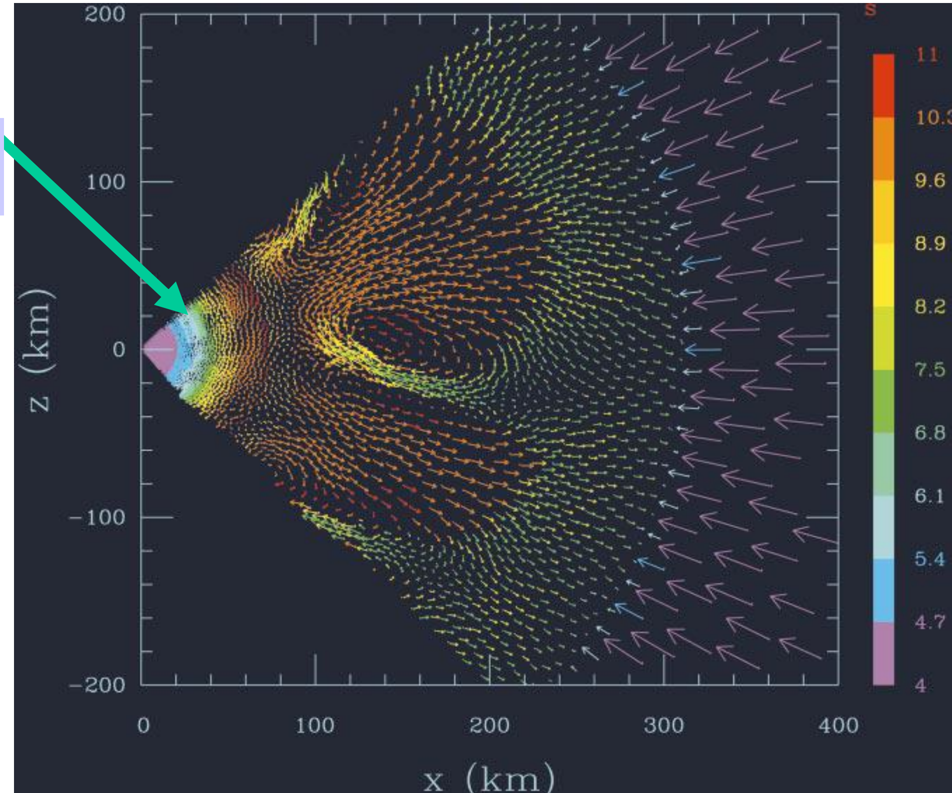
$$dH_\nu^2/dR \sim 8\pi GM\, n(R)/R^2$$

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

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

$R_\nu \sim 40$Km; ☟$R \sim 1$Km

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



NUCLEAR STATISTICAL EQUILIBRIUM
in Ultra-Strong Magnetic Fields

Entropy *S* extremum →

$$TdS = \sum_i \lambda_i dY_i = 0$$

Nuclear composition at temperature *T*

$$Y \propto \frac{G_A}{G_n^N G_p^Z} \exp\{B/kT\}$$

Binding Energy ***B***

spin-magnetic part in partition function

$$G_i = \sum_M \exp\{M \omega_L / kT\}$$

$$\omega_L = \mu_N H$$

Nuclear Shell Effects at *Ultra-Strong Magnetic Fields*

V.N.K. //PRL 2002. V.88, 221101 // J.Nucl.Sci.Technol. V.1 Sup.2. P.550 // J.Nucl.Radiochem.Sci. 2002. V.3. P.205 // PRC 2004 V.69, 038801/ЯФ. 2012

$$N = \int_{-\infty}^{\varepsilon_F} d\varepsilon\, \rho(\varepsilon)$$

Nucleons

Binding Energy

$$B = \int_{-\infty}^{\varepsilon_F} d\varepsilon\, \varepsilon\, \rho(\varepsilon) = B_{\mathrm{LDM}} + B^{\mathrm{sh}}$$

Level density

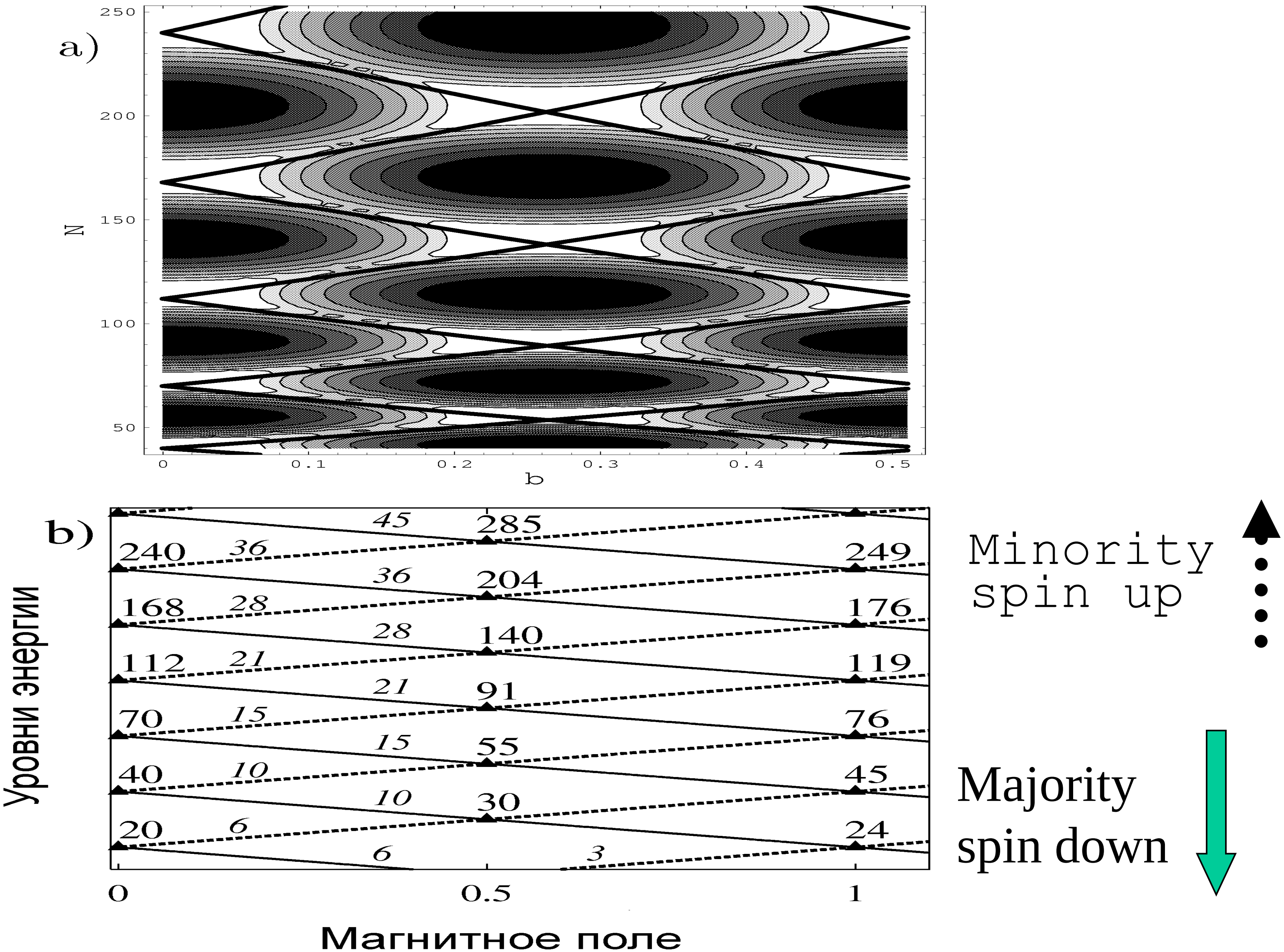
$$\rho = \sum_n \delta(\varepsilon - \varepsilon_n) = \rho_{\mathrm{sm}} + \rho^{\mathrm{sh}}$$

