Introduction to Pulsars

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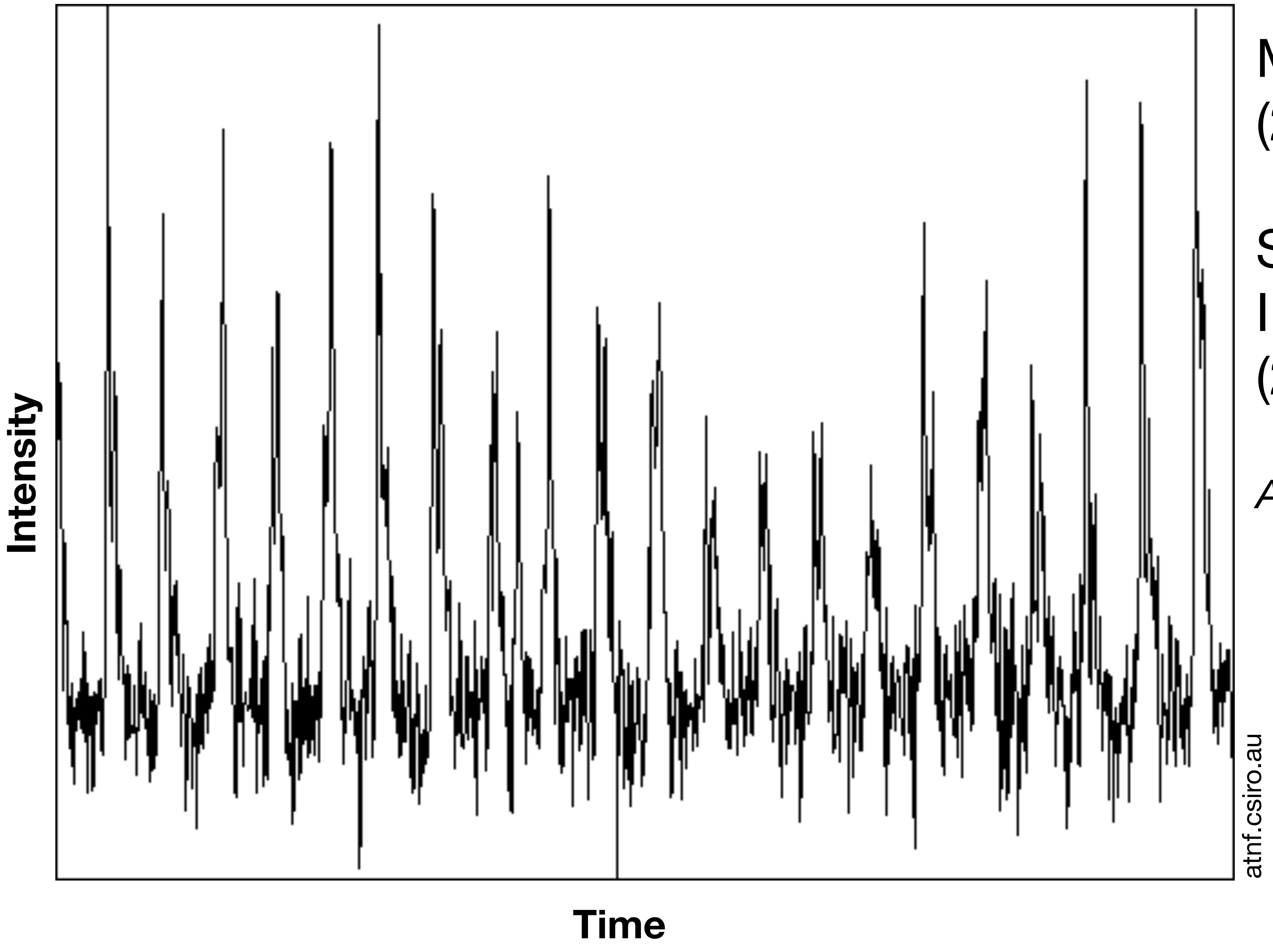
IUCAA, Pune

PULSARS

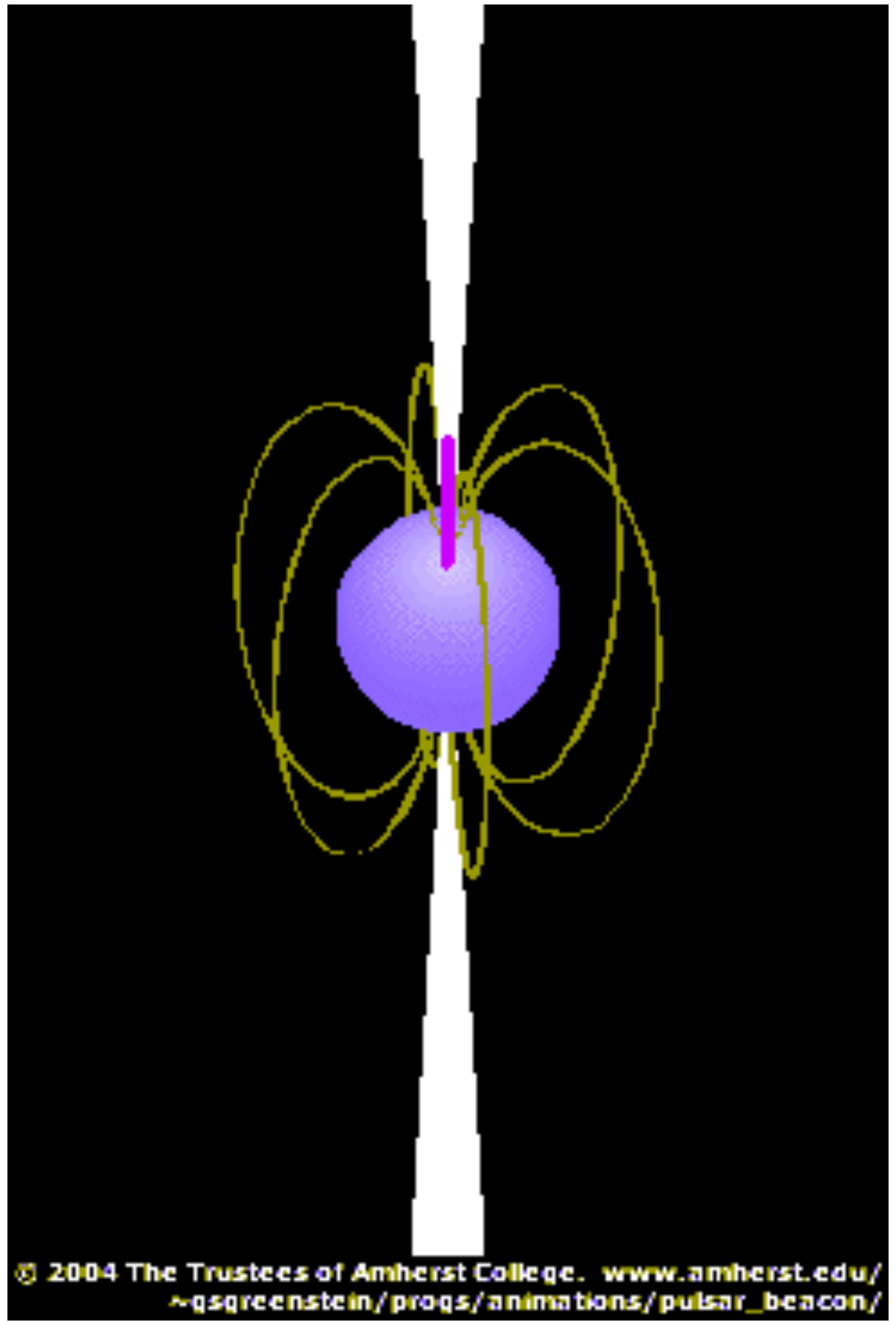
Emission received as a periodic sequence of pulses



Most seen in Radio band (2609)

Some at higher energy: IR-gamma rays (249)

ATNF catalogue June 2019



Spinning Neutron Star
Mag. axis inclined to spin
Radiation beam from magnetic poles

Neutron stars extremely dense objects - average density 10^{15} times that of water

Passage of matter to High Density

Air: ~10^{-3} g/cm^3

Diffuse gas: ~10^{-24} g/cm^3

Water: ~1 g/cm^3

Stars: ~10^{-2}—10^2 g/cm^3

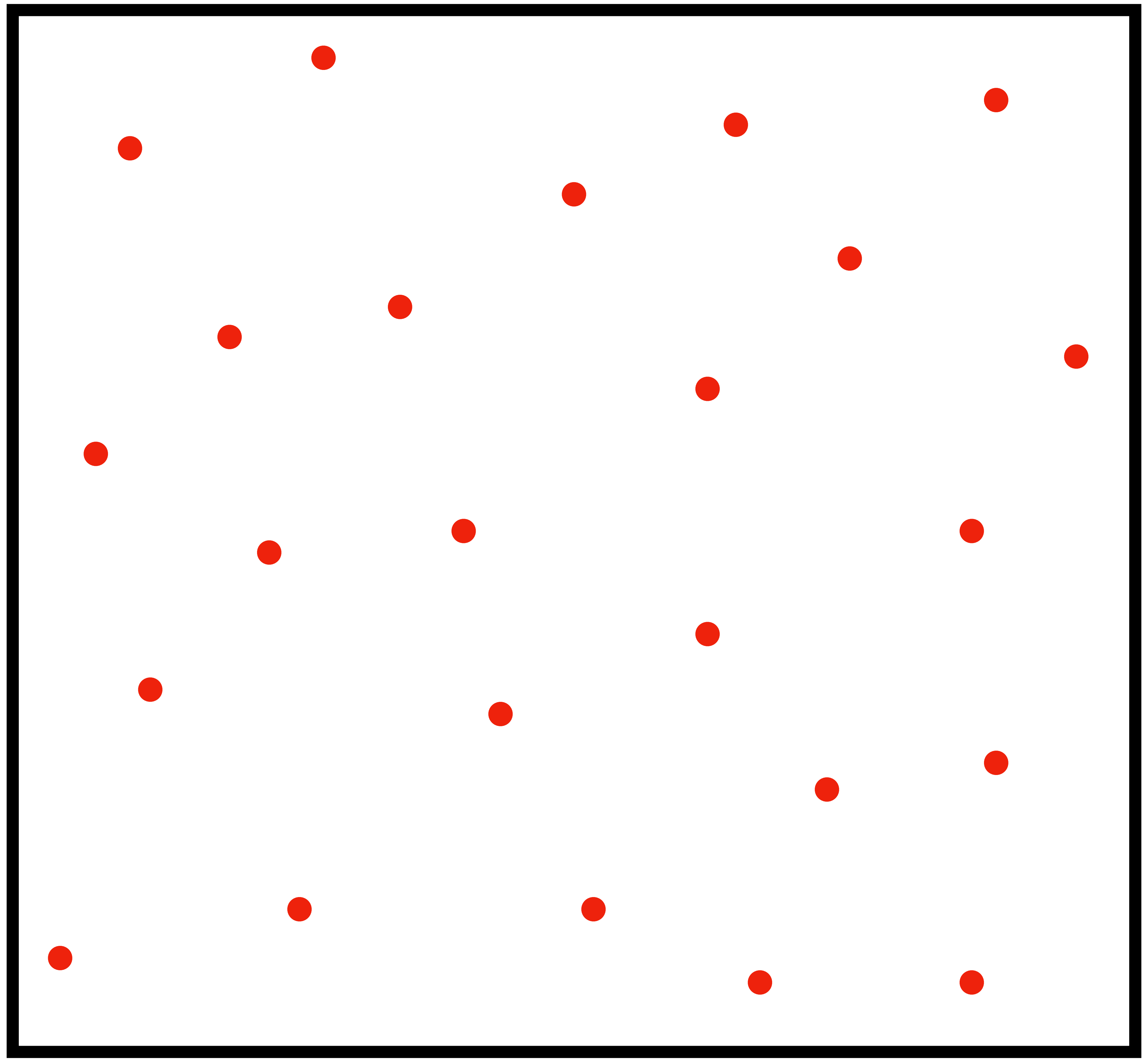
Heavy metals: ~20 g/cm^3

Planets: ~ 0.5-10 g/cm^3

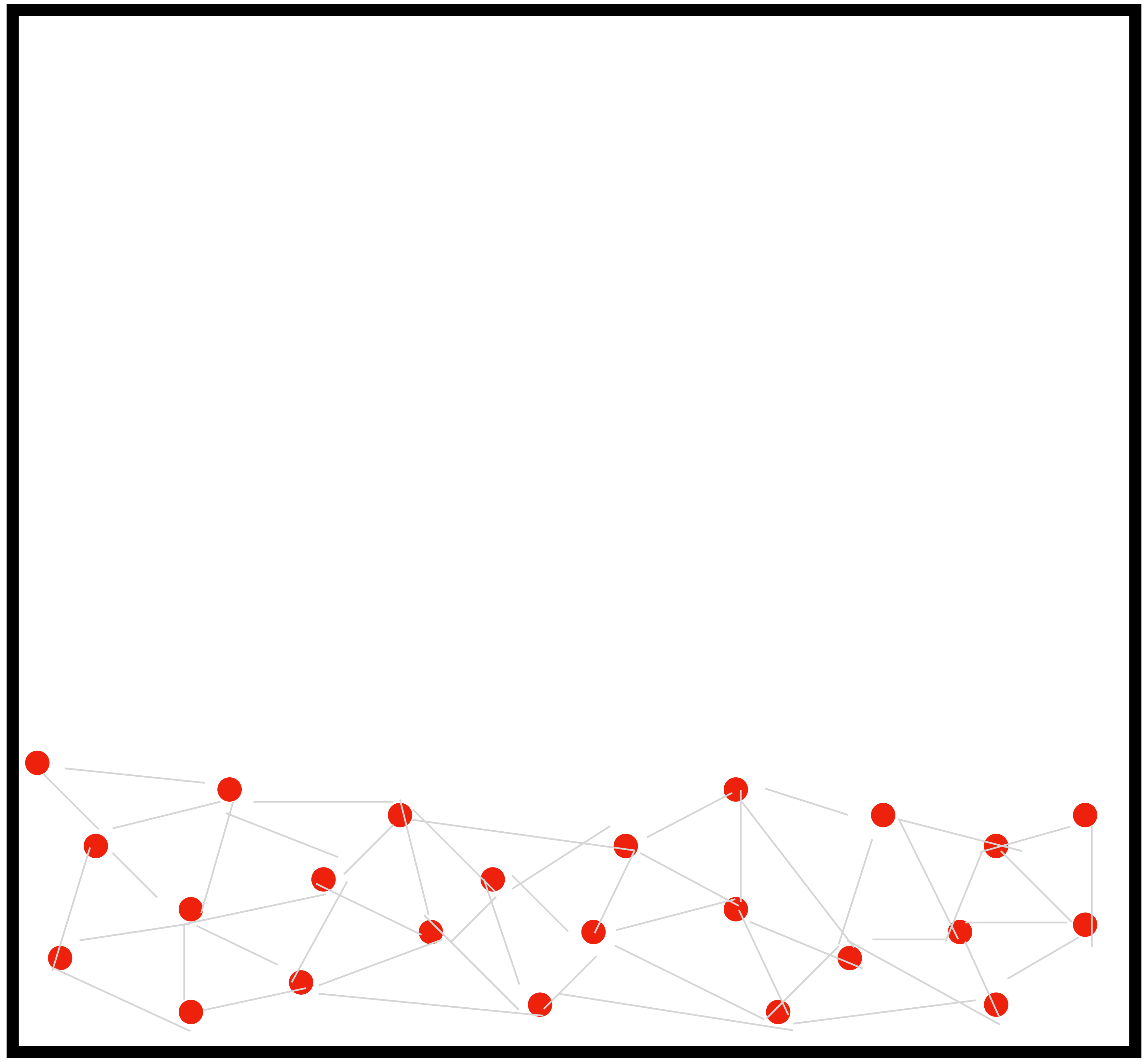
White Dwarf: ~10^6 g/cm^3

Neutron Star: ~10^{15} g/cm^3

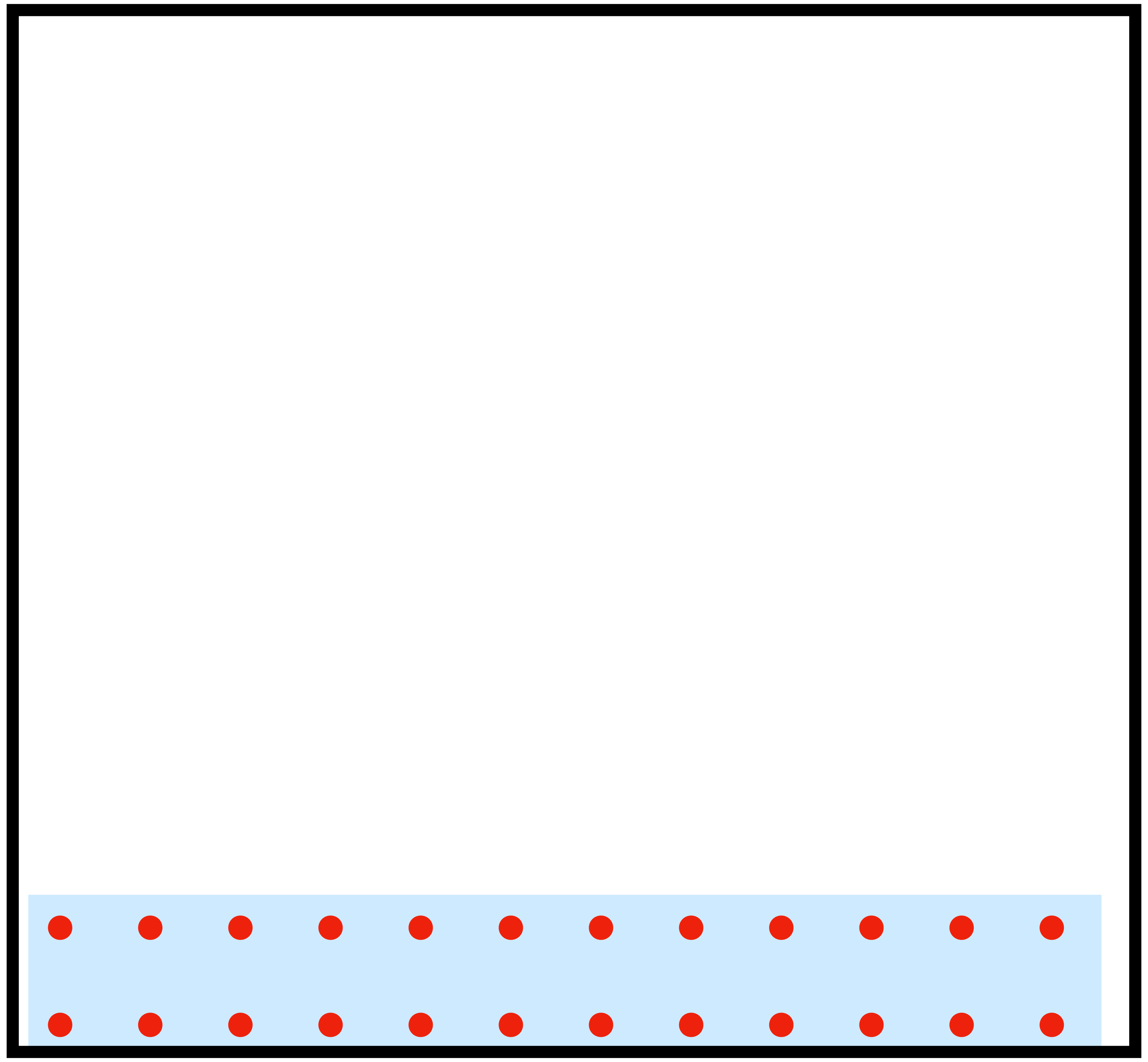
Gas: Atoms/molecules in thermal motion



Liquid: coulomb interaction



Solid: crystal order, free electrons,
stronger coulomb interactions



Terrestrial dense matter is held together by electrical forces

balance between attraction and repulsion

Getting denser

Apply a squeeze

Strip electrons from atoms

Under the influence of external force, ions can get closer

Density rises until coulomb repulsion balances external force

Natural source of external squeezing force: **Gravity**

Coulomb force balancing gravity: *planets* and *moons*

If more and more matter is added, gravity will eventually overcome the coulomb force

Planets cannot get heavier than about Jupiter

Getting denser

Stars too are held together by gravity

Much heavier than planets

Opposition to gravity comes from Thermal Pressure of gas

Gas is kept hot by nuclear fusion

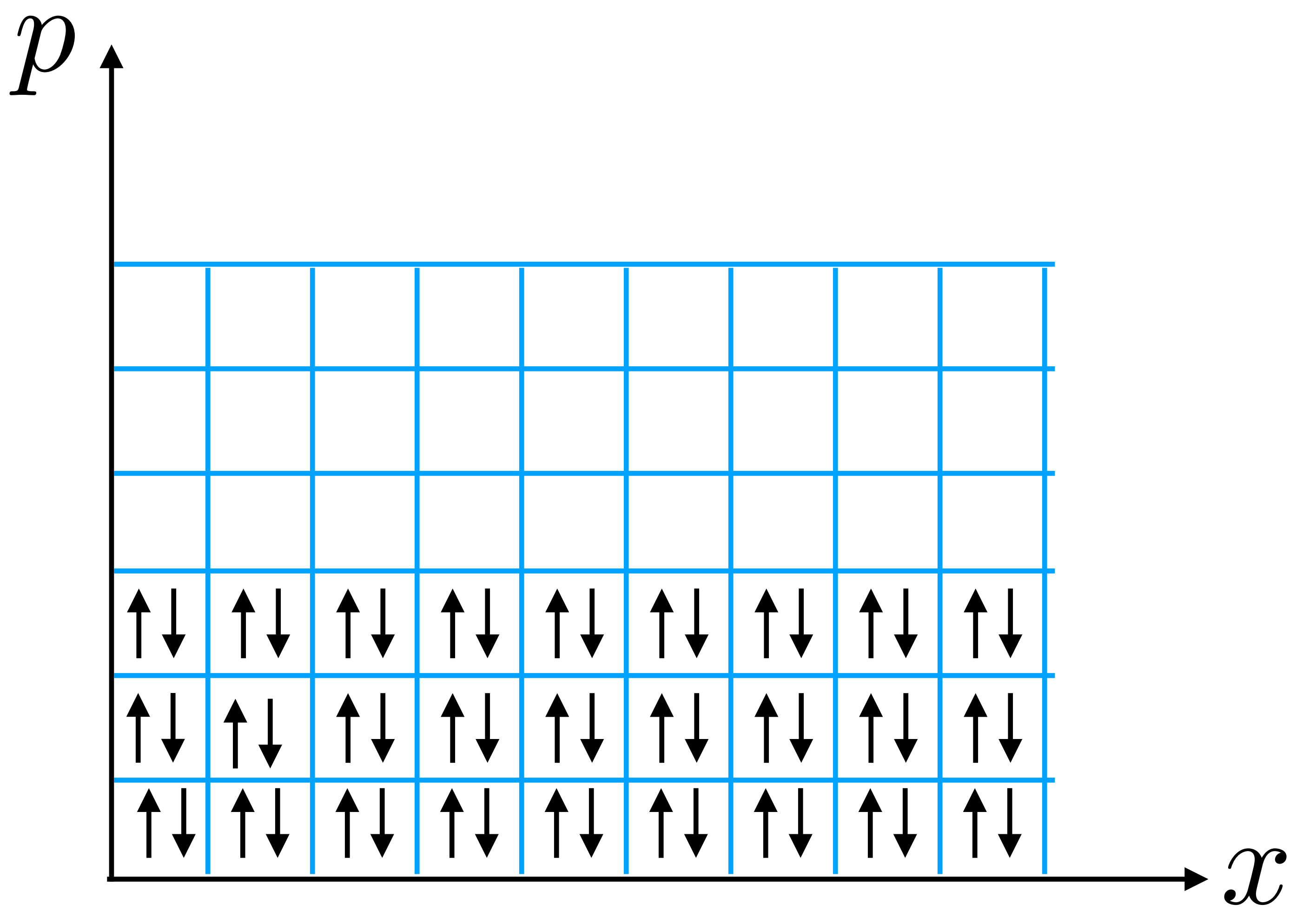
Eventually nuclear fuel will run out, gravity will win over thermal pressure

