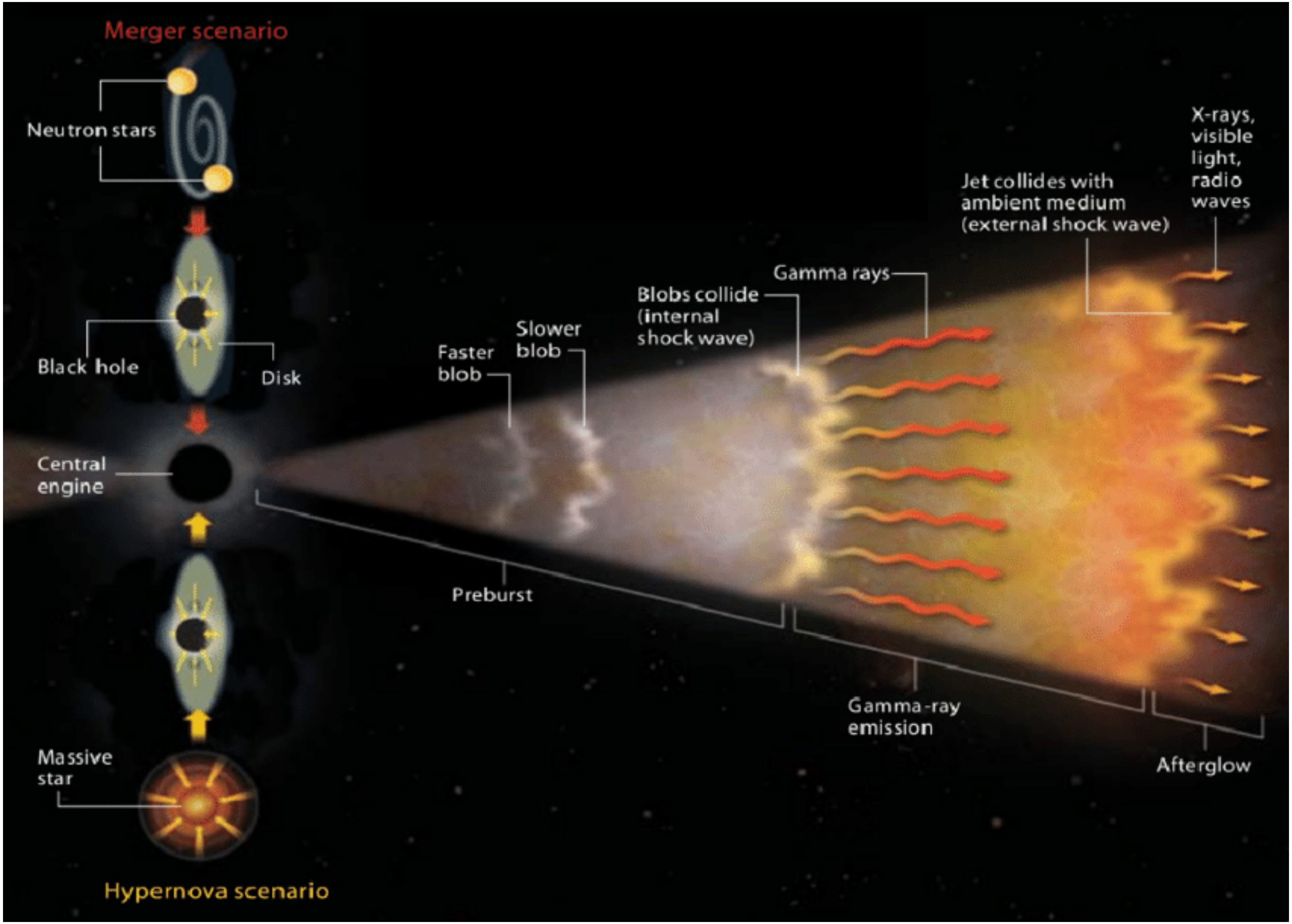
Astrofisica Nucleare e Subnucleare

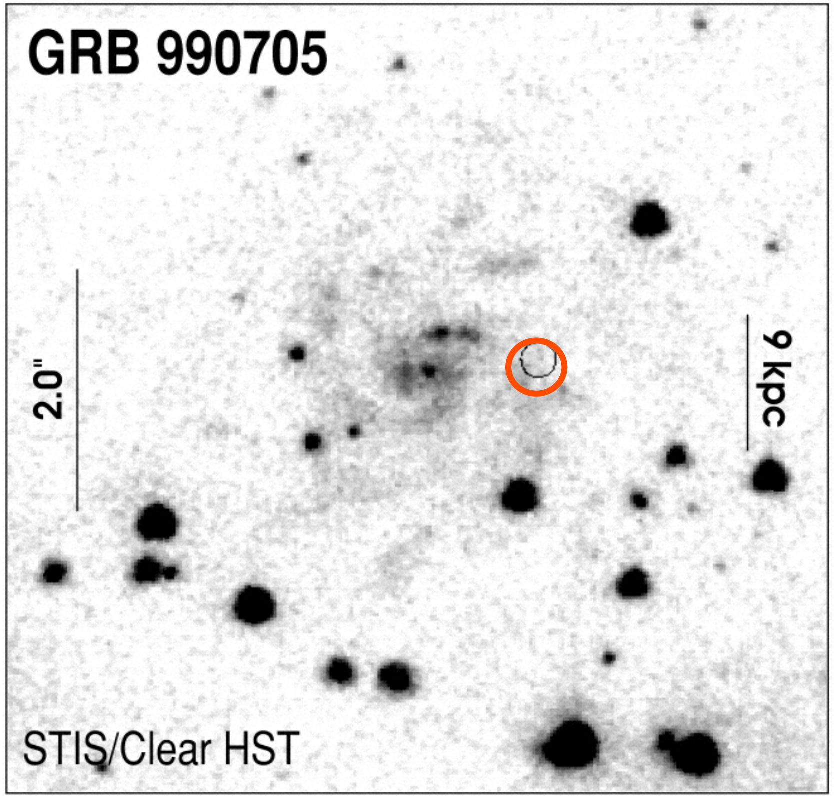
Neutrino Astrophysics


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

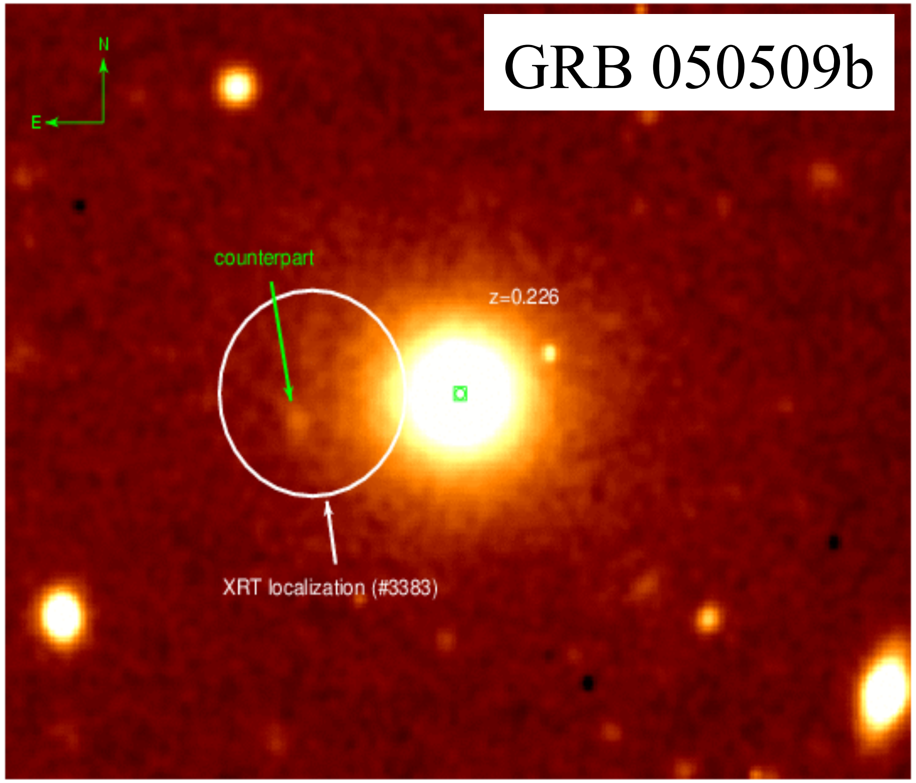
Unvealing the GRB progenitors

- 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

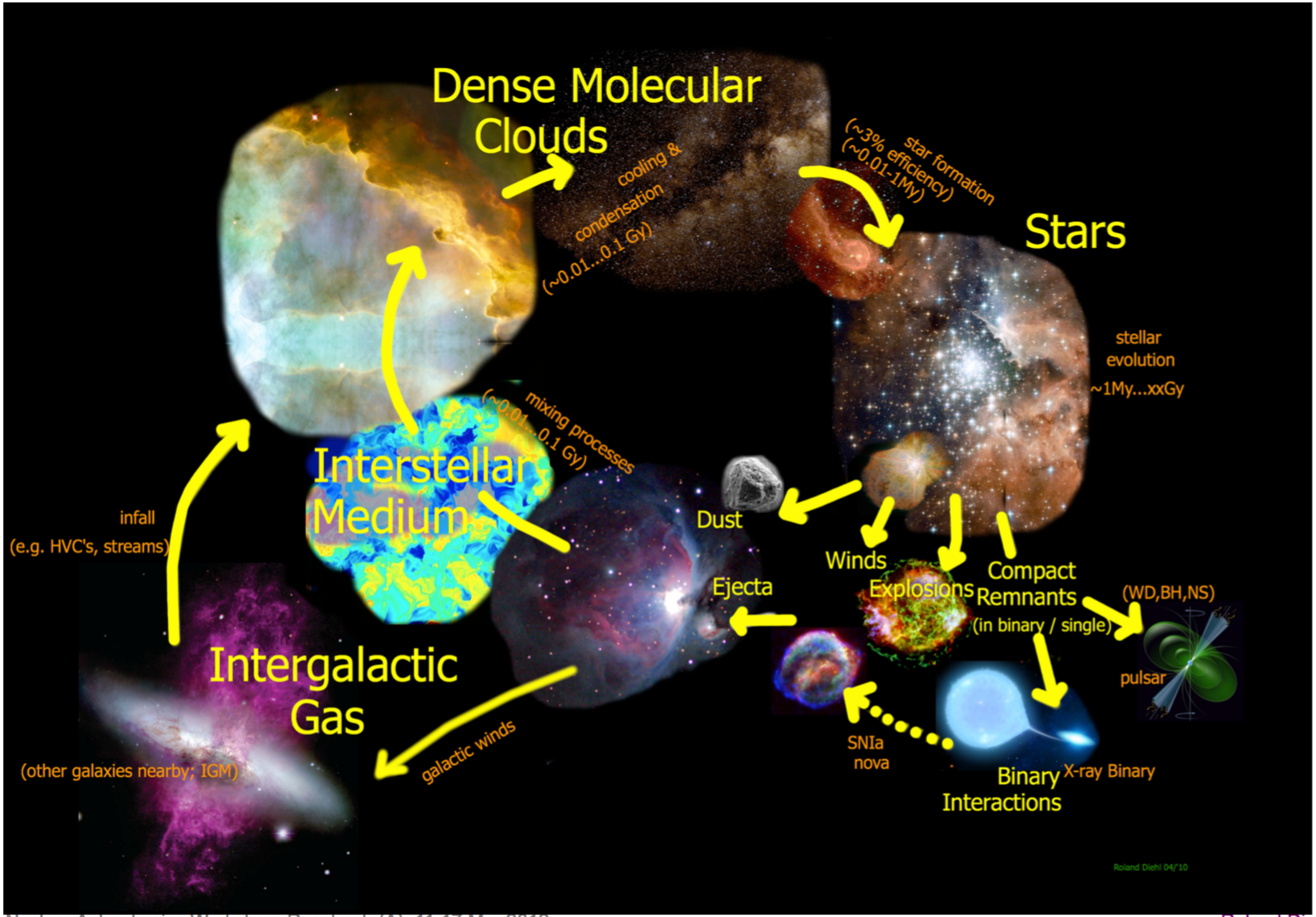
Long



Short



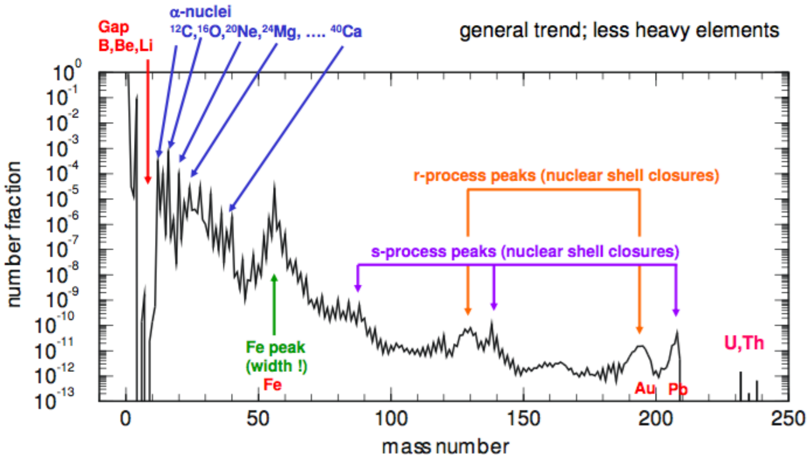
How Stars Shape Galaxies



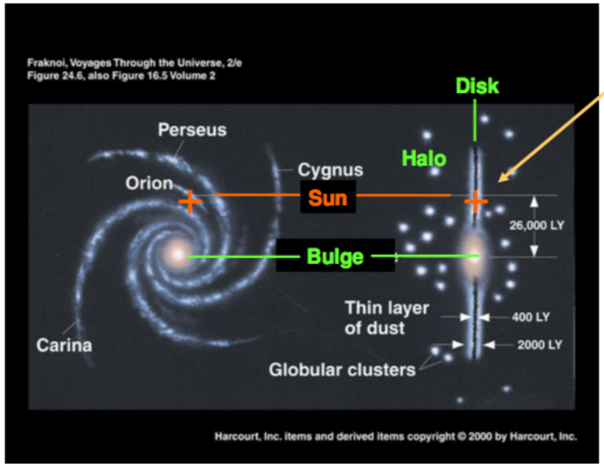
What is Nuclear Astrophysics?

- 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

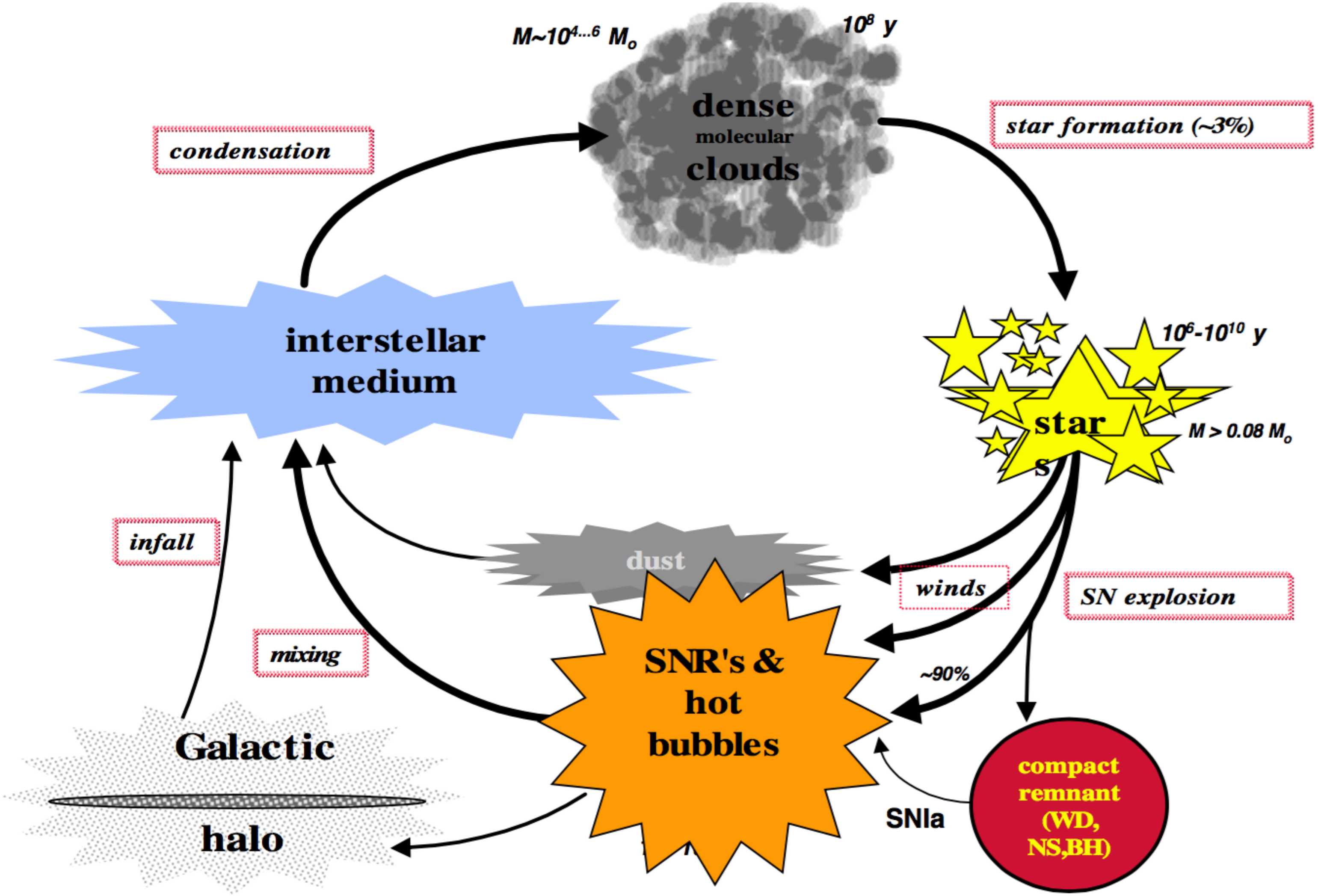


solar abundances:

