Neutron stars and the properties of matter under extreme conditions:

General introduction

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University of Illinois, Urbana

8th Huada School on QCD
Central China Normal University
Wuhan 武汉
May 6-10, 2019

ILLINOIS 150 1867-2017

華中師範大學
CENTRAL CHINA NORMAL UNIVERSITY

THE NEUTRON STAR NEWS

Special Wuhan Edition | FROM QUARKS TO THE COSMOS | - Since 1934

DIRECT DETECTION OF GRAVITATIONAL RADIATION FROM A BINARY NEUTRON STAR MERGER GW170817 – MULTI-MESSENGER ASTRONOMY –PRODUCING GOLD AND OTHER HEAVY ELEMENTS. TWO MERGER REPORTS APRIL 25 AND 26!!

DIRECT OBSERVATIONS OF 2.0 SOLAR MASS STARS AND ONE OF 2.17 ON APRIL 14

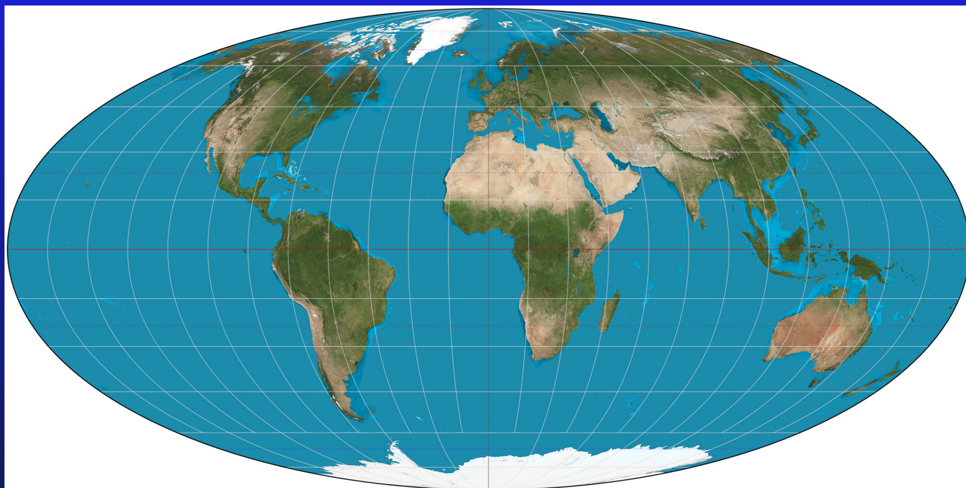
ONGOING DETERMINATIONS OF MASSES AND RADII CONSTRAINING NEUTRON STAR INTERIORS: NICER EXPERIMENT, ON INTERNATIONAL SPACE STATION

EMERGING UNDERSTANDING IN QCD OF HOW NUCLEAR MATTER TURNS INTO DECONFINED QUARK MATTER AT HIGH BARYON DENSITIES
(*complementary to studying dense matter in ultrarelativistic heavy ion collision experiments at RHIC and the LHC*)

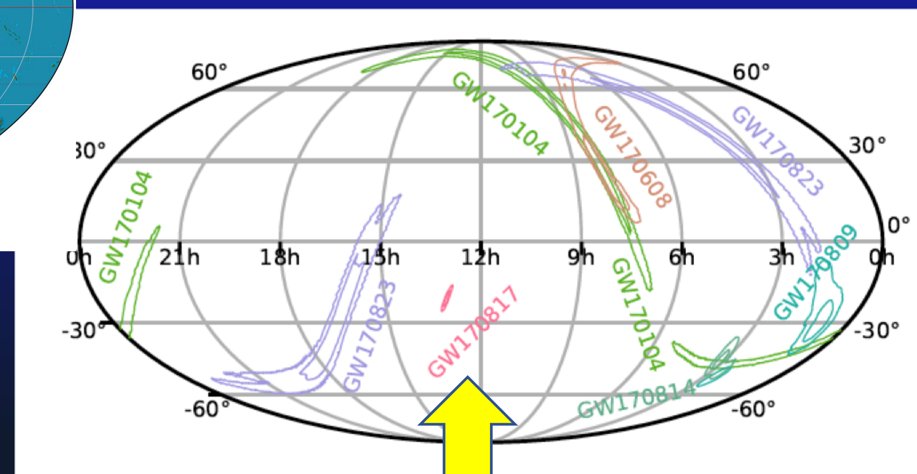
Neutron star – neutron star merger observed on 17 Aug. 2017

by LIGO and Virgo (gravitational radiation), FERMI (gamma ray telescope) + ~ 70 other electromagnetic observatories. GW170817

Merger was 130,000,000 light years = 40 MPc away



Mollweide projection

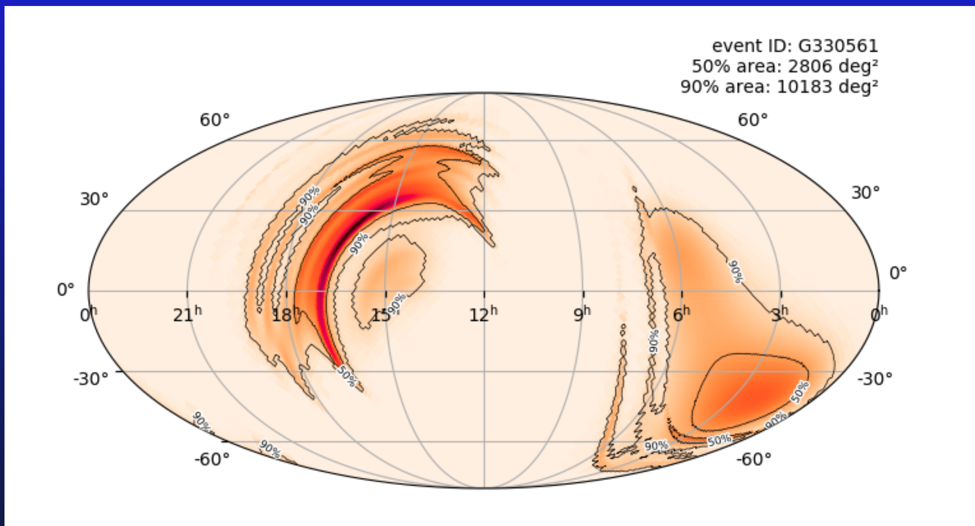


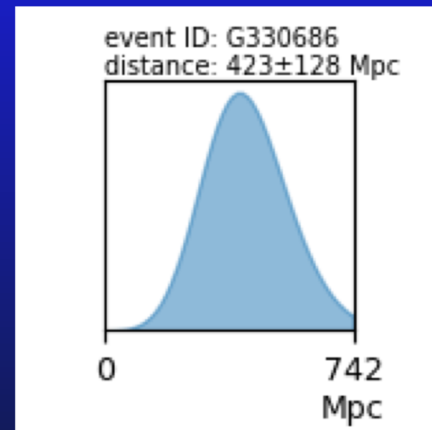
GW170817

Two binary neutron star merger candidates in LIGO/Virgo O3 run

S190425z LIGO (Livingston) + Virgo. 042519

Hanford detector of LIGO was down for 40 minutes when event occurred.



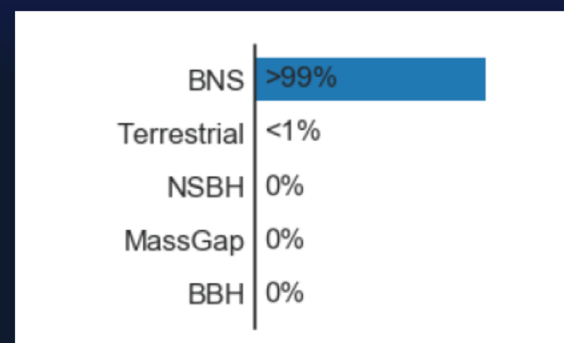


~1380 ly

False alarm rate: 1 per 69834 years

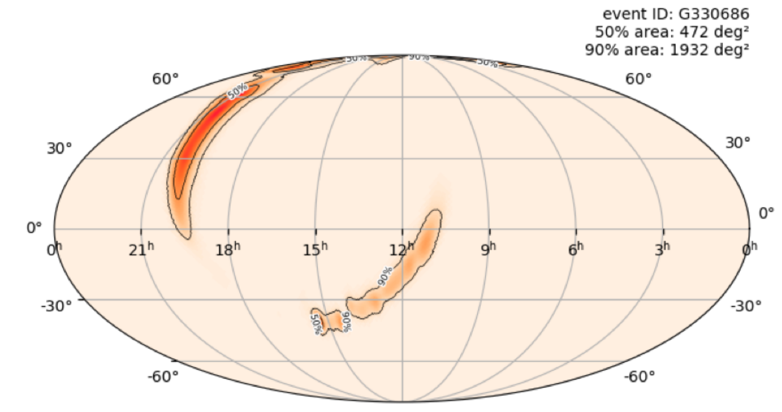
Neutron star-neutron star merger most likely.

Very poor localization in sky => difficult to carry out electromagnetic observations.

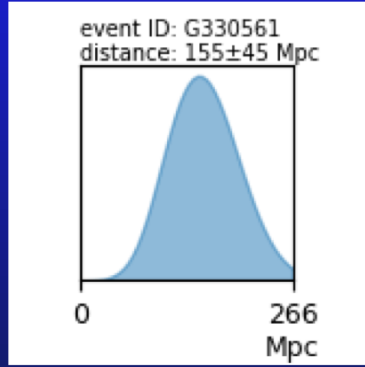


Source classification visualization from p_astro.json p_astro.png. Submitted by LIGO/Virgo EM Follow-Up on Apr 25, 2019 08:22:05 UTC

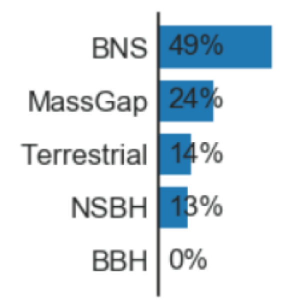
S190426c LIGO (H + L) + Virgo. 042619



Mollweide projection of bayestar1.fits bayestar1.png. Submitted by LIGO/Virgo EM Follow-Up on Apr 26, 2019 16:21:03 UTC



~500 ly



Source classification visualization from p_astro.json p_astro.png. Submitted by LIGO/Virgo EM Follow-Up on Apr 26, 2019 15:47:04 UTC

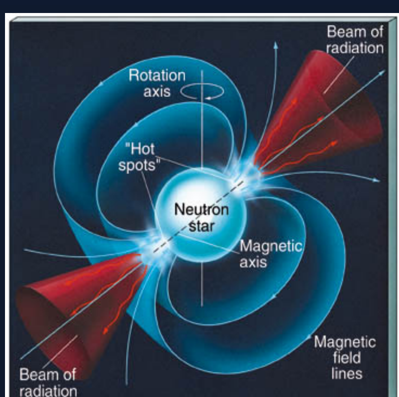
Low significance,
False alarm rate: 1 per 1.6276 years
15% chance of being spurious

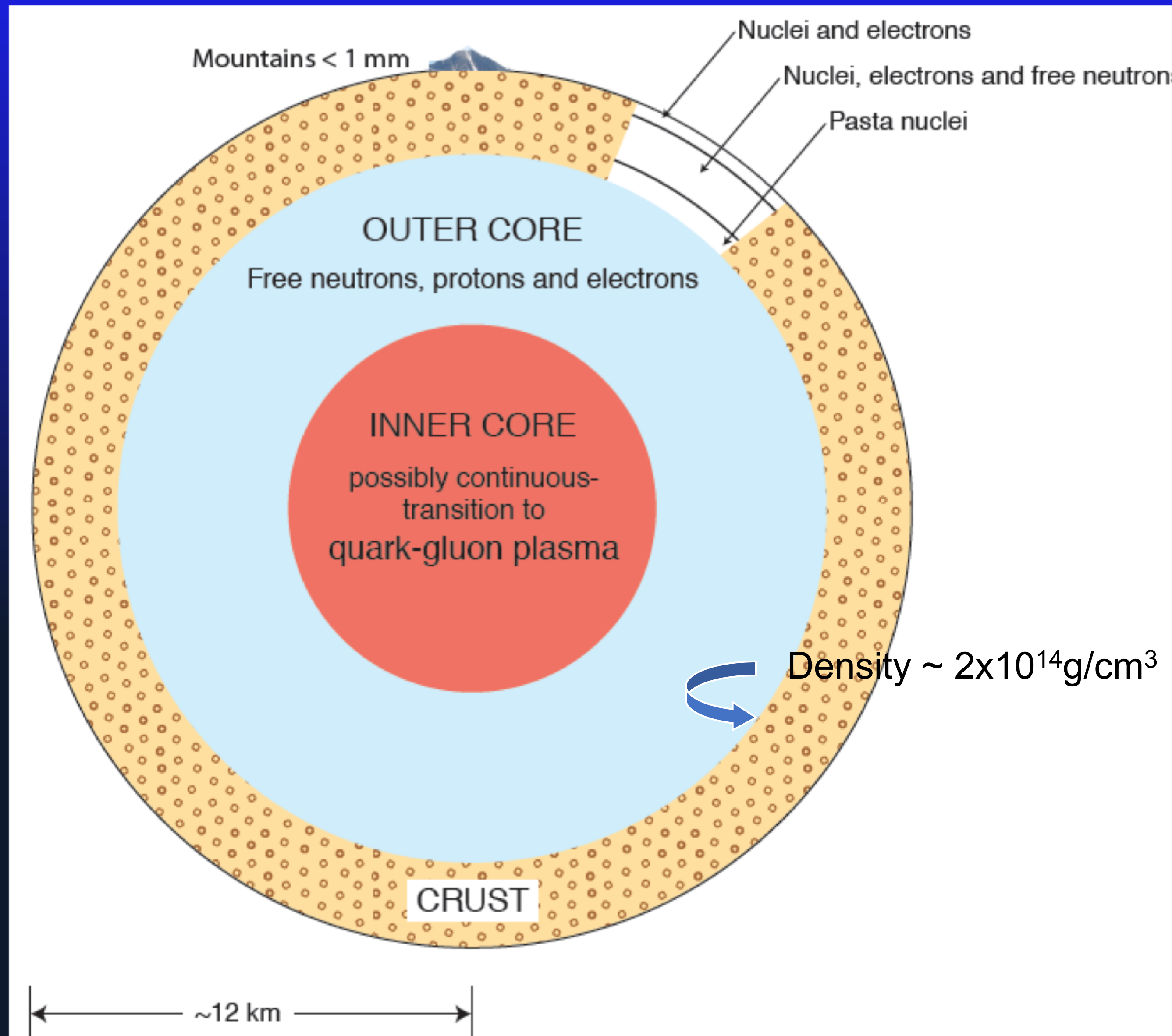
Binary neutron star merger?
Neutron star-black hole merger?
No electromagnetic observations yet!

Neutron star interior

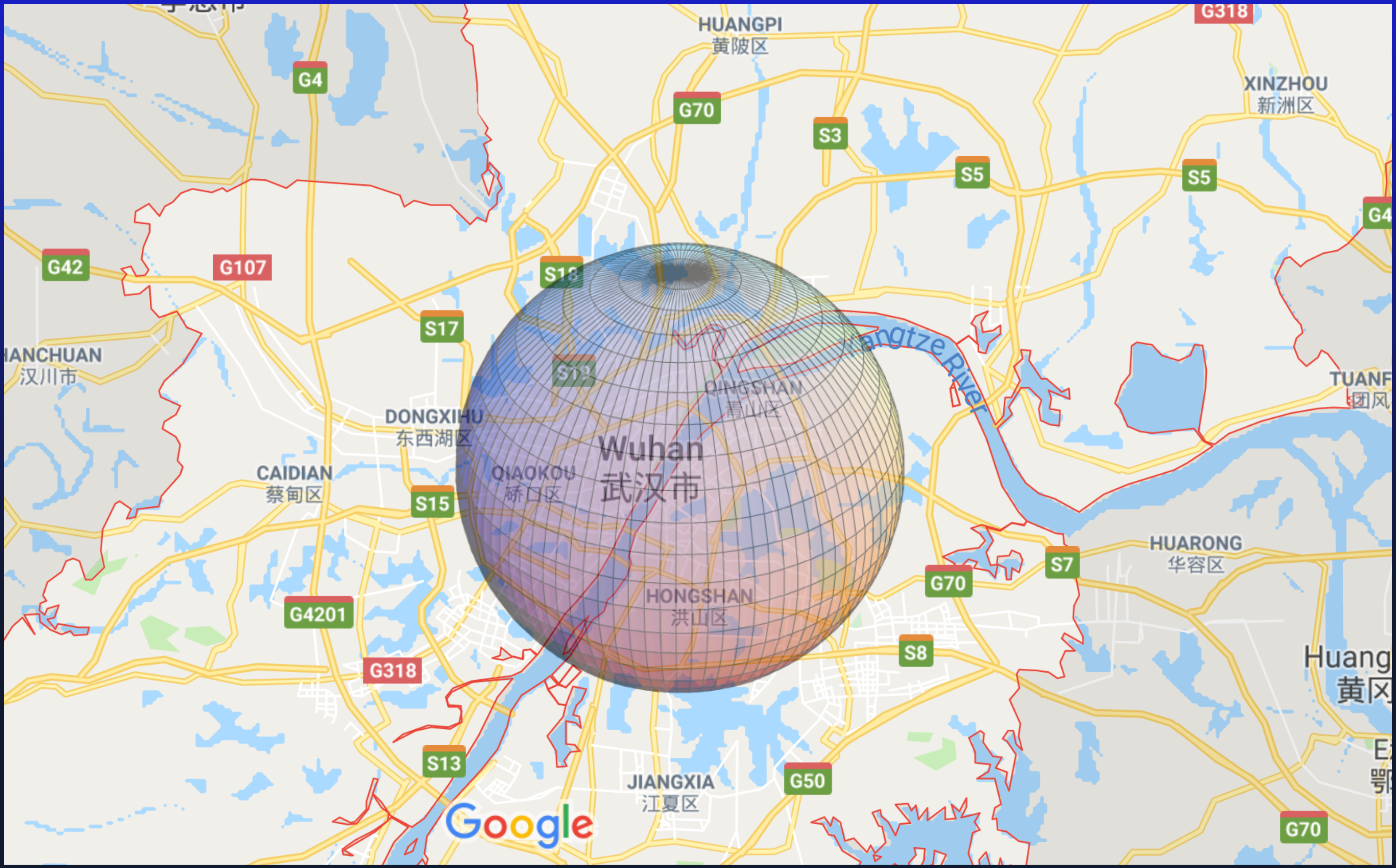
Mass ~ 1.4-2 M_{sun}
Radius ~ 10-12 km
Temperature
~ 10^6-10^9 K

Surface gravity
~10^{11} that of Earth
Surface binding
~ 1/10 mc^2





Neutron star over Wuhan



Masses ~ 1-2 $M_\odot$

Baryon number ~ 10^{57}

Radii ~ 10-12 km

Magnetic fields ~ 10^6 - 10^{15}G

Made in gravitational collapse of massive stars (supernovae)

Central element in variety of compact energetic systems:
pulsars, binary x-ray sources, soft gamma repeaters

Merging neutron star-neutron star and neutron star-black hole
sources of gamma ray bursts and gravitational waves

Matter in neutron stars is densest in universe:
baryon density n up to ~ 5-10 n_0 (ρ_0 = 3 X10^{14}g/cm^3 = density of matter in atomic nuclei = 0.16 /fm^3) 1 fm = 10^{-13} cm

