R-process with magnetized nuclei

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R-процессе с намагниченными ядрами

28_02_2023

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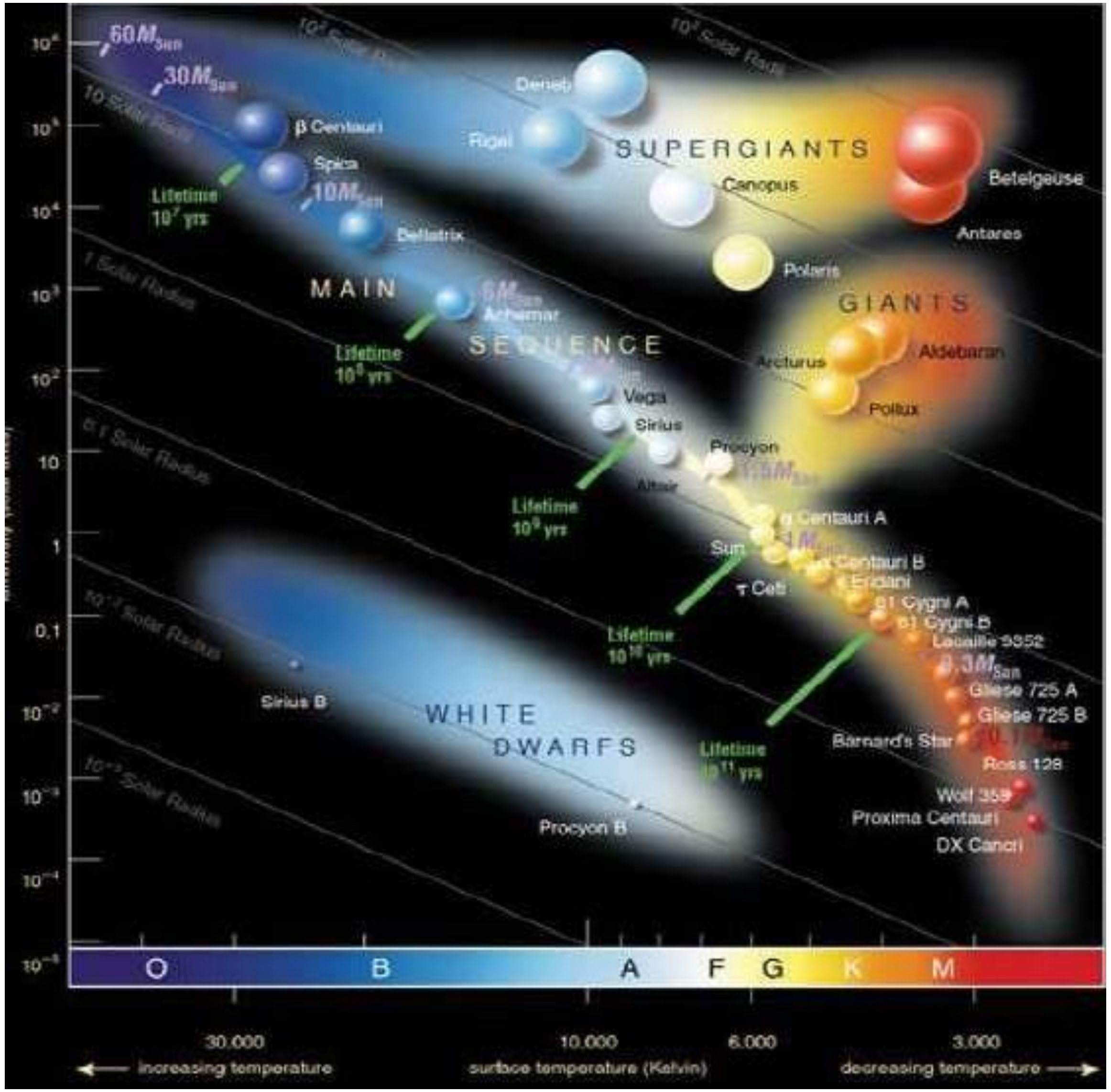
- Supernova
- in magnetic field

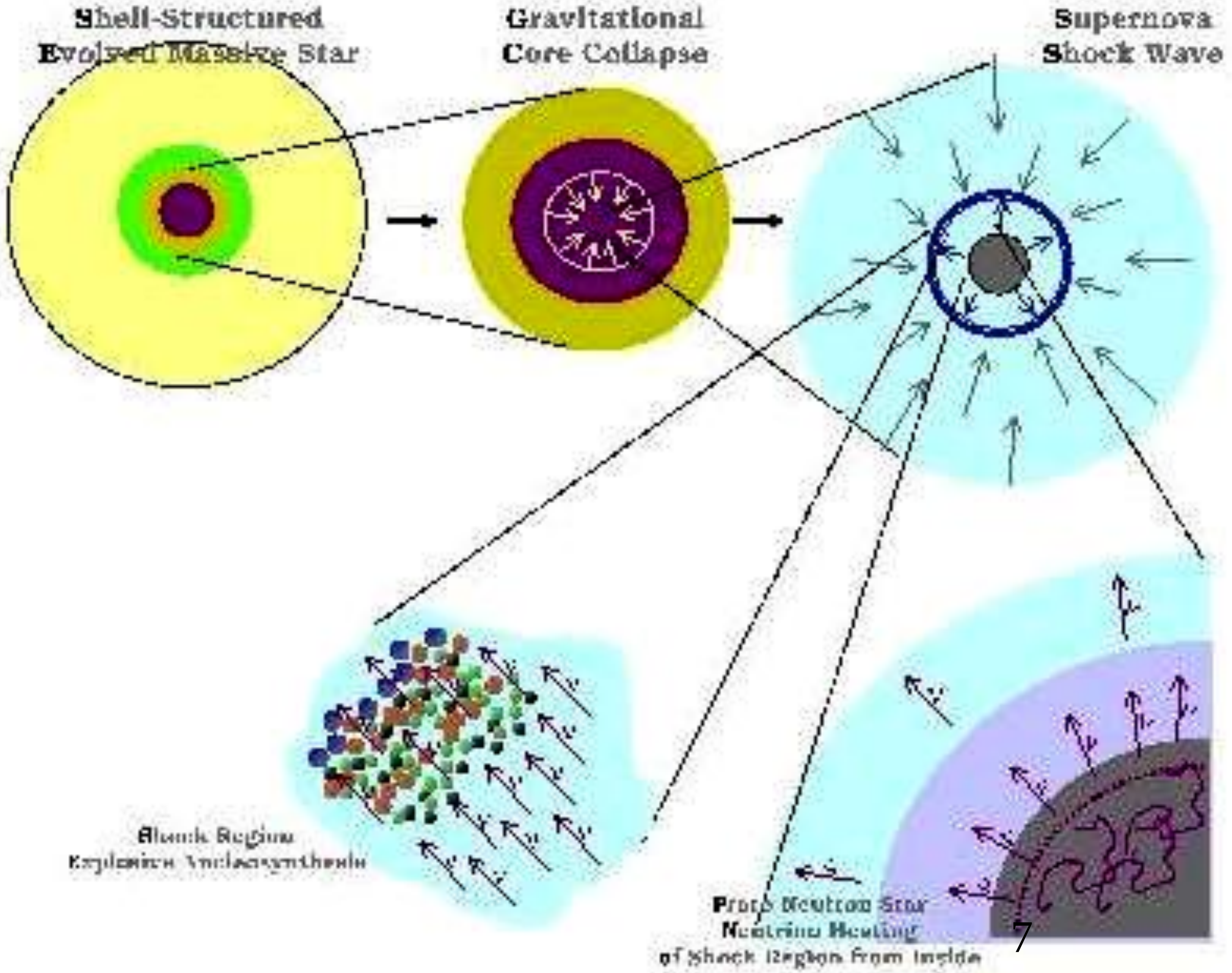
Before and after pictures of SN1987a

Hertzsprung- Russell (H-R) diagram



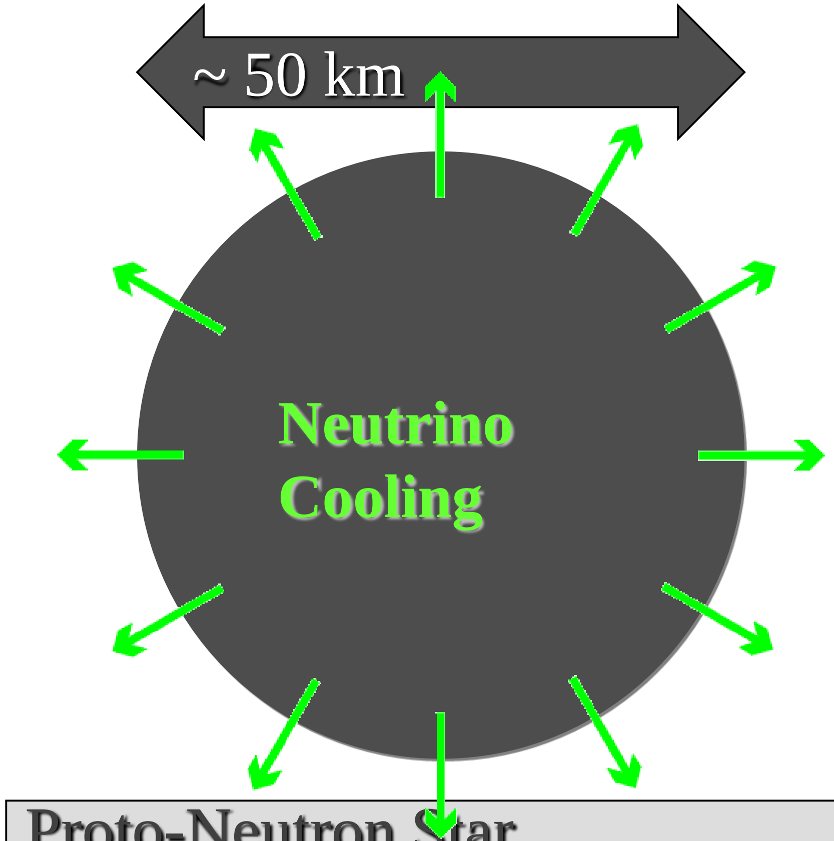
Stefan-Boltzmann
Law for flux

luminosity L
of a star with
radius R **&**
surface temperature T
L~(Surface)T^4~R^2T^4


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

Stellar Collapse and Supernova Explosion

Newborn Neutron Star



Proto-Neutron Star

$\rho \approx \rho_{nuc} = 3\times10^{14}\ \mathrm{g\ cm^{-3}}$

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

Gravitational binding energy

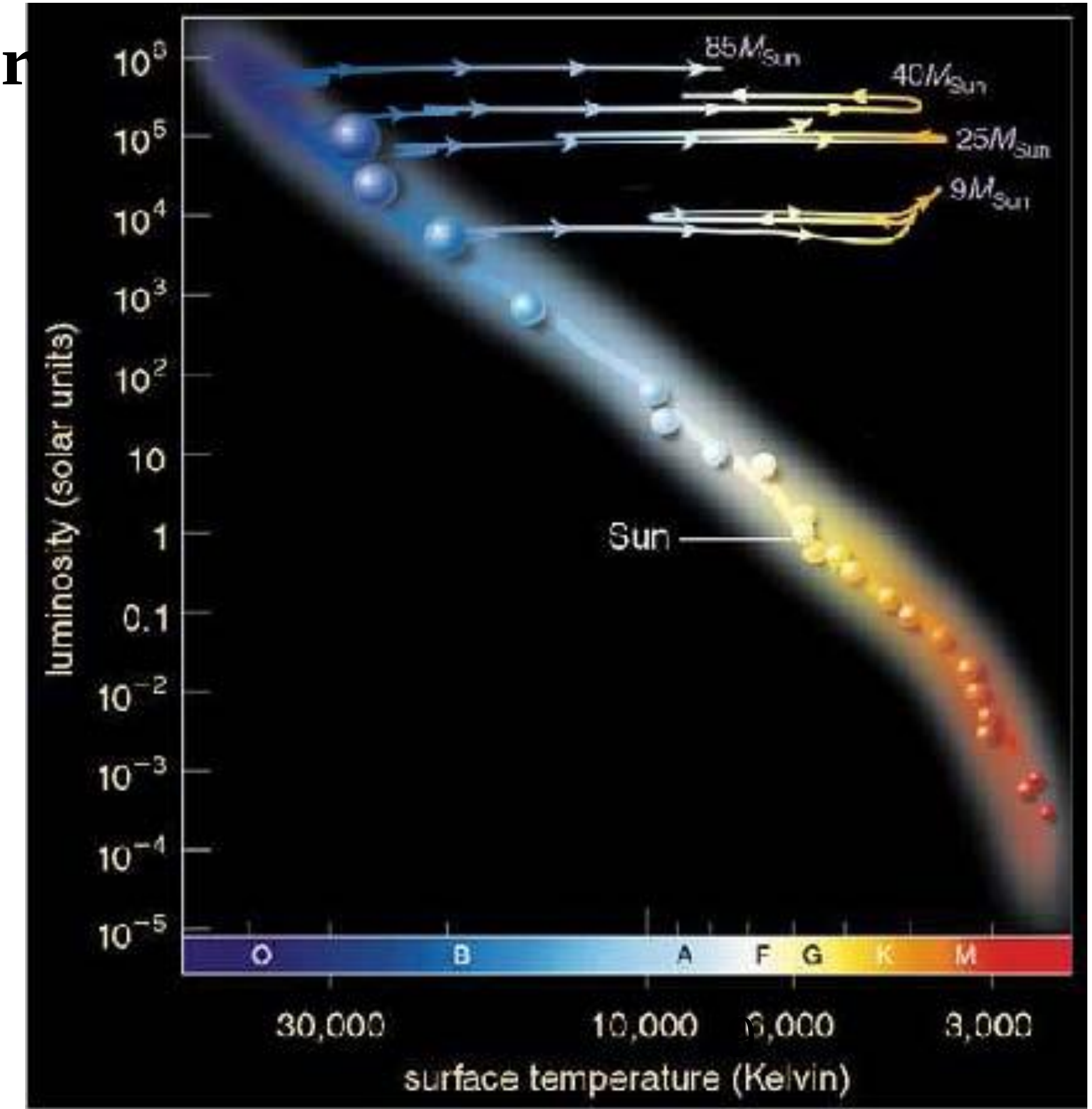
$E_b \approx 10^{53,5}\ \mathrm{erg} \approx 20\%\ M_{SUN}\, c^2$

