# Hadron-hadron interactions and the physics of neutron stars

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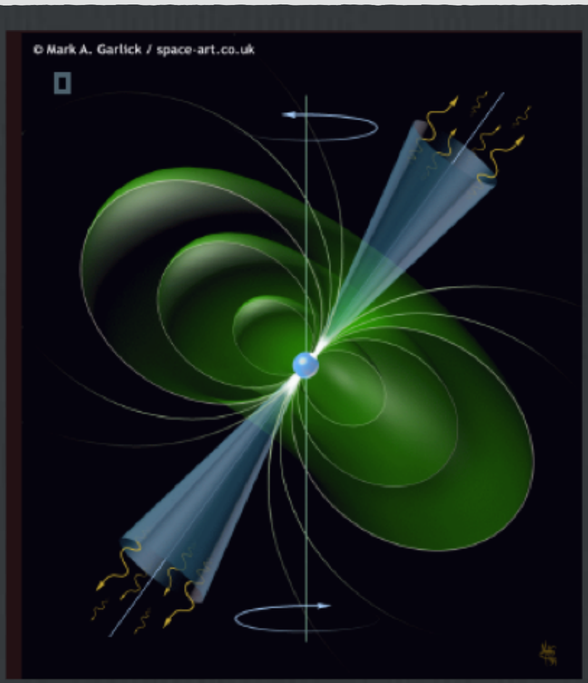
Indian Summer school 2022, Prague

# Facts about Neutron Stars



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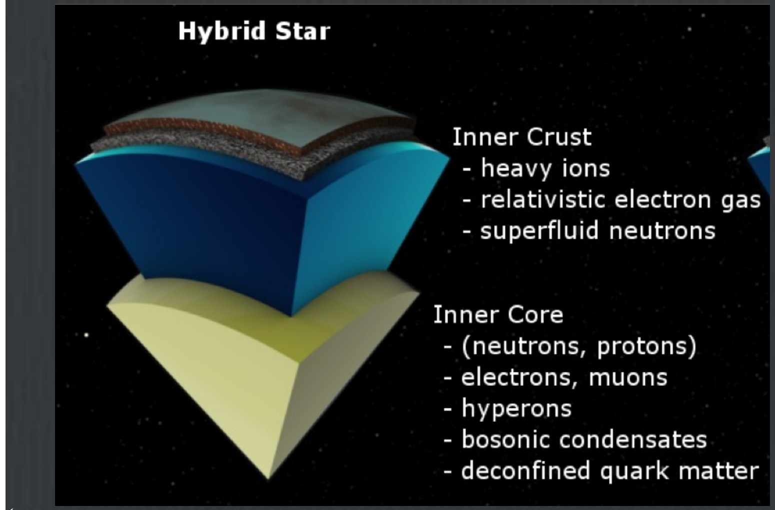
$R \sim 10\text{–}15$ km
$M \sim 1.5\,M_\odot$

density



## Which are the properties of Neutron Stars??

- Very high density in the interior
- Strong magnetic fields
- Rotating object emitting Synchrotron radiation in Radio-Frequency (Pulsar character)
- Mass measured in binary systems with White Dwarfs (Shapiro Delay, WD Spectroscopy)
- Radius Measurement via X-ray studies, less precise
- Gravitational waves
- Masses ranging from 1.1 $M_\odot$ to 2 $M_\odot$
- Radii between 10 and 15 Km

## What is inside Neutron Stars??

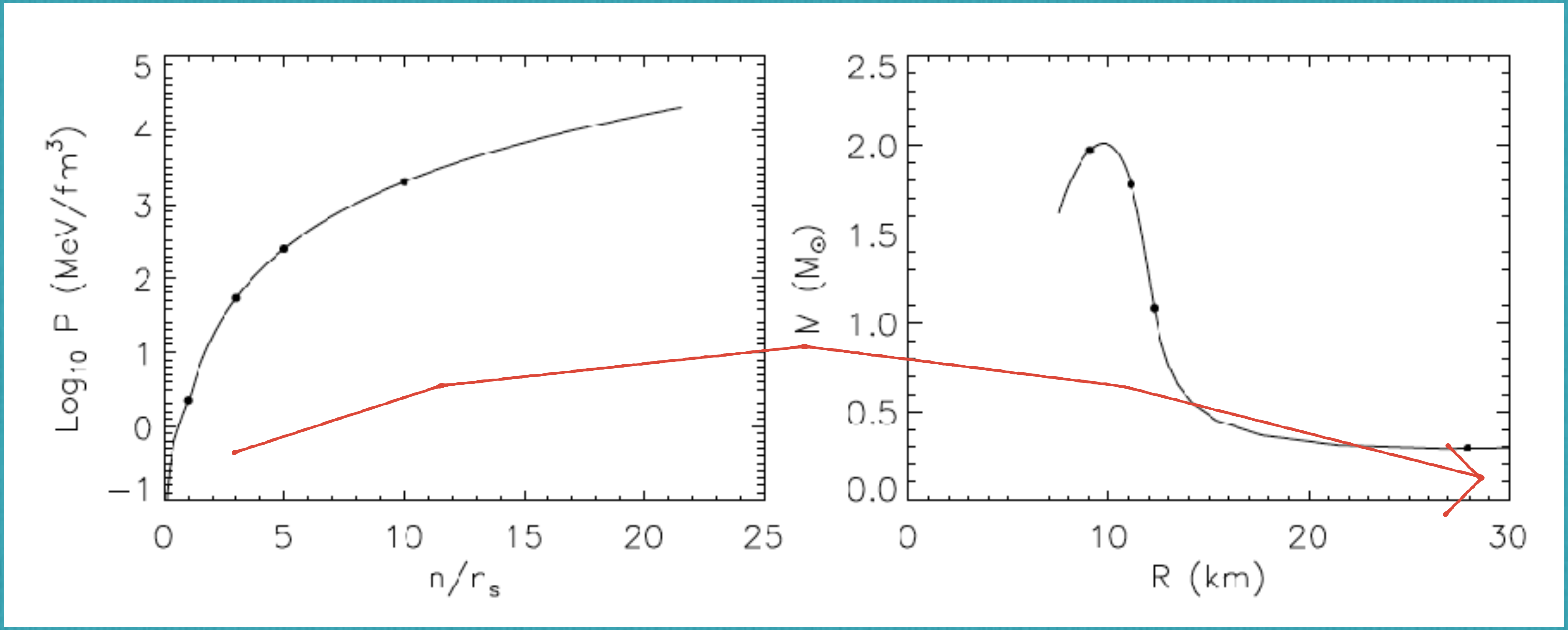
Experimentally one can try to measure NS properties such as Mass and radius and measure the hadron-hadron interactions to attack from problem from two sides.
Today we see (some of) the NS measurements
Tomorrow and on Sunday we focus on the measurements of the strong interaction

# Outline of this Lecture

- Shapiro delay measurement
- X-Ray Binary
- the NICER misison
- Gravitational waves measurements

# Mass versus Radius

The Equation of state can be translated 1:1 into a mass versus radius curve (next lecture) so that different EoS can be tested against mass and radii measurements.

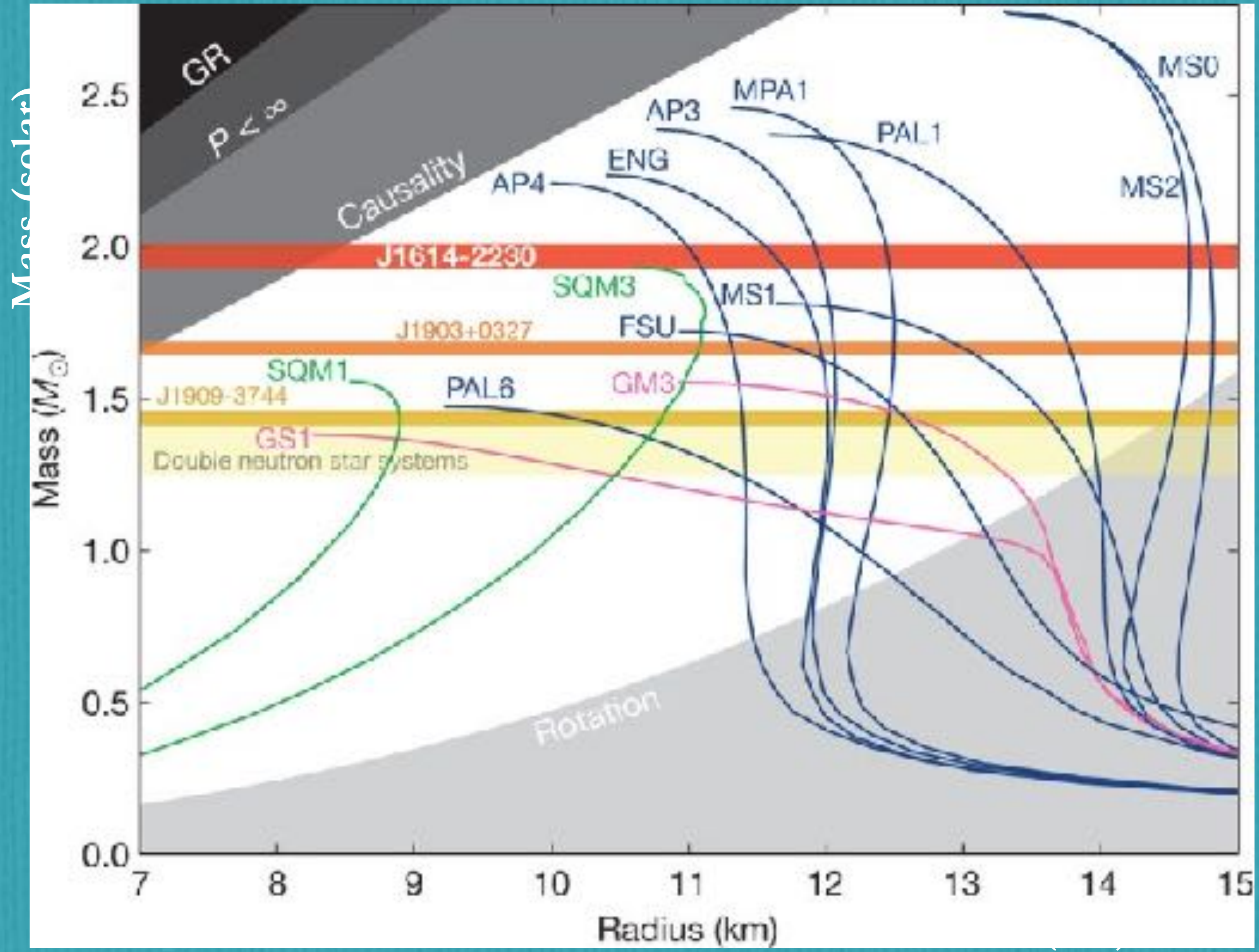


These lines are unique given an EOS

- Soft EOS: low maximum mass and small radii
- Stiff EOS: high maximum mass and large radii

# A famous figure about neutron star properties

P. Demorest et al. Nature (467) (2010) 1081



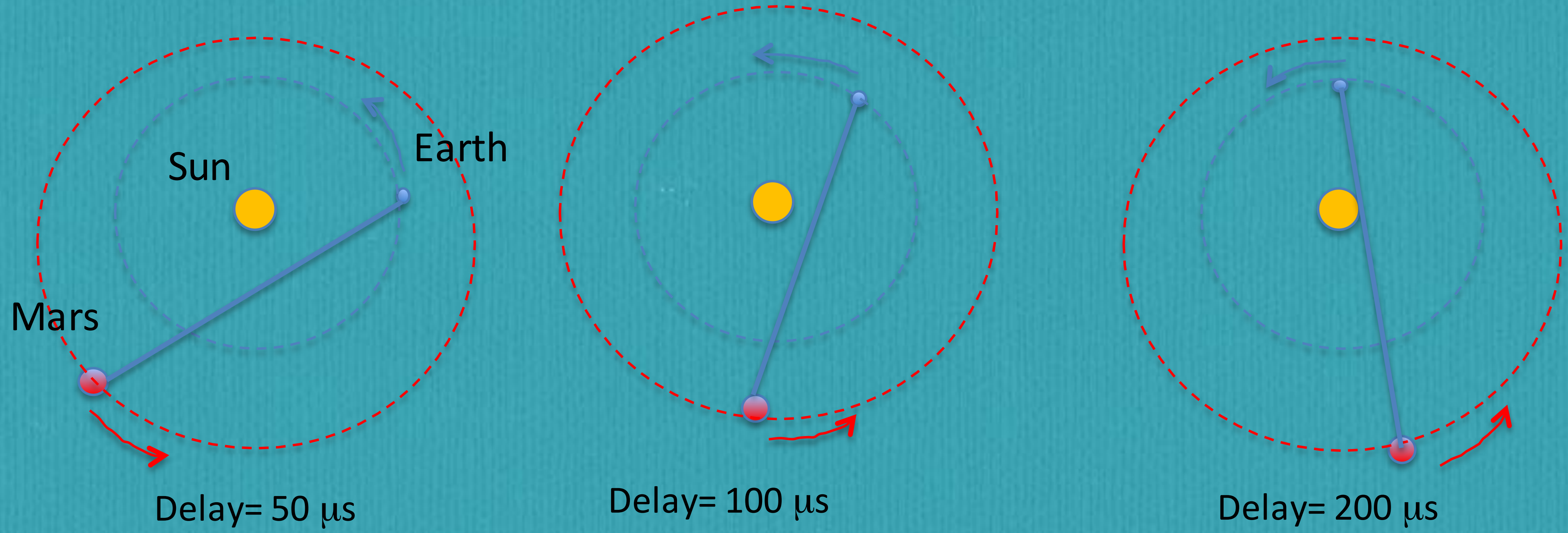
- Production of strangeness is energetically favourable
- It relieves the Fermi pressure of neutrons and protons
- But… a decrease of the pressure softens the EOS
- Decrease of the maximum mass of neutron stars
- 2 M neutron star measured
- EOS cannot be too soft ??? !!!

# Shapiro Delay

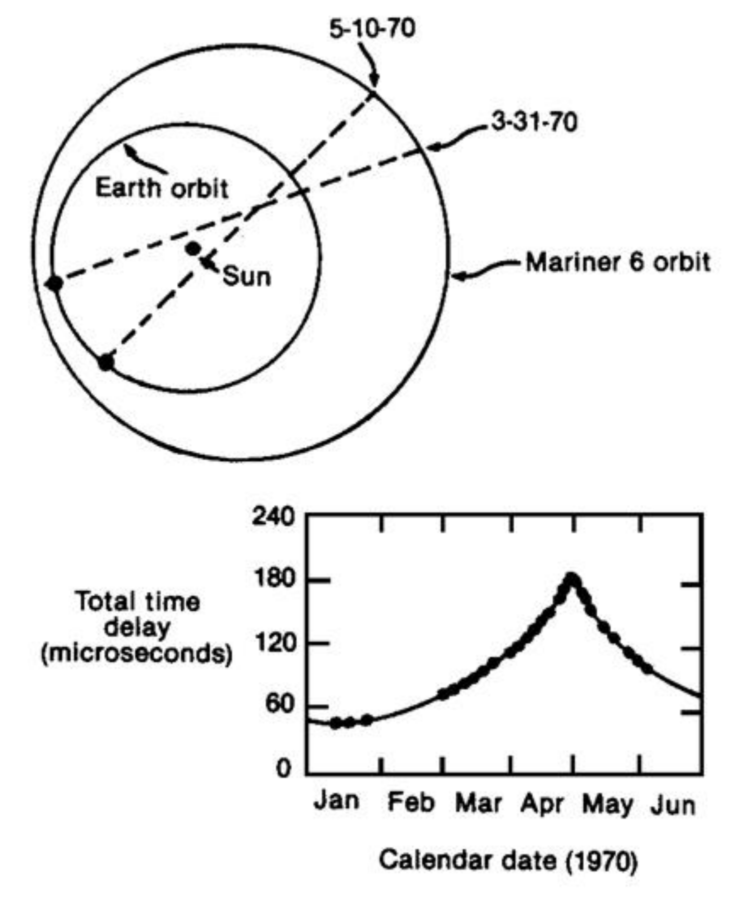
> *"...according to the general theory, the speed of a light wave depends on the strength of the gravitational potential along its path."*

