DTU Space
National Space Institute

Neutron stars

Jérôme Chenevez, DTU Space

NS in different astrophysical contexts

Energy source

- ○ Pulsar Wind Nebulae (PWNe)

  Rotation

- ○ Central Compact Objects (CCOs)

  Thermal (neutrino cooling)

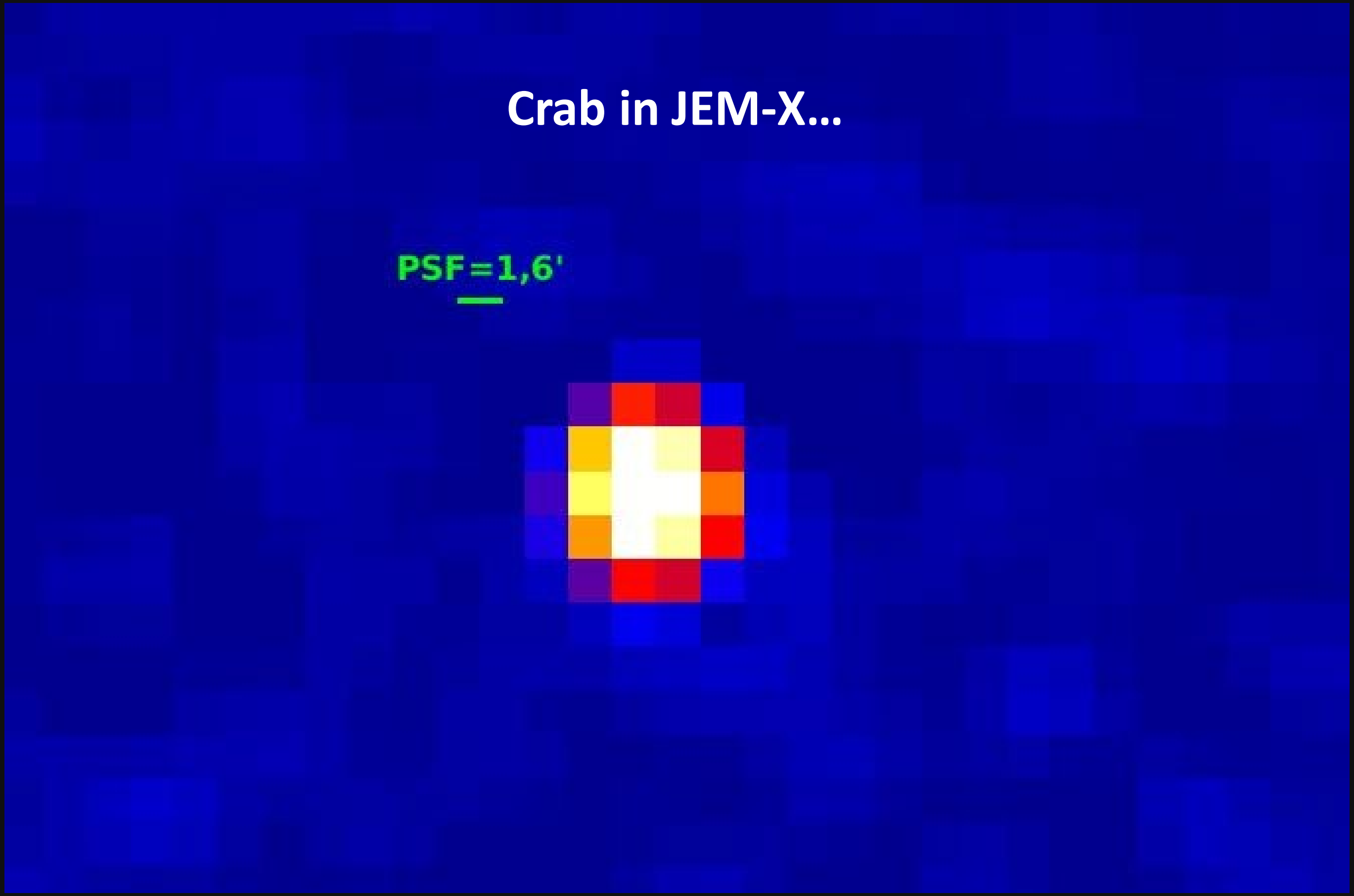
- ○ Magnetars
  - ○ Anomalous Pulsars (AXPs)
  - ○ Soft-Gamma Repeaters (SGRs)

  Magnetic field decay

- ○ X-ray Binaries (XrBs)

  Accretion

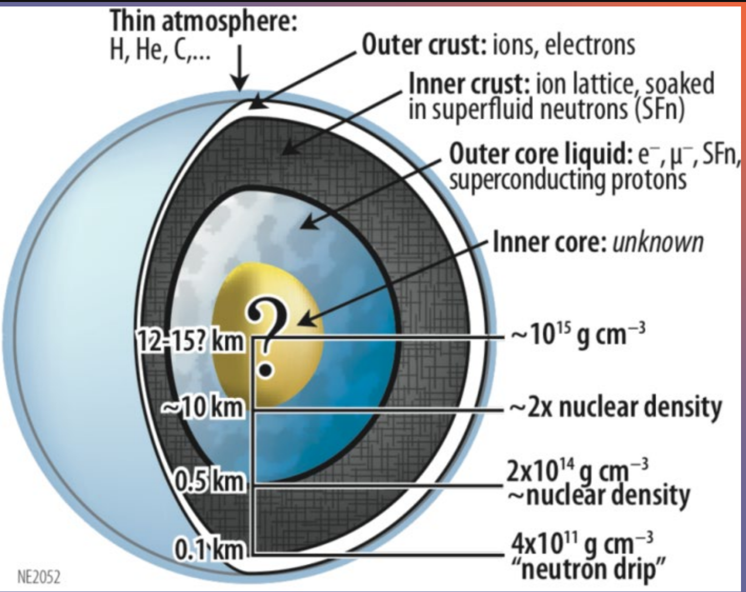
Crab as a calibration source



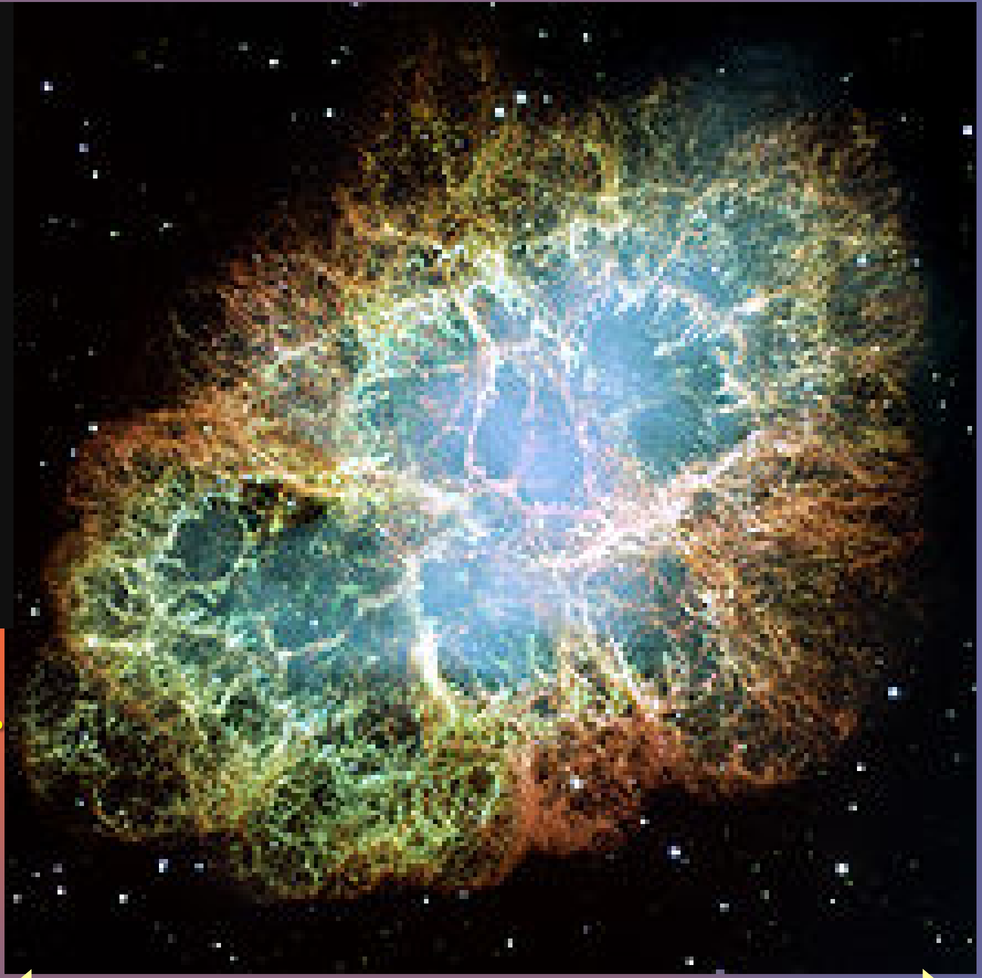
…despite still on-going activity

The Crab pulsar and nebula

D≈ 6500 ly



33 ms pulsar

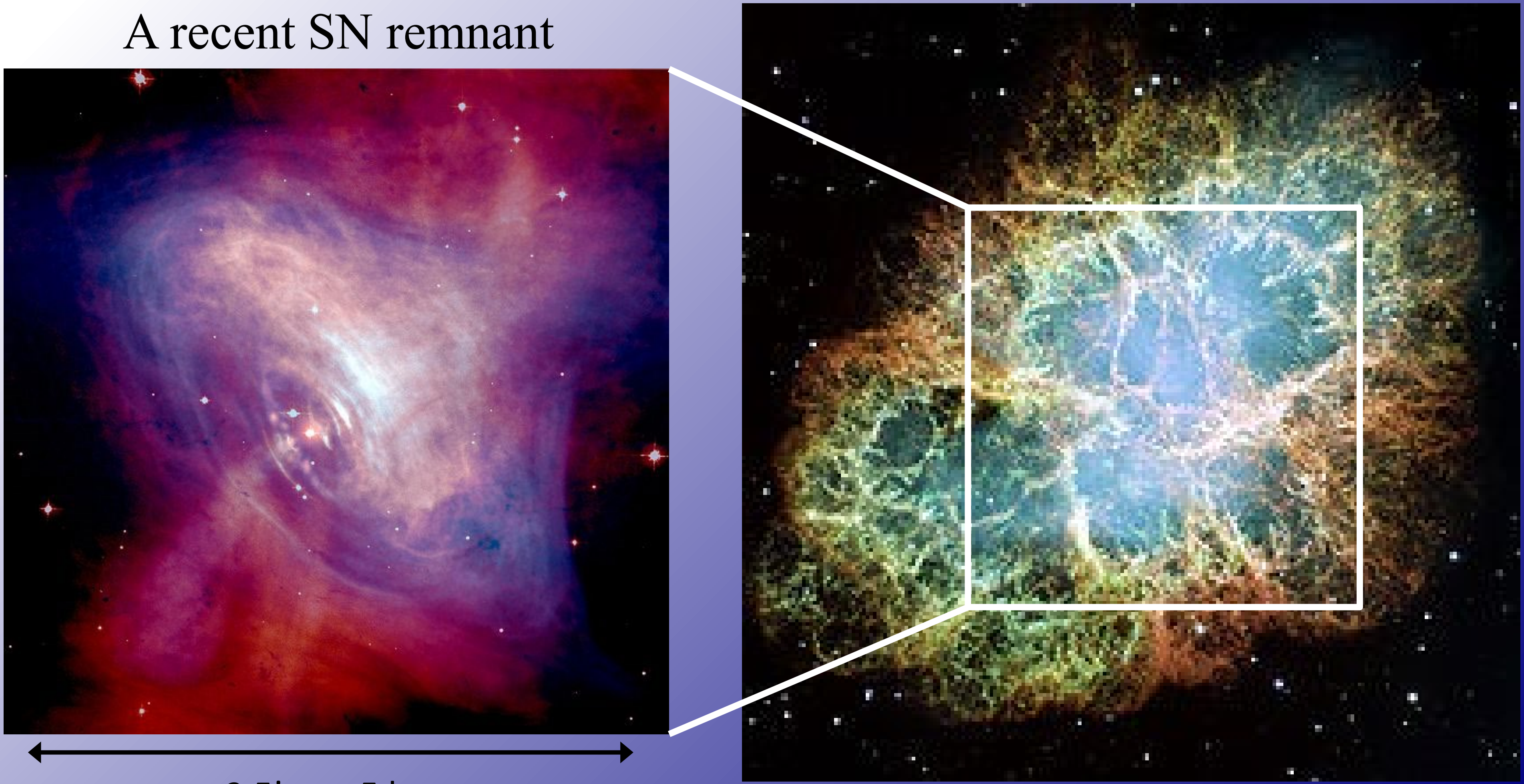


≈11 ly

A supernova remnant?