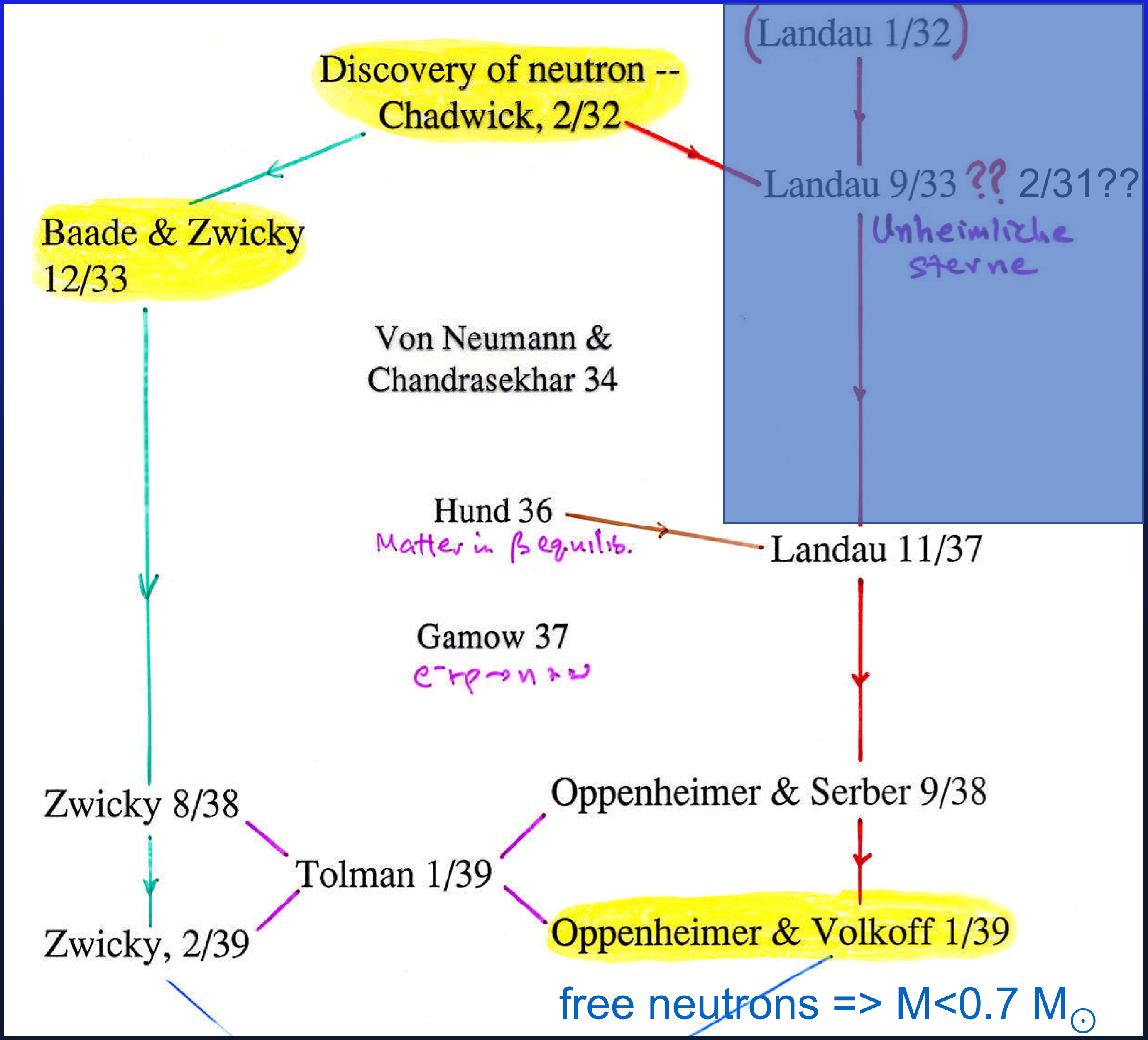
[cf. white dwarfs: ρ ~ 10^5-10^9 g/cm^3]

Supported against gravitational collapse by nucleon degeneracy pressure

Astrophysical laboratory for study of high density matter

What are states in interior? Existence of quark stars?

Early History of Neutron Stars



Chadwick to Bohr, 24 Feb. 1932 announcing the discovery of the neutron

Cavendish Laboratory,
Cambridge.

24 February 1932.

Dear Bohr,

I enclose the proof of a letter I have written to "Nature" and which will appear either this week or next. I thought you might like to know about it beforehand.

The suggestion is that α particles eject from beryllium (and also from boron) particles which have no nett charge, and which probably have a mass about equal to that of the proton. As you will see, I put this forward rather cautiously, but I think the evidence is really rather strong. Whatever the radiation from Be may be, it has most remarkable properties. I have made many experiments which I do not mention in the letter to "Nature" and they can all be interpreted readily on the assumption that the particles are neutrons. Feather has taken some pictures in the expansion chamber and we have already found about 20 cases of recoil atoms. About 4 of these show an abrupt bend or fork (and it is almost certain that the one arm of this fork represents a recoil atom and the other (some other particle, probably an α particle. These are disintegrations due to the capture of the neutron by N_{14} or O_{16}. I enclose two photographs one of which shows the simple recoil atom, and the other what we suppose is a disintegration. The photographs are not very good but they were printed in a hurry.

With best regards

Yours sincerely

J. Chadwick.

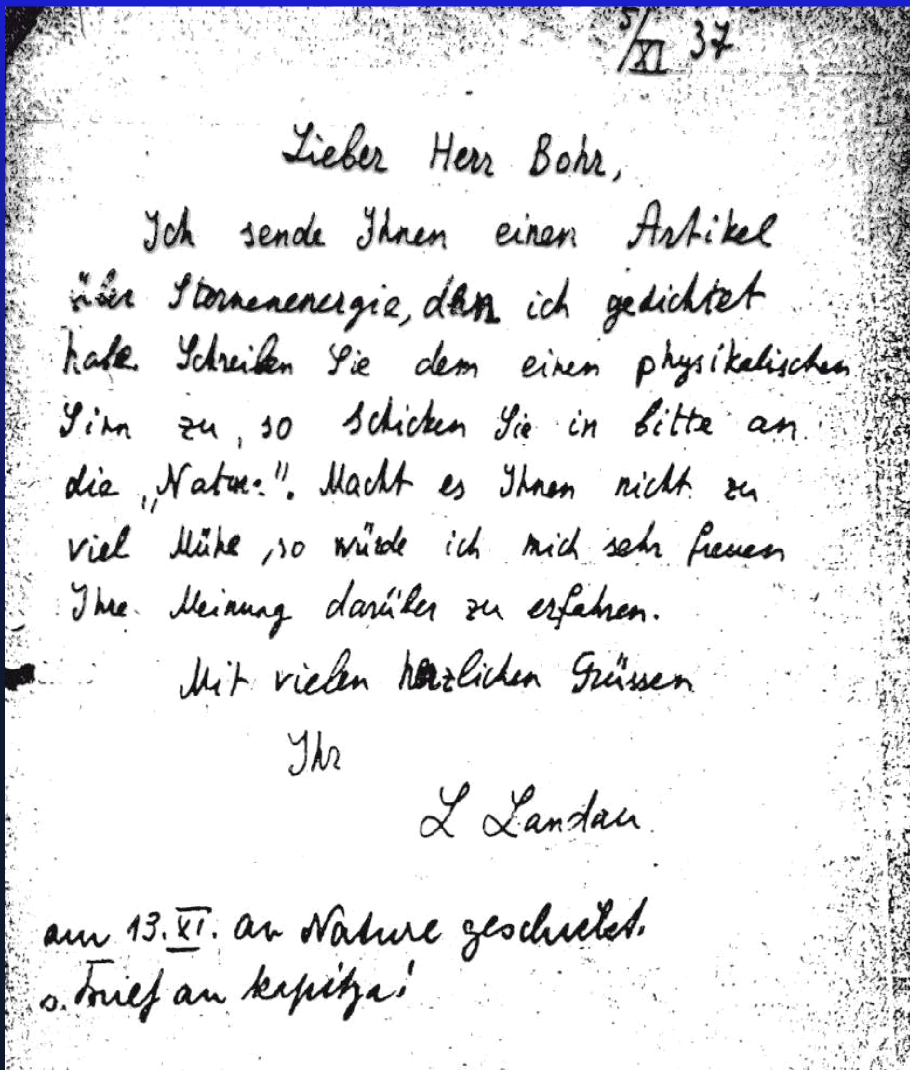
W. Baade and F. Zwicky

Stanford APS Meeting, 15-16 Dec. 1933

Phys. Rev. 45, 138 (1934)

38. Supernovae and Cosmic Rays. W. BAADE, *Mt. Wilson Observatory,* AND F. ZWICKY, *California Institute of Technology.*—Supernovae flare up in every stellar system (nebula) once in several centuries. The lifetime of a supernova is about twenty days and its absolute brightness at maximum may be as high as $M_{vis} = -14^M$. The visible radiation L_v of a supernova is about 10^8 times the radiation of our sun, that is, $L_v = 3.78 \times 10^{41}$ ergs/sec. Calculations indicate that the total radiation, visible and invisible, is of the order $L_\tau = 10^7 L_v = 3.78 \times 10^{48}$ ergs/sec. The supernova therefore emits during its life a total energy $E_\tau \geqq 10^5 L_\tau = 3.78 \times 10^{53}$ ergs. If supernovae initially are quite ordinary stars of mass $M < 10^{34}$ g, E_τ / c^2 is of the same order as M itself. In the *supernova* process *mass in bulk is annihilated*. In addition the hypothesis suggests itself that *cosmic rays are produced by supernovae*. Assuming that in every nebula one supernova occurs every thousand years, the intensity of the cosmic rays to be observed on the earth should be of the order $\sigma = 2 \times 10^{-3}$ erg/cm² sec. The observational values are about $\sigma = 3 \times 10^{-3}$ erg/cm² sec. (Millikan, Regener). With all reserve we advance the view that supernovae represent the transitions from ordinary stars into *neutron stars*, which in their final stages consist of extremely closely packed neutrons.

Landau to Bohr, 11 November 1937



5/XI 37

Lieber Herr Bohr,

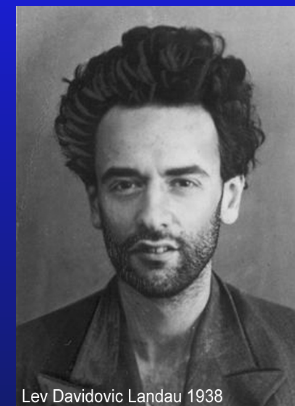
Ich sende Ihnen einen Artikel über Sternenenergie, den ich gedichtet habe. Schreiben Sie dem einen physikalischen Sinn zu, so schicken Sie ihn bitte an die „Nature“. Macht es Ihnen nicht zu viel Mühe, so würde ich mich sehr freuen Ihre Meinung darüber zu erfahren.

Mit vielen herzlichen Grüssen

Ihr

L Landau

am 13.XI. an Nature geschickt.
u. Brief an Kapitza!



Lev Davidovic Landau 1938

I send you an article about stellar energy, which I have written. If you think it makes physical sense, please send it to “Nature”. Do not put too much work into it, and it would make **me** very happy to learn what you think about it.

Izvestia to Bohr

TELEGRAM MOSCOU M279 30 17 2231 NORTHERN =

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KBH =

Tj. Bem.

Telegrafstation

KØBENHAVN
17.NOV.1937

Dato:

Kl. 2114 af

Lbnr. til den Kl. af

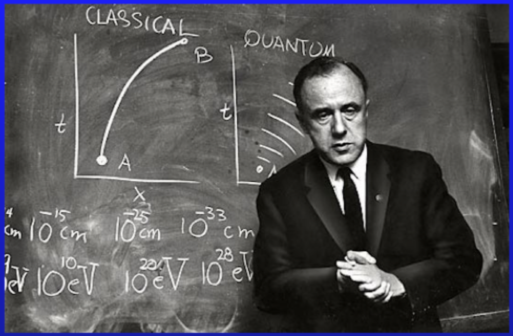
WE DESIRE PUBLISH YOUR OPINION IN OUR NEWSPAPER IN CONNECTION WITH DISCUSSIONS OF LANDAUS LAST WORK REGARDING NEUTRON CORE IN SCIENTIFIC ORGANIZATIONS =

IZVESTIA EDITORIAL OFFICE

Vedtagne Forkortelser: D Iltelegram. RP Svar betalt. TC Kollationering. Ouvert Udleveres aabent. MP Udlev. egenhændigt. FS Eftersendes. PC Modtagelsesbevis. XP Bud betalt.

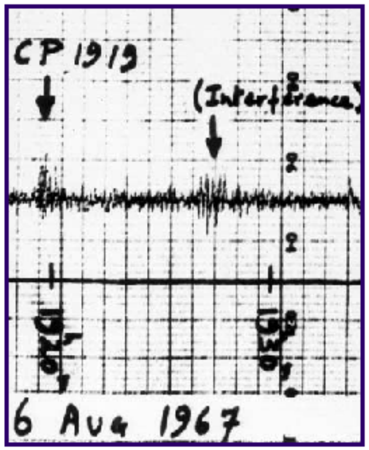
T. 4 (C 5)

J. Wheeler
Ann. Rev. Astronomy and Astrophysics, 1966

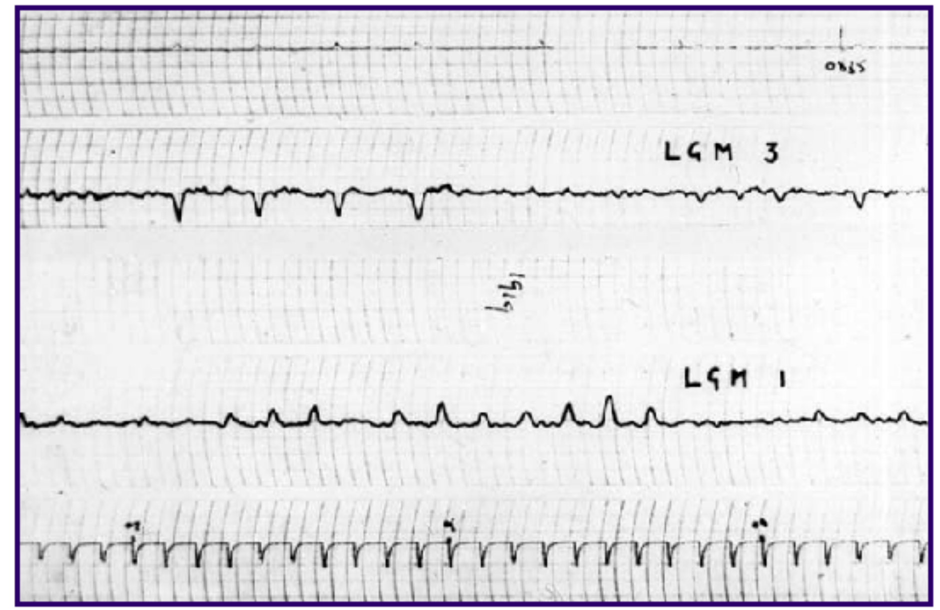


"So far no superdense star has been identified. Moreover, a `cool' superdense star -- with a radius of 10 km, with a surface temperature (after ~10^6 years of cooling) of 10^6 °K, and at a distance of 10pc, comparable to the distance of near-by stars -- is fainter than the 19th magnitude and therefore hardly likely to be seen. The rapidity of cooling makes detection even more difficult."

1967 (November) First pulsar detection: 1919+21
Bell & Hewish



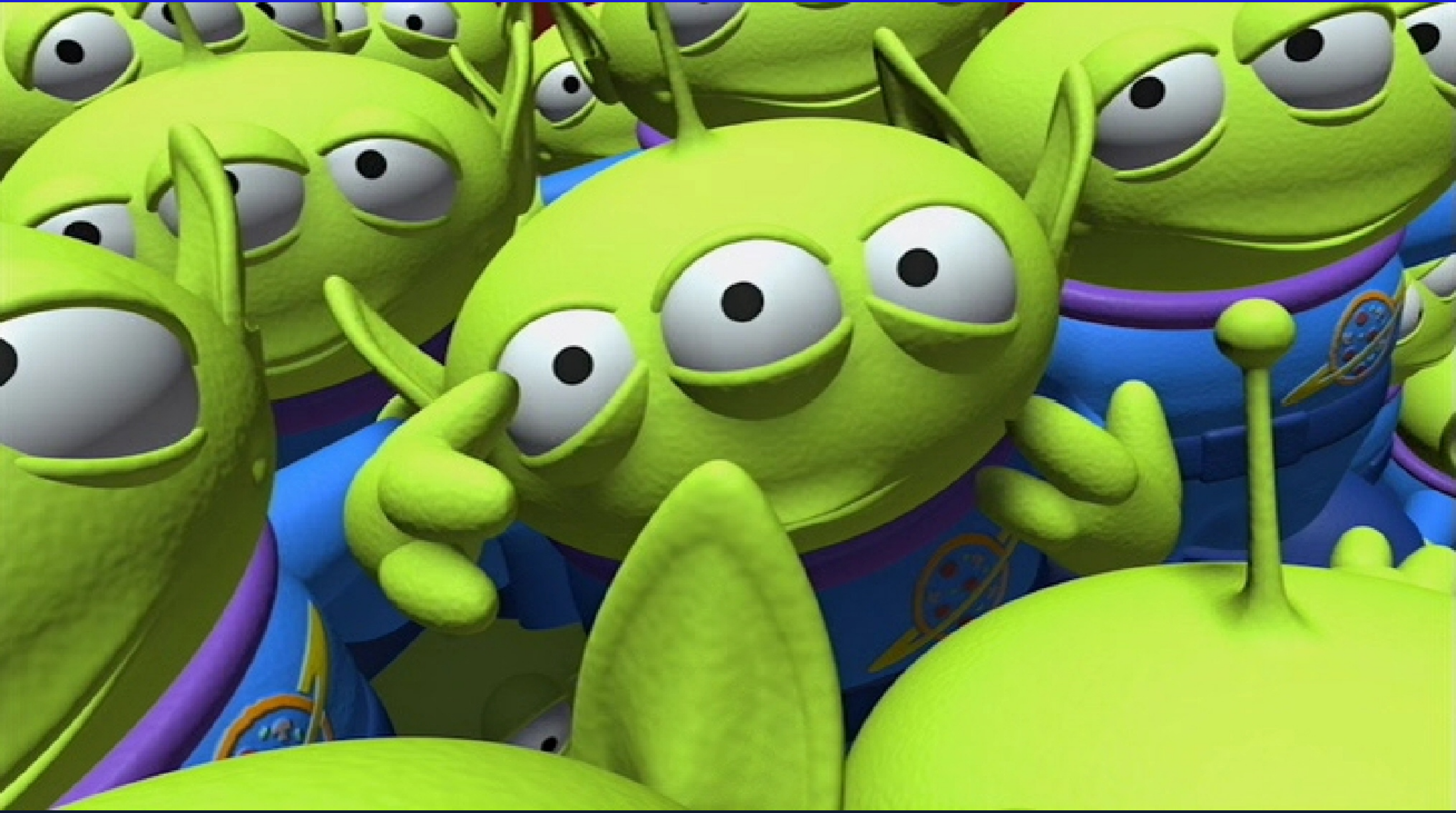
2: The first detection of the first pulsar, occupying about one-quarter inch of chart paper. About five minutes later is a short burst of low level interference. This signal has been high-pass filtered, to remove the telescope's interference pattern. (Mullard Radio Astronomy Observatory.)



3: The bottom trace is of broadcast one-second time pips. The middle trace shows the first recording to reveal the pulsed nature of the pulsar PSR1919. The top trace is of the third pulsar discovered, PSR0834.