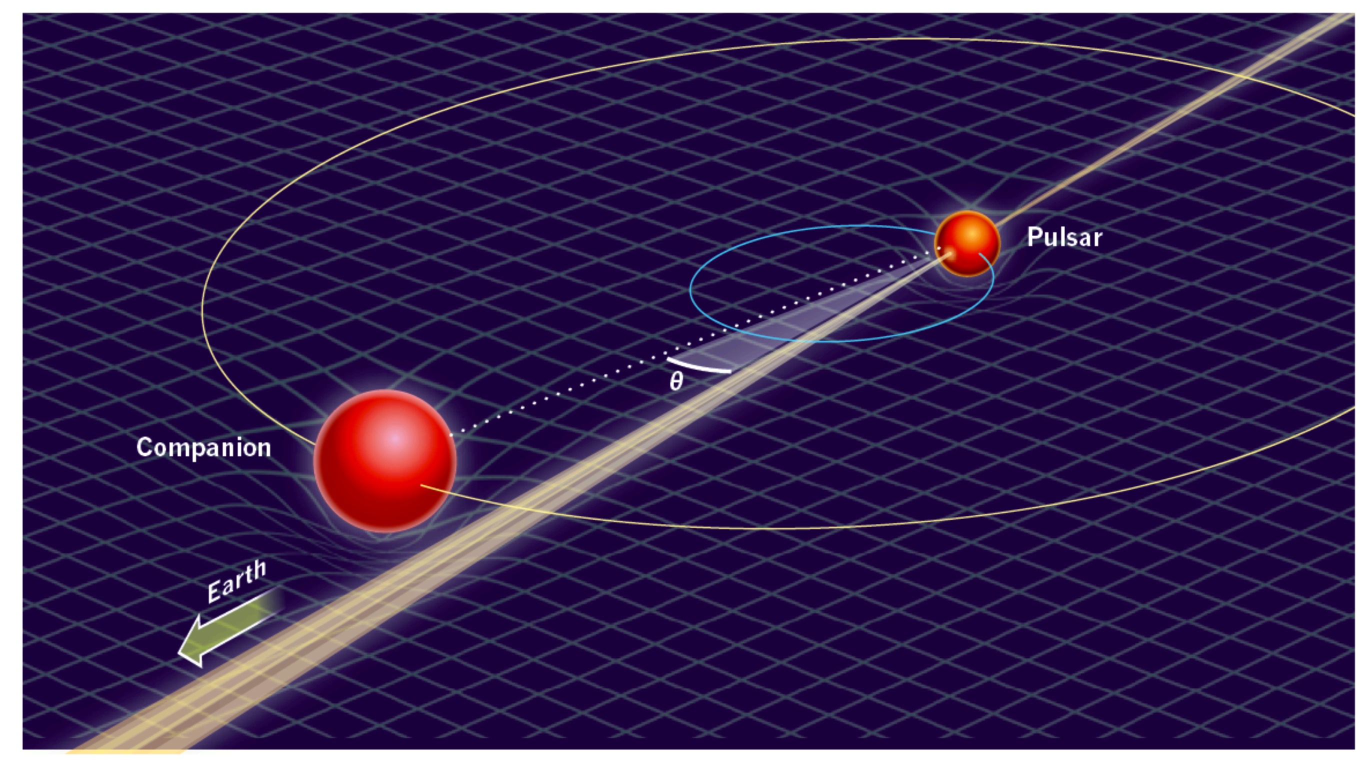
Dr. Irwin I. Shapiro

Easiest Test:
Send Radar beam from the Earth to Mars and measure the time the need return as a function of the distance of closest approach to the sun
The closest the beam comes to the sun, the largest should be the delay

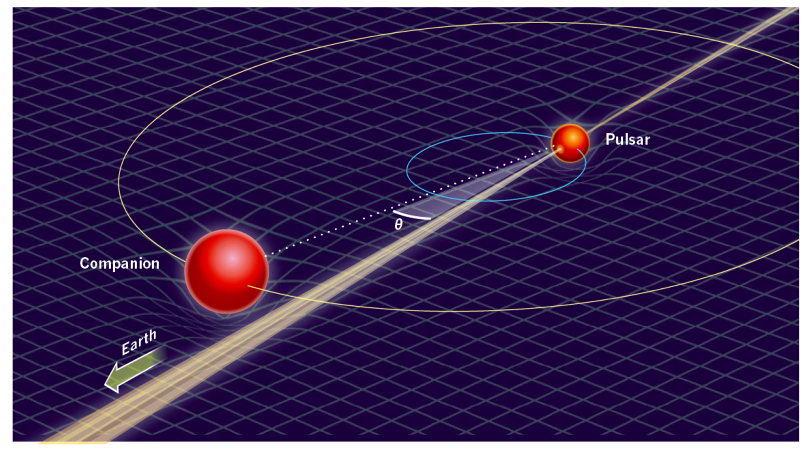


Signal returned by transponders on spacecrafts



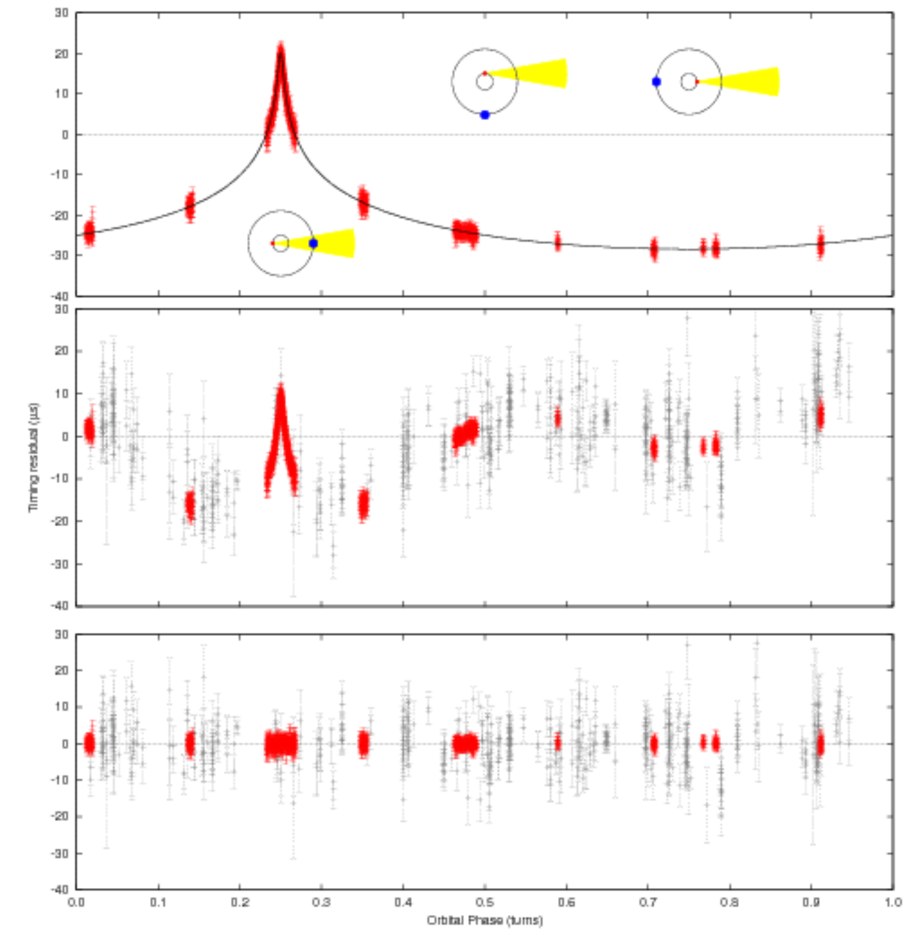


The pulsar emits radiowaves with a period of few milliseconds
Depending on the relative positions of the pulsar and the companion the
Radio beam “sees” more or less the gravitational field of the companion.
A periodic delay arises.
The period of the delay modification depends on the system inclination w.r.t. to the observer and companion mass.
If this measurement if compared to classical orbits the two masses can be extracted.



$$\Delta t = -(2GM/c^3)\ln(1 - \sin i \cos\theta)$$

M: companion mass
i: inclination angle of the orbital plane w.r.t. to the observer

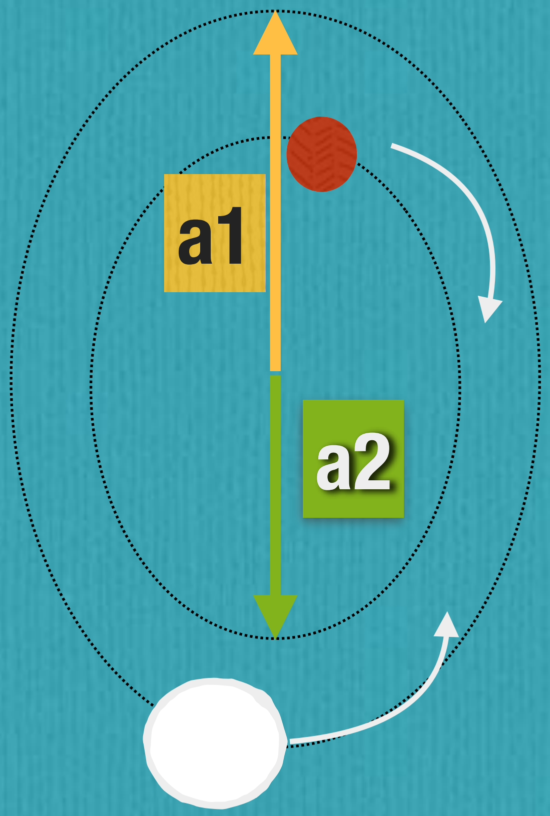


Demorest et al Nature 467 18081-1083 (2010).
J1614-2230: Binary millisecond Pulsar

**The delay is measured as a function of the orbital time**
**For J1614-2230 sin i = 90°**
**→ M companion mass can be determined very precisely**

→ time : rotation angle $\theta$

# Mass measurements for Radio pulsars in Binaries



$a_{1,2}$ = major half axis
$T_{1,2}$ = orbital period

The relation between the two orbits is

$$M_{NS} \cdot a_2 = M_c \cdot a_1$$

With the velocities of the two stars:

$$v_1 = \frac{2\pi a_1}{T_1} \quad v_2 = \frac{2\pi a_2}{T_2}$$

$$M_T = M_{NS} + M_C$$

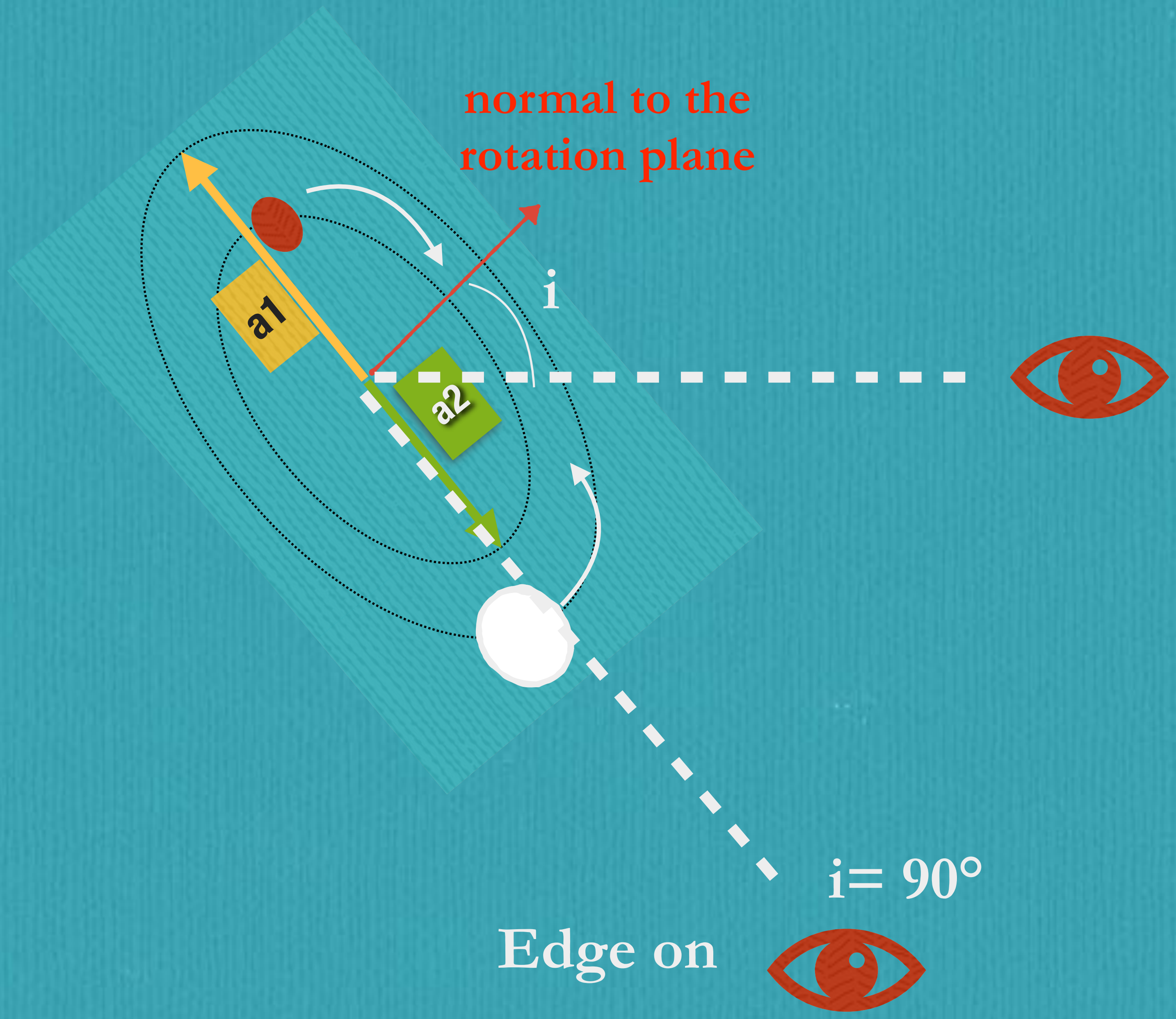
By measuring the binary orbital period $T_2$ for the NS pulsar and using the 3rd Kepler law:

$$T_{1,2}^2 = \frac{4\pi^2}{G \cdot M_T}(a_{1,2})^3$$

Substituting : $a = \frac{vT}{2\pi}$ ➡ $M_C + M_{NS} = \frac{T_2 v_2^3}{2\pi G}$

# Mass measurements for Radio pulsars in Binaries

Since one can only observe the radial component of the velocity ($v_r = v \cdot \sin i$):

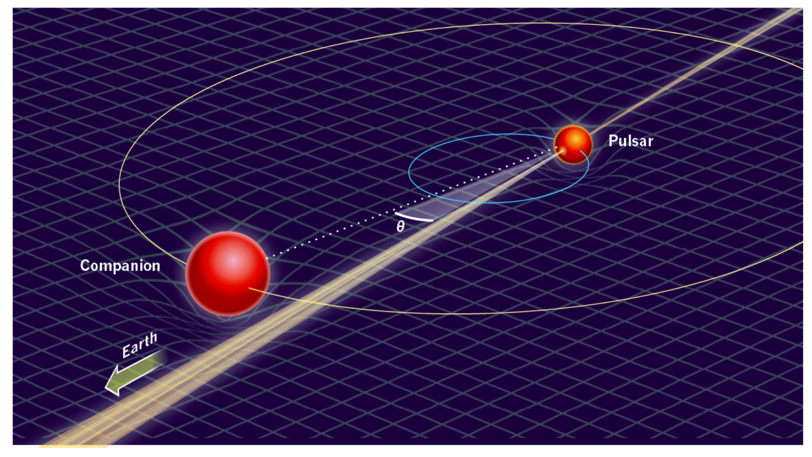


$$M_C + M_{NS} = \frac{T_2 v_2^3}{2\pi G}$$

$$\Downarrow$$

$$M_C + M_{NS} = \frac{T_2 v_2^3}{2\pi G \sin^3 i}$$

The velocity can be measured using the relativist Doppler effect!