Pulsar Wind Nebula (PWN)

A recent SN remnant



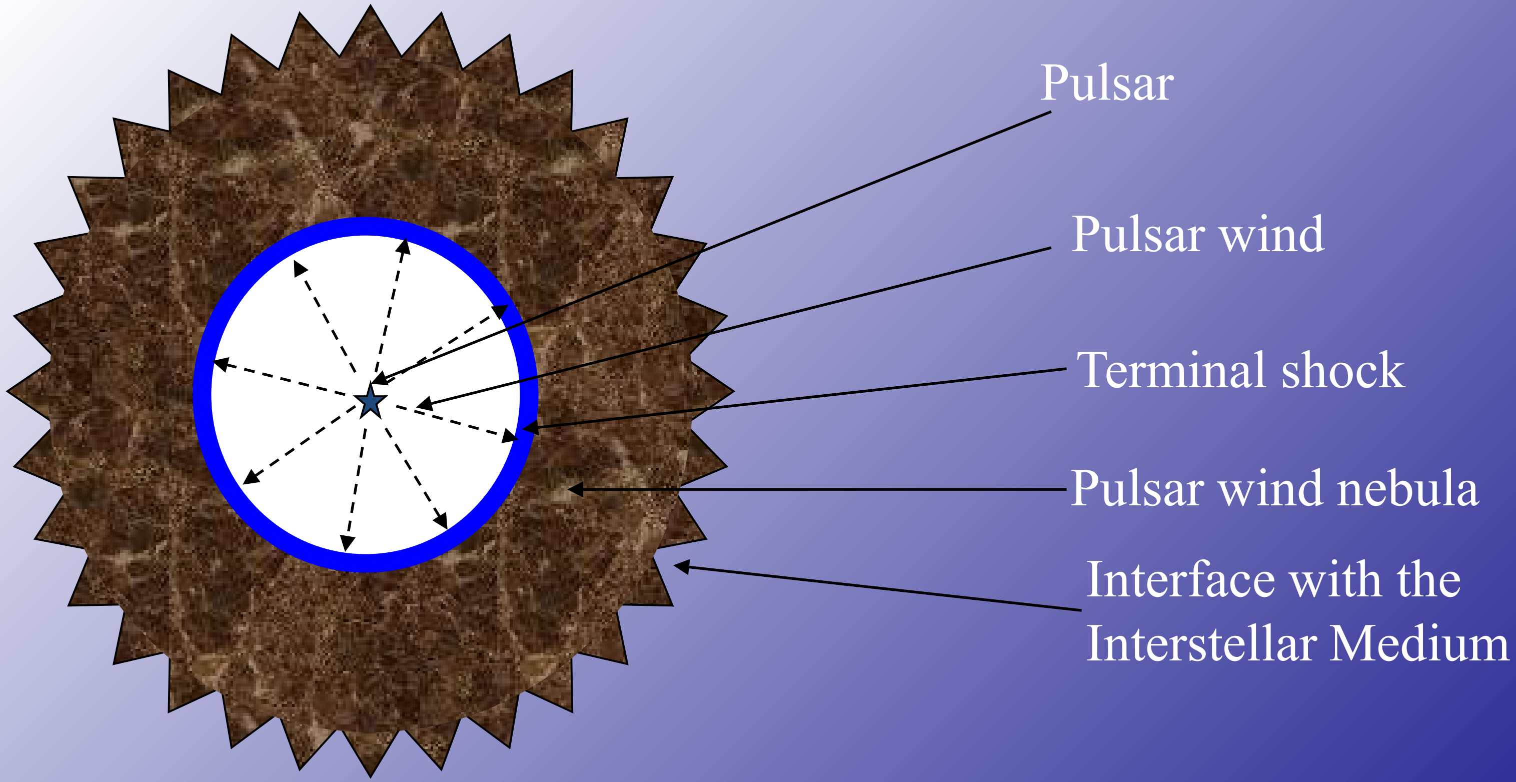
2,5′ ↔ ≈5 l.y.

Rotation-powered pulsar at 30 Hz

Plerion (no radio shell)

$L_{bol} = 1.8\times10^{38}$ erg/s $\approx 10^{5}\ L_{\odot}$

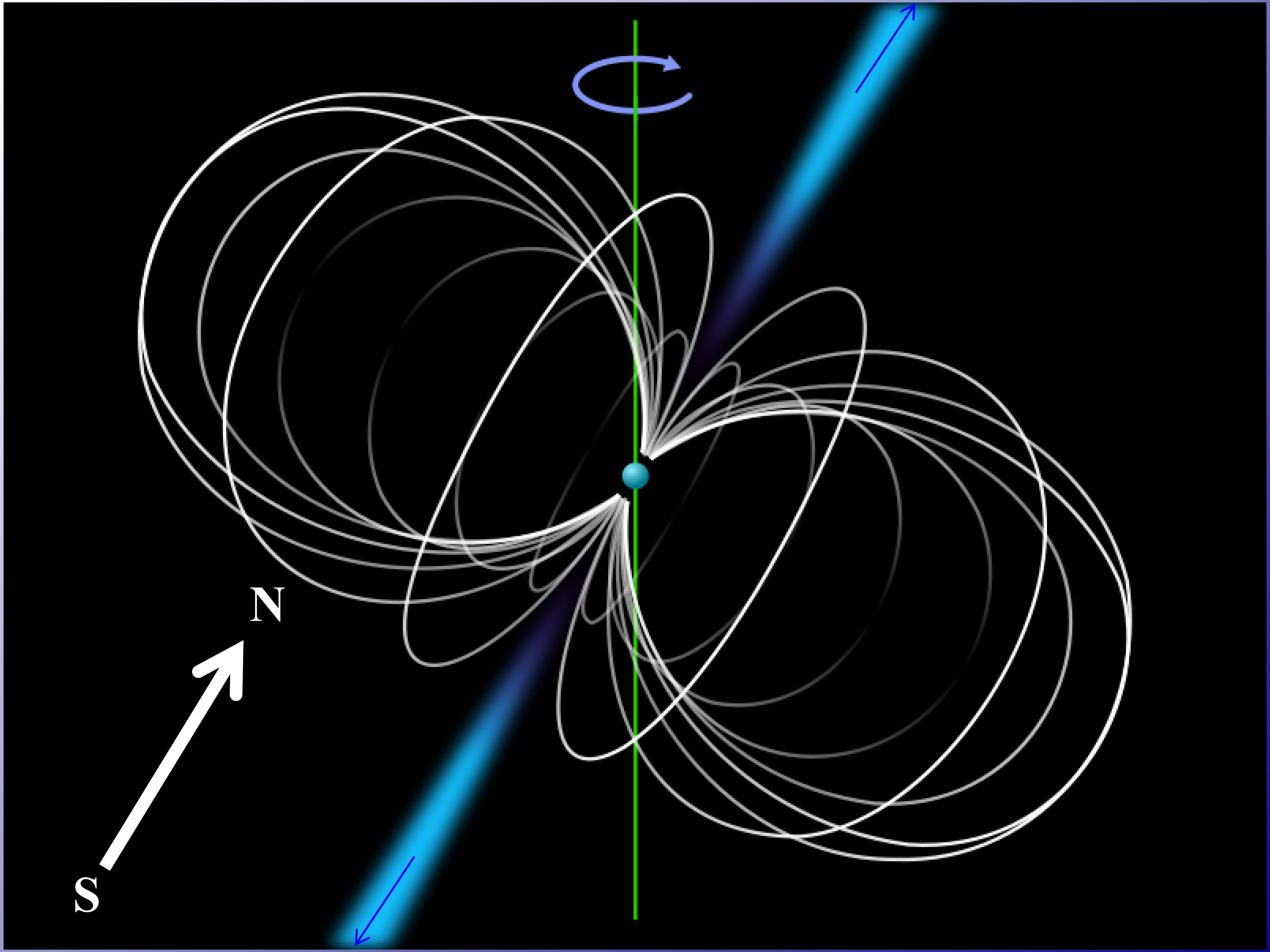
The basic configuration of a PWN (plerion)



- Most (90%) of the spin-down power of a pulsar is released via a relativistic wind.
- The magnetized pulsar wind leaves the pulsar with almost the speed of c.
- A termination shock forms at the radius where the wind ram-pressure balances the pressure of the environments, and over there the particles are randomized and probably accelerated and begin to emit **synchrotron** photons (radio to gamma).
- The PWN is a magnetized particle bubble surrounded by the ISM.

(Rees & Gunn 1974)

