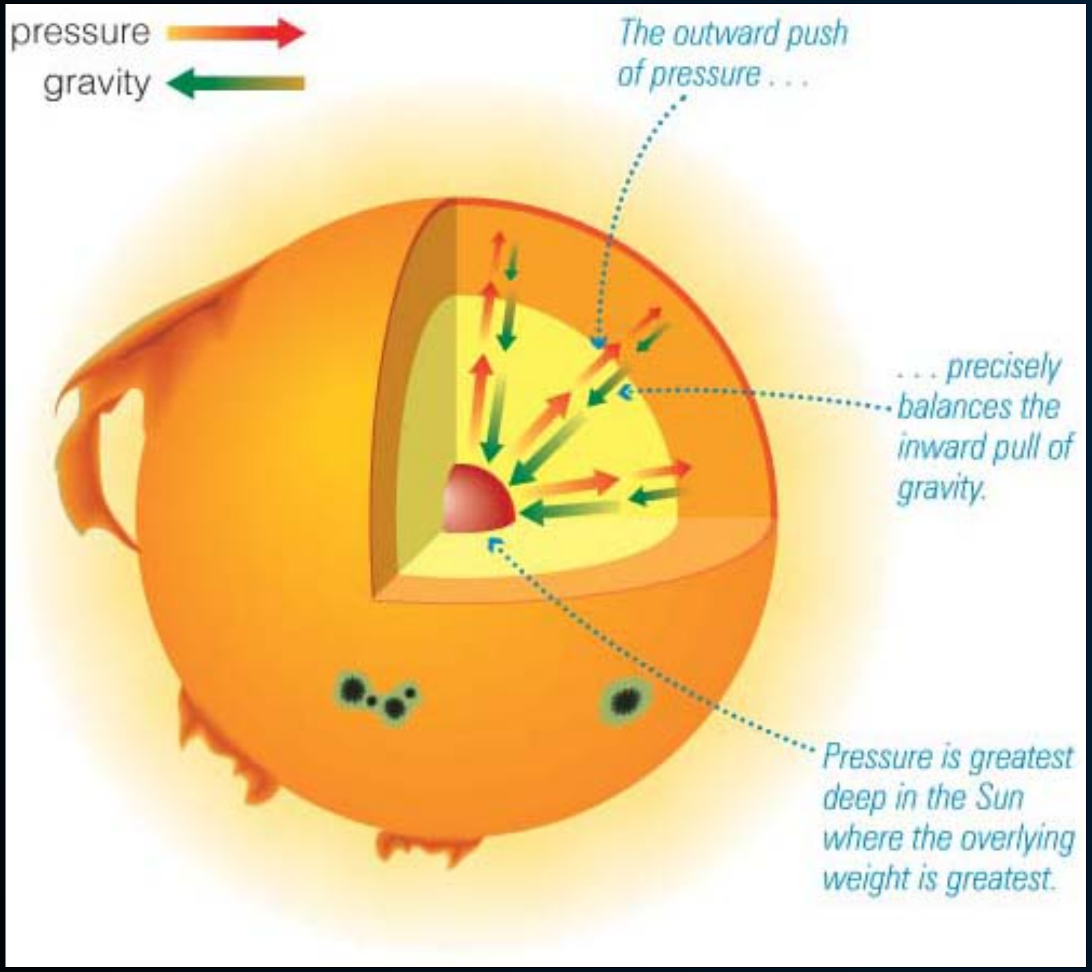
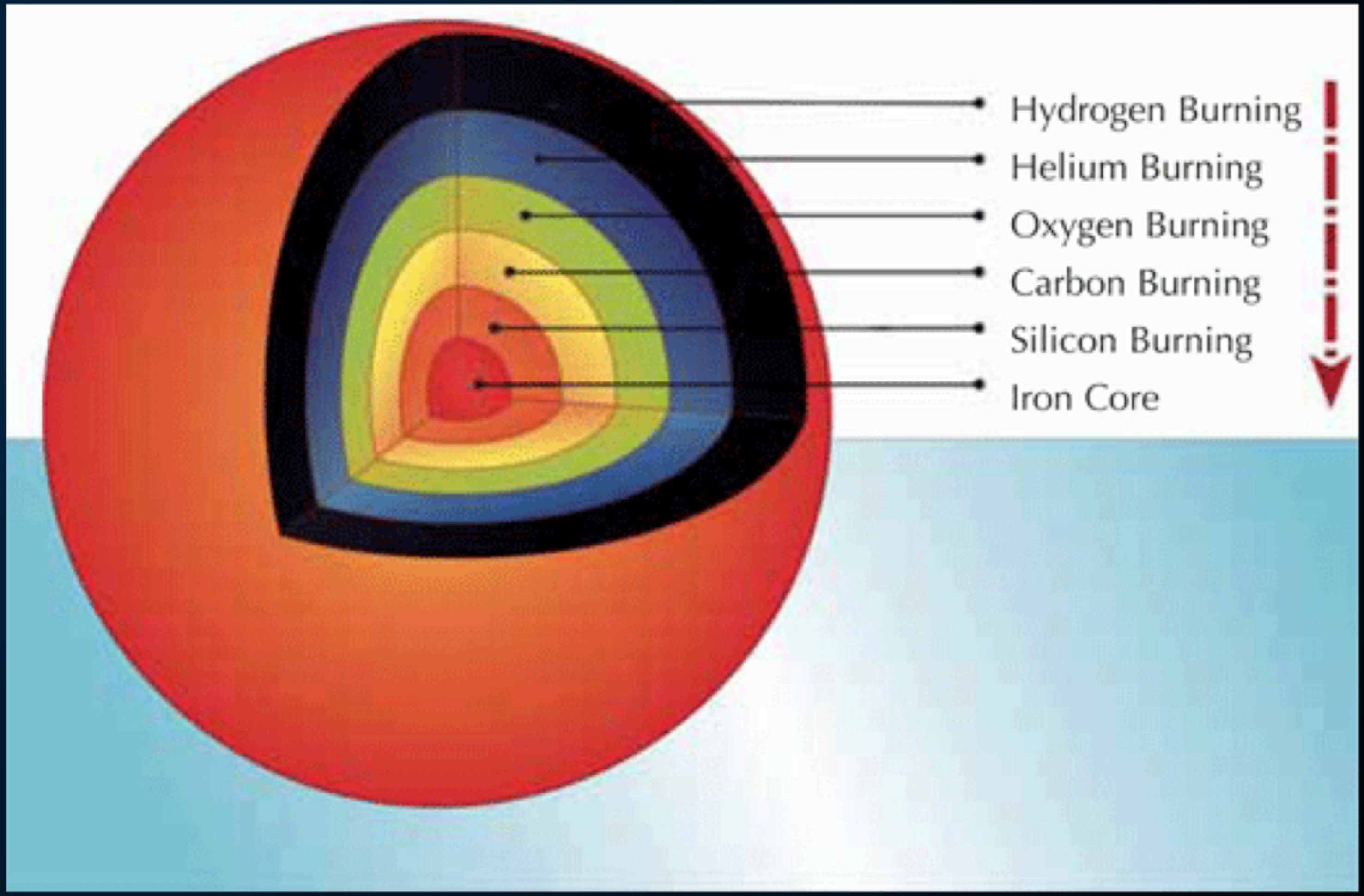
Massive Stars, their evolution, death and afterlives - a radio look

Poonam Chandra
National Centre for Radio Astrophysics
Tata Institute of Fundamental Research