This is distributed as

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

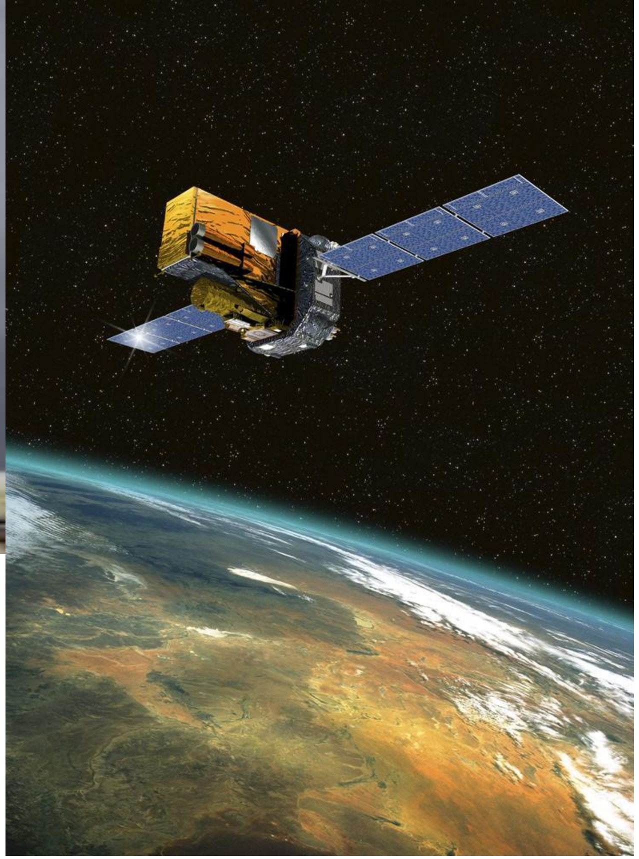
Core-collapse supernova

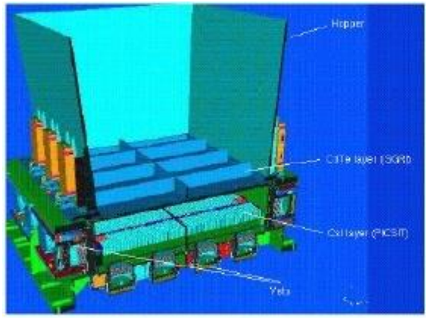
high-mass(M>10M$_o$)star
***Evolution* on HR diagram**



explosive nucleosynthesis
origin of
Heavy Nuclides

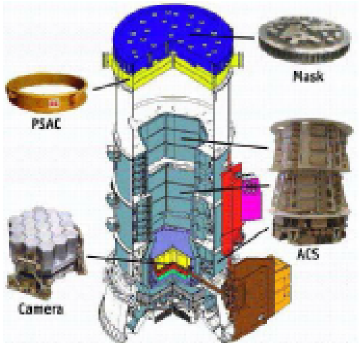
INTEGRAL
VIRGO.UA





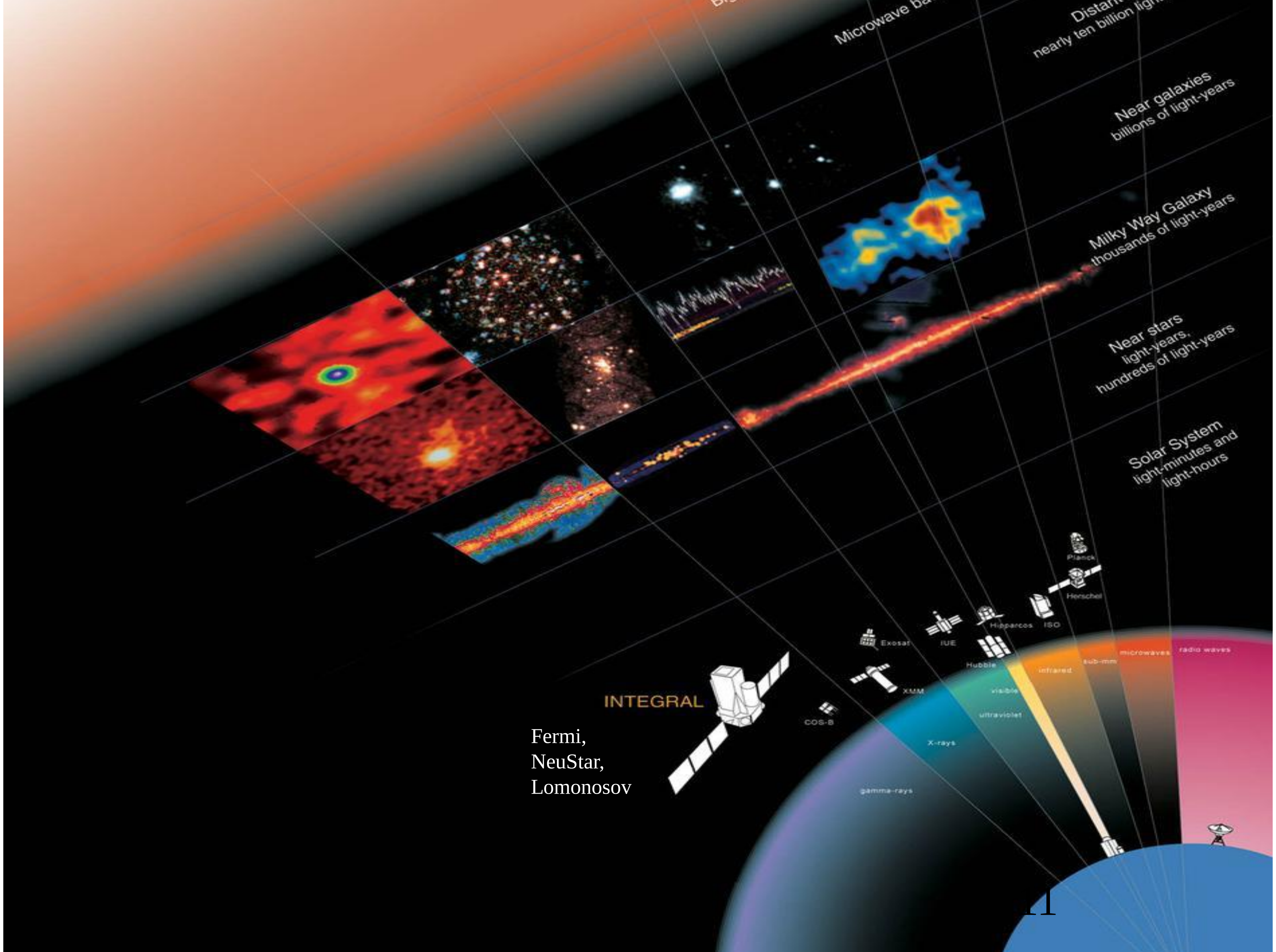
IBIS/ISGRI

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



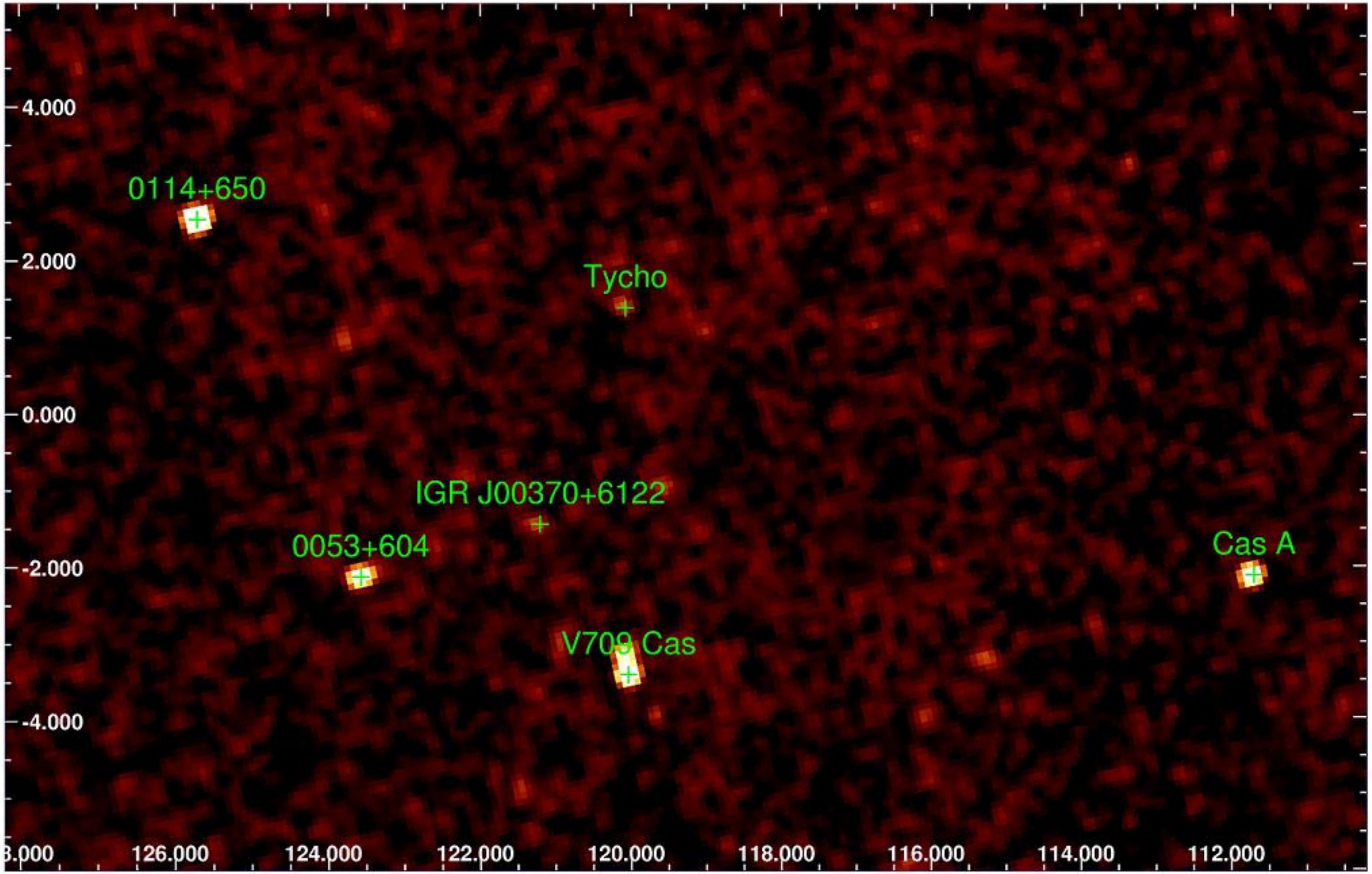
SPI

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



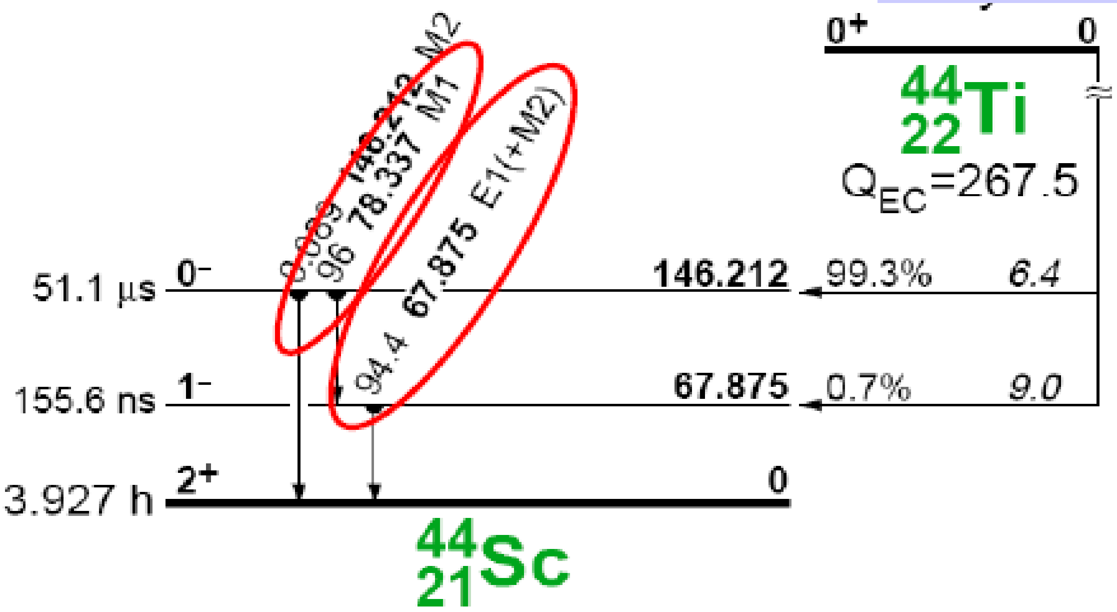
Investigated Supernovas

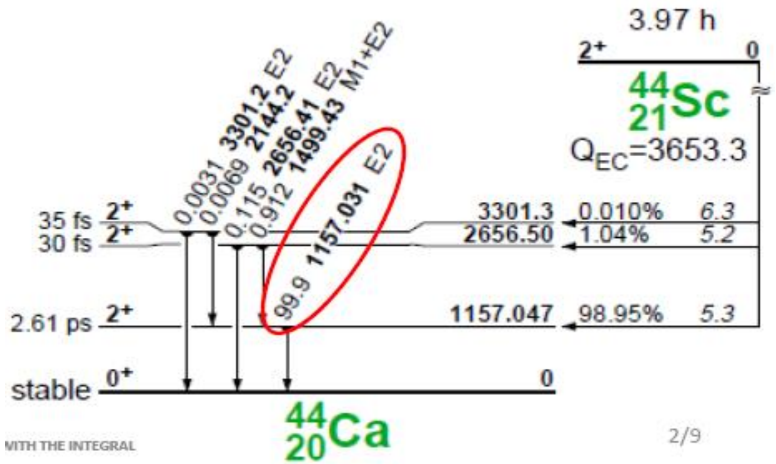
Name	Coordinate	Age
SN 1987A	- 279.7 -31.9,	**34 y**
Cas A	- 111.7 -2.1,	**330 y**
TYCHO	- 120.1 +1.4,	**440 y**
Vela Junior	- 266.3 -1.2	**?**

