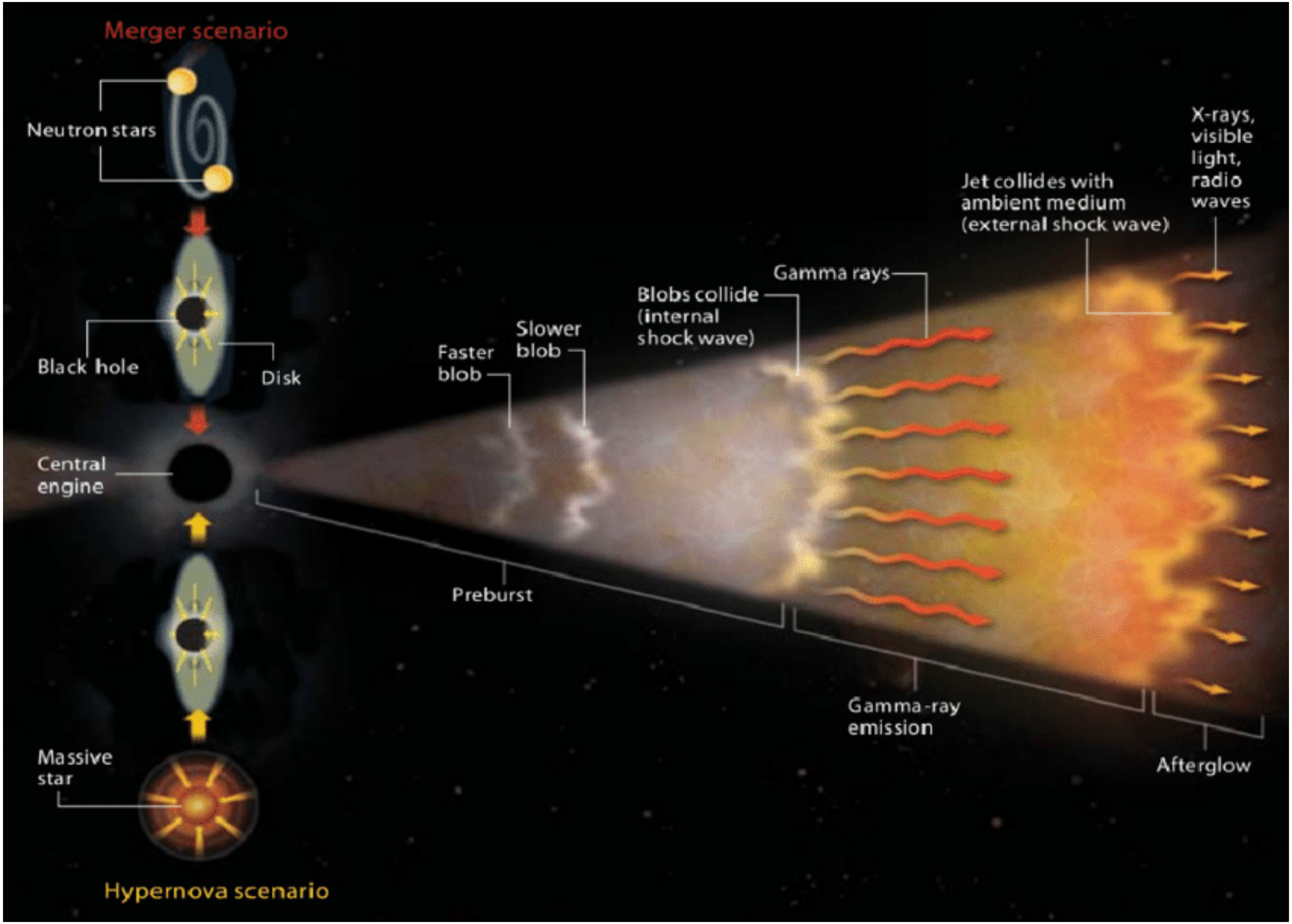
# Astrofisica Nucleare e Subnucleare

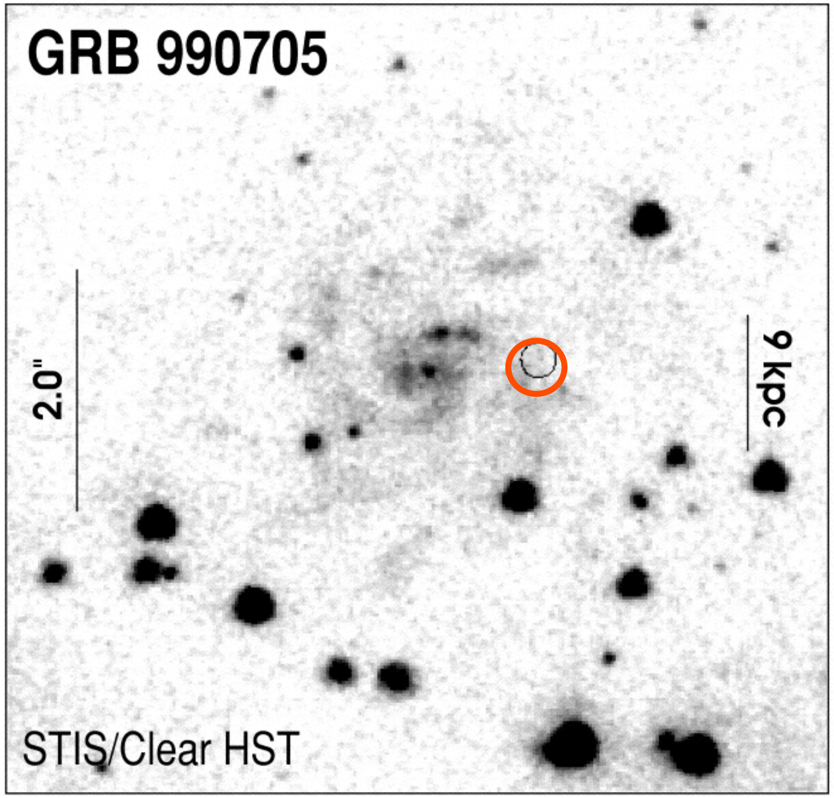
## Neutrino & Nuclear Astrophysics


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

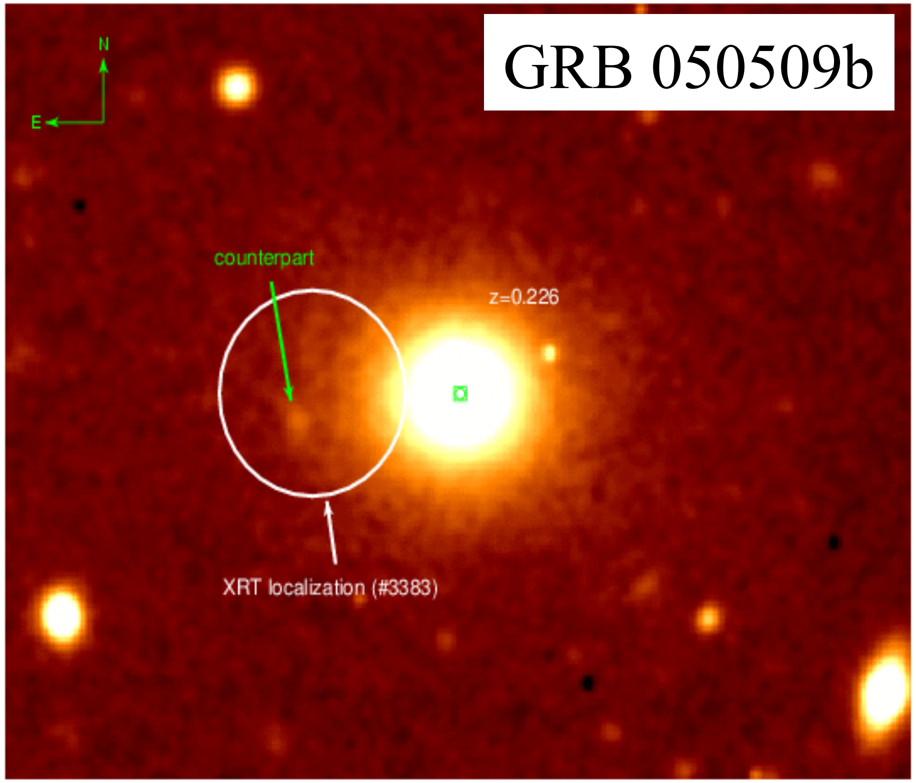
# Unvealing the GRB progenitors

- 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

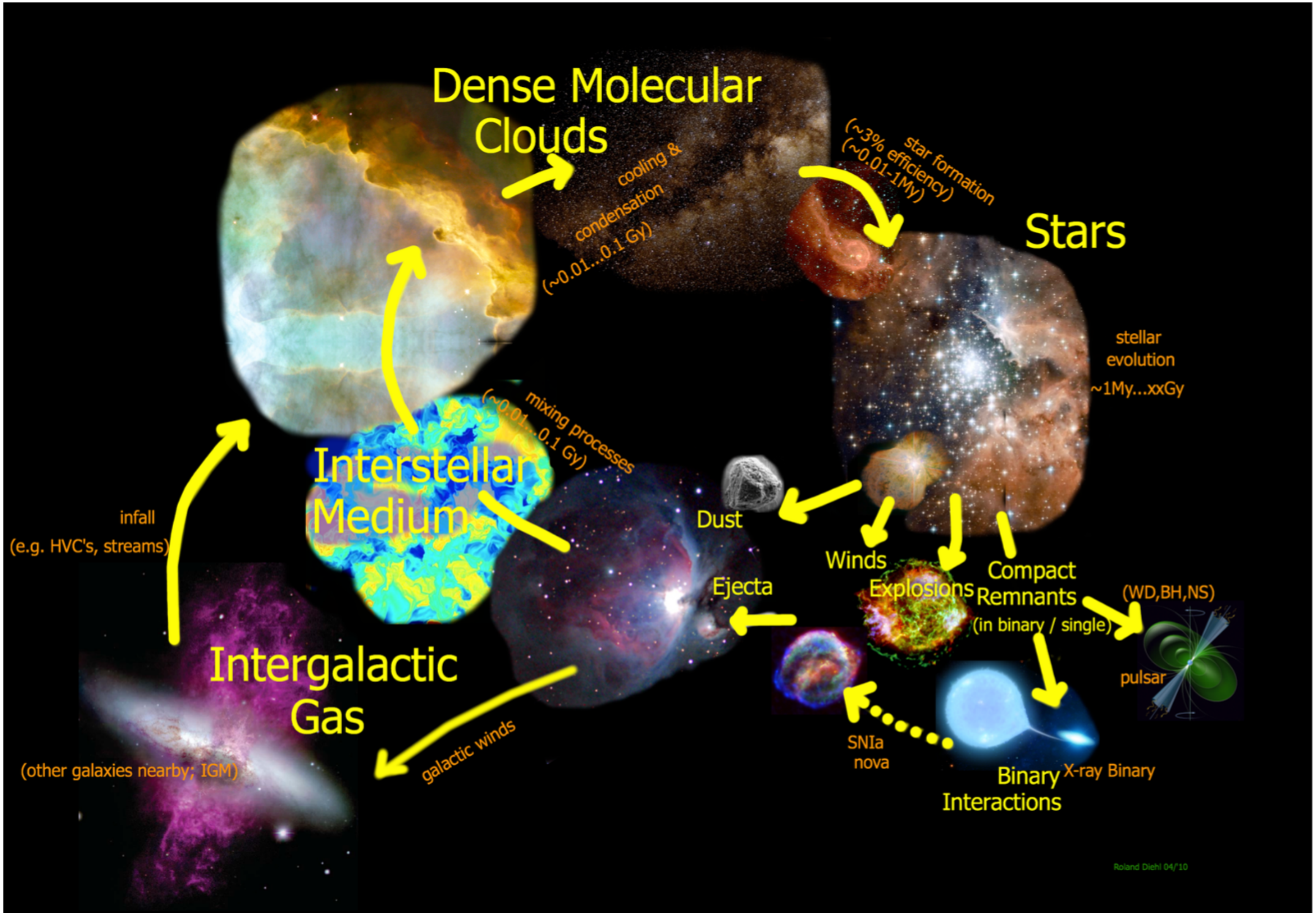
***Long***




***Short***



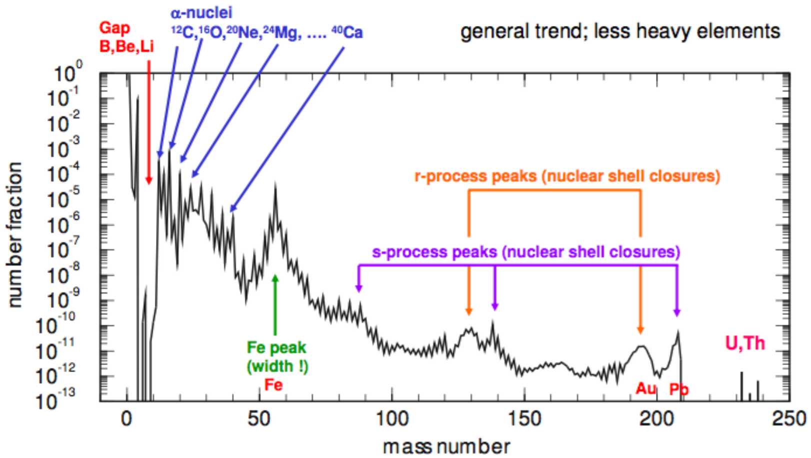
# How Stars Shape Galaxies



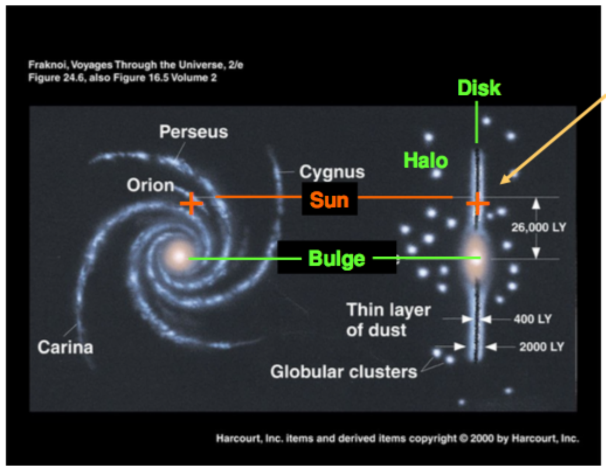
# What is Nuclear Astrophysics?