"It was highly unlikely that there would be two lots of little green men on opposite sides of the universe both deciding to signal at the same time to a rather inconspicuous star on a rather curious frequency." Jocelyn Bell

1968 (Spring): Pulsars identified as rotating neutron stars by Tommy Gold and Franco Pacini



Detection of neutron stars in x-ray

Early 1960's: observations of x-ray sources (Sco X-1) by balloon flights

1972: x-ray pulsars in binary stars: UHURU

(Ricardo Giacconi et al.)

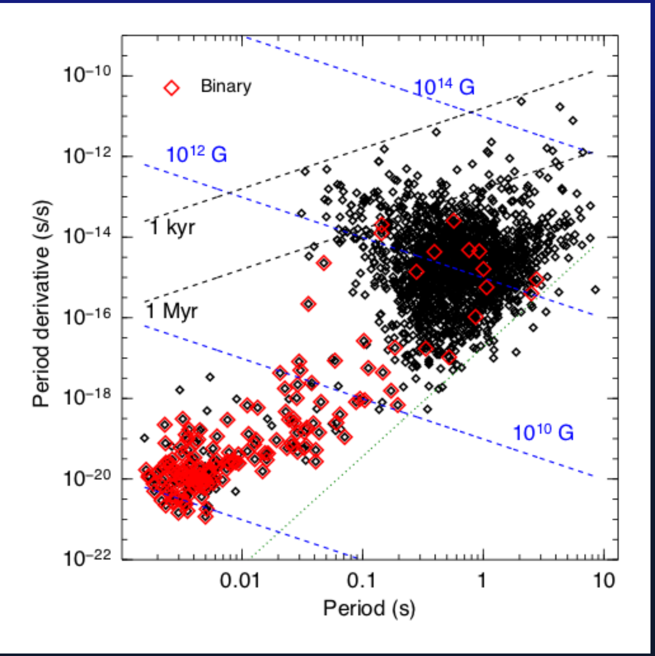
Observed neutron stars

> 1500 ns in isolated rotation-powered radio pulsars
~ 400 millisecond pulsars (1/716 < P <1/30 sec.)
https://apatruno.wordpress.com/about/millisecond-pulsar-catalogue/

> 100 ns in accretion-powered x-ray binaries
~ 50 x-ray pulsars
intense x-ray bursters
(thermonuclear flashes)

Short (10-100 s) gamma-ray bursts
(ns-ns, ns-bh? mergers)

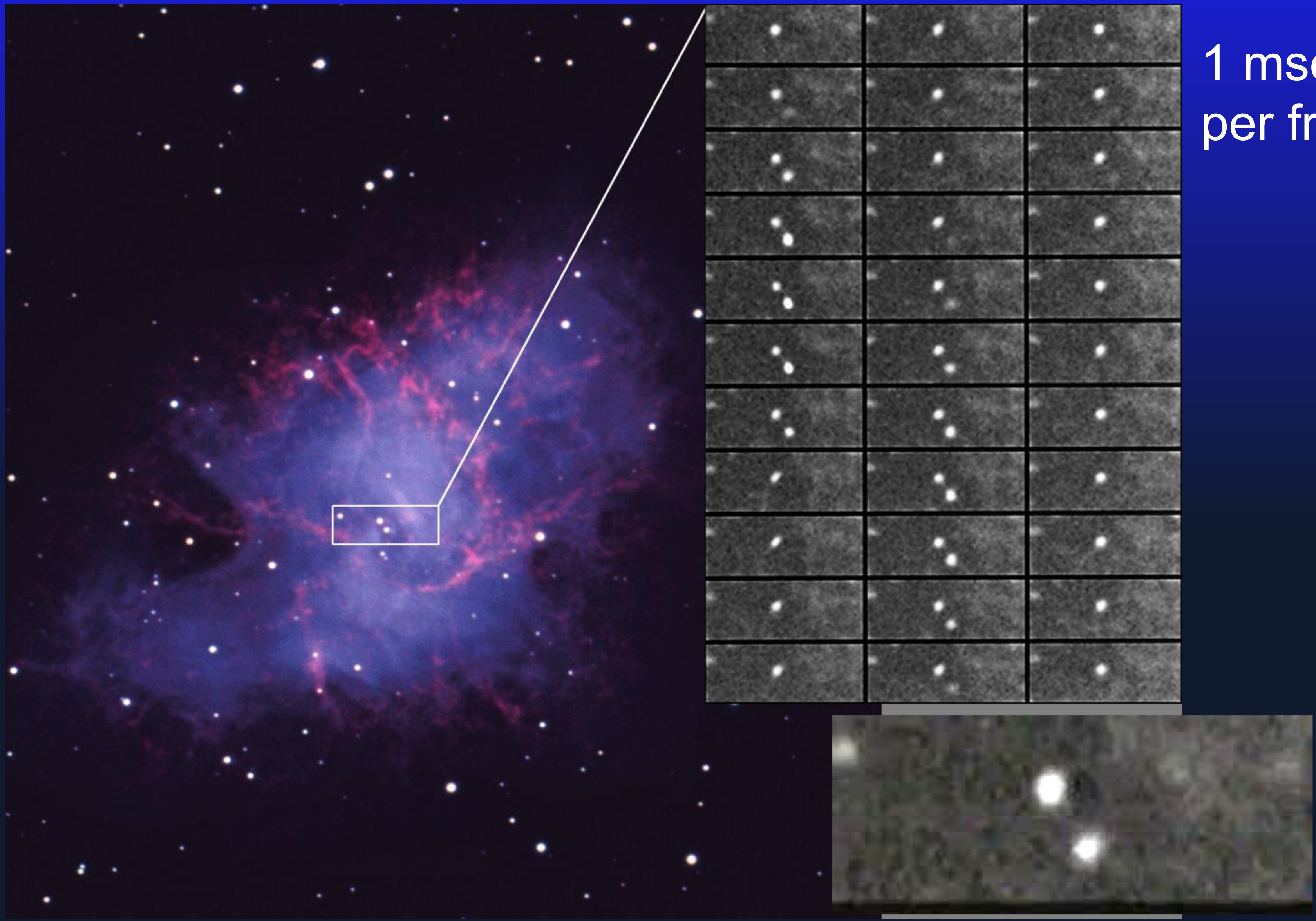
Soft gamma-ray repeaters
-- magnetars (B ~ 10^{14}-10^{15}G)



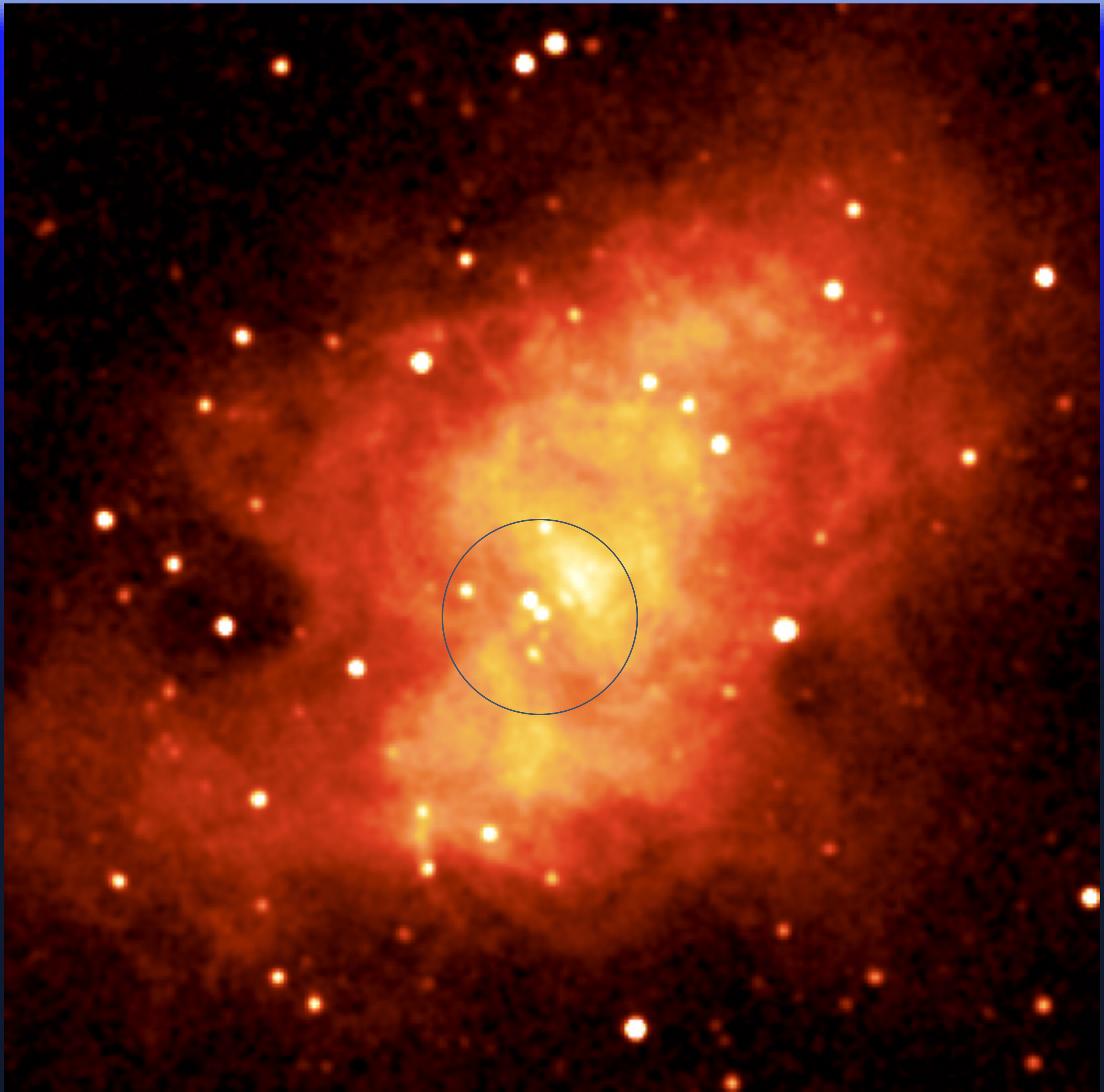
Period derivative vs period for known pulsars
Shown is dipolar magnetic field needed to give dP/dt.

Crab Pulsar (period = 33msec)

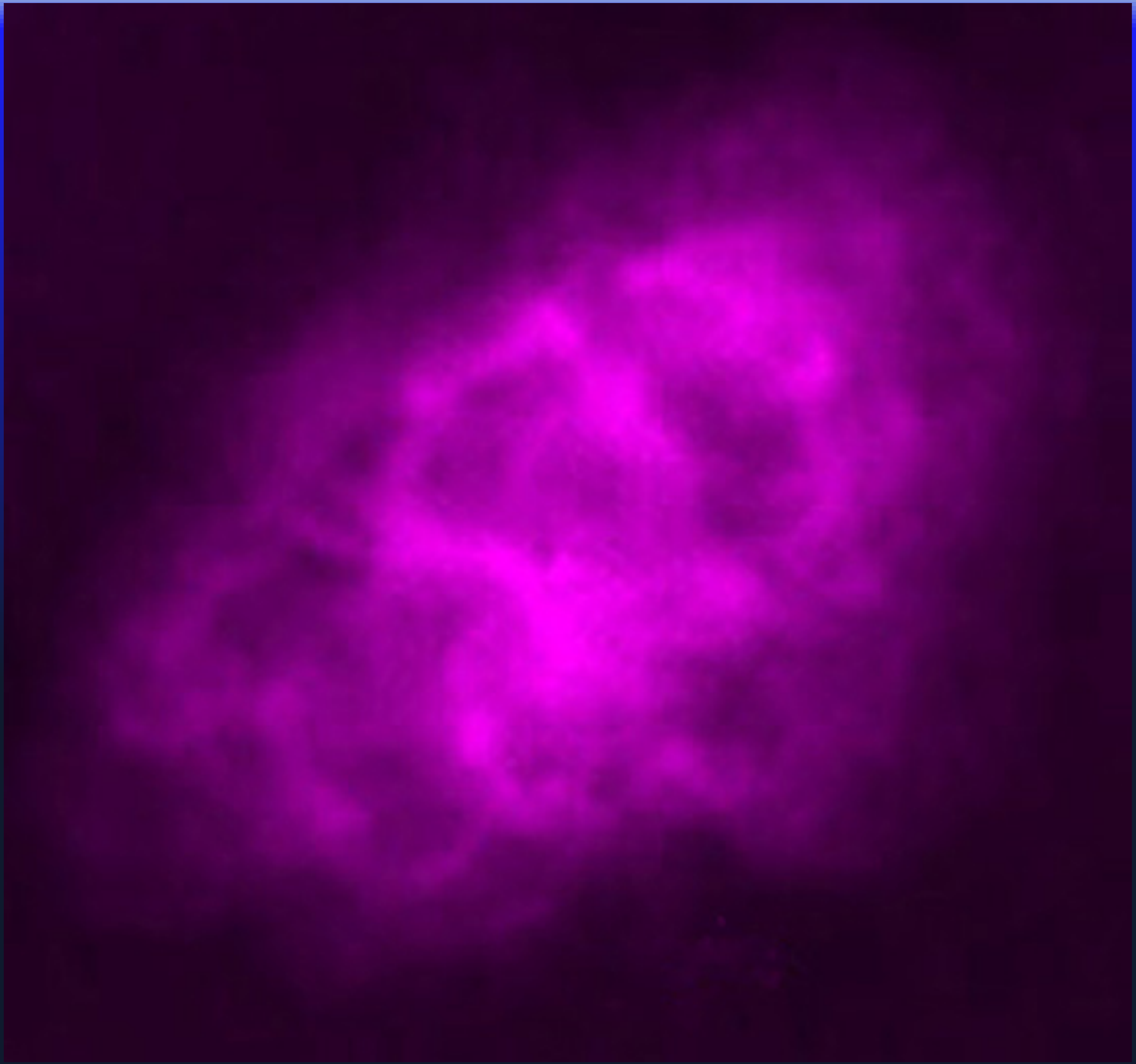
Supernova July 4, 1054



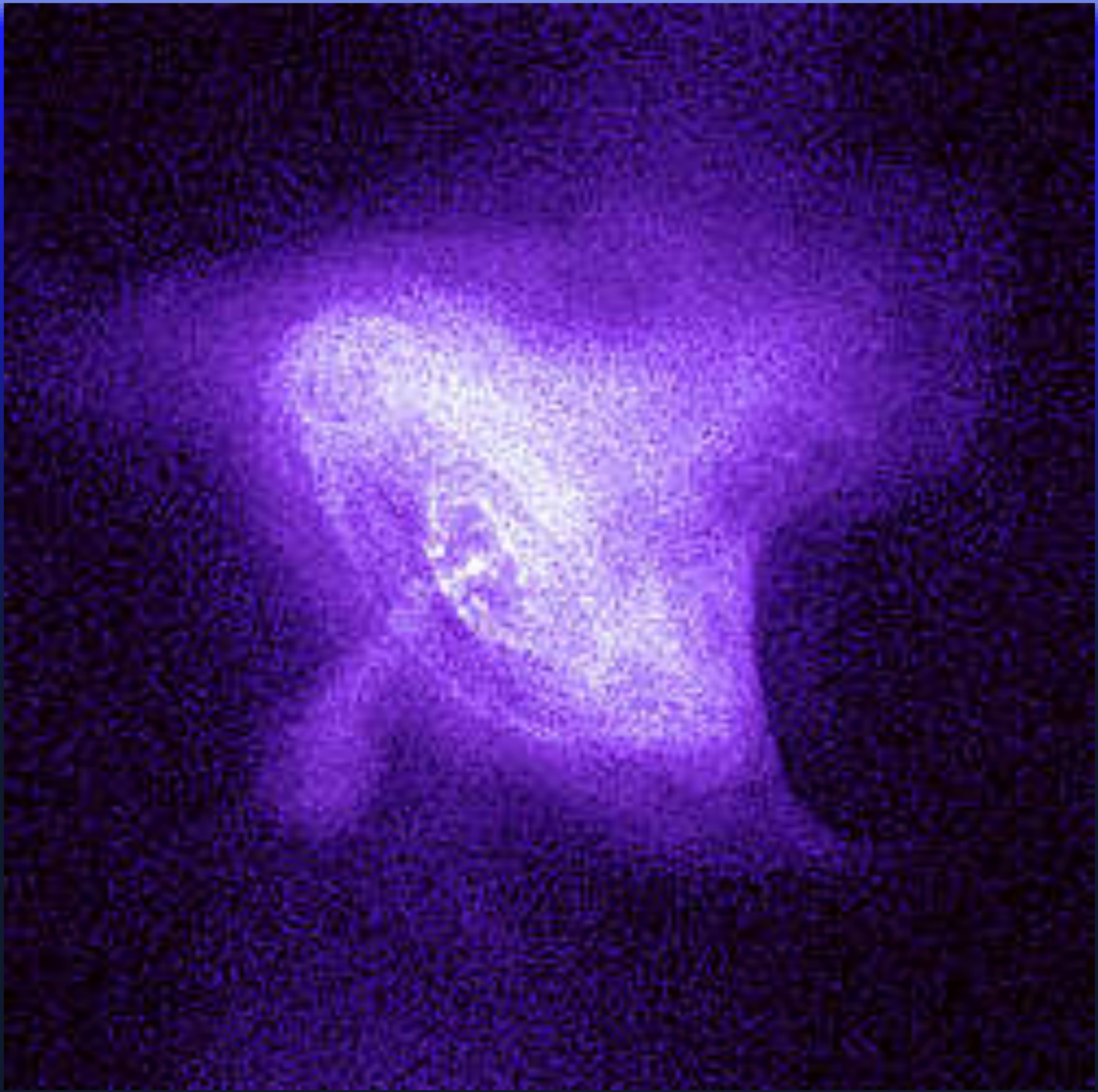
Crab nebula
in optical



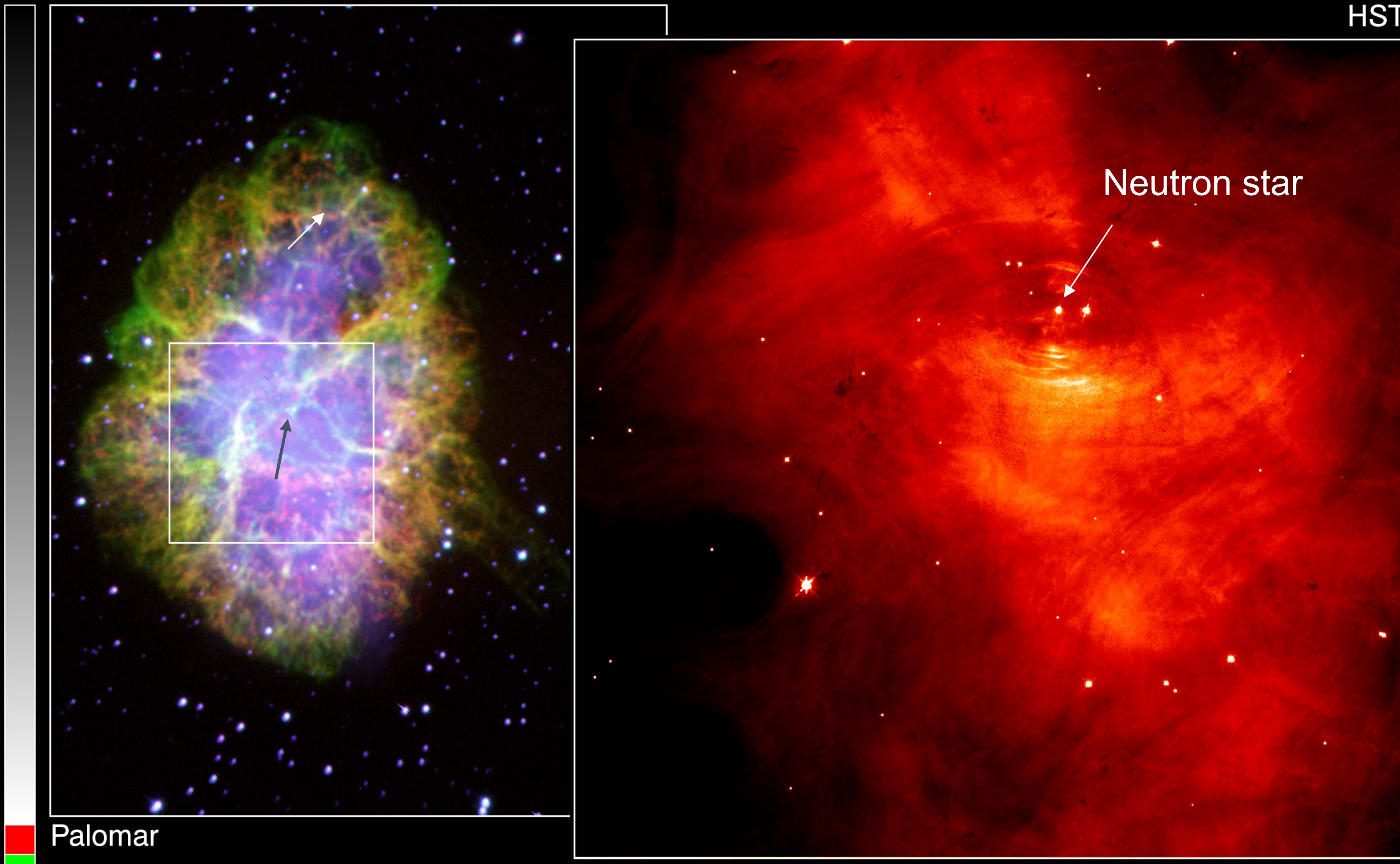
Crab nebula
in infrared



Crab nebula
in radio
(VLA)