The stellar core will collapse. Coulomb force inadequate to provide support, matter will continue to get much denser

A new type of pressure: Degeneracy

Electrons are elementary particles with half-integral spin: $\hbar/2$

Such particles obey Fermi-Dirac statistics, leading to Pauli's exclusion principle:



Phase space (6-dim): position and momentum

Divided into quantum cells of volume h^3

Each cell may contain at most 2 electrons of opposite spin

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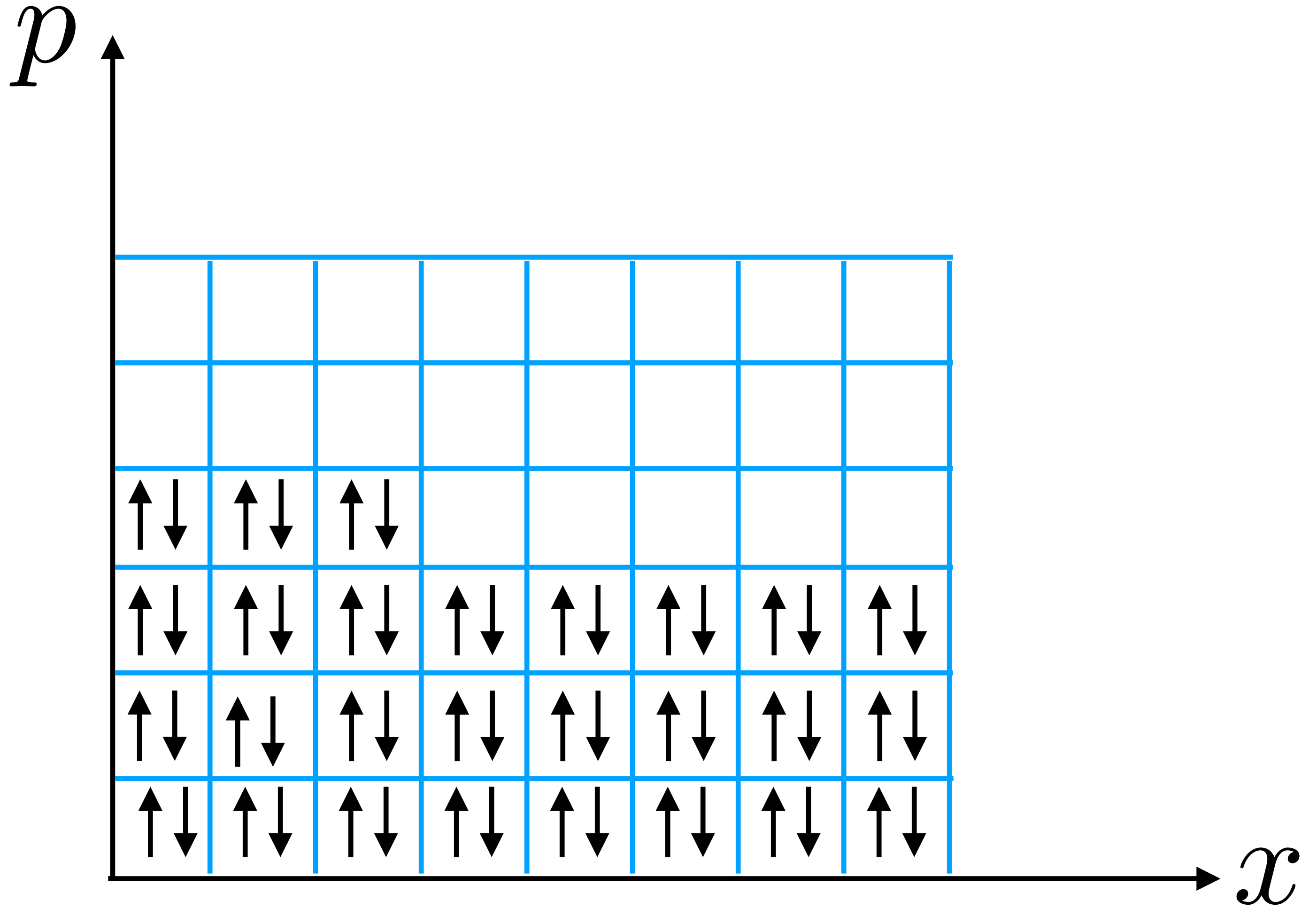

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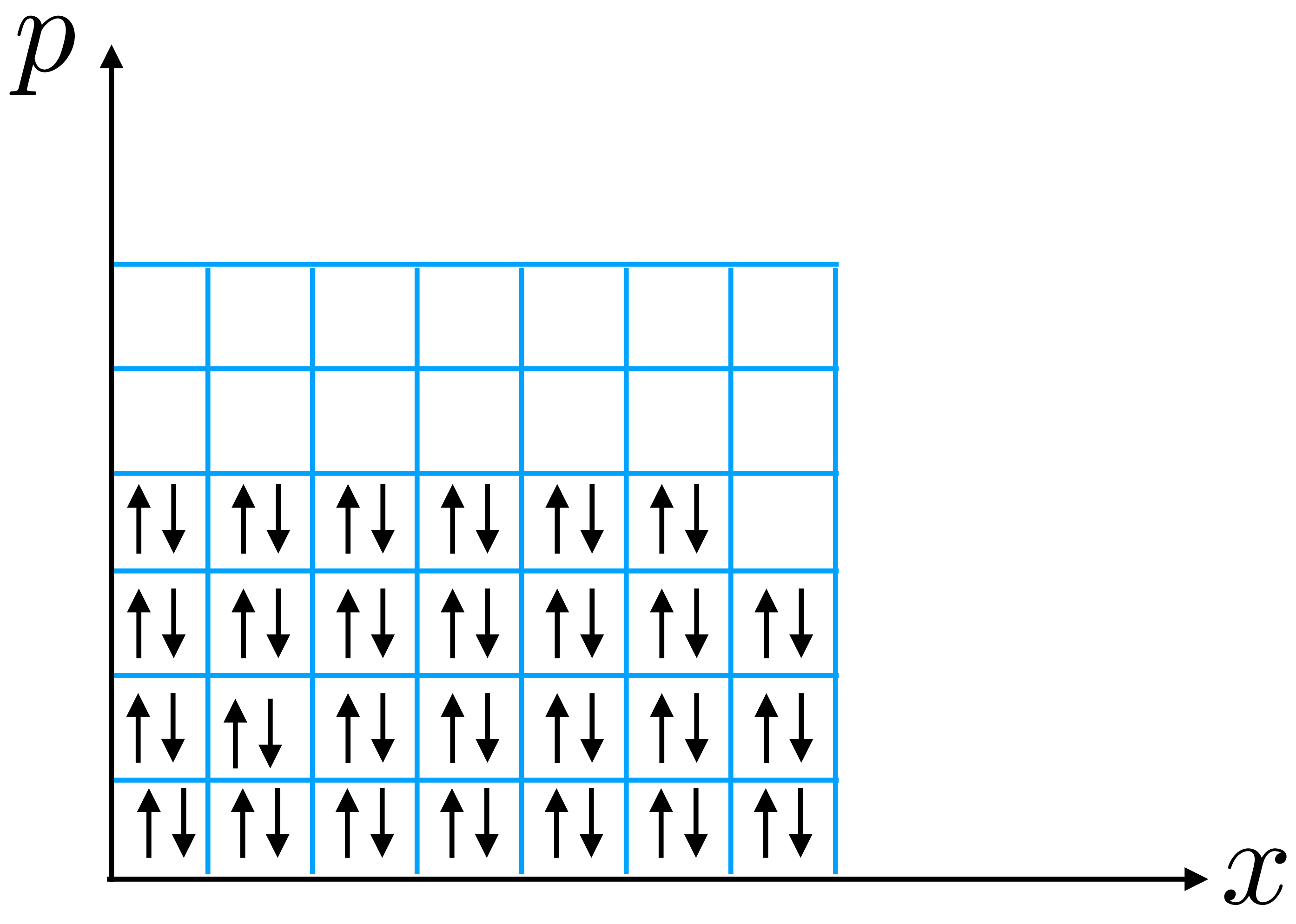

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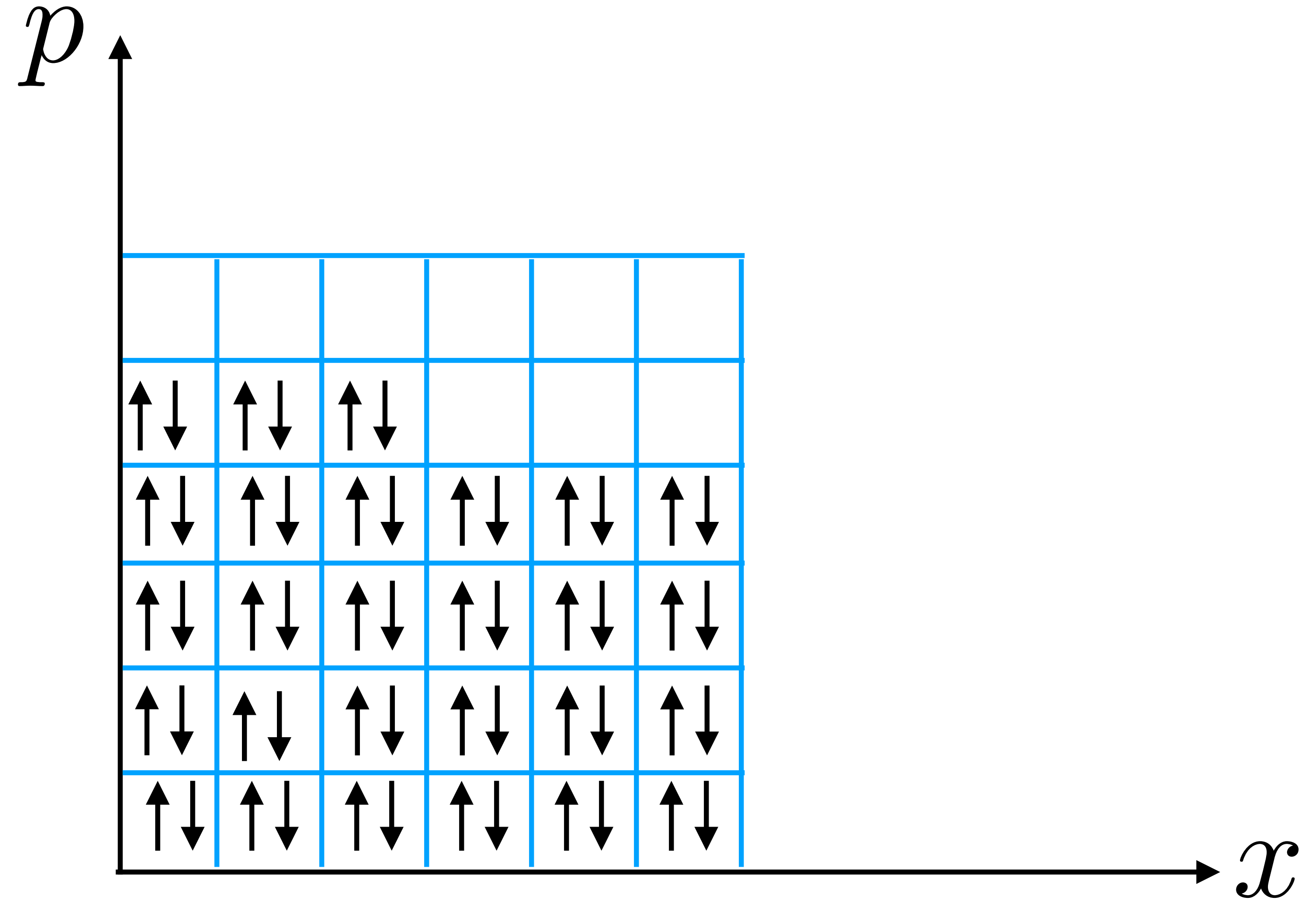


Phase space (6-dim): position and momentum

Divided into quantum cells of volume h^3

Each cell may contain at most 2 electrons of opposite spin

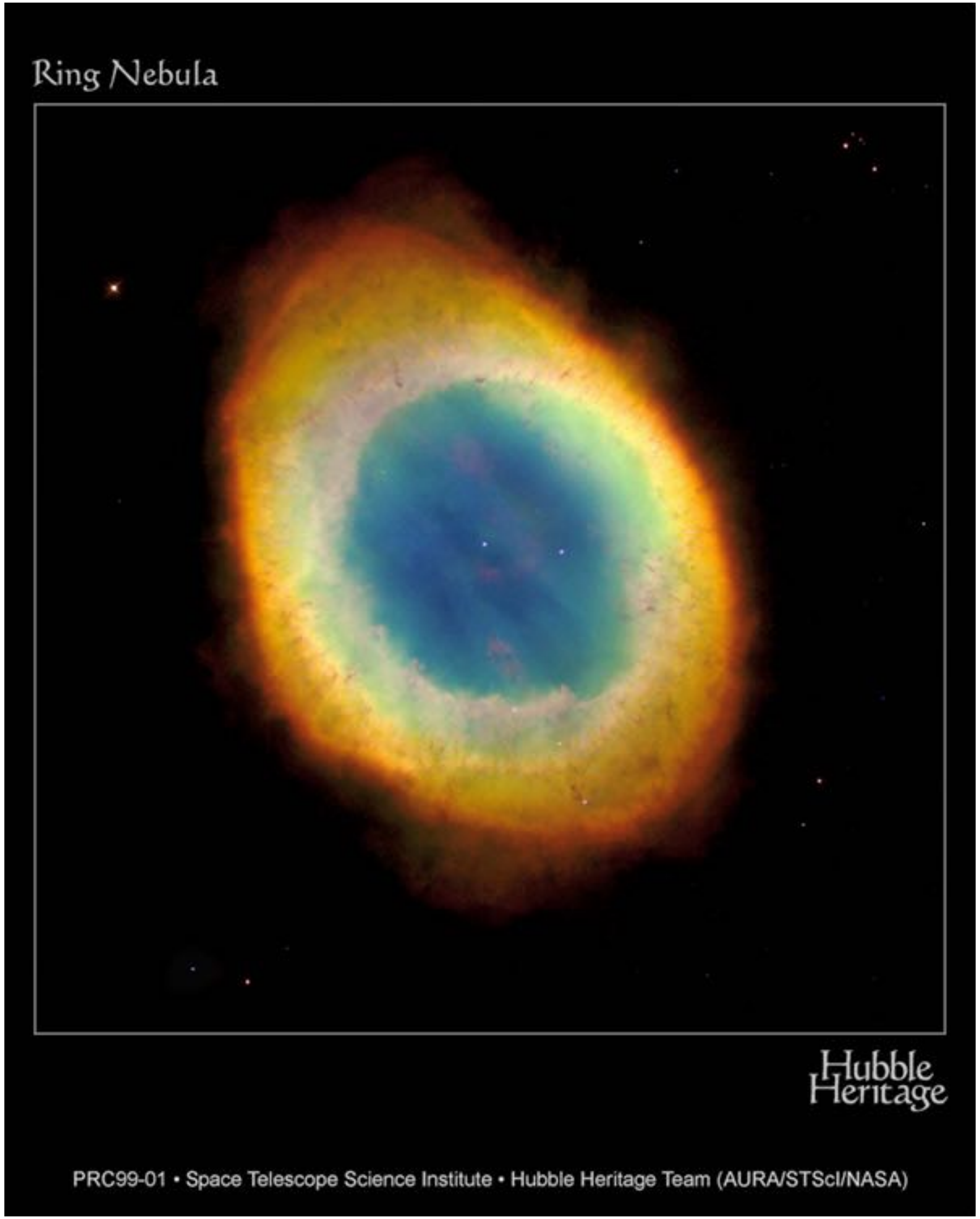
The denser the material gets, the higher the momentum rises

This momentum is the source of Degeneracy Pressure

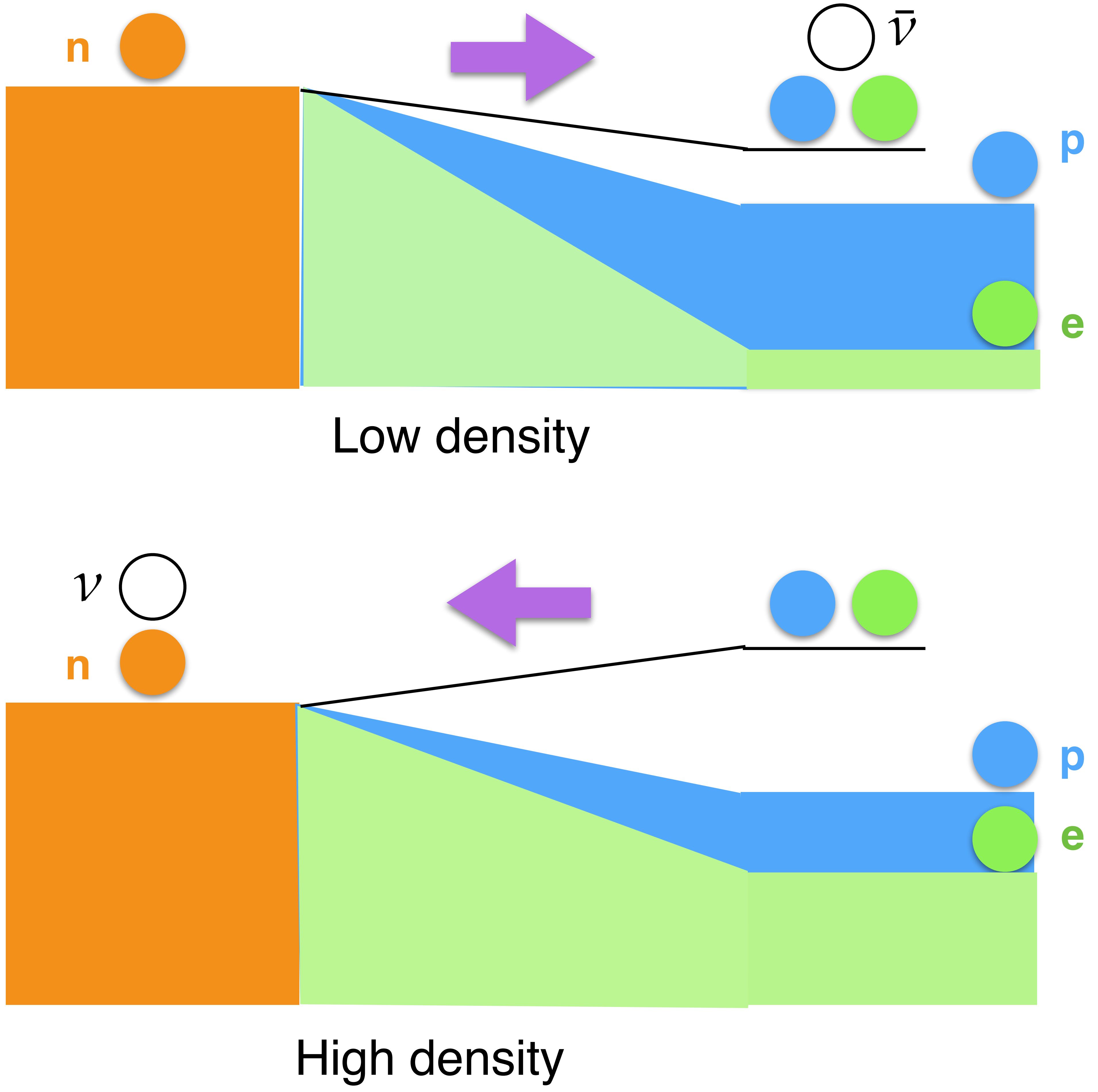
Stars held by electron degeneracy pressure:
White Dwarfs

Can support up to 1.4 Solar Mass
(Chandrasekhar Limit)

Heavier objects without nuclear burning
will be squeezed further => neutronisation



