

**End of**

Lecture 3

# Active galactic nuclei

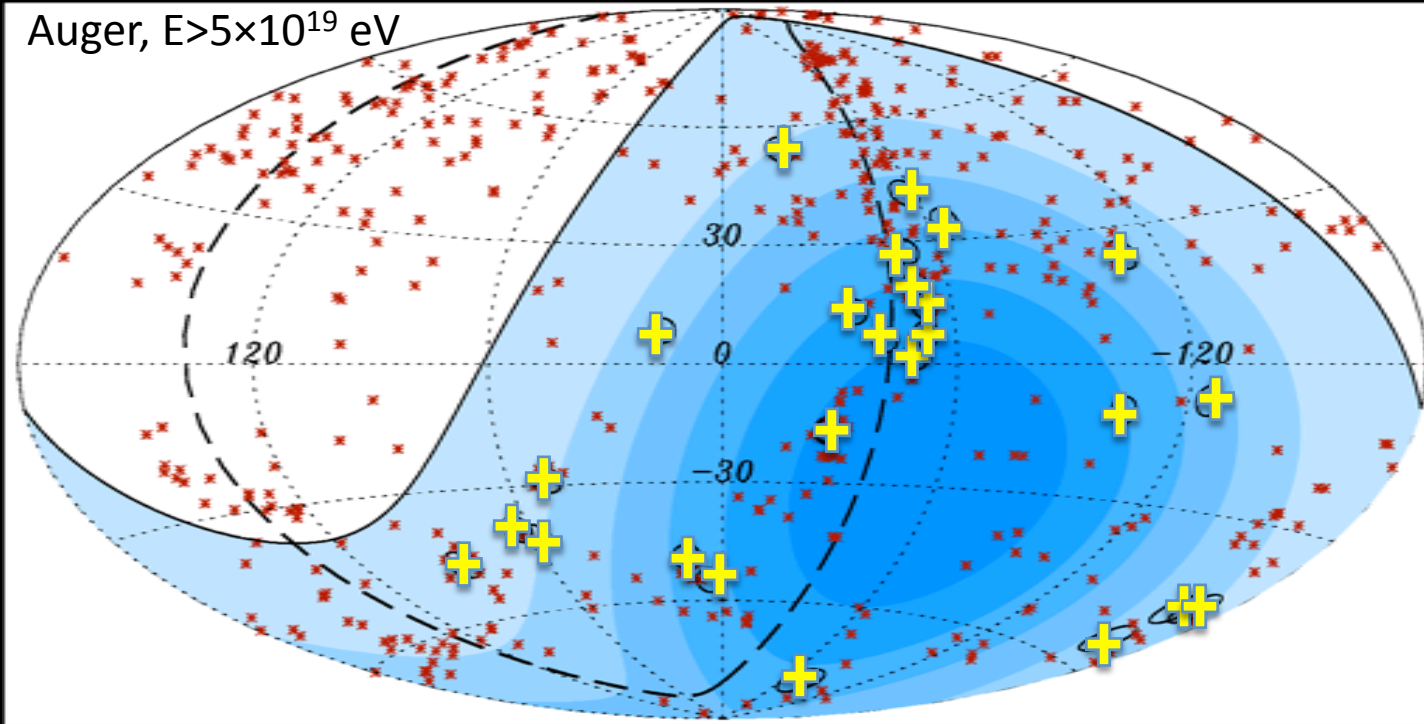
Andrii Neronov

ISDC Data Center for Astrophysics

# AGN as sources of UHECR?

Fermi, 1-300 GeV

Auger,  $E > 5 \times 10^{19}$  eV



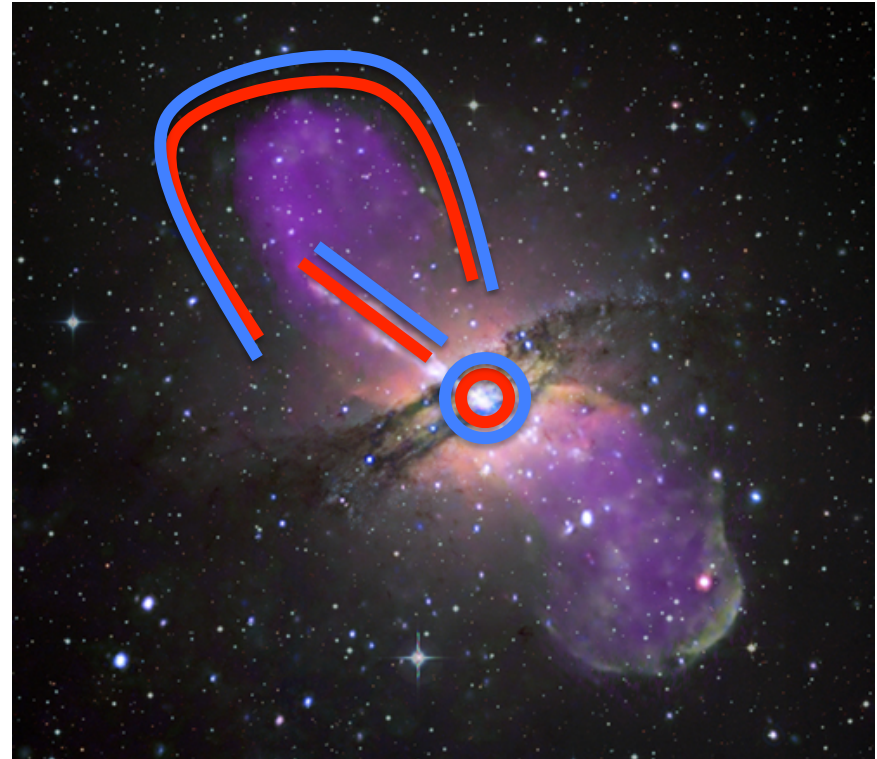
# AGN as sources of UHECR?

Possible cosmic ray acceleration sites:

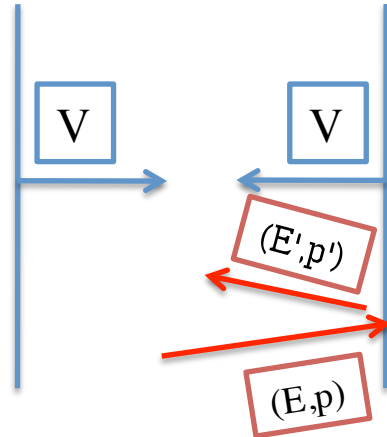
- a) AGN core
- b) AGN jet
- c) extended radio lobes

Possible cosmic ray acceleration mechanisms:

- a) diffusive shock acceleration
- b) acceleration by large scale electric fields



# Shock acceleration mechanism



Energy gain for a particle reflected from a moving shock wave (Lorentz transformation)

$$E' = \Gamma^2 \left( (1 + V^2)E + 2Vp \right) \sim (1 + V)E, \quad V \ll 1$$

$$\Delta E \sim VE = \beta E$$

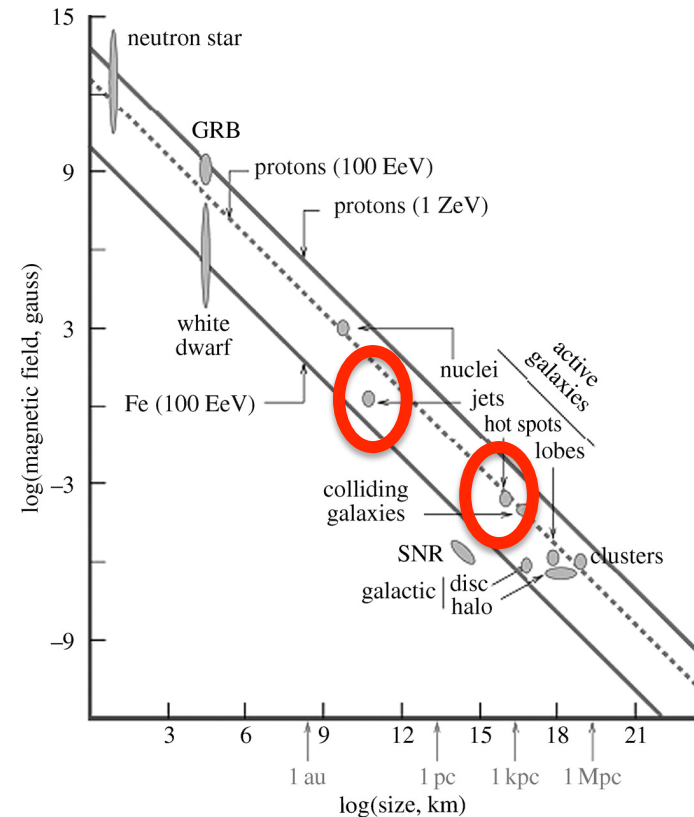
Energy gain rate  $\frac{dE}{dt} = \frac{\beta E}{T}$  where  $T$  is time interval between subsequent reflections.

Particles are deflected by magnetic field, so that  $T \sim R_L / c \sim \frac{E}{eBc}$

$$\frac{dE}{dt} = \beta eB, \quad \beta < 1$$

Maximal energies of particles are limited (a) by lifetime of the shock, (b) size of the shock, (c) energy losses

$$R_L < R, \quad E_{\max} < eBR \sim 10^{20} \left[ \frac{B}{10^{-6} \text{ G}} \right] \left[ \frac{R}{100 \text{ kpc}} \right] \text{ eV}$$





# Acceleration by large scale electric fields

Accretion flows generate magnetic fields

Rotating black hole drags of magnetic field into co-rotation.

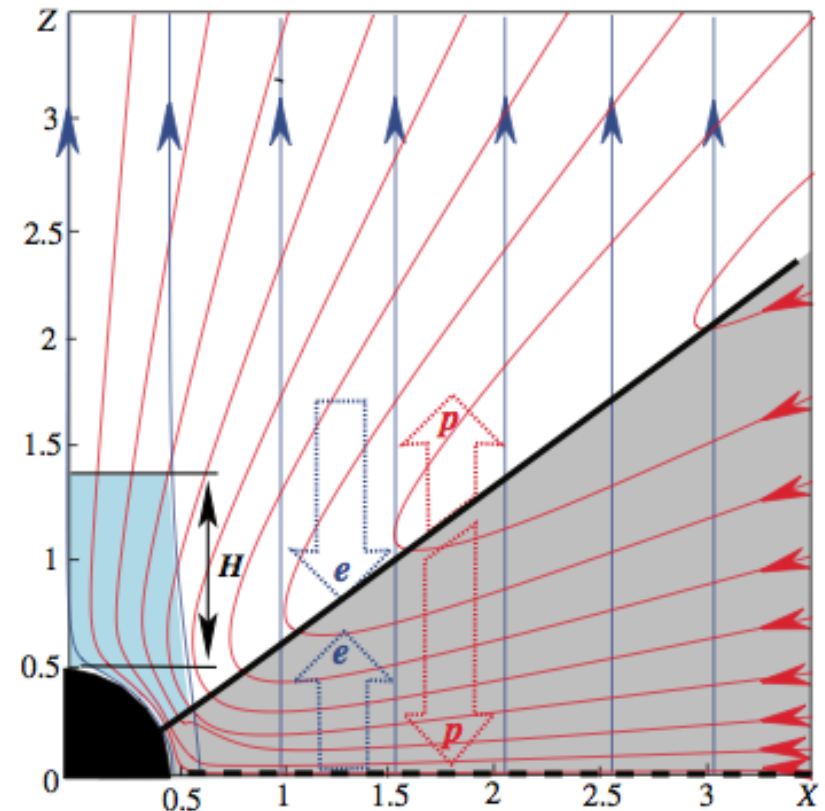
Rotating magnetic field generates electric field with the strength

$$|\vec{E}| \sim \frac{a}{M} |\vec{B}|, \quad a = \frac{J}{M} \leq M$$

Electric field lines are aligned with magnetic field lines in the "polar caps" (close to the North and South magnetic poles).

Polar caps work as linear particle accelerators.

$$\frac{dE}{dt} \sim e \frac{a}{M} B; \quad E_{\max} = \frac{dE}{dt} \frac{R_{\text{Schw}}}{c} \approx \frac{a}{M} e B R_{\text{Schw}} \approx 10^{20} \left[ \frac{B}{10^4 \text{ G}} \right] \left[ \frac{M_{\text{BH}}}{10^8 M_{\text{Sun}}} \right] \text{ eV}$$



AN et al. arxiv:0712.1737

# Blazars

Particle acceleration near black hole and/or in the innermost part of the jet is inevitably accompanied by electromagnetic emission.

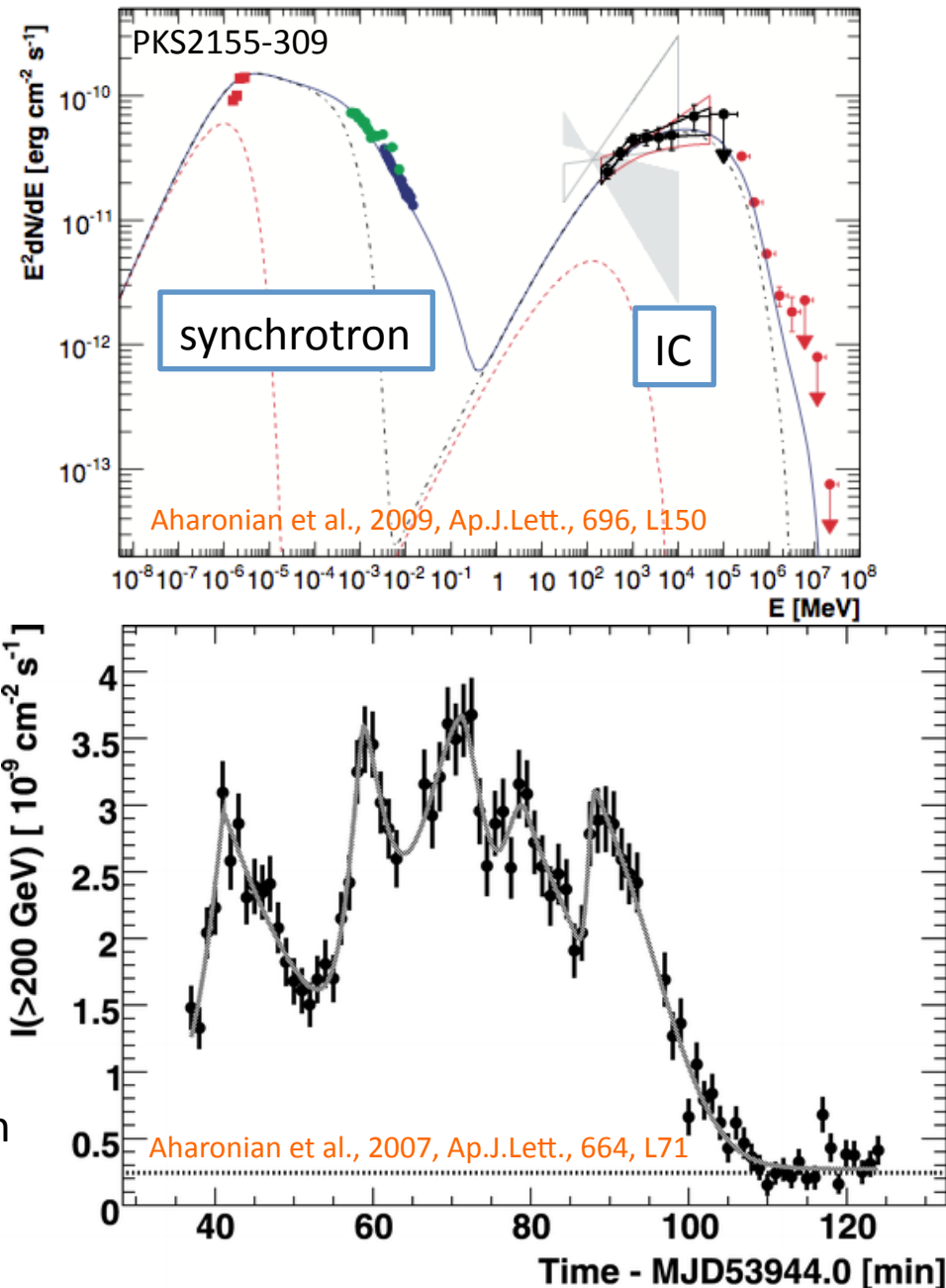
For electrons, main energy loss channels are synchrotron and inverse Compton emission.