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



$M \sim 10^{4 \ldots 6}\ M_o$

10^8 y

dense molecular clouds

star formation (~3%)

condensation

interstellar medium

stars

10^6-10^{10} y

$M > 0.08\ M_o$

infall

dust

winds

SN explosion

mixing

SNR's & hot bubbles

~90%

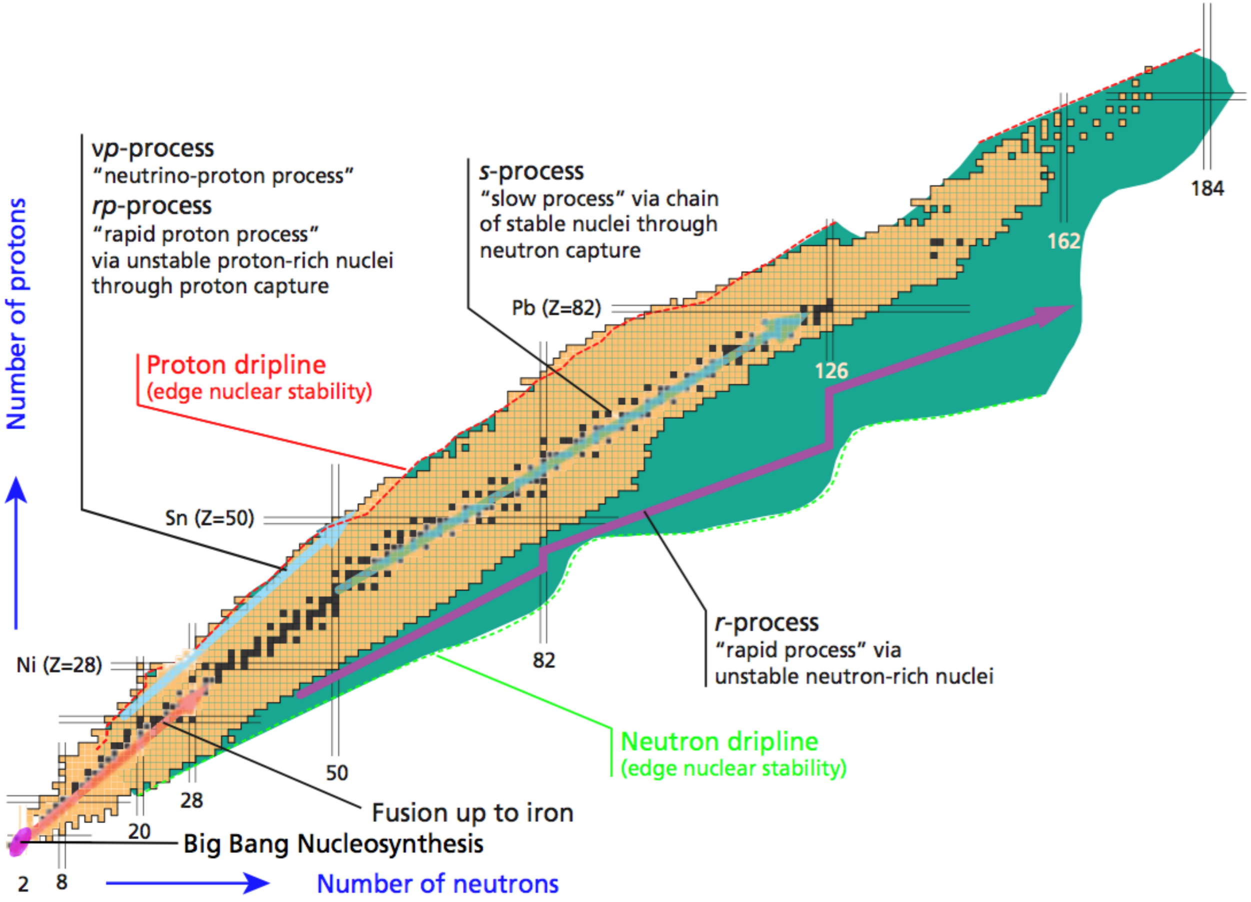
Galactic halo

SNIa

compact remnant (WD, NS,BH)

Nucleosynthesis processes

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



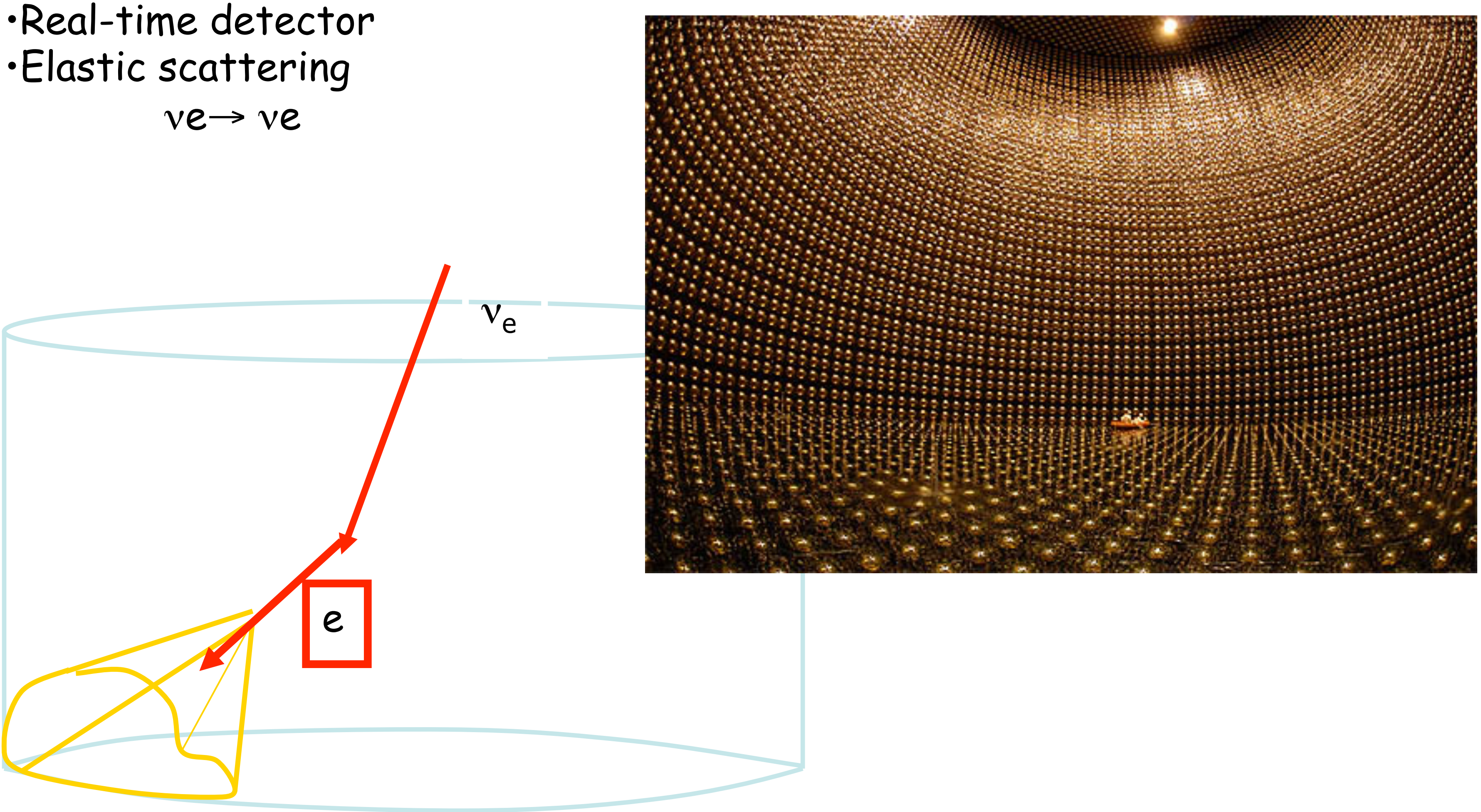
Astrofisica Nucleare e Subnucleare

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

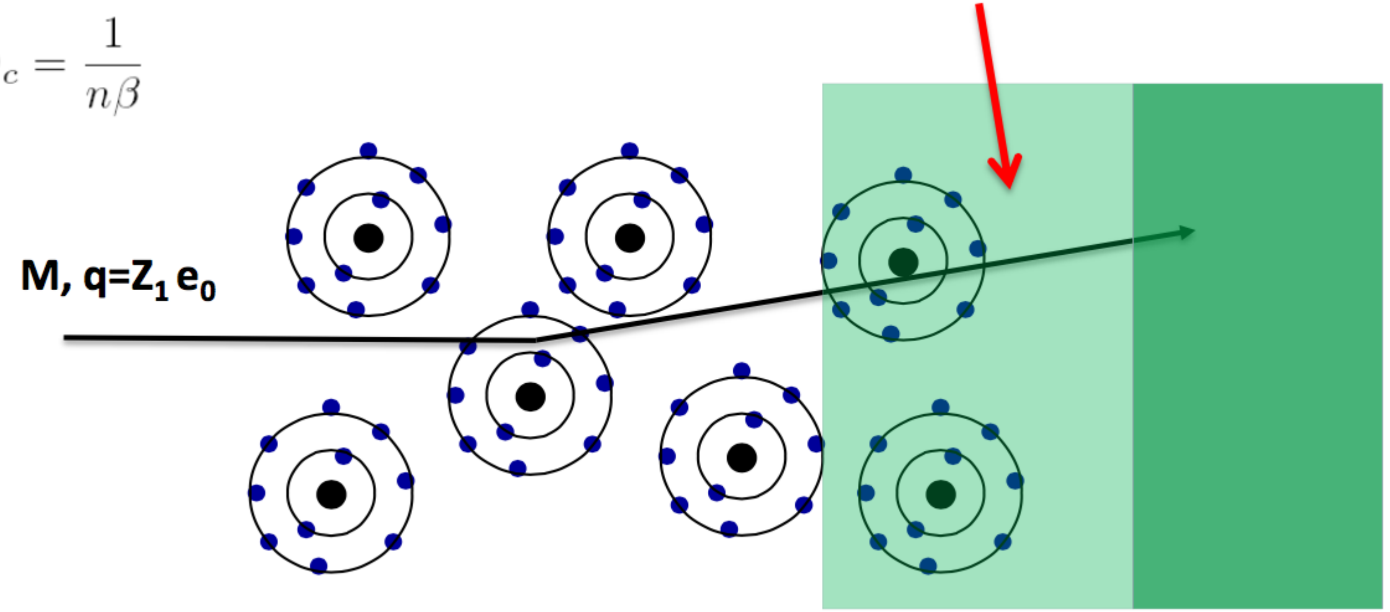
Cherenkov Radiation

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

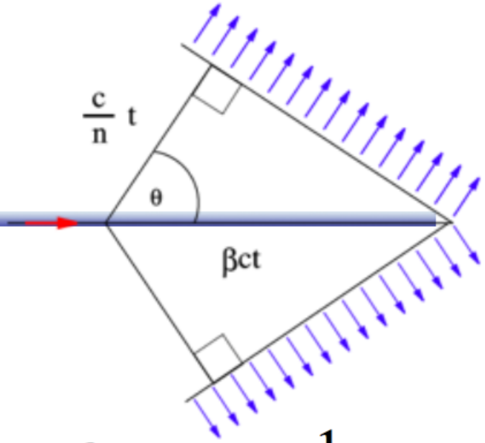
N is the number of Cherenkov Photons emitted per cm of material. The expression is in addition proportional to Z_1^2 of the incoming particle.

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 θ_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

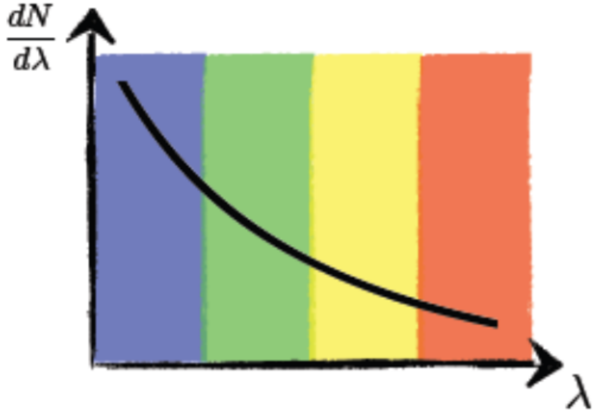
Visible photons:
E = 1 - 5 eV; λ = 300 - 600 nm

Cherenkov radiation

In a Cherenkov detector the produced photons are measured

Number of emitted photons per unit of length:

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



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

Integrate over sensitivity range:
[for typical Photomultiplier]

