# Whispers from space

# Remarkable implications of the double neutron star merger GW170817

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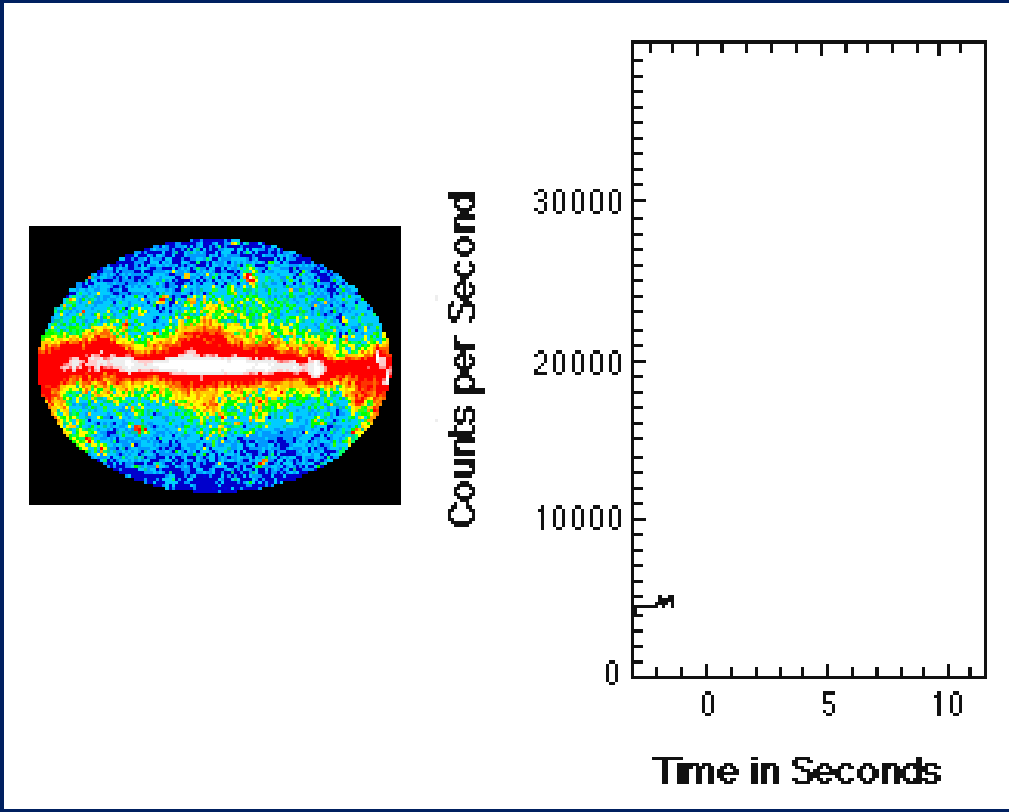
I. Short $\gamma$-ray bursts and NS-NS mergers
II. r-process elements
III. The equation of state (EOS) above nuclear density –the NS EOS.
IV. Tidal imprint on inspiral waveform
V. Implications of post-merger observations
VI. Hubble constant

Downloaded animations that were embedded in the powerpoint presentation are replaced in this pdf file by links to their locations on the web

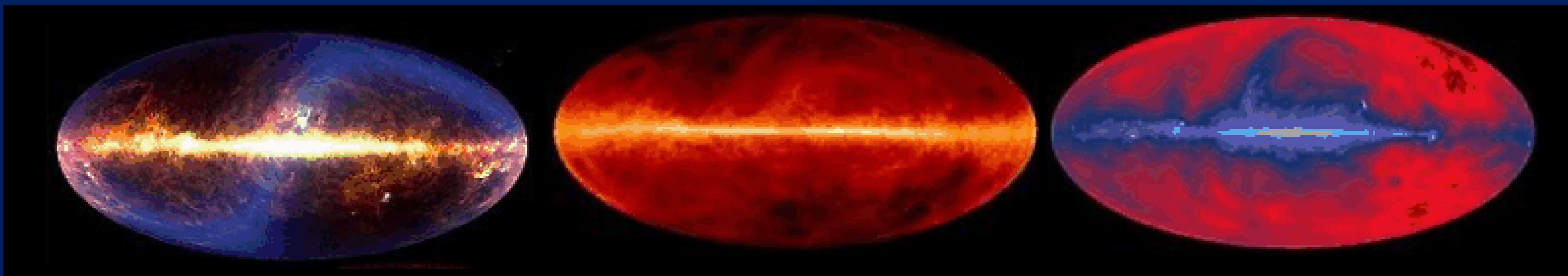
# I. $\gamma$-ray bursts and NS-NS mergers

In late 60s, the Vela satellites monitoring the recently signed nuclear test-ban treaty, saw occasional bursts of $\gamma$-rays, and their direction ruled out Sun and Earth as sources.



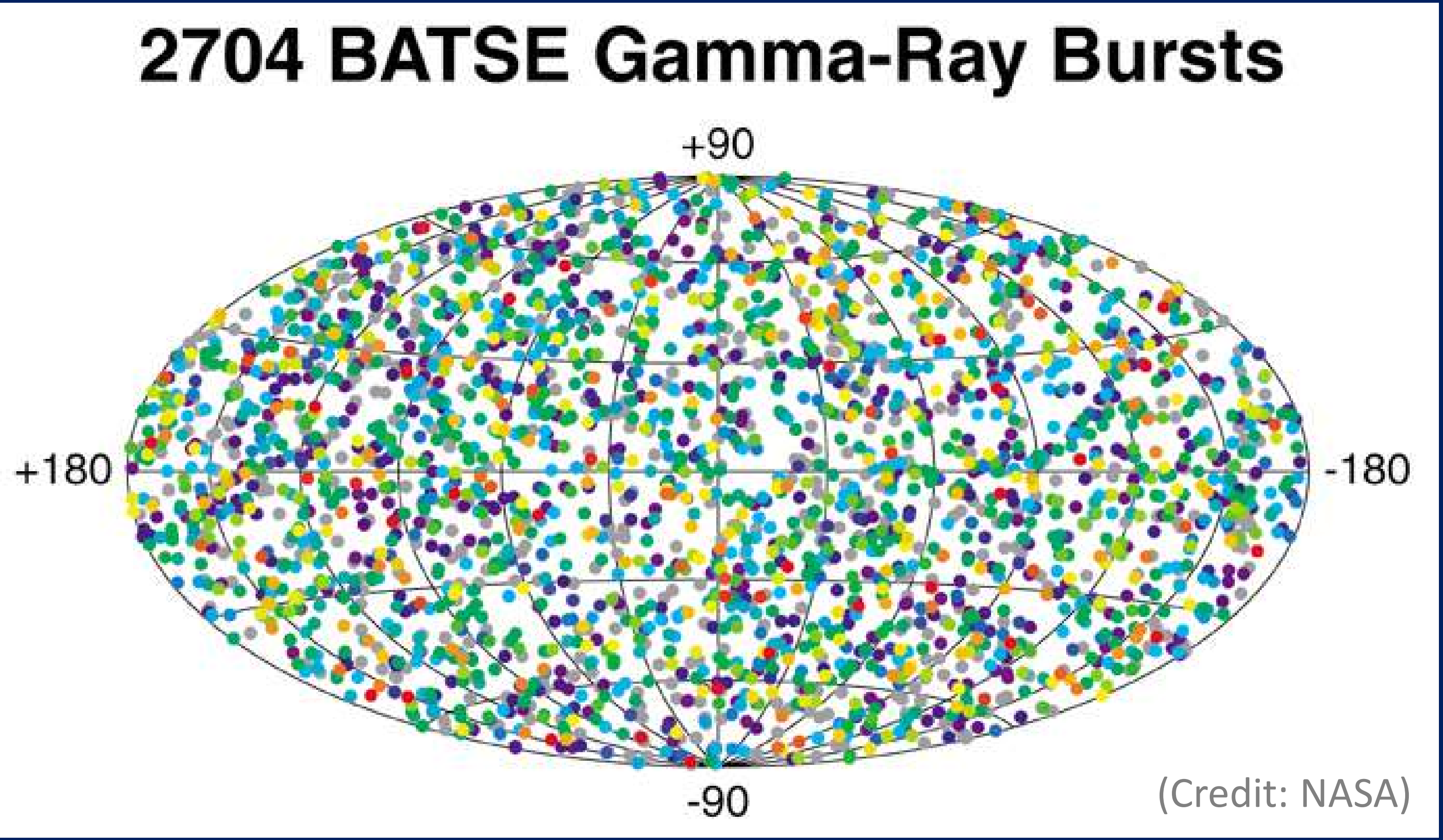

Pogosyan slide

# Had they come from the Milky Way, their distribution would look like this

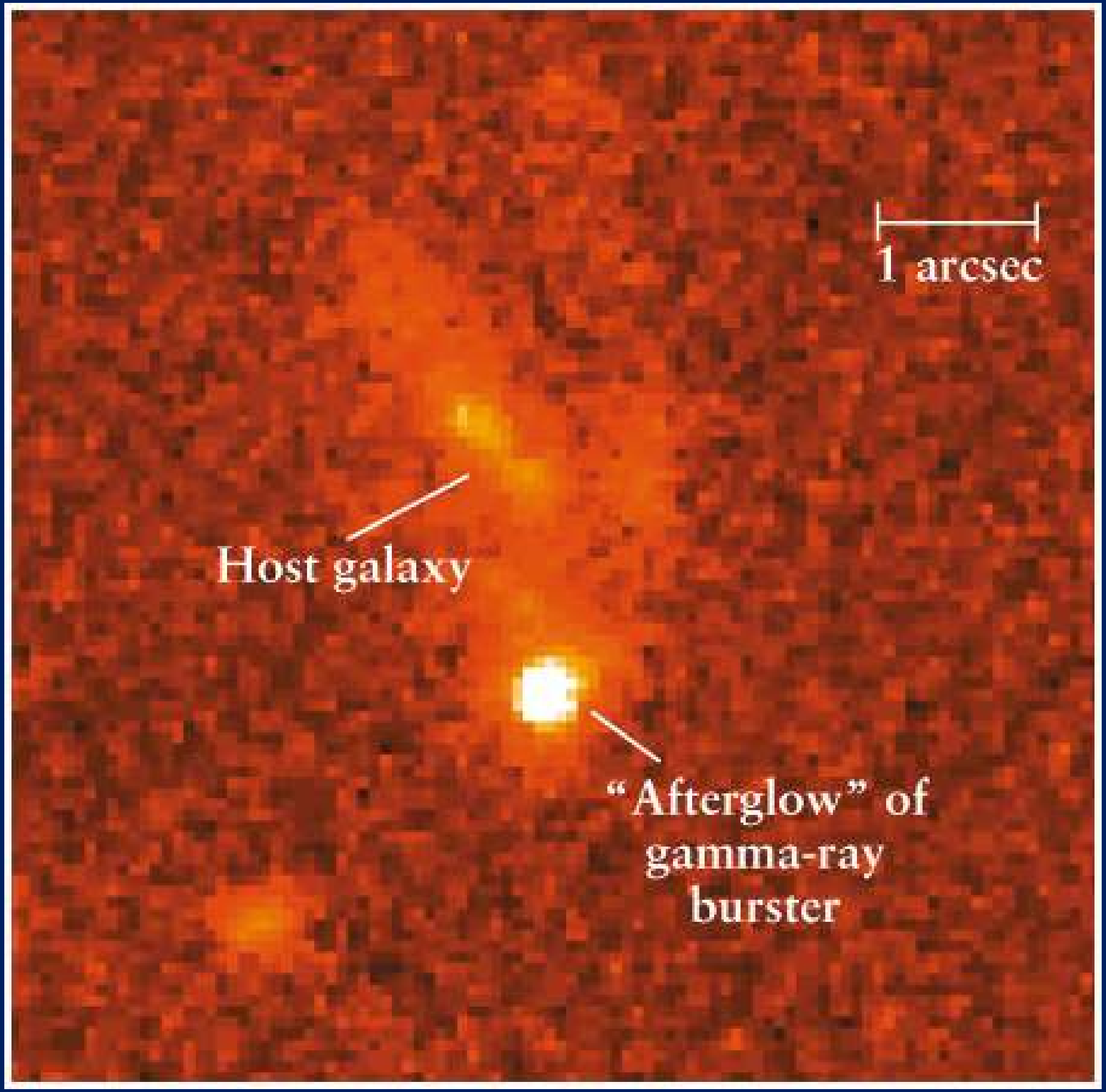


Infrared (DIRBE Team, COBE, NASA) | Radio 1420MHz (J. Dickey et.al. UMn. NRAO SkyView) | Radio 408MHz (C. Haslam et al., MPIfR, SkyView)

