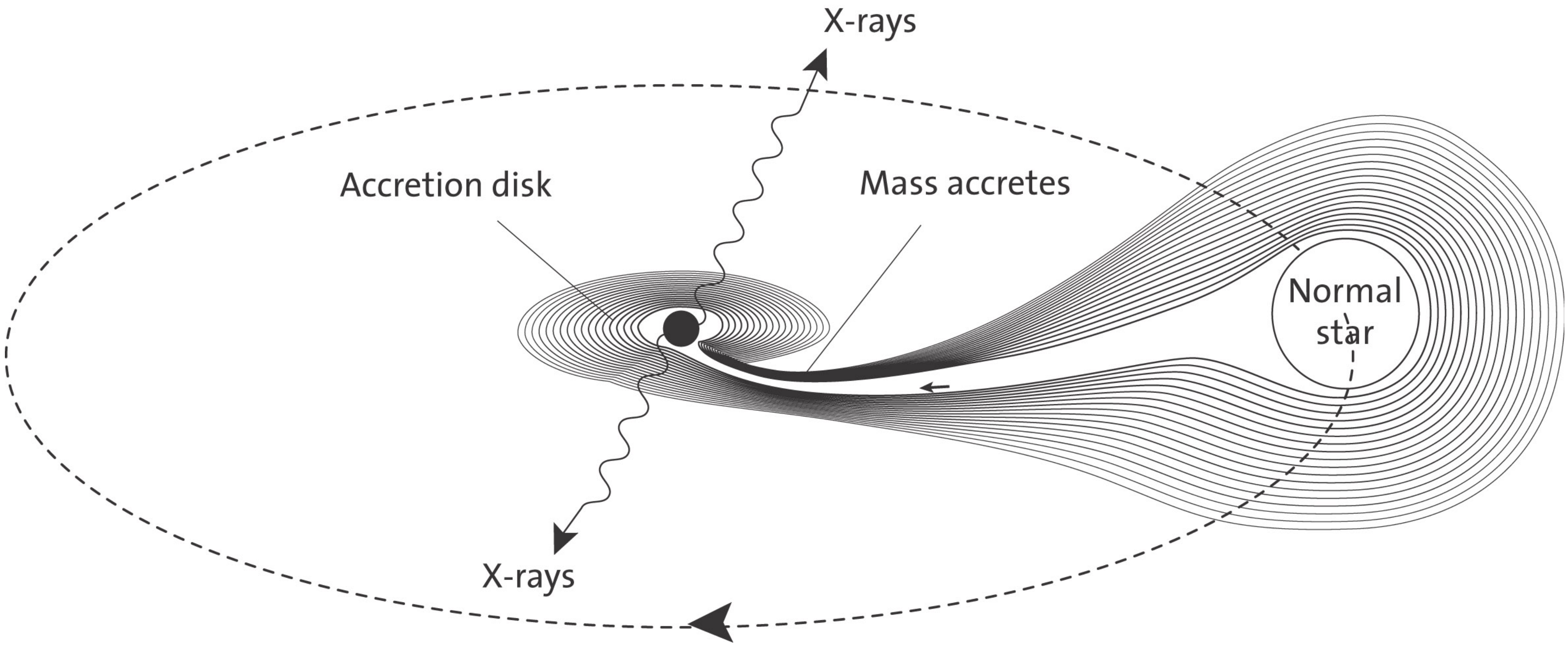
Astrofisica Nucleare e Subnucleare

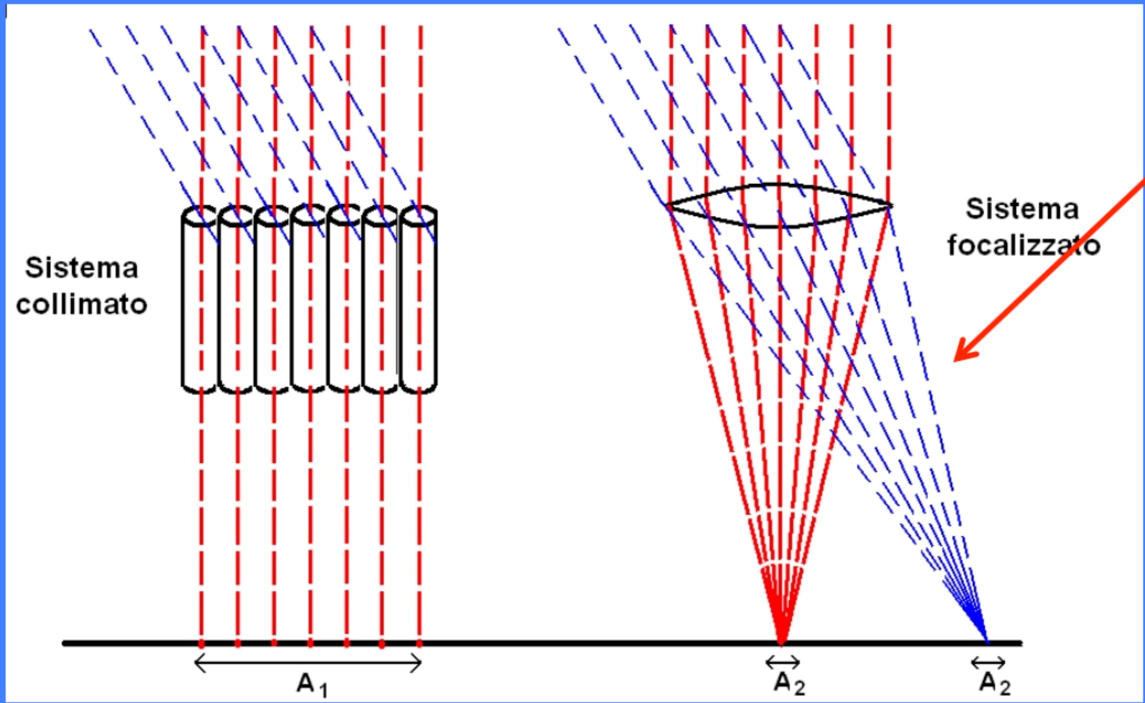
“X-ray” Astrophysics

Nobel prize 2002 – R.Giacconi



“ … for pioneering contributions to astrophysics,
which have led to the discovery of cosmic X-ray sources”

Focalizzazione vs collimazione



Proper imaging of X-rays below 20-40 keV

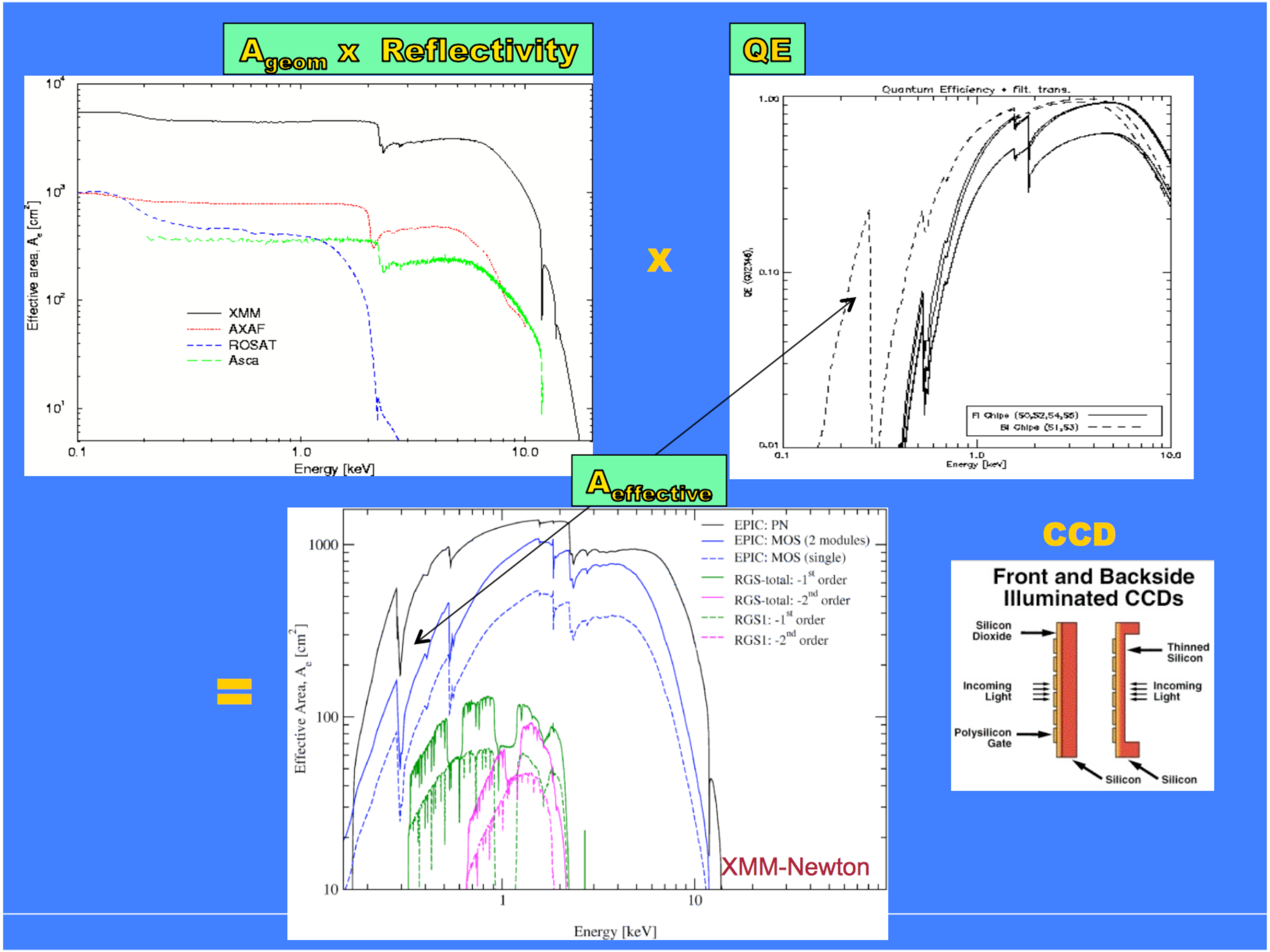
A_d= PSF projected on the focal plane

$$F_{\min} \approx n_\sigma \frac{\sqrt{2B}}{\sqrt{A_{det} T_{int} \Delta E}}$$

$$F_{\min} \approx n_\sigma \frac{\sqrt{B A_d}}{A_{eff} \sqrt{T_{int} \Delta E}}$$

Sistema collimato: limita la regione di cielo da cui puo' provenire un segnale, (quindi limita il background), non incrementandone la "densita"

Sistema focalizzato: fa corrispondere ad ogni sorgente un punto nel piano focale, e "concentra" il segnale, producendo un'immagine



A geom x Reflectivity
Effective area, Ae [cm2]
Energy [keV]
XMM
AXAF
ROSAT
Asca
x
QE
Quantum Efficiency + filt. trans.
Energy [keV]
FI Chips (S0,S2,S4,S5)
BI Chips (S1,S3)
=
A effective
Effective Area, Ae [cm2]
Energy [keV]
EPIC: PN
EPIC: MOS (2 modules)
EPIC: MOS (single)
RGS-total: -1st order
RGS-total: -2nd order
RGS1: -1st order
RGS1: -2nd order
XMM-Newton
CCD
Front and Backside Illuminated CCDs
Silicon Dioxide
Thinned Silicon
Incoming Light
Incoming Light
Polysilicon Gate
Silicon
Silicon

$$C_S = S_E\, A_e\, \Delta E\, \Delta t\, \eta_E$$

Detected signal

$$C_B = B\, \varepsilon\, A_d\, \Delta E\, \Delta t$$

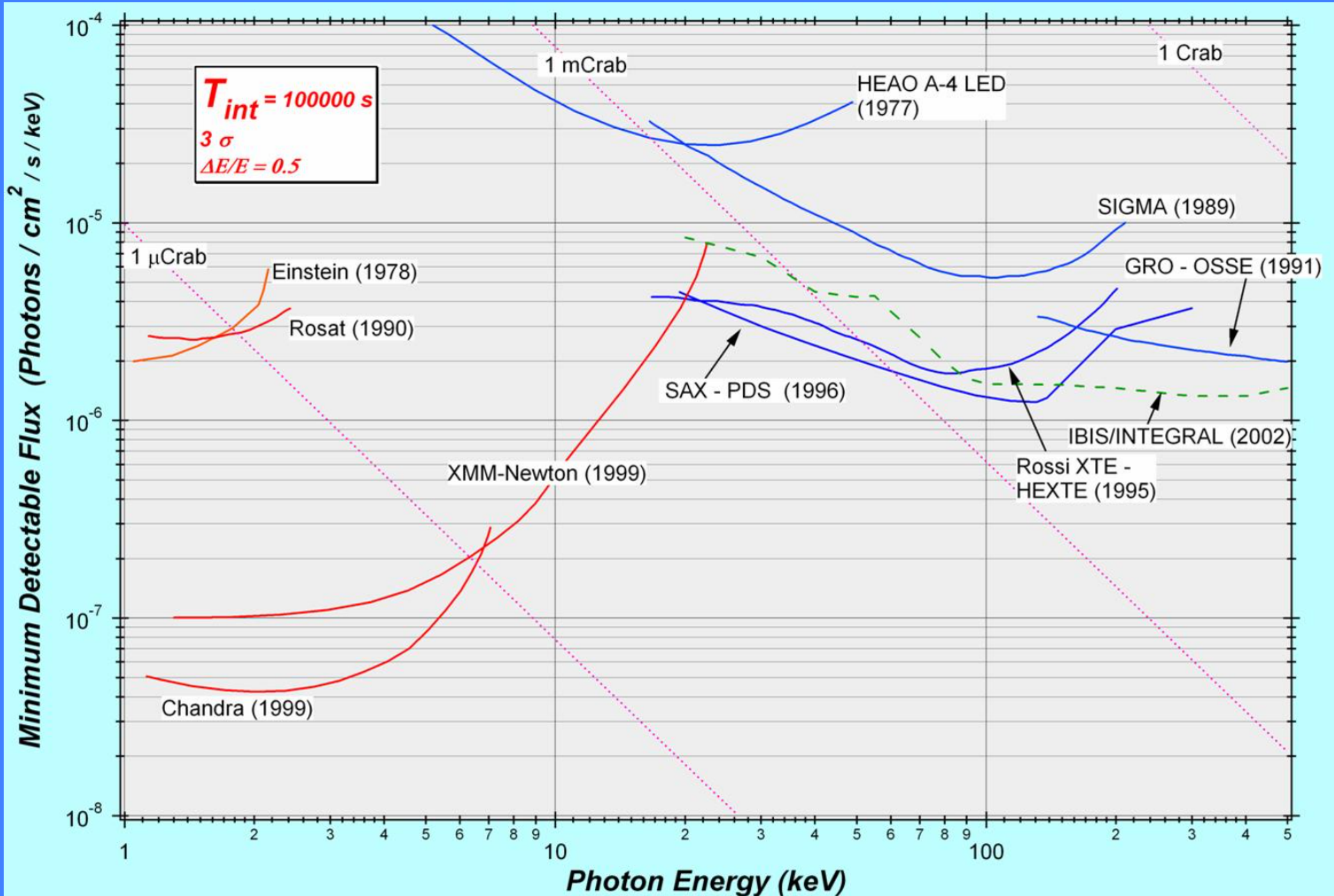
Background signal (ε: region of the detector where B counts are focused)

$$S/N = n_\sigma = \frac{C_S}{\sqrt{C_S + 2C_B}} \approx \frac{S_E\, A_e\, \Delta E\, \Delta t\, \eta_E}{\sqrt{2B\, \varepsilon\, A_d\, \Delta E\, \Delta t}}$$

$$S_{E,\min} = \frac{n_\sigma}{\eta_E}\, \frac{1}{\mathrm{A_e}} \sqrt{\frac{2B\, \varepsilon\, A_d}{\Delta t\, \Delta E}}$$

Weak sources

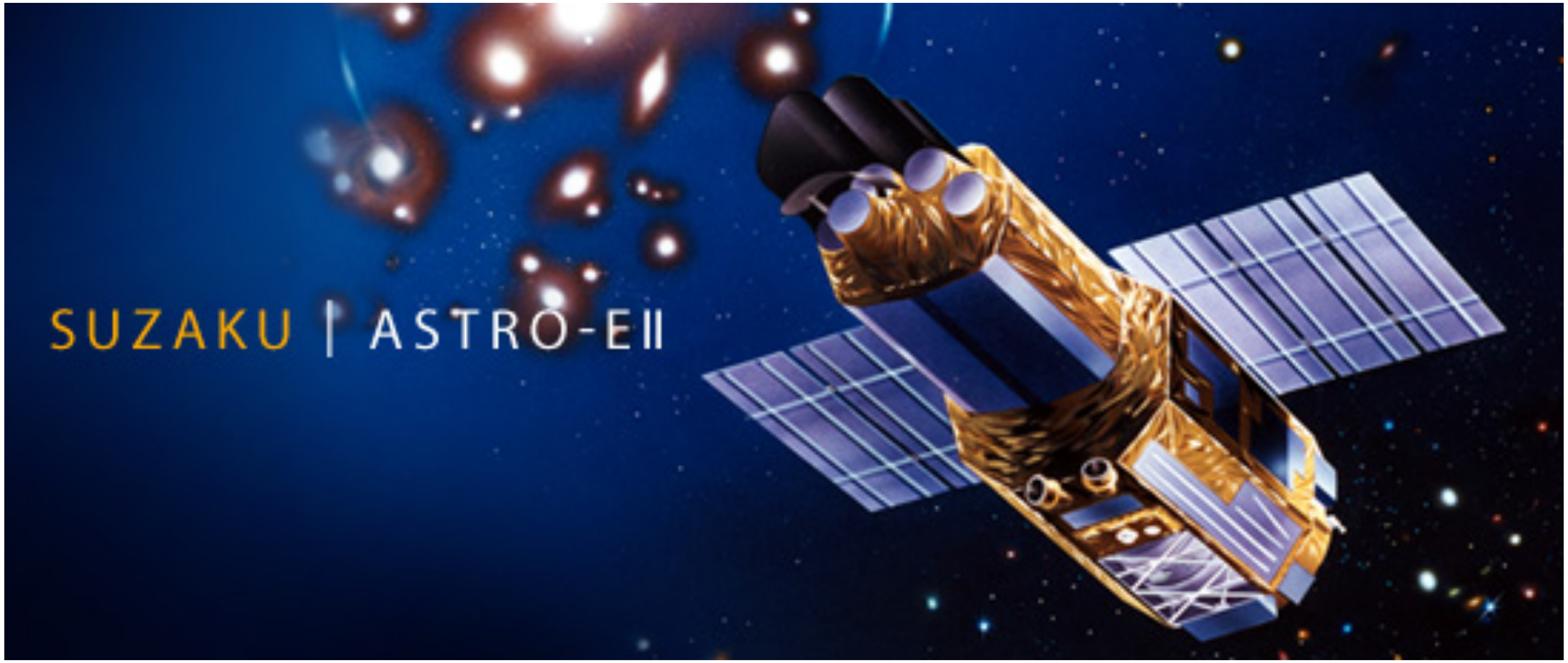
Old slide but *Chandra* and XMM-*Newton* still working



Suzaku

- Suzaku launched on July 10, 2005. Before launch it was called Astro-E2, and the name was changed to Suzaku shortly after the successful launch.

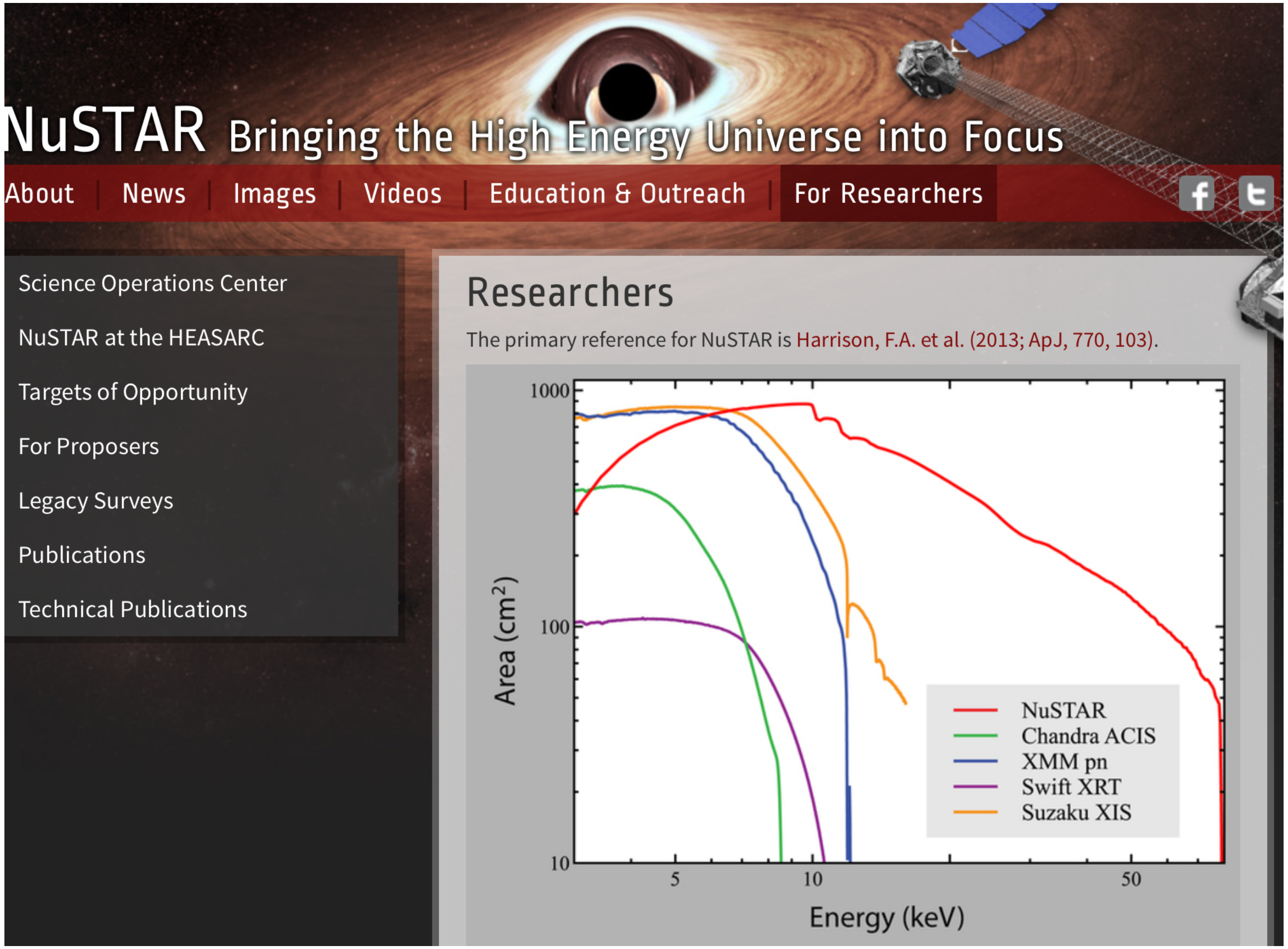
- Suzaku's four CCD cameras for low-energy X-rays and detector for high-energy X-rays continue to study the X-ray sky. In scientists' words, Suzaku is designed for "broad-band, high-sensitivity, high-resolution" spectroscopy.



http://www.isas.jaxa.jp/e/enterp/missions/suzaku/

NuSTAR

- The NuSTAR (Nuclear Spectroscopic Telescope Array) mission has deployed the first orbiting telescopes to focus light in the high energy X-ray (3 - 79 keV) region of the electromagnetic spectrum. Our view of the universe in this spectral window has been limited because previous orbiting telescopes have not employed true focusing optics, but rather have used coded apertures that have intrinsically high backgrounds and limited sensitivity.



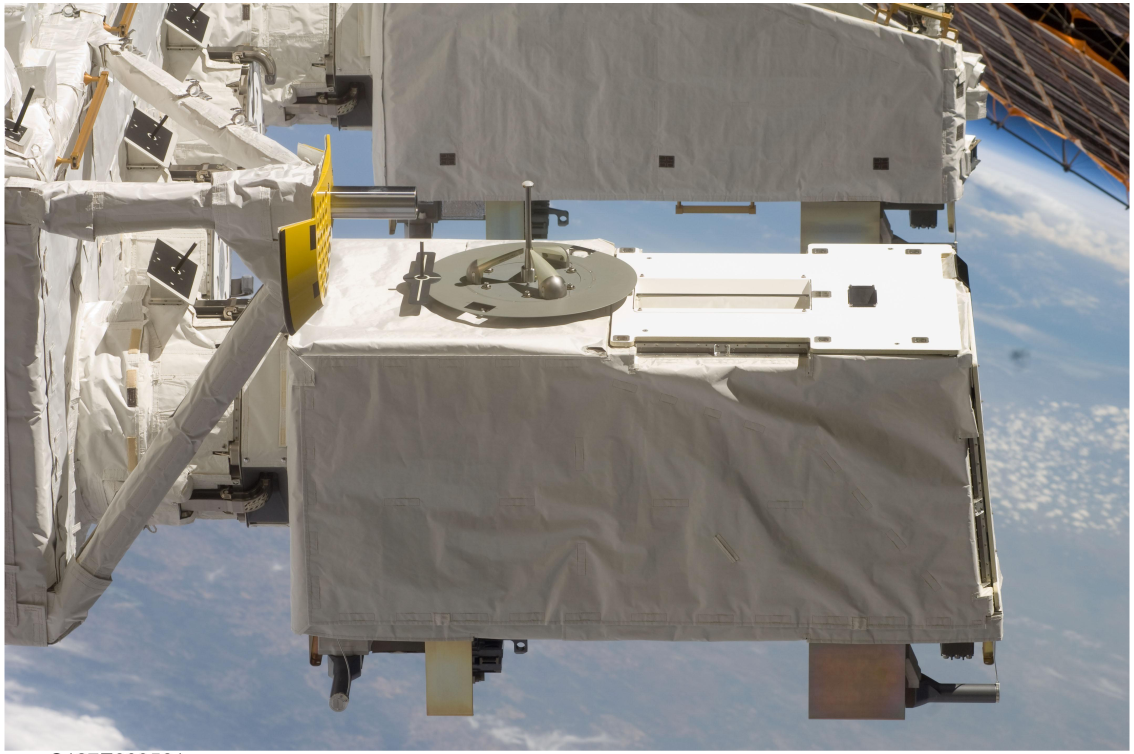
http://www.nustar.caltech.edu/

MAXI

The Monitor of All-sky X-ray Image, MAXI, is the first experiment installed on the Japanese Experiment Module Exposed Facility (JEM-EF or Kibo-EF) on the International Space Station (ISS) and the first high energy astrophysical experiment placed on the space station.

The main objectives of MAXI are early detection of X-ray transient events, and monitoring the intensity fluctuation of known X-ray sources over long periods by scanning the all sky in soft and hard X-ray.

- two semi-circular arc-shaped X-ray slit cameras with wide FOVs. In the 92 minutes it takes the ISS to orbit the earch, MAXI gets a 360 deg image of the entire sky.
- two kinds of X-ray detectors, collecting events from the slit cameras: a gas proportional counters, the Gas Slit Camera (GSC; 2-30 keV), and a X-ray CCD, Solid-state Slit Camera (SSC; 0.5-12 keV).

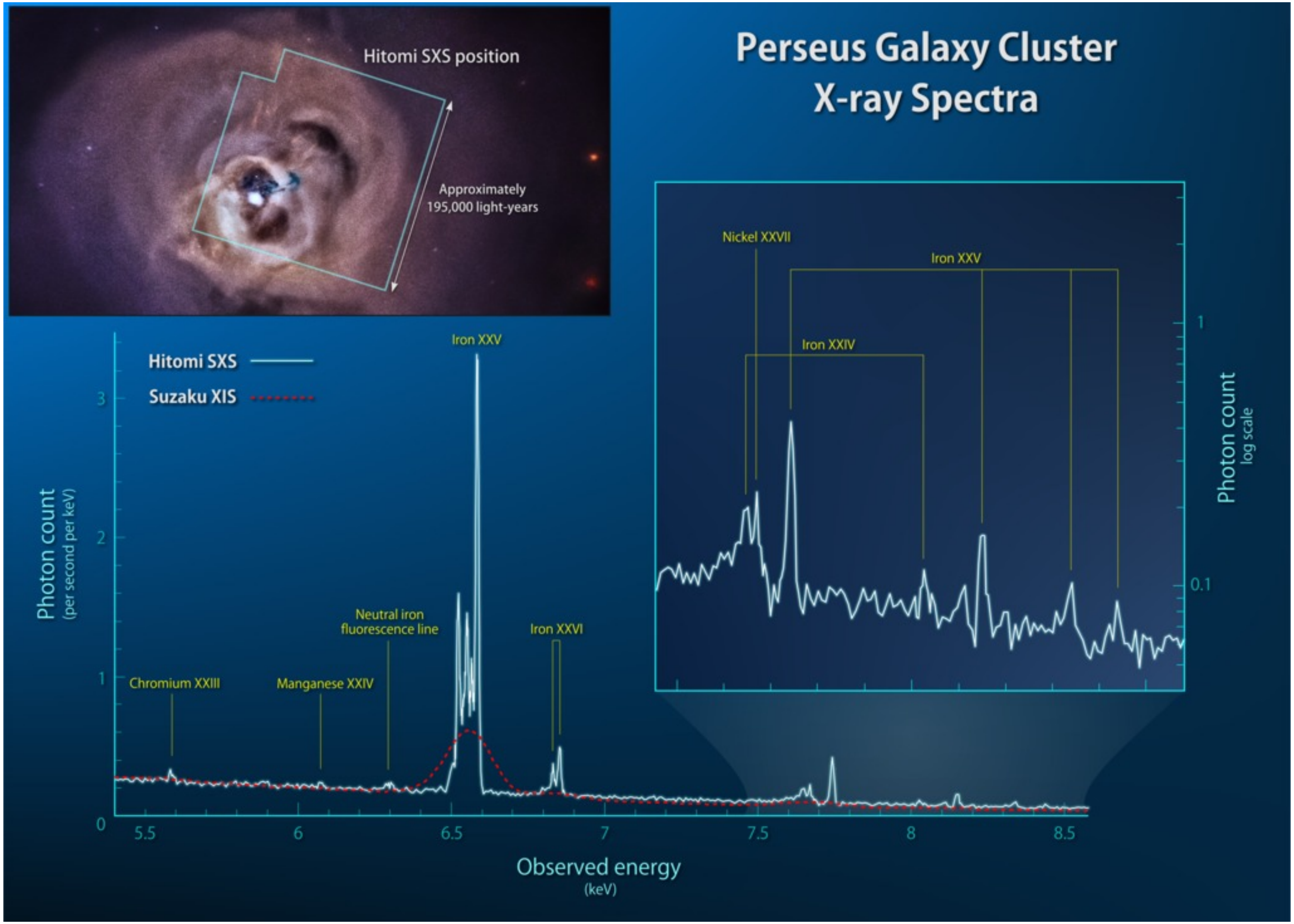


S127E009561

https://heasarc.gsfc.nasa.gov/docs/maxi/

Astro-H – Hitomi

http://astro-h.isas.jaxa.jp/en/



https://svs.gsfc.nasa.gov/12297

XRISM

National Aeronautics and Space Administration
Goddard Space Flight Center
Sciences and Exploration

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X-Ray Imaging and Spectroscopy Mission (XRISM)

The X-Ray Imaging and Spectroscopy Mission (XRISM), which was formerly known as XARM, is a JAXA/NASA collaborative mission, with ESA participation. The objective of the mission is to investigate celestial X-ray objects in the Universe with high-throughput imaging and high-resolution spectroscopy. XRISM is expected to launch in spring 2023 on a JAXA H-IIA rocket.