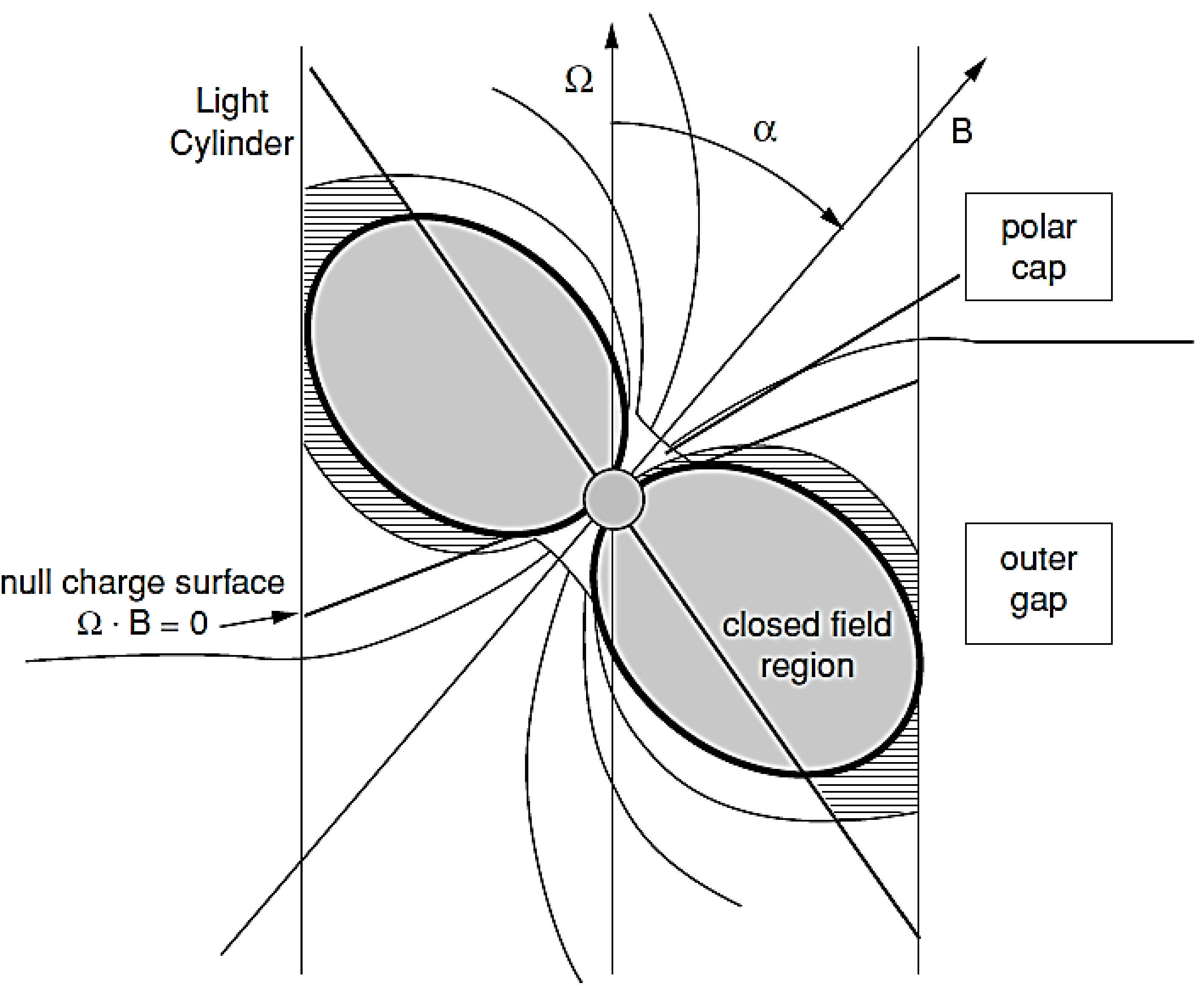
A stellar dynamo



$B \sim 10^{12}$ (– 10^{15}) Gauss

$B_{Earth} \approx 0{,}5$ Gauss

Emission models



Pair-particles produced from high E γ, accelerated in **B**-field eventually radiate synchrotron

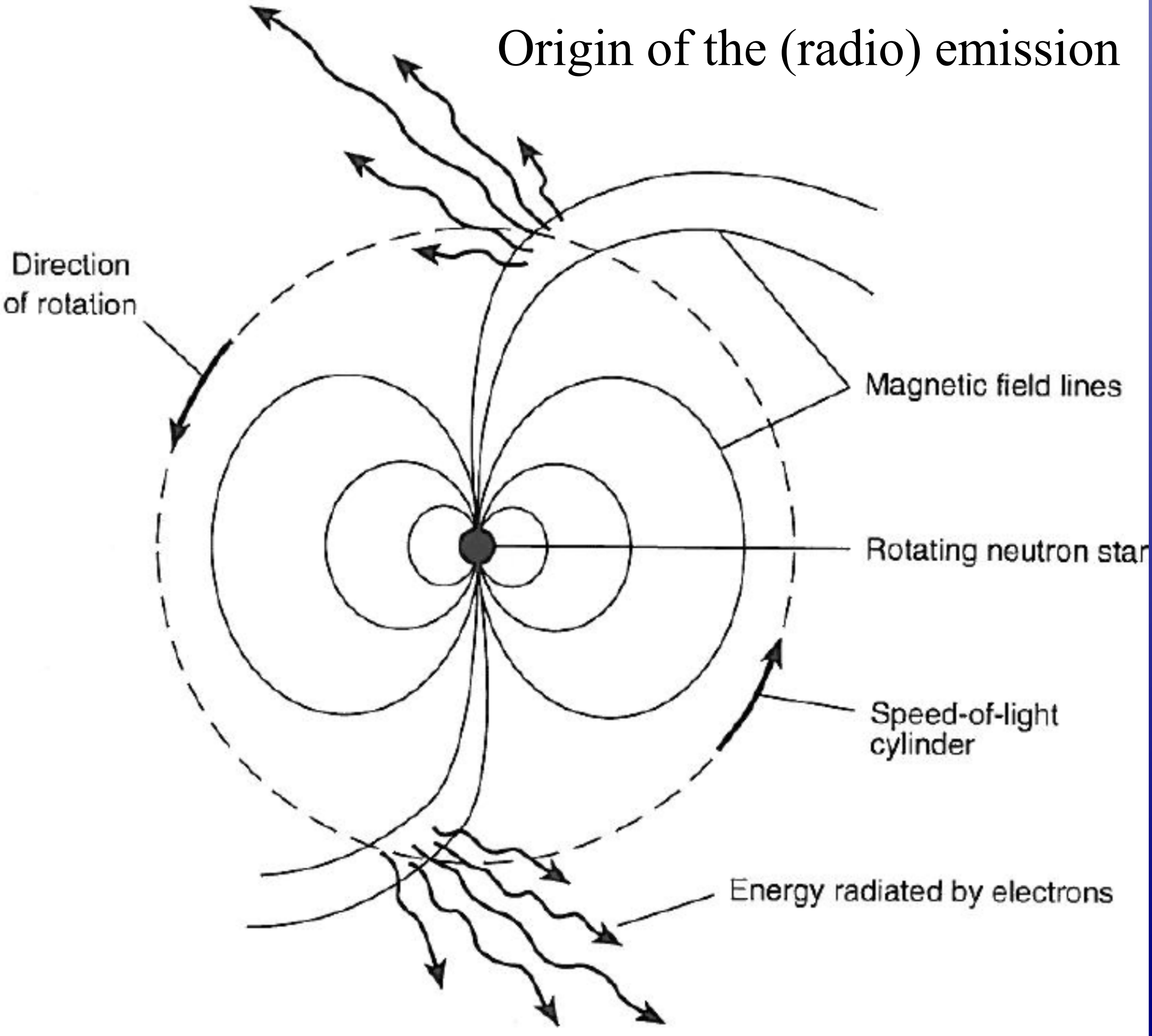
Rotation-powered pulsar

Moving **B**:

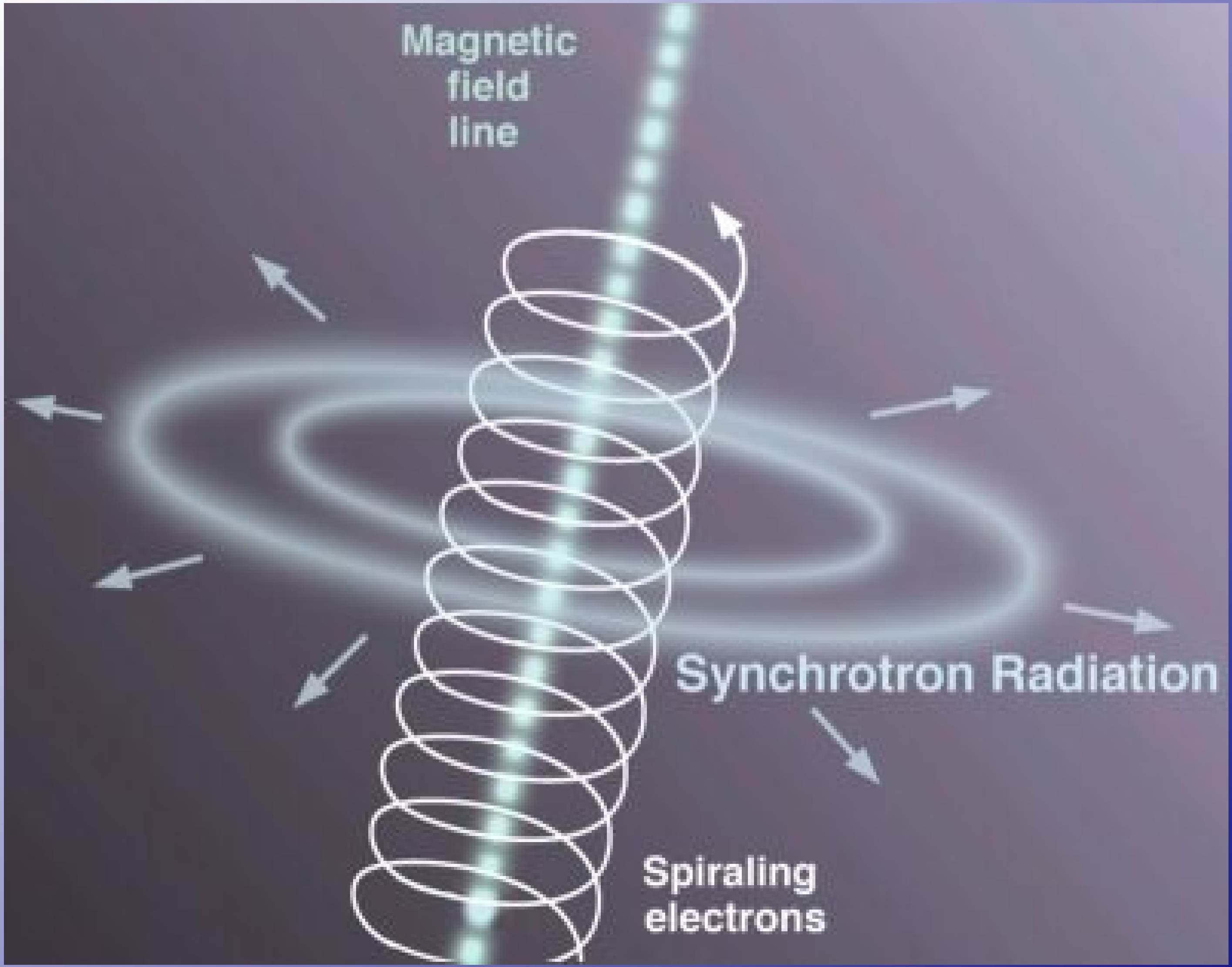
$$-\frac{\partial \boldsymbol{B}}{\partial t} = \boldsymbol{\nabla} \times \boldsymbol{E}$$

$\Rightarrow$ e$^-$ current

EM radiation



Emission mechanism



Power-law spectrum, X-ray photon index ≈ 2 (PWNe), ±1 (pulsars)

Pulsar Basics (Measurable quantities)