- 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

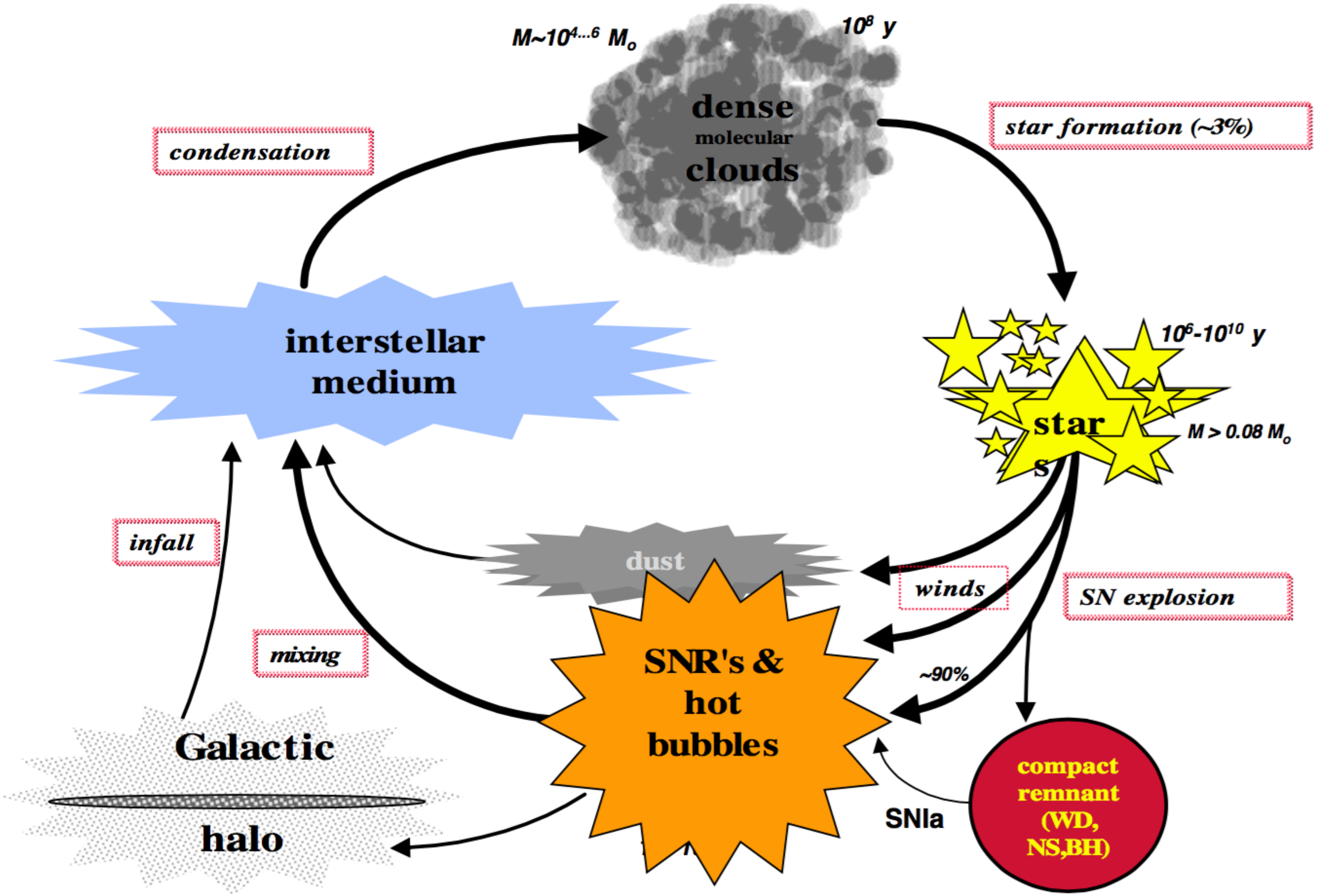



**solar abundances:**

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

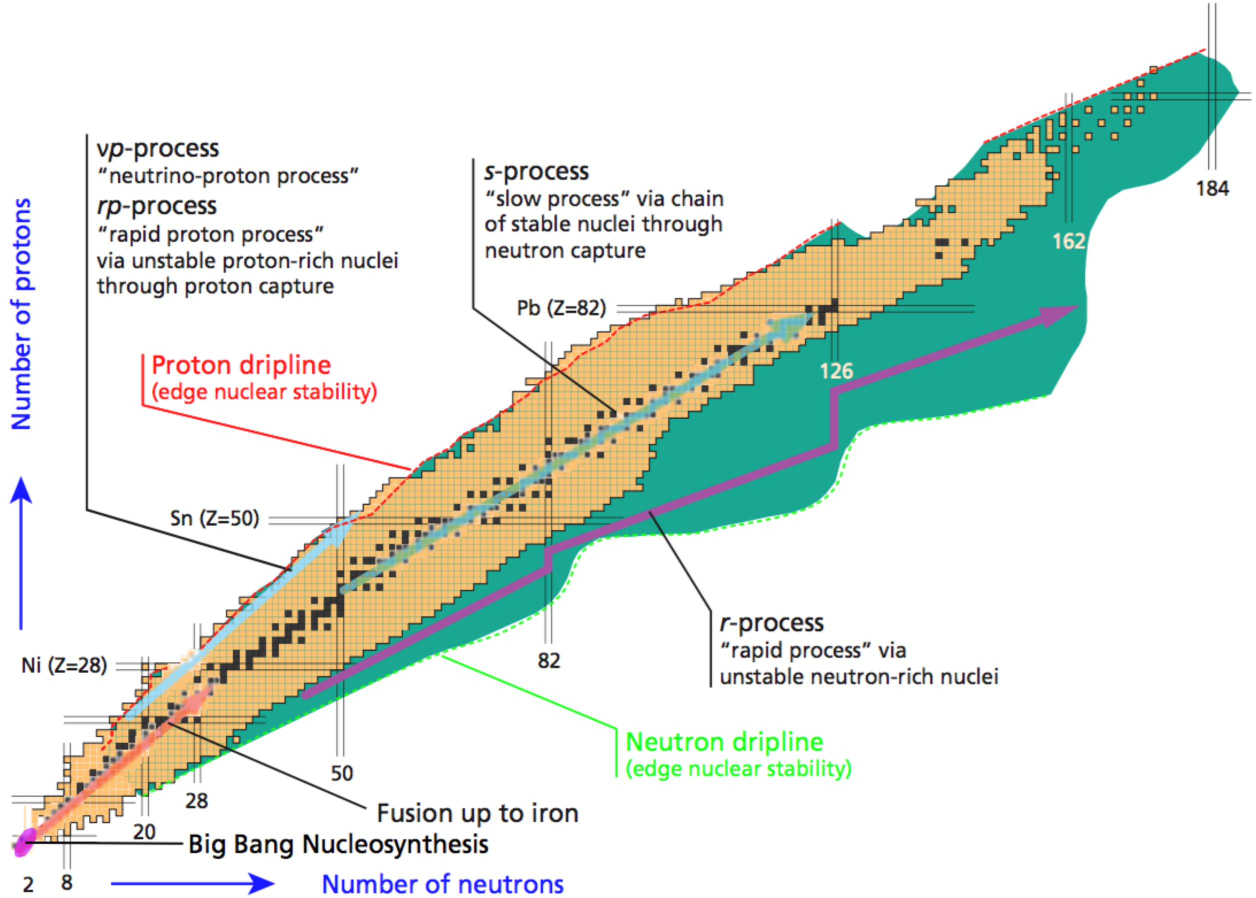
K. Lodders, Astrophys. J. **591**, 1220-1247 (2003)

# 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.

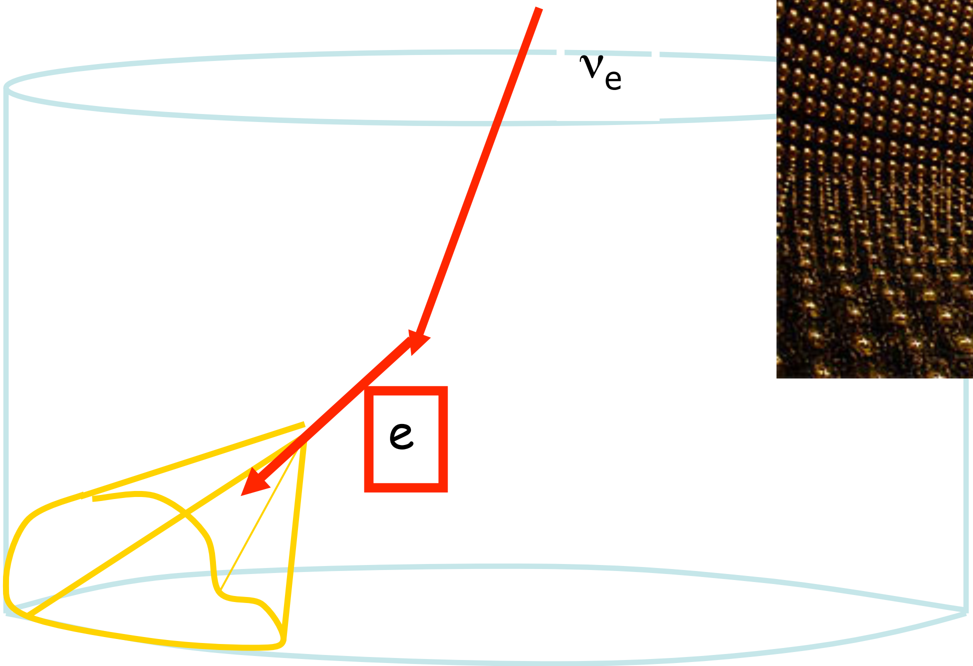


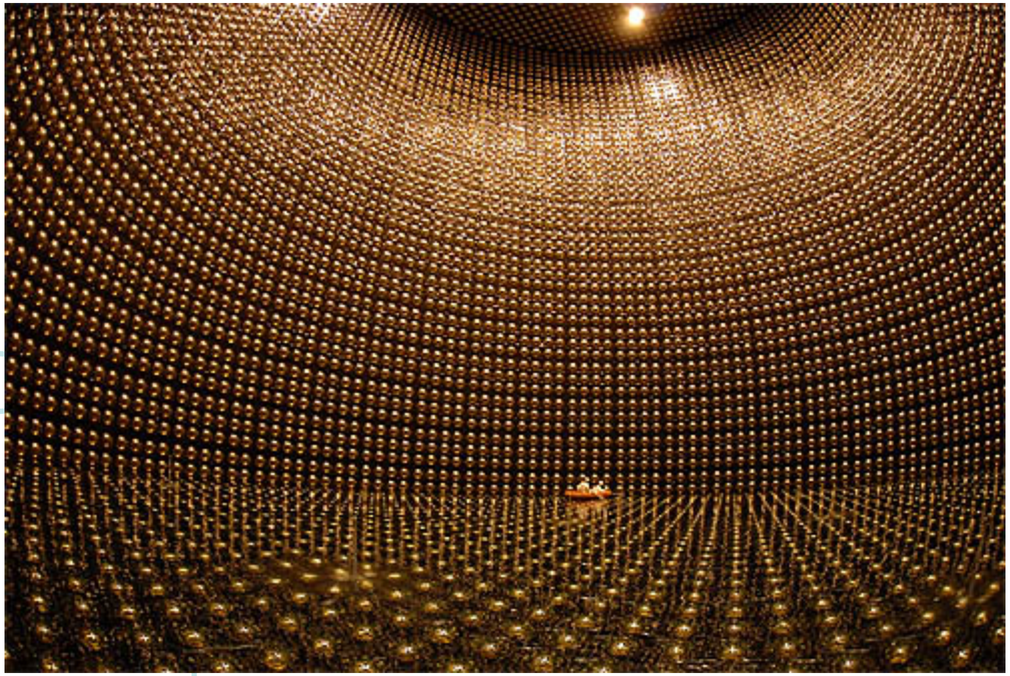
# Astrofisica Nucleare e Subnucleare

## 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

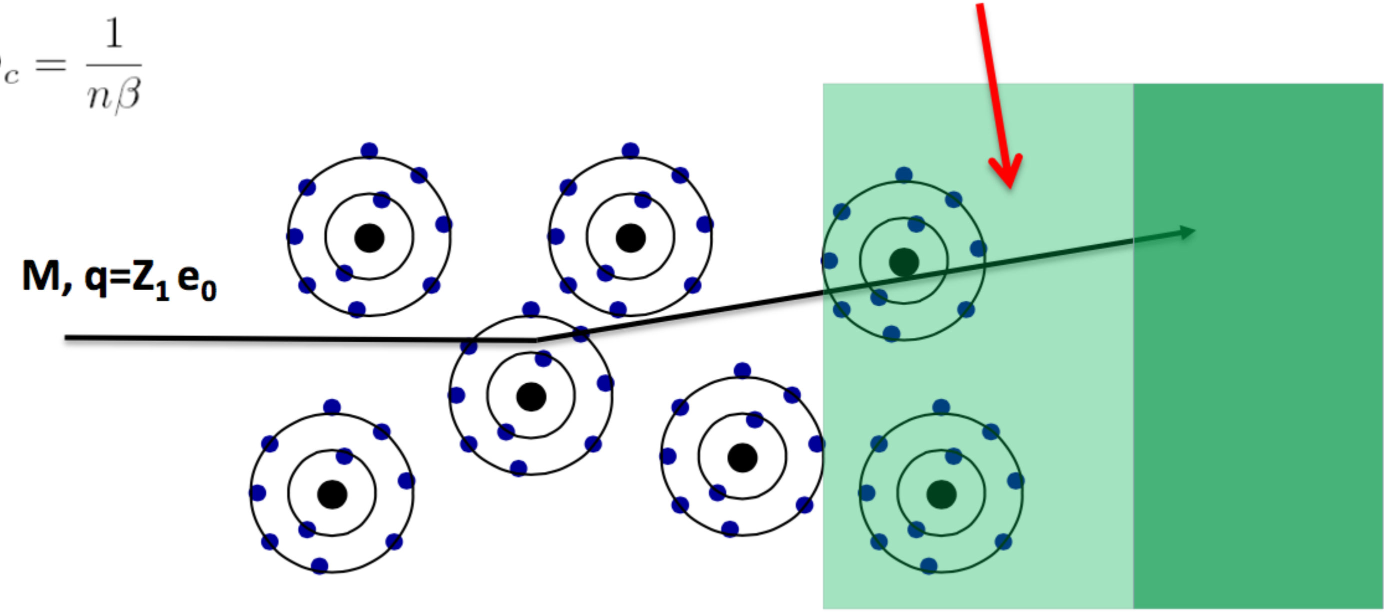
## Cherenkov effect

# Cherenkov Radiation

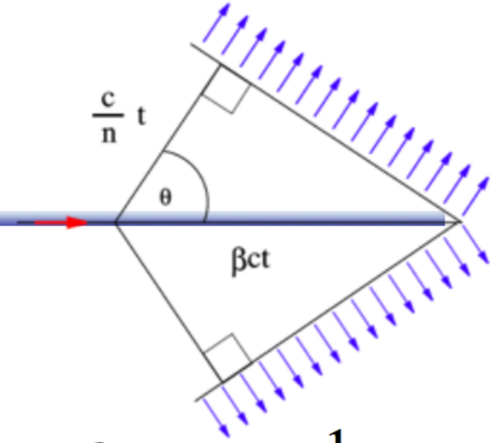
**If we describe the passage of a charged particle through material of dielectric permittivity ♏ (using Maxwell's equations) the differential energy crossection is >0 if the velocity of the particle is larger than the velocity of light in the medium**

**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 ❑$_c$ , 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 $\theta_c^{max}$ =11mrad

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

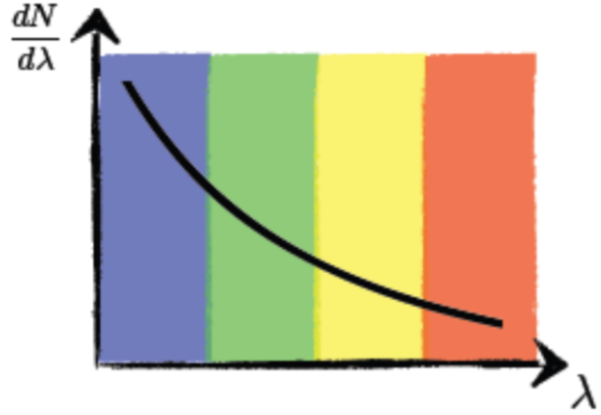
Visible photons:
E = 1 - 5 eV; λ = 300 - 600 nm

# Cherenkov radiation

In a Cherenkov detector the produced photons are measured

Number of emitted photons per unit of length:

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



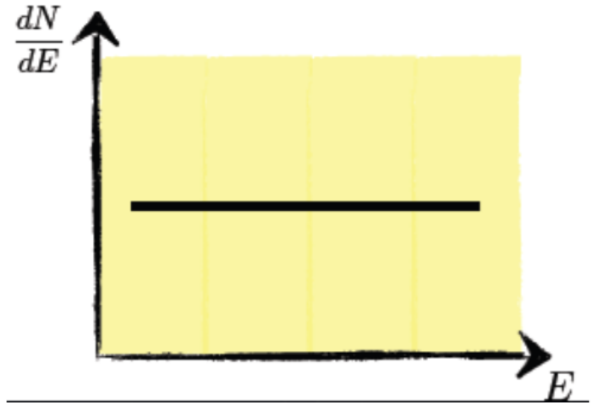

$$\frac{d^2N}{d\lambda dx} = \frac{2\pi\alpha z^2}{\lambda^2}\left(1 - \frac{1}{\beta^2 n^2(\lambda)}\right) = \frac{2\pi\alpha z^2}{\lambda^2}\sin^2\theta_C$$

Integrate over sensitivity range:
[for typical Photomultiplier]

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

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

- energy dependence ~ constant

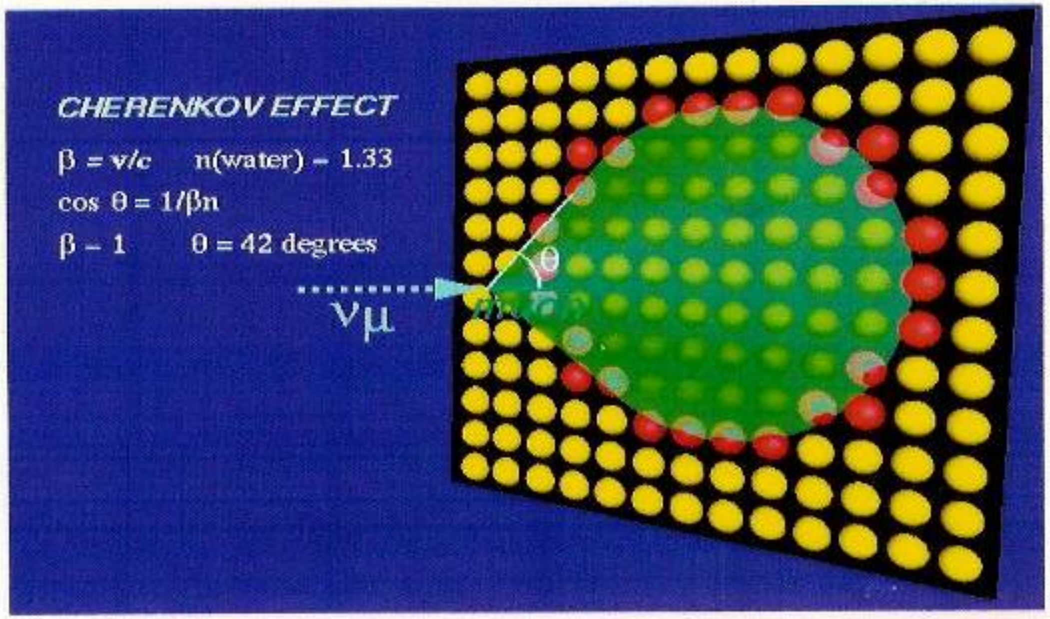



$$\frac{d^2N}{dEdx} = \frac{z^2\alpha}{\hbar c}\left(1 - \frac{1}{\beta^2 n^2(\lambda)}\right) = \frac{z^2\alpha}{\hbar c}\sin^2\theta_C$$

$$\approx \mathrm{const}$$

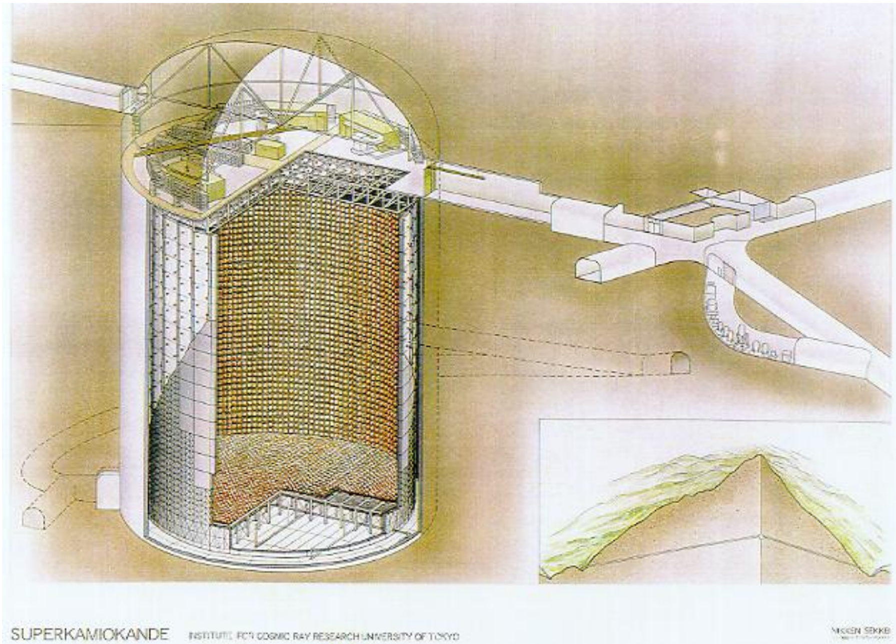
$$\frac{d^2N}{dEdx} = 370\ \sin^2\theta_C\ \mathrm{eV}^{-1}\ \mathrm{cm}^{-1}$$