The scheme of the ^{44}Ti decay

Earth environment

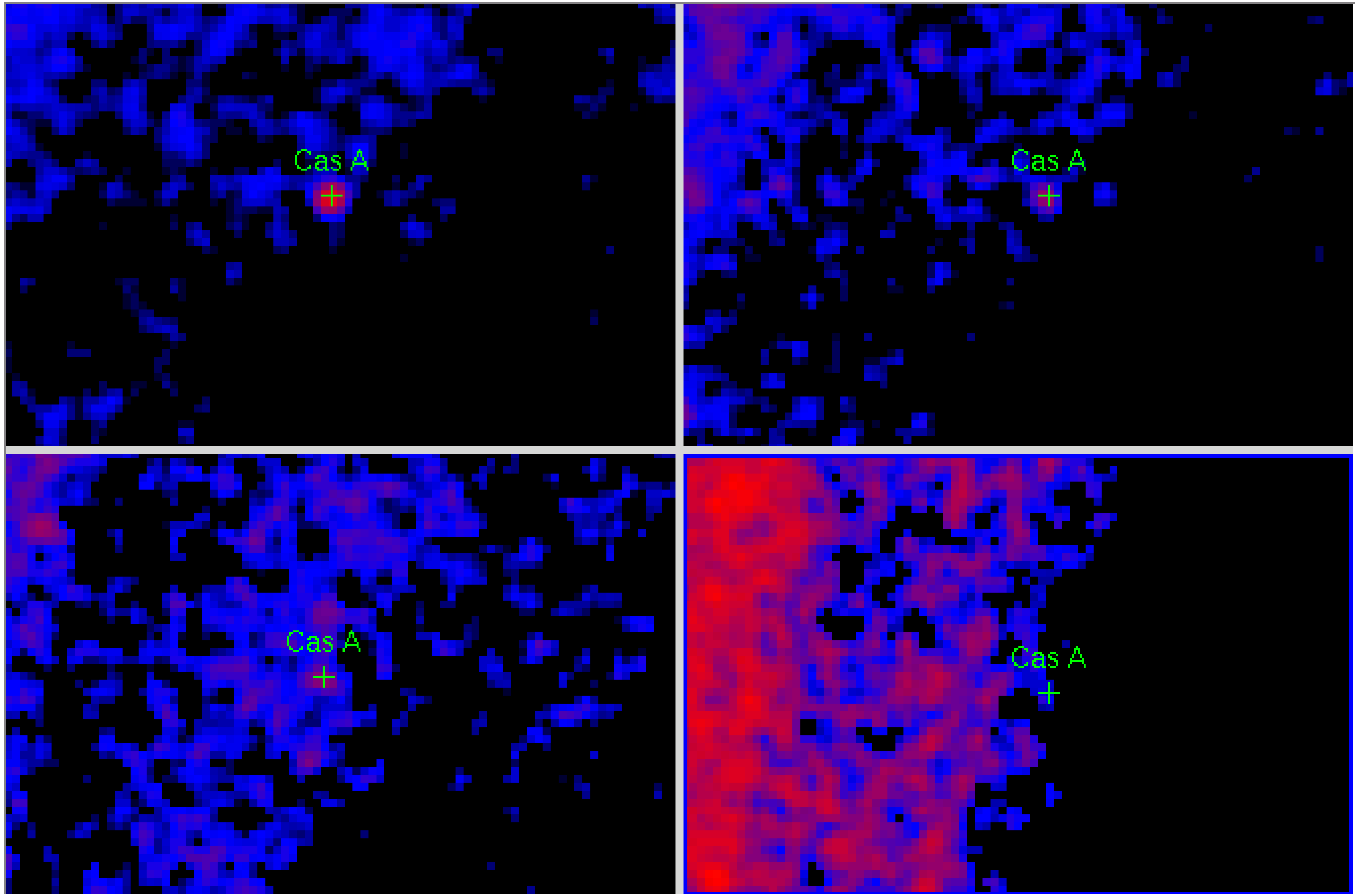
59 y

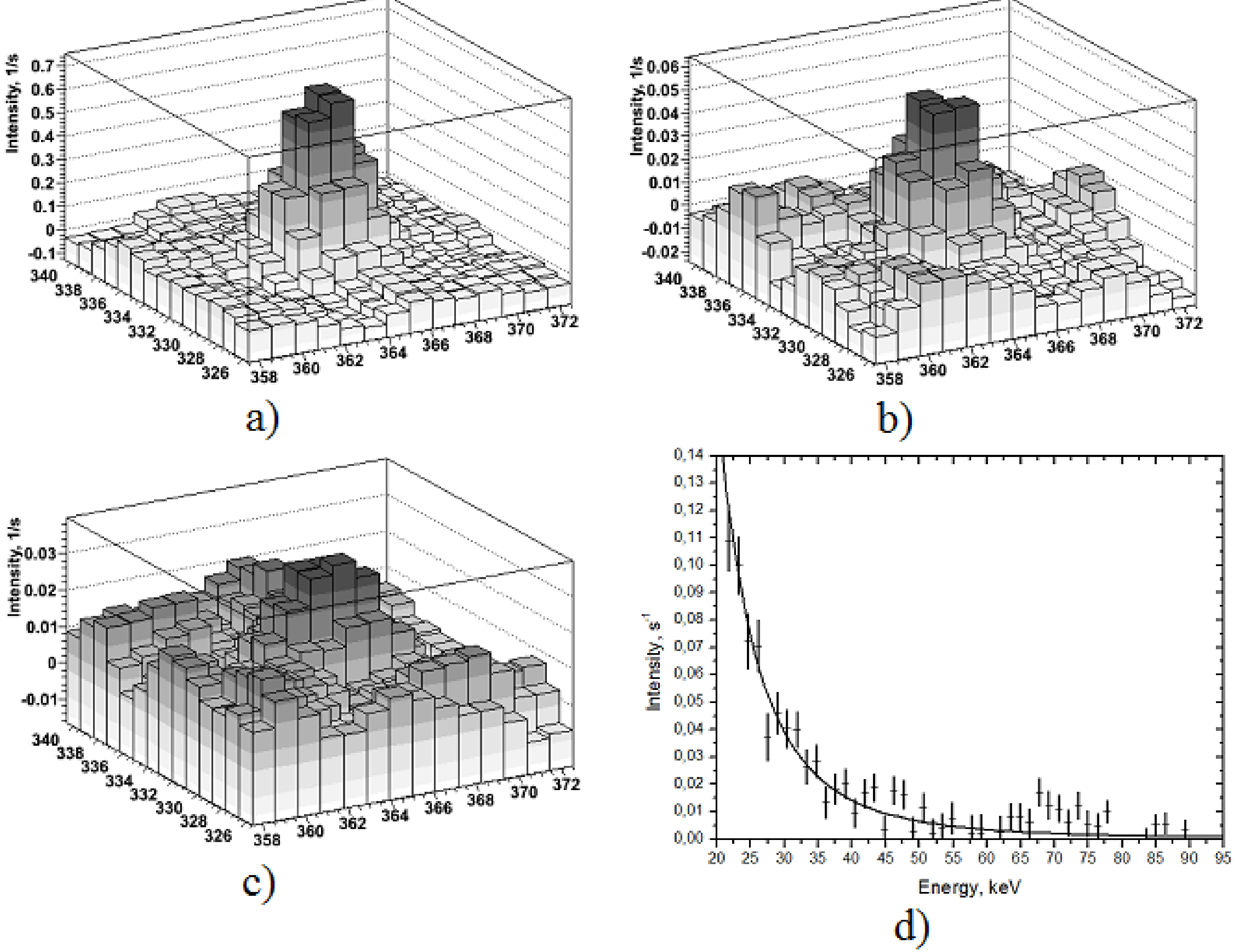




Cassiopeia A (3.4+0.3-0.1)kpc

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



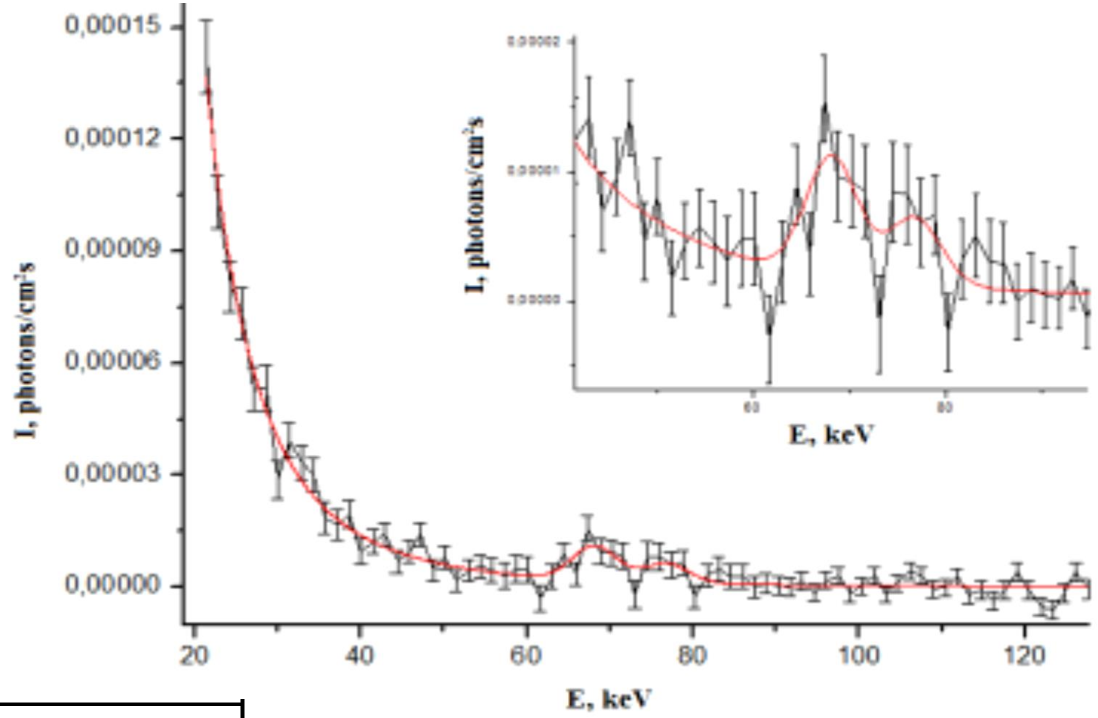


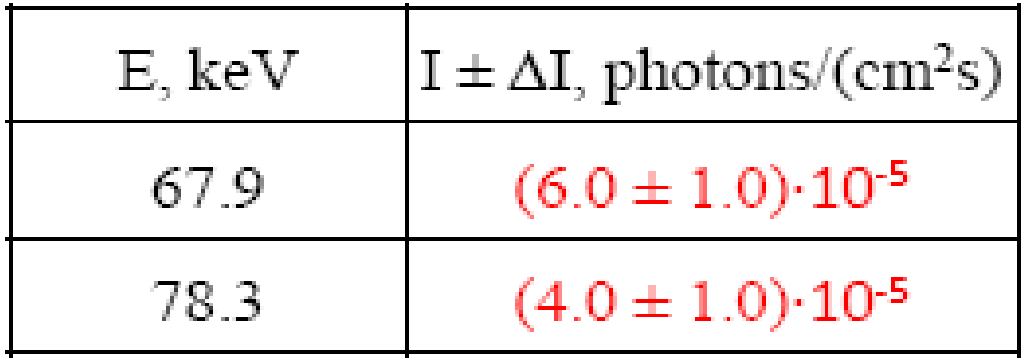
F The direction (i.e.. pixel number) dependence of the registered gamma-ray flux at different energy ranges: **20–62 keV - a, 62–72 keV - b, 72–82 keV – c**; for the angle region containing the Cassiopeia A SN remnant. The right bottom panel (d) represents the spectrum from the Cassiopeia A in the energy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