# Instead, they are distributed isotropically across the sky



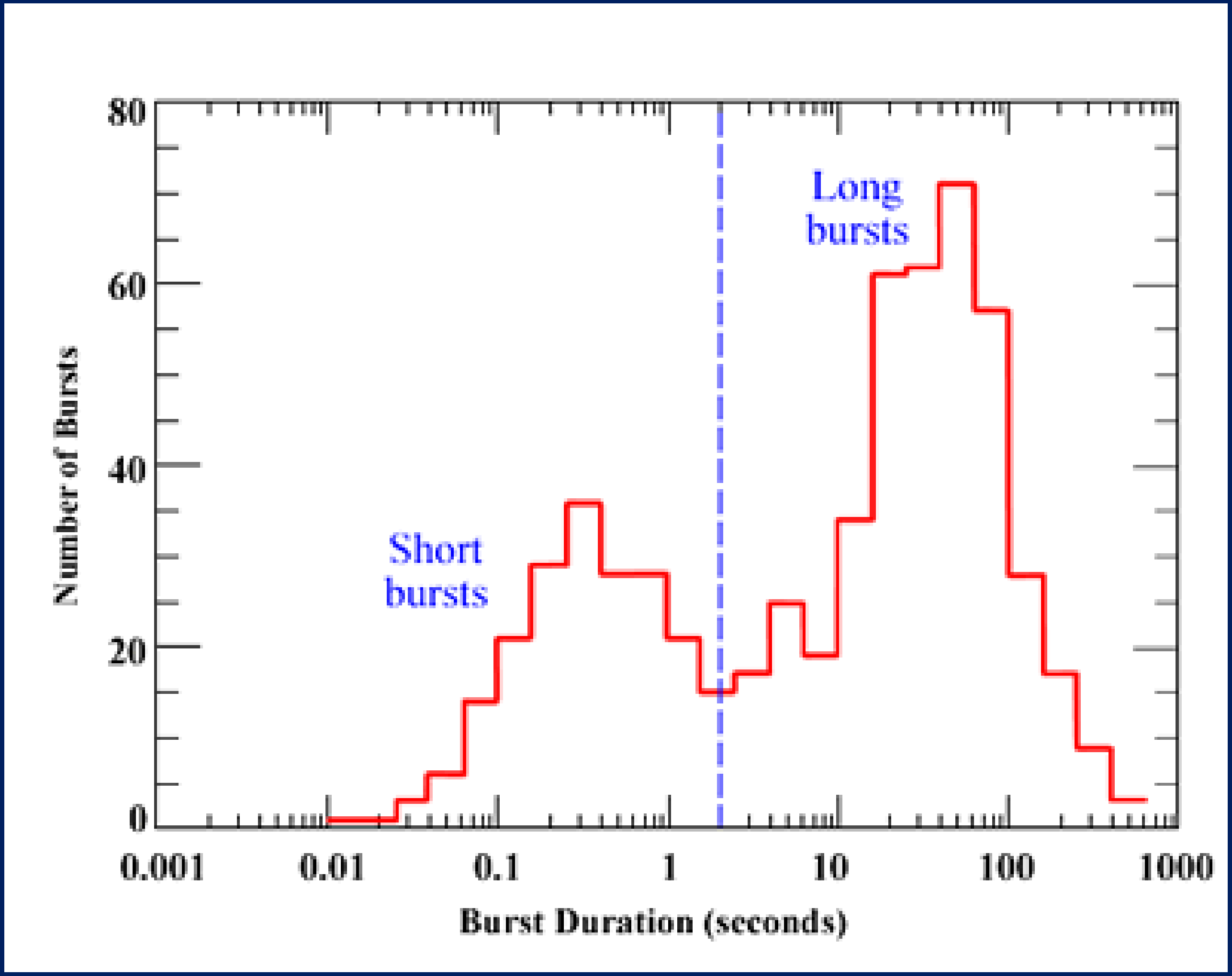
# Cosmological distance confirmed when found host galaxies



implying these are the brightest electromagnetically observed events in the universe, up to $10^{54}$ erg,
1000 times the energy emitted by the Sun over its 10-billion year lifetime

Two classes

Short 0.1 – 1 s Long > 1 s



Long gamma-ray bursts seen only in galaxies that have recently formed stars.  This is consistent with their identification with the most luminous supernovae:

Only stars with large mass end as supernovae, and large mass stars burn their fuel quickly, living for less than 50 million years.   So supernovae occur in star-forming galaxies.

Short gamma-ray bursts are generally associated with galaxies that have *no young stars or with no obvious galaxy at all*.

They are events with energy comparable to the energy of collapse to a NS, where no stars massive enough to collapse are present.  That fact made binary coalescence of dead stars – of NS-NS or NS-BH binaries –  the leading candidate.

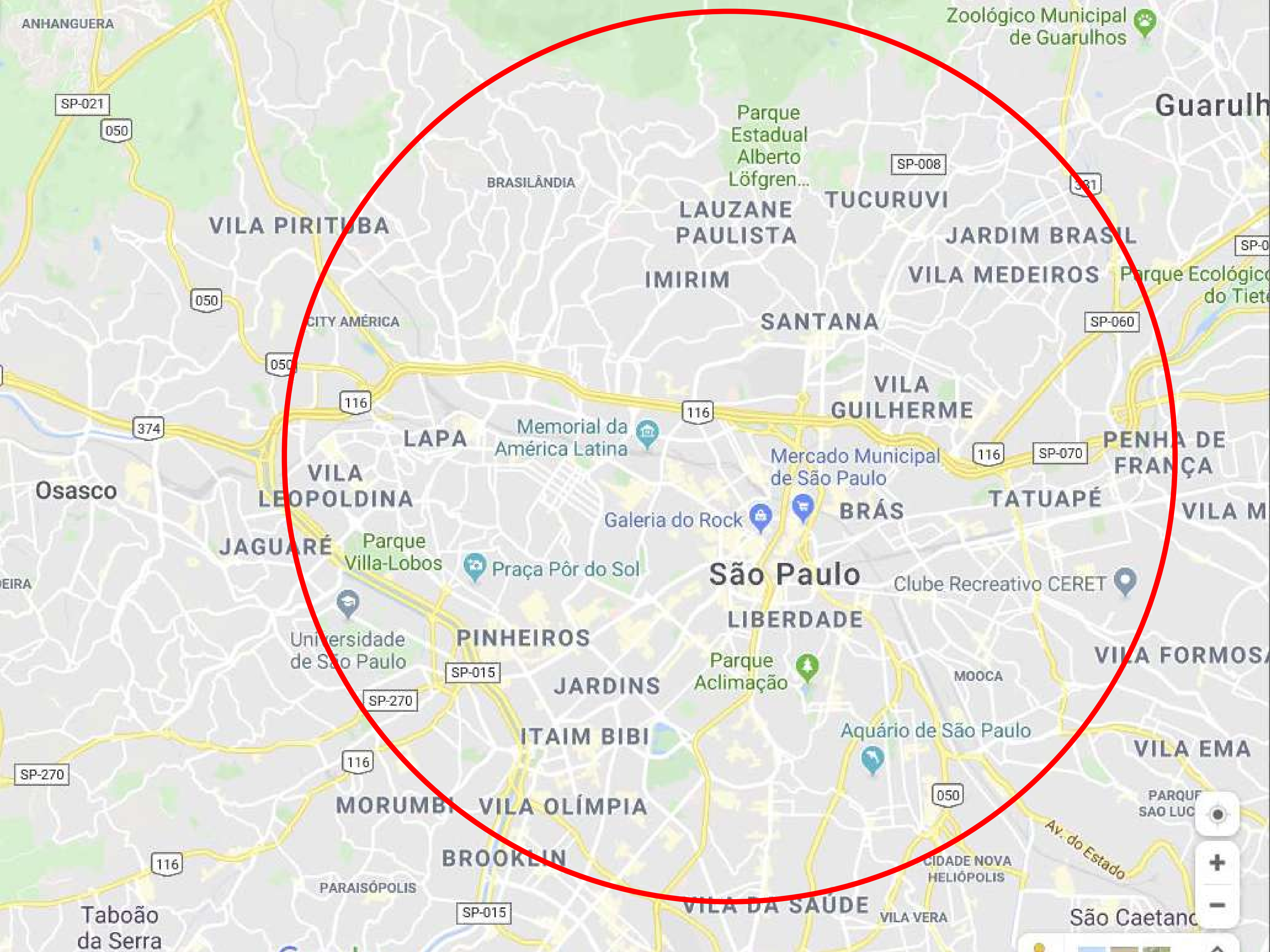
# Radius of a neutron star

neutron star of mass $1.4\, M_\odot = 2.8\times 10^{33}$g

nuclear density $\rho_n = \dfrac{M}{(4\pi/3)\ R^3} = 2.3\times 10^{14}$ g/cm$^3$

$$R = \left( \frac{1.4\, M_\odot}{4\pi/3\ \ \rho_n} \right)^{1/3} = 14 \text{ km}$$

Actual: average density somewhat
higher than nuclear density;
radius between 9 and 14 km



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Zoológico Municipal de Guarulhos
Guarulh
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Parque Estadual Alberto Löfgren...
SP-008
BRASILÂNDIA
TUCURUVI
LAUZANE PAULISTA
VILA PIRITUBA
JARDIM BRASIL
IMIRIM
VILA MEDEIROS
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CITY AMÉRICA
SANTANA
SP-060
VILA GUILHERME
116
374
LAPA
Memorial da América Latina
Mercado Municipal de São Paulo
PENHA DE FRANÇA
SP-070
Osasco
VILA LEOPOLDINA
TATUAPÉ
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JAGUARÉ
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Praça Pôr do Sol
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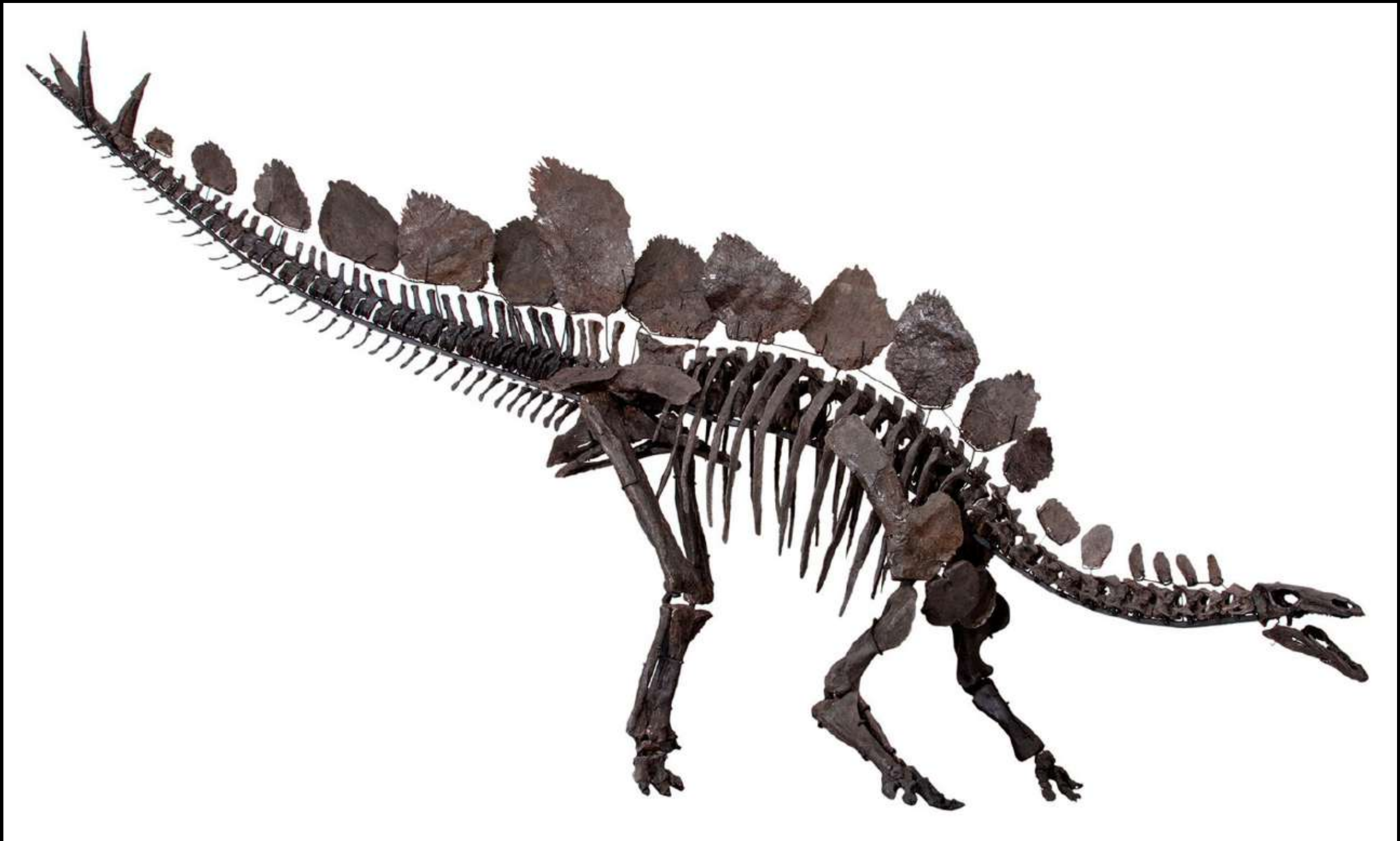
VILA DA SAÚDE
VILA VERA
Taboão da Serra
São Caetano

