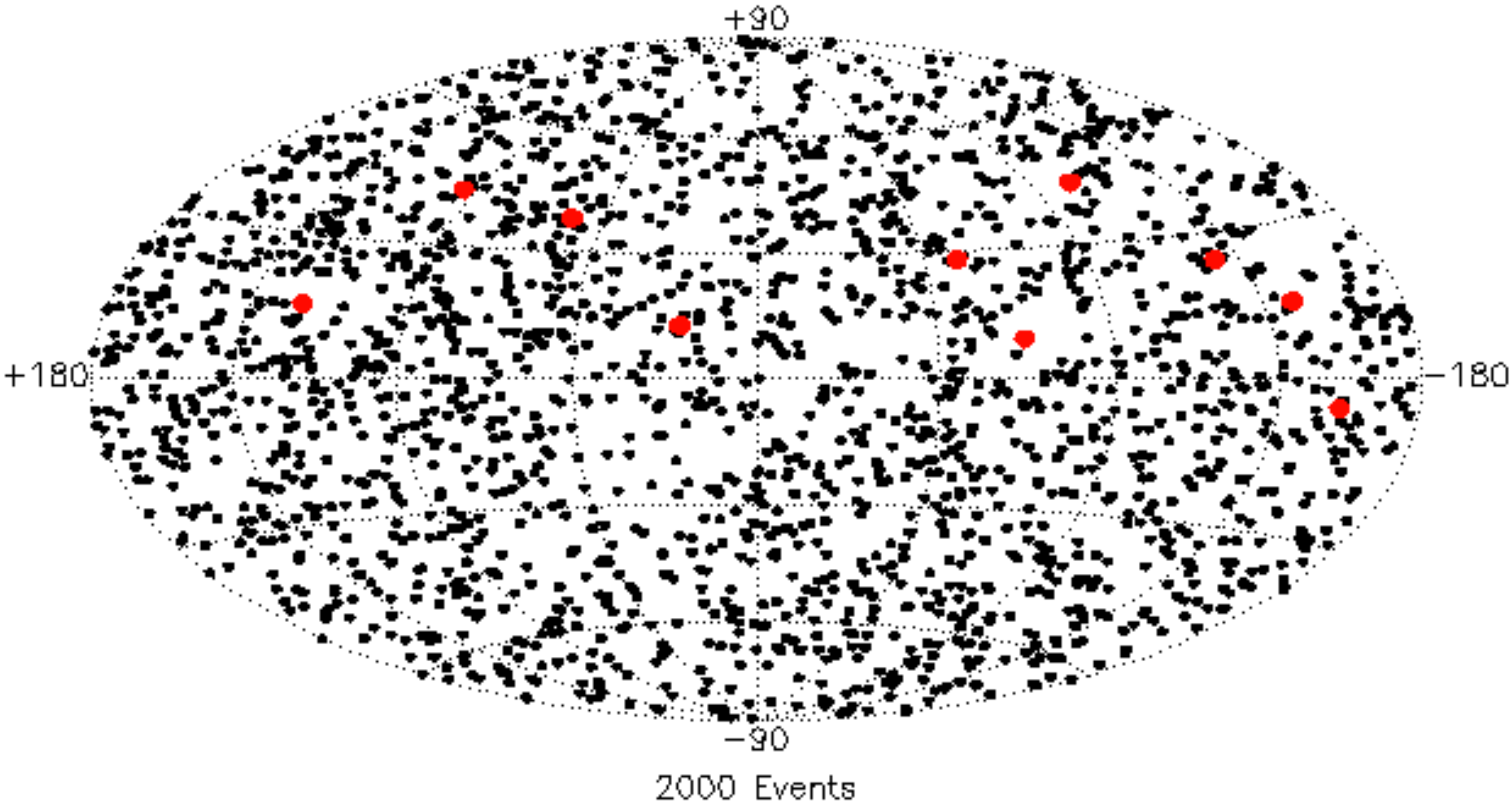
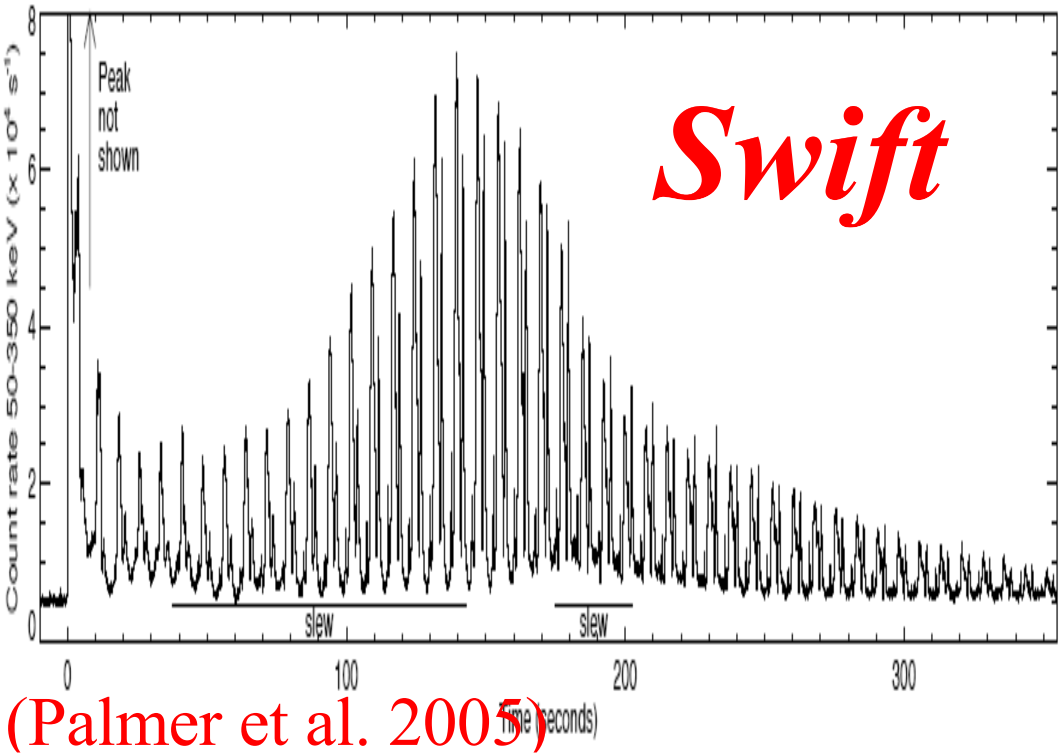
Soft Gamma ray Repeaters (SGRs)



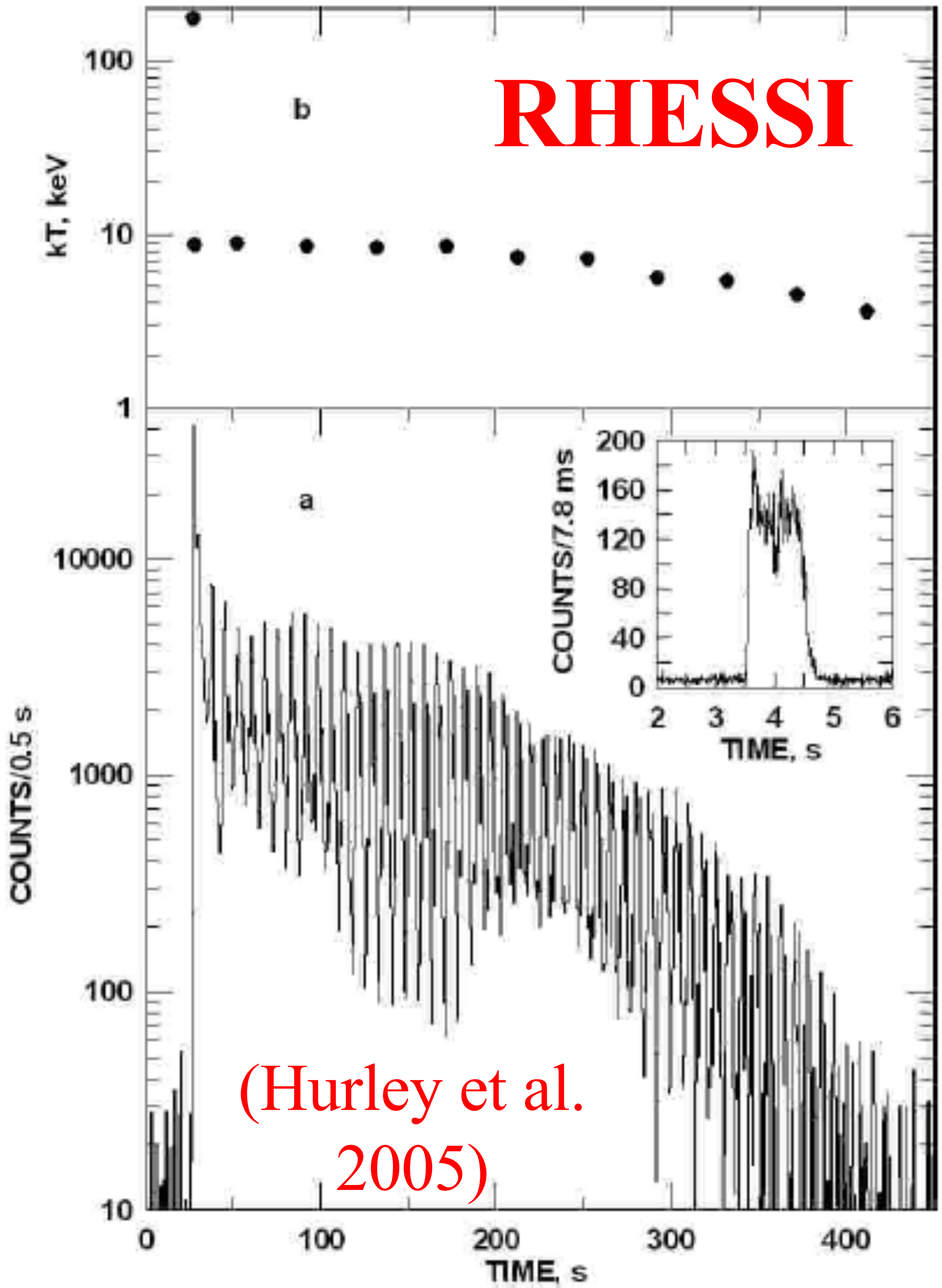
BATSE

The 2004 Dec. 27 Giant Flare

- SGR1806-20
- was ~5^{o} from the sun
- Its distance ≈ 15 kpc
- E_{iso} ~ 10^{46} erg

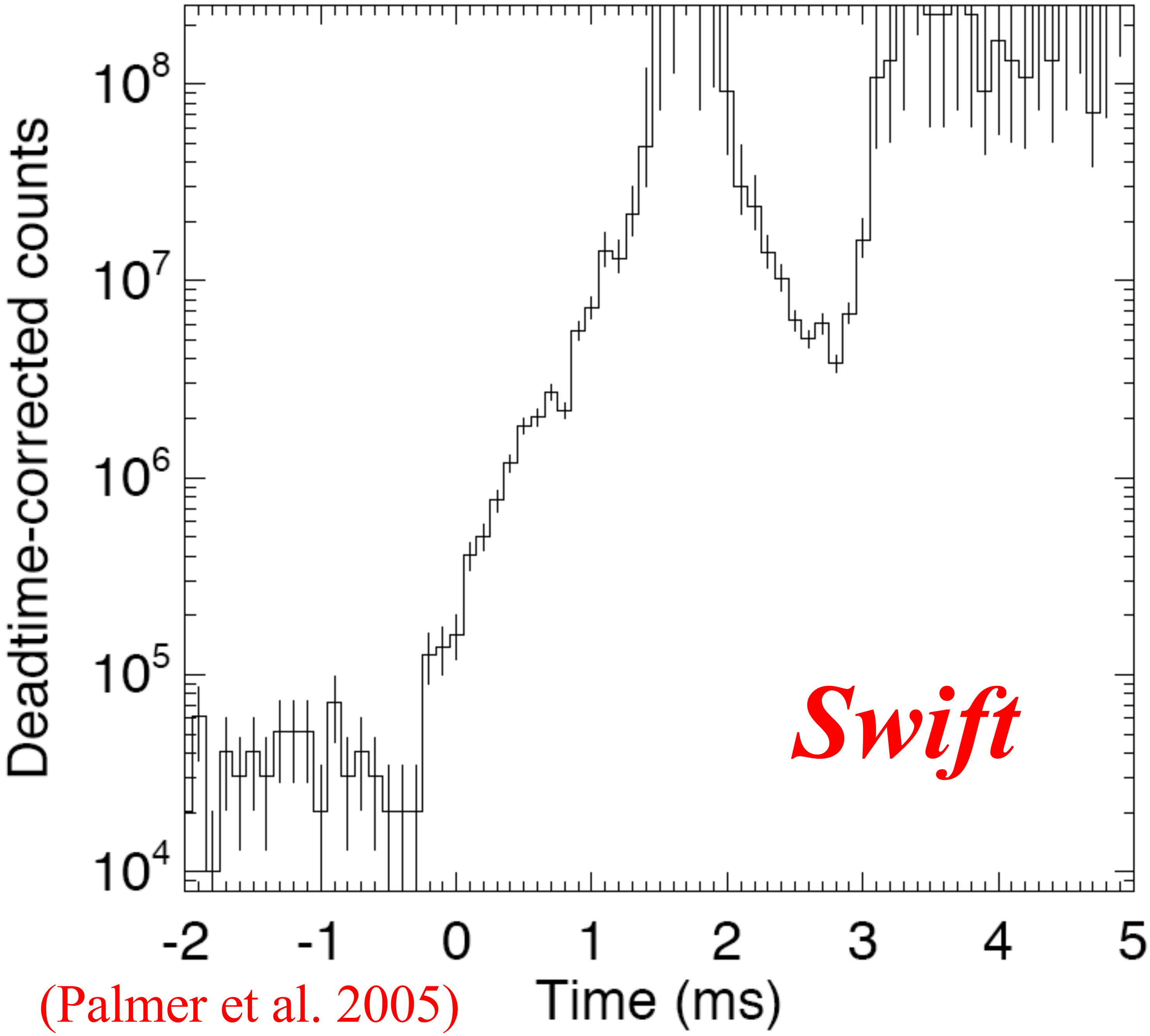


(Palmer et al. 2005)