Background estimate + Lines

$K \cdot E^{a}$

a=-3.64 +/- 0.09



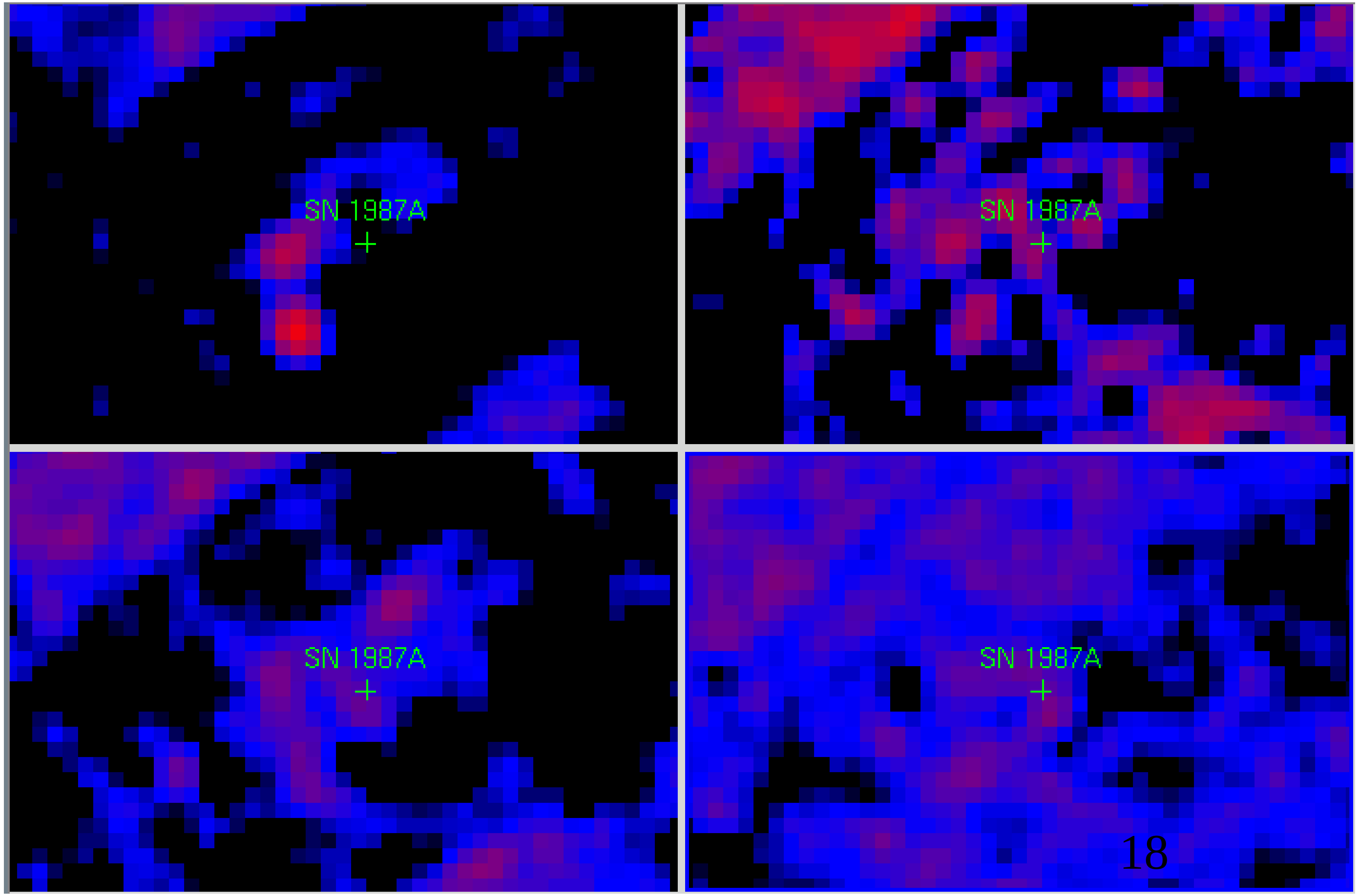


E, keV	I ± ΔI, photons/(cm²s)
67.9	$(6.0 \pm 1.0) \cdot 10^{-5}$
78.3	$(4.0 \pm 1.0) \cdot 10^{-5}$

T= 1.5Ms

SN1987 A (50kpc)

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



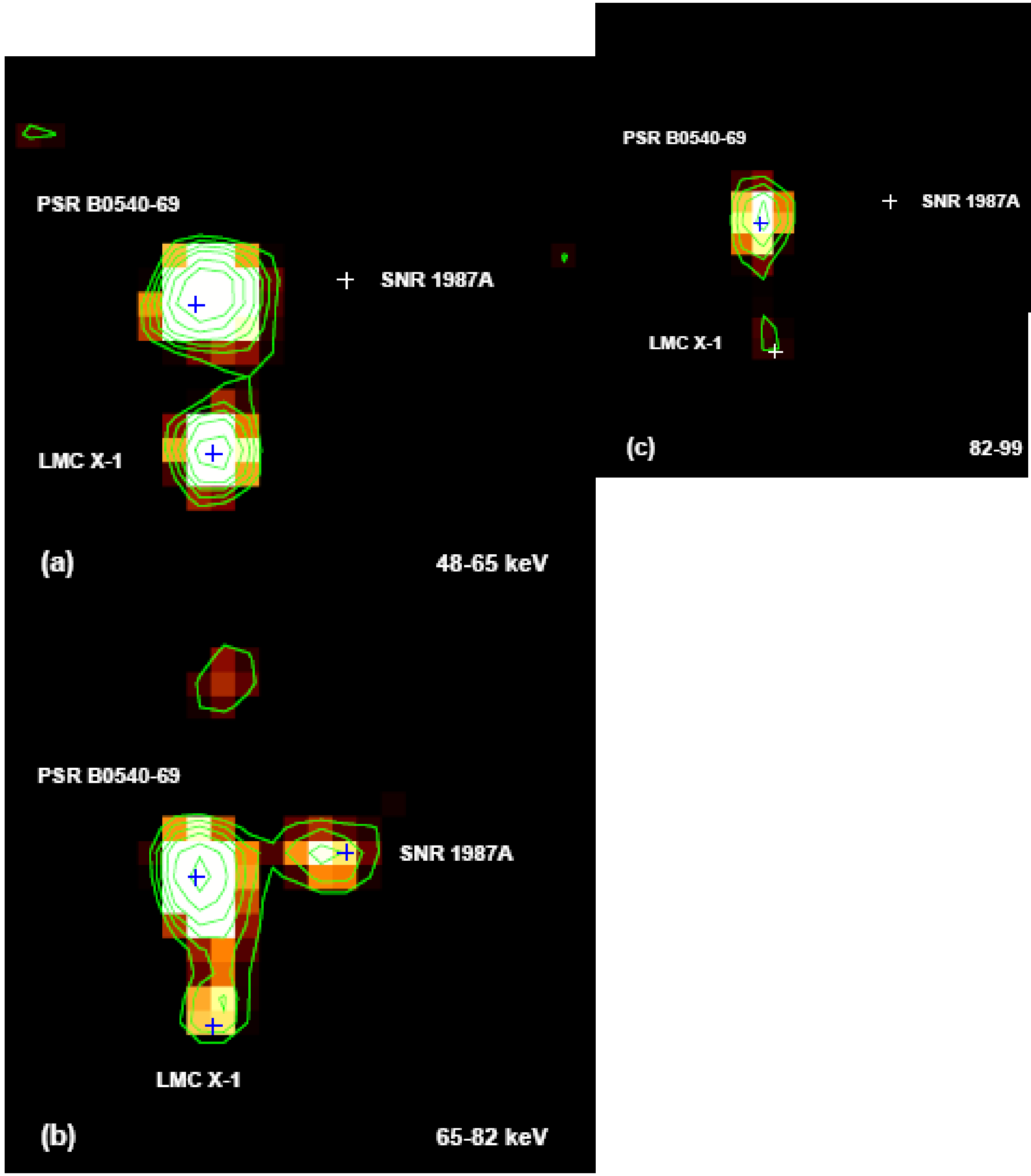
mass of ^{44}Ti synthesized at Cassiopeia A explosion [VNK et al *'Nucleus2004'; PhAN (2009)*]

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

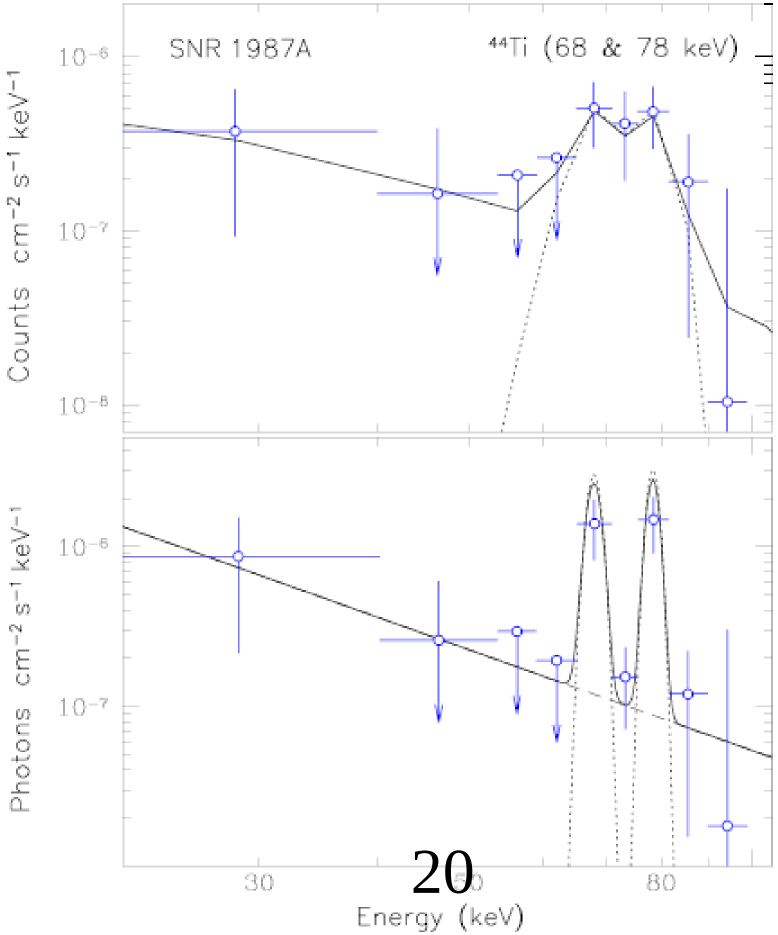
R–distance to the object,$T_{1/2}$–the element half-life, N_a–theAvogadro constant,M–mola rmass,I–γ-quanta flux,p-quantum yield, t–remnant age.

E, keV	I ± ΔI, 10^{-5} photons/cm^{2}s	m ± Δm, 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

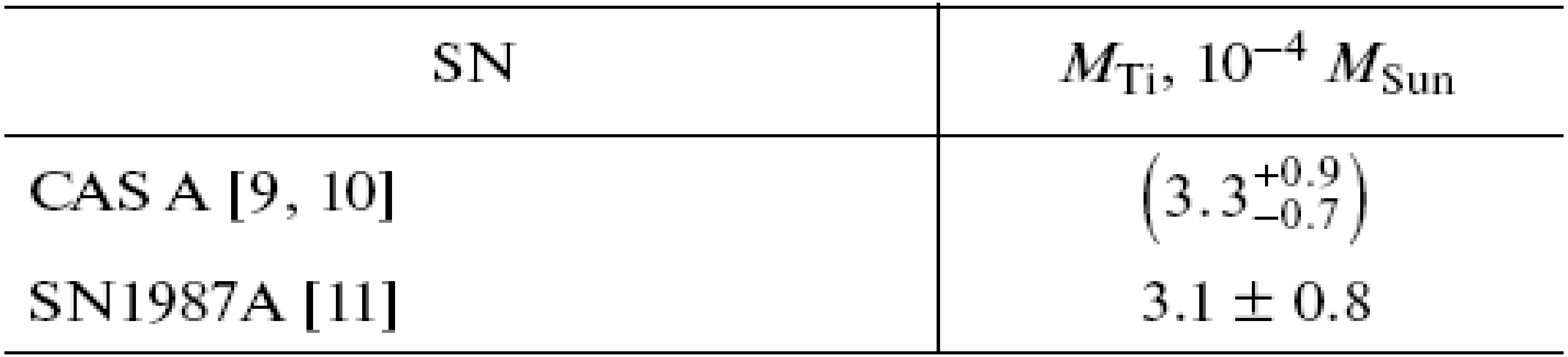
S.A.Grebenev et al *Nature*, *490*, *373-375 (2012)*.