Energy from collapse to neutron star or collision of two neutron stars

$$\frac{GM^2}{R_{\text{neutron star}}} = \frac{G(1.4M_\odot)^2}{(11\text{km})^2} = 4\times 10^{53}\ \text{erg}$$

Energy of $\gamma$-ray bursts = $10^{50}$ to $10^{54}$ erg in light, rest in neutrinos and gravitational waves

# 130 million years ago



Susannah Maidment et al. & Natural History Museum, London - Maidment SCR, Brassey C, Barrett PM (2015) https://commons.wikimedia.org/w/index.php?curid=45275061

# in a galaxy far away

Neutron star inspiral and merger by Dana Berry, produced by Erica Drezek:

https://www.youtube.com/watch?v=tjd_eyHe6PQ

GRMHD simulation by Ruiz, Tsokaros, Paschalidis, Shapiro at https://www.youtube.com/embed/d__Q7Yr5U_g?rel=0

August 17, 2017

FERMI

LIGO

Fermi and LIG0/Virgo signals from
GRB 170817A and
GW 170817A at
https://svs.gsfc.nasa.gov/12740

Credit: NASA's Goddard Space Flight Center, Caltech/MIT/LIGO Lab

The gravitational waves match the waveform from two neutron stars, each with mass approximately  1 ½ Msun

# From the glow hours after the collision


Carnegie Institute

# a galaxy was identified

NGC4993
distance
130 million light-years

and

# Speed of gravitational waves

Time from end of GW chirp to $\gamma$-ray burst $< 1.8$ s

($1.74 \pm .05$ s)

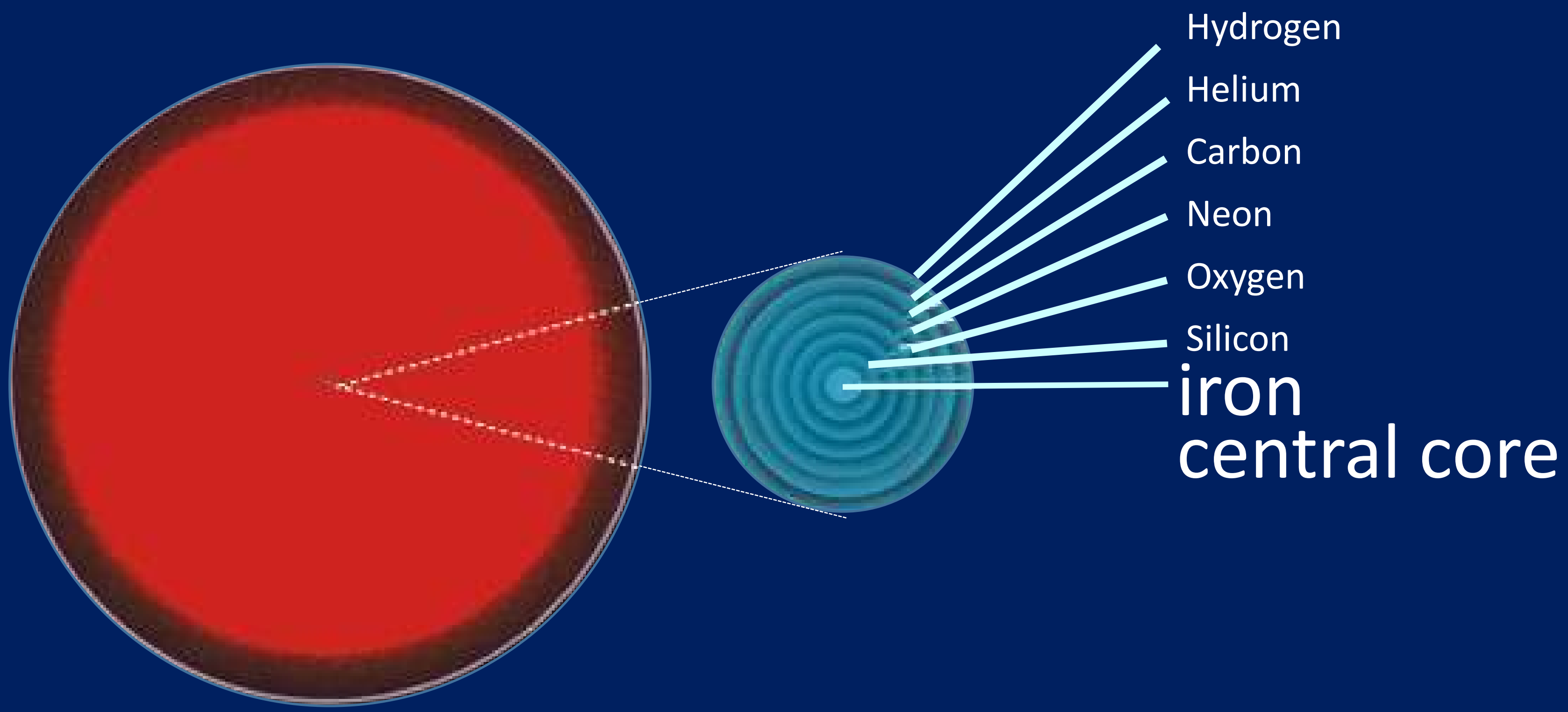
Because burst launched after merger - after end of chirp, if GW slower than light

$$(c - v_{GW})/c < 1.8 \text{ s}/130 \text{ Myr} < 5\text{x}10^{-16}$$

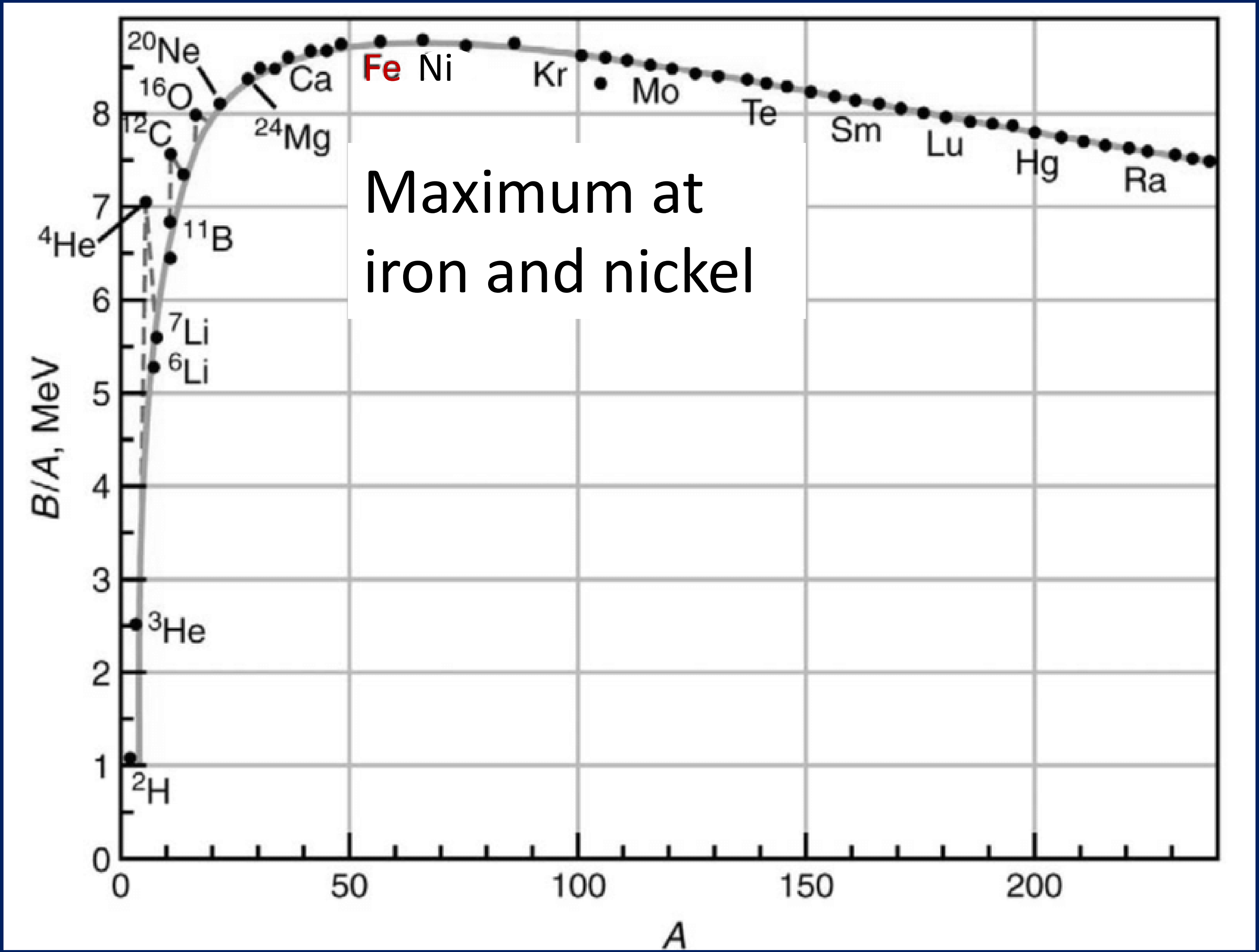
If light slower and emitted (conservatively) up to 10 s after burst, $(v_{GW} - c)/c < 3\text{x}10^{-15}$

# II. r-process elements

# The most massive stars fuse elements up to iron in their cores



# Binding energy per nucleon



No elements heavier than iron group

Heavier elements, with A>90-100 have lower energy/baryon than iron.

They form by successive capture of neutrons.

Hoyle and Fowler, with help from Margaret and Geoffrey Burbidge, elucidate pathways to form the heavier elements.

Burbidge  Fowler  Hoyle  Burbidge

# Fowler gets a Nobel prize

Not Hoyle

I have no idea how the Swedes decided to make an award to Chandrasekhar and Fowler but not to Hoyle. However, I think it would be widely accepted that it was an unfair misjudgment.

Sir Martin Rees

He was so critical of the committee that I imagine someone there just took a large pen and crossed his name off the list of those being considered for future prizes

Simon Mitton

s-process: slow bombardment.
Time between captures longer than time to decay (typically tens to thousands of years).

r-process: rapid bombardment.
Time between captures shorter than decay time (typically much shorter than a second)

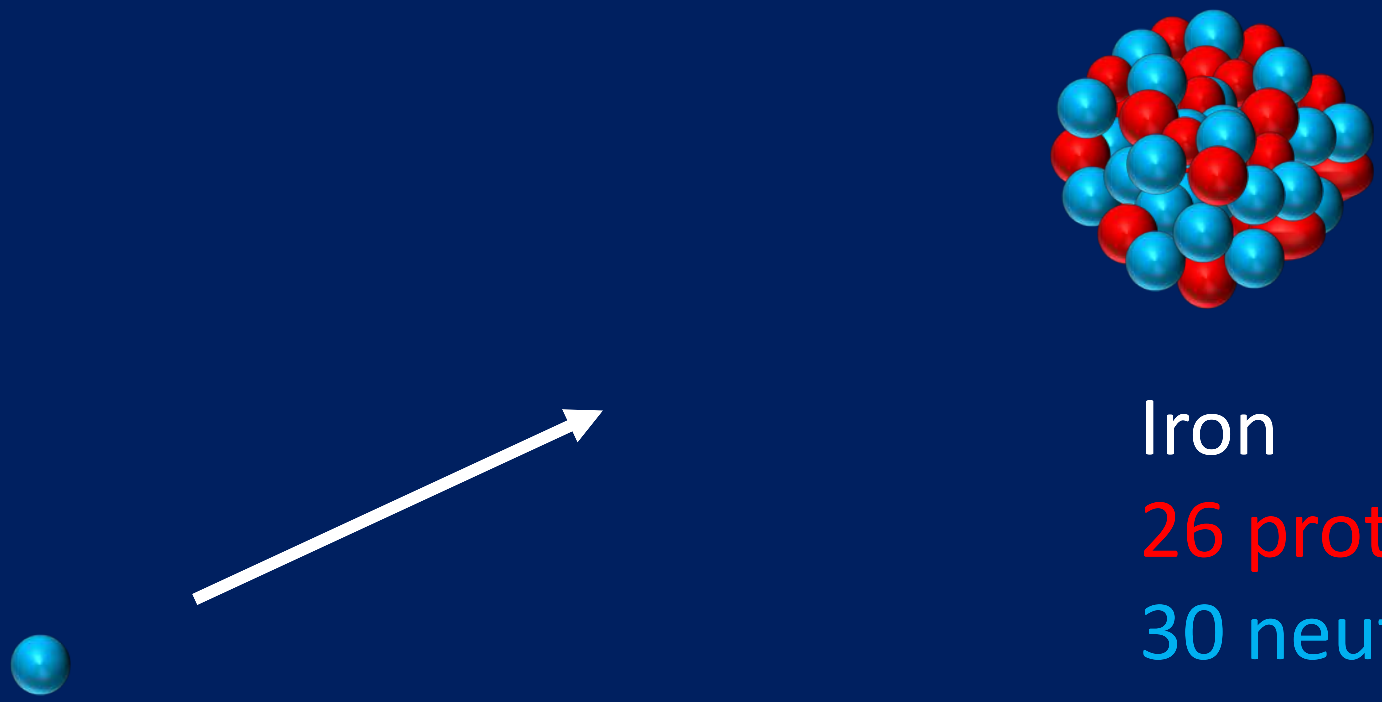
# s-process

Neutrons are produced in cores of red giants by helium nuclei hitting carbon and neon:

$$\alpha + {}_{13}C \rightarrow {}_{16}O + n$$

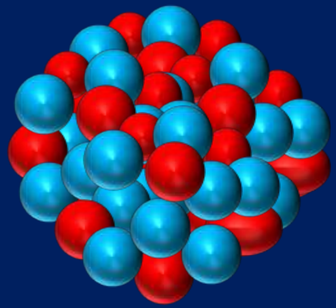
$$\alpha + {}_{22}Ne \rightarrow {}_{25}Mg + n$$