Electromagnetic emission is expected to be variable on the time scale comparable to the light-crossing time of the black hole.

$$t_{BH} \sim \frac{R_{Schw}}{c} \sim 10^2 \left[ \frac{M_{BH}}{10^7 M_{Sun}} \right] \text{ s}$$

Fast-variable gamma-ray outbursts are commonly observed in blazars (radio galaxies with jets aligned with the line of sight).

Monitoring of blazars in the GeV band with Fermi available since 2008 enables systematic study of blazar flares.



# Summary

AGN as candidate UHECR sources.

High-energy gamma-ray emission from AGN (blazars and radio galaxies).

Supermassive black holes and origin of AGN activity.

Phenomenology and origin of AGN jets.

Mechanisms of particle acceleration in AGN.

Lecture 4

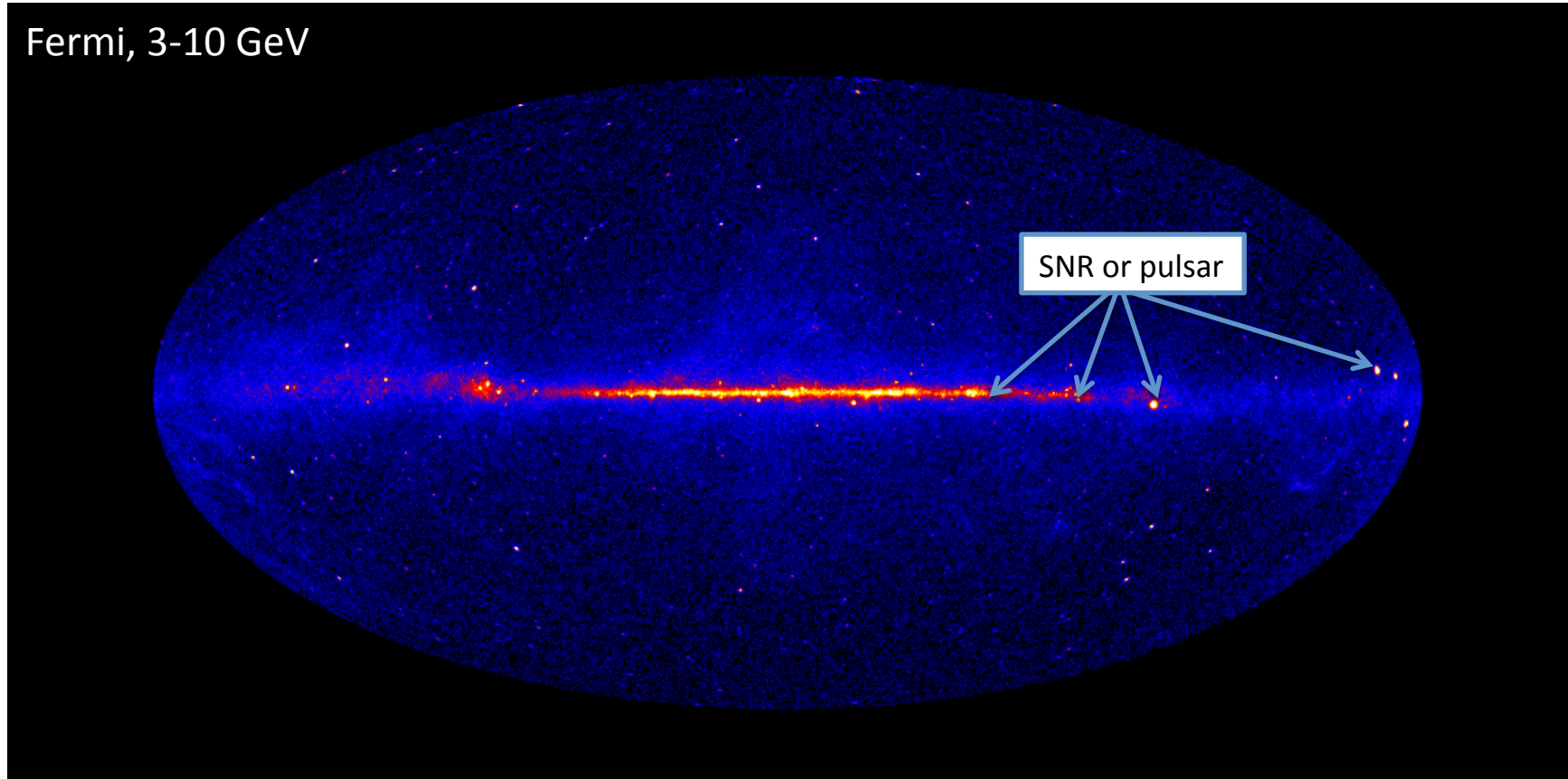
# **Supernovae, supernova remnants, pulsars & gamma-ray bursts**

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# Galactic gamma-ray source populations

Fermi, 3-10 GeV



Most of the identified Galactic high-energy or very-high-energy  $\gamma$ -ray sources are pulsars (together with the associated pulsar wind nebulae) or supernova remnants.

# Galactic cosmic ray sources

Phenomena associated to explosions of massive ( $M \geq 10M_{\text{Sun}}$ ) stars should be responsible for the production of the bulk of the observed Cosmic Ray flux.

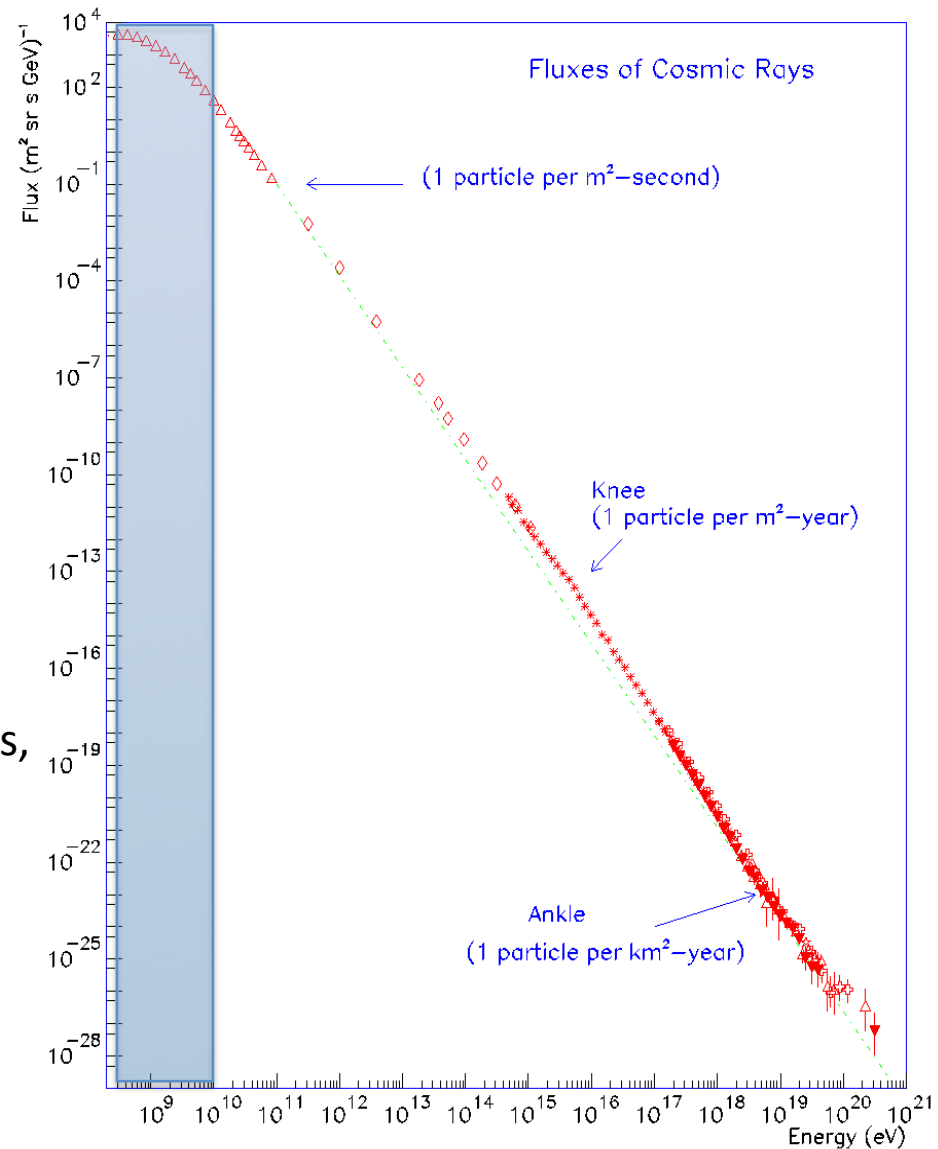
Overall luminosity of Cosmic Ray sources in the Galaxy  $L_{\text{CR}} \sim 10^{41}$  erg/s.

Two possible sources of energy in the Galaxy: nuclear reactions in stars and gravitational energy liberated in contraction and/or collapse.

Bulk of the power released by low mass stars,  $M < 10M_{\text{Sun}}$  comes from nuclear reactions, goes into photons (and neutrinos).

Bulk of the power released at the end of life of massive stars is gravitational energy released in stellar collapse

$$E = \frac{G_N M^2}{R} \sim 10^{53} \left[ \frac{M}{M_{\text{Sun}}} \right]^2 \left[ \frac{R}{10 \text{ km}} \right]^{-1} \text{ erg}$$



# Galactic cosmic ray sources

$$E = \frac{G_N M^2}{R} \sim 10^{53} \left[ \frac{M}{M_{\text{Sun}}} \right]^2 \left[ \frac{R}{10 \text{ km}} \right]^{-1} \text{ erg}$$

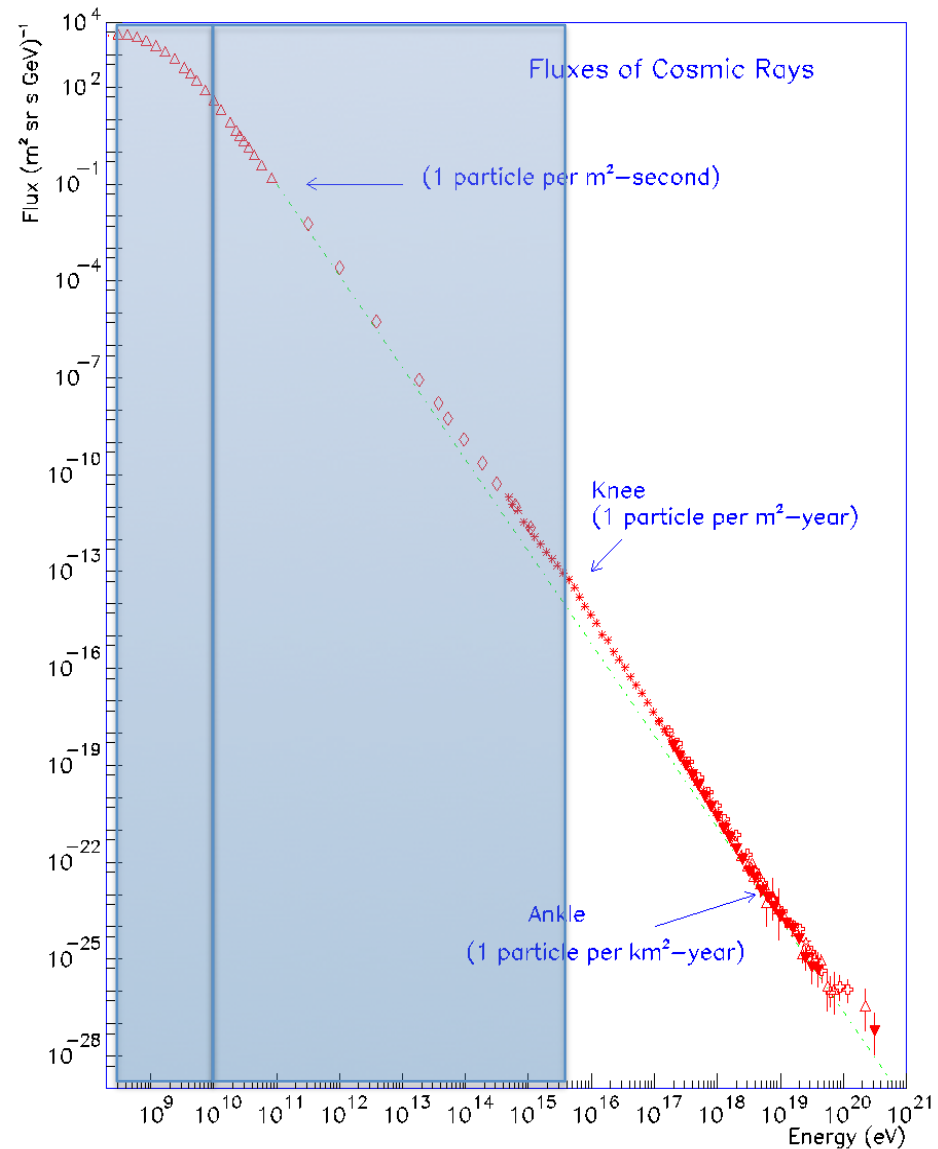
Only a small fraction of this energy is in the form of photons.

Rate of core-collapse supernovae ( $M > 10 M_{\text{Sun}}$  stars) is  $\sim 1/100$  yr. If a fraction  $\epsilon \sim 10^{-3}$  of the released energy is used to accelerate CRs, then

$$L_{\text{CR}} \sim \frac{\epsilon E}{100 \text{ yr}} \sim 10^{41} \text{ erg/s}$$

i.e. sufficient to explain the observed CR flux.

Three known phenomena, which might be associated to particle acceleration: gamma-ray bursts (core collapse itself), pulsars (compact remnant of explosion) and supernova remnant shells.