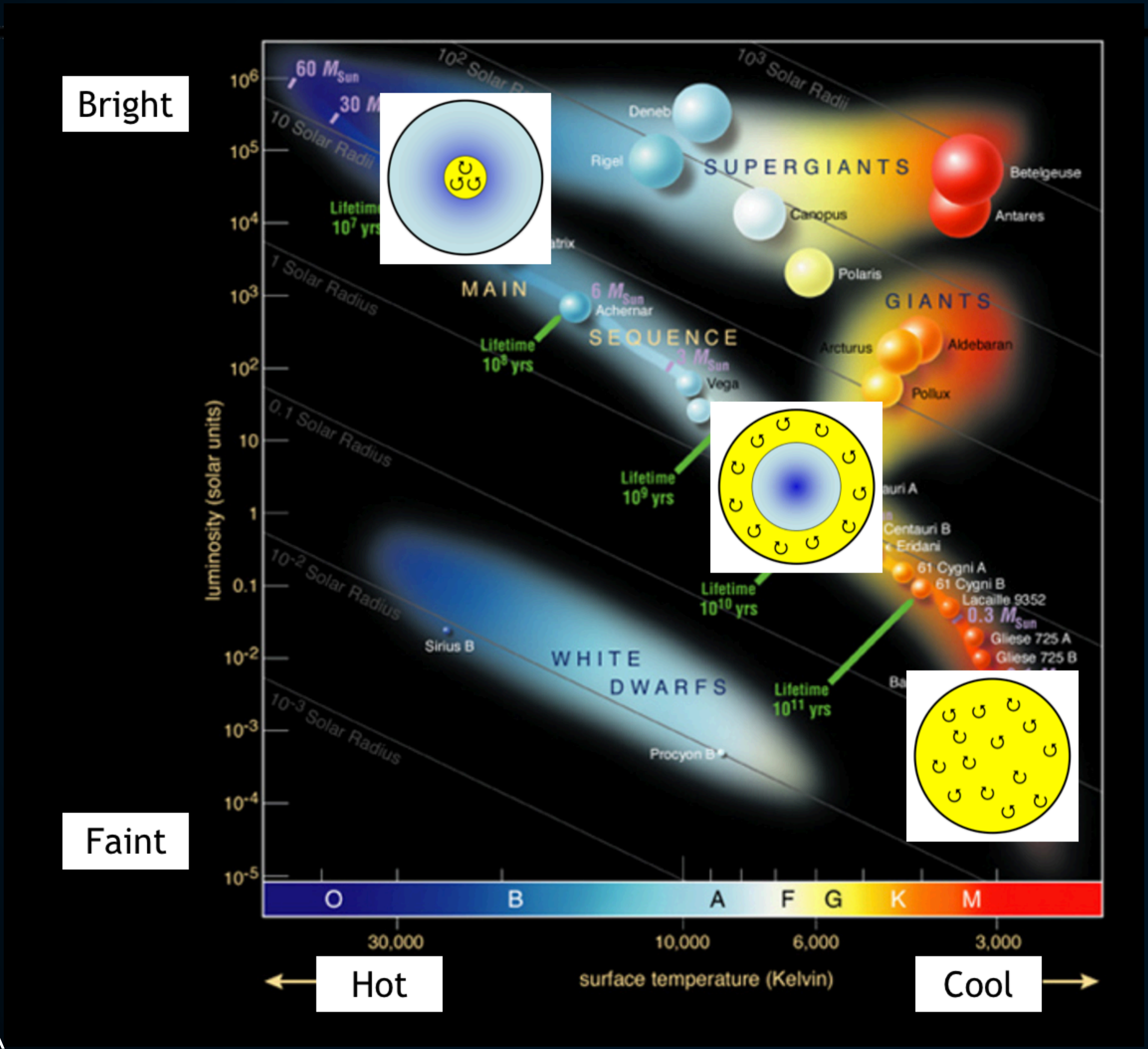
Non-thermal radio emission

What is the main difference between average and massive stars





Magnetic massive stars



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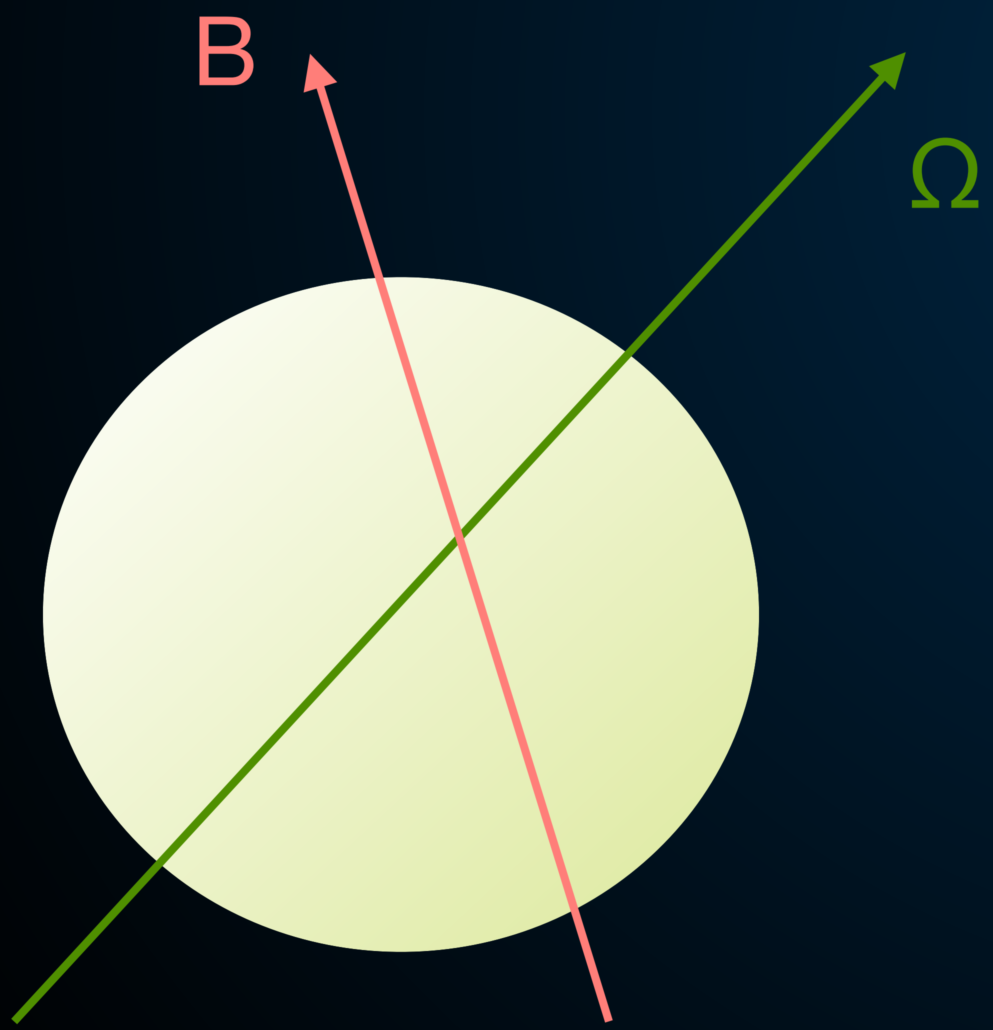
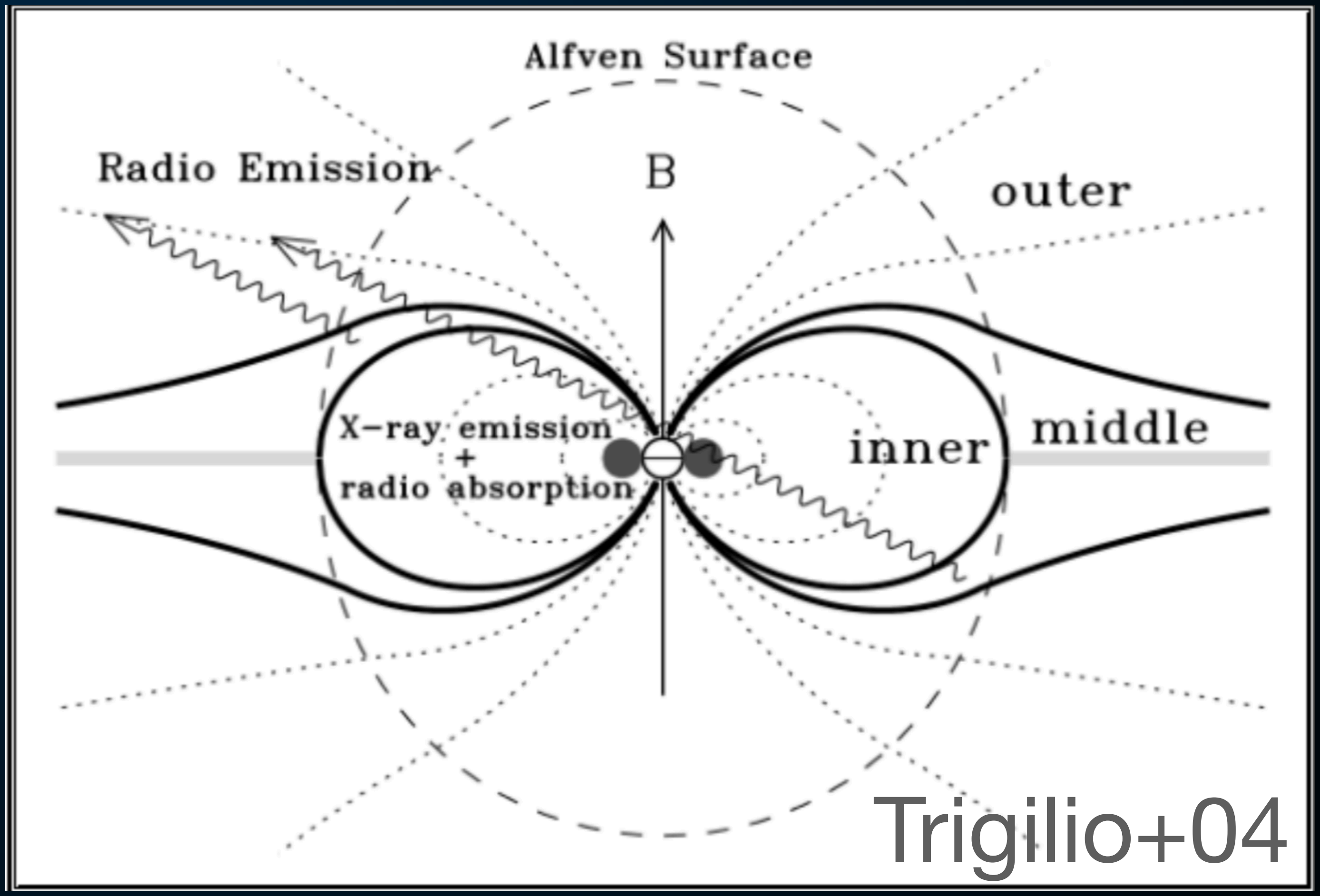
Magnetic massive stars

- Constitute 10% of the whole population (Grunhut et al. 2017).
- Magnetic field: mostly dipolar, inclined to the rotation axis.





Trigilio+04

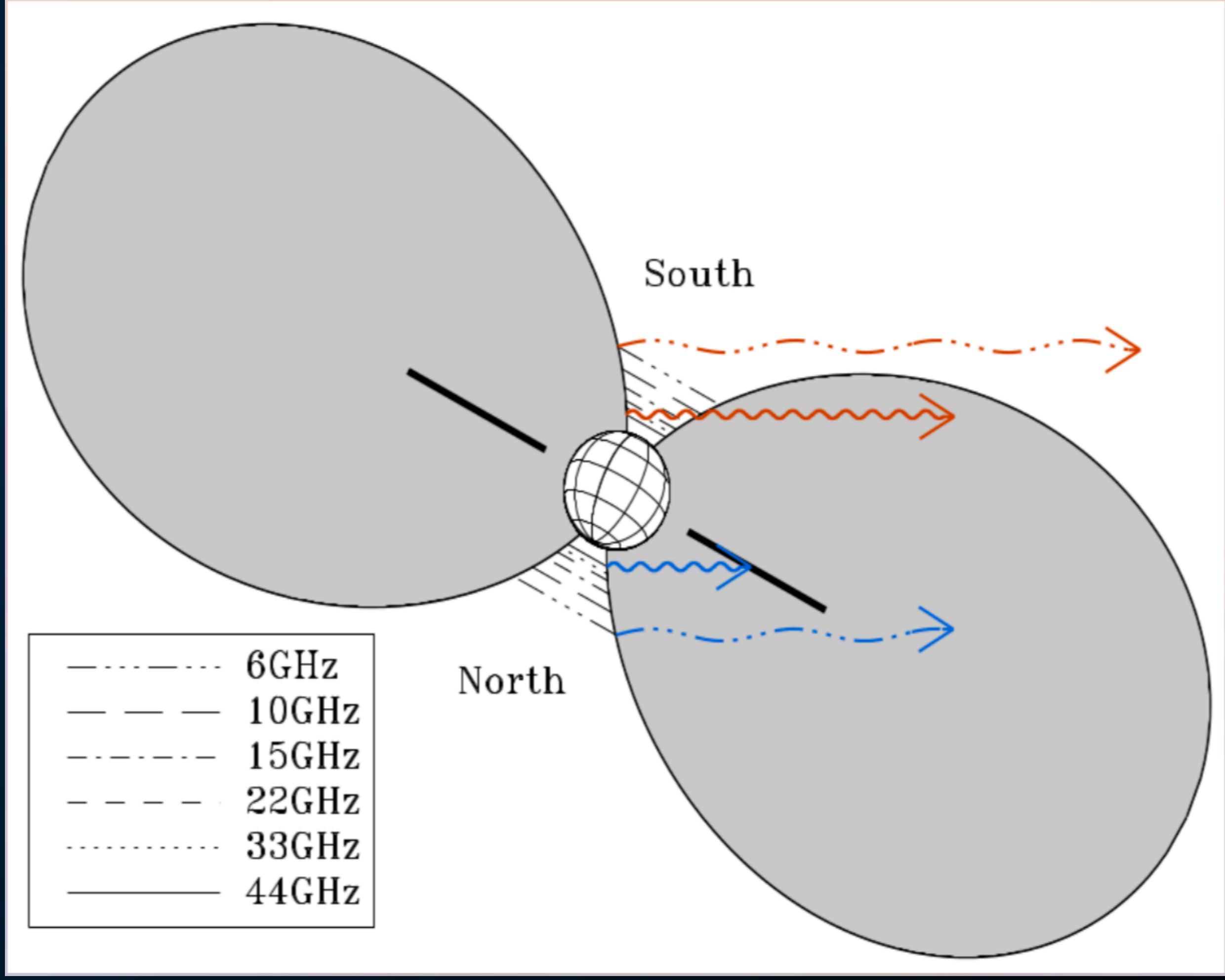
Emissions from magnetic massive stars

- Thermal emission ($F \propto \nu^{\alpha}$)
- Non-thermal (Gyrosynchrotron) - interaction of the stellar wind with the magnetic field.
- Non-thermal coherent - Electron Cyclotron Maser Emission (ECME)- Electrons traveling through the middle magnetosphere towards the stellar surface experience magnetic mirroring and a loss-cone distribution is produced.

Electron Cyclotron Maser Emission

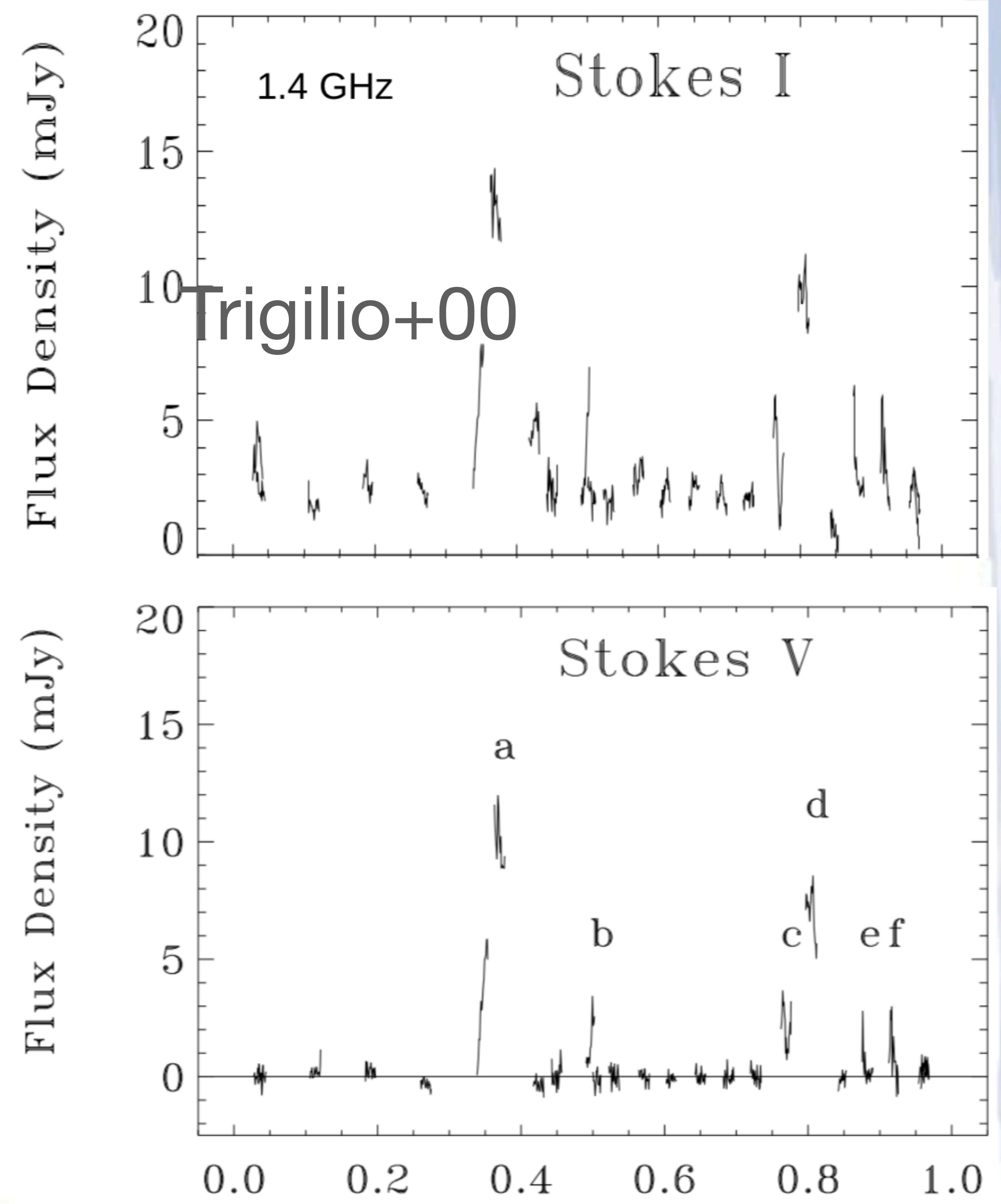
- Produces highly circularly polarised pulses, directed nearly perpendicular to the magnetic field.
- Frequency of emission ∝ electron gyrofrequency → higher frequency originates closer to the star than the lower frequency.
- Originates near the magnetic polar regions- amplifies one of the two modes - O and X modes - density constraints.