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

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

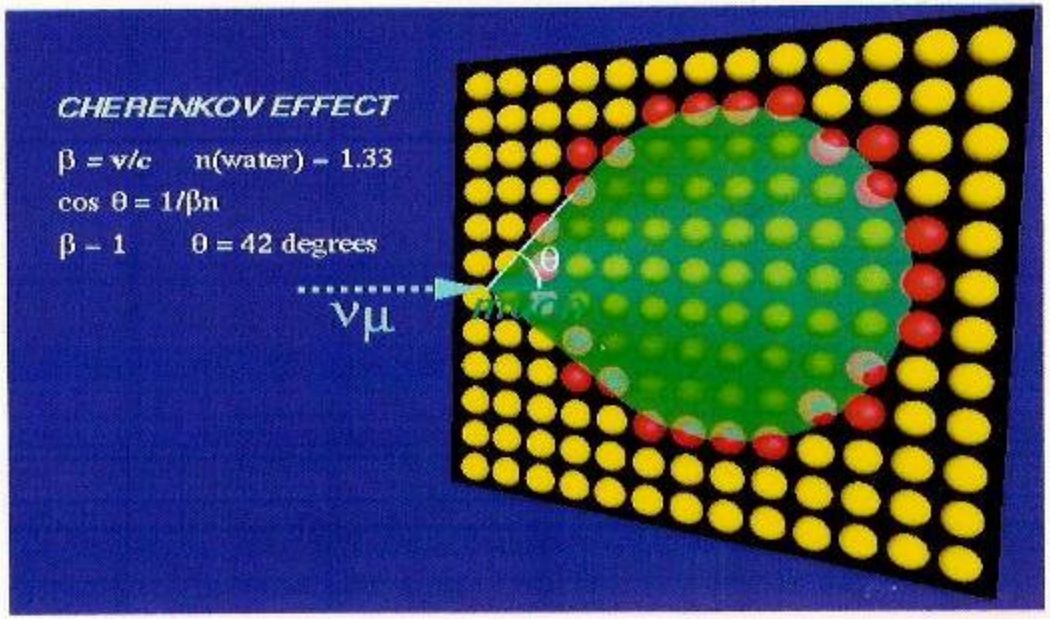
- energy dependence ~ constant

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

$$\approx \text{const}$$

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

Cherenkov Radiation



CHERENKOV EFFECT

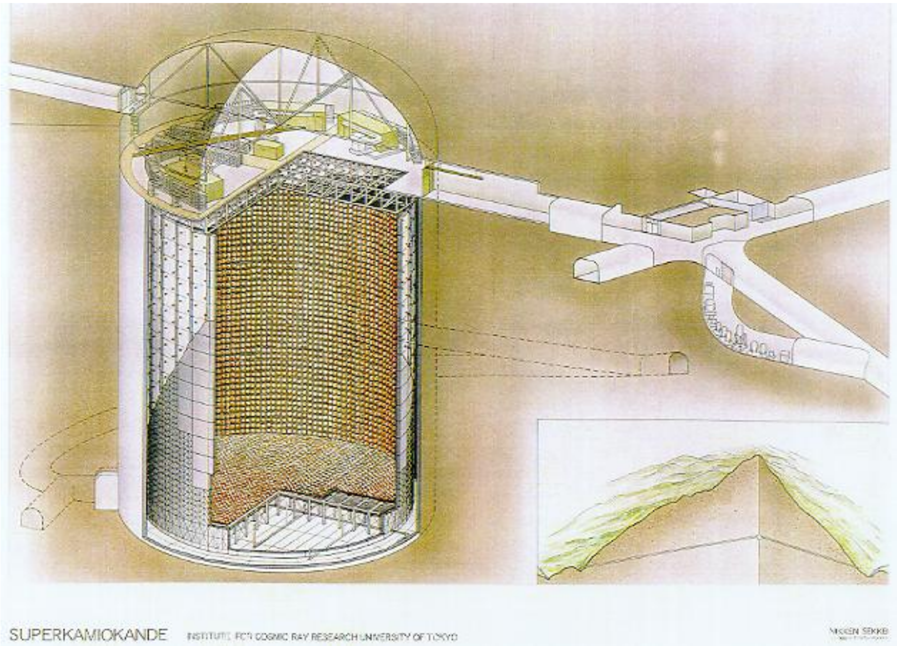
$\beta = v/c$ n(water) - 1.33

$\cos\theta = 1/\beta n$

$\beta - 1$ θ = 42 degrees

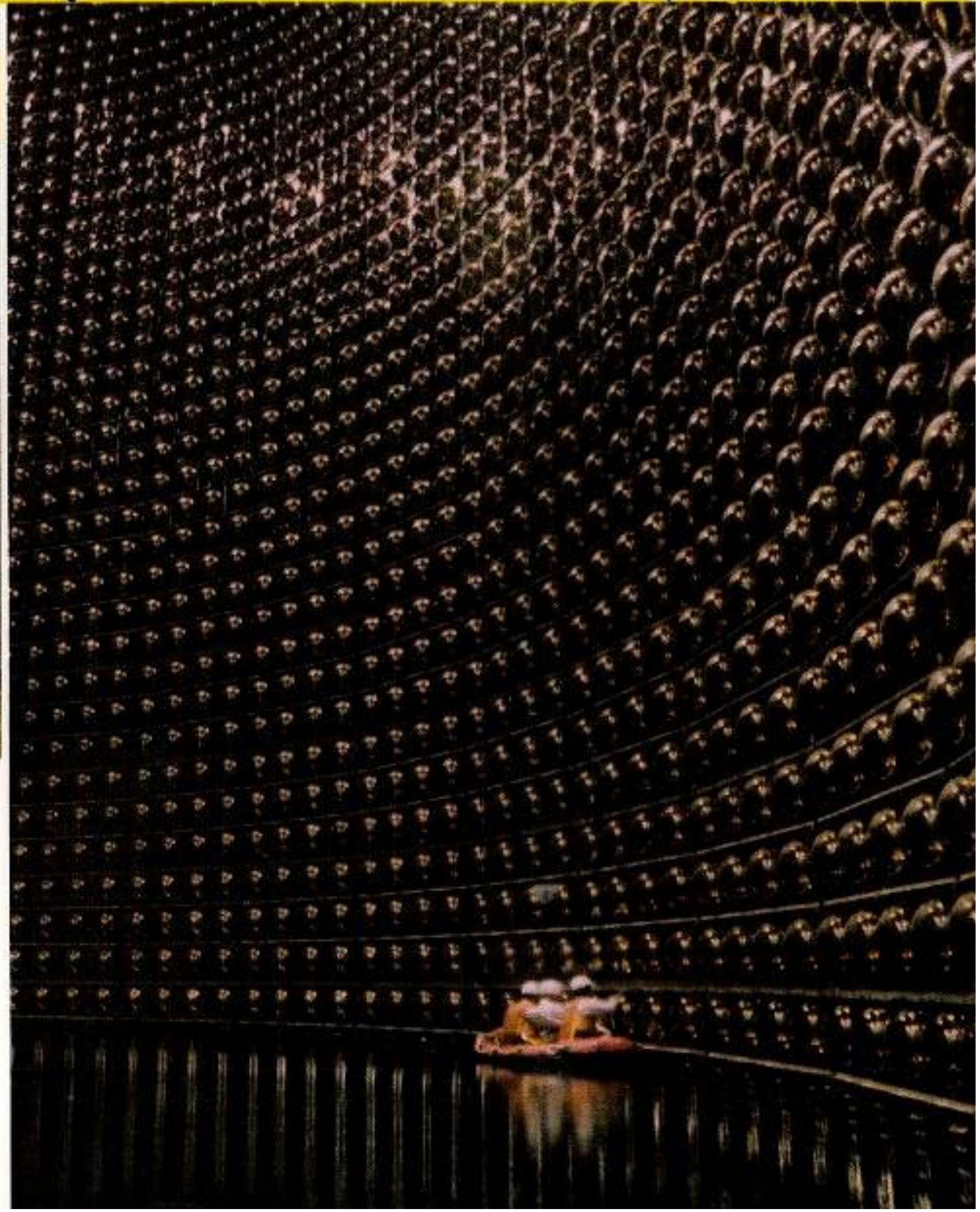
One of the
13000 PMT

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)

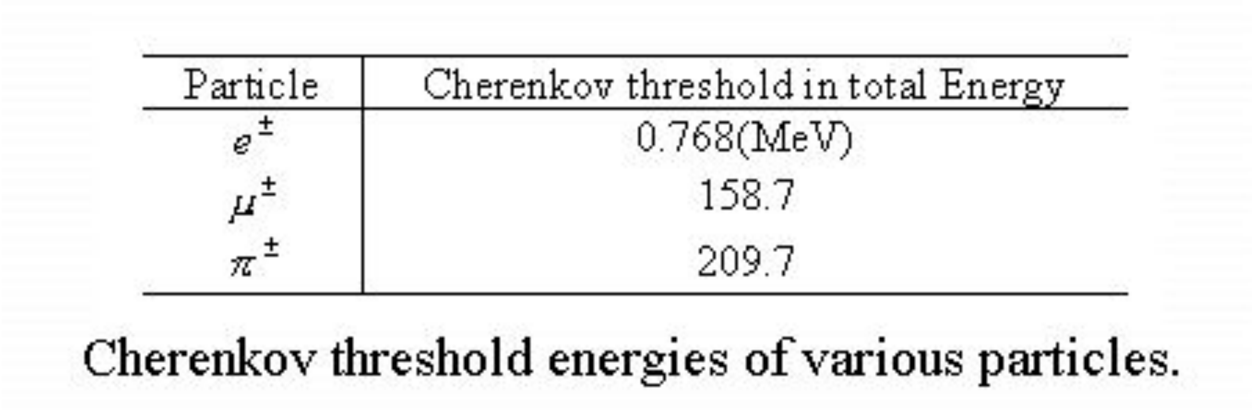


1000 m Deep Underground

50,000 ton of Ultra-Pure Water

11000 +2000 PMTs

Neutrino Scattering Experiments



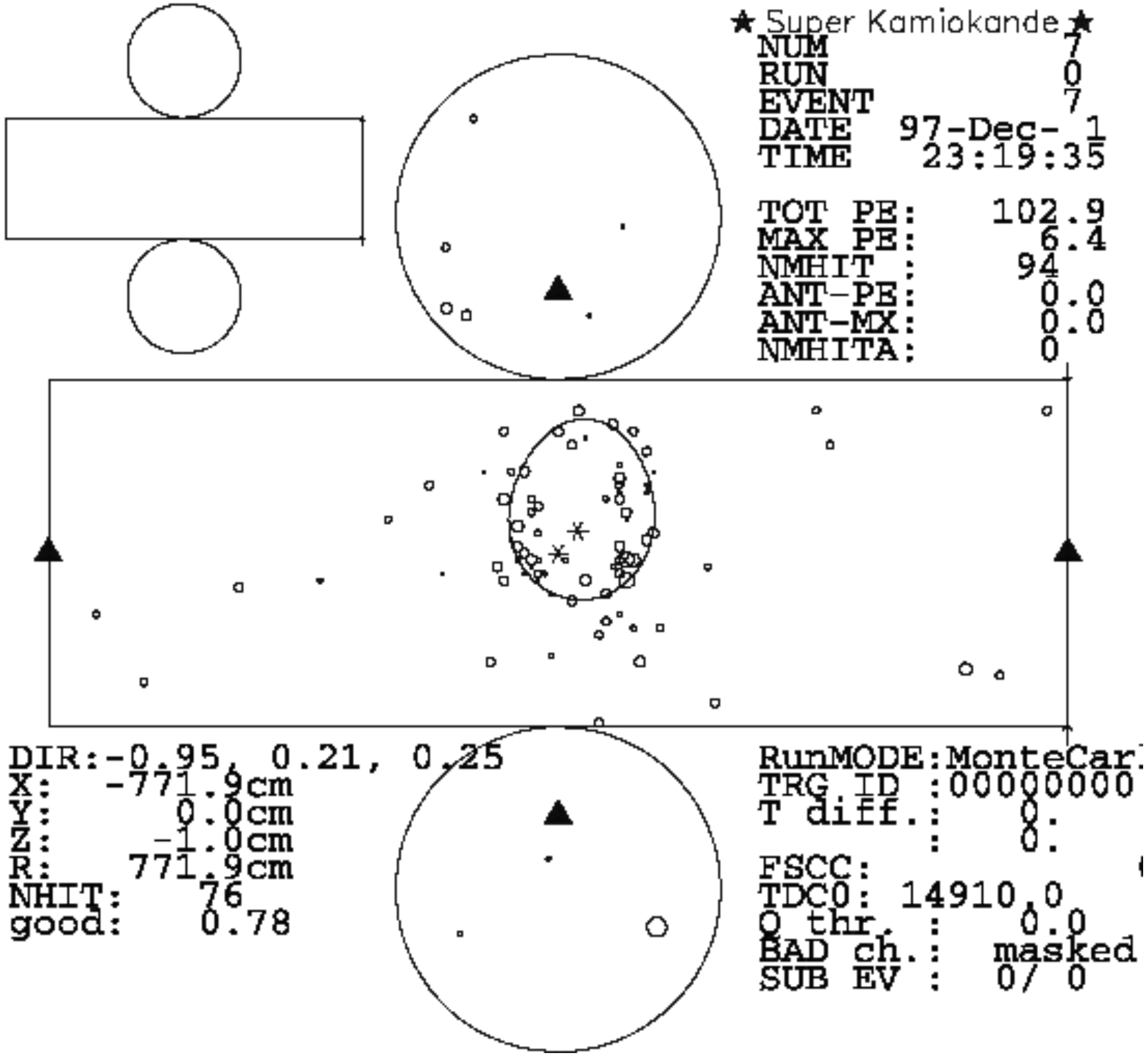
Particle	Cherenkov threshold in total Energy
$e^{\pm}$	0.768(MeV)
$\mu^{\pm}$	158.7
$\pi^{\pm}$	209.7

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



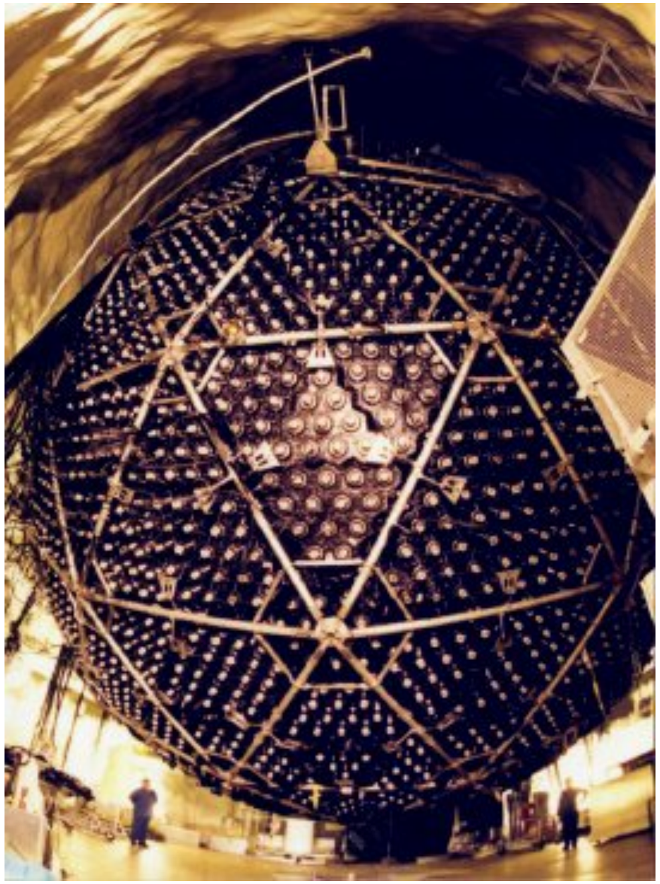
```
★ Super Kamiokande ★
NUM              7
RUN              0
EVENT            7
DATE    97-Dec- 1
TIME     23:19:35

TOT PE:     102.9
MAX PE:       6.4
NMHIT :      94
ANT-PE:       0.0
ANT-MX:       0.0
NMHITA:       0
```

```
DIR:-0.95, 0.21, 0.25
X:   -771.9cm
Y:      0.0cm
Z:     -1.0cm
R:    771.9cm
NHIT:    76
good:    0.78
```

```
RunMODE:MonteCarl
TRG ID :00000000
T diff.:   0.
       :   0.
FSCC:
TDC0: 14910.0
Q thr. :   0.0
BAD ch.:  masked
SUB EV :  0/ 0
```

Neutrino Detectors SNO

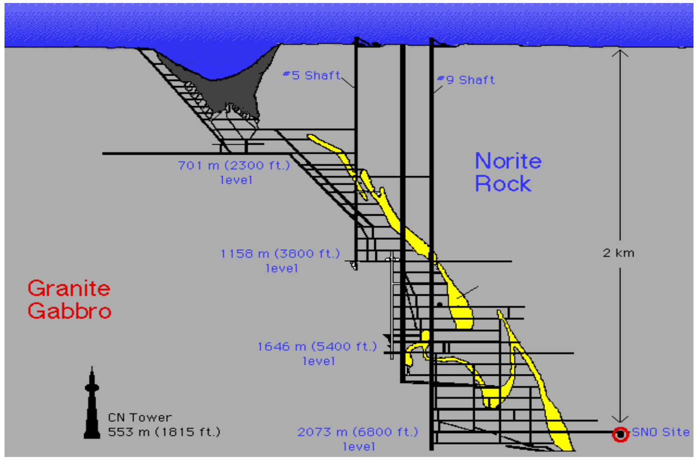


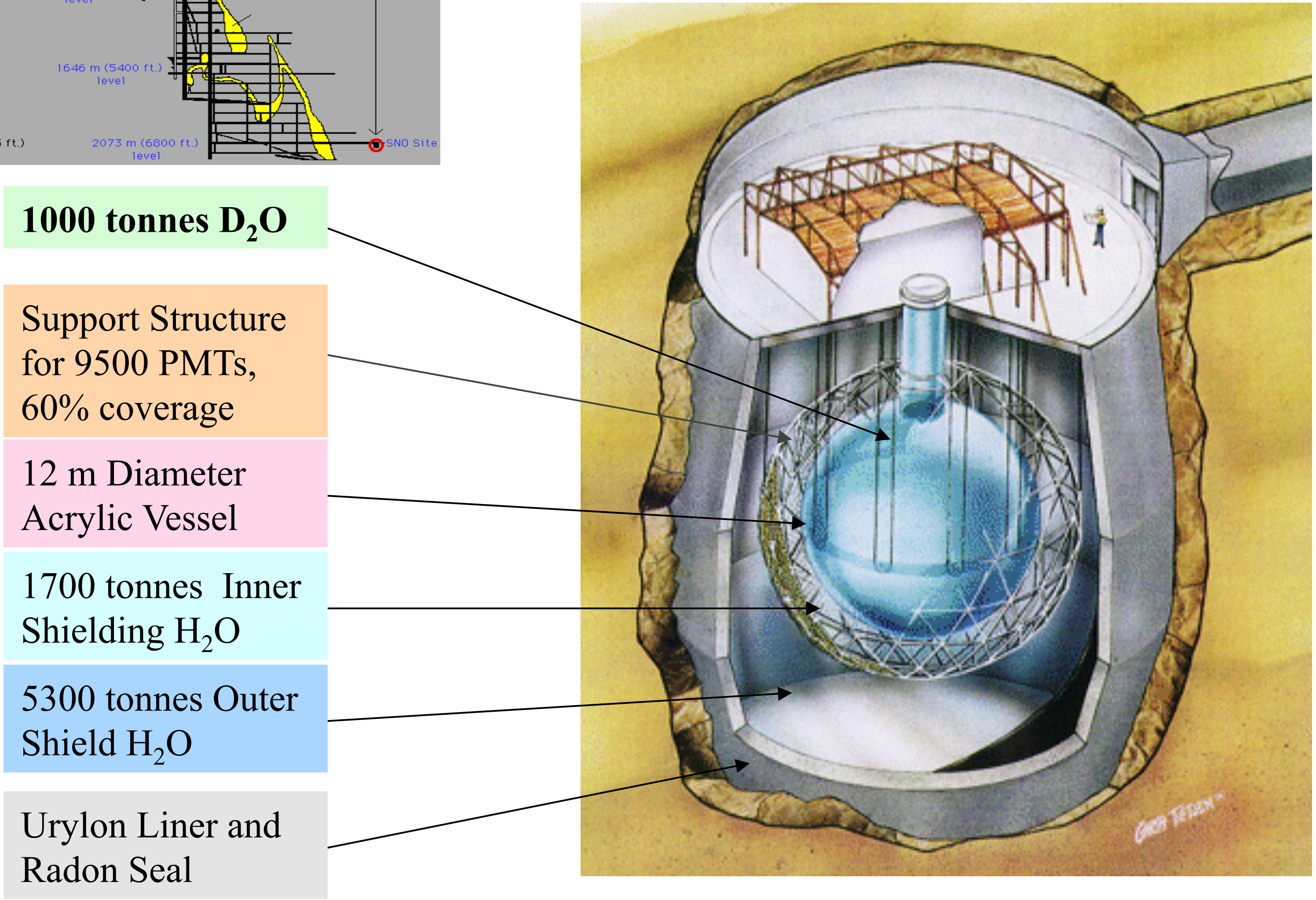
- 18m sphere, situated underground at about 2.5km underground, in Ontario
- 10,000 photomultiplier tubes (PMT)
- Each PMT collect Cherenkov light photons
- Heavy water (D_2O) inside a transparent acrylic sphere (12m diameter)
- Pure salt is added to increase sensitivity of NC reactions (2002)
- It can 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