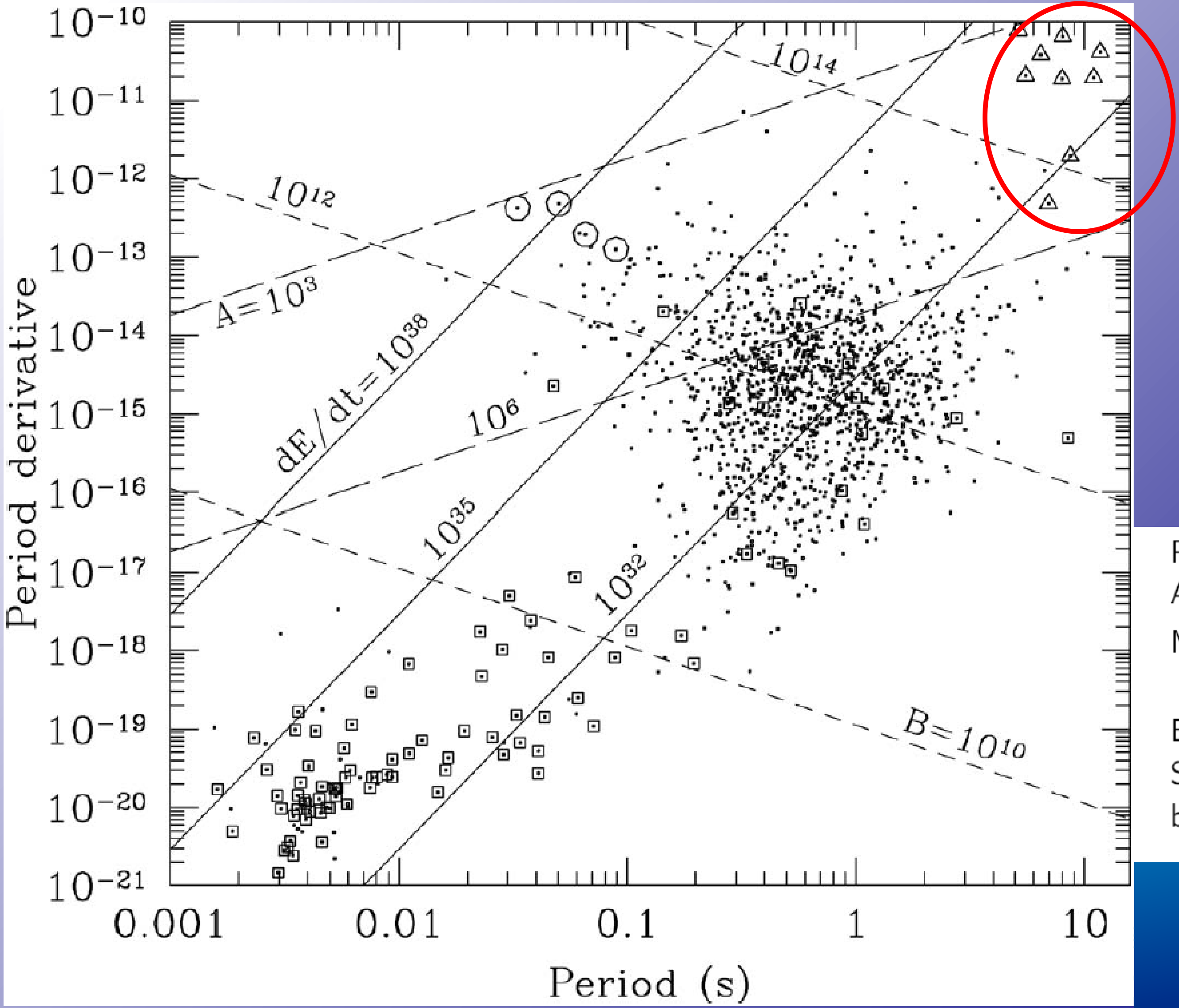
$$\dot{E} = \frac{d}{dt}\left(\frac{1}{2}I\omega^2\right) = I\omega\dot{\omega} = -4\pi^2 I\frac{\dot{P}}{P^3}$$

spin-down luminosity

Pulsar period	P	
Age of a Pulsar	$t_{characteristic} = \frac{P}{2\dot{P}}$	(Dipole limit)
Magnetic Field	$B^2 = \frac{3Ic^3}{8\pi^2 R^6}P\dot{P}$	
	$\rightarrow \dot{P} \sim B^2/P$	(Table 9.1)
Energy release	$\frac{dE}{dt} = -\frac{4\pi^2 I\dot{P}}{P^3}$	
Spindown rate	$\dot{P} \propto -P^n$	
Magnetic dipole braking index	$n = P\ddot{P}/\dot{P}^2$	
	$\Rightarrow P-\dot{P}$ diagram	

$n = 1$: pulsar wind, $n = 3$: magnetic dipole radiation, $n = 5$: Magnetic or gravitational quadrupole radiation, but $n > 3$ not observed (measured with young NS)

$P - \dot{P}$ pulsar diagram



MAGNETARS

Only 29 known (≈1%) so far

Anomalous X-ray Pulsars

Soft **G**amma-ray **R**epeaters

High P_{dot} ⇔ high B >10^{14} G

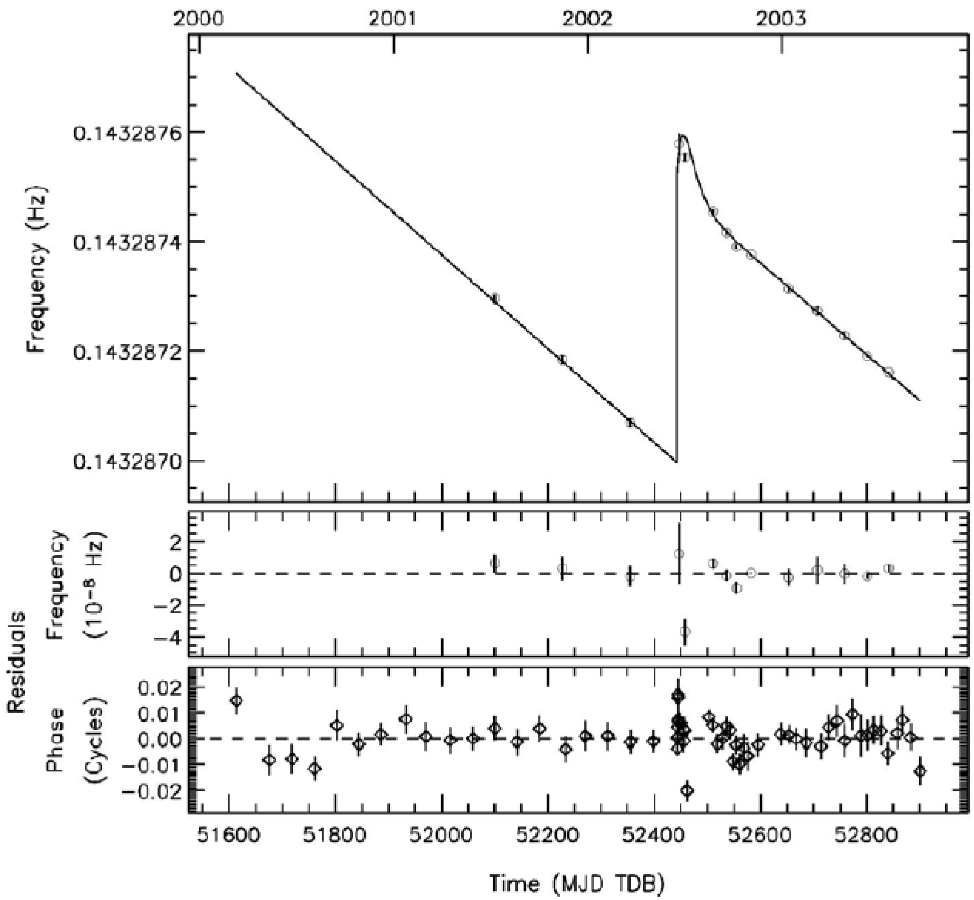
Pulsar period	P
Age of a Pulsar	$t_{characteristic} = \frac{P}{2\dot{P}}$
Magnetic Field	$B^2 = \frac{3Ic^3}{8\pi^2 R^6} P\dot{P}$ $\rightarrow \dot{P} \sim B^2/P$
Energy release	$\frac{dE}{dt} = \frac{4\pi^2 I \dot{P}}{P^3}$
Spindown rate	$\dot{P} \propto -P^n$
braking index	$n = P\ddot{P}/\dot{P}^2$

Mantle – crust interactions

1E 2259+586 2002 Glitch

- rotation glitch dP/P=4e-6
- Coincident with large flux flare, many other radiative changes