Image Credit: Barnali



Coherent Emission

- Trigilio et al. (2000) observed the star CU Vir with the VLA at 1.4, 5, 8.4 and 15 GHz.
- Identified as Electron Cyclotron Maser Emission (ECME, also observed from UCDs, e.g. Hallinan et al. 2006,2007).
- O and X modes - density constraints



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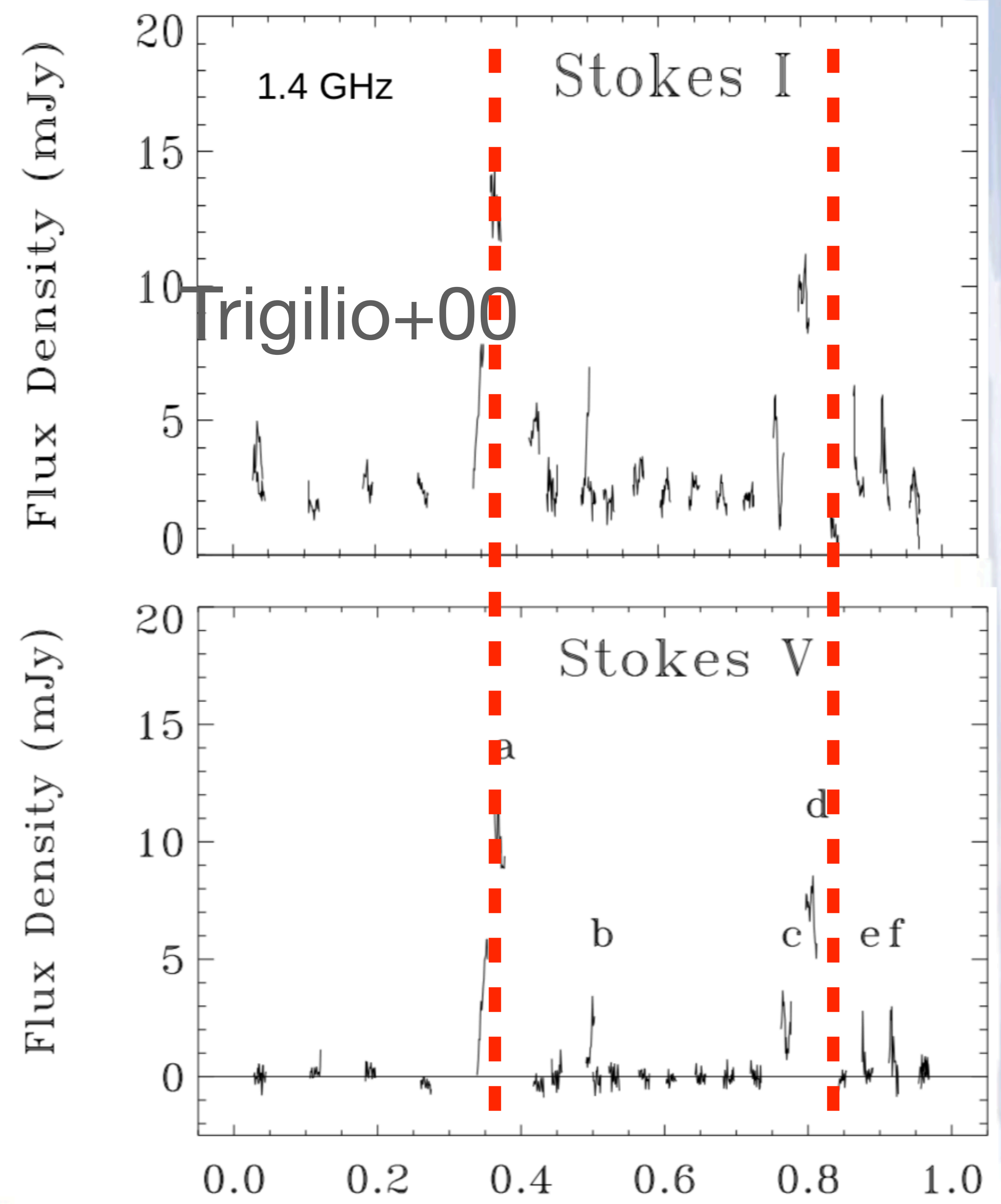
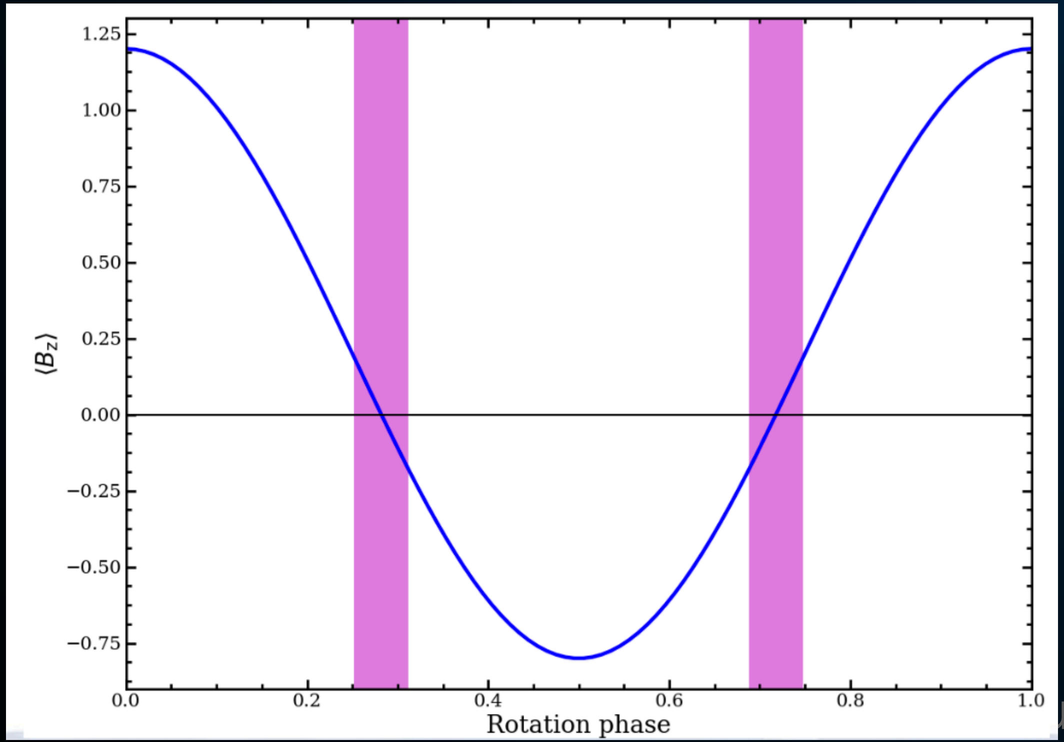
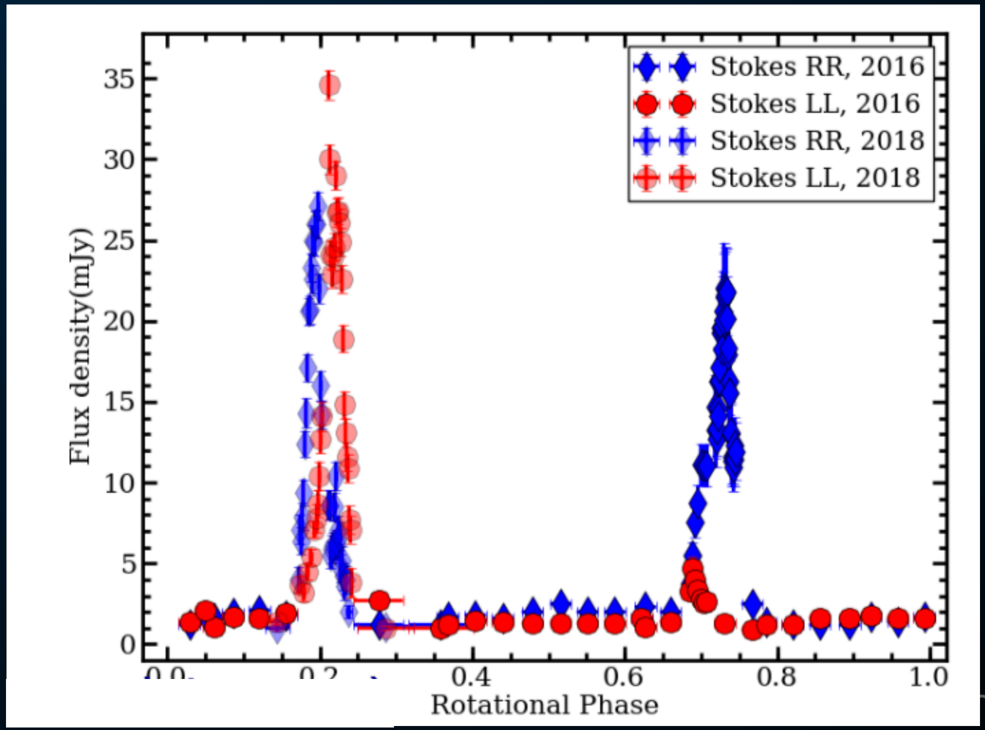


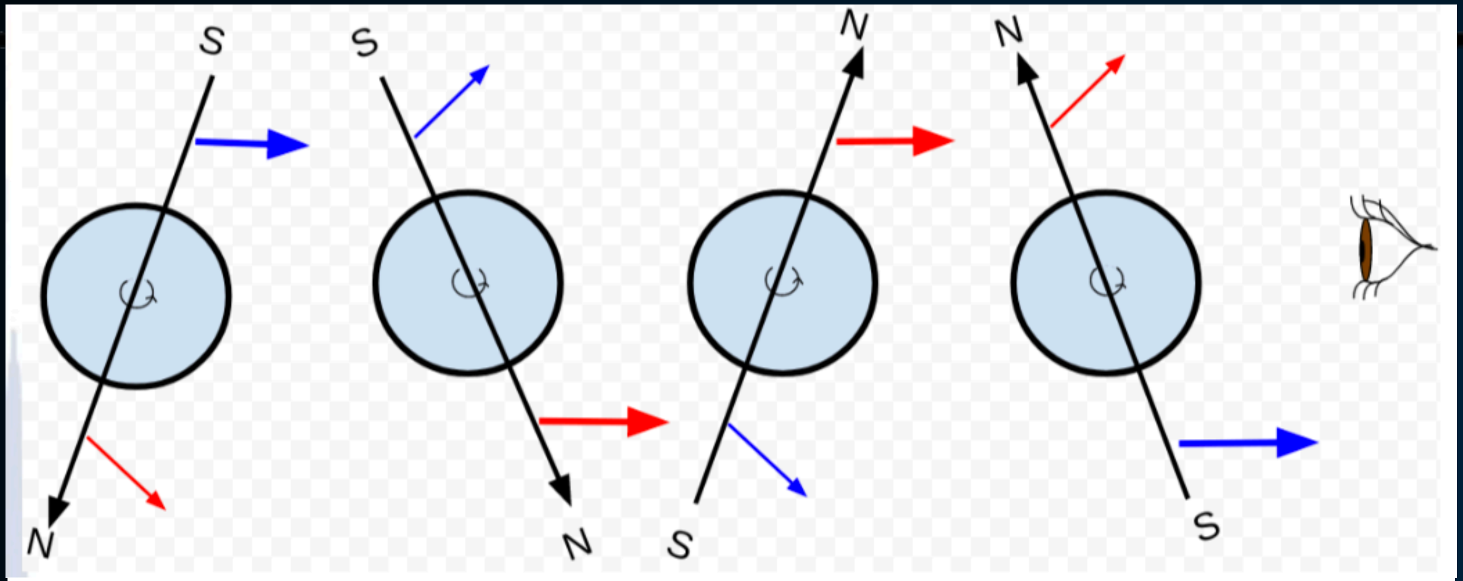
uGMRT survey of magnetic massive stars

- HD 133880 (PC+15, Das, PC+17).
- HD 142990 (Das, PC+18, also reported by Lenc+18 independently)
- HD 35298 (Das,PC+19, nearly accepted)
- HD 12247 (to be confirmed)
- HR 5907 (Leto+18) + CuVir (Trigilio+00)
- Confirmed 5 ECME, tentative 6 ECME.