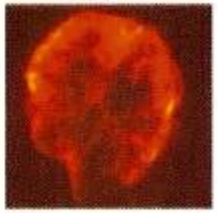
Supernovae Neutrinos

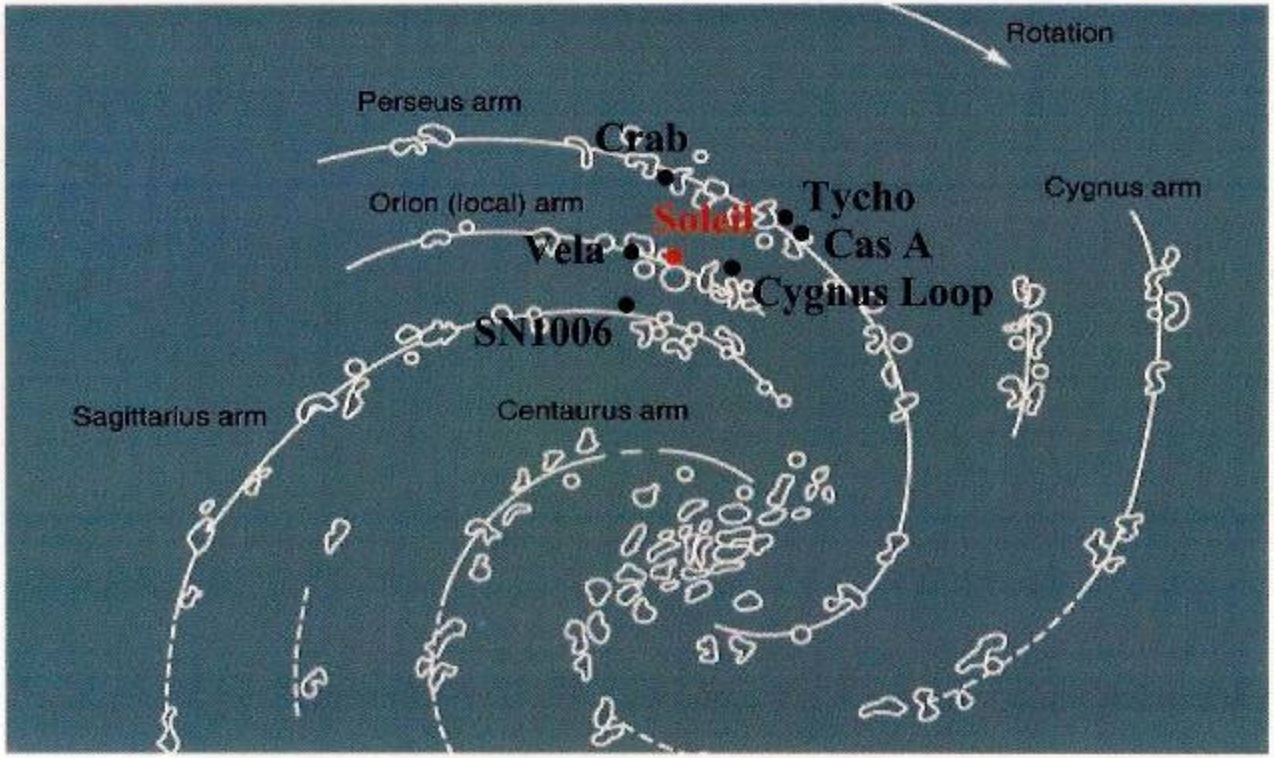
SuperNovae Remnants

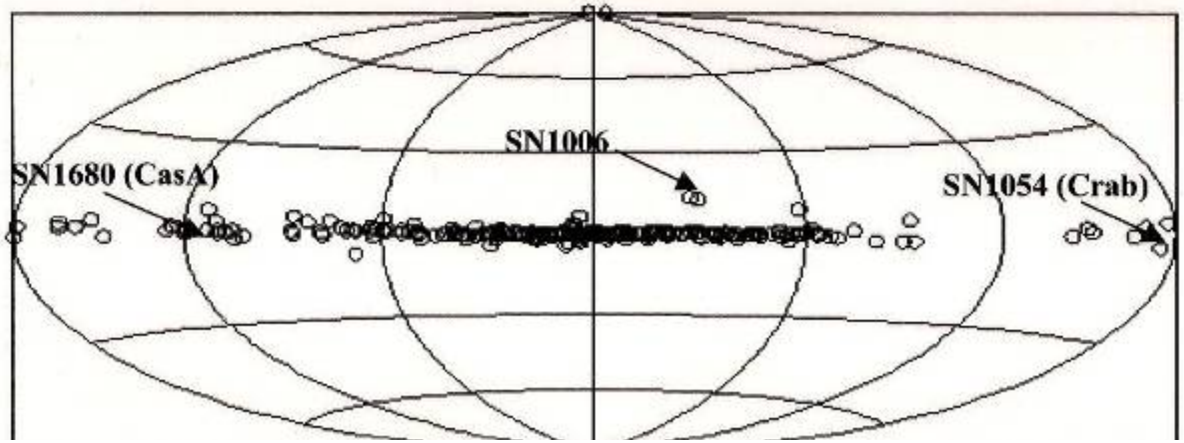
Vela

Tycho

Cygnus



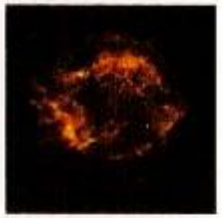




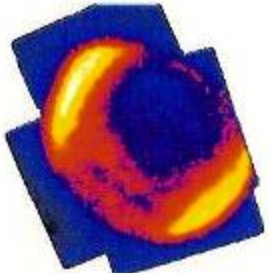
Crab

Kepler

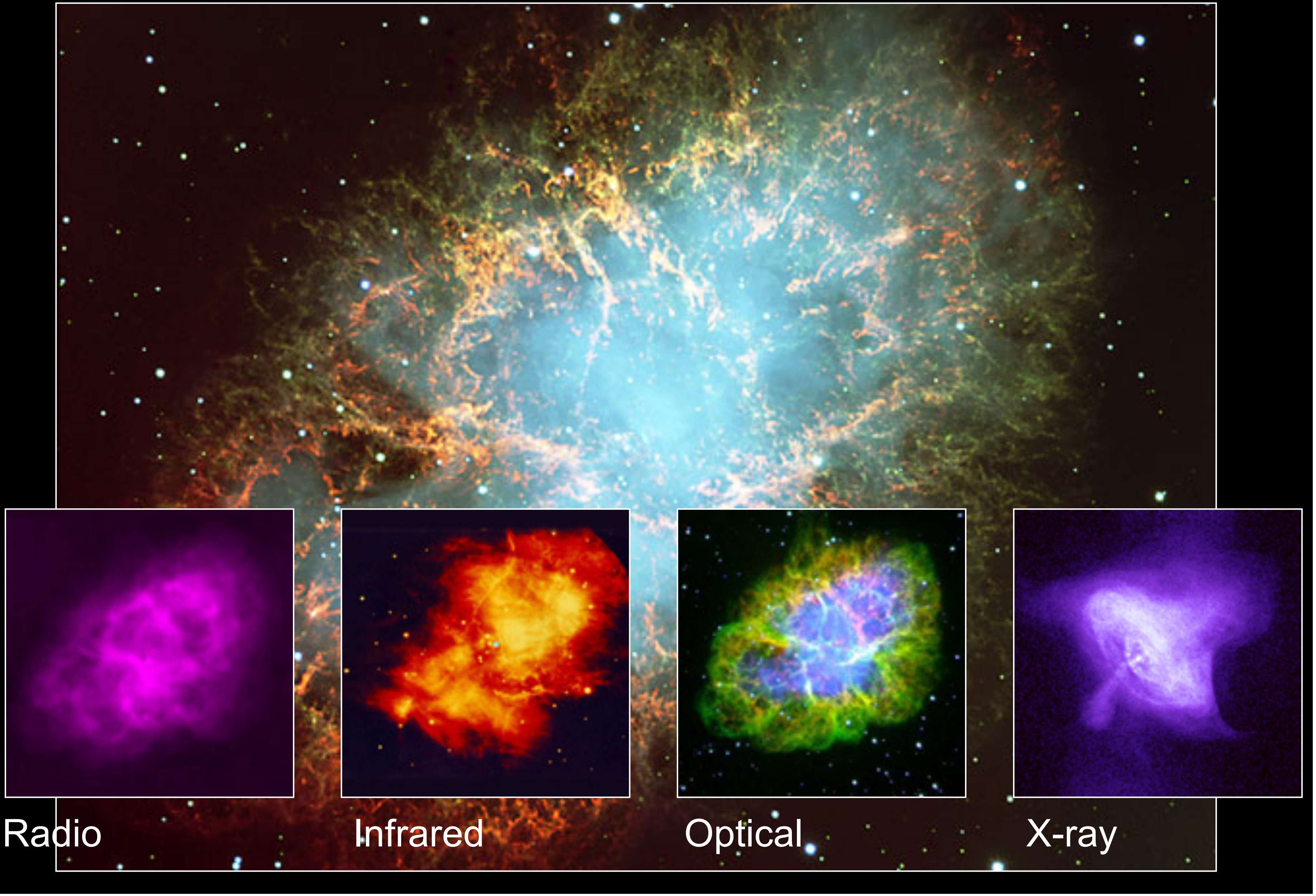
Cas A



SN1006



The Crab in Multi-Wavelengths Photons



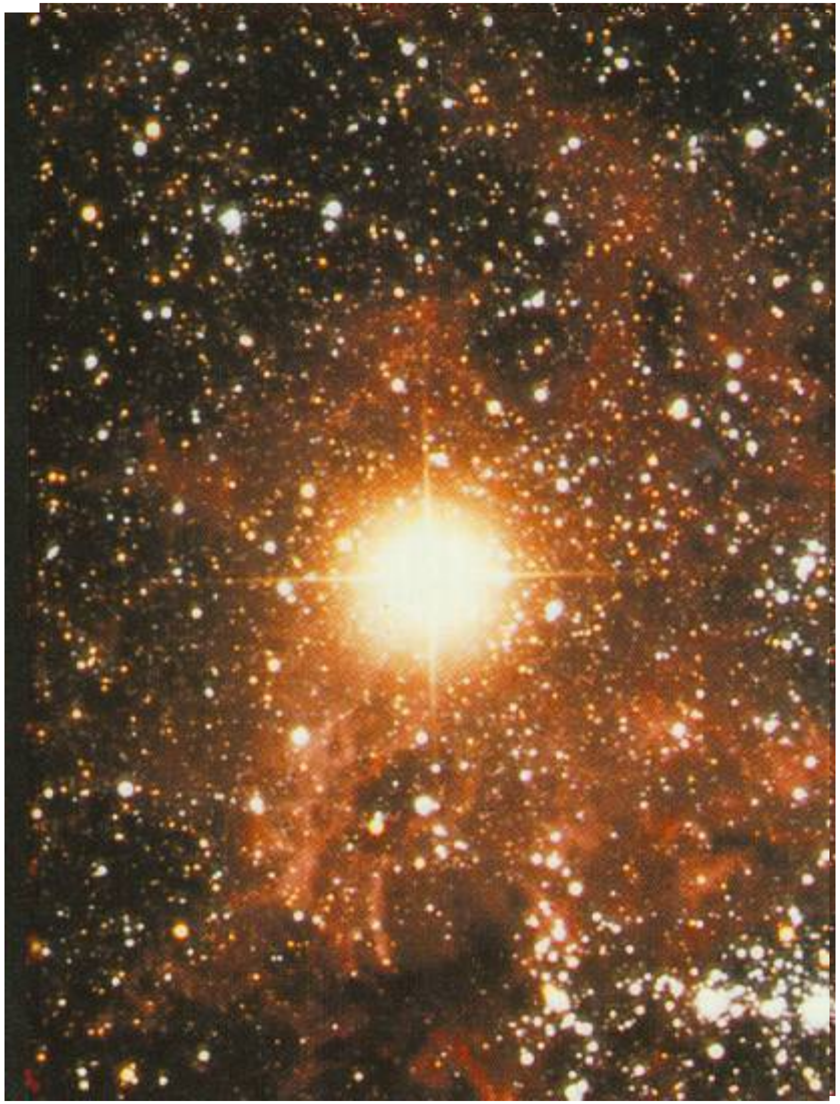
Radio

Infrared

Optical

X-ray

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.

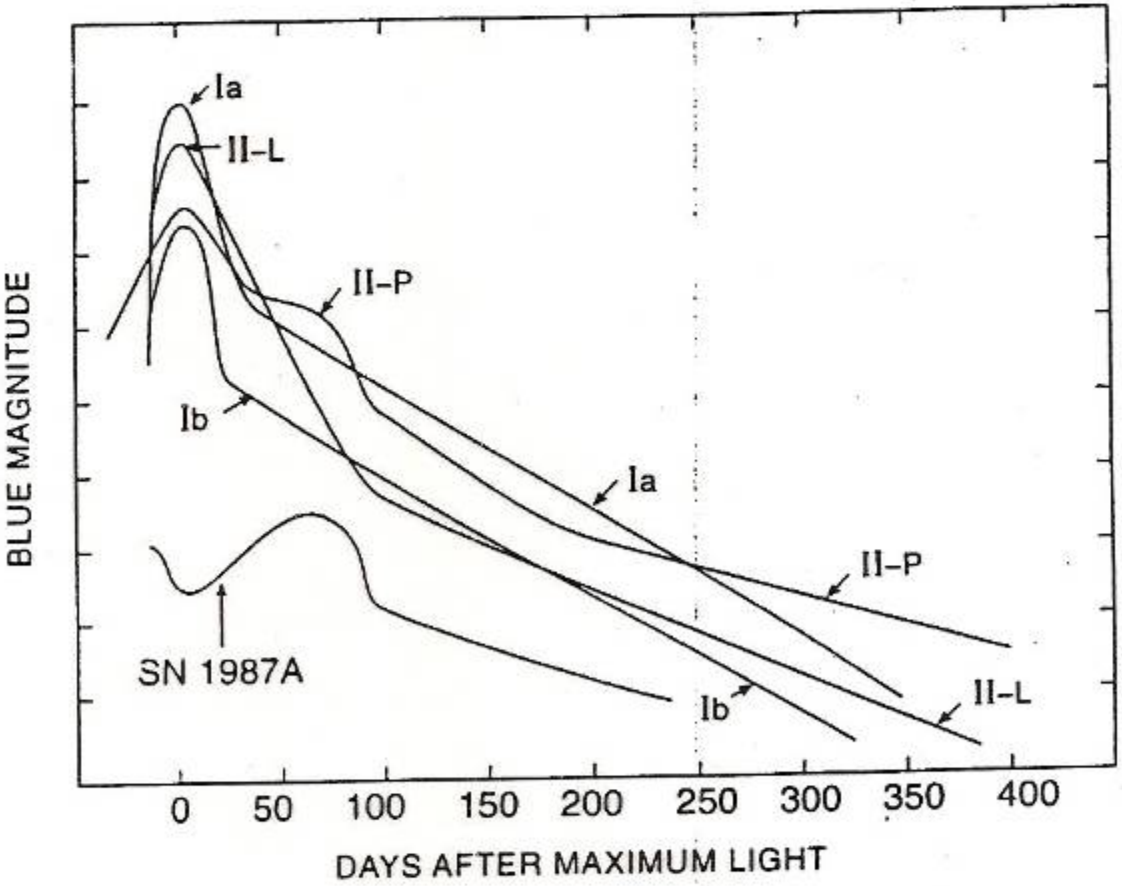


Figure 13.3. Brightness in the B-band for different supernova types. The deviation of supernova 1987a from the standard schemes can clearly be seen. Type II supernovae which have an almost linear decline after the maximum (II-L) are distinguished from those which remain almost constant over a longer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

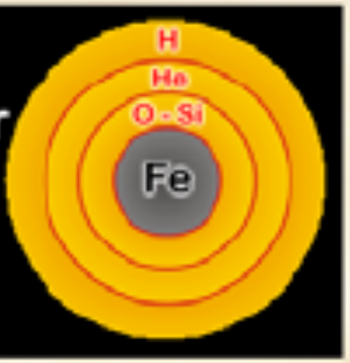
Type Ia vs. Core-Collapse Supernovae

Type Ia

- Carbon-oxygen white dwarf (remnant of low-mass star)
- Accretes matter from companion

Core collapse (Type II, Ib/c)