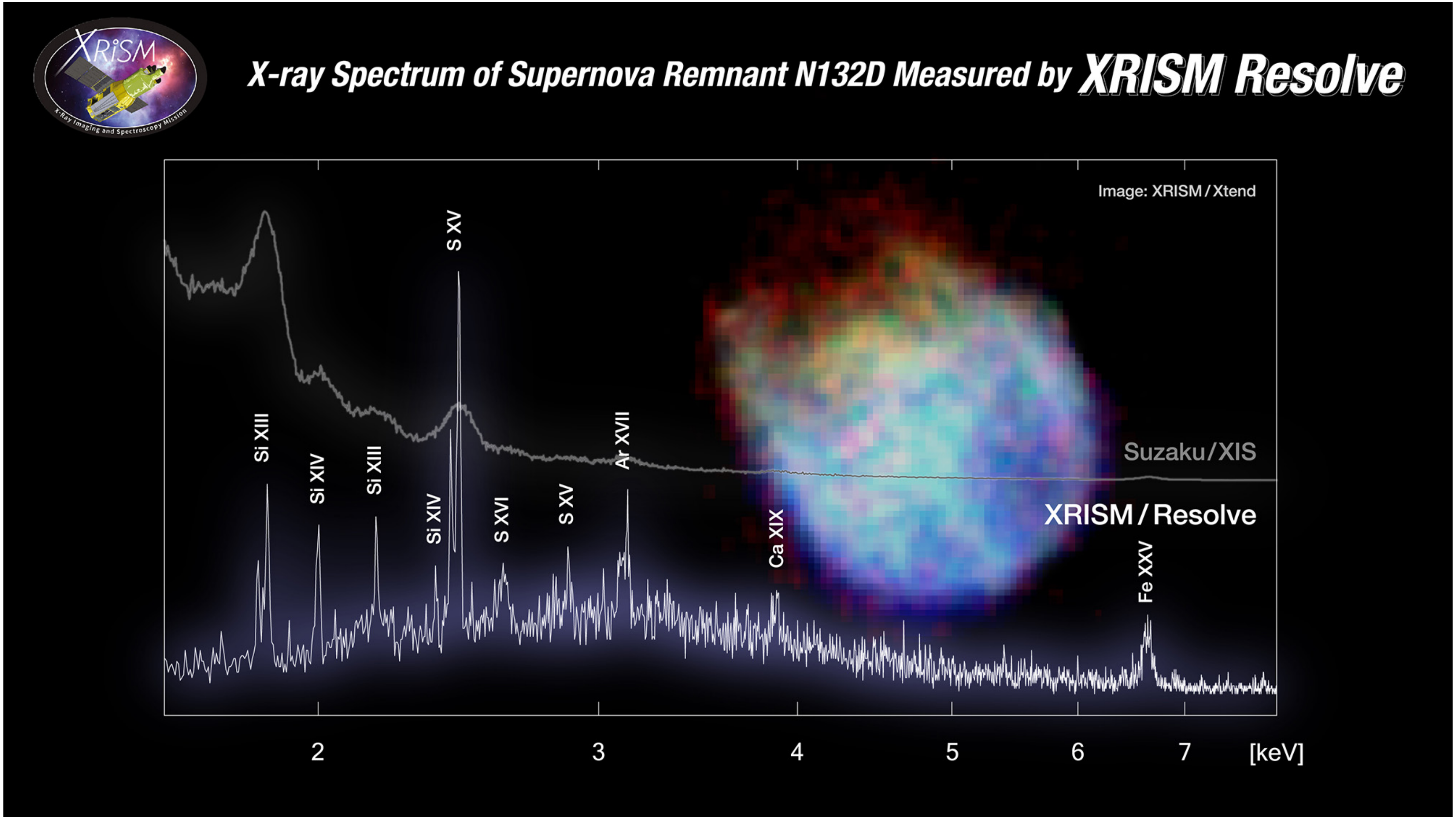
XRISM Site for the Public at NASA

Latest News

- **The 1st XRISM Data Analysis Workshop: Feb. 22-23, 2023** (26 Oct 2022)
This workshop is to prepare the astronomical community for the upcoming Cycle 1 General Observer Call for Proposals for XRISM. There is no registration fee; however, registration is required. Deadline for in-person participation is Dec 6, 2022.

https://heasarc.gsfc.nasa.gov/docs/xrism/

XRISM



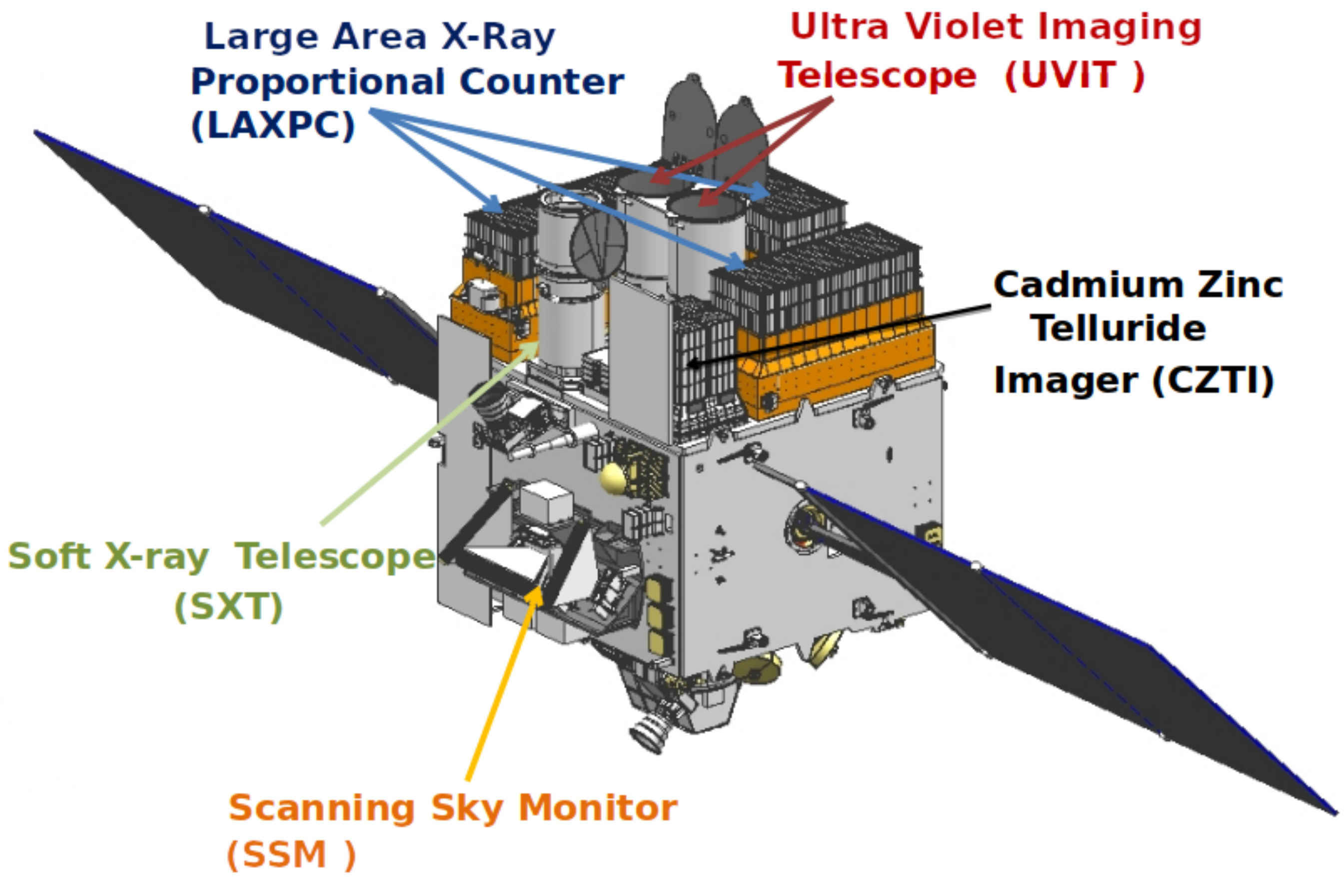
https://www.xrism.jaxa.jp/wp-content/uploads/2024/01/N132D_s.jpg

NICER

https://heasarc.gsfc.nasa.gov/docs/nicer/

ASTROSAT

https://www.isro.gov.in/Spacecraft/astrosat

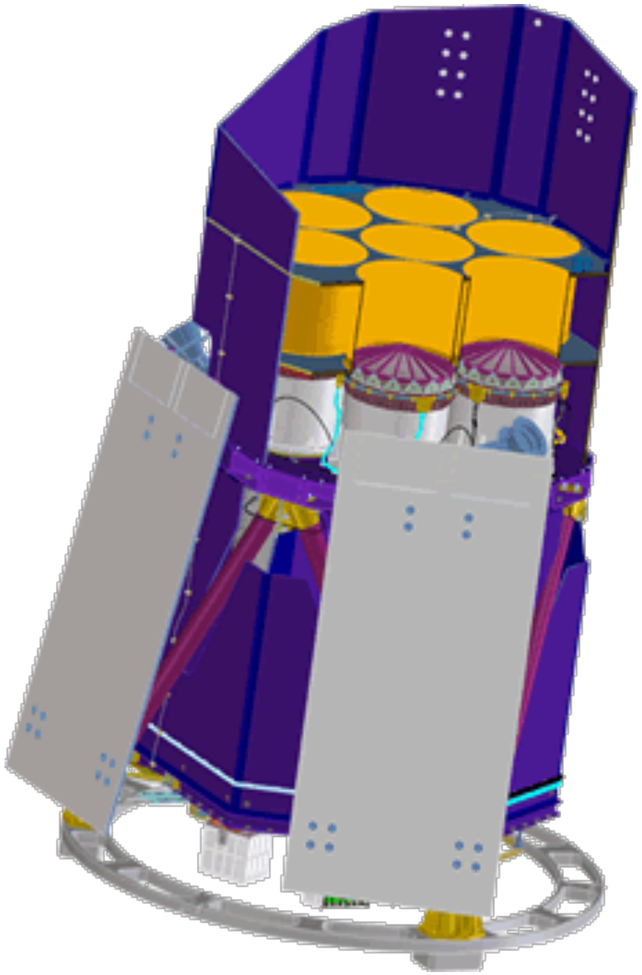


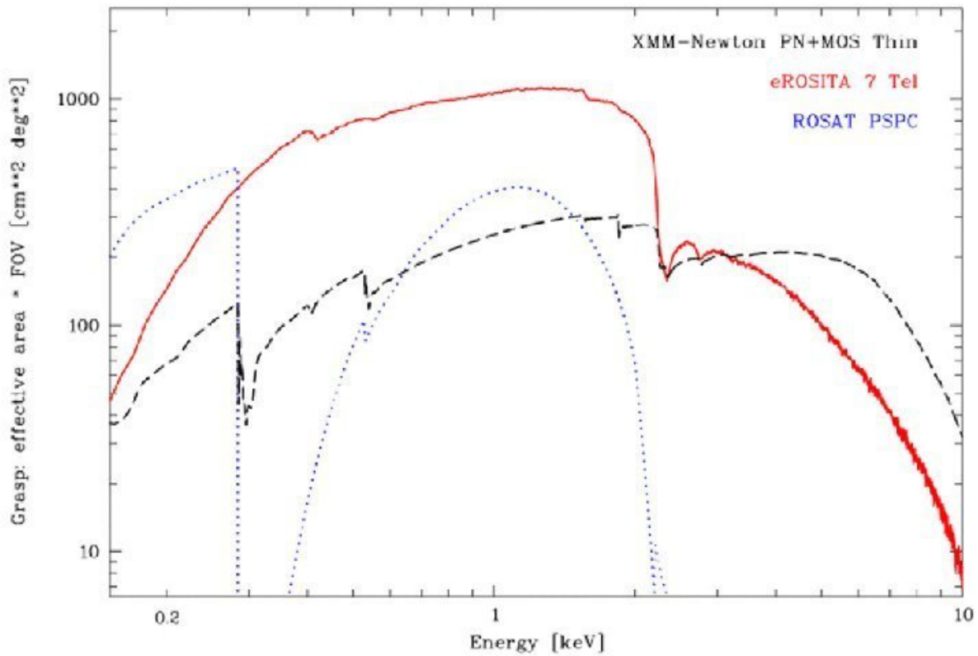
https://astrobrowse.issdc.gov.in/astro_archive/archive/Home.jsp

HMXT

http://hxmten.ihep.ac.cn/

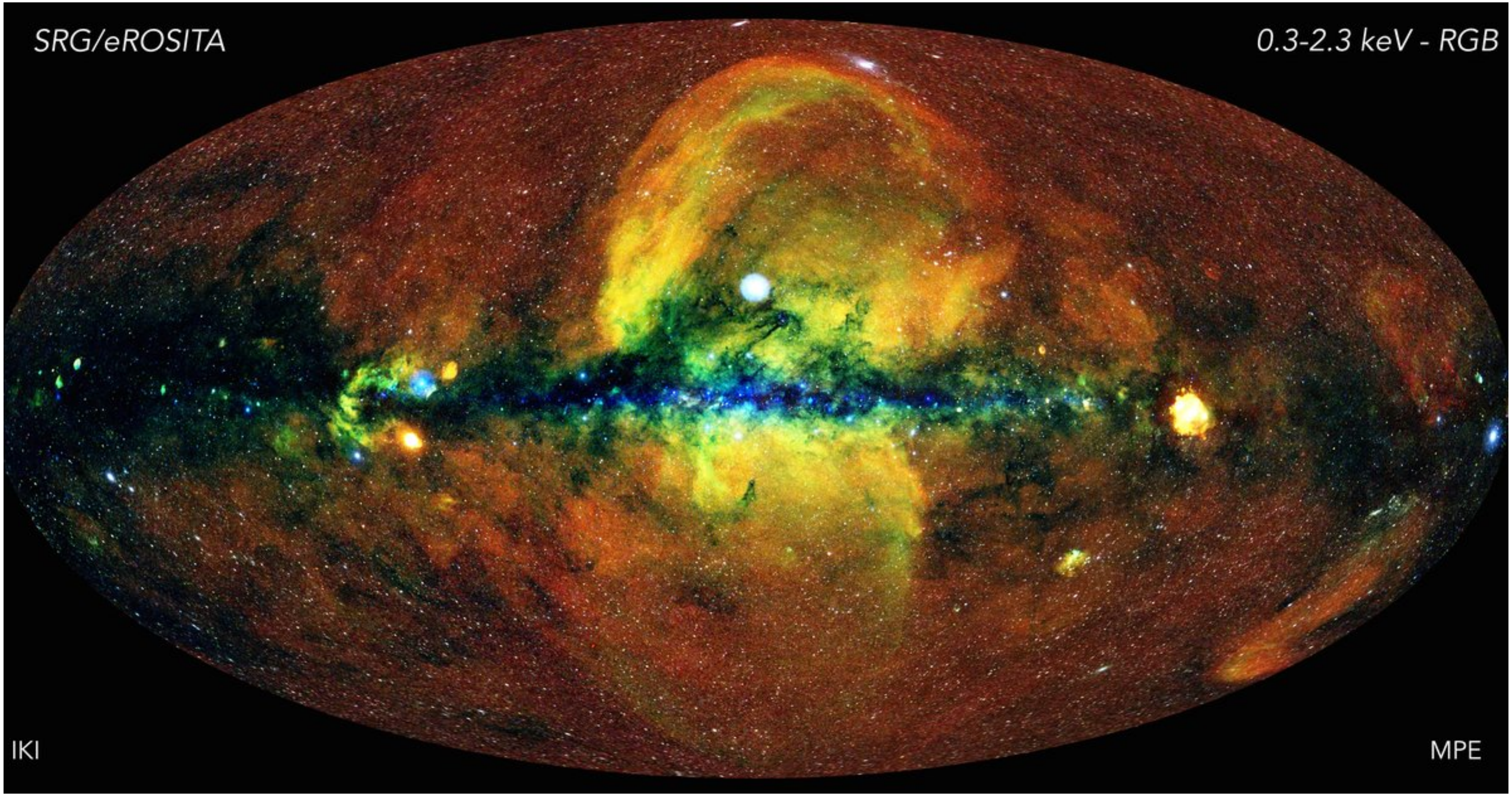
eROSITA





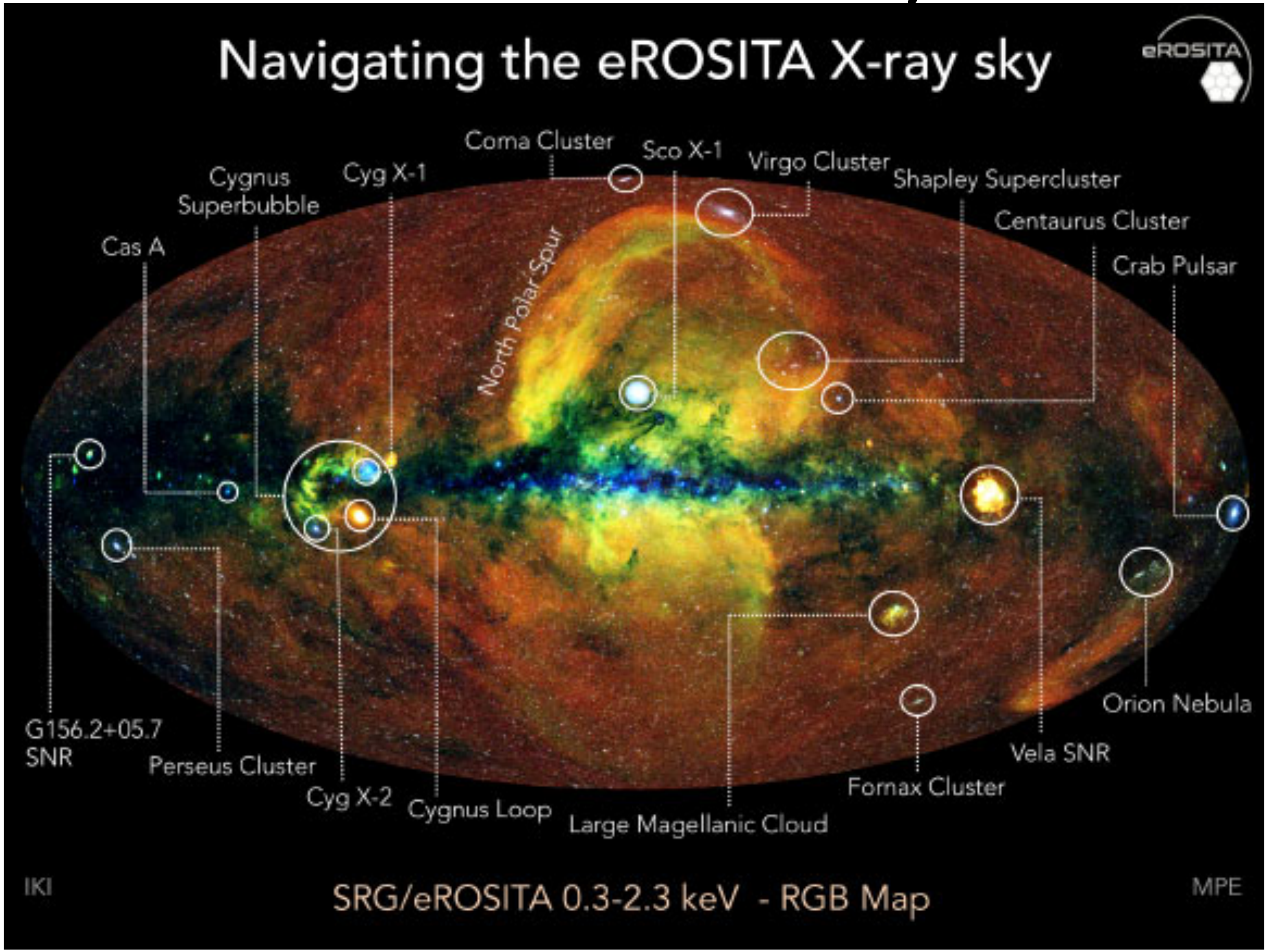
https://www.mpe.mpg.de/eROSITA

eROSITA survey



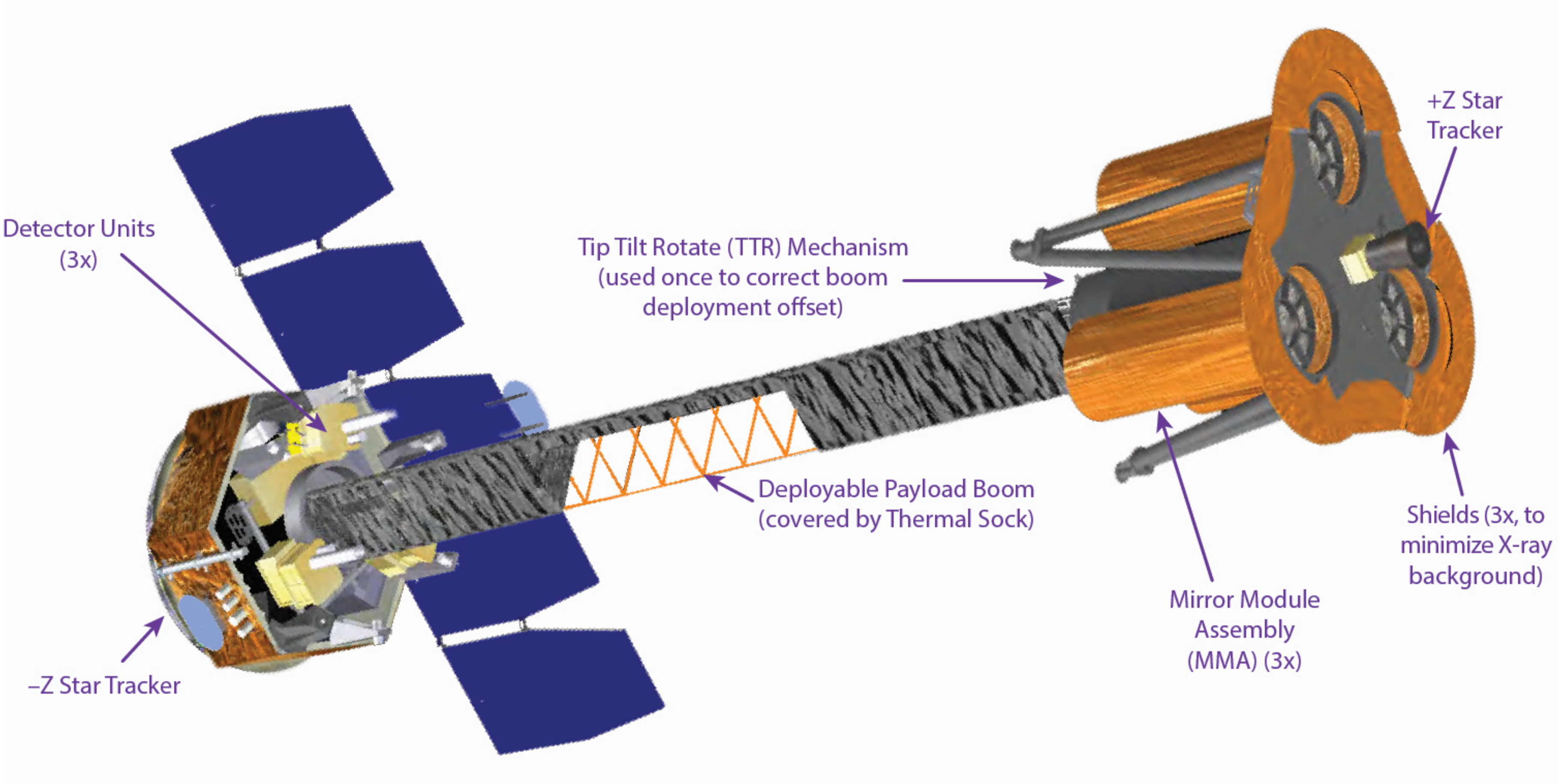
https://www.mpe.mpg.de/7461761/news20200619

eROSITA survey



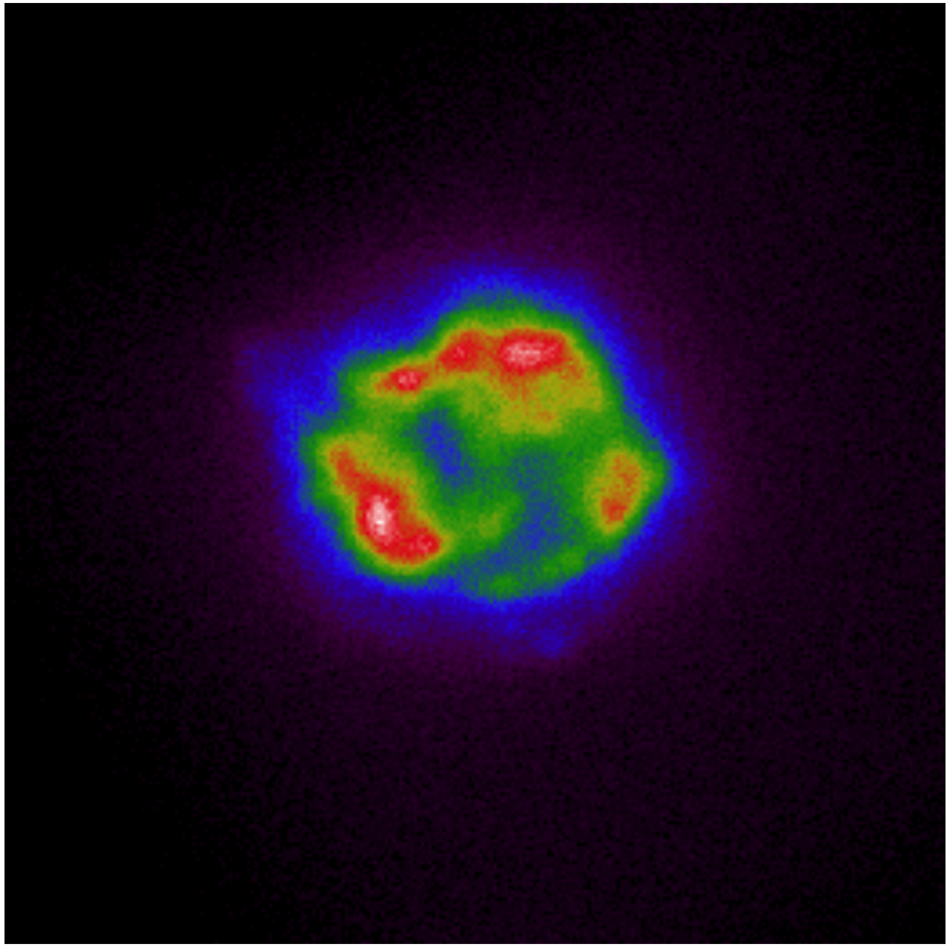
https://www.mpe.mpg.de/7461950/erass1-presskit