# Neutrons fly from the core



Iron
26 protons
30 neutrons

# Neutrons fly from the core

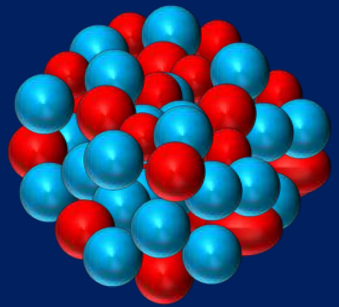


Iron

26 protons

31 neutrons

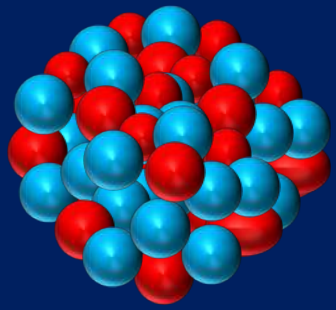
100,000 years later . . .



Iron

26 protons

31 neutrons

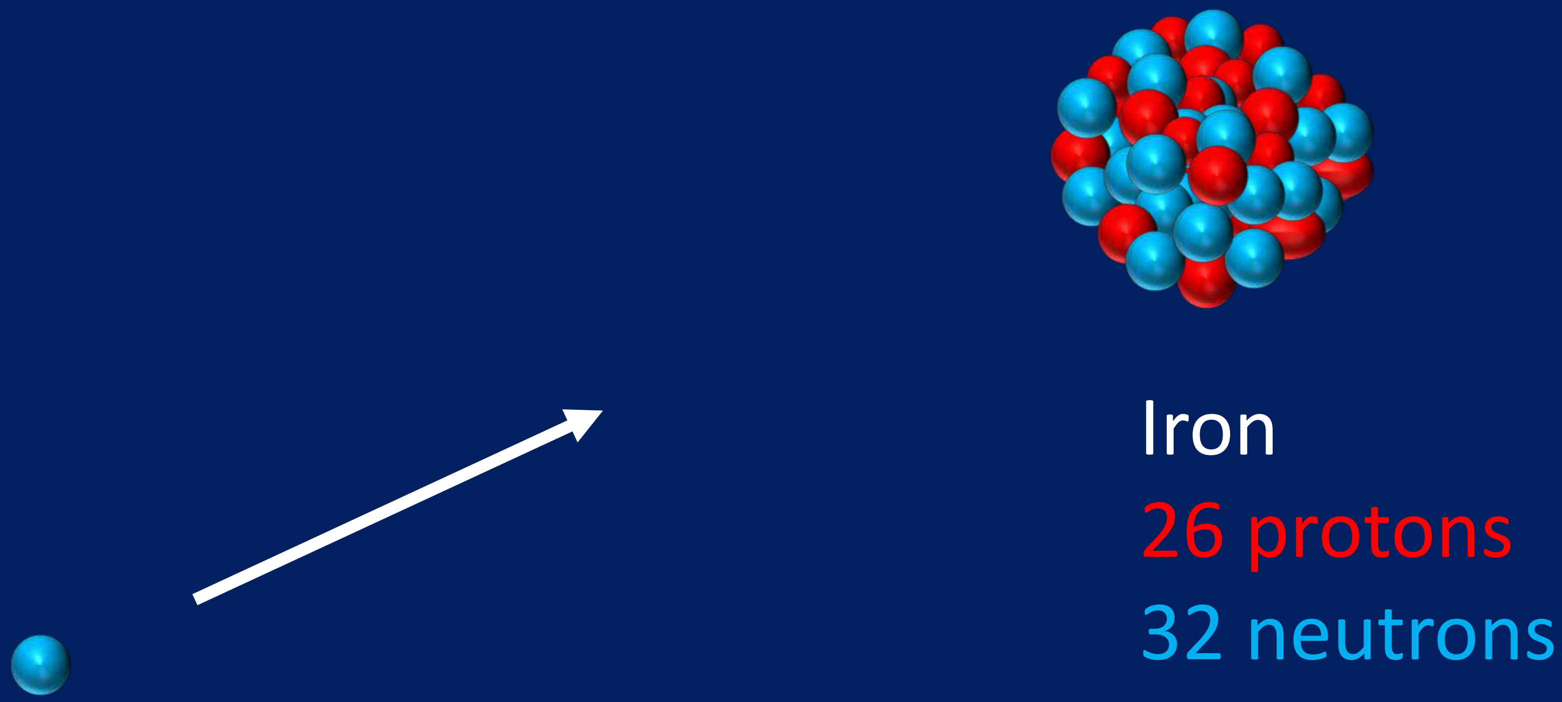


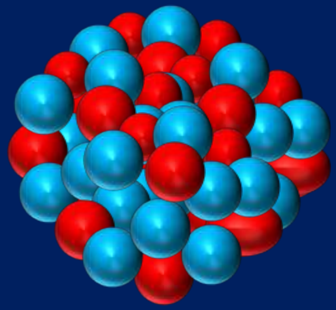
Iron

26 protons

32 neutrons

100,000 years later . . .


Iron
26 protons
32 neutrons

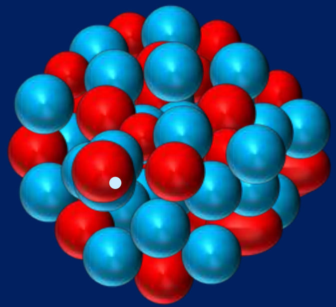


Iron

26 protons

33 neutrons

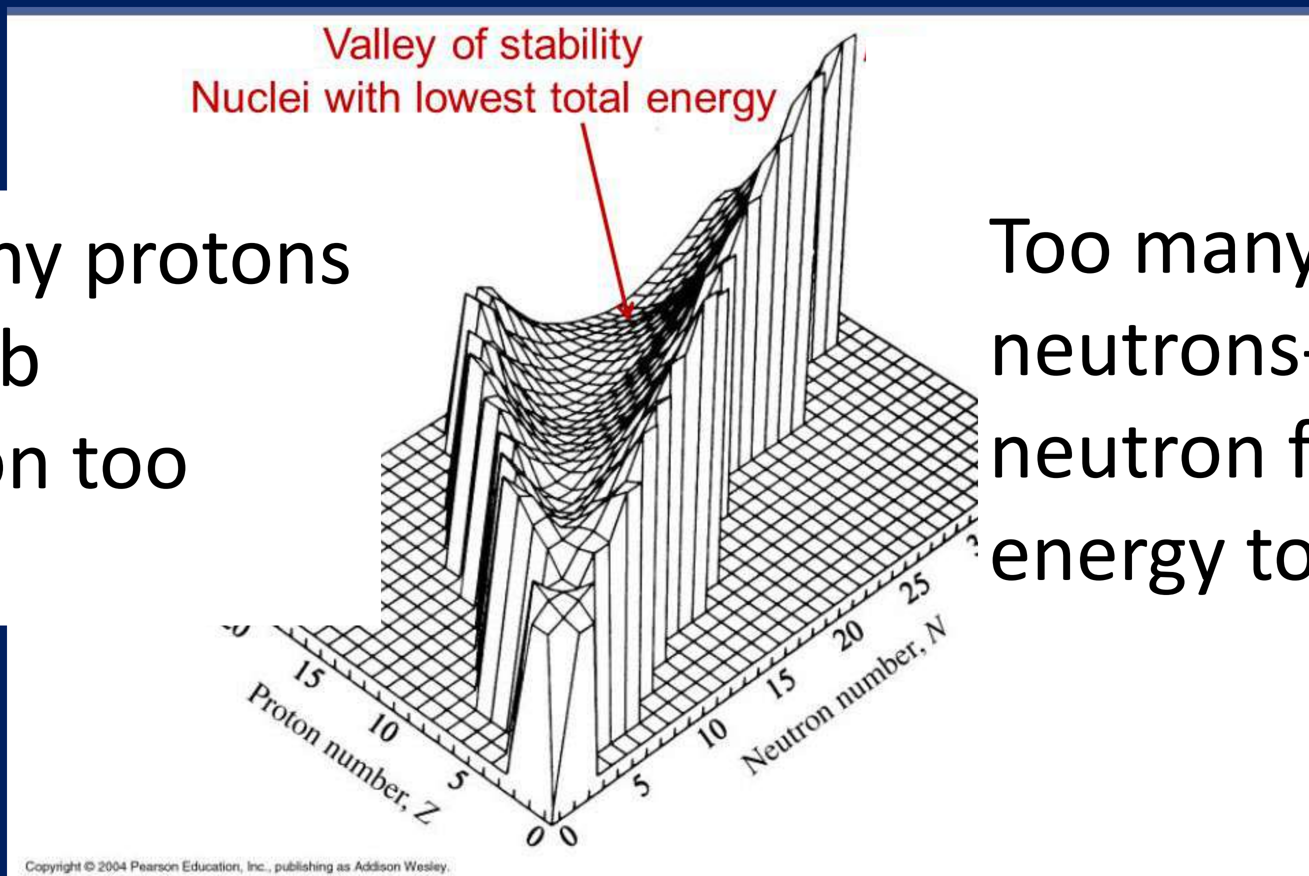
45 days later . . .



Cobalt
27 protons
32 neutrons

# Slow bombardment moves you through stable nuclei until you reach an unstable nucleus that then decays back to the “valley of stability.”

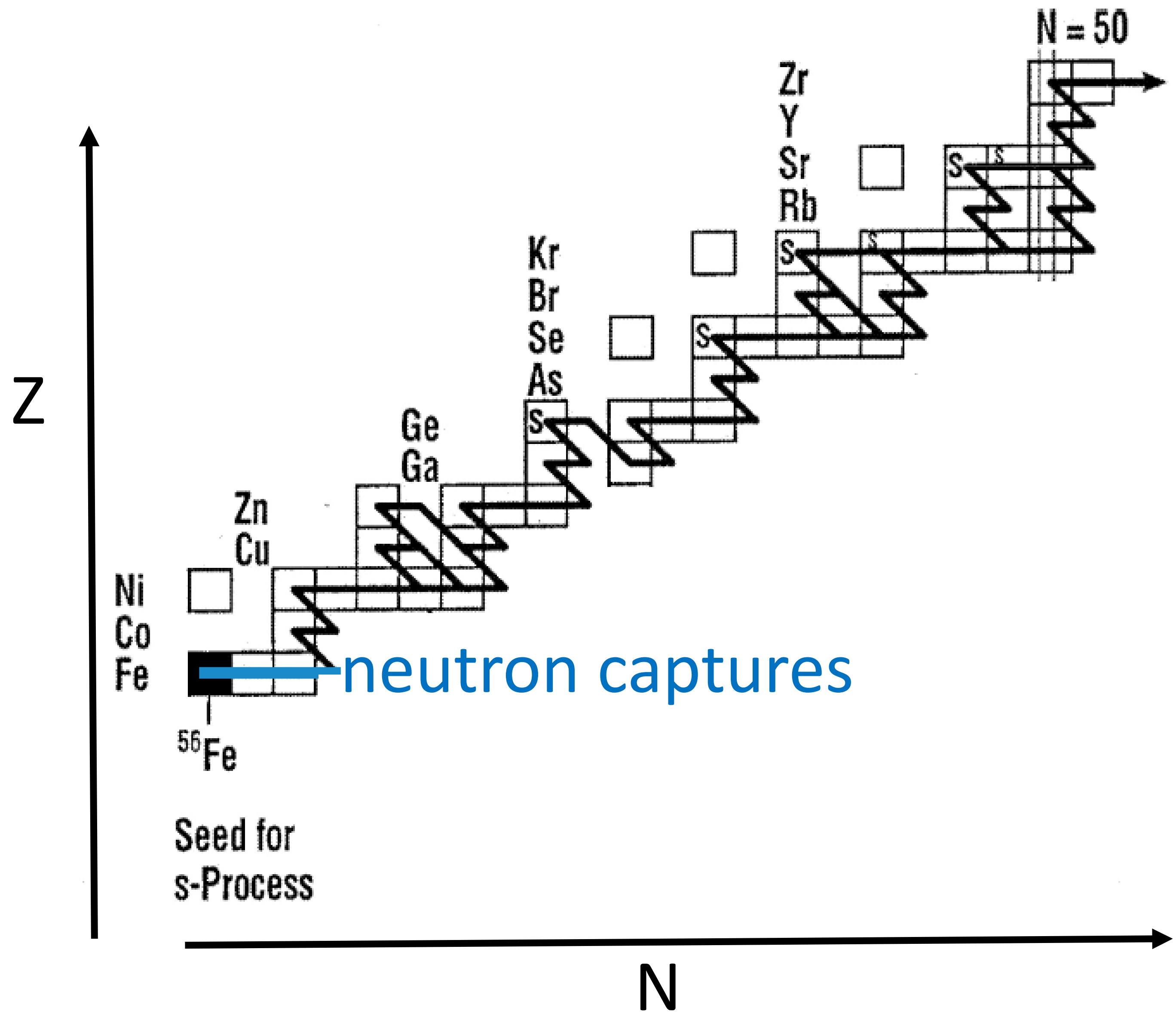
Too many protons Coulomb repulsion too large