# Evolution of massive stars

Luminous massive stars are supported by the radiation pressure

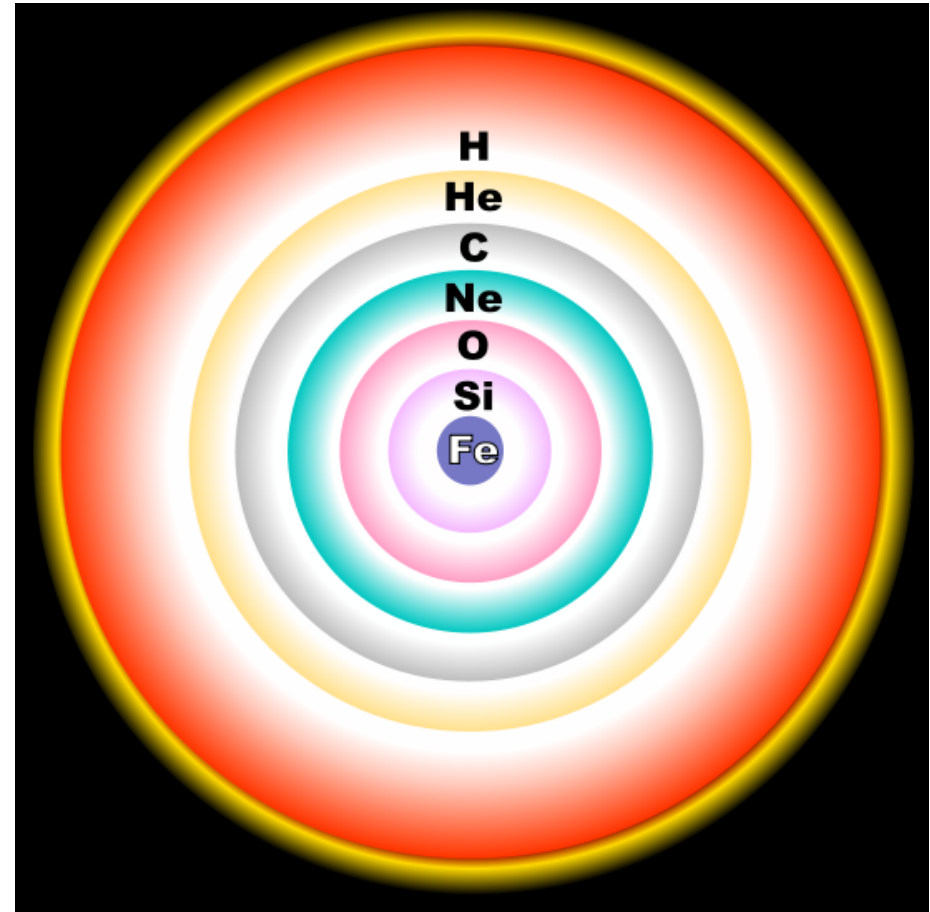
$$\frac{G_N M m}{R^2} \sim \frac{\sigma_T L_{Edd}}{4\pi R^2}$$
$$L_{Edd} \sim 10^{38} \left[ \frac{M}{M_{Sun}} \right] \text{ erg/s}$$

After exhausting the available nuclear power source from  $\text{H} \rightarrow \text{He}$  reactions, the star contracts.

Contraction leads to heating

$$\frac{dP}{dr} = \frac{G_N M \rho}{r^2}, \quad P \sim T^4$$
$$T \sim \frac{(G_N M^2)^{1/4}}{R}$$

Temperature increase switches on next level of nuclear fusion reactions ( $\text{He} \rightarrow \text{C}, \text{N}, \text{O} \rightarrow \dots \rightarrow \text{Fe}$ ).



# Iron core of an evolved star

Iron core could not be supported by radiation pressure

Instead, it is supported by the pressure of degenerate electron gas.

$$\Delta p_e \Delta x \sim 1, \quad m_e (\Delta v_e) \cdot \frac{1}{n_e^{1/3}} \sim 1$$

$$P = n_e p_e v_e \sim n_e^{5/3}$$

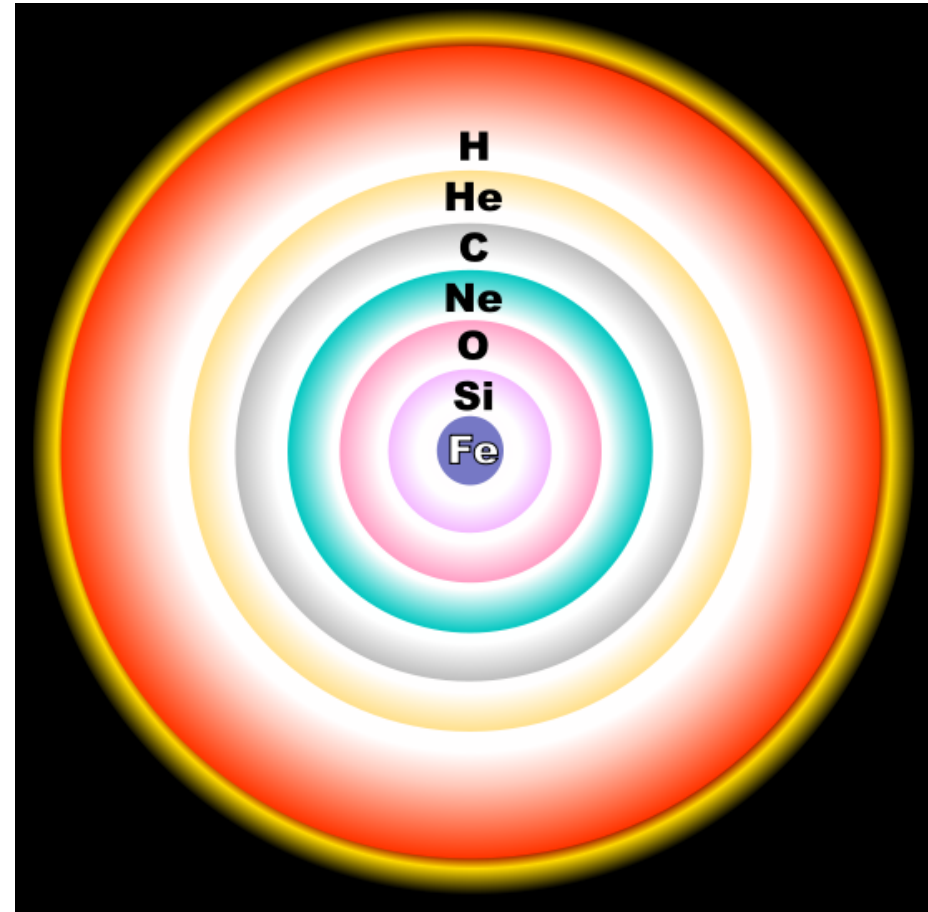
Hydrostatic equilibrium equations:

$$\frac{dP}{dr} \sim \frac{P}{R} \sim \frac{n_e^{5/3}}{R} \sim \frac{Y_e^{5/3} M^{5/3}}{m_p^{5/3} R^{8/3}} \sim \frac{G_N M \rho}{R^2}$$

$$R \sim \frac{Y_e^{5/3}}{m_p^{5/3} m_e G_N M^{1/3}}$$

Accumulation of "iron waste" leads to contraction of the core and increase of the density up to  $n_{e,Crit}$

$$m_e c \cdot \frac{1}{n_{e,Crit}^{1/3}} \sim 1$$



# Gravitational collapse

No solution of hydrostatic equilibrium equations could be found for  $n_e > n_{e,Crit}$

The core becomes unstable as soon as it reaches the mass

$$M_{Crit} = m_p n_{e,Crit} Y_e^{-1} R_{Crit}^3 \sim \frac{Y_e^2}{m_p^2 G_N^{3/2}} \sim$$

$$\frac{Y_e^2 M_{Pl}^2}{m_p^2} M_{Pl} \approx 1.4 M_{Sun} \left[ \frac{Y_e}{0.5} \right]^2$$

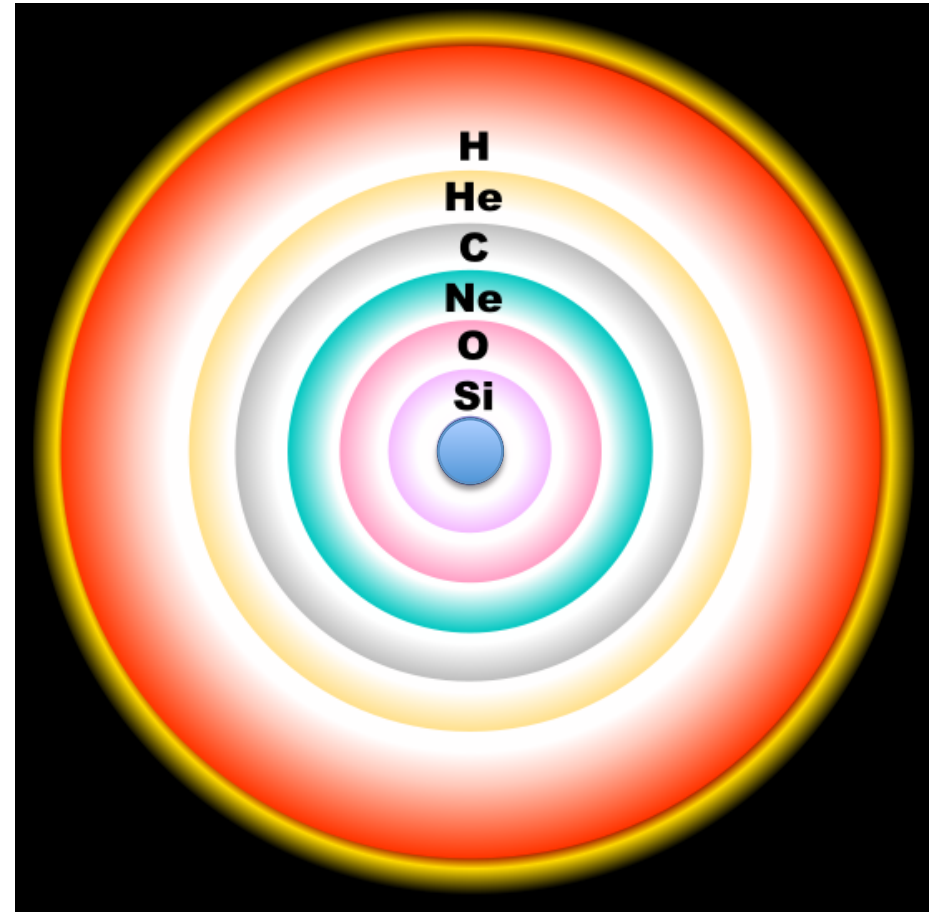
Called Chandrasekhar mass.

The core collapses from the initial size

$$R_{Crit} = \frac{Y_e M_{Pl}}{m_e m_p} \sim 10^8 \left[ \frac{Y_e}{0.5} \right] \text{ cm}$$

down to a (possibly) new stable configuration (what?) within the free-fall time

$$t_{ff} \sim \frac{R_{Crit}}{v_{ff}} \sim \frac{R_{Crit}^{3/2}}{(G_N M_{Crit})^{1/2}} \sim 1 \text{ s}$$



# Neutrino cooling of collapsing core

Collapse is possible only if the released gravitational energy is radiated away. At the initial stage the released energy goes into heating of the collapsing matter

$$T \sim \frac{G_N M_{\text{crit}} m_p}{R_{\text{crit}}} \sim 10 \text{ MeV}$$

Core density is  $n \geq m_e^3 \sim 10^{31} \text{ cm}^{-3}$ . Gamma-ray mean free path  $\lambda_\gamma \sim (\sigma_T n)^{-1} \sim 10^{-7} \text{ cm} \ll R_{\text{crit}}$ . Emission of electromagnetic radiation can not be the source of cooling.

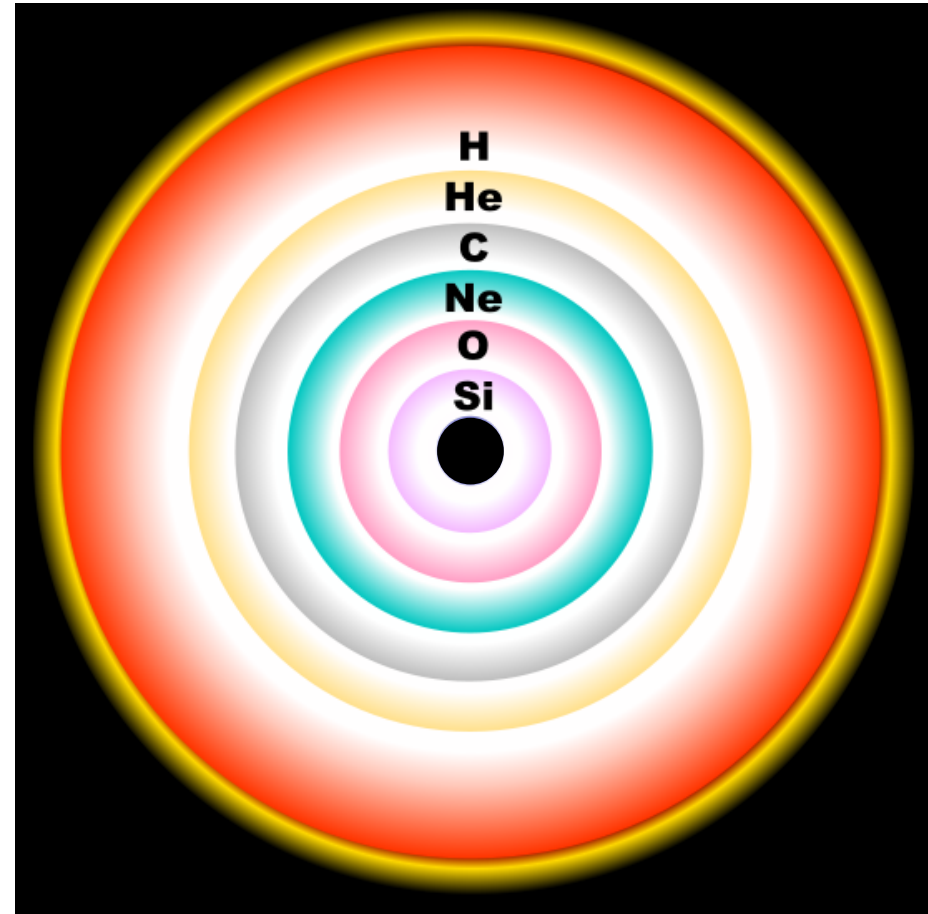
Neutrino cross-section is

$$\sigma_\nu \sim G_F^2 T^2 \sim 10^{-41} \left[ \frac{T}{10 \text{ MeV}} \right]^2 \text{ cm}^2$$

Neutrino mean free path

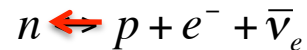
$$\lambda_\nu \sim (\sigma_\nu n)^{-1} \sim 10^9 \left[ \frac{T}{10 \text{ MeV}} \right]^{-2} \left[ \frac{R}{R_{\text{crit}}} \right]^3 \text{ cm} \sim R_{\text{crit}}$$

Neutrino emission provides the main source of cooling of the collapsing core.



# Neutronization of the core

The collapsing core is in thermal equilibrium (compare with the Universe before the BBN):



Neutron decays get suppressed because of the large occupation numbers of electrons.

The new stable configuration is supported by the pressure of degenerate neutron gas.