ECME - constrains on magnetosphere and plasma density



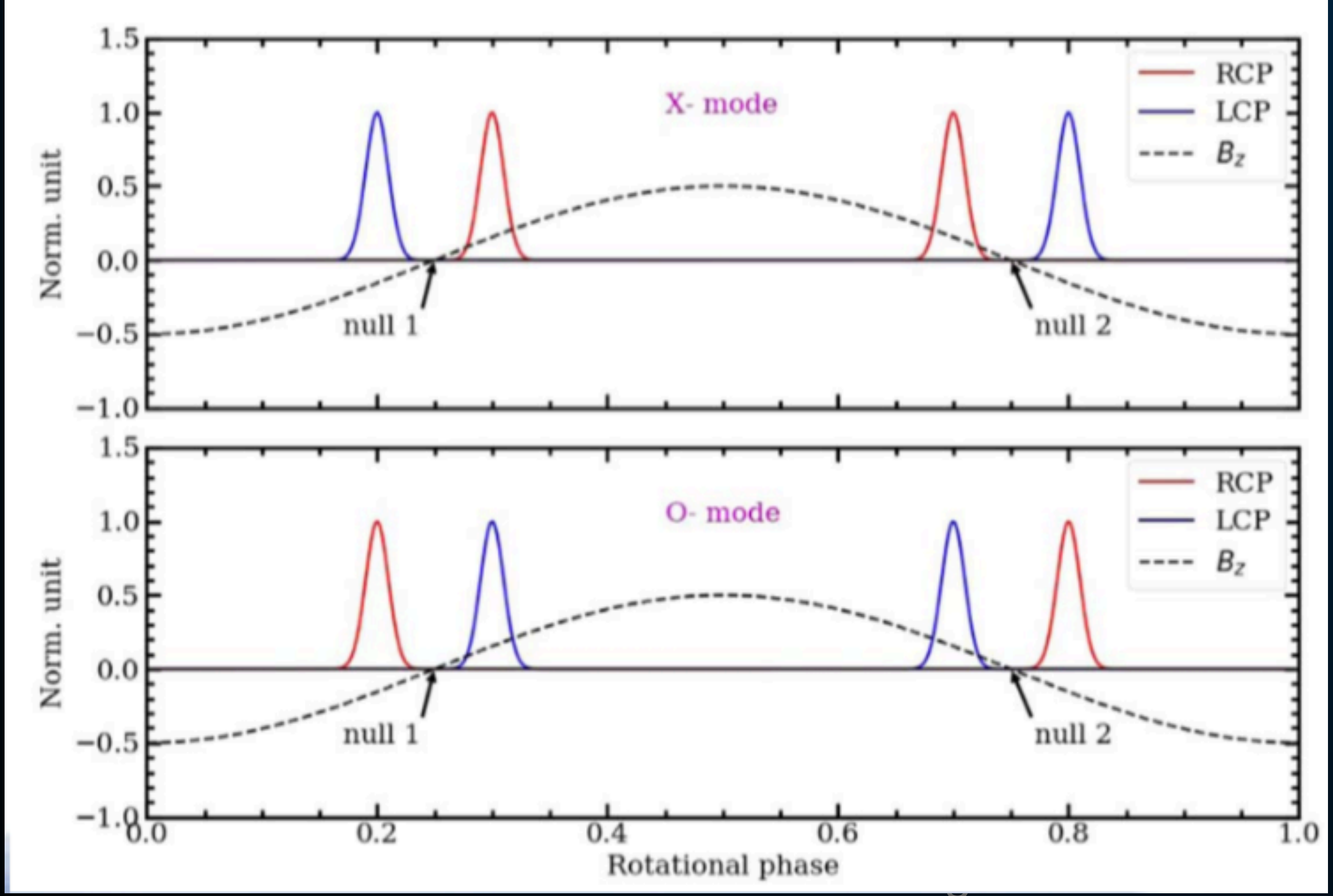
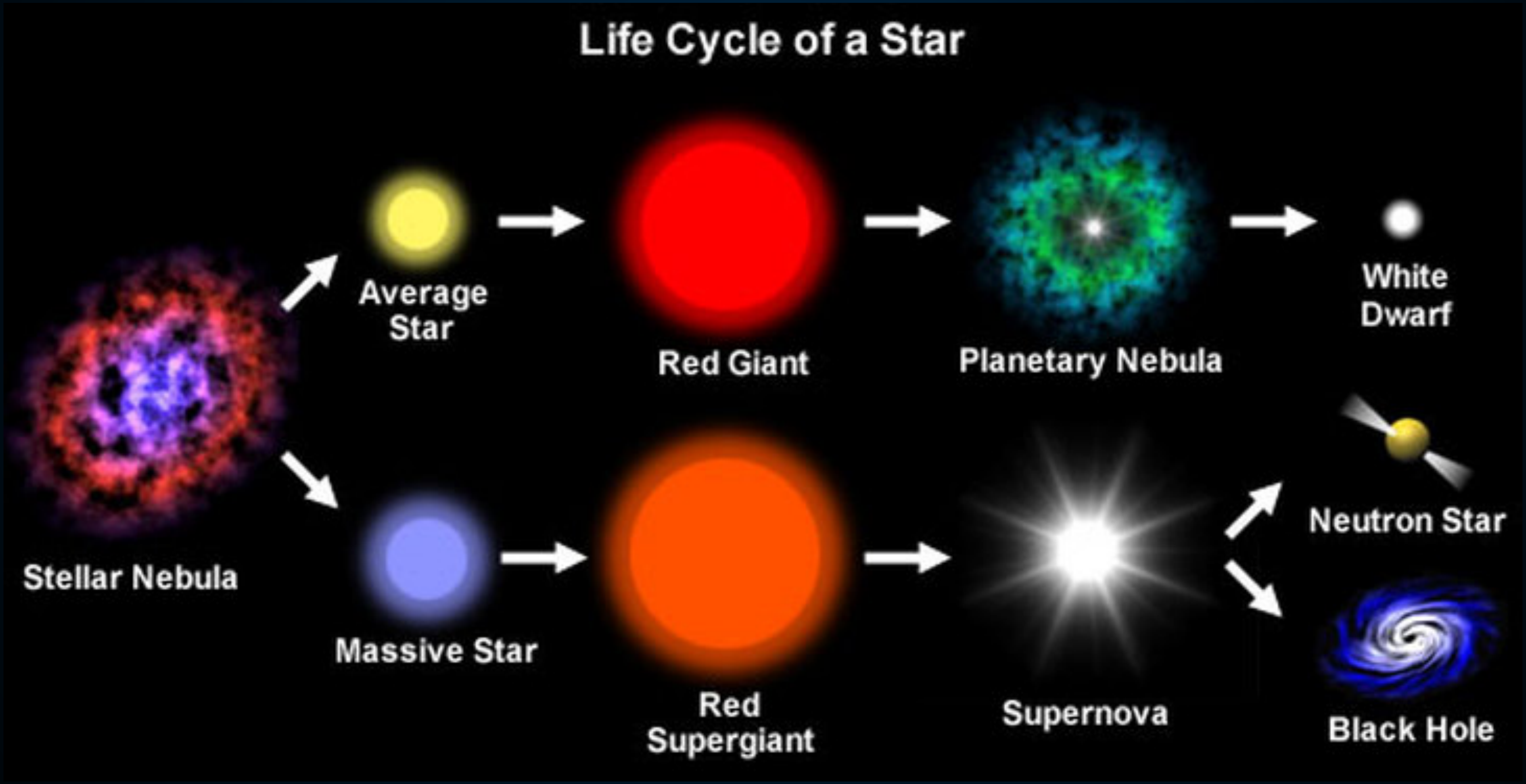
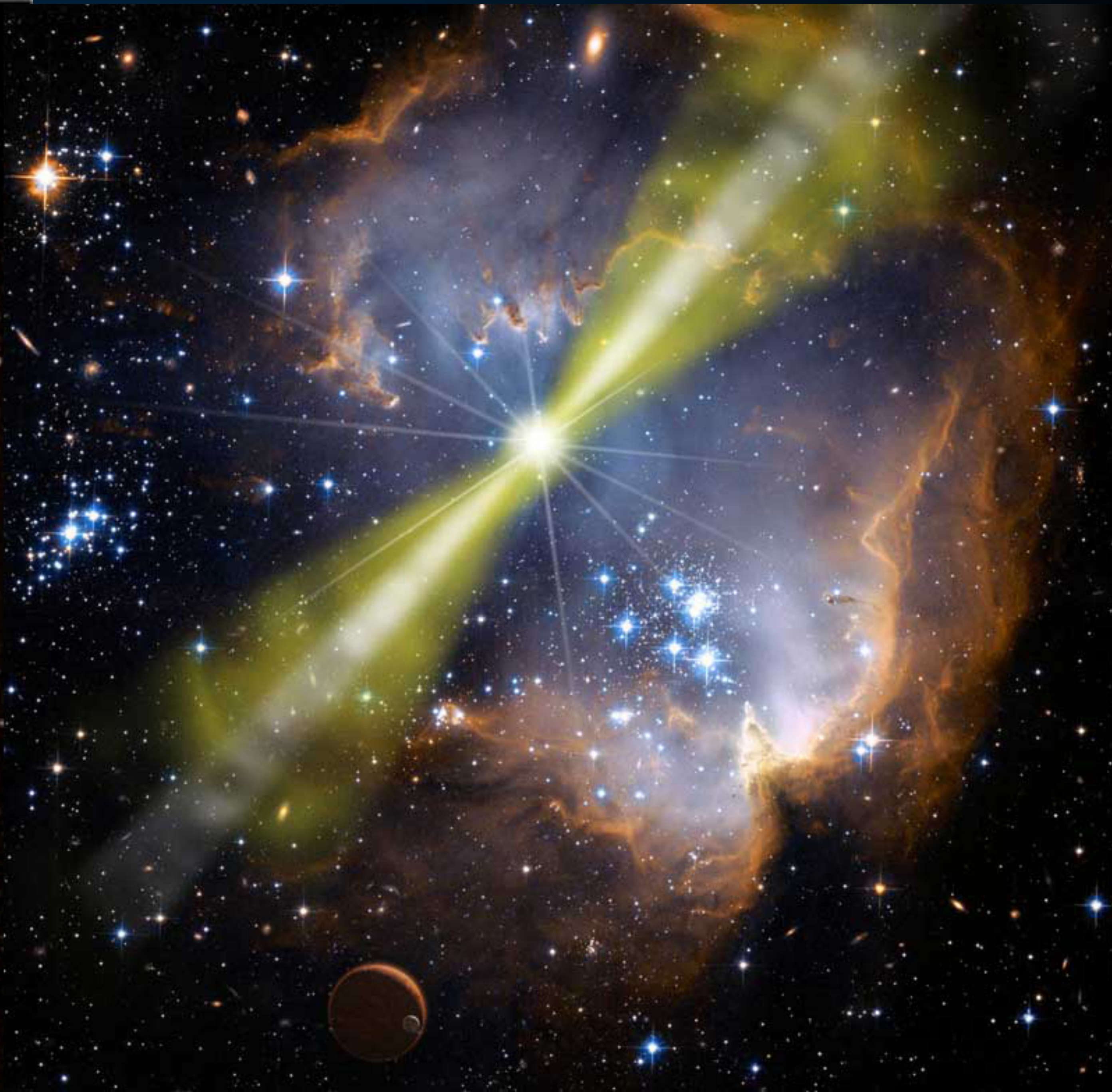