With Single particle levels ε_n ***filled up to the Fermi energy*** ε_F

the Hartree self-consistent mean field approach in magnetic field : h

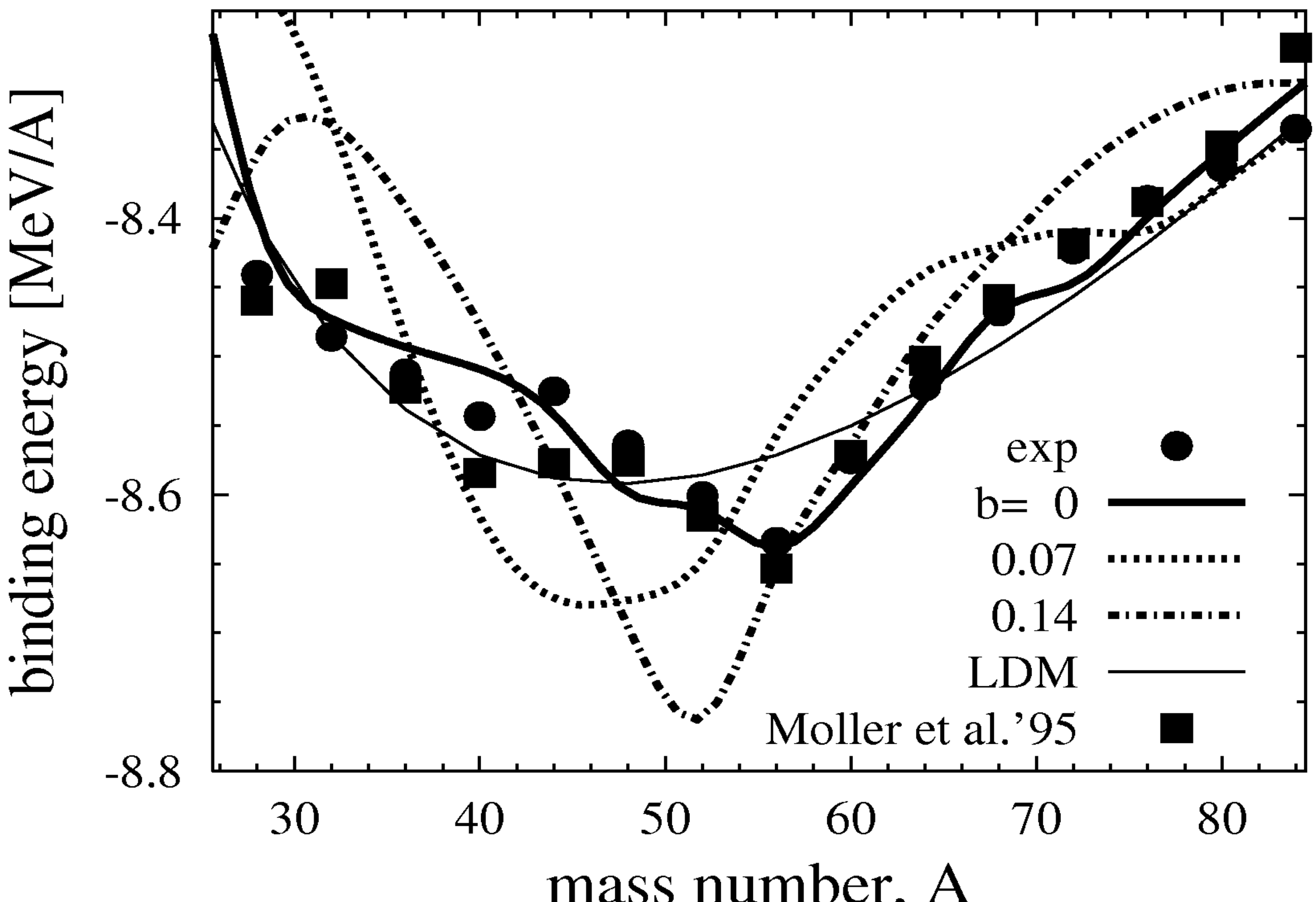
- Single particle Hamiltonian
- **$H = H_{MF}$ + (so)*(*ls*) +** *(Magnetic terms)*
- Pauli–spin (*S*) → **- M (h*S*)**
- Landau–orbital (*l*) → **- M (h*l*) :protons**

Neutrons



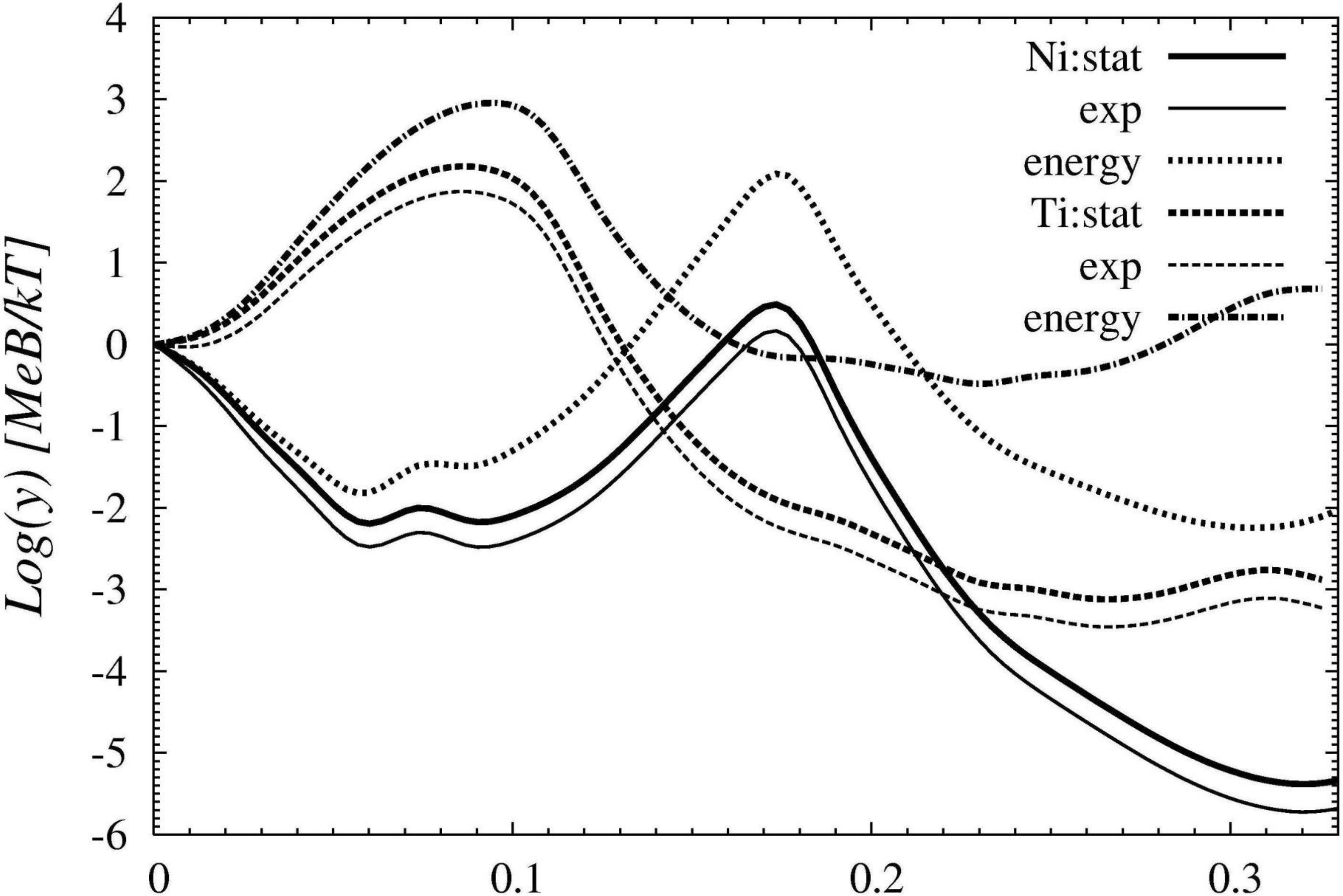
a)
250
200
150
100
50
N
0
0.1
0.2
0.3
0.4
0.5
b
b)
Уровни энергии
285
204
140
91
55
30
240
168
112
70
40
20
249
176
119
76
45
24
45
36
36
28
28
21
21
15
15
10
10
6
6
3
0
0.5
1
Магнитное поле
Minority
spin up
Majority
spin down