- Risetime ~seconds

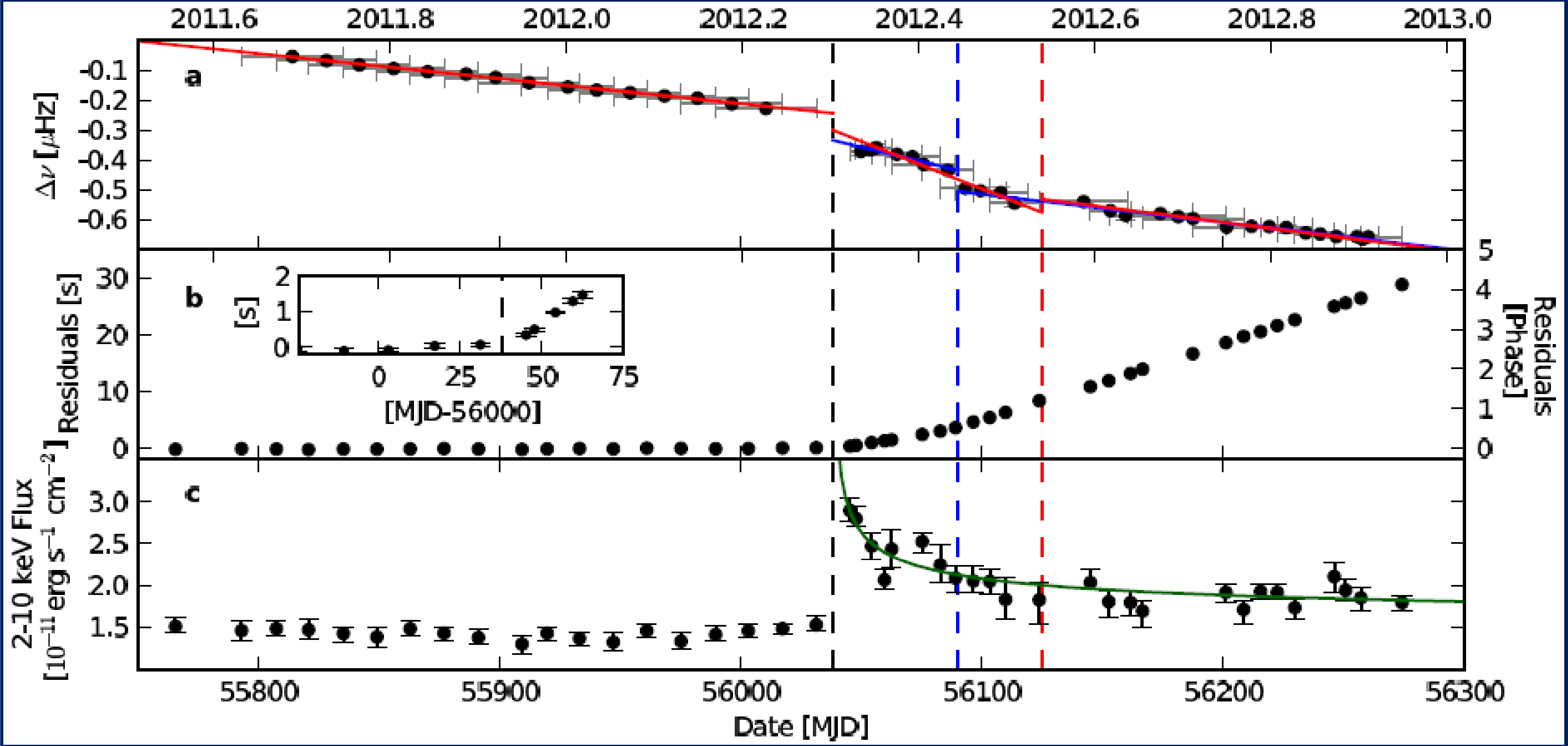


VK et al. 2003; Woods et al 2004

Effect of *mantle* **superfluid vortices** in the *crust*

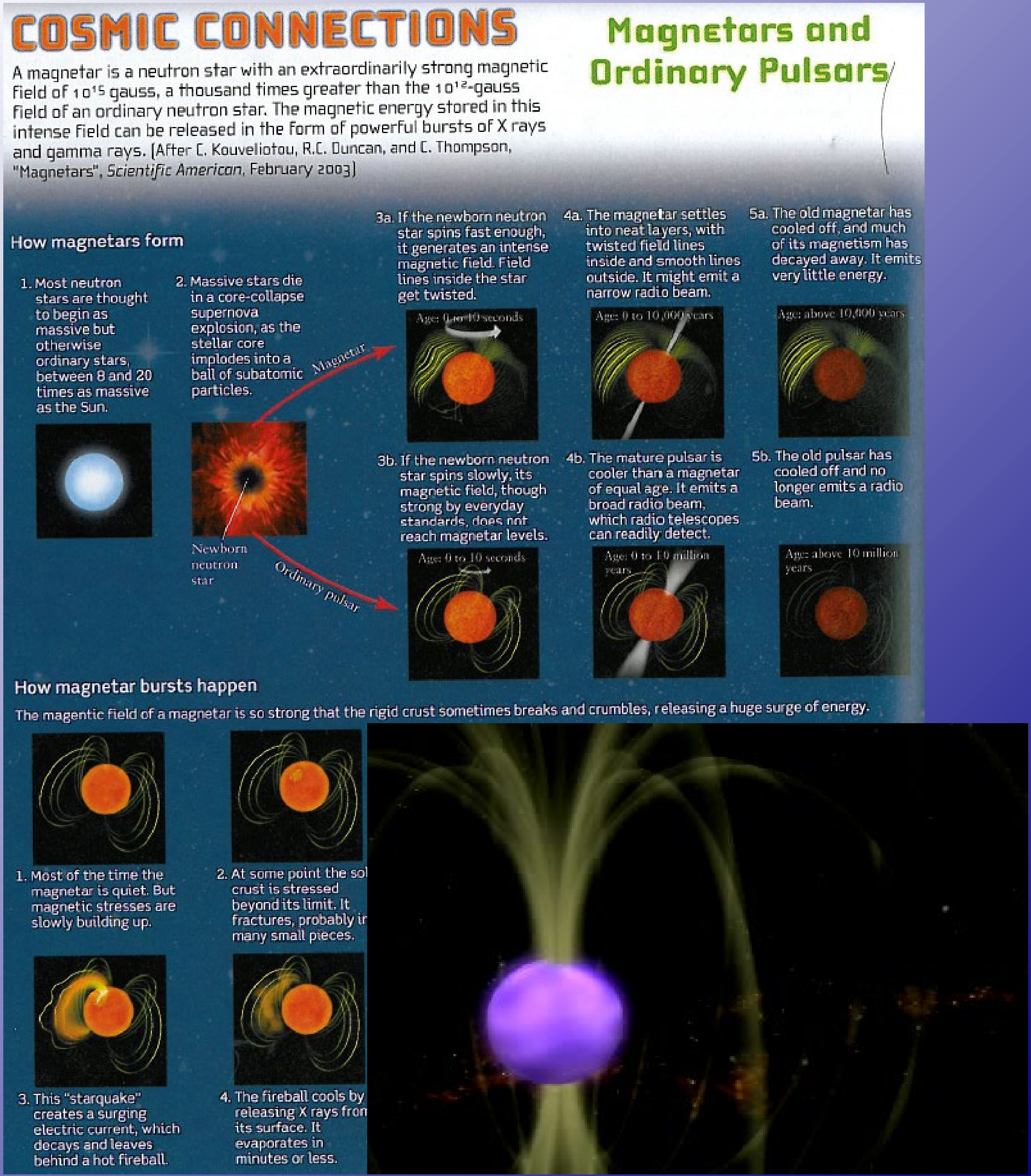
Mantle – crust interactions

… and 2012 Anti-Glitch!



Archibald R., Kaspi V. et al. 2013

Differential rotation due to strong magnetic field?



COSMIC CONNECTIONS

Magnetars and Ordinary Pulsars

A magnetar is a neutron star with an extraordinarily strong magnetic field of 10^{15} gauss, a thousand times greater than the 10^{12}-gauss field of an ordinary neutron star. The magnetic energy stored in this intense field can be released in the form of powerful bursts of X rays and gamma rays. [After C. Kouveliotou, R.C. Duncan, and C. Thompson, "Magnetars", *Scientific American*, February 2003]

How magnetars form

1. Most neutron stars are thought to begin as massive but otherwise ordinary stars, between 8 and 20 times as massive as the Sun.

2. Massive stars die in a core-collapse supernova explosion, as the stellar core implodes into a ball of subatomic particles.

3a. If the newborn neutron star spins fast enough, it generates an intense magnetic field. Field lines inside the star get twisted.

4a. The magnetar settles into neat layers, with twisted field lines inside and smooth lines outside. It might emit a narrow radio beam.

5a. The old magnetar has cooled off, and much of its magnetism has decayed away. It emits very little energy.

3b. If the newborn neutron star spins slowly, its magnetic field, though strong by everyday standards, does not reach magnetar levels.

4b. The mature pulsar is cooler than a magnetar of equal age. It emits a broad radio beam, which radio telescopes can readily detect.

5b. The old pulsar has cooled off and no longer emits a radio beam.

How magnetar bursts happen

The magentic field of a magnetar is so strong that the rigid crust sometimes breaks and crumbles, releasing a huge surge of energy.

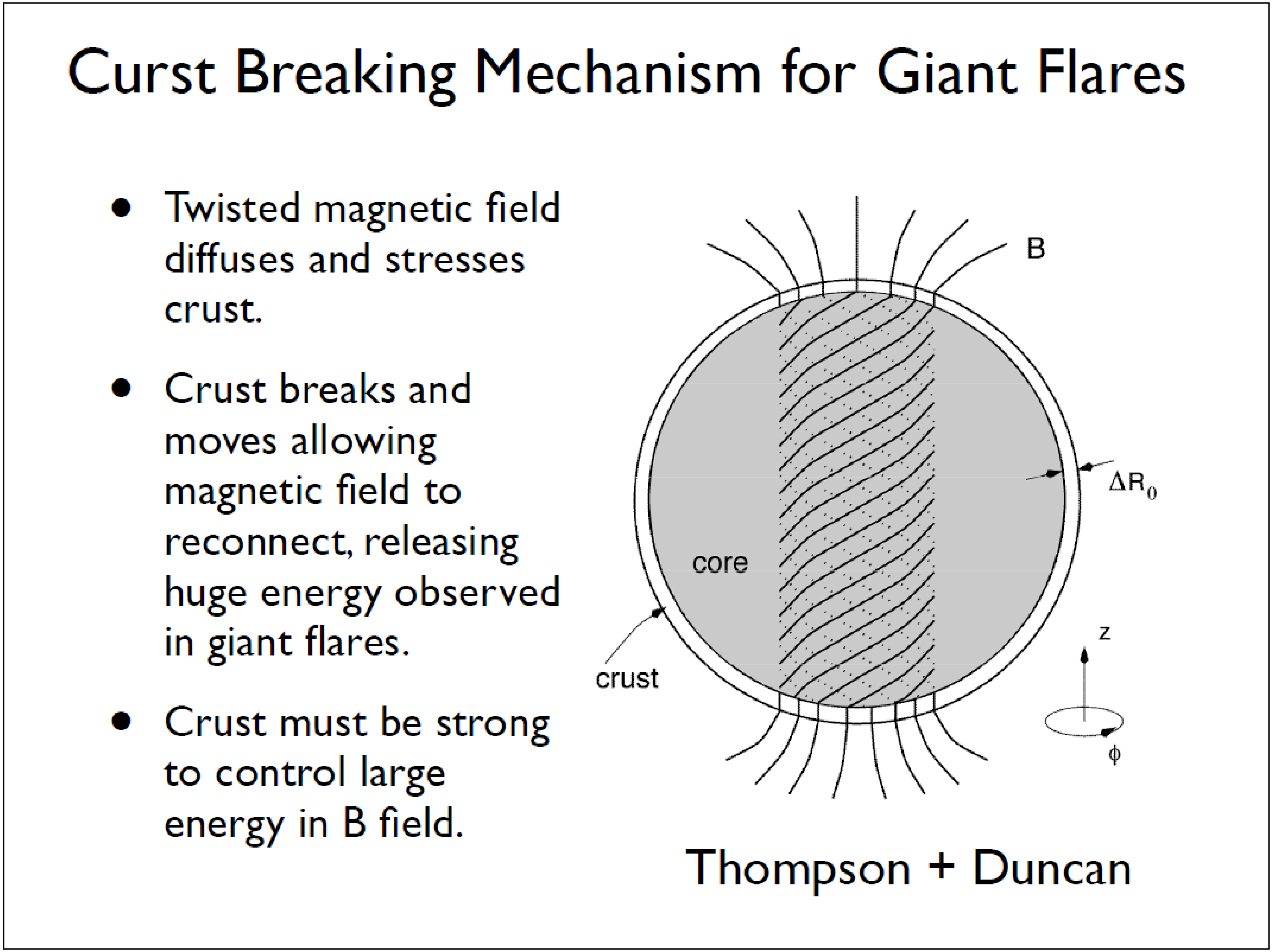
1. Most of the time the magnetar is quiet. But magnetic stresses are slowly building up.

2. At some point the so crust is stressed beyond its limit. It fractures, probably i many small pieces.

3. This "starquake" creates a surging electric current, which decays and leaves behind a hot fireball.

4. The fireball cools by releasing X rays fro its surface. It evaporates in minutes or less.

MAGNETARS / Soft Gamma-ray Repeaters



Curst Breaking Mechanism for Giant Flares

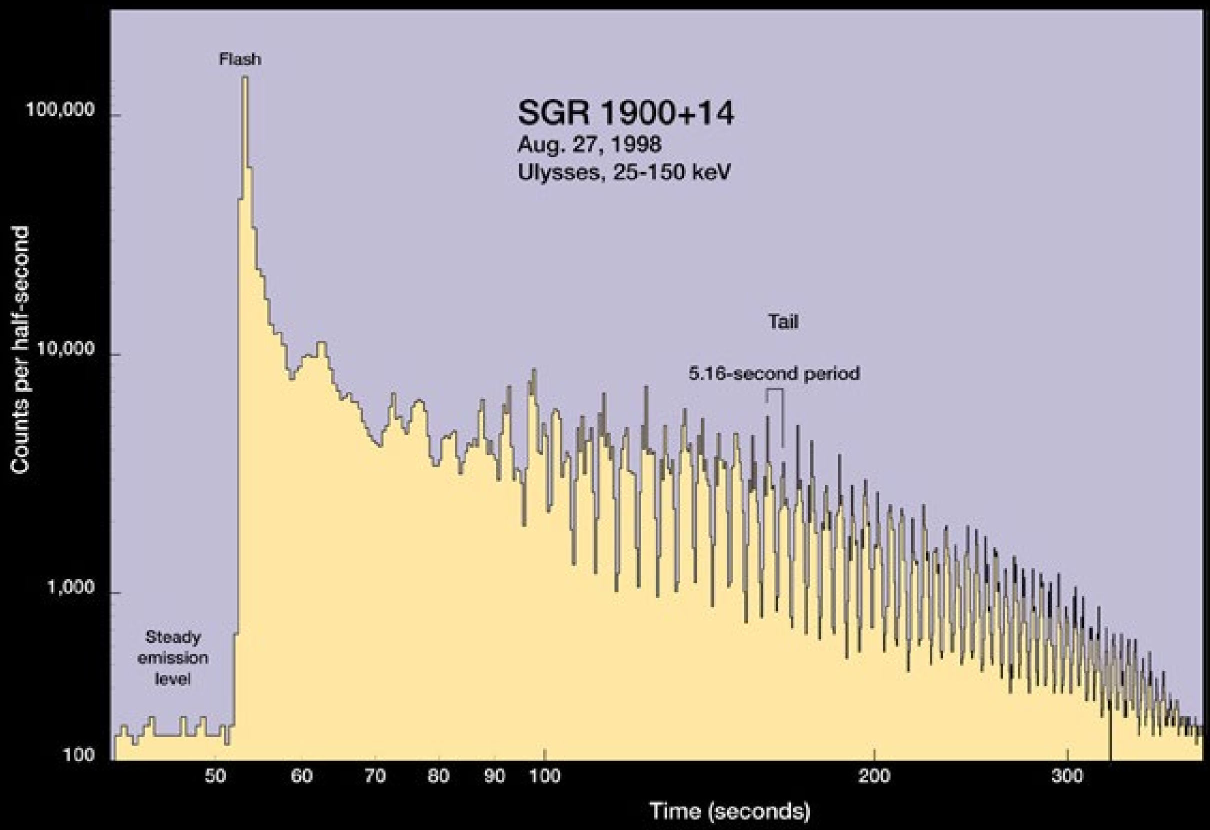
- Twisted magnetic field diffuses and stresses crust.
- Crust breaks and moves allowing magnetic field to reconnect, releasing huge energy observed in giant flares.
- Crust must be strong to control large energy in B field.