Image Credit: Barnali

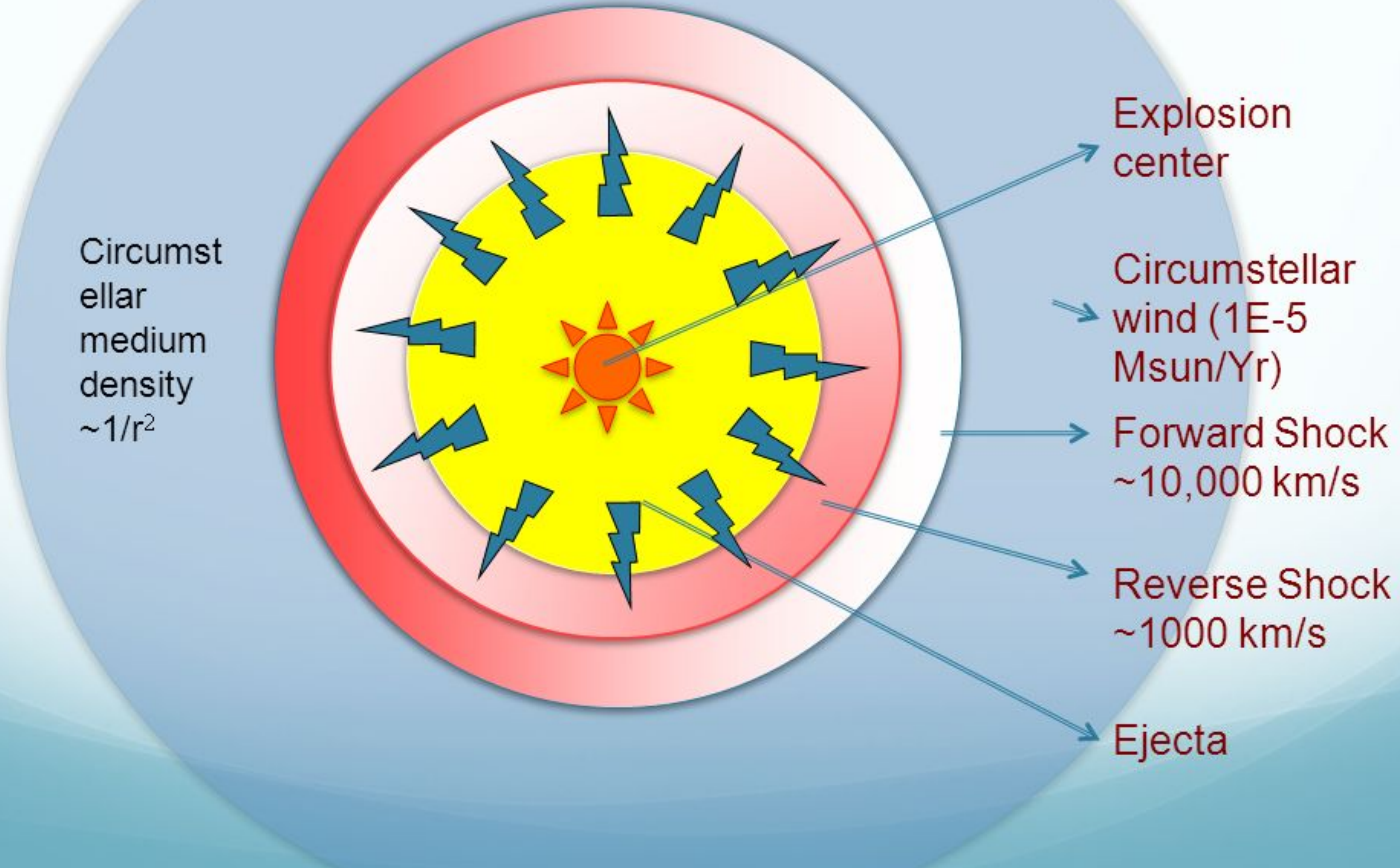
End stages of massive stars



Supernovae & gamma-ray burst



Circumstellar interaction



Circumstellar medium density $\sim 1/r^2$

Explosion center

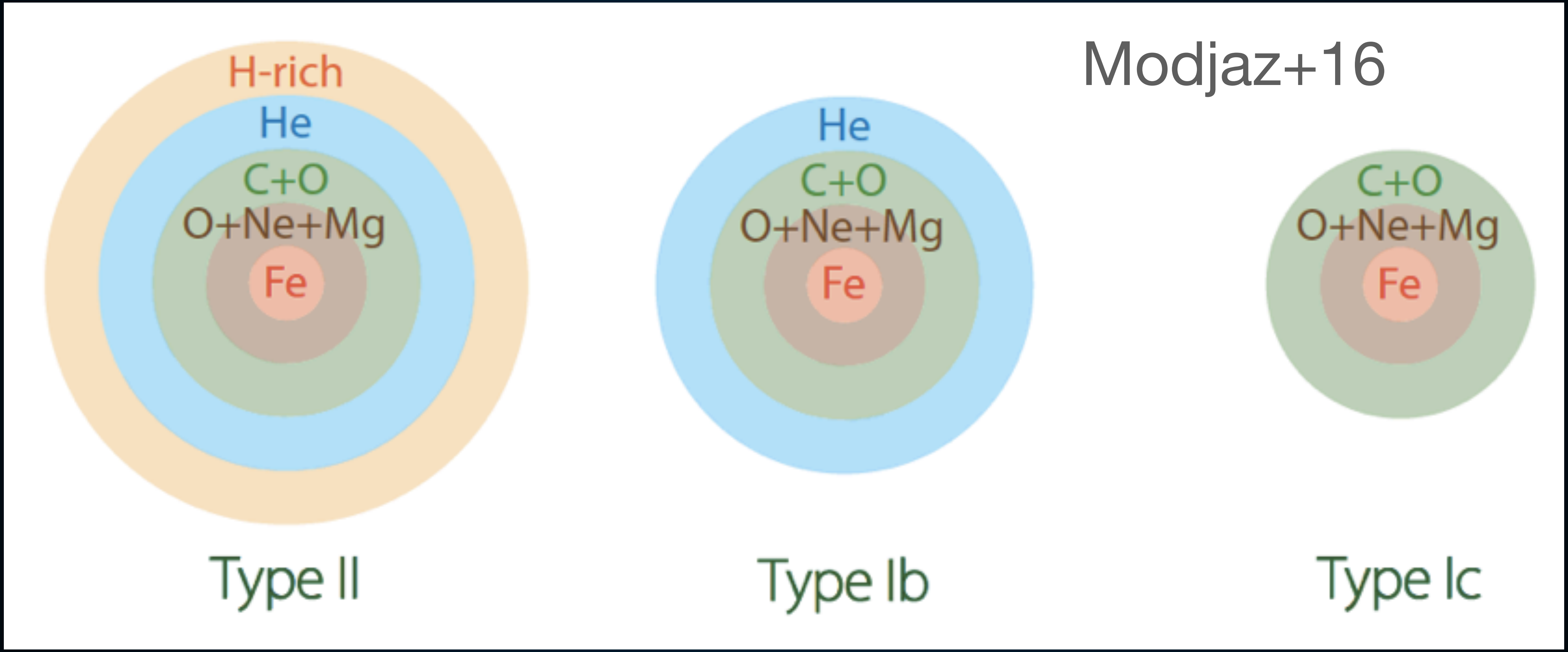
Circumstellar wind (1E-5 Msun/Yr)