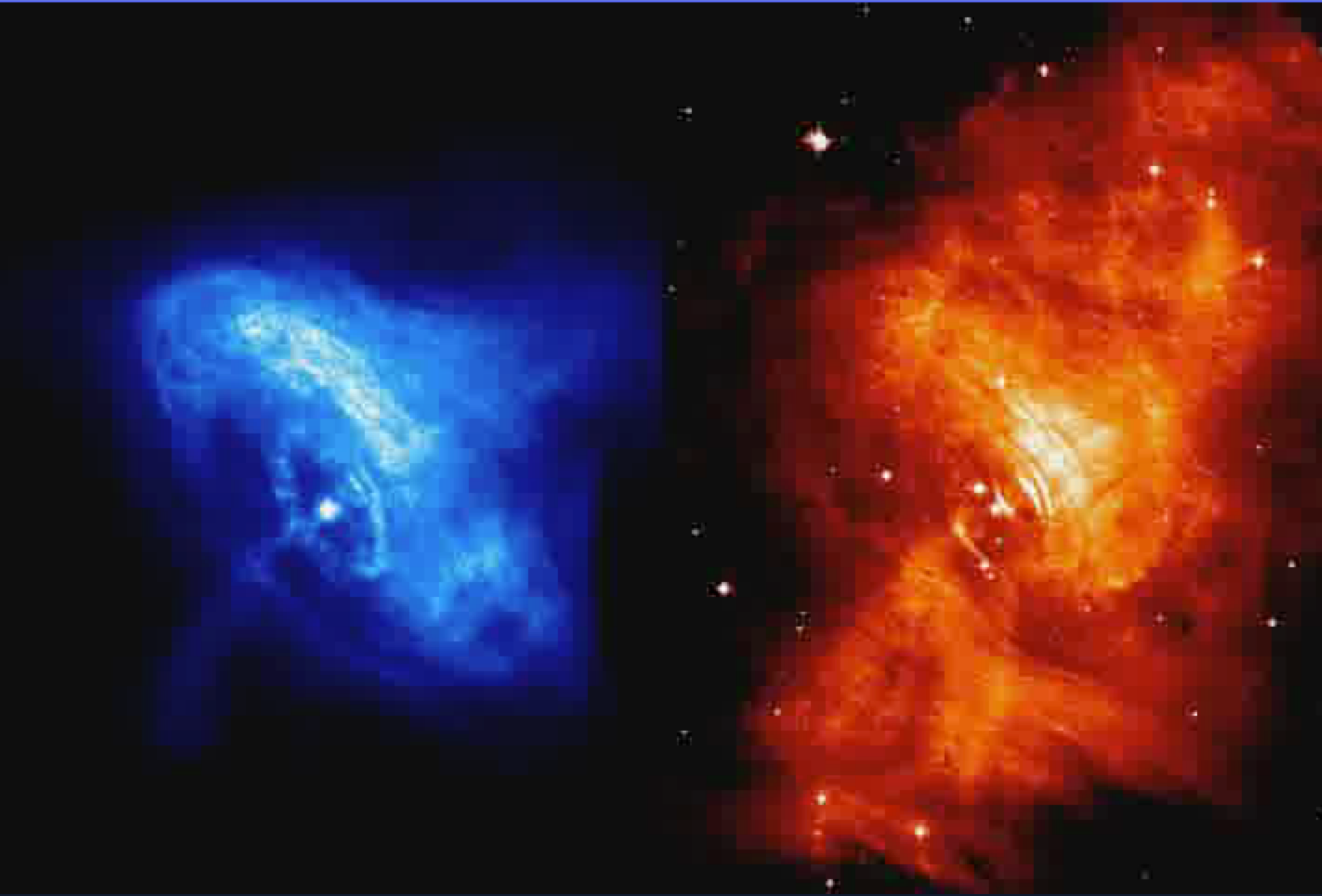
Crab nebula
in x-ray
(Chandra)



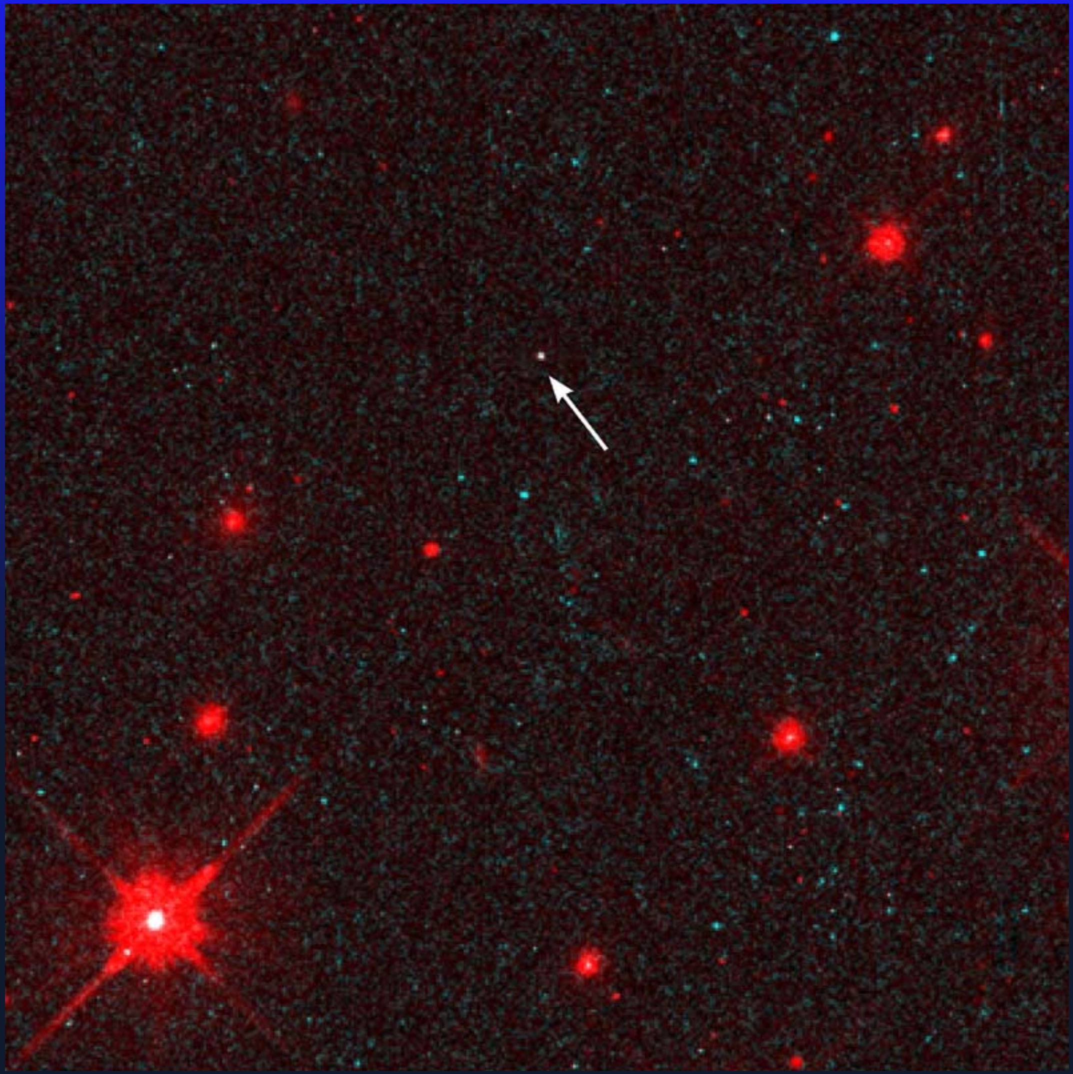
Crab Nebula

Hubble Space Telescope • Wide Field Planetary Camera 2

PRC96-22a • ST ScI OPO • May 30, 1996 • J. Hester and P. Scowen (AZ State Univ.) and NASA

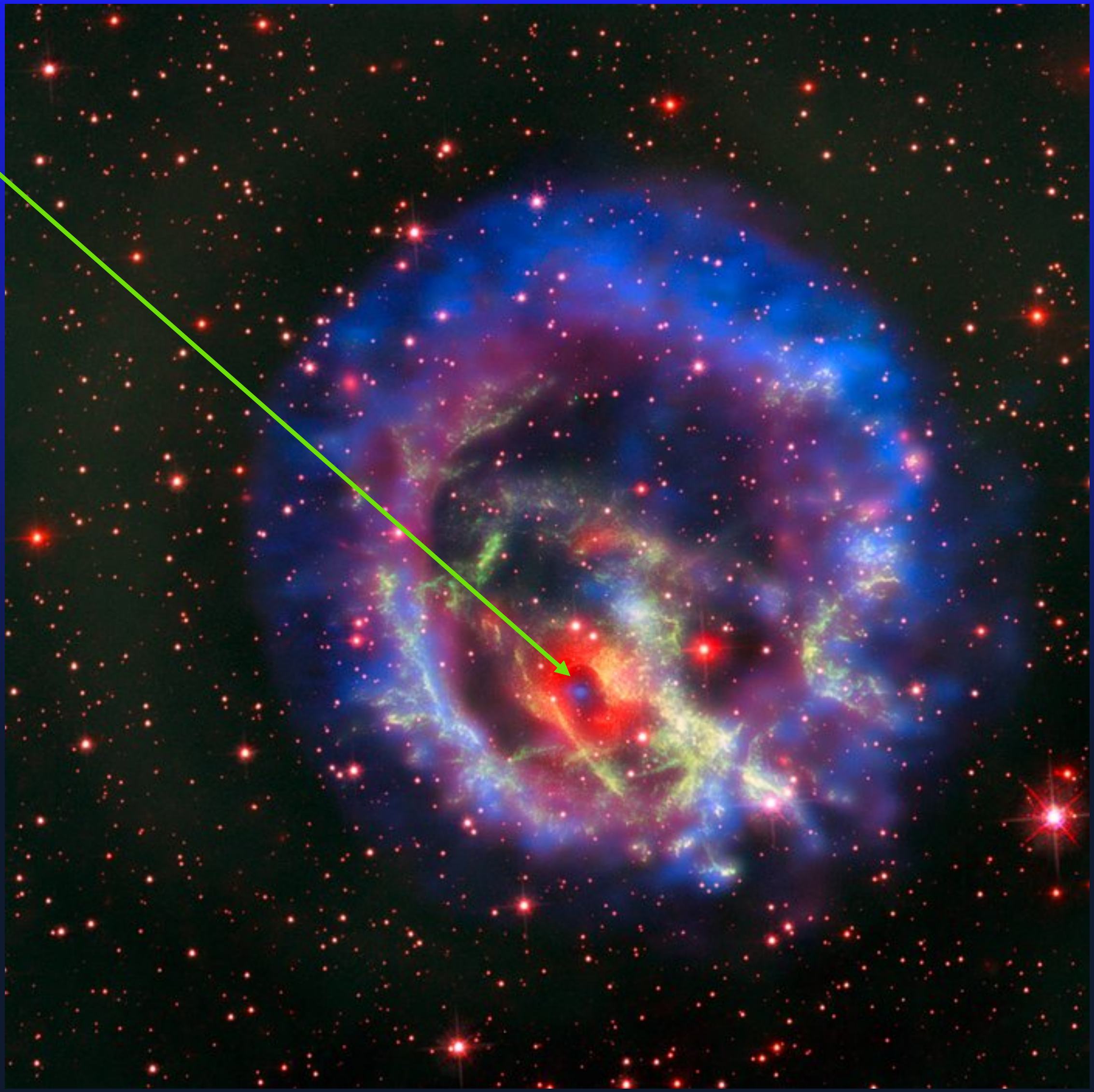


Isolated neutron star RX J185635-3742 HST WFPC2

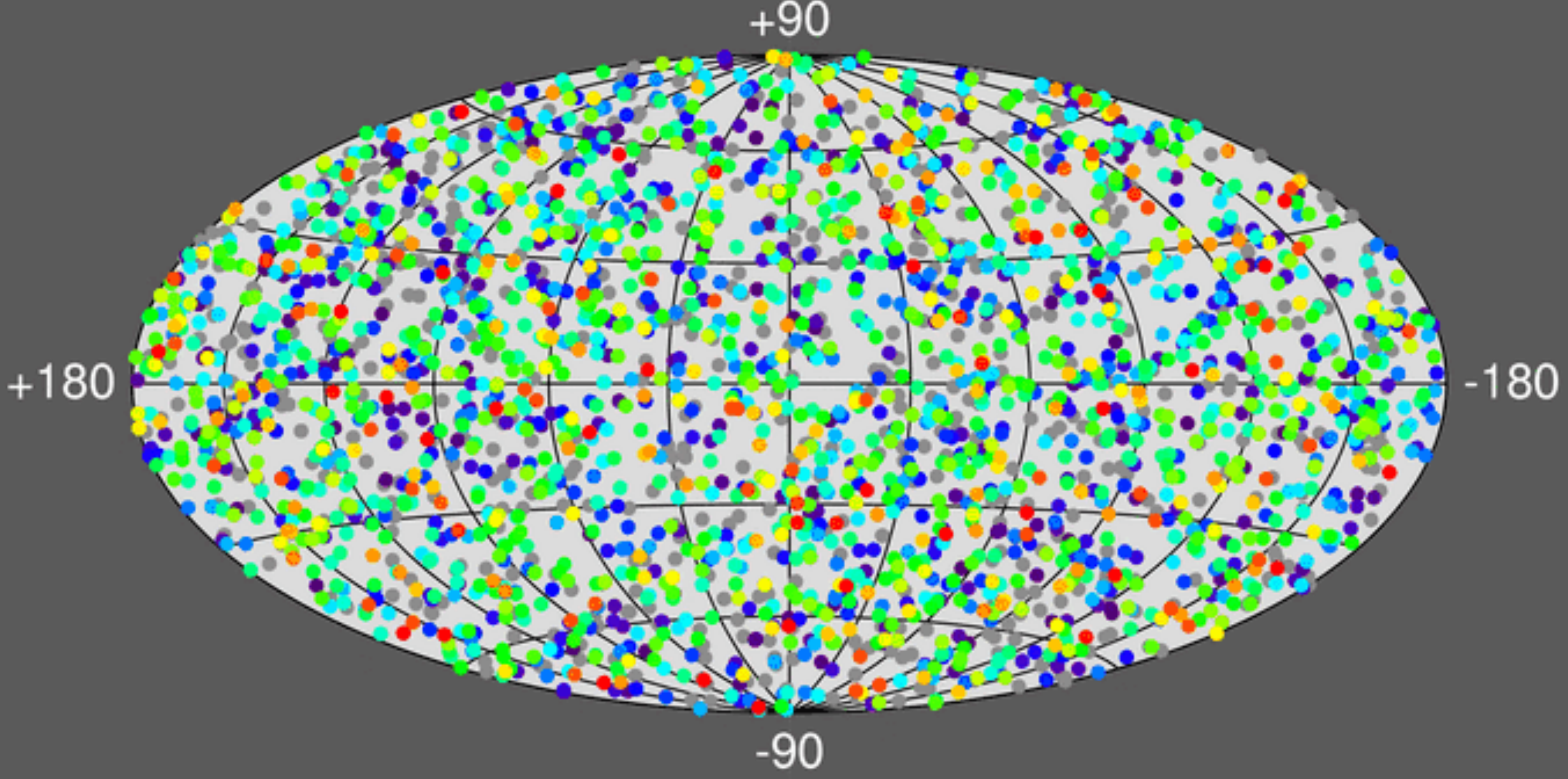


Distance ~ 117 pc ~ 400 l.y. Radius of emitting region ~ 17 km

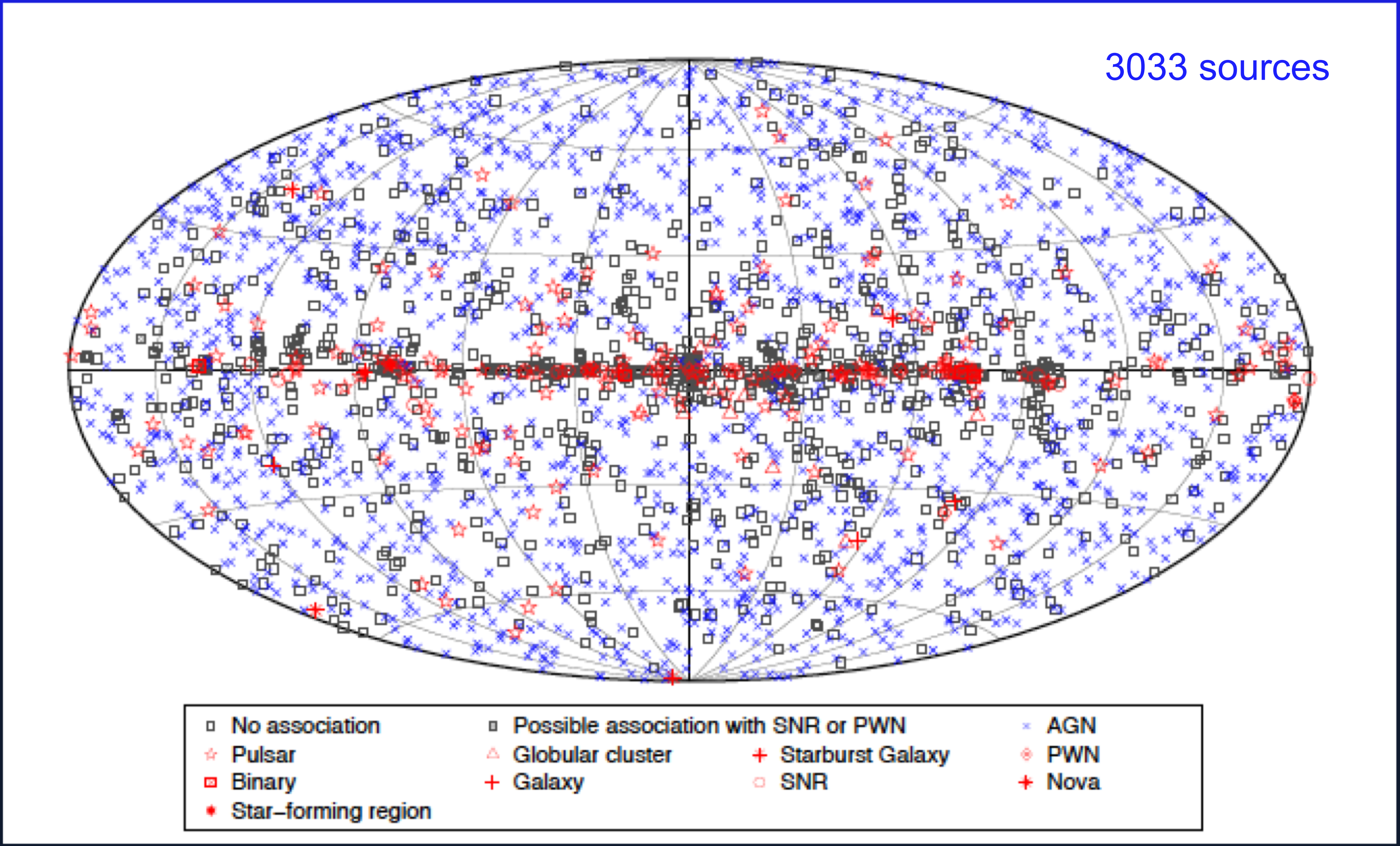
Isolated neutron star in supernova remnant (green) 1E 0102.2-7219 in the Small Magellanic Cloud