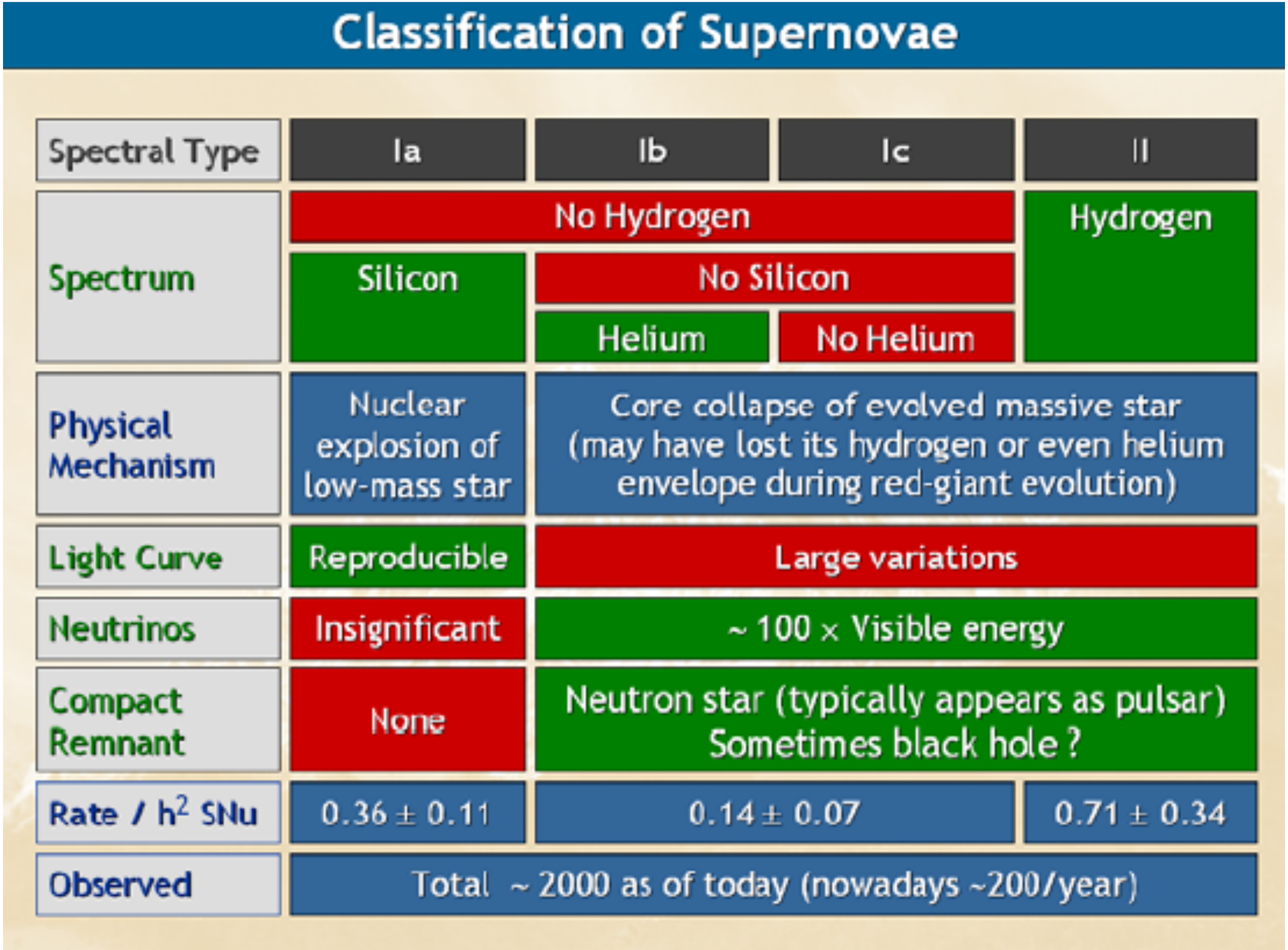
- Degenerate iron core of evolved massive star
- Accretes matter by nuclear burning at its surface



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

COLLAPSE SETS IN

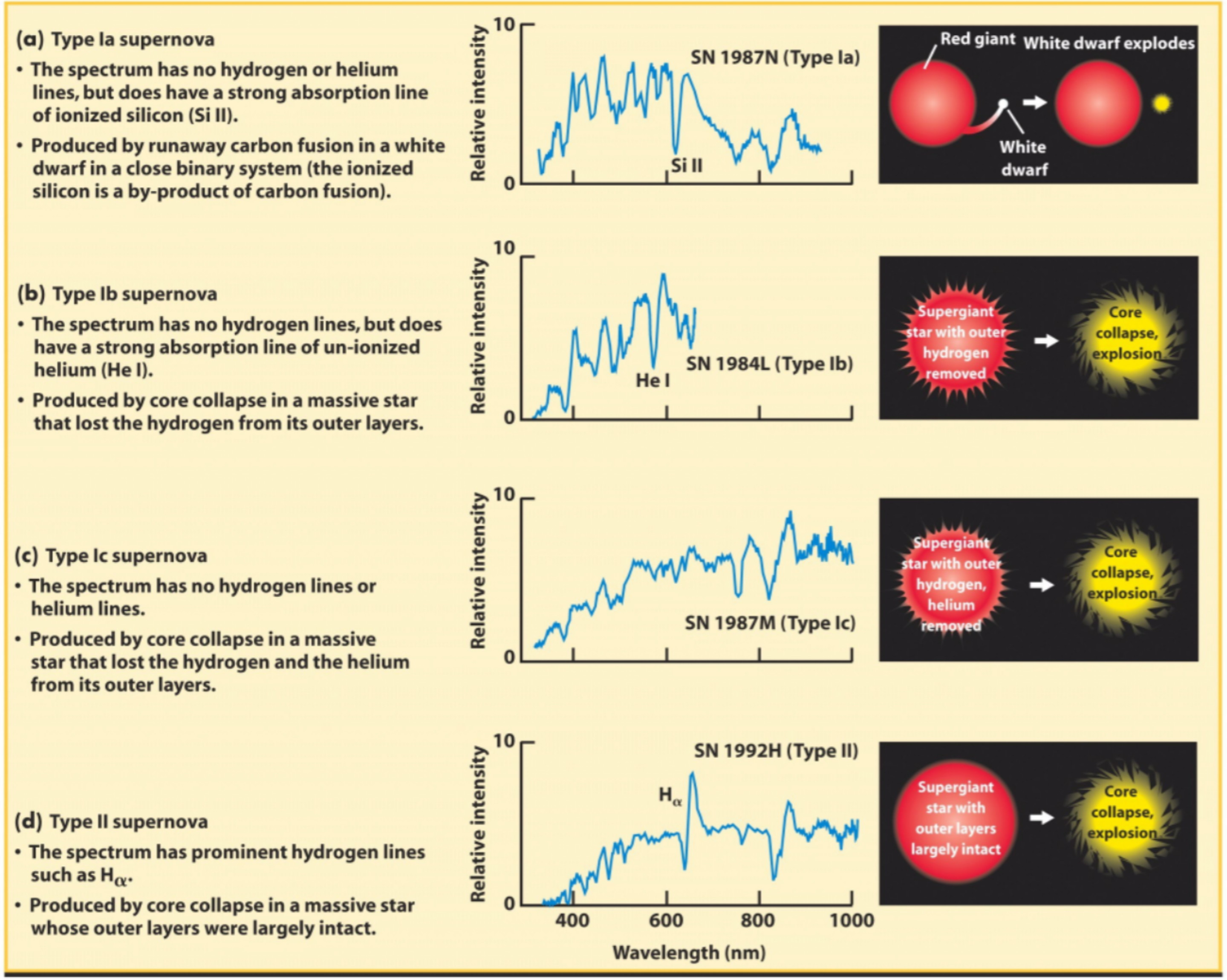
Nuclear burning of C and O ignites → Nuclear deflagration ("Fusion bomb" triggered by collapse)	Collapse to nuclear density Bounce & shock Implosion → Explosion
Powered by nuclear binding energy	Powered by gravity
Gain of nuclear binding energy ~ 1 MeV per nucleon	Gain of gravitational binding energy ~ 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



(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

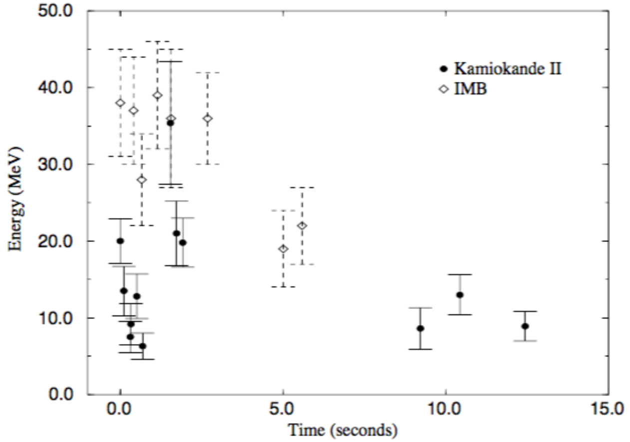
- The spectrum has prominent hydrogen lines such as H_α.
- Produced by core collapse in a massive star whose outer layers were largely intact.

SN1987A

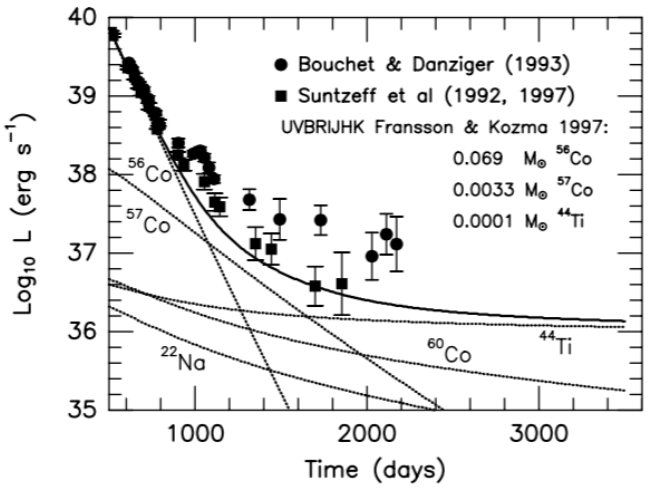
Type II supernova in LMC
(~ 55 kpc)

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

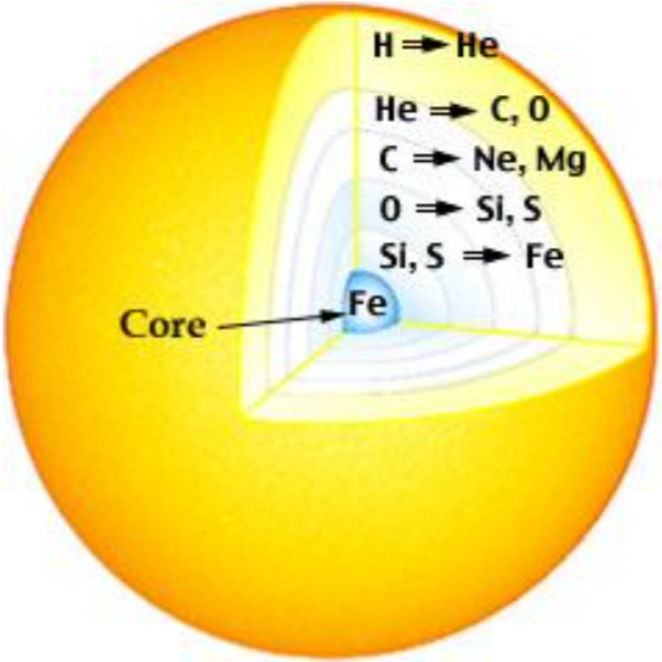
neutrinos $E_\nu \approx 2.7 \times 10^{53}$ erg



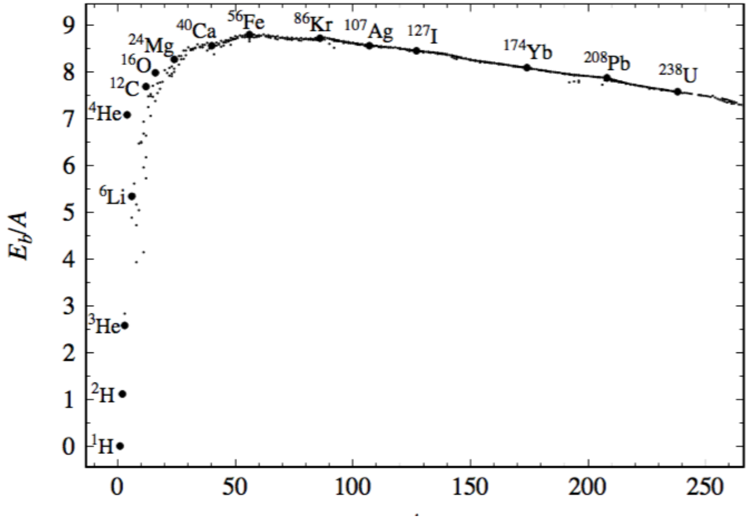
light curve



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 $M_\odot$.