Neutronisation and β-equilibrium



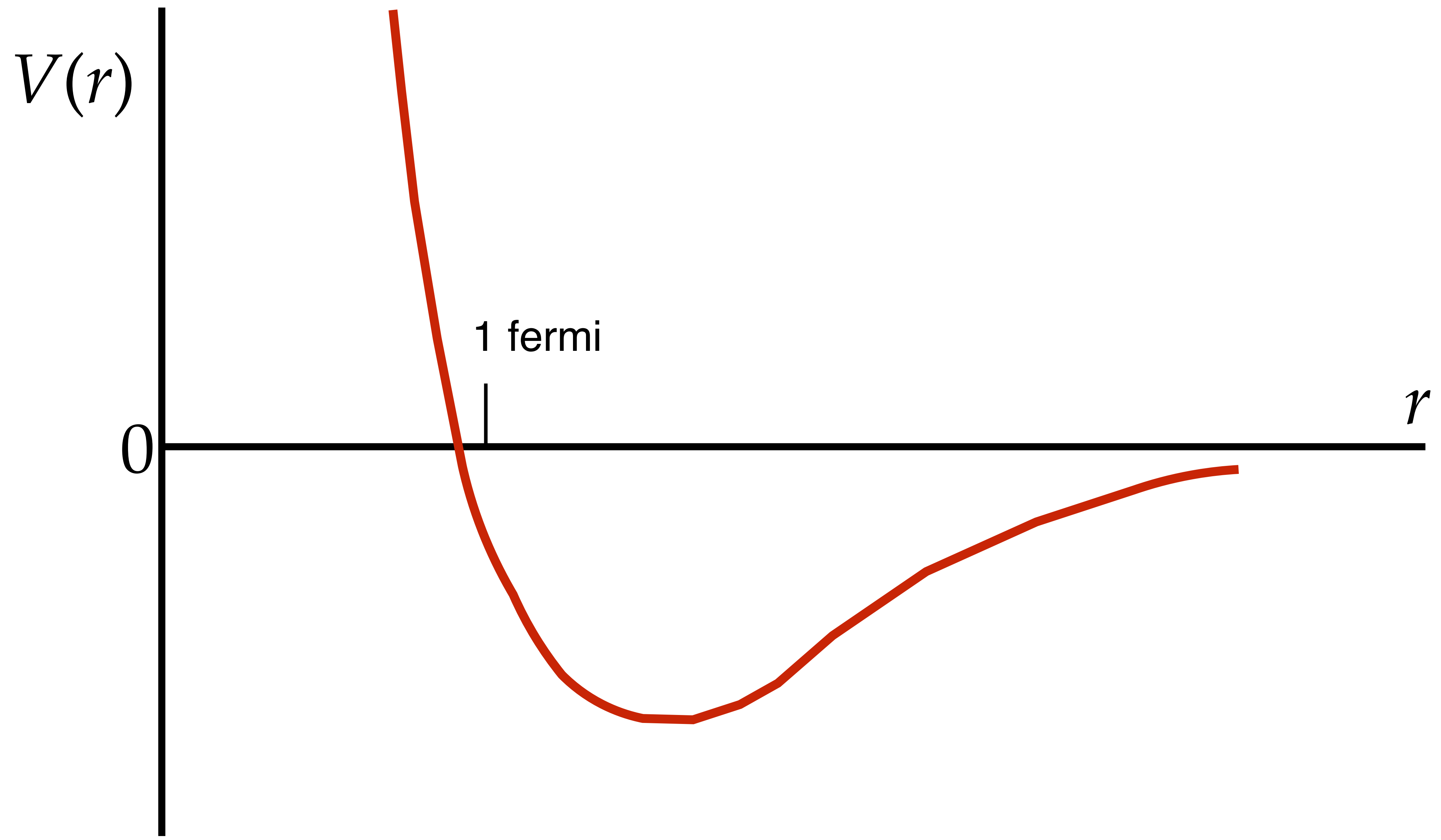
$$\mu_n = \mu_p + \mu_e$$

$$\mu = \sqrt{p_\mathrm{F}^2 c^2 + m^2 c^4}$$

The neutron-rich matter produces pressure via

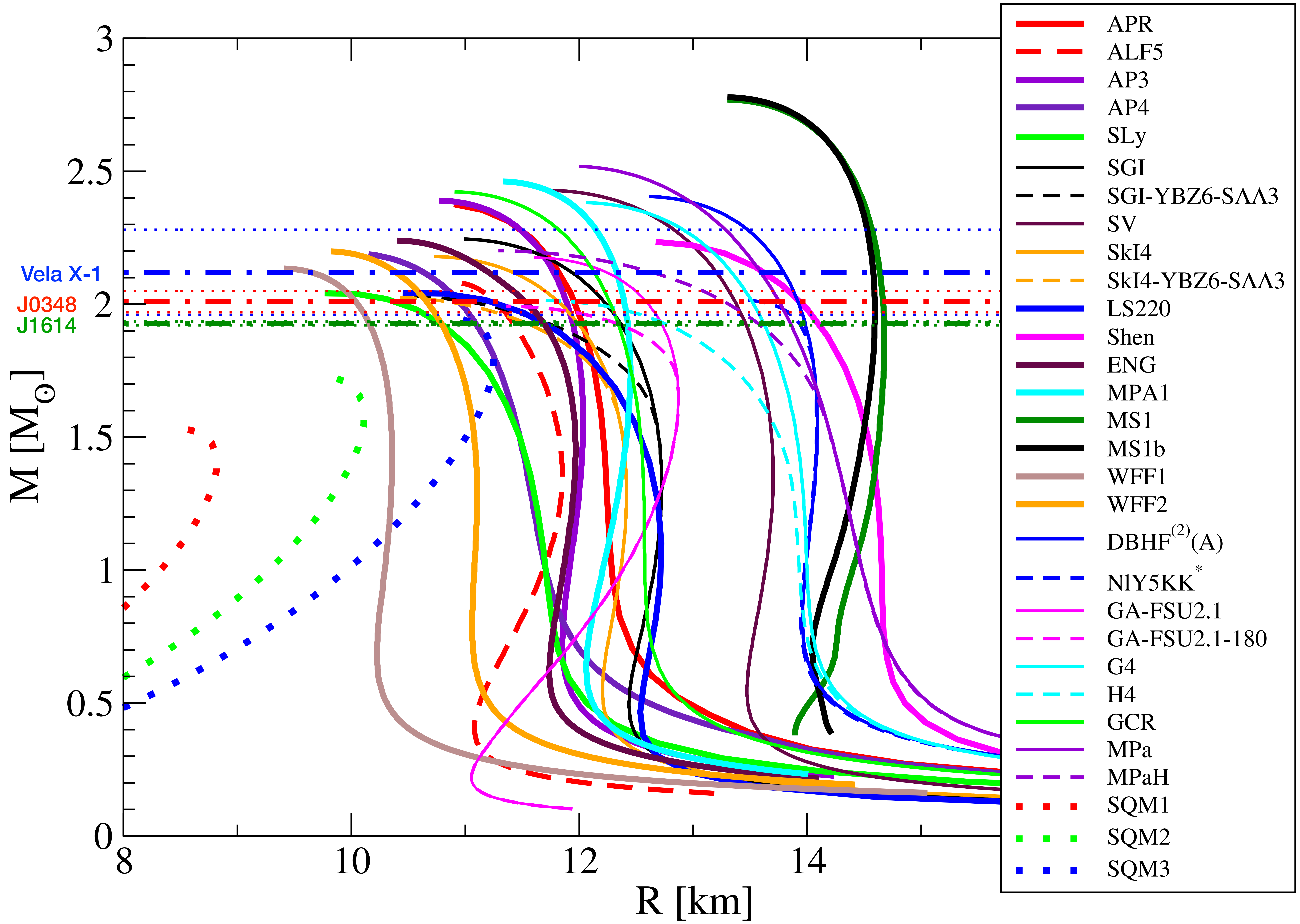
- Neutron degeneracy

- Repulsive strong interaction



At inter-nucleon distance below 1 fermi, strong interaction is repulsive, thus resists gravity.

Nature of the repulsive strong interaction not yet known in detail. This leads to uncertainty in Pressure-Density relation (Equation of State)



Yagi & Yunes 2017

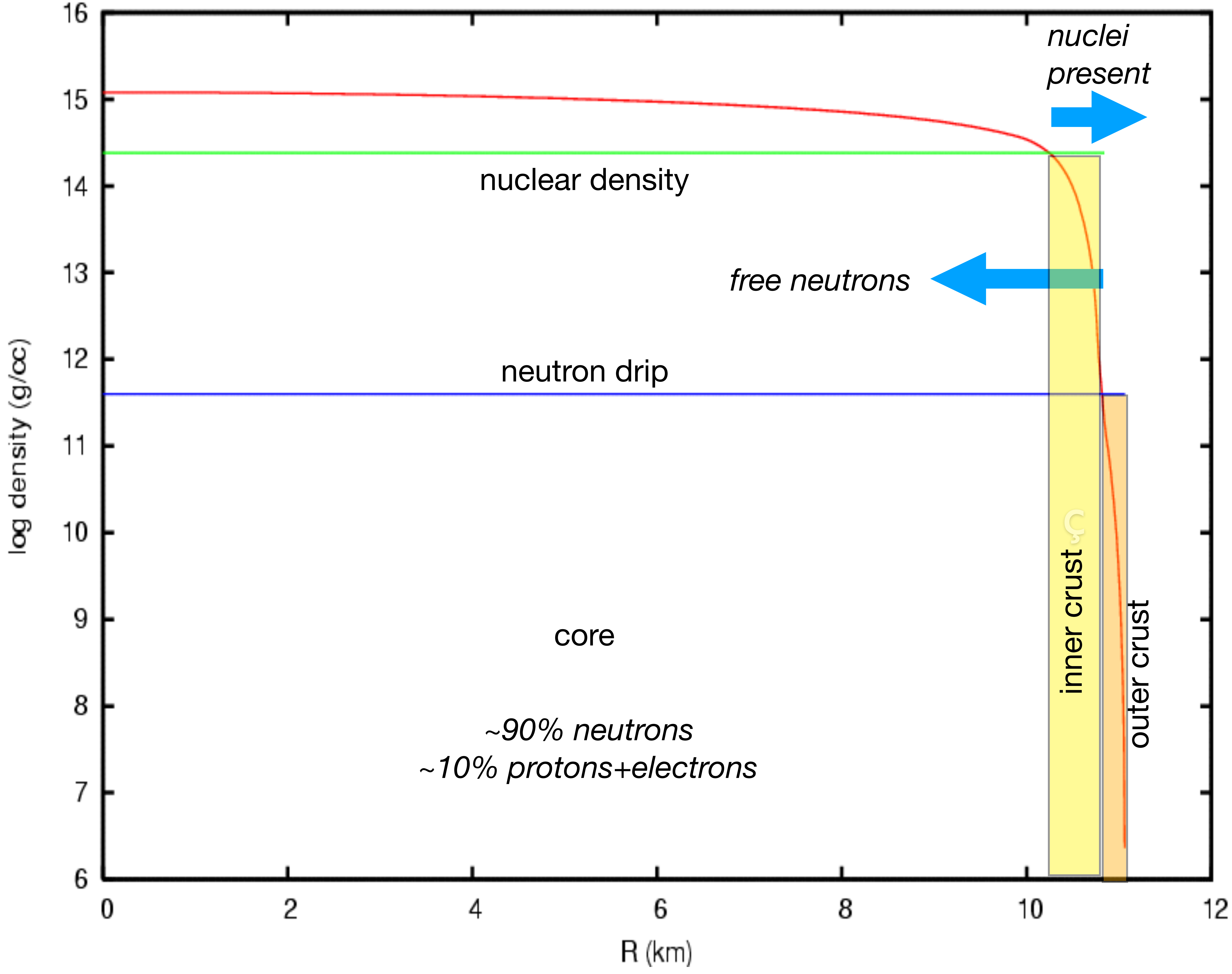
Current knowledge of nuclear forces is inadequate to accurately predict the pressure-density relation (Equation Of State) at very high density.

Leads to uncertainty in neutron star Mass-Radius relation

Measurement of NS mass, radius can thus unveil the fundamental physics involved

Pulsar timing a key technique for NS mass measurement

Neutron Star Density Profile in a typical EoS



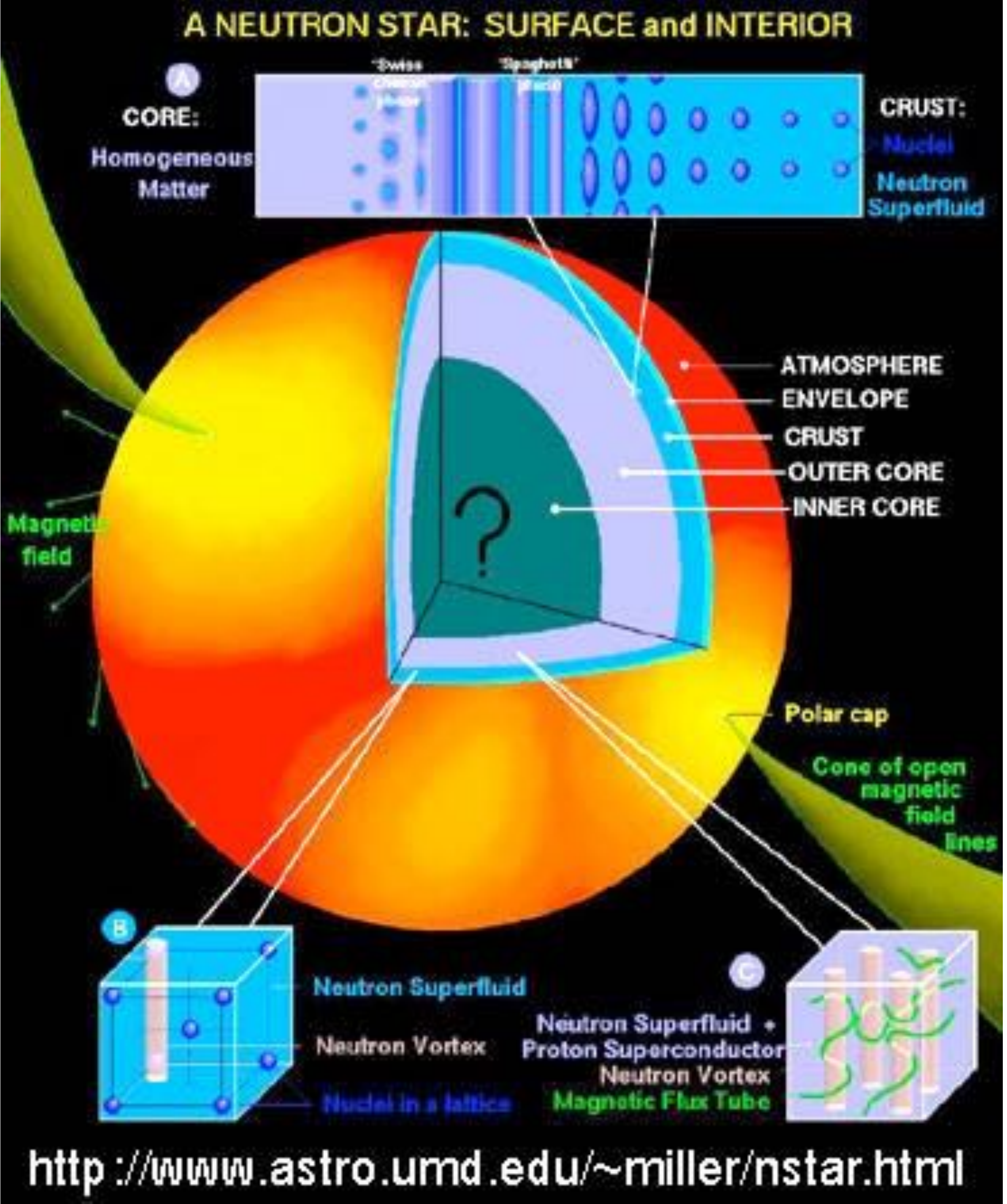
Mass ~ 1.4 M_{sun}

Radius ~ 10 km

Sun squeezed into a city

Gravity ~10^{11} times Earth's

Tidal force on a "human" ~10^9 kg



In Neutron Star interior, free neutrons form a superfluid

and the protons form a superconductor

These are the highest T_c superconductor/superfluid known in nature. Cooper pairs are formed due to strong interaction. $T_c \sim 10^{8-10}$ K

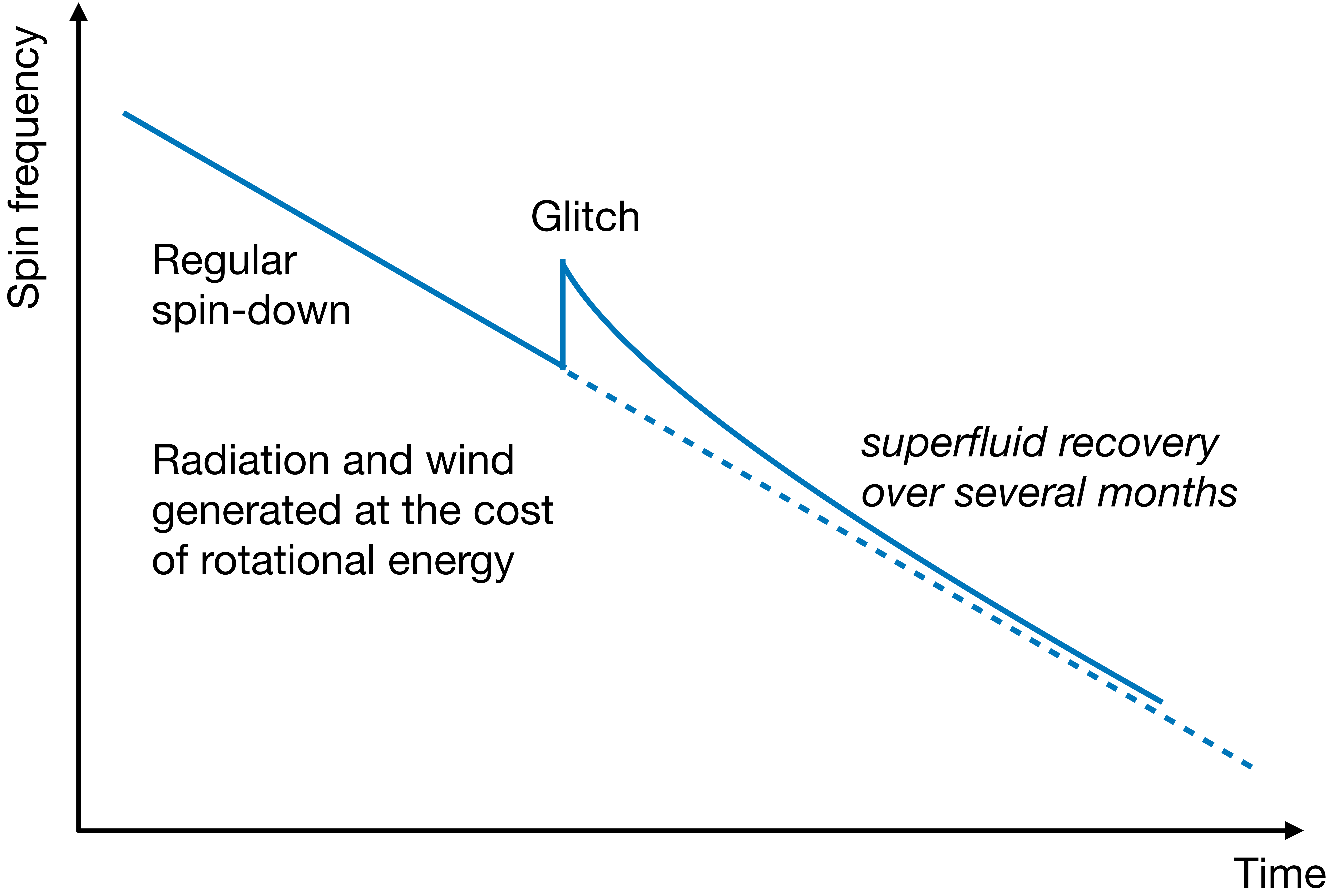
Neutron stars rotate fast (P ~ ms - min) and have strong magnetic fields (Teragauss)

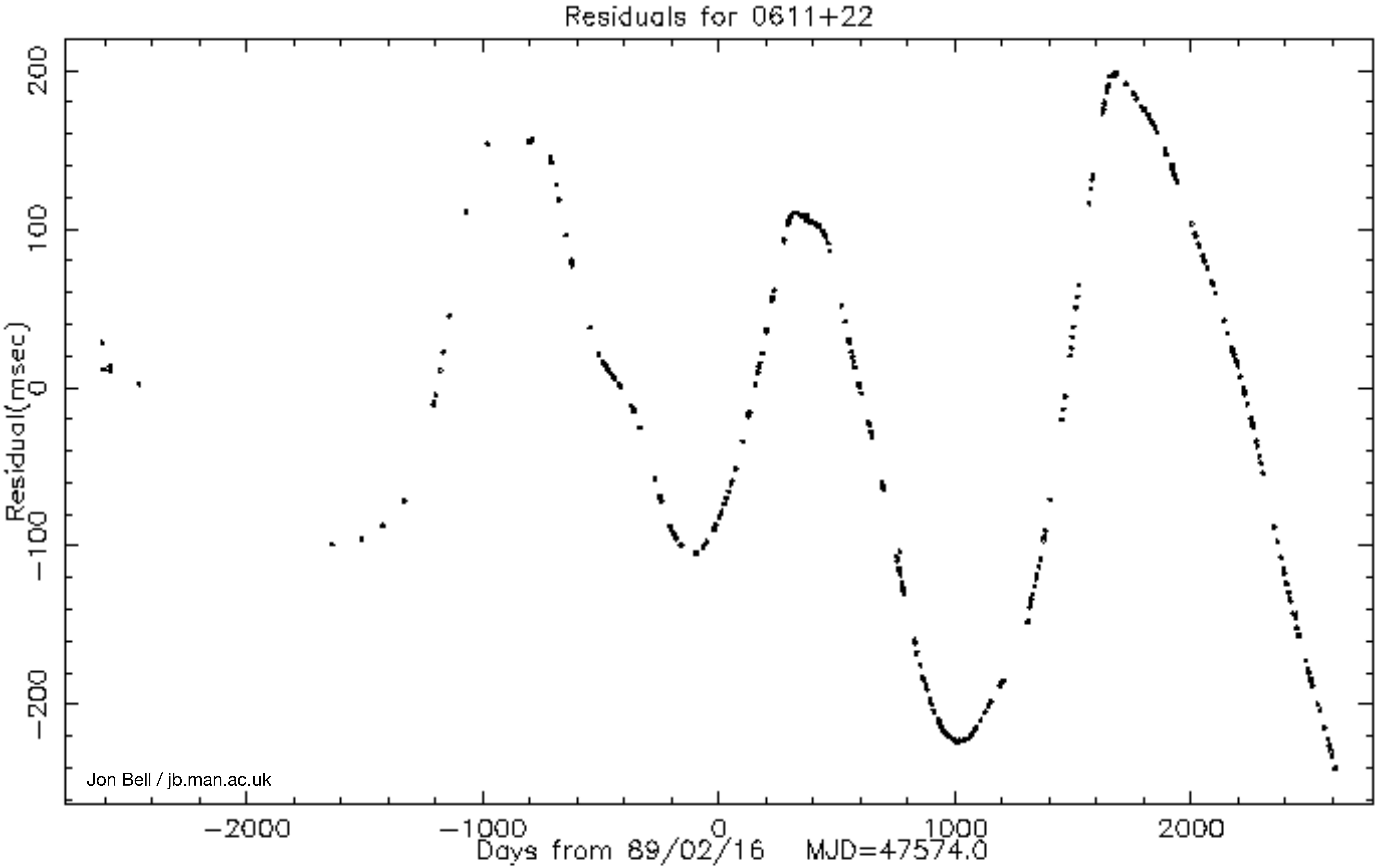
Quantized Vortices carry rotation through the Superfluid, fluxoids carry magnetic field through the Superconductor

Dynamics of superfluid vortices show up in Pulsar timing: Glitches and Glitch recovery

Pulsar Spin Evolution

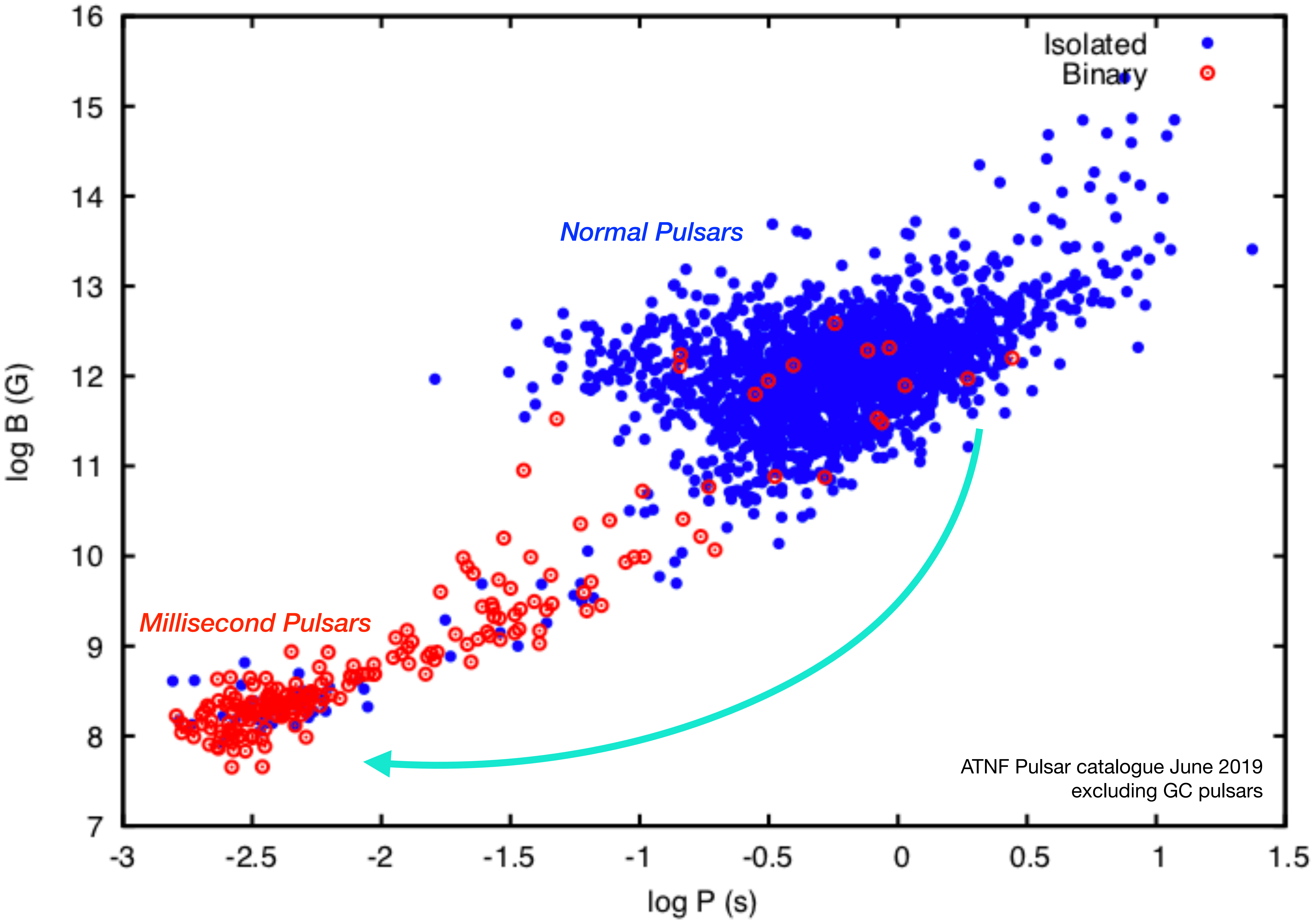
Evidence of interior superfluid





Apart from glitches, random wanderings of pulse arrival time indicate jitter in spin period