Forward Shock ~10,000 km/s

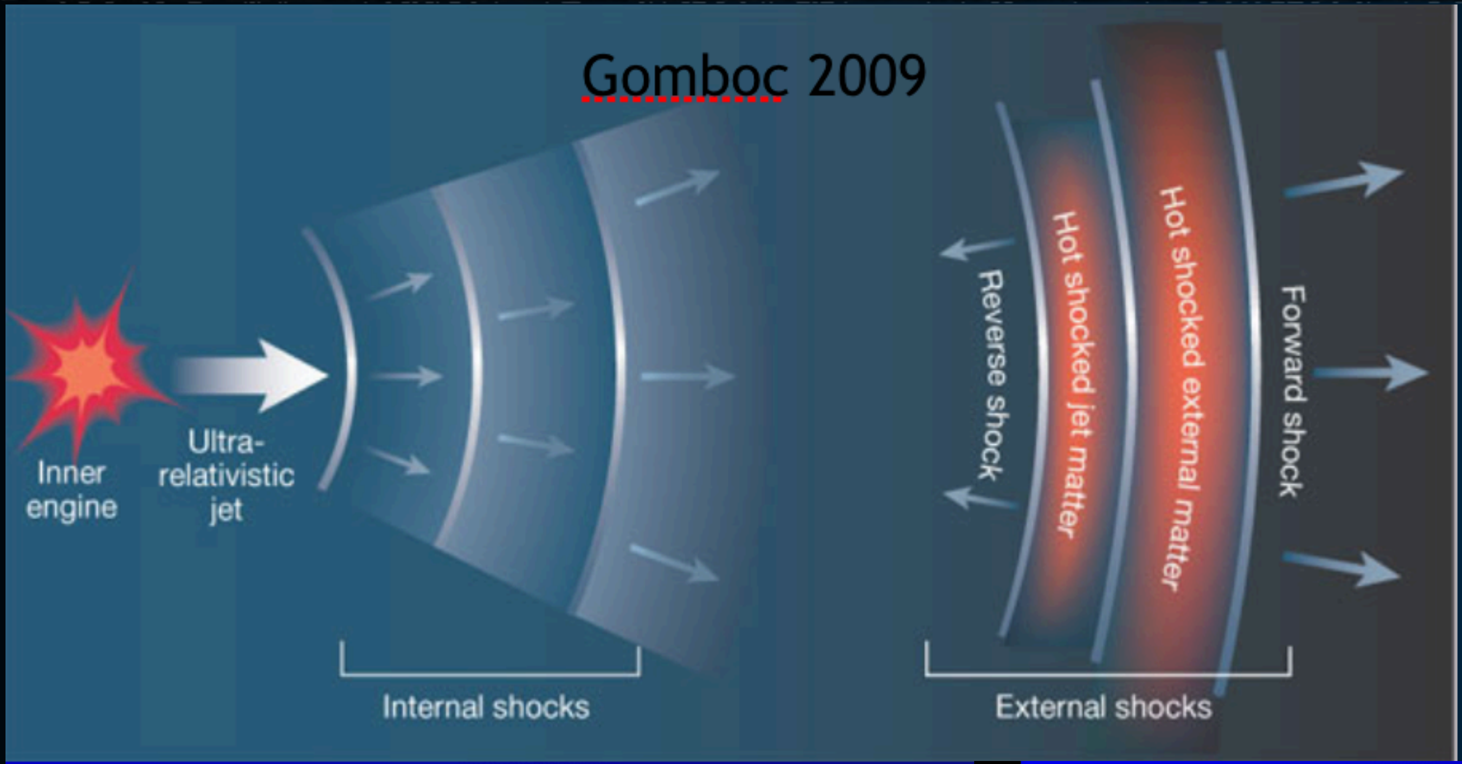
Reverse Shock ~1000 km/s

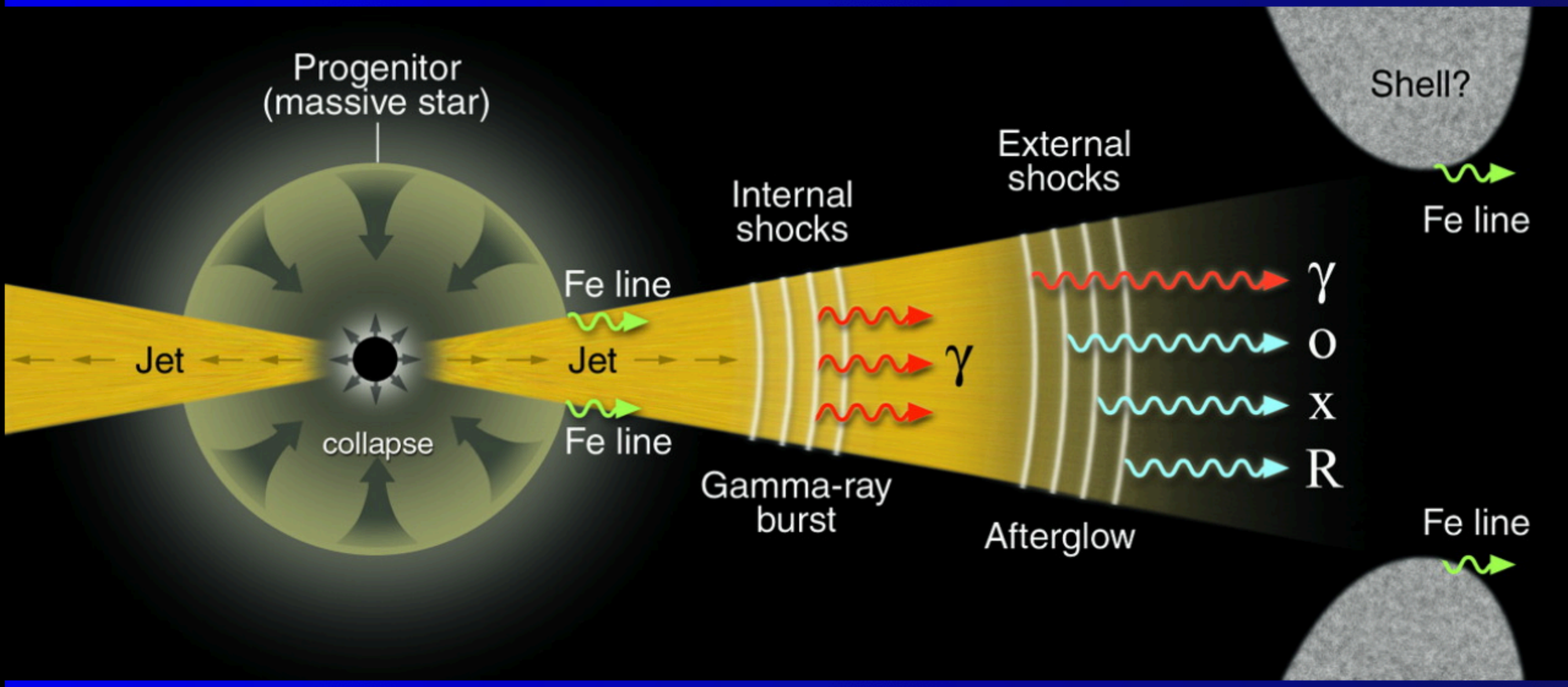
Ejecta

Diversity in supernovae



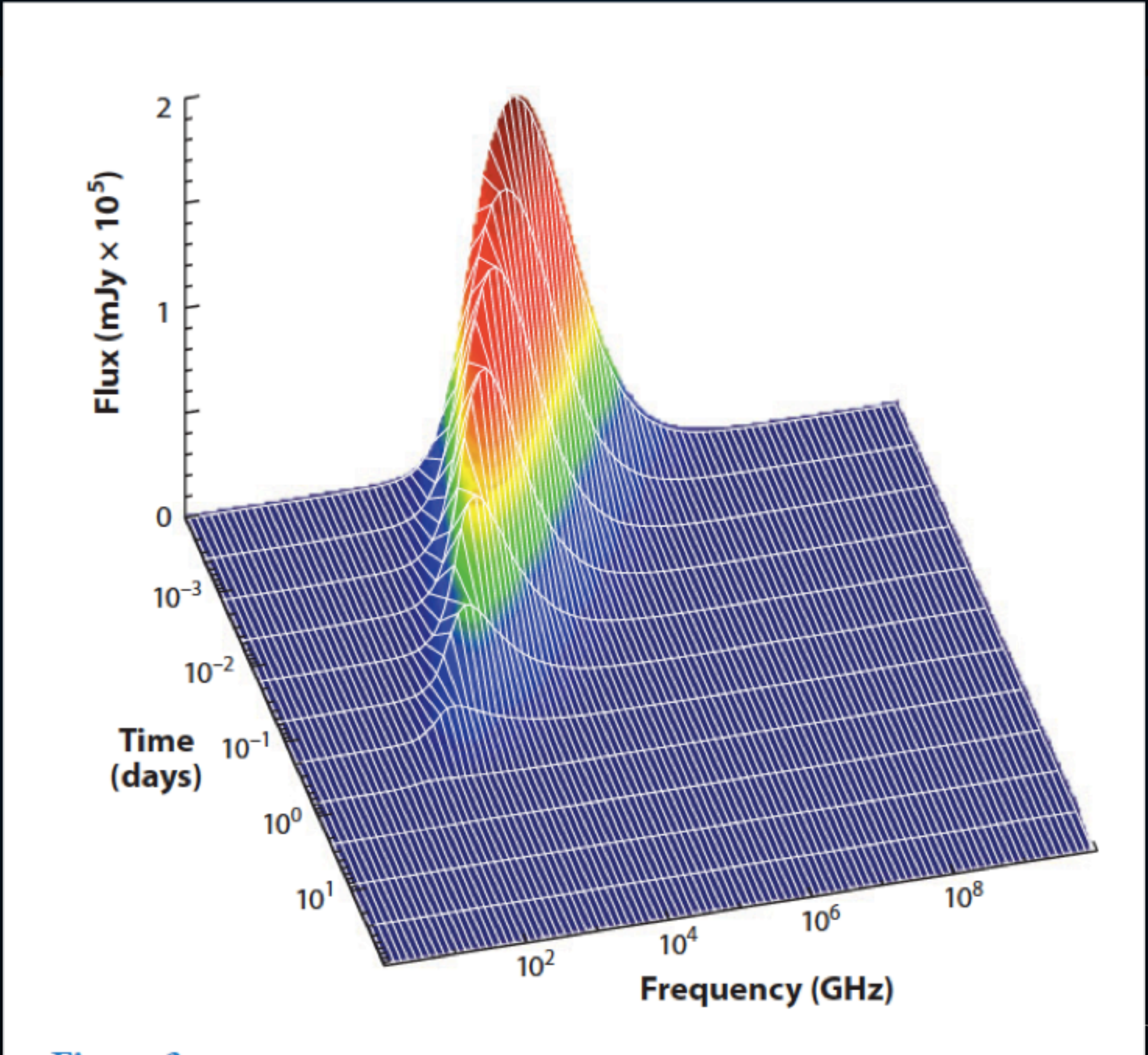
Gamma-ray bursts- collimated emission





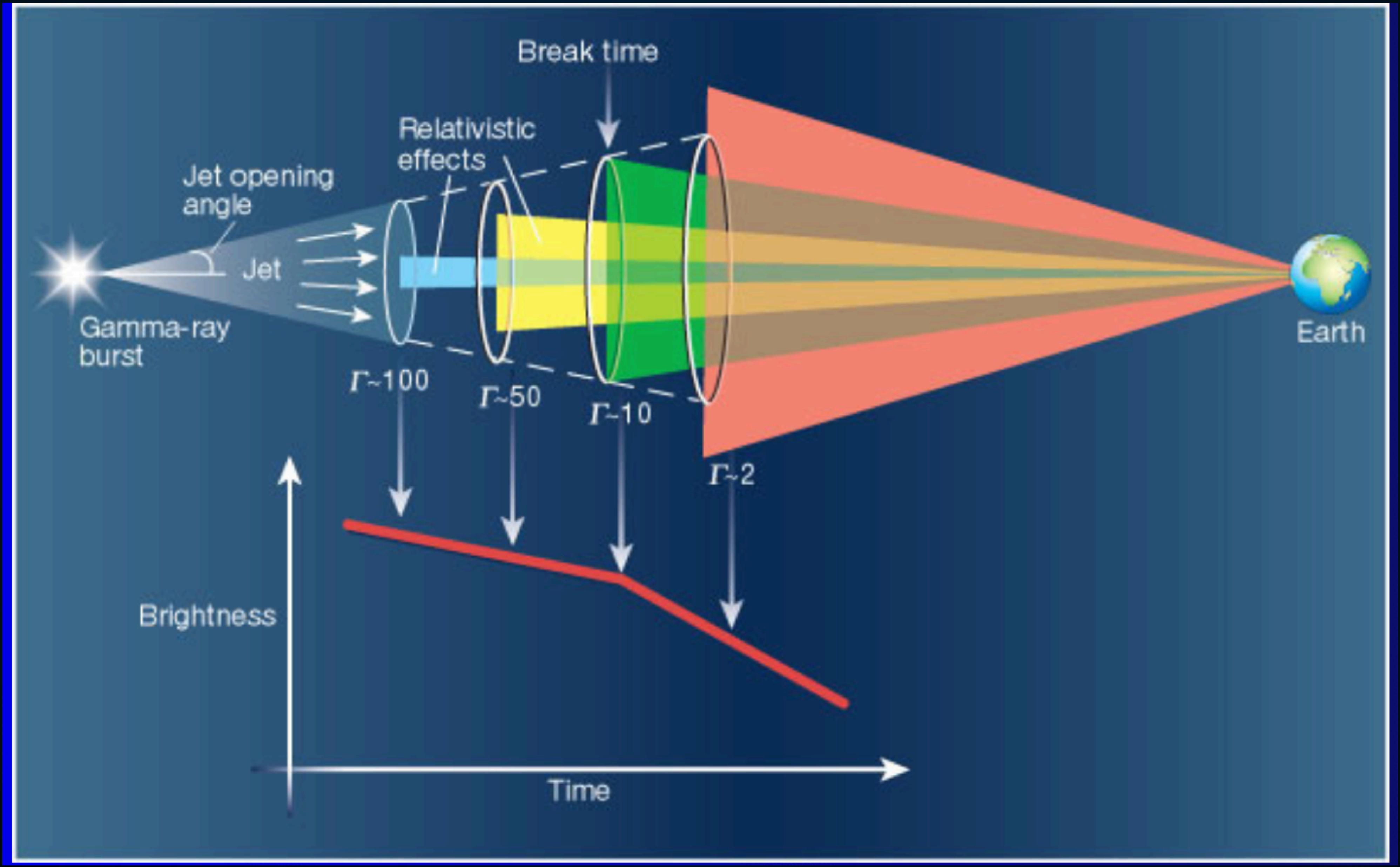
RAS

Synchrotron emission

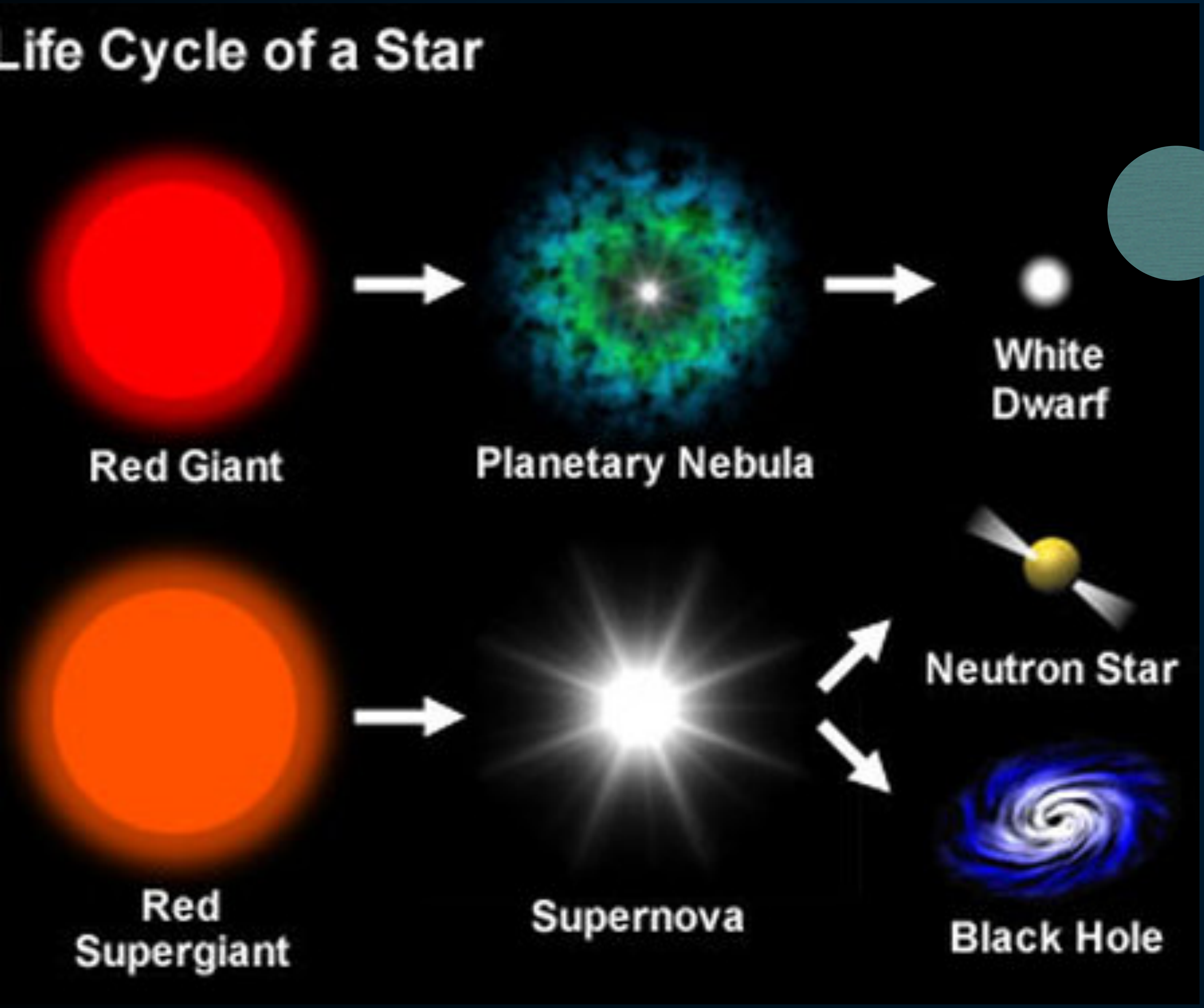


n Chandra

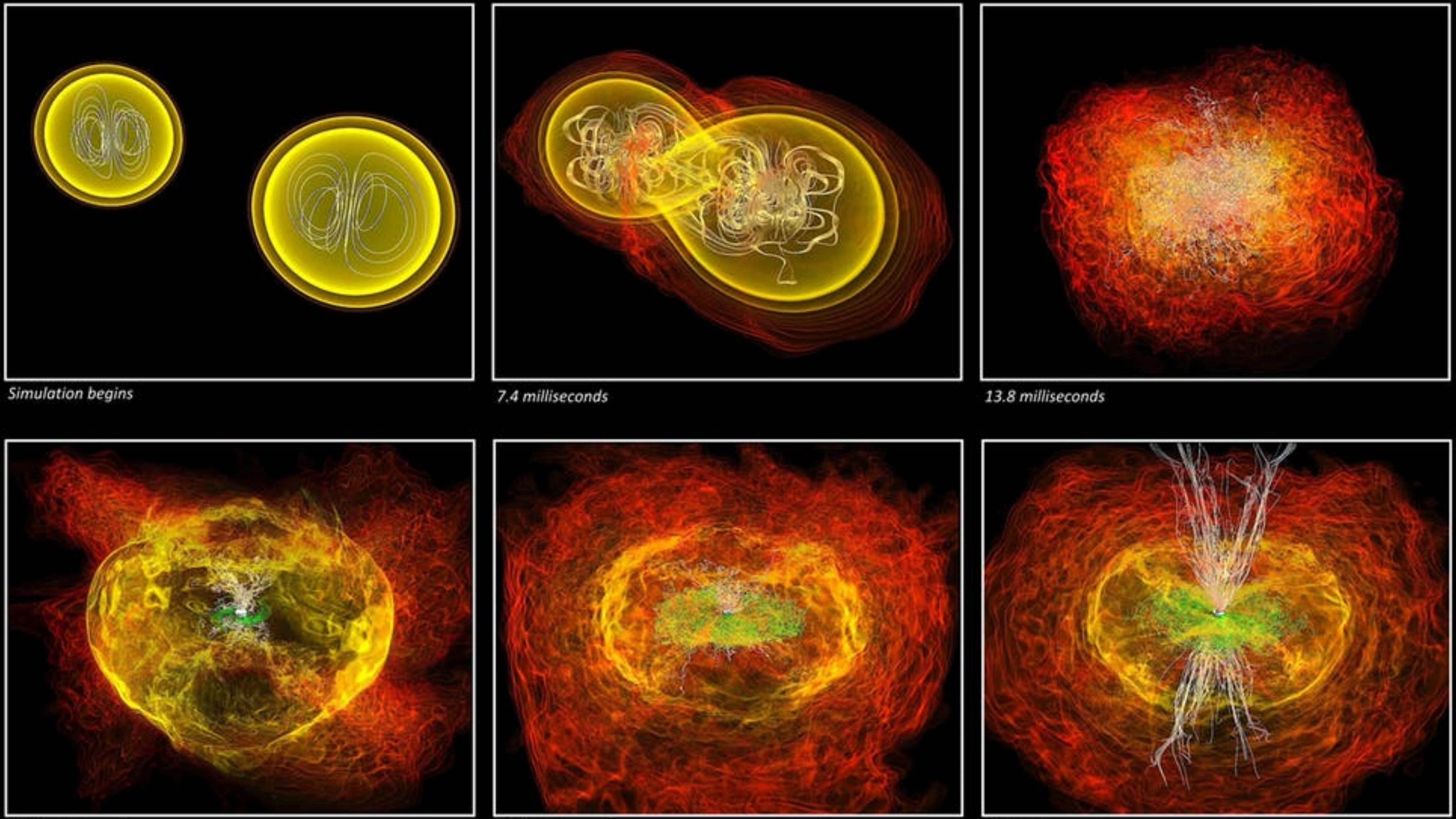
Jet-break


Break time
Relativistic effects
Jet opening angle
Jet
Gamma-ray burst
Γ~100
Γ~50
Γ~10
Γ~2
Earth
Brightness
Time

Thermonuclear supernovae - no radio emission so far!!!!