# Cherenkov Radiation



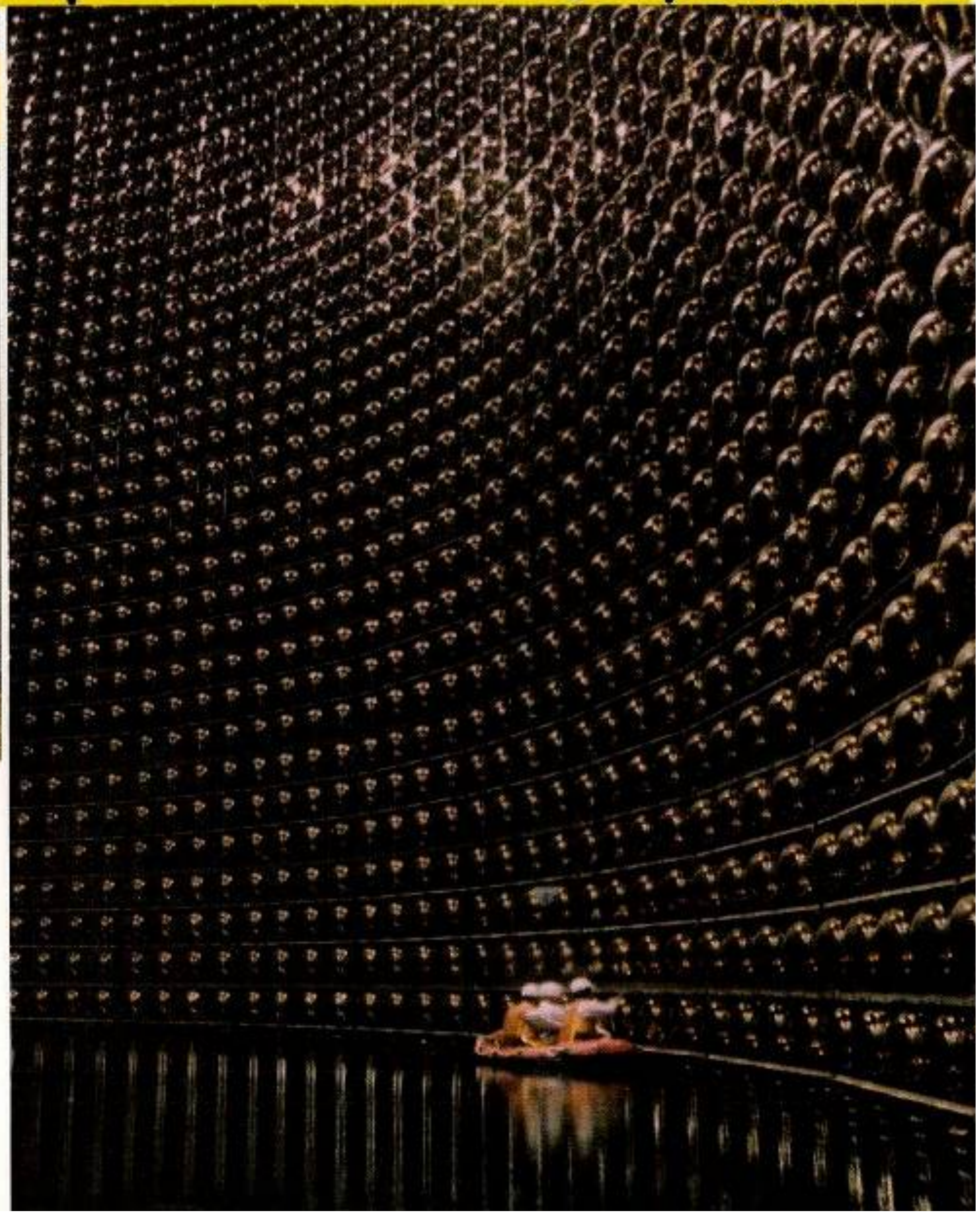

One of the
13000 PMT

# 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

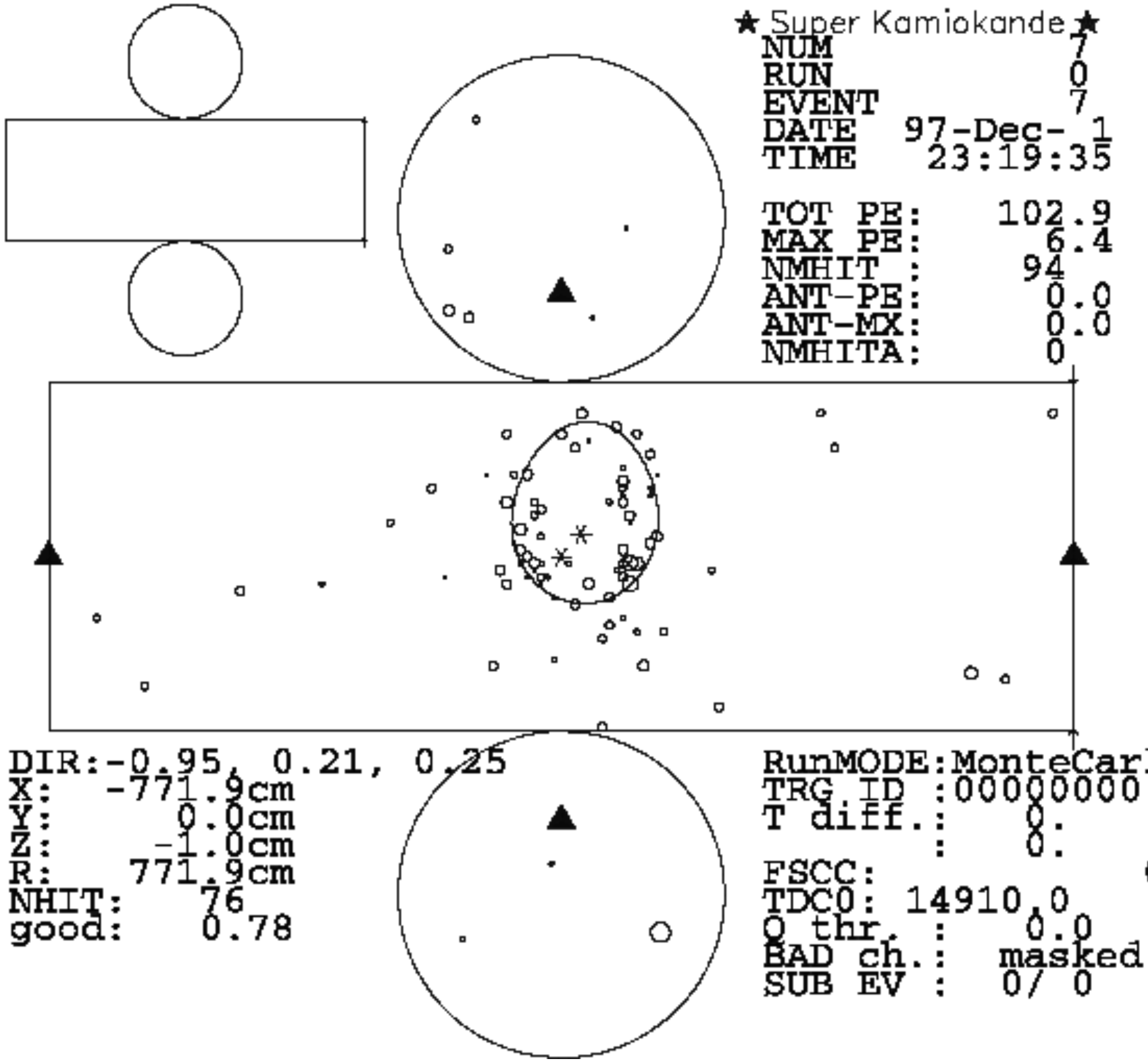
| Particle | Cherenkov threshold in total Energy |
|---|---|
| $e^{\pm}$ | 0.768(MeV) |
| $\mu^{\pm}$ | 158.7 |
| $\pi^{\pm}$ | 209.7 |

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

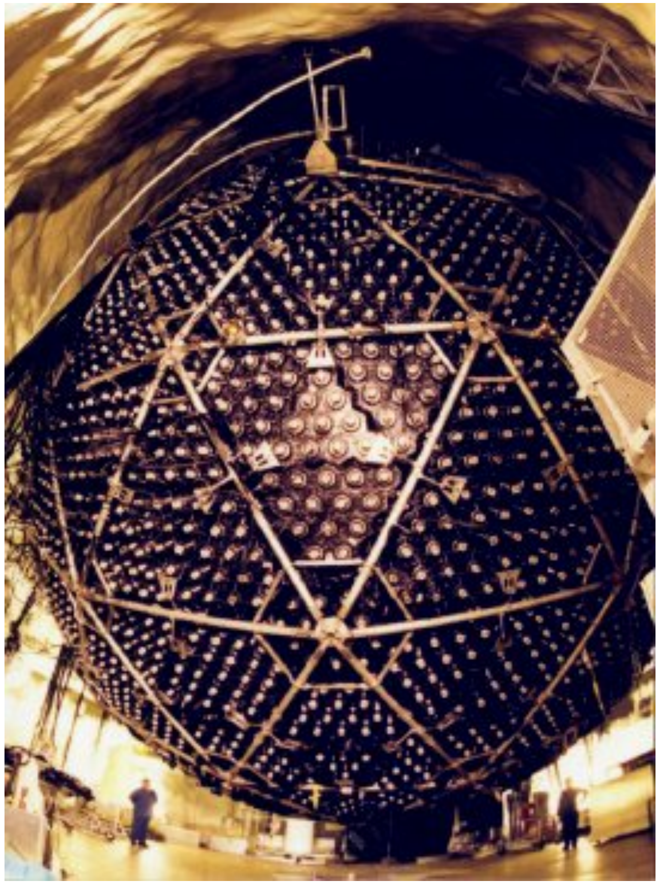
# Neutrino Scattering Experiments



# Neutrino Detectors SNO

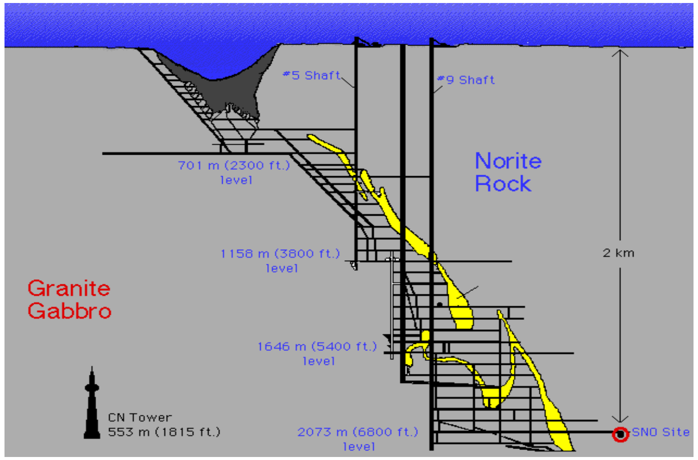
- 18m sphere, situated underground at about 2.5km underground, in Ontario
- 10,000 photomultiplier tubes (PMT)
- Each PMT collect Cherenkov light photons
- Heavy water ($D_2O$) inside a transparent acrylic sphere (12m diameter)
- Pure salt is added to increase sensitivity of NC reactions (2002)
- It can measure the flux of all neutrinos '$\Phi(\nu_x)$' and electron neutrinos '$\Phi(\nu_e)$'
- The flux of non-electron neutrinos

$$\Phi(\nu_\mu, \nu_\tau) = \Phi(\nu_x) - \Phi(\nu_e)$$



- These fluxes can be measured via the 3 different ways in which neutrinos interact with heavy water

# Sudbury Neutrino Observatory




**1000 tonnes $D_2O$**

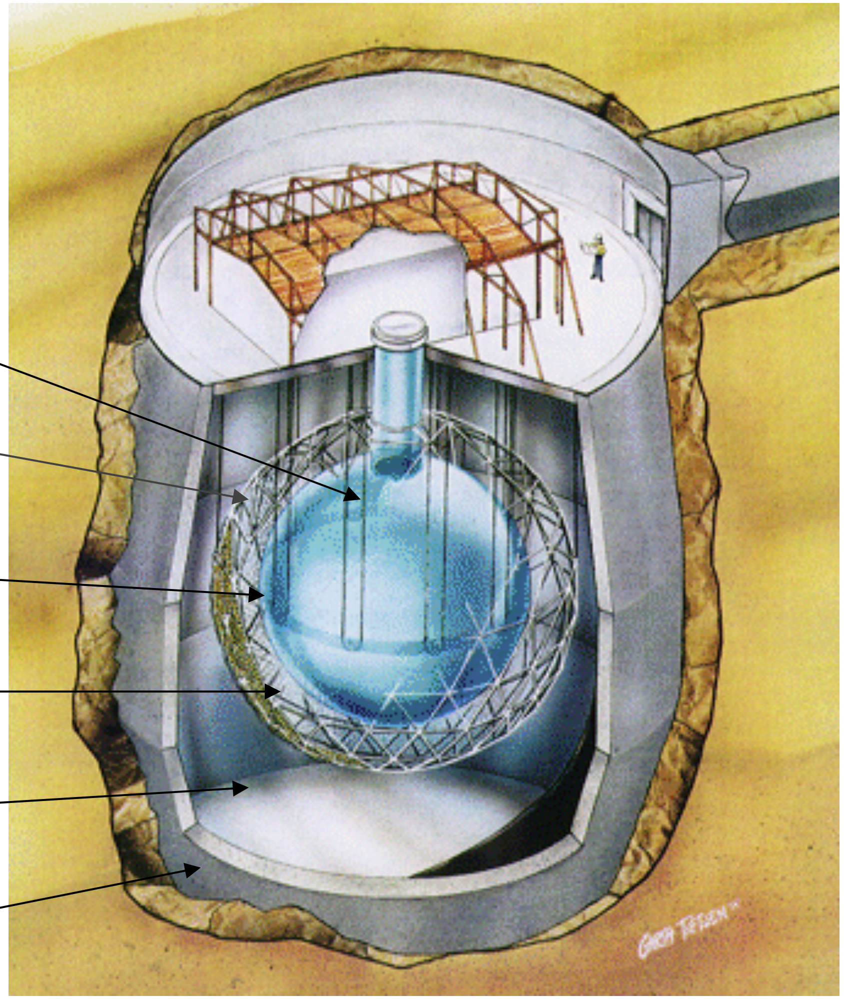
Support Structure for 9500 PMTs, 60% coverage