2704 BATSE Gamma-Ray Bursts



Fermi Gamma-ray LAT burst catalog 3FGL (2015)



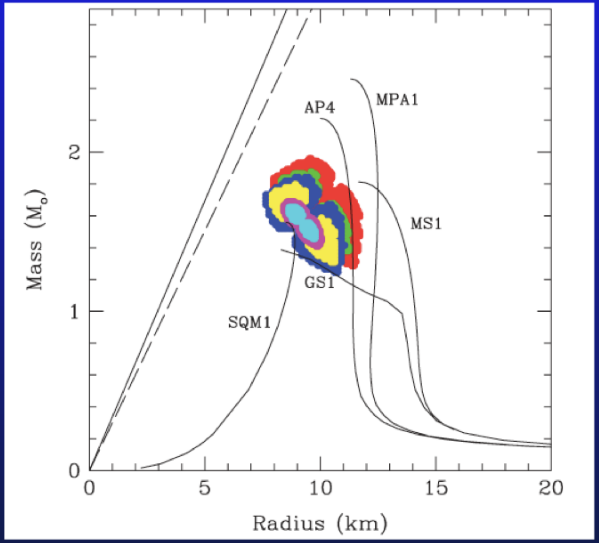
PSR = pulsar, PWN = pulsar wind nebula, AGN = active galactic nebula

Learning about dense matter from neutron star observations

Challenges to nuclear theory!!

Learning about dense matter from neutron star observations

Masses and radii of neutron stars
- Binary systems: stiff e.o.s
- Thermonuclear bursts in X-ray binaries => Mass vs. Radius, strongly constrains eq.of state.



NICER to measure M/R directly

Gravitational waves from ns-ns and ns-bh mergers explore masses, radii, and tidal deformabilities

Glitches: probe n,p
- superfluidity and crust

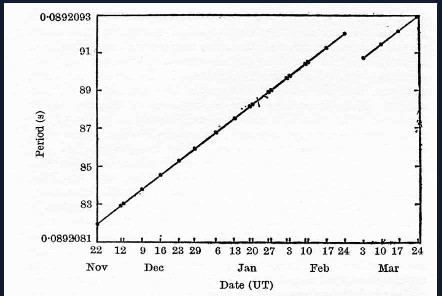
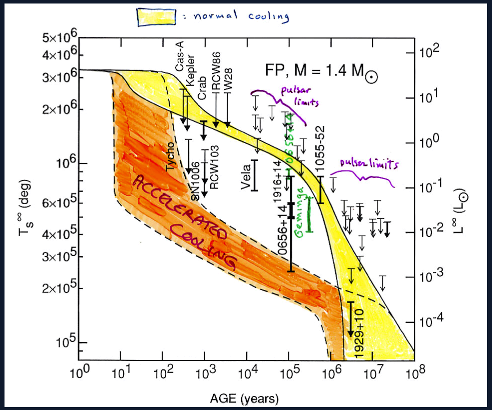


Fig. 1. The barycentric period of *PSR* 0833–45 as observed from November 22, 1968, to March 24, 1969, showing the 134 ns decrease between February 24 and March 3.

Cooling of n-stars: search for exotica

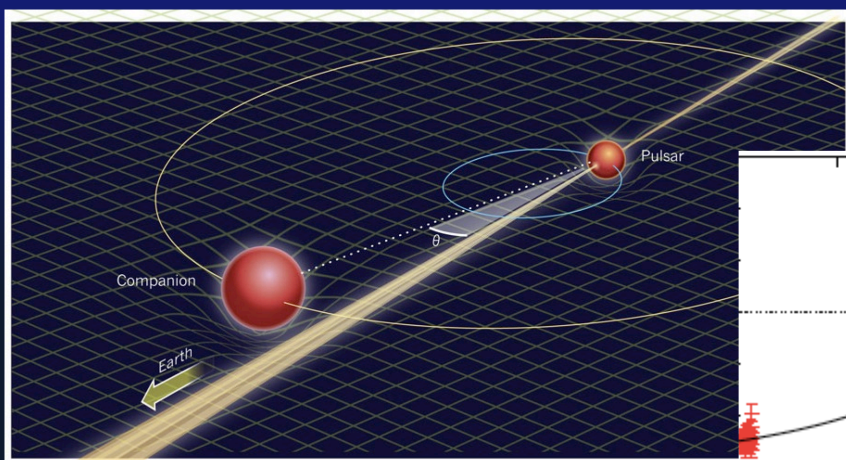


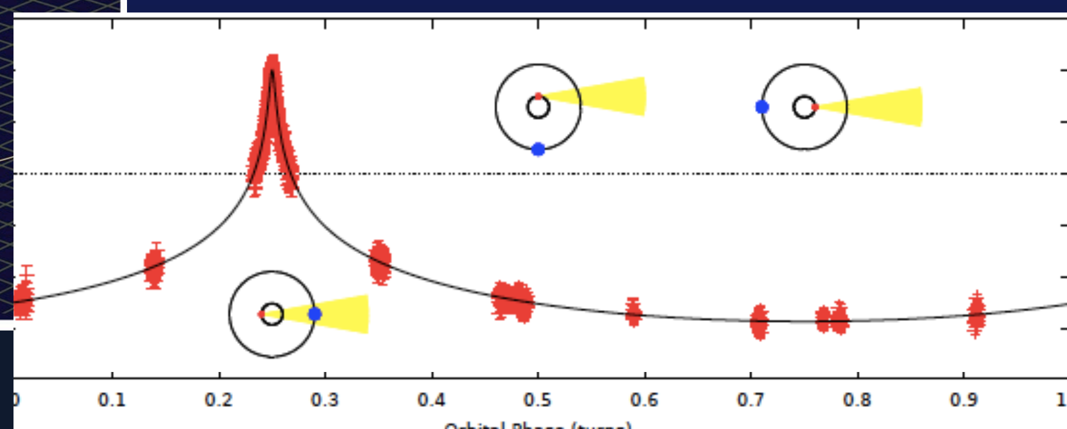
Measuring equation of state in crust

First firm high mass neutron star, PSR J1614-2230 -- in neutron star-white dwarf binary

Demorest et al., Nature 467, 1081 (2010); E. Fonseca et al., ApJ. 832, 16 (2016).

Spin period = 3.15 ms; orbital period = 8.7 day
Inclination = 89:17° ± 0:02° : edge on
$M_{\text{neutron star}} = 1.928 \pm 0.017 M_\odot$; $M_{\text{white dwarf}} = 0.500 \pm 0.006 M_\odot$



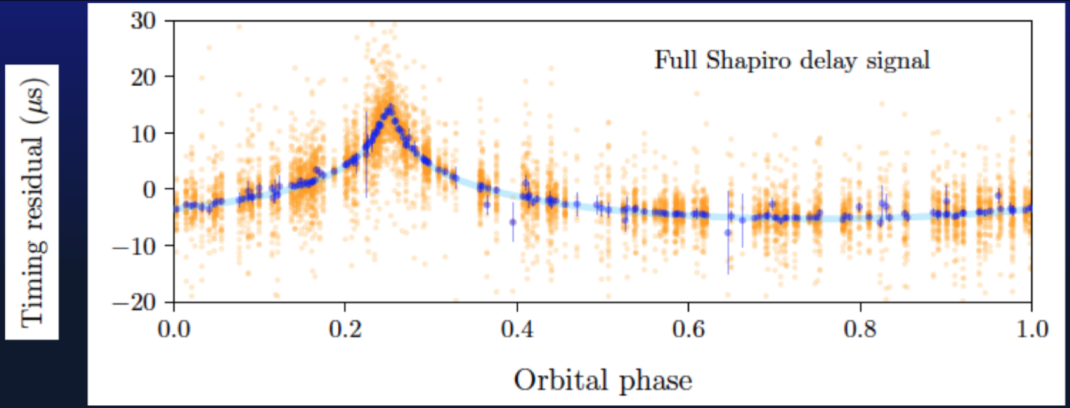


(Gravitational) Shapiro delay of light from pulsar when passing the companion white dwarf

Highest mass neutron star, PSR J0740+6620 -- in neutron star-white dwarf binary

Chromartie et al., arXiv:1904.06759. (April 14, 2019)

Spin period = 2.89 ms; orbital period = 4.77 day
Nearly circular orbit (eccentricity = $5X10^{-6}$)
Inclination = $87.44^o \pm 0{:}01^o$: edge on
$M_{neutron\ star} = 2.17 \pm 0.1 M_{\odot}$; $M_{white\ dwarf} = 0.26 \pm 0.01 M_{\odot}$

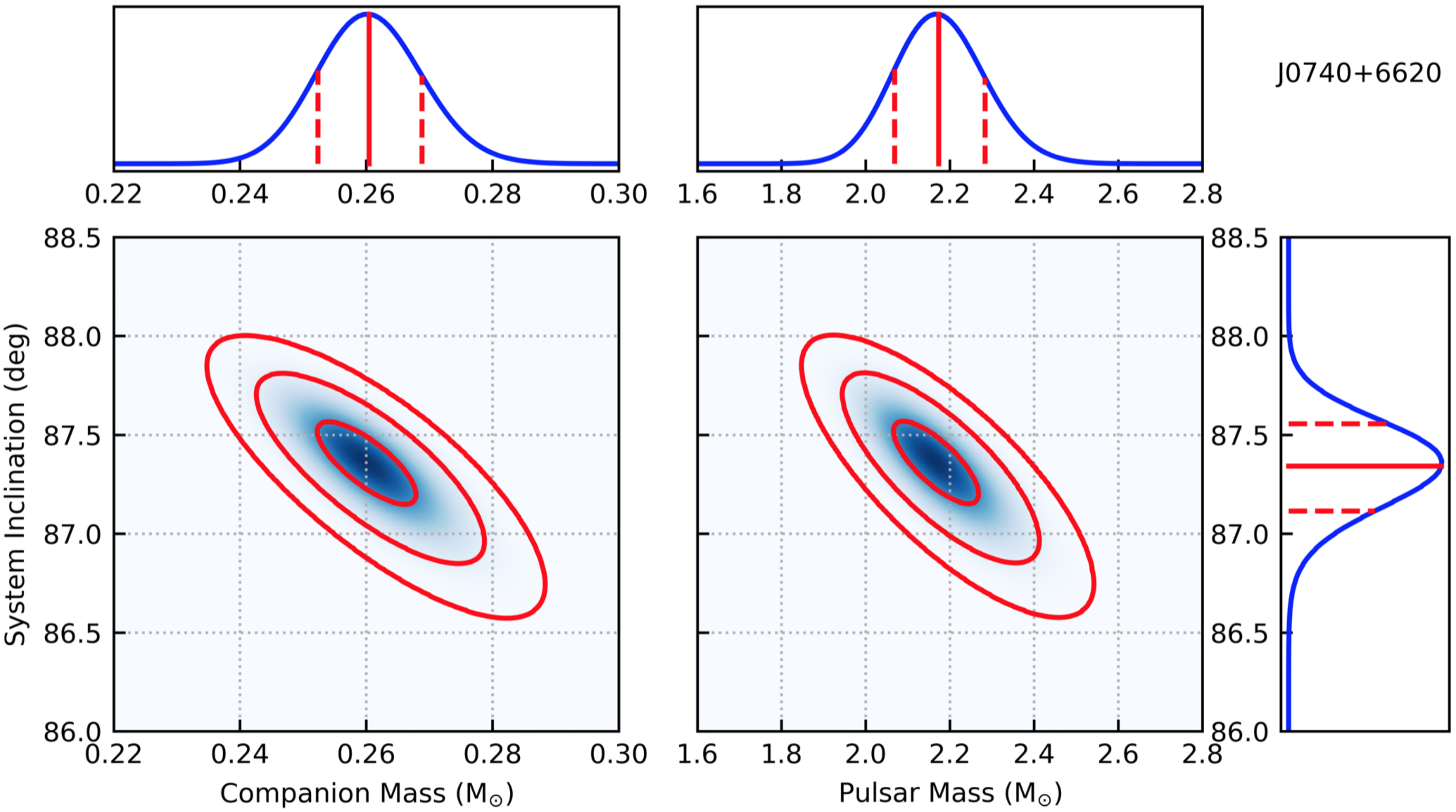


(Gravitational) Shapiro delay of light from pulsar

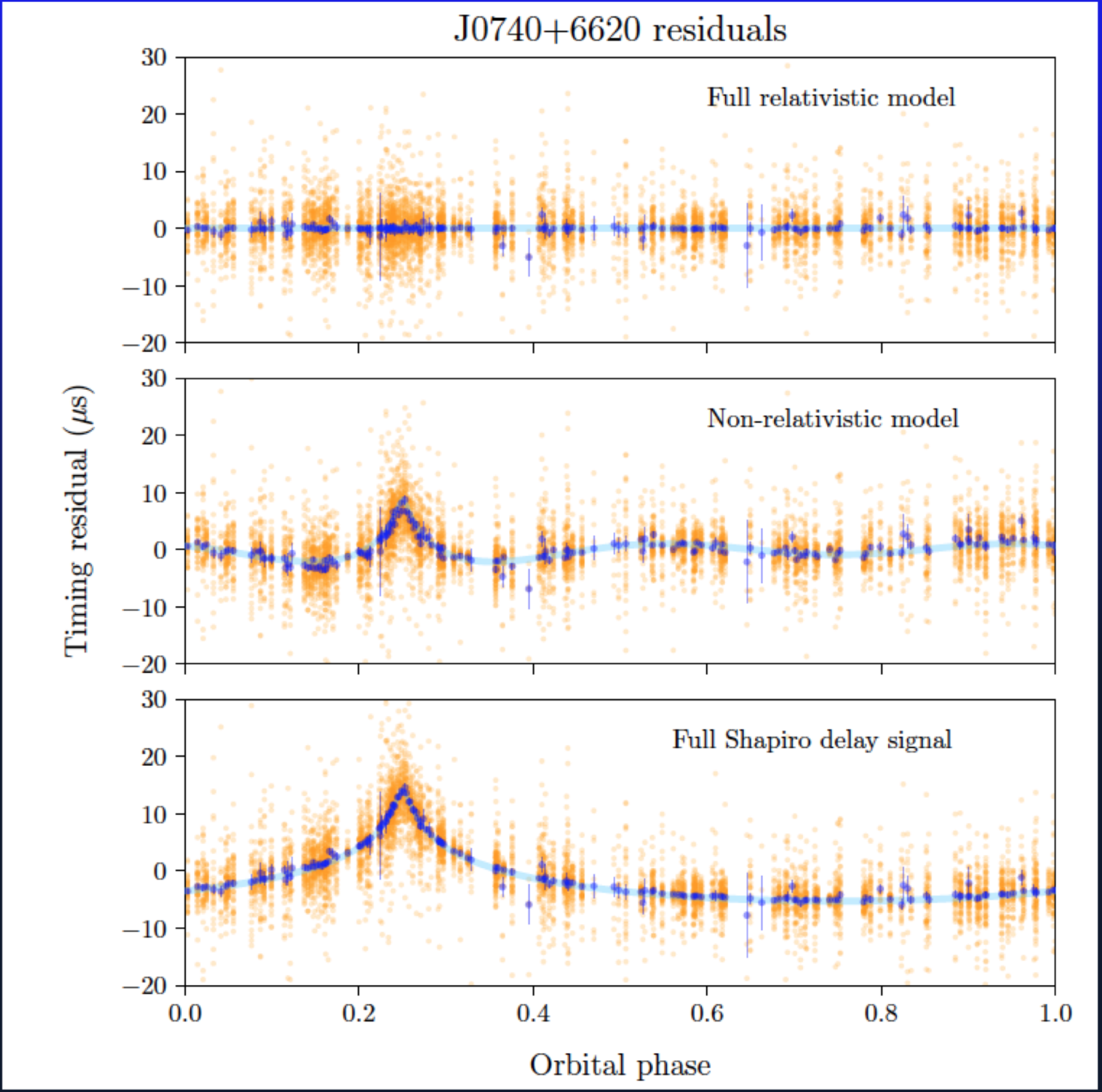
NICER is also observing J0740+6620 in the X-ray

Firm test of the equation of state!!!