IXPE



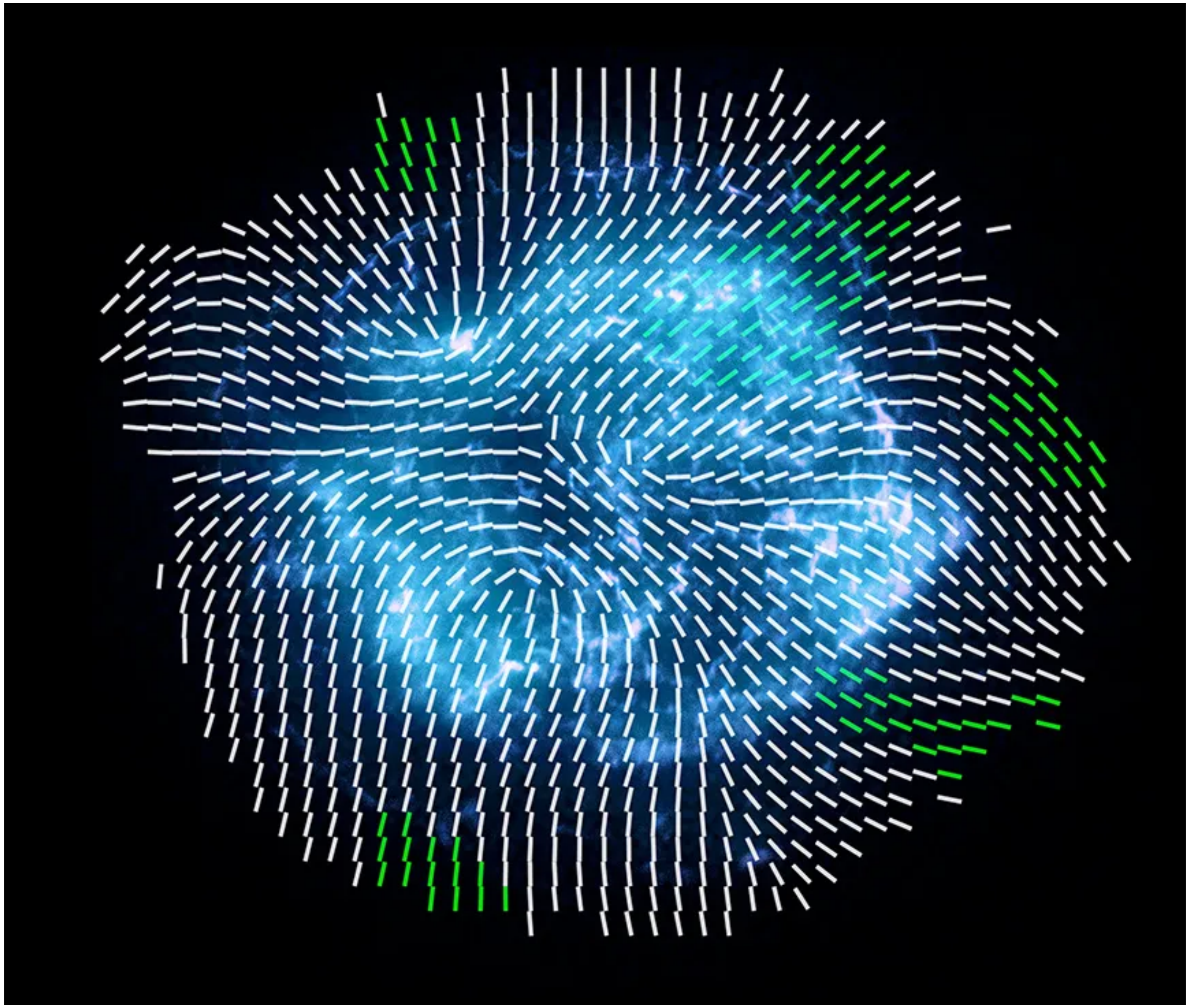
https://wwwastro.msfc.nasa.gov/ixpe/

IXPE



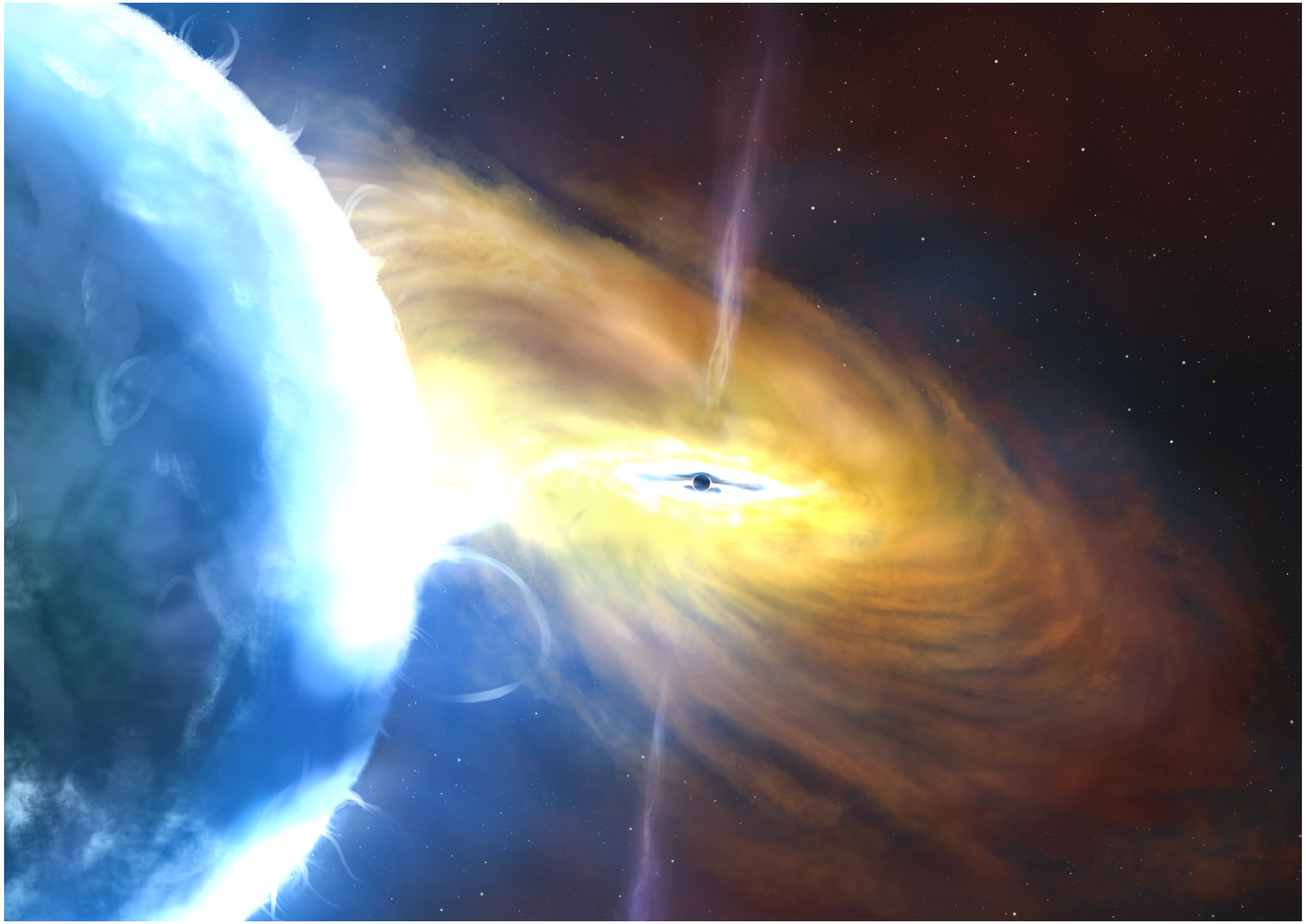
https://www.nasa.gov/mission_pages/ixpe/news/nasa-s-ixpe-sends-first-science-image.html

IXPE



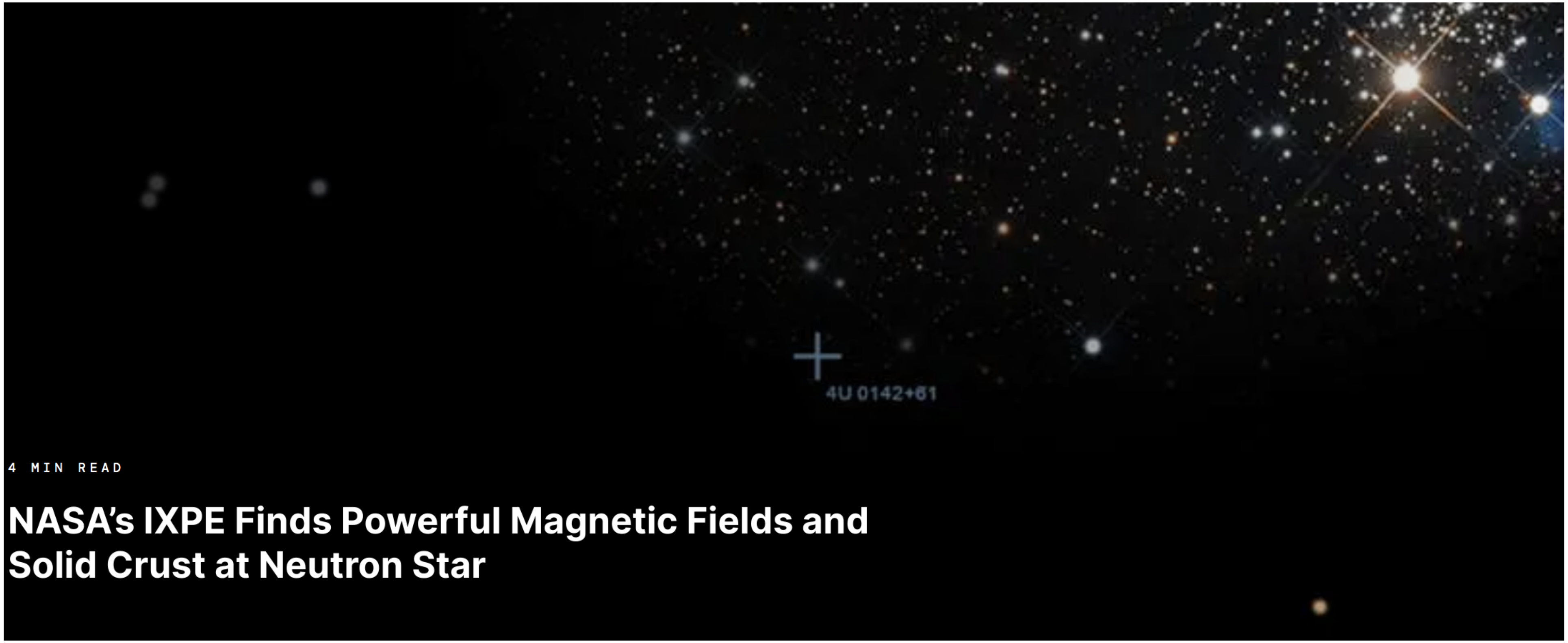
https://www.nasa.gov/missions/chandra/nasas-ixpe-helps-unlock-the-secrets-of-famous-exploded-star/

IXPE



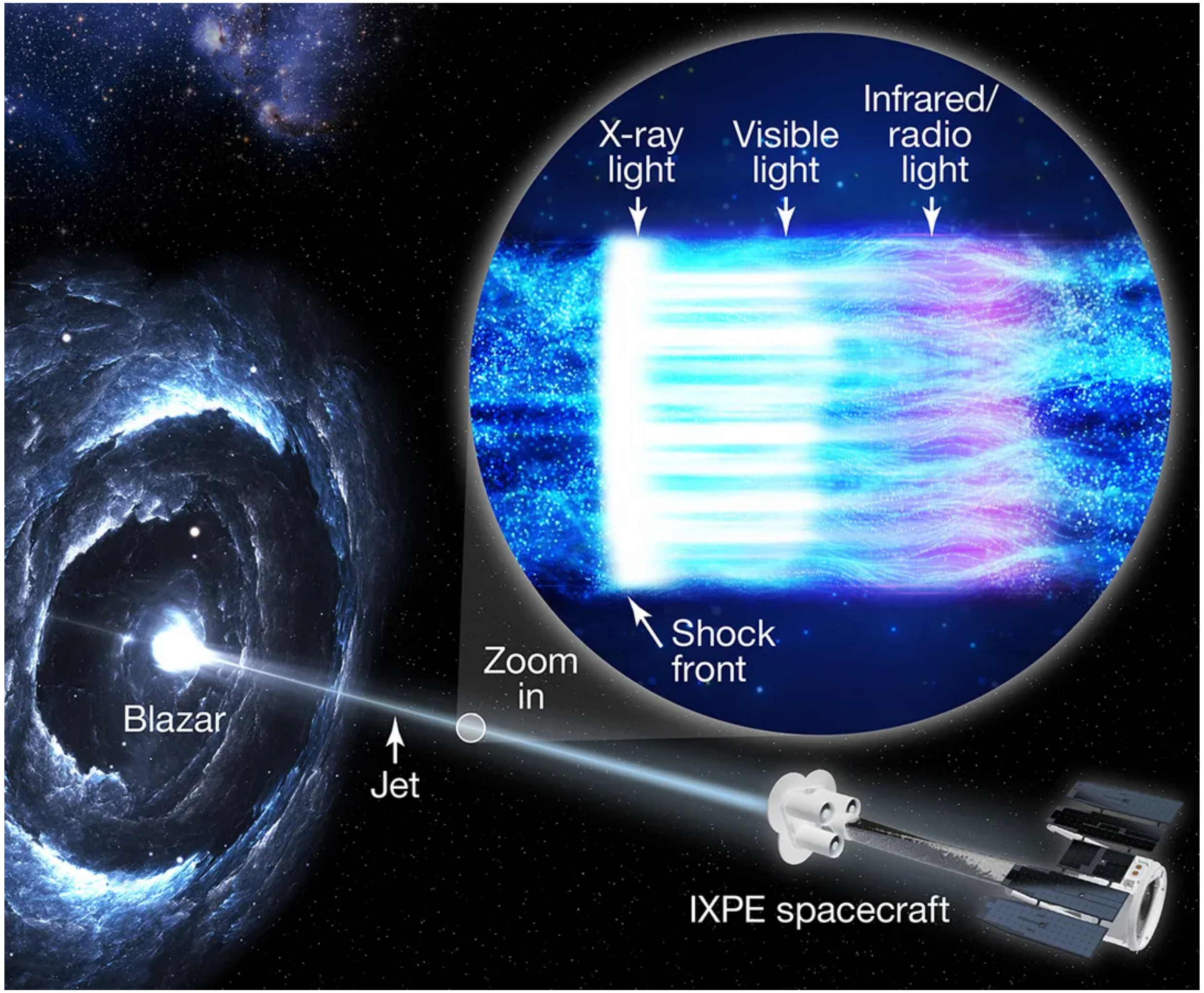
https://www.nasa.gov/universe/nasas-ixpe-reveals-shape-orientation-of-hot-matter-around-black-hole/

IXPE



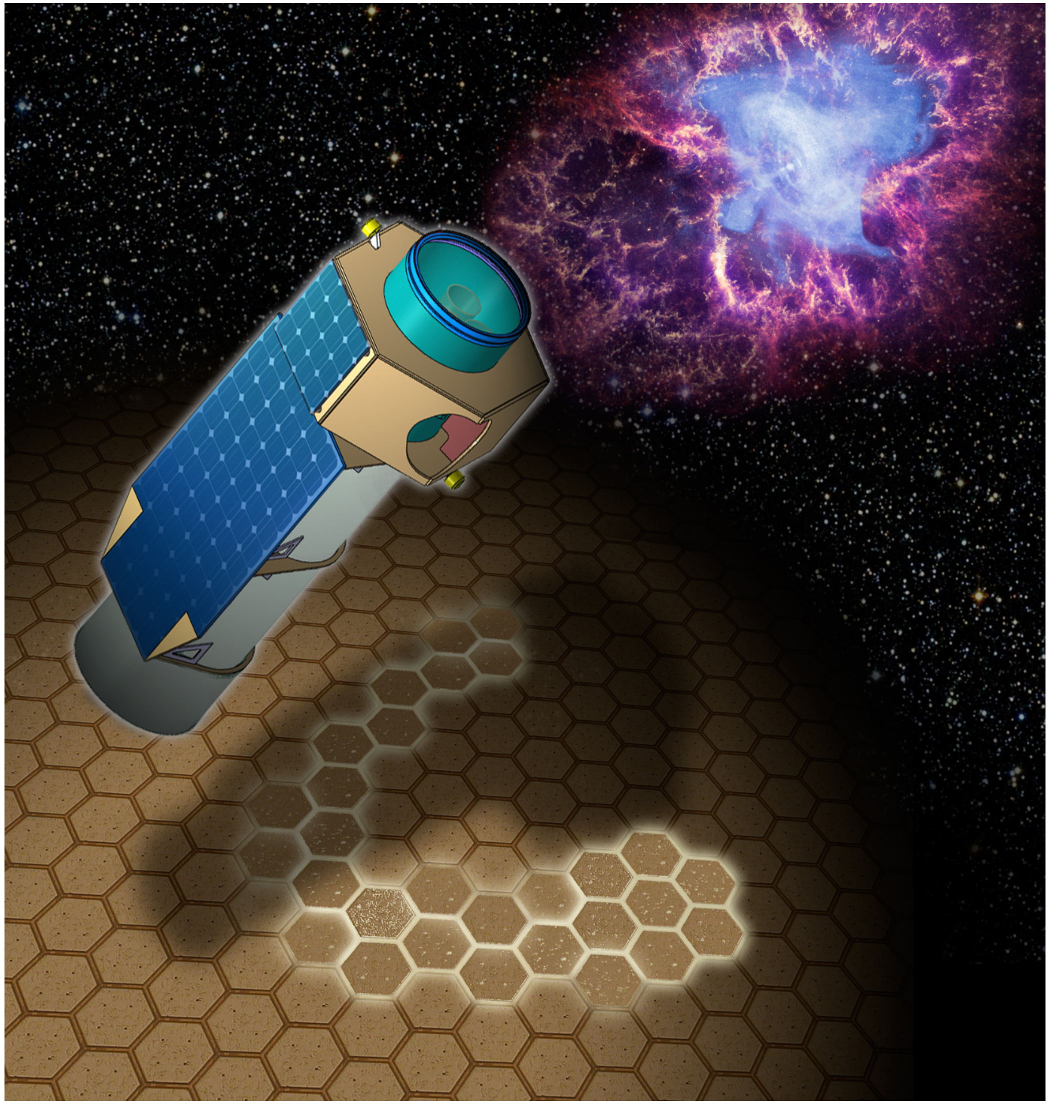
https://www.nasa.gov/centers-and-facilities/marshall/nasas-ixpe-finds-powerful-magnetic-fields-and-solid-crust-at-neutron-star/

IXPE



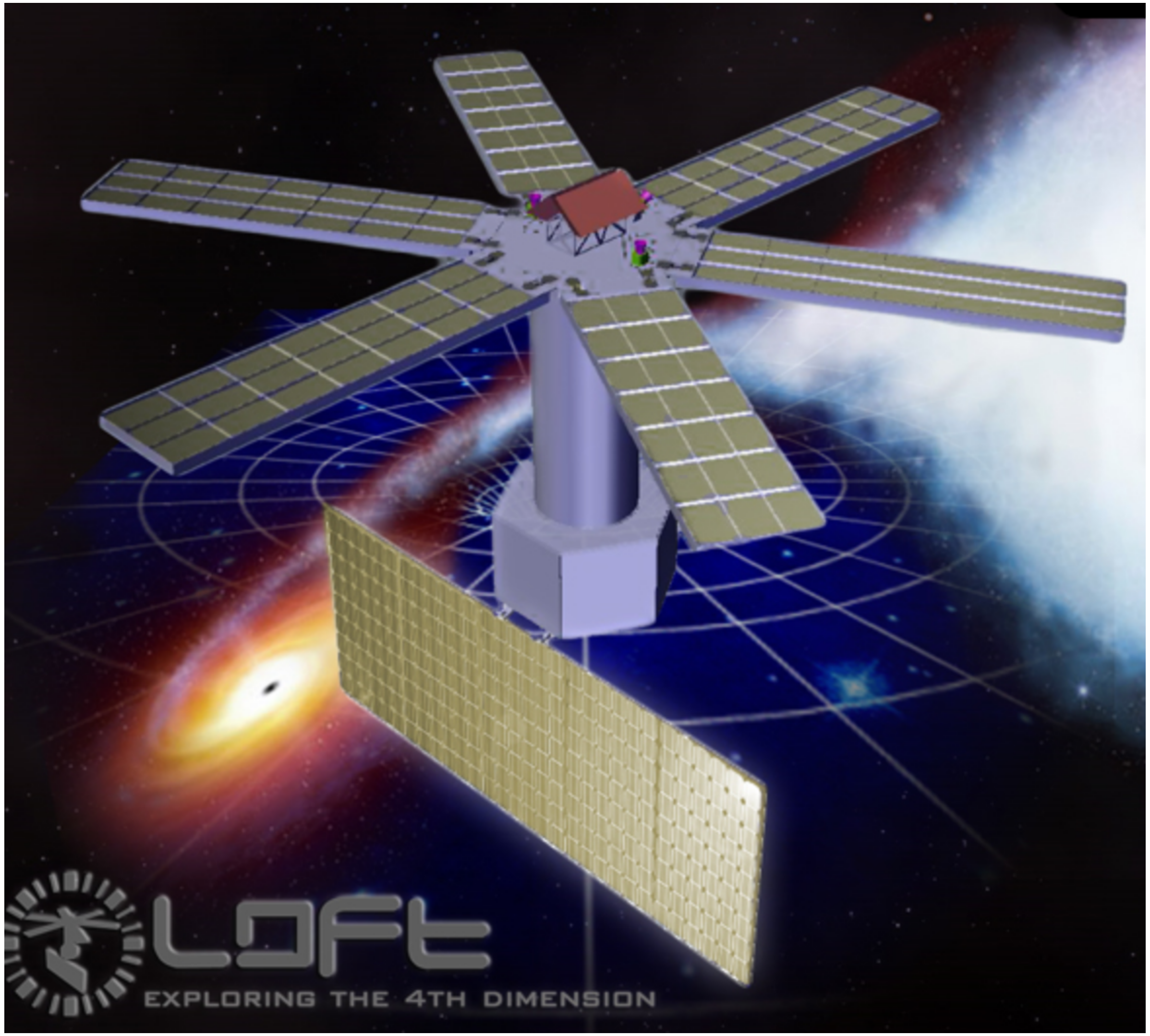
https://www.nasa.gov/universe/nasas-ixpe-helps-solve-black-hole-jet-mystery/

XIPE



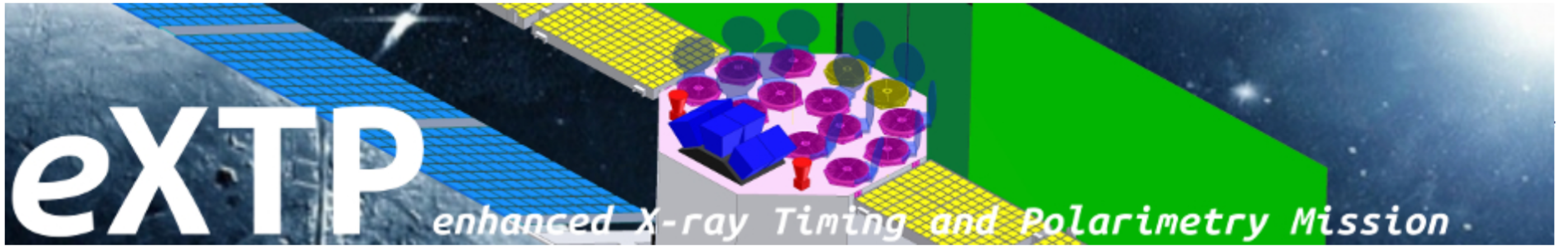
http://www.isdc.unige.ch/xipe/

LOFT



http://www.isdc.unige.ch/loft/

eXTP



The eXTP Mission

- The eXTP mission
- The eXTP Payload
- Science with eXTP
- SPIE 2016 paper
- Publications on eXTP
- Public Response Files

eXTP Teams

- WG1 - Dense Matter
- WG2 - Strong Field Gravity
- WG3 - Strong Magnetism
- WG4 - Observatory Science
- WG5 - Synergy with GWs
- WG6 - Simulations
- Instrument Working Group
- Consortium

The eXTP Mission

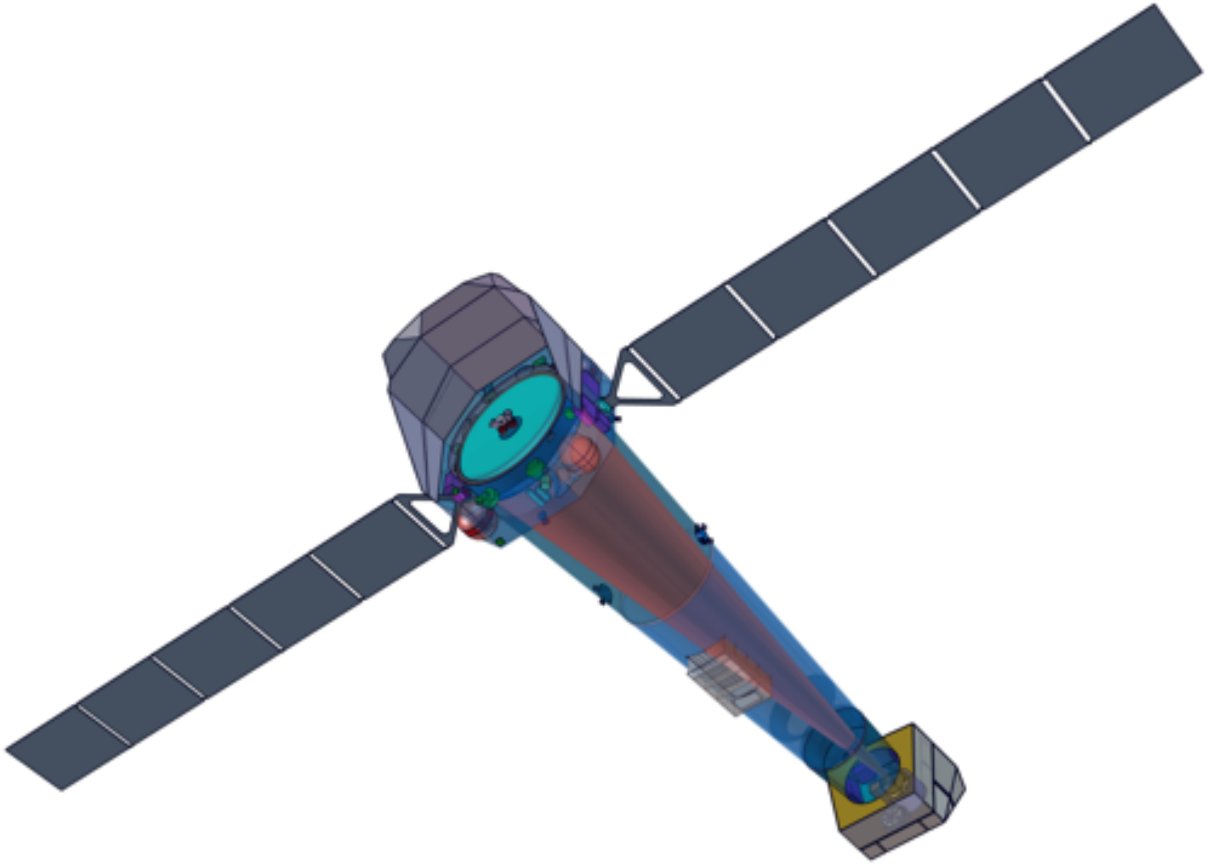
The enhanced X-ray Timing and Polarimetry mission (eXTP) is a science mission designed to study the state of matter under extreme conditions of density, gravity and magnetism. Primary goals are the determination of the equation of state of matter at supra-nuclear density, the measurement of QED effects in highly magnetized star, and the study of accretion in the strong-field regime of gravity. Primary targets include isolated and binary neutron stars, strong magnetic field systems like magnetars, and stellar-mass and supermassive black holes.

The mission carries a unique and unprecedented suite of state-of-the-art scientific instruments enabling for the first time ever the simultaneous spectral-timing-polarimetry studies of cosmic sources in the energy range from 0.5-30 keV (and beyond). Key elements of the payload are:

- **the Spectroscopic Focusing Array** (**SFA**): a set of 11 X-ray optics operating in the 0.5-10 keV energy band with a field-of-view (FoV) of 12 arcmin each and a total effective area of ~0.9 m^2 and 0.6 m^2 at 2 keV and 6 keV respectively. The telescopes are equipped with Silicon Drift Detectors offering <180 eV spectral resolution.
- **the Large Area Detector** (**LAD**): a deployable set of 640 Silicon Drift Detectors, achieving a total effective area of ~3.4 m^2 between 6 and 10 keV. The operational energy range is 2-30 keV and the achievable spectral resolution better than 250 eV. This is a non-imaging instrument, with the FoV limited to <1° FWHM by the usage of compact capillary plates.
- **the Polarimetry Focusing Array** (**PFA**): a set of 2 X-ray telescope, achieving a total effective area of 250 cm^2 at 2 keV, equipped with imaging gas pixel photoelectric polarimeters. The FoV of each telescope is 12 arcmin and the operating energy range is 2-10 keV.
- **the Wide Field Monitor** (**WFM**): a set of 3 coded mask wide field units, equipped with position-sensitive Silicon Drift Detectors, covering in total a FoV of 3.7 sr and operating in the energy range 2-50 keV.

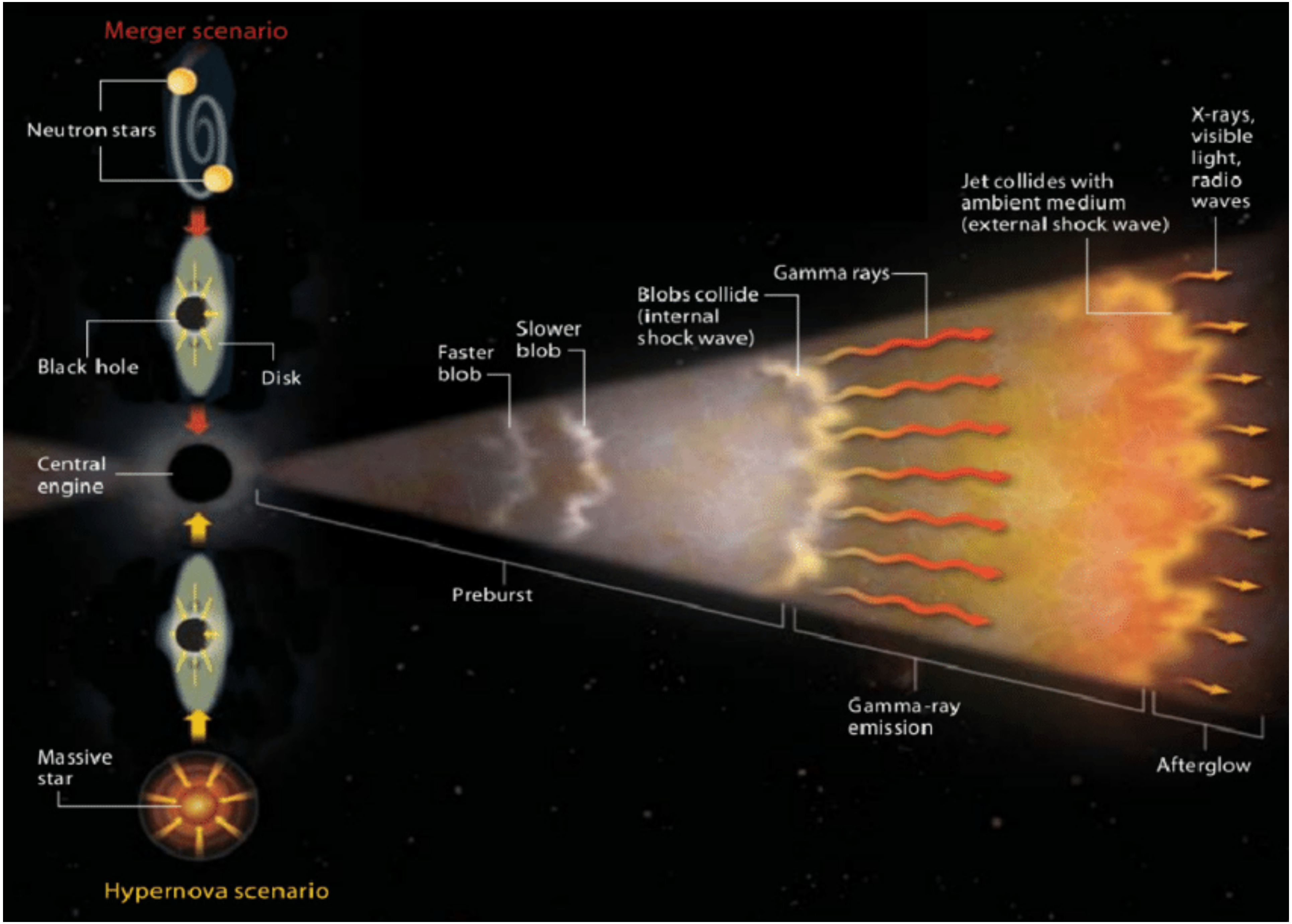
http://www.isdc.unige.ch/extp/

Athena



https://www.the-athena-x-ray-observatory.eu

Astrofisica Nucleare e Subnucleare
Neutrino Astrophysics

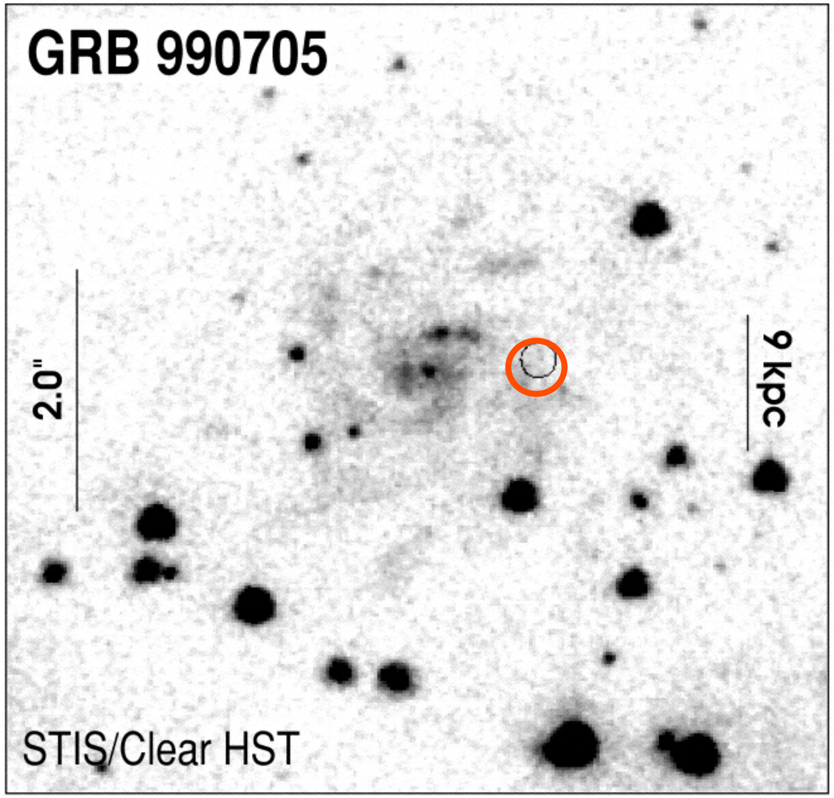


Merger scenario
Neutron stars
Black hole
Disk
Central engine
Massive star
Hypernova scenario
Faster blob
Slower blob
Blobs collide (internal shock wave)
Gamma rays
Jet collides with ambient medium (external shock wave)
X-rays, visible light, radio waves
Preburst
Gamma-ray emission
Afterglow