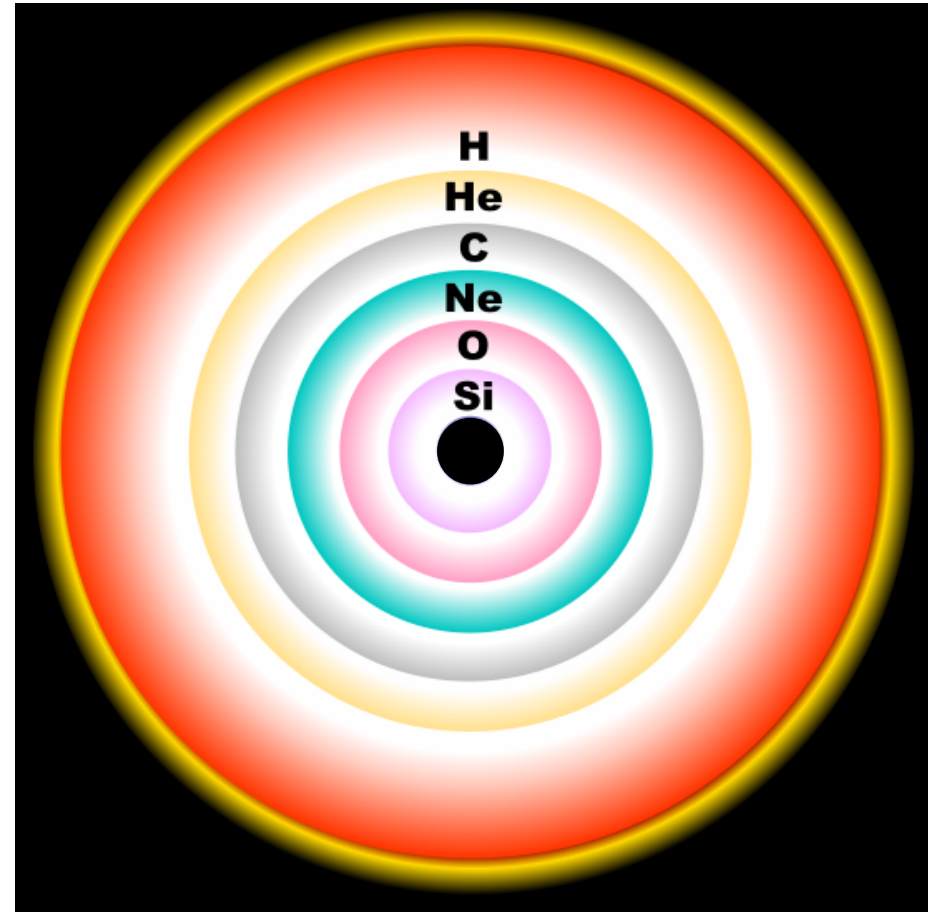
Estimate of the size

$$R \sim \frac{1}{m_p^{8/3} G_N M^{1/3}} \approx 10 \left[ \frac{M}{M_{Sun}} \right]^{-1/3} \text{ km}$$

Estimate of the critical mass

$$M_{Crit} \sim \frac{M_{Pl}^2}{m_p^2} M_{Pl} \approx (3 - 4) M_{Sun}$$

(taking into account a numerical coefficient from calculations assuming certain equation of state)



# Neutron stars

Core collapse leads to formation of a "proto-neutron star" of the mass  $M_{NS} \sim 1.4 M_{Sun}$  (Chandrasekhar mass). The mass of the proto-neutron star grows via accretion of the matter from stellar envelope

Proto-neutron star could be fast-rotating

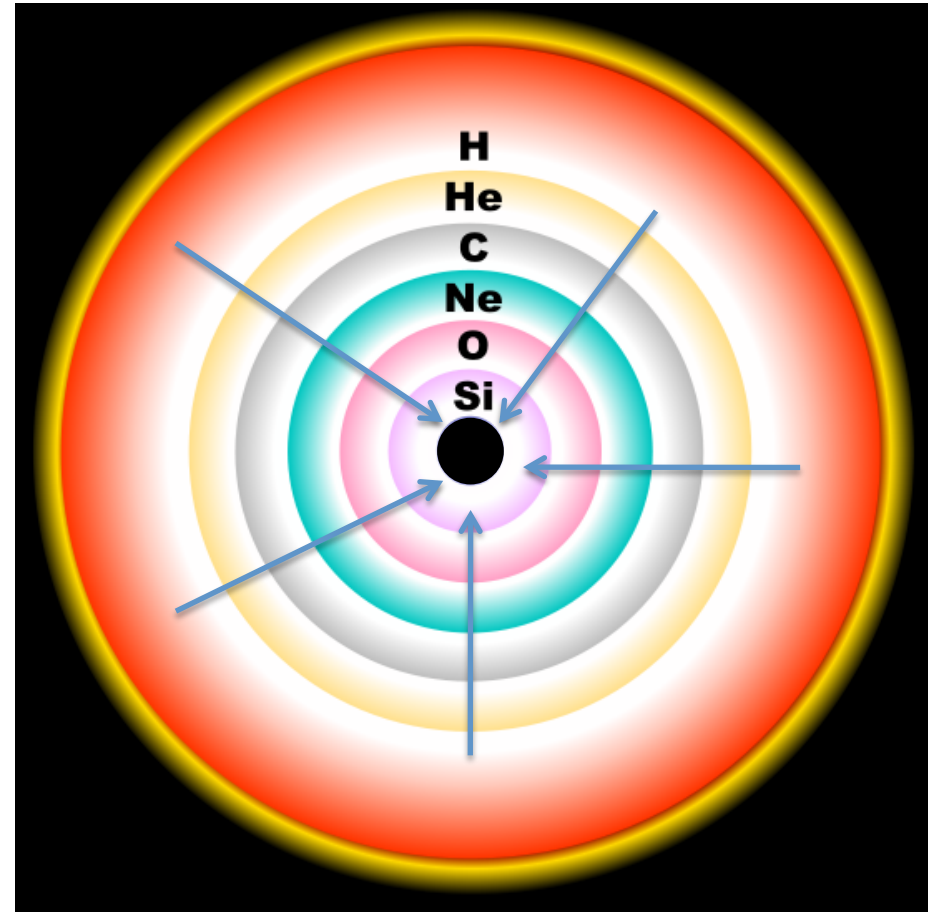
$$M\Omega R^2 = const, \quad \Omega = \Omega_0 \frac{R_0^2}{R_{NS}^2}$$

(e.g. for the Sun  $\Omega_0 = 2\pi/(25 \text{ d})$ ,  $R_0 \sim 10^{11} \text{ cm}$ , an estimate for the period of rotation after the collapse would be  $T = 2\pi/\Omega \sim 0.4 \text{ ms}$ , close to the minimal-possible period,

$$T_{NS} \geq \frac{2\pi R_{NS}}{v_{Kepler}} \sim 1 \text{ ms}$$

Neutron stars should possess high magnetic fields

$$BR^2 = const, \quad B = B_0 \frac{R_0^2}{R_{NS}^2} \sim 10^{12} \left[ \frac{B_0}{10^2 \text{ G}} \right] \left[ \frac{R_0}{R_{Sun}} \right]^2 \text{ G}$$





# Supernova explosions

Marek, Janka, 2009, Ap.J., 694,664

Accretion of the envelope on the proto-neutron star is stopped (by what process) and converted into ejection, giving rise to a supernova explosion.

About 1% of the liberated gravitational energy

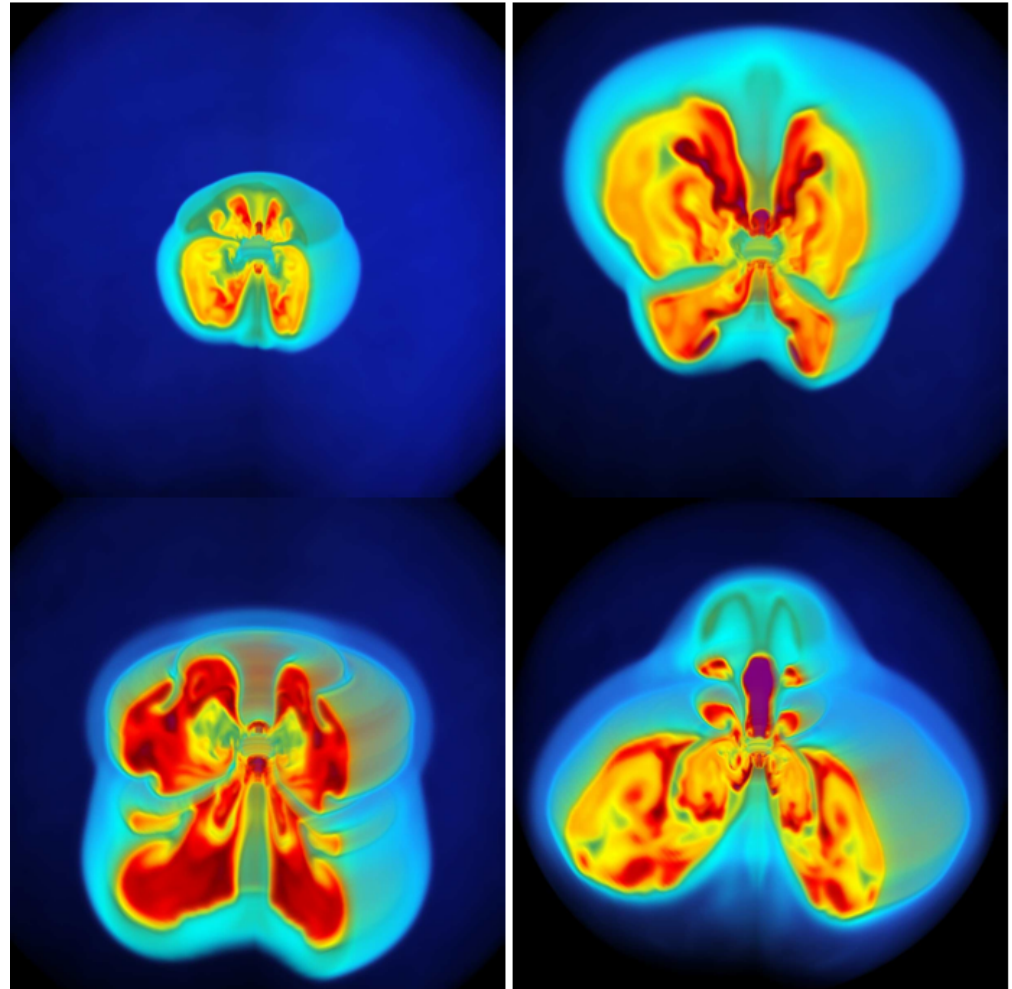
$$E = \frac{G_N M^2}{R_{NS}} \sim 10^{53} \left[ \frac{M}{M_{Sun}} \right]^2 \left[ \frac{R_{NS}}{10 \text{ km}} \right]^{-1} \text{ erg}$$

is converted into the kinetic energy of supernova ejecta.

Mechanism responsible for conversion of collapse into explosion is not clear.

Dominant hypothesis is "neutrino-driven" supernova explosions: ejection of outer layer of the envelope is due to the pressure produced by neutrino flux.

Neutrino-drive supernova mechanism might work only if assisted by a strong mixing of envelope layers produced by global 3-d instability of accretion.



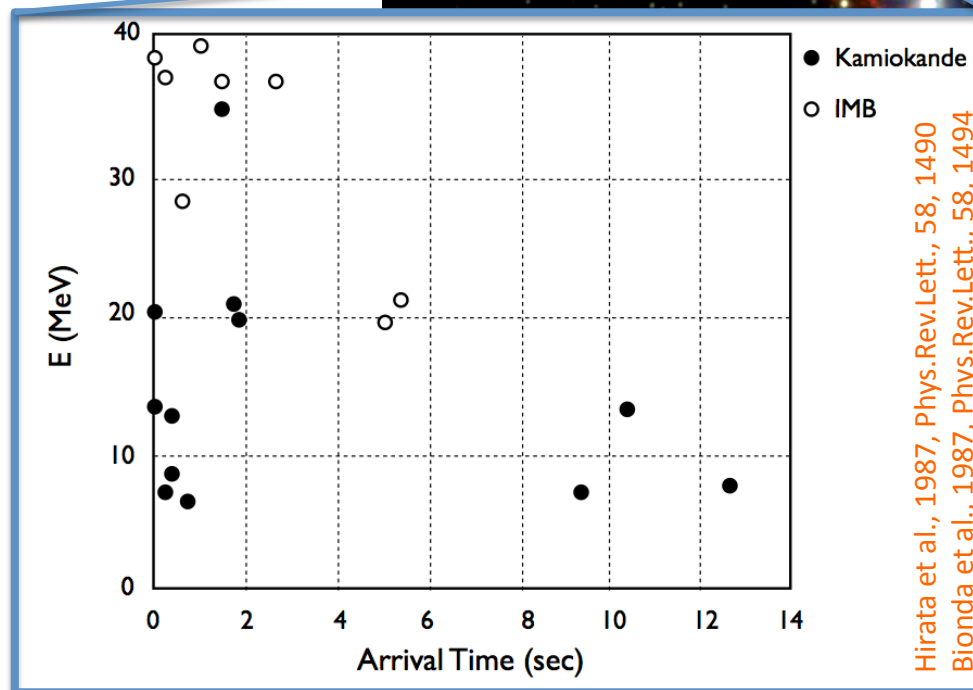
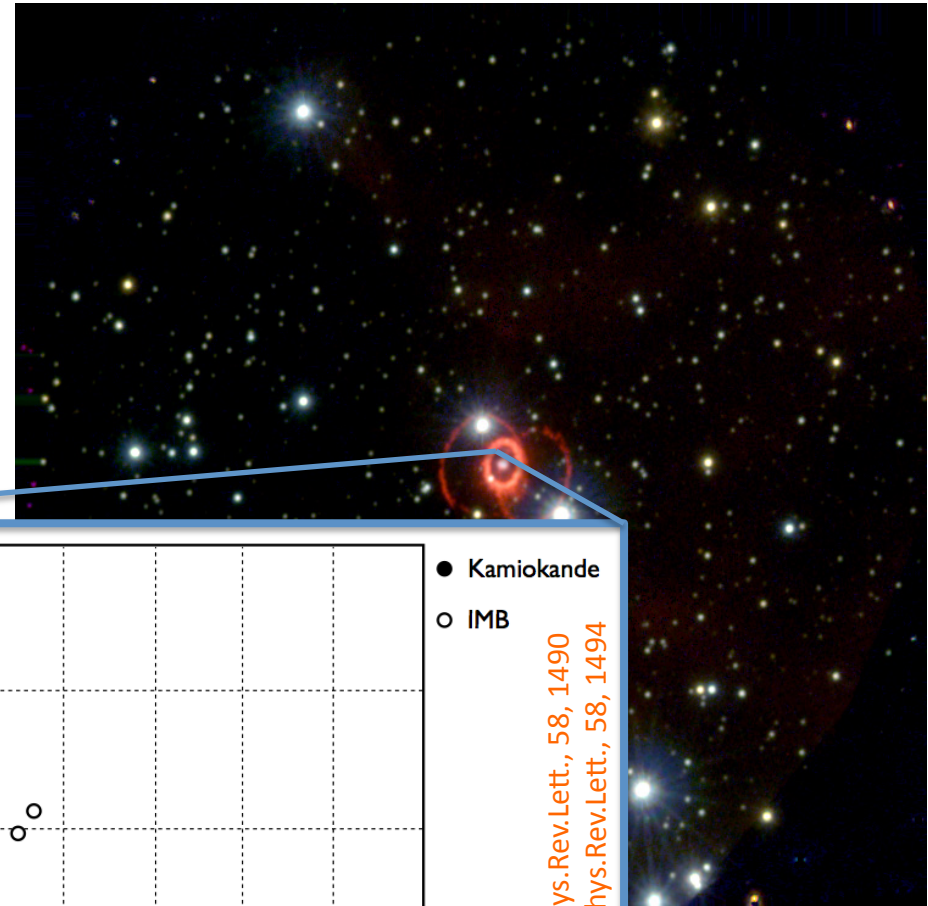


# Supernova neutrinos

Neutrinos with energies  $\sim 10$  MeV are detected from a supernova SN 1987A (in Large Magellanic Cloud,  $D \approx 50$  kpc), by Kamiokande detector.

Neutrino flux and timing are consistent with model expectations.

Supernova rate  $\sim 1 / 100$  yr / Galaxy.