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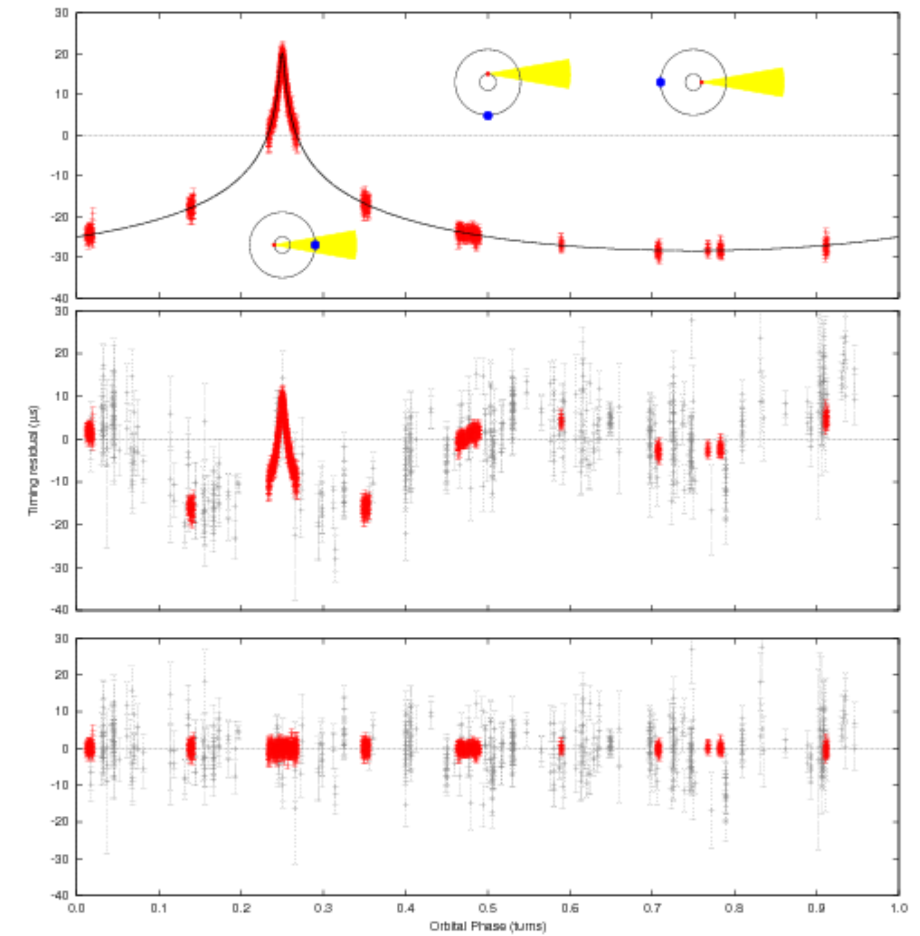
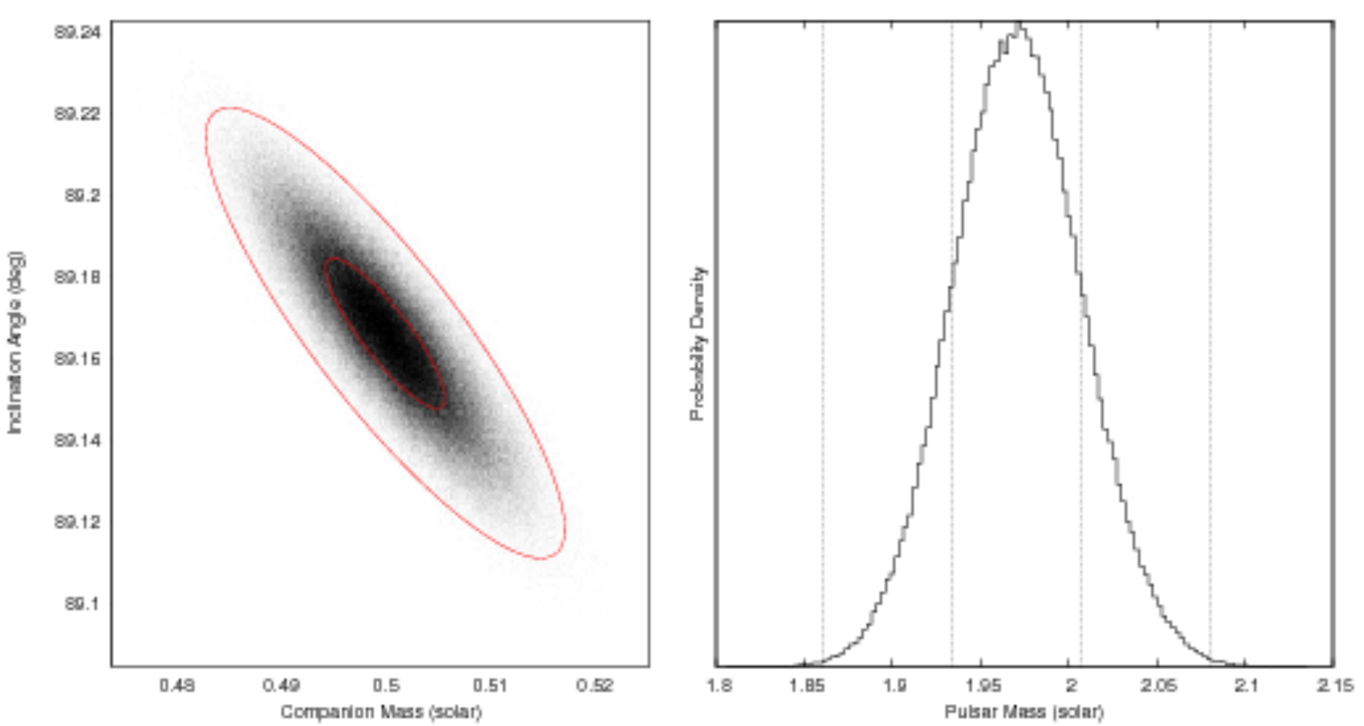




Demorest et al Nature 467 18081-1083 (2010).
J1614-2230: Binary millisecond Pulsar

$$M = 1.97 \pm 0.04\, M_\odot$$

# Recent measurements of High NS masses

- **PSR J164-2230** (Demorest et al. 2010)

  ✓ binary system (P=8.68 d)

  ✓ low eccentricity (ε=1.3 x $10^{-6}$)

  ✓ companion mass: $\sim 0.5 M_\odot$

  ✓ pulsar mass: $M = 1.928 \pm 0.017 M_\odot$

- **PSR J0348+0432** (Antoniadis et al. 2013)

  ✓ binary system (P=2.46 h)

  ✓ very low eccentricity

  ✓ companion mass: $0.172 \pm 0.003 M_\odot$

  ✓ pulsar mass: $M = 2.01 \pm 0.04 M_\odot$

In this decade NS with 2M have been observed by measuring Post-Keplerian parameters of their orbits

- Advance of the periastron $\dot{\omega}$
- Shapiro delay (range & shape)
- Orbital decay $\dot{P}_b$
- Grav. redshift & time dilation γ

- **MSP J0740+6620** (Cromartie et al. 2020)

  ✓ binary system (P=4.76 d)

  ✓ low eccentricity (ε=5.10(3) x $10^{-6}$)

  ✓ companion mass: $0.258(8) M_\odot$

  ✓ pulsar mass: $M = 2.14^{+0.10}_{-0.0.9} M_\odot$ (68.3% c.i.)

  $\odot$ (95.4% c.i.)