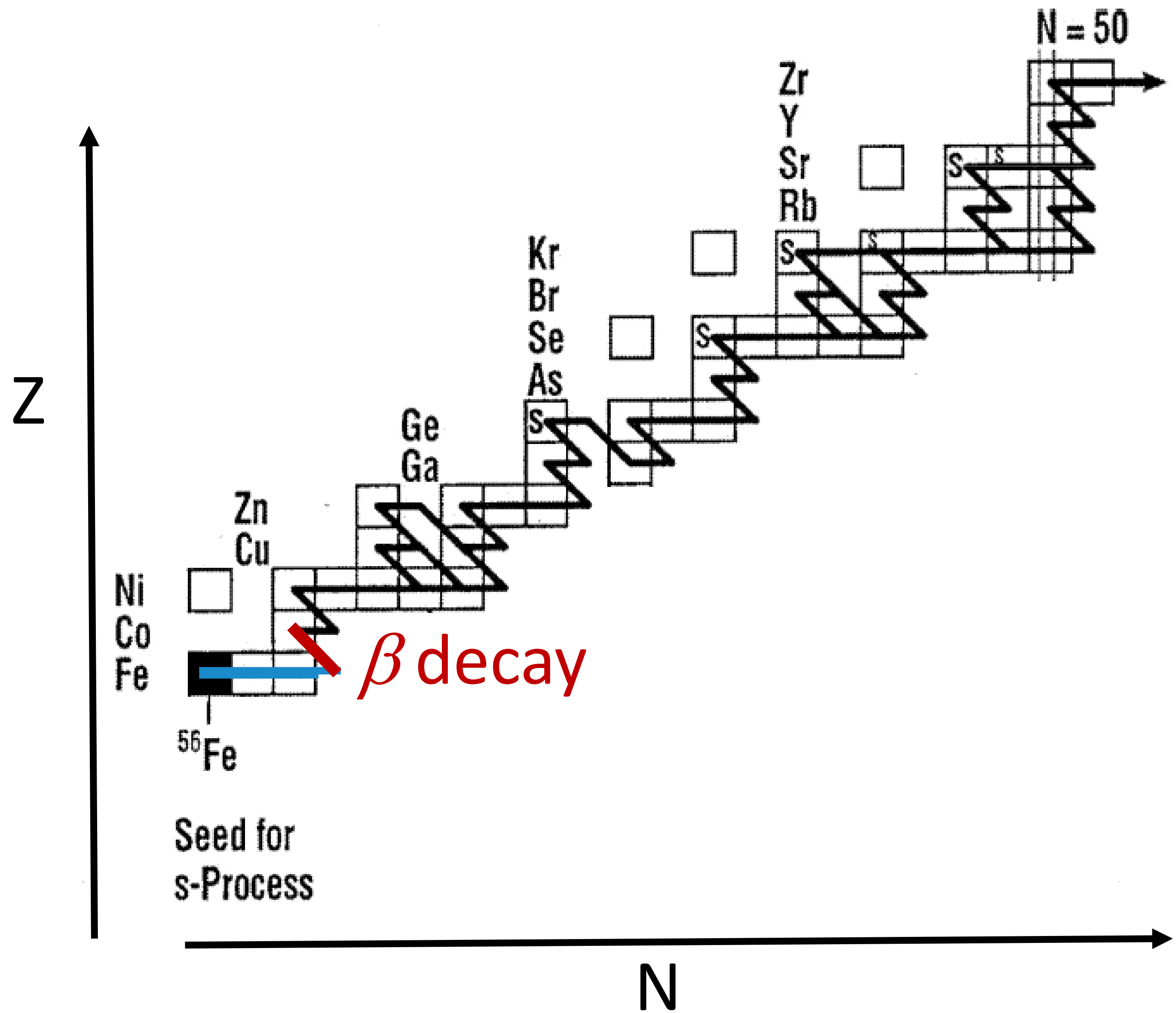

Too many neutrons- neutron fermi energy too high

# s-process



N = 50
Zr
Y
Sr
Rb
Kr
Br
Se
As
Ge
Ga
Zn
Cu
Ni
Co
Fe
56Fe
Seed for
s-Process
neutron captures
Z
N

# s-process



N = 50
Zr
Y
Sr
Rb
Kr
Br
Se
As
Ge
Ga
Zn
Cu
Ni
Co
Fe
s
$^{56}$Fe
Seed for
s-Process
$\beta$ decay
Z
N

There's a problem:

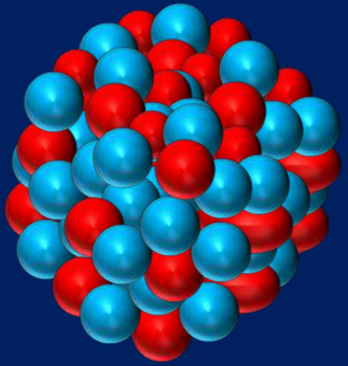
Too many large nuclei are unstable.

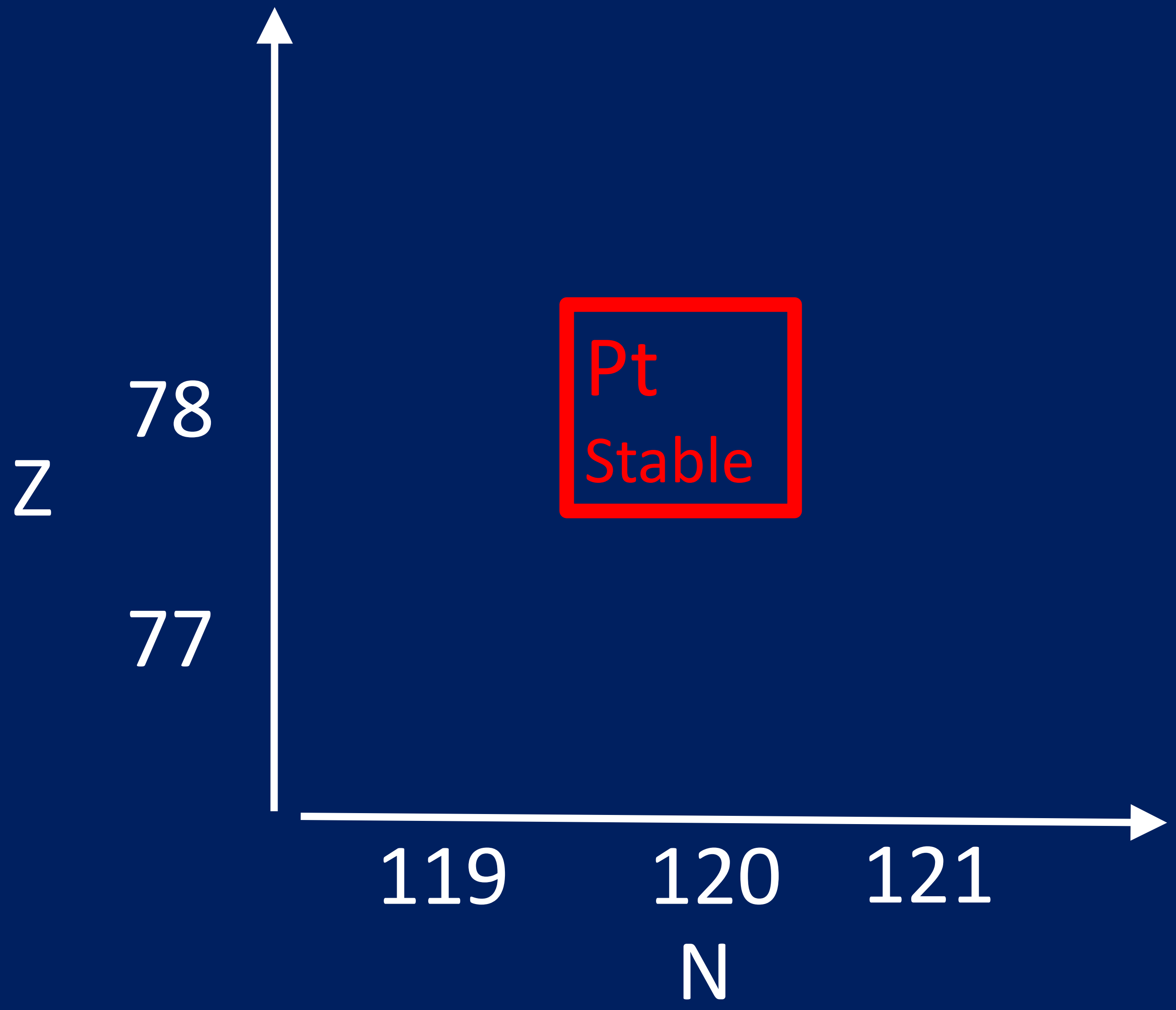
Large stable nuclei may have no stable guy with an extra neutron that can reach them by decay.