# Gamma-ray bursts

Bursts of  $\sim 0.1$ -10 MeV radiation of duration 0.1 – 100 s, arriving at the rate  $\sim 1/\text{day}$  from random directions on the sky.

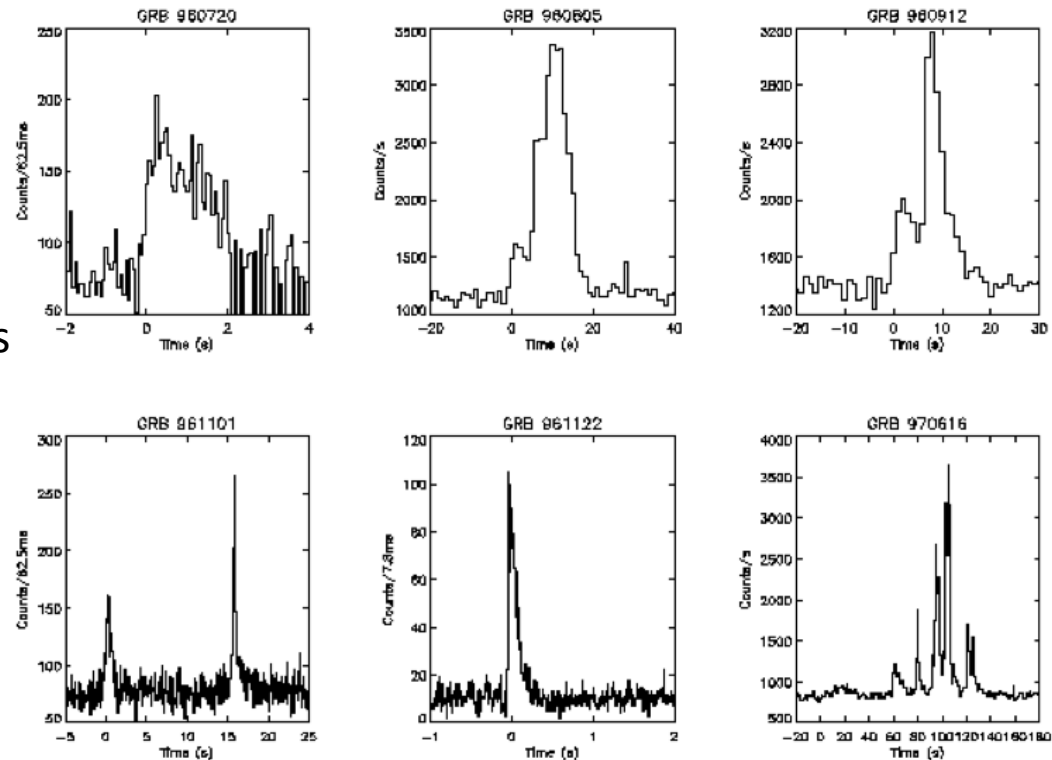
Isotropic distribution on the sky indicates extragalactic origin.

Observations of GRB "afterglows" in optical band reveal broad distribution of redshifts up to  $z=8.2$  (GRB 090423).

Energy fluxes reach  $10^{-5} \text{ erg/cm}^2/\text{s}$  i.e. the luminosities reach

$$L \sim 4\pi D^2 F \sim 10^{51} \left[ \frac{D}{1 \text{ Gpc}} \right]^2 \text{ erg/s}$$

Direct evidence for association with supernova explosions is observed in several cases.



## Gamma astronomy

Low-energy gamma-rays: 0.1-10 MeV

**INTEGRAL**

High-energy gamma-rays: 0.1-10 GeV

**Fermi**

Very-high-energy gamma-rays:

0.1-10 TeV

**HESS**

**Veritas**

**MAGIC**

## X-ray astronomy

Soft X-rays: 0.1-10 keV

**Chandra**

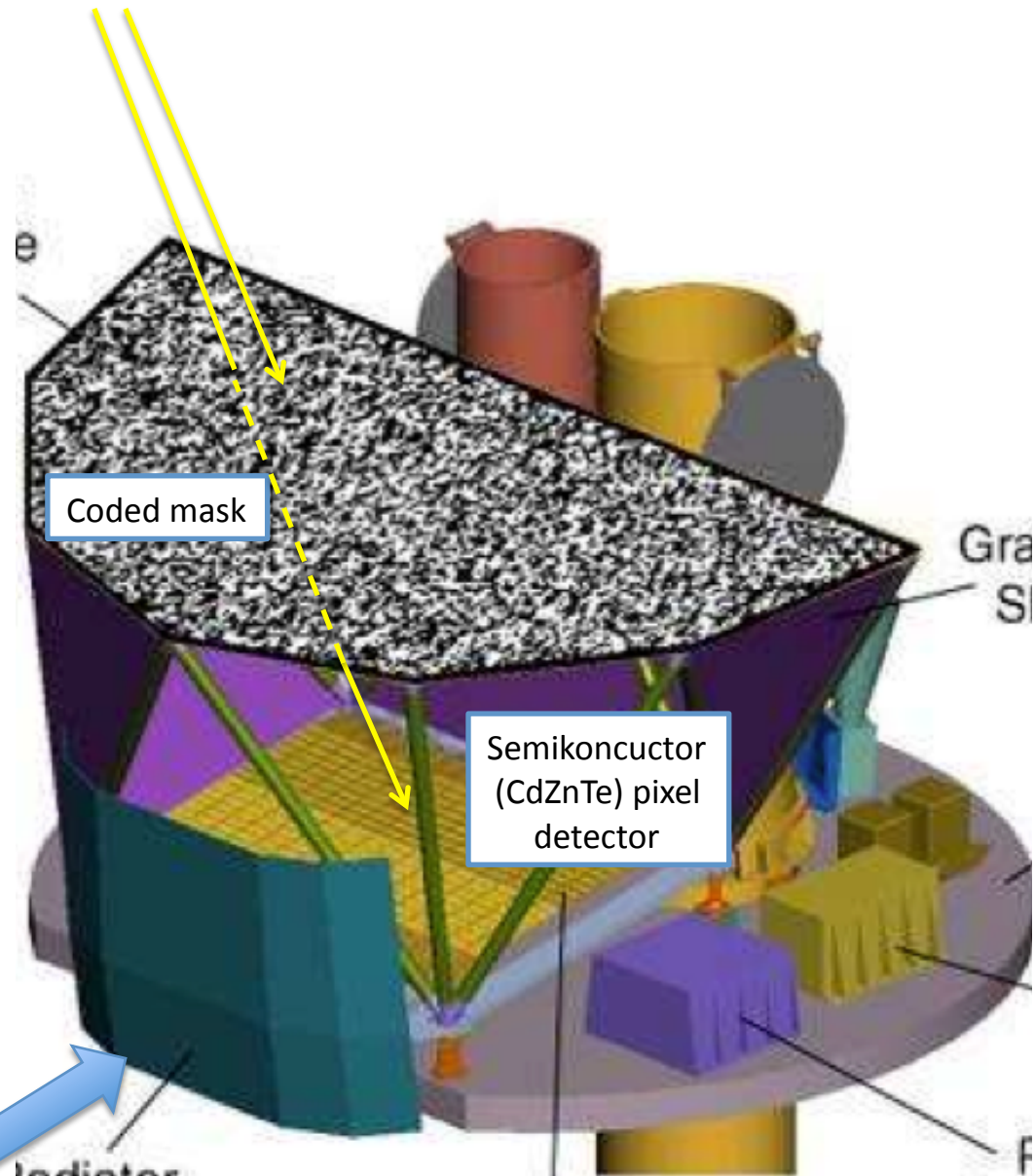
**XMM-Newton**

Hard X-rays: 10 - 100 keV

**INTEGRAL**

**SWIFT**

**Suzaku**



## Gamma astronomy

Low-energy gamma-rays: 0.1-10 MeV

**INTEGRAL, Fermi/GBM**

High-energy gamma-rays: 0.1-10 GeV

**Fermi**

Very-high-energy gamma-rays:

0.1-10 TeV

**HESS  
Veritas  
MAGIC**

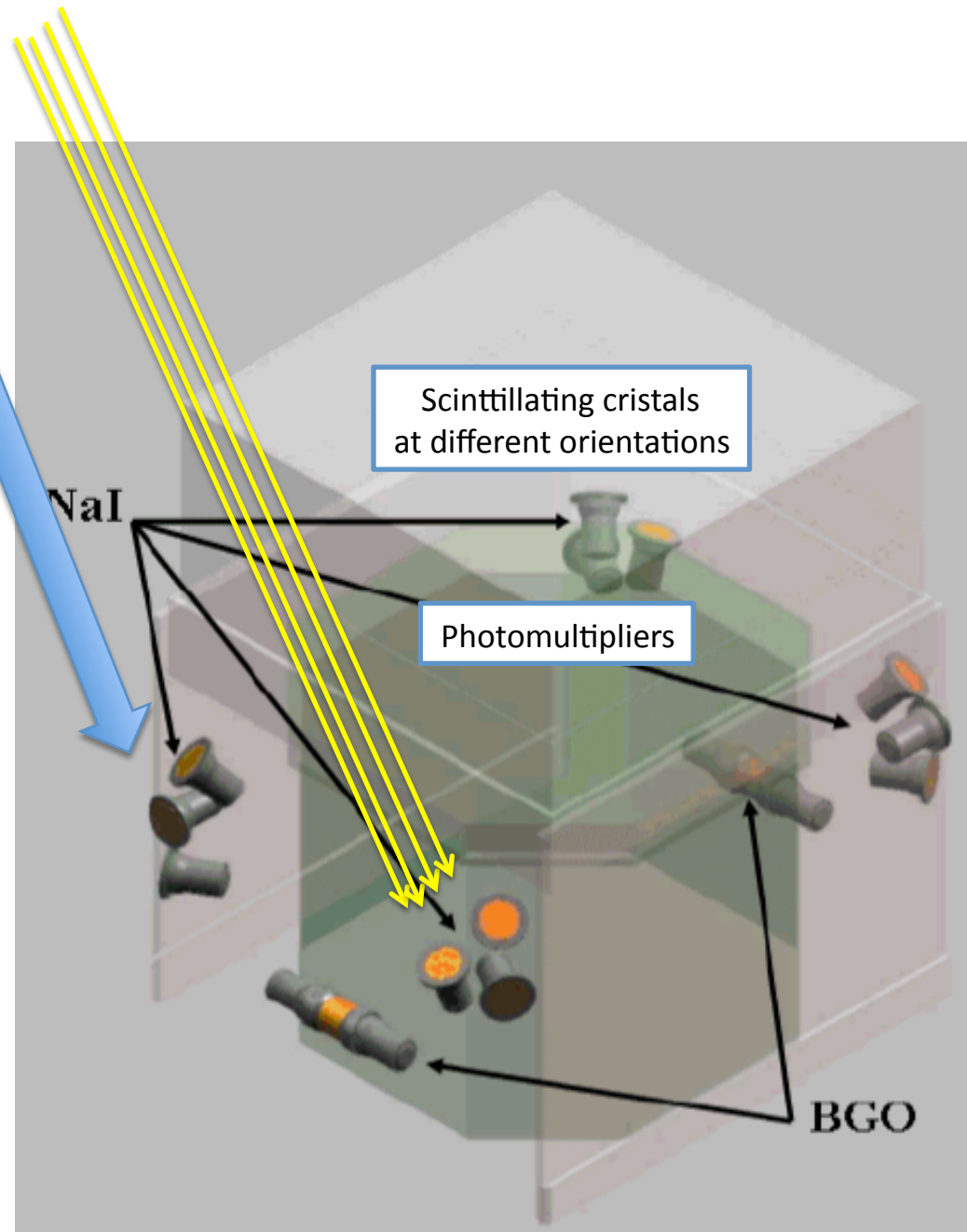
## X-ray astronomy

Soft X-rays: 0.1-10 keV

**Chandra  
XMM-Newton**

Hard X-rays: 10 - 100 keV

**INTEGRAL  
SWIFT  
Suzaku**



# GeV component of gamma-ray bursts

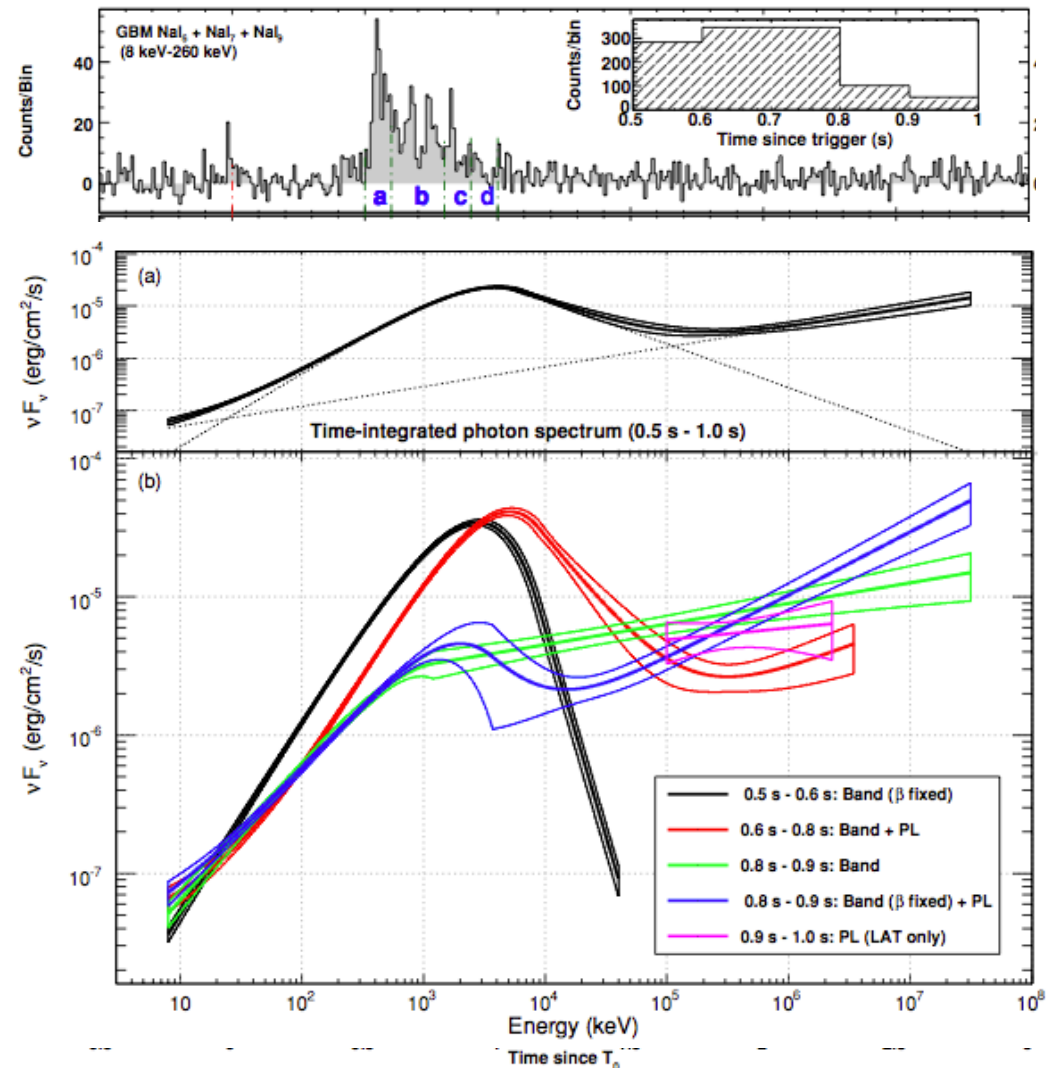
GRBs are sources of gamma-rays with energies reaching  $\sim 30$  GeV ( $\sim 100$  GeV at the source).