This is called ***Timing Noise***



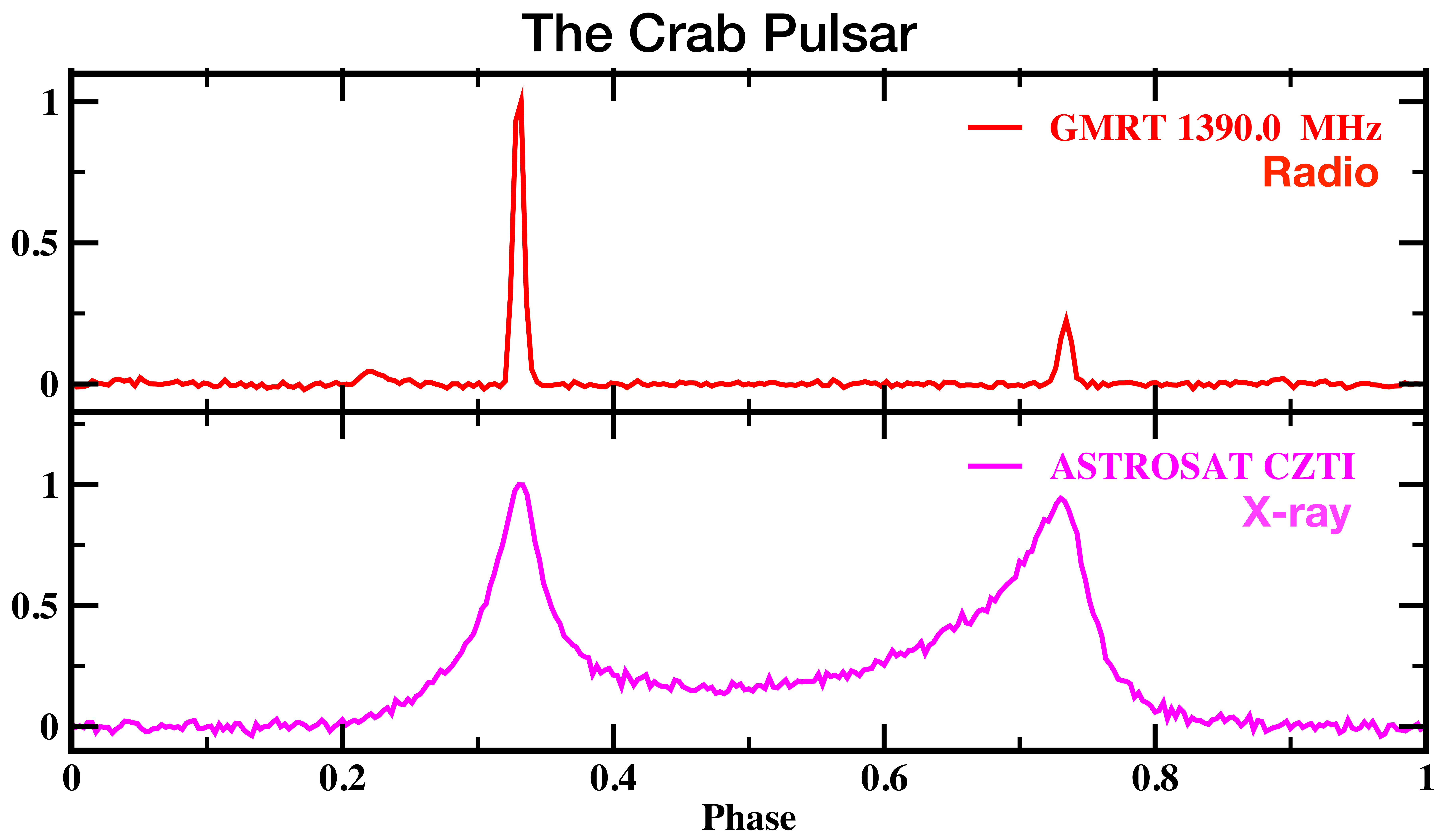
Spin period P and spin-down rate $\dot{P}$ measured by pulsar timing can be used to estimate the magnetic field strength assuming dipole torque

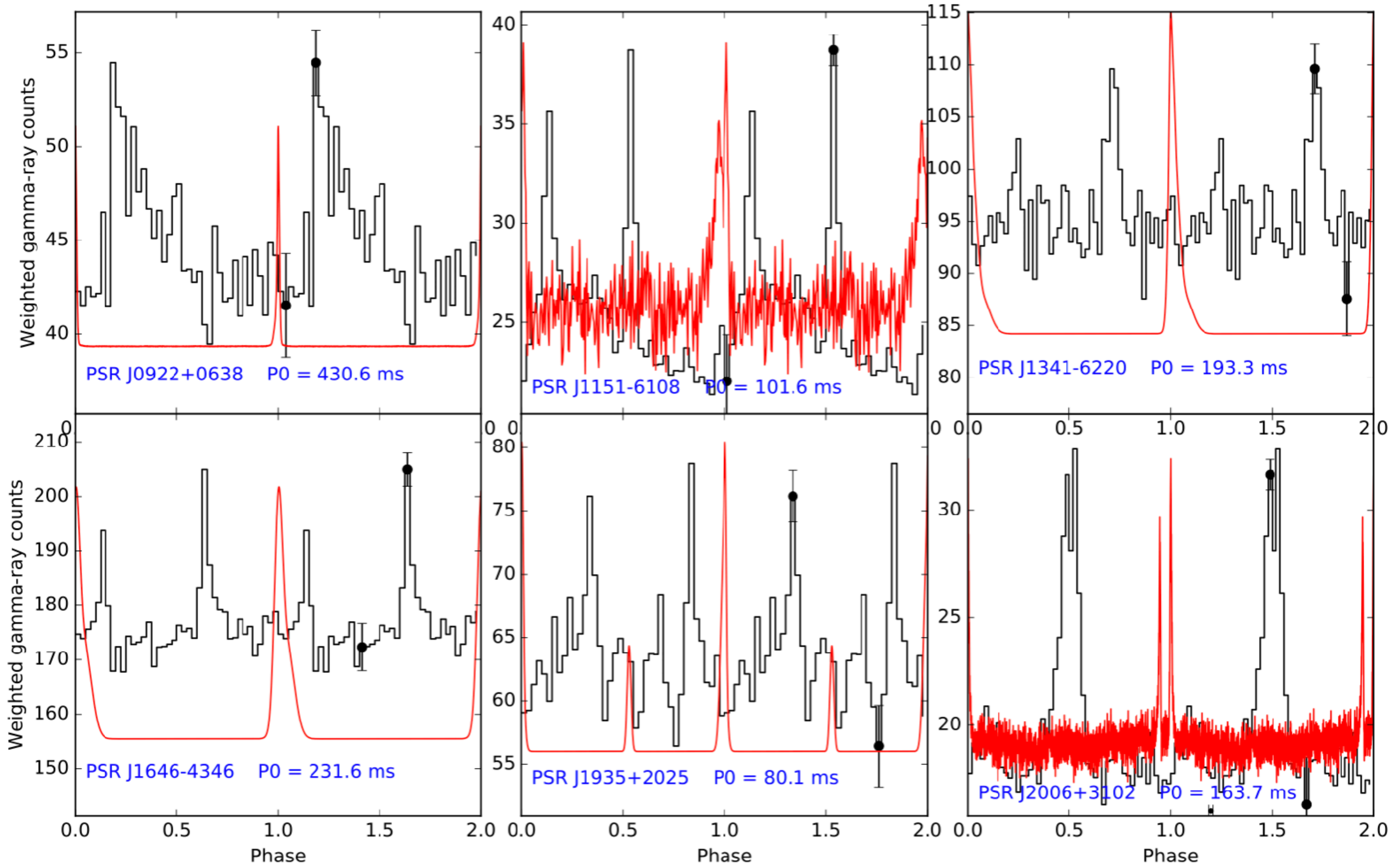
$$B_{12} \approx \sqrt{P\dot{P}_{-15}}$$

Magnetic field strength appears to reduce by processing in a binary system

Accretion in a binary also spins up the neutron star

Pulsar Emission





Smith et al 2017

Radio and High Energy emission typically originate in different regions

Coherent emission in Radio, Incoherent in High Energy

Most of the radiative luminosity emerges at High Energy. Radio carries a very small fraction

A Radiation Primer

An accelerated charge emits radiation: Power $P = \frac{2}{3c^3} q^2 a_0^2$; $a_0^2 = \gamma^4(|a_\perp|^2 + \gamma^2 a_\parallel^2)$; $\gamma = (1 - v^2/c^2)^{-1}$

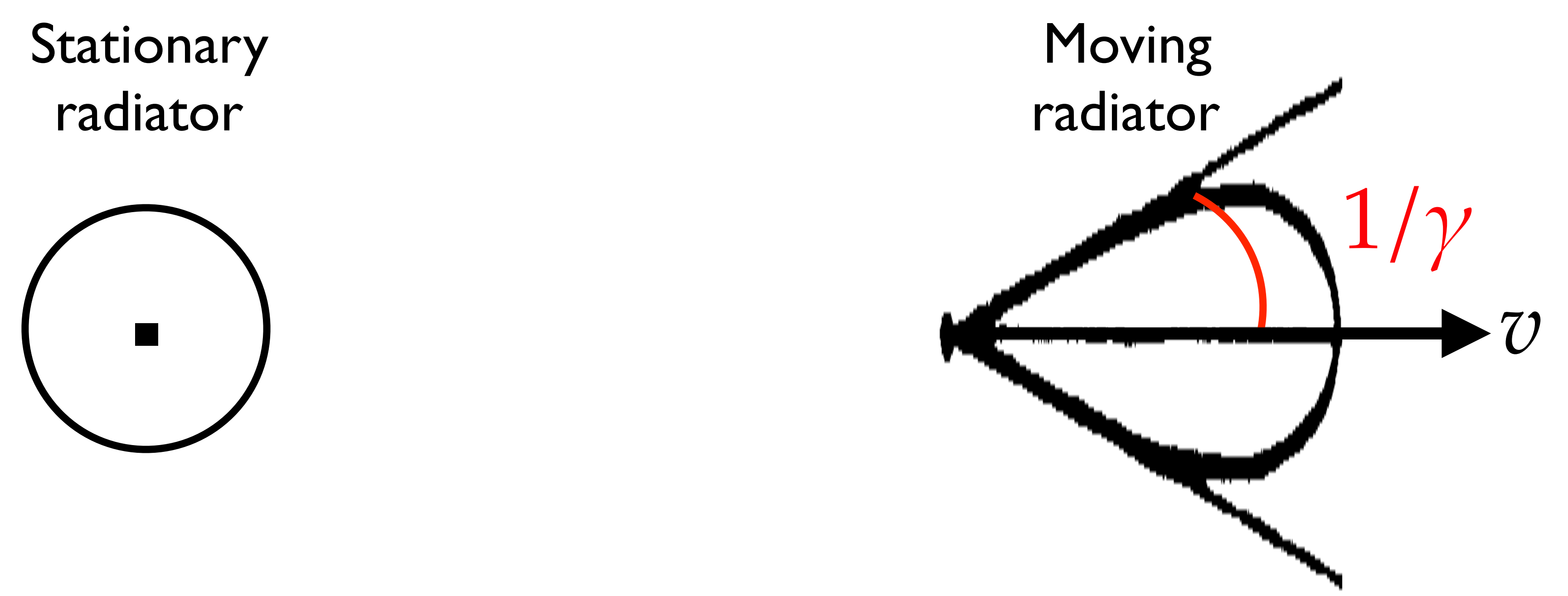
For N charges:

Incoherent emission: $P \rightarrow NP$

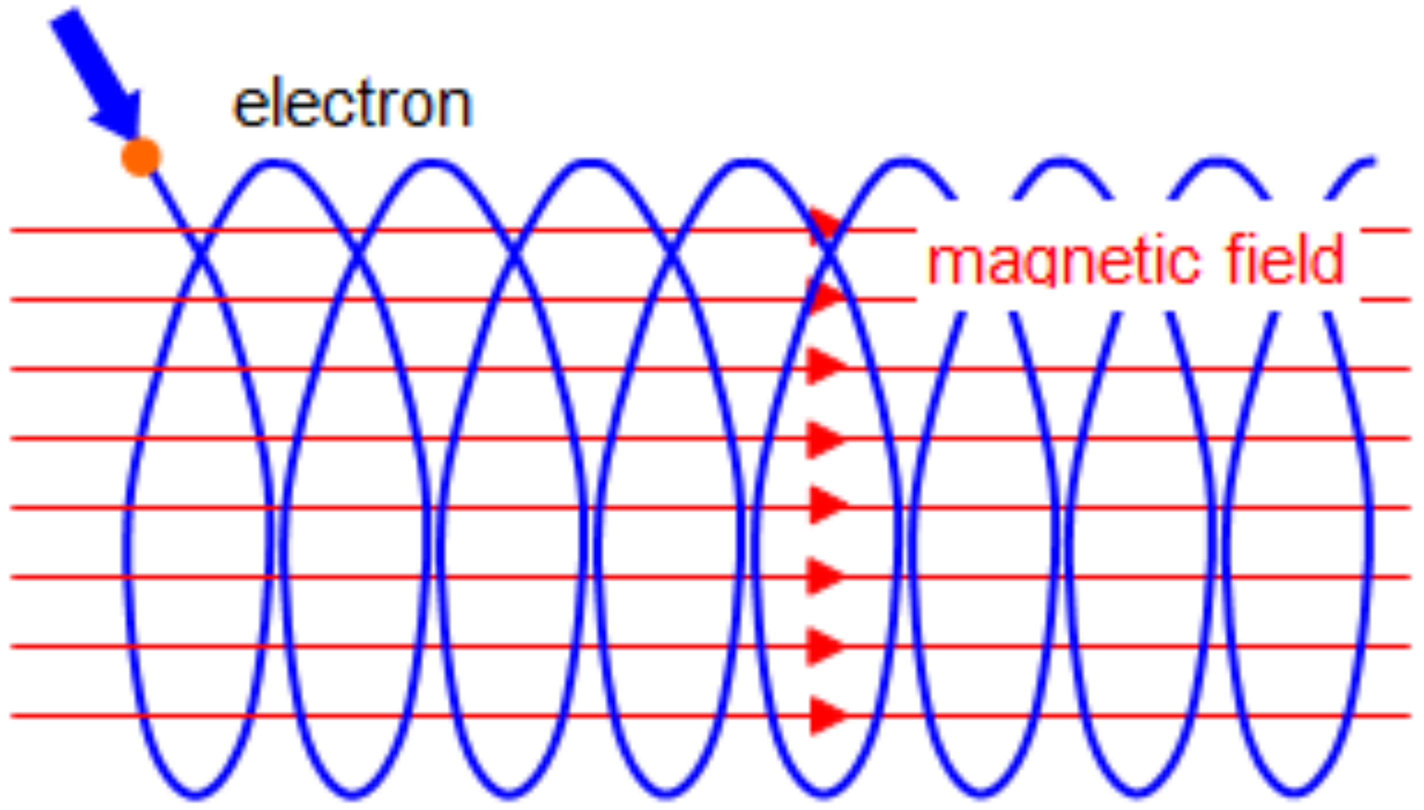
Coherent emission: $q \rightarrow Nq$
hence $P \rightarrow N^2 P$
requires bunching in a scale $\ll \lambda$

Polarisation $\vec{E} \propto \hat{n} \times [(\hat{n} - \vec{\beta}) \times \dot{\vec{\beta}}]$

Beaming



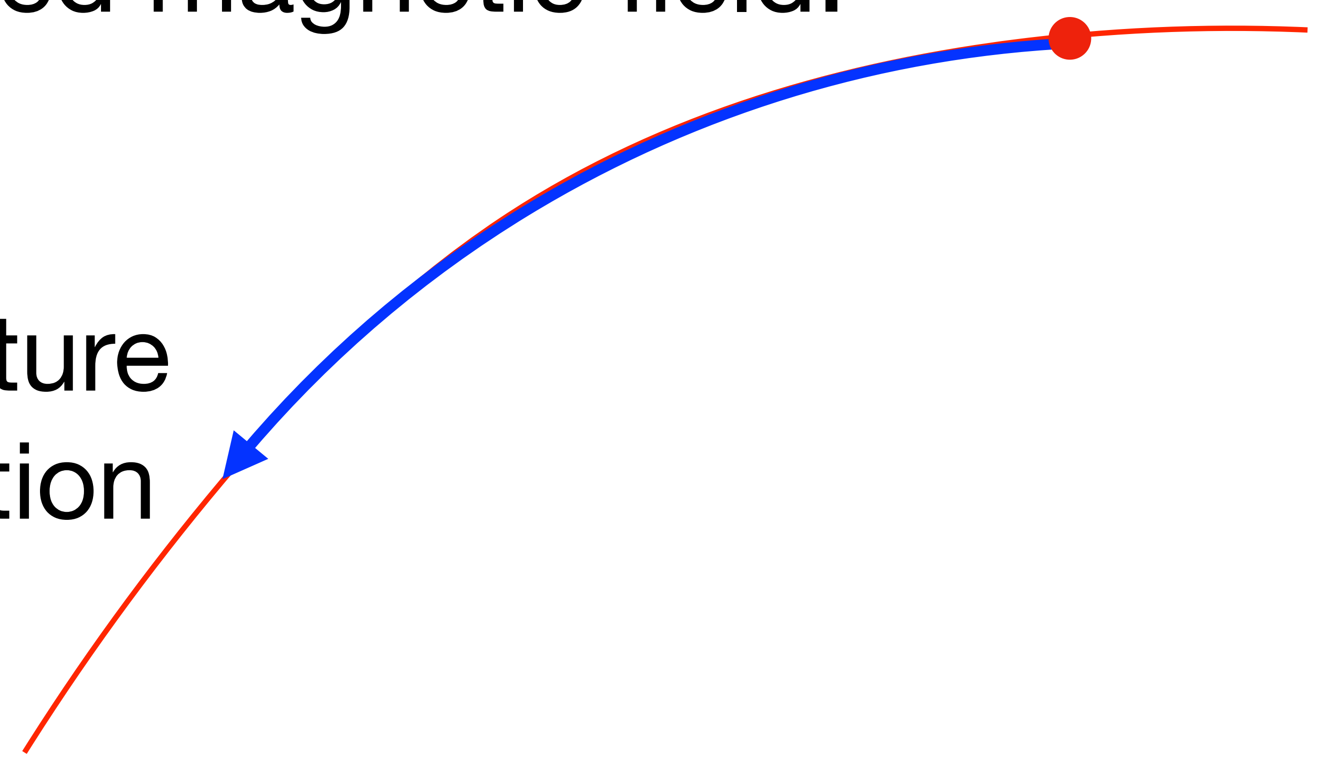
Relativistic electron gyrating in a magnetic field:



schoolphysics.co.uk

Synchrotron Radiation

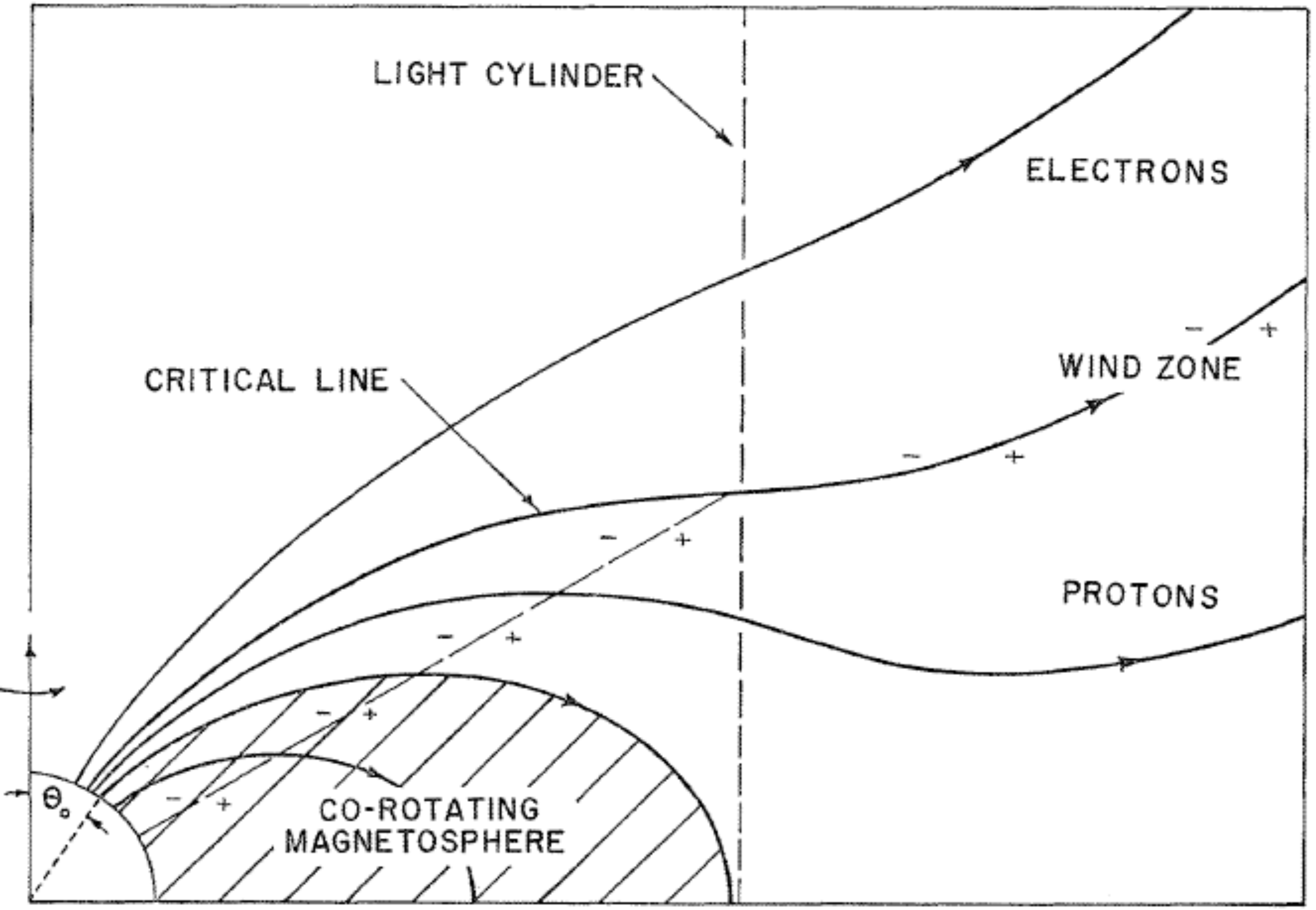
Relativistic electron following a curved magnetic field:



Curvature Radiation

The Pulsar Magnetosphere

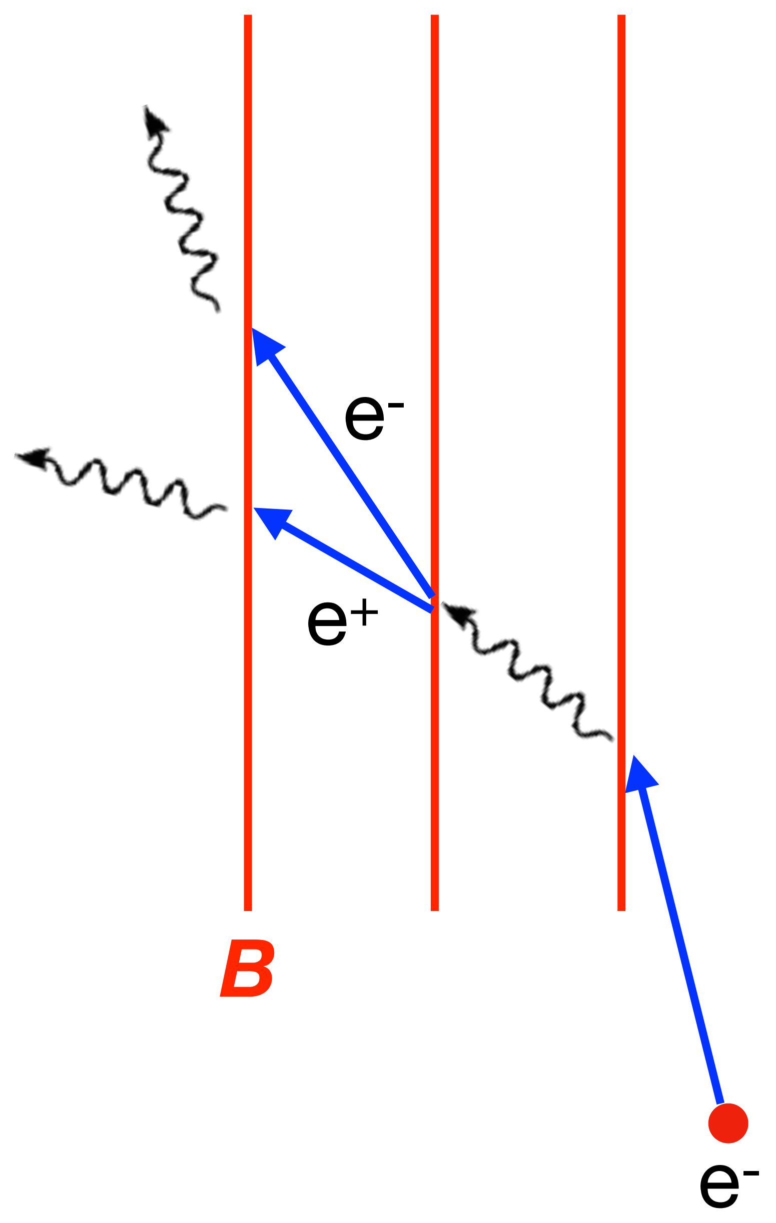
Basic concepts: Goldreich & Julian 1969



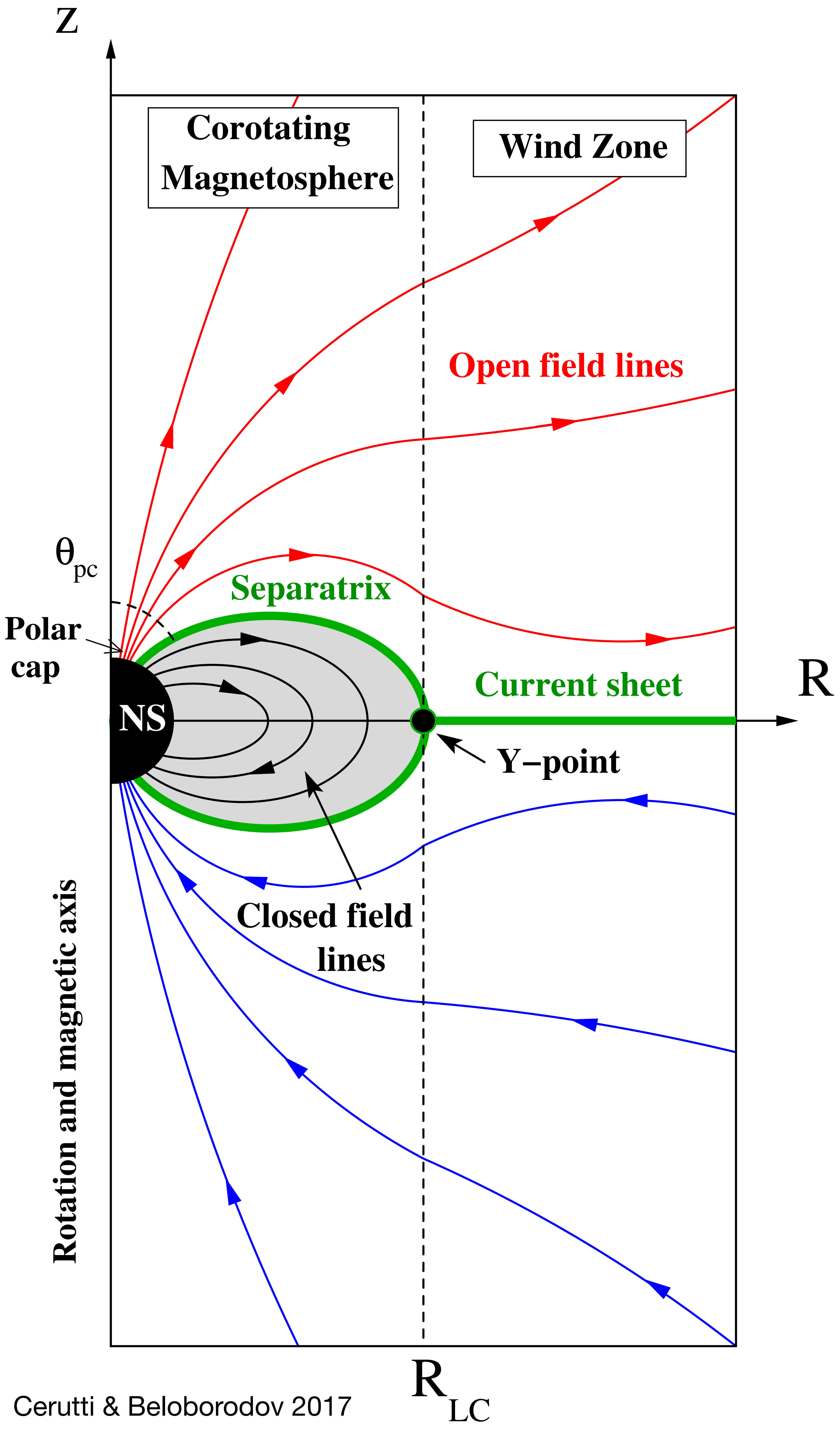
Plasma on open field lines cannot co-rotate. Current flows out along these lines, creates toroidal mag. field which provides the dipole spin-down torque.

- A vacuum exterior would have potential drop exceeding 10^{15} V
- Space charge must exist, $\boldsymbol{E}\cdot\boldsymbol{B}=0$
- Co-rotating magnetosphere can be maintained up to the light cylinder, $\rho \simeq -\boldsymbol{\Omega}\cdot\boldsymbol{B}/2\pi c$
- With pair production, no. density of charged particles may far exceed ρ
- ρ passes through 0 and changes sign in the magnetosphere

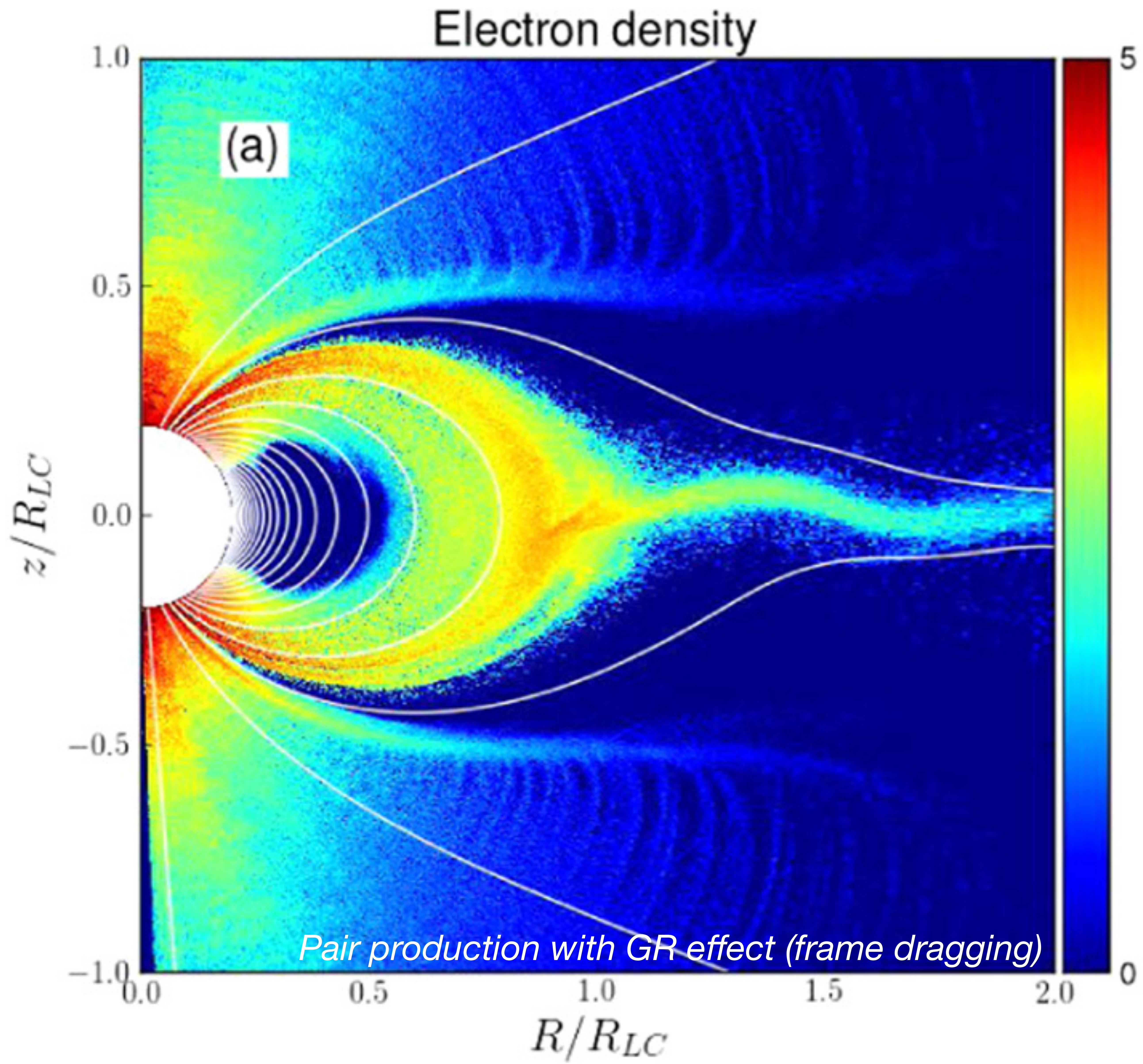
Pair Cascade



Charge bunching likely due to beam-plasma instability (primary particles moving through the secondary plasma)

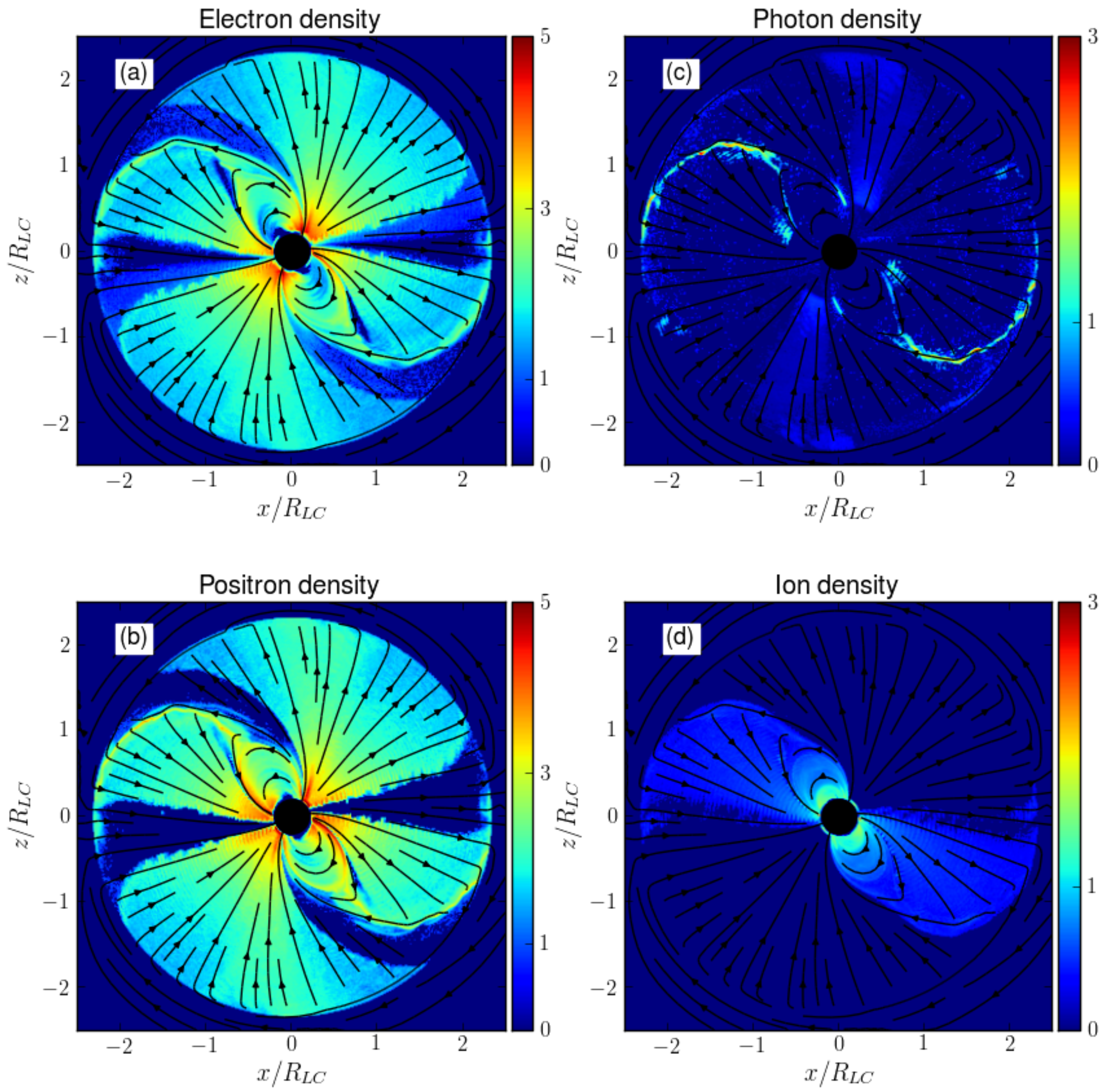


Cerutti & Beloborodov 2017



Philippov et al 2015

GR-induced pair production



Inclination

60°

Philippov & Spitkovsky 2017

Coherent Emission at Radio wavelengths

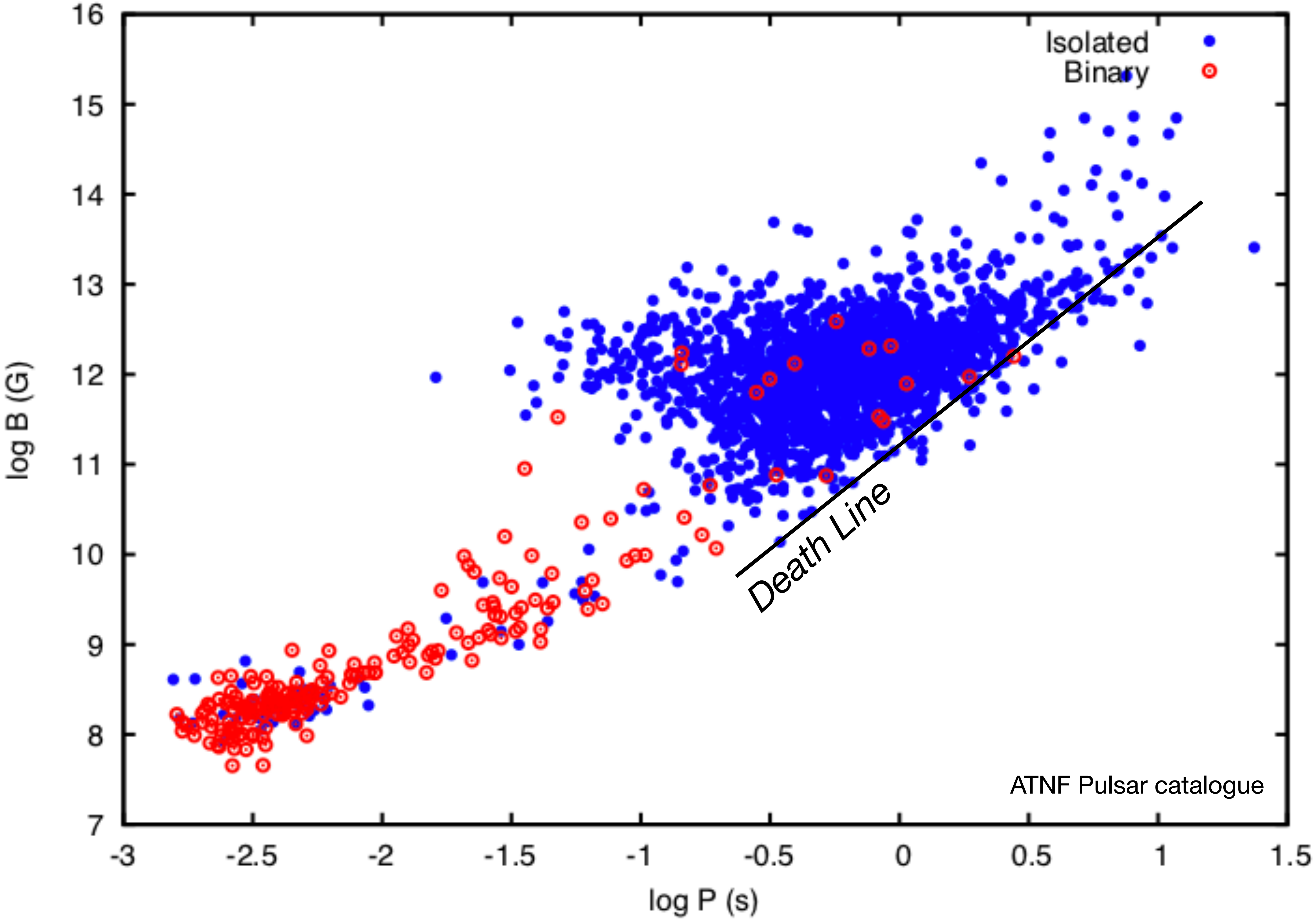
Ruderman and Sutherland (1975) model

- Charge bunching at sub-wavelength scale
- Active pair production at Polar Cap
- Bunch dynamics in local E, B fields

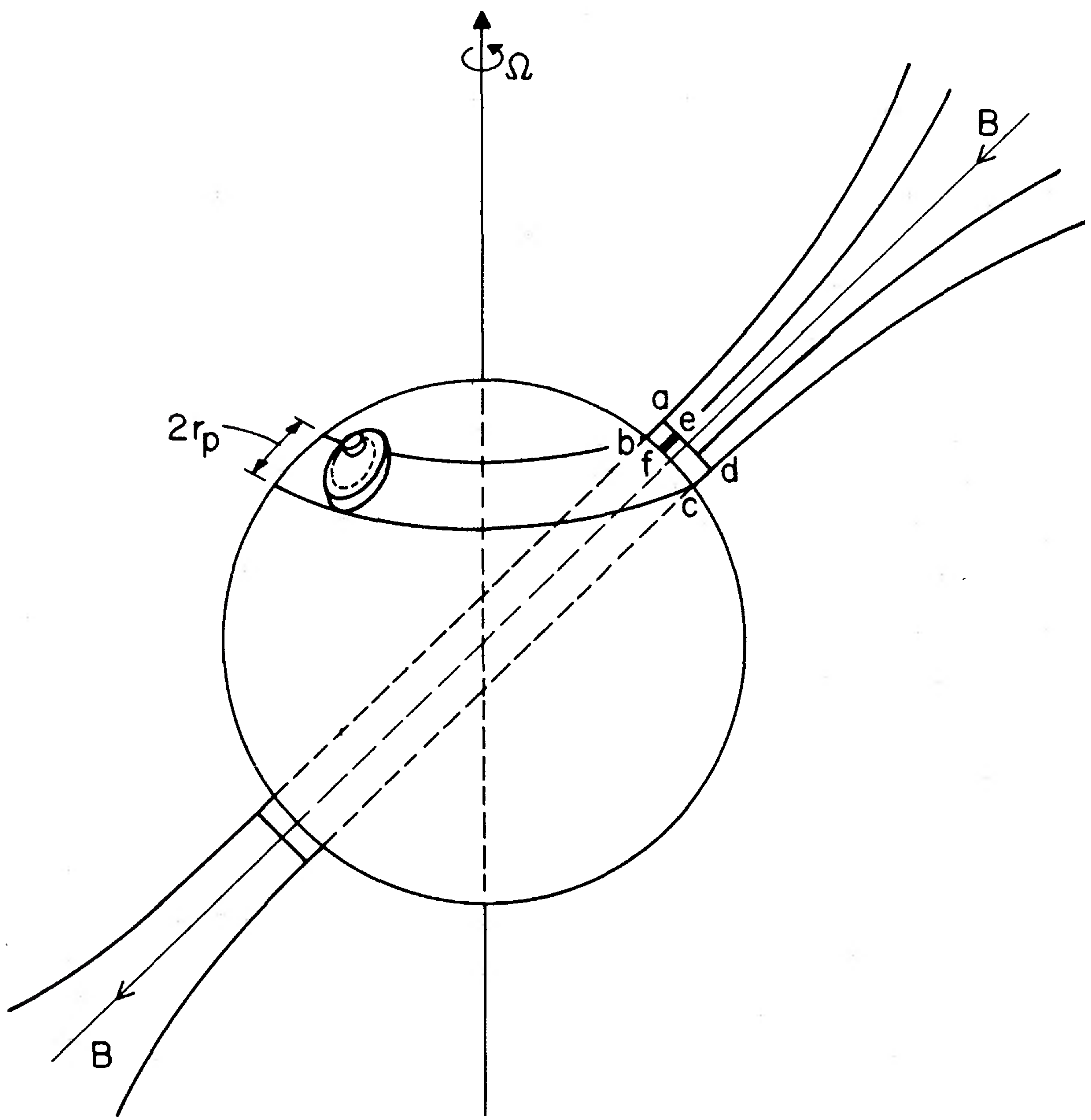
pair sustenance:

$$P_{\rm crit} = 1.7 B_{12}{}^{8/13} R_6{}^{21/13} \rho_6{}^{-4/13} (15\chi)^{-2/3} \ {\rm s}$$

$$\chi \equiv \frac{\hbar\omega}{2mc^2}\frac{B_\perp e\hbar}{m^2c^3} \geqslant \frac{1}{15}$$