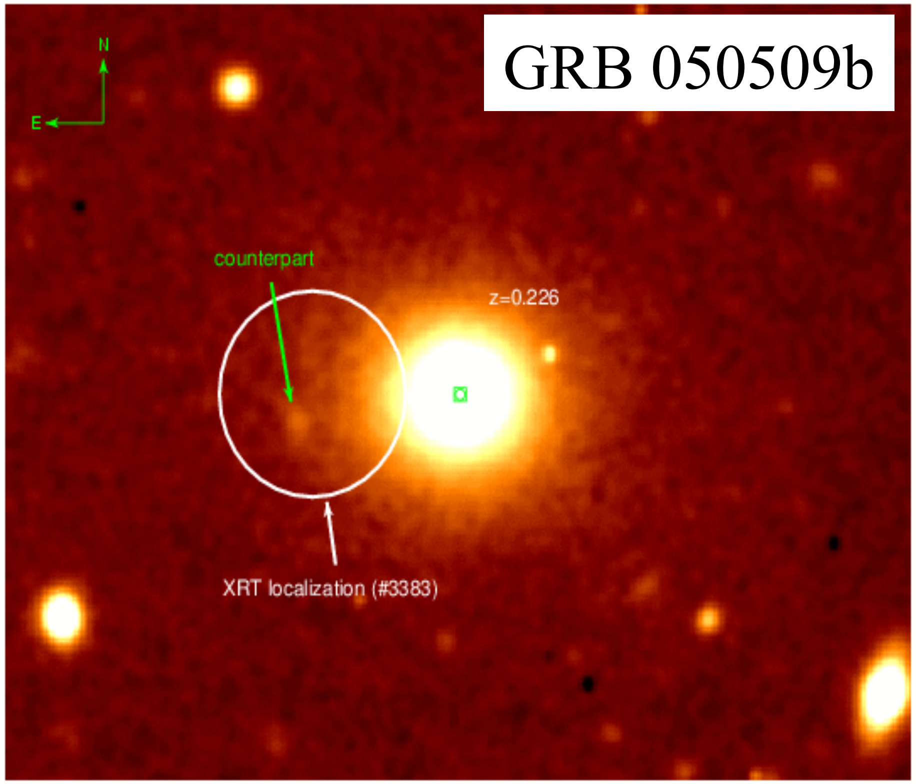
Unvealing the GRB progenitors

- host galaxies long GRBs: blue, usually regular and high star forming, GRB located in star forming regions
- host galaxies of short GRBs: elliptical, irregular galaxies, away from star forming region

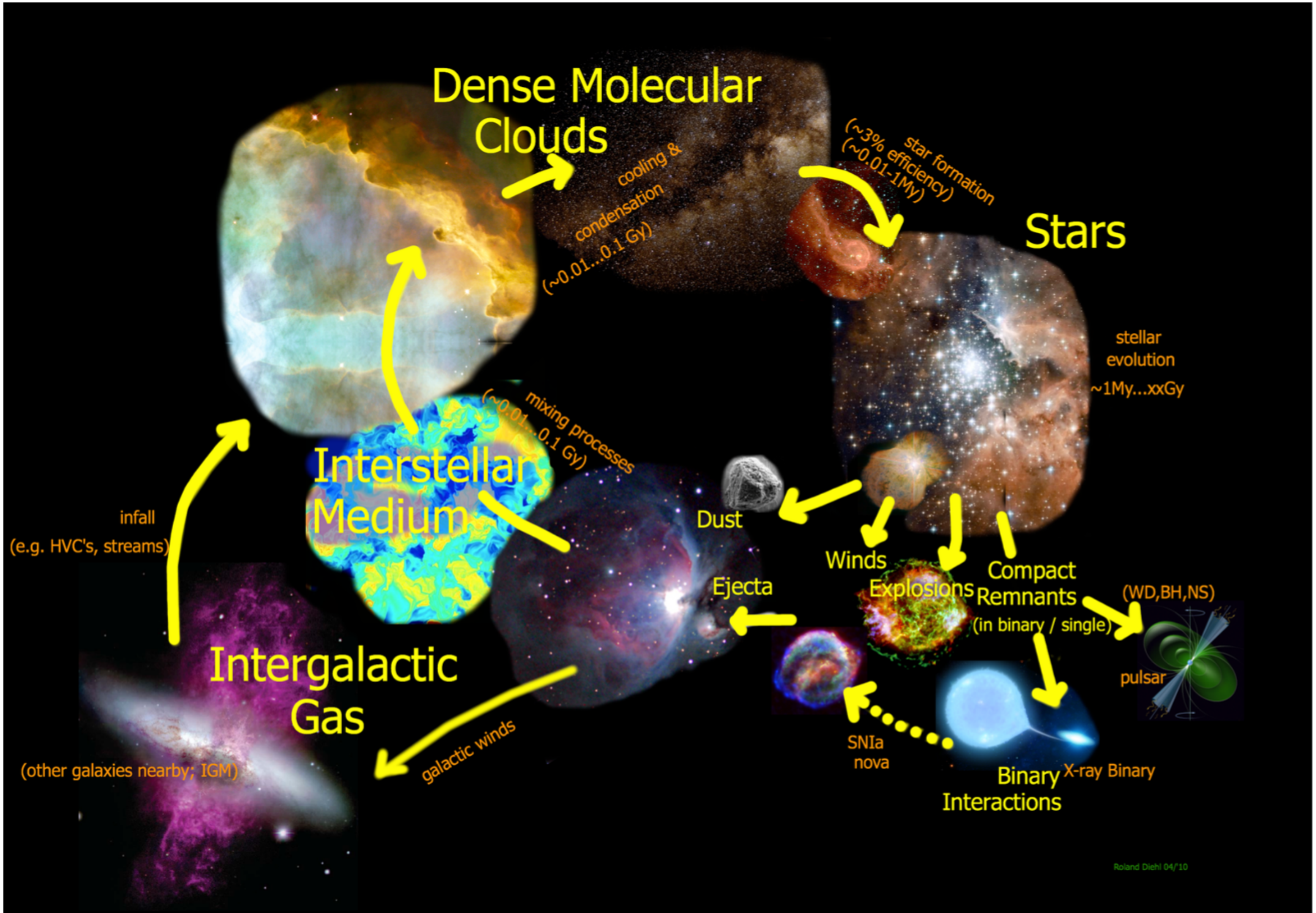
Long



Short



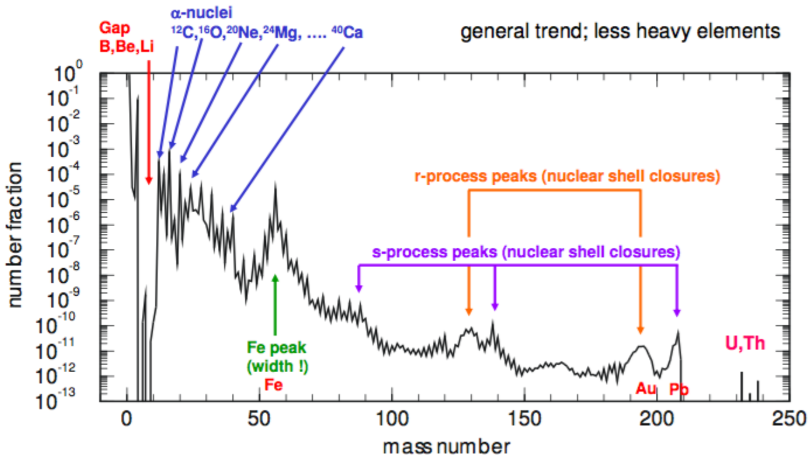
How Stars Shape Galaxies



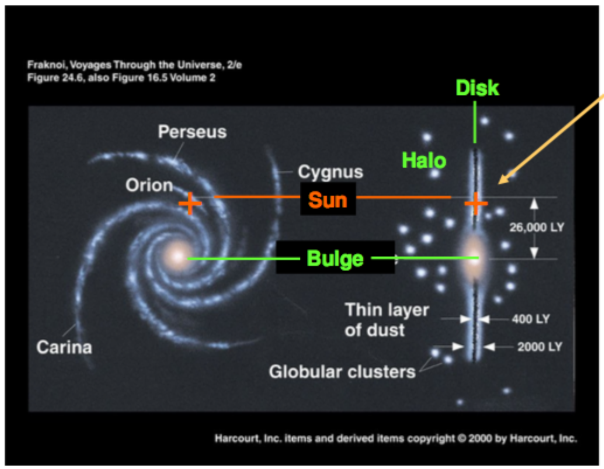
What is Nuclear Astrophysics?

- Nuclear astrophysics aims at understanding the nuclear processes that take place in the universe.
- These nuclear processes generate energy in stars and contribute to the nucleosynthesis of the elements and the evolution of the galaxy.

Hydrogen mass fraction	X = 0.71
Helium mass fraction	Y = 0.28
Metallicity (mass fraction of everything else)	Z = 0.019
Heavy Elements (beyond Nickel) mass fraction	4E-6



3. The solar abundance distribution

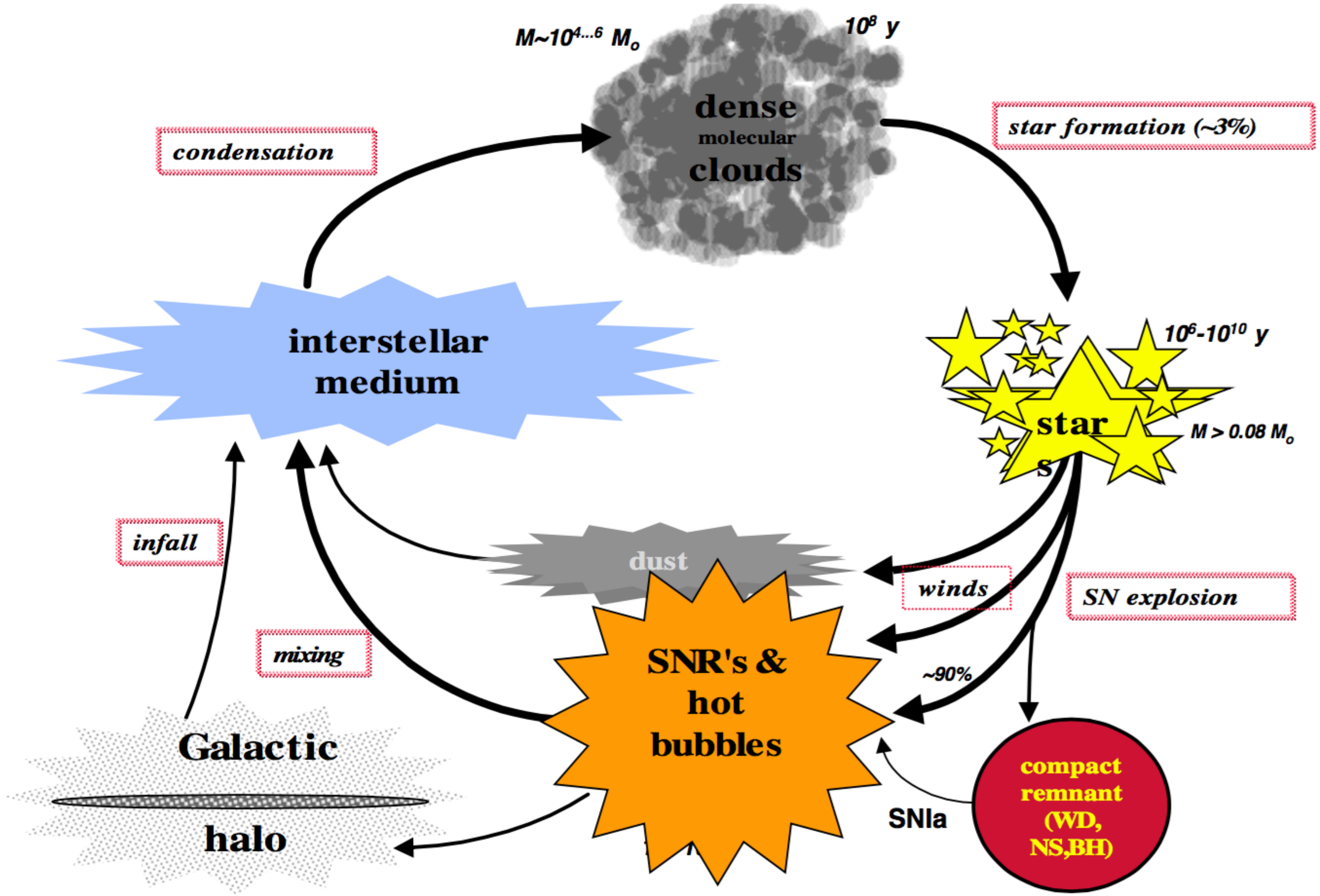


solar abundances:

Elemental (and isotopic) composition of Galaxy at location of solar system at the time of it's formation

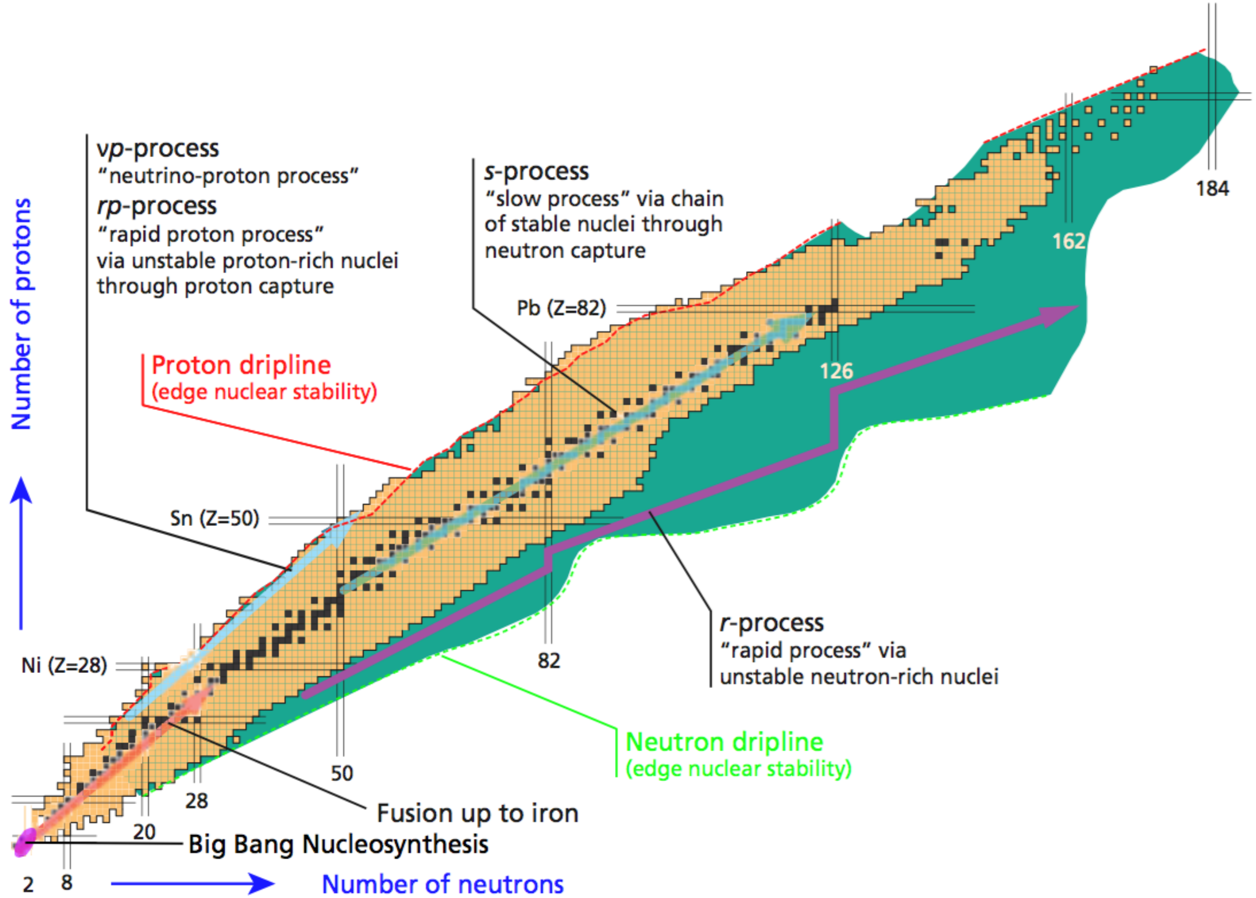
K. Lodders, Astrophys. J. **591**, 1220-1247 (2003)

Cosmic Cycle



Nucleosynthesis processes

In 1957 Burbidge, Burbidge, Fowler and Hoyle and independently Cameron, suggested several nucleosynthesis processes to explain the origin of the elements.



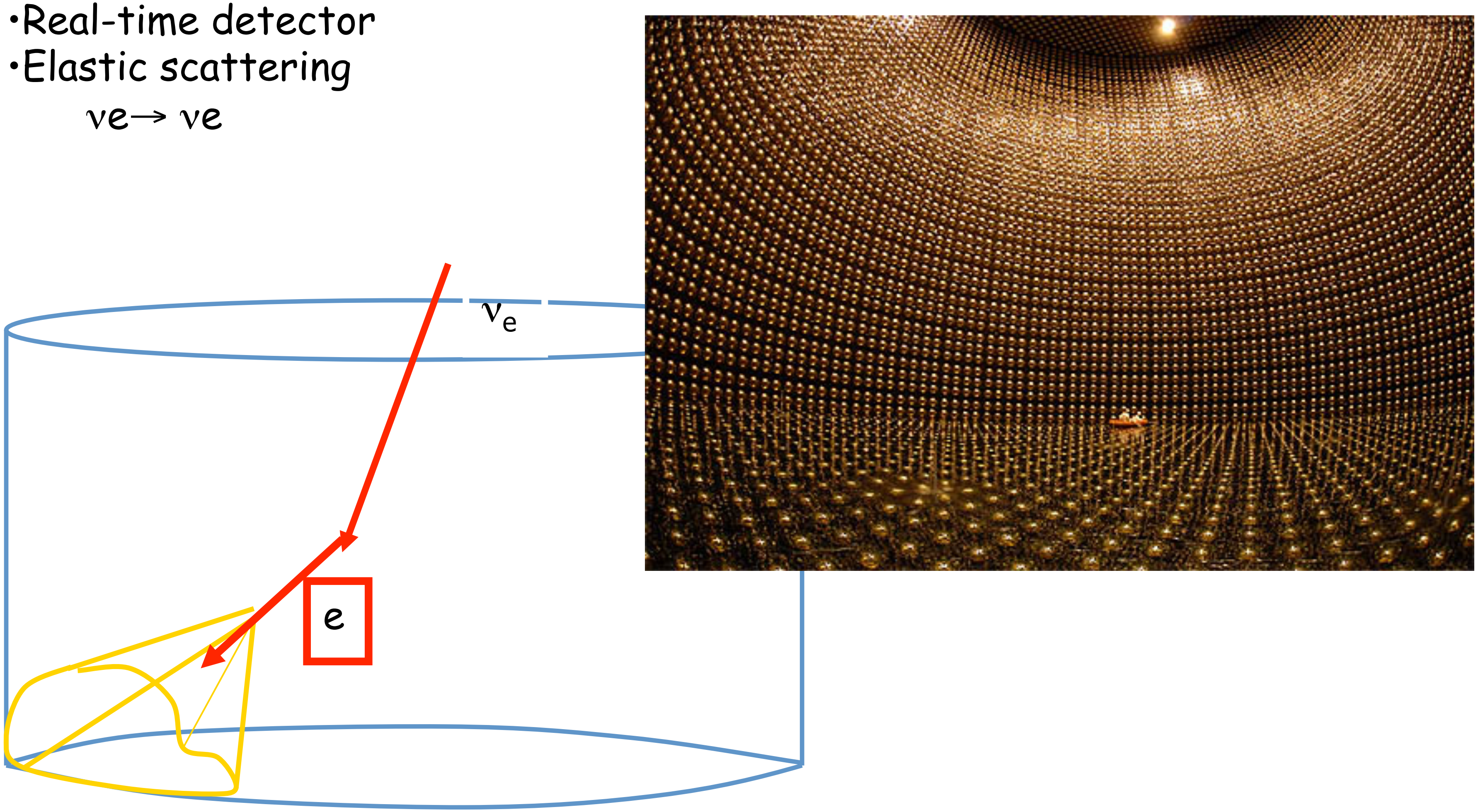
Astrofisica Nucleare e Subnucleare

Neutrino Detectors

The SK way- The elastic scattering of neutrinos on electrons

- Real-time detector
- Elastic scattering

  $\nu e \rightarrow \nu e$



Astrofisica Nucleare e Subnucleare

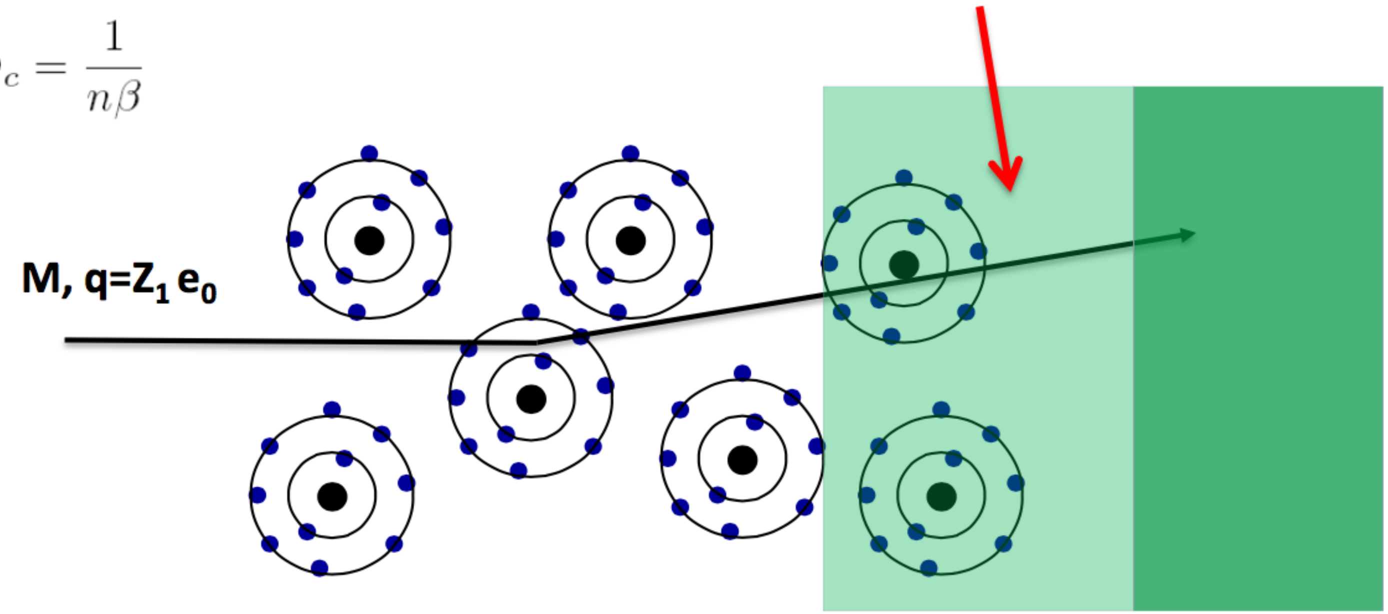
Cherenkov effect

Cherenkov Radiation

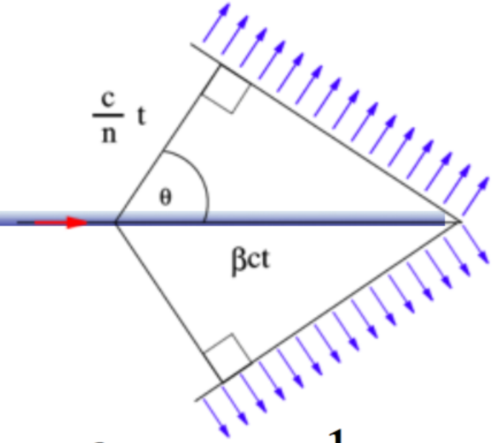
If we describe the passage of a charged particle through material of dielectric permittivity ε (using Maxwell's equations) the differential energy crossection is >0 if the velocity of the particle is larger than the velocity of light in the medium

N is the number of Cherenkov Photons emitted per cm of material. The expression is in addition proportional to Z_1^2 of the incoming particle.
The radiation is emitted at the characteristic angle Θ_c , that is related to the refractive index n and the particle velocity by

$$\cos\Theta_c = \frac{1}{n\beta}$$



Cherenkov radiation



Velocity of the particle: v
Velocity of light in a medium of refractive index n: c/n

Threshold condition for Cherenkov light emission: $v_{th} \geq \frac{c}{n} \Rightarrow \beta_{th} \geq \frac{1}{n}$

$$-\left\langle \frac{dE}{dx} \right\rangle_{Cherenkov} \propto z^2 \sin^2 \theta_c \qquad \cos\theta_c = \frac{1}{n\beta}$$

for water $\theta_c^{max} = 42°$
for neon at 1 atm $\theta_c^{max} = 11$mrad

Energy loss by Cherenkov radiation very small w.r.t. ionization (< 1%)

Typically O(1-2 keV / cm) or O(200-1000) visible photons / cm

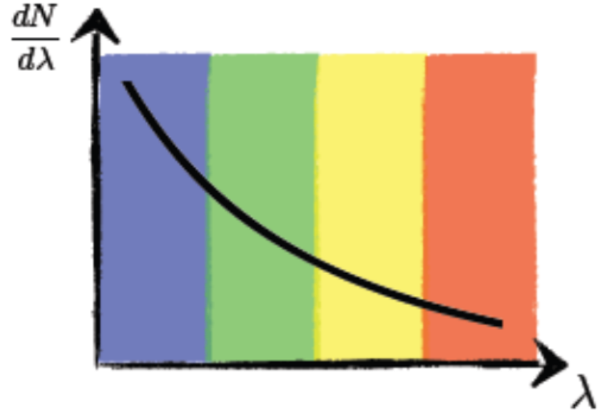
Visible photons:
E = 1 - 5 eV; λ = 300 - 600 nm

Cherenkov radiation

In a Cherenkov detector the produced photons are measured

Number of emitted photons per unit of length:

- wavelength dependence ~ $1/\lambda^2$



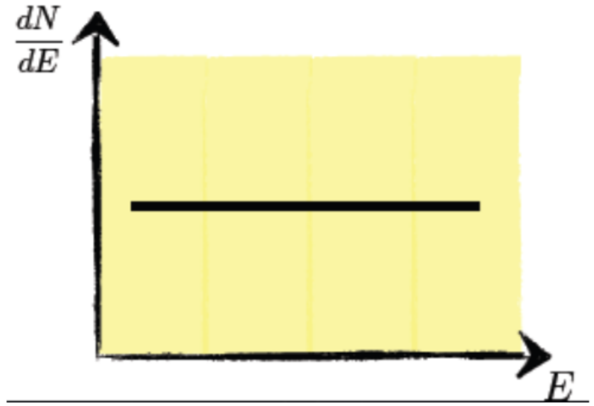
$$\frac{d^2N}{d\lambda dx} = \frac{2\pi\alpha z^2}{\lambda^2}\left(1 - \frac{1}{\beta^2 n^2(\lambda)}\right) = \frac{2\pi\alpha z^2}{\lambda^2}\sin^2\theta_C$$