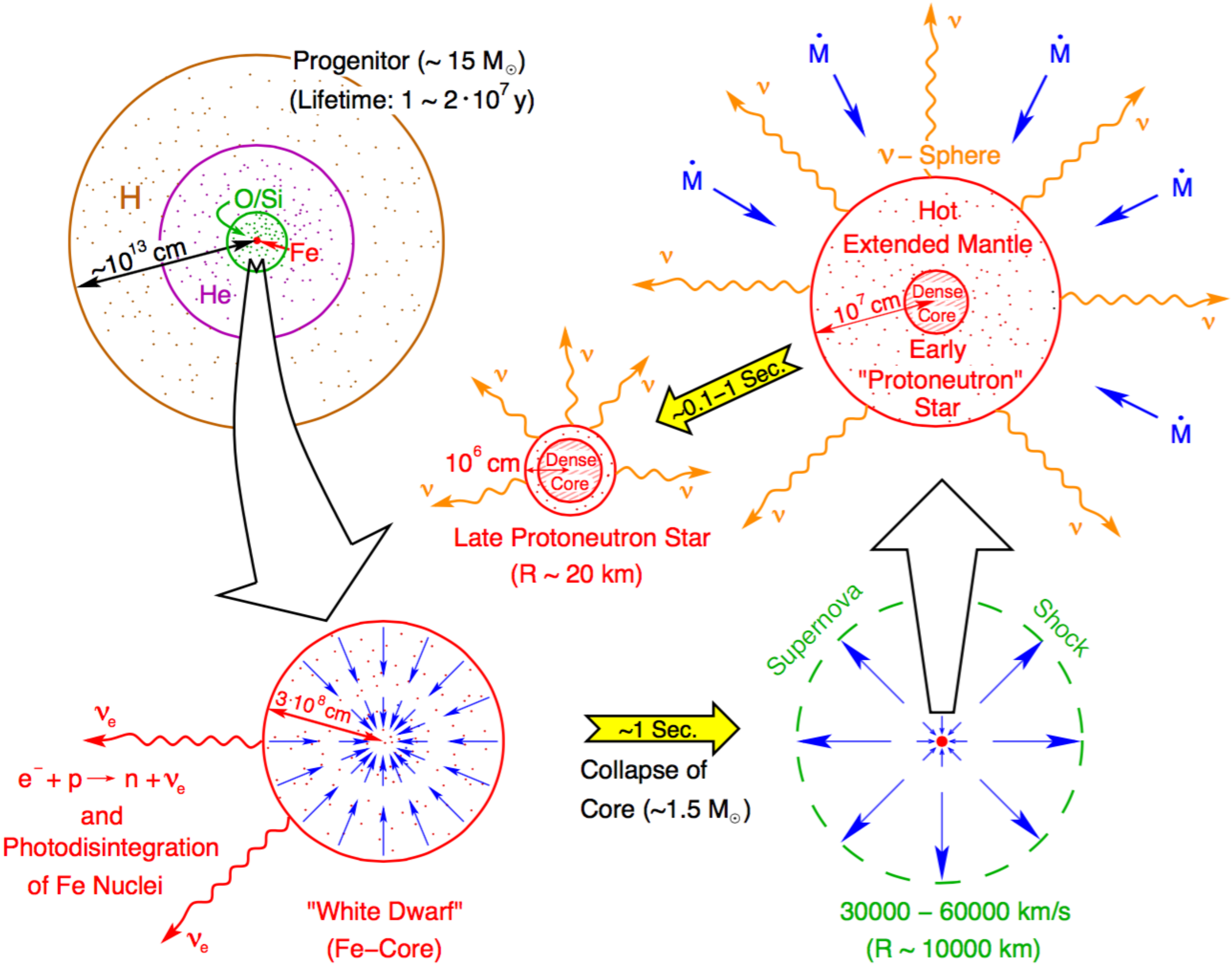


Early iron core

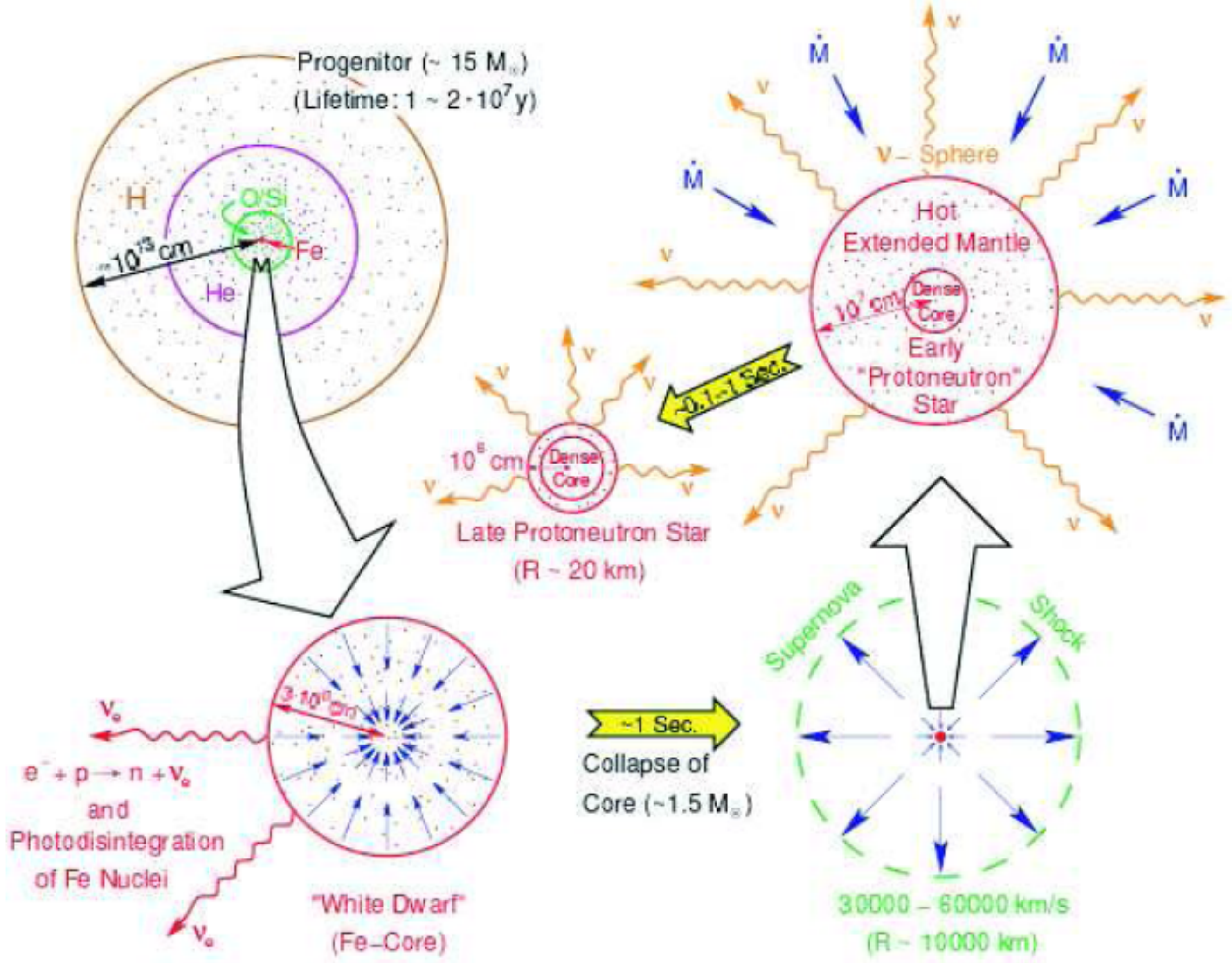
- The core is made of heavy nuclei (iron-mass range $A = 45\text{–}65$) and electrons. Composition given by Nuclear Statistical Equilibrium. There are Y_e electrons per nucleon.
- The mass of the core M_c is determined by the nucleons.
- There is no nuclear energy generation which adds to the pressure. 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.

- 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**.

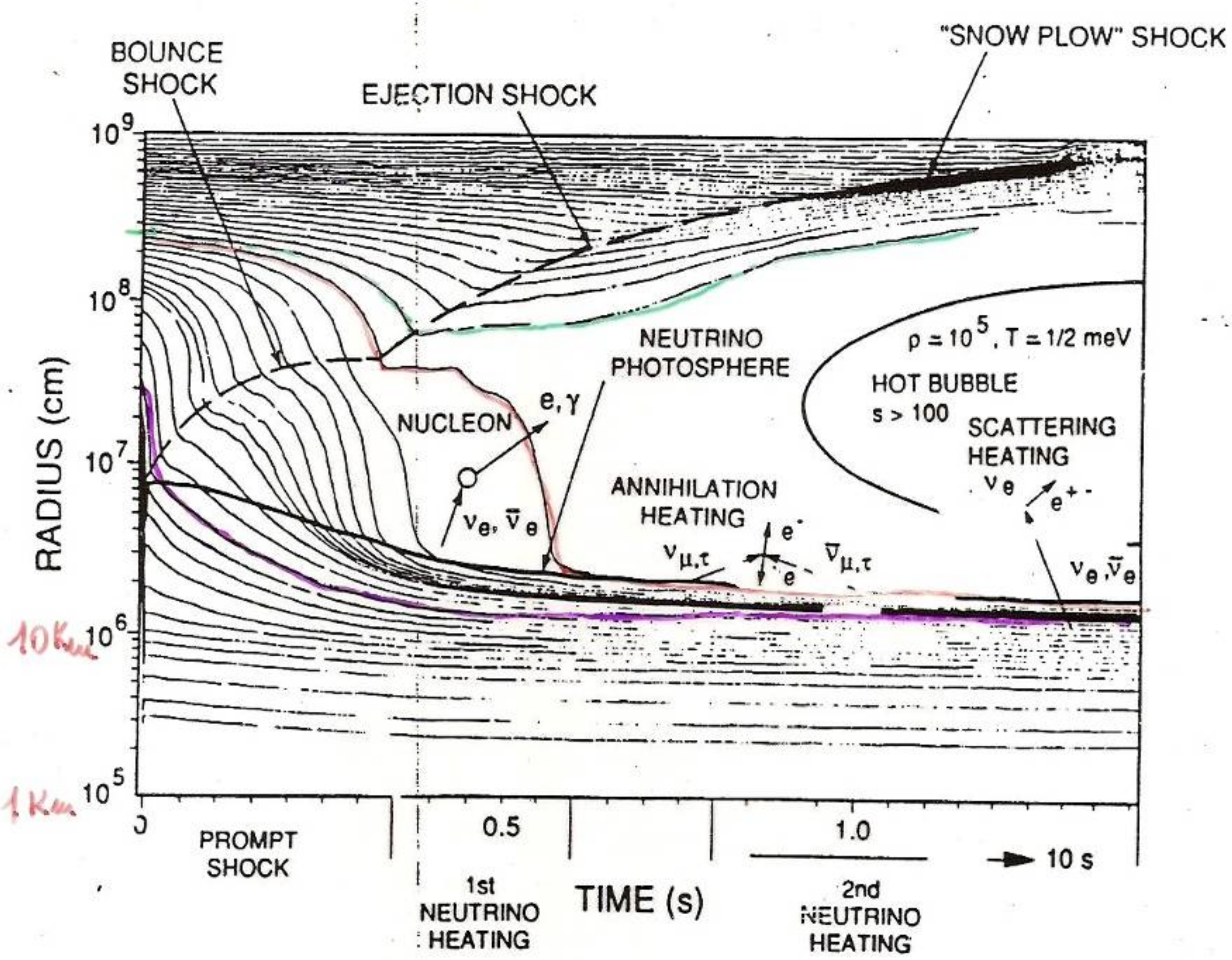
Schematical Evolution



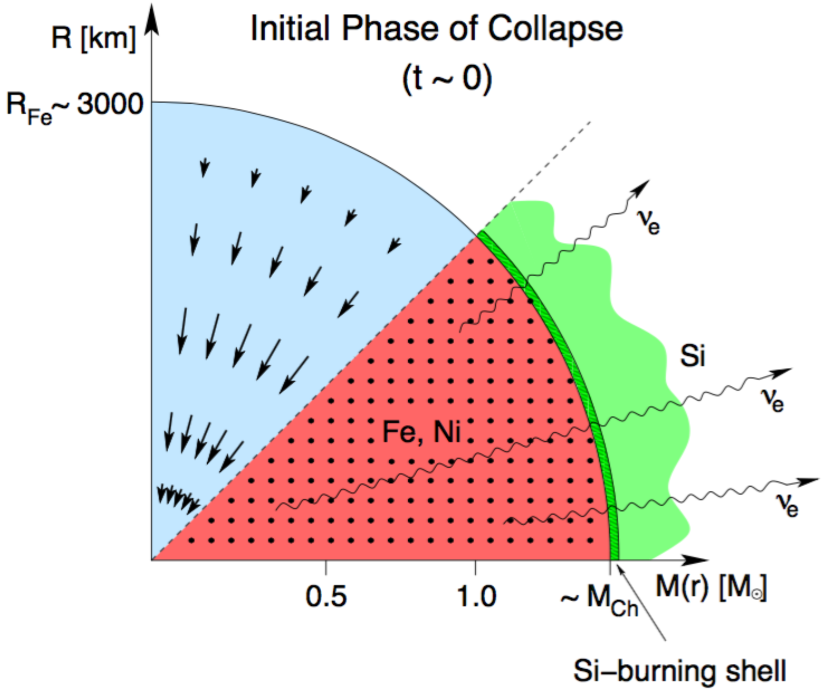
- 99% of the binding energy E_b, of the protoneutron star is released in the following ~ 10 seconds primarily via β-decay (providing a source of electron antineutrinos), v_e, anti-v_e and e+e− annihilation and nucleon bremsstrahlung (sources for all flavors of neutrinos including v_μ, anti-v_μ, v_t and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

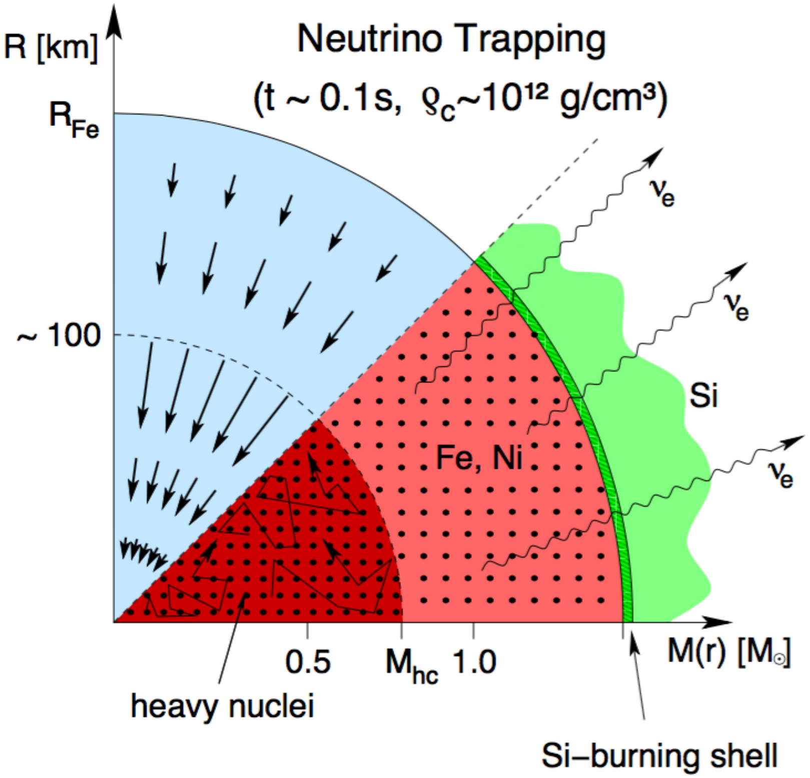

BOUNCE SHOCK
EJECTION SHOCK
"SNOW PLOW" SHOCK
10^9
10^8
10^7
10^6
10^5
10 Km
1 Km
RADIUS (cm)
NEUTRINO PHOTOSPHERE
$\rho = 10^5$, T = 1/2 meV
HOT BUBBLE
s > 100
NUCLEON
e, γ
$\nu_e, \bar{\nu}_e$
ANNIHILATION HEATING
$\nu_{\mu,\tau}$
e^-
$\bar{\nu}_{\mu,\tau}$
SCATTERING HEATING
ν_e
e^{+-}
$\nu_e, \bar{\nu}_e$
0
0.5
1.0
→ 10 s
PROMPT SHOCK
1st NEUTRINO HEATING
TIME (s)
2nd NEUTRINO HEATING

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: $e^- + (N, Z) \rightarrow (N+1, Z-1) + \nu_e$
    - β^- decay: $(N, Z) \rightarrow (N-1, Z+1) + e^- + \bar{\nu}_e$
- 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



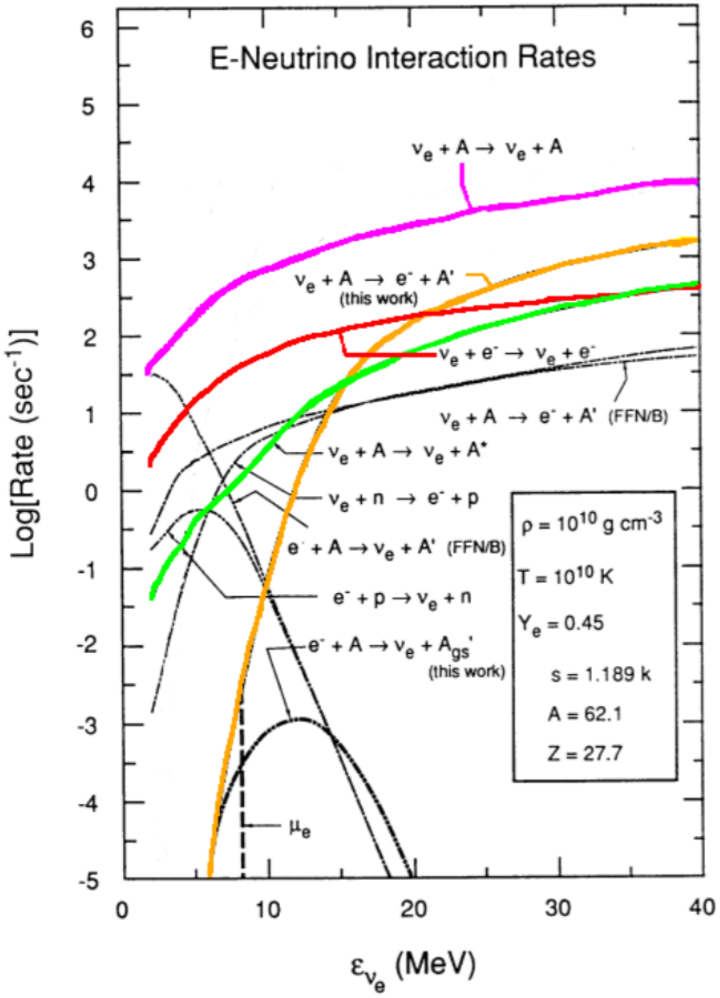
Important processes:

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

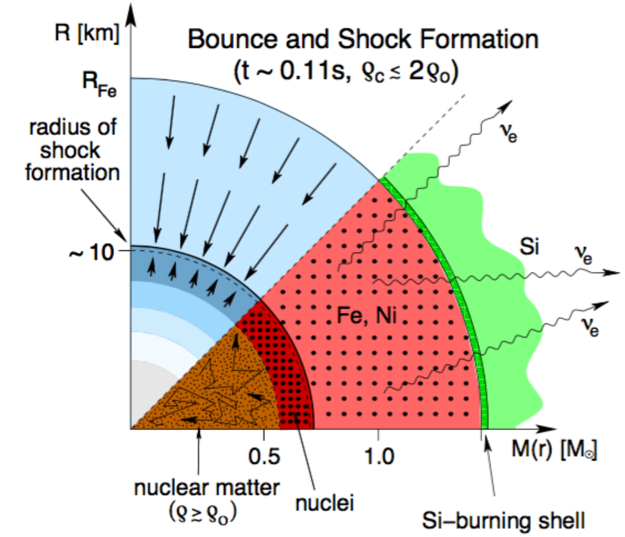
Neutrino interactions in the collapse

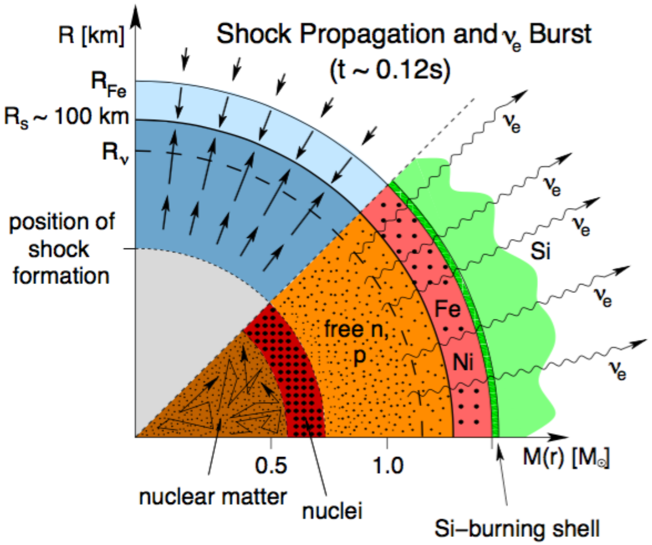
Bruenn and Haxton (1991)
Based on results for ^{56}Fe