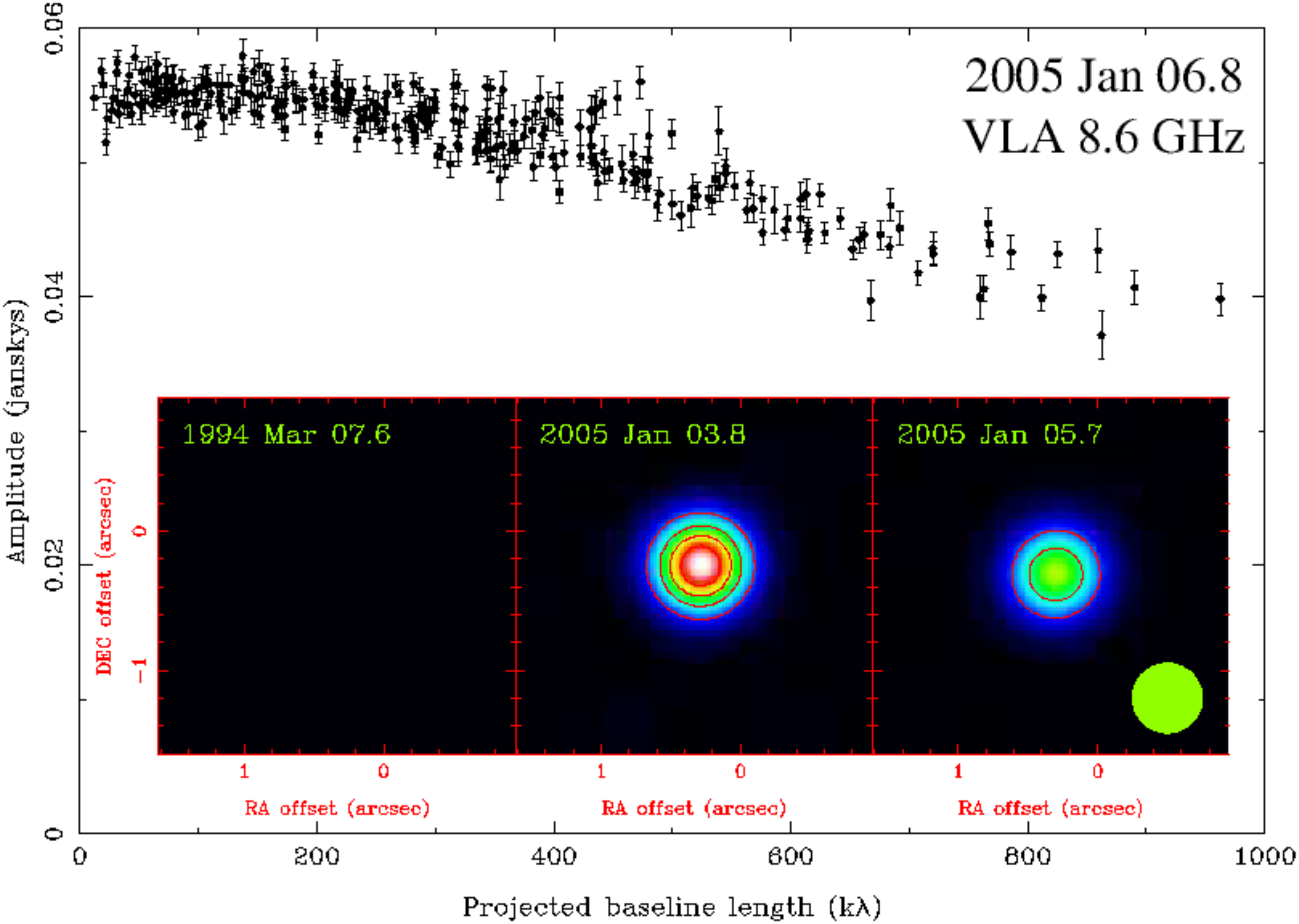


(Hurley et al. 2005)

Rise time: < 1 ms



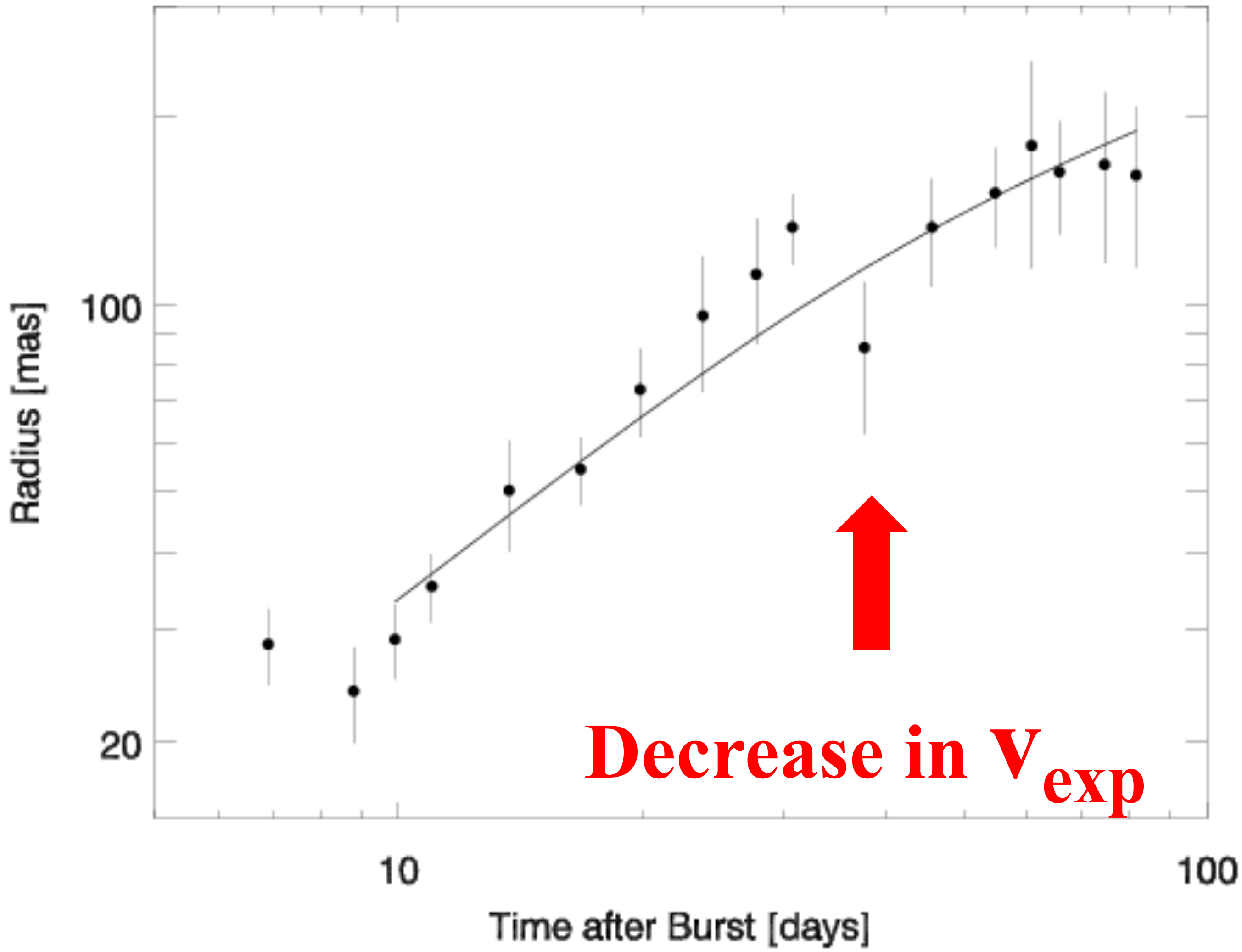
(Palmer et al. 2005)



2005 Jan 06.8
VLA 8.6 GHz
Amplitude (janskys)
0.06
0.04
0.02
0
0
200
400
600
800
1000
Projected baseline length (kλ)
1994 Mar 07.6
2005 Jan 03.8
2005 Jan 05.7
DEC offset (arcsec)
0
−1
1
RA offset (arcsec)
RA offset (arcsec)
RA offset (arcsec)

Growth of the Radio Afterglow

Size at
t+7 days
10^{16} cm
(1000 AU)