12 m Diameter Acrylic Vessel

1700 tonnes Inner Shielding $H_2O$

5300 tonnes Outer Shield $H_2O$

Urylon Liner and Radon Seal



# Astrofisica Nucleare e Subnucleare

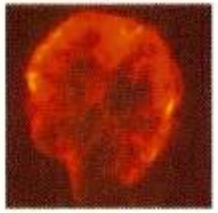
## Supernovae Neutrinos

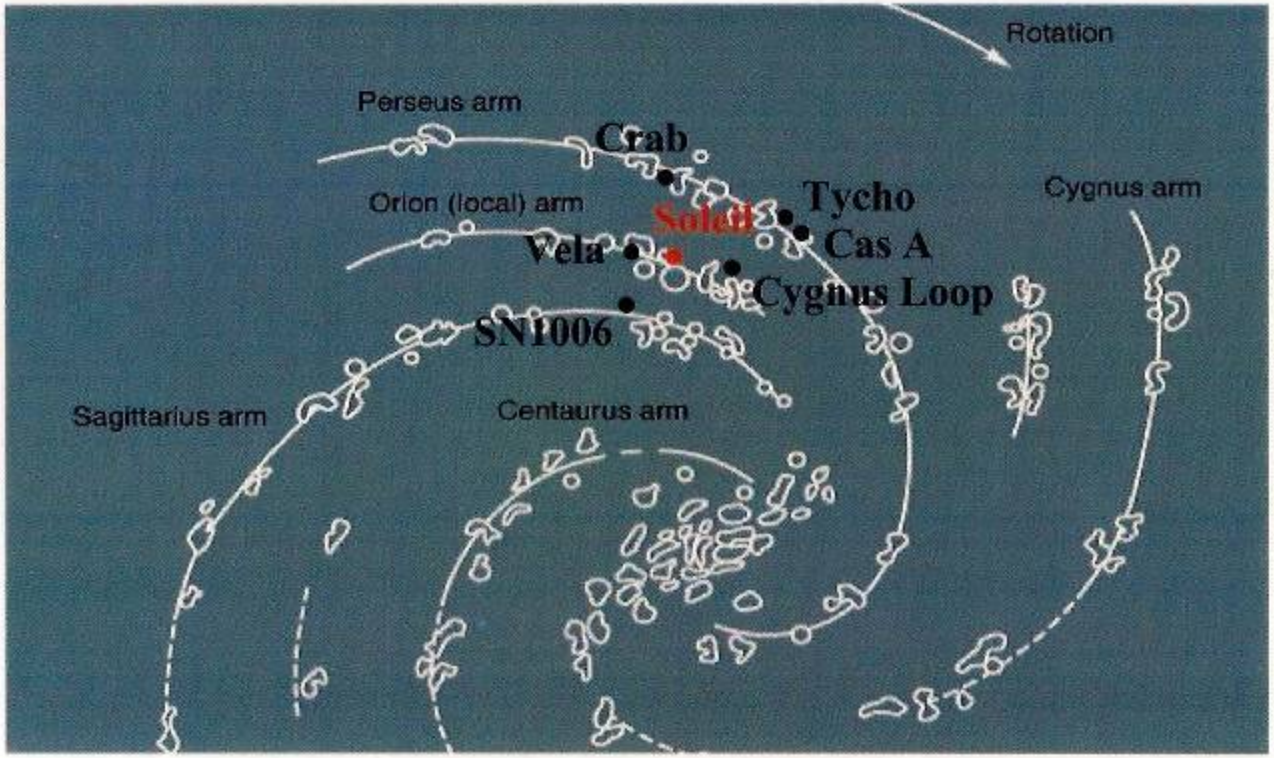
# SuperNovae Remnants

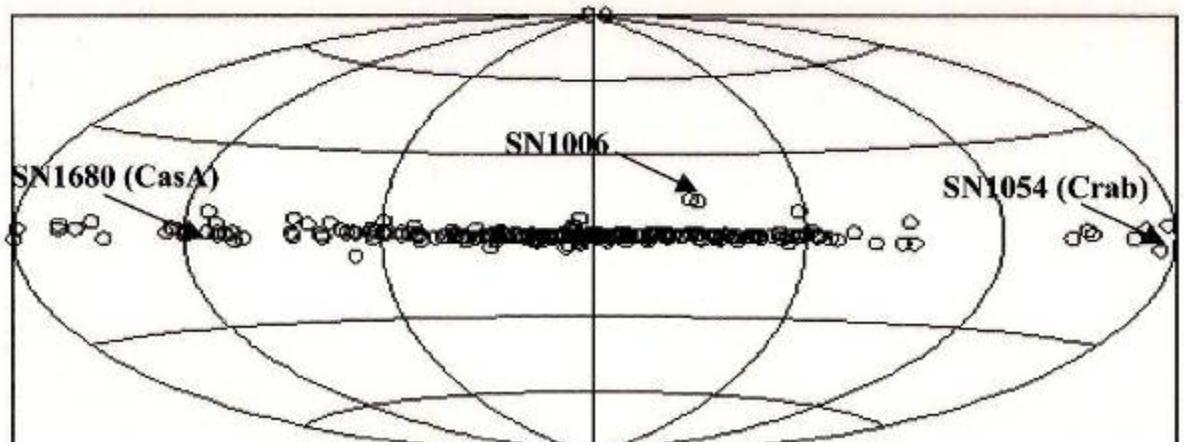
Vela

Tycho

Cygnus



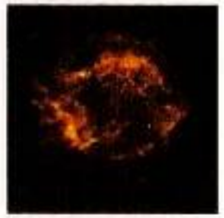


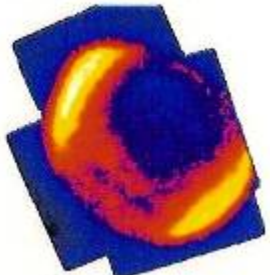

Crab

Kepler

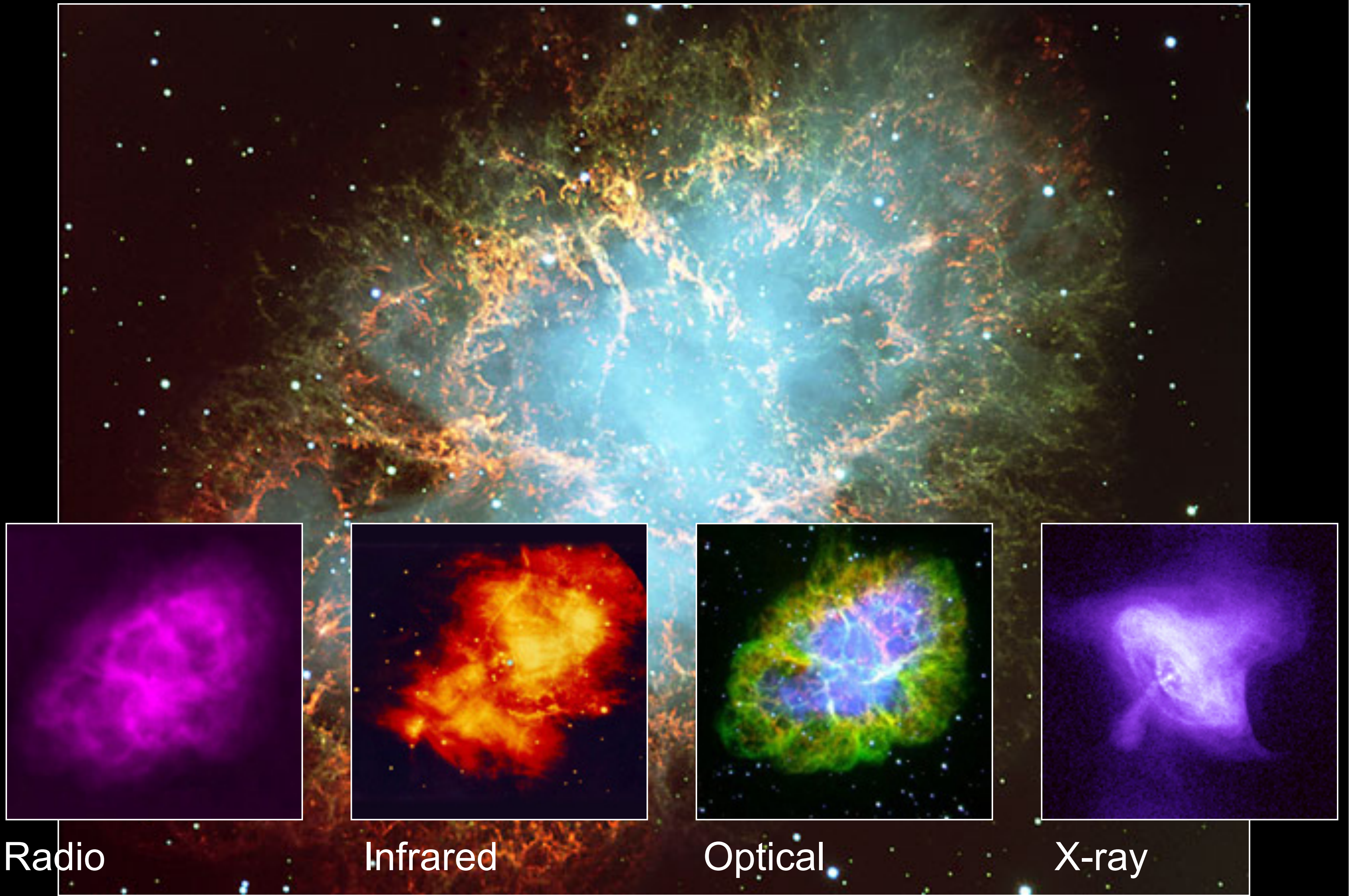
Cas A



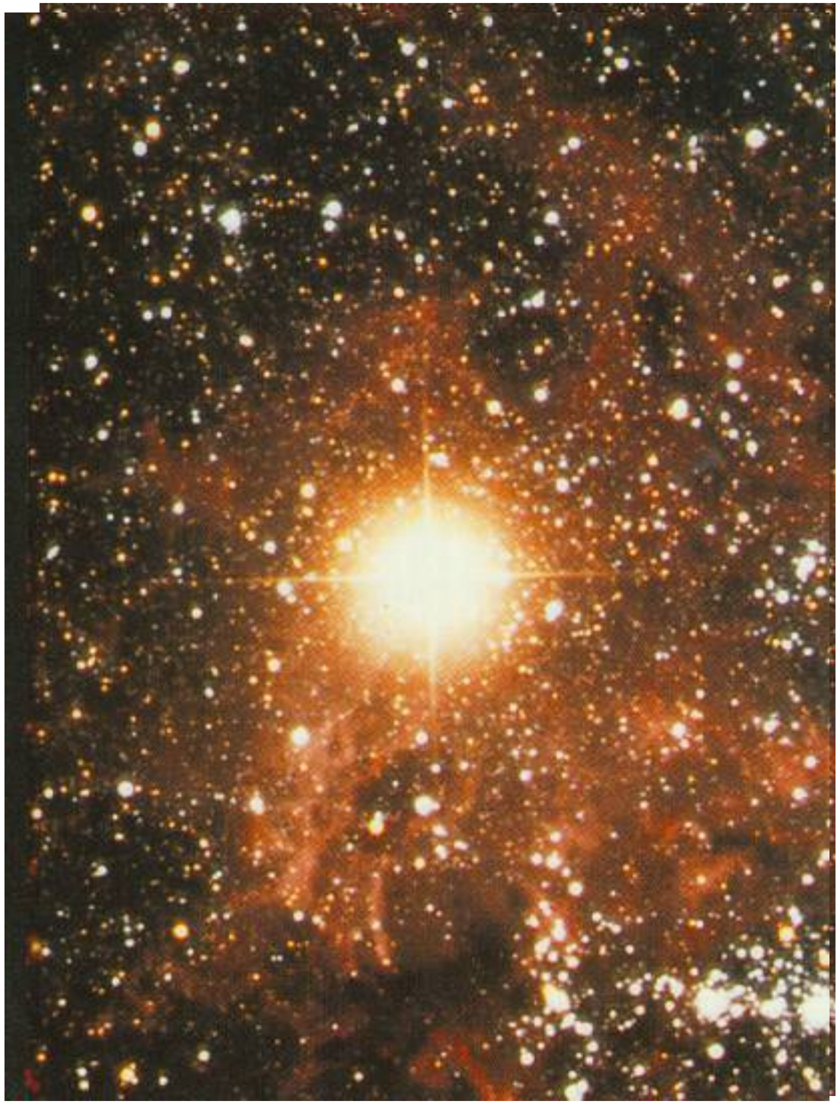
SN1006



# 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.

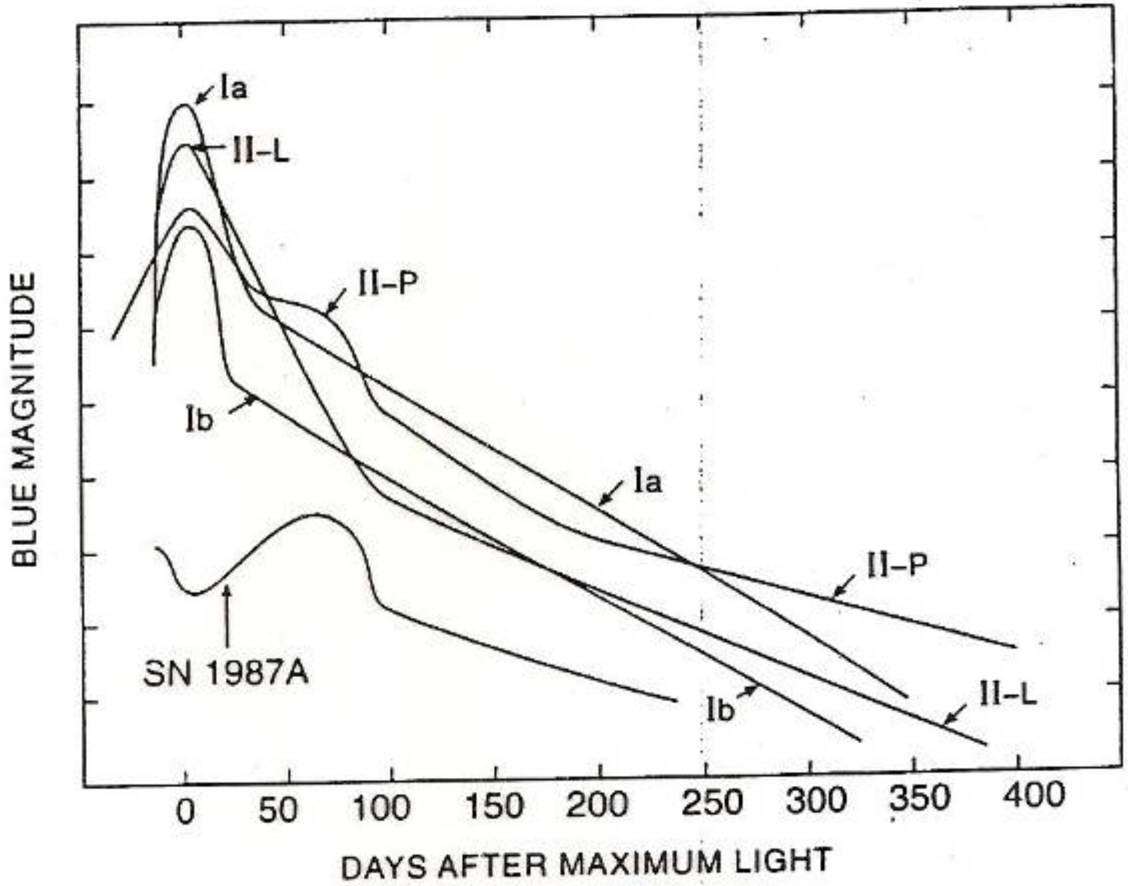
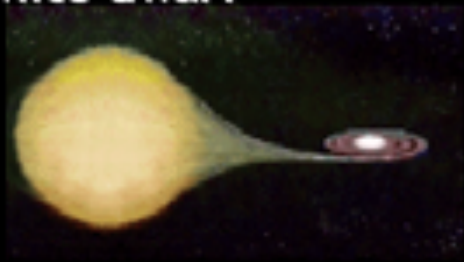
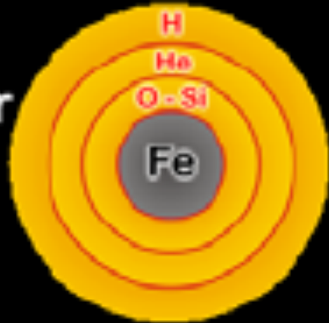



**Figure 13.3.** Brightness in the B-band for different supernova types. The deviation of supernova 1987a from the standard schemes can clearly be seen. Type II supernovae which have an almost linear decline after the maximum (II-L) are distinguished from those which remain almost constant over a longer 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)<br>• Accretes matter from companion | • Degenerate iron core of evolved massive star<br>• 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<br>→ Nuclear deflagration<br>("Fusion bomb" triggered by collapse) | Collapse to nuclear density<br>Bounce & shock<br>Implosion → Explosion |
| Powered by nuclear binding energy | Powered by gravity |
| Gain of nuclear binding energy<br>~ 1 MeV per nucleon | Gain of gravitational binding energy<br>~ 100 MeV per nucleon<br>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 | $0.36 \pm 0.11$ | $0.14 \pm 0.07$ | | $0.71 \pm 0.34$ |
| Observed | Total ~ 2000 as of today (nowadays ~200/year) | | | |

# Supernova types

**(a) Type Ia supernova**

- The spectrum has no hydrogen or helium lines, but does have a strong absorption line of ionized silicon (Si II).
- Produced by runaway carbon fusion in a white dwarf in a close binary system (the ionized silicon is a by-product of carbon fusion).

**(b) Type Ib supernova**

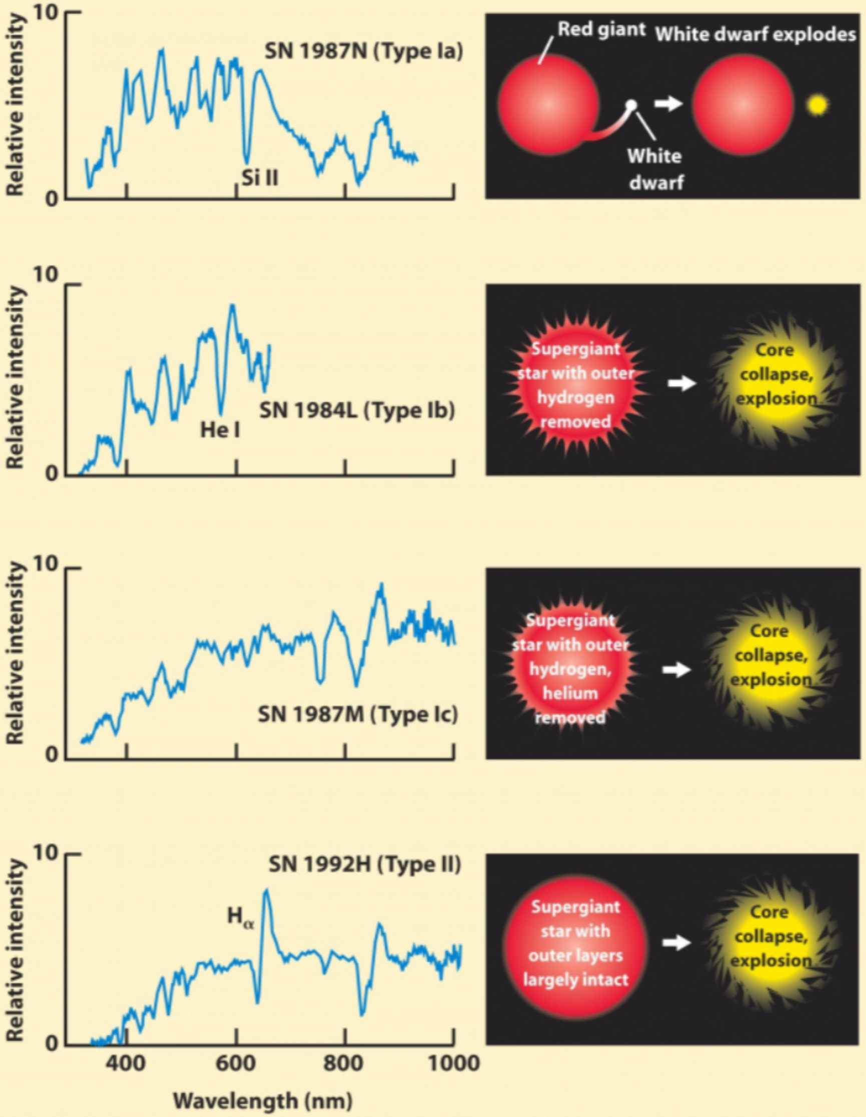
- The spectrum has no hydrogen lines, but does have a strong absorption line of un-ionized helium (He I).
- Produced by core collapse in a massive star that lost the hydrogen from its outer layers.

**(c) Type Ic supernova**

- The spectrum has no hydrogen lines or helium lines.
- Produced by core collapse in a massive star that lost the hydrogen and the helium from its outer layers.

**(d) Type II supernova**

- The spectrum has prominent hydrogen lines such as $H_\alpha$.
- Produced by core collapse in a massive star whose outer layers were largely intact.