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

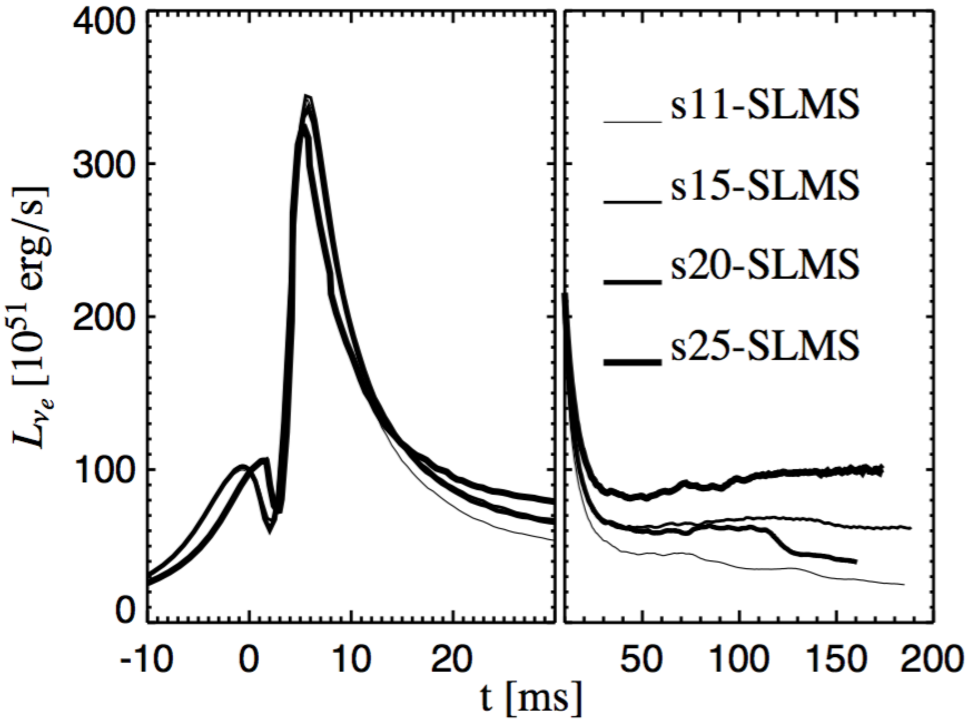
Bounce and ν_e burst





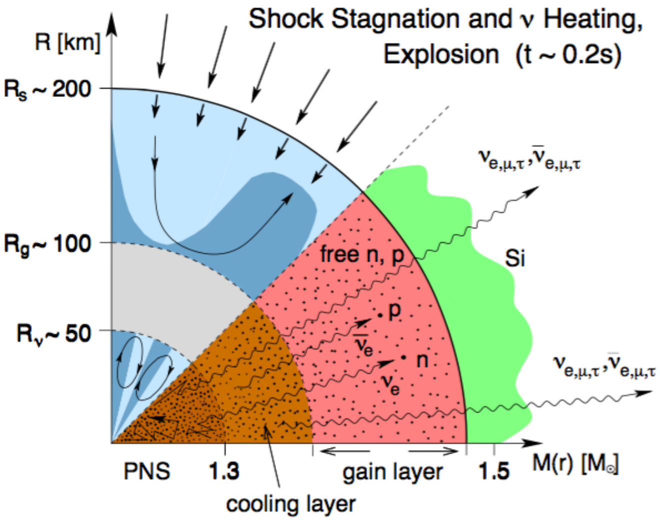
- Collapse continues until central density becomes around twice nuclear matter density.
- Sudden increase in nuclear pressure stops the collapse and a shock wave is launched at the sonic point. The energy of the shock depends on the Equation of State.
- The passage of the shock dissociates nuclei into 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.

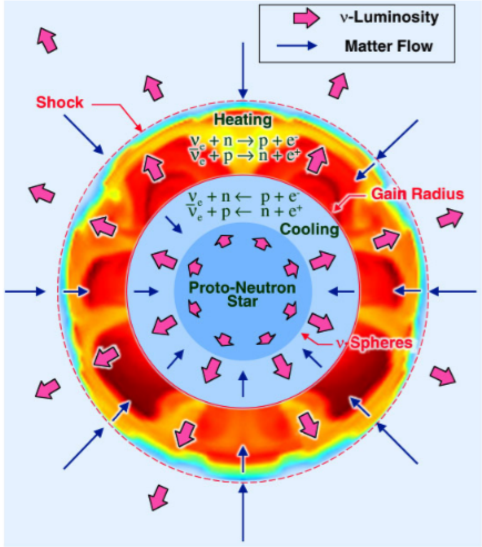
Neutrino burst



- 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.

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:

$E_b \approx 3 \times 10^{53}$ 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

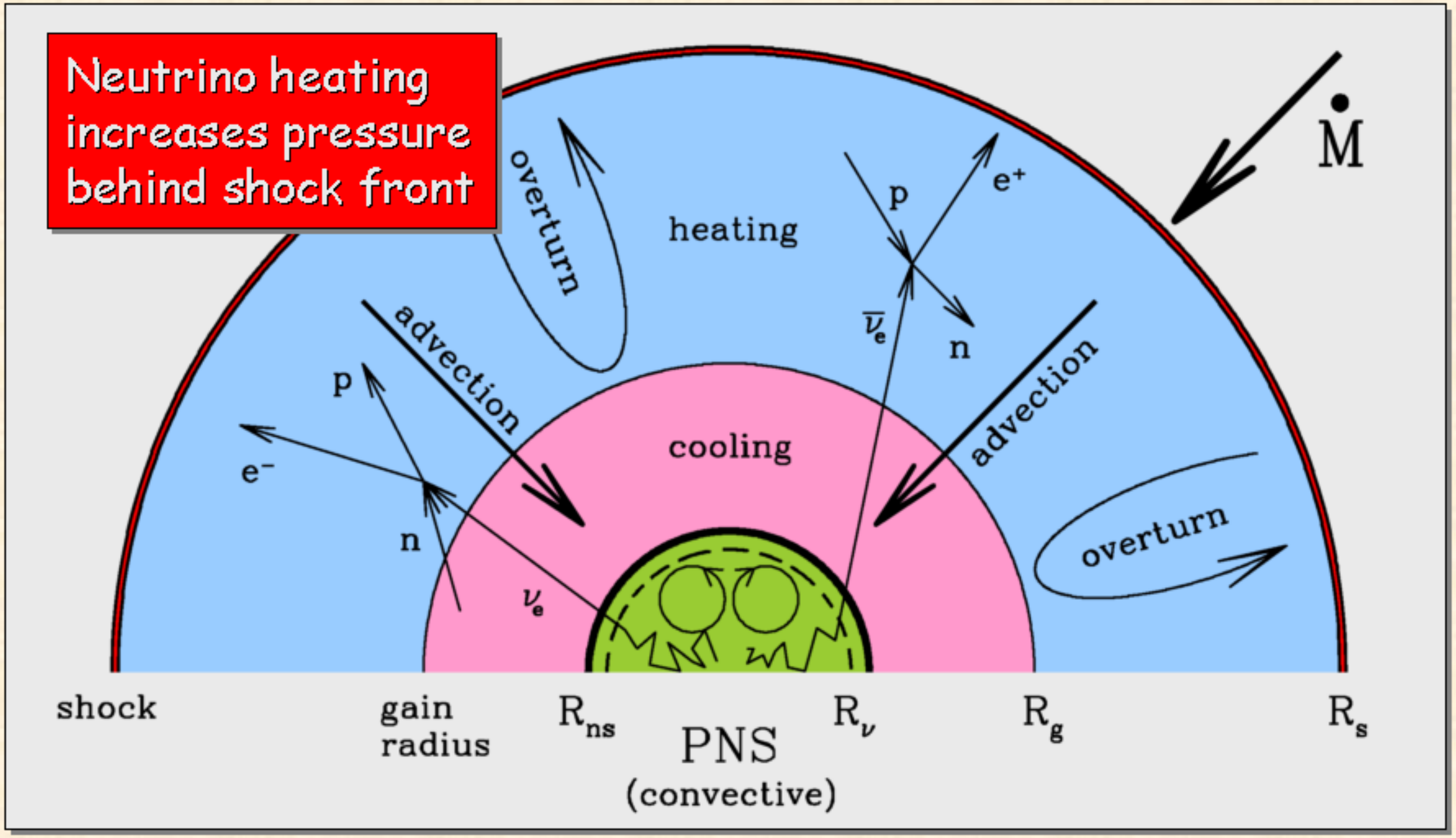
$L_\nu \approx 3\times10^{53}$ erg / 3 sec $\approx 3\times10^{19}\ L_{SUN}$

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

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

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 $\underline{\nu}_e + p \to n + e^+$)
Pair annihilation ($\nu + \underline{\nu} \to e^- + e^+$) negligible

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

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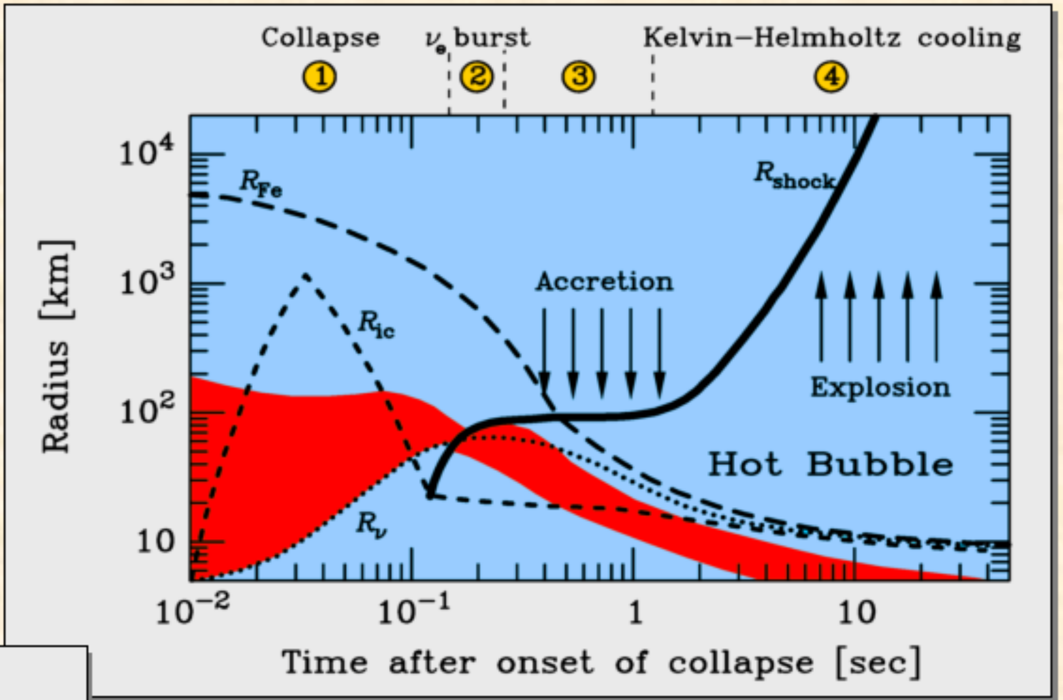
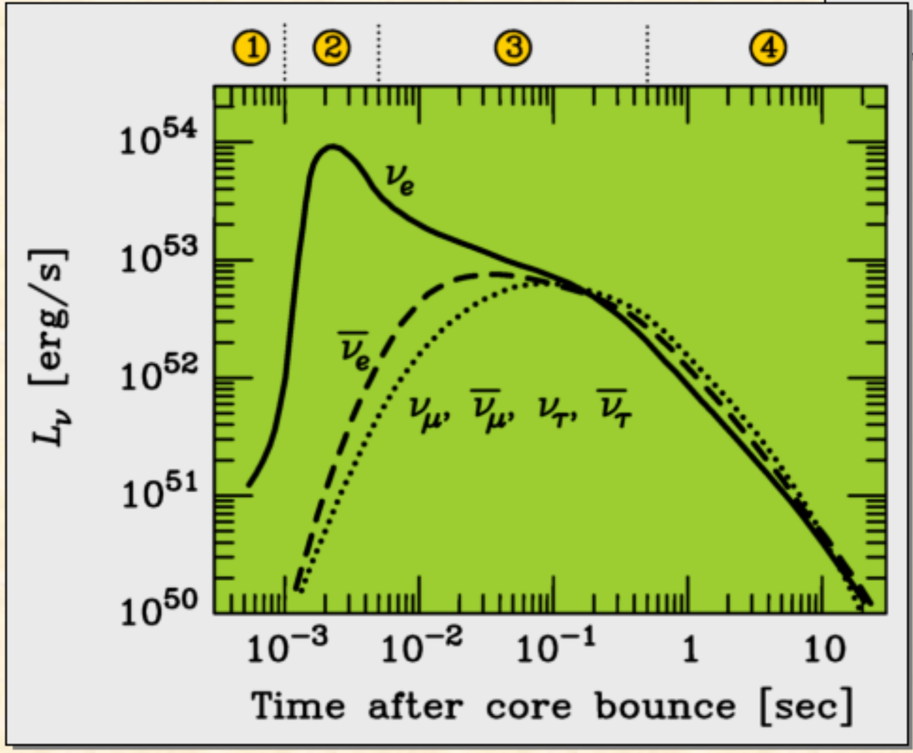
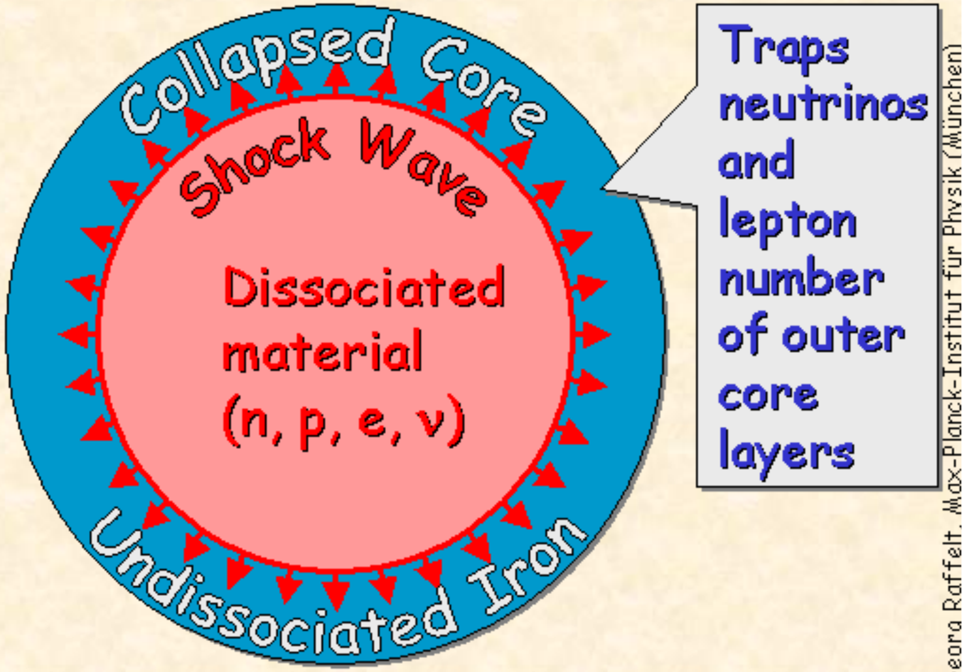
Supernova Neutrino Signal