Crashing neutron stars can make gamma-ray burst jets



Simulation begins

7.4 milliseconds

13.8 milliseconds

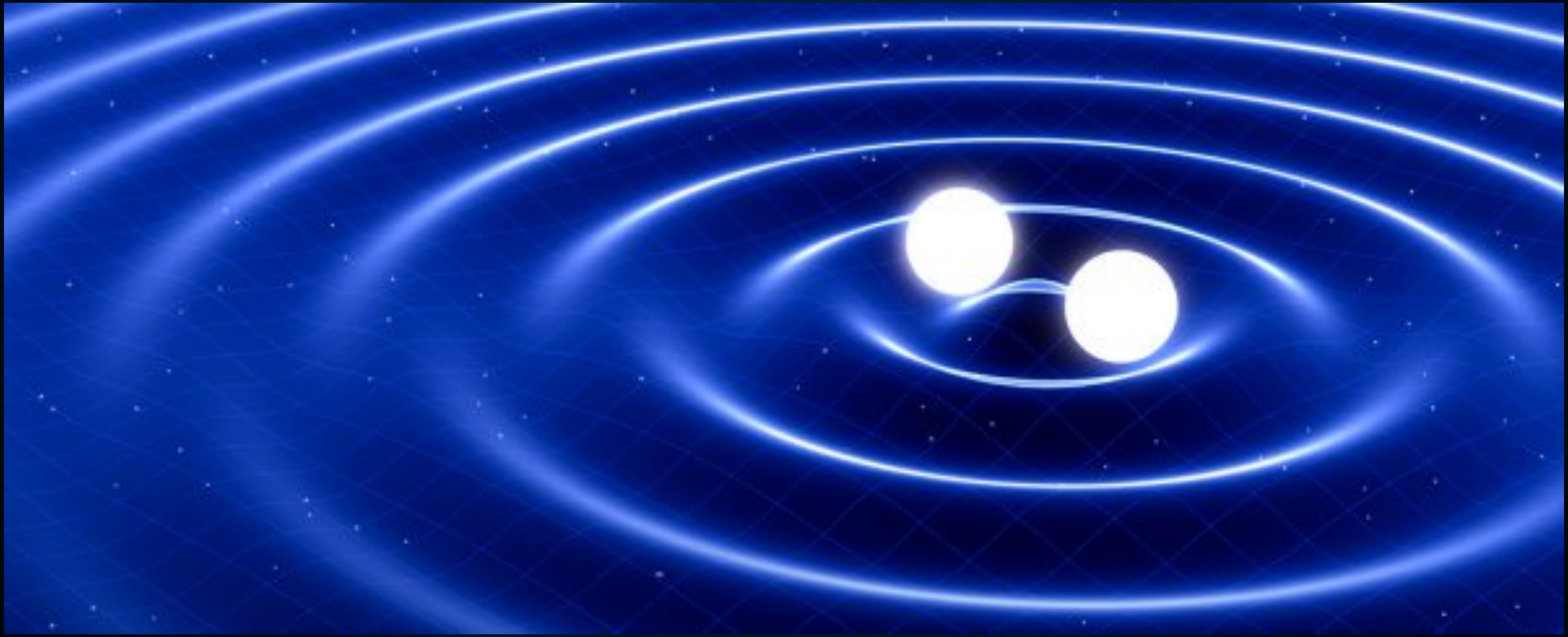
15.3 milliseconds

21.2 milliseconds

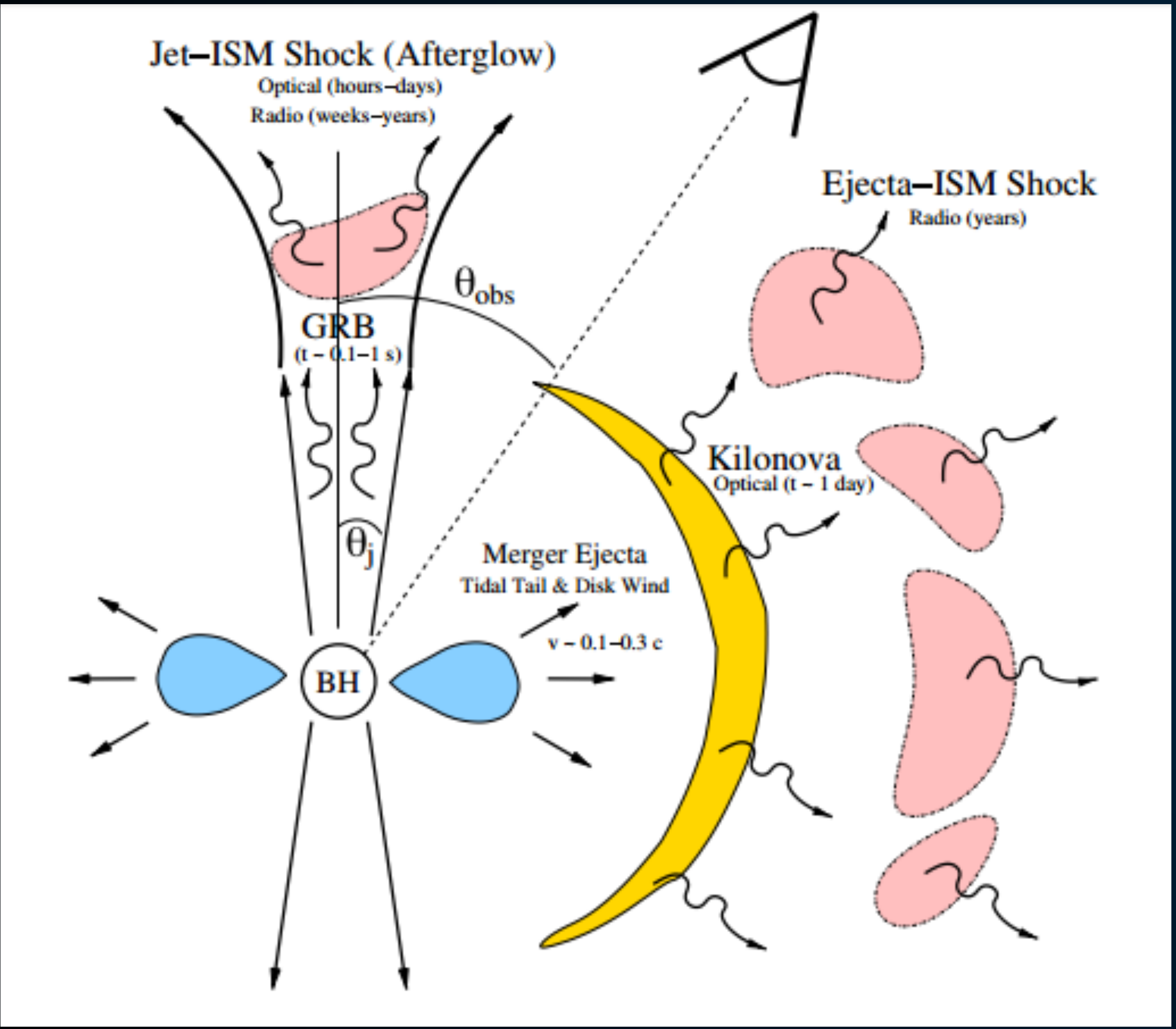
26.5 milliseconds

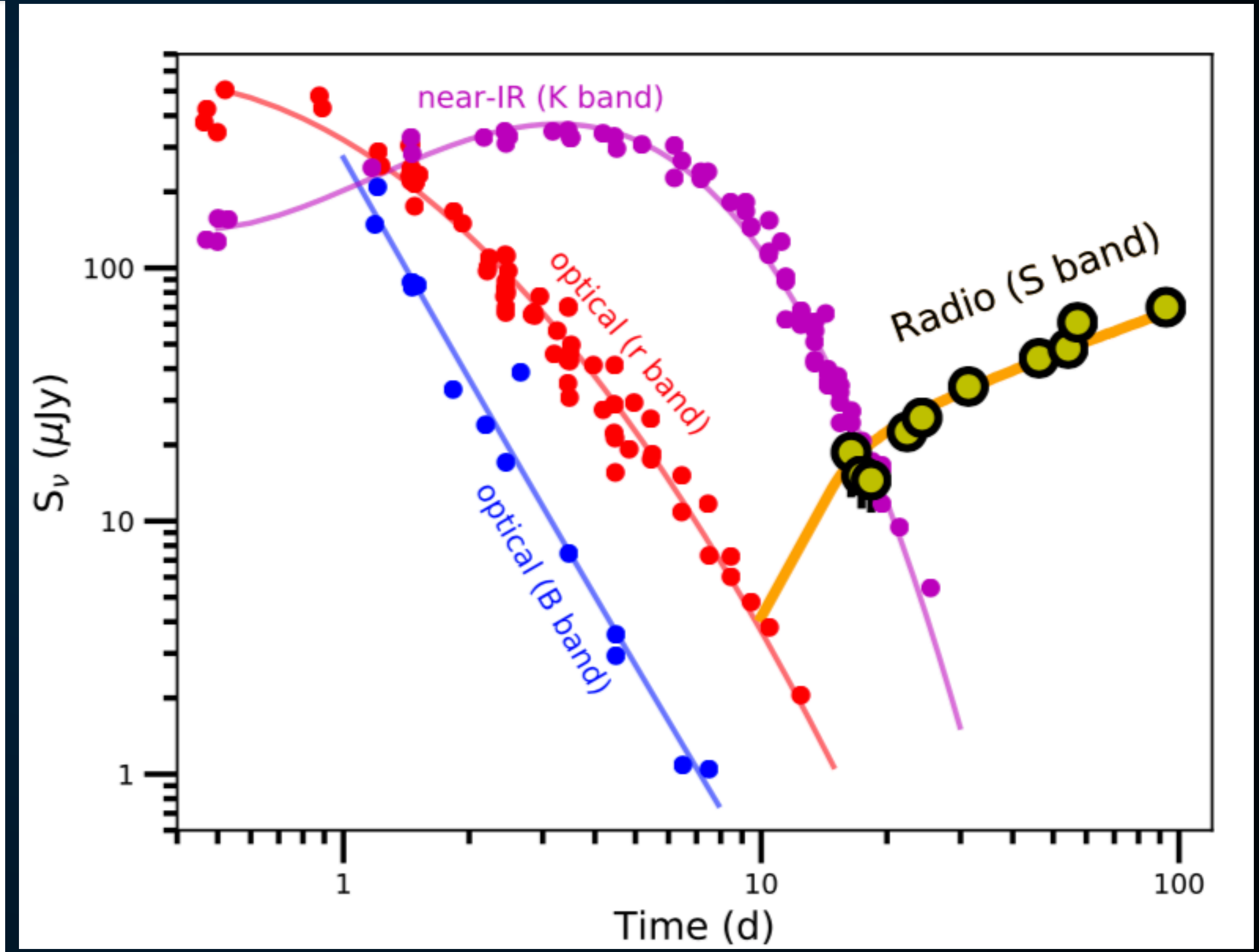
Credit: NASA/AEI/ZIB/M. Koppitz and L. Rezzolla