Integrate over sensitivity range:
[for typical Photomultiplier]

$$\frac{dN}{dx} = \int_{350\text{ nm}}^{550\text{ nm}} d\lambda \frac{d^2N}{d\lambda dx}$$

$$= 475\, z^2 \sin^2\theta_C \text{ photons/cm}$$

- energy dependence ~ constant

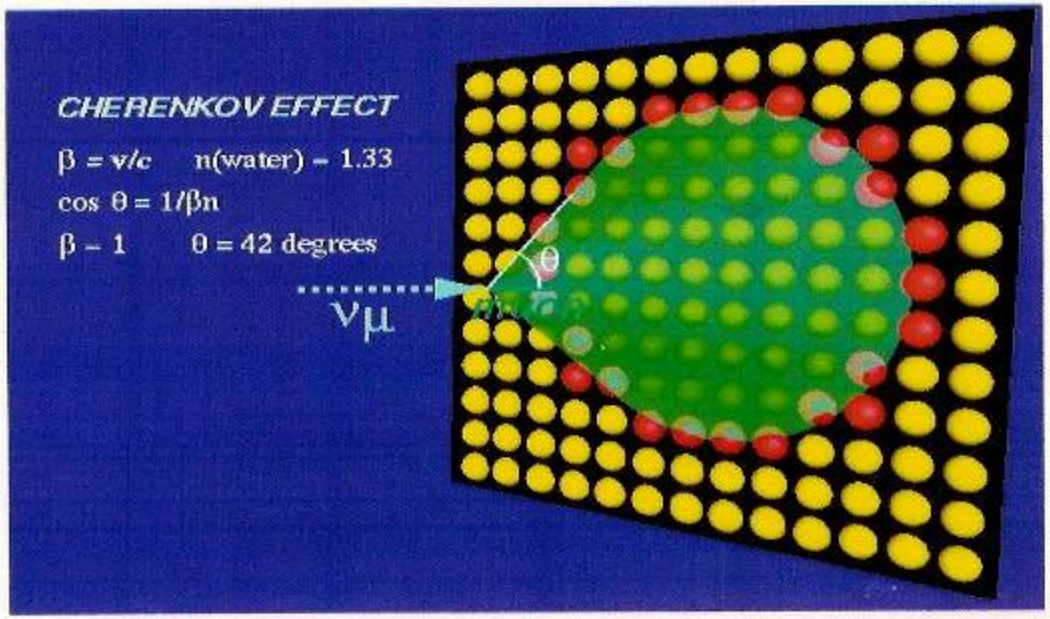


$$\frac{d^2N}{dE dx} = \frac{z^2\alpha}{\hbar c}\left(1 - \frac{1}{\beta^2 n^2(\lambda)}\right) = \frac{z^2\alpha}{\hbar c}\sin^2\theta_C$$

$$\approx \text{const}$$

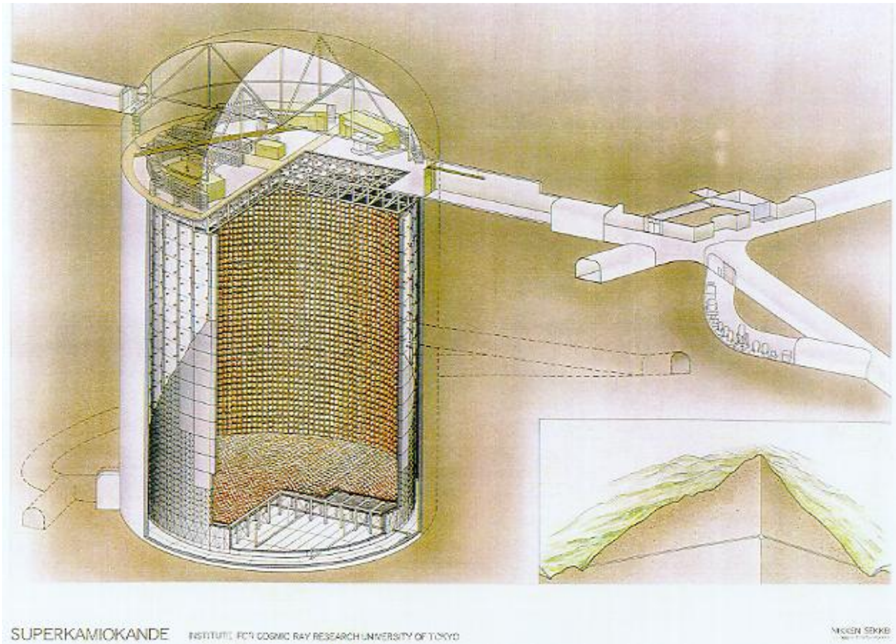
$$\frac{d^2N}{dE dx} = 370 \sin^2\theta_C \text{ eV}^{-1}\text{ cm}^{-1}$$

Cherenkov Radiation



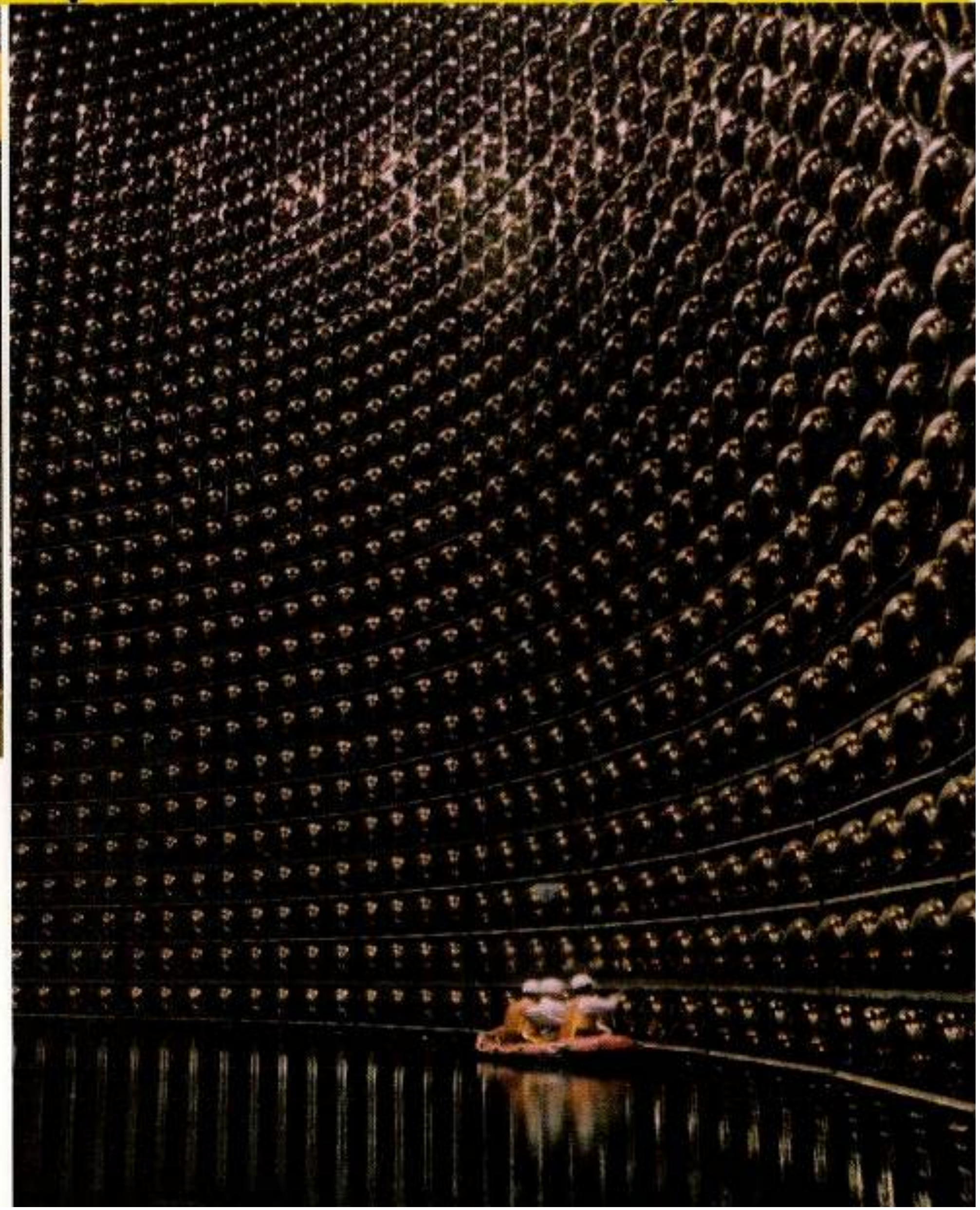
One of the 13000 PMT

Neutrino Scattering Experiments - SuperKamiokande



- **Size: Cylinder of 41.4m (Height) x 39.3m (Diameter)**
- **Weight: 50,000 tons of pure water**
- **Light Sensitivity: 11,200 photomultiplier tubes (50cm each in diameter -the biggest size in the world)**
- **Energy Resolution: 2.5% (at 1 GeV)**
  ~16% (at 10 MeV)
- **Energy Threshold 5 MeV**

2.2 First method to detect neutrinos: contained events and SuperKamiokande (Japan)



1000 m Deep Underground
50,000 ton of Ultra-Pure Water
11000 +2000 PMTs

Neutrino Scattering Experiments

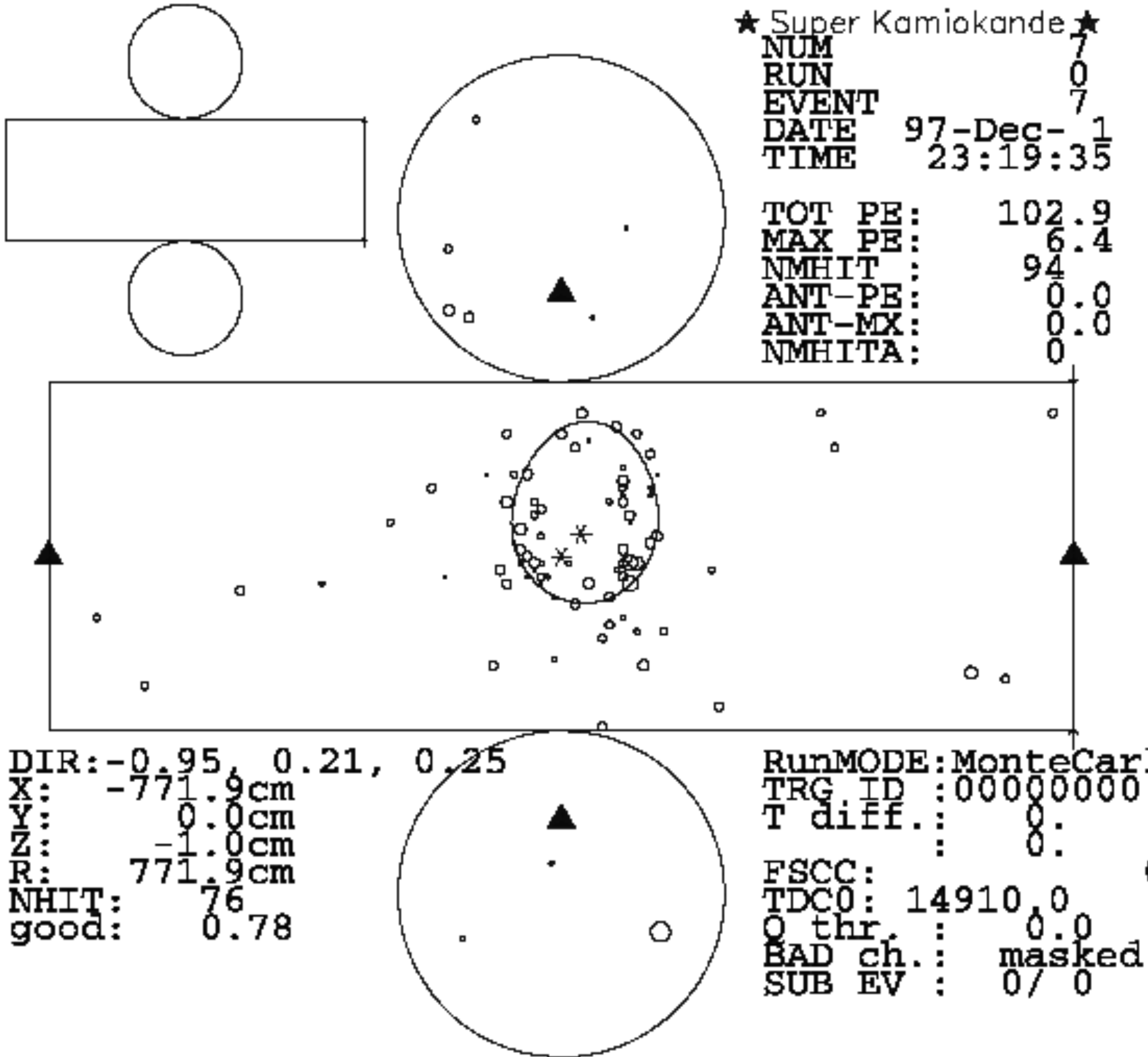
Particle	Cherenkov threshold in total Energy
$e^{\pm}$	0.768(MeV)
$\mu^{\pm}$	158.7
$\pi^{\pm}$	209.7

Cherenkov threshold energies of various particles.

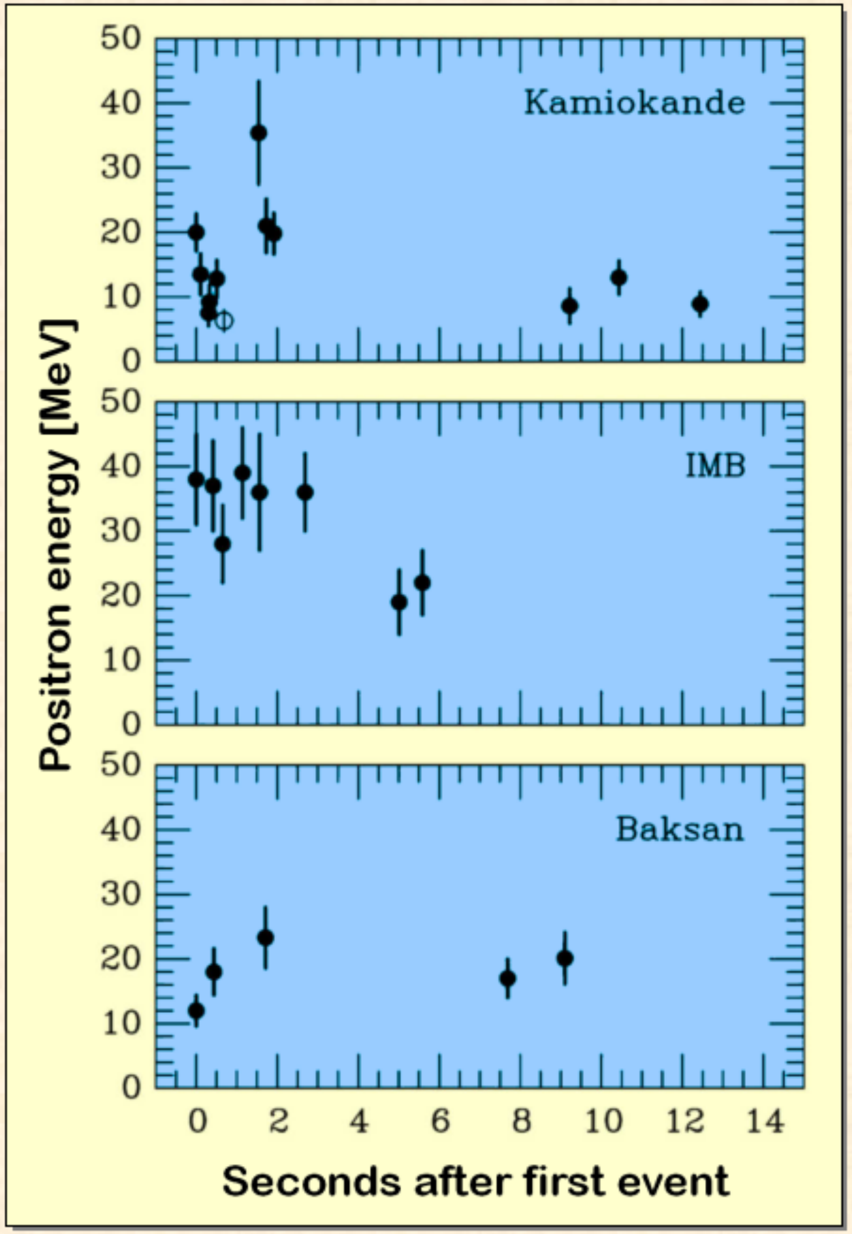
$$\cos\theta = \frac{1}{n\beta'}$$

Cherenkov light is emitted in a cone of half angle θ from the direction of the particle track

Neutrino Scattering Experiments



Neutrino Signal of Supernova 1987A



Kamiokande (Japan)
Water Cherenkov detector
Clock uncertainty ±1 min

Irvine-Michigan-Brookhaven (USA)
Water Cherenkov detector
Clock uncertainty ±50 ms

Baksan Scintillator Telescope (Soviet Union)
Clock uncertainty +2/-54 s

Within clock uncertainties, signals are contemporaneous

Astrofisica Nucleare e Subnucleare

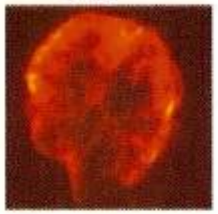
Supernovae Neutrinos

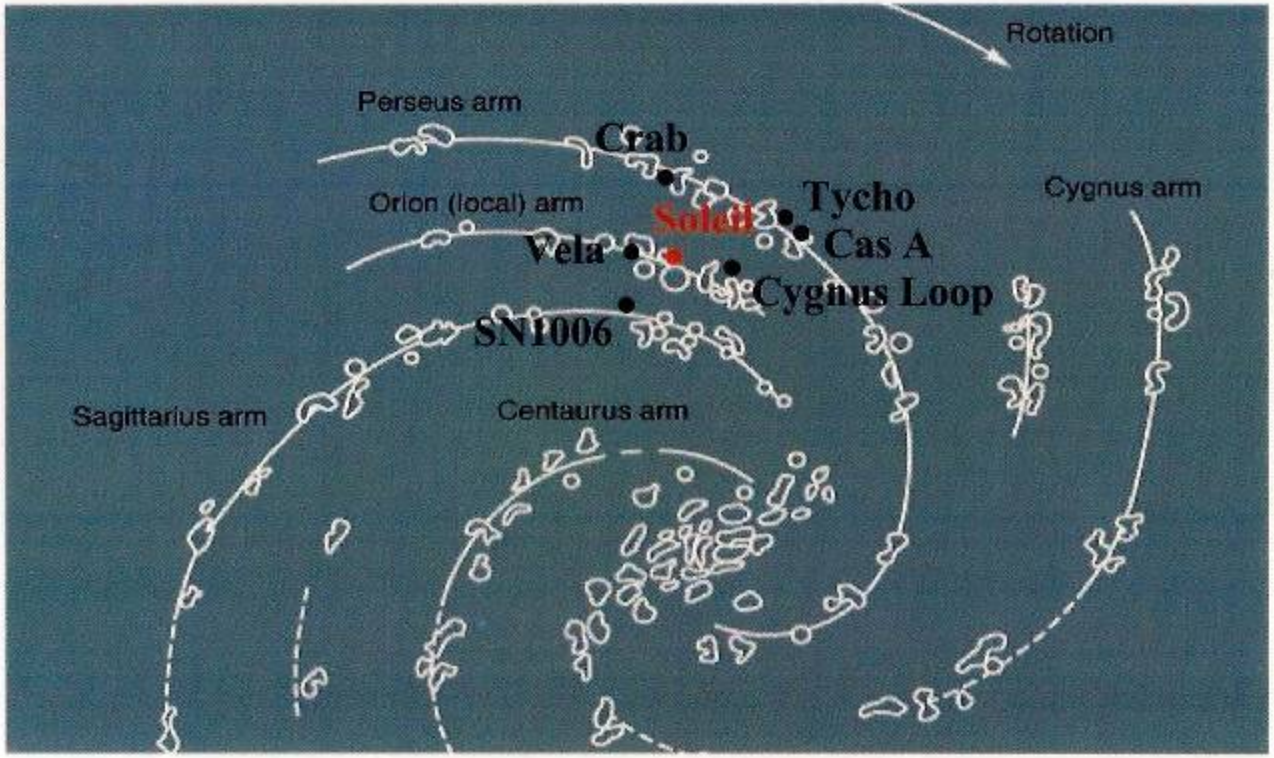
SuperNovae Remnants

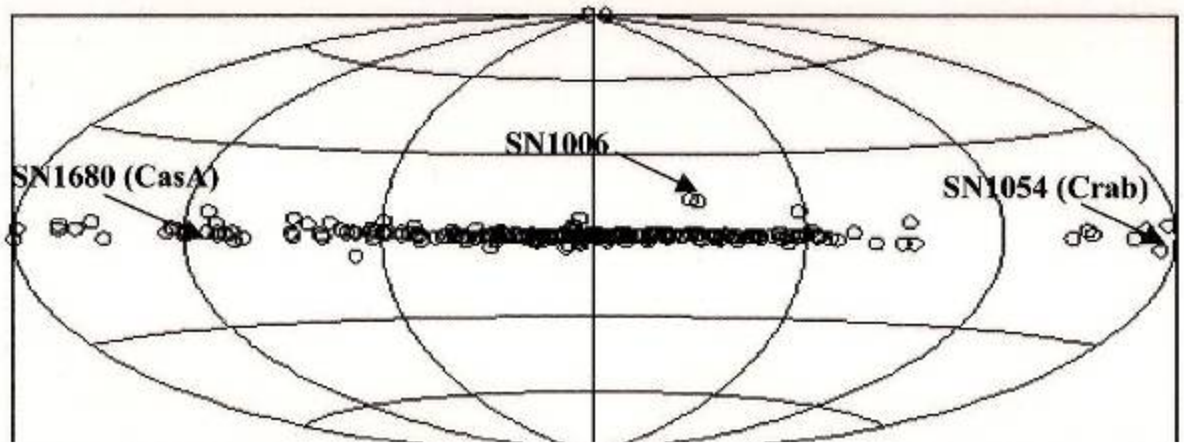
Vela

Tycho

Cygnus



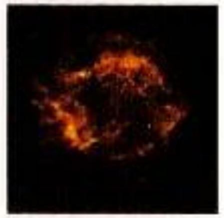




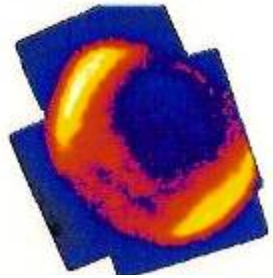
Crab

Kepler

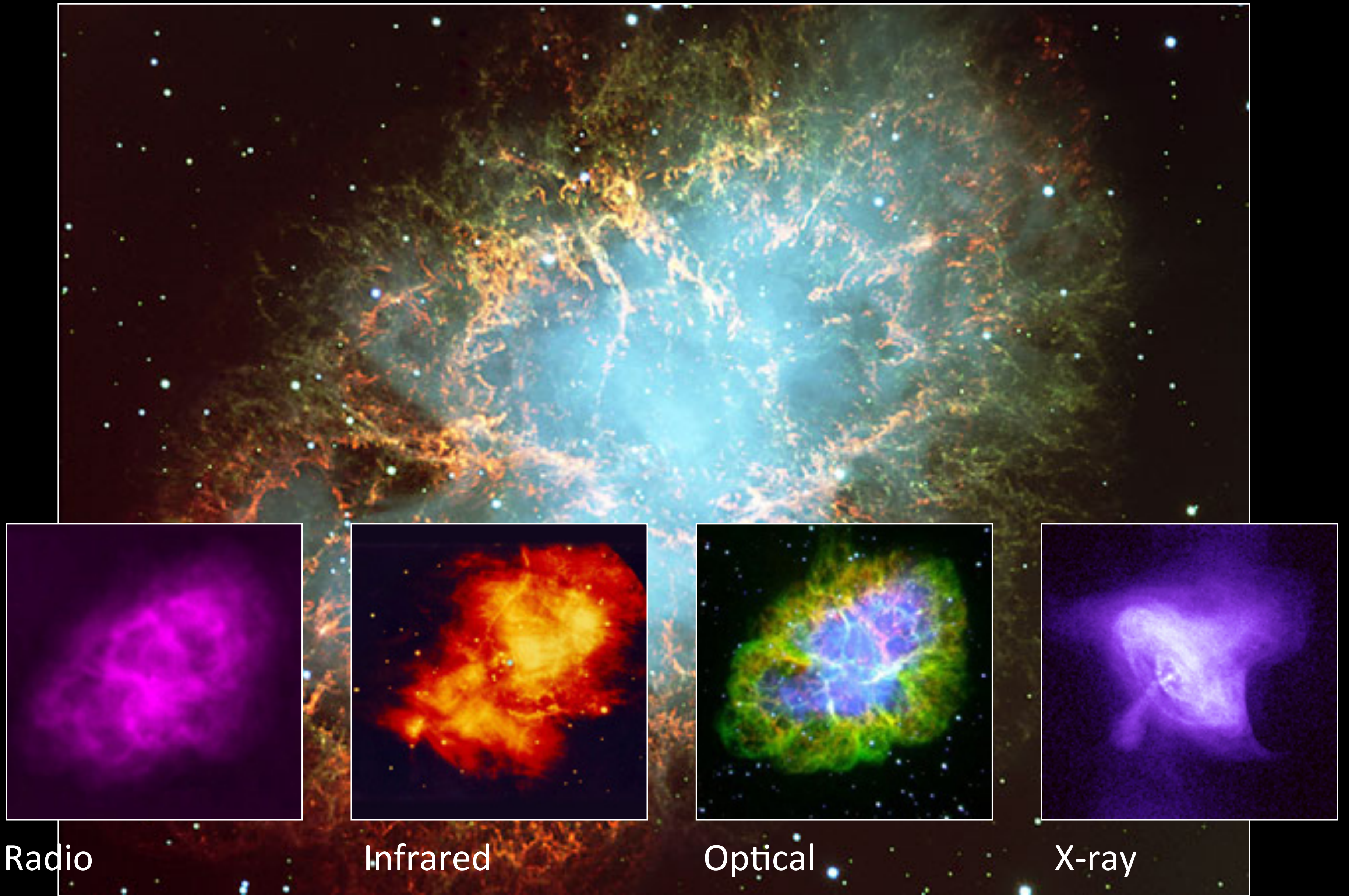
Cas A



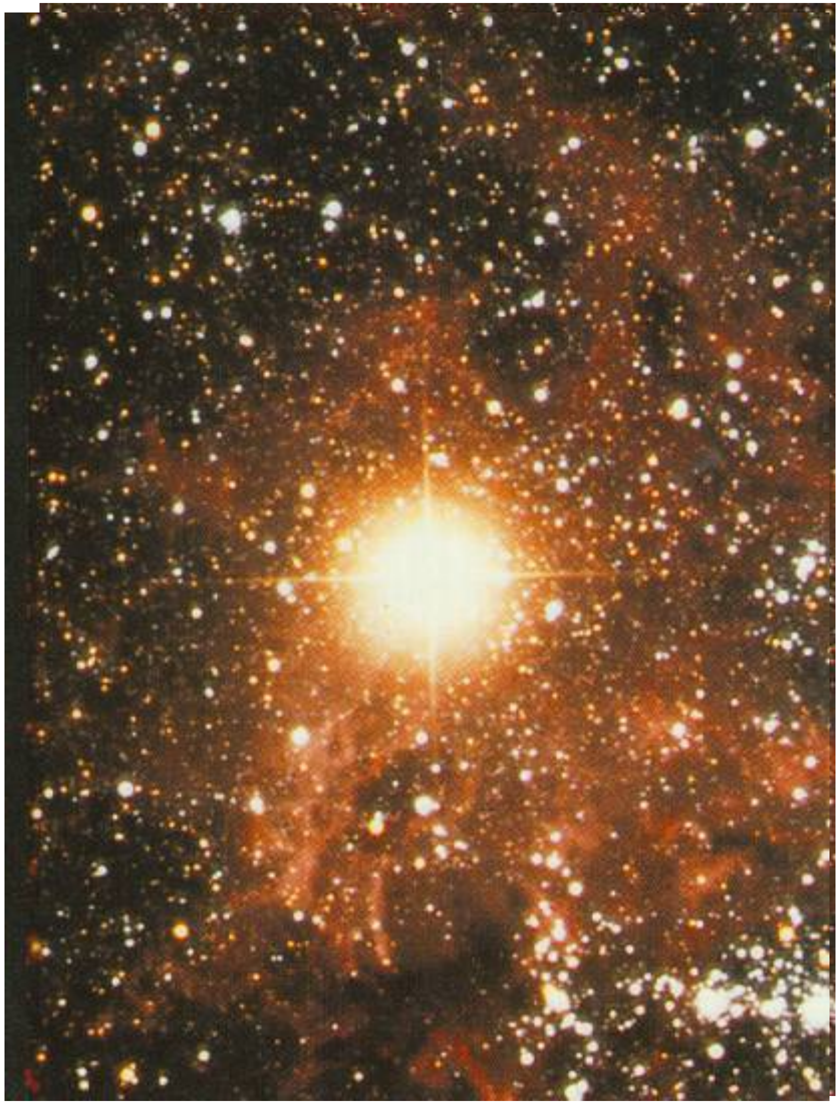
SN1006



The Crab in Multi-Wavelengths Photons



Supernovae



Anglo-Australian Telescope

The field of the supernova SN1987A after 23 February 1987.

This picture shows a small area of sky in the **Large Magellanic Cloud**, the nearby dwarf companion galaxy to our own Galaxy.

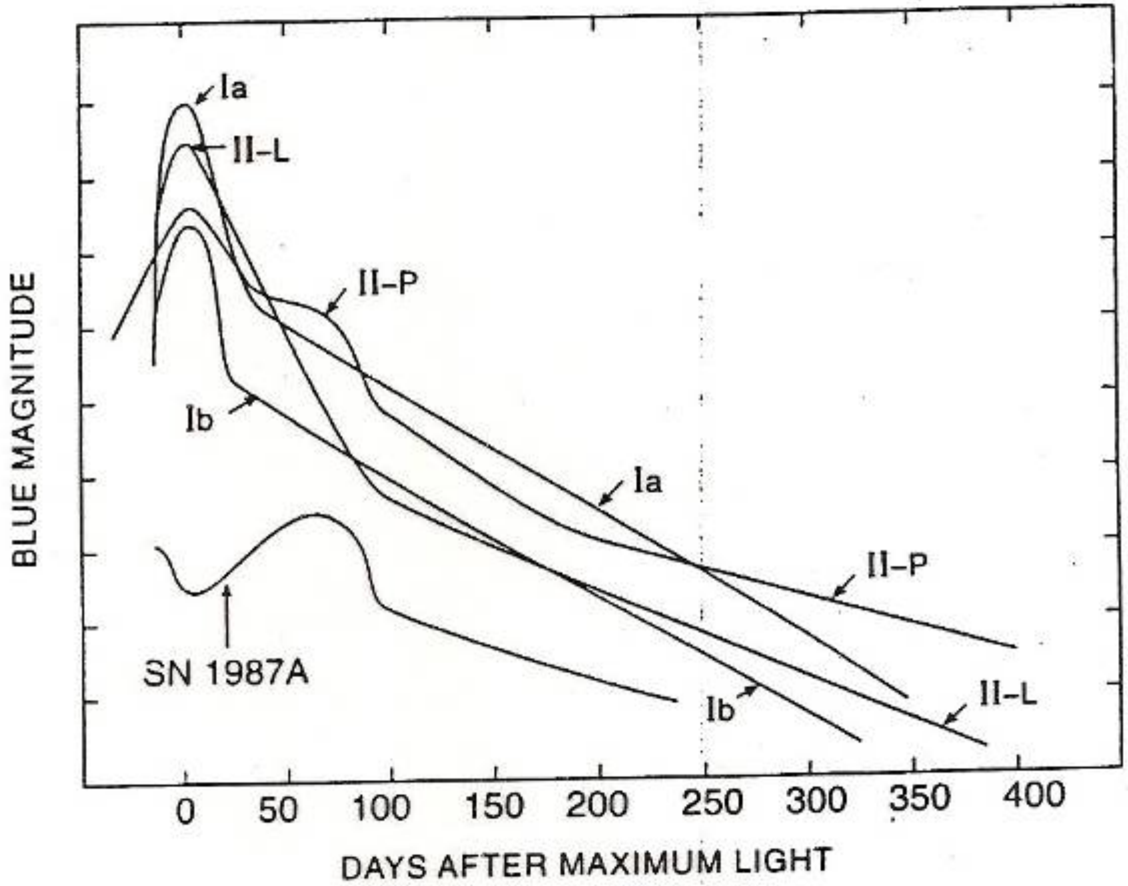
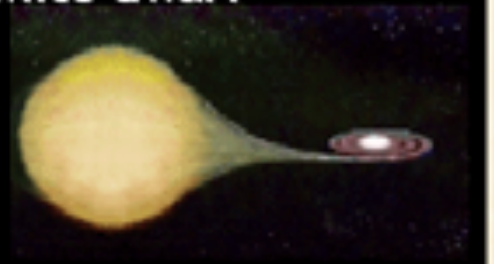
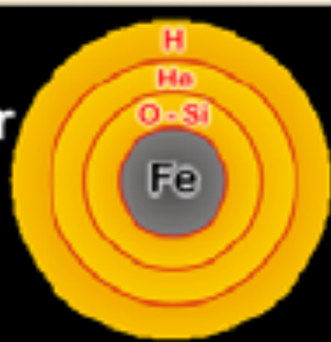


Figure 13.3. Brightness in the B-band for different supernova types. The deviation of supernova 1987a from the standard schemes can clearly be seen. Type II supernovae which have an almost linear decline after the maximum (II-L) are distinguished from those which remain almost constant over a longer time and display a form of plateau (II-P). SN 1987a appears from its characteristics to be a new form (from [Whe90]).