# Platinum

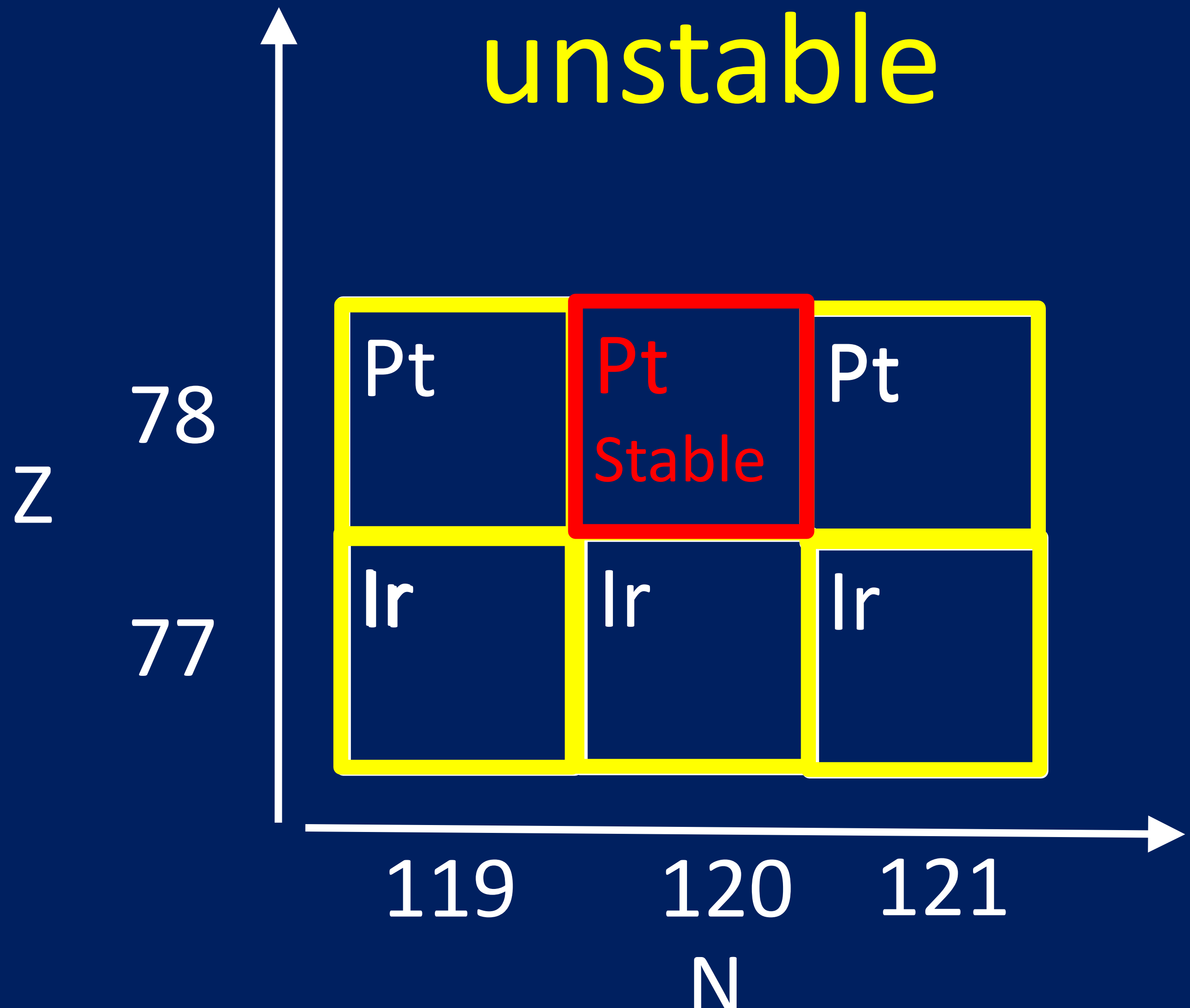
78 protons

120 neutrons




Pt
Stable
78
Z
77
119
120
121
N

# unstable

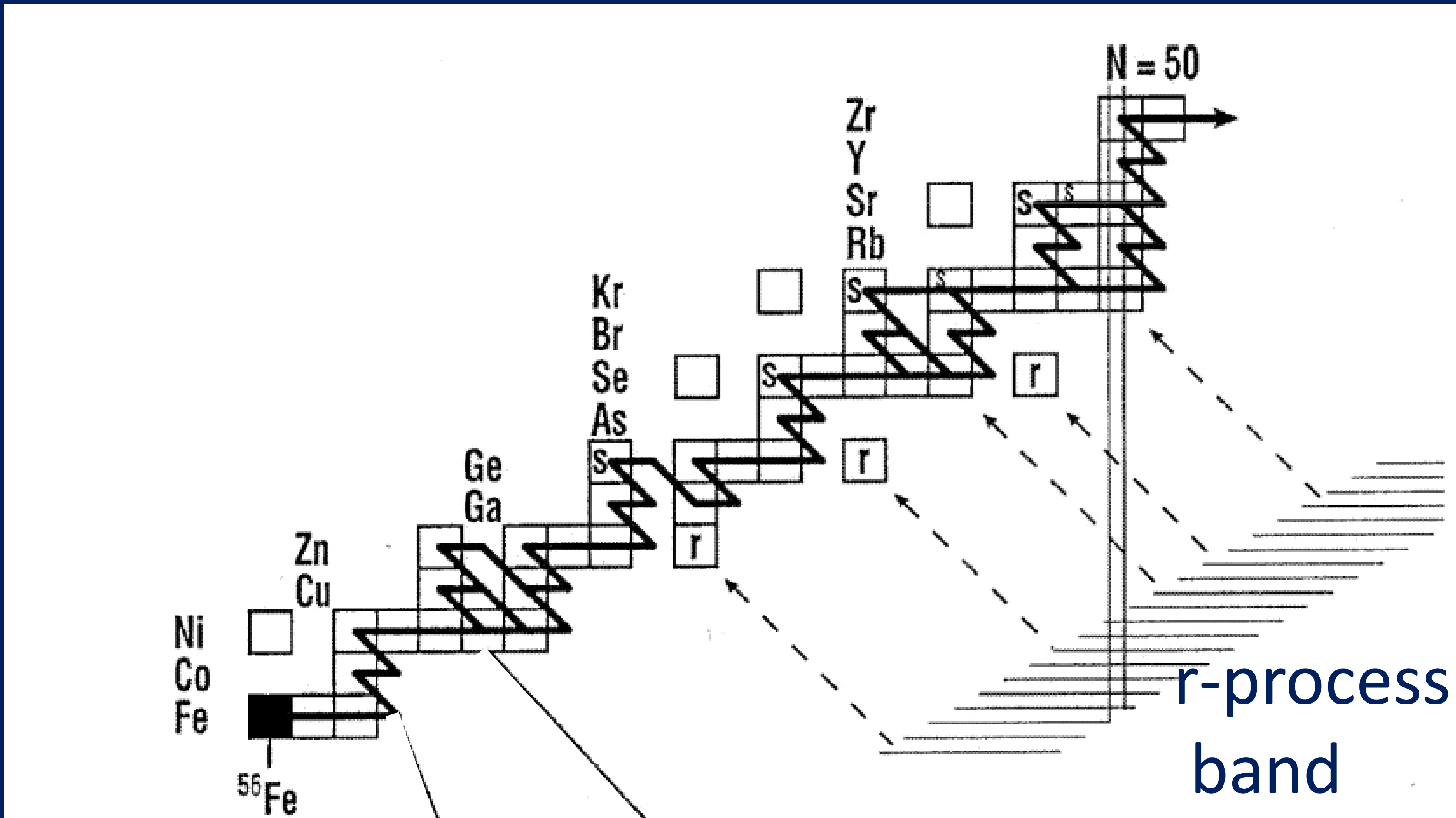



decay in less than a day

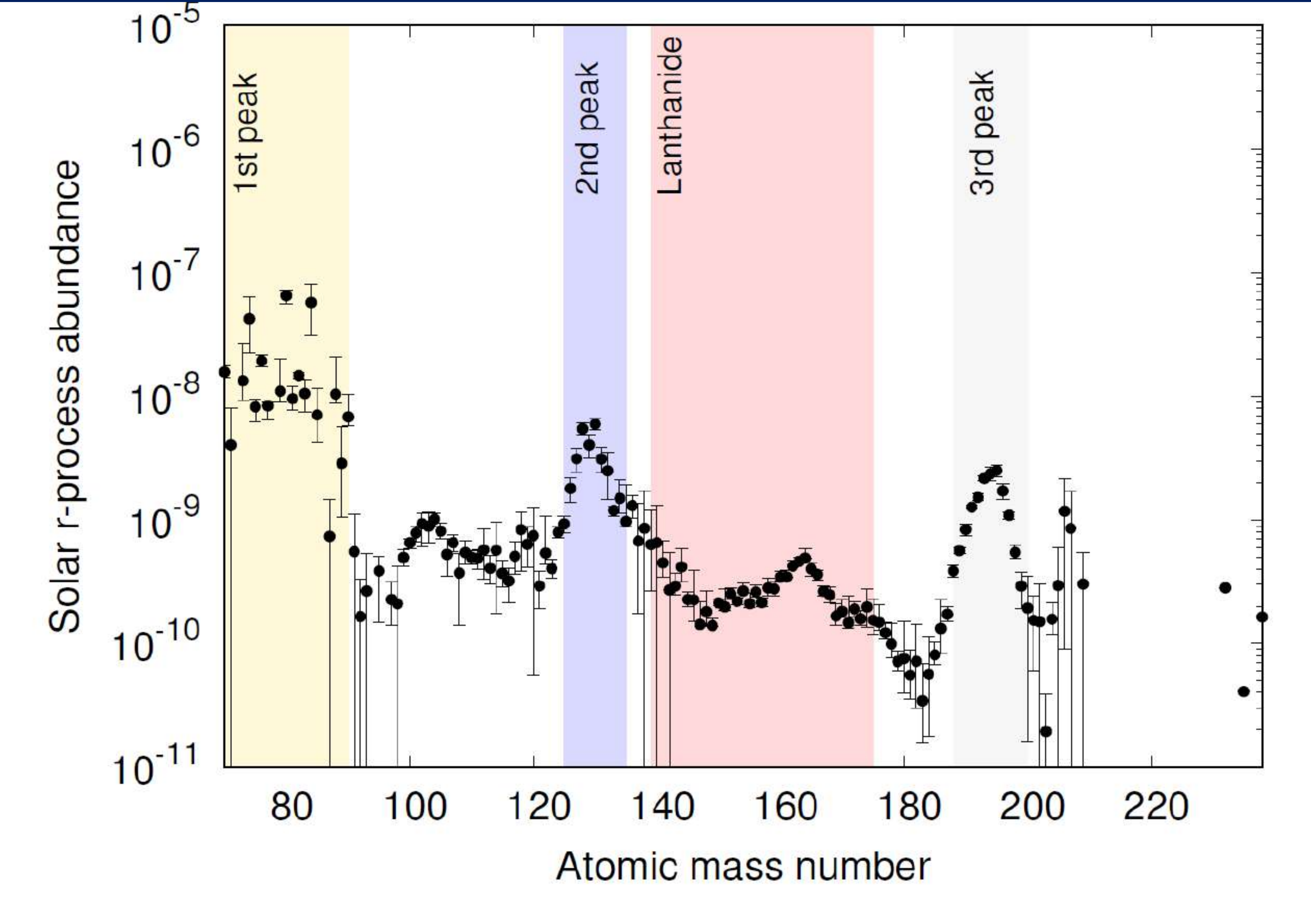
To get to platinum, neutrons need to bombard nuclei before they can decay.

After the bombardment stops, unstable nuclei with too many neutrons are left.

The extra neutrons decay to protons, leaving a final stable nucleus.


N = 50
Zr
Y
Sr
Rb
Kr
Br
Se
As
Ge
Ga
Zn
Cu
Ni
Co
Fe
56Fe
s
r
r-process
band

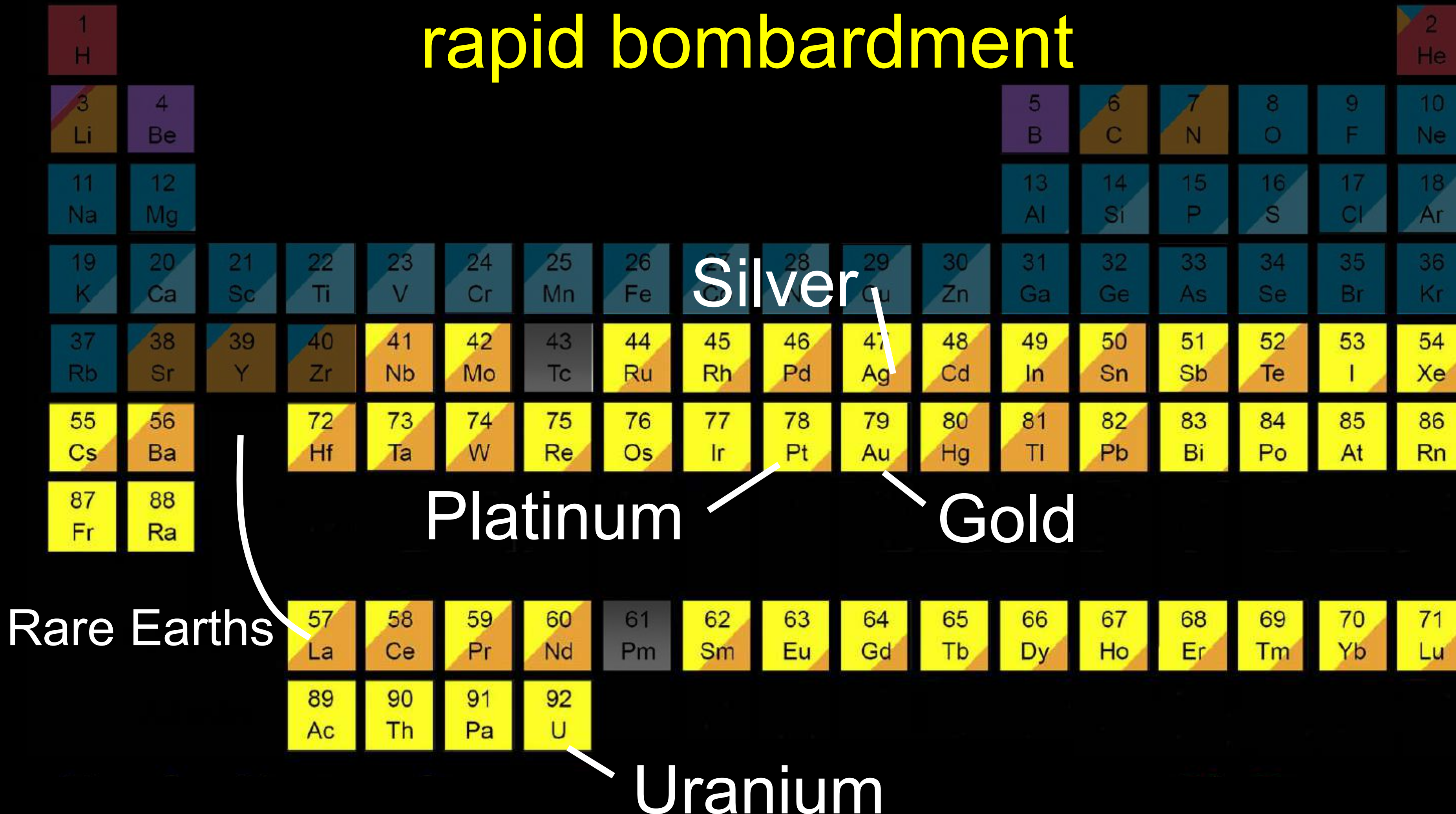
# Abundance peaks at *magic numbers,* at filled neutron shells in nucleus

r-process simulation Wanajo et al.

http://www.ph.sophia.ac.jp/~shinya/research/research.htm
l

# r-process elements: elements built primarily or exclusively by rapid bombardment




by

*The tidal breakup of a neutron star near a black hole is examined. . . the estimated quantity of ejected material is found to be roughly comparable to the abundance of r-process material.*

Lattimer, Schramm 1974 . . .