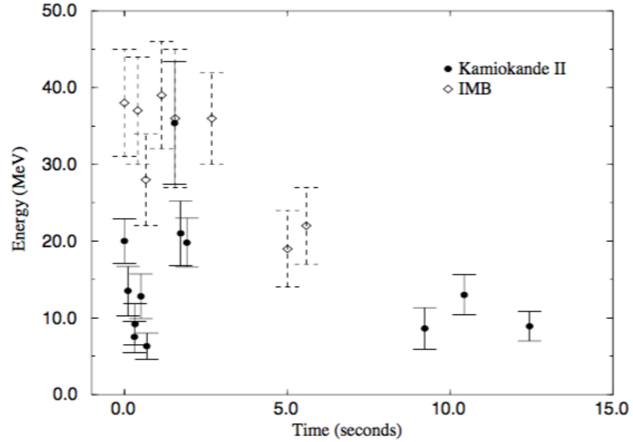


# SN1987A

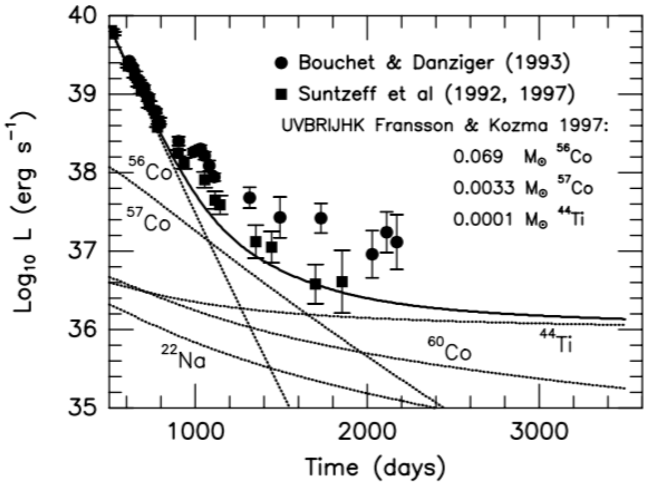
Type II supernova in LMC
(~ 55 kpc)

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

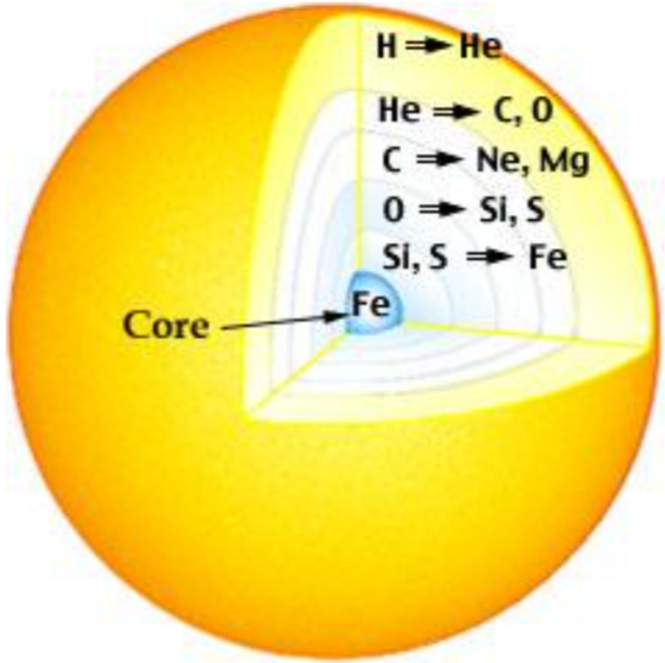
neutrinos $E_{\nu} \approx 2.7 \times 10^{53}$ erg



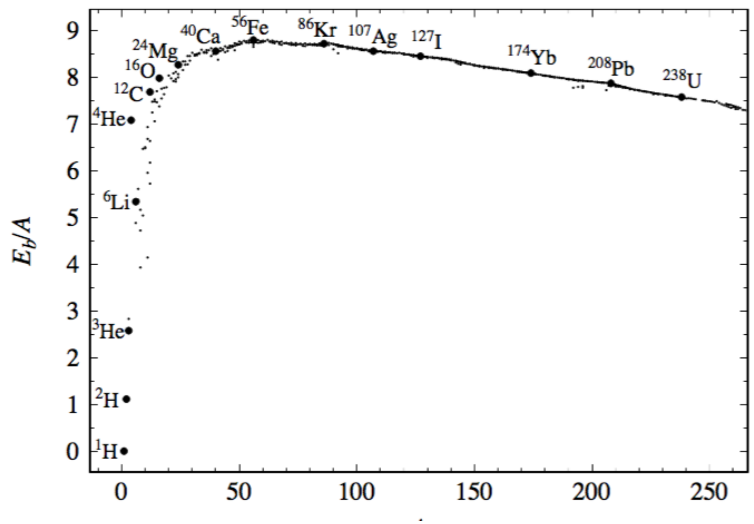

light curve



# Presupernova Star



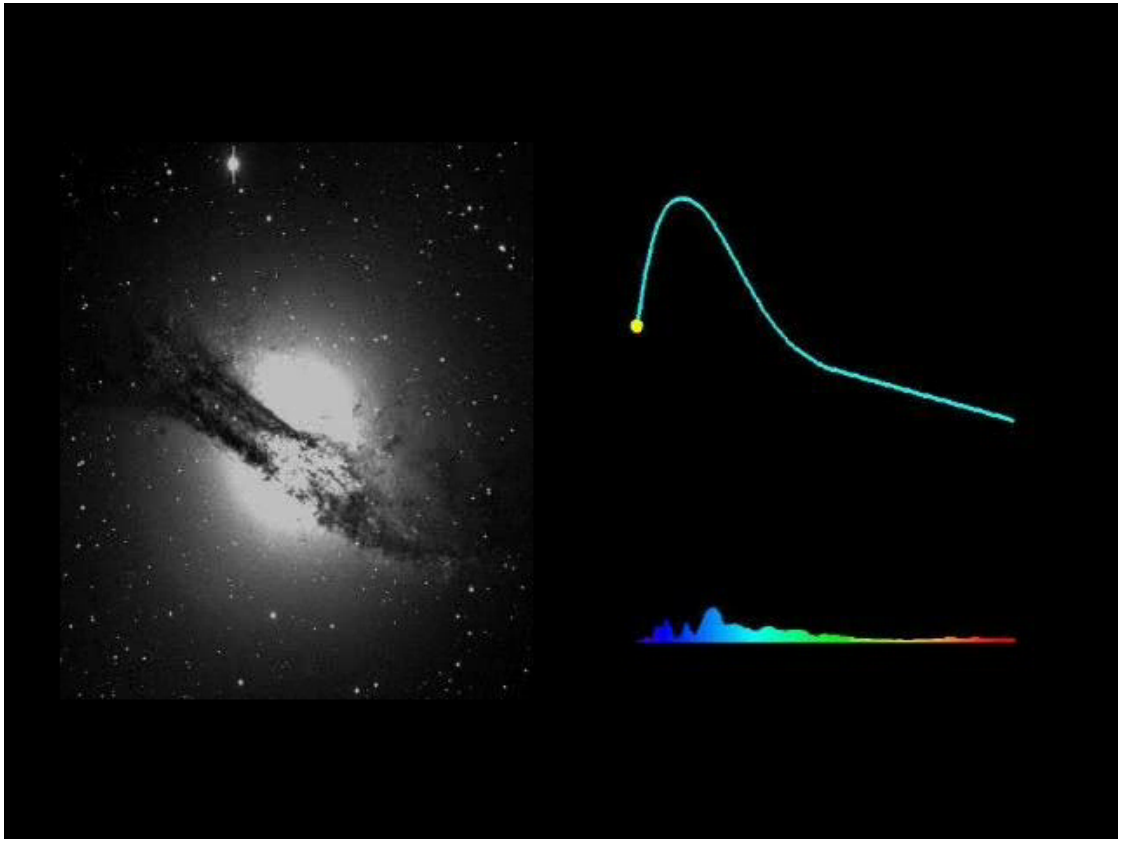

- Star has an onion like structure.
- Iron is the final product of the different burning processes.
- As the mass of the iron core grows it becomes unstable and collapses when it reaches around 1.4 $M_{\odot}$.



# Early iron core

- The core is made of heavy nuclei (iron-mass range $A = 45$–$65$) and electrons. Composition given by Nuclear Statistical Equilibrium. There are $Y_e$ electrons per nucleon.
- The mass of the core $M_c$ is determined by the nucleons.
- There is no nuclear energy generation which adds to the pressure. Thus, the pressure is mainly due to the degenerate electrons, with a small correction from the electrostatic interaction between electrons and nuclei.
- As long as $M_c < M_{\text{ch}} = 1.44(2Y_e)^2 M_\odot$ (plus slight corrections for finite temperature), the core can be stabilized by the degeneracy pressure of the electrons.

# Neutrinos from a Stellar Gravitational Collapse

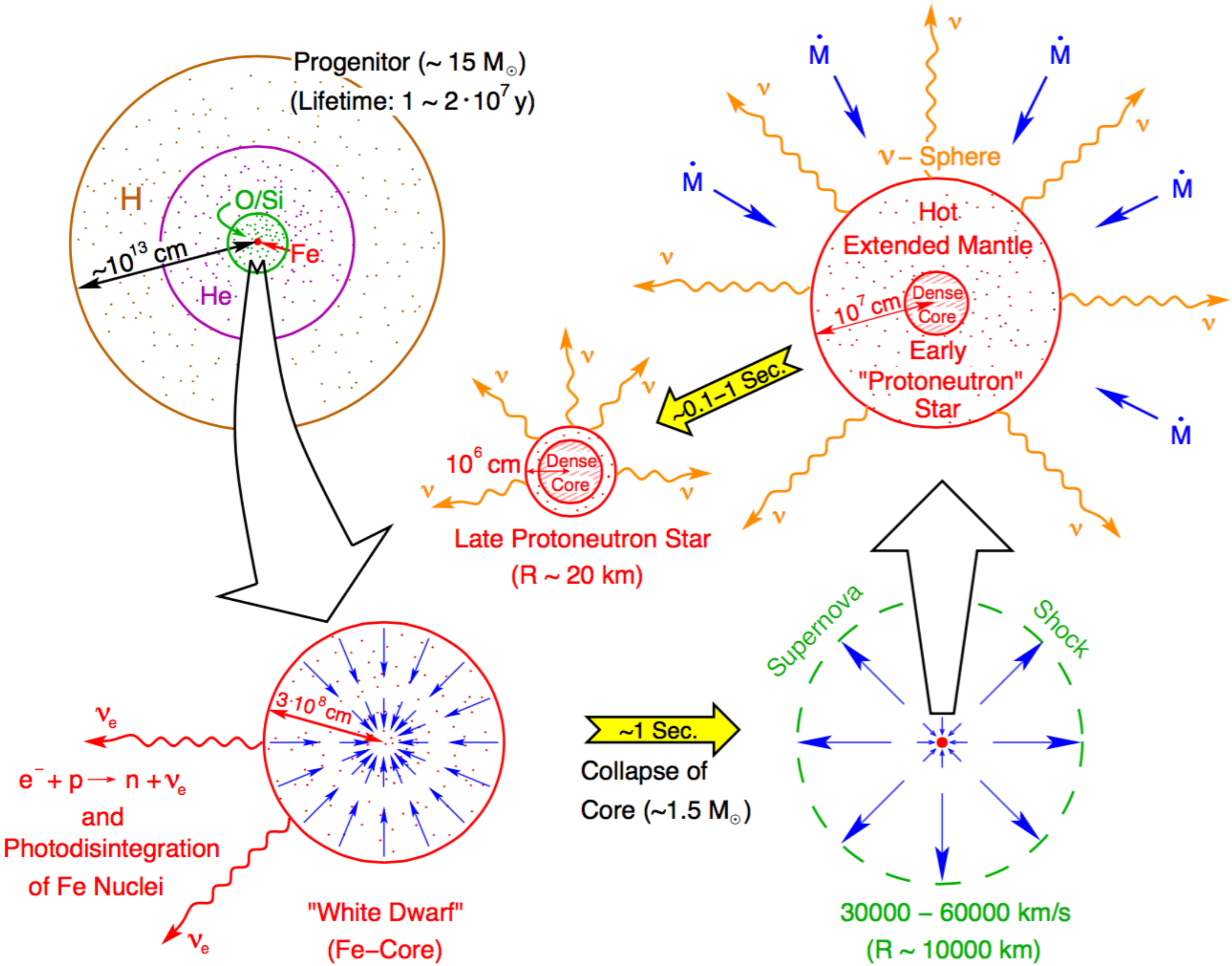


Una supernova nella Galassia Centaurus A.  Il clip è stato preparato dal “Supernova Cosmology Project” (P. Nugent, A. Conley) con l’aiuto del Lawrence Berkeley National Laboratory's Computer Visualization Laboratory (N. Johnston: animazione) al “ National Energy Research Scientific Computing Center”

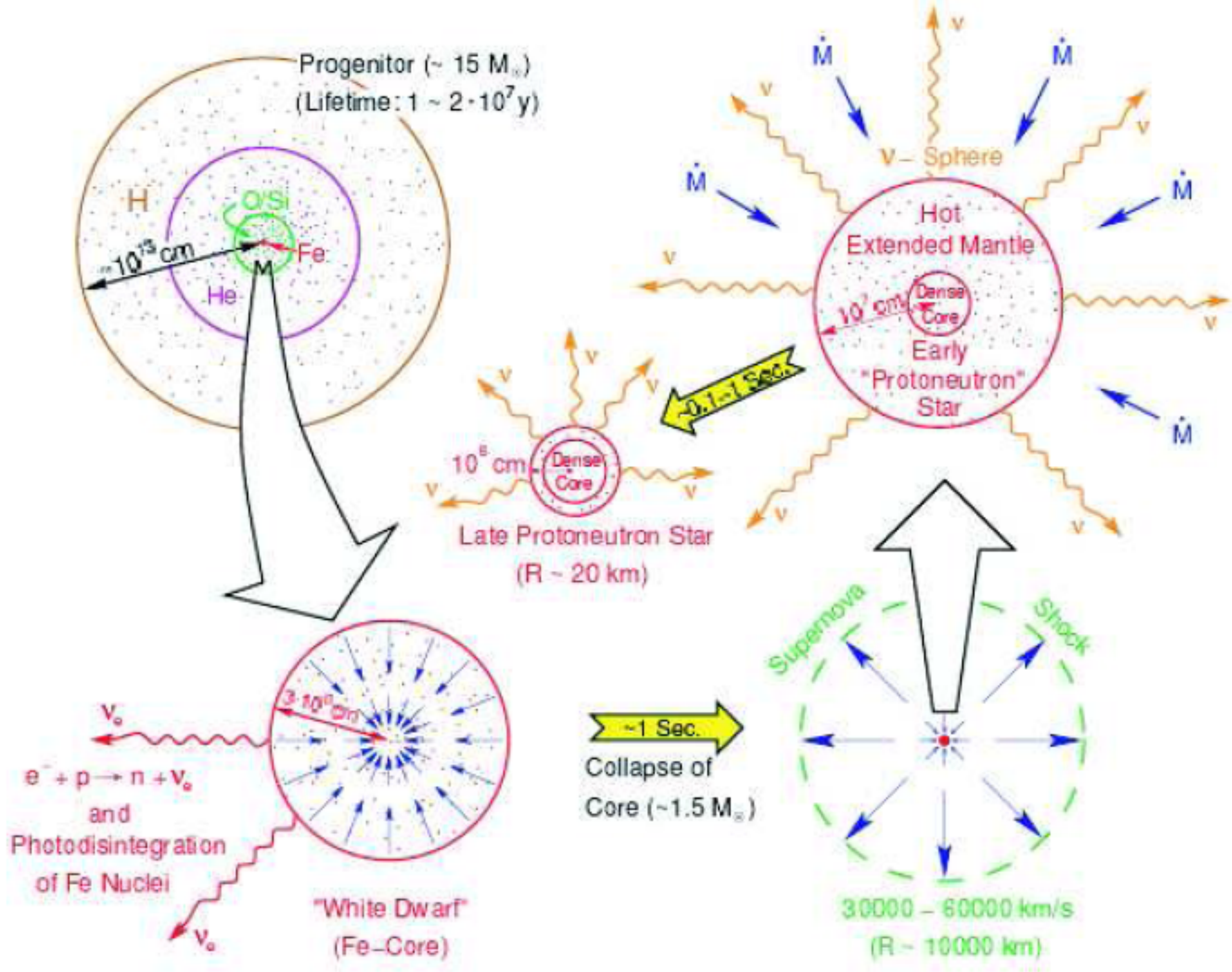
**http://supernova.lbl.gov**

- 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**.

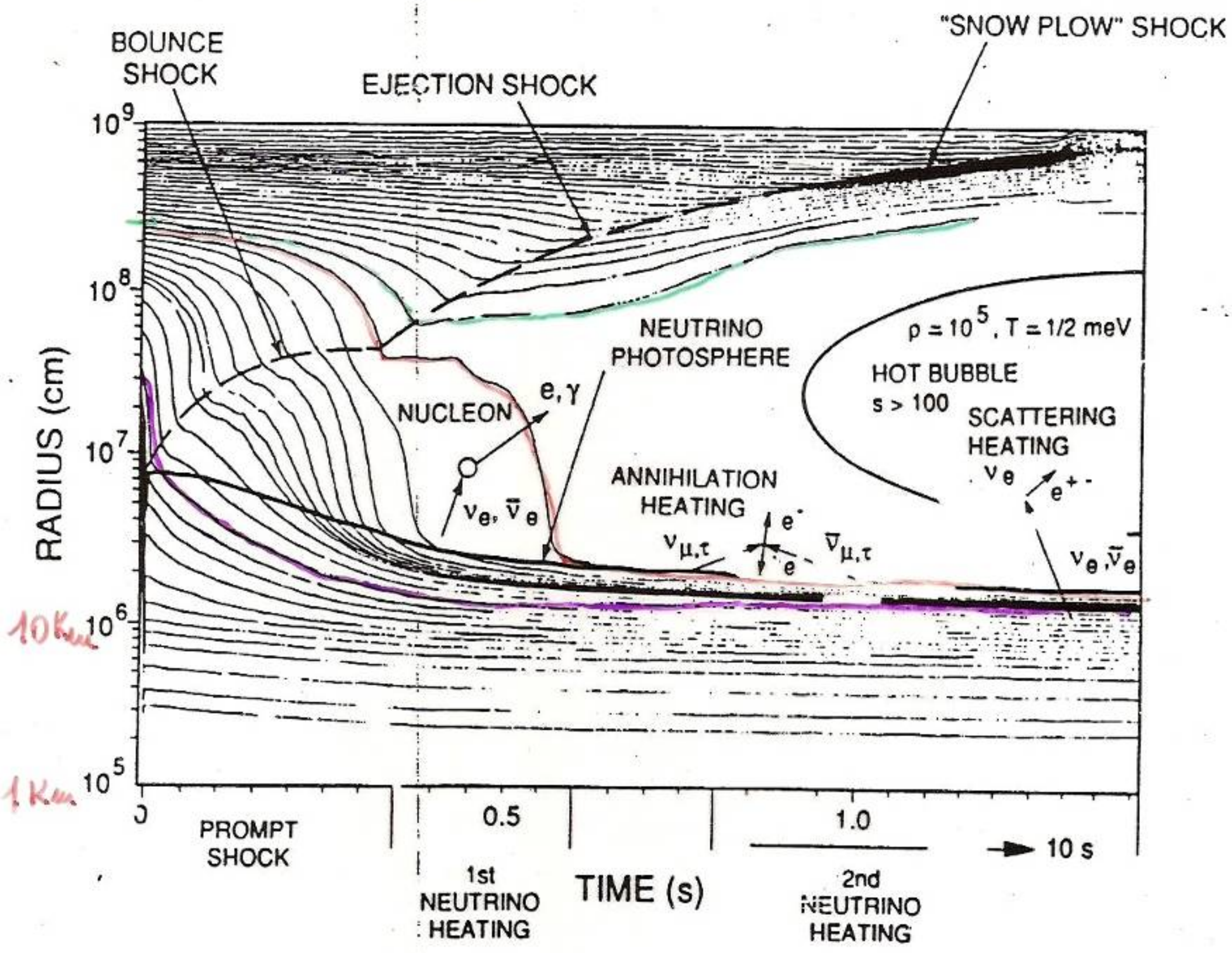
# Schematical Evolution



- 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), $v_e$, anti-$v_e$ and e+e− annihilation and nucleon bremsstrahlung (sources for all flavors of neutrinos including $v_\mu$, anti-$v_\mu$, $v_t$ and anti-$v_t$ ), in addition to electron capture.