# Neutron Stars radii

The radius of a neutron star with mass M cannot be arbitrarily small

General Relativity:
a Neutron Star is not a
Black Hole

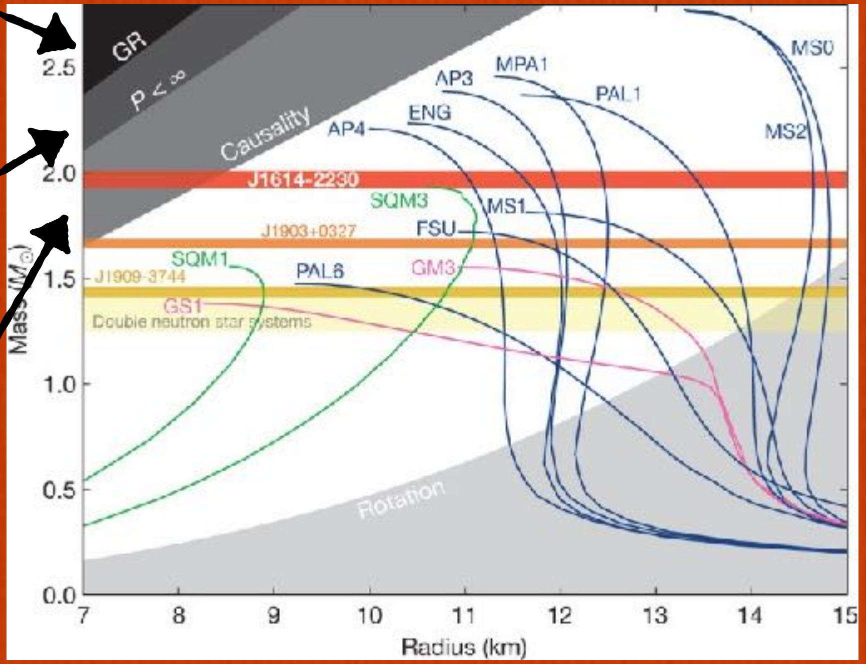
$$R > \frac{2GM}{c^2}$$

Finite Pressure:
Neutron Star matter cannot
be arbitrarily compressed

$$R > \frac{9}{4}\frac{GM}{c^2}$$

Causality:
speed of sound must
be smaller than c

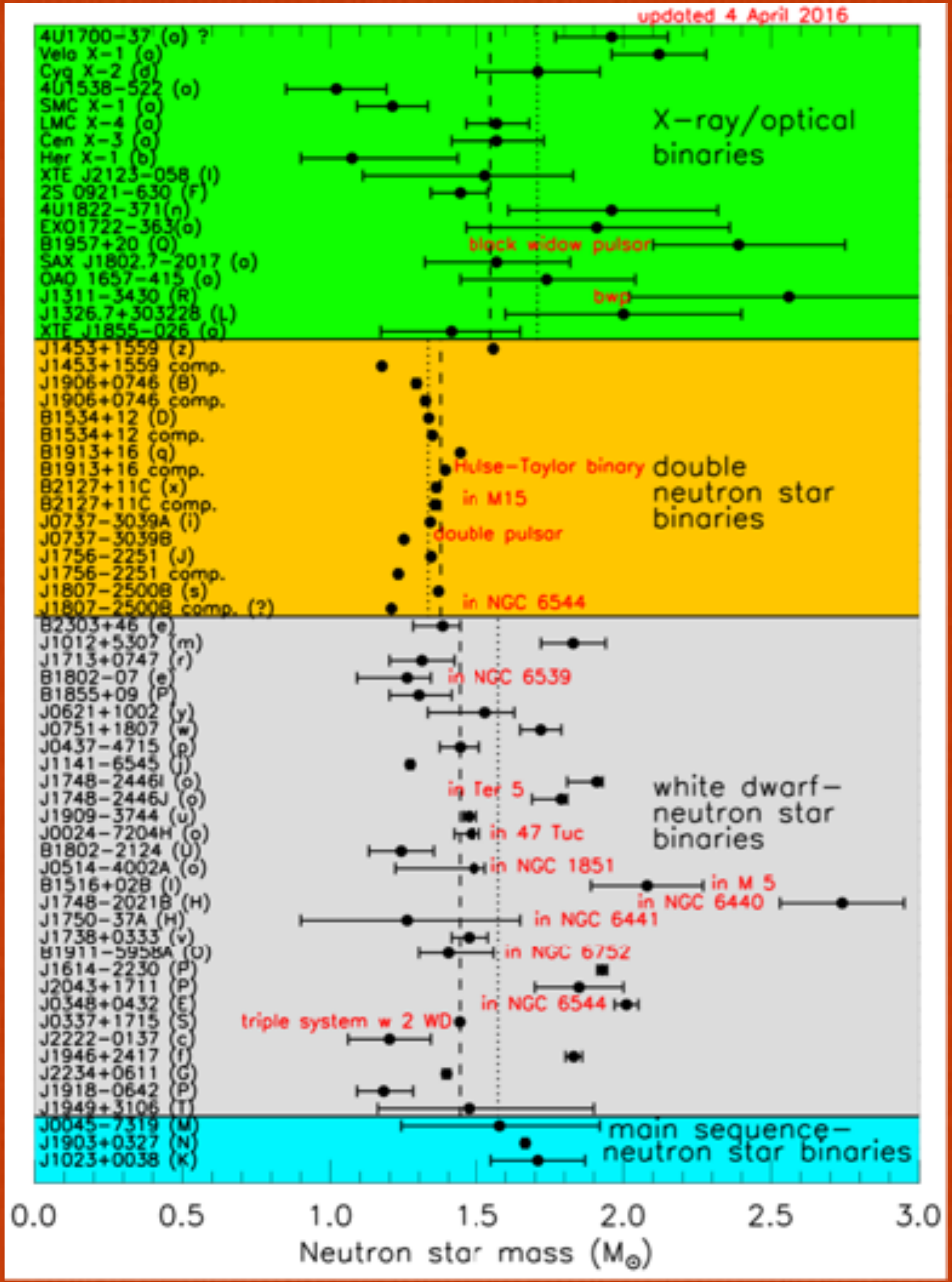
$$R > 2.9\frac{GM}{c^2}$$

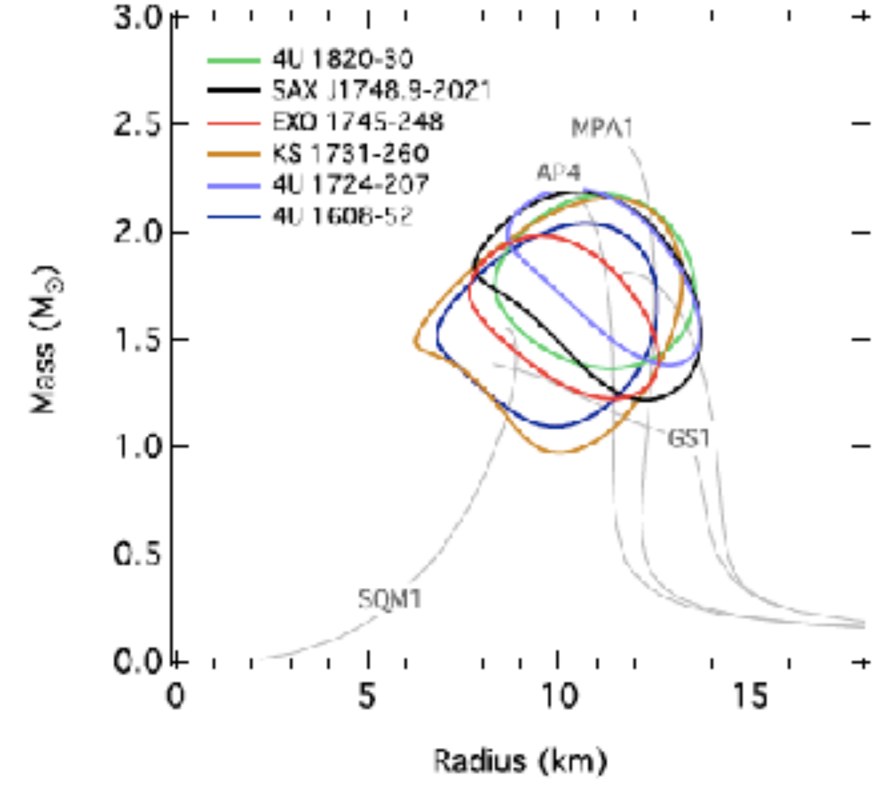


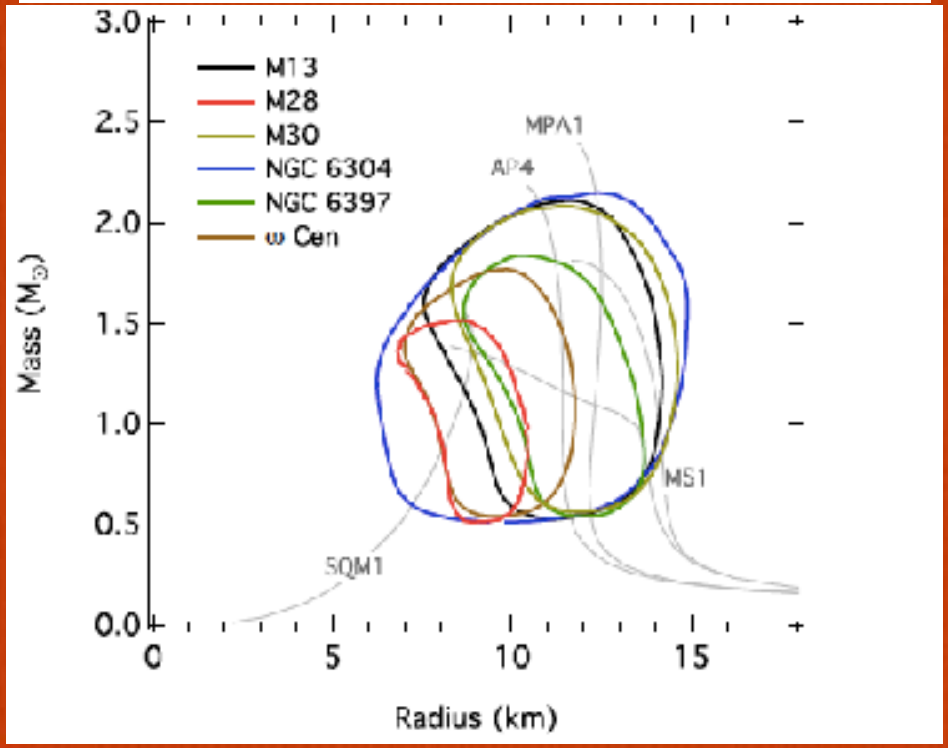
# Mass and Radii Measurements

https://stellarcollapse.org/nsmasses

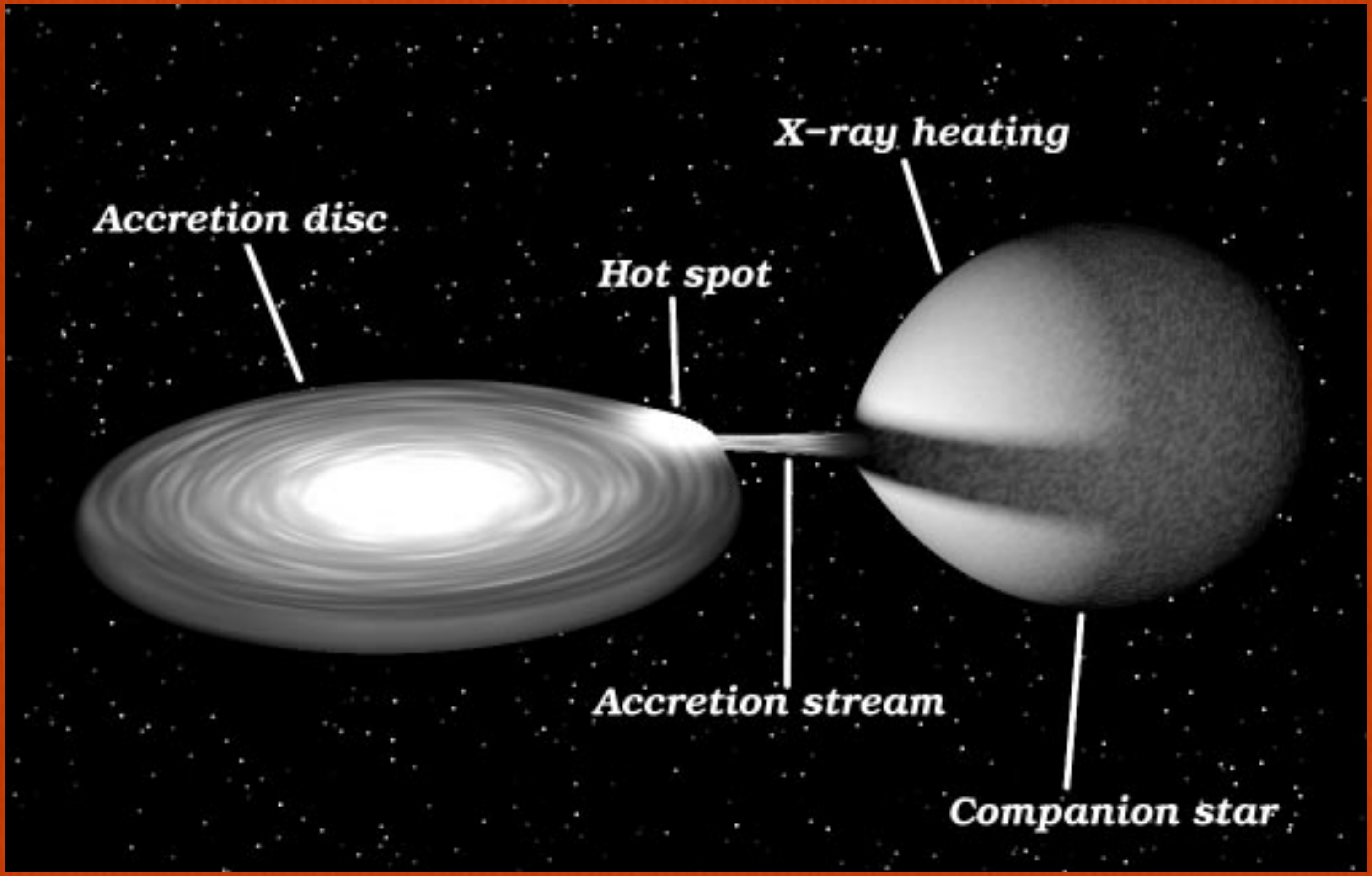
Ozel et al. 2016, ApJ, in press (arXiv:1505.05155)







# X-Ray Binary

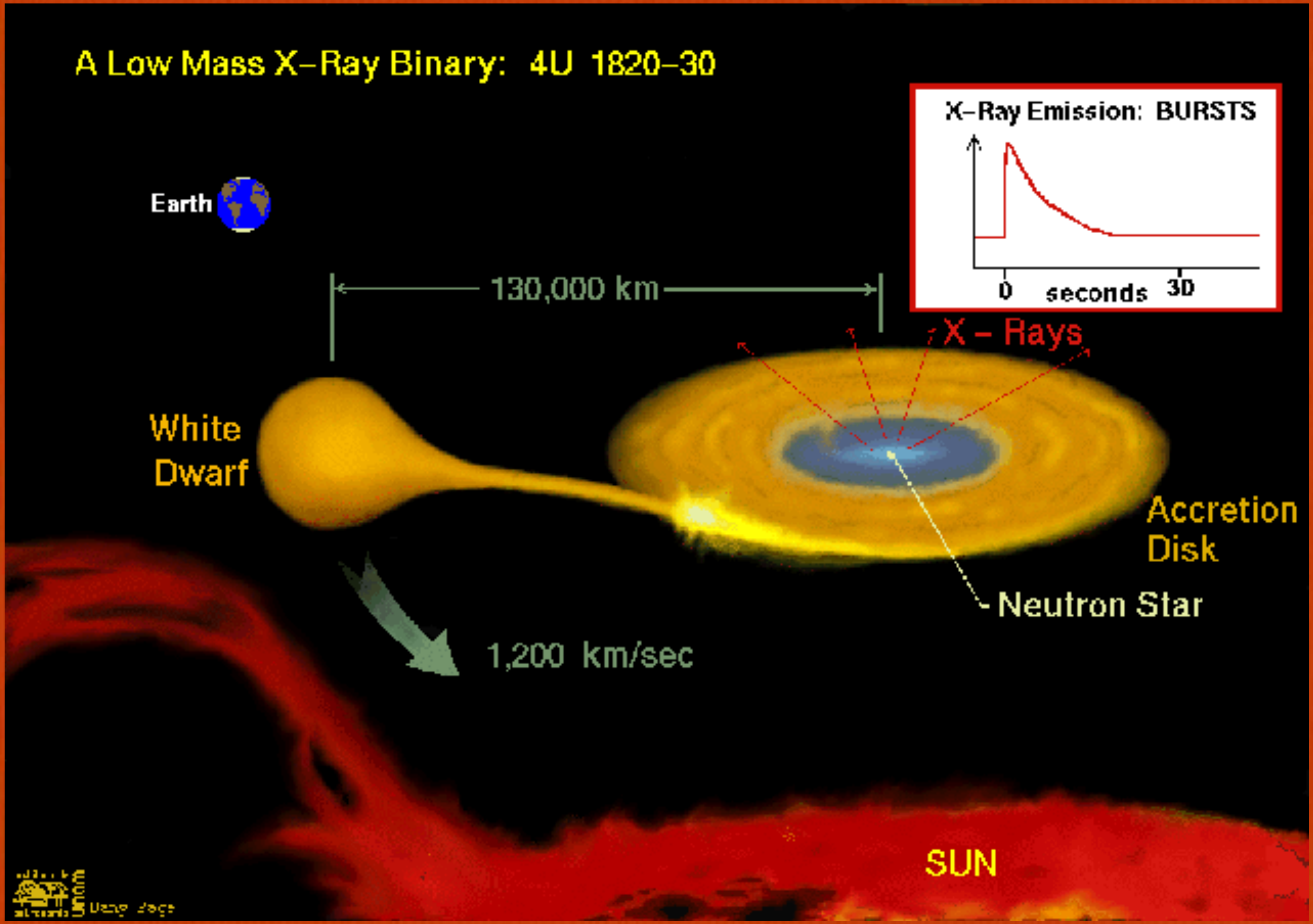


X-ray binary is a class of binary stars.(a binary star is a star system consisting of two star orbiting around a common barycenter). The x-rays are produced by matter falling from one component, called the donor (usually a normal star), to the other component, called the accretor, which is very compact: a neutron star for example

https://physicsknowledgezone.files.wordpress.com/2016/06/1820-30_l.gif

# Low Mass X-Ray Binary

1 NS + 1 White Dwarf



X-Ray Burst from accreted matter on the NS surface

Rise-time ~0.5-5 sec

Decay Time ~10-100 sec ( depends on the temperature)

Energy release in 10 sec $\sim 10^{39}$ ergs

# Radius Measurement

Observable: thermonuclear bursts (X-rays) from accreting neutron stars

12 Sources
Compact Source spins at moderate high rate

Measure Thermal Flux (F) and Temperature $T_C$

$$A_\infty = \frac{F}{\sigma_B \cdot T^4}$$

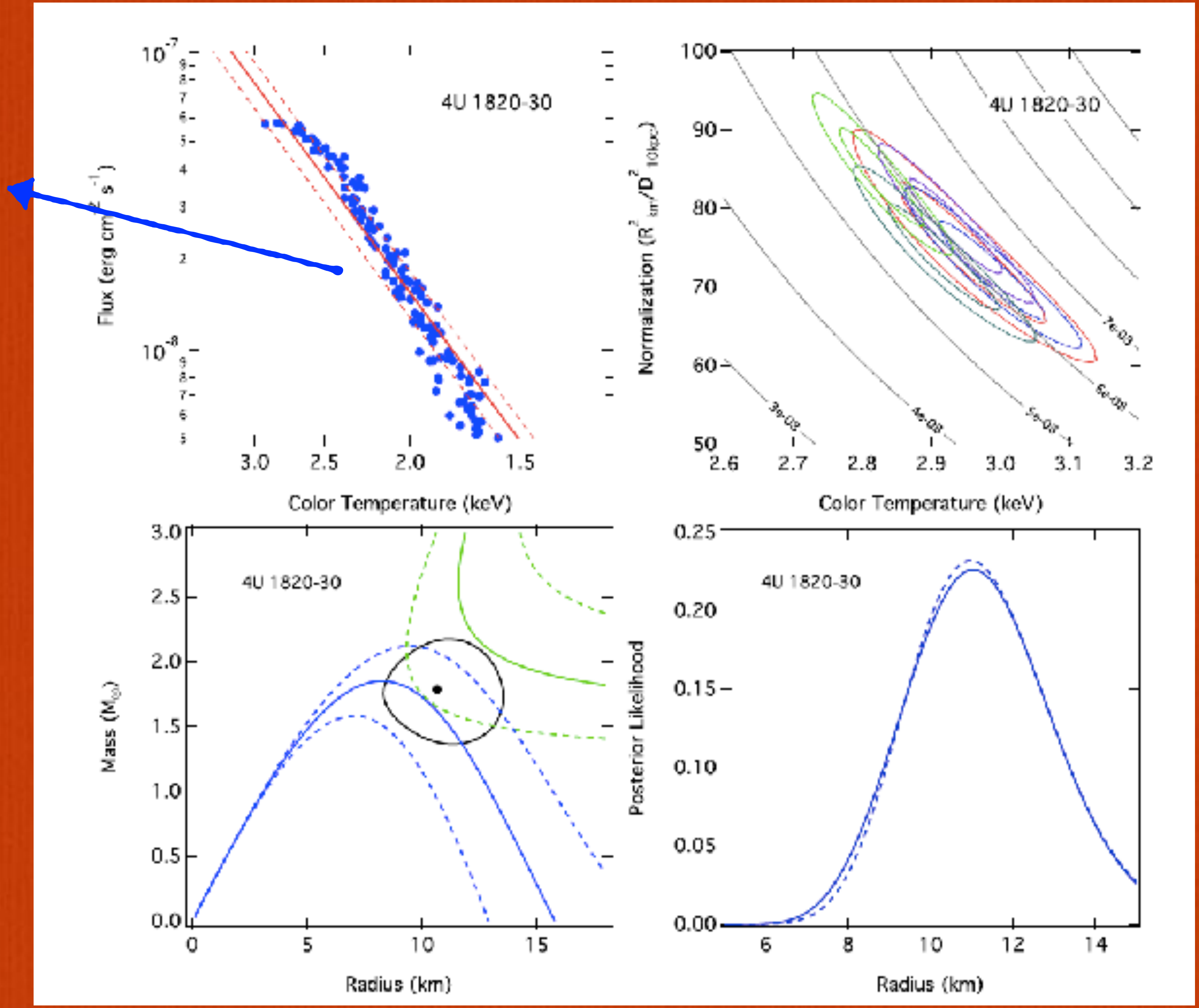
$$A_\infty = \frac{R^2}{D^2 f_c^4}\left(1 - \frac{2GM}{Rc^2}\right)^{-1}$$

Distance NS-Observer

Correction factor because of the <u>Atmosphere</u> → Extremely model dependent !!!

+ Doppler corrections + spinning corrections

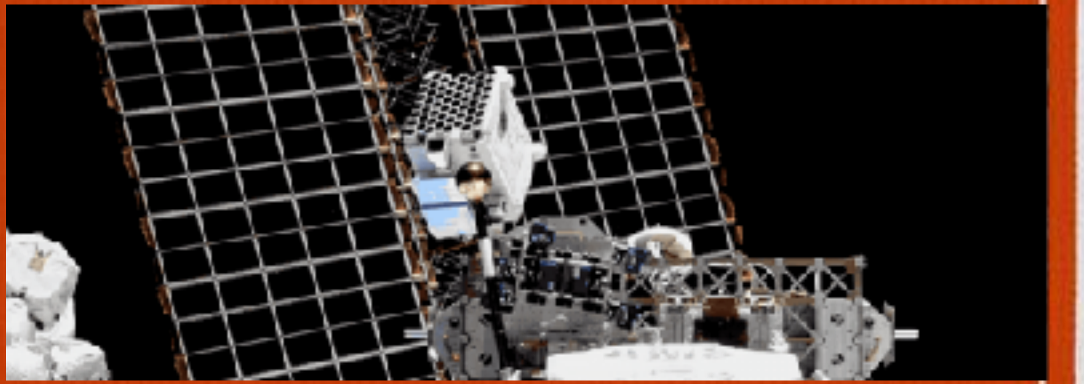
Each point corresponds to a spectrum where the Flux and the temperature are extracted, T extracted via thermal fit.



New more accurate measurements by the NICER x-ray detector are expected

# Recent measurements of radii AND masses

NICER (Neutron star Interior Composition ExploreR) detector on the ISS station



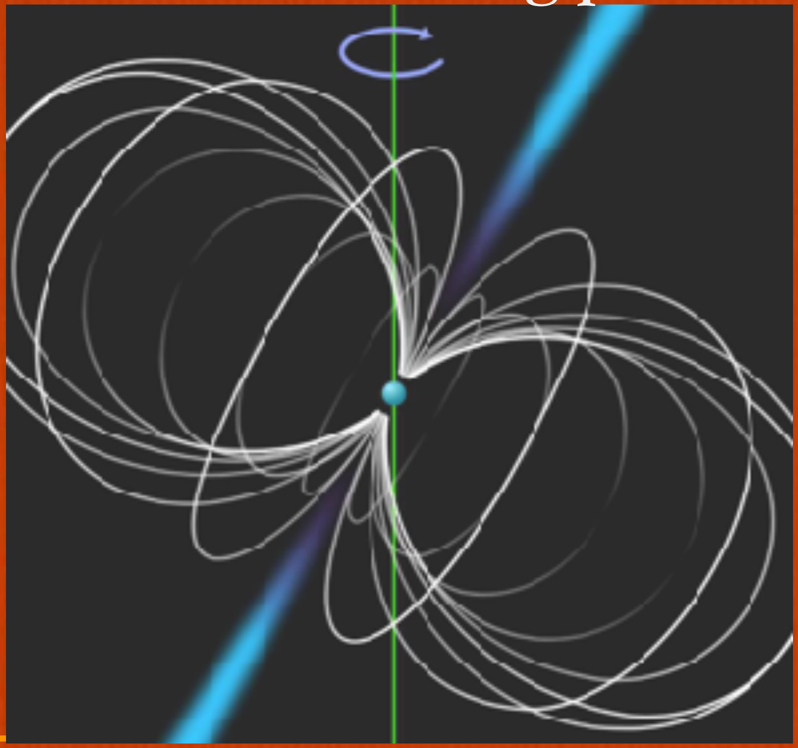
measures the size of the neutron star by tracking the x-ray emission from ‘hot-spots’ on the surface as the star rotates.