Binding energy of even-even symmetric nuclei *at magnetic fields h*



relative yield $y=Y(H)/Y(0)$

^{56}Ni(solid) i ^{44}Ti(dashed line)



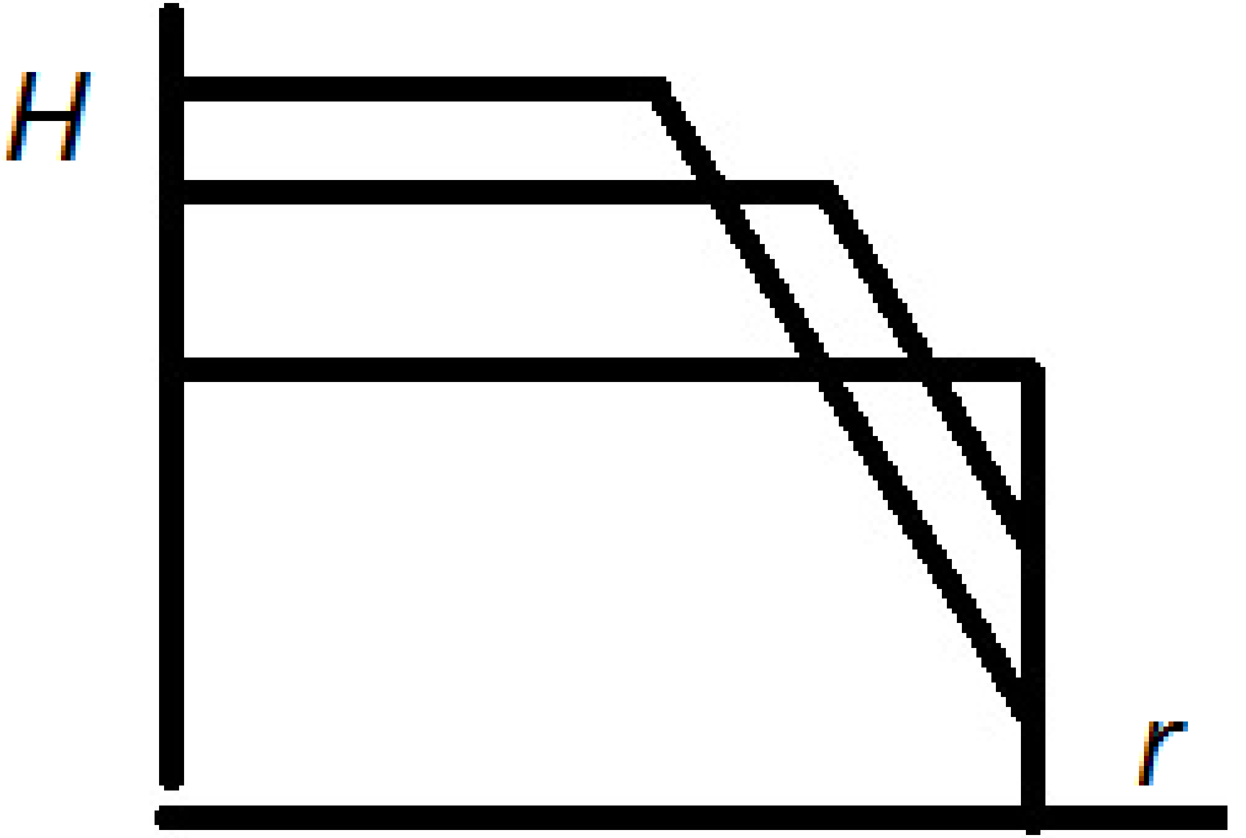
Магнитное поле, *h*

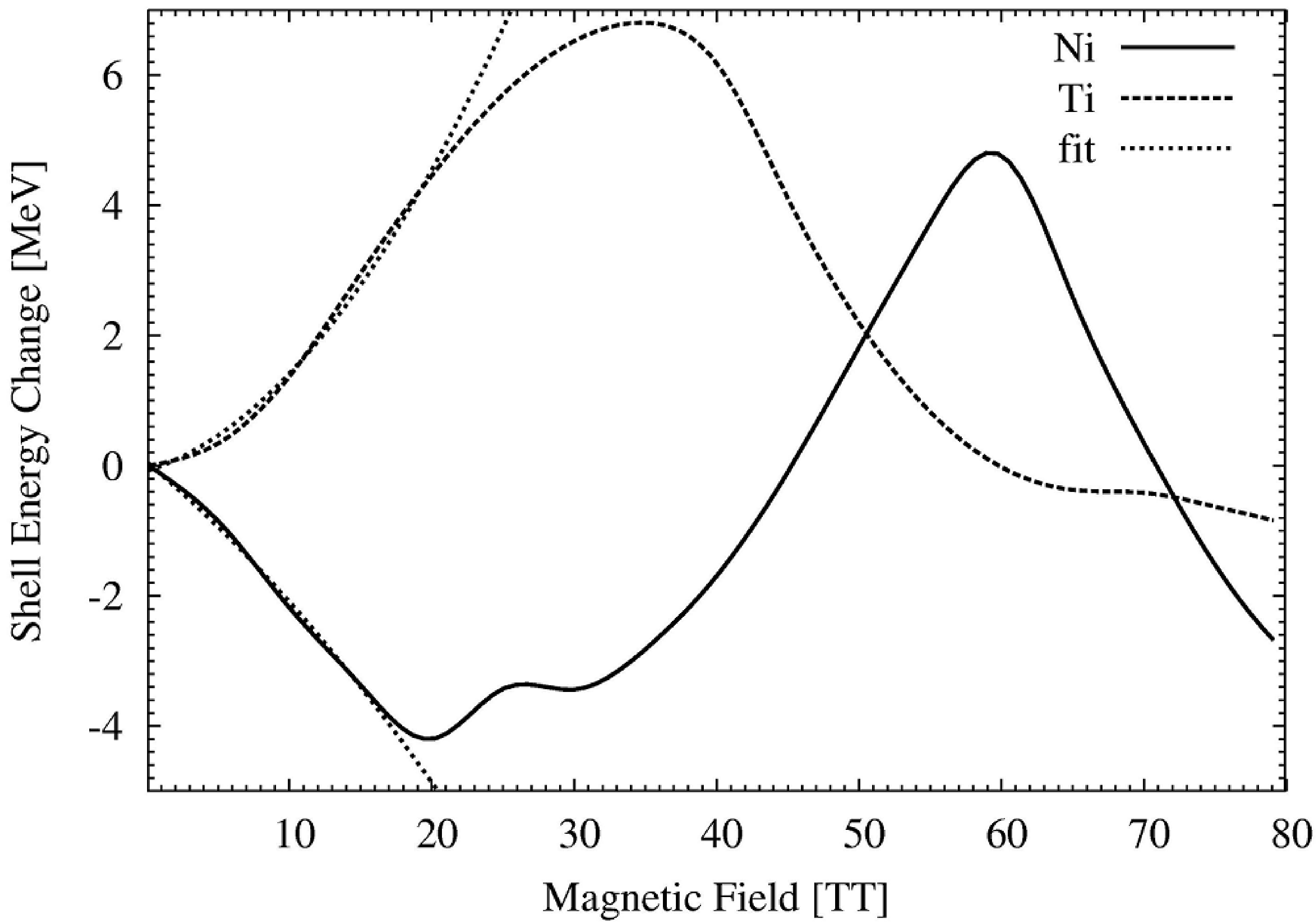
Magnetic field geometry at MRI

$$H(r)=\begin{cases} H_q & \text{at} \quad r<r_0 \\ \dfrac{H_q}{r^2} & \text{at} \quad r>r_0 \end{cases}$$

$$H_q=\frac{H_\nu}{q(2-q)}$$

$q=(r_0/r_a)^2$