Type Ia vs. Core-Collapse Supernovae

Type Ia	Core collapse (Type II, Ib/c)
• Carbon-oxygen white dwarf (remnant of low-mass star) • Accretes matter from companion	• Degenerate iron core of evolved massive star • Accretes matter by nuclear burning at its surface





Chandrasekhar limit is reached – $M_{Ch} \approx 1.5\, M_{sun}\, (2Y_e)^2$

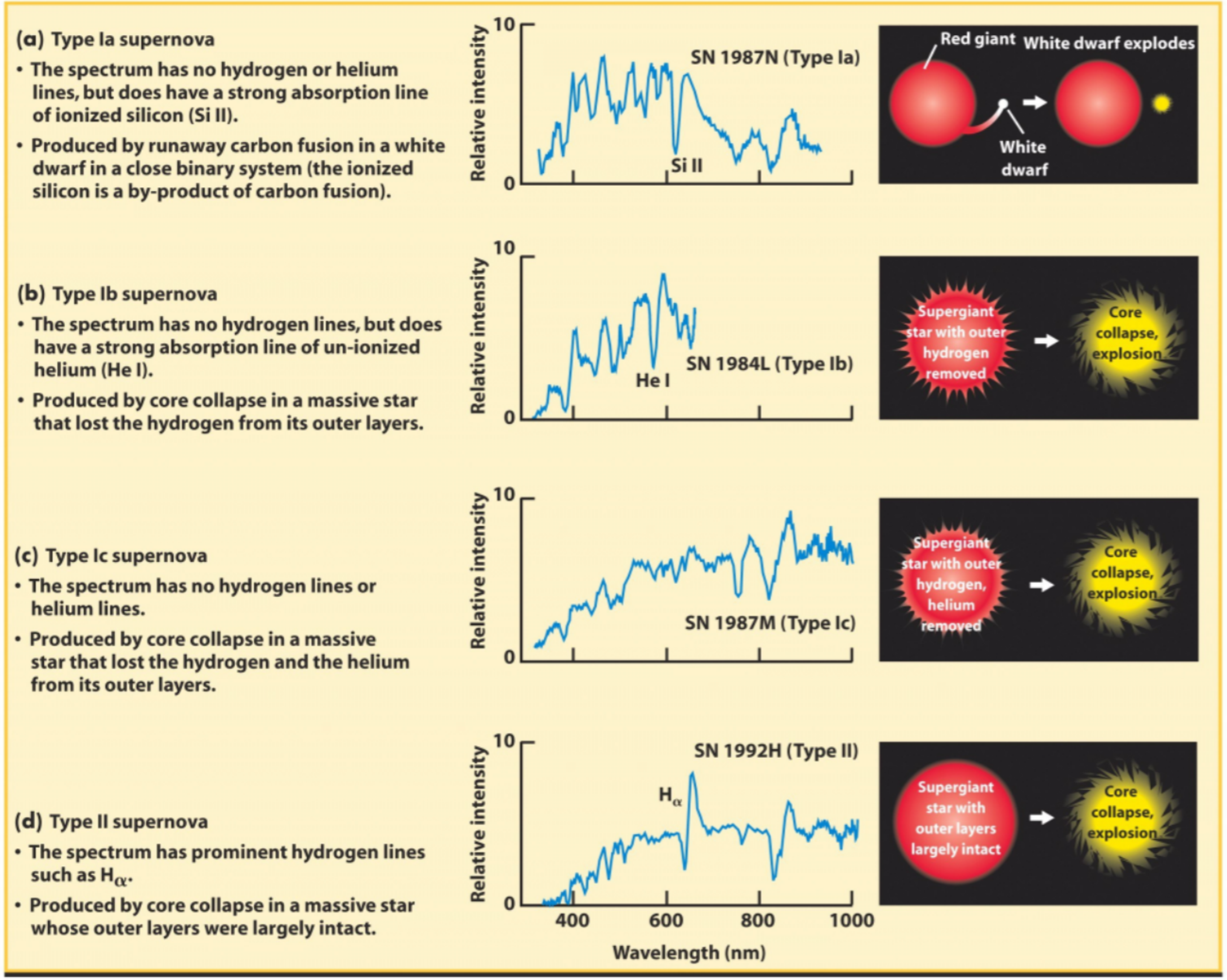
COLLAPSE SETS IN

Type Ia	Core collapse (Type II, Ib/c)
Nuclear burning of C and O ignites → Nuclear deflagration (“Fusion bomb” triggered by collapse)	Collapse to nuclear density Bounce & shock Implosion → Explosion
Powered by nuclear binding energy	Powered by gravity
Gain of nuclear binding energy ~ 1 MeV per nucleon	Gain of gravitational binding energy ~ 100 MeV per nucleon 99% into neutrinos

Classification of Supernovae

Spectral Type	Ia	Ib	Ic	II
Spectrum	No Hydrogen			Hydrogen
	Silicon	No Silicon		
		Helium	No Helium	
Physical Mechanism	Nuclear explosion of low-mass star	Core collapse of evolved massive star (may have lost its hydrogen or even helium envelope during red-giant evolution)		
Light Curve	Reproducible	Large variations		
Neutrinos	Insignificant	~ 100 × Visible energy		
Compact Remnant	None	Neutron star (typically appears as pulsar) Sometimes black hole ?		
Rate / h^2 SNu	0.36 ± 0.11	0.14 ± 0.07		0.71 ± 0.34
Observed	Total ~ 2000 as of today (nowadays ~200/year)			

Supernova types

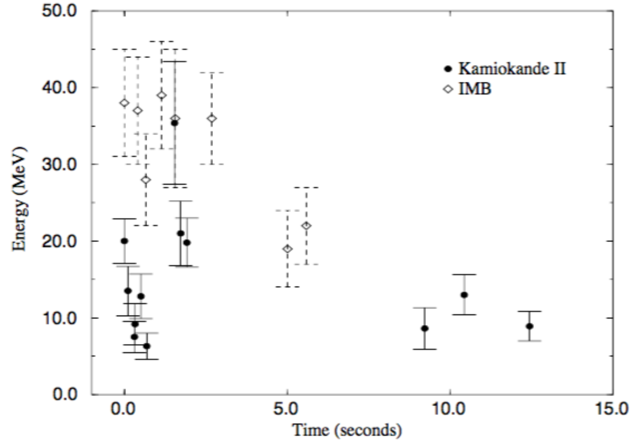


SN1987A

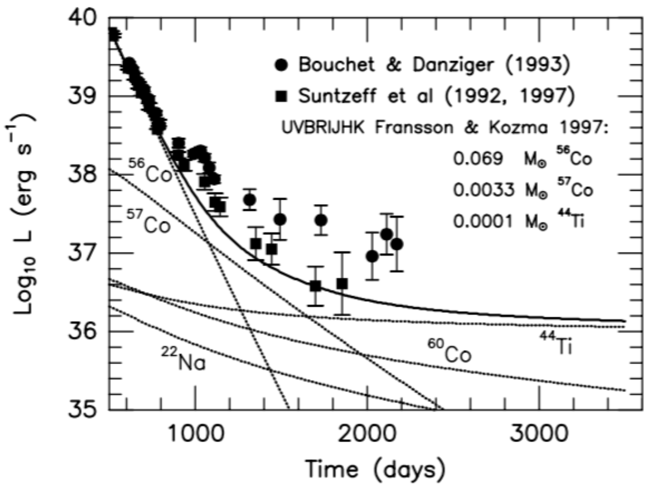
Type II supernova in LMC
(~ 55 kpc)

- $E_{\text{grav}} \approx 10^{53}$ erg
- $E_{\text{rad}} \approx 8 \times 10^{49}$ erg
- $E_{\text{kin}} \approx 10^{51}$ erg = 1 Bethe

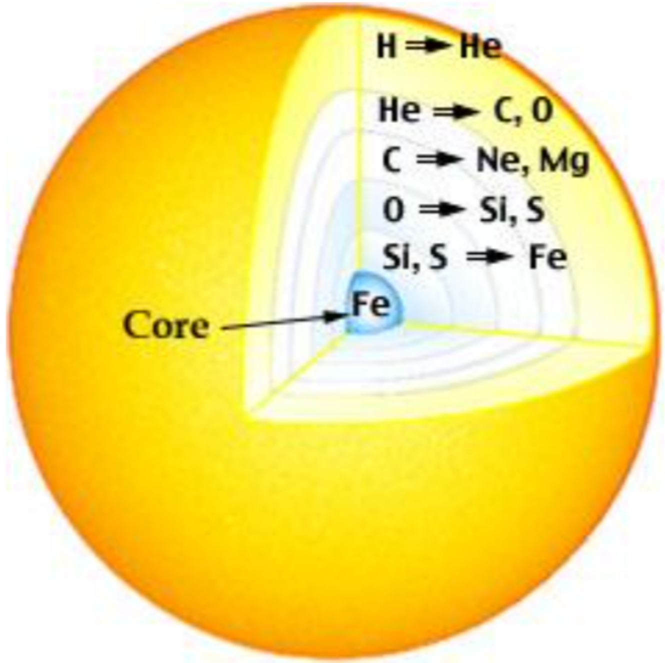
neutrinos $E_\nu \approx 2.7 \times 10^{53}$ erg



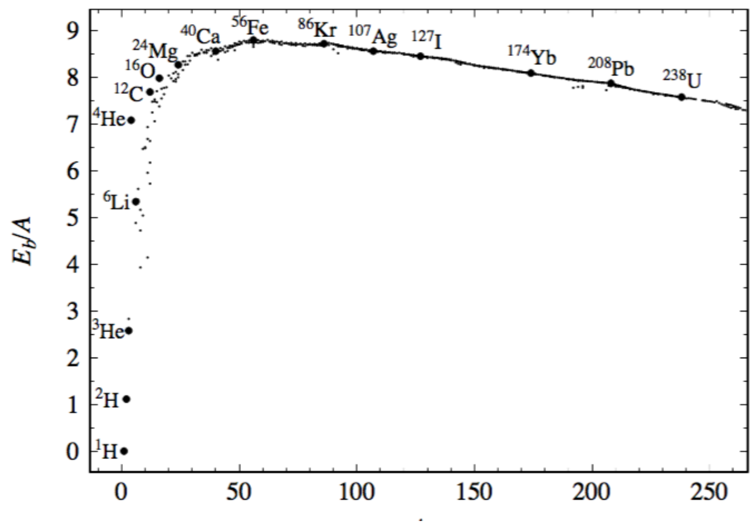
light curve



Presupernova Star

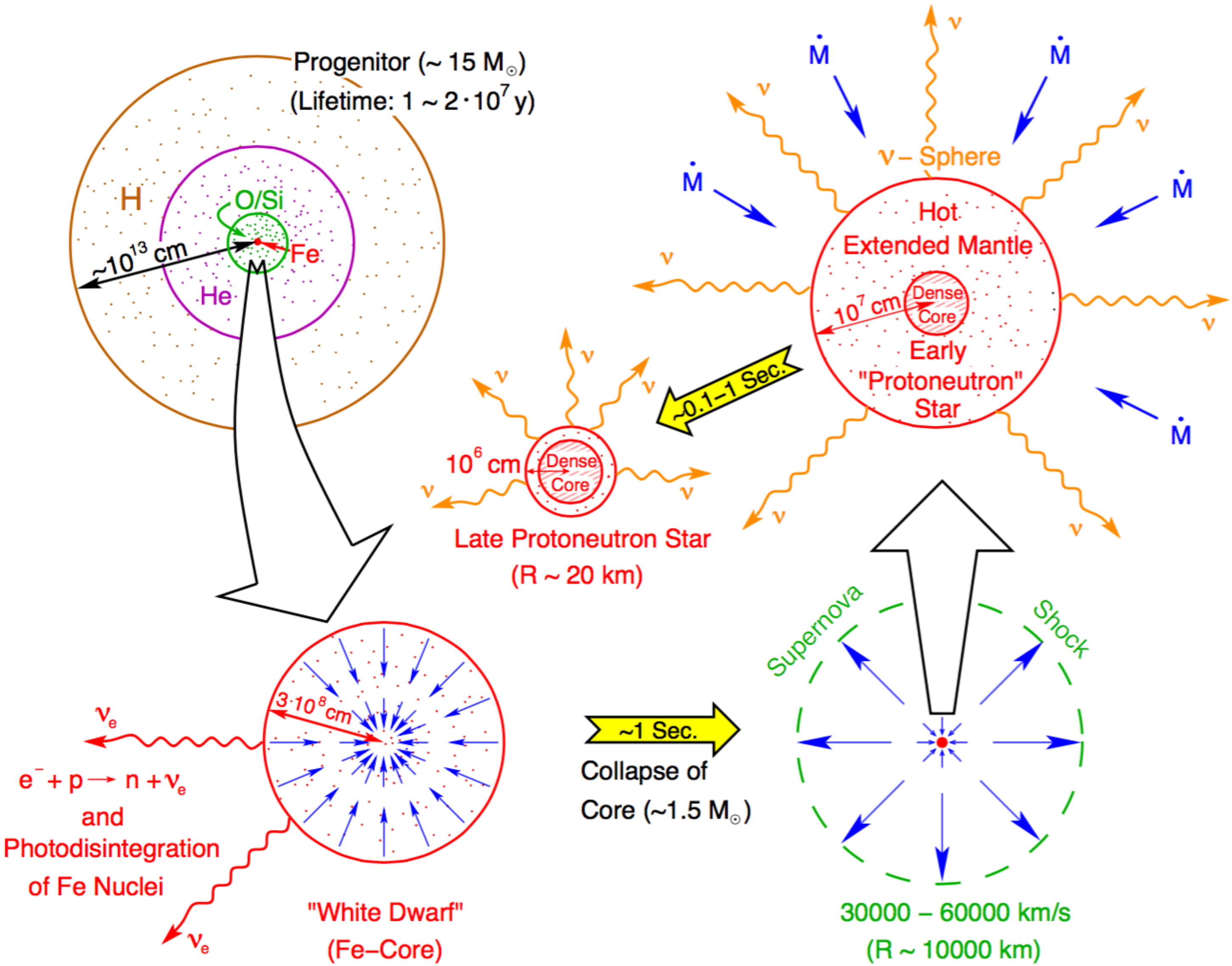


- Star has an onion like structure.
- Iron is the final product of the different burning processes.
- As the mass of the iron core grows it becomes unstable and collapses when it reaches around 1.4 $M_\odot$.

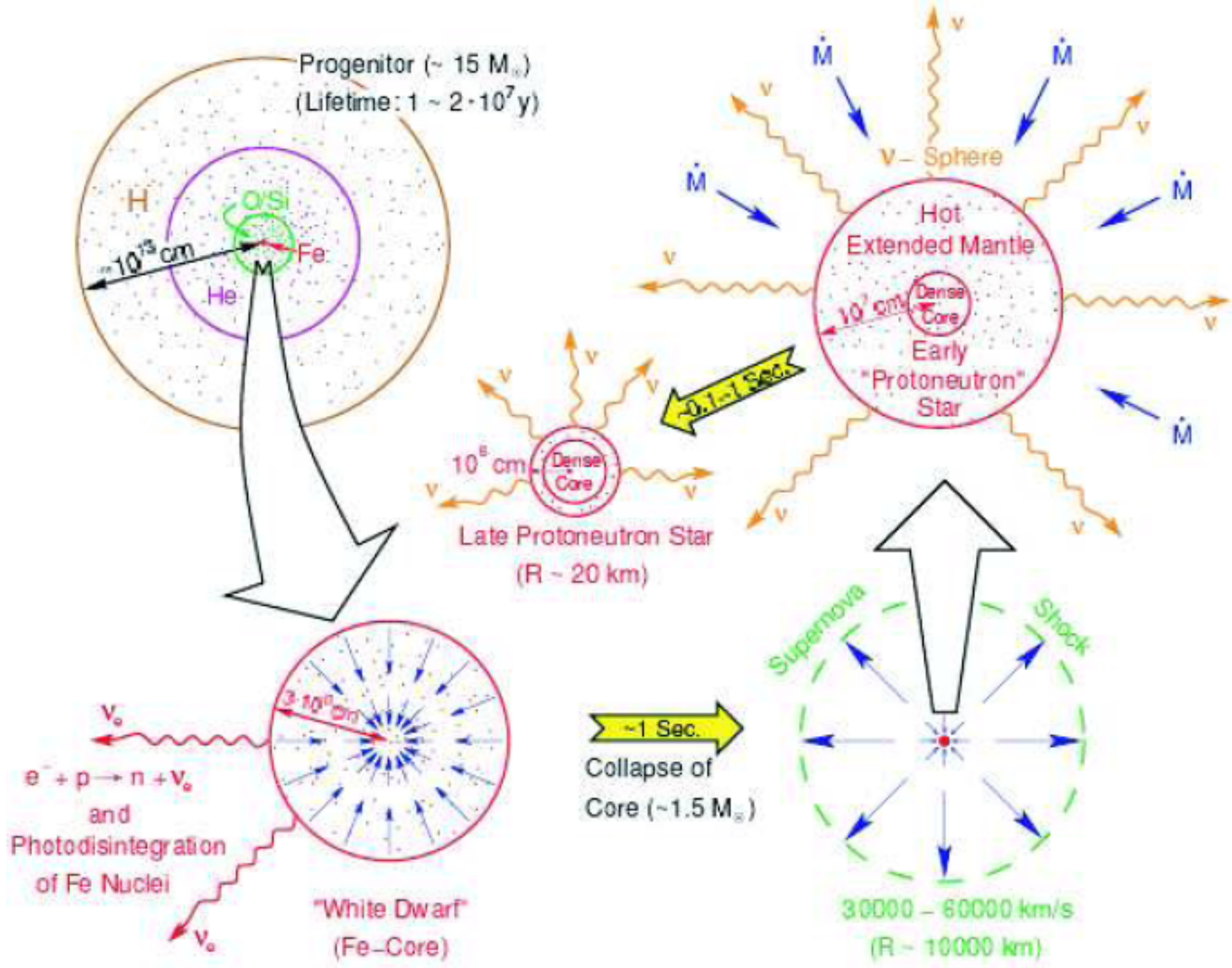


- Stars with masses above eight solar masses undergo ***gravitational collapse***.
- Once the core of the star becomes constituted primarily of iron, further compression of the core does not ignite nuclear fusion and the star is unable to thermodynamically support its outer envelope.
- As the surrounding matter falls inward under gravity, the temperature of the core rises and iron dissociates into α particles and nucleons.
- Electron capture on protons becomes heavily favored and electron neutrinos are produced as the core gets neutronized (a process known as ***neutronization***).
- When the core reaches densities above 10^{12} g/cm^3, neutrinos become trapped (in the so-called neutrinosphere).
- The collapse continues until 3 − 4 times nuclear density is reached, after which the inner core rebounds, sending a shock-wave across the outer core and into the mantle.
- This shock-wave loses energy as it heats the matter it traverses and incites further electron-capture on the free protons left in the wake of the shock.
- During the few milliseconds in which the shock-wave travels from the inner core to the neutrinosphere, electron neutrinos are released in a pulse. This neutronization burst carries away approximately **10^{51} ergs of energy**.

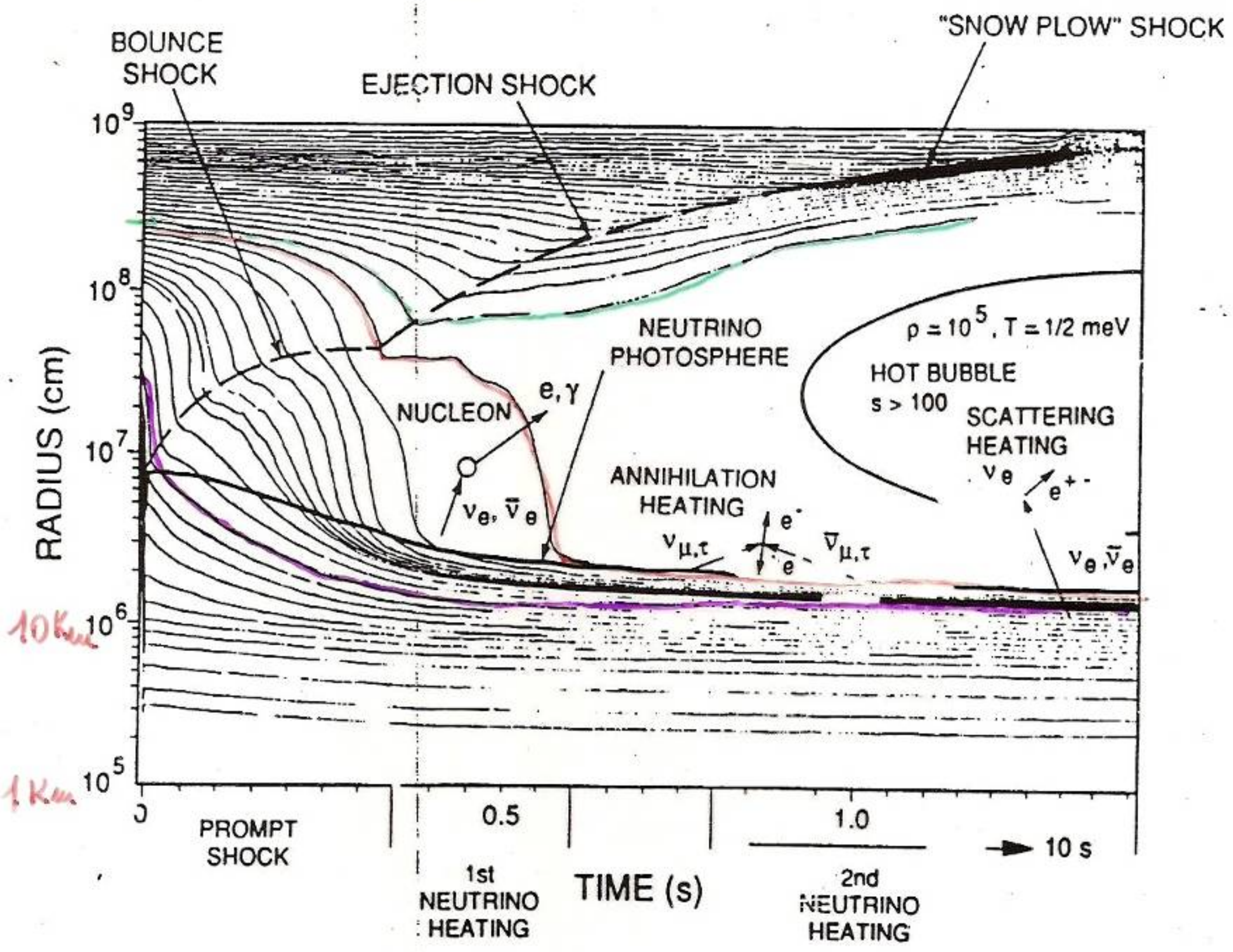
Schematical Evolution



- 99% of the binding energy E_b, of the protoneutron star is released in the following ~ 10 seconds primarily via β-decay (providing a source of electron antineutrinos), ν_e, anti-ν_e and e+e− annihilation and nucleon bremsstrahlung (sources for all flavors of neutrinos including ν_μ, anti-ν_μ, ν_t and anti-ν_t), in addition to electron capture.



Schematic illustration of a SN explosion. The dense Fe core collapses in a fraction of a second and gets neutronized (lower-left). The inner core rebounds and gives rise to a shock-wave (lower-right). The protoneutron star cools by the emission of neutrinos.


"SNOW PLOW" SHOCK
BOUNCE SHOCK
EJECTION SHOCK
10^9
10^8
10^7
10^6
10^5
10 Km
1 Km
RADIUS (cm)
NEUTRINO PHOTOSPHERE
ρ = 10^5, T = 1/2 meV
HOT BUBBLE
s > 100
NUCLEON
e, γ
SCATTERING HEATING
ν_e
e^+-
ANNIHILATION HEATING
ν_e, ν̄_e
e^-
ν_μ,τ
ν̄_μ,τ
e
ν_e, ν̄_e
0
0.5
1.0
10 s
PROMPT SHOCK
1st NEUTRINO HEATING
TIME (s)
2nd NEUTRINO HEATING

Onset of collapse

There are two processes that make the situation unstable:

1. Silicon burning is continuing in a shell around the iron core. This adds mass to the iron core increasing M_c.
2. Electrons can be captured by protons (free or in nuclei):

$$e^- + A(Z,N) \rightarrow A(Z-1,N+1) + \nu_e.$$

This reduces the pressure and keep the core cold, as the neutrinos leave. The net effect is a reduction of Y_e and consequently of the Chandrasekhar mass (M_{ch})

Initial conditions

The dominant contribution to the pressure comes from the electrons. They are degenerate and relativistic:

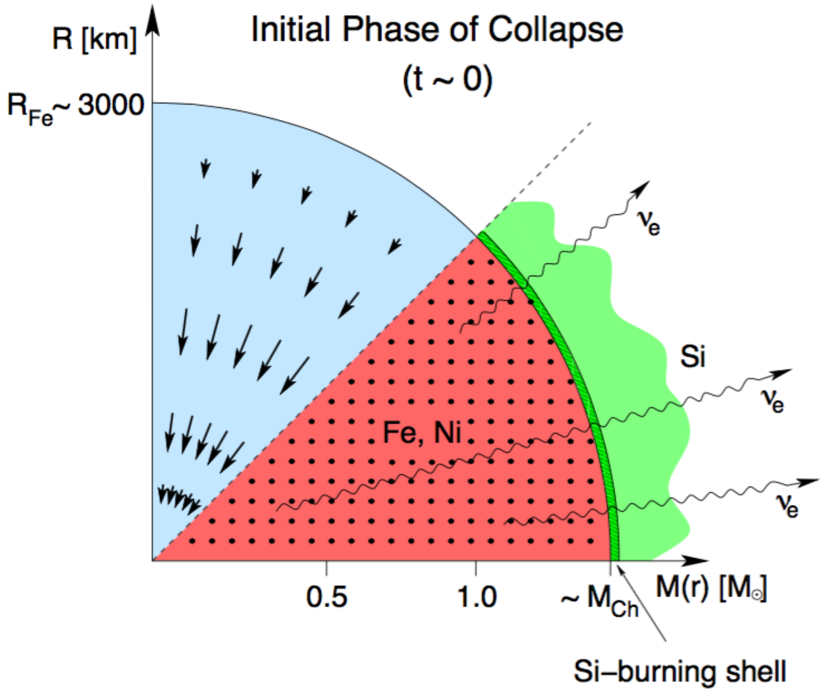
$$P \approx n_e \mu_e = n_e \varepsilon_F$$

μ_e is the chemical potential, fermi energy, of the electrons:

$$\mu_e \approx 1.11(\rho_7 Y_e)^{1/3}\ \mathrm{MeV}, \quad \frac{\rho Y_e}{m_u} = n_e$$

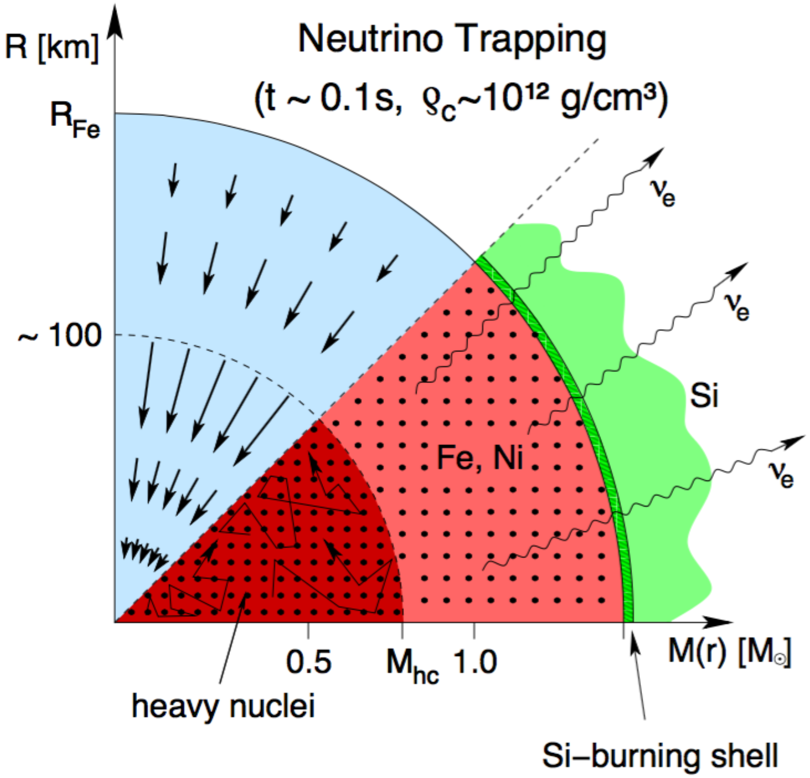
For $\rho_7 = 1$ ($\rho = 10^7$ g cm^{-3}) the chemical potential is 1 MeV, reaching the nuclear energy scale. At this point is energetically favorable to capture electrons by nuclei.