*A natural consequence of the binary pulsar's evolution is a neutron star collision. . . Taking reasonable estimates for the number of such events over the history of the galaxy, it may be that they account for all of the [remaining] nuclei.*

Symbalisty, Schramm 1982

# Galactic mass of r-process elements

$= 10^{-7}\ M_{galaxy}$

$= 10^{4}\ M_{\odot}$

Can NS-NS mergers produce almost all of this?

Simulations of neutron star collisions (before GW1701817 and then afterwards with observations at all wavelengths to match) give

10 times the mass of the earth in platinum and gold

$> 10^{-2} M_{\odot}$

in heavy elements

## Rate of neutron-star mergers:

Closest seen is GW170817 at 40 Mpc (130 Mly)
about 1 merger every (.5 – 10) years within this distance,

$$V = \frac{4}{3}\pi(40\text{Mpc})^3 = 2.7\times10^5\text{Mpc}^3$$

With, say, 2 years per merger within this distance, merger rate is

$$\frac{1}{2(2.7\times10^5\text{Mpc}^3)} \approx 4\times10^{-6}\text{Mpc}^{-3}\text{yr}^{-1}$$

Per galaxy: About 100 $\text{Mpc}^3$ per
Milky-Way equivalent galaxy, giving

merger rate ≈ $10^{-4}$ $\text{MWEG}^{-1}\text{yr}^{-1}$

galactic mass of r-process elements

$= 10^4 M_\odot$

r-process mass per merger

$\gtrsim 10^{-2} M_\odot$ /merger

r-process mass in Galaxy produced in age of universe

$= (10^{-4}$ mergers/yr$)(10^{-2} M_\odot$ /merger$)(10^{10}$ yr$)$

$\approx 10^4 M_\odot$

with uncertainties in amount per merger and in merger rate giving range

$7 \times 10^3 M_\odot$ to $10^5 M_\odot$

# Prediction

Radioactive decay powers an afterglow, *a kilonova,* that dims as the decays lead to stable nuclei

# The glow hours after the collision

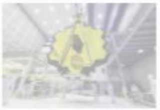
The rate at which the glow faded and the shift to lower wavelengths, agreed with predictions from decay of r-process elements.

Discovery Image
August 17, 2017

The rate at which the glow faded and the shift to lower wavelengths, agreed with predictions from decay of r-process elements.


OPINION
Once Bitten, Beyoncé Turns the Other Cheek


OPINION
Maybe the Drop in Student Visas Isn't All That Bad


U.S. NEWS
NASA Delays James Webb Space Telescope By About a Year


U.S. NEWS
The Decision That Hurts Your Chances of Getting Into Harvard


ART
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Rev
Lett



# A Clash of Neutron Stars Forges Gold

Researchers say this is the first time a cosmic event has been seen both with gravitational waves and with the full electromagnetic spectrum

*By* Robert Lee Hotz

Oct. 16, 2017 10:00 a.m. ET

Vox

EXPLAINERS POLITICS & POLICY WORLD CULTURE SCIENCE & HEALTH IDENTITIES MORE

# Gravitational waves just led us to the incredible origin of gold in the universe

LIGO kick-started an astronomical treasure hunt that ended with colliding neutron stars and gold.

By Brian Resnick | @B_resnick | brian@vox.com | Updated Oct 16, 2017, 6:28pm EDT

**PhysOrg**

## Gold origin confirmed with first ever gravitational wave sighting

# III. Equation of state (EOS) above nuclear density

Because neutron stars are cold
(kT << Fermi energy of neutrons and protons)
the EOS is essentially the zero-temperature EOS,
depending on only one parameter:

$$p = p(\rho)$$
$$\epsilon = \epsilon(\rho)$$

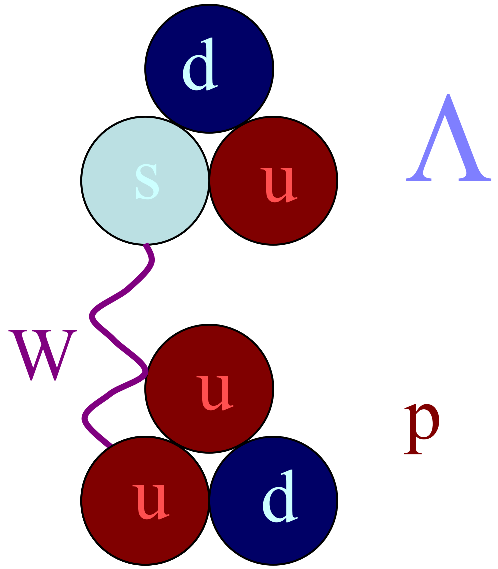
$\rho =$ rest mass density
$\epsilon =$ energy density
$p =$ pressure

Is the core dense enough to create strange quarks

–to push the Fermi energy of some down quarks above the threshold to convert to strange quarks

e.g., Fermi energy of neutron pushed above mass of Λ:

$$n\, p \rightarrow p\, \Lambda$$

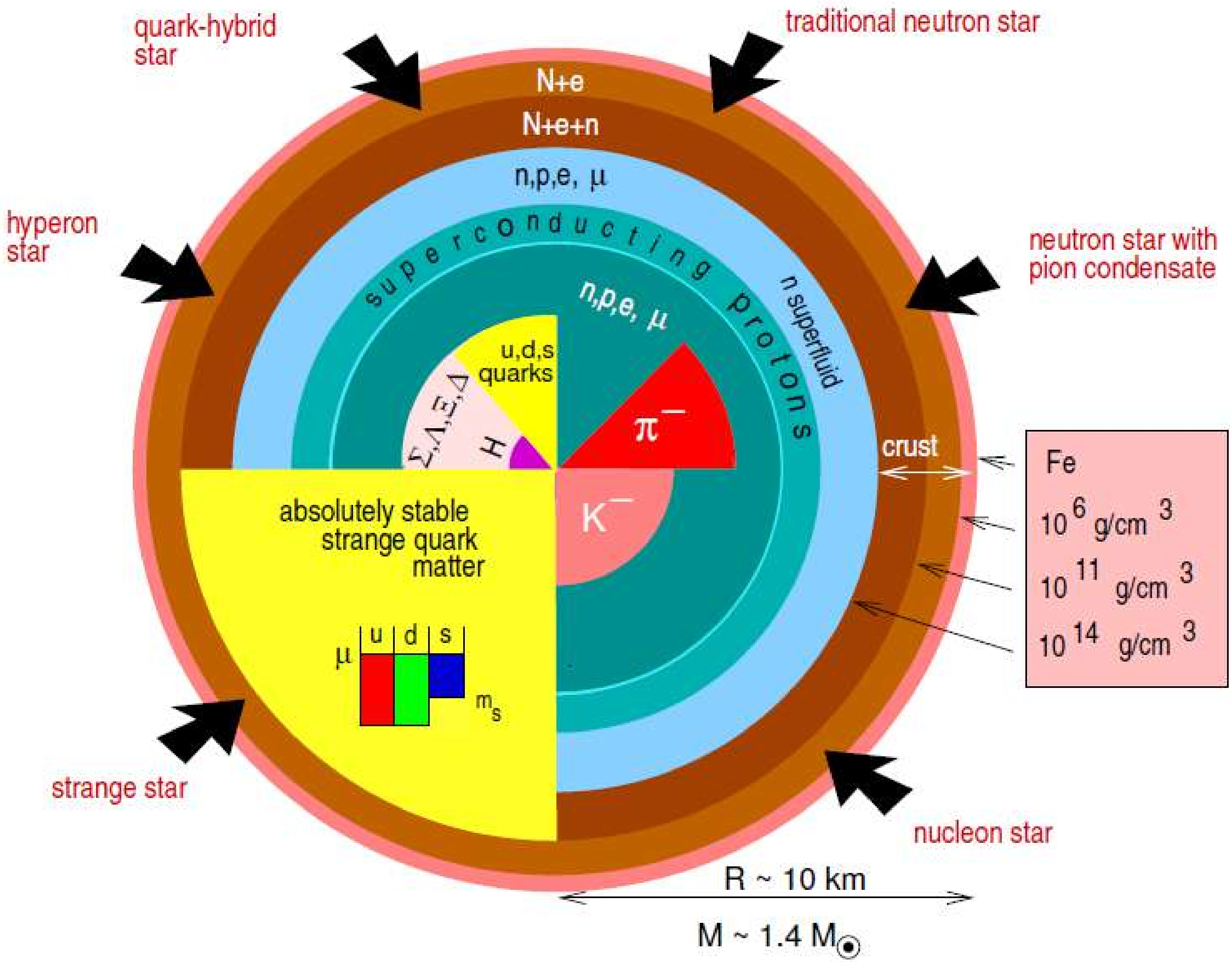


If so, do the quarks group as hyperons in core?

Is the core dense enough to dissolve nucleons into strange quark matter:  a large bag of free up, down and strange quarks?

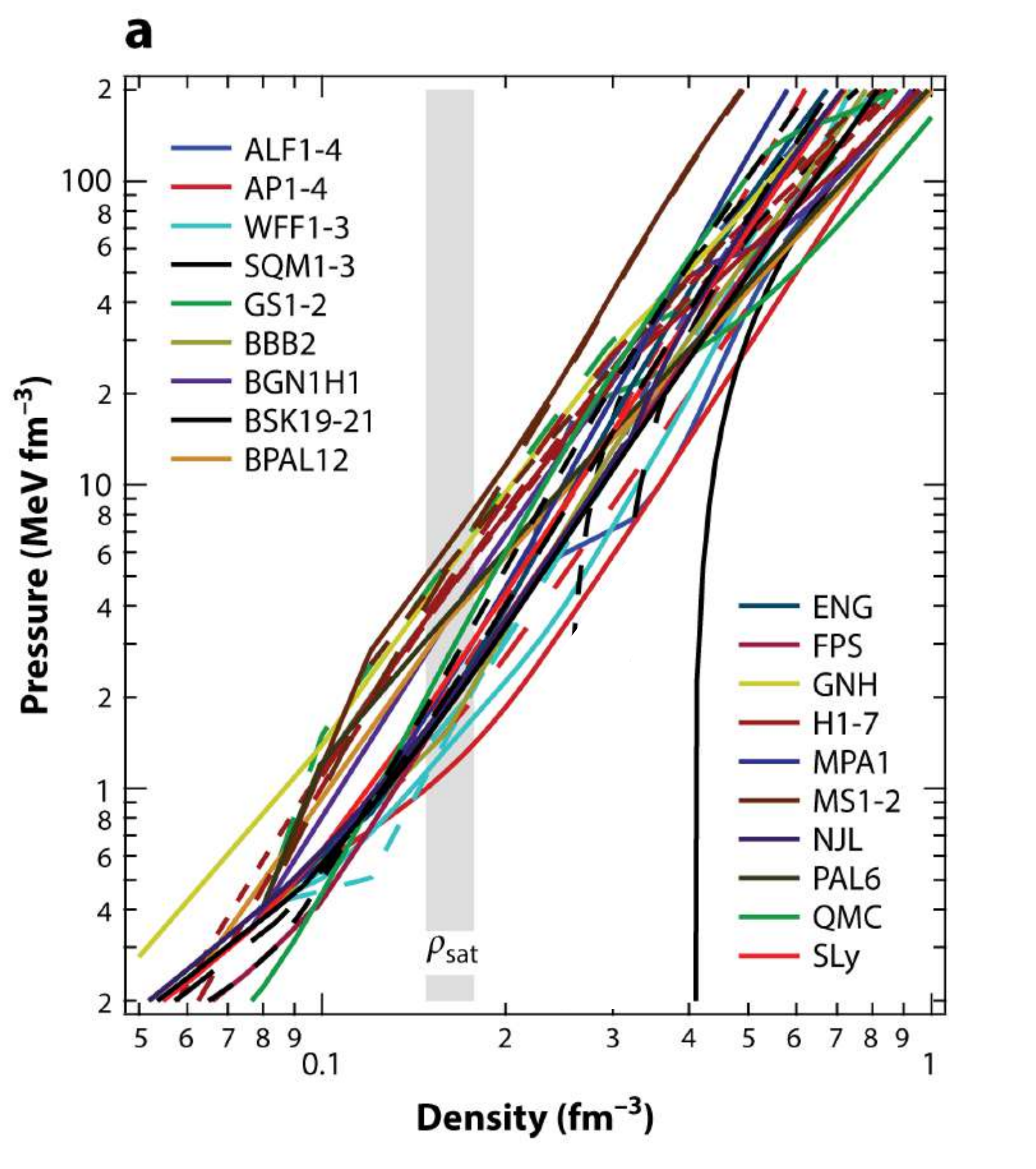
Is the true ground state of cold matter strange quark matter, for any collection larger than a few hundred quarks (Bodmer, Witten)?