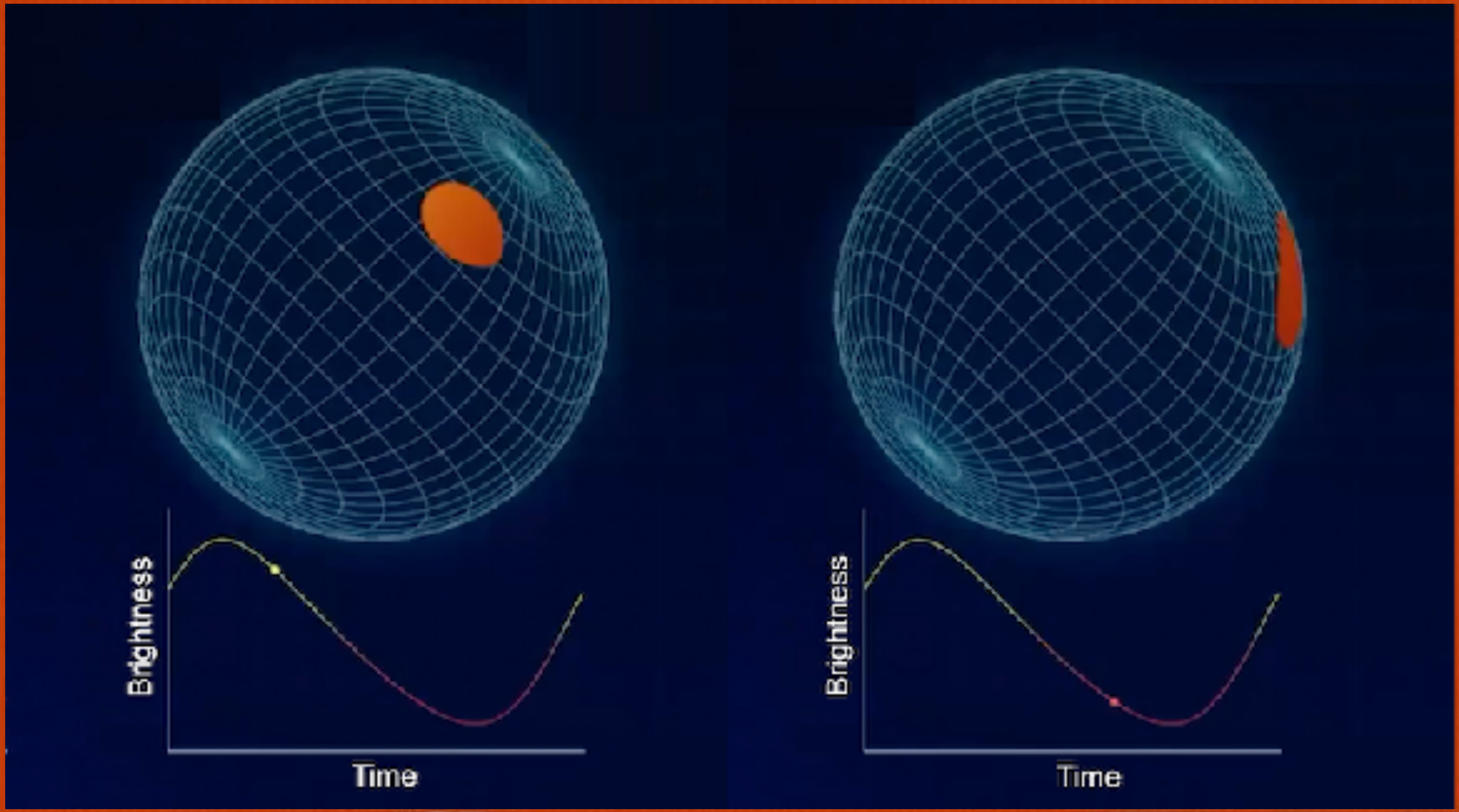
- X-ray spectroscopy [0.12; 12] keV of millisecond pulsars after accretion is completed

Measurements are carried out for single pulsar and for binaries!

Only for binaries they can obtain an independent constraint on the mass of the star

One needs rotating pulsars

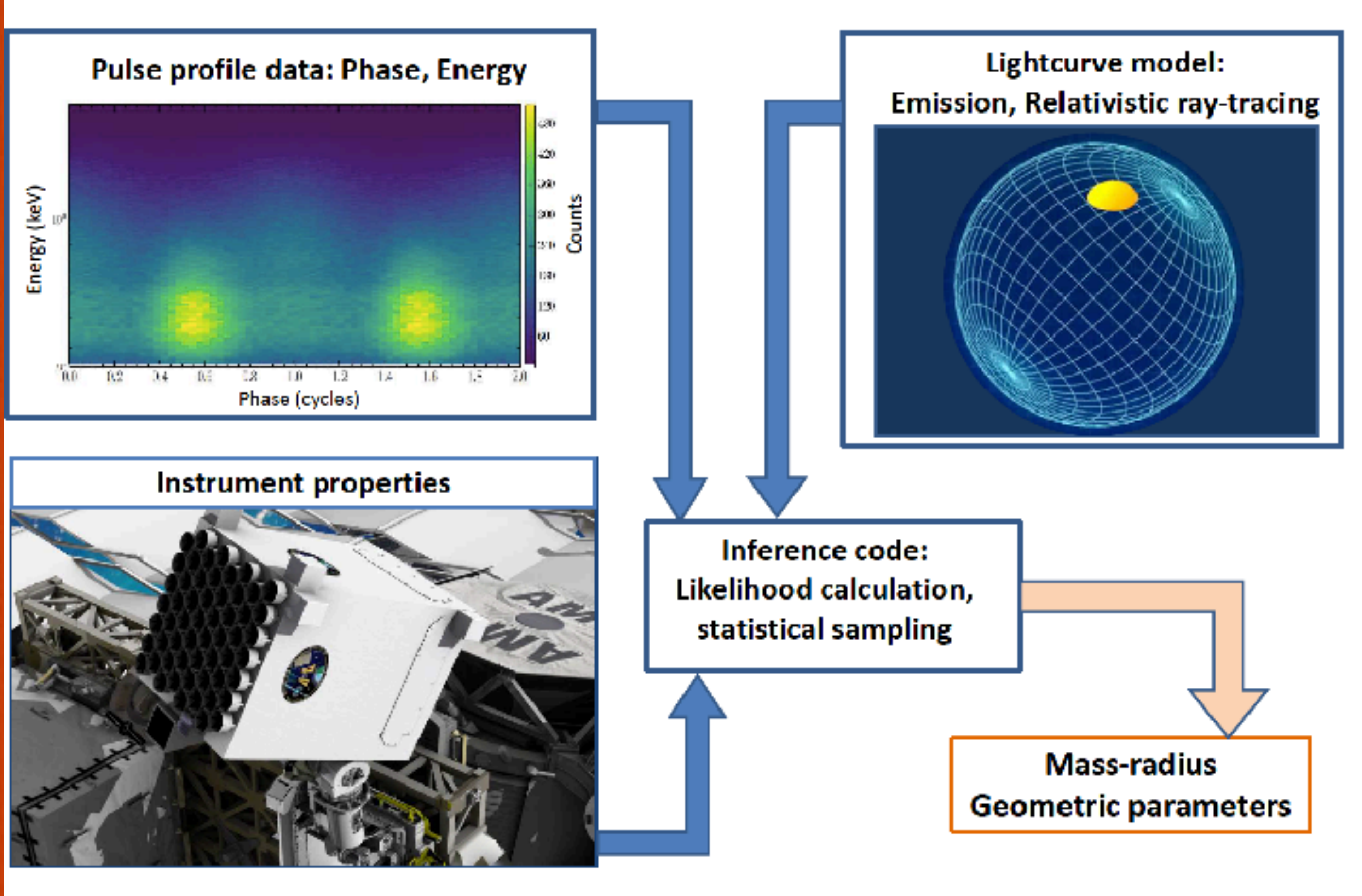




# The pulse profile modeling process

Data measured

simulation of certain spots on NS with certain emission and propagation of x-Ray to the detector



**Pulse profile data: Phase, Energy**

**Lightcurve model:**
**Emission, Relativistic ray-tracing**

**Instrument properties**

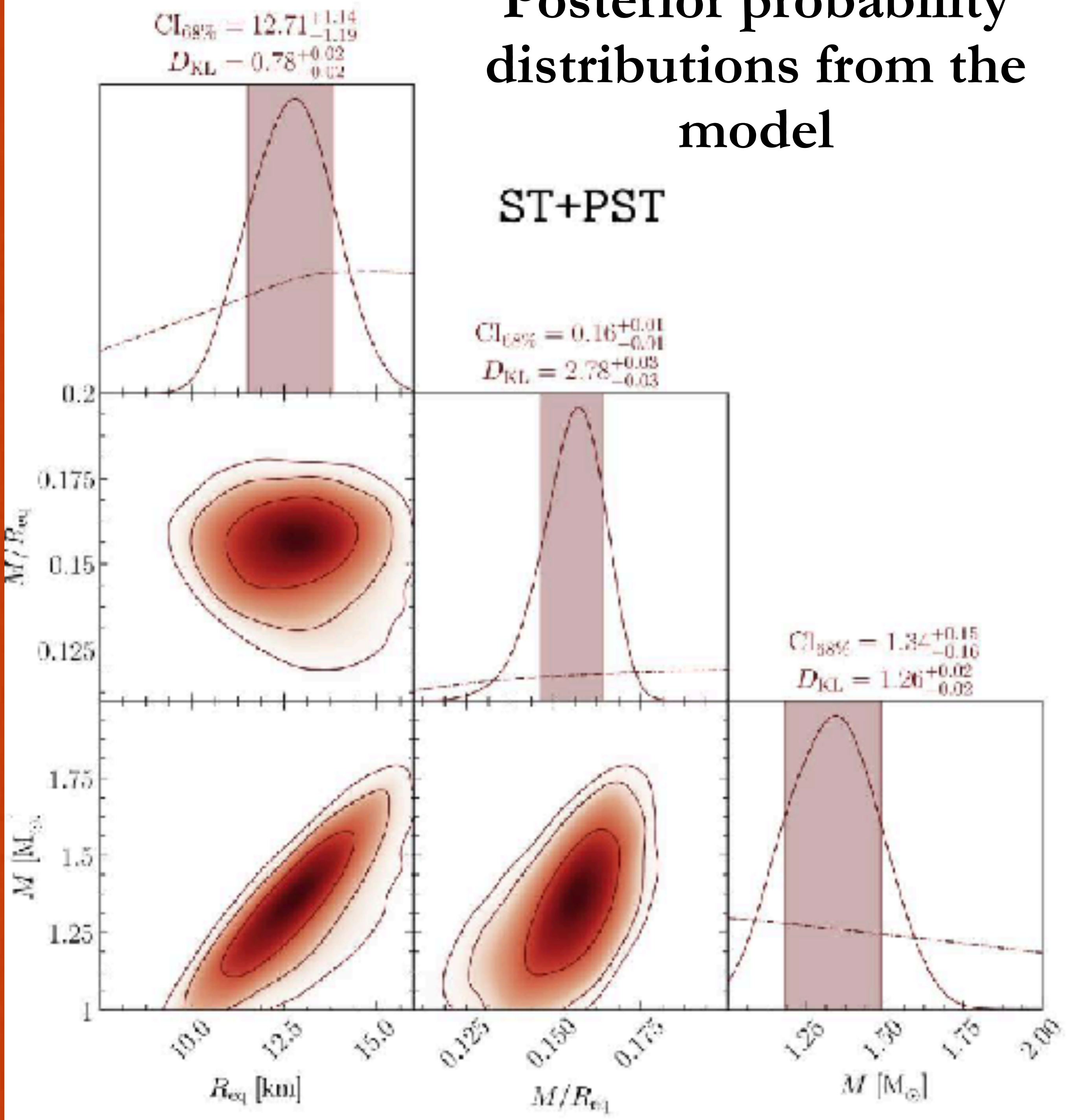
**Inference code:**
**Likelihood calculation, statistical sampling**

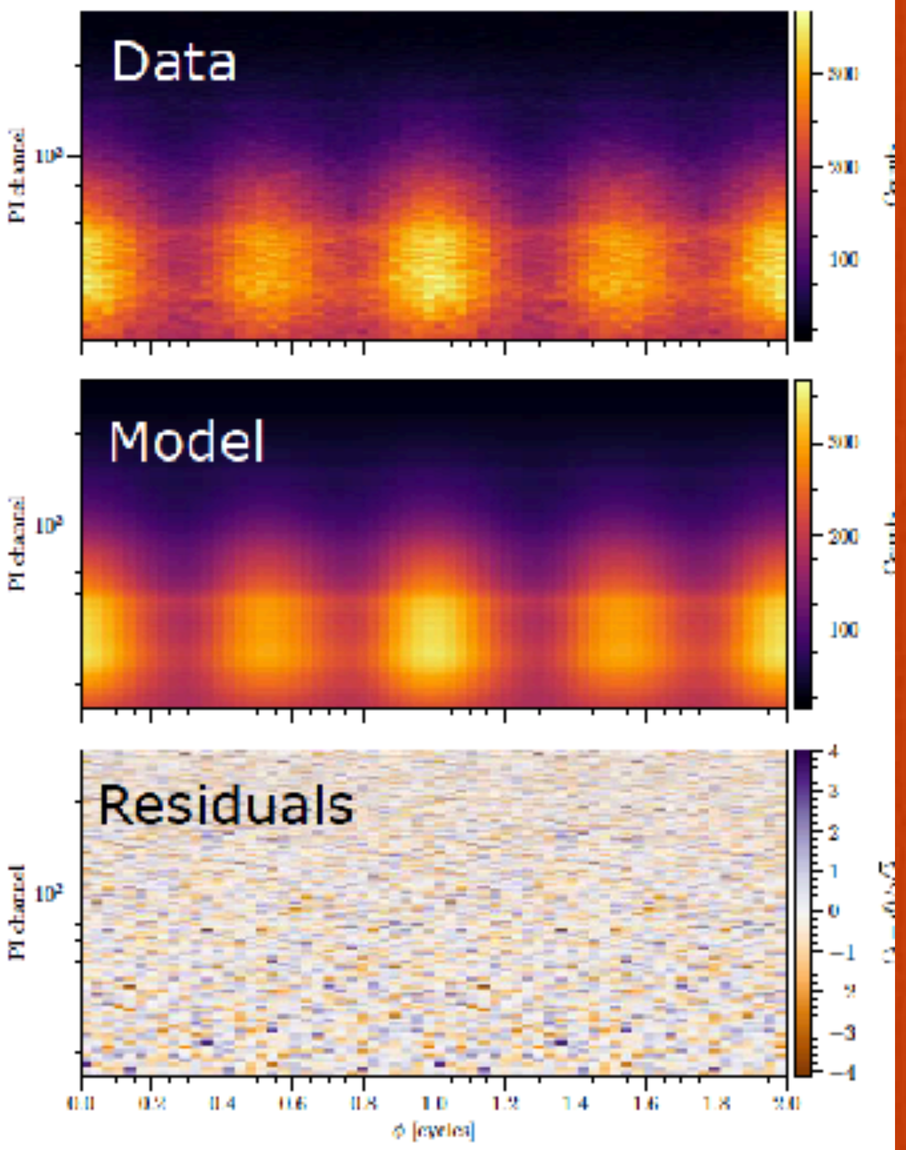
**Mass-radius**
**Geometric parameters**

A. Watts, Youtube

# Example: PSR J0030 + 0451

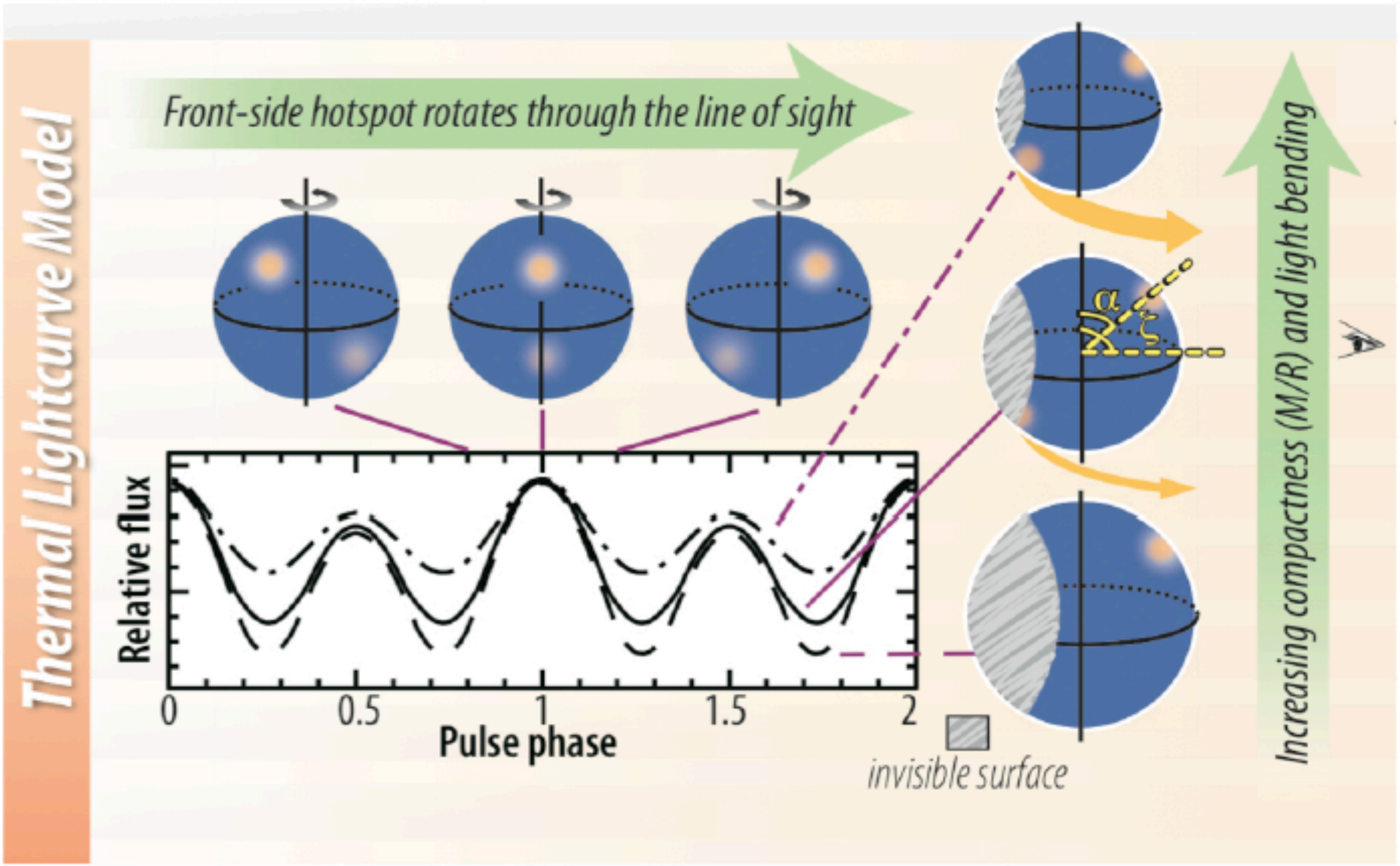
Posterior probability distributions from the model