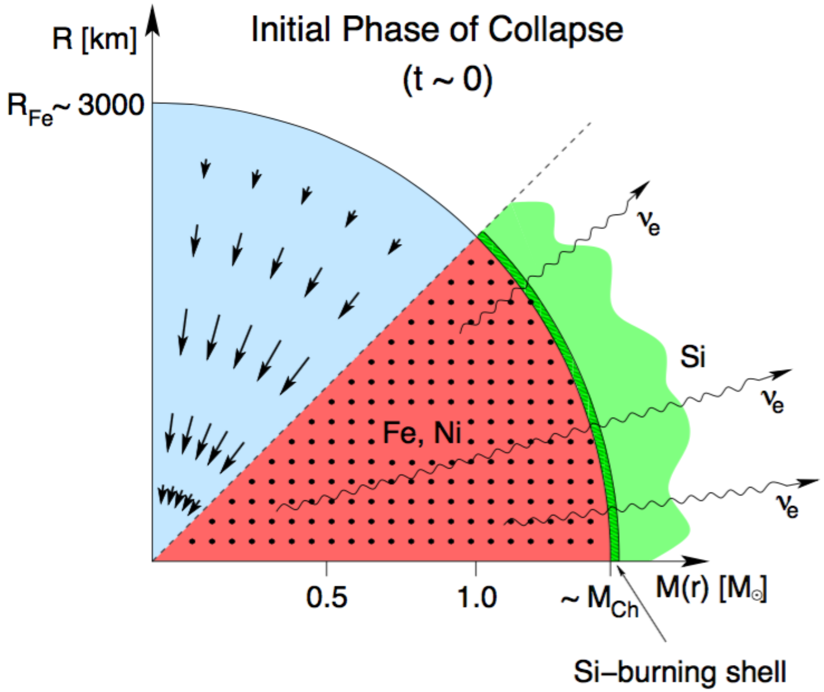



Schematic illustration of a SN explosion. The dense Fe core collapses in a fraction of a second and gets neutronized (lower-left). The inner core rebounds and gives rise to a shock-wave (lower-right). The protoneutron star cools by the emission of neutrinos.



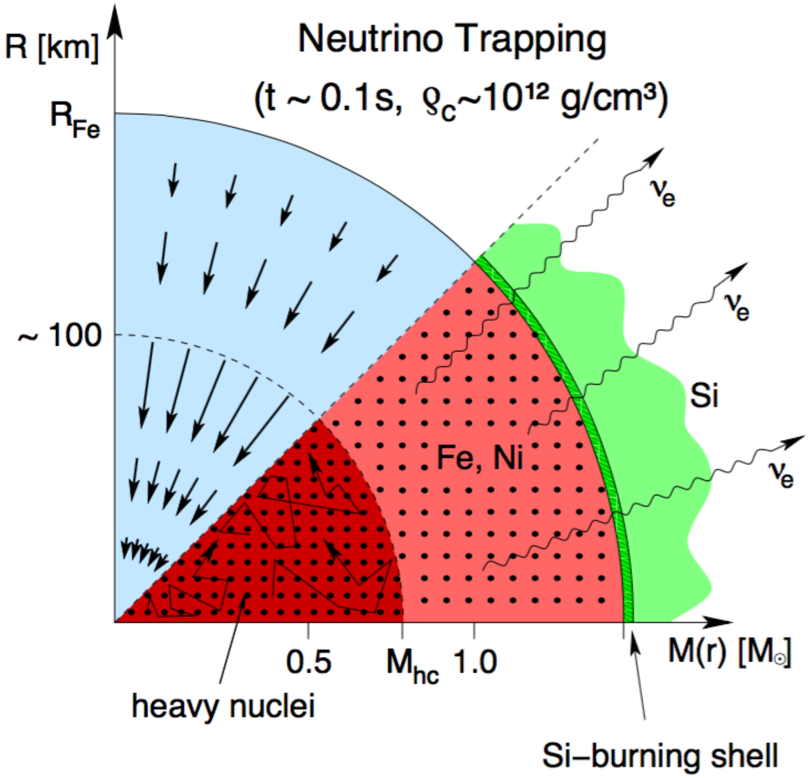
BOUNCE SHOCK
EJECTION SHOCK
"SNOW PLOW" SHOCK
10^9
10^8
10^7
10^6
10^5
10 Km
1 Km
RADIUS (cm)
NEUTRINO PHOTOSPHERE
ρ = 10^5, T = 1/2 meV
HOT BUBBLE
s > 100
NUCLEON
e, γ
ν_e, ν̄_e
SCATTERING HEATING
ANNIHILATION HEATING
ν_μ,τ
ν̄_μ,τ
e⁻
ν_e
e⁺⁻
ν_e, ν̄_e
0
0.5
1.0
→ 10 s
PROMPT SHOCK
1st NEUTRINO HEATING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

# Presupernova evolution




- $T = 0.1\text{–}0.8$ MeV, $\rho = 10^7\text{–}10^{10}$ g cm$^{-3}$. Composition of iron group nuclei.
- Important processes:
  - electron capture:
    $e^- + (N,Z) \to (N+1, Z-1) + \nu_e$
  - $\beta^-$ 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 ($M_{\rm ch} \approx 1.4(2Y_e)^2 M_\odot$)

# Collapse phase



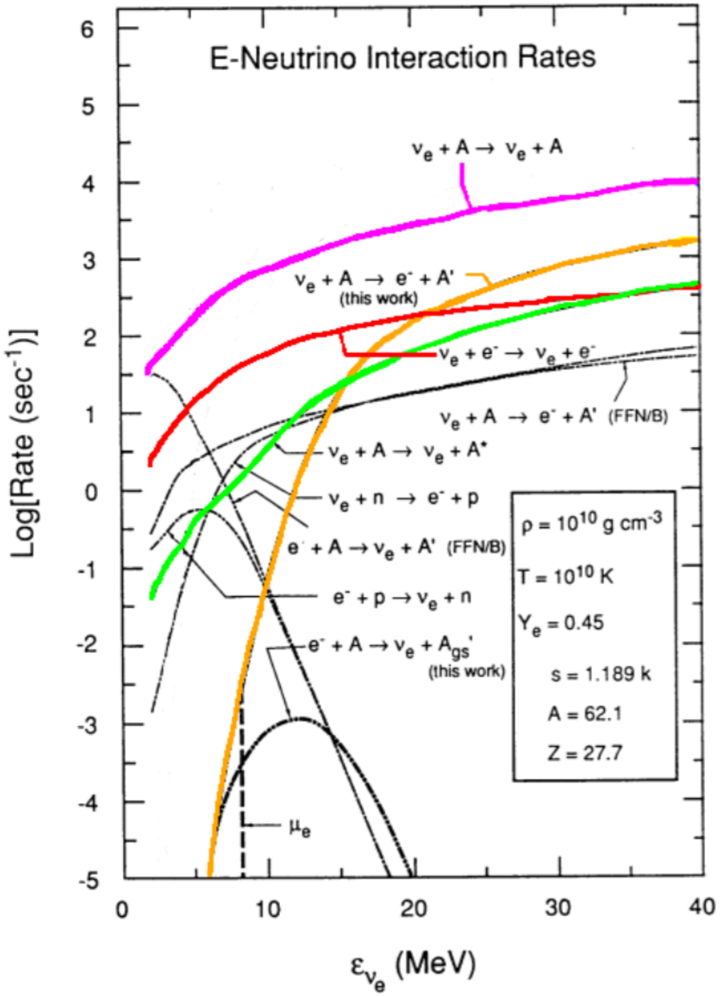

Important processes:

- 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:
  $e^- + A(Z,N) \rightleftarrows A(Z-1,N+1) + \nu_e$

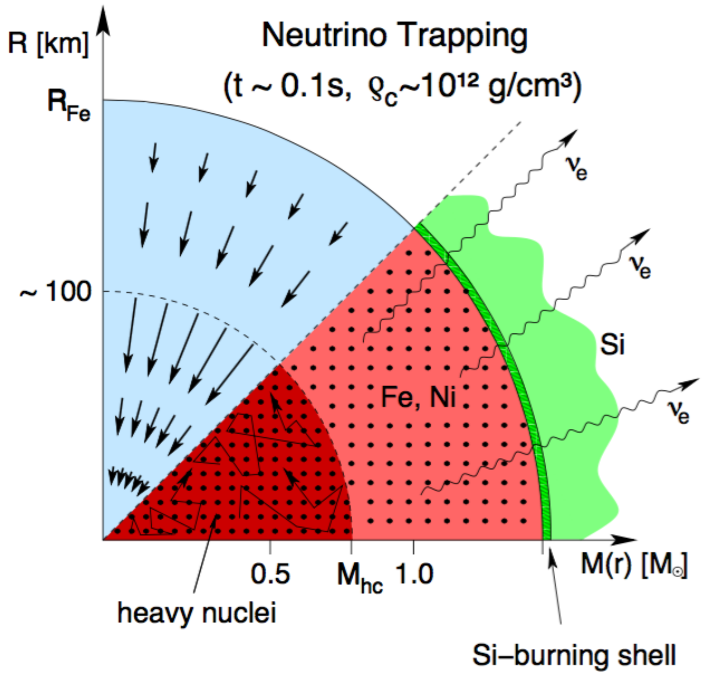
# Neutrino interactions in the collapse

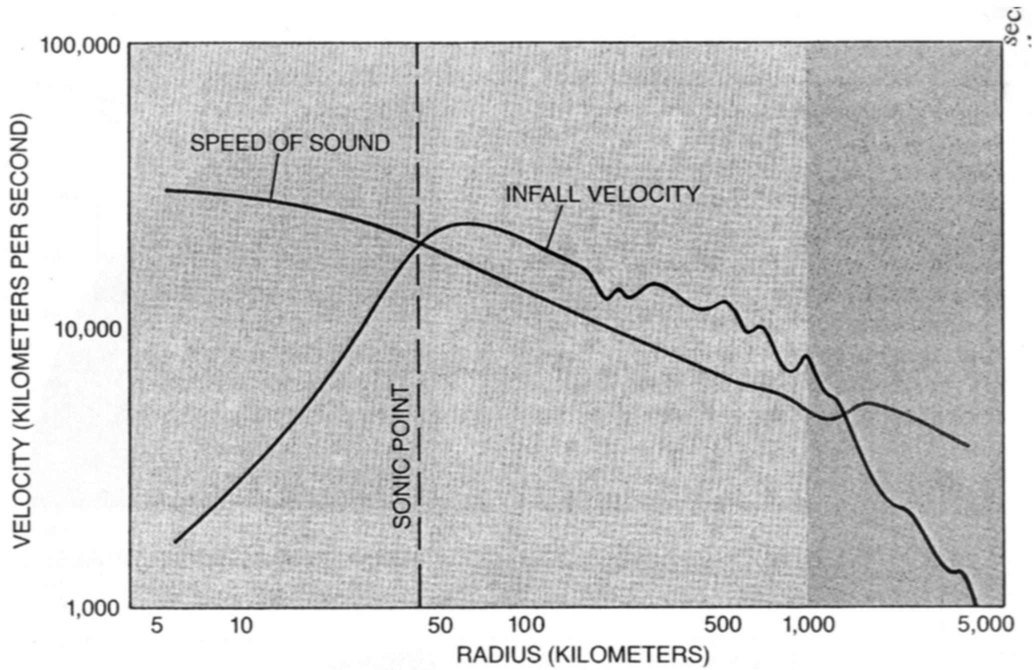
Bruenn and Haxton (1991)
Based on results for $^{56}$Fe




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

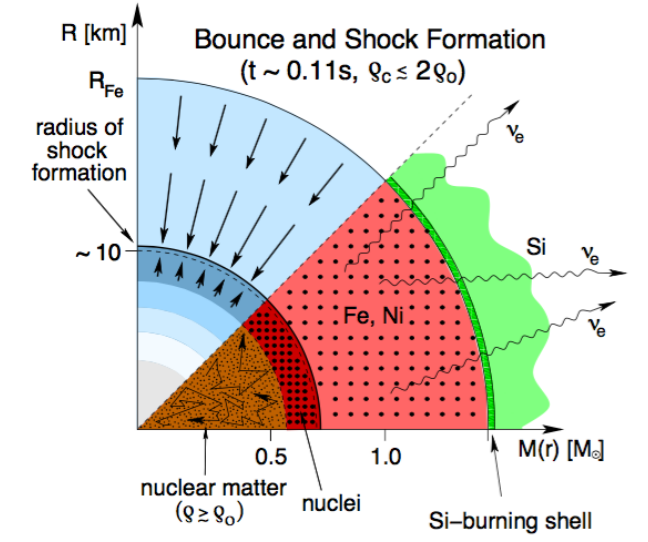
# Homologous collapse

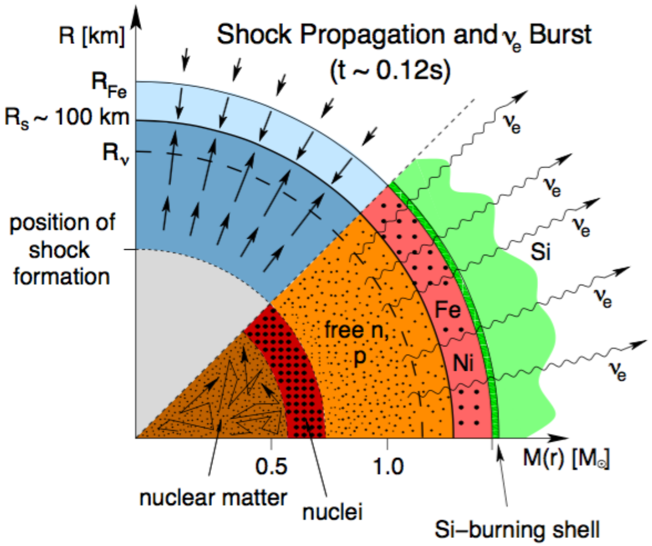



- After thermalization an inner homologous core forms in which the local sound velocity is larger than the infall velocity.
- Matter in the outer core falls at supersonic velocities.

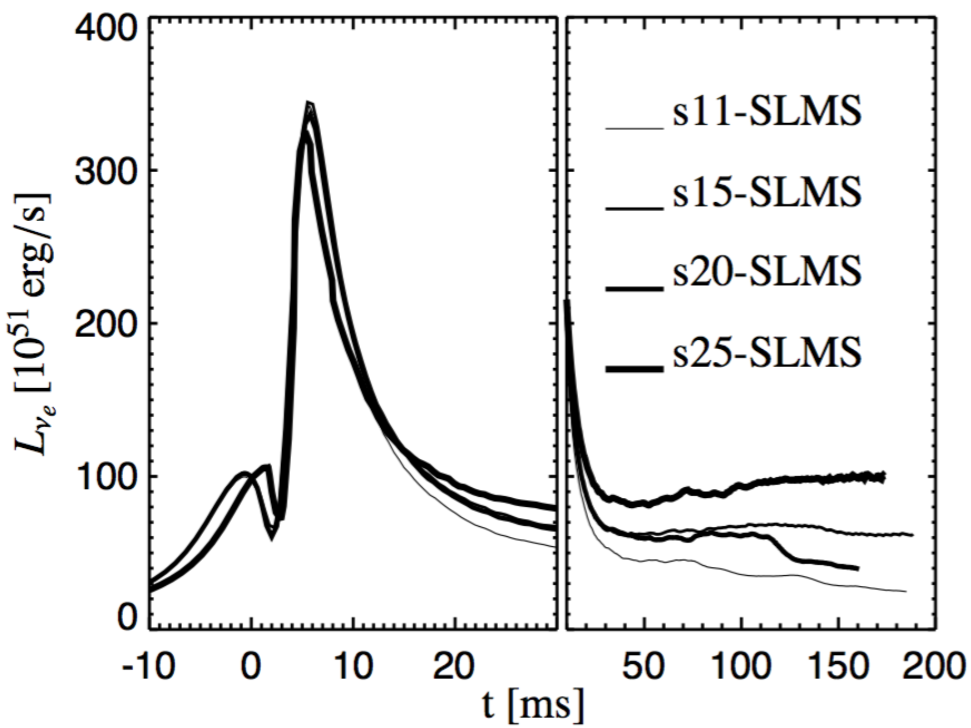
# Bounce and $\nu_e$ burst



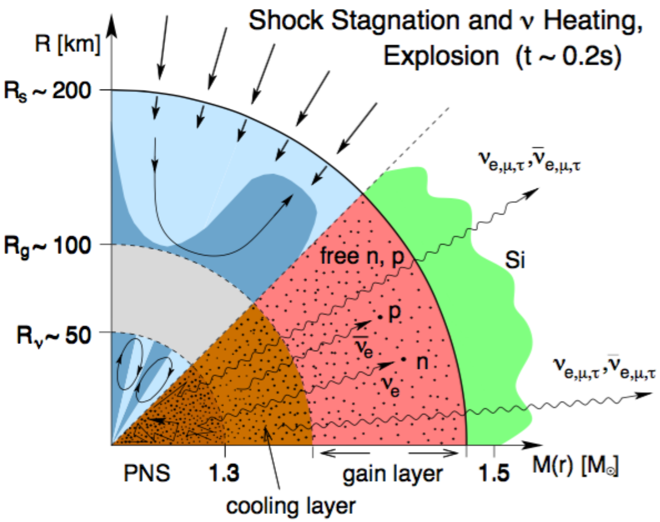

- Collapse continues until central density becomes around twice nuclear matter density.
- Sudden increase in nuclear pressure stops the collapse and a shock wave is launched at the sonic point. The energy of the shock depends on the Equation of State.
- The passage of the shock dissociates nuclei into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

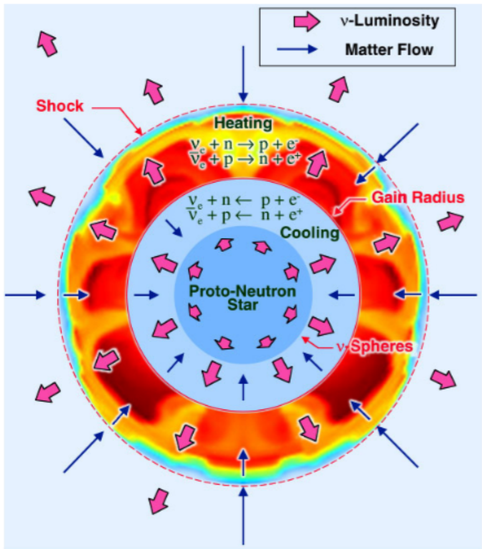
# Neutrino burst




- 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.