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



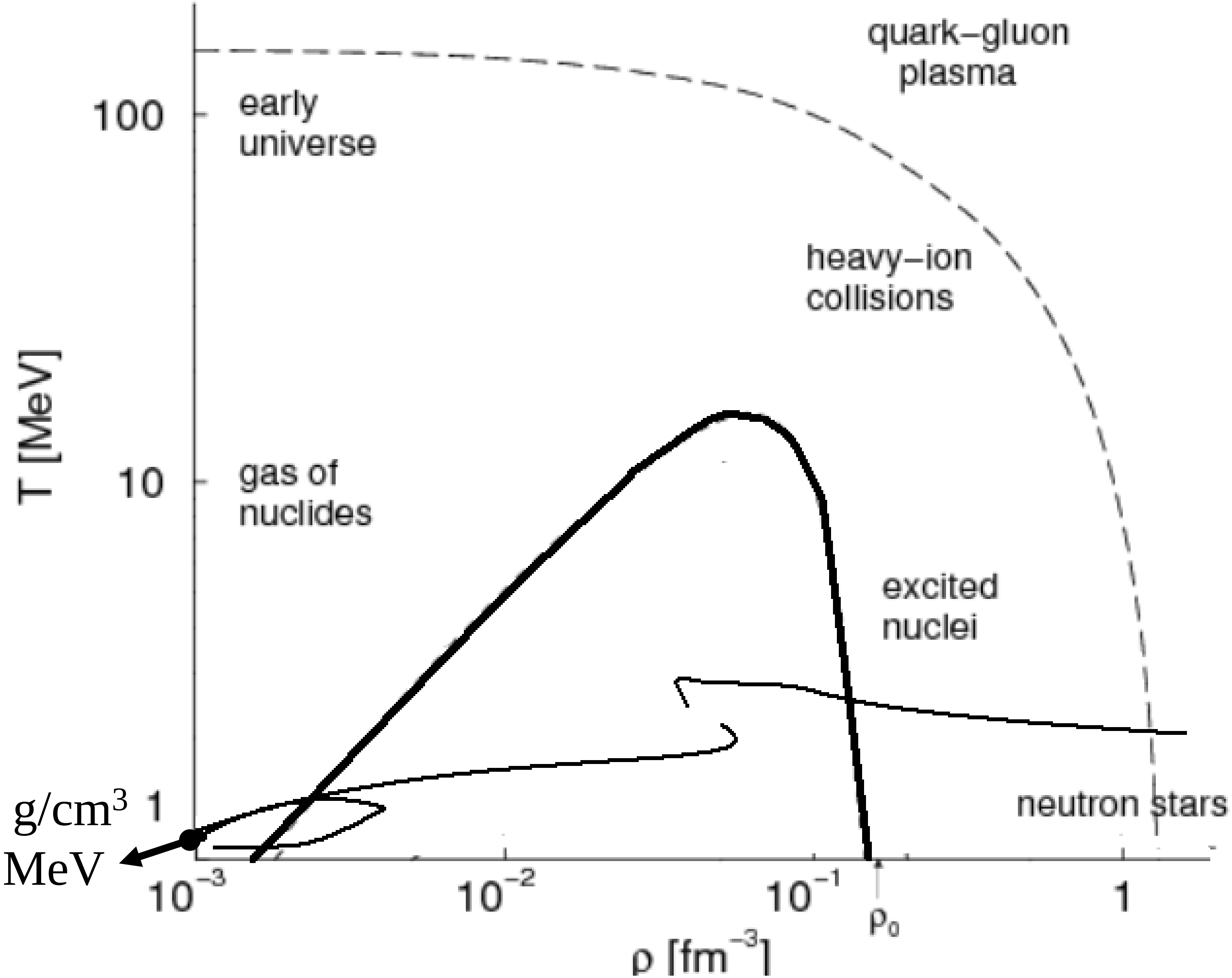
THEORY
& Observations



SN	M_{Ti}, 10^{-4} M_{Sun}
CAS A [9, 10]	$\left(3.3^{+0.9}_{-0.7}\right)$
SN1987A [11]	3.1 ± 0.8

SN1a Model	10^{-1}

Symmetric nuclear matter: Phase diagram



D=10^9 g/cm^3

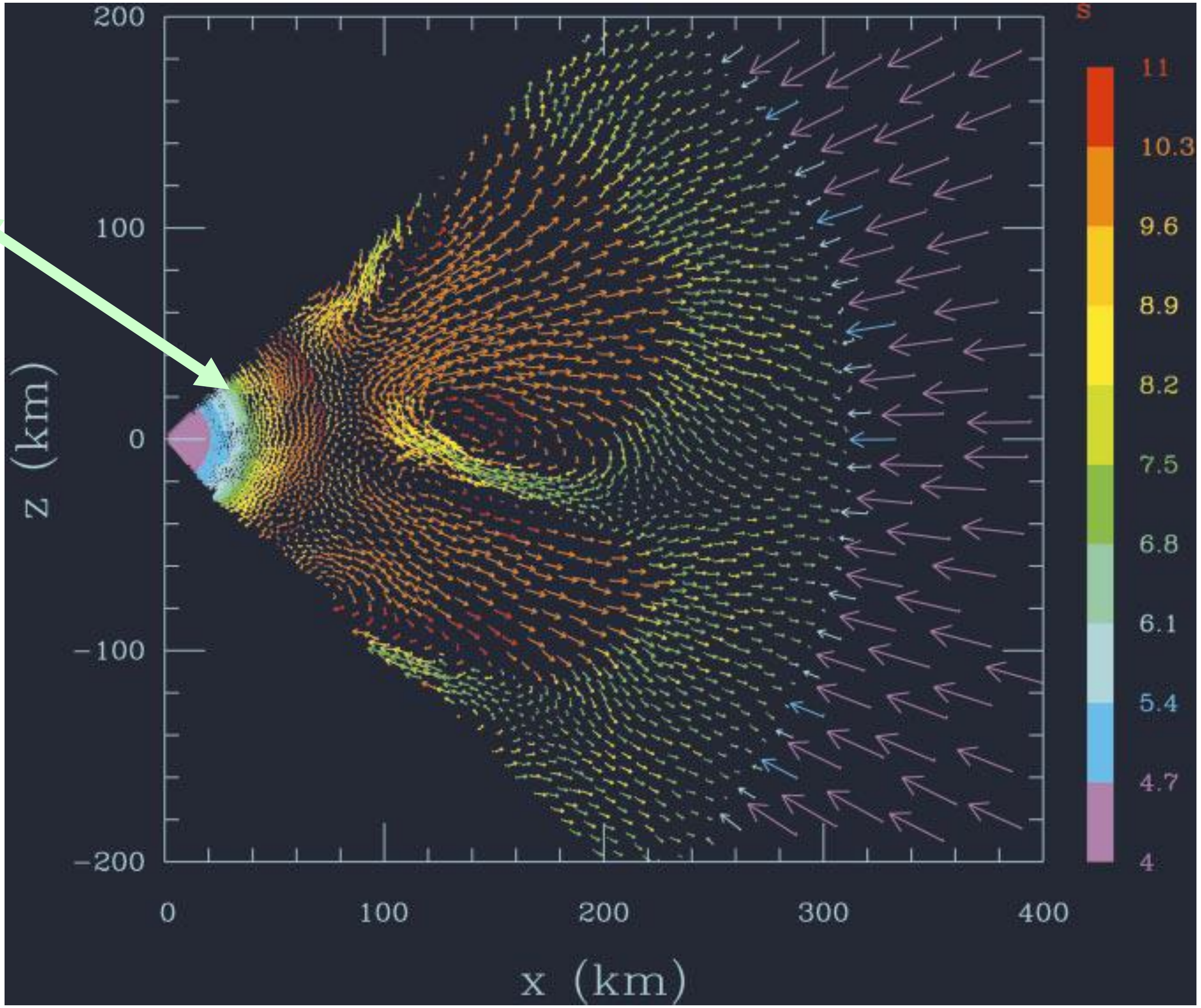
T=0.1 MeV

explosion proceeds through convection processes

ν-sphere

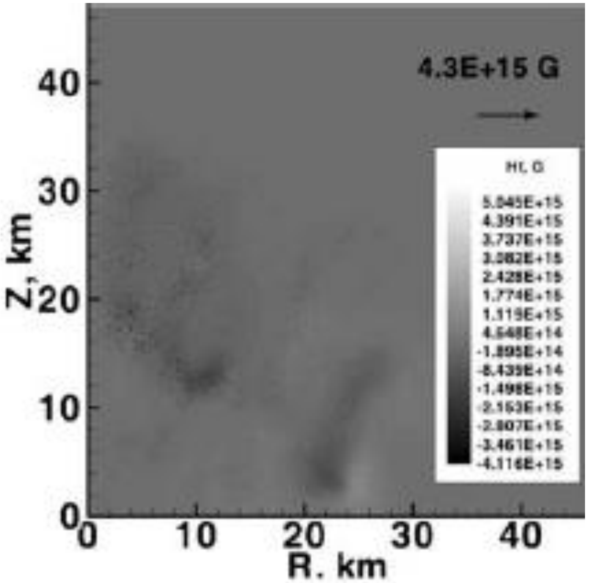
magneto-rotational
instabilities &
dynamo-action
→ amplifying

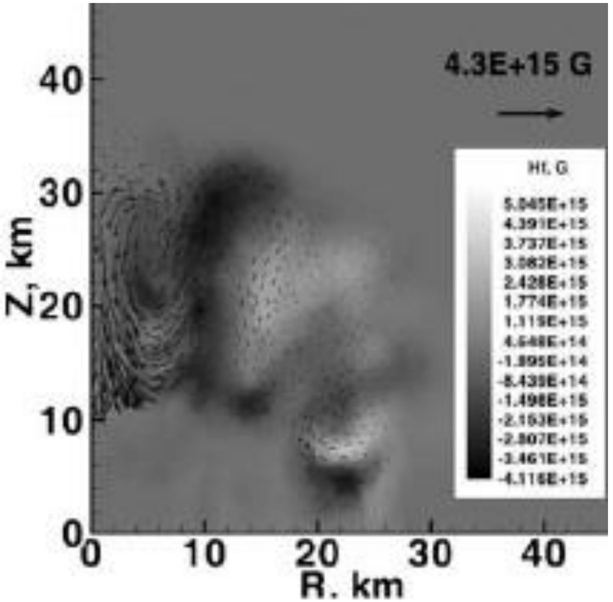
Magnetic fields
up to strengths
hundred *tera-tesla*