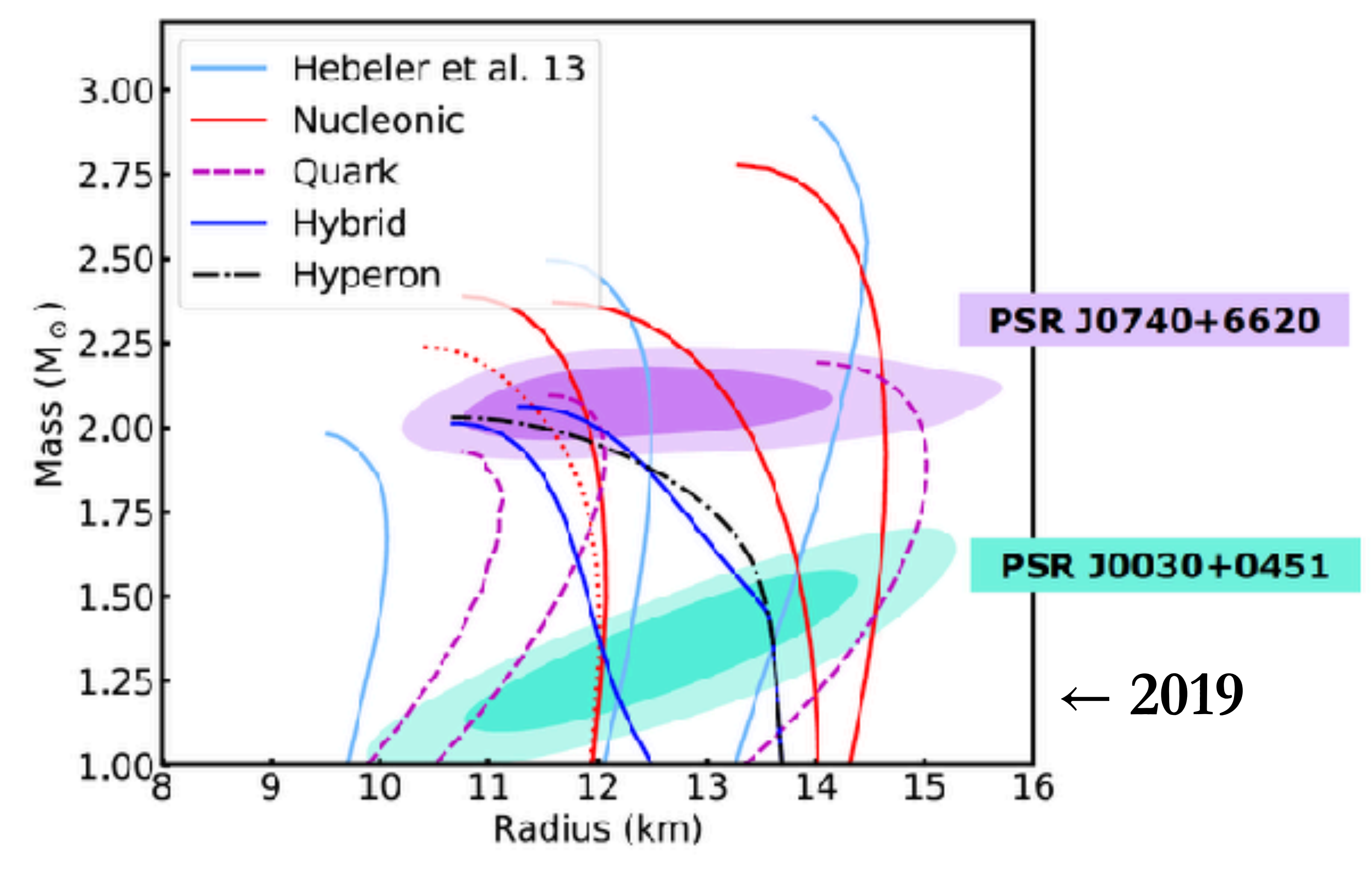


Riley et al. 2019

# Recent measurements of radii AND masses



# How do the NICER results fit into the EoS landscape?



← 2019

68% and 95% confidence level

PSR J0740+6620: highest mass known!
very faint source though!
combined measurement by NICER and XMM telescopes!

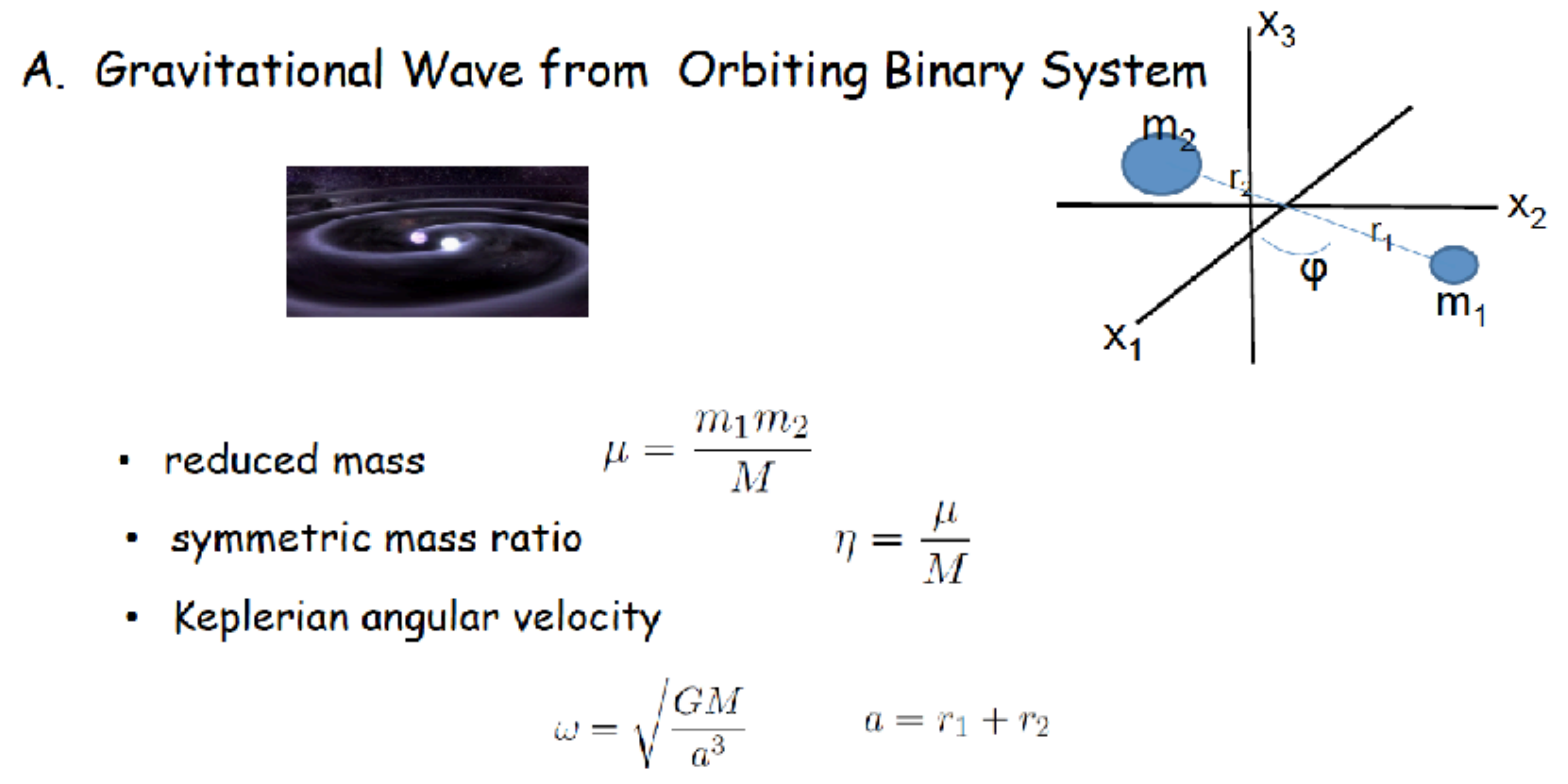
No large differences in the radii for a very heavy and a light neutron star
This prefers stiff EoS among the nuclear ones.

A. Watts, Youtube

# Neutron Star Mergers

NS + NS -> hypermassive NS which is in metastable equilibrium
? What happen next ? BH + GWs?

Plenty of matter is ejected in NS mergers, nucleosynthesis of heavy elements such as Gold!

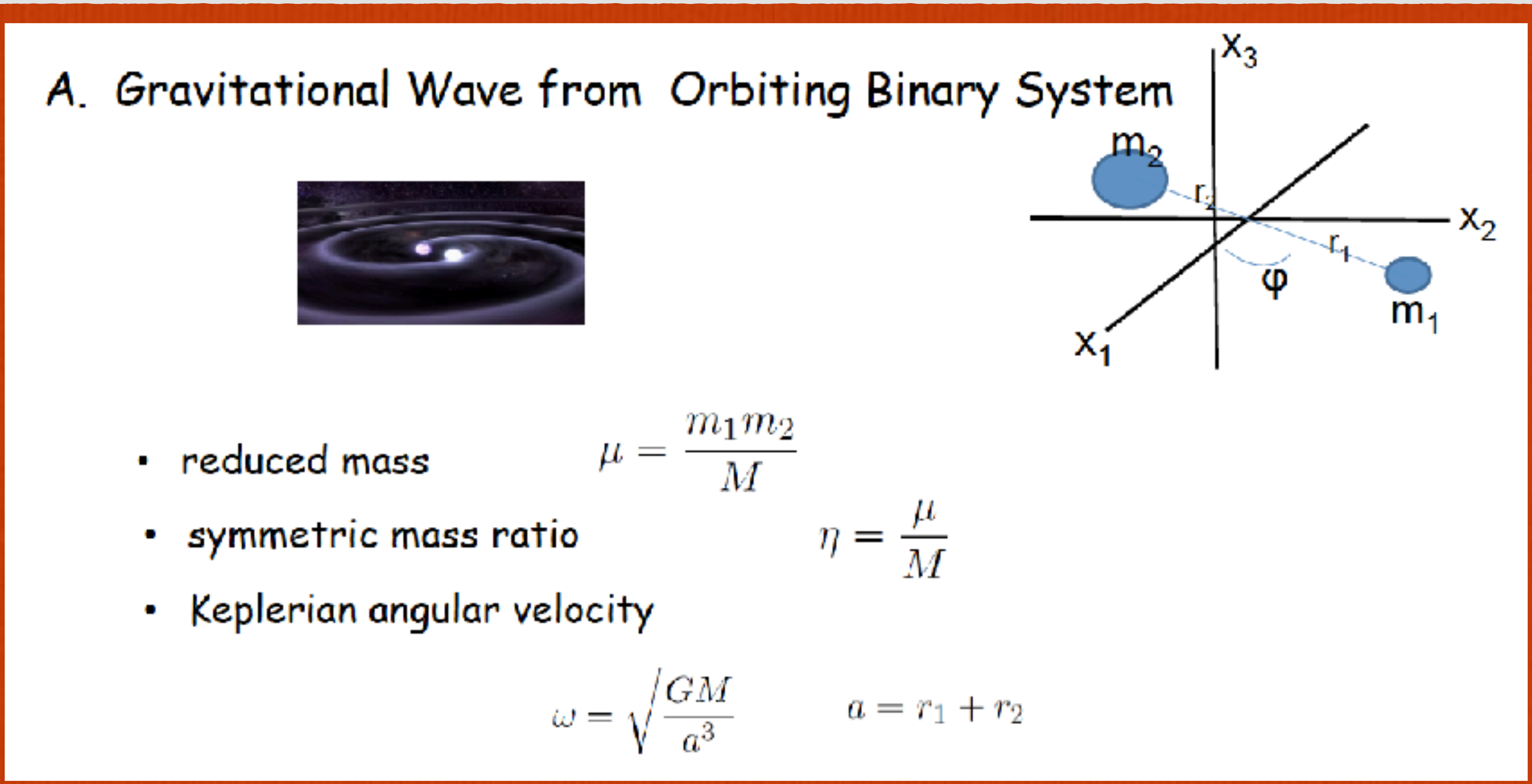


## A. Gravitational Wave from Orbiting Binary System

- reduced mass $\mu = \frac{m_1 m_2}{M}$
- symmetric mass ratio $\eta = \frac{\mu}{M}$
- Keplerian angular velocity

$$\omega = \sqrt{\frac{GM}{a^3}} \qquad a = r_1 + r_2$$

# Gravitational waves signal



## A. Gravitational Wave from Orbiting Binary System

- reduced mass $\mu = \frac{m_1 m_2}{M}$
- symmetric mass ratio $\eta = \frac{\mu}{M}$
- Keplerian angular velocity

$$\omega = \sqrt{\frac{GM}{a^3}} \qquad a = r_1 + r_2$$

When the gravitational tidal field of a source change with time, gravitational radiation is emitted, eventually gravitational waves if the changes are oscillatory. The tidal field g' (gravity gradient) represent a relative acceleration between two test masses. This field can be measured by considering the dimensionless parameter h **(STRAIN)**

$$h = 2\int\!\!\int g' dt^2$$

h is twice the fractional change in displacement between two nearby masses due to the gravitational wave → $h = \frac{\Delta d}{d}$

# The Strain parameters

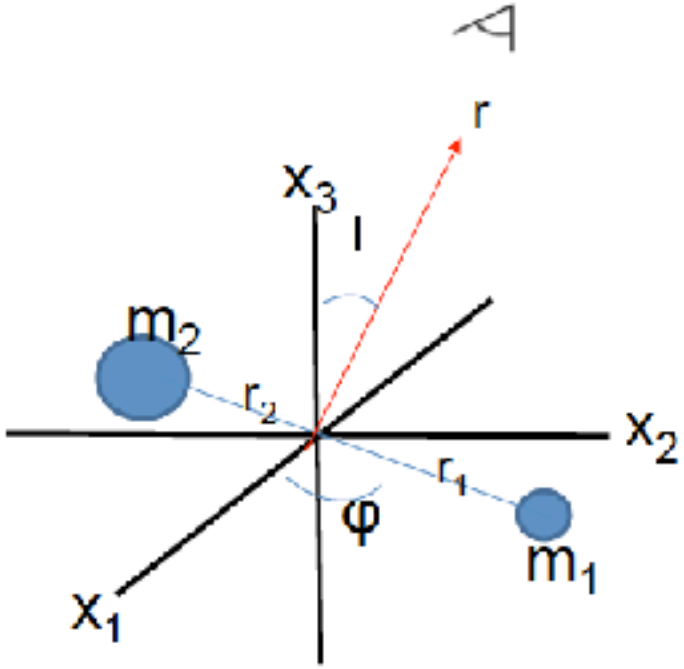
- Gravitational wave

$$h_+ = -\frac{2G\mu}{c^2 r}(1+\cos^2\iota)\left(\frac{\nu}{c}\right)^2\cos 2\phi$$