Mass distribution



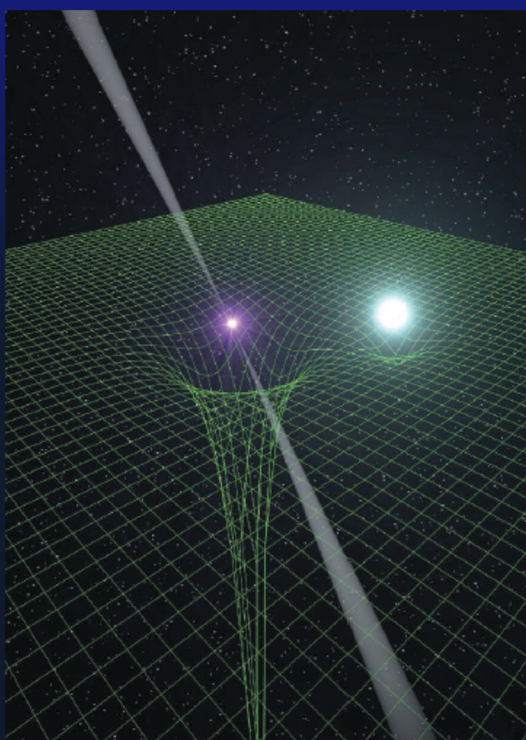
Timing Residuals

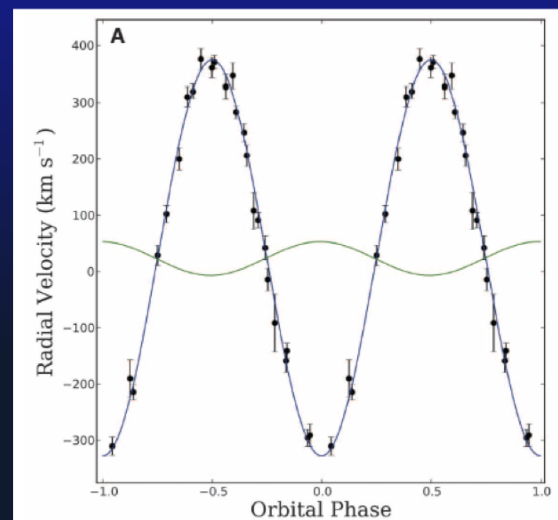


Second highest mass neutron star, PSRJ0348+0432 -- in neutron star-white dwarf binary

Antonidas et al., Science 340 1233232 (2013)

Spin period = 39 ms; orbital period = 2.46 hours
Inclination =40.2^o
$M_{neutron\ star}$ =2.01 ± 0.04$M_{\odot}$; $M_{white\ dwarf}$ = 0.172 ±0.003$M_{\odot}$





Significant gravitational radiation

$$\dot{P}/\dot{P}_{GR} = 1.05 \pm 0.18$$

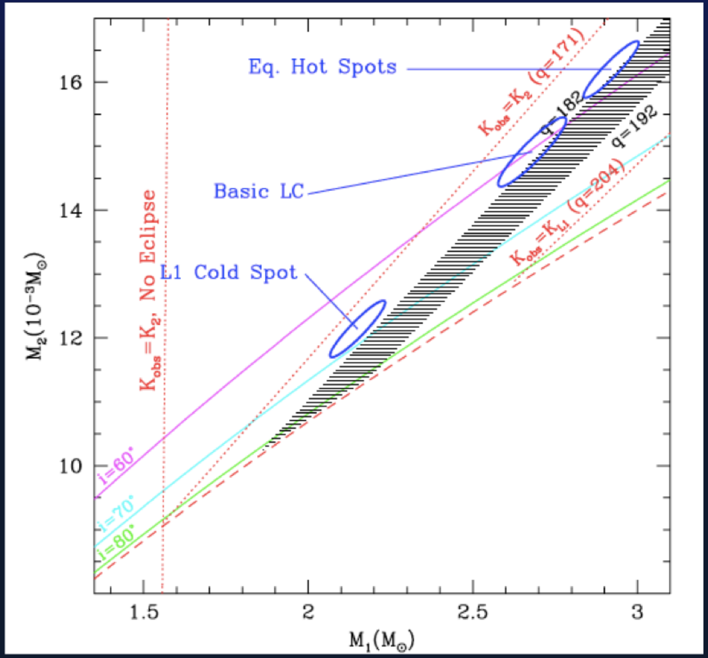
400 Myr to coalescence! AAAALigo

Possible high mass neutron stars (< 2.7$M_\odot$) in extreme "black widow pulsars" J1311-3430, B1957+20, J2215+5135 (neutron star - He star binaries)

Romani et al. (1311-3430), Ap. J. Lett., 760:L36 (2012), Ap. J. 804:115R (2015),
van Kerkwijk, Breton, &. Kulkarni (B1957+20)," Ap.J. 728, 95 (2011),
Schroeder & Halpern (J2215+5135), Ap. J. 793, 78 (2014).

$M_{ns\text{-}J1311} \sim 1.8 - 2.7\ M_\odot$; $M_{companion} \sim 0.01 M_\odot$

Uncertainties arise from incomplete modeling of heating of the companions by the neutron stars.



Neutron star masses

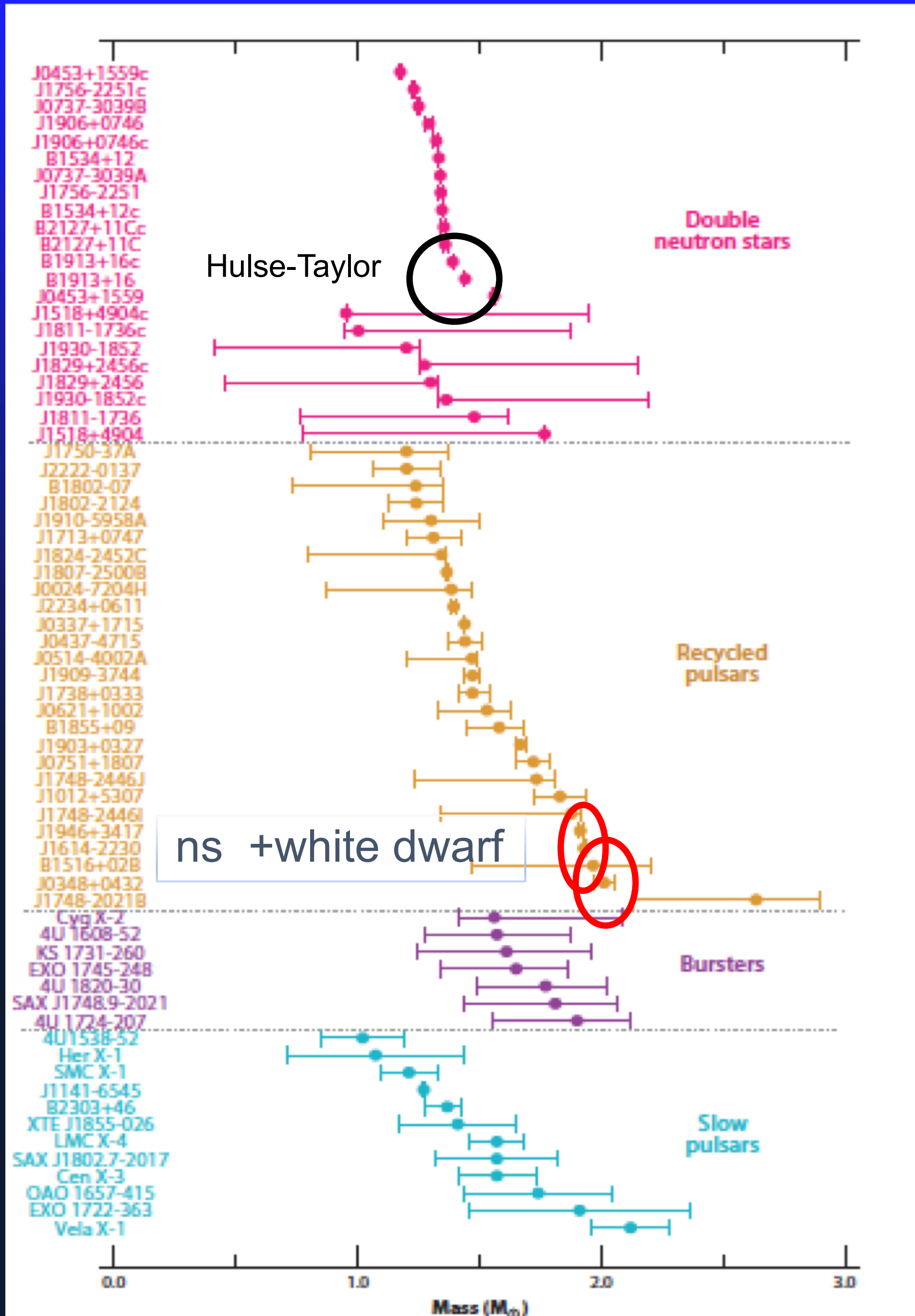
Özel & Freire, Ann Rev AA (2016)

PSR J1614-2230 :

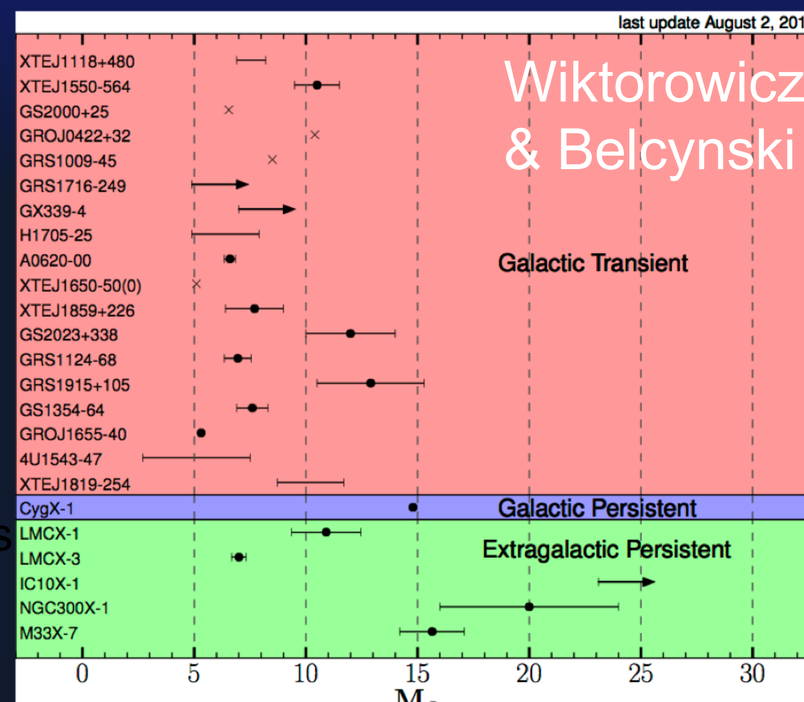
$M_{nstar} = 1.928 \pm 0.017 M_{\odot}$

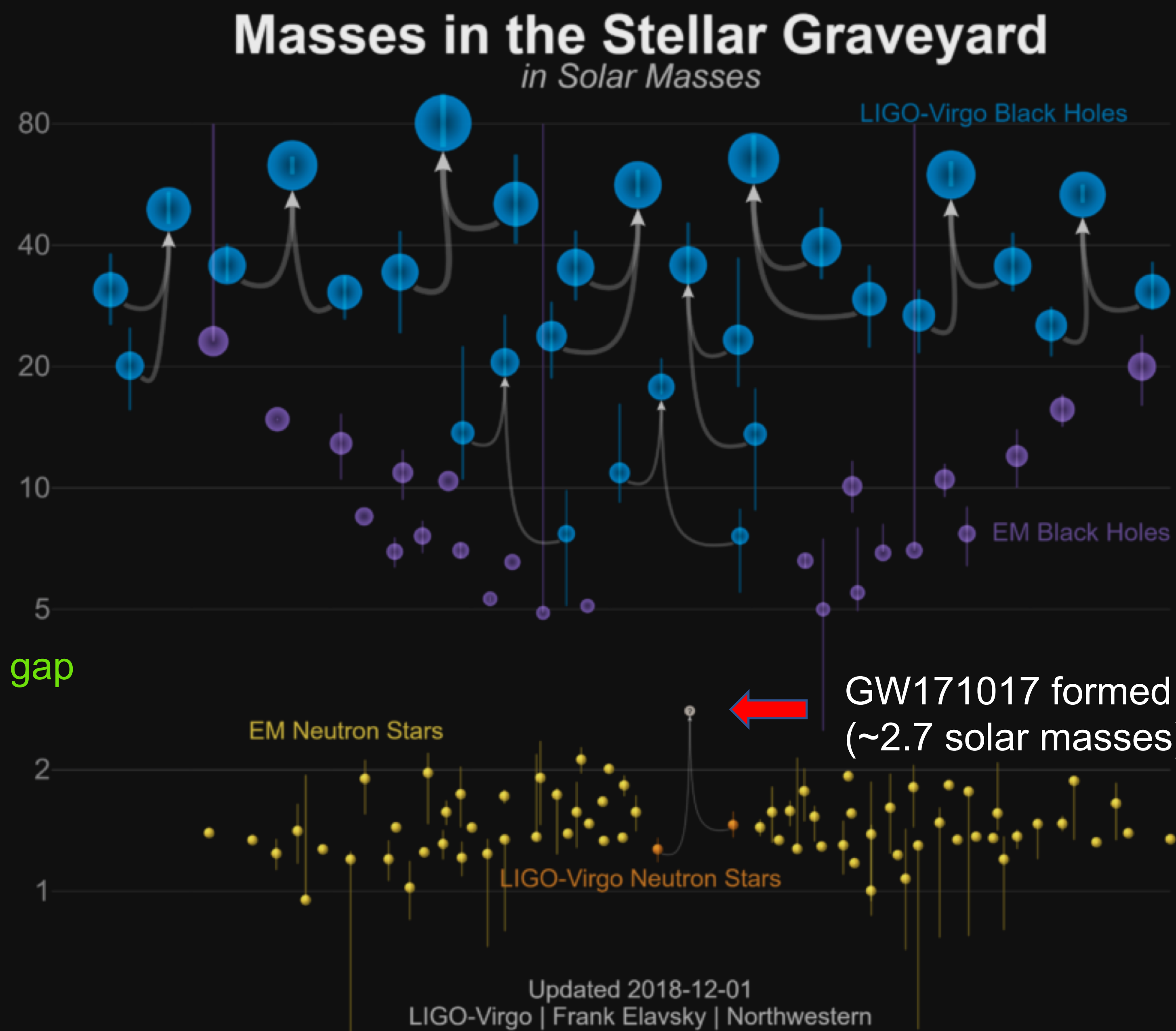
PSR J0348+0432:

$M_{nstar} = 2.01 \pm 0.04 M_{\odot}$



Galactic black hole masses

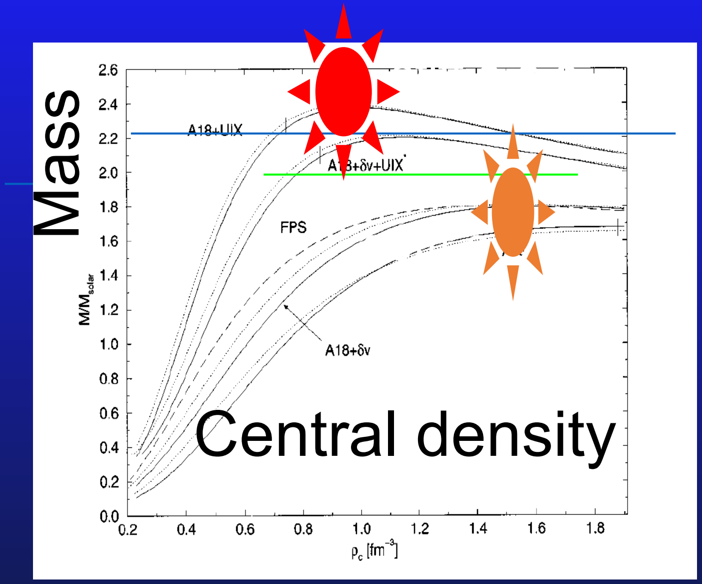




Mass gap

GW171017 formed a low mass (~2.7 solar masses) black hole

The equation of state is very stiff



Softer equation of state => lower maximum mass and higher central density

Binary neutron stars ~ 1.4 $M_\odot$: consistent with soft eq. of state

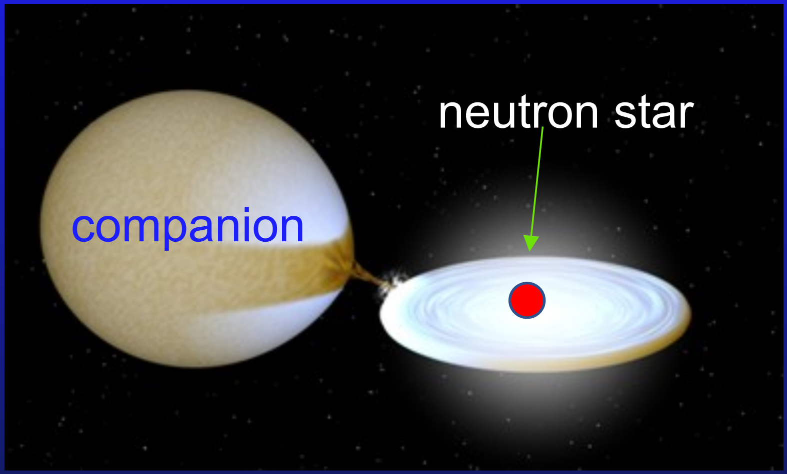
PSR J1614-2230 : $M_{\text{neutron star}} = 1.93 \pm 0.02 M_\odot$

PSR J0348+0432: $M_{\text{neutron star}} = 2.01 \pm 0.04 M_\odot$

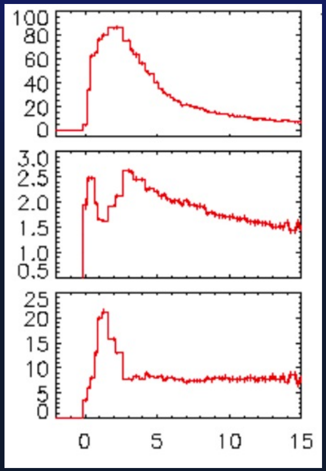
PSR J0740+6620 : $M_{\text{neutron star}} = 2.17 \pm 0.1 M_\odot$

require very stiff equation of state! How possible?

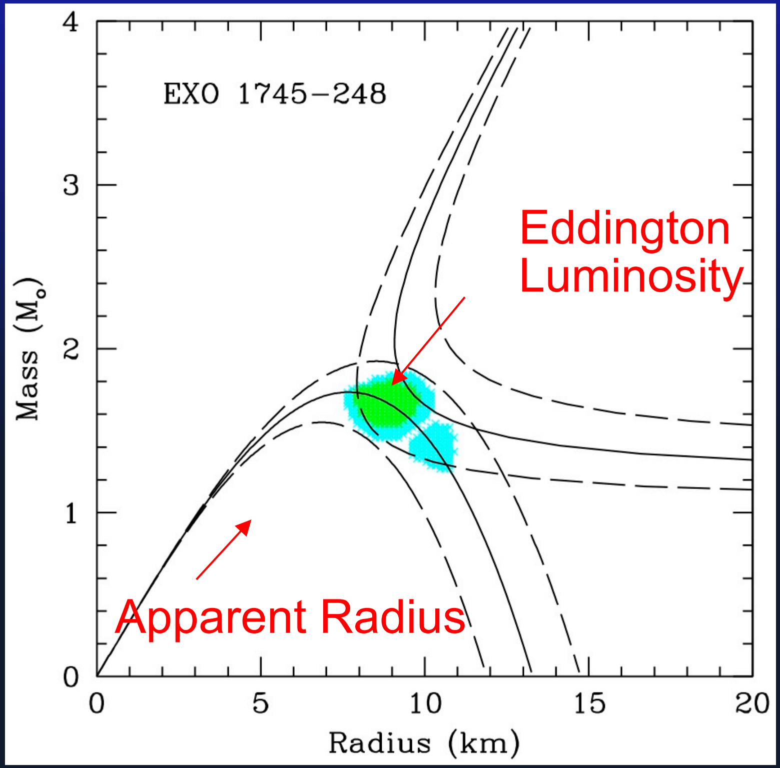
Measuring masses and radii of neutron stars in thermonuclear bursts in X-ray binaries



F. Özel, GB., T. Güver, PRD 82, 101301 (2010); J.M. Lattimer & A. W. Steiner, Ap .J, 784, 123 (2014). F. Özel, D. Psaltis, T. Guver, GB, C. Heinke, & S. Guillot, Ap. J. 820, 28:1 (2016).