Ni
Ti
fit
Shell Energy Change [MeV]
Magnetic Field [TT]
6
4
2
0
-2
-4
10
20
30
40
50
60
70
80

Averaging over MRI Volume

$$\langle y \rangle = V^{-1} \int_V d^3 r y\left(H(\mathbf{r})\right)$$

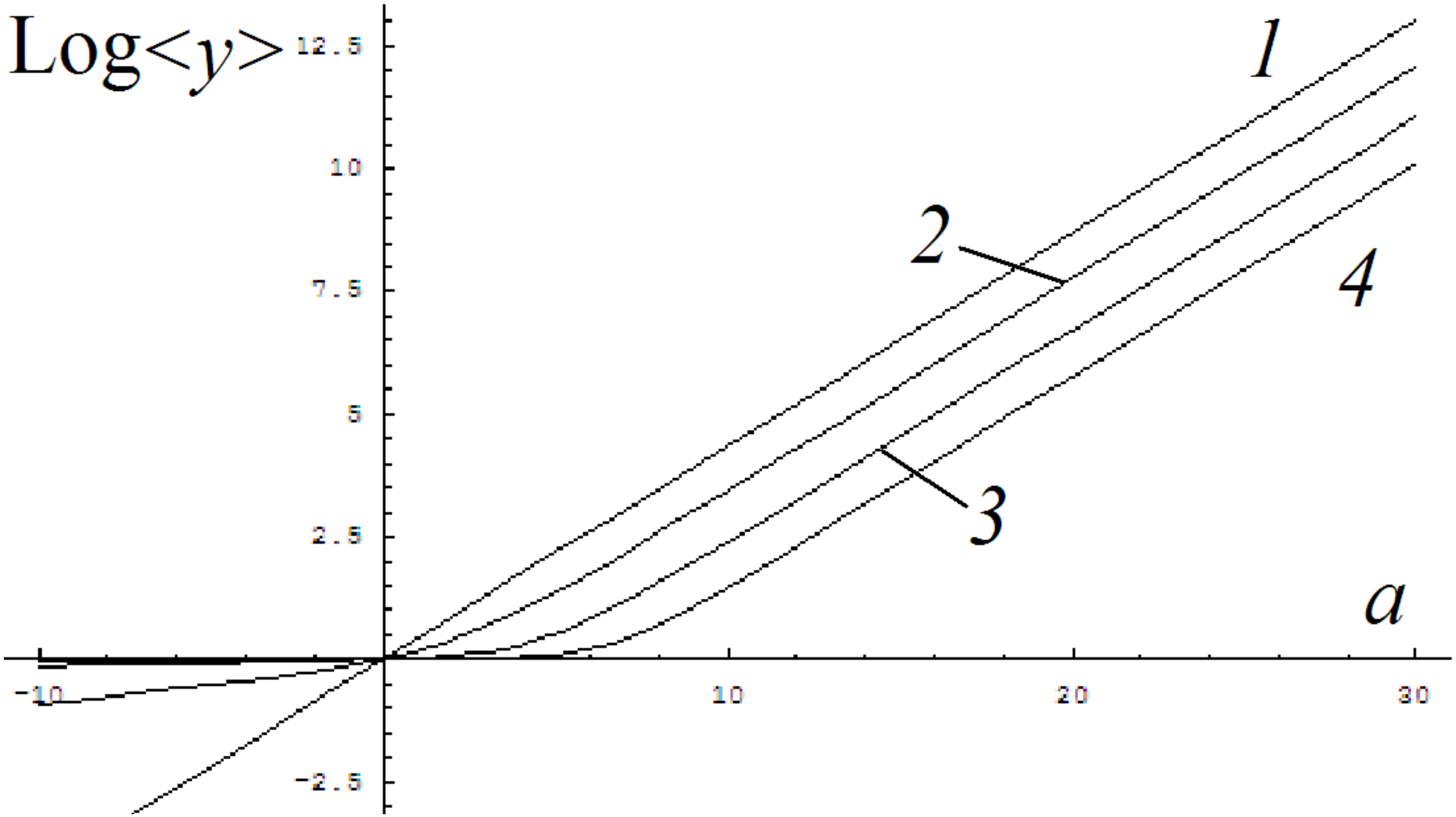
$$\langle y \rangle = b^{-1} \left(\exp\{a\} + \int_1^b \exp\{a/x\}\, dx \right) =$$

$$= \left(\exp\{a/b\} + \frac{a}{b}\left[\mathrm{Ei}(a) - \mathrm{Ei}(a/b) \right] \right)$$