VLA
8.5 GHz

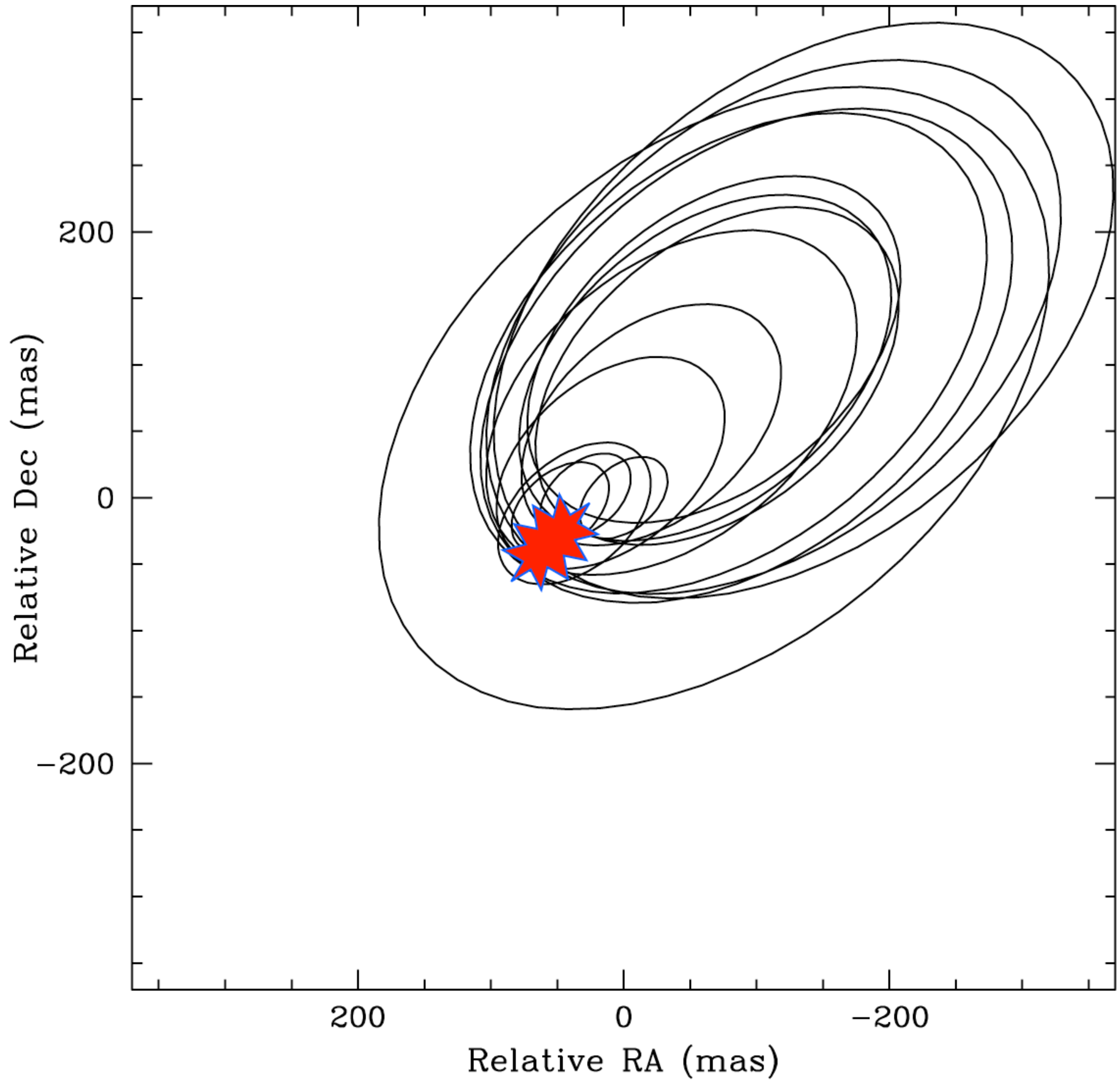
Velocity to
t + 30 days
~ 0.8 c

Image Evolution

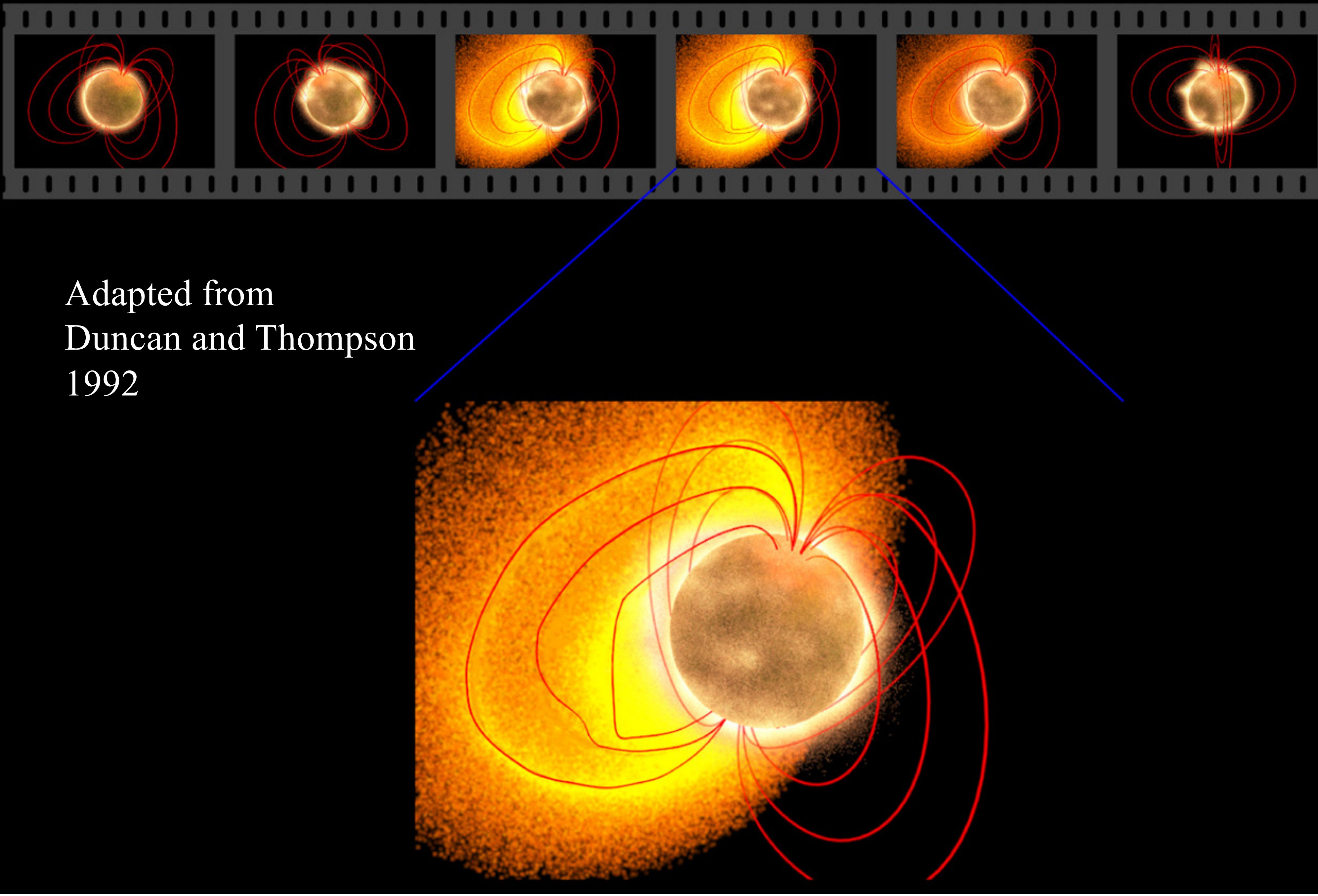
VLA 8.5 GHz

E ~ 10^45 ergs

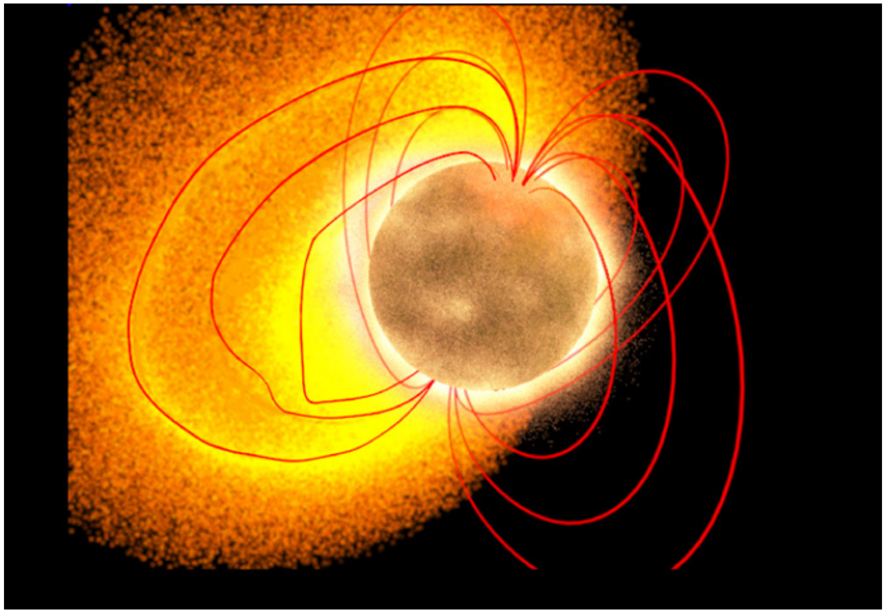
One-sided (anisotropic) outflow

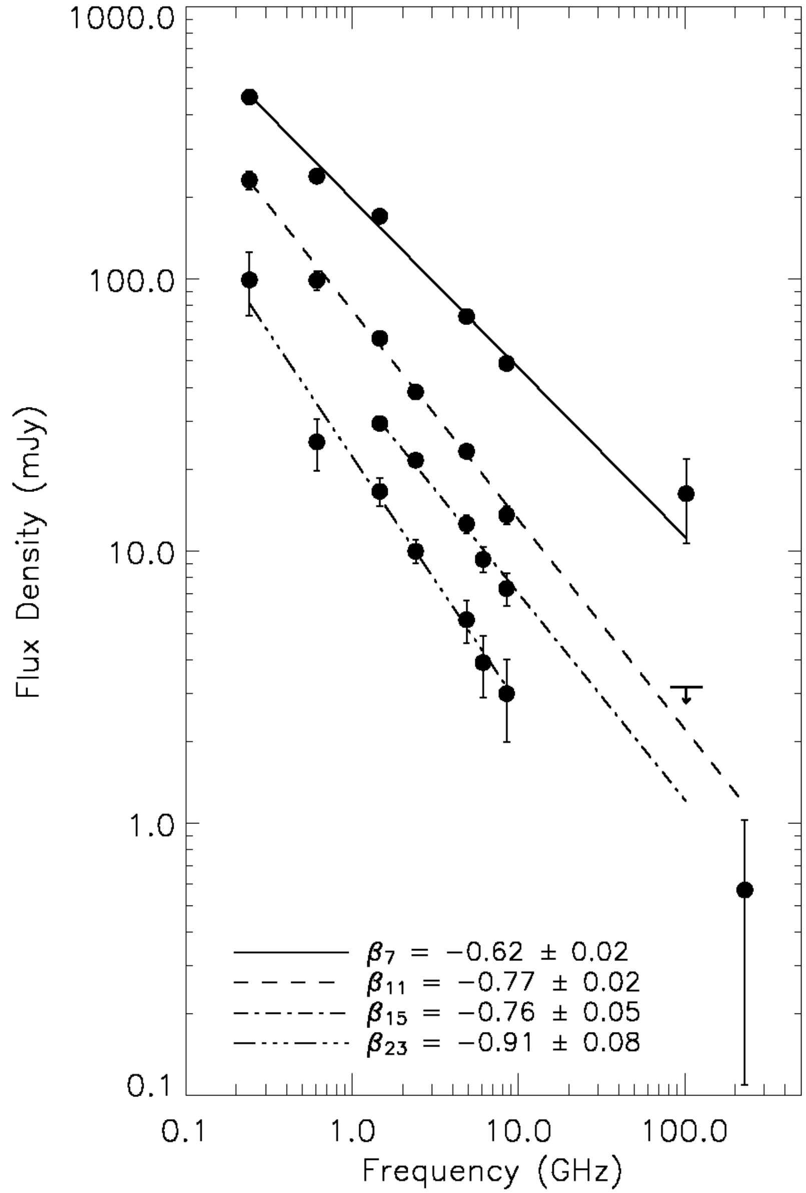


Magnetar burst sequence



Adapted from
Duncan and Thompson
1992





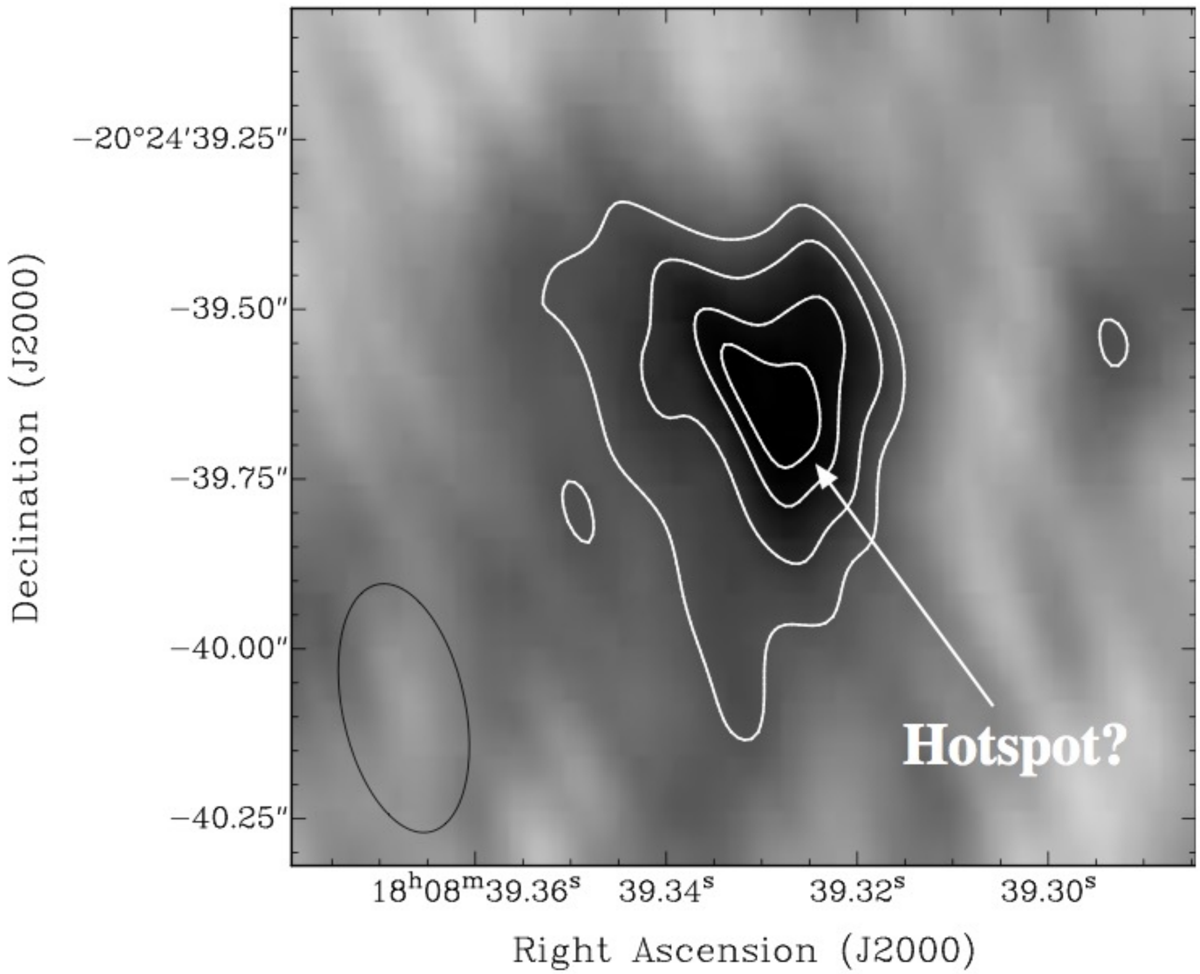
SGR1806-20 : Radio Afterglow has a Steep Spectrum ~ $\nu^{-0.6}$ at t+7 days down to at least 220 MHz

Flux > 1 Jy at early times and low frequencies.

Visible out to ~ 1 Mpc

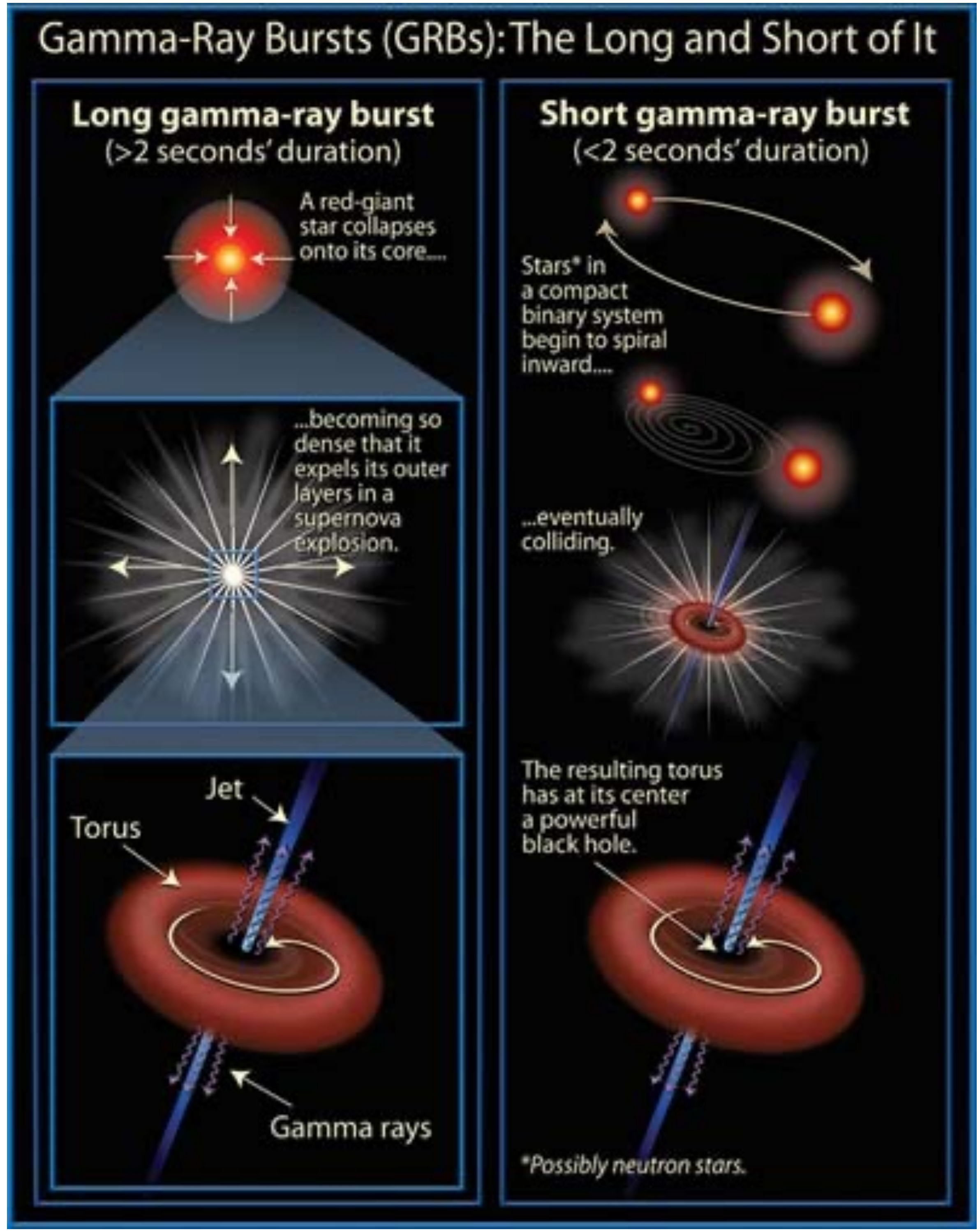
8.4 GHz Image of SGR1806

VLA + PT
t+430 days



- Long GRBs associated with supernovae

- Short GRBs associated with star-forming and elliptical galaxies (old stellar population, broadly consistent with NS and/or BH coalescence. Compact merger or giant flare from magnetar



Test 3 Review

Test covers Ch. 13, 15, 16 and 17 (except neutron stars).
All constants needed will be given on test.

Two equations from A2110/2115:

Small angle formula

$$D = \frac{\alpha d}{206265}$$

Parallax

$d = 1/p$

Stellar evolution

Stars have many properties:

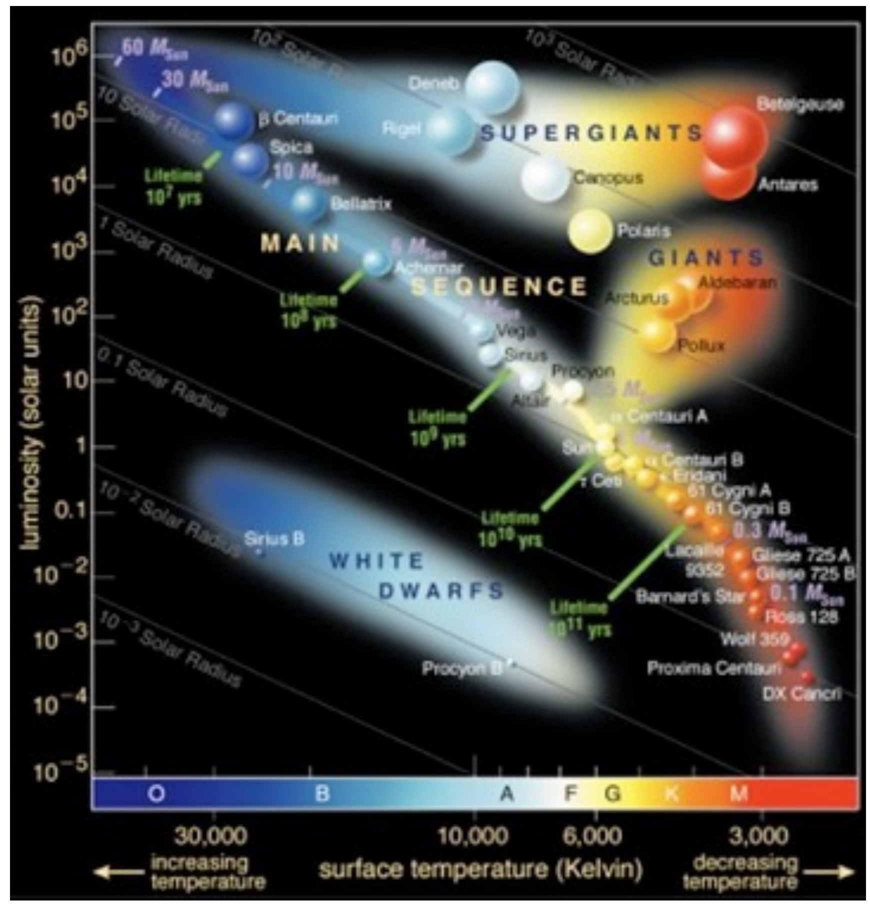
mass, luminosity, radius, chemical composition, surface temperature, core temperature, core density etc..

However, only two properties, the mass and initial chemical composition, dictate the other properties as well as the star's evolution (at least for isolated stars)

This is the Vogt-Russell "theorem".

There is only one way to make a star with a given mass and chemical composition.

=> If we have a protostar with a given mass and composition, we can calculate how that star will evolve over its entire life.



How bright can a star be?