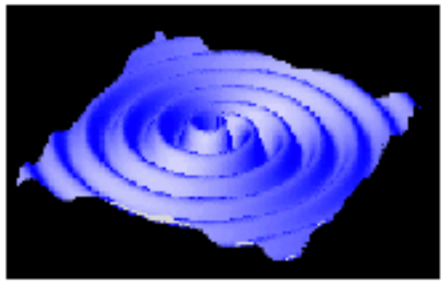
$$h_\times = -\frac{2G\mu}{c^2 r}\cos^2\iota\left(\frac{\nu}{c}\right)^2\sin 2\phi$$

$$\nu = (2\pi G M f)^{1/3}$$

$$\phi = \omega t \qquad f = 2 f_{orbital} = \omega/\pi$$



- Ripples in the curvature of space-time

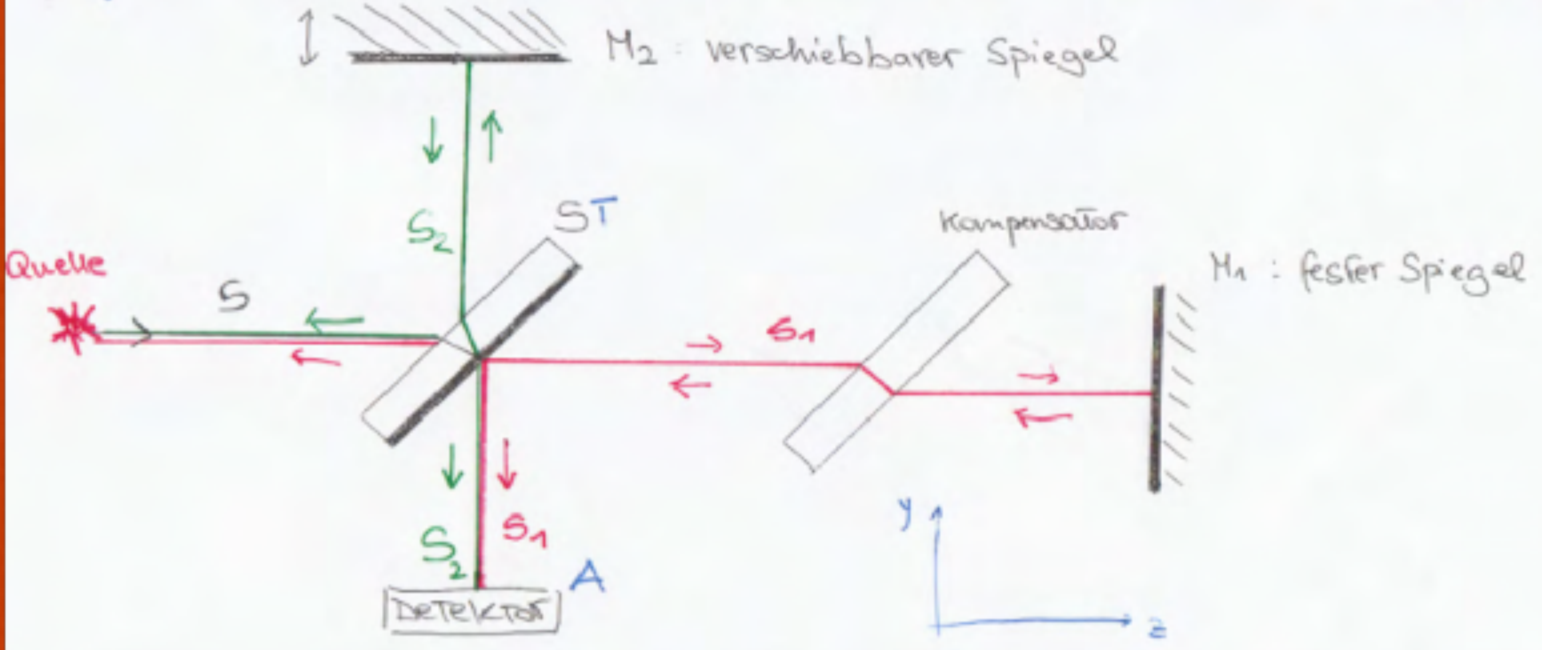


strain contains information about the reduced mass of the system
One uses here the Chirp Mass

$$M = \frac{(m_1 m_2)^{3/5}}{(m_1+m_2)^{-1/5}}$$

# How to measure the strain?

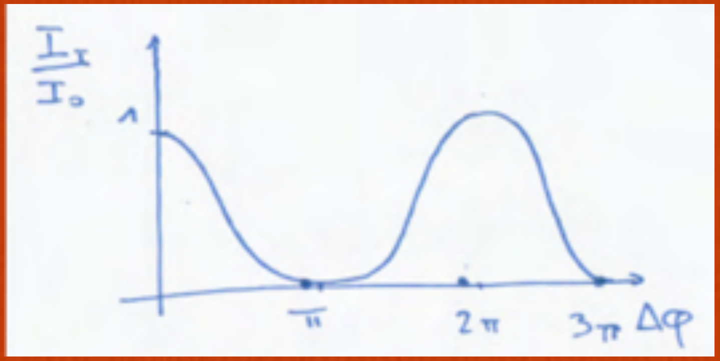
## Reminder of the Michelson interferometer



$$I = 2\overline{I_0}RT(1+\cos(\Delta\phi))$$

$$\Delta\phi = (2m+1)\pi$$

Interference pattern



If you send a laser with a fixed $\lambda$, for a fixed variation of the path $\Delta s$

$$\Delta s = (m + \frac{1}{2})\lambda \quad \text{Minima}$$

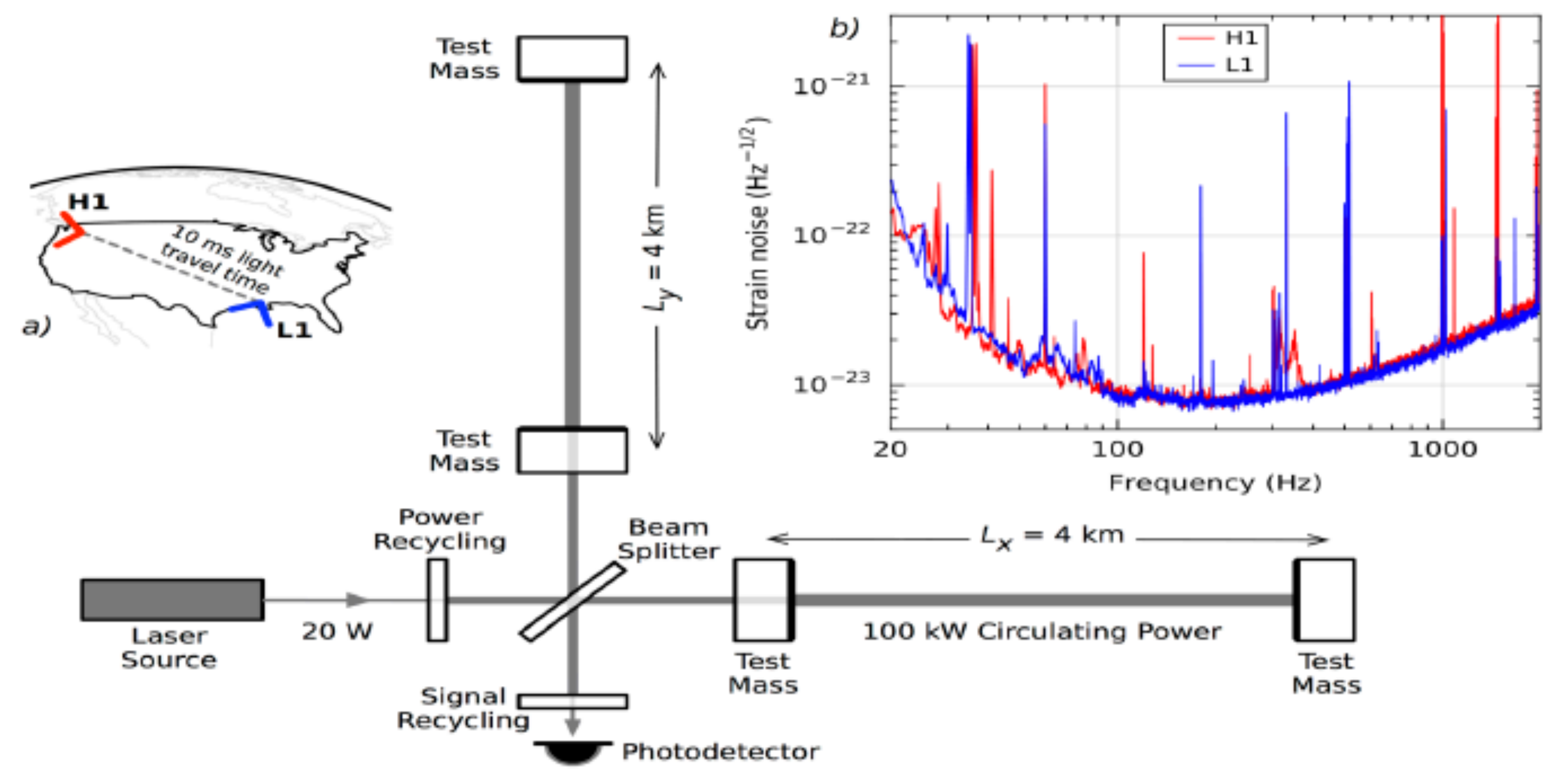
$$\Delta s = m\lambda \quad \text{Maxima}$$

Interference pattern allows to measure the variation of the path $\Delta s$

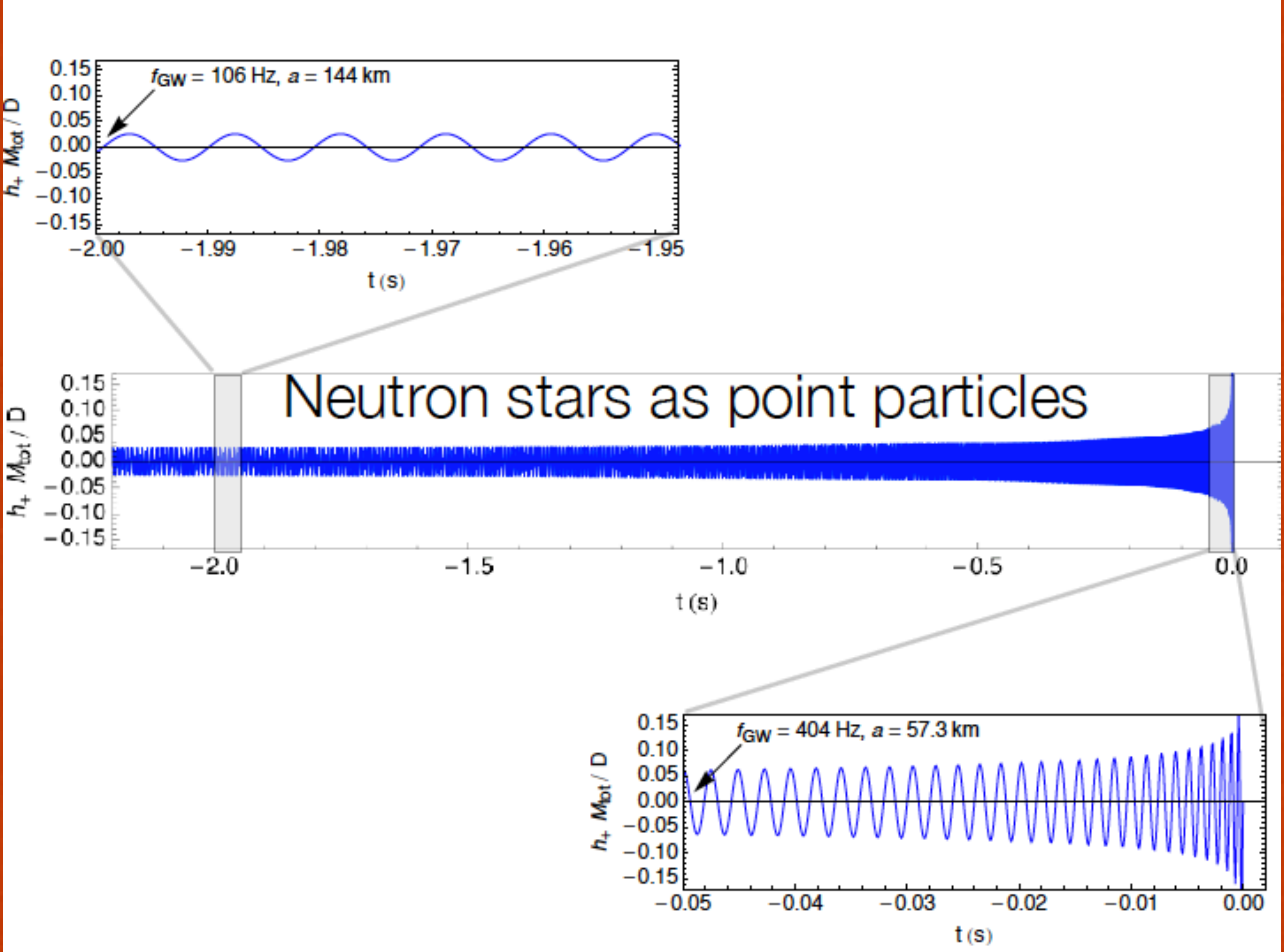
# How to measure the strain?

The change of arm lengths measurable with LIGO or VIRGO $\Delta l$ can be related to the strain h. Also the frequency of the deformation can be measured