Thompson + Duncan

MAGNETARS / Soft Gamma-ray Repeaters

Magnetar bursts (~10^{14} gauss)

Magnetic reconnection

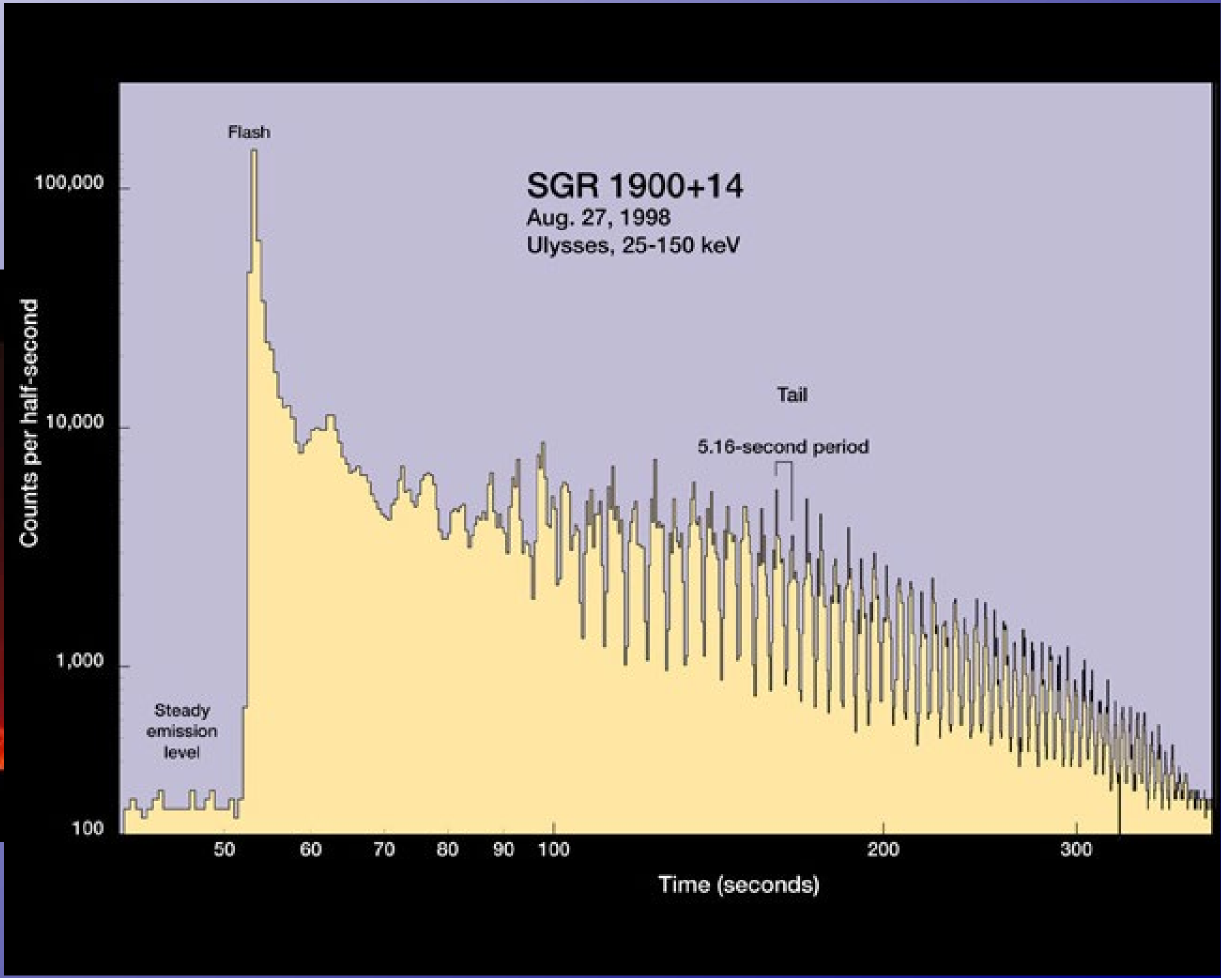


Giant flare E ~10^{45} ergs

MAGNETARS / Soft Gamma-ray Repeaters

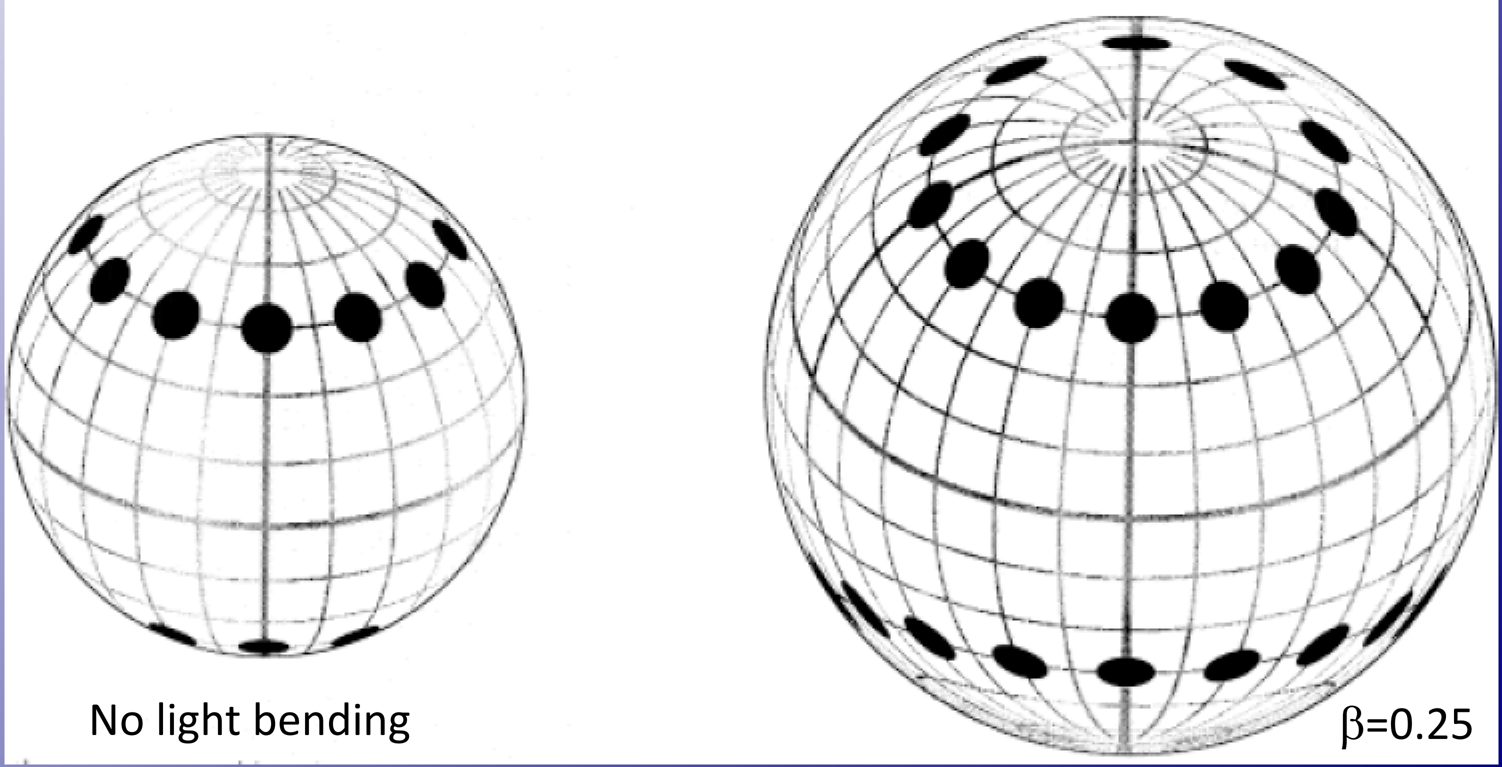
Sun coronal loop (≈5 gauss)

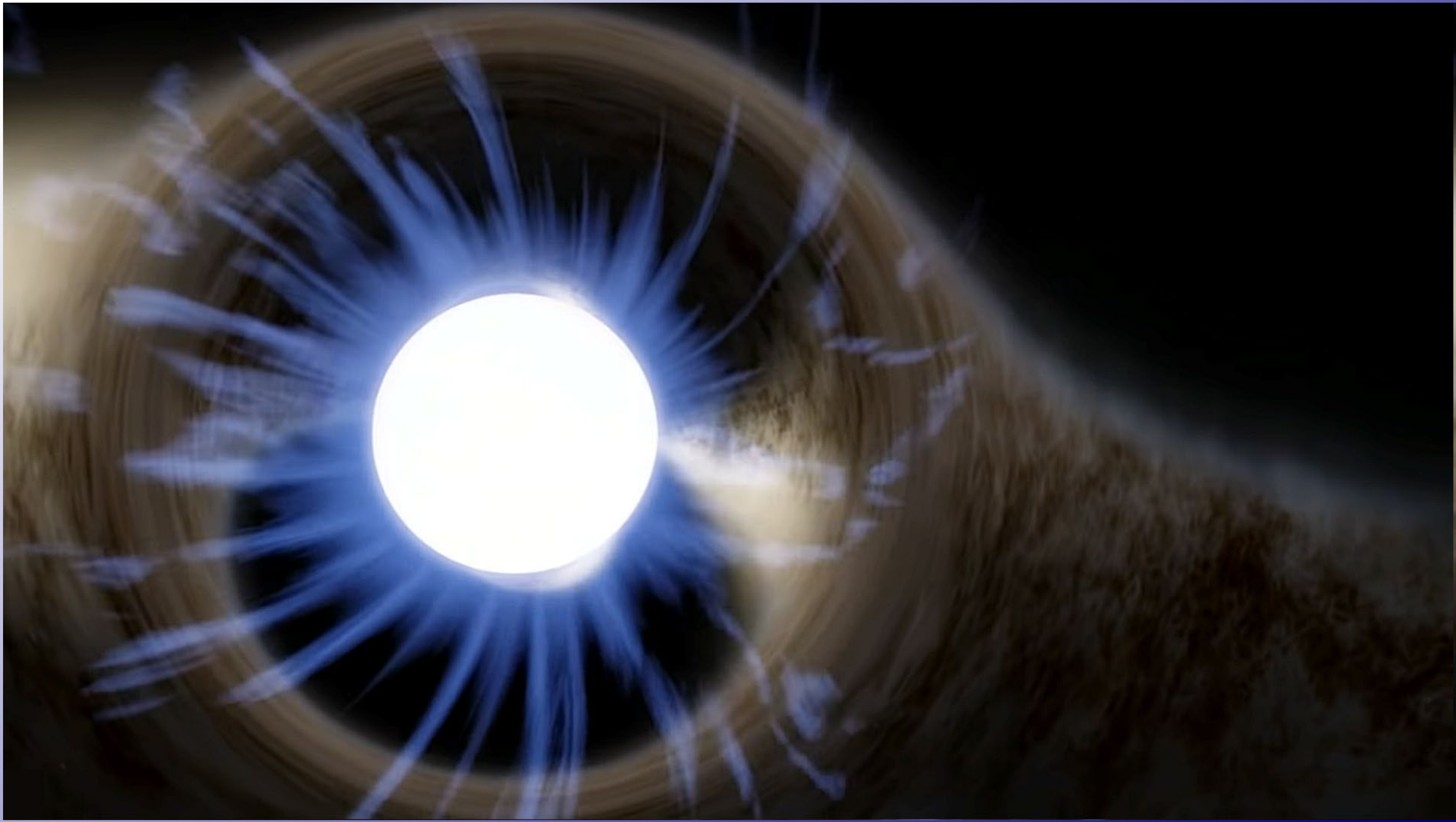
Magnetic reconnection



(Expected) observable phenomena

Measurement	*M*, *R* dependence	Approach
Redshift/compactness	$\beta = GM/Rc^2$	Lightcurves and spectra
Surface gravity	$g = GM/R^2$	Lightcurves and spectra
Light-bending magnified radius	$R_\infty = R\Big/\sqrt{1-2GM/Rc^2}$	Thermal spectra
Maximum mass	$M \le M_{\max}$, for all R	Pulse timing
Minimum spin period	$P_{\min} \propto \sqrt{R^3/M}$	Pulsation searches
Fractional moment of inertia in crustal superfluid	$\Delta I/I \propto R^4/M^2$	Glitch monitoring
Seismic vibrations	Mode-dependent	Flux oscillations in flares, bursts