There is a physical limit to how bright a star can be. Recall total pressure is the sum of ideal gas pressure and radiation pressure:

$$P = \frac{\rho k T}{\mu m_H} + \frac{1}{3} a T^4$$

For high *T*, low ρ, radiation pressure can dominate. In this case, the pressure gradient is:

$$\frac{dP_{rad}}{dr} = -\frac{\overline{\kappa}\rho}{c} F_{rad}$$

$$\Rightarrow \quad \frac{dP}{dr} = -\frac{\overline{\kappa}\rho}{c} \frac{L}{4\pi r^2}$$

To remain in hydrostatic equilibrium:

$$\frac{dP}{dr} = -g\rho = -G\frac{M\rho}{r^2}$$

This leads to maximum radiative luminosity a star can have and be stable, the *Eddington Limit*

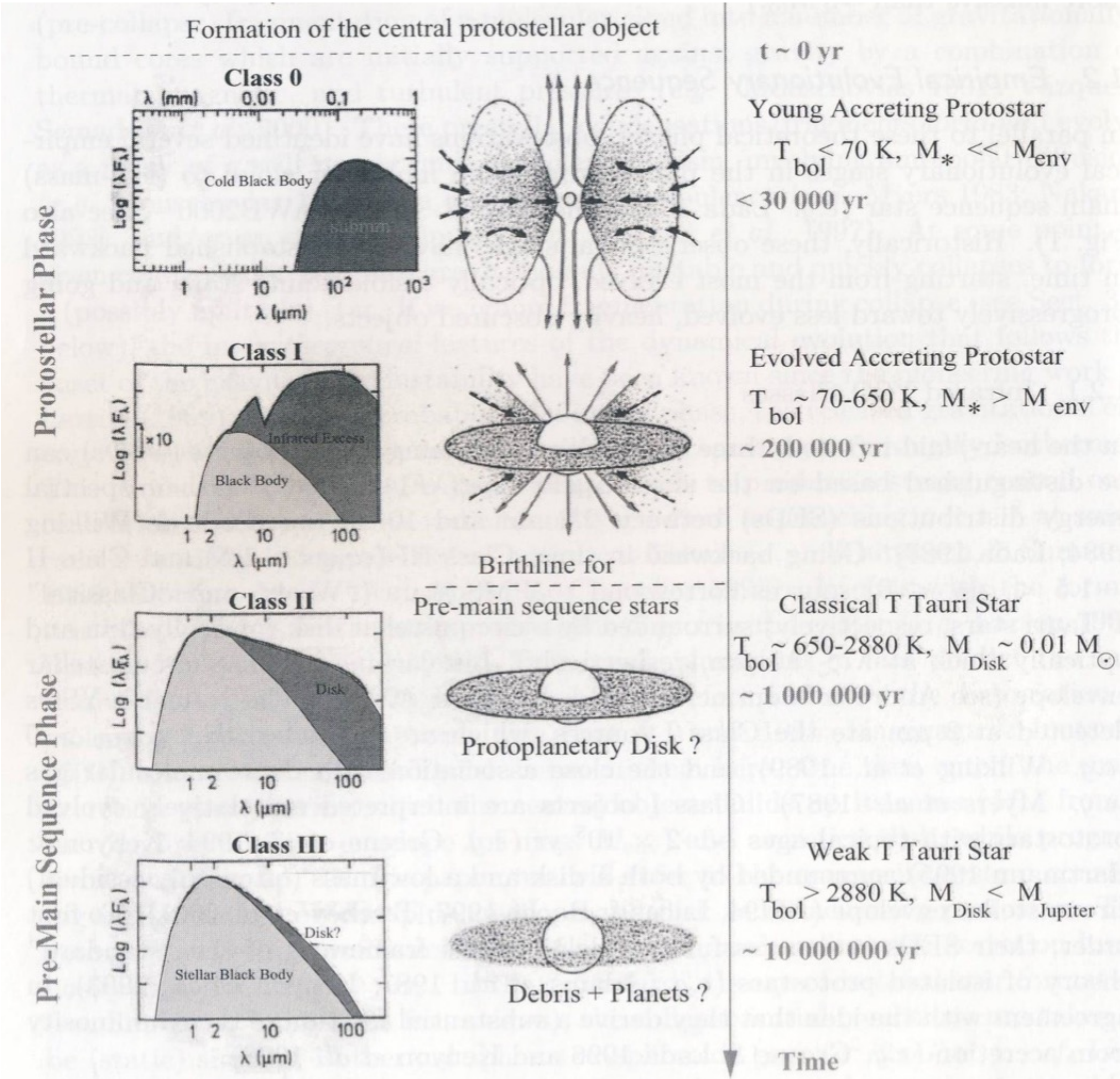
$$\boxed{L_{edd} = \frac{4\pi Gc}{\overline{\kappa}} M}$$

Observations: massive stars tend to have L near L_{edd}. What happens if $L > L_{edd}$?

$$\frac{L_{edd}}{L_\odot} \simeq 38,000\frac{M}{M_\odot}$$

Thus, for $M > 100\ M_\odot$, there is huge mass loss, unstable.
Example is Eta Carina, M ~ 120 $M_\odot$.

YSOs


Formation of the central protostellar object
t ~ 0 yr
Class 0
λ (mm) 0.01 0.1 1
Cold Black Body
submm
Log (λF_λ)
1 10 10^2 10^3
λ (μm)
Young Accreting Protostar
T_bol < 70 K, M_* << M_env
< 30 000 yr
Protostellar Phase
Class I
×10
Infrared Excess
Black Body
1 2 10 100
λ (μm)
Evolved Accreting Protostar
T_bol ~ 70-650 K, M_* > M_env
~ 200 000 yr
Birthline for
Pre-main sequence stars
Class II
Disk
Classical T Tauri Star
T_bol ~ 650-2880 K, M_Disk ~ 0.01 M_⊙
~ 1 000 000 yr
Protoplanetary Disk ?
Pre-Main Sequence Phase
Class III
Disk?
Stellar Black Body
Weak T Tauri Star
T_bol > 2880 K, M_Disk < M_Jupiter
~ 10 000 000 yr
Debris + Planets ?
Time

Stellar wind

Most likely a large radiation pressure at top of AGB phase drives mass loss. Particles can absorb photons and be accelerated to escape the gravitational potential well.

Observations of red giants and supergiants (more massive evolved stars) suggest mass loss rates of 10^{-9} - 10^{-4} $M_\odot$/yr (cf Sun 10^{-14} $M_\odot$/yr).

Two types of mass loss:

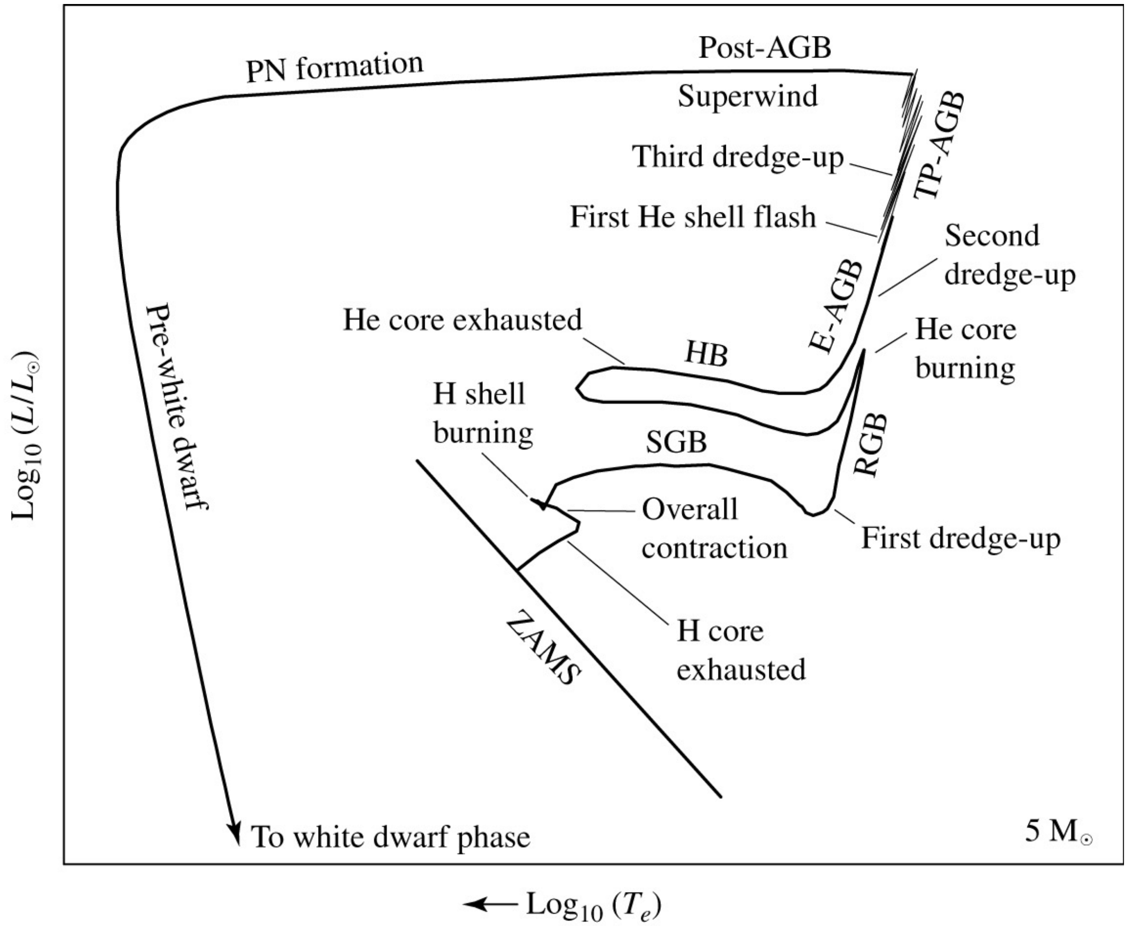
1) Stellar wind - described by a formula linking mass, radius, luminosity with a simple relation and a constant obtained from observations. Wind mass loss rates ~ 10^{-6} $M_\odot$/yr.

2) Superwind - stronger wind responsible for stellar ejecta observed in shell surrounding central star, Wind mass loss rates ~ 10^{-4} $M_\odot$/yr.

Summary of 5 $M_\odot$ evolution

Typical timescales:

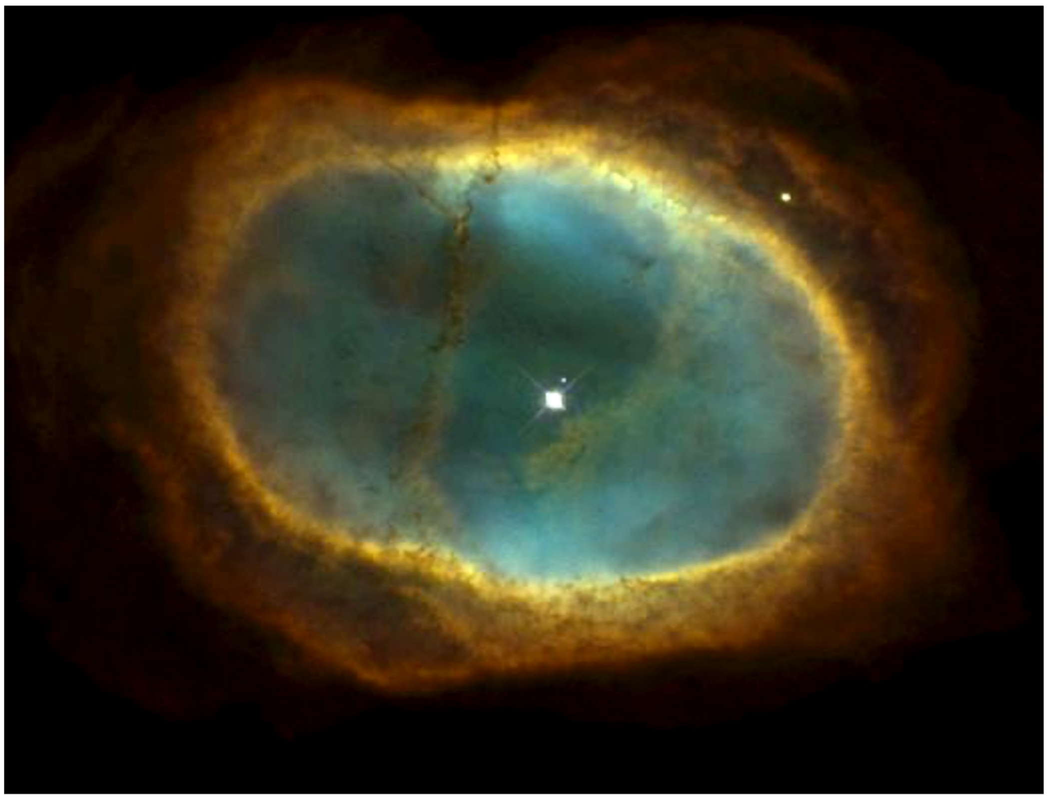
MS	9×10^7 yrs
Subgiant	3×10^6
Red Giant Branch	5×10^5
Horizontal Branch	1×10^7
AGB evolution	1×10^6
PN	1×10^5



Planetary nebulae

High mass loss rates during this phase, up to 10^{-4} $M_\odot$ yr^{-1}. Eventually, rest of envelope expelled at speeds 10-30 km/s after a few 100 years it will be visible as a "planetary nebula" (PN). PN lasts for ~10^5 yrears

Inert, degenerate C,O core (with residual layer of H, He) remains, a *white dwarf* (WD), Earth size. *M* ~ few 10ths $M_\odot$. Cools over billions of years. Degenerate.



Cosmic Explosions

Energy

Flare stars

Novae (detonations on the surface of a star)

[Magnetar Flares and Giant Flares]

Supernovae (detonations of a star)

[Gamma Ray Bursts (formation of a black hole?)]