GeV luminosity of GRB might be comparable to its MeV luminosity.

GeV emission forms a distinct spectral component, with a powerlaw type spectrum extending from X-rays to high-energy gamma-ray band.

No high-energy cut-offs in the gamma-ray spectra are seen.

GRBs work as particle accelerators.



Ackerman et al., 2010, Ap.J., 716, 1178



# Gamma-ray burst relativistic outflow

GRB emission is variable on the time scales down to  $\sim 1$  ms. The variability time scale limits the size of GRB production region to

$$R < ct_{\text{var}} \sim 3 \times 10^7 \left[ \frac{t_{\text{var}}}{1 \text{ ms}} \right] \text{ cm}$$

High luminosity combined with compact size make the source opaque to  $\gamma$ -rays.

$$\gamma + \gamma \rightarrow e^+ + e^-$$

$$n_{ph} = \frac{L_{GRB}}{4\pi R^2 c E_\gamma} \approx 10^{30} \left[ \frac{L_{GRB}}{10^{51} \text{ erg/s}} \right] \left[ \frac{R}{10^7 \text{ cm}} \right]^{-2} \left[ \frac{E_\gamma}{1 \text{ MeV}} \right]^{-1} \text{ cm}^{-3}$$

$$\lambda_{\gamma\gamma} = (\sigma_{\gamma\gamma} n_{ph})^{-1} \approx 10^{-5} \left[ \frac{L_{GRB}}{10^{51} \text{ erg/s}} \right]^{-1} \left[ \frac{R}{10^7 \text{ cm}} \right]^2 \left[ \frac{E_\gamma}{1 \text{ MeV}} \right] \text{ cm} \ll R$$

The "compactness problem" could be overcome if the source is moving relativistically toward the observer with a bulk Lorentz factor  $\Gamma$ . In the frame comoving with the source

$$R' \sim \Gamma R; \quad L'_{GRB} \sim L \Gamma^{-4}; \quad E'_\gamma \sim E_\gamma \Gamma^{-1} \quad n'_{ph} \sim n_{ph} \Gamma^{-5}$$

$$\lambda'_{\gamma\gamma} \sim \Gamma^5 \lambda_{\gamma\gamma}; \quad \tau'_{\gamma\gamma} = \frac{R'}{\lambda'_{\gamma\gamma}} \sim \Gamma^{-4} \tau_{\gamma\gamma} \approx \left[ \frac{\Gamma}{10^3} \right]^4 \left[ \frac{L_{GRB}}{10^{51} \text{ erg/s}} \right] \left[ \frac{t_{\text{var}}}{1 \text{ ms}} \right]^{-2} \left[ \frac{E_\gamma}{1 \text{ MeV}} \right]^{-1}$$

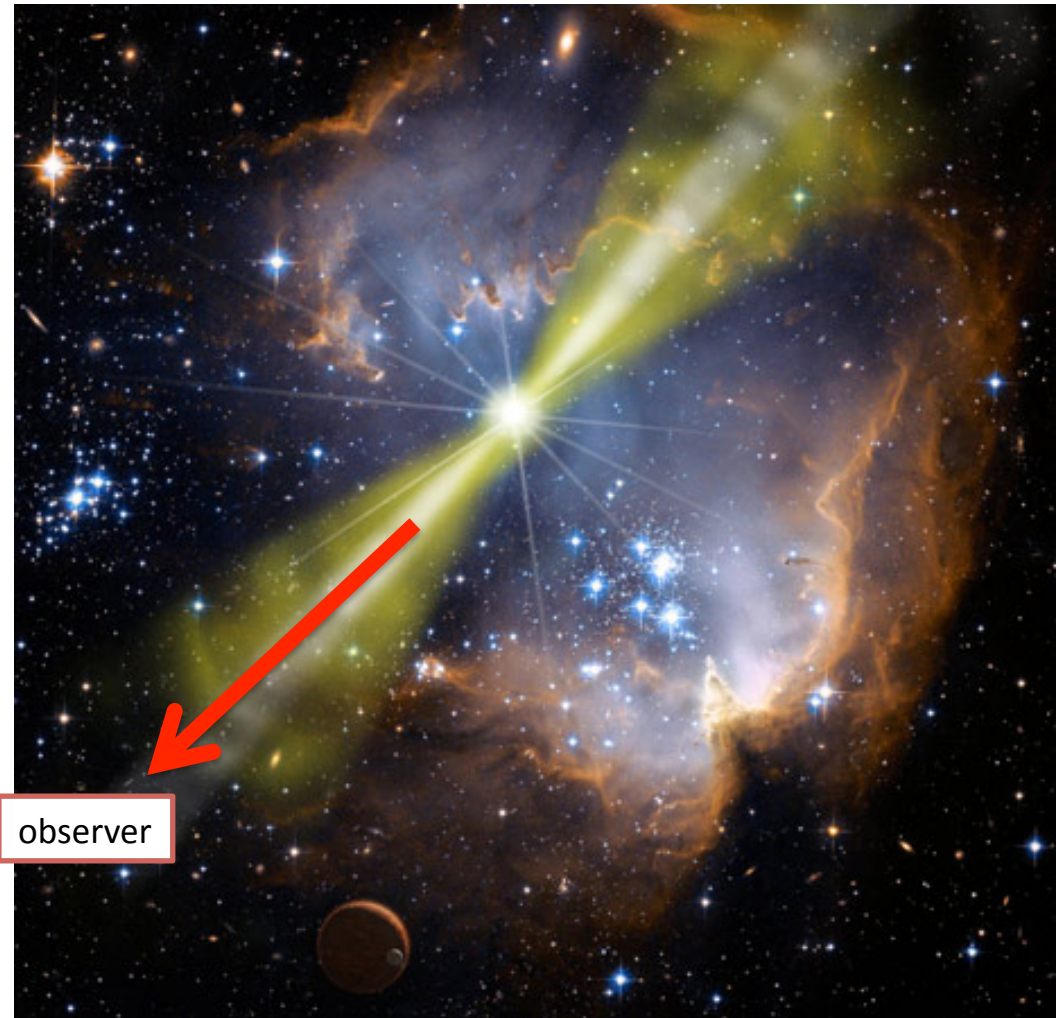
# Gamma-ray burst relativistic outflow

GRB outflow is a relativistic jet pointing produced at the moment of supernova explosion and aligned with the line of sight.

Mechanism of formation of jet like outflow at the moment of supernova explosion is not clear.

Possible mechanisms of particle acceleration are

- a) acceleration by the shocks propagating in the jet ("internal" shocks)
- b) by the shock at the interface of the jet with external medium, e.g. ISM
- c) in the "central engine" of the GRB, the collapsed core of a massive star.





# Magnetars

GRB-like events are sometimes produced by known Galactic sources, Soft Gamma Repeaters (SGR).

They are distinguished from regular GRBs by

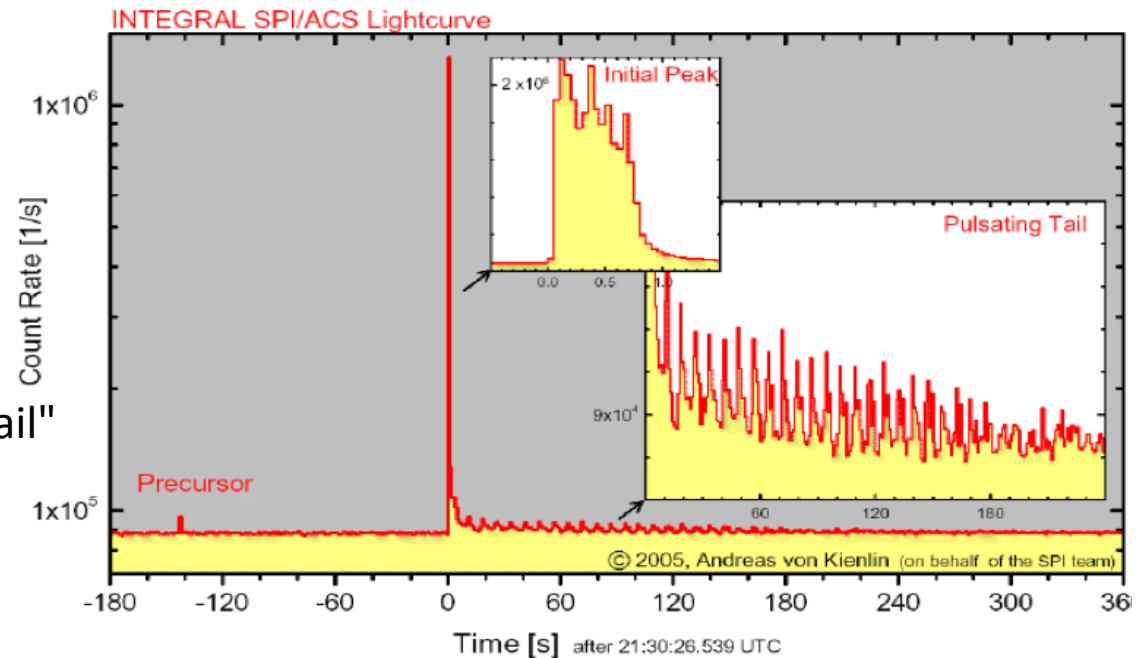
- a) repeated bursts from the same sky direction;
- b) pulsed emission in the burst "tail"

Pulsed emission with the same period (2-6 s) is observed also in quiescent state of the source.

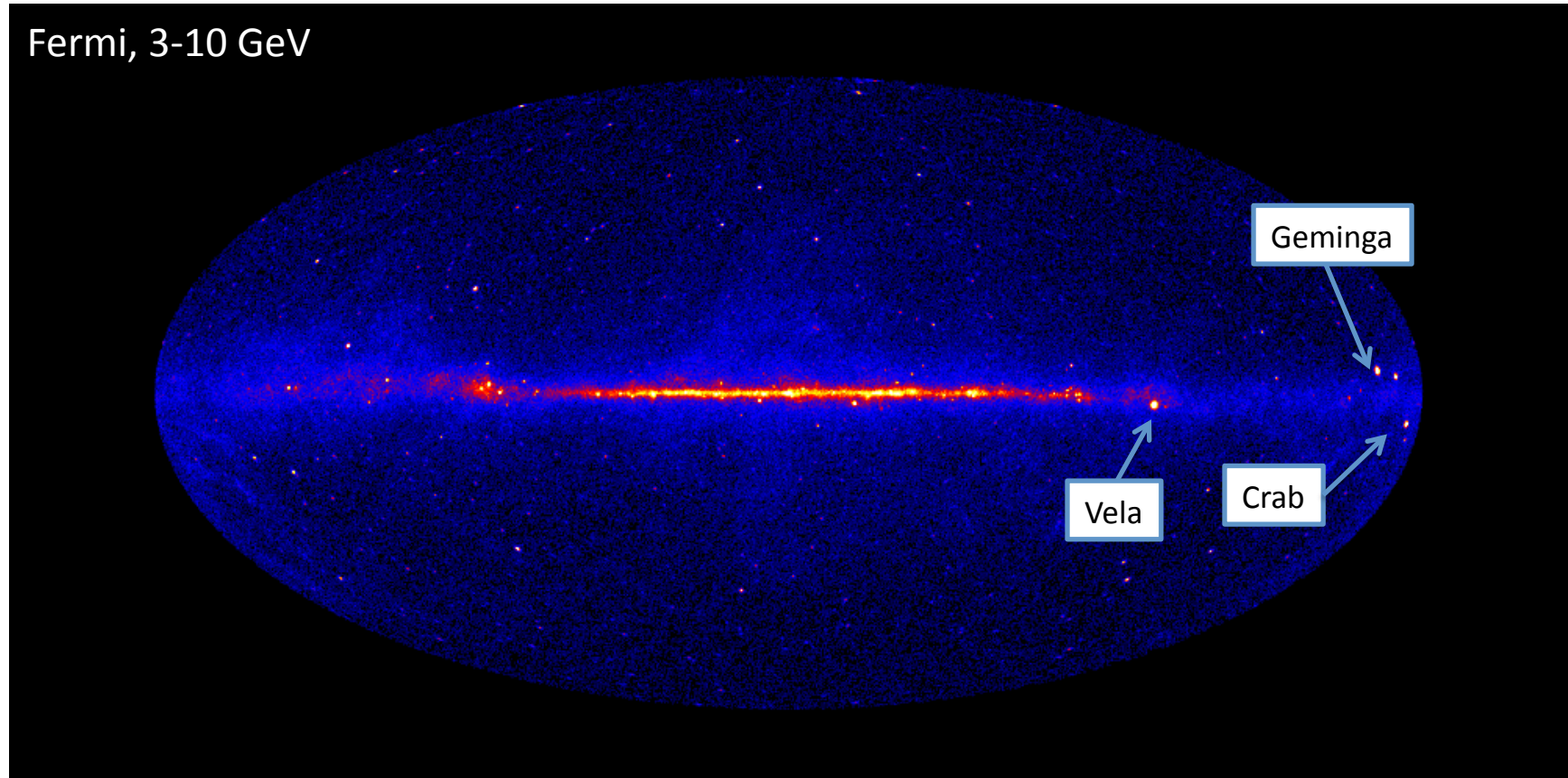
SGR are believed to be pulsars with extremely high magnetic field, in excess of

$$B_{Schwinger} = \frac{m_e^2}{e} \approx 4 \times 10^{13} \text{ G}$$

SGR 1806-20 Outburst on December 27, 2004



# Pulsars



Pulsars together with associated pulsar wind nebulae are brightest individual sources of HE gamma-rays.

Closest-to-up pulsars, like Vela and Geminga ( $\sim 100$  pc distance) were conjectured to be sources of the highest energy (TeV) CR electrons and/or positrons.

# Pulsars

Compact object of the size

$$R \leq \frac{ct}{2\pi} \sim 30 \left[ \frac{T}{1 \text{ ms}} \right] \text{ km}$$

often found in the centers of supernova remnants (e.g. Vela)

The compact object is a rotating magnetized neutron star.