Gravitational waves

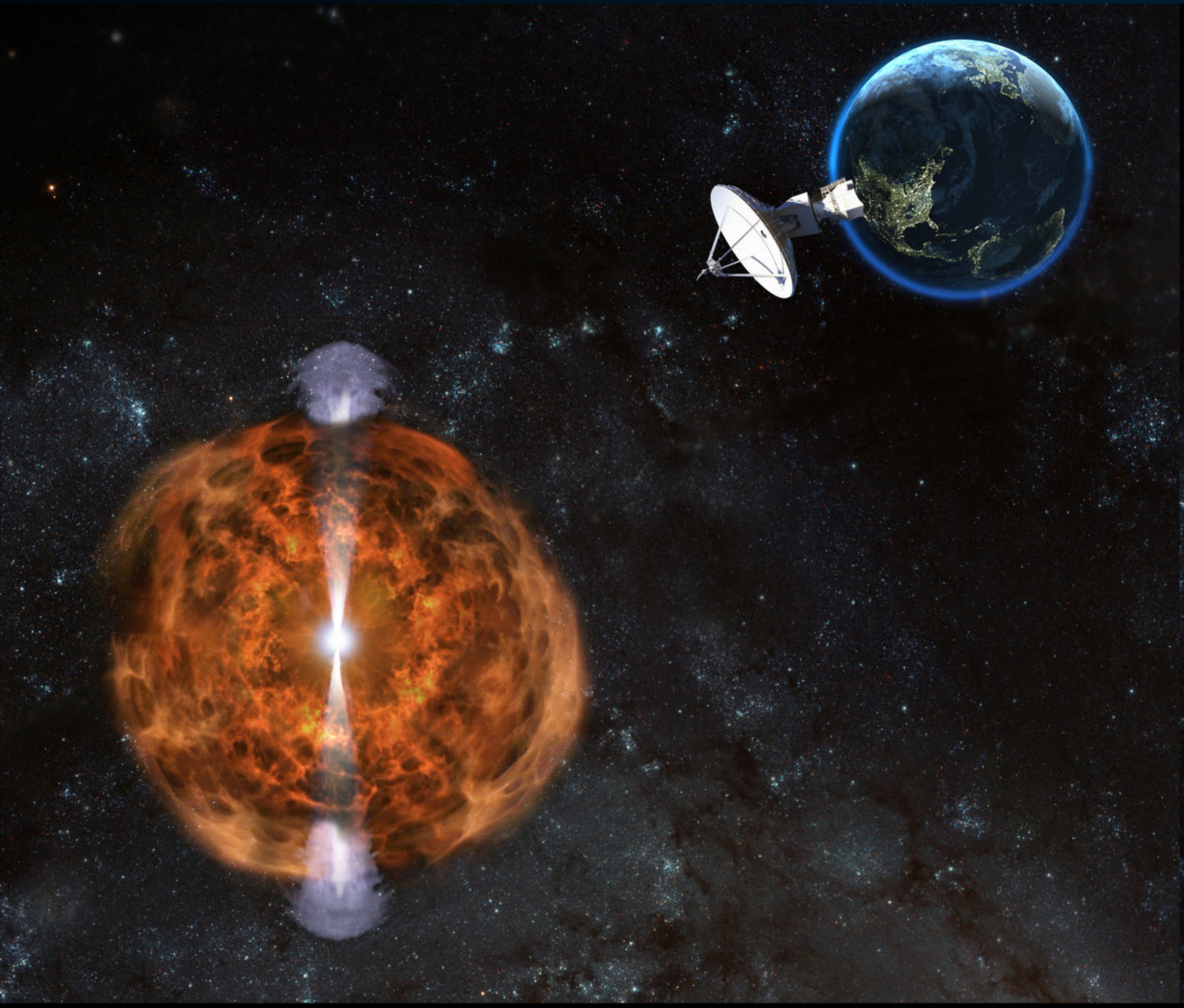


Radio emission from gravitational wave events (with NS)

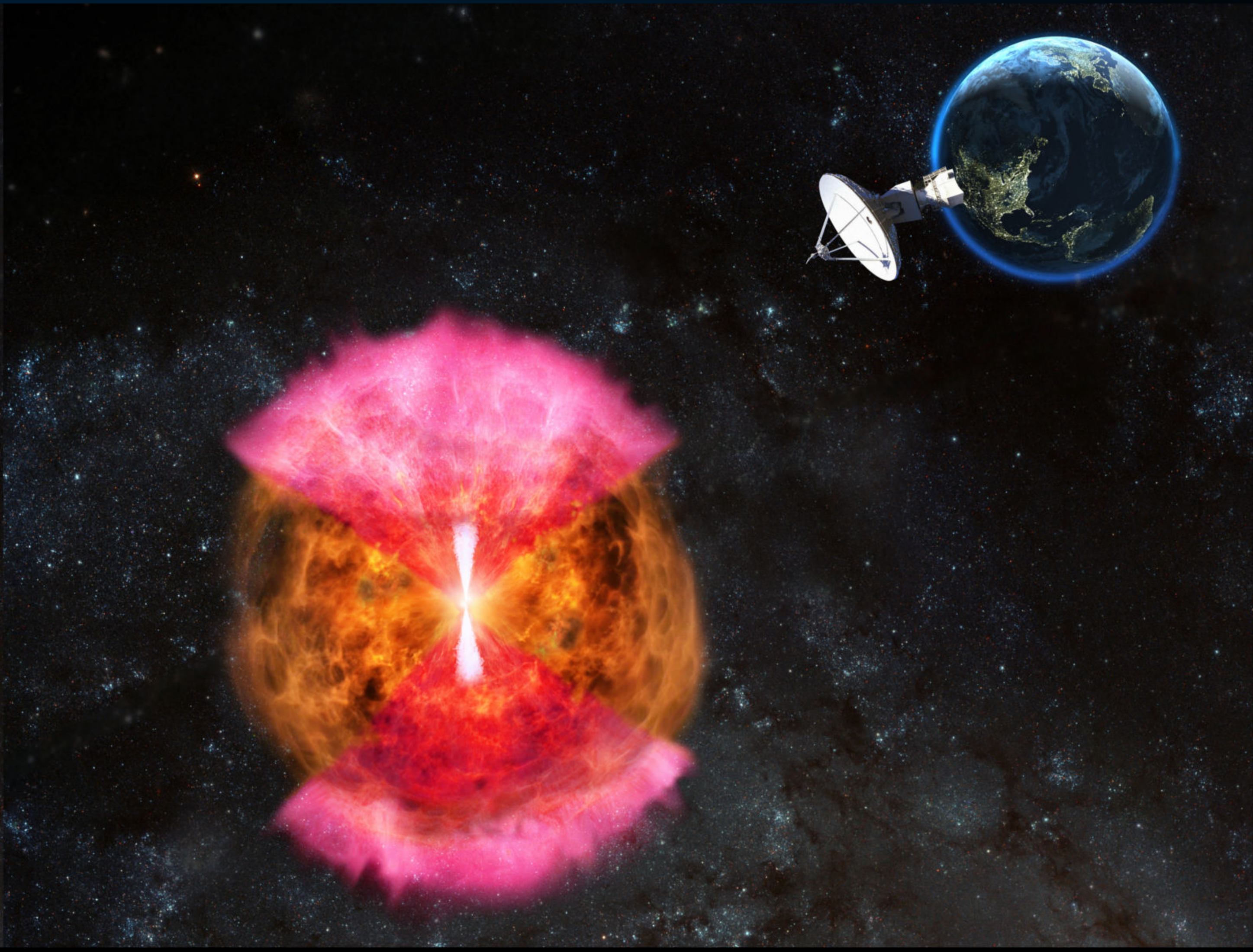




GW 170817 - radio VLBI

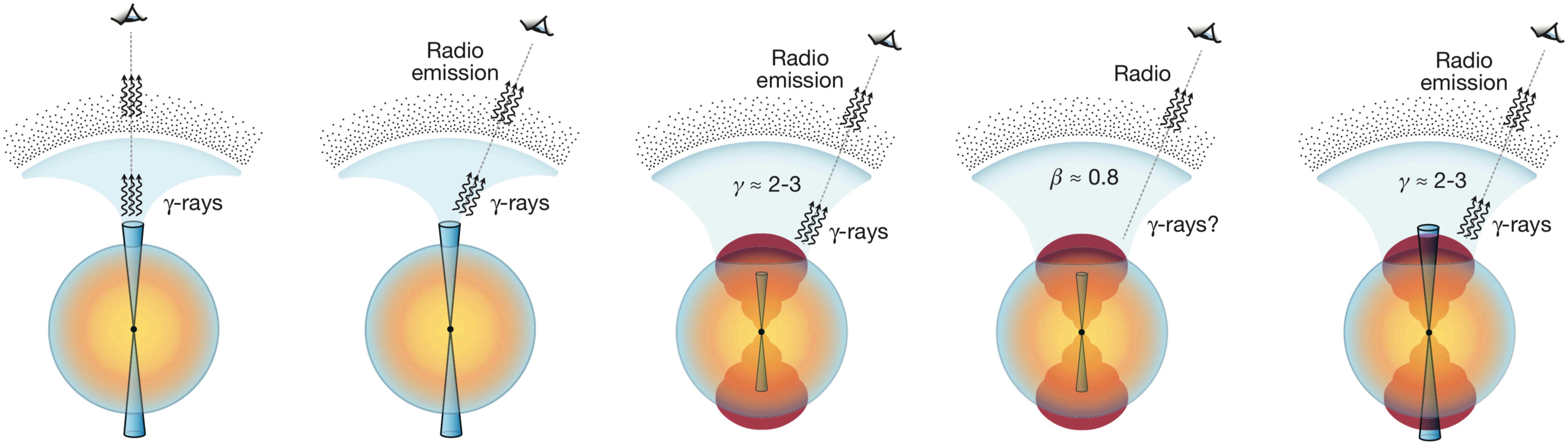


Off-Axis Jet SGRB



Choked Jet Cocoon

GW 170817 - radio VLBI



(A) On-axis jet
SGRB and afterglow

(B) Off-axis jet
SGRB and afterglow

(C) Choked jet
Cocoon γ-rays
and afterglow

(D) Choked jet
Fast ejecta afterglow

(E) Successful hidden jet
Cocoon γ-rays
and afterglow

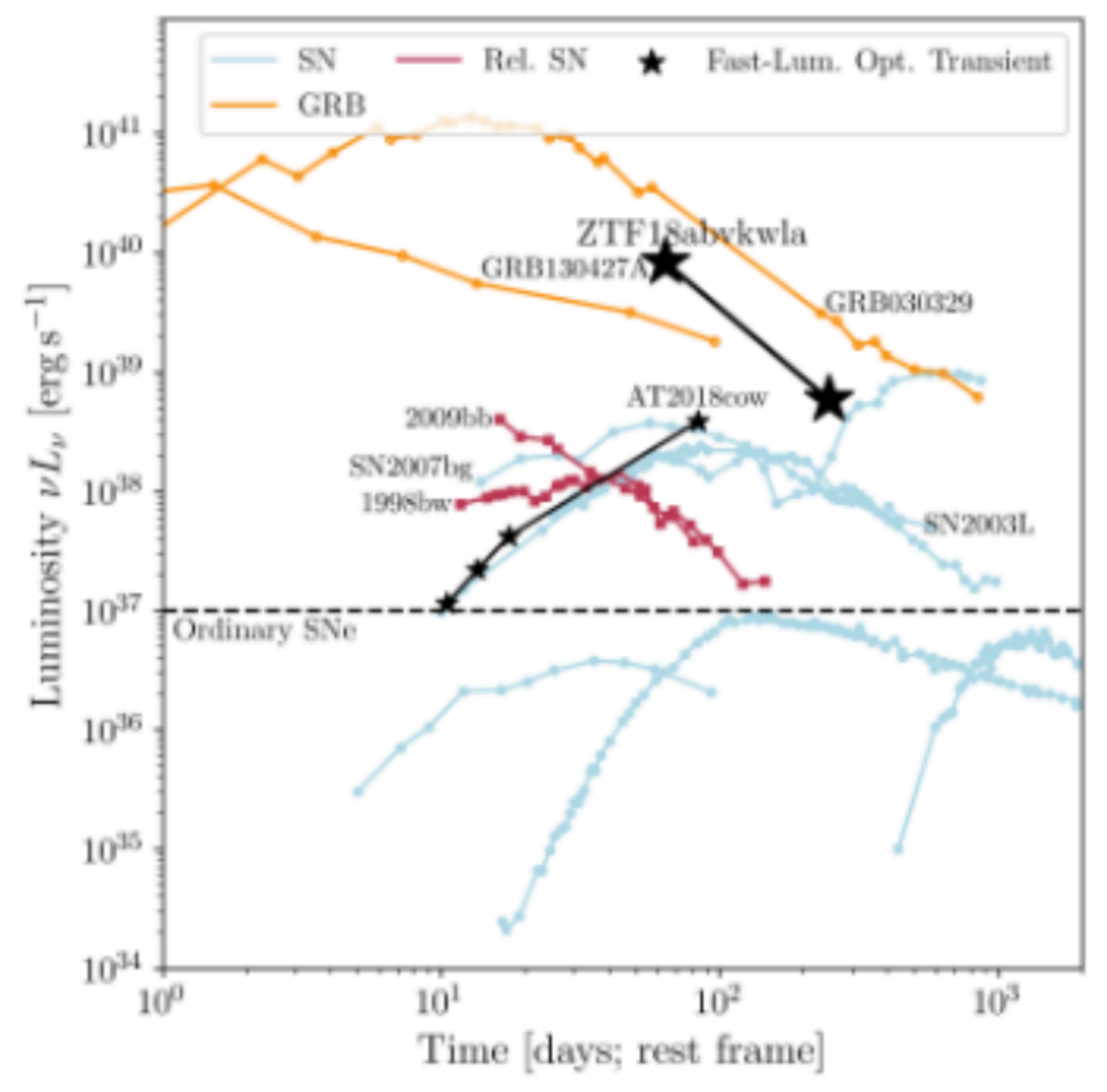
Ruled out

Most likely

Less likely

Radio emission

Image Credit: Anna Ho



ECME

- Electrons gyrating in a magnetized plasma interacts with EM waves.
- Resonance condition: $\omega = s\Omega_B/\gamma + k_{||}v_{||}$.
- Unstable electron distribution: in the process of restoring the stable distribution, electrons get rid of the excess energy by radiation.
- Electrons traveling through the middle magnetosphere towards the stellar surface experience magnetic mirroring and a loss-cone distribution is produced.
- Loss-cone distribution: one way to induce instability, produced by magnetic mirroring effect.
- Particle gets reflected if $\sin^2(\theta) > B_0/B_1$, → magnetic mirroring