Post MS stellar evolution - high mass stars $M > 8M_\odot$

Rapid: approximately $\tau \propto M^{-2}$

High mass

=> high gravity

=> high core T

=> rapid burning

=> can burn beyond C,O to Fe, Ni.

e.g. $^{12}_{6}C + ^{4}_{2}He \rightarrow ^{16}_{8}O + \gamma$

$$^{12}_{6}C + ^{12}_{6}C \rightarrow ^{24}_{12}Mg + \gamma$$

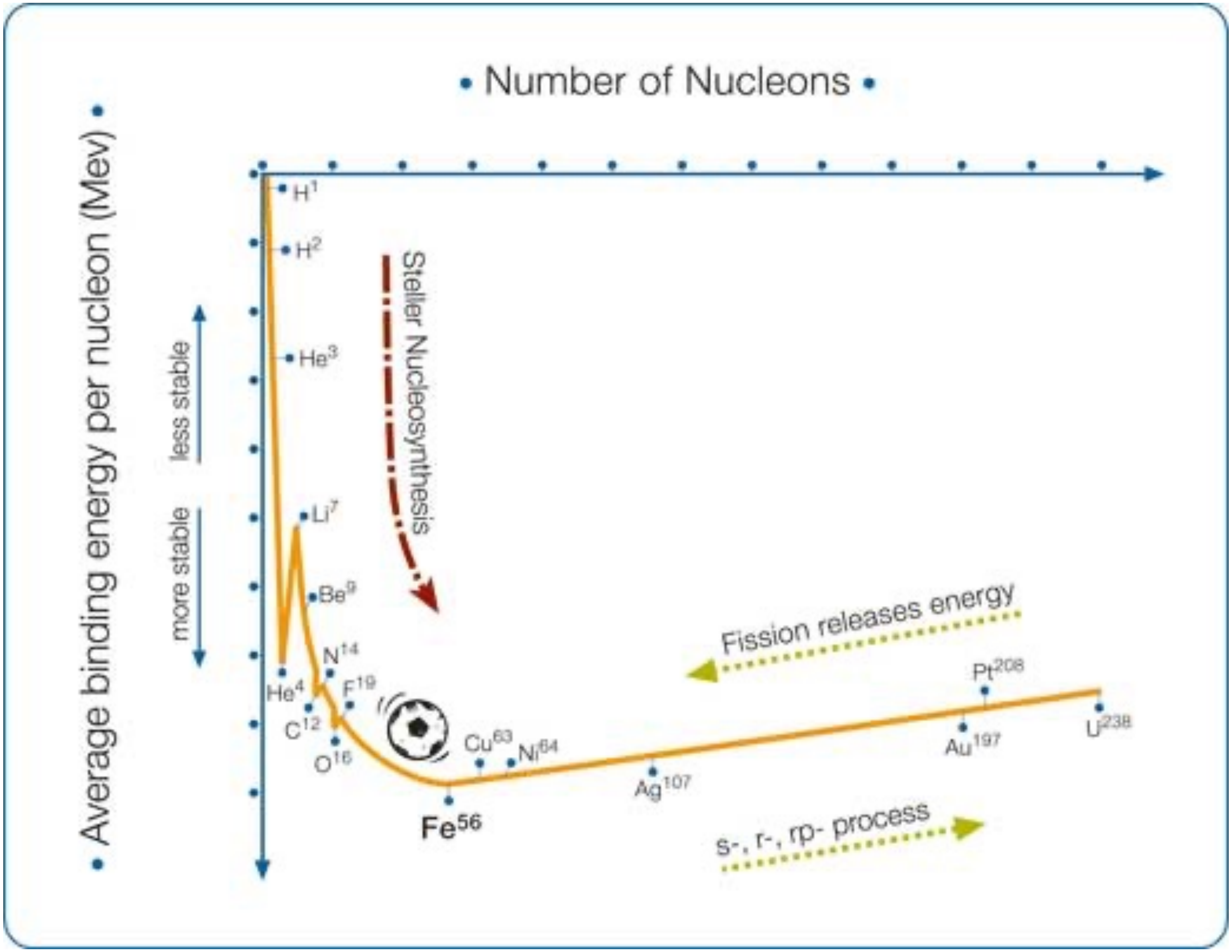
$$^{16}_{8}O + ^{16}_{8}O \rightarrow ^{24}_{14}Si + ^{4}_{2}He$$

$$^{16}_{8}O + ^{16}_{8}O \rightarrow ^{32}_{16}S + \gamma$$

$$^{28}_{14}Si \rightarrow ^{56}_{26}Fe,\ ^{54}_{26}Fe,\ ^{56}_{28}Ni$$

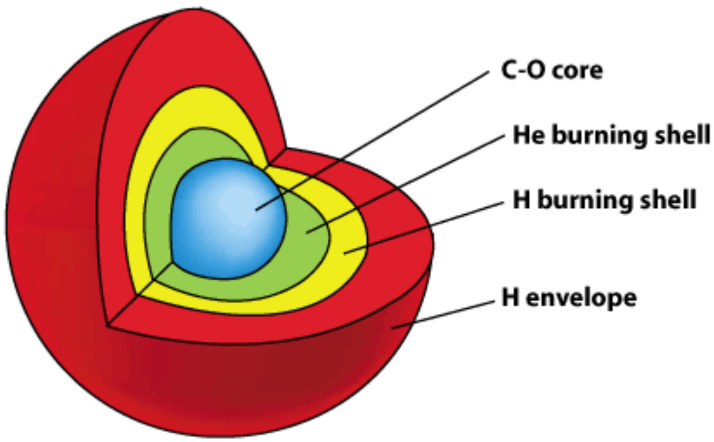
1) Fuel in core exhausts
2) Inert core contracts
3) Shell burning of “previous” element begins
4) Formerly inert core ignites etc….

Binding Energy per nucleon

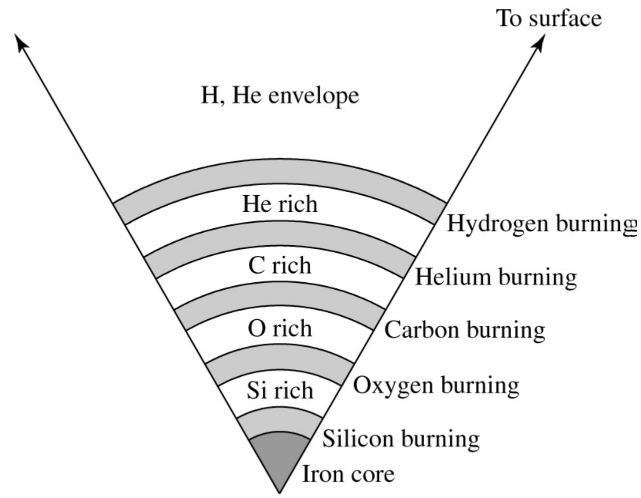


Compare structure of AGB star to that of a massive star:

AGB star



massive star



<u>20 $M_\odot$</u>

Core H burning time	10^7 yrs
Core He burning time	10^6 yrs
Core C burning time	300 yrs
Core O burning time	200 days
Core Si burning time	2 days

Core masses range from 1.3 $M_\odot$ for a 10 $M_\odot$ star to 2.5 $M_\odot$ for a 50 $M_\odot$ star.

Types of Supernovae

Supernova are classified by the optical lines in the spectra of the debris. Must then go back to figure out what explosive processes can produce such spectra.

Type I – No H lines in spectrum →
- Type Ia – a strong Si II line at 615 nm
- Type Ib – weak Si II, but He lines
- Type Ic – weak Si II, no He lines

Type II – H lines

Type II's are core-collapse SNe, with H from envelope
Type Ib's are as well, but H envelope previously completely lost through winds (see Wolf-Rayet stars in C+O 15.1)
Type Ic's are as well, but also lost He shell
Type Ia's are due to accretion-induced collapse of a white dwarf in a close binary.

Cosmic rays

Discovered by Victor Hess in 1912

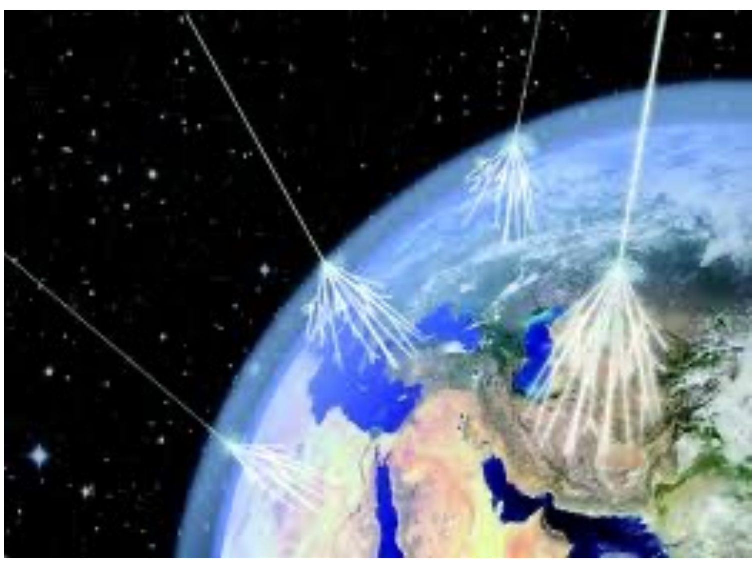
Cosmic rays are high energy particles producing radiation when interacting with the atmosphere of the Earth.

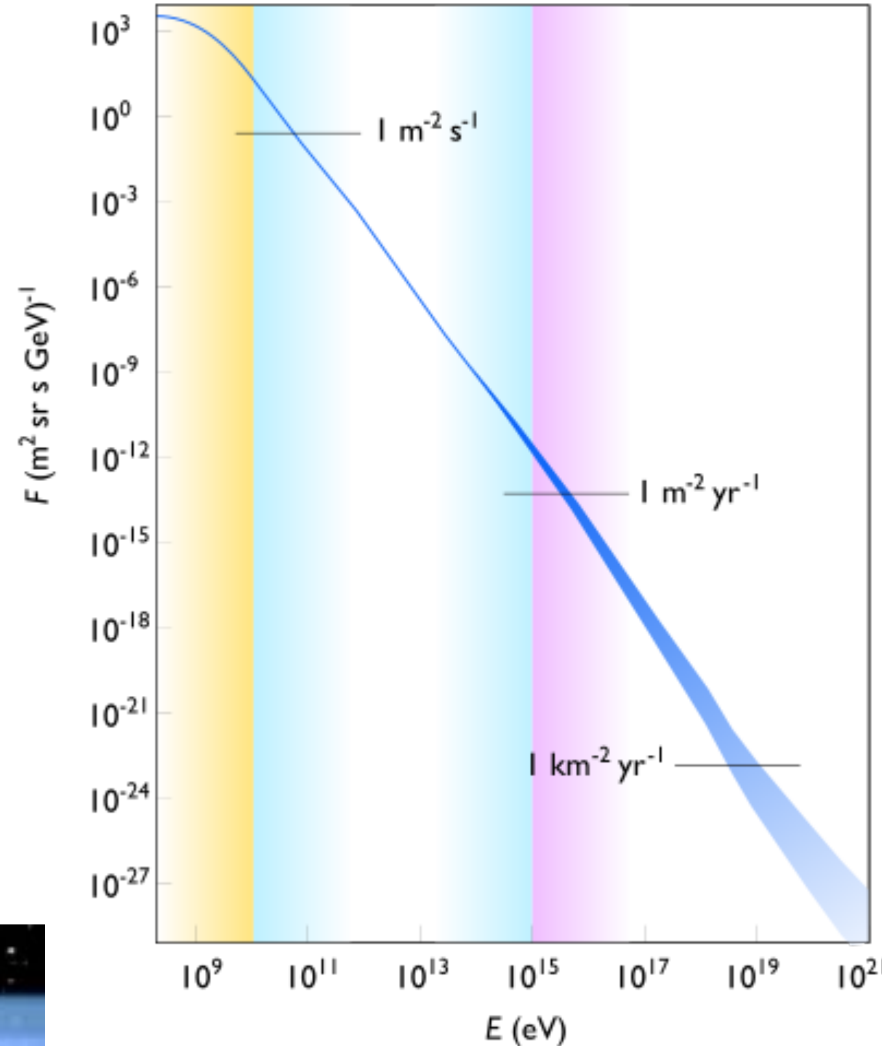
What are they?

Solar particles

Supernova accelerated particles

AGN???





End states of stars

Possibilities:

1. Violent explosion, no remnant (Type Ia SN)

2. White dwarf
    - $M \sim 0.6\mathrm{M}_\odot$
    - $R \sim \mathrm{R}_\oplus$
    - $\rho \sim 10^9$ kg m^{-3}

3. Neutron star
    - $M \sim 1.4\mathrm{M}_\odot$
    - $R \sim 10$ km
    - $\rho \sim 10^{17}$ kg m^{-3}

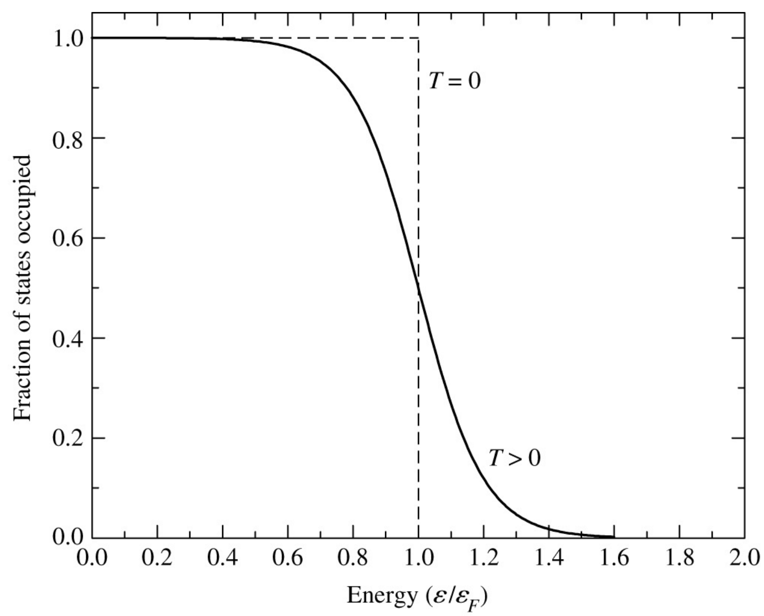
4. Black hole
    - $M \geq 3\mathrm{M}_\odot$

The Fermi Energy

The highest energy of an electron in a collection of electrons at a temperature of absolute zero.

In classical statistical mechanics, temperature of a system is the measure of its average kinetic energy.

In quantum statistical mechanics, Fermi energy corresponds to last filled level at absolute zero, and the corresponding temperature is the Fermi temperature.



Fraction of energy states occupied by fermions.

If the temperature is low enough, electrons start arranging themselves in their lowest possible energy states. Approximately, gas gets close to degeneracy when typical electron energy, *3kT/2* , gets close to E_F. Since E_F is bigger for electrons, they will become degenerate at a lower temperature than the protons or neutrons.

Thus, electrons degenerate when:

$$E = \frac{3kT}{2} < \frac{\hbar^2}{2m_e}\left[3\pi^2\left(\frac{Z}{A}\right)\frac{\rho}{m_H}\right]^{2/3}$$

$$\boxed{\frac{T}{\rho^{2/3}} < \frac{\hbar^2}{3m_e k}\left[\frac{3\pi^2}{m_H}\left(\frac{Z}{A}\right)\right]^{2/3}}$$

For Z/A=0.5, this is 1261 K m^2 $kg^{-2/3}$.