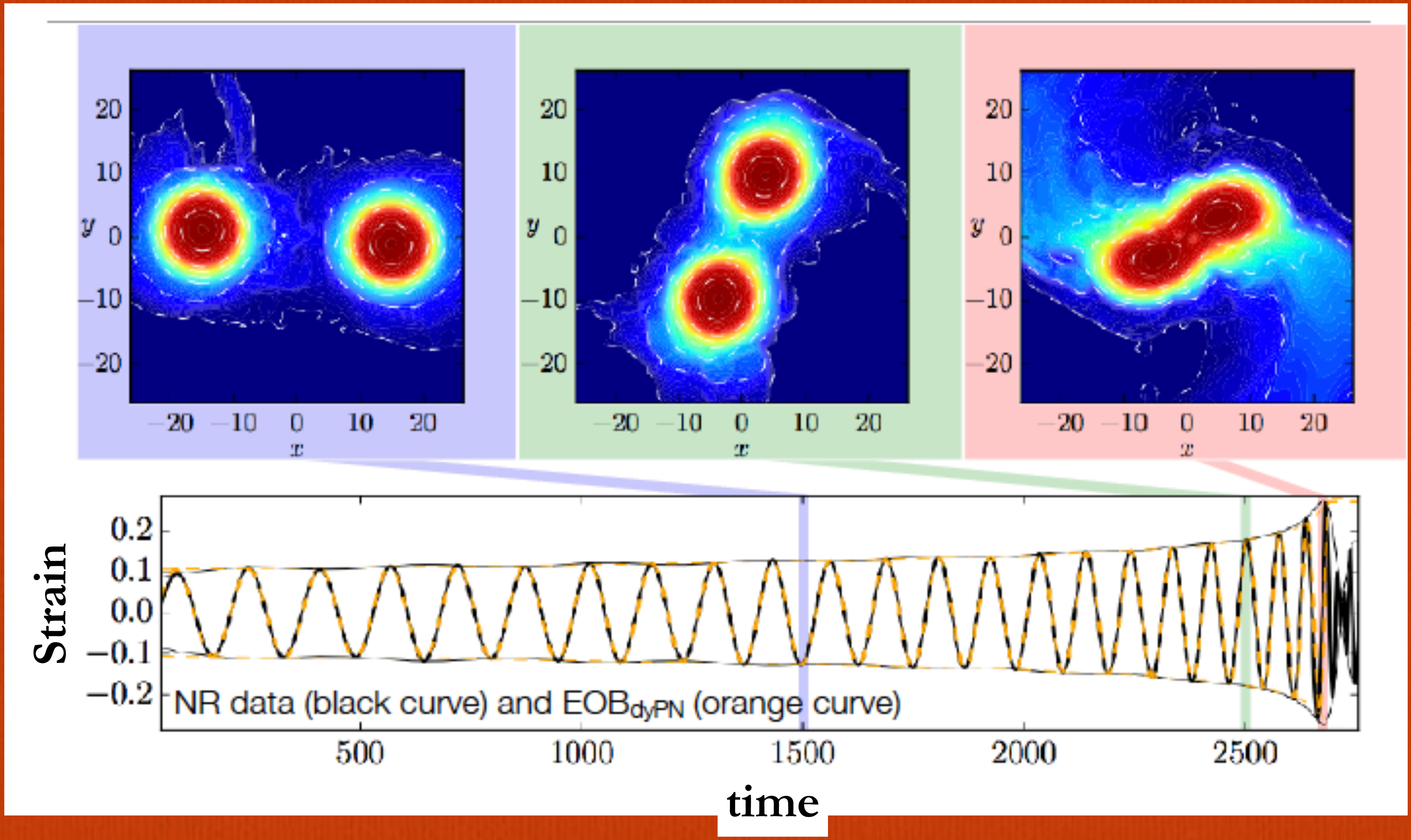
$$\Delta l / l \approx h$$



# Typical gravitational wave signal



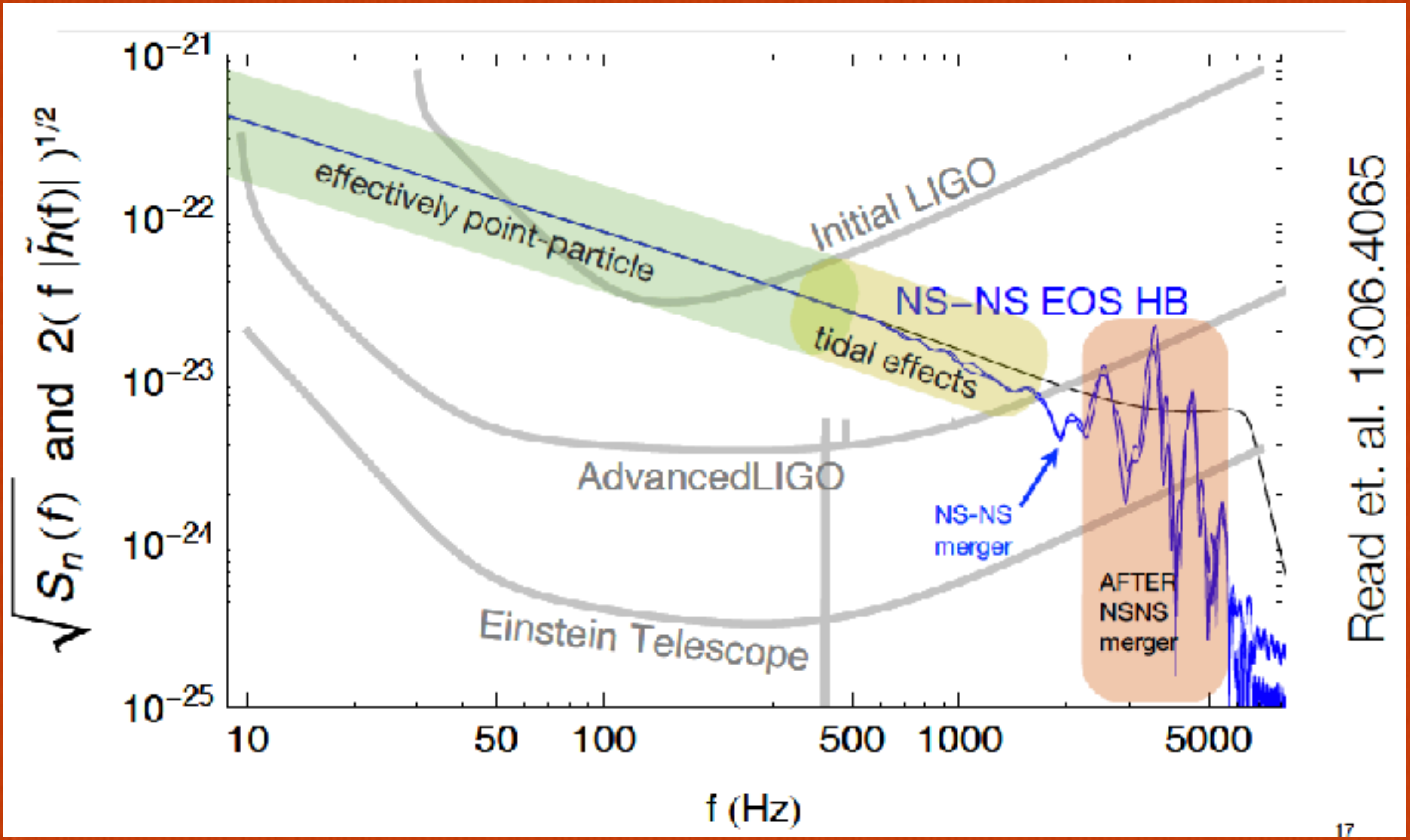
# The gravitational wave for a neutron star merger event



Dietrich and Hinderer, arXiv:1702.02053

# Frequency Range of the different systems

Sensitivity of the Gravitational arrays, hence minimum detectable strain strenght. LIGO is currently at the edge of the sensitivity of tidal effects.



# Tidal effects for neutron stars mergers

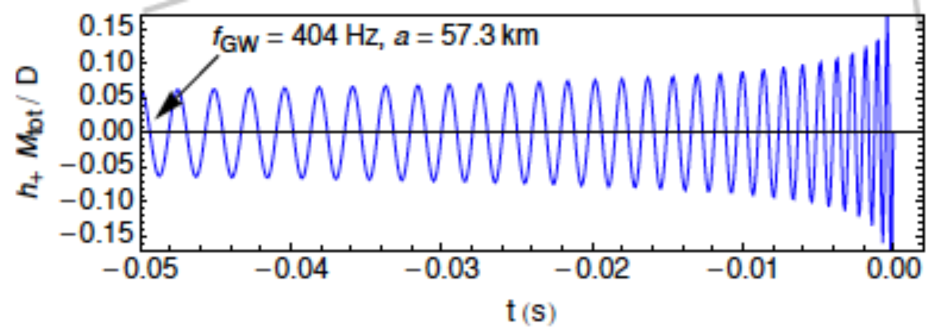

Haas et al arXiv:1604.00782

During the orbitation of the two NS energy goes into deforming the neutron stars and the tidal bulges modify the gravitational radiation!

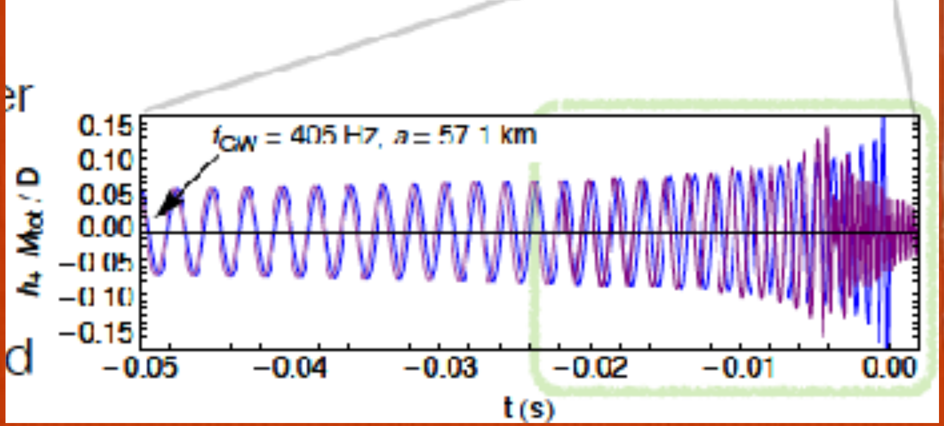
The deformation is expressed as tidal deformability $\Lambda$

$$\Lambda = \frac{2}{3} k_2 \left(\frac{R}{M}\right)^5$$

## Signal for pointlike NS



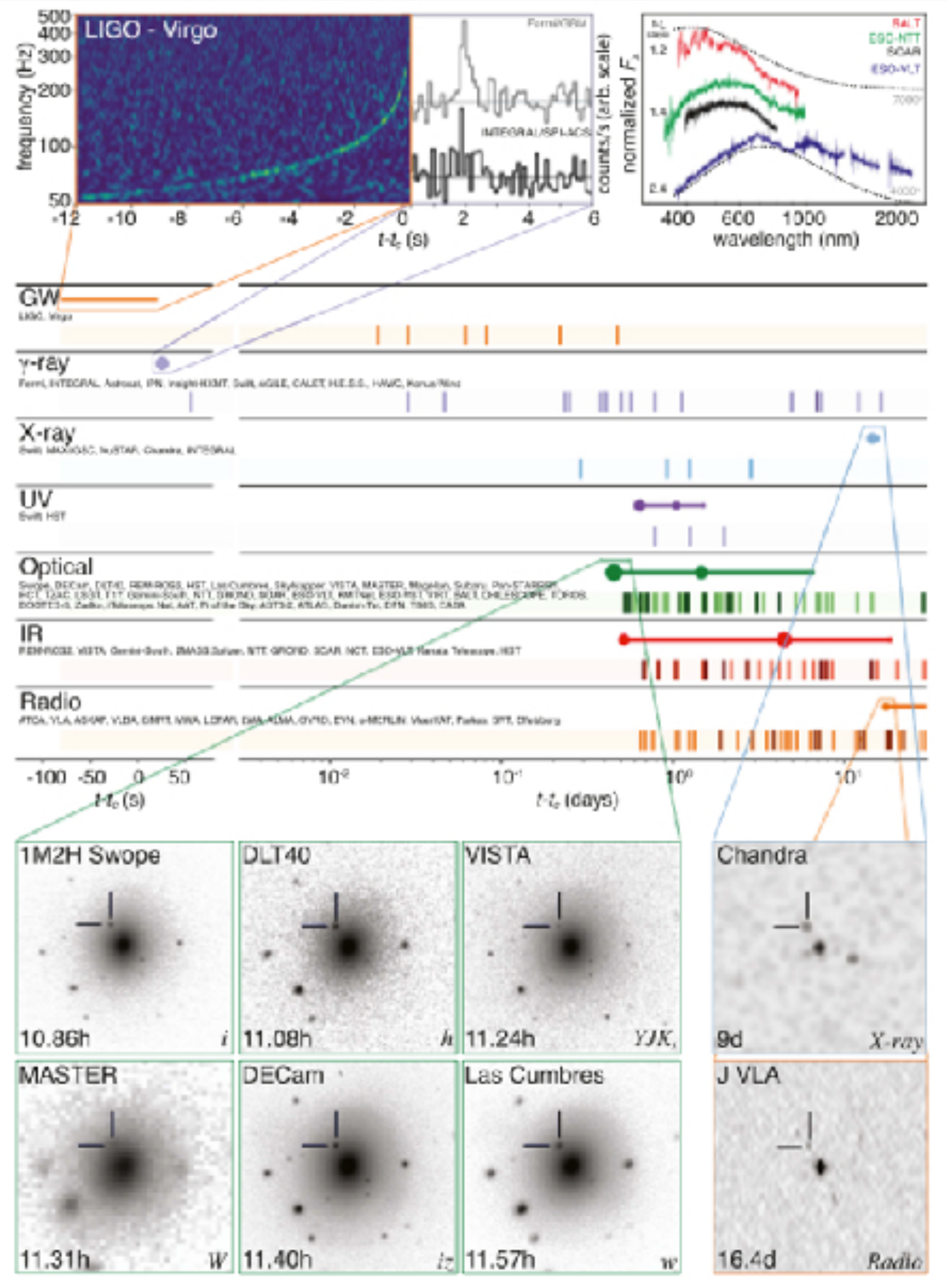
## Impact of matter $\Lambda$



Tidal interactions lead to accumulated phase shift at **higher frequencies!**
The measured gravitational wave is compared to models to extract :

$\Lambda$ and reduced mass ( see formula of h)

# GW170817



LIGO/VIRGO GW detection with associated electromagnetic events observed by over 70 observatories

- August 17th 2017 12:41:04 UTC

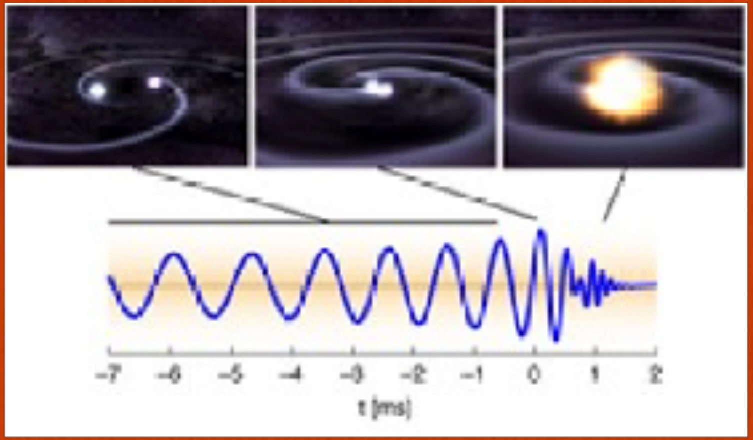
  GW from a BNS merger detected by Adv. LIGO & Adv. VIRGO

- + 1.7 seconds

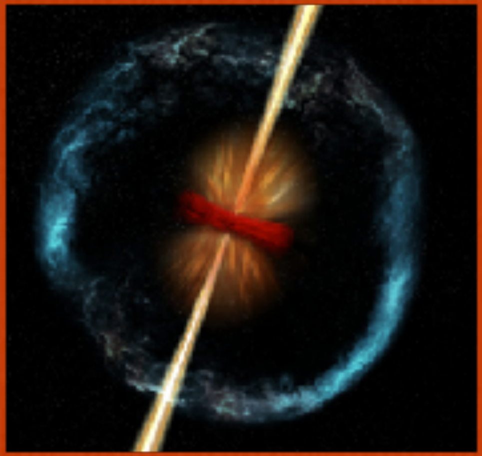
  GRB (GRB170817A) detected by FERMI γ-ray Burst Monitor & INTEGRAL

- Next hours & days
  - New bright source of optical light (SSS17a) detected in the galaxy NGC 4993 in the Hydra constellation (+10h 52m)
  - Infrared emission observed (+11h 36m)
  - Bright ultraviolet emission detected (+15h)
  - X-ray emission detected (+9d)
  - Radio emission detected (+16d)

# Importance of the Event GW170817



Detecting GW from a NS merger allows us to learn more about the EoS & structure of these compact objects



This multi-messenger event provides confirmation that NS mergers can produce short GRBs

The observation of a kilonova allows us to show that NS mergers could be responsible for the production of most of the heavy elements, like gold and platinum, in the universe

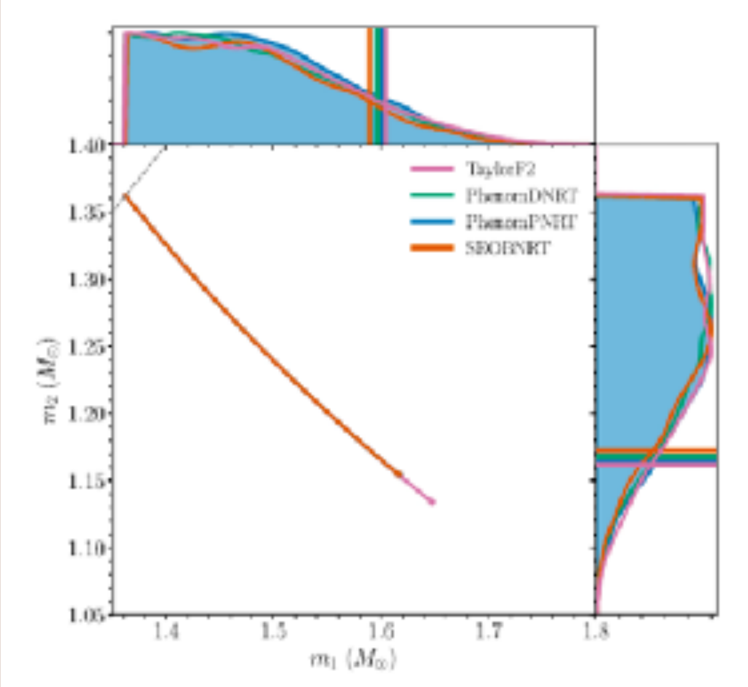
# What can be estimated?

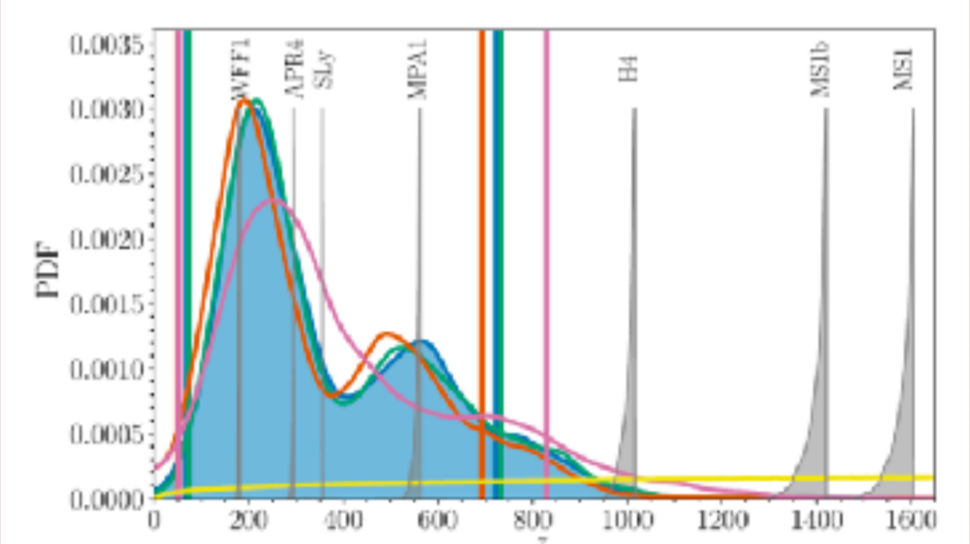
- Masses estimated from the chirp mass

$$M_c = \frac{(m_1 m_2)^{3/5}}{(m_1 + m_2)^{1/5}}$$

- Radius from the tidal deformability

$$\tilde{\Lambda} = \frac{16}{13} \frac{(1+12q)\Lambda_1 + (q+12)\Lambda_2}{(1+q)^5}$$





A $1.36M_\odot$ has a radius of 10.4 km (WFF1), 11.3 km (APR4), 11.7 km (Sly), 12.4 km (MPA1), 14.0 (H4), 14.5 (MS1b) and 14.9 km (MS1

# Combined analysis of the astrophysical data

- NICER PSR J0740+6620 & PSR J0030+0451 (bands)
- GW170817 (from tidal deformability, orange solid/dashed lines)
- RXTE results for the cooling tail spectra of 4U1702-429 (violet line)