Source of energy is the rotational energy of the neutron star.

$$E_{\text{rot}} = M_{\text{NS}} R_{\text{NS}}^2 \Omega^2 \sim$$

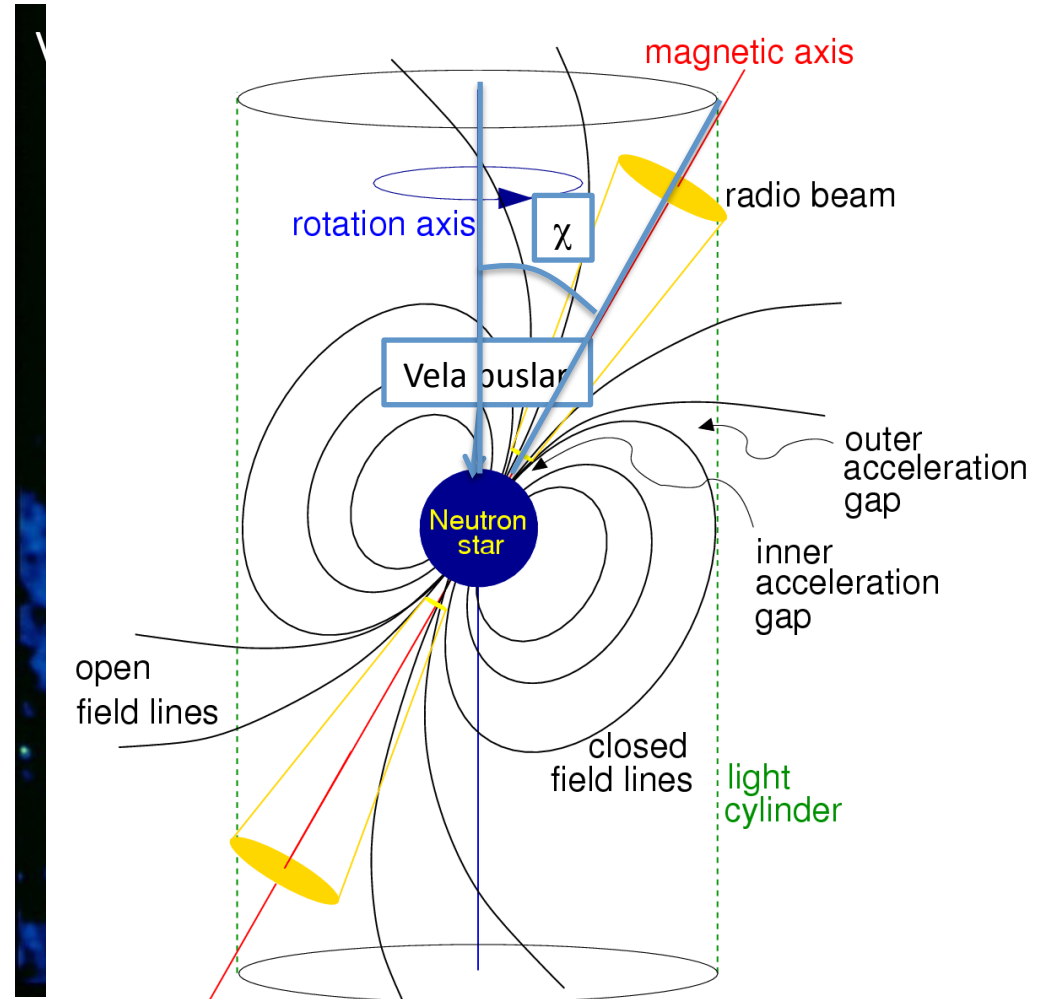
$$10^{52} \left[ \frac{T}{1 \text{ ms}} \right]^2 \left[ \frac{M}{M_{\text{Sun}}} \right] \left[ \frac{R}{10 \text{ km}} \right] \text{ erg}$$

The energy is dissipated via magnetic dipole radiation

$$\dot{E}_{\text{rot}} = M_{\text{NS}} R_{\text{NS}}^2 \Omega \dot{\Omega} \sim B^2 \Omega^4 R_{\text{NS}}^6 \sin^2 \chi$$

Magnetic field strength is derived from the known spin-down rate

$$B = \frac{M_{\text{NS}}^{1/2} \dot{\Omega}^{1/2}}{R_{\text{NS}}^2 \Omega^{3/2} \sin \chi} = \frac{M_{\text{NS}}^{1/2} \dot{T}^{1/2} T^{1/2}}{R_{\text{NS}}^2 \sin \chi} \approx 10^{12} \left[ \frac{T}{33 \text{ ms}} \right]^{1/2} \left[ \frac{\dot{T}}{10^{-14} \text{ s/s}} \right]^{1/2} \text{ G}$$



# Particle acceleration in pulsars

Lorentz force leads to charge redistribution at the surface of the neutron star.

Charge redistribution creates an electric field of quadrupole geometry

$$\vec{E}(r) \sim r^{-4}$$

Large scale electric field accelerates particles in the north and south polar caps.

Rotation-induced electric field

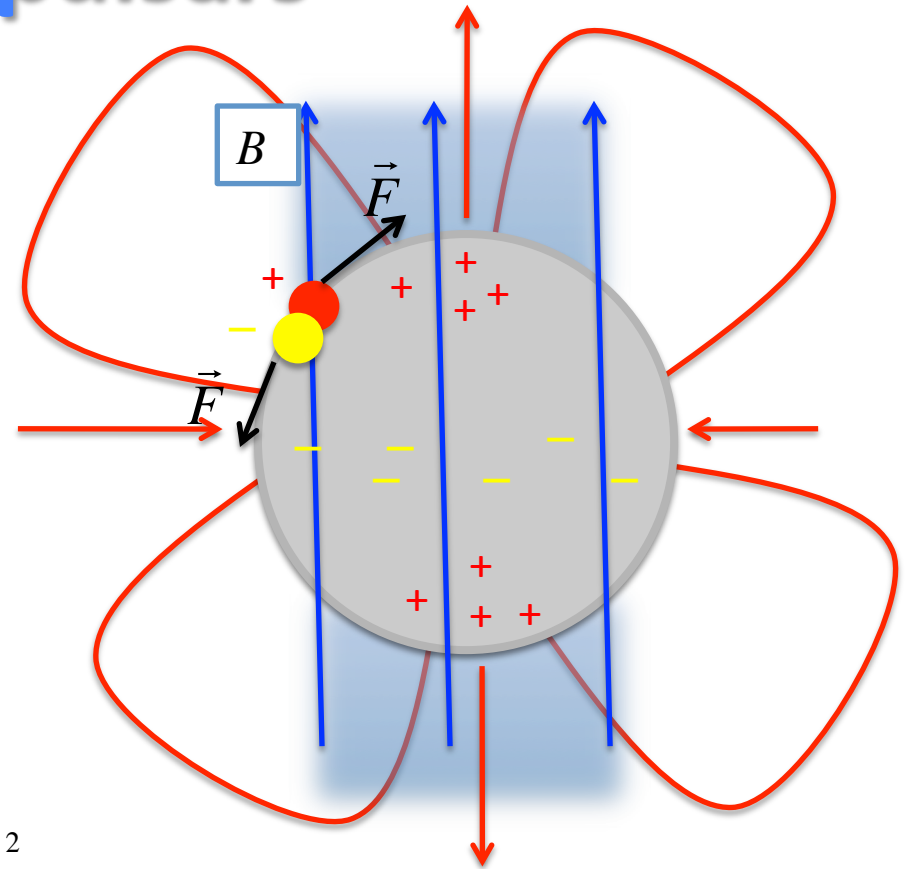
$$|\vec{E}_{\parallel}| \sim \Omega R_{NS} B$$

Maximal particle energies

$$E_{\max} \sim e |\vec{E}_{\parallel}| R_{NS} \sim e \Omega R_{NS}^2 B \approx 10^{16} \left[ \frac{P}{33 \text{ ms}} \right] \left[ \frac{B}{10^{12} \text{ G}} \right]^2 \text{ eV}$$

Particle acceleration is accompanied by curvature emission

$$E_{\text{curv}} \sim \frac{E^3}{R_{\text{Curv}} m^3} \approx 10 \left[ \frac{R_{\text{Curv}}}{R_{NS}} \right]^{-1} \left[ \frac{\gamma}{10^7} \right]^3 \text{ GeV}$$



# Particle acceleration in pulsars

Curvature radiation quanta produce pairs in the magnetic field. Photon mean free path

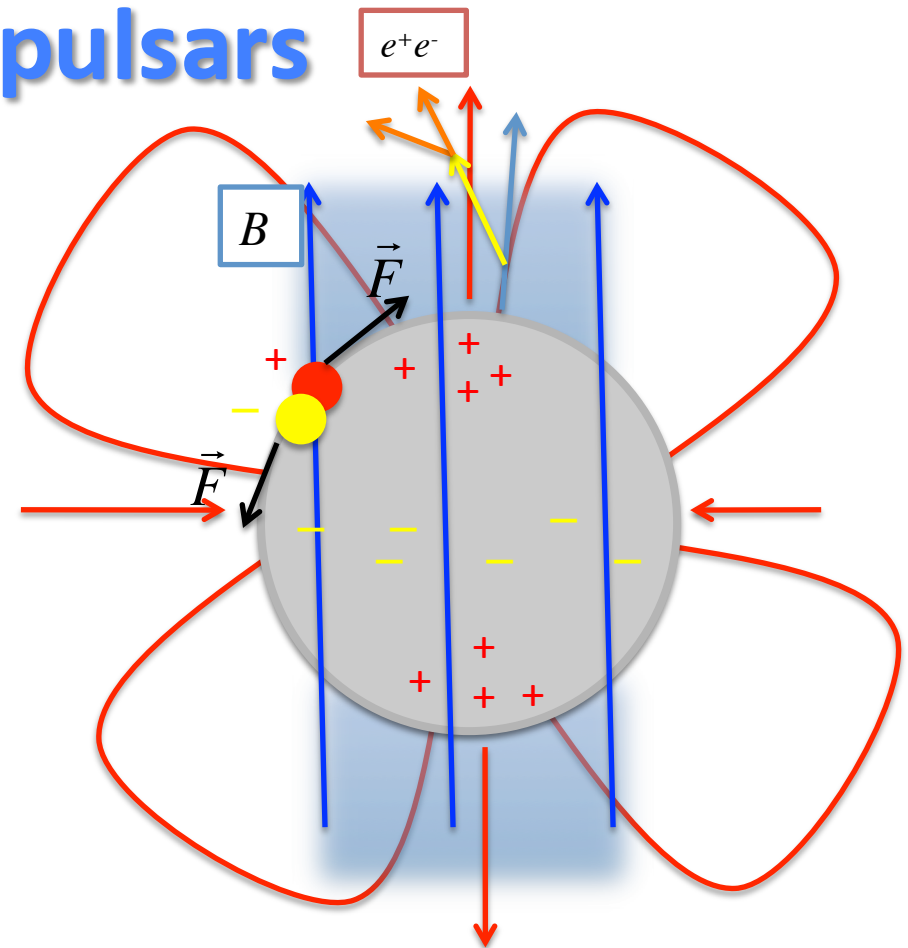
$$\lambda_{\gamma B} \approx R_{Curv} \frac{B}{B_{Schwinger}} \frac{m_e^2}{E_{Curv}} \ll R_{NS} \text{ for } E_{Curv} \gg m_e$$

The space around the neutron star gets filled with  $e^+e^-$  plasma which screens the initial accelerating magnetic field.  $e^+e^-$  plasma forms a "magnetosphere" around the neutron star.

Charges are continuously "washed out" of the magnetosphere into the pulsar wind.

The screening is not perfect: "vacuum gaps" should be left to allow continuous charge supply in the magnetosphere via  $\gamma B$  pair production.

There is no commonly accepted model of pulsar magnetospheres and mechanisms of production of pulsar winds.



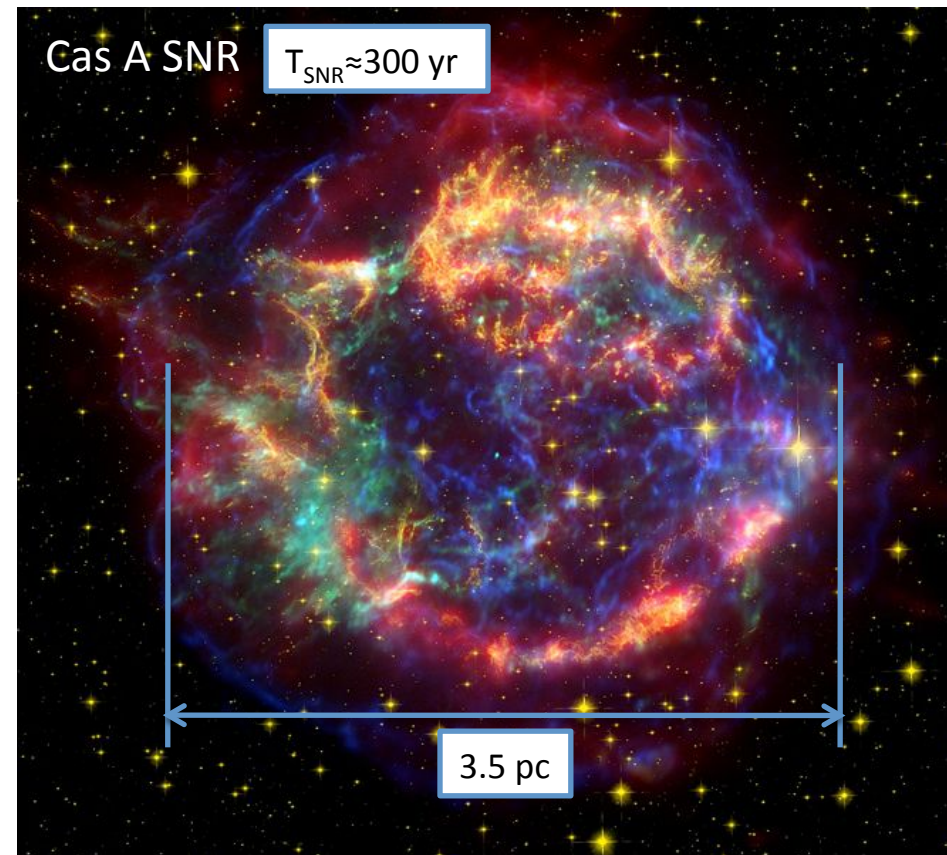
# Supernova remnants

Most of the gravitational energy of the collapsed star ( $\sim 10^{53}$  erg) is emitted in the form of 10-30 MeV neutrinos.

Some  $\sim 10\%$  ( $\sim 10^{51}$  erg) of the released energy is transferred to the kinetic energy of supernova explosion.

This energy is used to expel the outer layers of the stellar envelope with the speed  $\sim (1-5) \times 10^3$  km/s.

Expanding shells of supernova ejecta are visible as supernova remnants (SNR).





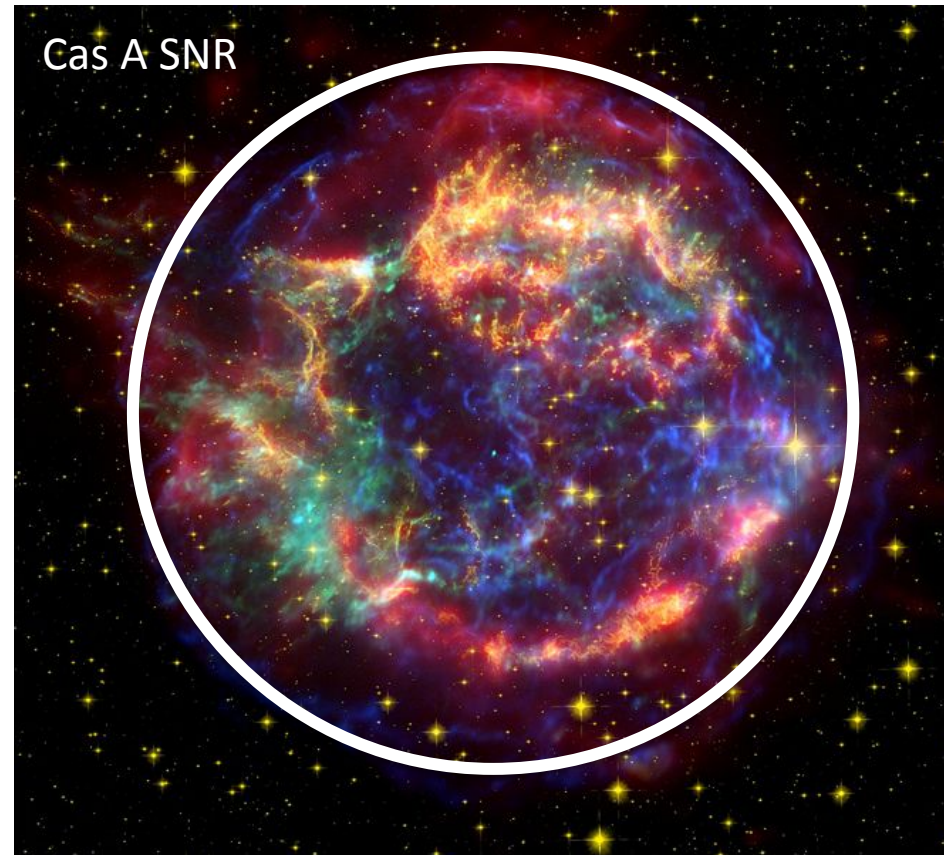
# Supernova remnants

Fast expanding ejecta of supernova explosion pick up interstellar medium. A shock wave is formed at the interface of ejecta and ISM.