So, using the expression for the pressure:

$$P = \frac{1}{3} n_e v p \approx \frac{1}{3} \frac{\hbar^2}{m_e} \left[\left(\frac{Z}{A} \right) \frac{\rho}{m_H} \right]^{5/3}$$

Exact calculation gives:

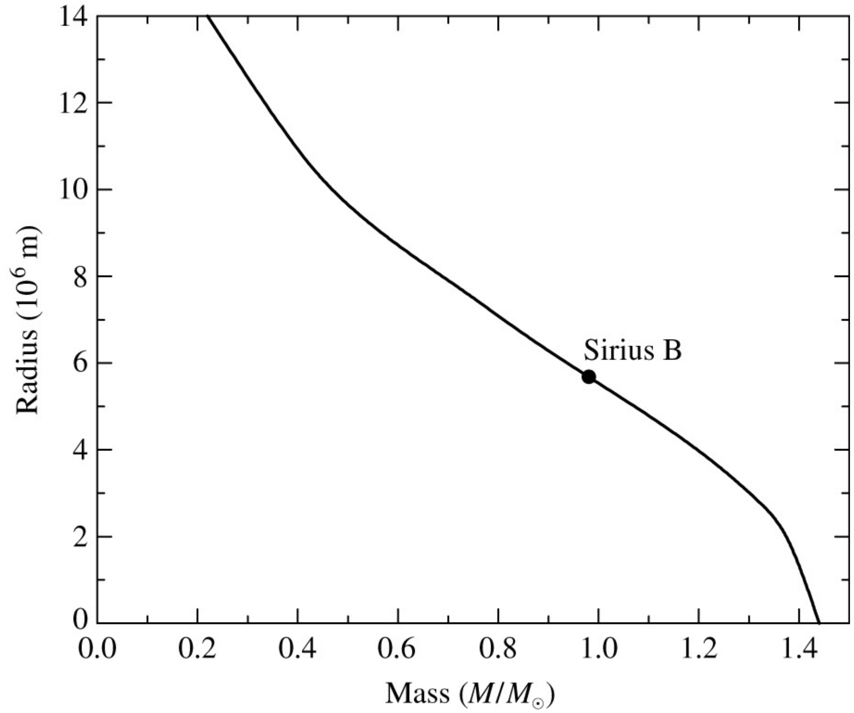
$$P = \frac{(3\pi^2)^{2/3}}{5} \frac{\hbar^2}{m_e} \left[\left(\frac{Z}{A} \right) \frac{\rho}{m_H} \right]^{5/3}$$

Electron degeneracy pressure (non-relativistic)

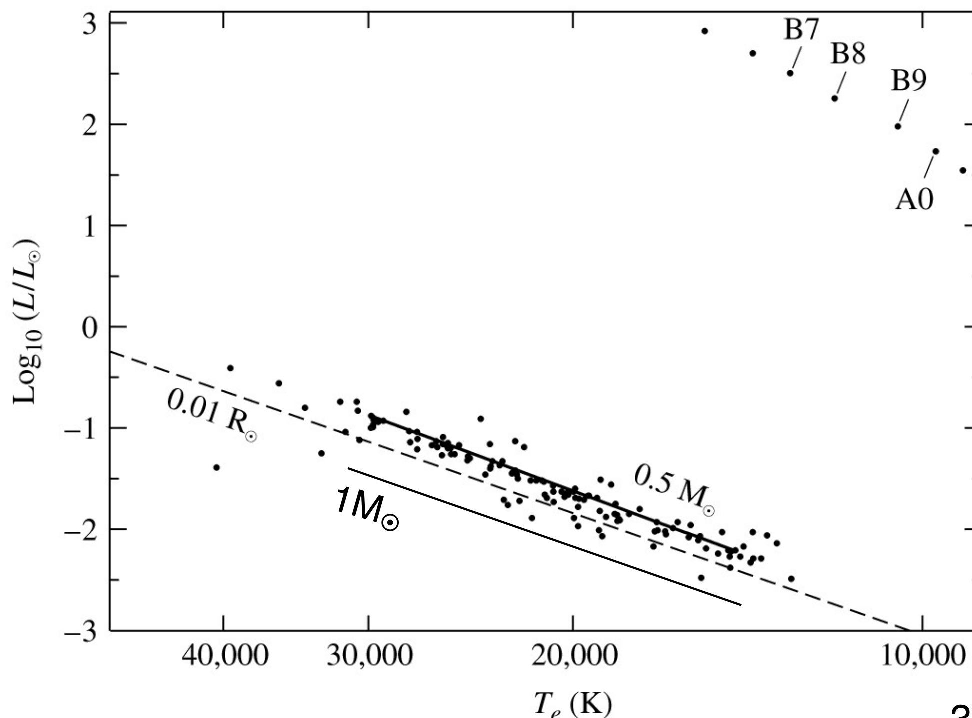
Key point: $P \propto \rho^{5/3}$ - independent of *T* !

P non-zero even if classically *T* -> 0. Any energy generation which raises *T* will not increase *P*. Recall He flash. Runaway fusion until $T/\rho^{2/3}$ high enough.

Strange implication: More massive WD's have *smaller R* to provide needed P_{degen}.



Location on H-R diagram:



White Dwarfs

Electron degeneracy condition

$$\frac{T}{\rho^{2/3}} < \frac{\hbar^2}{3m_e k}\left[\frac{3\pi^2}{m_H}\left(\frac{Z}{A}\right)\right]^{2/3}$$

(for a fully ionized gas:

$$n_e = \frac{Z}{A}\frac{\rho}{m_H}$$

)

Non-relativistic electron degeneracy pressure:

$$P = \frac{(3\pi^2)^{2/3}}{5}\frac{\hbar^2}{m_e}\left[\left(\frac{Z}{A}\right)\frac{\rho}{m_H}\right]^{5/3}$$

Relativistic:

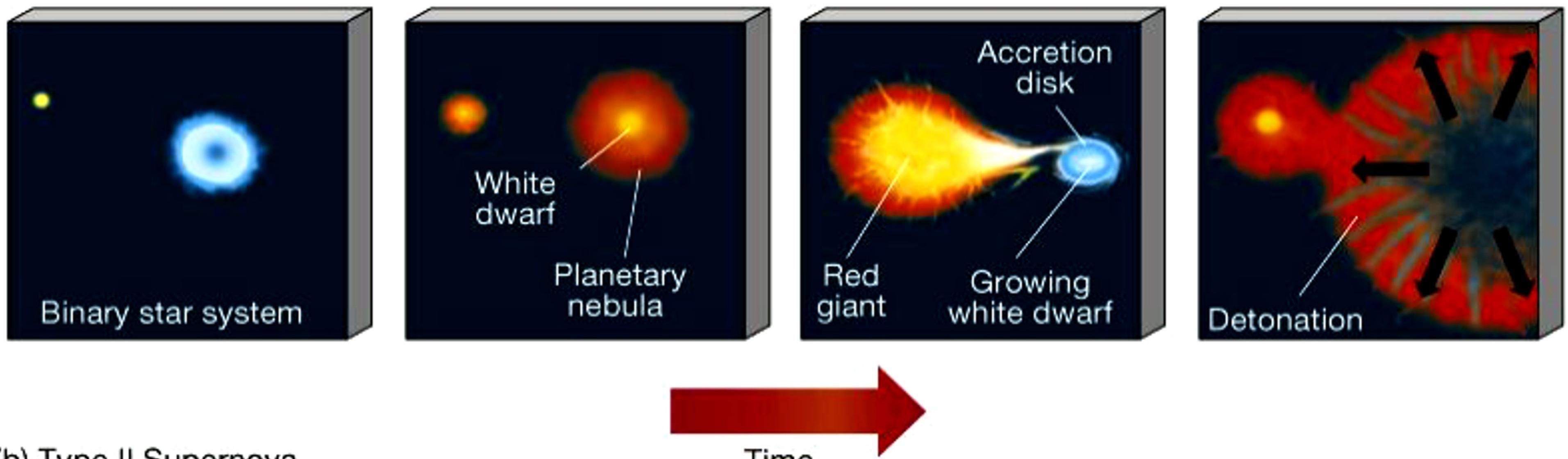
$$P = \frac{(3\pi^2)^{1/3}}{4}\hbar c\left[\left(\frac{Z}{A}\right)\frac{\rho}{m_H}\right]^{4/3}$$

Mass-volume relation:

*Mass * Volume = constant*

Type Ia supernovae

If enough mass dumped onto WD by binary companion to push it over Chandrasekhar limit, starts collapsing until hot enough for C,O fusion. Proceeds rapidly through WD, explosion, no remnant.



(b) Type II Supernova

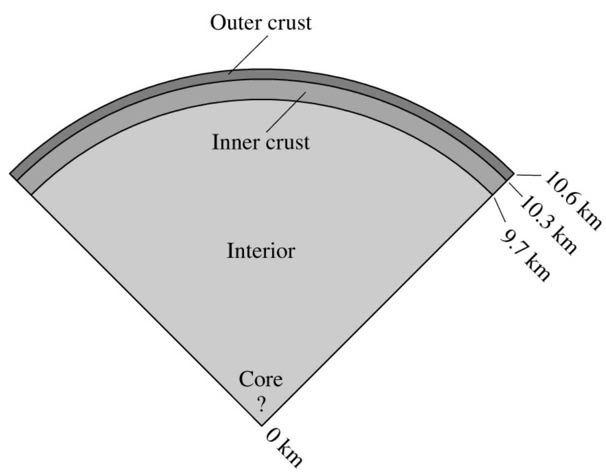
Neutron stars

Typical values:

- $M \sim 1.4M_{\odot}$
- $R \sim 10$ km
- $\rho \sim 10^{18}$ kg m^{-3} (neutrons nearly "touch" each other)

The support is provided by *neutron degeneracy pressure.*

C&O describe a complex and uncertain structure.



The interior is mostly neutrons, with outer crust of some iron nuclei and charged particles. There may be a core of pions and other subatomic particles.

Predicted to exist in 1934 by Baade and Zwicky. Discovered as pulsars in 1967 by Bell.

Pulsars

Periodic sources, discovered at radio wavelengths by Bell in 1967. Now over 2000 known.

Extremely regular, most have $P \sim 0.25\text{-}2$ sec. Some are measured to ~15 significant figures and rival the best atomic clocks on earth.

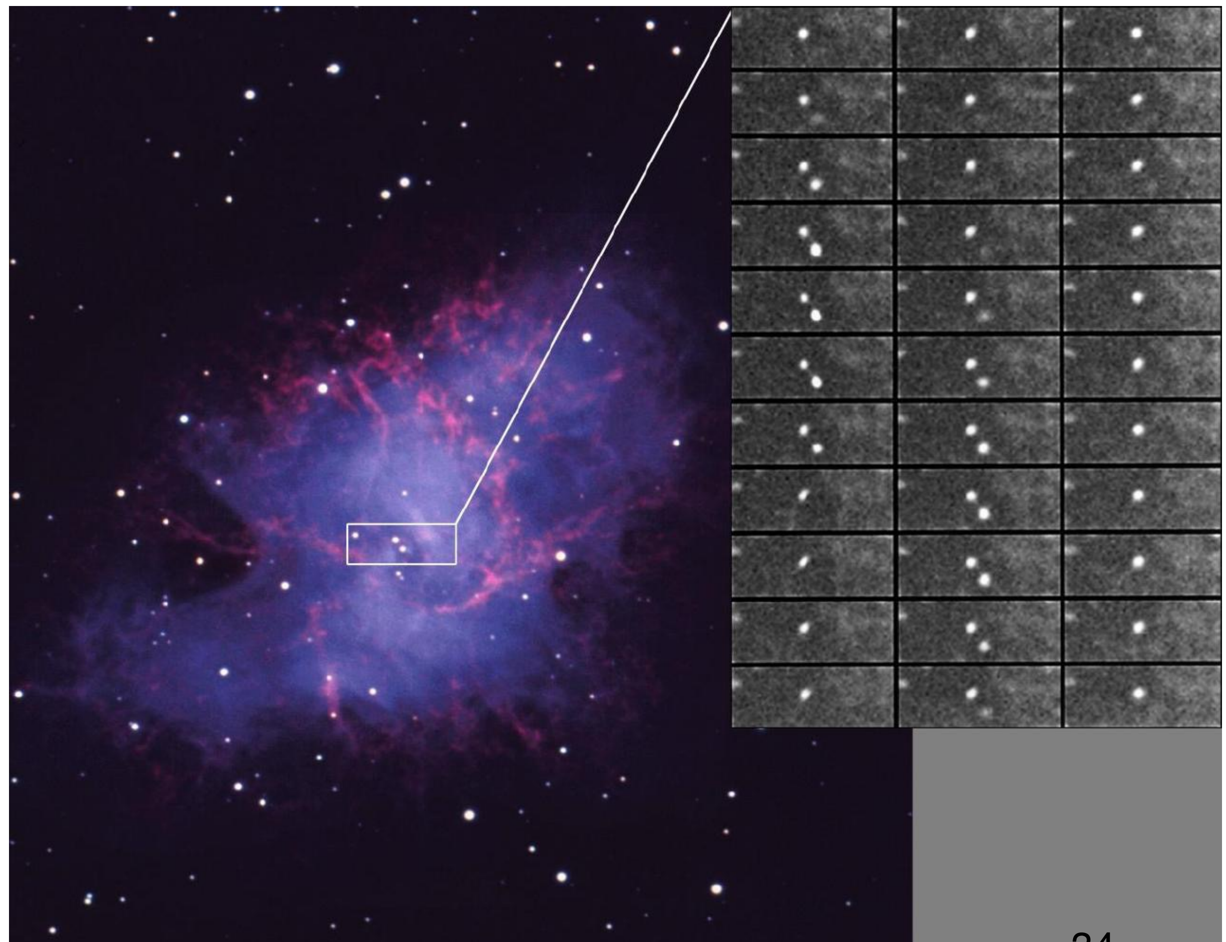
They slow down, but very slowly:

$$\frac{dP}{dt} = \dot{P} \approx 10^{-14} - 10^{-16}$$

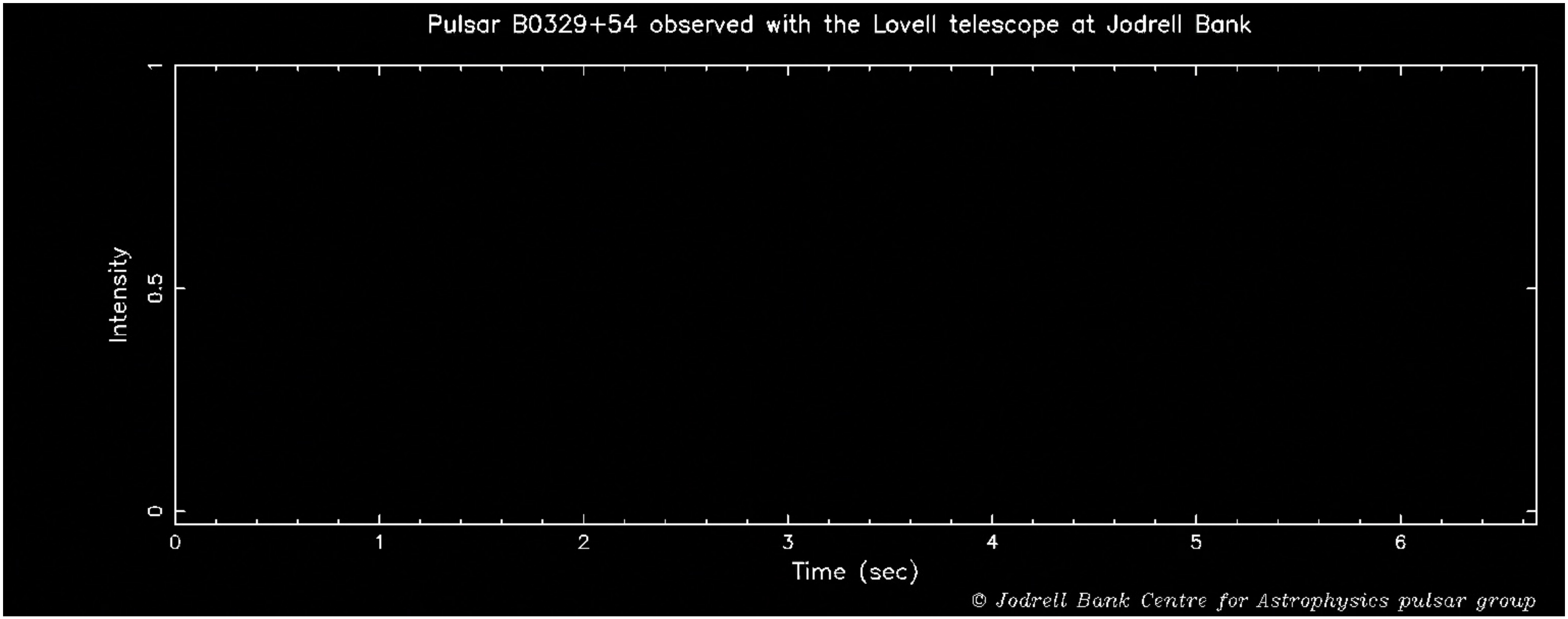
for most.

Characteristic lifetime would correspond to $\sim 10^7$ years.