Presupernova evolution



- $T = 0.1–0.8$ MeV, $\rho = 10^7–10^{10}$ g cm^{-3}. Composition of iron group nuclei.
- Important processes:
  - electron capture: $e^- + (N,Z) \to (N+1, Z-1) + \nu_e$
  - β^- decay: $(N,Z) \to (N-1, Z+1) + e^- + \bar{\nu}_e$
- Dominated by allowed transitions (Fermi and Gamow-Teller)
- Evolution decreases number of electrons (Y_e) and Chandrasekar mass ($M_{ch} \approx 1.4(2Y_e)^2 M_\odot$)

Collapse phase



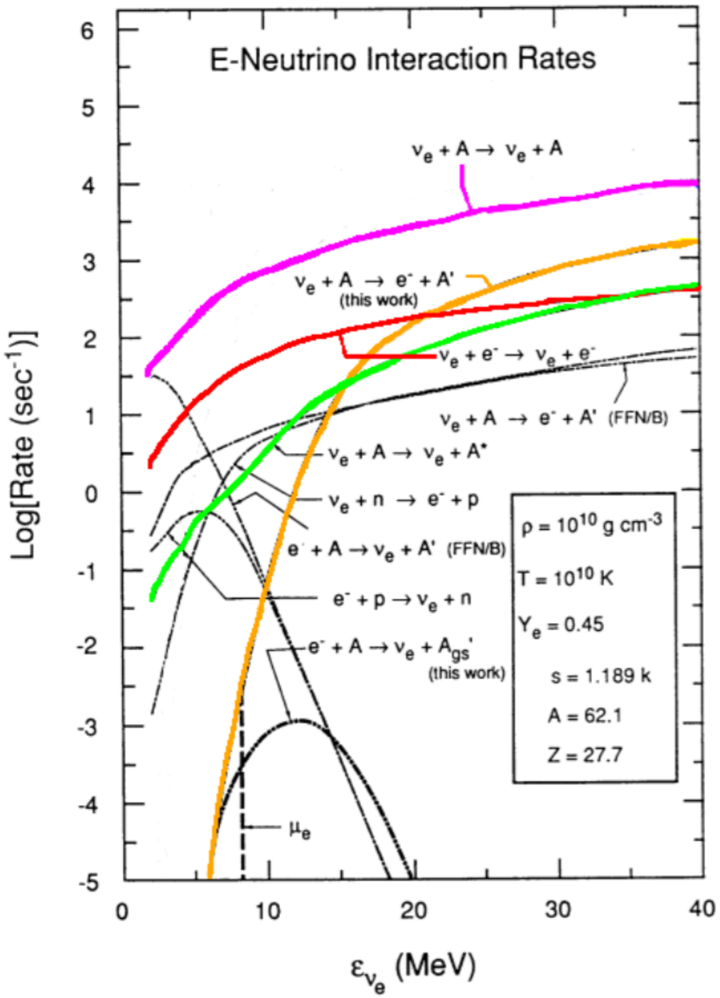
Important processes:

- Neutrino transport (Boltzmann equation):
  $\nu + A \rightleftarrows \nu + A$ (trapping)
  $\nu + e^- \rightleftarrows \nu + e^-$ (thermalization)

  cross sections $\sim E_\nu^2$
- electron capture on protons:
  $e^- + p \rightleftarrows n + \nu_e$
- electron capture on nuclei:
  $e^- + A(Z, N) \rightleftarrows A(Z-1, N+1) + \nu_e$

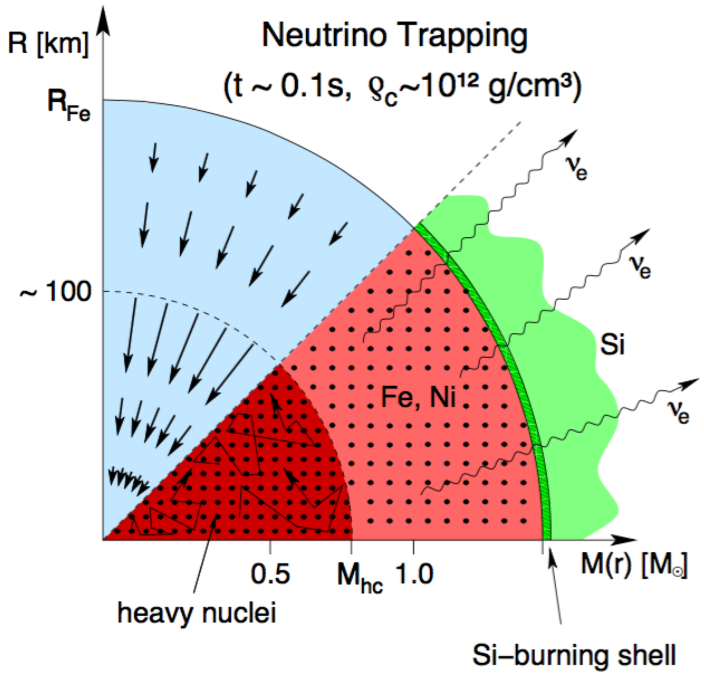
Neutrino interactions in the collapse

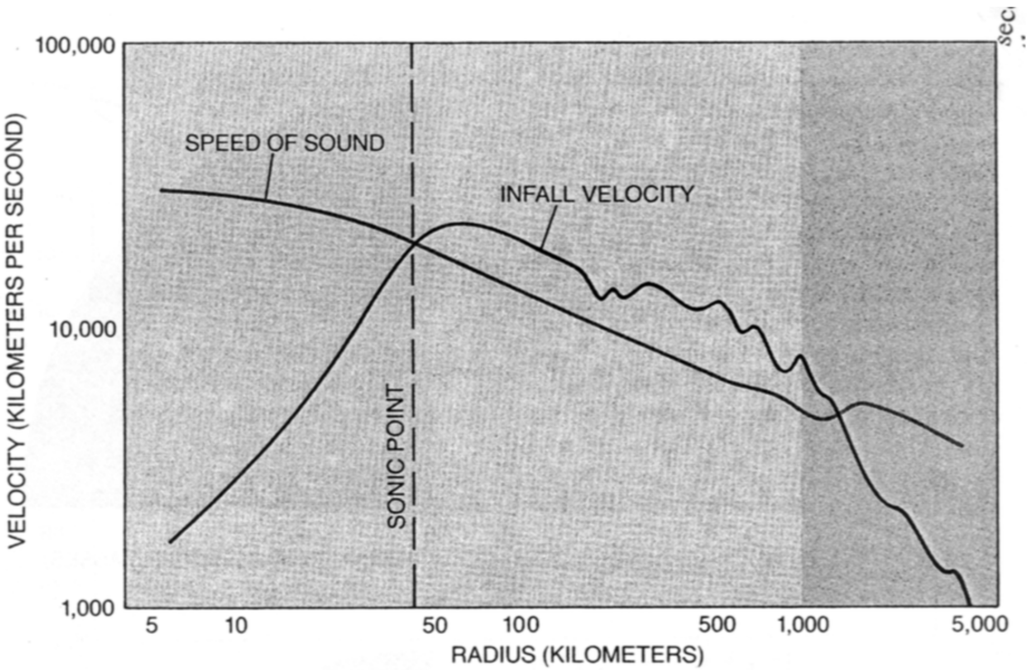
Bruenn and Haxton (1991)
Based on results for ^{56}Fe



- Elastic scattering:
  $\nu + A \rightleftarrows \nu + A$ (trapping)
- Absorption:
  $\nu_e + (N,Z) \rightleftarrows e^- + (N-1, Z+1)$
- ν-e scattering:
  $\nu + e^- \rightleftarrows \nu + e^-$ (thermalization)
- Inelastic ν-nuclei scattering:
  $\nu + A \rightleftarrows \nu + A^*$

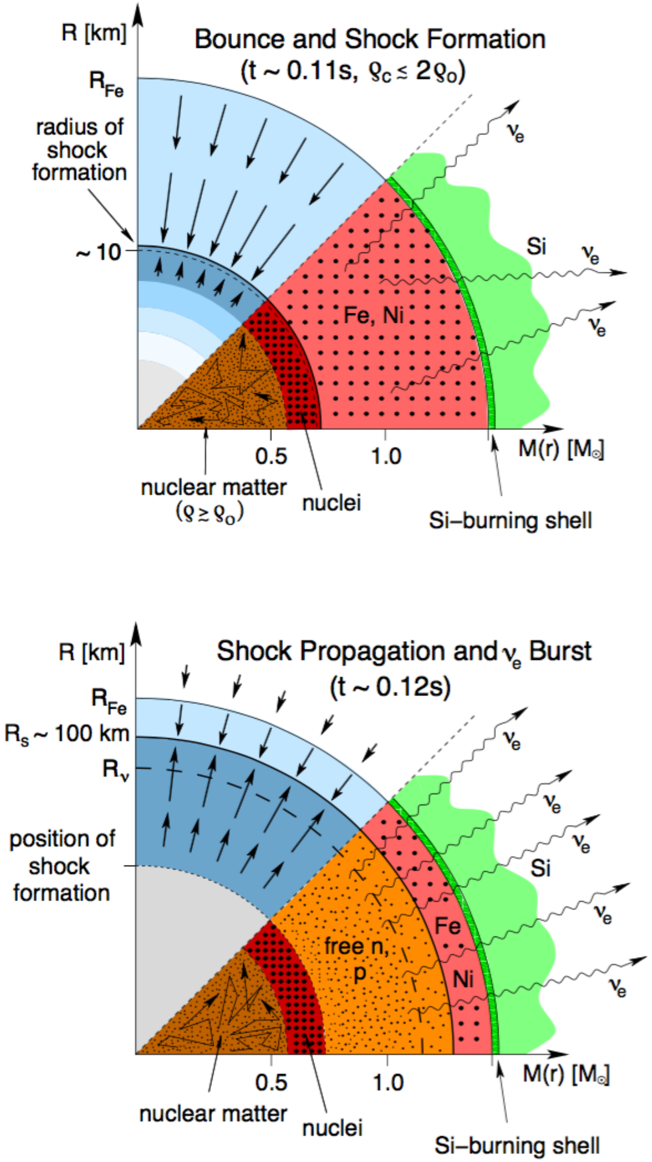
Homologous collapse





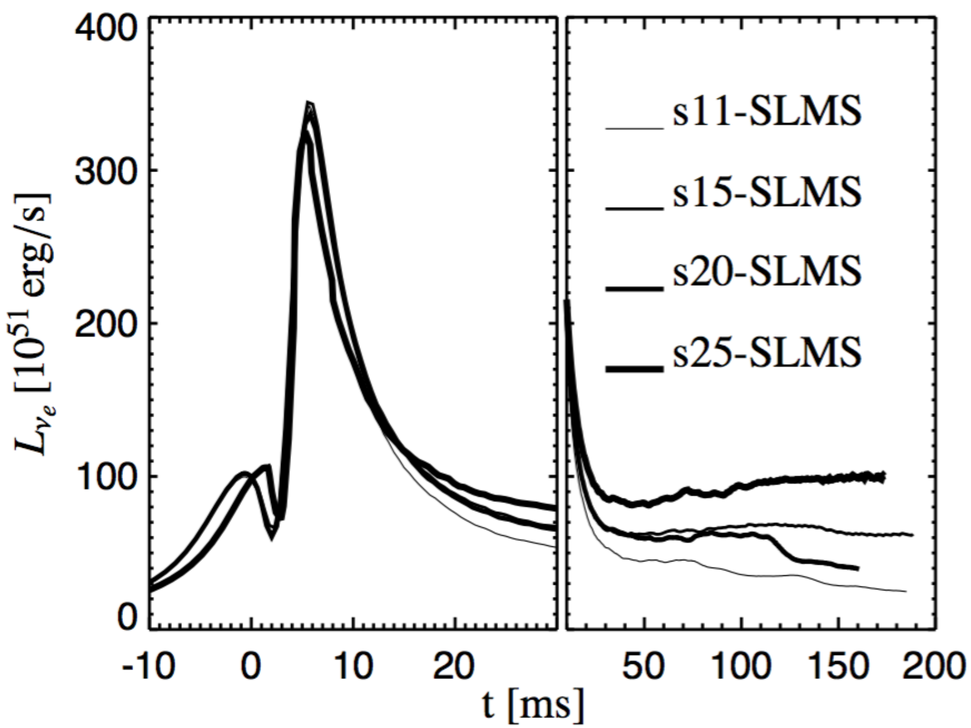
- After thermalization an inner homologous core forms in which the local sound velocity is larger than the infall velocity.
- Matter in the outer core falls at supersonic velocities.

Bounce and ν_e burst



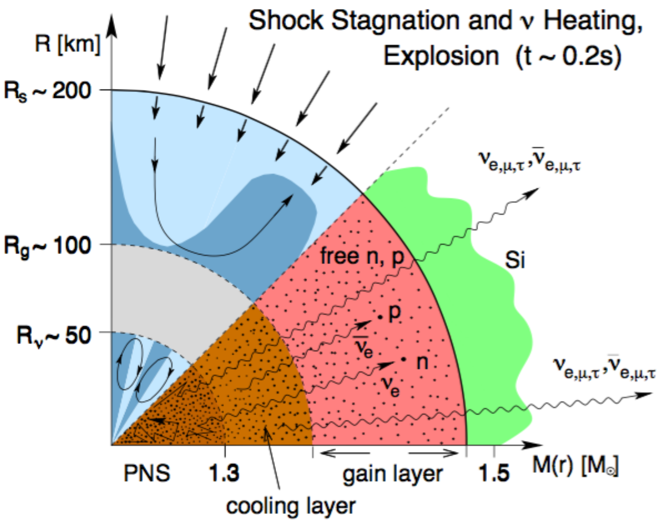
- Collapse continues until central density becomes around twice nuclear matter density.
- Sudden increase in nuclear pressure stops the collapse and a shock wave is launched at the sonic point. The energy of the shock depends on the Equation of State.
- The passage of the shock dissociates nuclei into free nucleons which costs ~ 8 MeV/nucleon. Additional energy is lost by neutrino emission produced by electron capture (ν_e burst).
- Shock stalls at a distance of around 100 km.

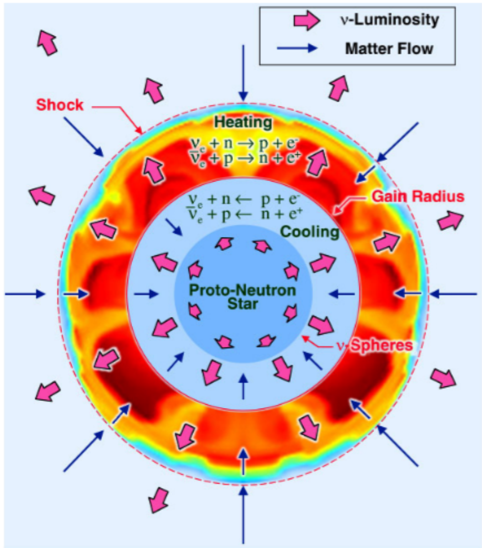
Neutrino burst



- Burst is produced when shock wave reaches regions with densities low enough to be transparent to neutrinos
- Burst structure does not depend on the progenitor star.
- Future observation by a supernova neutrino detector. Standard neutrino candles.

Delayed explosion mechanism: neutrino heating





Main processes:

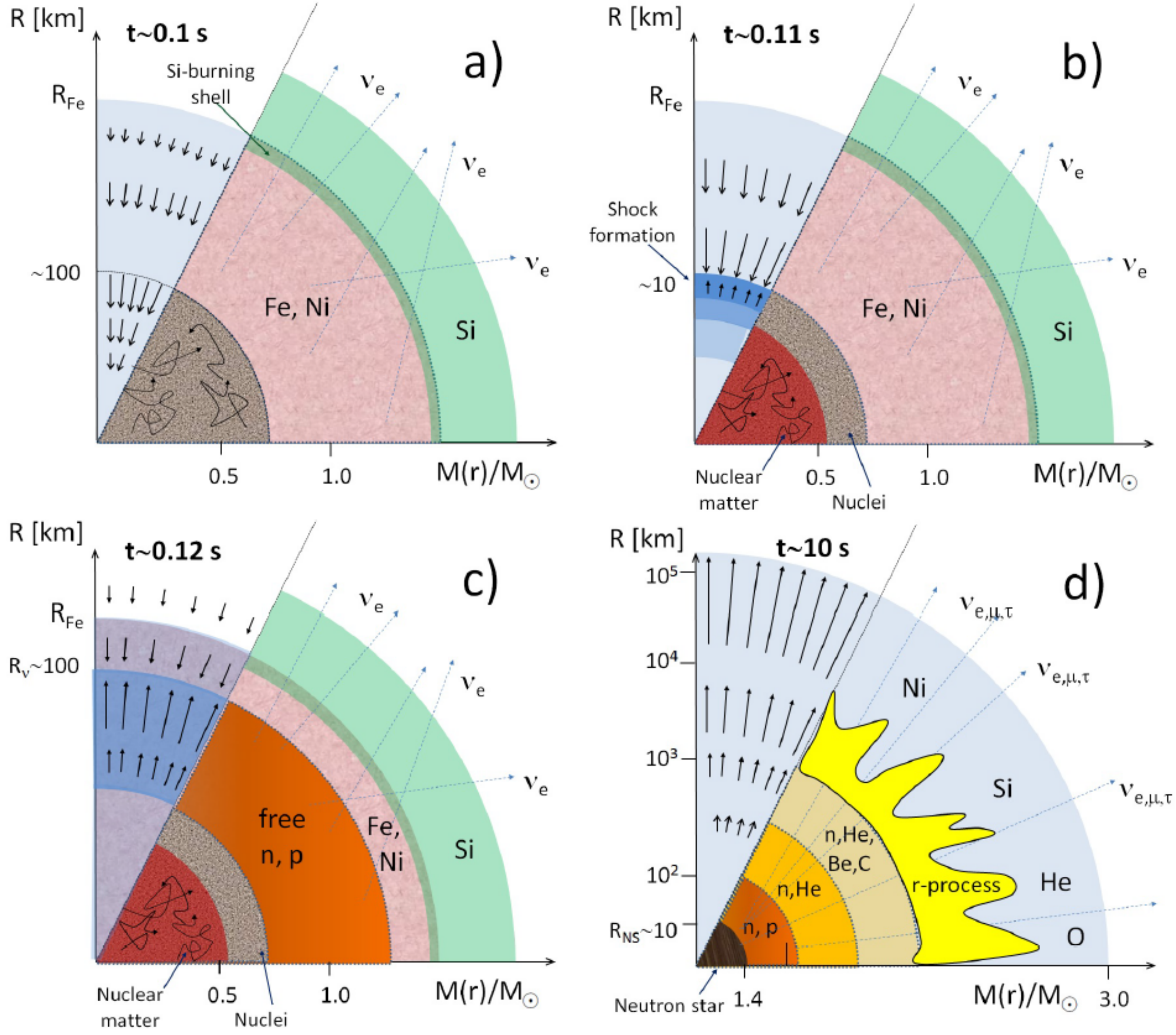
$$\nu_e + n \rightleftarrows p + e^-$$
$$\bar{\nu}_e + p \rightleftarrows n + e^+$$

Concept of gain radius due to Bethe.
Corresponds to the region where cooling (electron positron capture) and heating (neutrino antineutrino absorption) are equal.

$$\text{Cooling: } 143 \left(\frac{kT}{2\,\text{MeV}}\right)^6 \text{ MeV/s}$$

$$\text{Heating: } 110 \left(\frac{L_{\nu_e,52}\epsilon^2_{\nu_e}}{r_7^2} Y_n + \frac{L_{\bar{\nu}_e,52}\epsilon^2_{\bar{\nu}_e}}{r_7^2} Y_p\right) \text{ MeV/s}$$

Gravitational energy of a nucleon at 100 km: 14 MeV
Energy transfer induces convection and requires multidimensional simulations.



R [km]
t~0.1 s
a)
Si-burning shell
R_{Fe}
ν_e
ν_e
ν_e
~100
Fe, Ni
Si
0.5
1.0
$M(r)/M_\odot$
R [km]
t~0.11 s
b)
R_{Fe}
ν_e
ν_e
ν_e
Shock formation
~10
Fe, Ni
Si
Nuclear matter
0.5
Nuclei
1.0
$M(r)/M_\odot$
R [km]
t~0.12 s
c)
R_{Fe}
ν_e
ν_e
ν_e
R_ν~100
free n, p
Fe, Ni
Si
Nuclear matter
0.5
Nuclei
1.0
$M(r)/M_\odot$
R [km]
t~10 s
d)
10^5
10^4
10^3
10^2
R_{NS}~10
$\nu_{e,\mu,\tau}$
$\nu_{e,\mu,\tau}$
$\nu_{e,\mu,\tau}$
Ni
Si
He
O
n,He, Be,C
n,He
n, p
r-process
Neutron star
1.4
$M(r)/M_\odot$
3.0

Naked eye Supernovae

SN1987A

Recorded explosions visible to naked eye:

Year (A.D.)	**Where observed**	**Brightness**
185	Chinese	Brighter than Venus
369	Chinese	Brighter than Mars or Jupiter
1006	China, Japan, Korea, Europe, Arabia	Brighter than Venus
1054	China, SW India, Arabia	Brighter than Venus
1572	Tycho	Nearly as bright as Venus
1604	Kepler	Brighter than Jupiter
1987	Ian Shelton (Chile)	

Core Collapse Supernova Energetics

Liberated gravitational binding energy of neutron star:

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

This shows up as

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

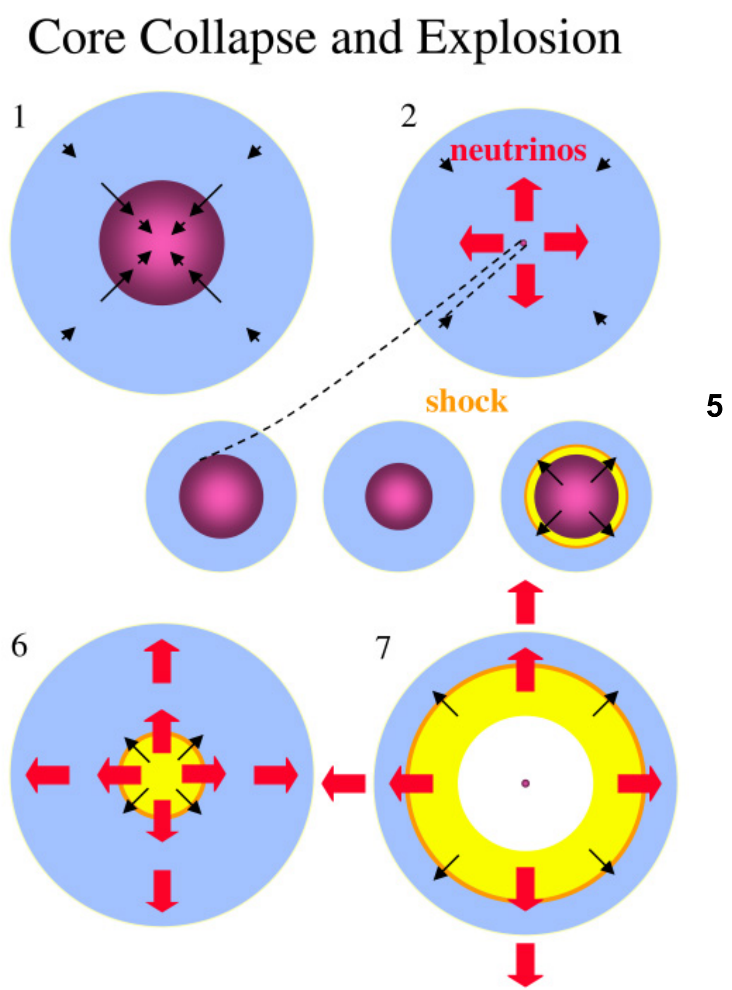
Neutrino luminosity

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

While it lasts, outshines the photon luminosity of the entire visible universe!

Georg Raffelt, Max-Planck-Institut für Physik (München)

Explosion

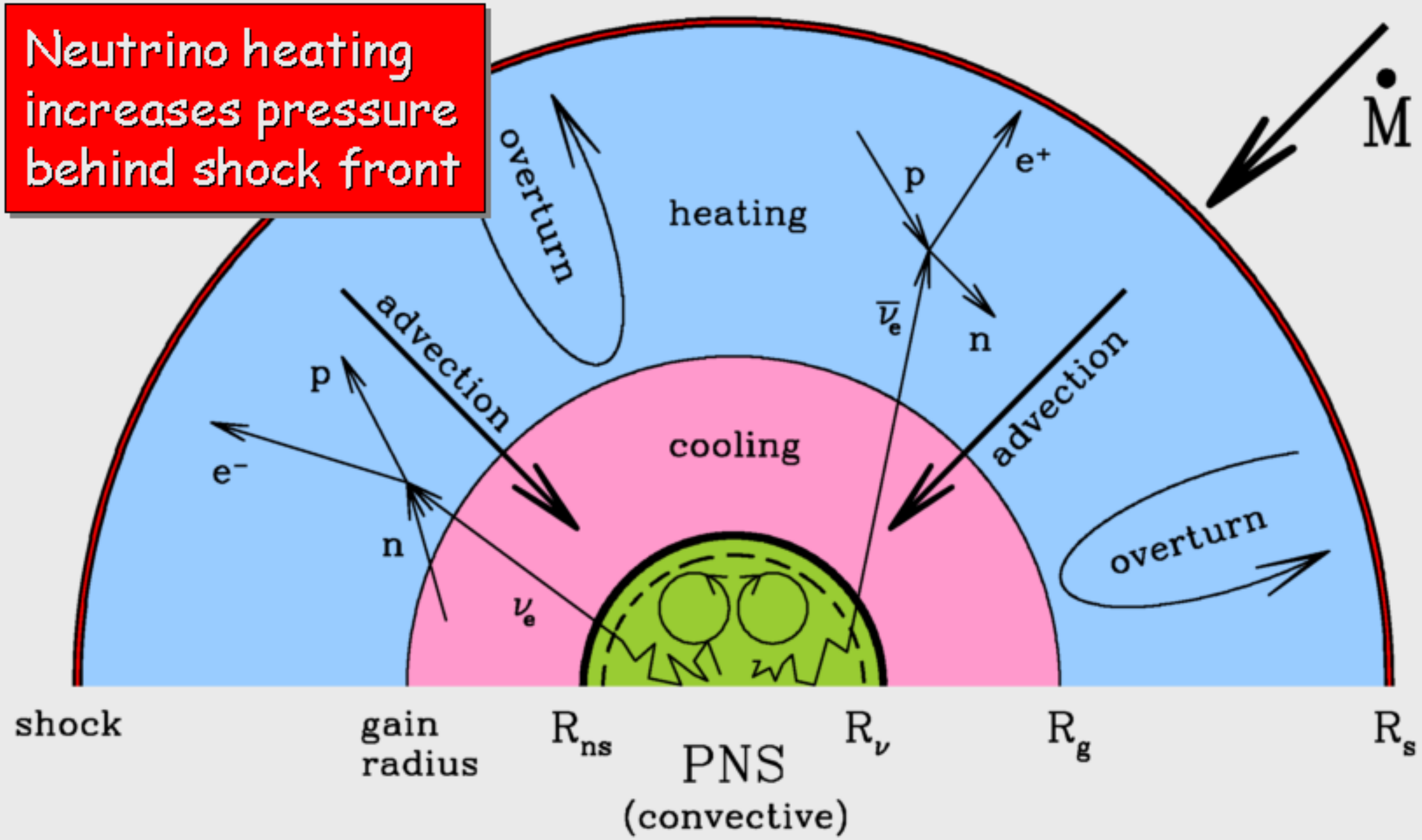


- Collapse and re-bound(1-4) creates a shock wave(5) propagating outward from center of core(6) , meeting in falling outer core material
- Shock stalls due to neutrino escape & nuclear dissociation
- Deleptonisation of the core creates intensive neutrino flux (99% of energy)
- Neutrino interactions behind the shock reheat the shock and drive it outwards(7)
- Measuring $^{56}Fe(\nu_e ,e^-)\ ^{56}Co$ provides valuable data to guide shock formation models.
- Other cross sections, ^{28}Si, should also play an important role.