$a =$ 👎$B(H_0)\ kT$ $\qquad$ $b = (r_a/r_0)^2$

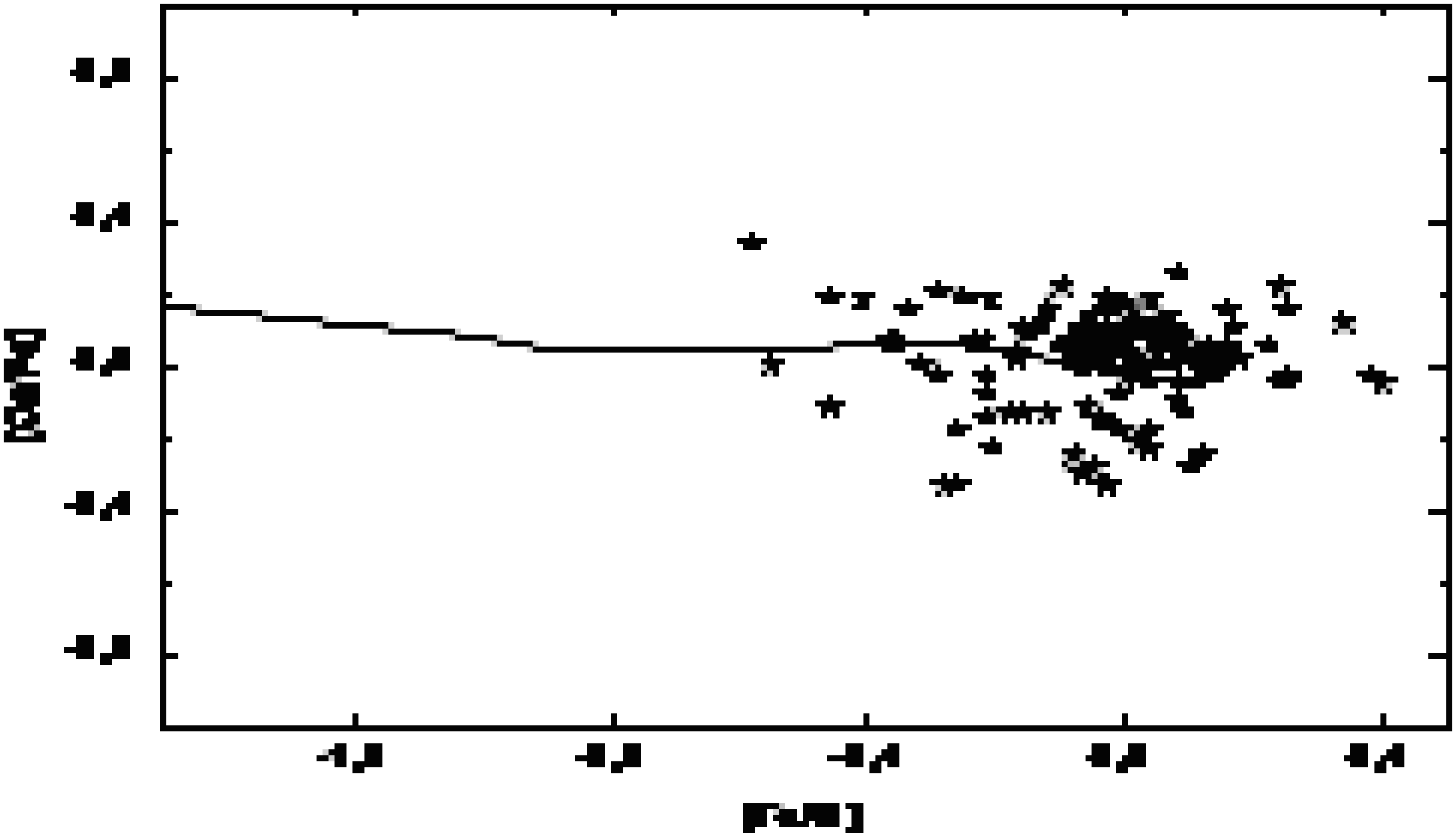
$$\mathrm{Ei}(x) = \int_{-\infty}^{x} \frac{\exp\{t\}}{t}\, \mathrm{d}t$$