First explanation as NS by Pacini ’67, Gold ’68 (Gold predicted $\dot{P} > 0$)

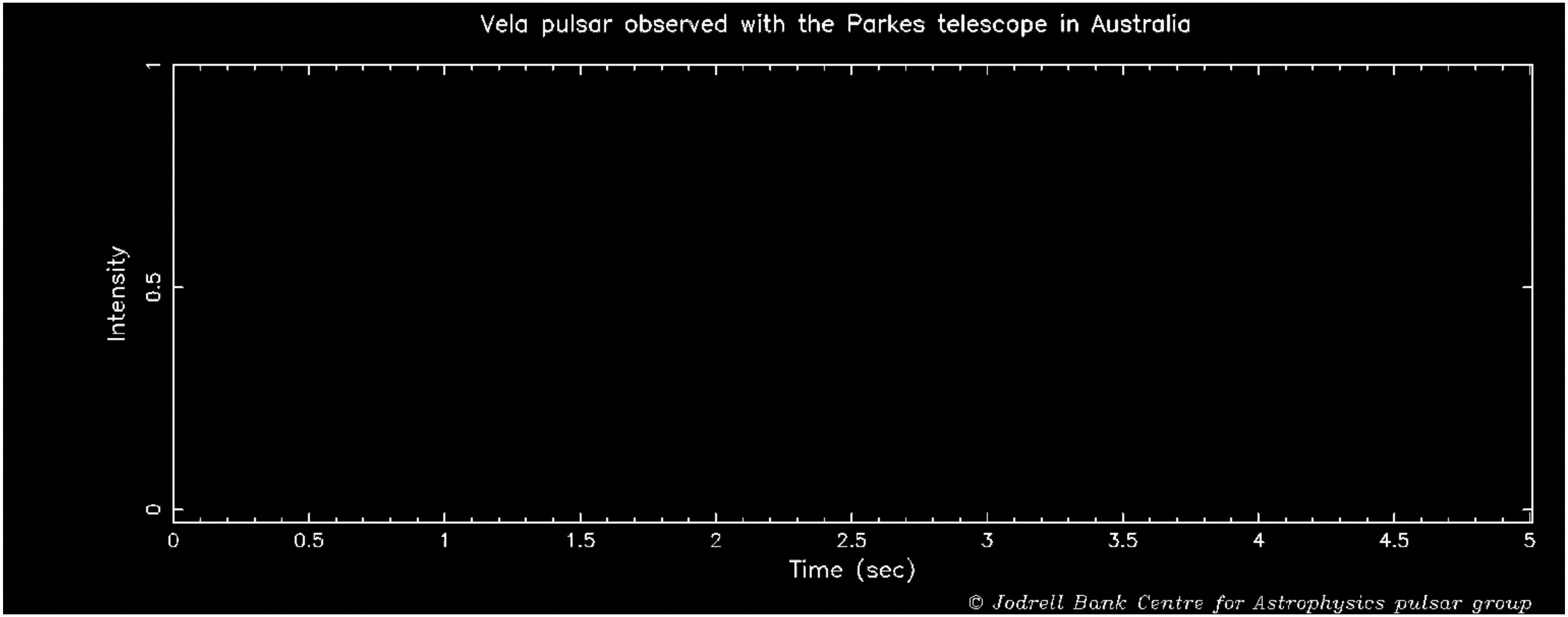


The Sound of Pulsars



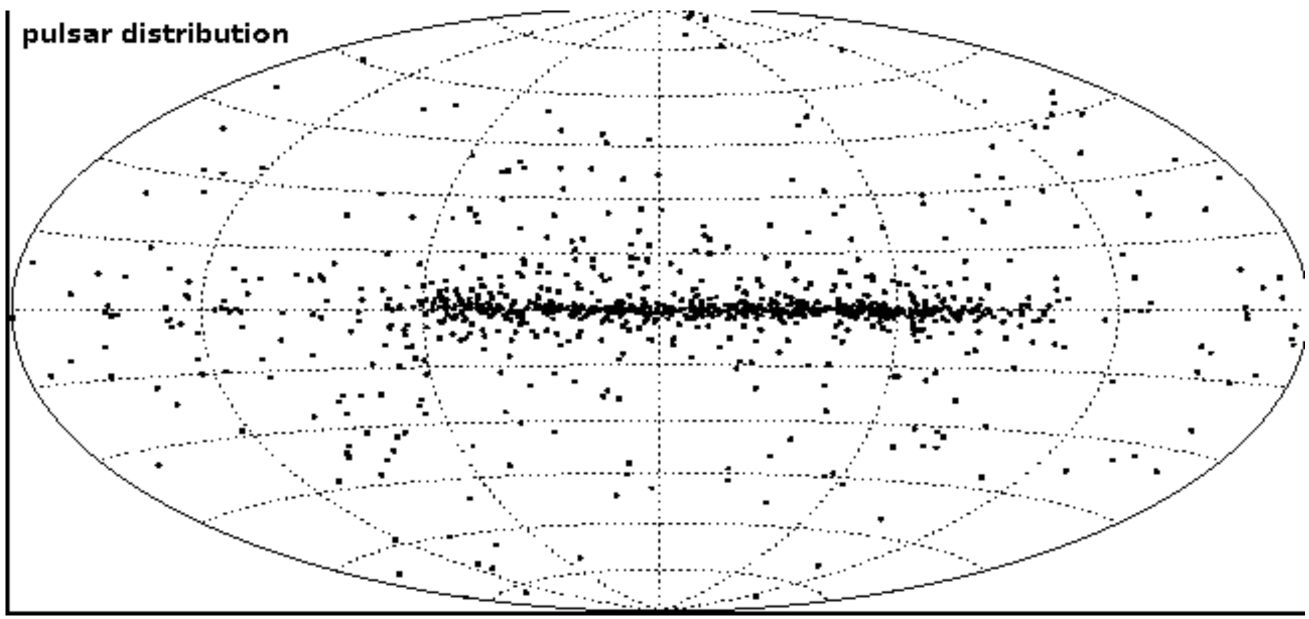
B0329+54, A bright pulsar with period 0.714520 sec

The Sound of Pulsars



Vela Pulsar, A young (age=10,000 years) pulsar with period 0.089 sec

Pulsar Distribution in Galactic Coordinates. Found mostly near the Galactic Plane.

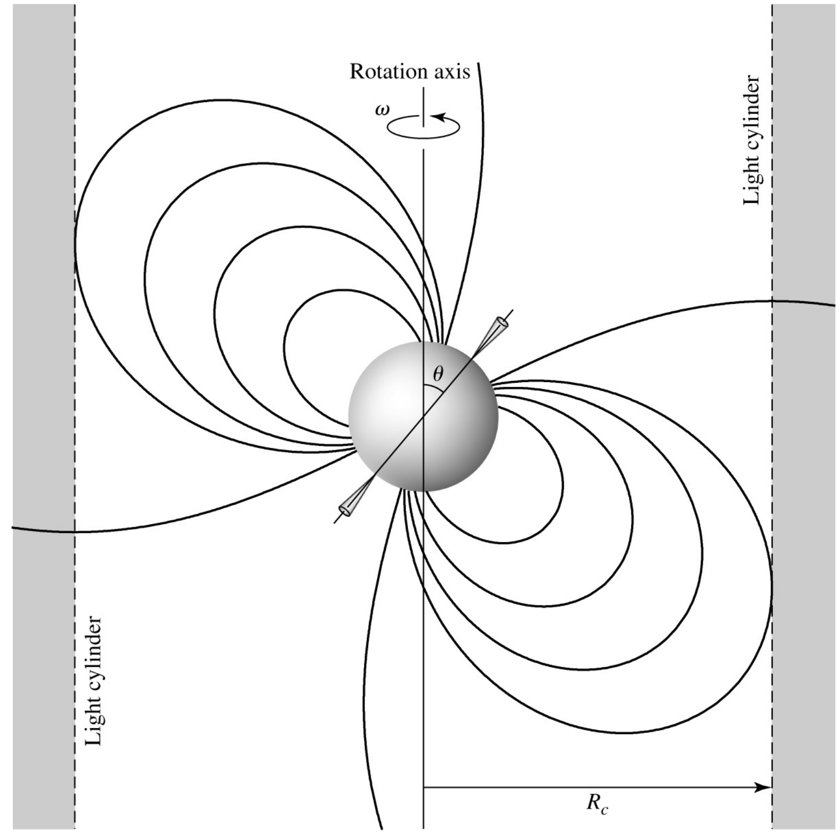


Pulsar model

Magnetic axis need not be aligned with rotation axis.

Rapidly changing magnetic field near rotating pulsar induces a huge electric field at the surface:

$$\epsilon = -\frac{d\Phi_B}{dt}$$



Φ_B is the magnetic flux through a given area.

The *B* field is strongest at the poles, thus the *E* field as well, about 10^{14} Volts/m.

=> Charged particles drawn off surface at the poles.

Neutron Stars

Conservation of angular momentum. When

$$L = MR^2\omega$$

is conserved,

$$P_f = P_i \left(\frac{R_f}{R_i}\right)^2$$

The equivalence principle

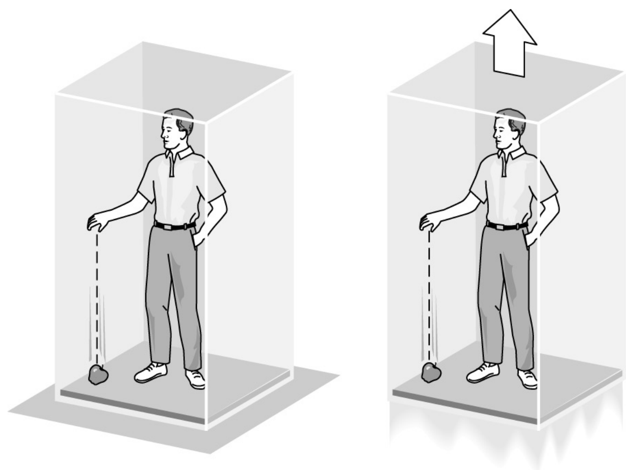
Special relativity: reference frames moving at constant velocity.

General relativity: accelerating reference frames and equivalence gravity.

<u>Equivalence Principle of general relativity:</u>

The effects of gravity are equivalent to the effects of acceleration.

Lab on Earth



(a) (b)

Lab accelerating in free space with upward acceleration g

In a local sense it is impossible to distinguish between the effects of a gravity with an acceleration *g,* and the effects of being far from any gravity in an upward-accelerated frame with *g*.

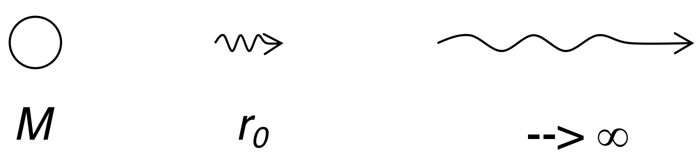
Thus gravity is producing a *redshift*

$$\frac{\Delta\nu}{\nu_0} = -\frac{v_1}{c} = -\frac{gh}{c^2} = \frac{GMh}{r^2c^2}$$

Since acceleration is equivalent to gravity, photons redshift as they move away from gravity source.

Exact GR expression for redshift at an infinite distance away:

$$\frac{\nu_\infty}{\nu_0} = \left(1 - \frac{2GM}{r_0 c^2}\right)^{1/2}$$



For photon going to ∞ from r_0.

Schwarzschild Metric

The Schwarzschild metric is a metric at distance *r* from mass *M*. Not valid inside *M*, and defined for vacuum only.

$$(ds)^2 = (cdt\sqrt{1 - 2GM/rc^2})^2 - (\frac{dr}{\sqrt{1 - 2GM/rc^2}})^2 - (rd\theta)^2 - (r\sin\theta d\phi)^2$$

This metric is needed to calculate any meaningful physical quantities.

Note that only *dt* and *dr* are modified from flat metric. Also note that *dt*, *dr*, $d\theta$ and $d\varphi$ are the incremental coordinates used by an observer at infinity where spacetime is flat. That is, at $r \to \infty$ (or $M \to 0$), the Schwarzschild metric reverts to flat spacetime metric.

ds still invariant.

Black holes

Consider a star of mass *M* , collapsed to radius less than

$$R_s = \frac{2GM}{c^2} \text{ Schwarzschild radius}$$

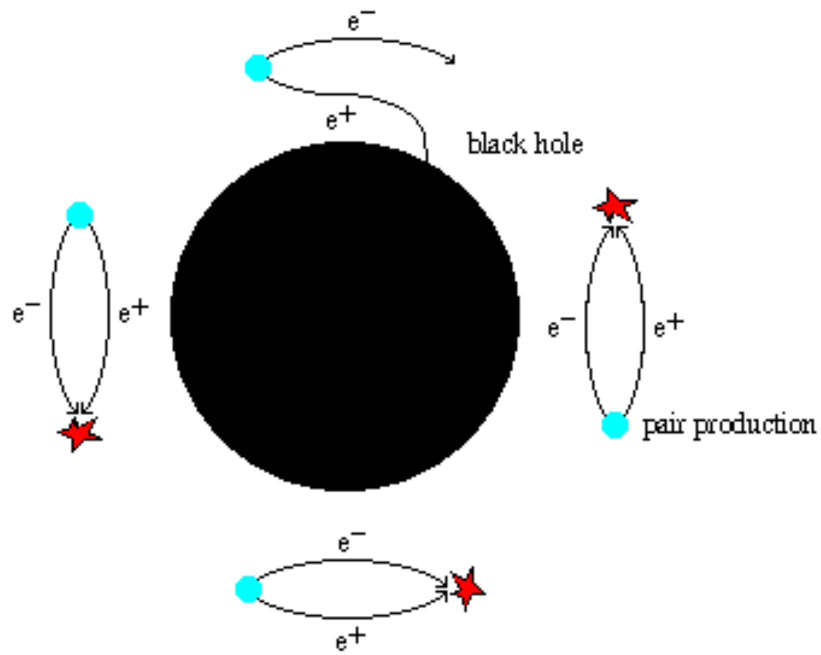
$$\text{Recall } d\tau = \frac{ds}{c} = dt\sqrt{1 - \frac{2GM}{rc^2}}$$

$$\text{at } r = R_s \ dt = \frac{d\tau}{\sqrt{1 - Rs/Rs}} \rightarrow \infty$$

That is, a clock measuring proper time approaching R_S will appear to a distant observer to be going slower and slower. Would take infinite time to reach R_s. Also gravitational redshift: photons approach infinite wavelength.

Hawking Radiation

the strong gravitational field around a black hole causes pair production



if a pair is produced outside the event horizon, then one member will fall back into the black hole, but the other member will escape and the black hole loses mass

$$T = \frac{\hbar c^3}{8\pi G M k_B}$$

$T \sim 10^{-7}\, M_{Sun}/M$ K

- BHs slowly lose mass and energy by Hawking Radiation

$$t_{evap} \approx \left(\frac{M}{M_{\odot}}\right)^3 x\ 2x10^{67} yrs$$

BHs of mass < 10^{11} kg would have evaporated by now.

Ideal Gas Law

$P = nkT$ or $P = \dfrac{\rho k T}{\mu m_H}$

Maxwell Boltzmann velocity distribution

$$n_V dv = n \left(\frac{m}{2\pi kT} \right)^{3/2} e^{-mv^2/2kT} 4\pi v^2 dv$$

Most probable speed $v_{mp} = \sqrt{\dfrac{2kT}{m}}$

Root mean-square speed $v_{rms} = \sqrt{\dfrac{3kT}{m}}$

Black Holes, General Relativity and Spacetime

Metric: differential distance formula:

$$(ds)^2 = (cdt)^2 - (dx)^2 - (dy)^2 - (dz)^2$$

is metric for flat spacetime

Schwarzschild Metric

$$(ds)^2 = (cdt\sqrt{1 - 2GM/rc^2})^2 - (\frac{dr}{\sqrt{1 - 2GM/rc^2}})^2 - (rd\theta)^2 - (r\sin\theta d\phi)^2$$

for vacuum at distance *r* from mass *M*.