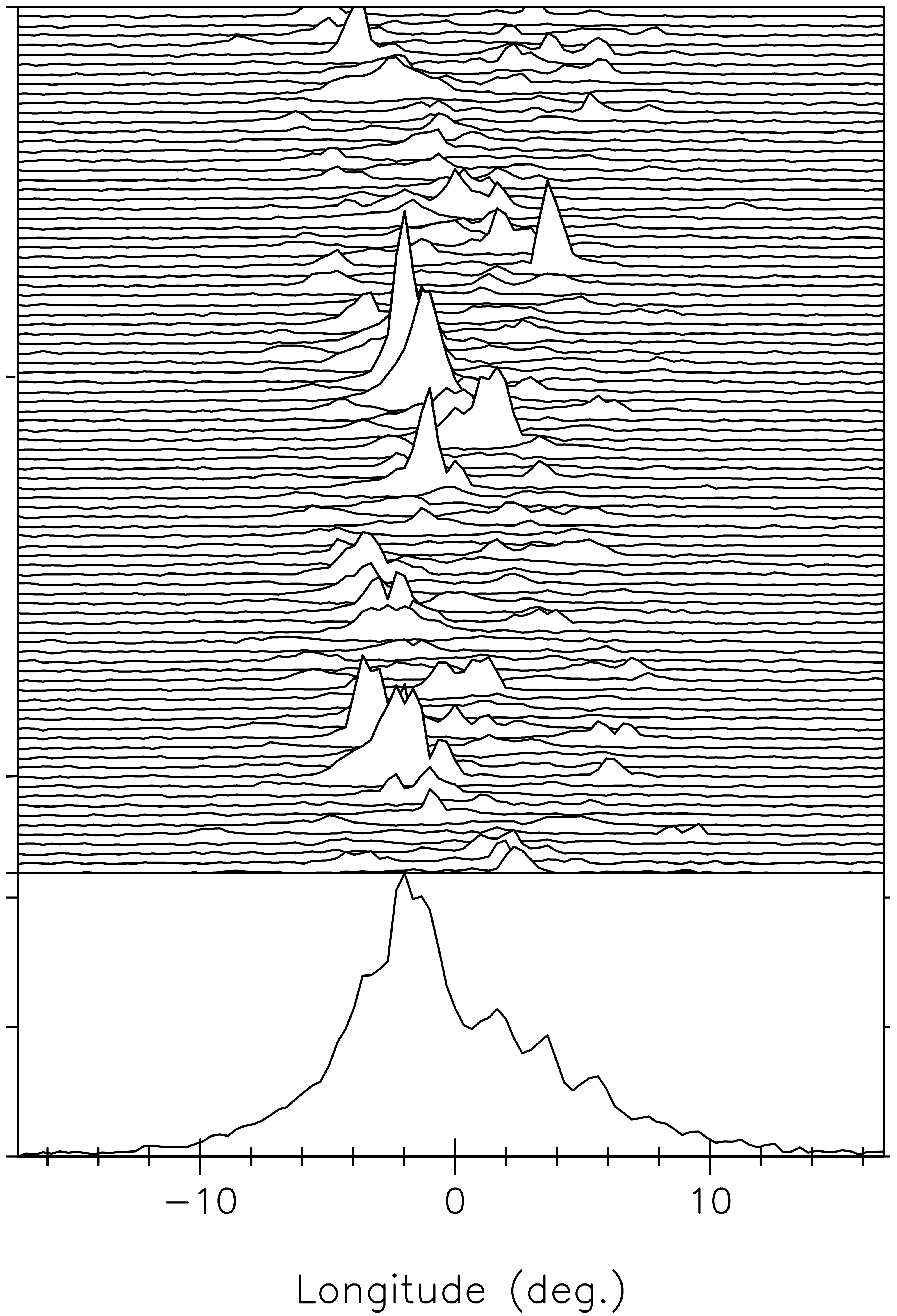


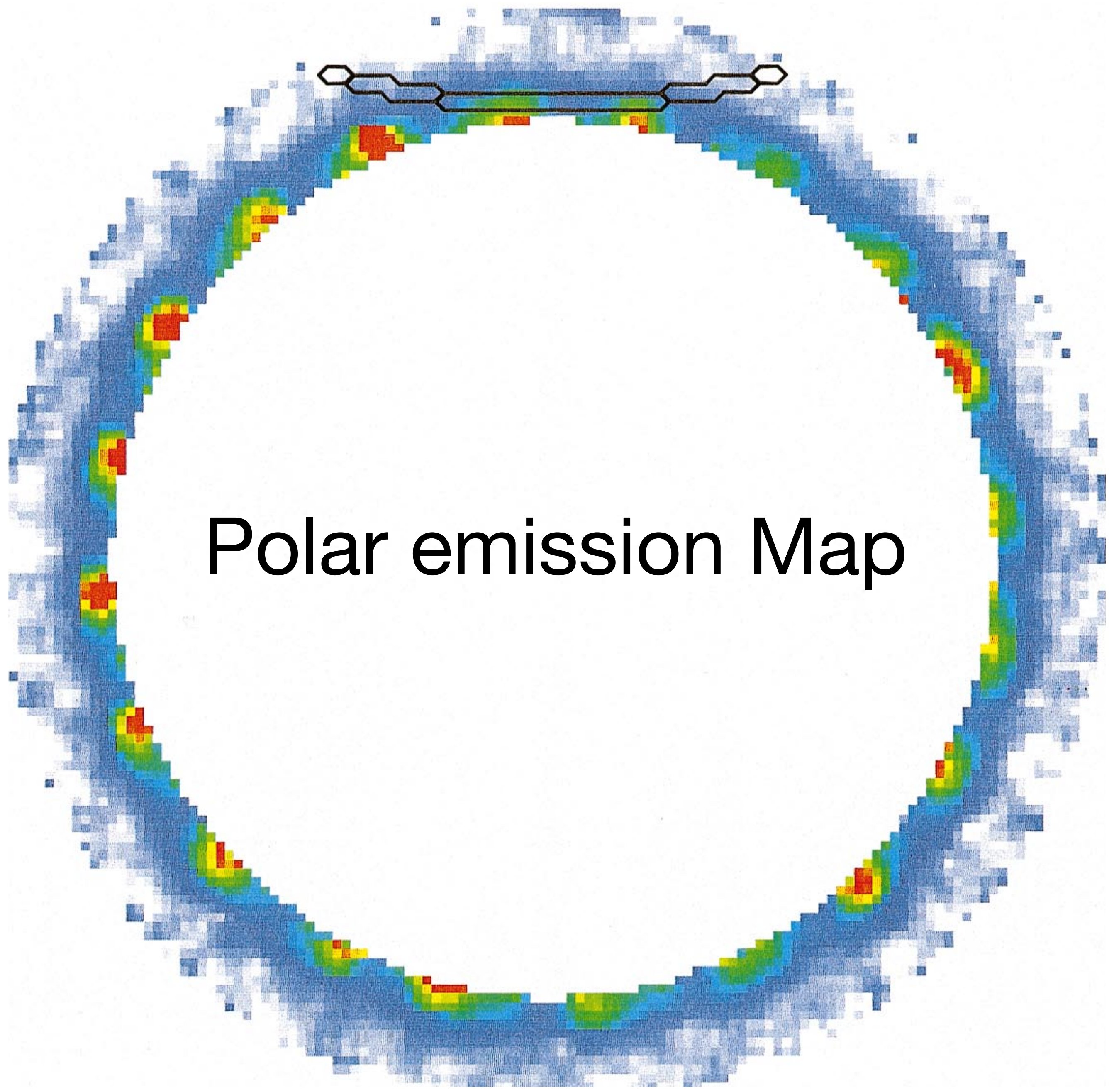
Charge bunches should rotate due to ***E*x*B*** drift