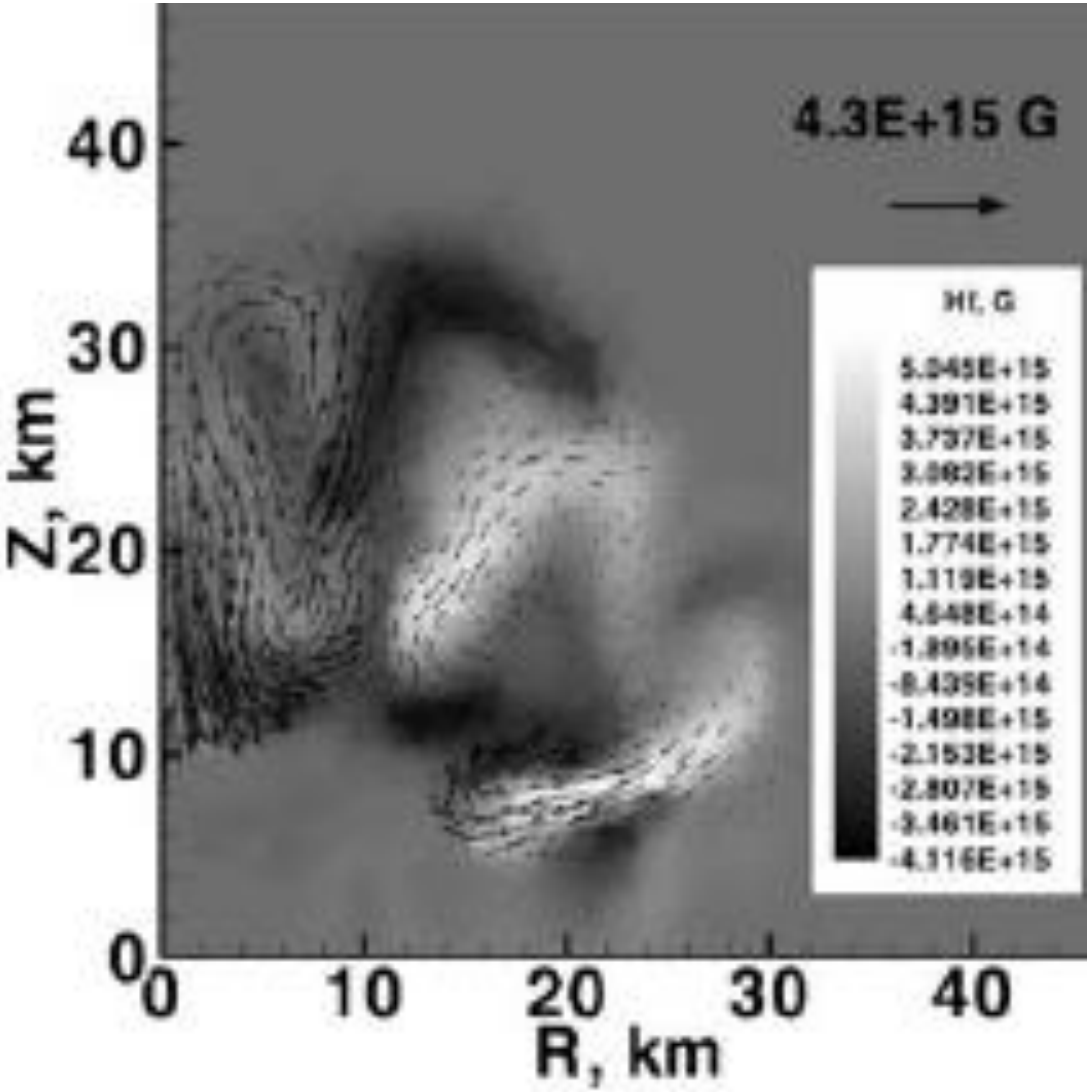


The magnetic field evaluation

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







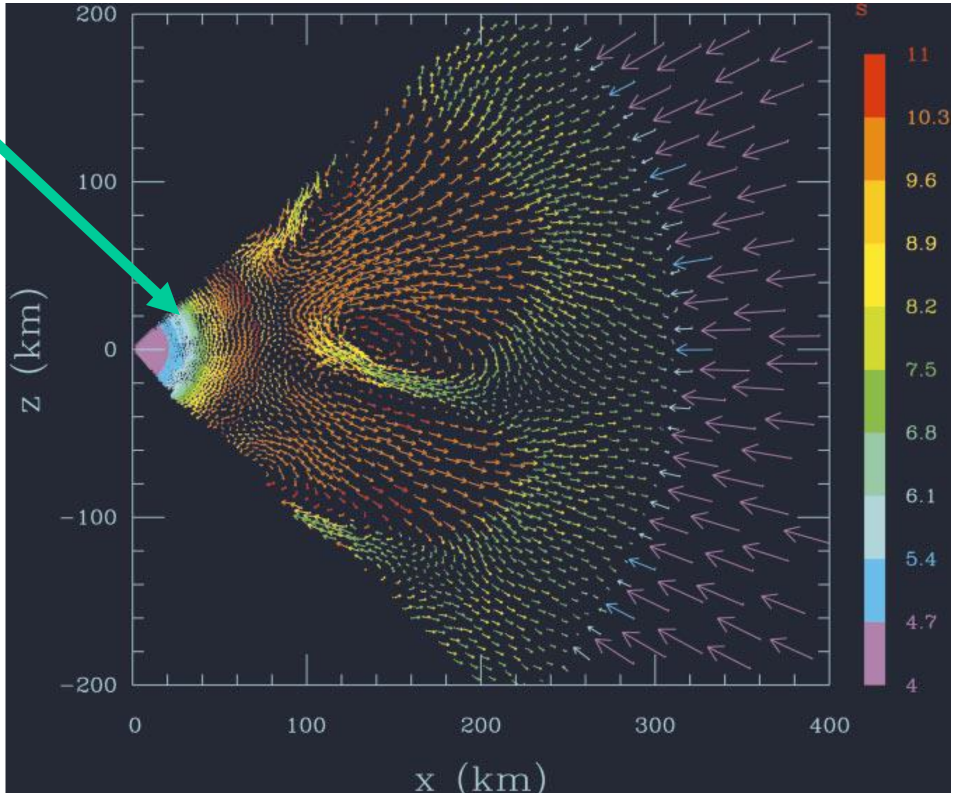
Magnetic field estimates

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

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

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

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



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

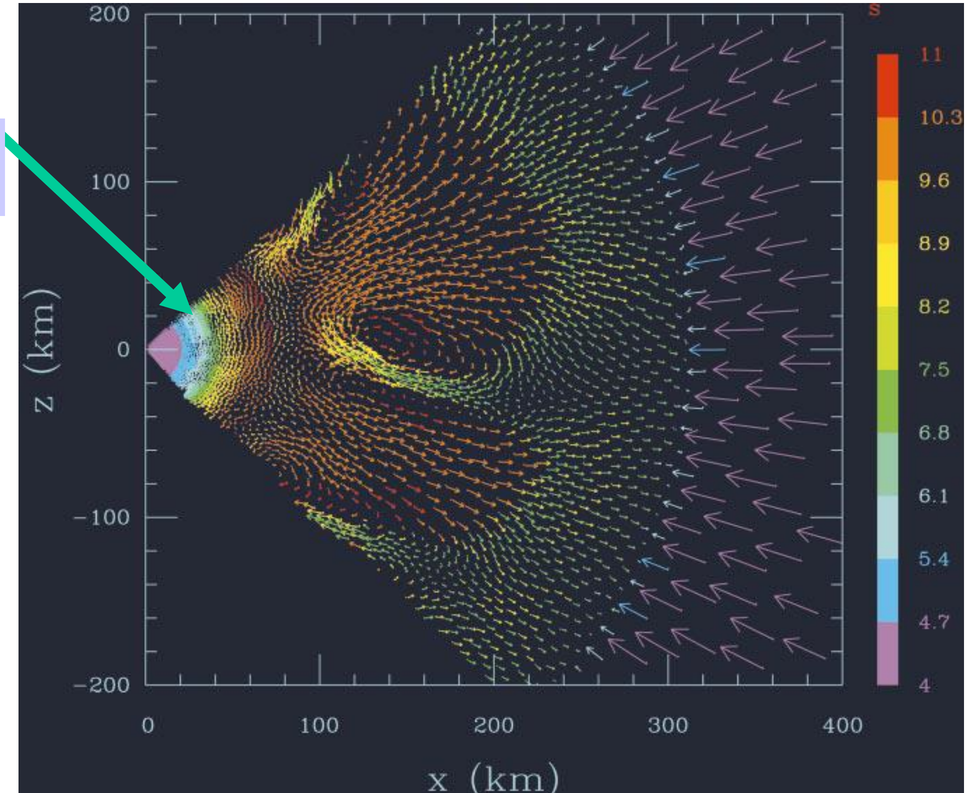
Magnetic field estimates

`Magnetic and gravitational forces`

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

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

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

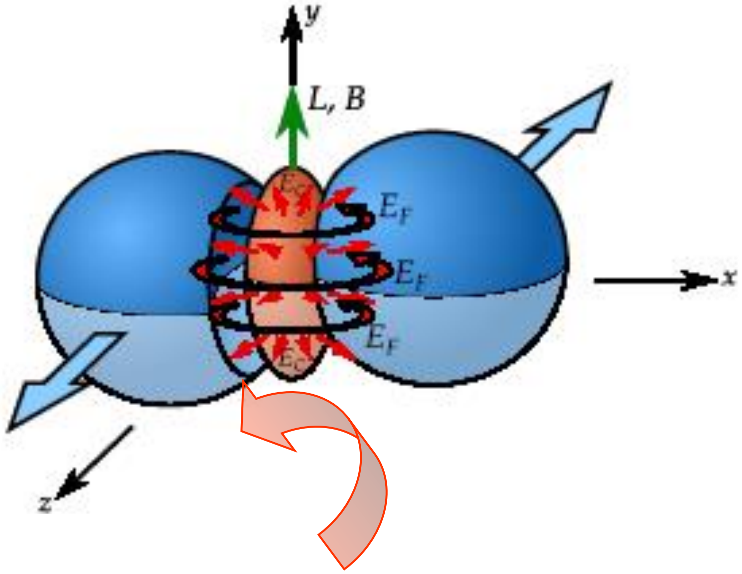


$R_\nu \sim 40$ Km; $\Delta R \sim 1$ Km

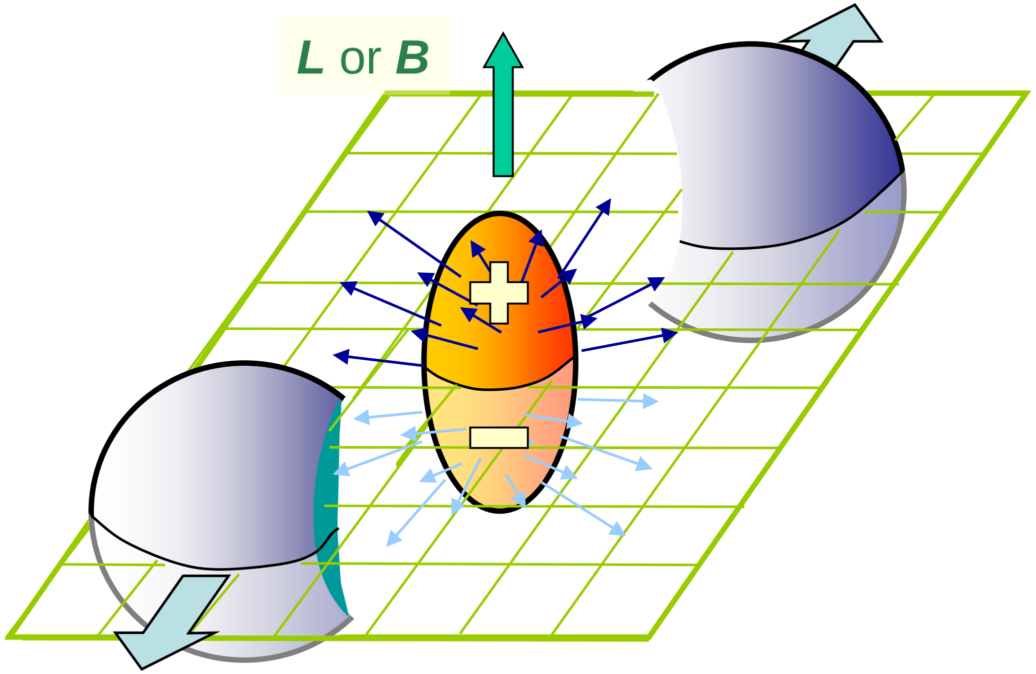
$B_\nu \sim 10^1 - 10^2$ TeraTesla

Magnetic fields **in HIC**

Magnetic field is induced through the axial anomaly



Non-zero angular momentum
(or equivalently magnetic field)
in heavy-ion collisions



$B \sim 10^{1.5}$ TeraTesla $(E/E_o)^{1/2}$

NUCLEAR STATISTICAL EQUILIBRIUM
in Ultra-Strong Magnetic Fields

Entropy *S* extremum →

$$TdS = \sum_i \mu_i dY_i = 0$$

Nuclear composition at temperature *T*

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

Binding Energy ***B***

spin-magnetic part in partition function

[illegible]

$$\omega_\mathrm{L} = \mu_\mathrm{N} H$$

Структура намагниченных ядер

$$\hat{\mathrm{H}} = \hat{\mathrm{H}}^0 - \hat{\mathrm{H}}_{\mathrm{M}}, \quad \hat{\mathrm{H}}_{\mathrm{M}} = \sum_{i=1}^{A}((\hat{\tau}_3^i + 1/2)\hat{\mathrm{l}}_i + g(\hat{\tau}_3^i)\hat{\mathrm{s}}_i)\omega_{\mathrm{L}}$$

Гамильтониан для изолированных ядер, в отсутствие магнитного поля.

Взаимодейтсвие дипольного магнитного момента нуклонов с полем представлены слагаемыми:

$w_L = \mu_N H$ μ_N =обозначает ядерный магнетон

g−фактор для протона $g(1/2) \approx 5.586$ и для нейтрона $g(-1/2) \approx -3.826$

$$\Delta B_m = B_m(H) - B_m(0) = \sum_{\mathrm{occ}} \langle nljm_j|\hat{\mathrm{H}}_{\mathrm{M}}|nljm_j\rangle$$

$$\Delta B_m = \kappa\omega_{\mathrm{L}},$$

$$\kappa = \sum_{i-\mathrm{v};m,s} |\langle l^i m, \frac{1}{2}s|j^i m_j^i\rangle|^2((\tau_3^i + 1/2)m + g(\tau_3^i)s)$$

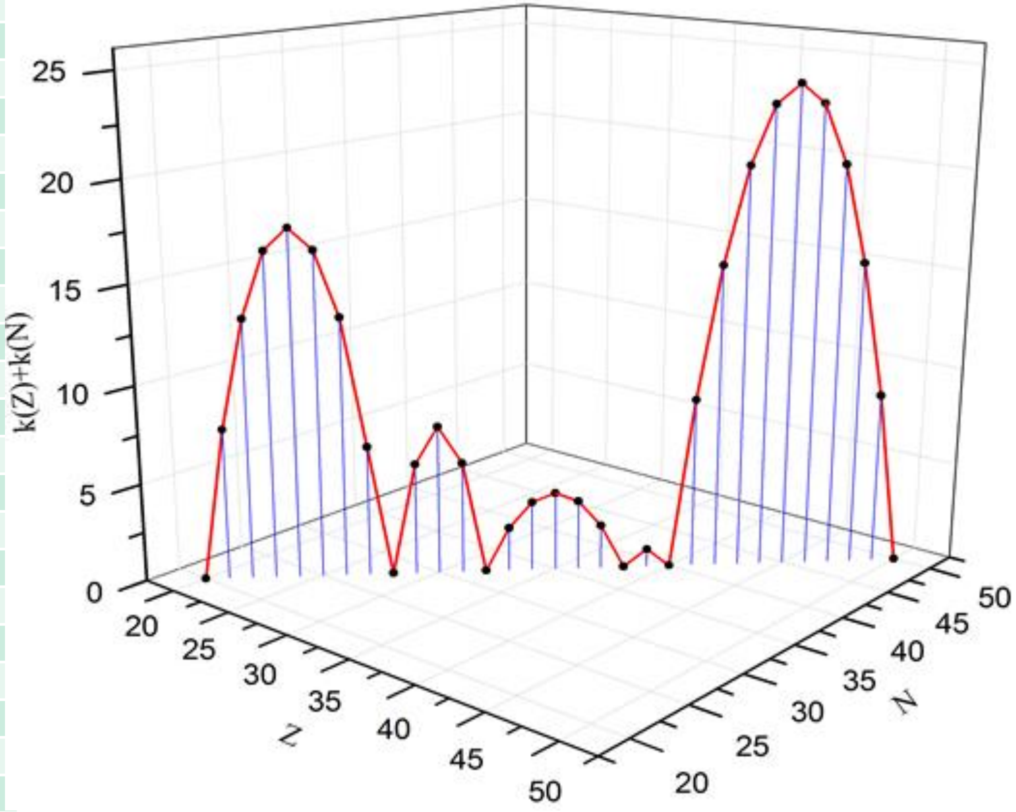
Таким образом, значение k существенно отличается от g-фактора, соответствующего взаимодействию магнитного момента ядра в основном состоянии с полем. Важным отличием от g-фактора является то, что все нуклоны валентного оболочка дают вклад на магнитный отклик.