интегральная показательная функция

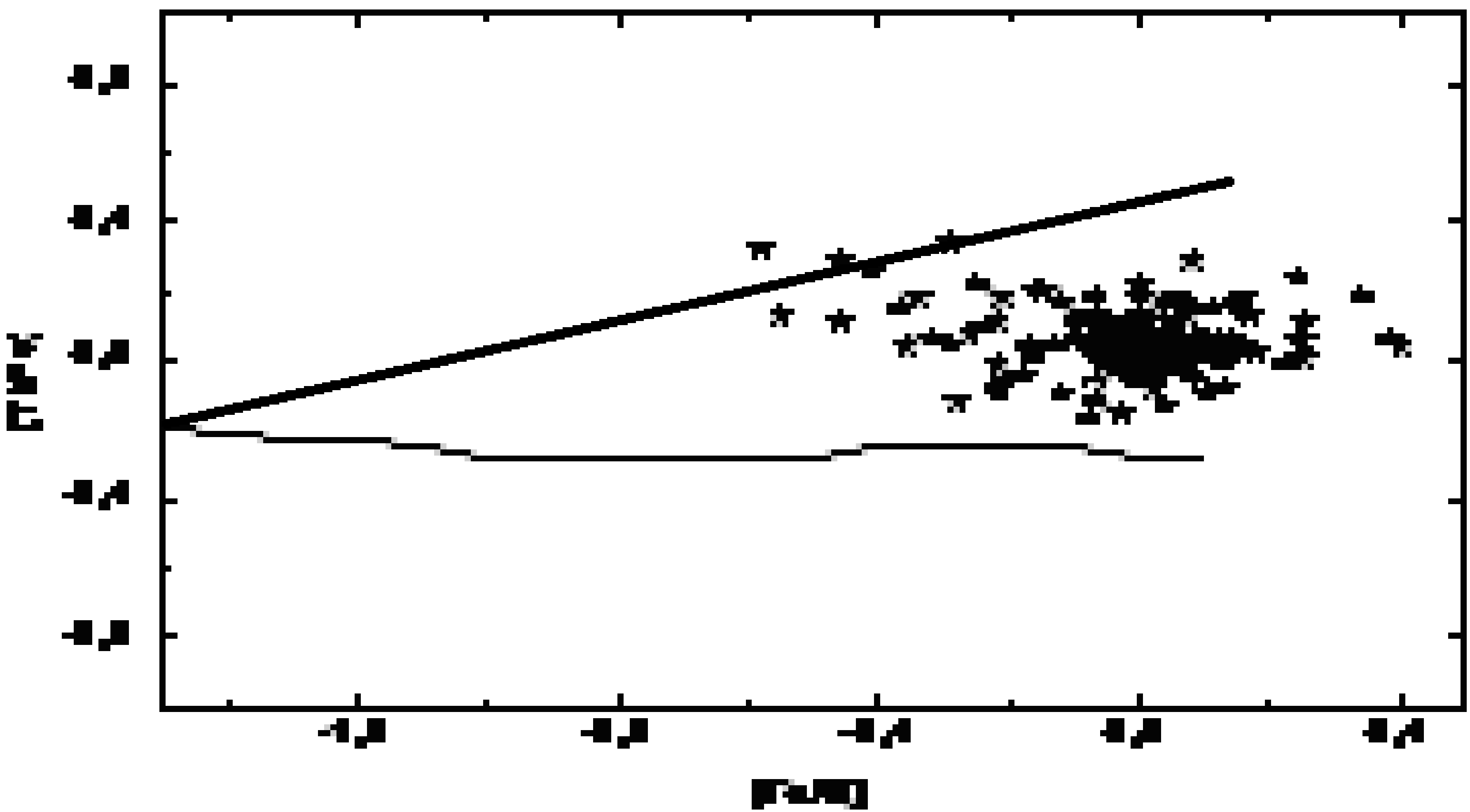


Log<y>
12.5
10
7.5
5
2.5
-2.5
-10
10
20
30
1
2
3
4
a

Galactic chemical evolution Ca-40



Galactic chemical evolution Ti-48



SUMMARY

- We analyze the synthesis and decay of ^{n} nuclides in SNRs
- Obtained the spectra and flux for the specific lines of decay products

SUMMARY

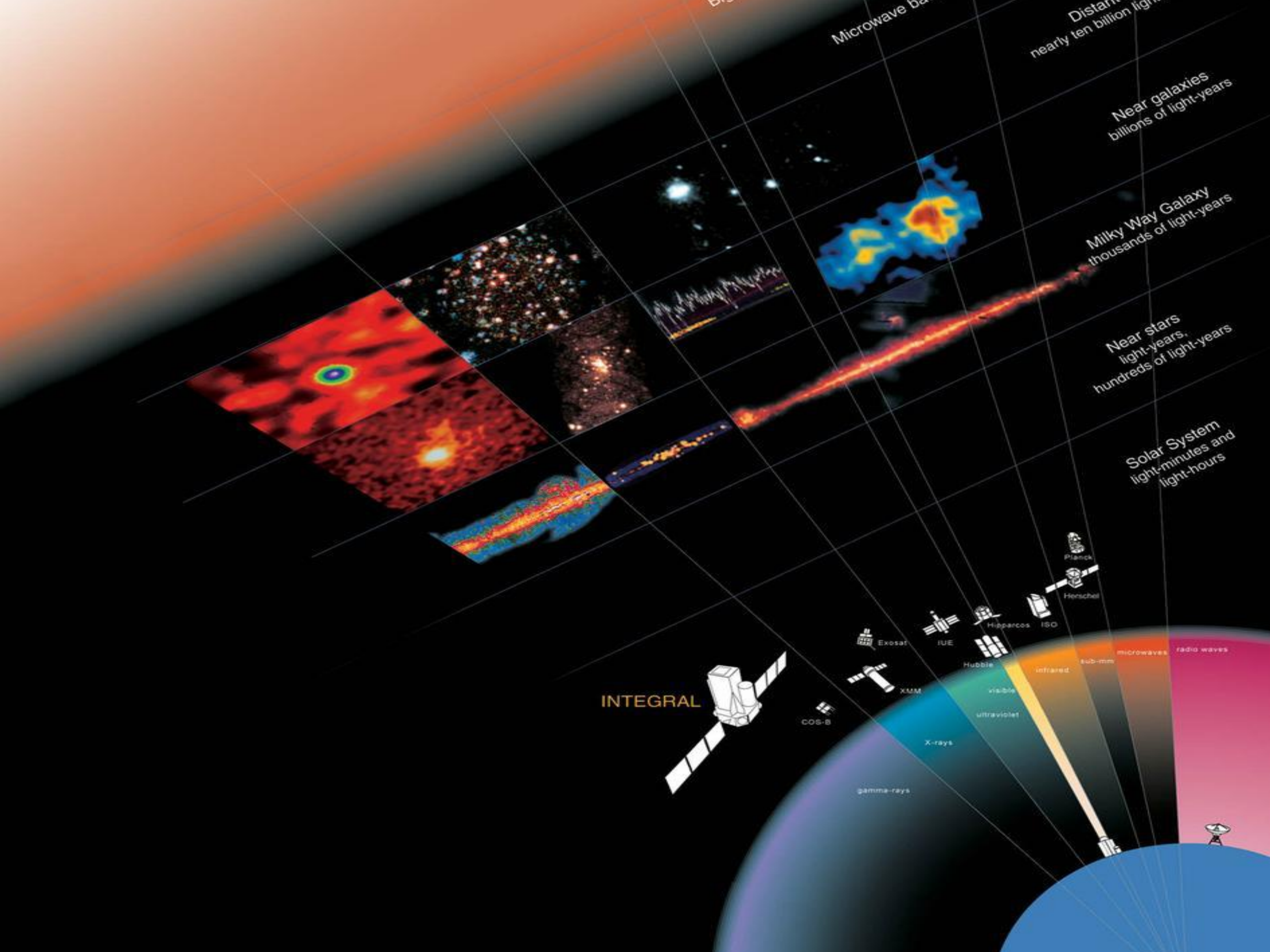
- Magnetism of Atomic Nuclei
  Thermodynamic formalism
- Magnetic field effect on Nuclear Shell Structure
  Phase-shift in shell oscillations of Nuclear Masses
- Pauli type Paramagnetic Response
- Landau-type Orbital Magnetism
- Magnetic fields of Tera-Tesla shift
  Nuclear Magics of Iron region towards
  Smaller Masses approaching Ti
- Enhancement in Yield at nucleosynthesis

SUMMARY

- We analyze the synthesis and decay of ^{44}Ti in SNRs
- Obtained the spectra and flux for the lines of ^{44}Sc

Investigated Supernovas

Name	Coordinate	Age
SN 1987A	**-** 279.7 -31.9,	**29 y**
Cas A	**-** 111.7 -2.1,	**330 y**
TYCHO	**-** 120.1 +1.4,	**440 y**
Vela Junior	**-** 266.3 -1.2	**?**