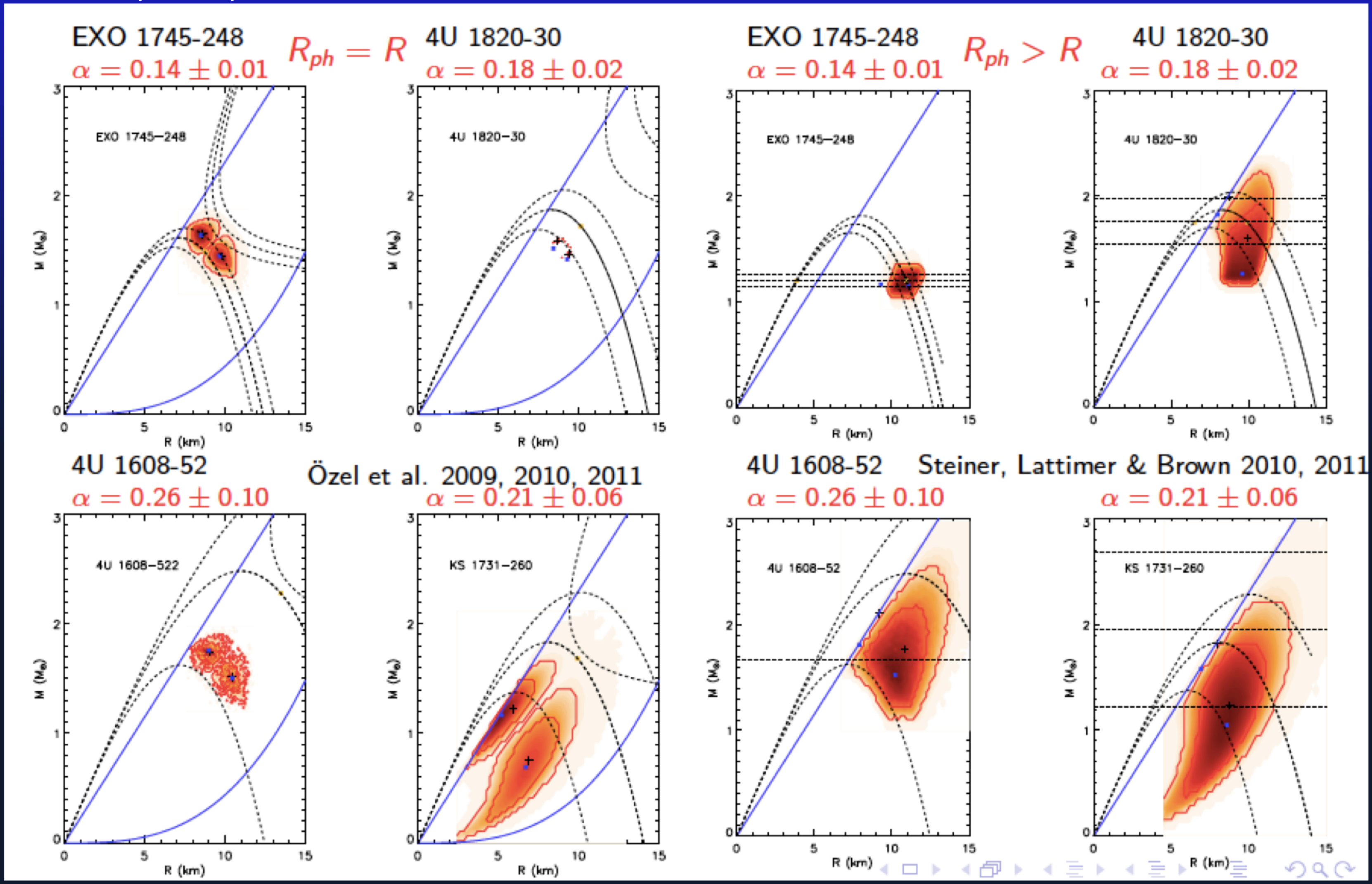
Time (s)



Measurements of *apparent* surface area, flux at Eddington limit (radiation pressure = gravity), combined with distance to star, constrains M and R.

Mass vs. radius determination of neutron stars in burst sources (low mass x-ray binaries). R ~ 9-13 km

F. Özel, GB., T. Güver, PRD 82, 101301 (2010); J.M. Lattimer and A. W. Steiner, Ap J, 784, 123 (2014). F. Özel, D. Psaltis, T. Güver, GB, C. Heinke, and S. Guillot, Ap. J. 820, 28:1 (2016).



NICER = **N**eutron star **I**nterior **C**omposition **E**xplore**R**

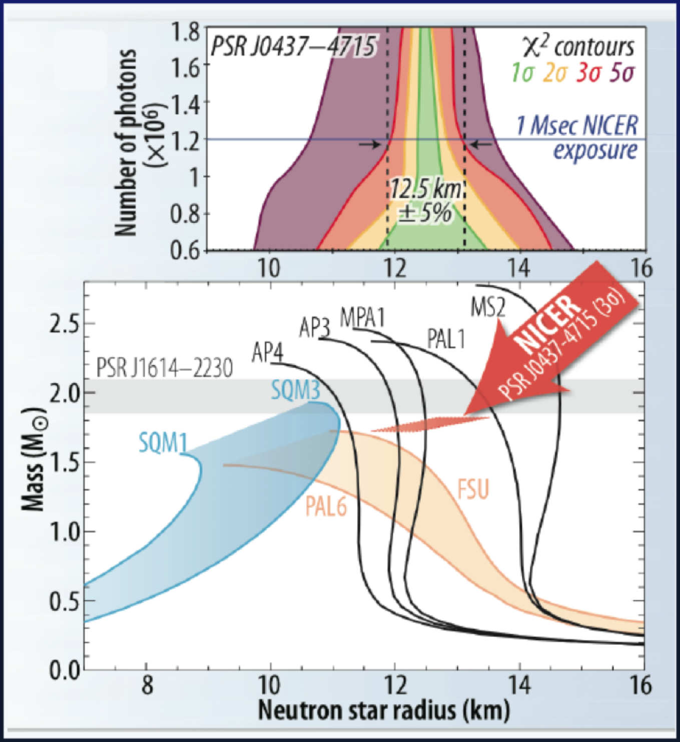
X-ray timing (GPS to 300 nsec) & spectroscopy (0.12-12 KeV)

Measure masses and radii (5%) by monitoring X-ray pulse profiles of nearby neutron stars (J0437, ...)

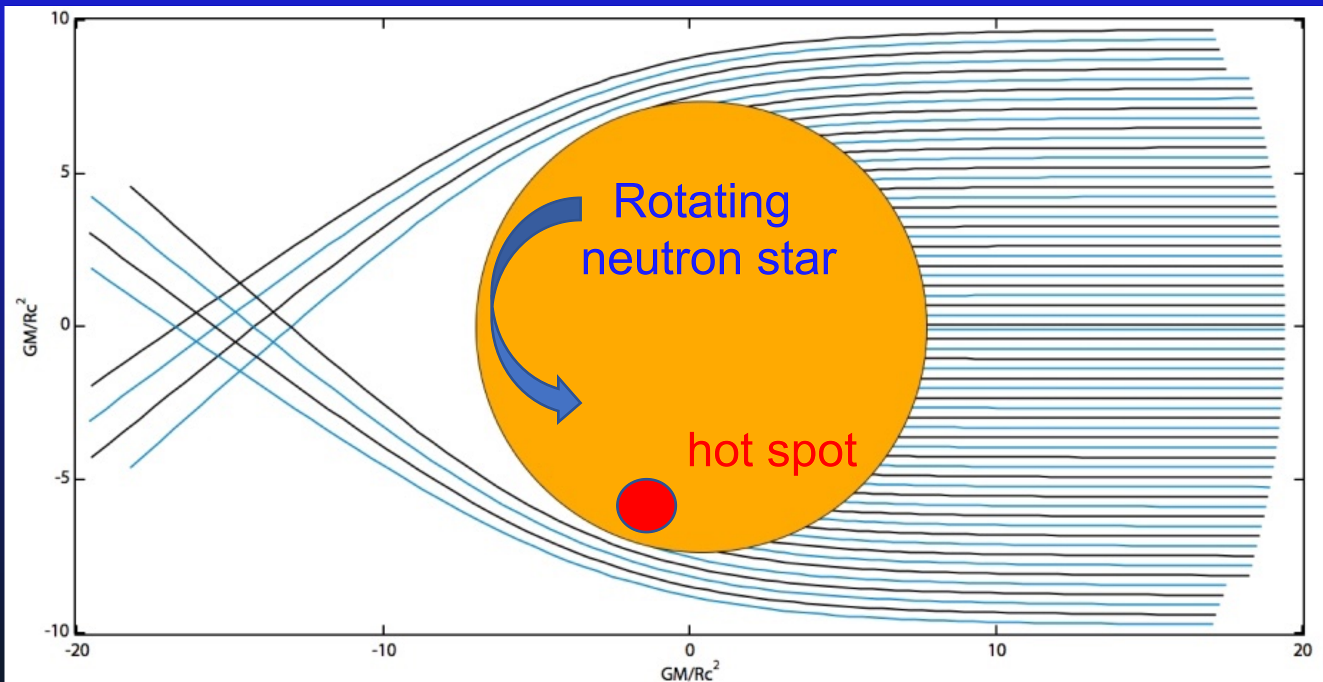
Properties of ns crusts via astroseismology

Periodic pulsations from transient & steady systems

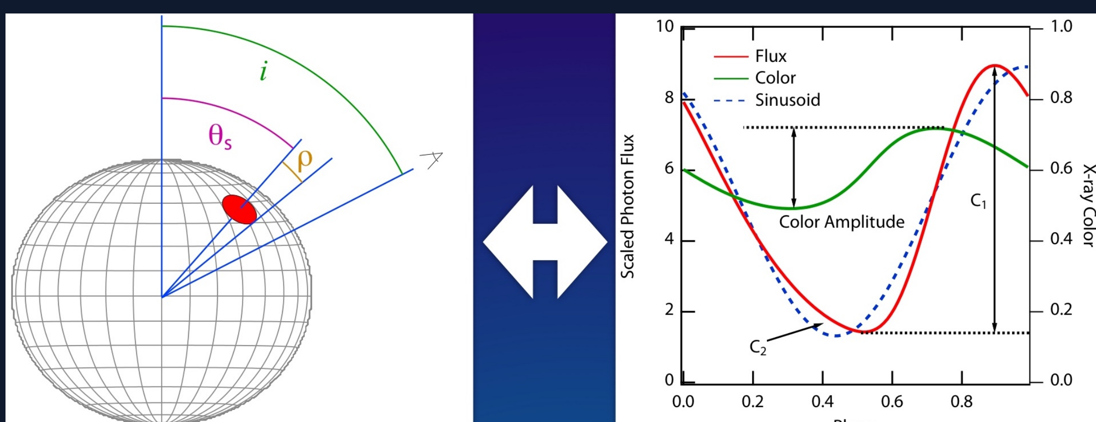
Now taking data!



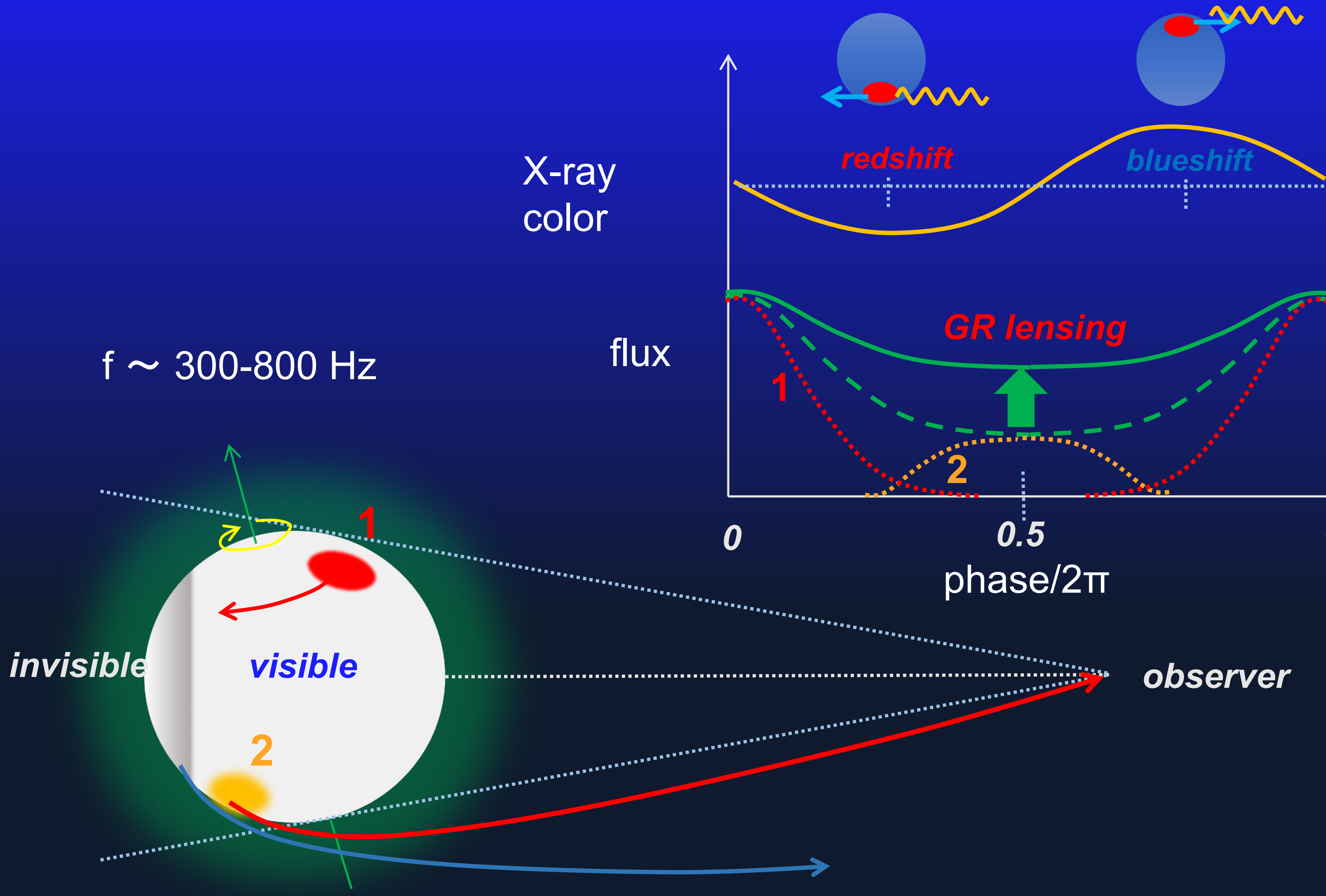
Track hot spots on neutron star. Light bending by star enables one to see spot “behind” star. Bending depends on M and R.

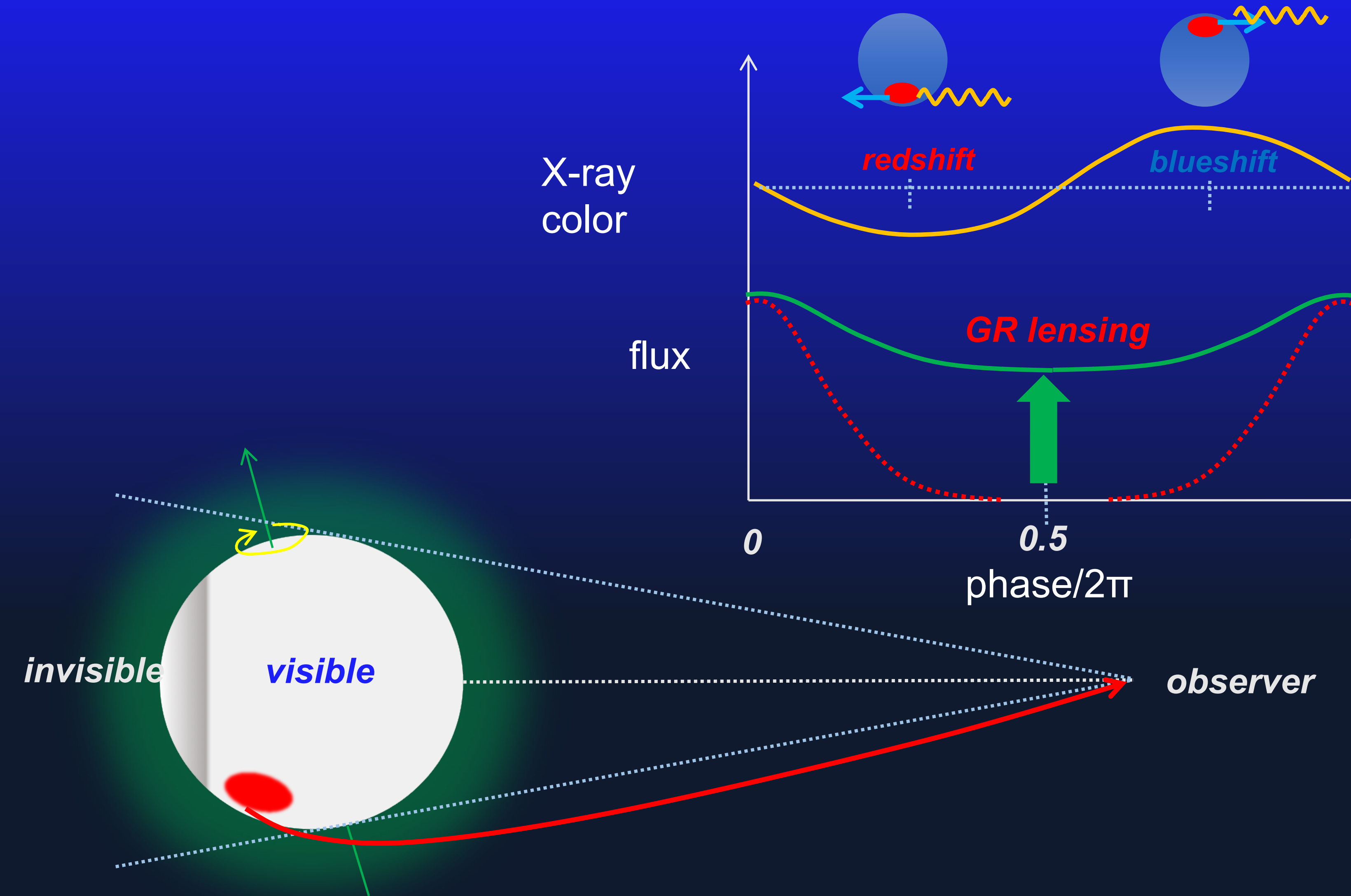


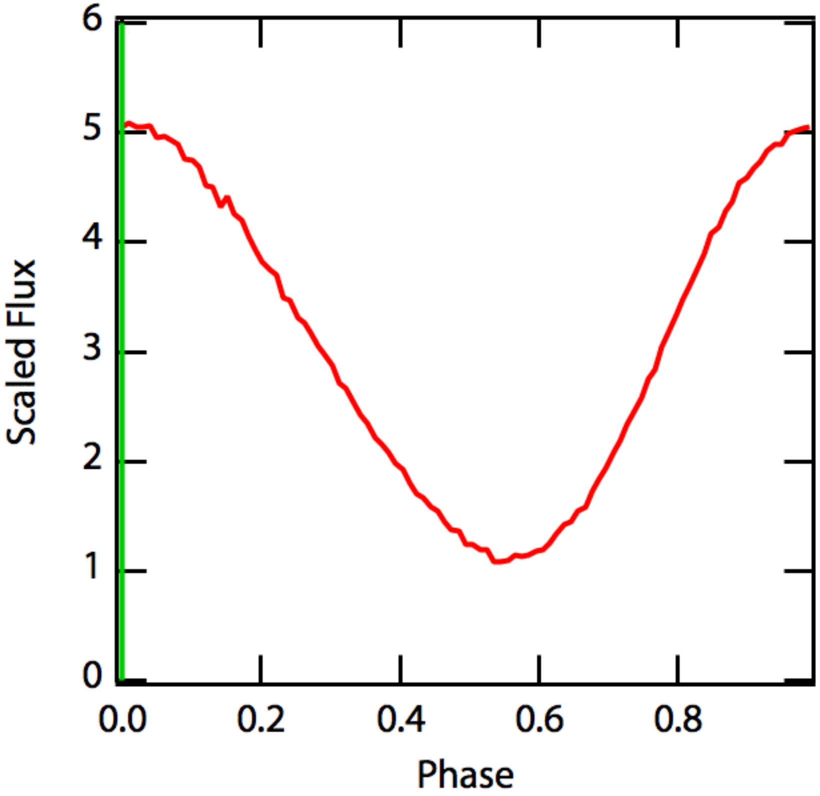
Observer = NICER

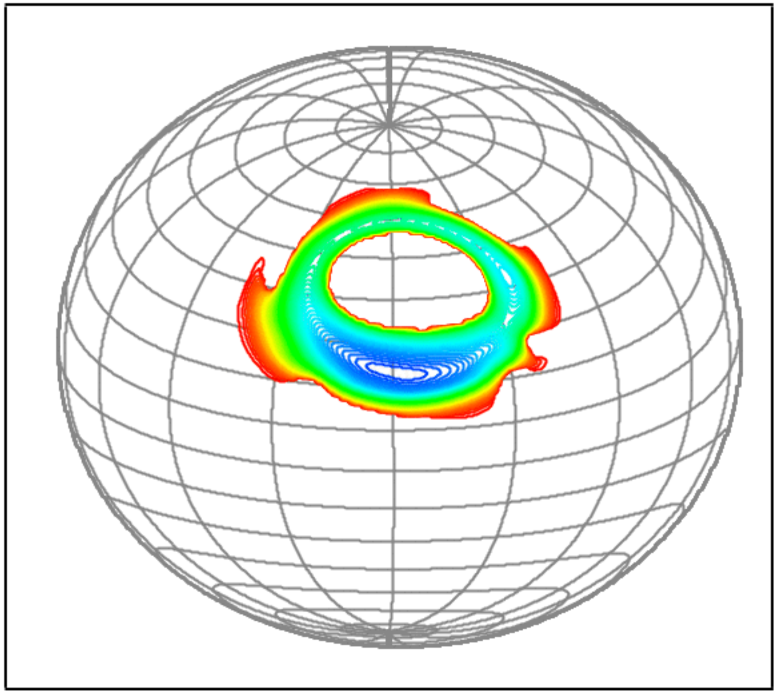


Measure amplitudes and phases in different colors (frequencies)