Ejecta freely expand until the mass of the picked-up matter becomes comparable to the mass of the SN ejecta.

After this moment SNR expansion decelerates (Sedov phase), so that the radius grows as  $R \sim t^{2/5}$  (compare with  $R \sim t$  during the free expansion phase).

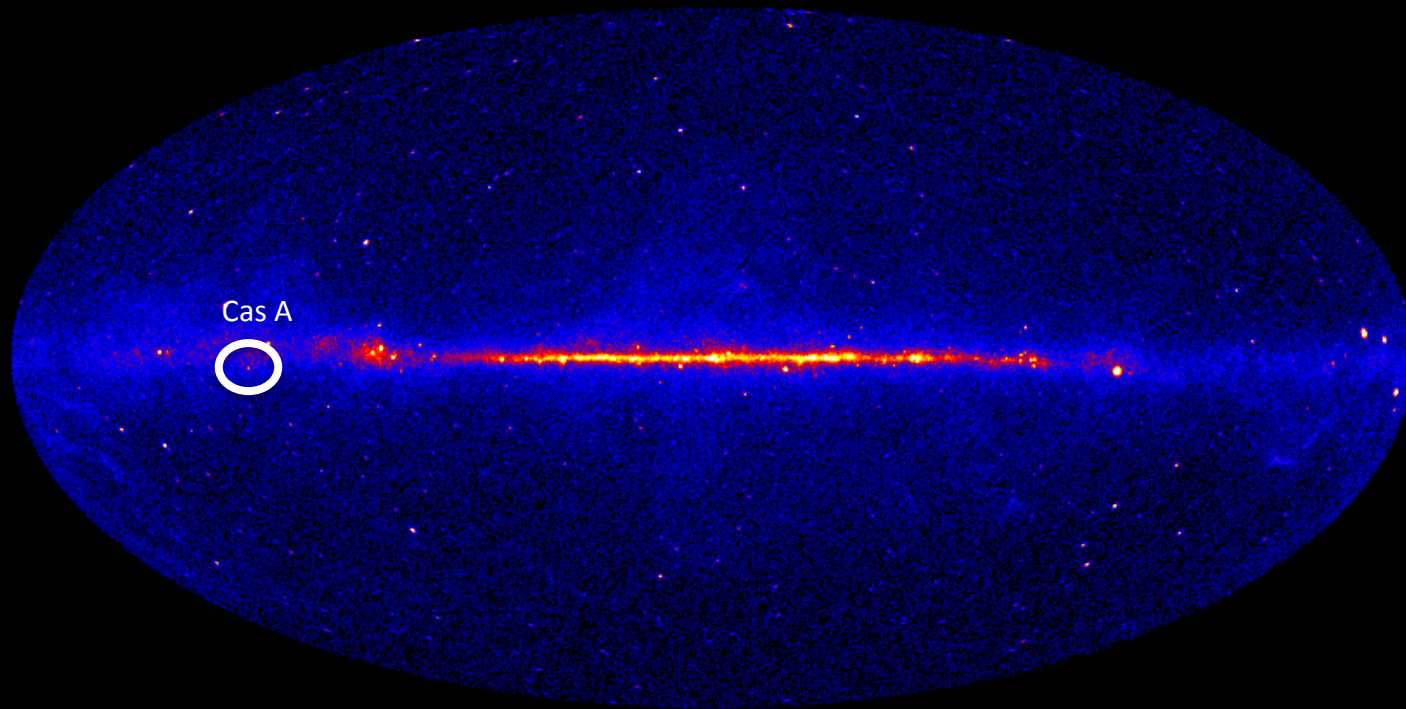
Shock formed at the interface of supernova ejecta with ISM could be efficient particle accelerator.





# Cas A

Fermi, 3-10 GeV



# Cas A in gamma-rays

Cas A is detected in the HE and VHE gamma-ray bands.

Emission spectrum is consistent with that expected from the decay of  $\pi^0$  produced in interactions of shock-accelerated protons with ISM.

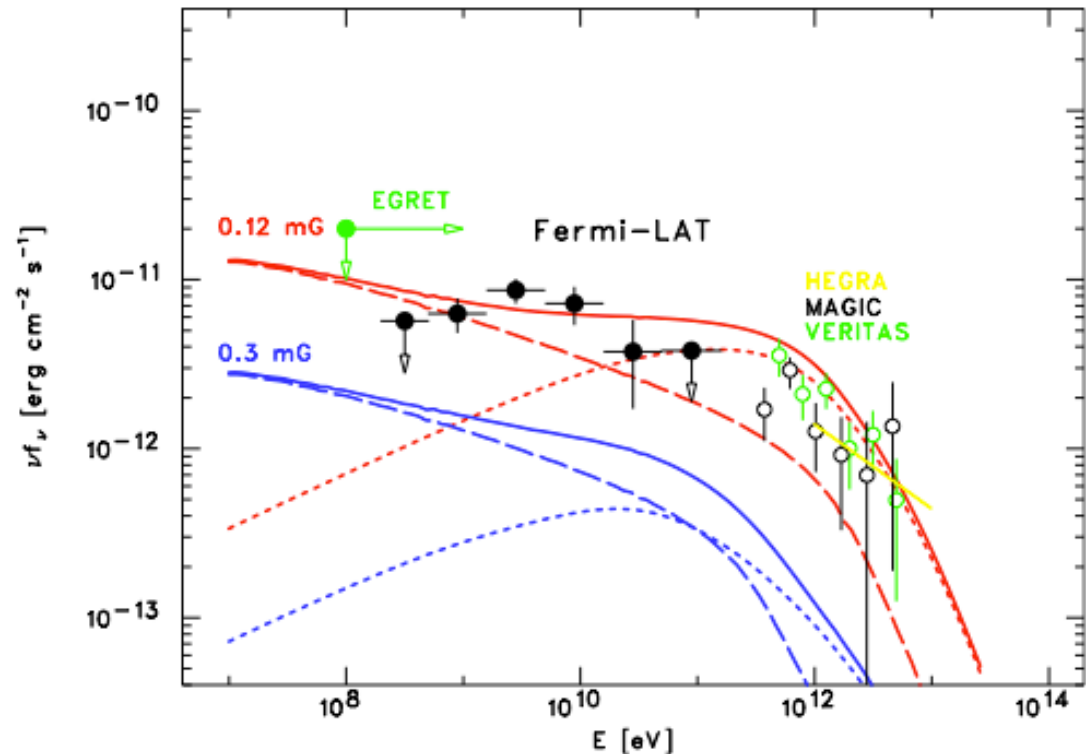
Cosmic ray content of the SNR is  $\sim (1-4) \times 10^{49}$  erg/s.

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Gamma-ray spectrum is also consistent with a "leptonic" model (particles responsible for gamma-ray emission are electrons).

The gamma-ray production mechanism could be electron Bremsstrahlung.

The amount of Bremsstrahlung emission could be readily estimated, because the density of the medium in the SNR is measured.

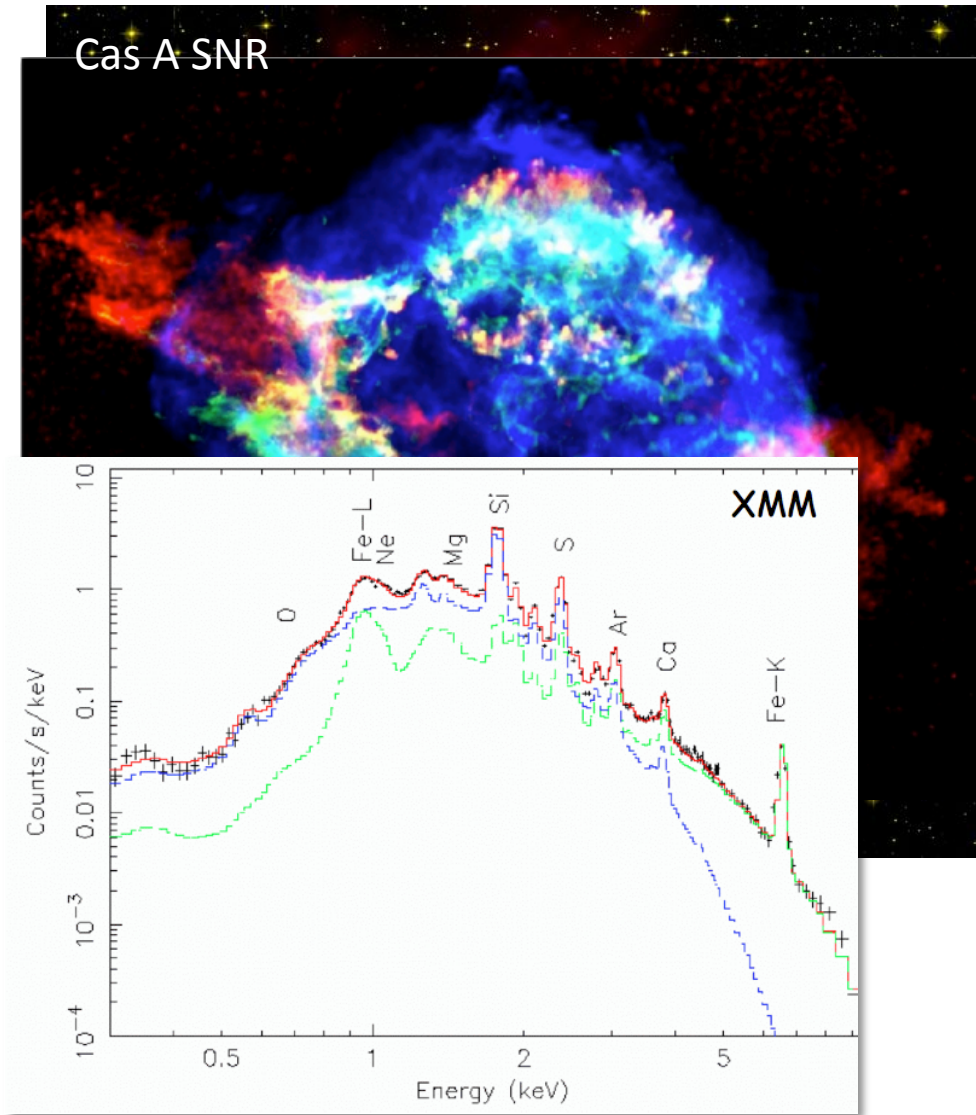


# Cas A in X-rays

Detailed content of the ejecta in different elements is known from X-ray observations.

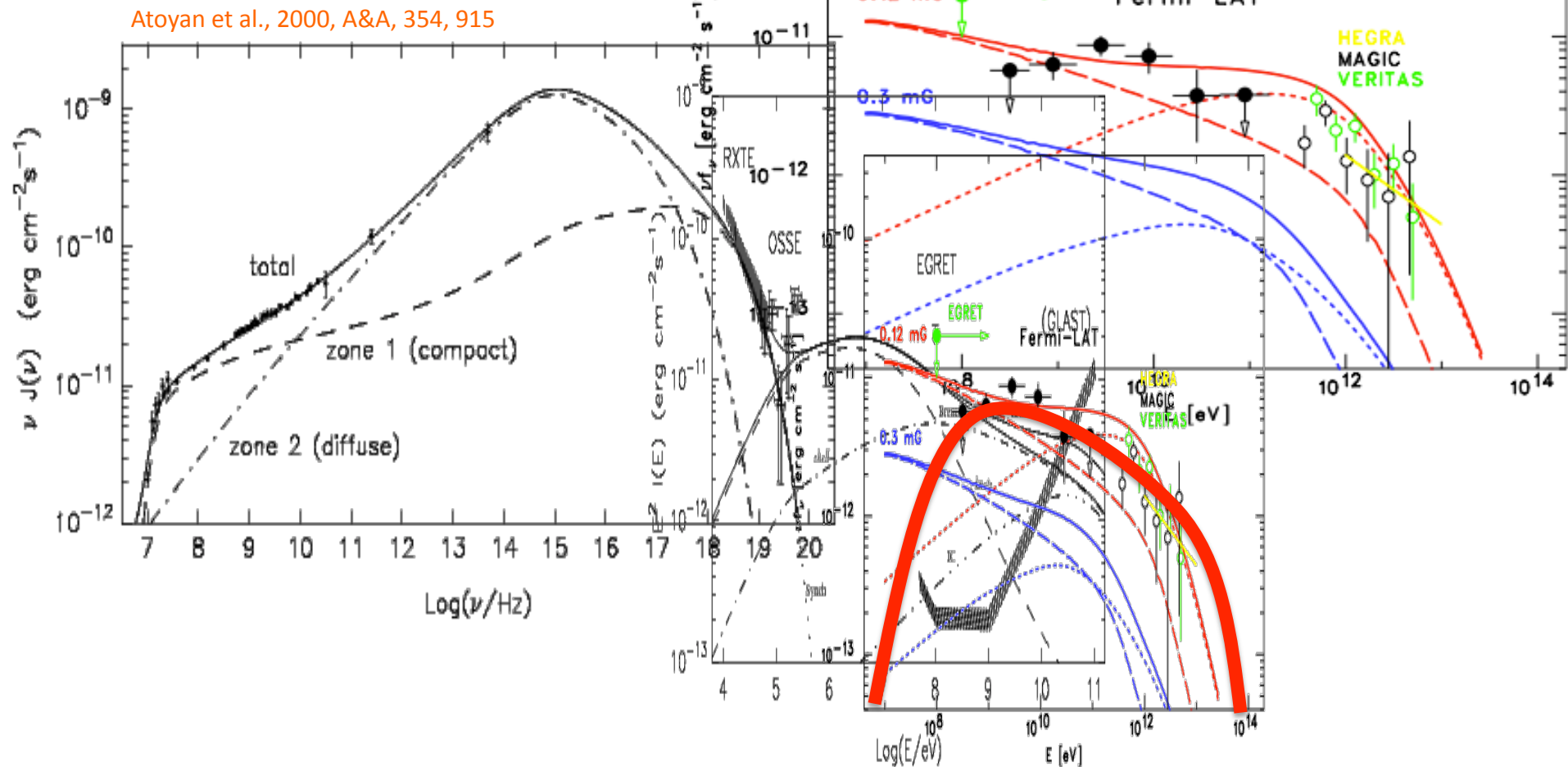
Detailed spatial distribution of density is known.

X-ray emission is dominated by thermal component, with strong line emission.



# Cas A spectral energy distribution

Observation of suppression of the flux just below 100 MeV will be an important test allowing to distinguish between hadronic and leptonic models.



# Summary

Evolution of massive stars up to the moment of core collapse.

Core collapse and supernova explosion mechanism(s).

Neutrino emission in supernova explosions.

Gamma-ray bursts and their association with supernova explosions.

Formation of neutron stars.

Particle acceleration by neutron stars.

Supernova remnants and particle acceleration in SNR.