Neutrinos to the Rescue

Adapted from Janka, astro-ph/0008432

Neutrino heating increases pressure behind shock front



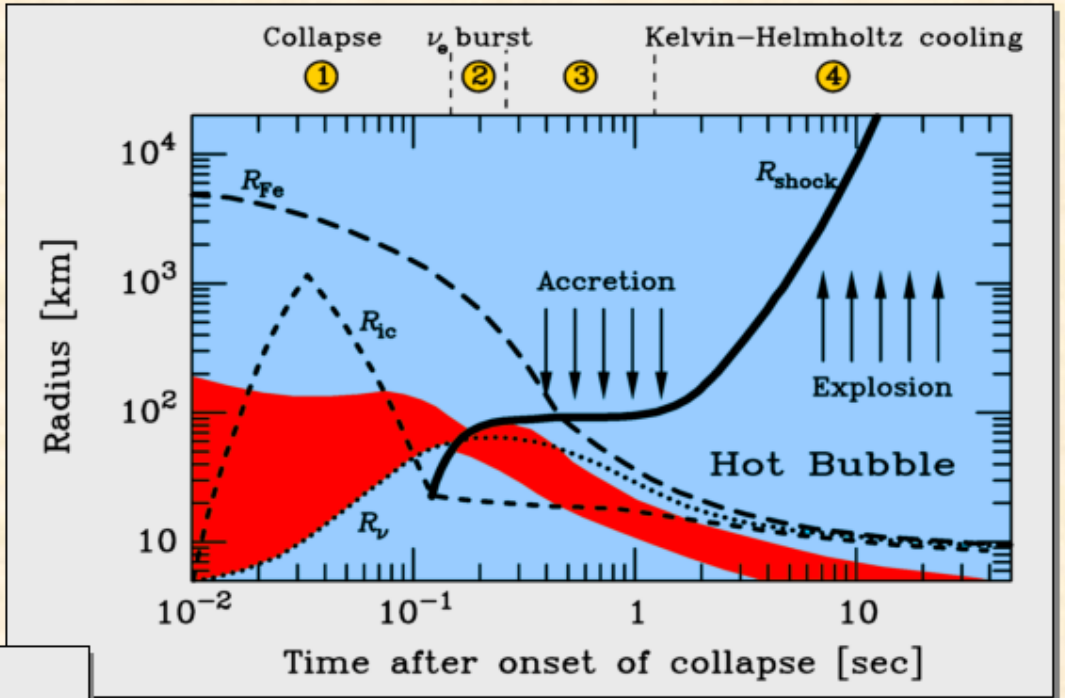
Heating mostly by β processes ($\nu_e + n \to p + e^-$ and $\bar{\nu}_e + p \to n + e^+$)
Pair annihilation ($\nu + \bar{\nu} \to e^- + e^+$) negligible

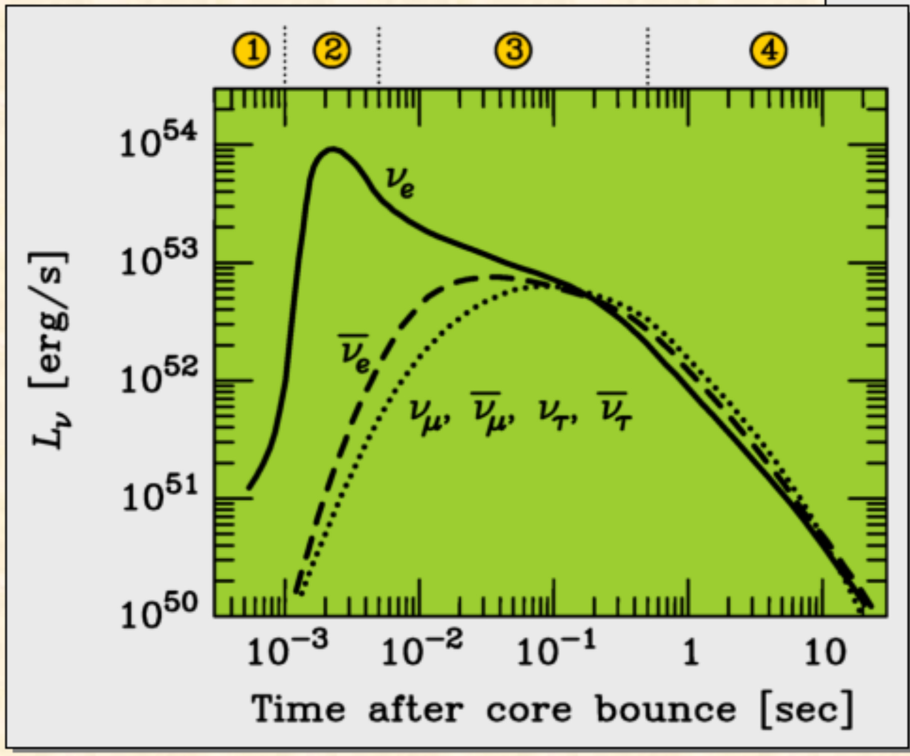
Mu- and tau-neutrino fluxes and spectra not crucial for explosion

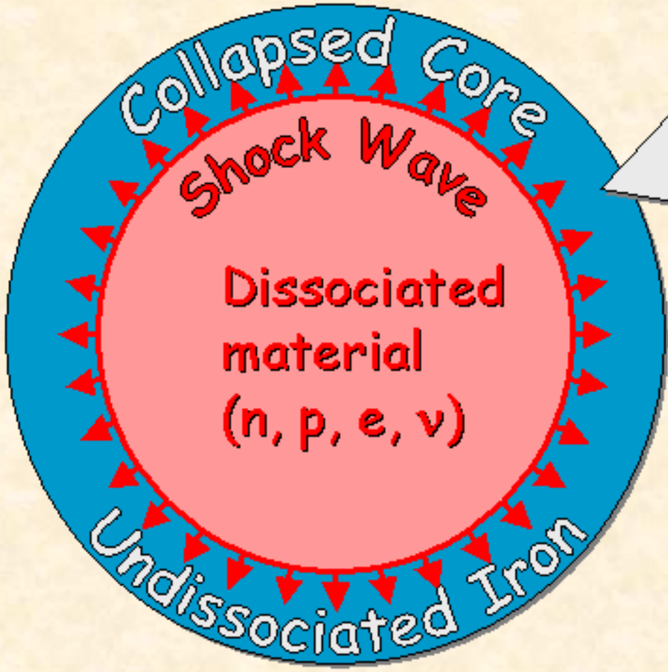
Georg Raffelt, Max-Planck-Institut für Physik (München)

Supernova Neutrino Signal

1. Collapse (infall phase)
2. Shock break out
3. Matter accretion
4. Kelvin-Helmholtz cooling

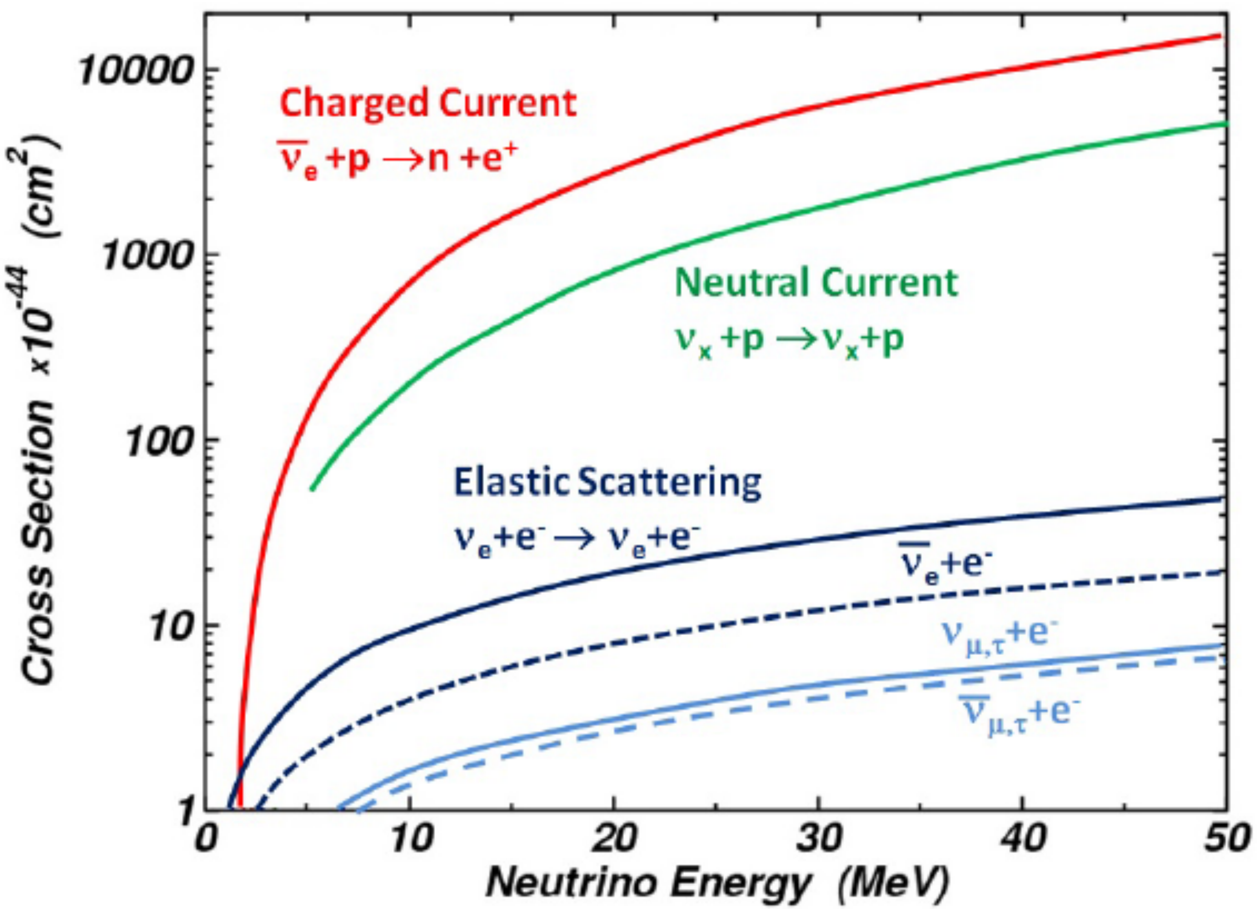






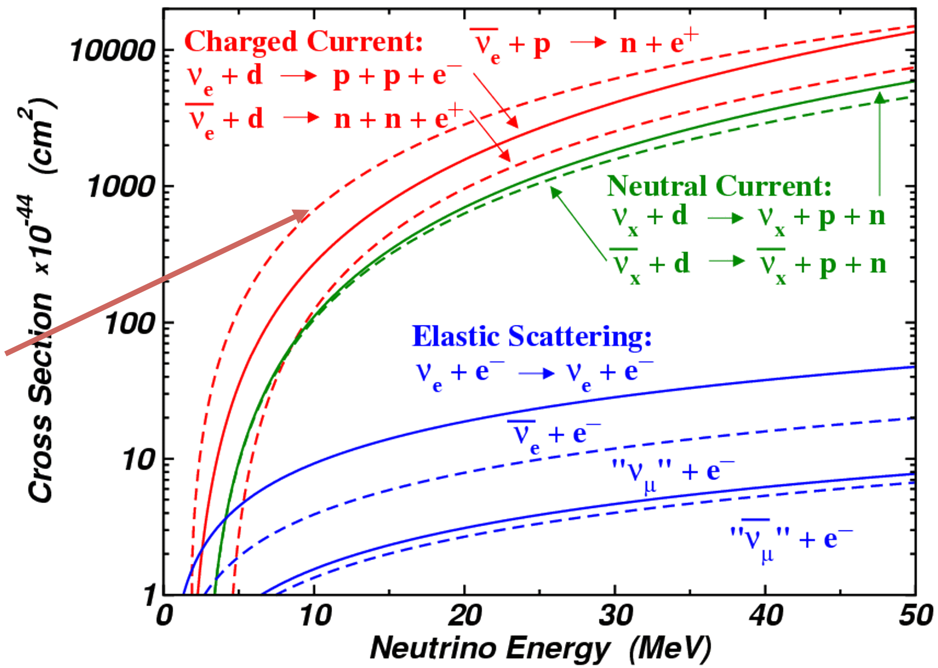
Traps neutrinos and lepton number of outer core layers

The SN neutrino signal



8.6 The SN1987A

Neutrino cross sections:



Distance: 52 kpc (LMC)

Introduction: Core collapse of type-II SN

- *Neutronization*, ~10 ms
- 10^{51} erg, ν_e only

$$e^- + p \rightarrow n + \nu_e$$ → t=0

- *Thermalization:* ~10 s
- 3×10^{53} erg
- $L_{\nu_e}(t) \approx L_{anti\text{-}\nu_e}(t) \approx L_{\nu_x}(t)$

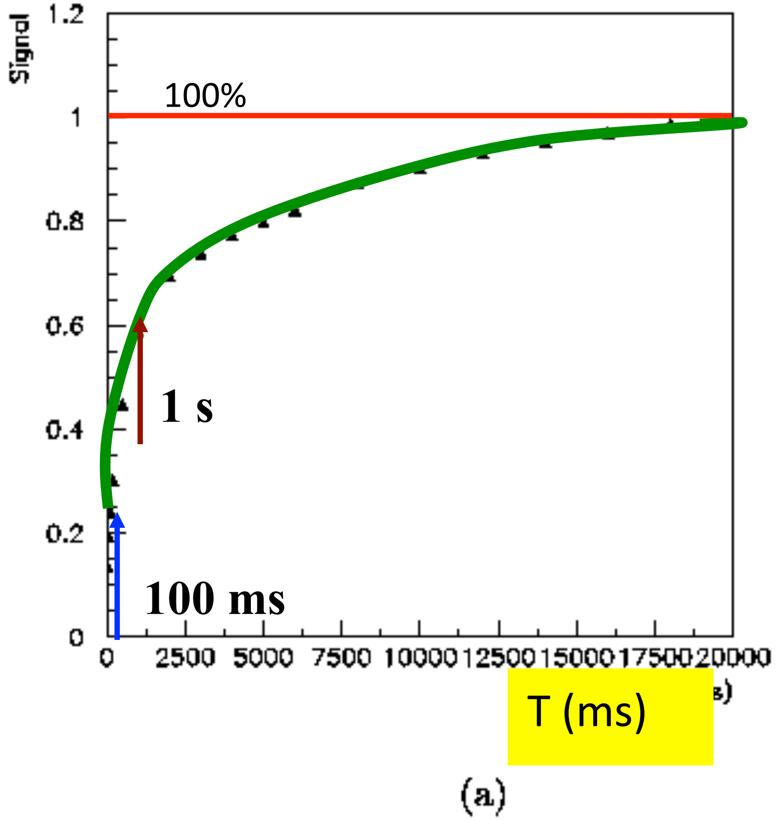
$$e^- + e^+ \rightarrow \bar{\nu} + \nu$$

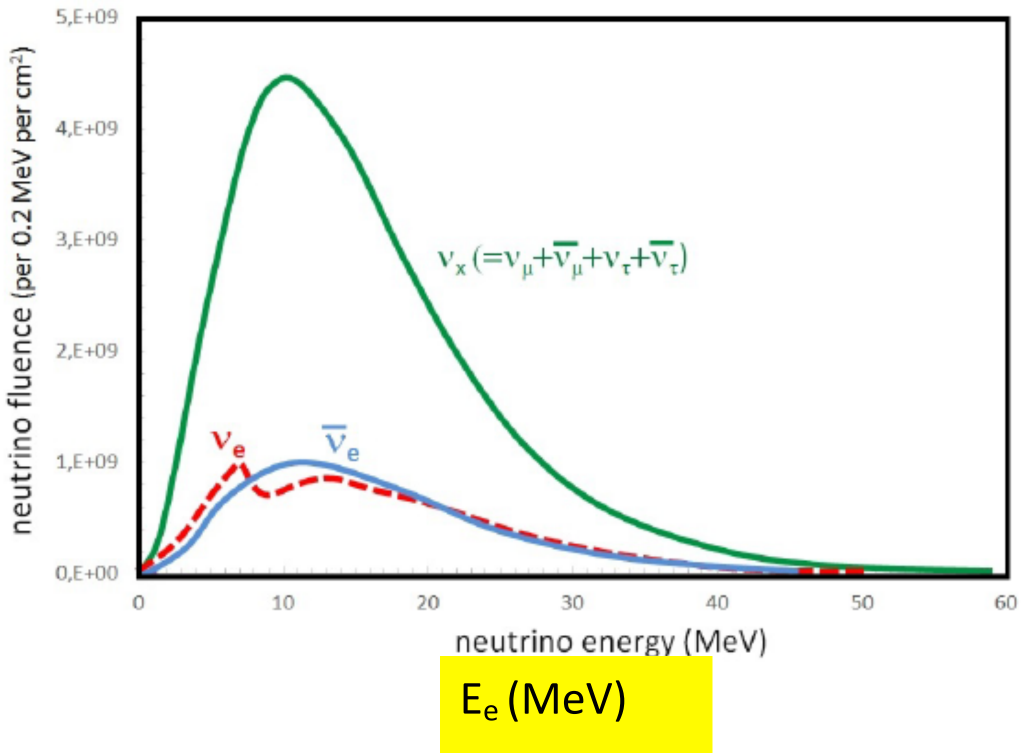
Detection: mainly through $\bar{\nu}_e + p \rightarrow n + e^+$

~300 events/kt (@GC)

Supernovae explode in Nature, but non in computers (J. Beacom, ν2002)

Time-energy





(a) Time-integrated fraction of the SN positrons produced in the detector versus time. 24% of the signal it is produced in the first 100 ms after the *neutronization* burst. It is 60% after 1 second.

(b) Differential energy spectrum (arbitrary units) of positrons. A SN1987A-like stellar collapse was assumed.

The SN1987A: how many events?

1- Energy released 2.5 10^{53} erg
2- Average ν_e energy $\approx$ 16 MeV = 2.5 10^{-5} erg
3- N_{source}= (1/6) $\times$ 2.5 10^{53}/ (2.5 10^{-5})= 1.7 10^{57} ν_e

4- LMC Distance : D=52 kpc = 1.6 10^{23} cm
5- Fluency at Earth: $F = N_{Source}/4\pi D^2$ = 0.5 10^{10} cm^{-2}
6- Targets in 1 Kt water: **N_t = 0.7 10^{32}** protons
7- cross section: $\sigma(anti\nu_e+p)$ ~ **2×10^{-41} cm^2**

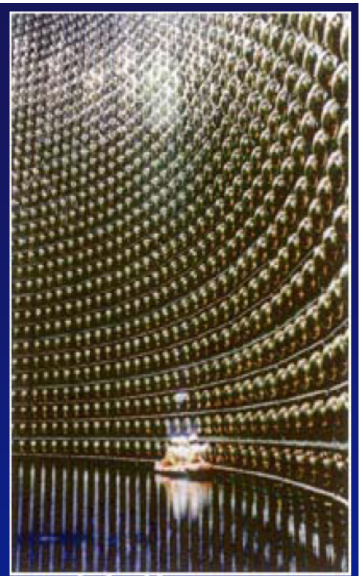
8- N_{e^+} = F (cm^{-2})$\times$ σ (cm^2)$\times$ N_t (kt^{-1})= 0.5 10^{10} $\times$ $2\times10^{-41}$$\times$ 0.7 10^{32}
= 7 positrons/kt
9 – M(Kam II) = 2.1 kt, efficiency ε~ 80%
10 – Events in Kam II = 7 x 2.1 x ε ~ **12 events**

For a SN @ Galactic Center (8.5 kpc) :
N_{events}= $7\times(52/8.5)^2$ = 260 e^+/kt

The Detectors

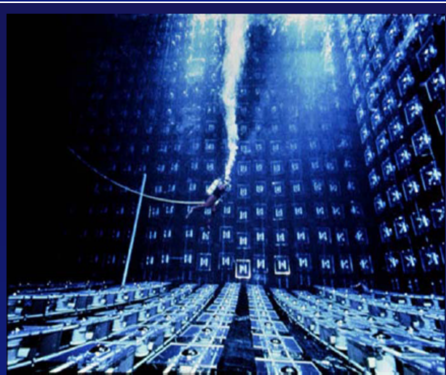
- Water Cherenkov detectors
  - Kamiokande (Japan)
  - IMB (Ohio)
- Liquid scintillation telescopes
  - Baksan – USSR Academy of Sciences, in North Caucasus Mountains, Russia
  - Mont Blanc – Italian Soviet collaboration, in Mont Blanc Laboratory, France

Kamiokande II



- Located in the Kamioka mine in Japan
- 1000m underground
- Cylindrical tank
  - d = 15.6m, h = 16m
- Large (D = 20 inches) photomultipliers
- Volume of water weighs 3000 metric tons

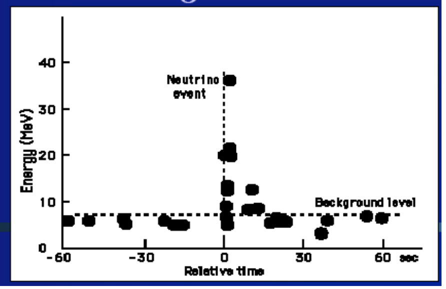
IMB



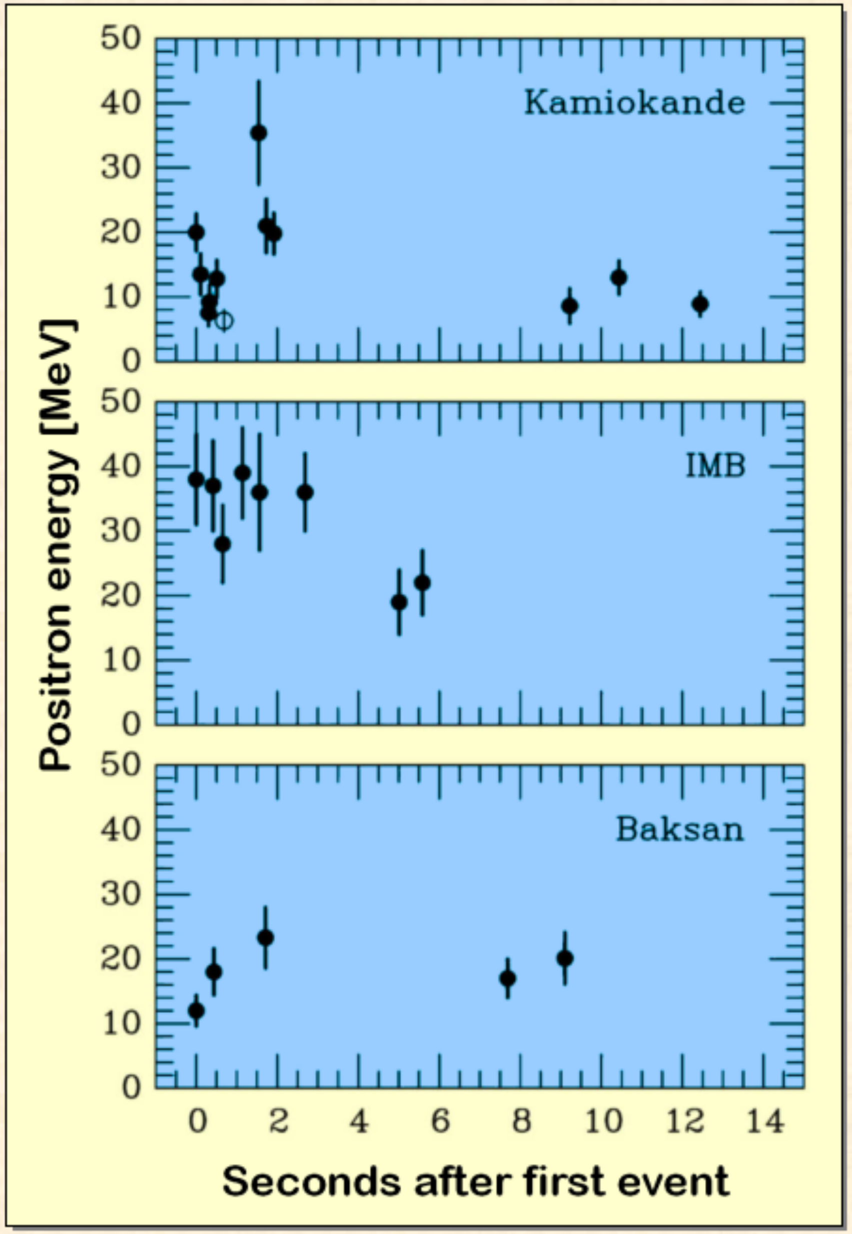
- Located in the Morton Thiokol mine in Ohio
- 580m underground
- Rectangular tank
  - 18 by 17 by 23 m
- 2048 8” photomultipliers
- 2.5 million gallons of water
- Compared to Kamiokande II: Larger volume, but not as deep

Results

- Feb 23, 7:36 UT:
  - K II records 9 neutrinos within 2 sec, 3 more neutrinos 9-13 seconds later
  - IMB records 8 neutrinos within 6 seconds
  - Baksan records 5 neutrinos within 5 seconds
- 25 neutrinos detected!



Neutrino Signal of Supernova 1987A



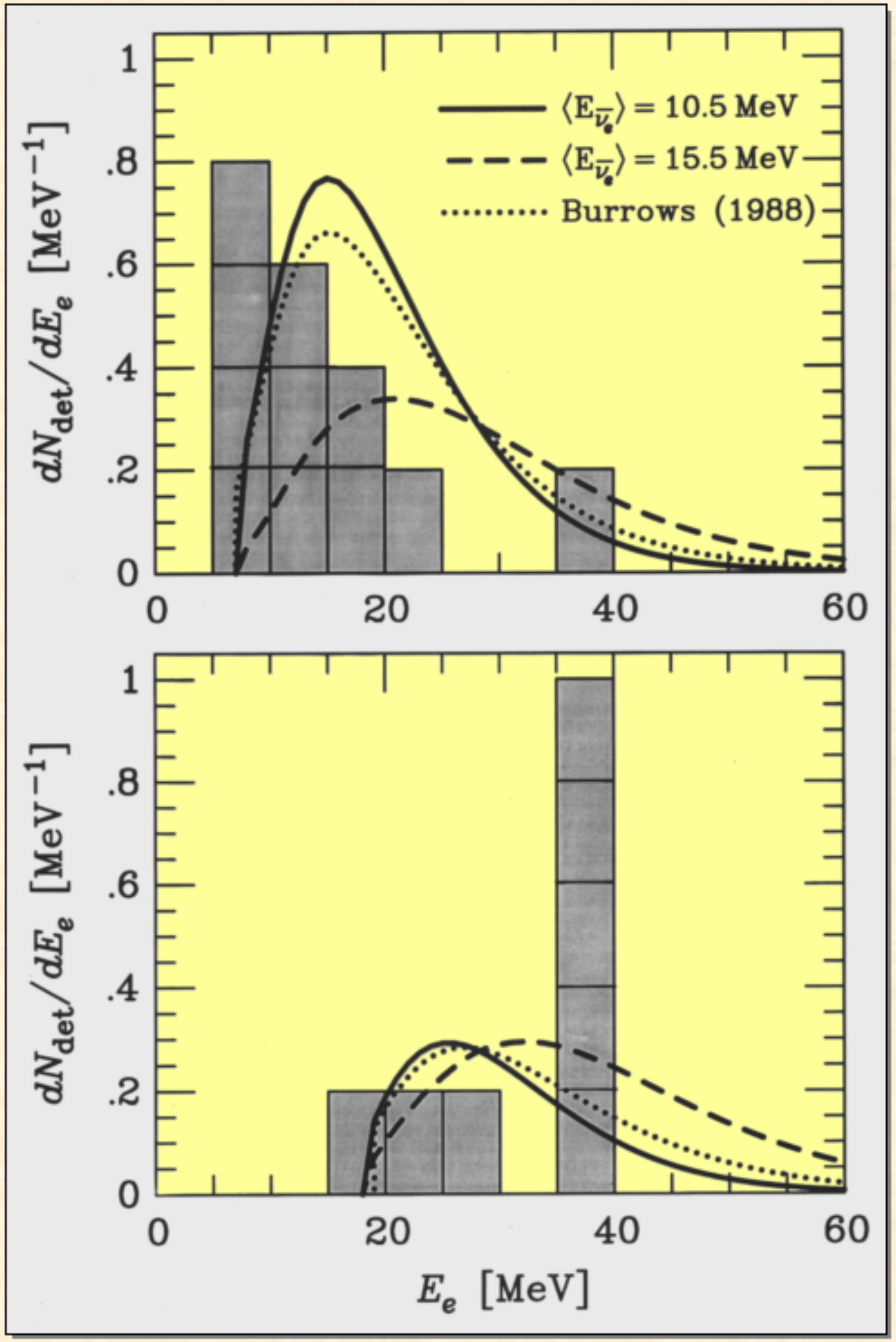
Kamiokande (Japan)
Water Cherenkov detector
Clock uncertainty ±1 min

Irvine-Michigan-Brookhaven (USA)
Water Cherenkov detector
Clock uncertainty ±50 ms

Baksan Scintillator Telescope (Soviet Union)
Clock uncertainty +2/-54 s

Within clock uncertainties, signals are contemporaneous

Energy Distribution of SN 1987A Neutrinos



Kamiokande II

IMB

Georg Raffelt, Max-Planck-Institut für Physik (München)

LVD detector

LVD

Abstract

The Large Volume Detector (LVD) at the INFN Gran Sasso National Laboratory (LNGS), Italy, is an underground neutrino observatory mainly designed to study neutrinos from core-collapse supernovae. It is in operation since 1992, under different larger configurations. The final upgrade took place in 2001, when LVD became fully operational, with an active mass M=1000 t. LVD consists of an array of 840 scintillator counters, arranged in a compact and modular geometry. The experiment has been monitoring our Galaxy since June 1992. No neutrino burst candidate has been found, the resulting 90% C.L. upper limit to the rate of gravitational stellar collapses being the most stringent among the existing limits.

https://www.lngs.infn.it/en/lvd

Neutrino mass from SN

• The observation of supernova neutrinos should bring a better understanding of the core collapse mechanism from the feature of the time and energy spectra, and constraints the supernova models.

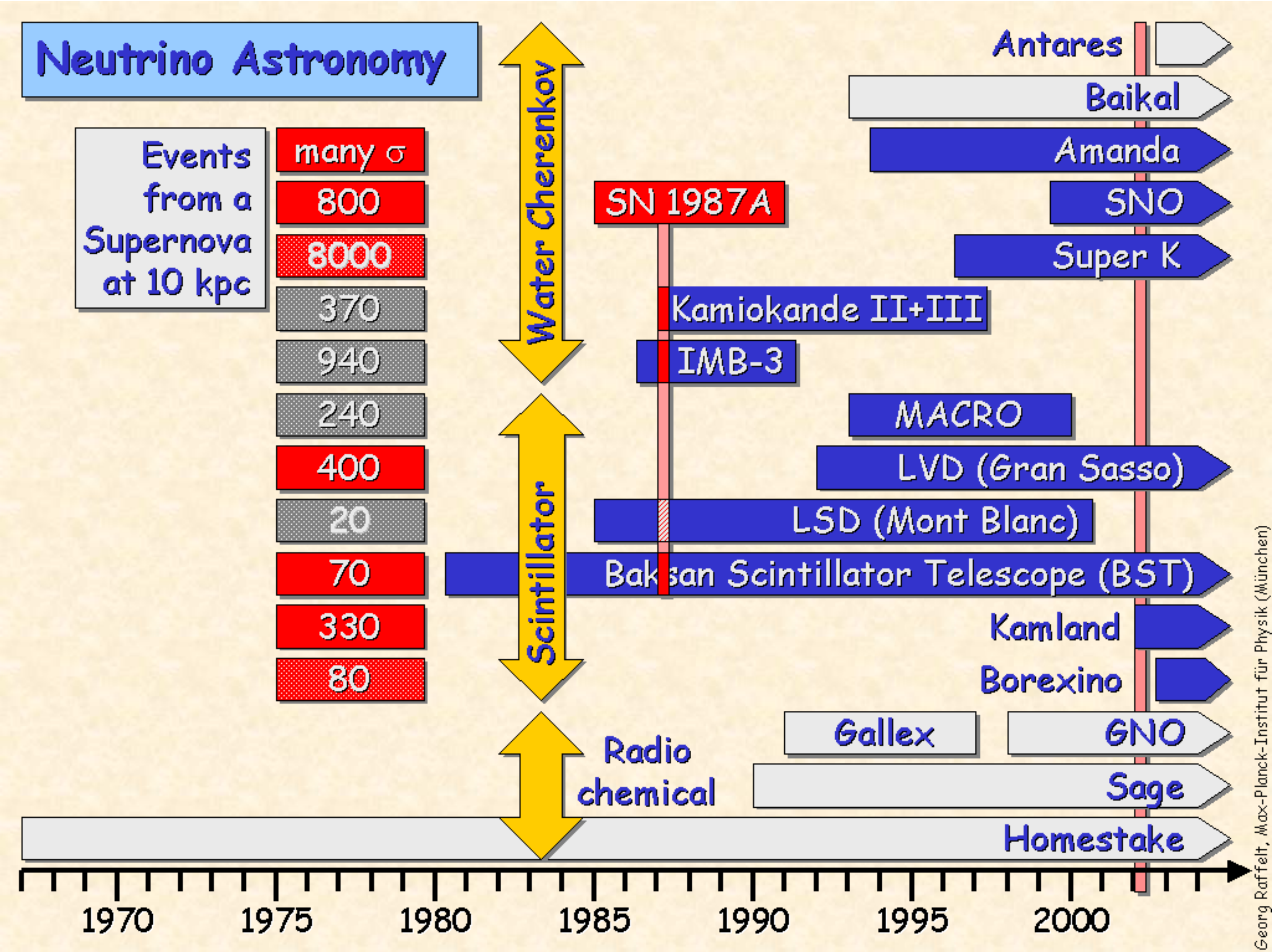
• Moreover, an estimation of the neutrino masses could be done in the following manner. The velocity of a particle of energy *E* and mass *m*, with $E >> m$, is given by (with c = 1):

$$v = \frac{p}{E} = \frac{(E^2 - m^2)^{1/2}}{E} \approx 1 - \frac{m^2}{2E} \quad .$$

•Thus, for a supernova at distance *d*, the delay of a neutrino due to its mass is, expressed in the proper units:

$$\Delta t_{[s]} \approx 0.05 \frac{m_{[eV]}^{\;2}}{E_{[MeV]}} d_{[kpc]} \quad .$$

• Therefore, neutrinos of different energies released at the same instant should show a spread in their arrival time.



Neutrino Astronomy
Events from a Supernova at 10 kpc
many σ
800
8000
370
940
240
400
20
70
330
80
Water Cherenkov
Scintillator
Radio chemical
SN 1987A
Antares
Baikal
Amanda
SNO
Super K
Kamiokande II+III
IMB-3
MACRO
LVD (Gran Sasso)
LSD (Mont Blanc)
Baksan Scintillator Telescope (BST)
Kamland
Borexino
Gallex
GNO
Sage
Homestake
1970
1975
1980
1985
1990
1995
2000
Georg Raffelt, Max-Planck-Institut für Physik (München)

Neutrino Astrophysics

- The only SN seen with neutrino was SN1987a
- Small experiments, small statistics
- Qualitative agreement with the SN models
- Wait for the next near SN with the new larger experiments (SK, SNO, Borexino, LVD…)
- → neutrino properties (mass, livetime, magnetic moment) from astrophysics