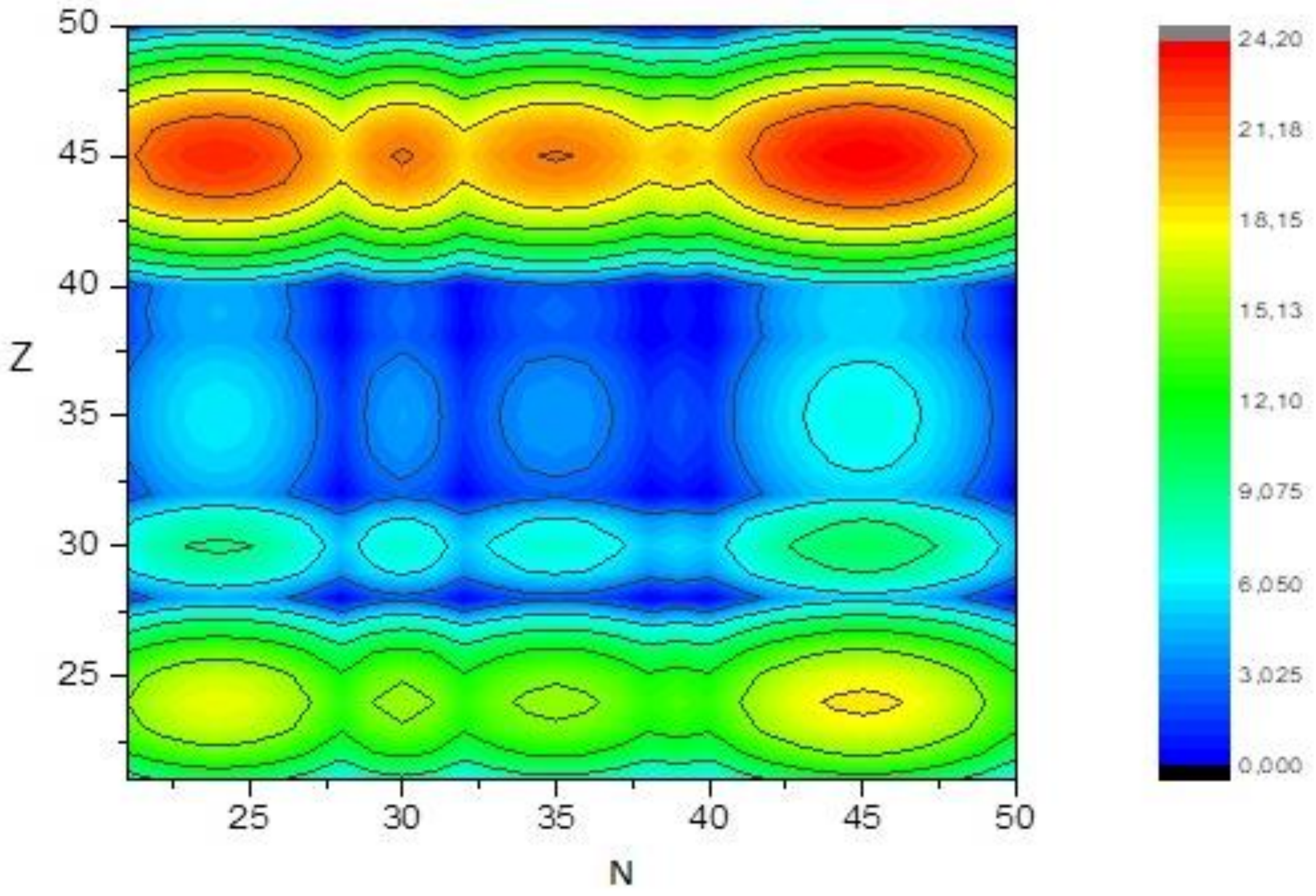
Уравнение дает более надежную энергию ядер в магнитных полях H > 0.1 ТТл по сравнению с g-фактором ядра в основном состоянии.

Таб.1

For symmetric nuclei

	Z	k(1/2)	N	K(-1/2)
j=3/2	20	0.00	20	0.00
j=7/2	21	5.793	21	1.913
	22	9.931	22	3.279
	23	12.414	23	4.099
	24	13.241	24	4.373
	25	12.414	25	4.099
	26	9.931	26	3.279
	27	5.793	27	0.862
	28	0.00	28	0.00
j=3/2	29	3.793	29	1.913
	30	5.057	30	2.551
	31	3.793	31	1.913
	32	0.00	32	0.00
j=5/2	33	0.862	33	1.366
	34	1.379	34	2.186
	35	1.55	35	2.459
	36	1.379	36	2.185
	37	0.862	37	1.366
	38	0.00	38	0.00
j=1/2	39	0.264	39	0.638
	40	0.00	40	0.00
j=9/2	41	6.793	41	1.913
	42	12.076	42	3.401
	43	15.85	43	4.464
	44	18.115	44	5.101
	45	18.869	45	5.314
	46	18.115	46	5.101
	47	15.85	47	4.464
	48	12.076	48	3.401
	49	6.793	49	1.913
	50	0.00	50	0.00

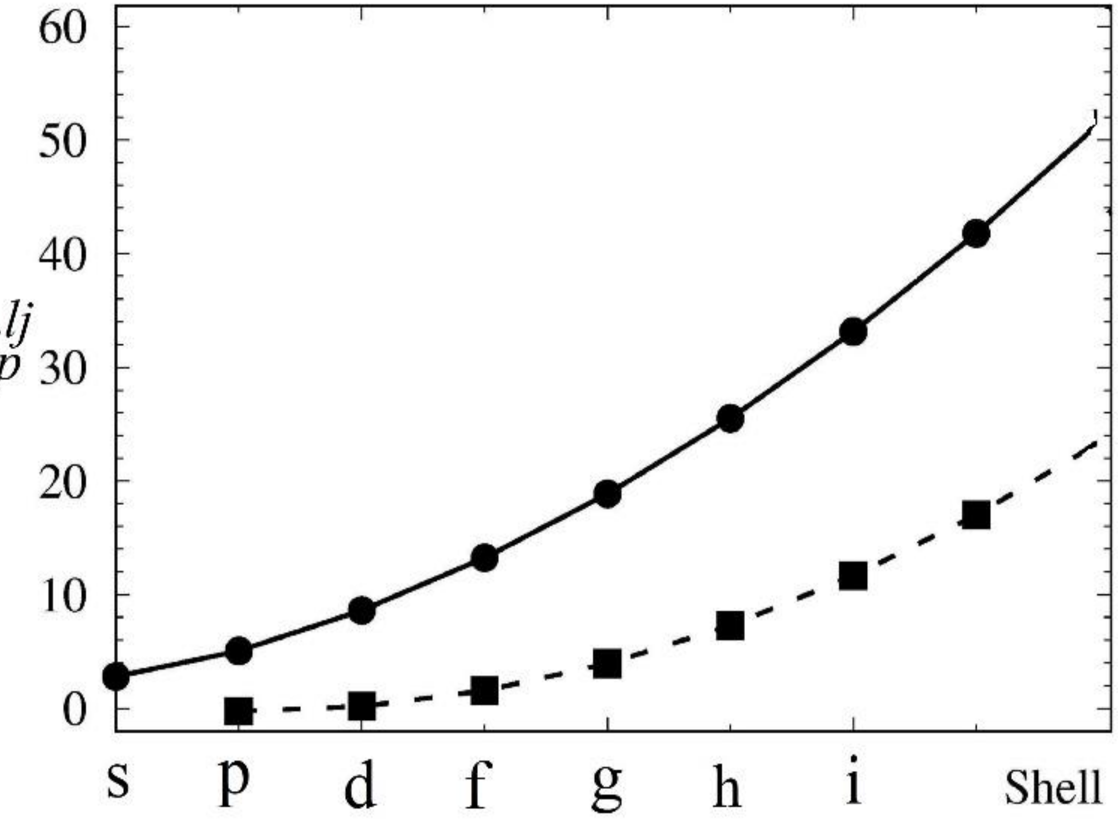



50
45
40
Z
35
30
25
25
30
35
40
45
50
N
24,20
21,18
18,15
15,13
12,10
9,075
6,050
3,025
0,000

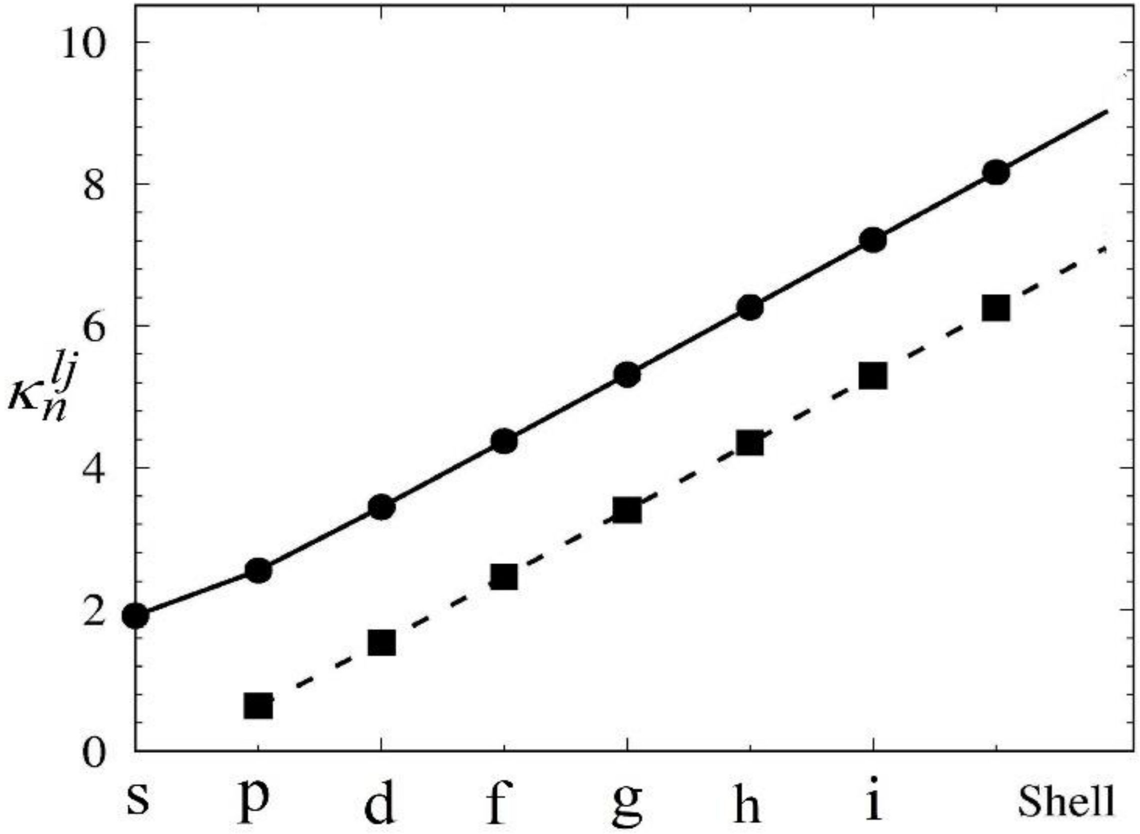
Maximum magnetic susceptibility of a half-filled shells

Solid lines and circles -- j = l + 1/2, dashed lines and squares -- j = l – 1/2

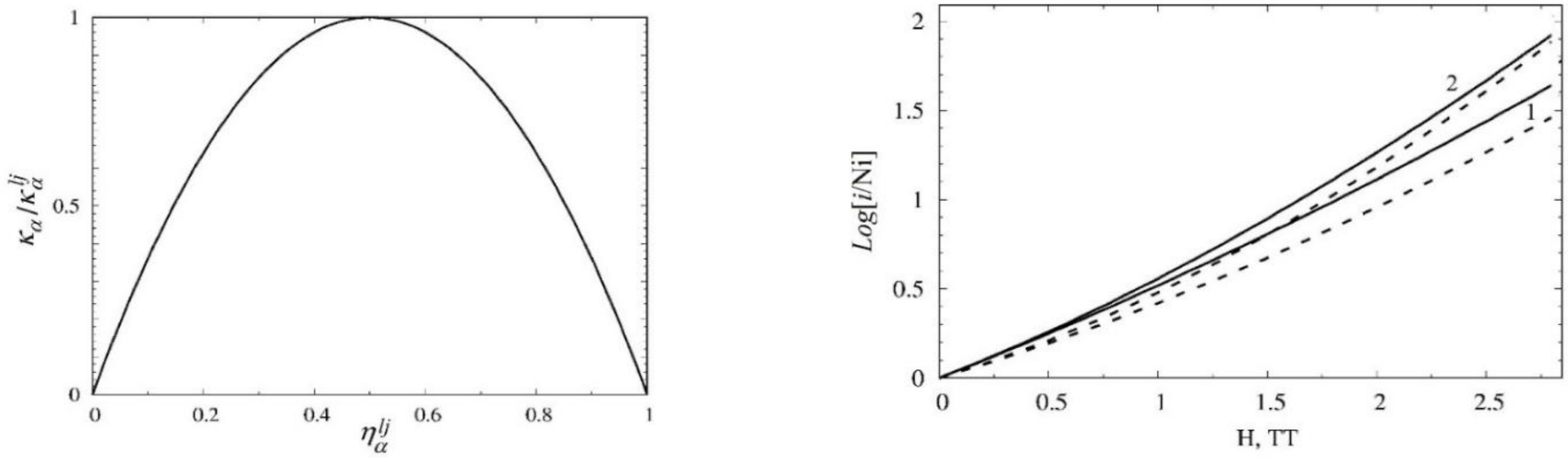
protons – (a)



neutrons – (b)



Отношение выхода Ti к Ni



(a)

(b)

- Зависимость магнитной восприимчивости от параметра заполнения оболочки η_α^{lj}. (б) Отношения выхода [i /Ni] для ^{56}Ni в зависимости от магнитного поля для i $=$ ^{48}Cr — сплошные линии и ^{44}Ti — штриховые линии. Кривые 1 и 2 представляют результаты уравнения Саха и приближения свободной энергии соответственно

r – процесс. Уравнения Саха.