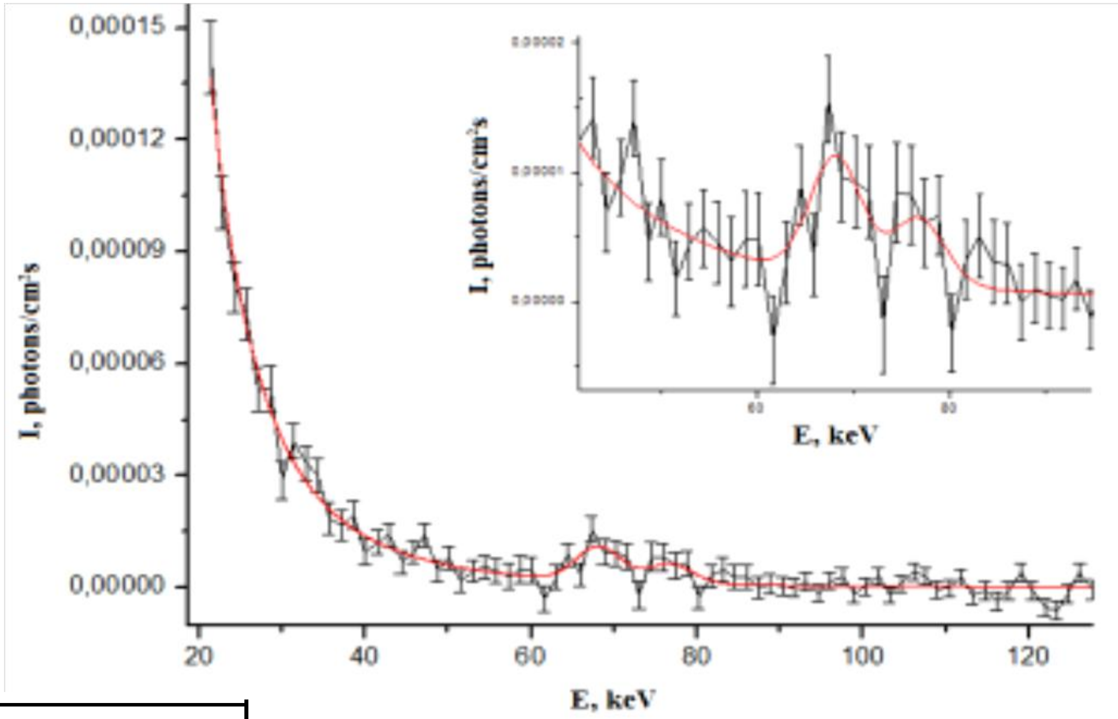


Microwave ba
Distant
nearly ten billion ligh
Near galaxies
billions of light-years
Milky Way Galaxy
thousands of light-years
Near stars
light-years,
hundreds of light-years
Solar System
light-minutes and
light-hours
Planck
Herschel
Hipparcos
ISO
Exosat
IUE
Hubble
XMM
INTEGRAL
COS-B
radio waves
microwaves
sub-mm
infrared
visible
ultraviolet
X-rays
gamma-rays

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

THEORY

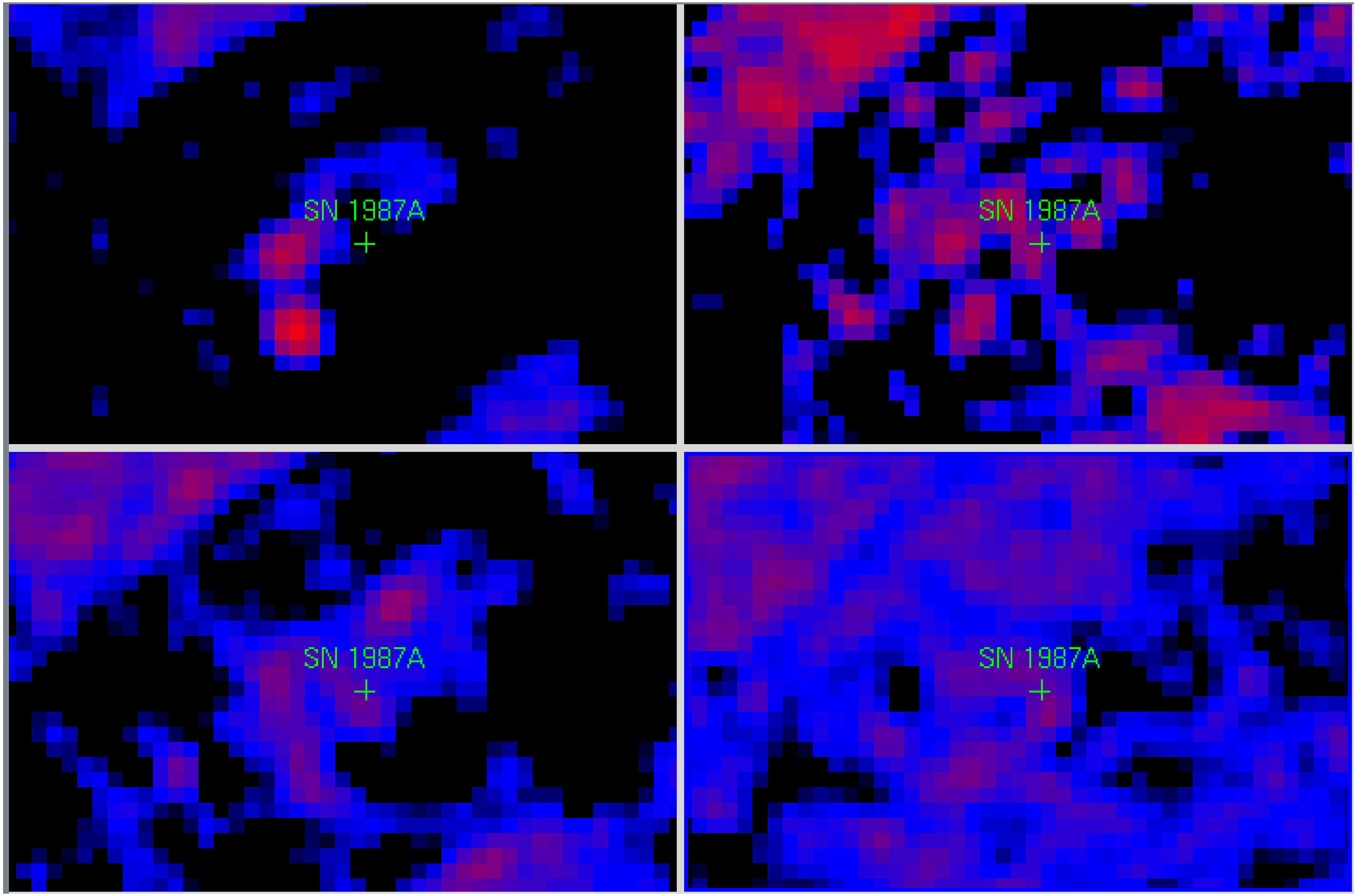
$$(0.02 - 2.5) \times 10^{-4} \quad M_{\odot}$$

Thielemann, F.-K., Hashimoto, M. & Nomoto, K. Explosive nucleosynthesis in SN1987A. II. Composition, radioactivities, and the neutron star mass. *Astrophys. J.* ***349, 222–240 (1990)***

Woosley, S.E., & Hoffman, R. D. 57Co and 44Ti production in SN1987A. *Astrophys. J.*, ***368, L31-L34*** (1991).