X-ray
color
redshift
blueshift
flux
GR lensing
1
2
0
0.5
1
phase/2π
f ~ 300-800 Hz
1
invisible
visible
2
observer


X-ray color
redshift
blueshift
flux
GR lensing
0
0.5
1
phase/2π
invisible
visible
observer


Scaled Flux
Phase
0
1
2
3
4
5
6
0.0
0.2
0.4
0.6
0.8



NICER sources being studied:

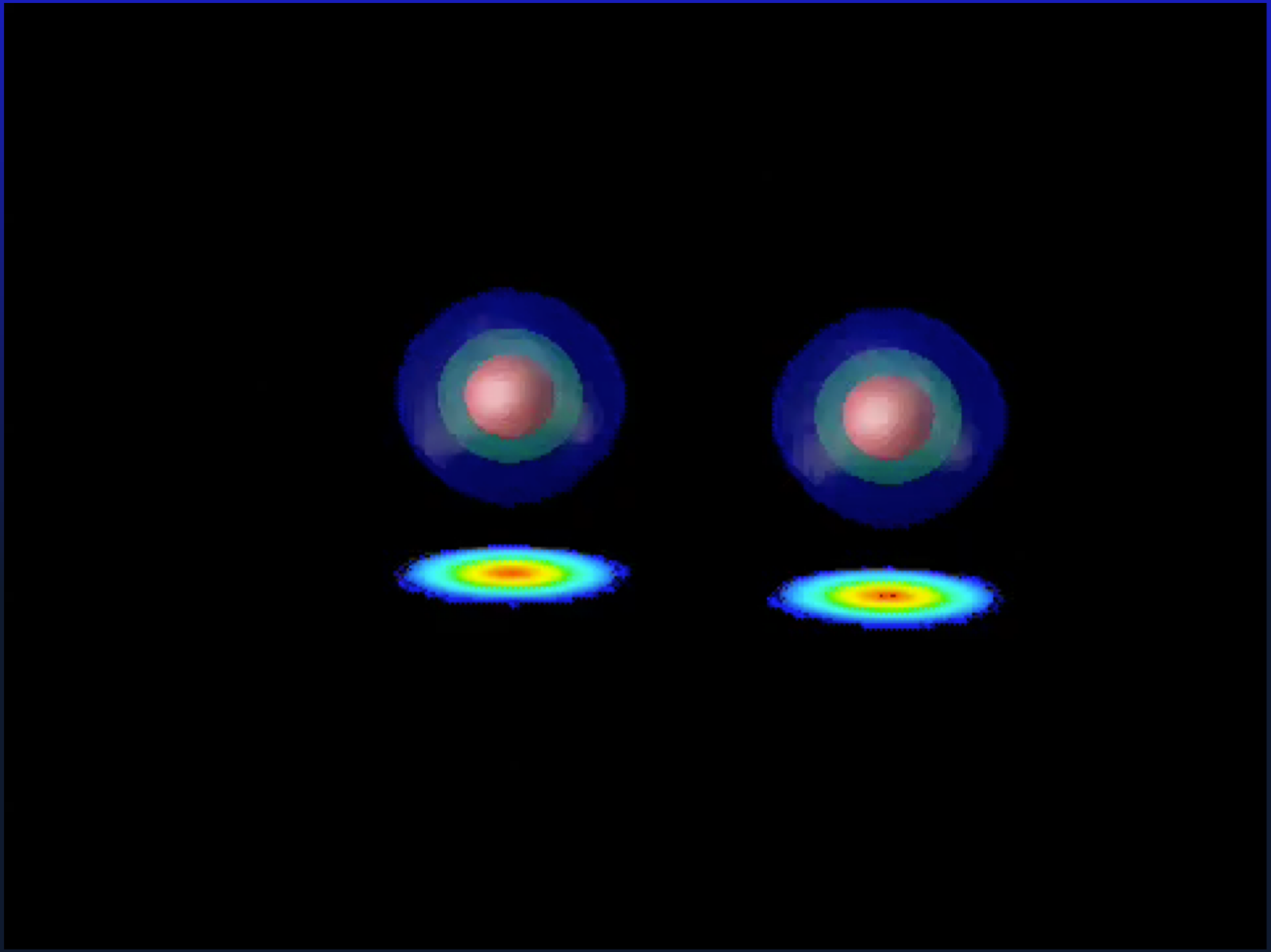
PSR J0030+0541 d=244pc age= 7580Myr
P = 4.865 ms

PSR J0437-4715 156pc 1590Myr
P = 5.75 ms
closest & brightest ms. pulsar known

PSR J1231−1411 440pc
P=3.684 ms
3rd suitable millisecond pulsar has a waveform apparently simpler to analyze

Neutron star - neutron star binary inspiral

(Fred Rasio, 2005)



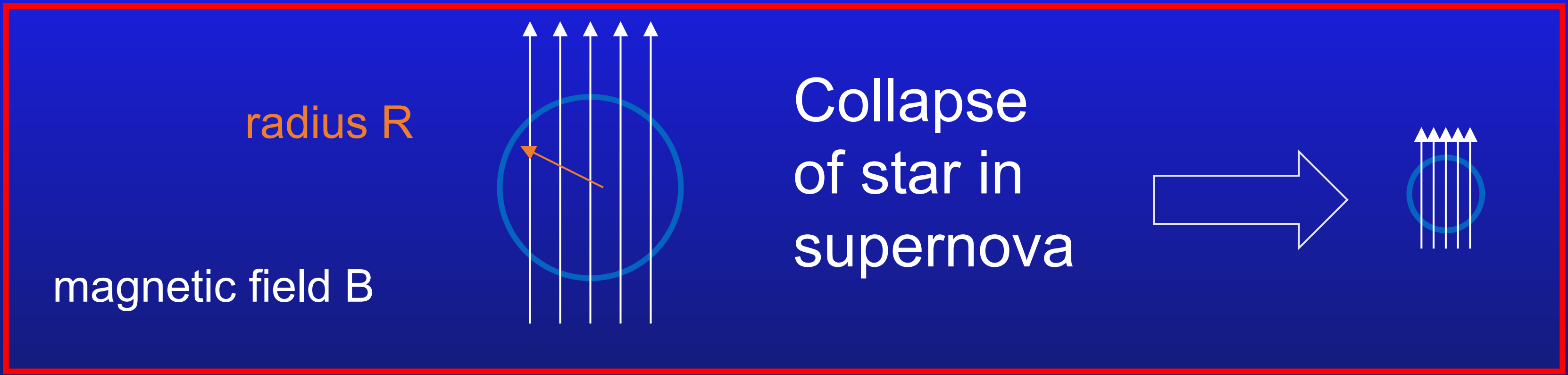
$dE/dt_{grav\ rad} = -\ (G/5c^5)h\ (d^3Q/dt^3)^2 \sim m^2R^4\omega^6$

Neutron star – neutron star merger observed on 17 Aug. 2017

by LIGO and Virgo (gravitational radiation), FERMI (gamma ray telescope) and ~ 70 other electromagnetic observatories.

Merger was 130,000,000 light years = 40 MPc away

Scaling of magnetic fields and periods



Conservation of flux => BR^2 = constant

R: 10^{11} cm => 10^{6} cm

B: 10^{2} G => 10^{12} G

Conservation of angular momentum

=> $I\,\Omega \sim R^2\,\Omega$ = constant

Period = $2\pi/\Omega$: 10^{7} s => 10^{-3} s

Mass and radius scales of neutron stars

$$\frac{\partial P}{\partial R} = -\frac{G\rho(r)M(r)}{r^2}$$

Non-relativistic equation of hydrostatic balance.

$$M(r) \sim \frac{4\pi}{3}\rho_c r^3$$

Mass within radius r

ρ_c = central mass density

dP = n dμ + S dT => n dμ at zero temperature T

μ = baryon chemical potential

$$\frac{1}{\rho}\frac{\partial P}{\partial r} = \frac{n}{\rho}\frac{\partial \mu}{\partial r} = \frac{1}{m}\frac{\partial \mu}{\partial r} \sim \frac{4\pi}{3}G\rho_c r$$

m = nucleon mass

$$\mu(r) \sim \mu(0) - \frac{2\pi}{3}G\rho_c r^2$$

R = neutron star radius

At surface, $\mu(R)$ = m =>

$$\mu(0) \sim m + \frac{2\pi}{3}G\rho_c R^2$$

$$\boxed{\mu(r) \sim m + \frac{2\pi}{3}G\rho_c(R^2 - r^2)}$$

Newton's gravitational constant

G= 6.67 X 10^{-8} cgs.

Electrodynamic fine structure constant: $$\frac{e^2}{\hbar c} = \frac{1}{137}$$

Gravitational fine structure constant:

$$\frac{Gm_p^2}{\hbar c} \equiv \alpha_G \simeq 0.589 \times 10^{-38} \equiv N_0^{-2/3}$$

m_p = proton mass

N_0 = 2.21 X 10^{57}, $m_n N_0$ = 1.189 $M_\odot$= solar mass

N_0 sets the scale of the masses of stars

Virial theorem for gravitating systems:

kinetic energy = -potential energy/2

Potential energy: $-\frac{M^2 G}{R}$

Classical stars: Kinetic energy $\sim NT$

Total energy = -kinetic energy => as stars lose energy they heat up. Negative specific heat!!! Burning fuel => cooling. Negative feedback keeps star stable as it burns fuel.

$$M = m_n N \qquad N \sim n_c R^3 \quad \Rightarrow \quad N^{2/3} \sim \frac{T}{\hbar c n_c^{1/3}} \alpha_G^{-1}$$

$$\hbar c = 2\,\mathrm{KeV}\,\mathrm{\AA}$$

$$N \sim \frac{(T[\mathrm{KeV}])^{3/2}}{(n_c[\mathrm{\AA}^{-3}])^{1/2}} \alpha_G^{-3/2}$$

Scale of stellar masses ~ $m_n \alpha_G^{-3/2}$

Neutron stars with free degenerate neutron Fermi gas

Mass density $\rho = \frac{m p_F^3}{3\pi^2 \hbar^3}$ Chemical potential $\mu = m + \frac{p_f^2}{2m}$

Neutron star structure: $\mu(0) \sim m + \frac{2\pi}{3} G \rho_c R^2$

$$R \sim \frac{3\sqrt{\pi}}{2} N_0^{1/3} \frac{\hbar}{m_n c} \left(\frac{mc}{p_F}\right)^{1/2} = \frac{12\,\mathrm{km}}{\sqrt{p_F(\mathrm{fm}^{-1})}}$$

1 fm $=10^{-13}$ cm

Typically, $n = \frac{p_F^3}{3\pi^2 \hbar^3} \sim 1/\mathrm{fm}^3$ $\Rightarrow$ $\frac{p_F}{mc} \sim 0.6$

$$M \sim \frac{4\pi}{3} \rho_c R^3 \sim m N_0 \left(\frac{p_F}{mc}\right)^{3/2} \sim M_\odot$$

$$\frac{M}{M_\odot} \left(\frac{R}{10\mathrm{km}}\right)^3 \sim 1$$

Neutron star surface

Surface gravity: $g^* = MG/R^2 \sim 10^{14}$ cm/sec$^2 \sim 10^{11}\, g_{earth}$

Gravitational binding energy at surface:

$E_{grav}(m) = -mMG/R = -mc^2R_s/2R \sim -mc^2\,(1.5 \text{ km}/R)\,(M/M_\odot)$

($R_s = 2M\,G/c^2$ = Schwarzschild radius = 2.94 km for Sun)

E_{grav}(proton) > 100 MeV, $m_p\, c^2 = 938$ MeV

Neutron star atmosphere

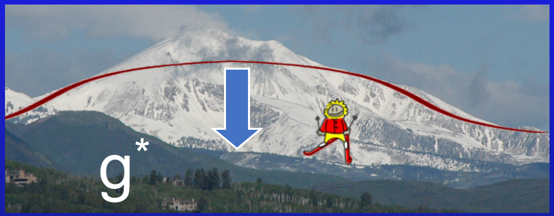
$$\frac{\partial P}{\partial r} = -\rho g^*$$

P = pressure = $T\,\rho/m_{atom}$, $m_{atom} = A m_p$

Scale height of atmosphere, ℓ: $\frac{1}{\rho}\frac{\partial \rho}{\partial r} \equiv \frac{1}{\ell}$ $\rho(h) = \rho(0)\, e^{-h/\ell}$

$\ell = T/m_{atom}g^* \sim (10/A)$ cm (compared with $\ell_{earth} \sim 7$ km)

Mountain on a neutron star



Mountain of mass M, area A, height h

stress = force/area ~ $Mg^*/A \sim \rho g^* h$, $\rho = m_{atom} n_{atom}$

stress = ν X strain, ν = shear modulus ~ $E_{binding} n_{atom}$

strain ~ $m_{atom} g^* h/E_{bind}$

When strain ~ 10^{-2}, mountain breaks

$h \sim 10^{-2} E_{bind} /Am\, g^* \sim T_m/Am\, g^*$ $T_m \sim 10^{-2} E_{bind}$

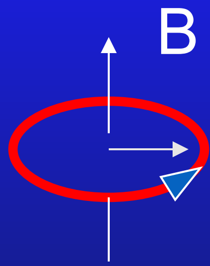
= scale height at melting temperature, T_m

⇒ $h_{max} << 1$ cm $h_{earth} \sim T_m /m_{rock\text{-}atoms}\, g_{earth} \sim 20$ km

Mountains are source of low level gravitational radiation – so far unseen

Magnetic fields can make deformations ~ $10^{-6}(B/10^{15}G)^2$

Atoms in strong magnetic fields

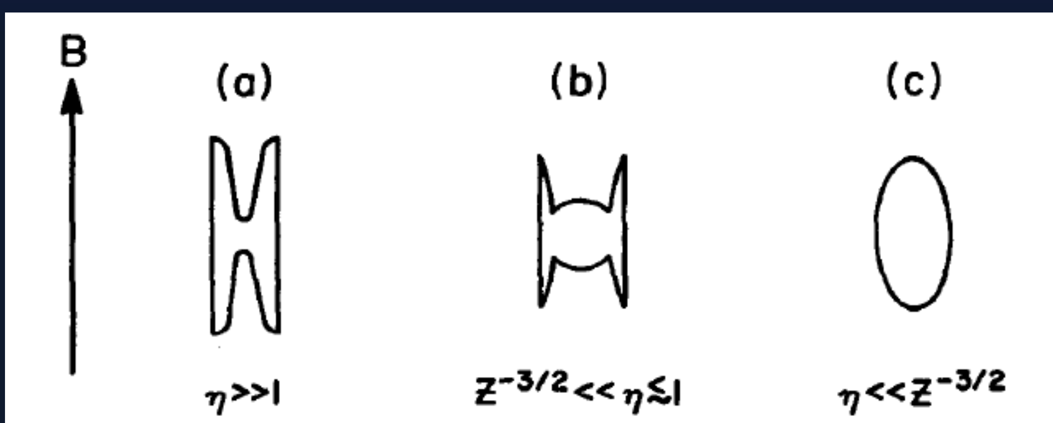


$\rho = (\hbar / m_e B)^{1/2}$ = cyclotron radius

$\omega_c = eB/m_e c$

In atom, last filled orbit at $\rho_Z \sim (2Z)^{1/2}\rho$;   Z = proton no.

Atomic shape determined by competition between atomic (Bohr) orbits in Coulomb potential and Landau orbits in magnetic field



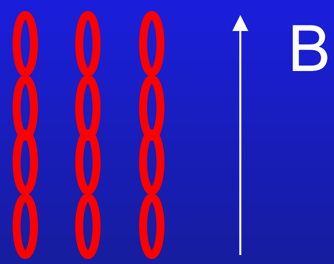
$\eta \equiv a_0/Z\rho_Z$

$= (B/4.6 \times 10^9\ G)^{1/2}/Z^{3/2}$

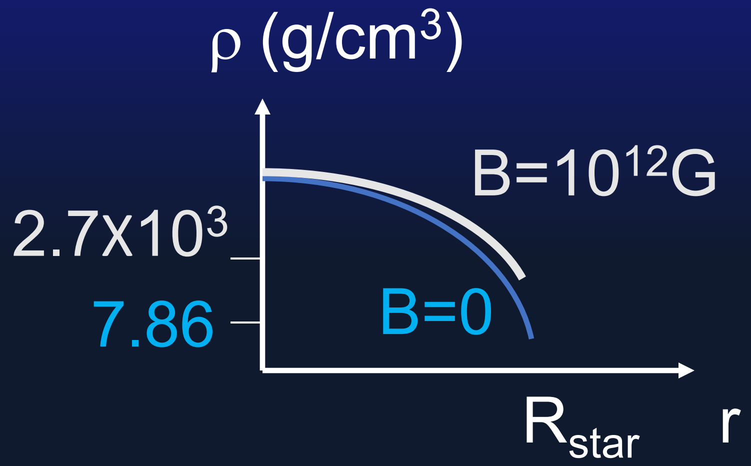
$a_0 = \hbar / m_e e^2$

Surface effects of strong magnetic fields

Atoms form covalently bonded chains parallel to magnetic field. Chains electrostatically bonded to each other.



Surface density is raised considerably:



Neutron stars are not black bodies. Difficult to absorb or emit radiation polarized perpendicular to magnetic field. Very important in interpretation of detected x-ray emission from neutron stars.

Outline

General structure of neutron stars (with a little history).

Neutron star models, masses, and observations

Nuclear physics of the crust

Liquid interior: equation of state.

Quark matter/ g_V and H

Glitches, superfluidity and vortices

dark matter in neutron stars -- Sanjay