Ruderman & Sutherland 1975

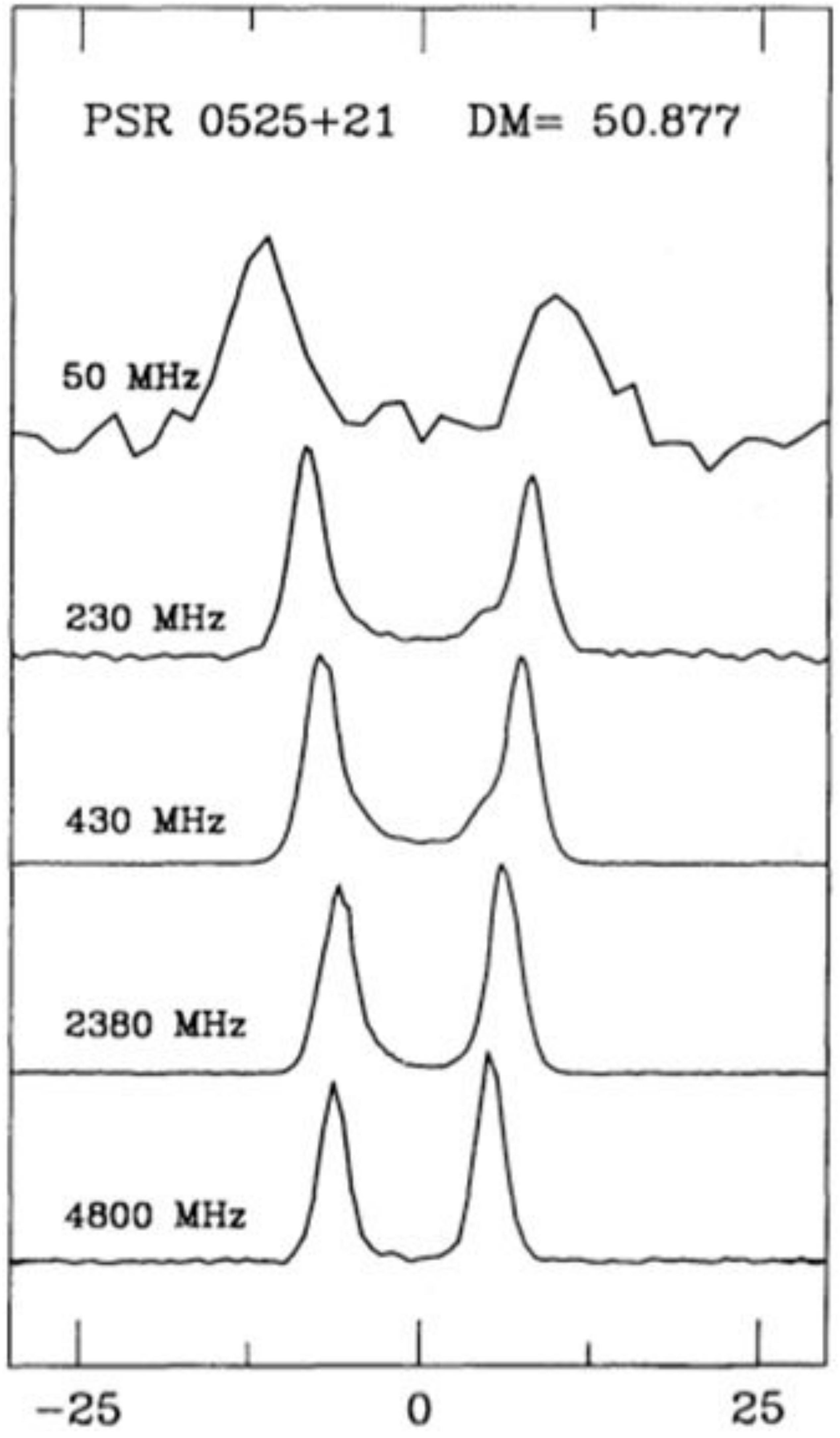
PSR 0943+10 drifting surpluses

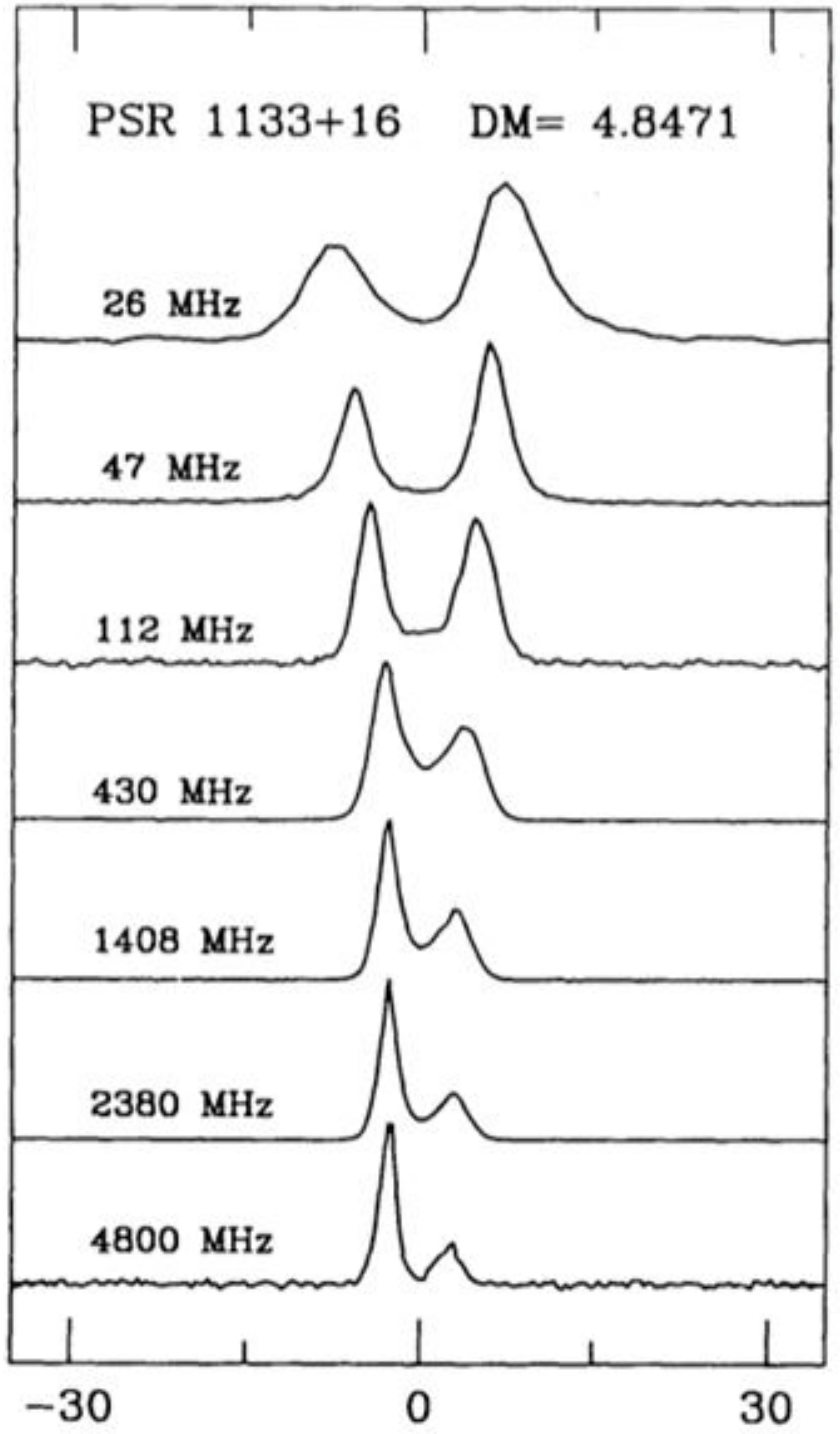




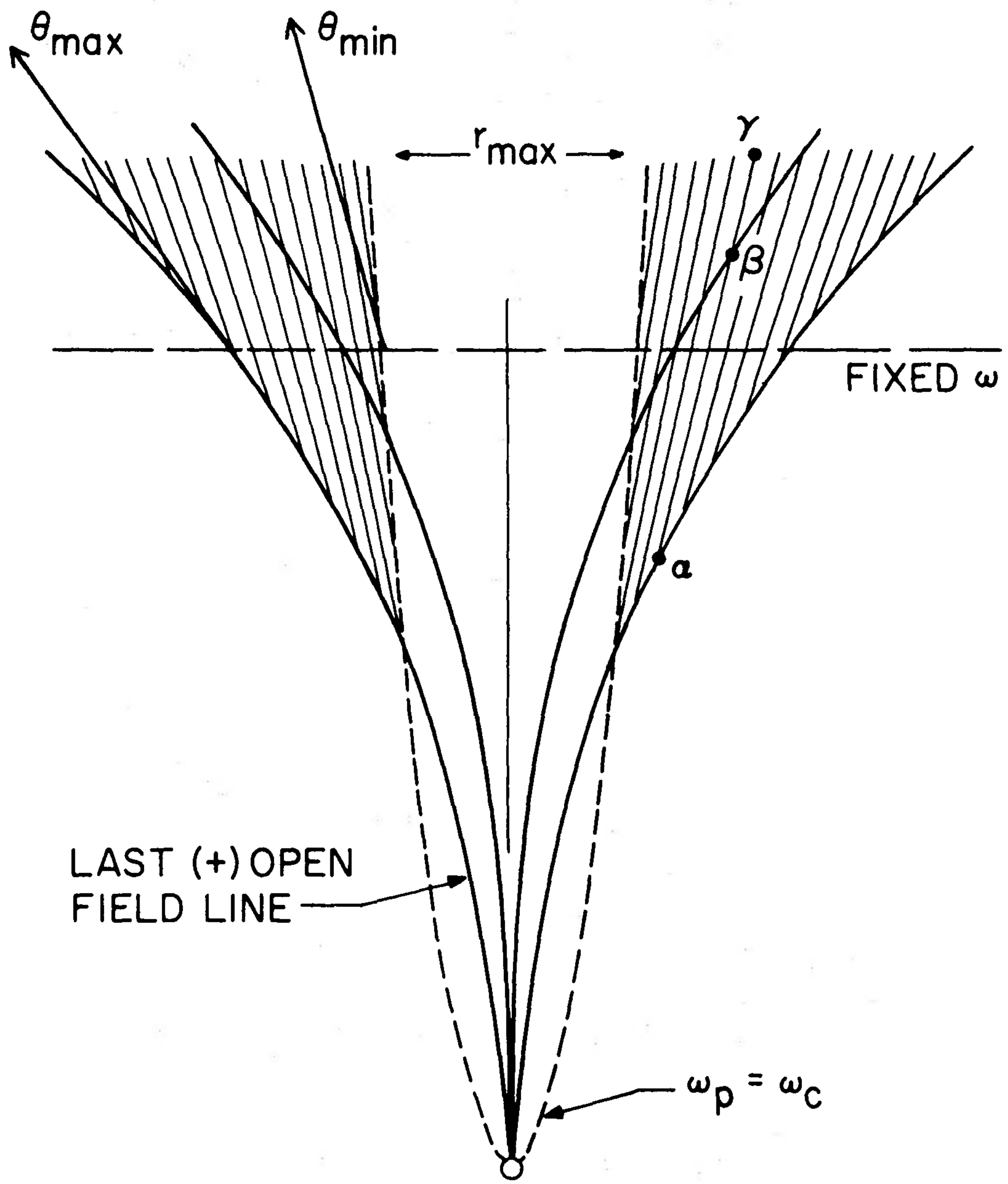
Deshpande & Rankin 1999

Radio pulse shape: radius-to-frequency mapping





R.N. Manchester

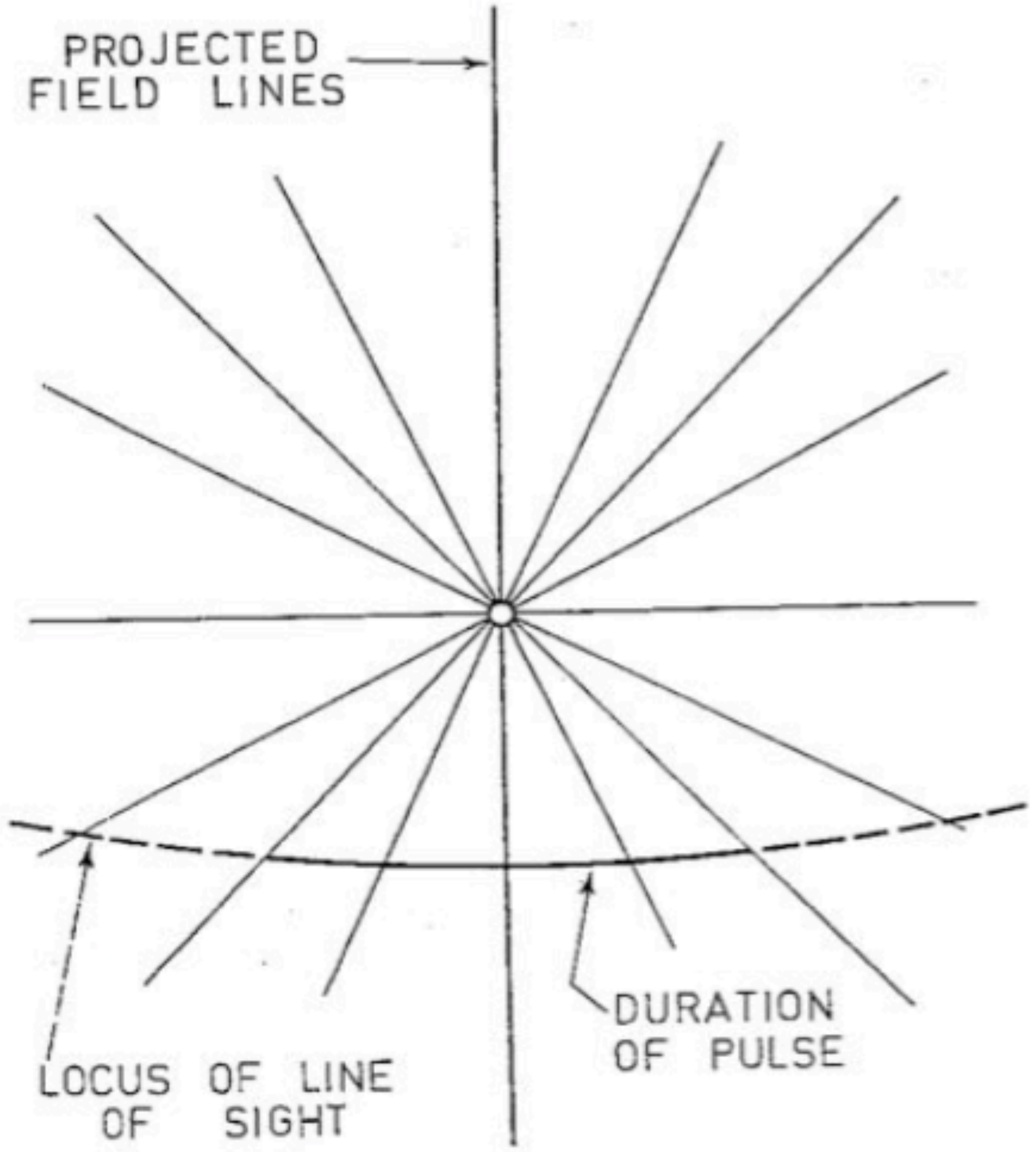


Ruderman & Sutherland 1975

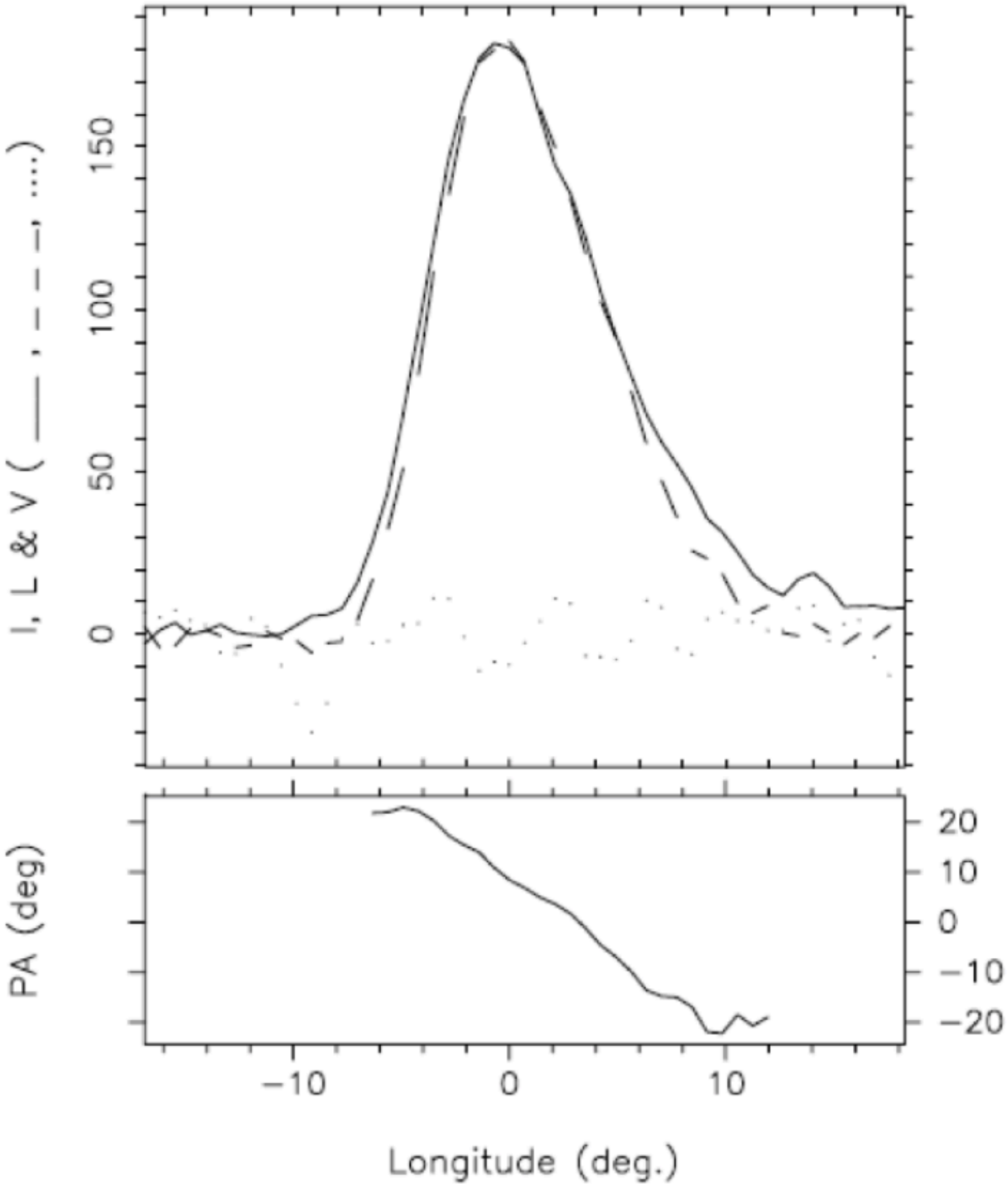
Polarization of pulsar radio emission

Strong linear polarization with S-pattern position-angle sweep:

curvature radiation, rotating vector model



Radhakrishnan & Cooke 1969



Ramkumar & Deshpande 2001

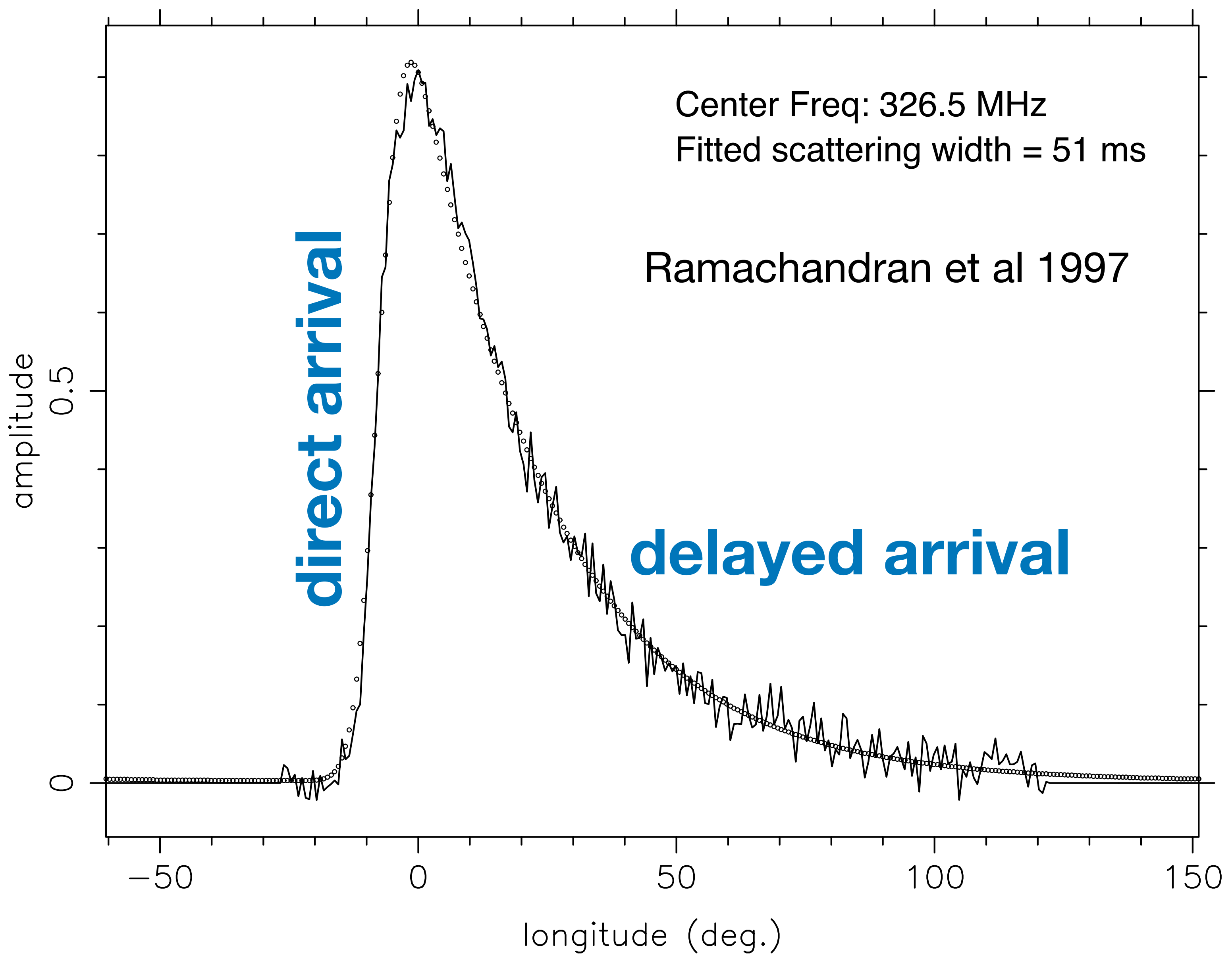
Propagation effects on pulsar signal

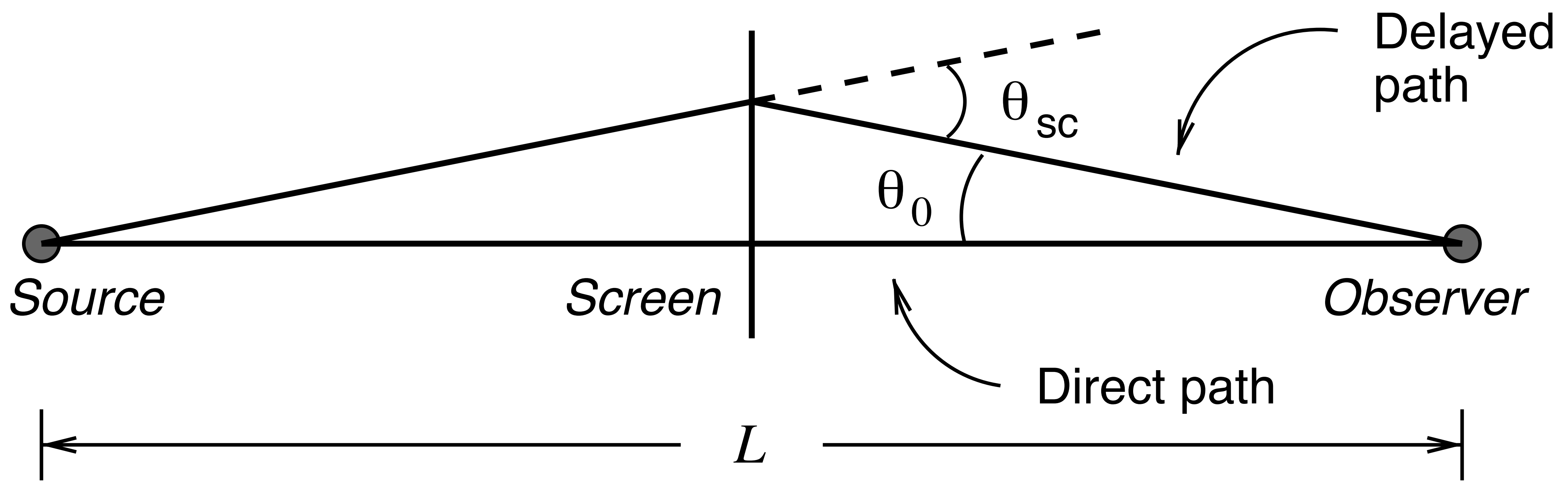
Dispersion $\frac{v_{ph}}{c} = \left(1 - \frac{\omega_p^2}{\omega^2}\right)^{-1/2}$ *frequency dependent propagation time*

$$DM = \int_0^L n_e dl$$

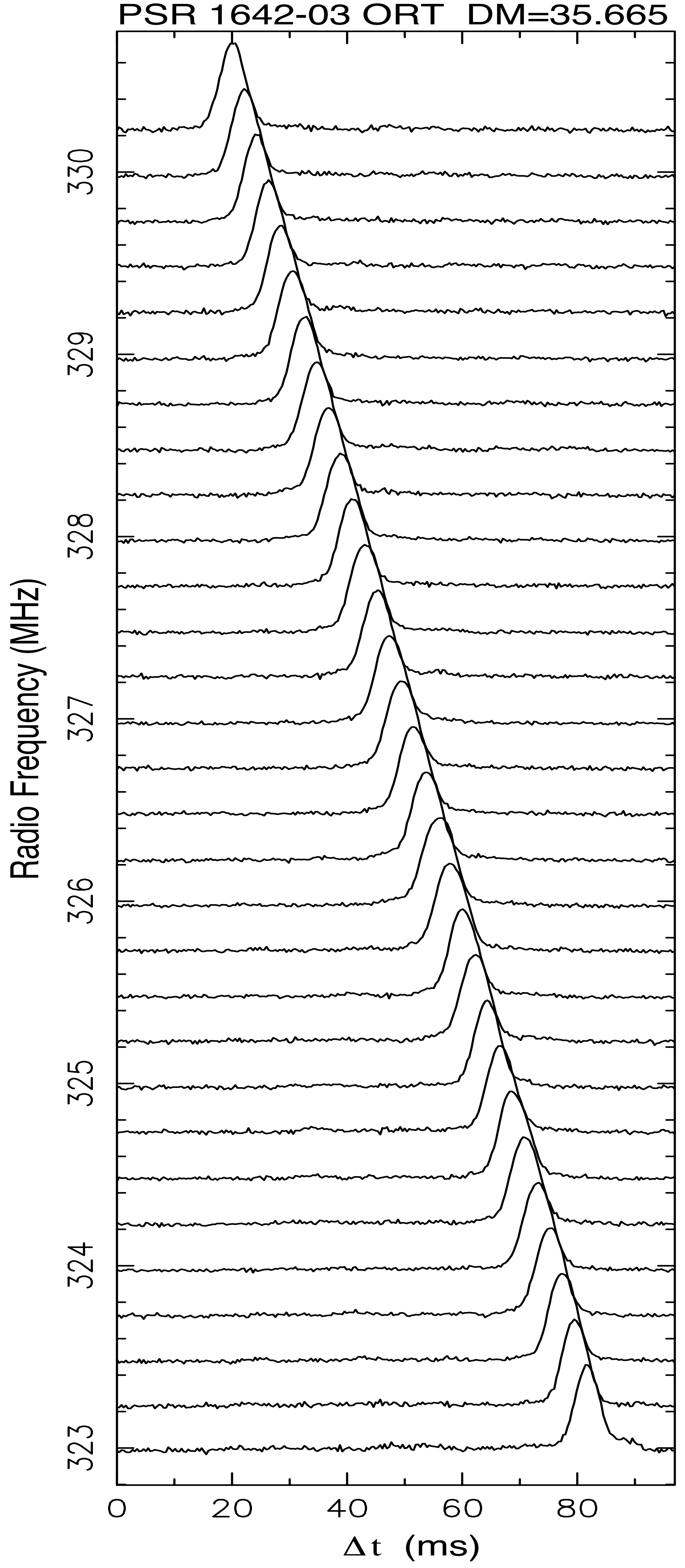
Dispersion Measure

Scattering





$$\tau_{scat} \propto (DM/\nu)^{4.4}$$ approx.



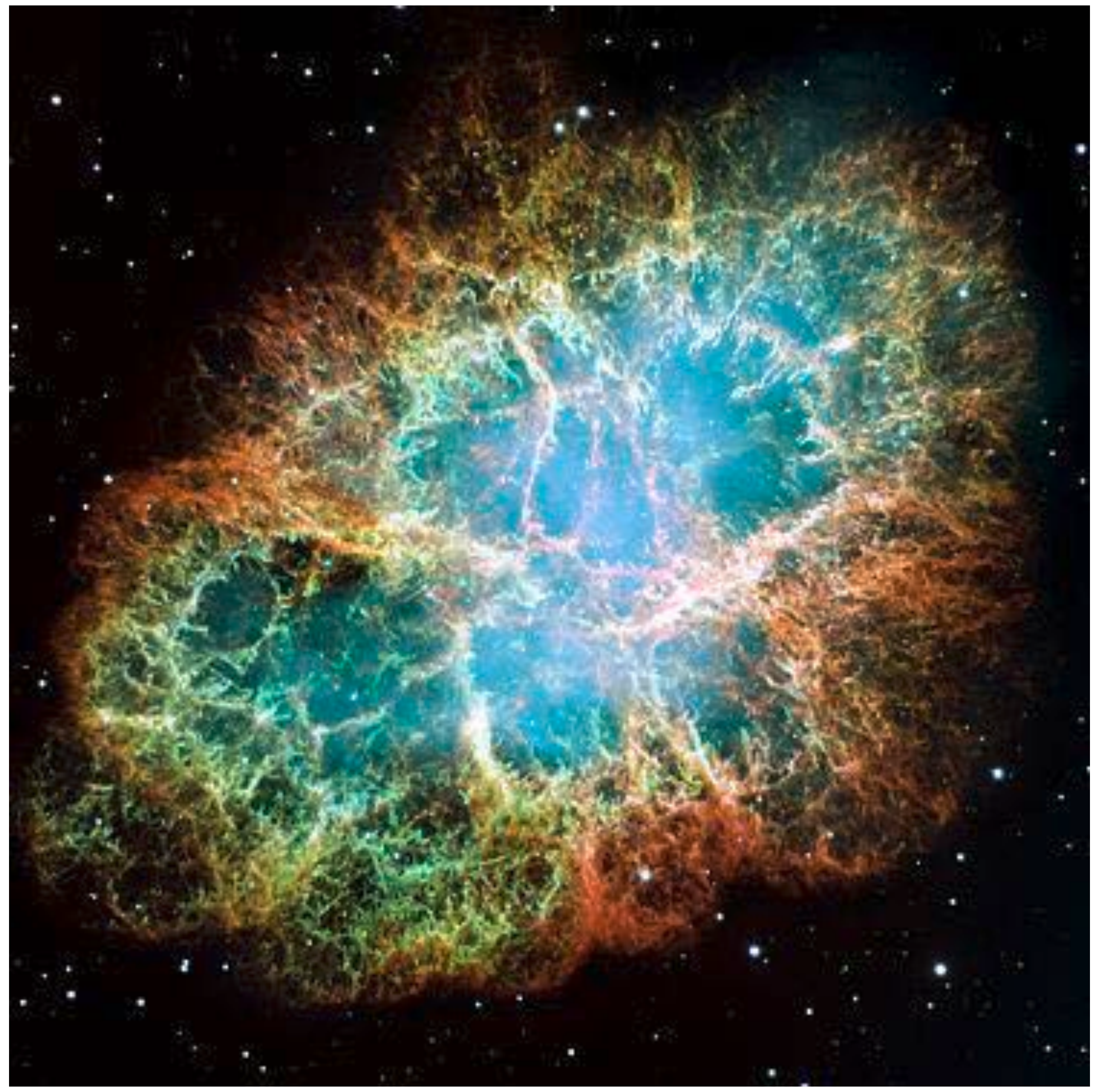
Faraday Rotation $\left(\frac{v_{ph}}{c}\right)_{R,L} = \left(1 - \frac{\omega_p^2}{\omega(\omega \pm \omega_B)}\right)^{-1/2}$

$$RM = \int_0^L n_e B_{||} dl$$

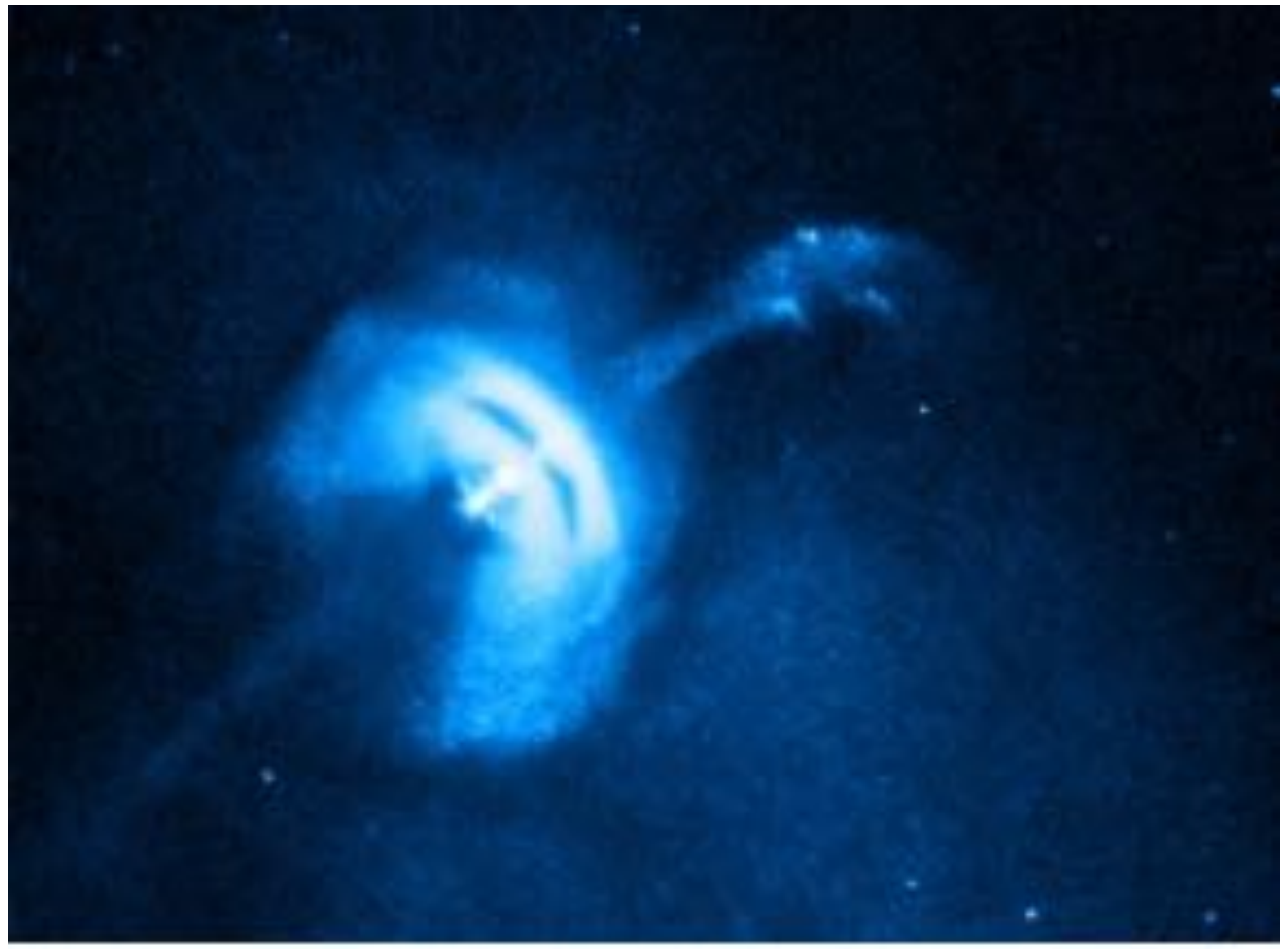
Rotation Measure

Matter around pulsars

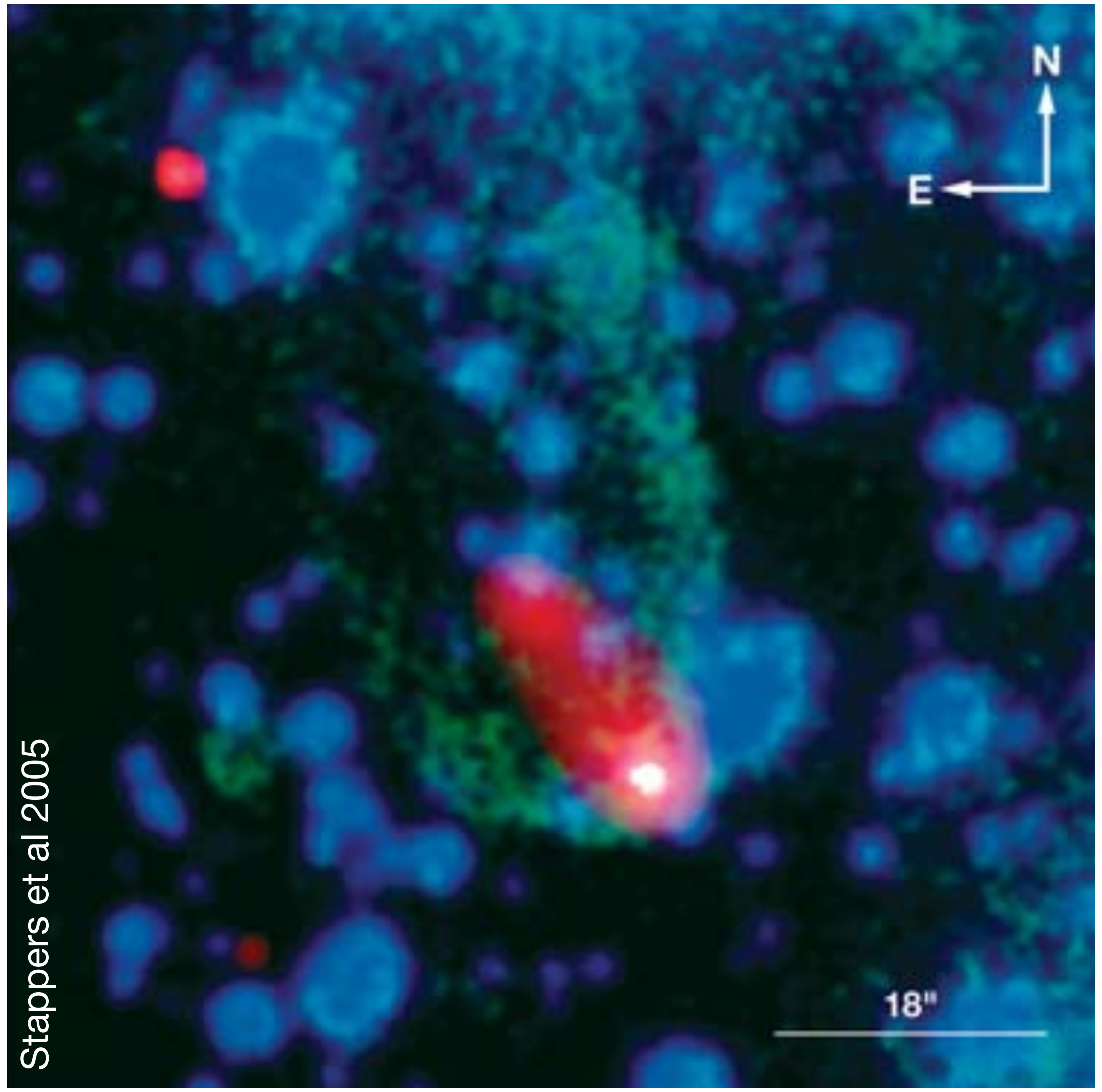
- Neutron Stars are born in supernova explosions
- Young pulsars are often found in supernova remnants
- Relativistic pair wind from the pulsar creates a nebula
- Fast moving pulsar through interstellar medium can also display a Pulsar Wind Nebula with bow shock
- Similar structures are seen in Black Widow pulsars