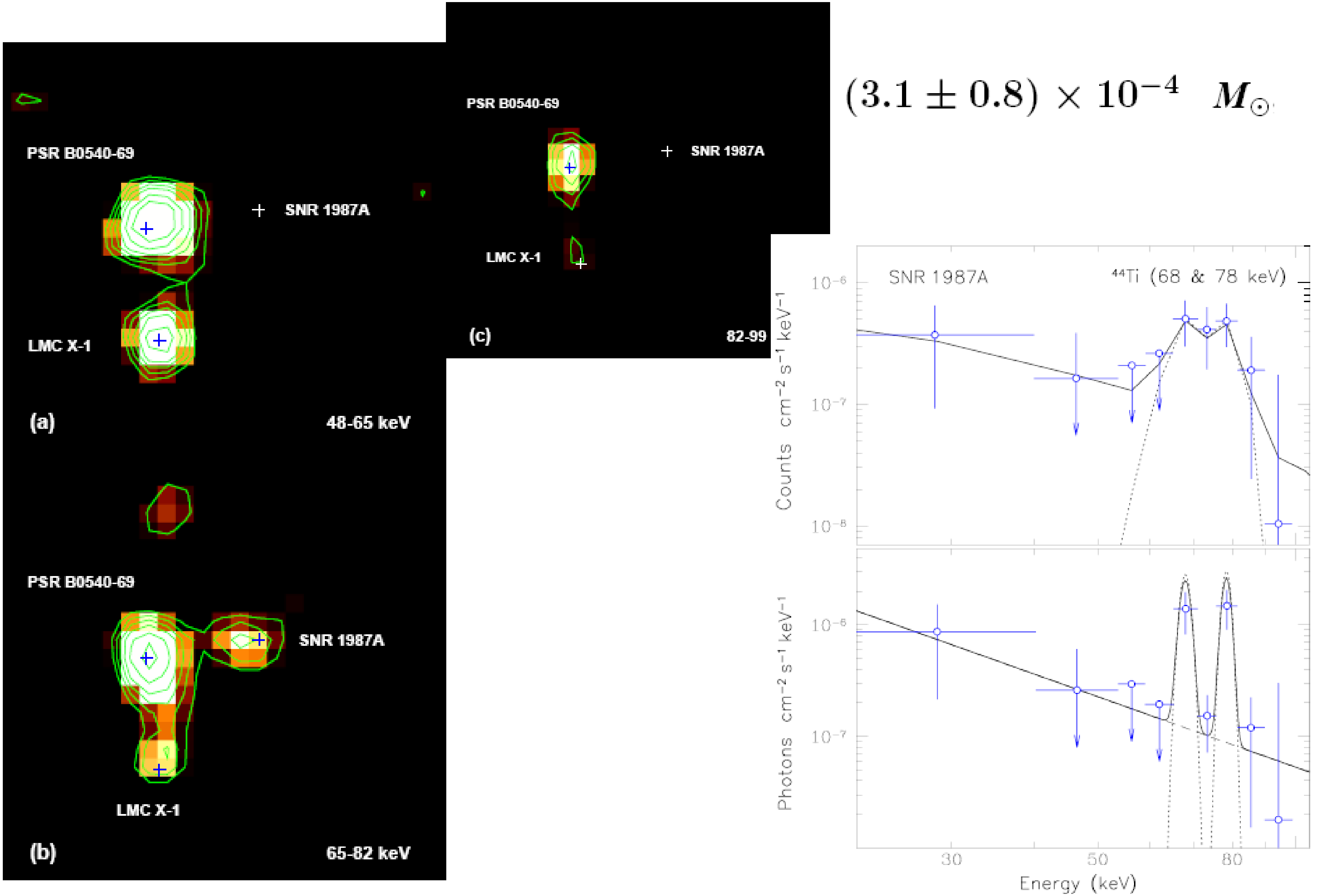
SN1987 A (50kpc)

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

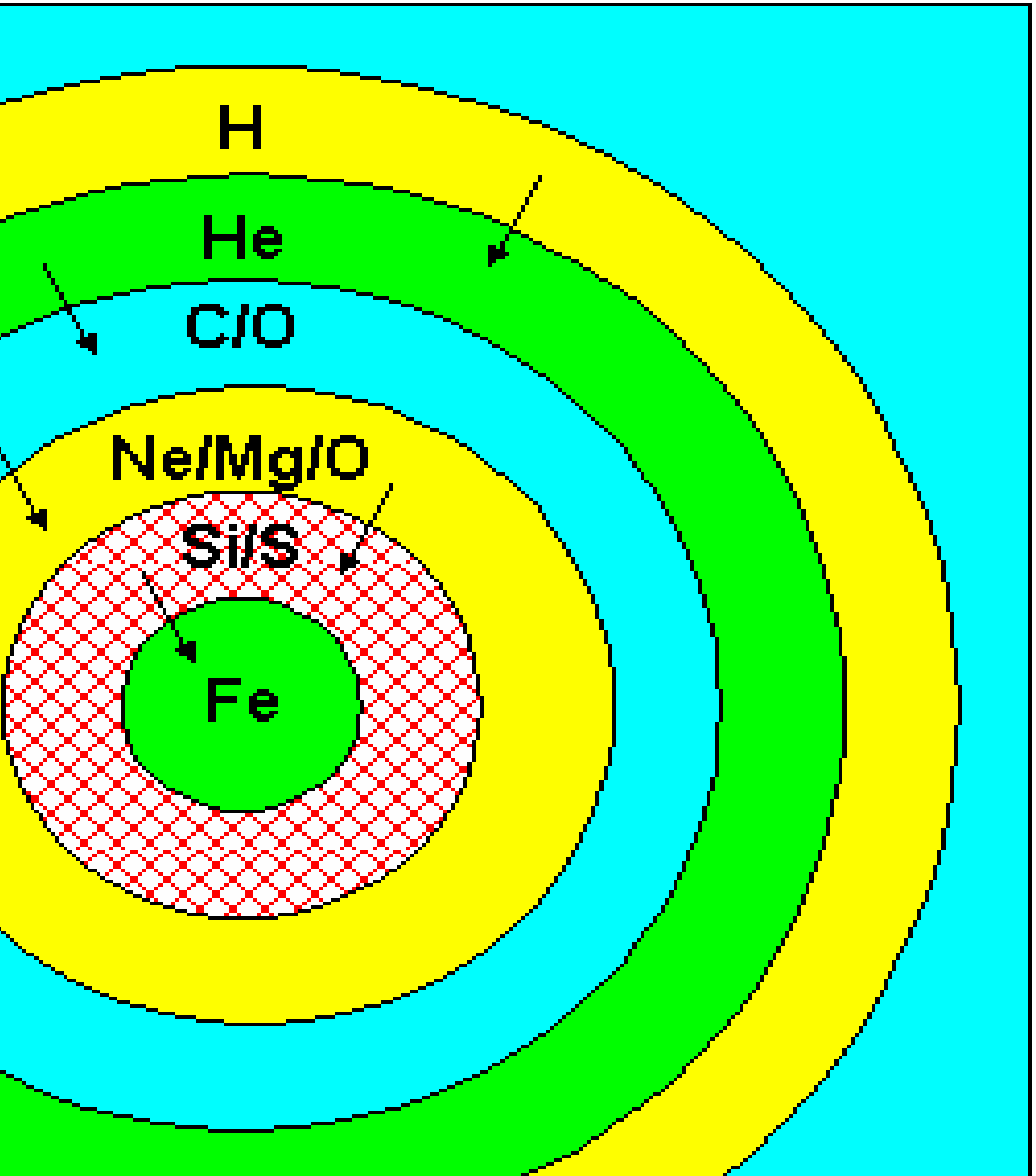


S.A.Grebenev et al *Nature, 490, 373-375 (2012)*.

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



Massive Star, ***M > 8 M$_o$***   *onion*



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

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

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

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

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

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

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

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

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

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

1kpc = $3.08567758 \times 10^{19}$ метра