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

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

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

# Naked eye Supernovae


**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:**

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

**This shows up as**

| | |
|---|---|
| 99% | Neutrinos |
| 1% | Kinetic energy of explosion<br>(1% of this into cosmic rays) |
| 0.01% | Photons (outshine host galaxy) |

**Neutrino luminosity**

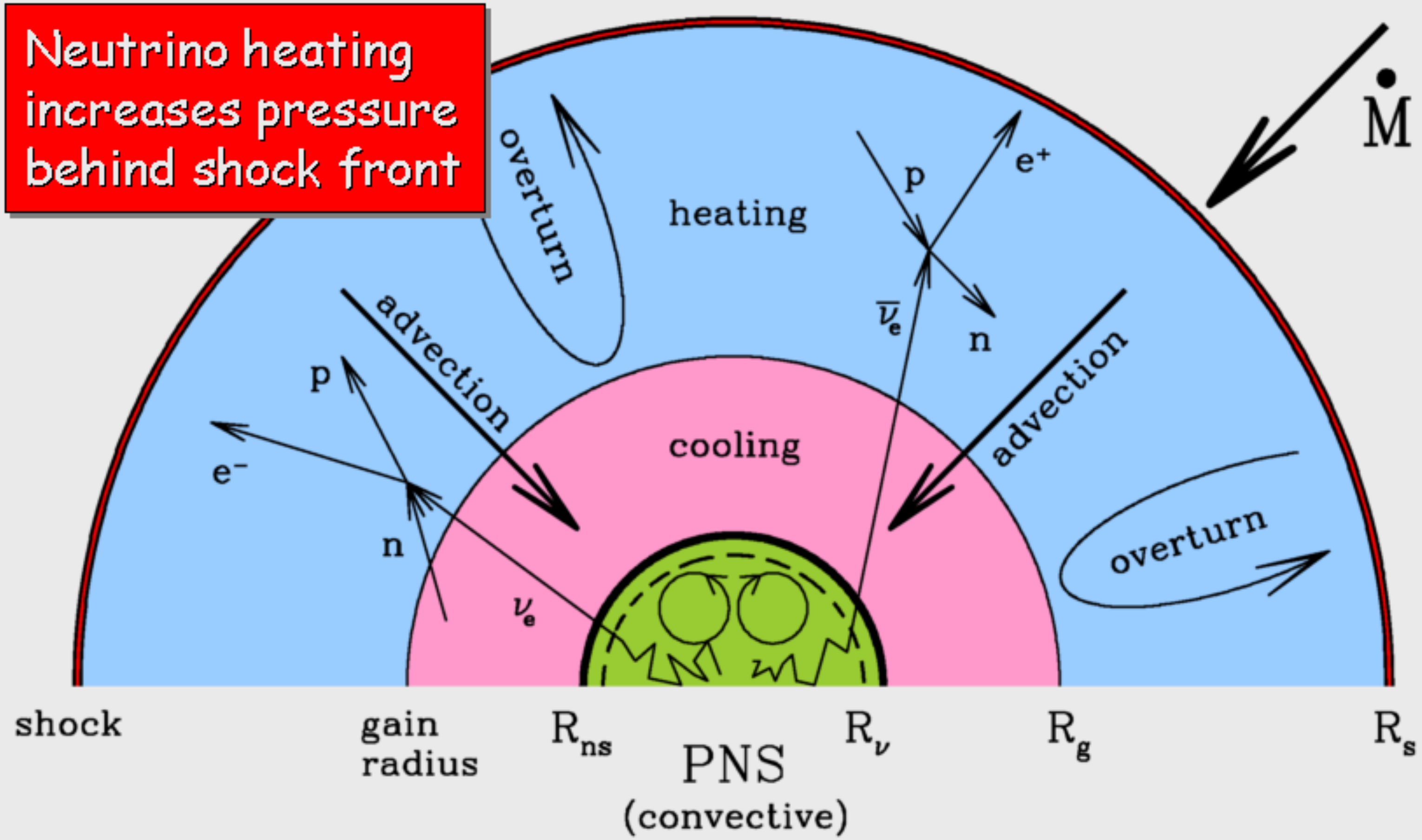
$$L_\nu \approx 3\times10^{53}\ \text{erg} / 3\ \text{sec} \approx 3\times10^{19}\ L_{SUN}$$

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

# Neutrinos to the Rescue

Adapted from Janka, astro-ph/0008432

Neutrino heating increases pressure behind shock front

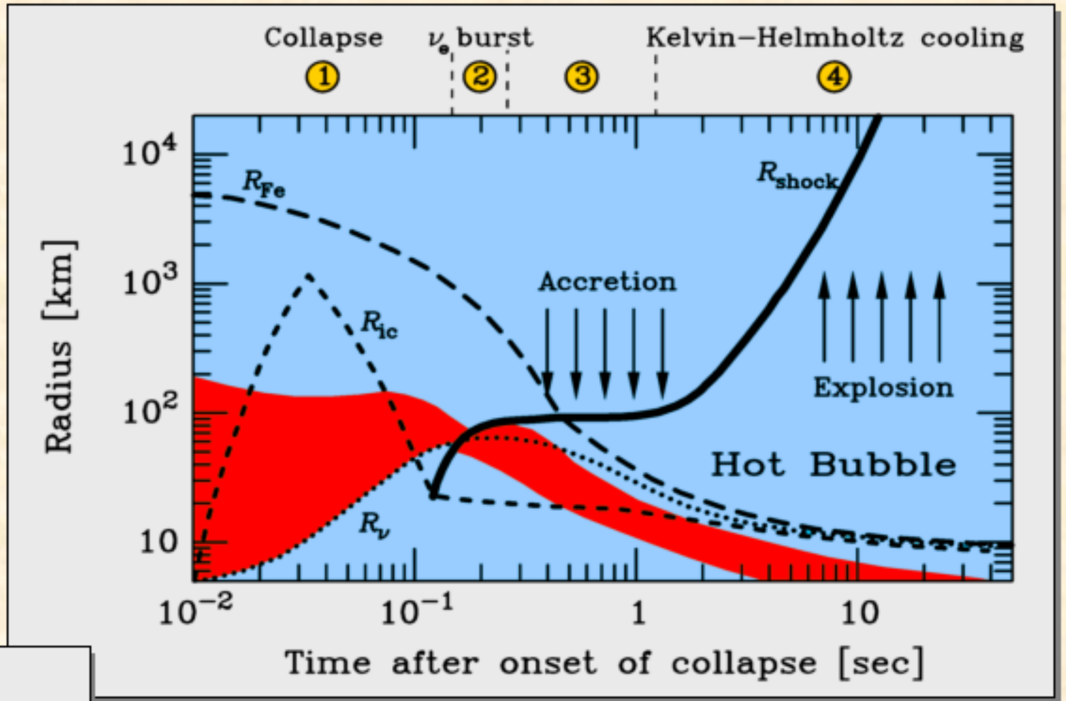


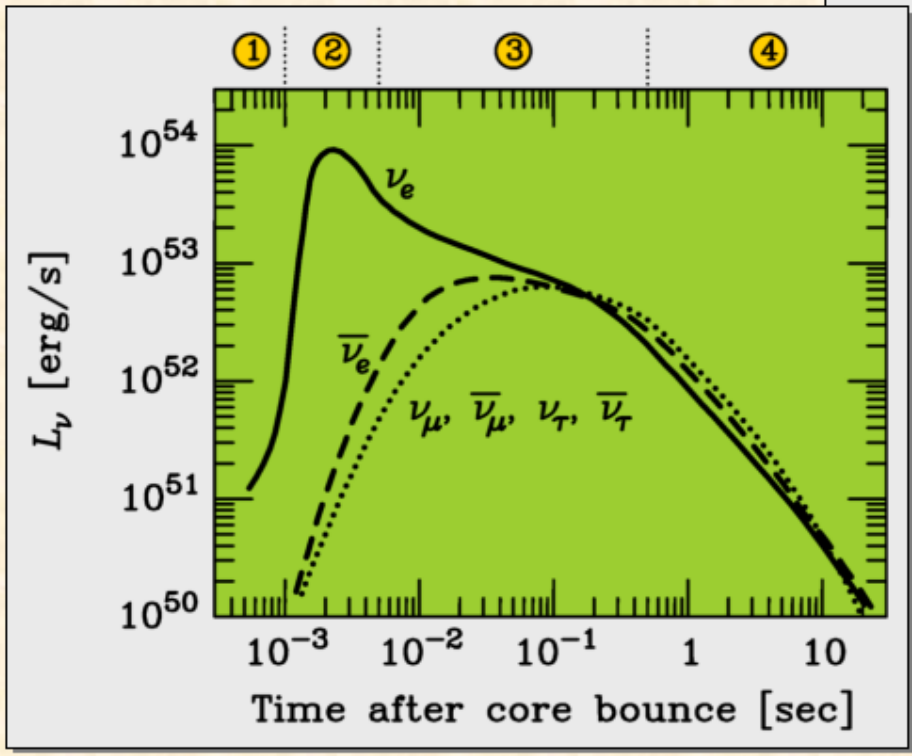

Heating mostly by β processes ($\nu_e + n \to p + e^-$ and $\bar{\nu}_e + p \to n + e^+$)
Pair annihilation ($\nu + \bar{\nu} \to e^- + e^+$) negligible

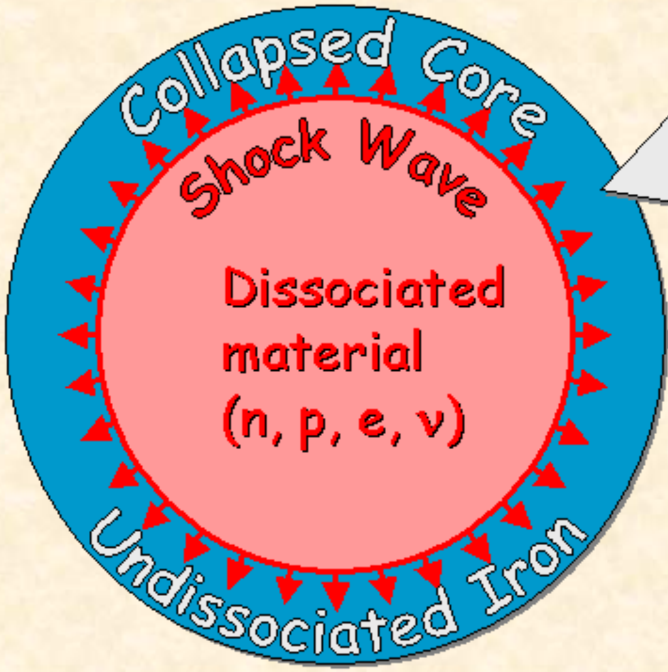
Mu- and tau-neutrino fluxes and spectra not crucial for explosion

# Supernova Neutrino Signal

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



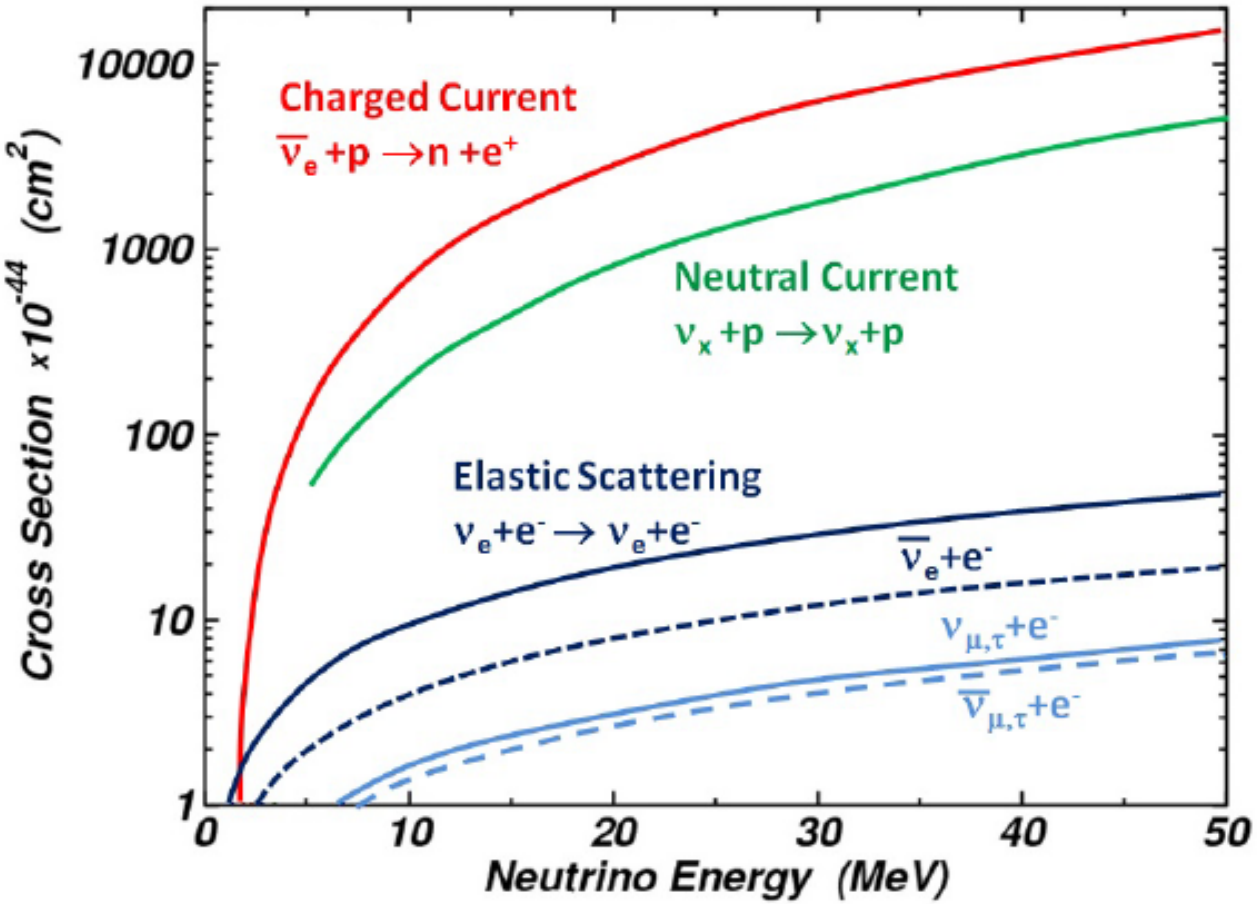




Traps neutrinos and lepton number of outer core layers

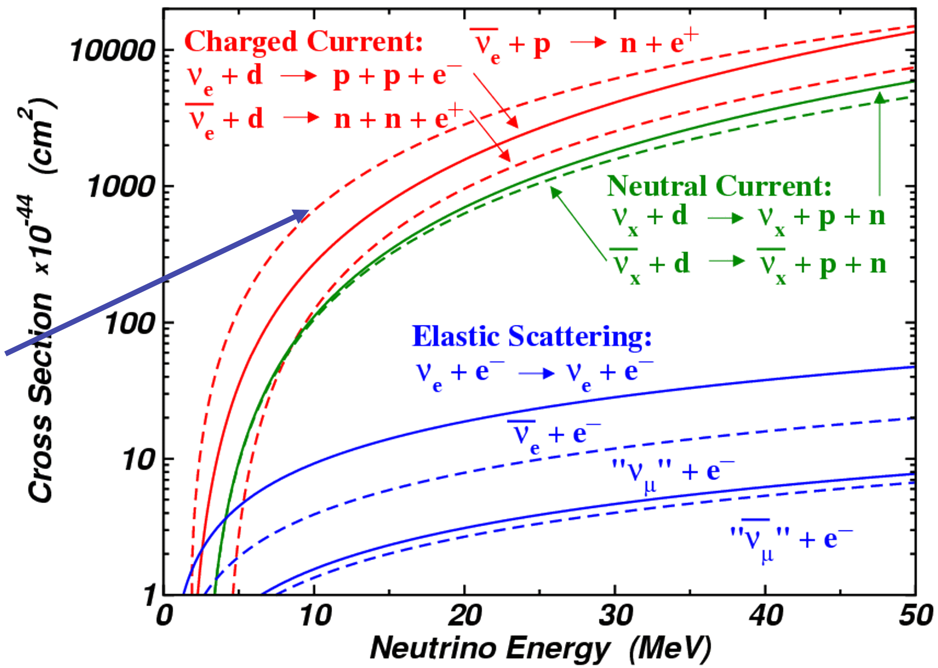
Georg Raffelt, Max-Planck-Institut für Physik (München)

# 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, $\nu_e$ only

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

- *Thermalization:* ~10 s
- $3\times10^{53}$ erg
- $L_{\nu_e}(t) \approx L_{anti-\nu_e}(t) \approx L_{\nu_x}(t)$