Crab Nebula HST

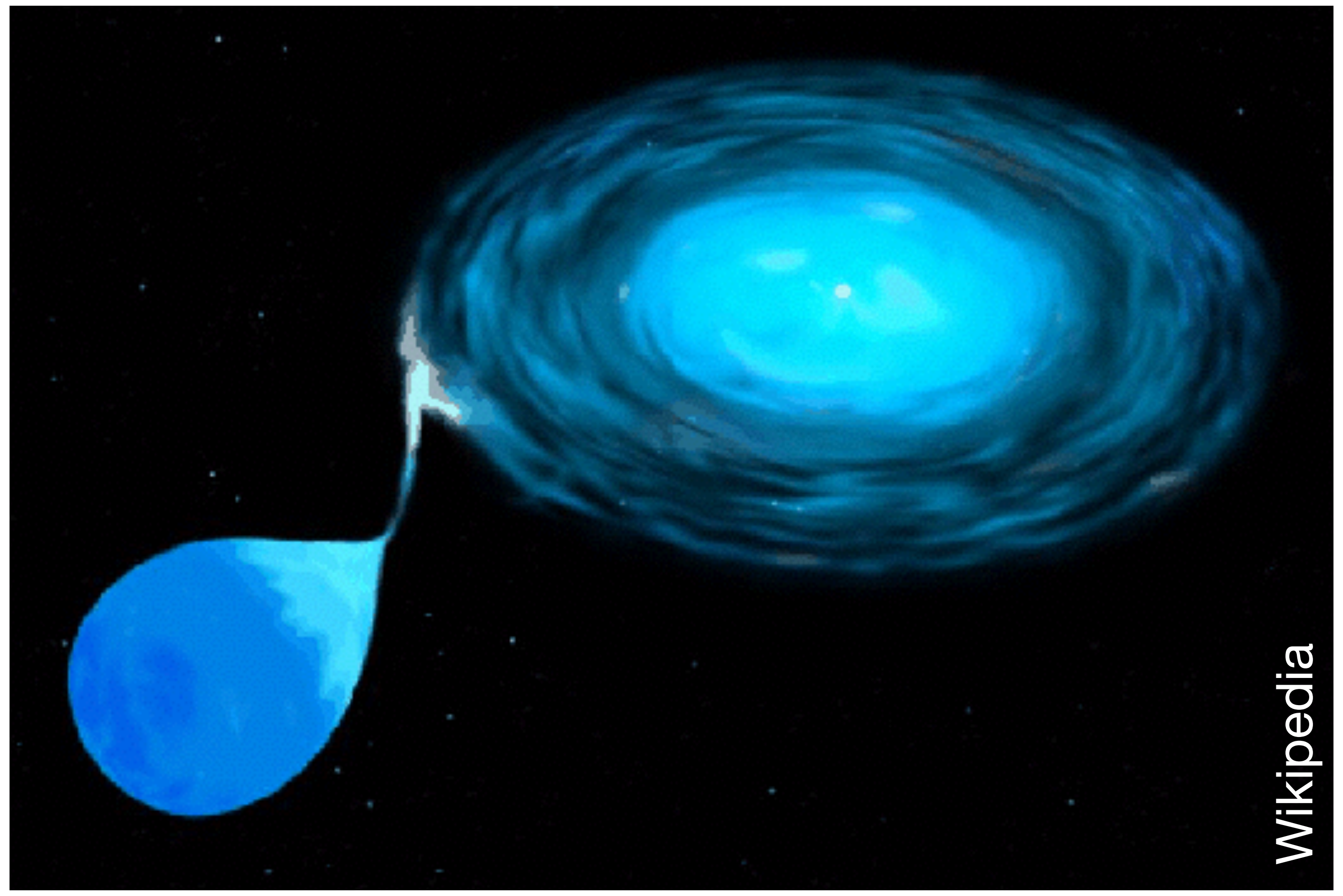


Vela PWN CXO

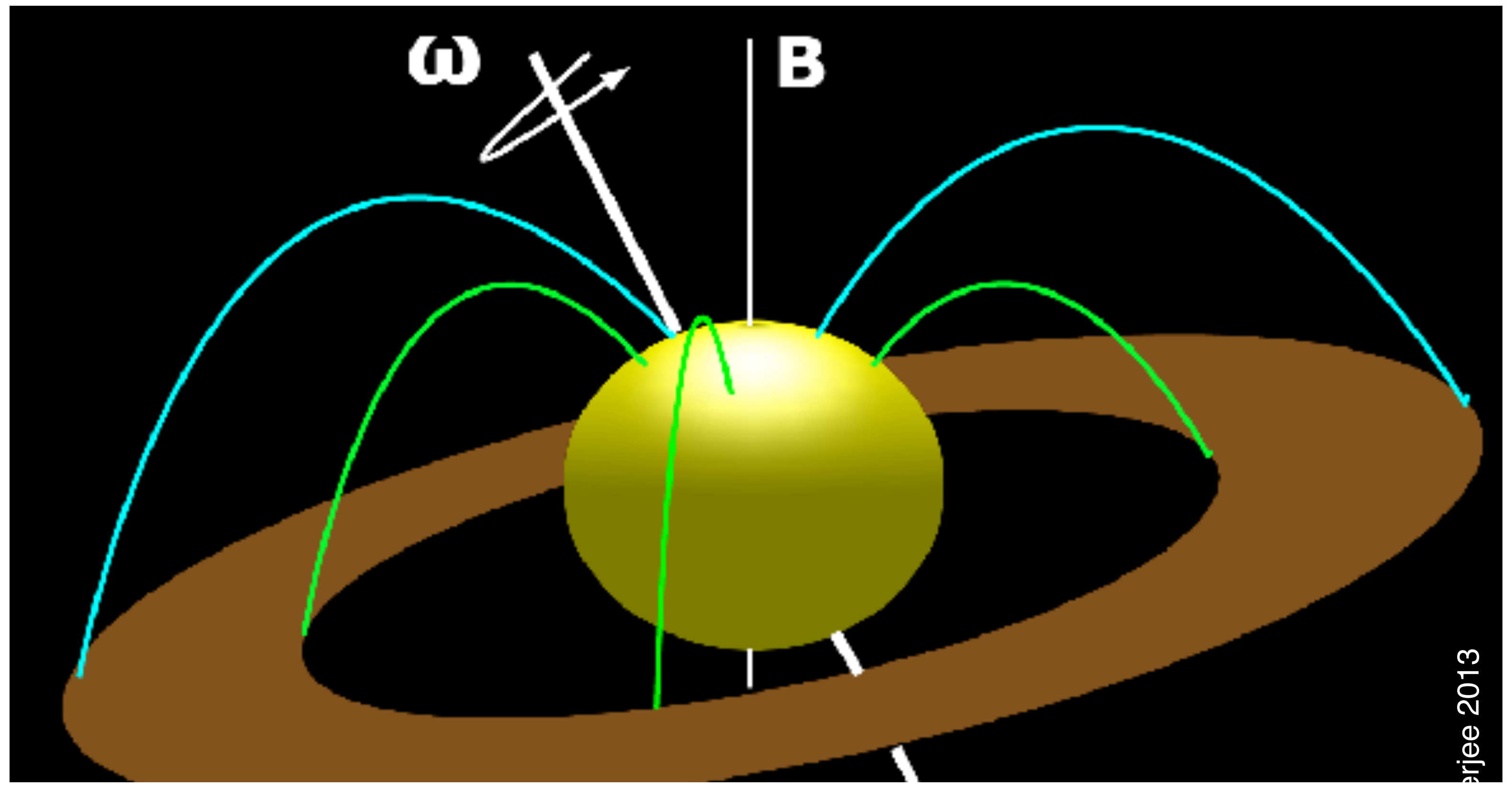


PSR B1957+20

Evolution of a neutron star in a binary



Matter approaching from a companion has angular momentum, may affect the spin of the Neutron Star



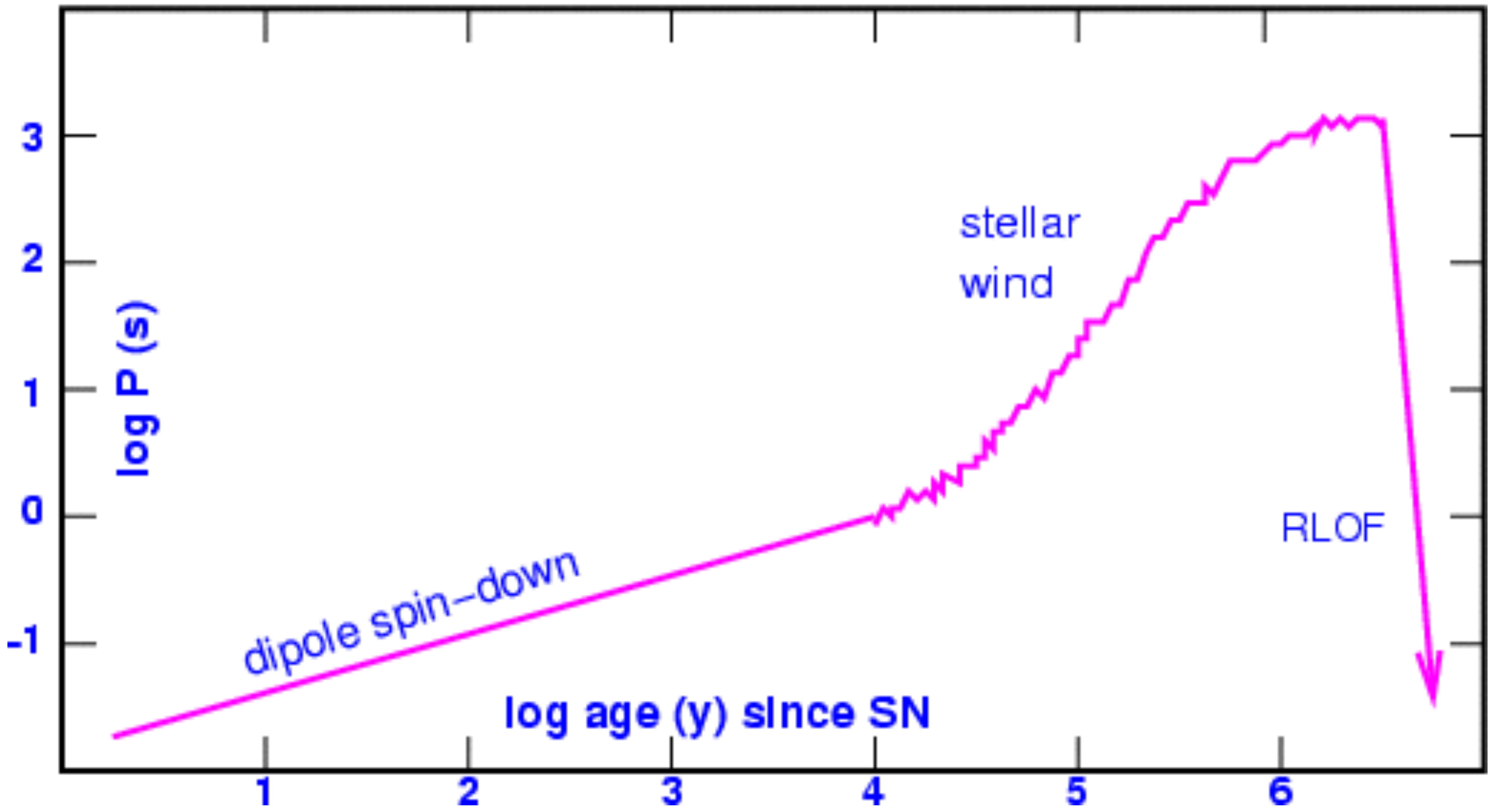
Disk-magnetosphere interaction at Alfven radius

$$R_A \sim \left(\frac{B_*^2 R_*^6}{\dot{M}\sqrt{2GM}}\right)^{2/7}$$

$\omega_{\rm kep}(R_A) > \omega_*$: spin-up

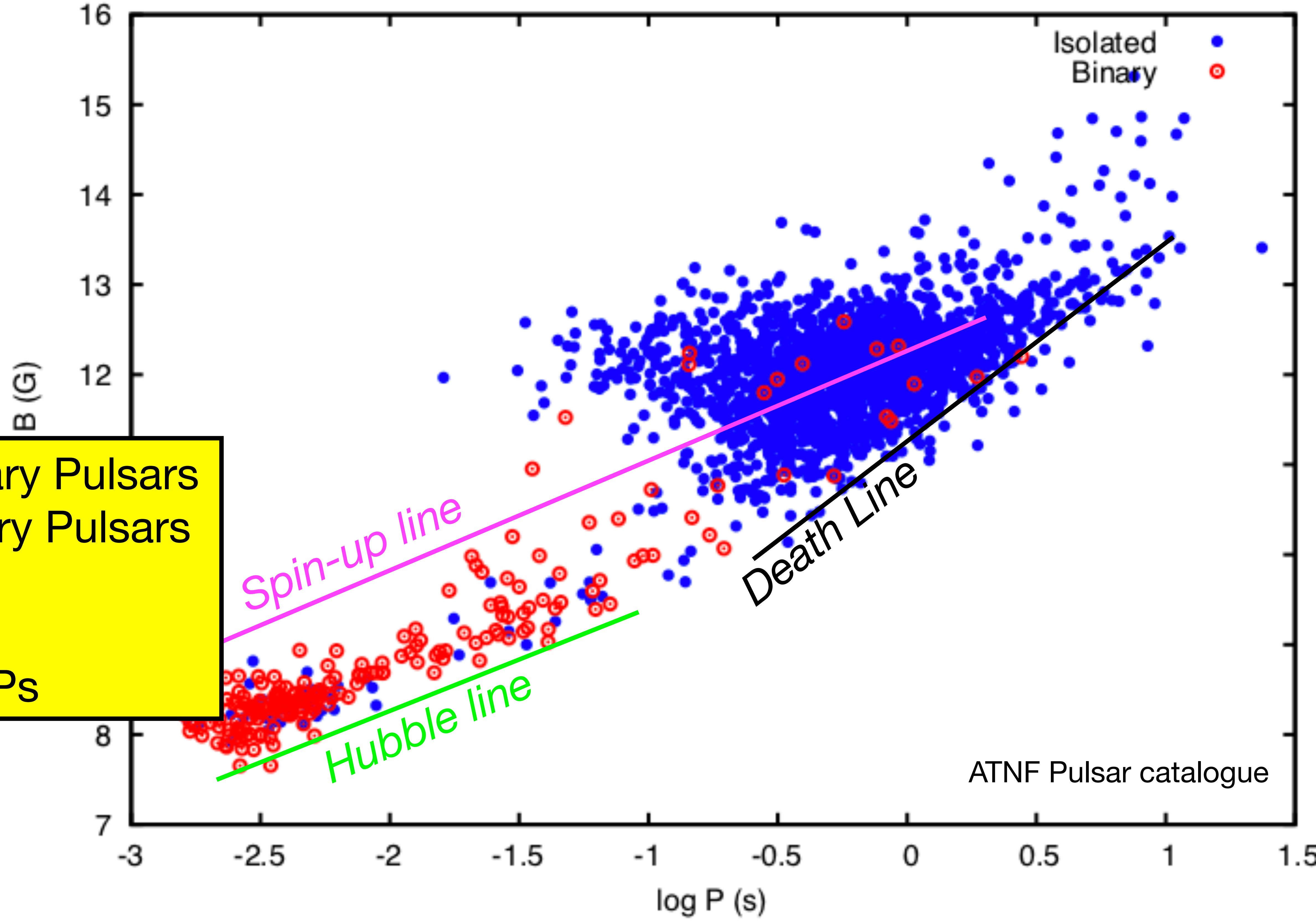
$\omega_{\rm kep}(R_A) < \omega_*$: spin-down

$\omega_{\rm kep}(R_A) = \omega_*$: equilibrium $\quad P_{\rm eq} \propto B^{6/7}\dot{M}^{-3/7}$



Recycled pulsars

High Mass Binary Pulsars
Low Mass Binary Pulsars
Black Widows
Redbacks
Transitional msPs

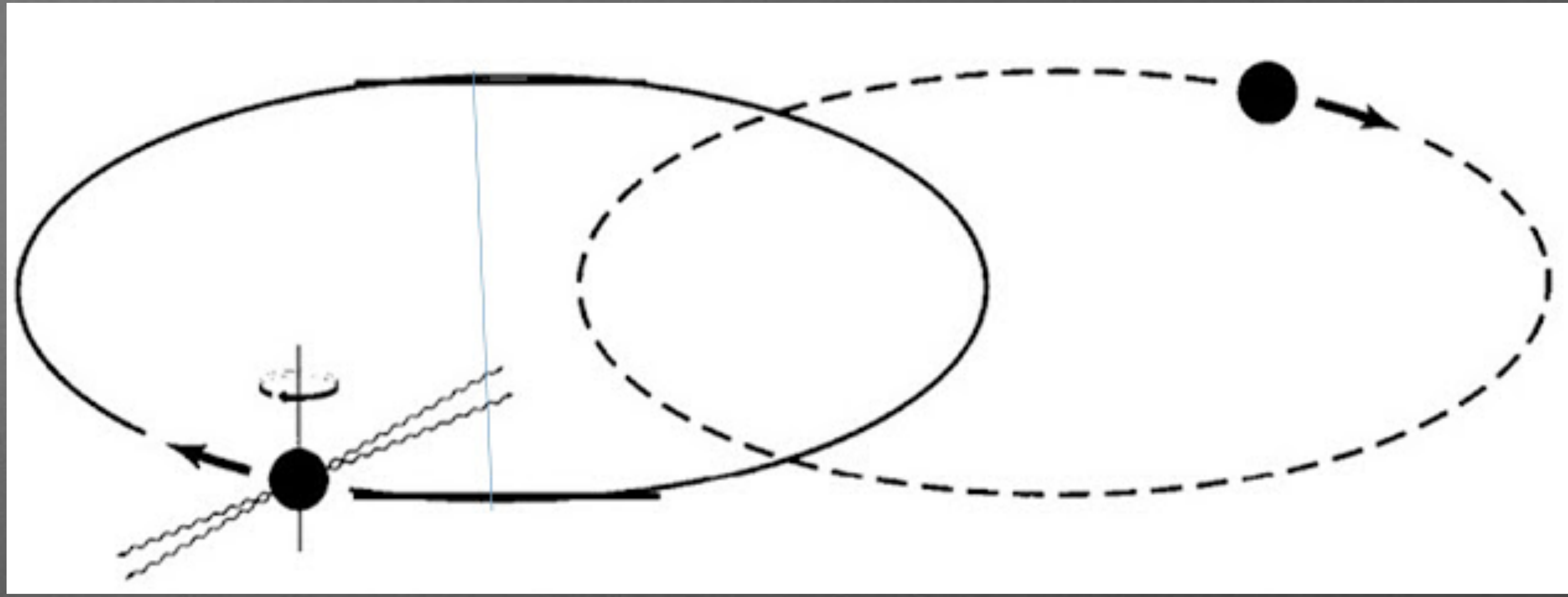


Timing relativistic binaries

Neutron Stars in Binaries:
Keplerian and Post-Keplerian
relativistic parameters

P_b, e, ω

dP_b/dt, $d\omega/dt$, γ, r, s



R. Hulse, Nobel Lecture

$$\dot{\omega} = 3\left(\frac{P_b}{2\pi}\right)^{-5/3} (T_\odot M)^{2/3}(1-e^2)^{-1},$$

$$\gamma = e\left(\frac{P_b}{2\pi}\right)^{1/3} T_\odot^{2/3} M^{-4/3} m_2(m_1+2m_2),$$

$$\dot{P}_b = -\frac{192\pi}{5}\left(\frac{P_b}{2\pi}\right)^{-5/3}\left(1+\frac{73}{24}e^2+\frac{37}{96}e^4\right)(1-e^2)^{-7/2} T_\odot^{5/3} m_1 m_2 M^{-1/3},$$

$$r = T_\odot m_2,$$

$$s = x\left(\frac{P_b}{2\pi}\right)^{-2/3} T_\odot^{-1/3} M^{2/3} m_2^{-1}.$$

$$\boxed{T_\odot \equiv GM_\odot/c^3}$$

Damour & Deruelle 1986

- Measure Neutron Star Masses
- Test GR predictions
- First evidence of Gravitational Waves from orbital decay

Concluding Remarks

- Combination of extreme density, gravity, magnetic field and spin make pulsars some of the most exotic objects in the universe
- Pulsars and neutron stars aid the study of fundamental physics - including nuclear forces and the theory of gravity
- Pulsar timing is the most accurate tool of astronomical measurements in existence today, and is continuously improving
- Pulsar timing is also finding application in the area of space navigation
- With new surveys, particularly with the SKA, promising to discover many more pulsars the future of pulsar science is rich and bright