Light bending as around black holes

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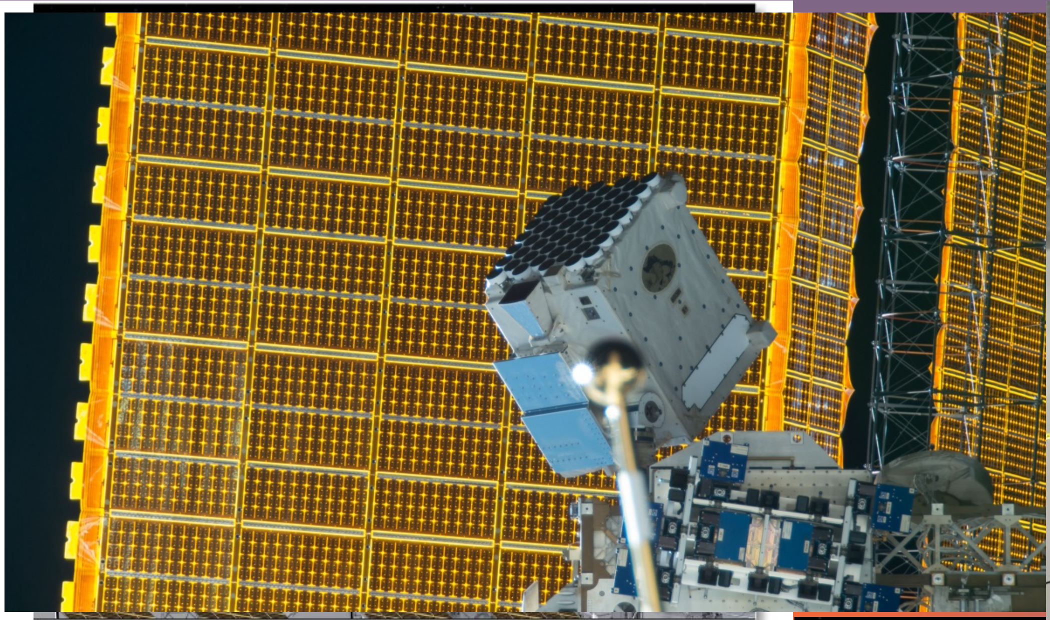
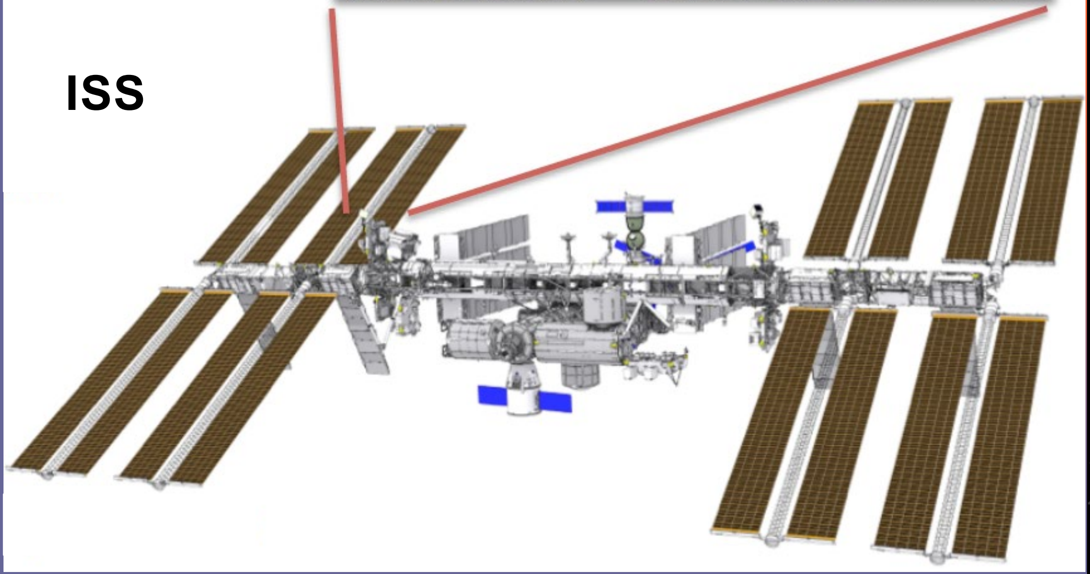
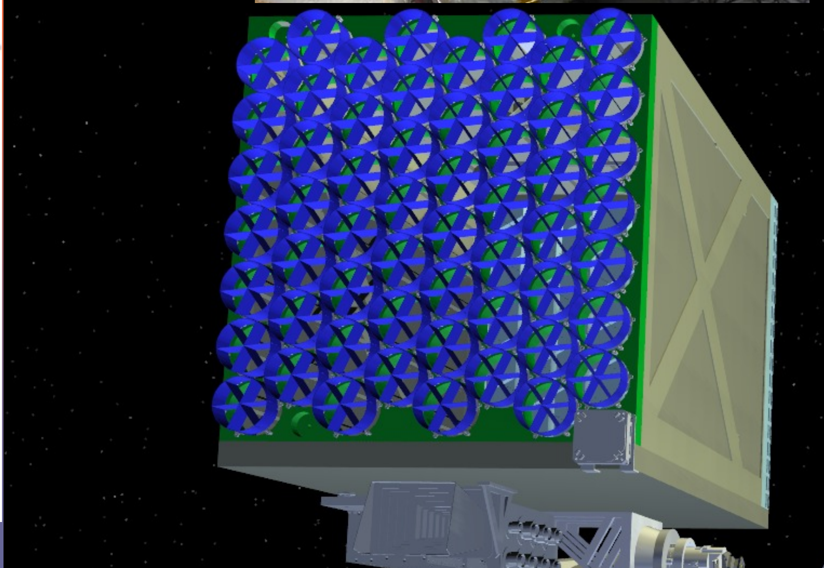
NICER