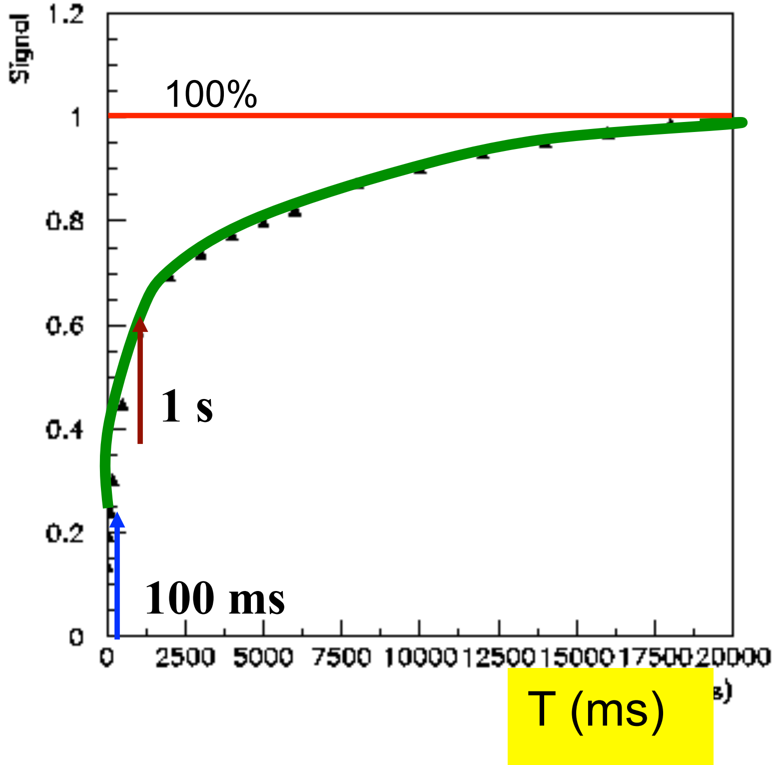
$$e^- + e^+ \rightarrow \bar{\nu} + \nu$$

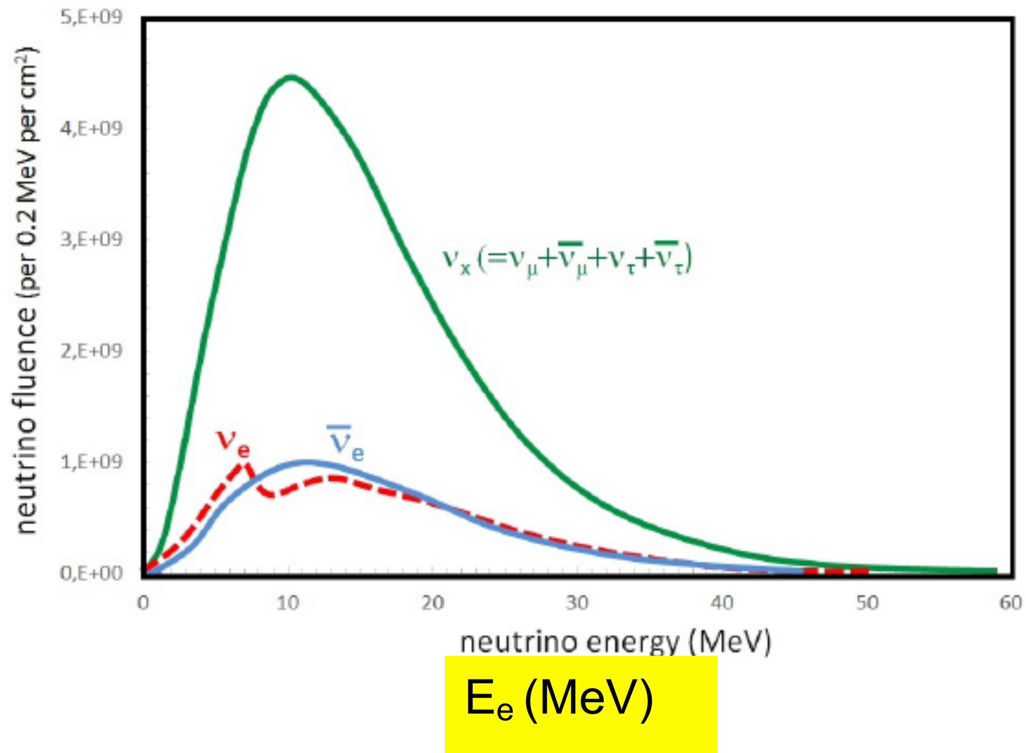
Detection: mainly through $\bar{\nu}_e + p \rightarrow n + e^+$

~300 events/kt (@GC)

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

# Time-energy




(a)

**(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 $\nu_e$ energy ≈ 16 MeV = 2.5 $10^{-5}$ erg
3- $N_{source}$= (1/6) × 2.5 $10^{53}$/ (2.5 $10^{-5}$)= 1.7 $10^{57}$ $\nu_e$

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: $\sigma(anti\nu_e+p)$ ~ **2x$10^{-41}$ $cm^2$**

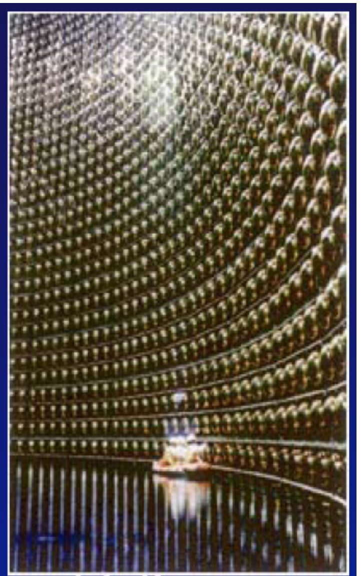
8- $N_{e^+}$ = F ($cm^{-2}$)× σ ($cm^2$)× $N_t$ ($kt^{-1}$)= 0.5 $10^{10}$ × 2x$10^{-41}$× 0.7 $10^{32}$
= 7 positrons/kt
9 – M(Kam II) = 2.1 kt, efficiency ε~ 80%
10 – Events in Kam II = 7 x 2.1 x ε ~ **12 events**

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

# The Detectors

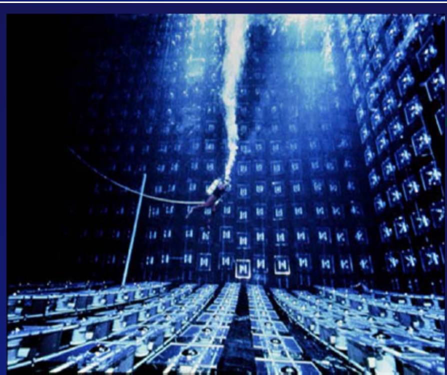
- Water Cherenkov detectors
  - Kamiokande (Japan)
  - IMB (Ohio)
- Liquid scintillation telescopes
  - Baksan – USSR Academy of Sciences, in North Caucasus Mountains, Russia
  - Mont Blanc – Italian Soviet collaboration, in Mont Blanc Laboratory, France

# 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

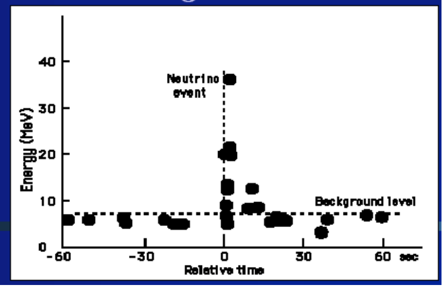
# IMB



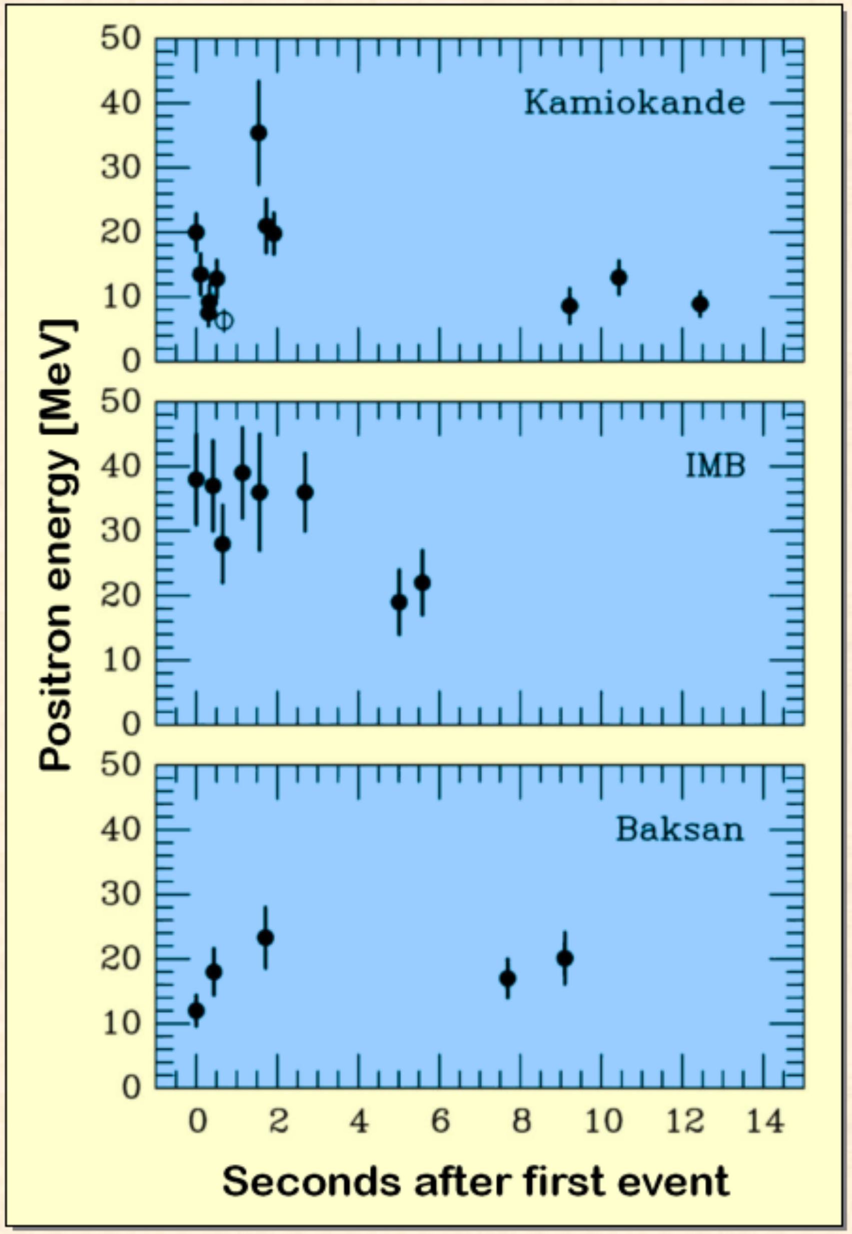
- Located in the Morton Thiokol mine in Ohio
- 580m underground
- Rectangular tank
  - 18 by 17 by 23 m
- 2048 8” photomultipliers
- 2.5 million gallons of water
- Compared to Kamiokande II: Larger volume, but not as deep

# 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



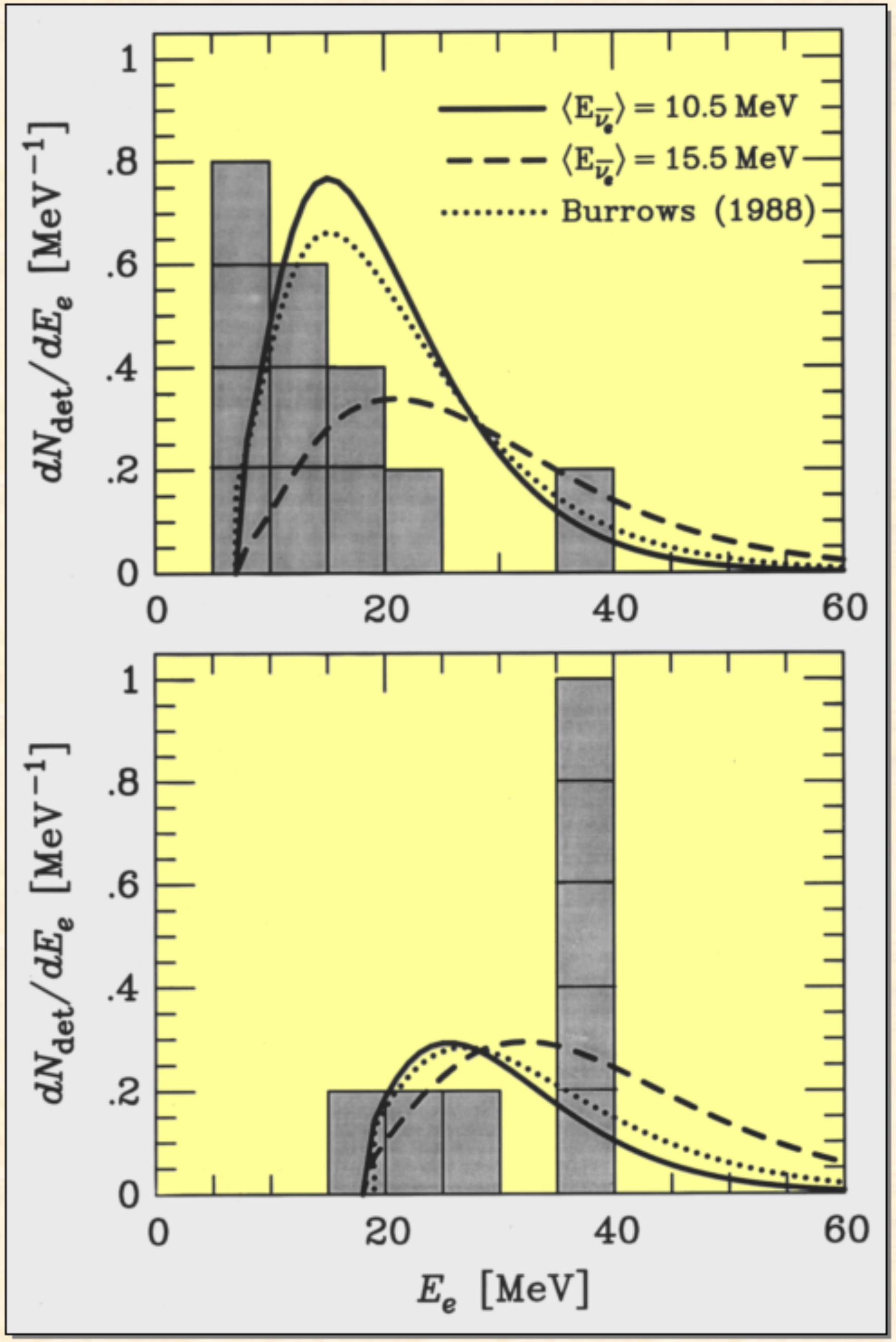

Kamiokande (Japan)
Water Cherenkov detector
Clock uncertainty ±1 min

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)

# Neutrino mass from SN

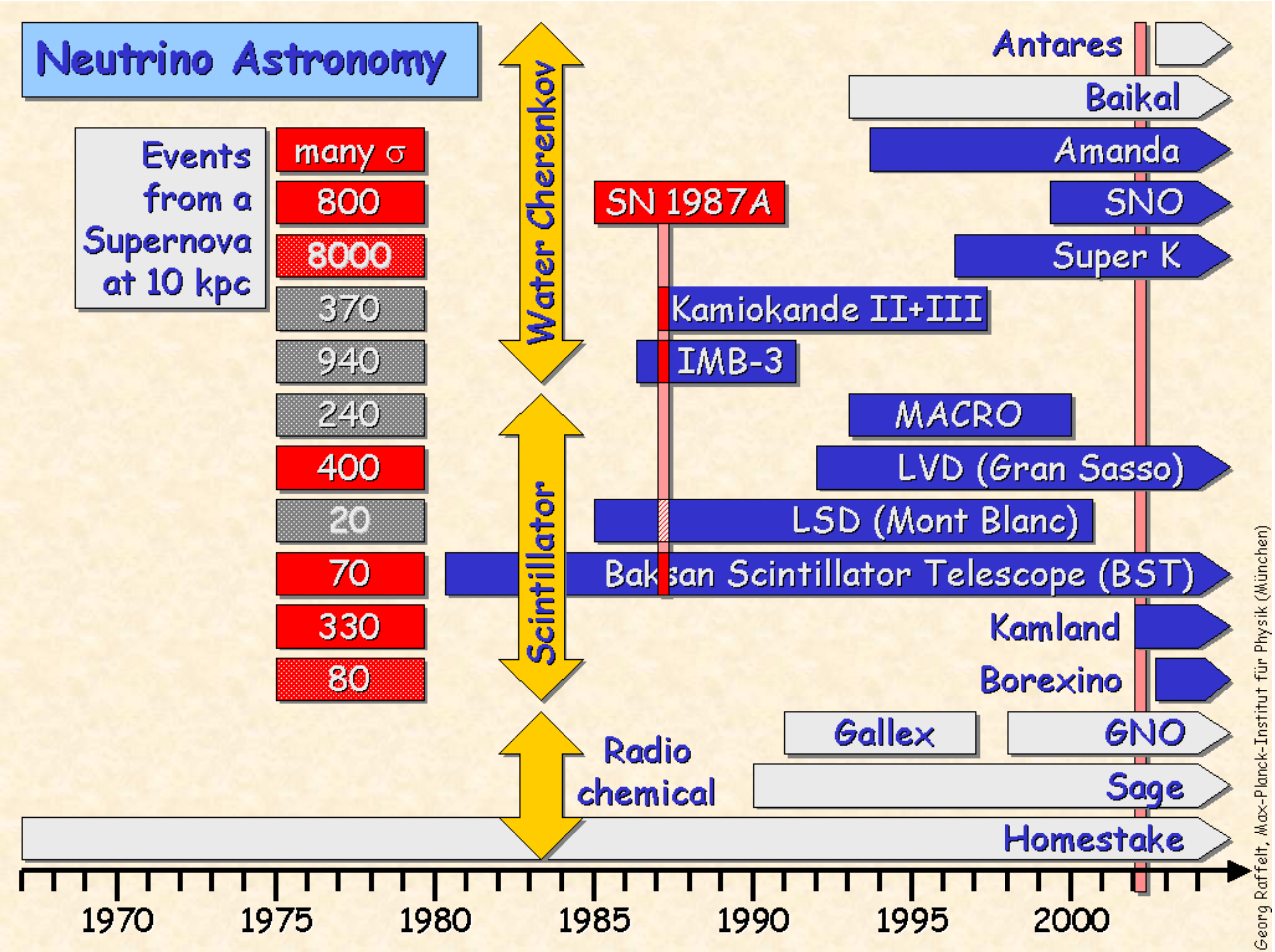
• The observation of supernova neutrinos should bring a better understanding of the core collapse mechanism from the feature of the time and energy spectra, and constraints the supernova models.
• Moreover, an estimation of the neutrino masses could be done in the following manner. The velocity of a particle of energy *E* and mass *m*, with $E >> m$, is given by (with c = 1):

$$v = \frac{p}{E} = \frac{(E^2 - m^2)^{½}}{E} \approx 1 - \frac{m^2}{2E} \quad .$$

•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
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# 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