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







Traps neutrinos and lepton number of outer core layers

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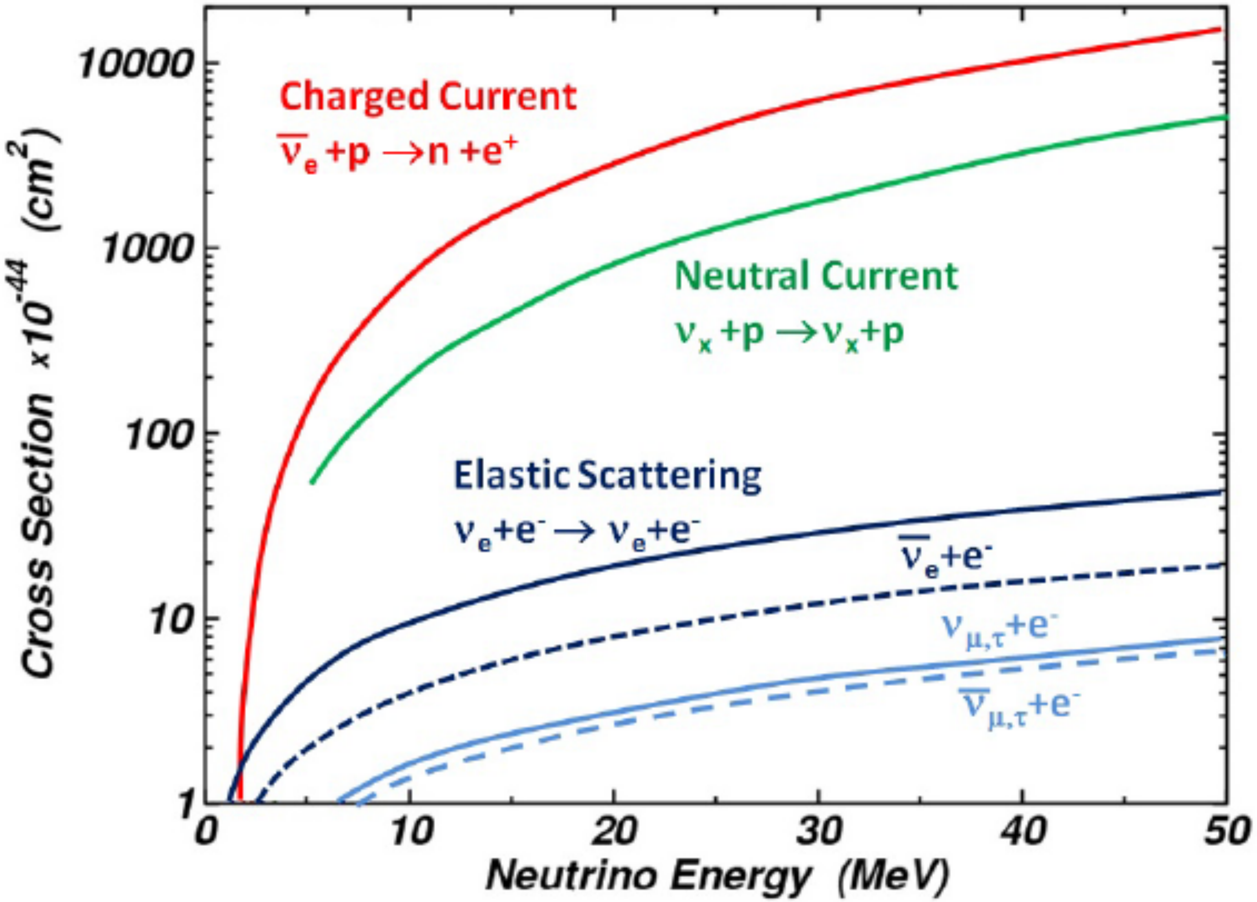
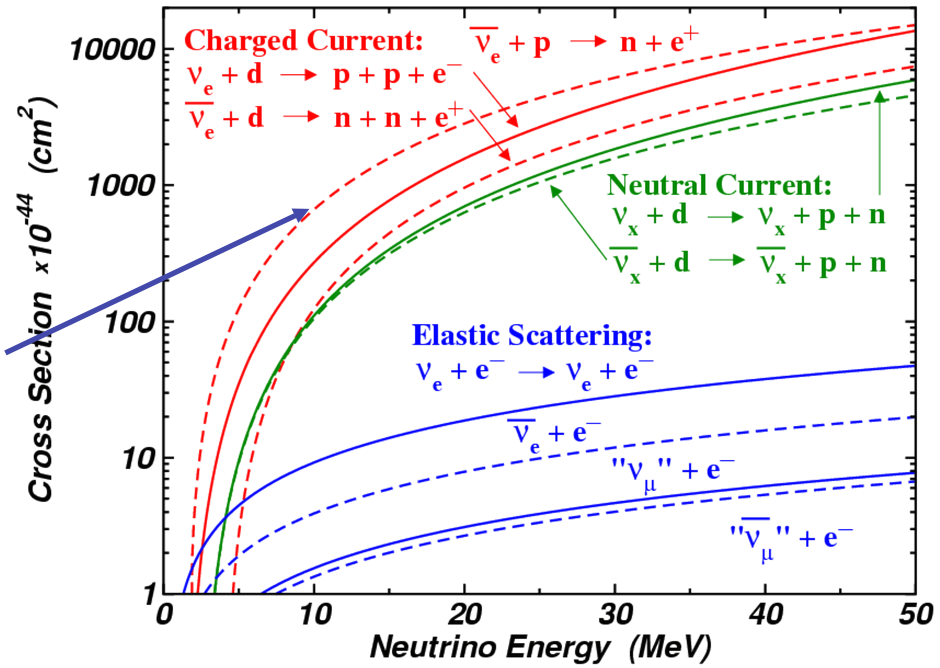
The SN neutrino signal



8.6 The SN1987A

Neutrino cross sections:



Distance: 52 kpc (LMC)

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) × 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**

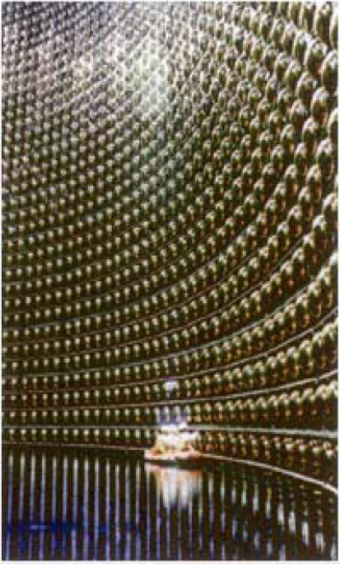
8- $N_{e^+} = F\,(cm^{-2}) \times \sigma\,(cm^2) \times N_t\,(kt^{-1}) = 0.5\,10^{10} \times 2\times10^{-41} \times 0.7\,10^{32}$
= 7 positrons/kt
9 – M(Kam II) = 2.1 kt, efficiency ε~ 80%
10 – Events in Kam II = 7 x 2.1 x ε ~ **12 events**

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

The Detectors

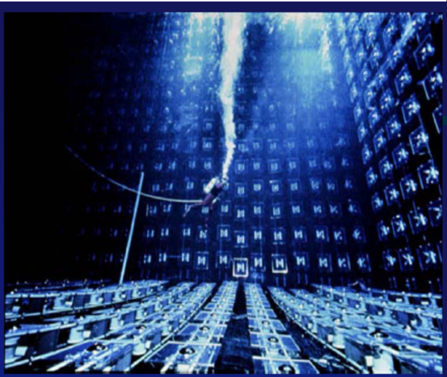
- Water Cherenkov detectors
  - Kamiokande (Japan)
  - IMB (Ohio)
- Liquid scintillation telescopes
  - Baksan – USSR Academy of Sciences, in North Caucasus Mountains, Russia
  - Mont Blanc – Italian Soviet collaboration, in Mont Blanc Laboratory, France

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

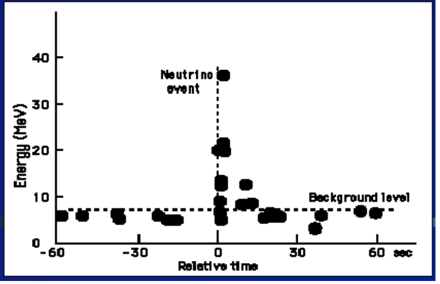
IMB



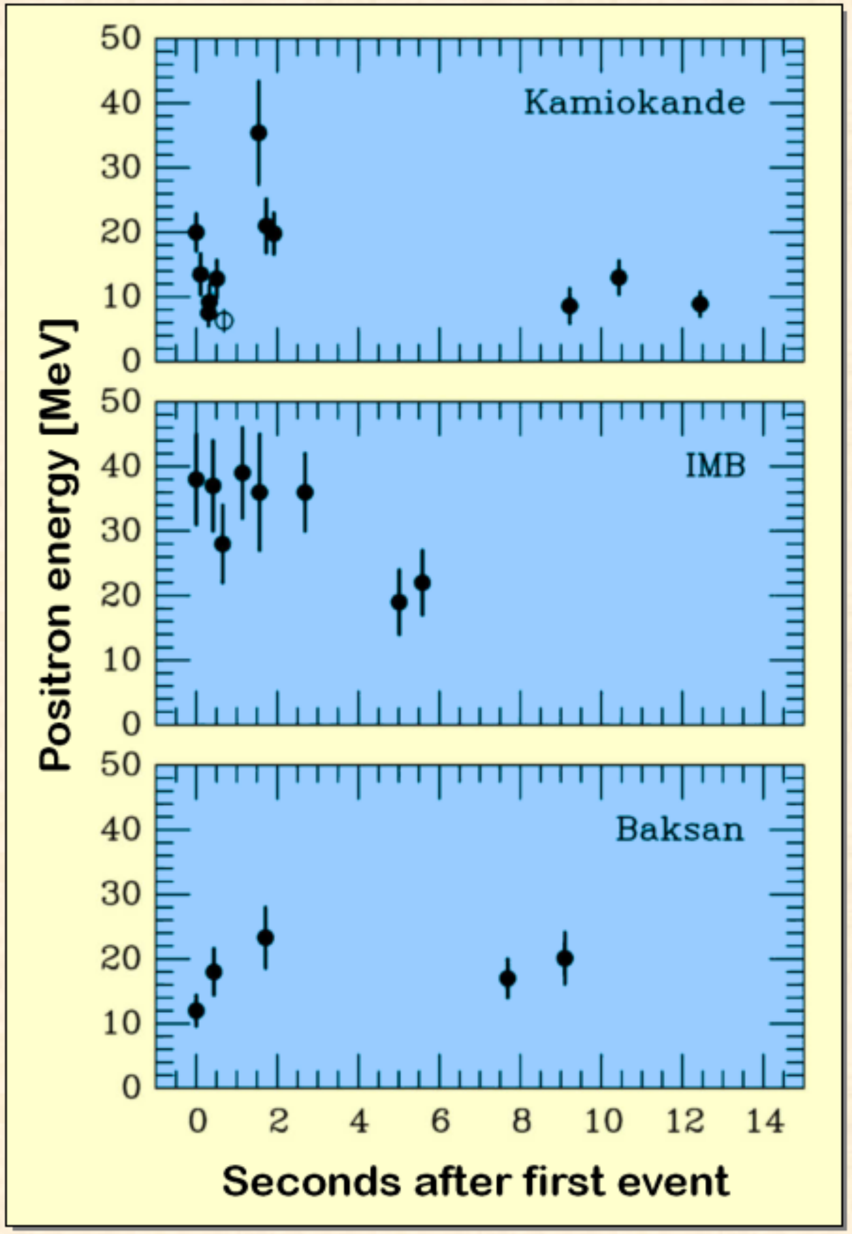
- Located in the Morton Thiokol mine in Ohio
- 580m underground
- Rectangular tank
  - 18 by 17 by 23 m
- 2048 8” photomultipliers
- 2.5 million gallons of water
- Compared to Kamiokande II: Larger volume, but not as deep

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

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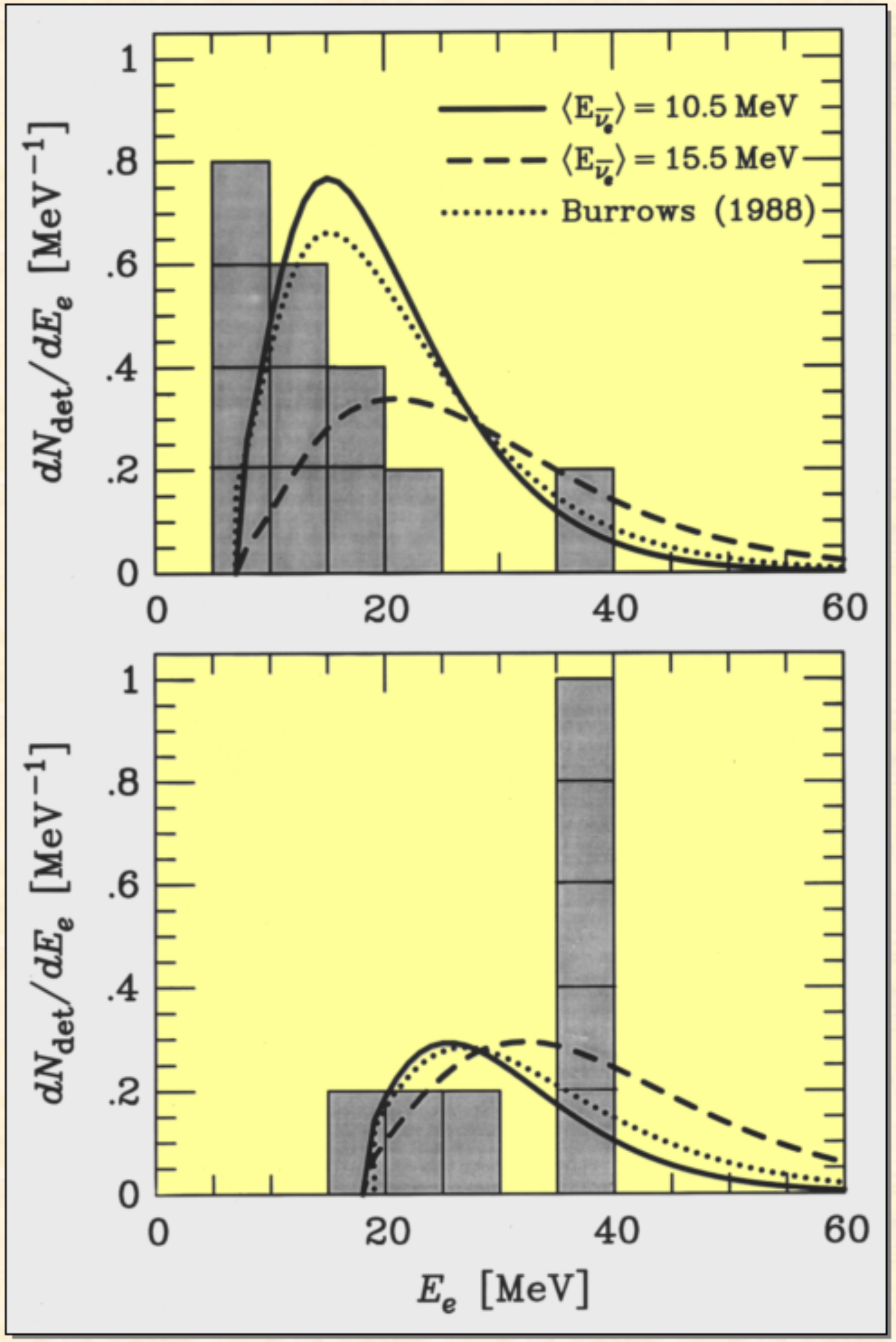
Energy Distribution of SN 1987A Neutrinos



Kamiokande II

IMB

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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):

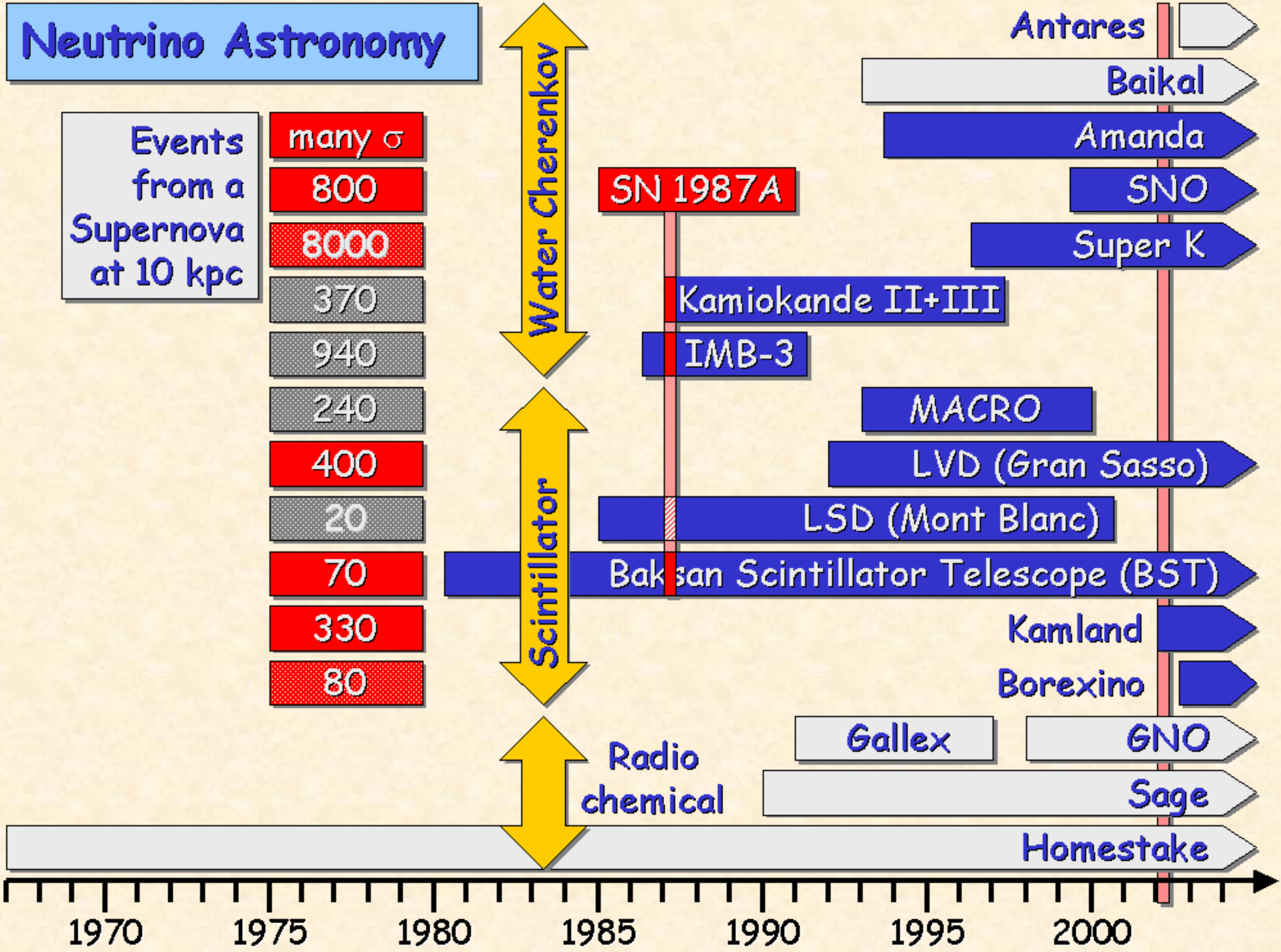
$$v = \frac{p}{E} = \frac{(E^2 - m^2)^{1/2}}{E} \approx 1 - \frac{m^2}{2E} \quad .$$

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

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

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

Neutrino Astronomy



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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