Gravitational time dilation:

$$d\tau = \frac{ds}{c} = dt\sqrt{1 - \frac{2GM}{rc^2}}$$

$$dt > d\tau$$

(a clock measuring proper time intervals at *r* appears to run slower as seen from a great distance)

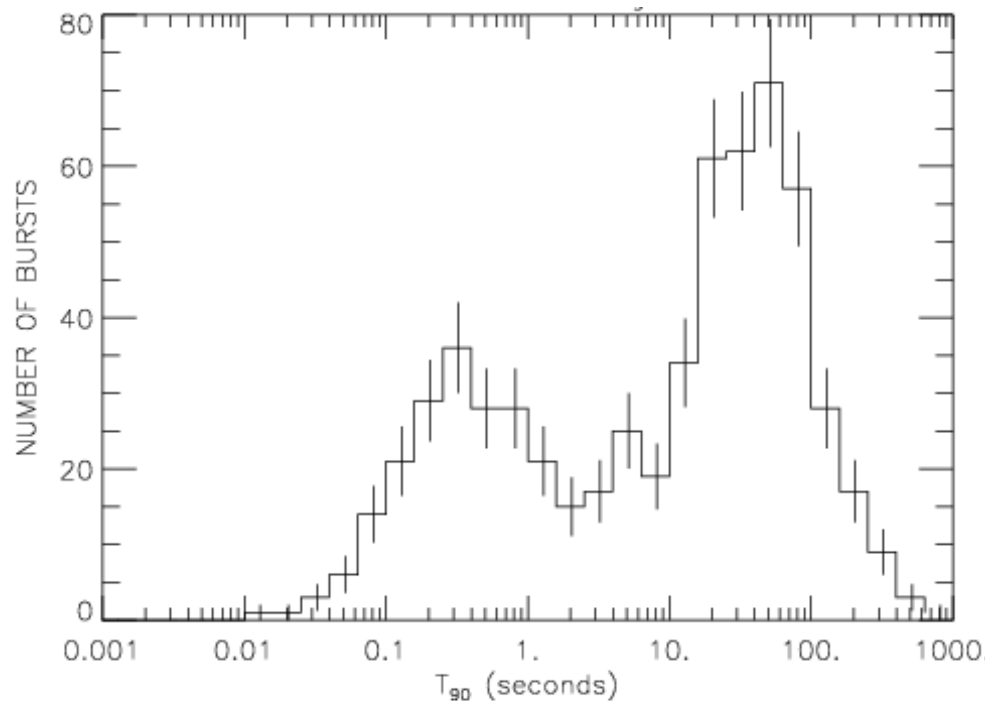
GRB classification

Long bursts

- > 2 sec, mean 30 sec
- Afterglows commonly observed
- From massive stars

Short bursts

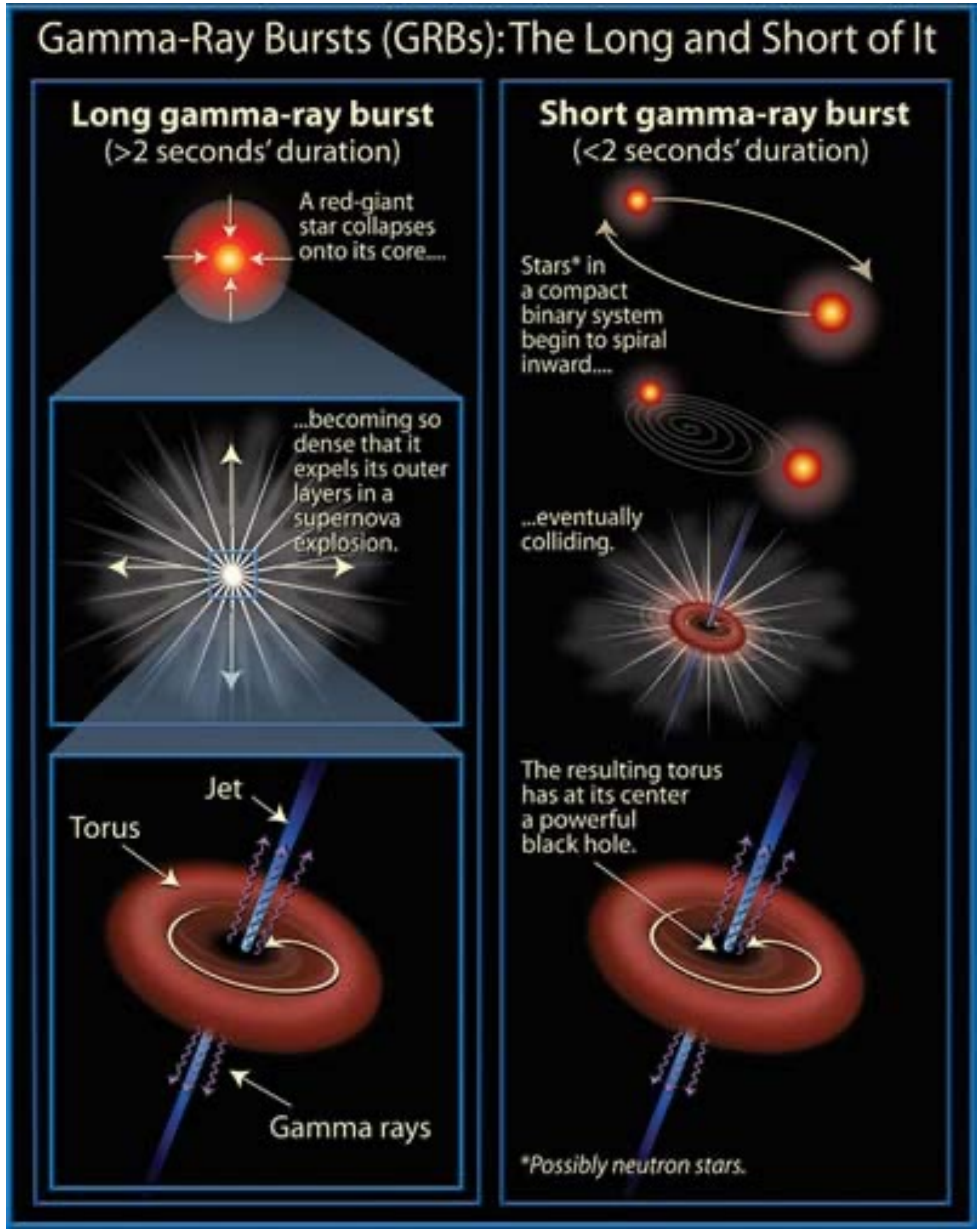
- < 2 sec, mean 0.3 sec
- Fewer afterglows observed
- From compact binaries and/or neutron stars



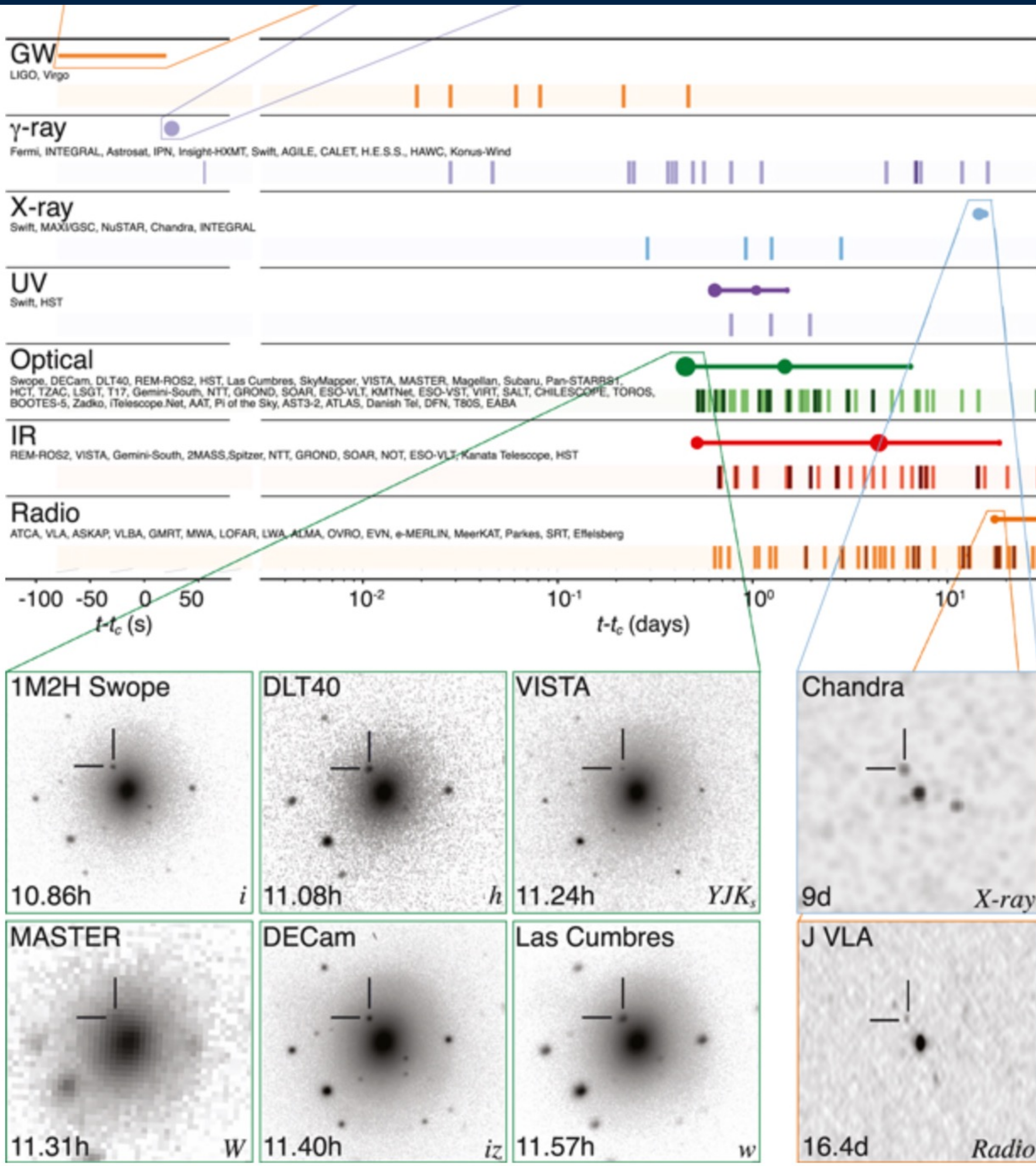
BATSE burst duration

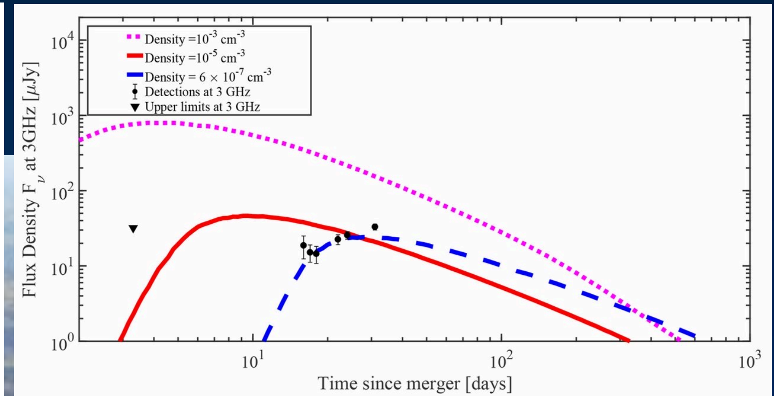
Long GRBs associated with supernovae

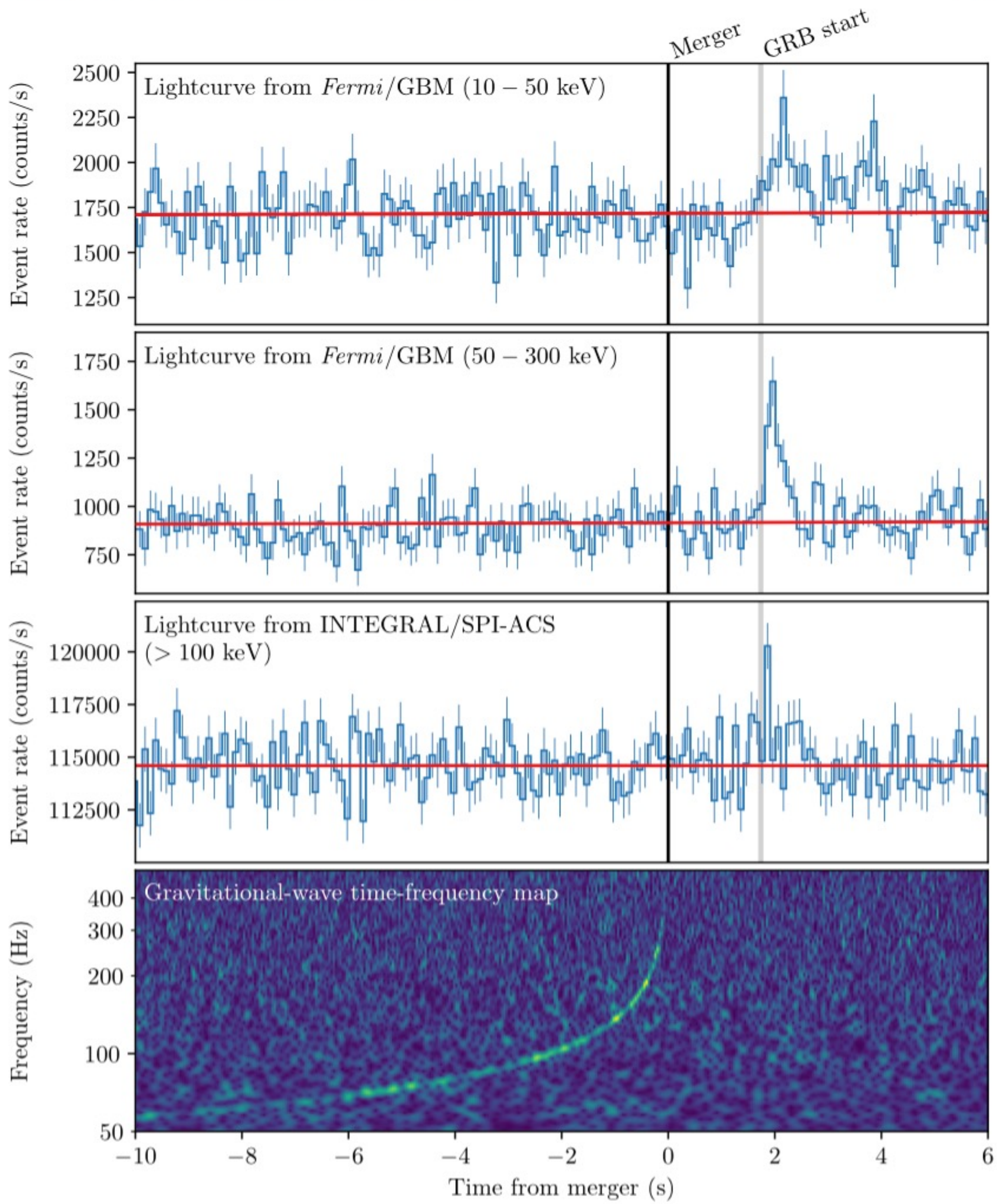
Short GRBs associated with star-forming and elliptical galaxies (old stellar population, broadly consistent with NS and/or BH coalescence. Compact merger or giant flare from magnetar



NGC 4993 Kilonova GW170817







Gamma-rays look like a short GRB

Little or no delay between arrival of photons and GWs over 100 Ml-y