Neutron star
Interior
Composition
Explore**R**

Launch
June 2017

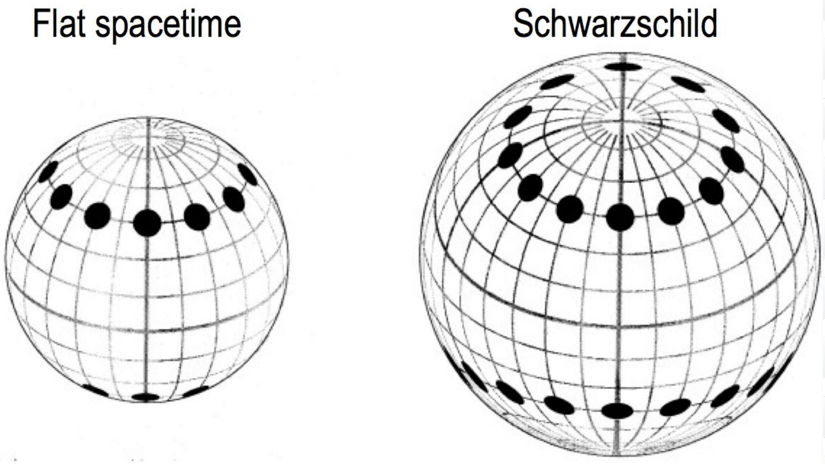


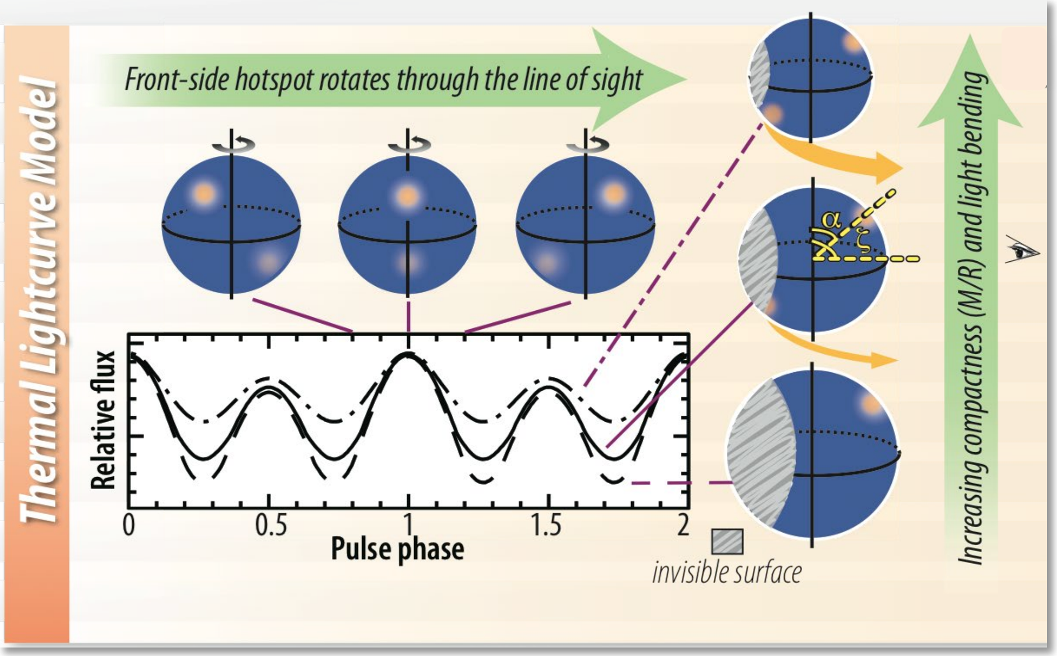


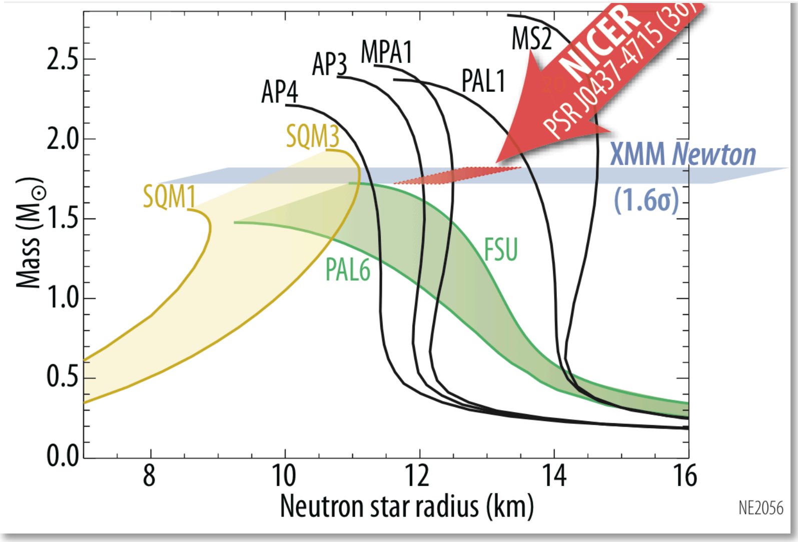


NICER Science objectives
I — Neutron Star Structure

Probing ultra-dense matter through soft X-ray timing spectroscopy







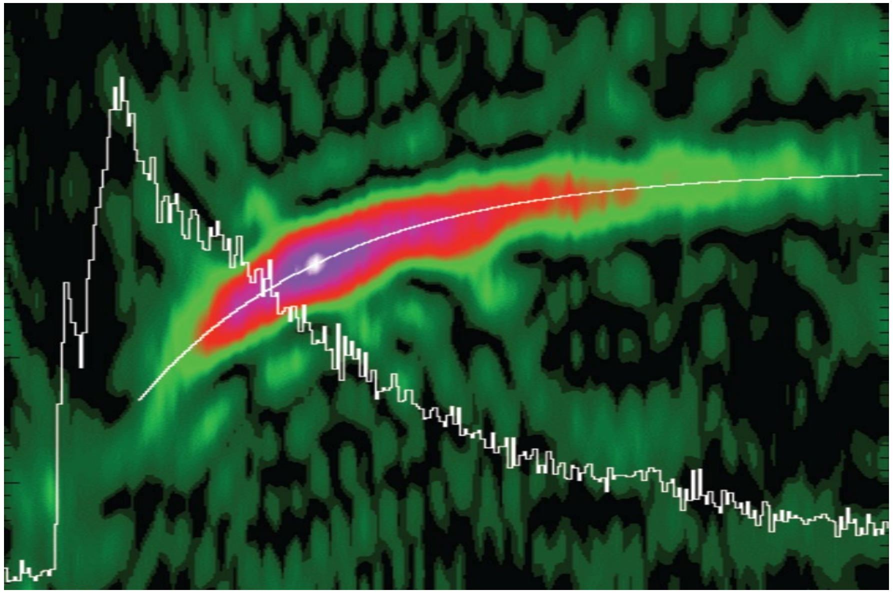
Objective	Measurements
Structure — Uncover the nature of matter in the interiors of neutron stars	Neutron star radii to ±5%, masses, & Cooling timescales
Dynamics — Reveal physics of dynamic phenomena associated with neutron star variability on many timescales	Stability of pulsars as clocks. Properties of outbursts, oscillations, and precession
Energetics — Determine how energy is extracted from neutron stars.	Intrinsic radiation patterns, spectra, and luminosities

NICER Science objectives
II — Neutron Star Dynamics

Characterizing dynamic behavior due to spin, accretion, and starquakes

RXTE Puffed Accretion Disk
Version 2 with NO Wobble

Animation by
Dana Berry
SkyWorks Digital Animation
310-441-1735



Clock stability, starquakes, **thermonuclear explosions**, and bulk quantum phenomena (cooling)

Objective	Measurements
Structure — Uncover the nature of matter in the interiors of neutron stars	Neutron star radii to ±5%, masses, & Cooling timescales
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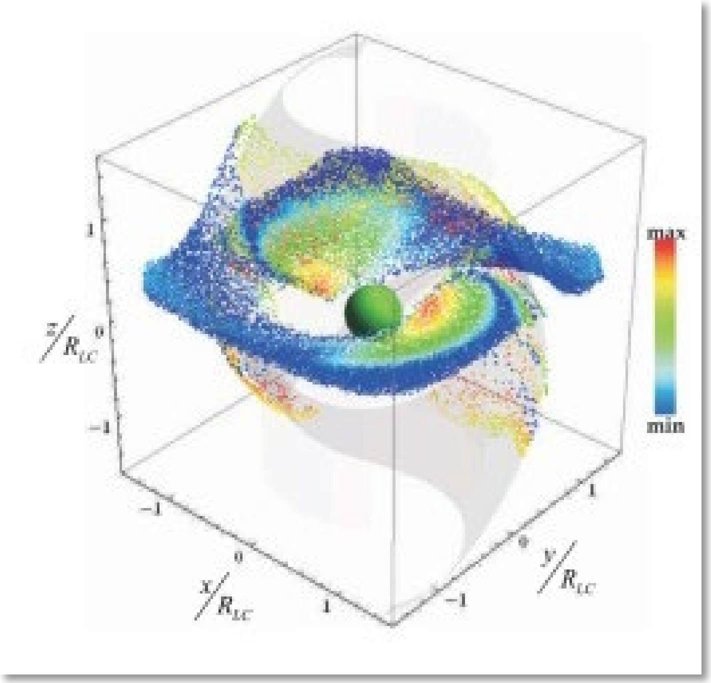
NICER Science objectives
III — Neutron Star Energetics

Establishing sites & mechanisms of radiation in neutron star magnetospheres



The most powerful magnetospheres known anywhere, only now beginning to be understood…

Objective	Measurements
Structure — Uncover nature of matter in the interiors of neutron stars	Neutron star radii to ±5%, masses, & Cooling timescales
Dynamics — Reveal physics of dynamic phenomena associated with neutron star variability on many timescales	Stability of pulsars as clocks. Properties of outbursts, oscillations, and precession
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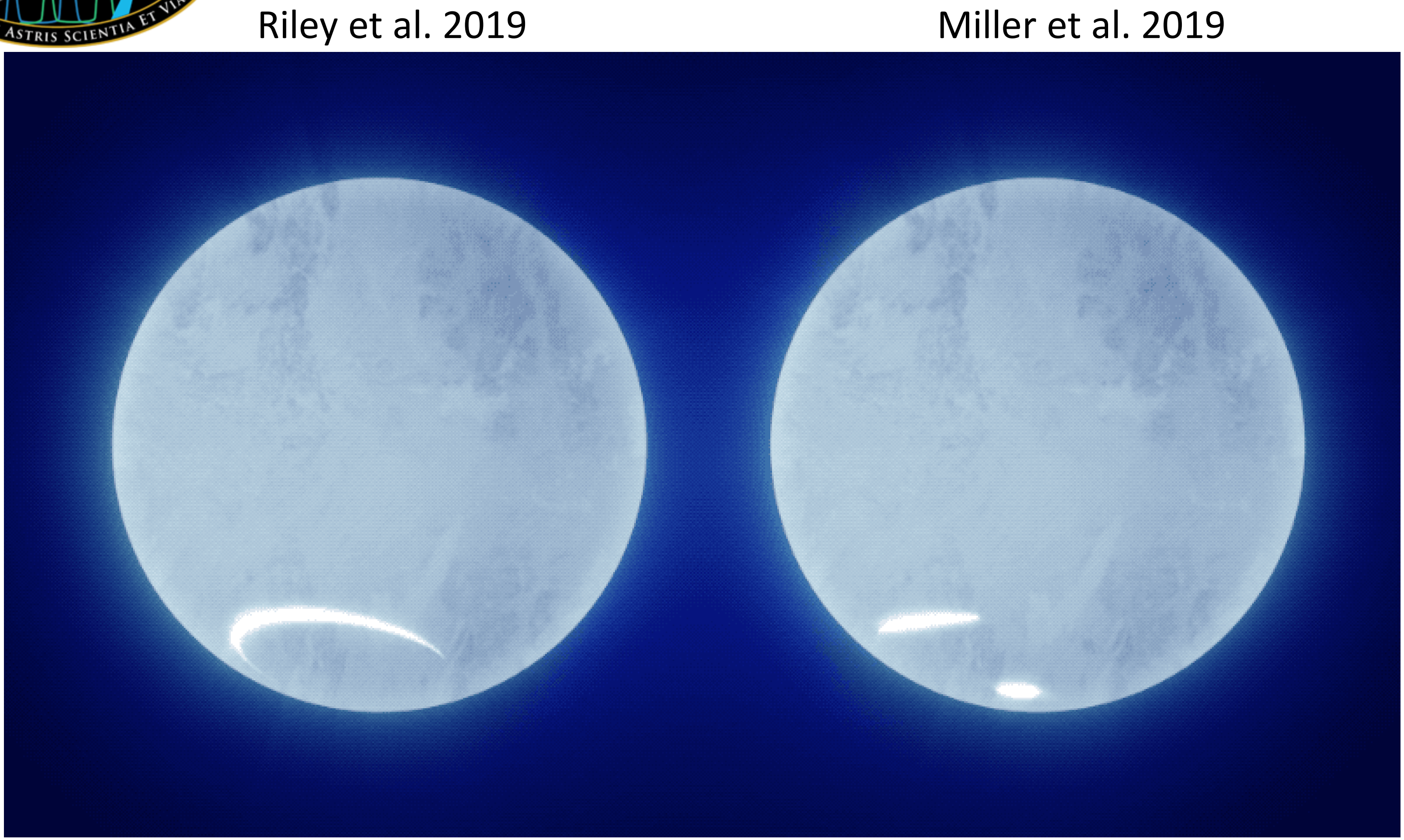
NICER view of PSR J0030+045

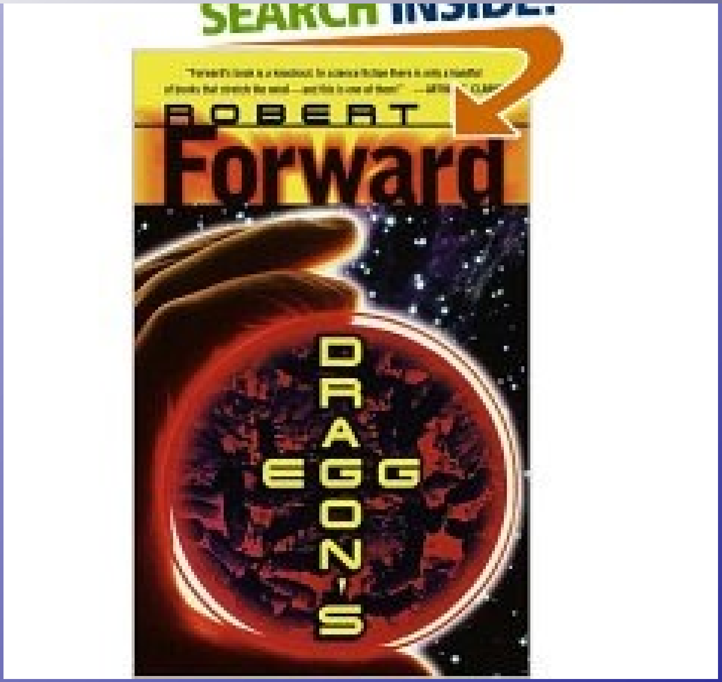


Lightcurve modeling constrains the compactness (*M/R*) and viewing geometry of a millisecond pulsar through the depth of modulation and harmonic content of emission from rotating hot-spots, thanks to gravitational light-bending

The end!

THE END ?

Suggested literature: “Dragon’s egg” by Robert Forward



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2. Supernovae (CasA ν*): Grefenstette et al. 2014, Nature 506, 339

3. Cataclysmic Variables: Mukai 2003, Adv. Space Res. 32, 2067