Исследование *(n, γ)* ←→ *(γ, n)* при ЯСР

A + n ←→ (A+1) + γ

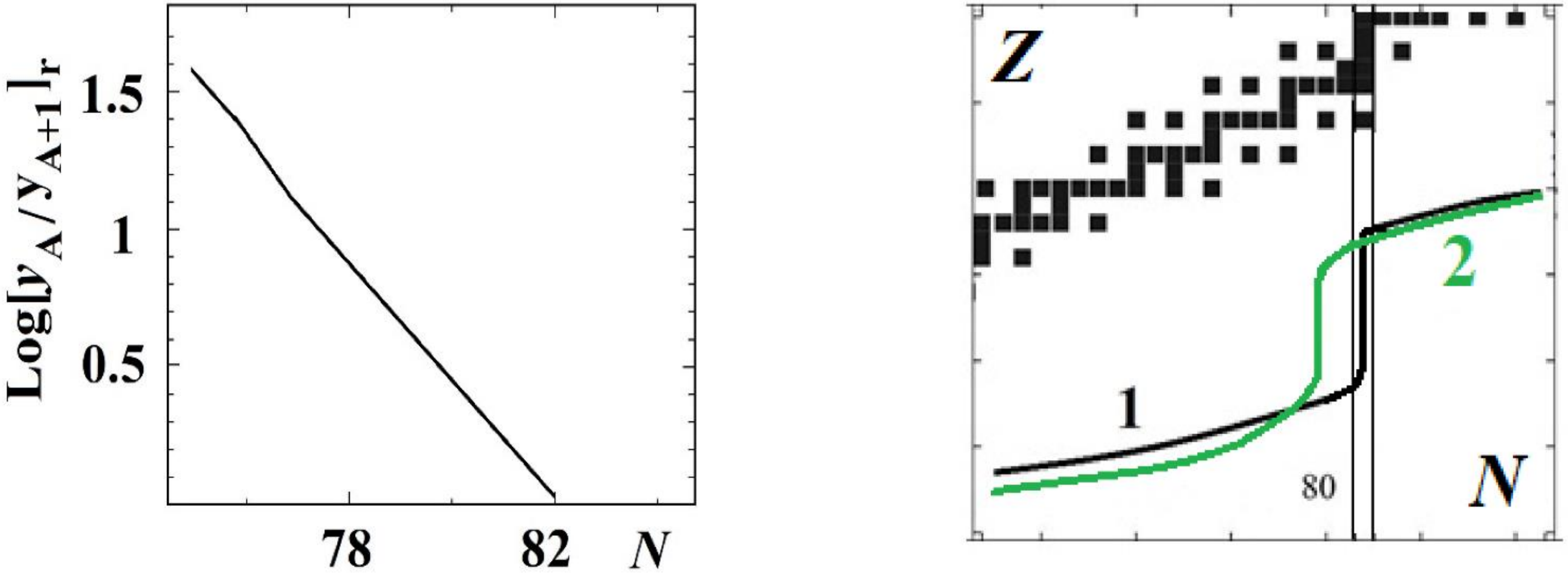
$$N_{A+1} = N_A N_n \frac{g_{A+1}}{g_A g_n} \left(\frac{2\pi\hbar^2}{\mu kT} \right)^{3/2} \exp\{B/kT\}$$

$$N_n = 2\frac{N_{A+1} g_A}{N_A g_{A+1}} \left(\frac{\mu kT}{2\pi\hbar^2} \right)^{3/2} \exp\{-B/kT\}$$

$N_n \sim 10^{23.5}$/cc & $T_9 \sim 1$ |→ binding energy B~2.4 MeV

$\sim 10^{1.5}$ *kT*

Путь r – процесса



(a) (b)

- *.(а) Магнитное усиление выхода ядер с открытыми оболочками при напряженности поля* $\mathrm{H} = 2$ *Тл и температуре* $\mathrm{T} = 10^9$ *K. (б) Магнитный эффект на пути r-процесса схематично показан линией 2 по отношению к стандартному сценарию линия 1.*

SUMMARY

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

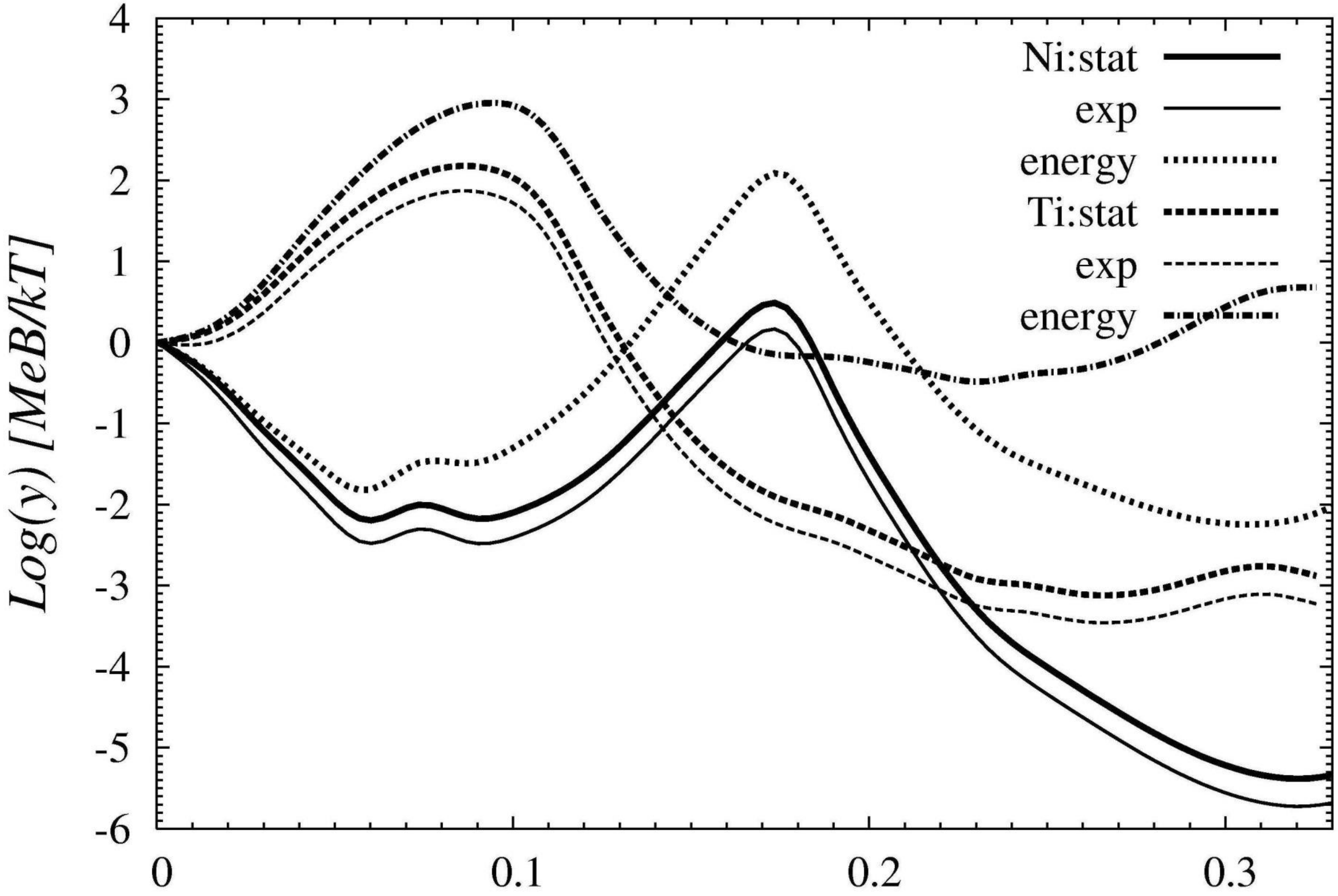
SUMMARY

- Magnetism of Atomic Nuclei

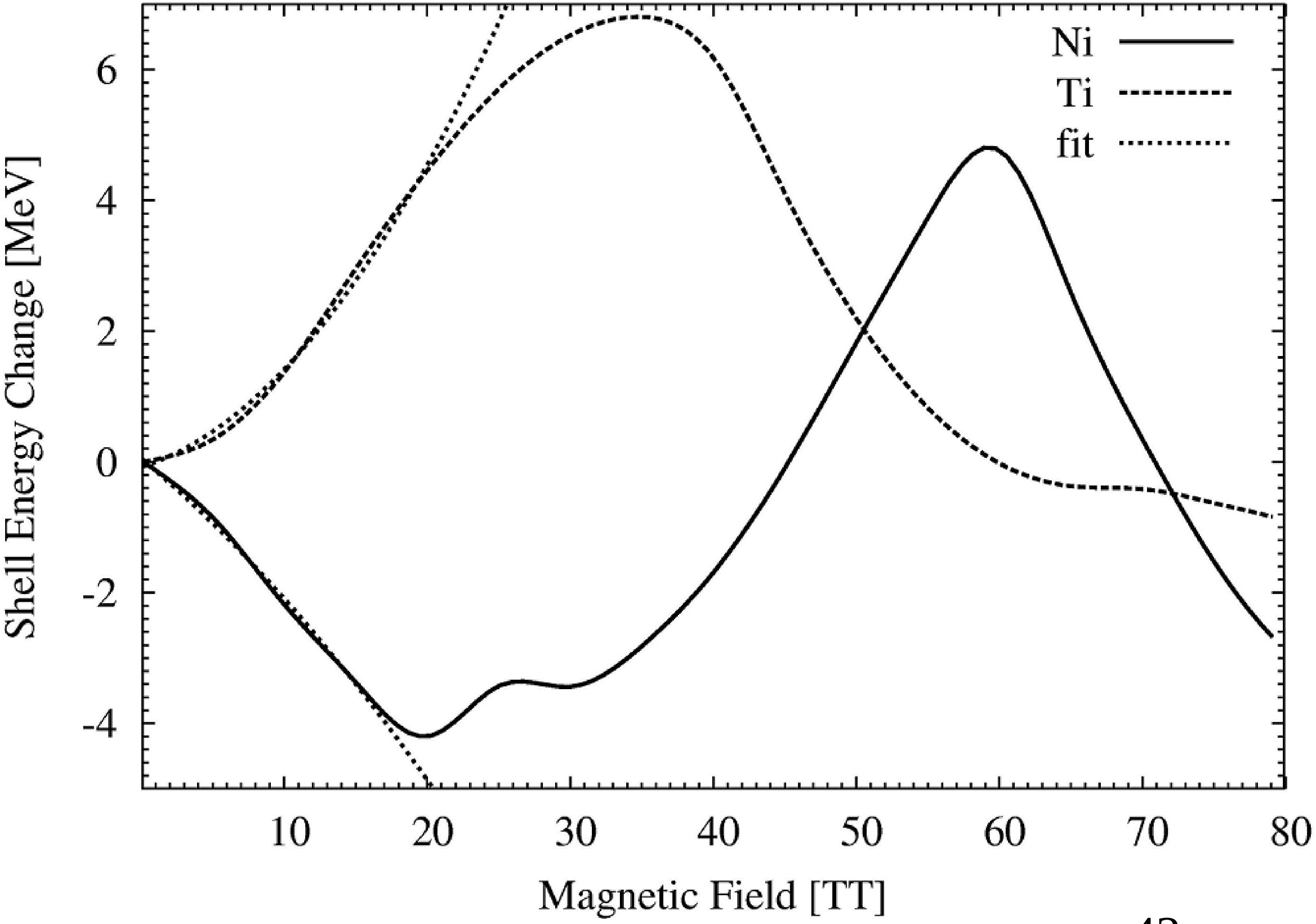
  Thermodynamic formalism
- Magnetic fieldы less 10 Tera-Tesla --- linear Magnetic Response due to Zeeman splitting
- Pauli type Paramagnetic Response --- Neutrons
- Landau-type Orbital Magnetism --- Protons
- Magnetic fields of Tera-Tesla shift Nuclear Magics of Iron region towards Smaller Masses → new seed Ti-44, Ti-48
- Enhancement in Yield Smaller Masses of R-process nuclei

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

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



Магнитное поле, *h*


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

1kpc = 3.08567758 × 10^19 метра