# Internal structure of compact stars




[Weber, J. Phys. G **27**, 465 (2001)]

# EOS based on the different alternatives




Ozel & Freire '16
Ann Rev A & Ap

Can approximate log p (log r) for universe of candidate EOS by piecewise linear curves to about 3% ac )

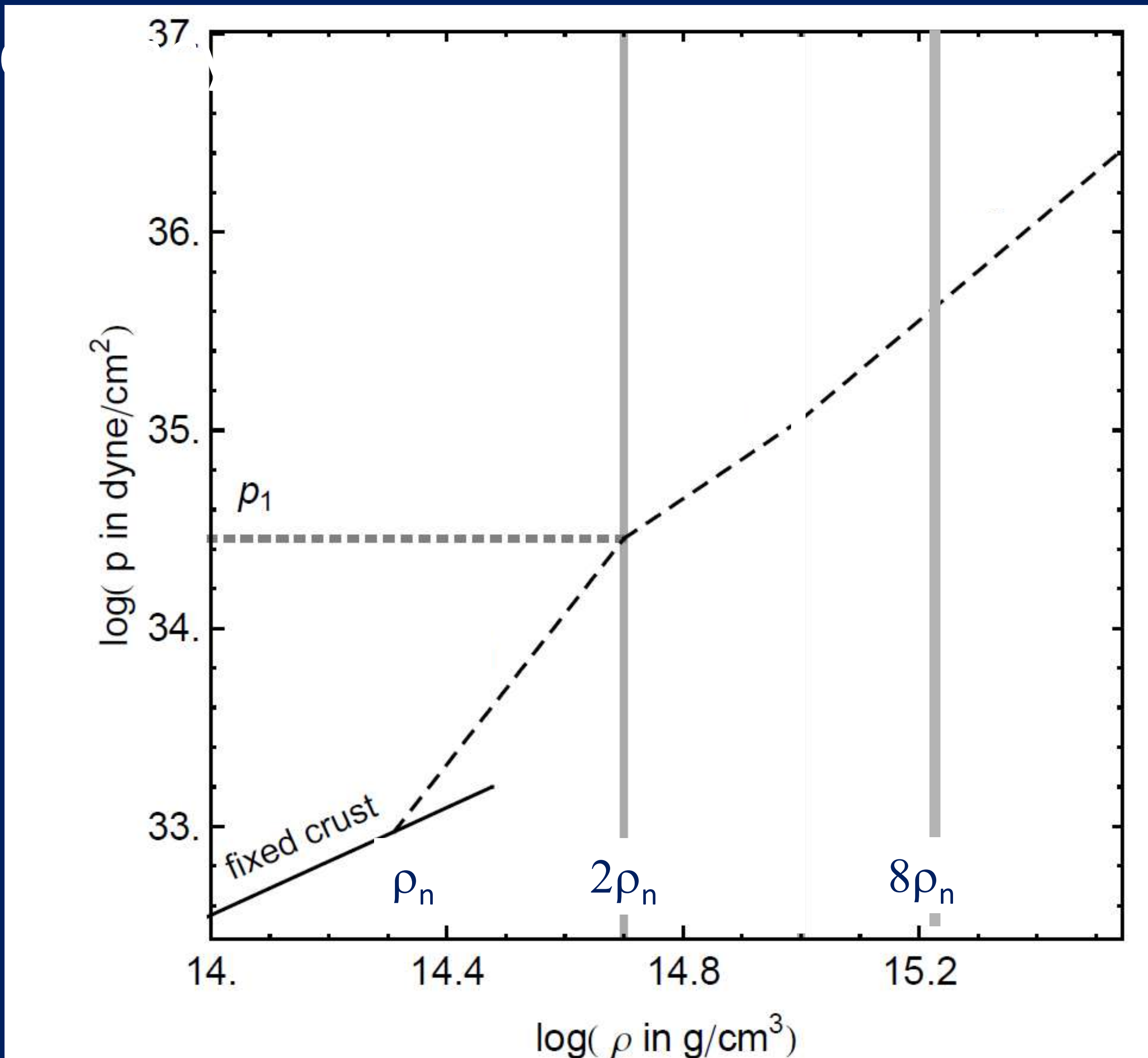
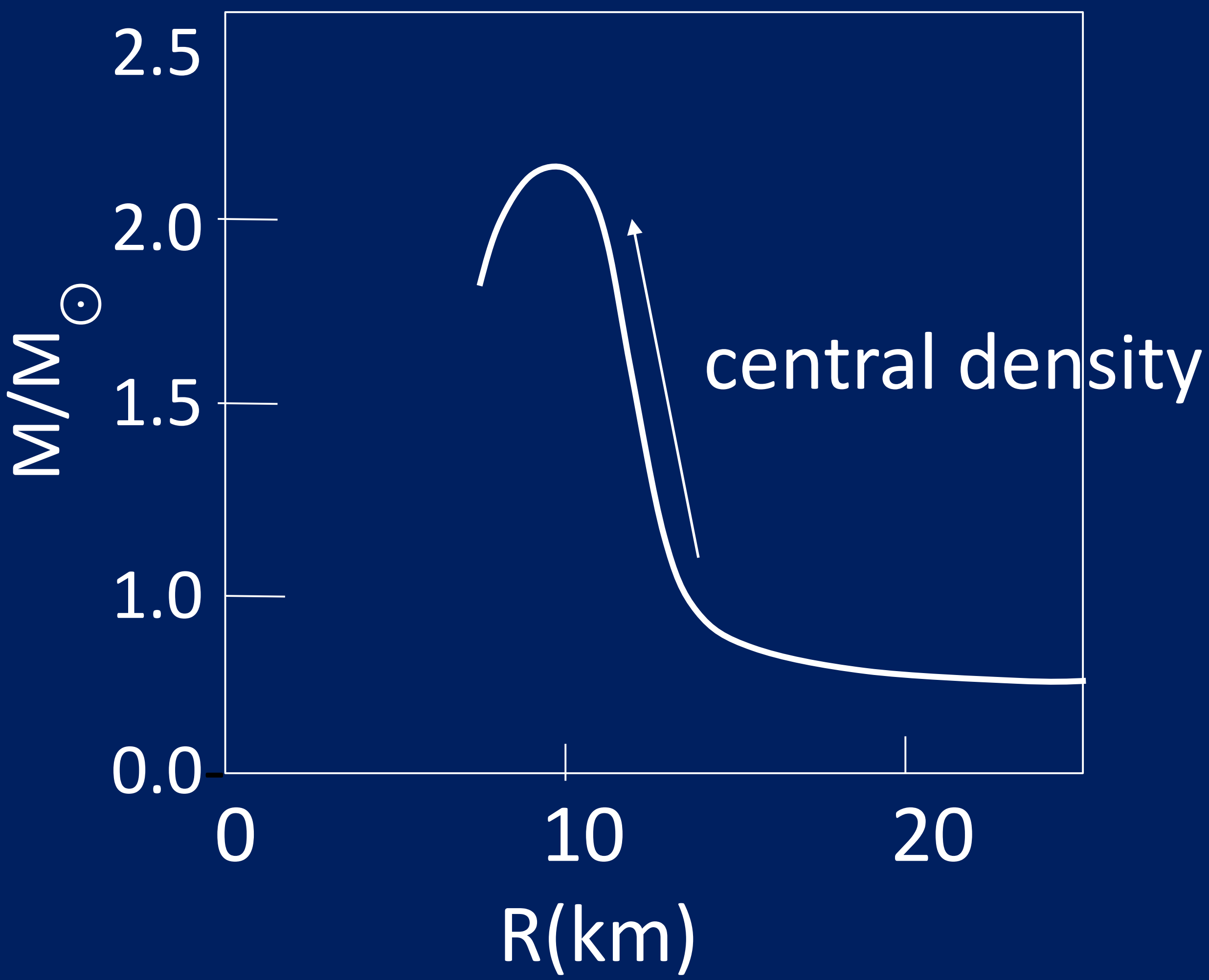
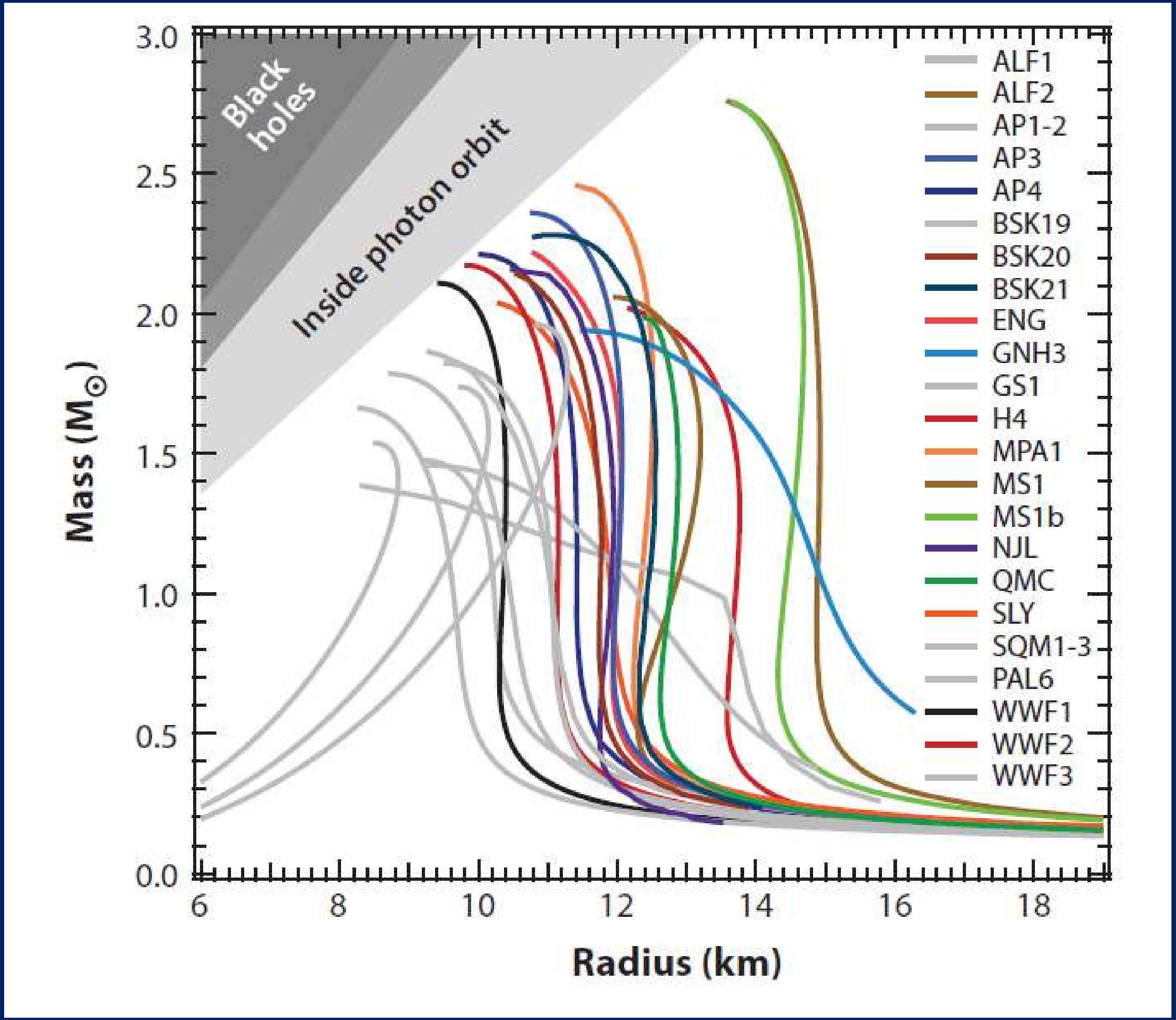



Fig modified from Read, Lackey, Owen, JF

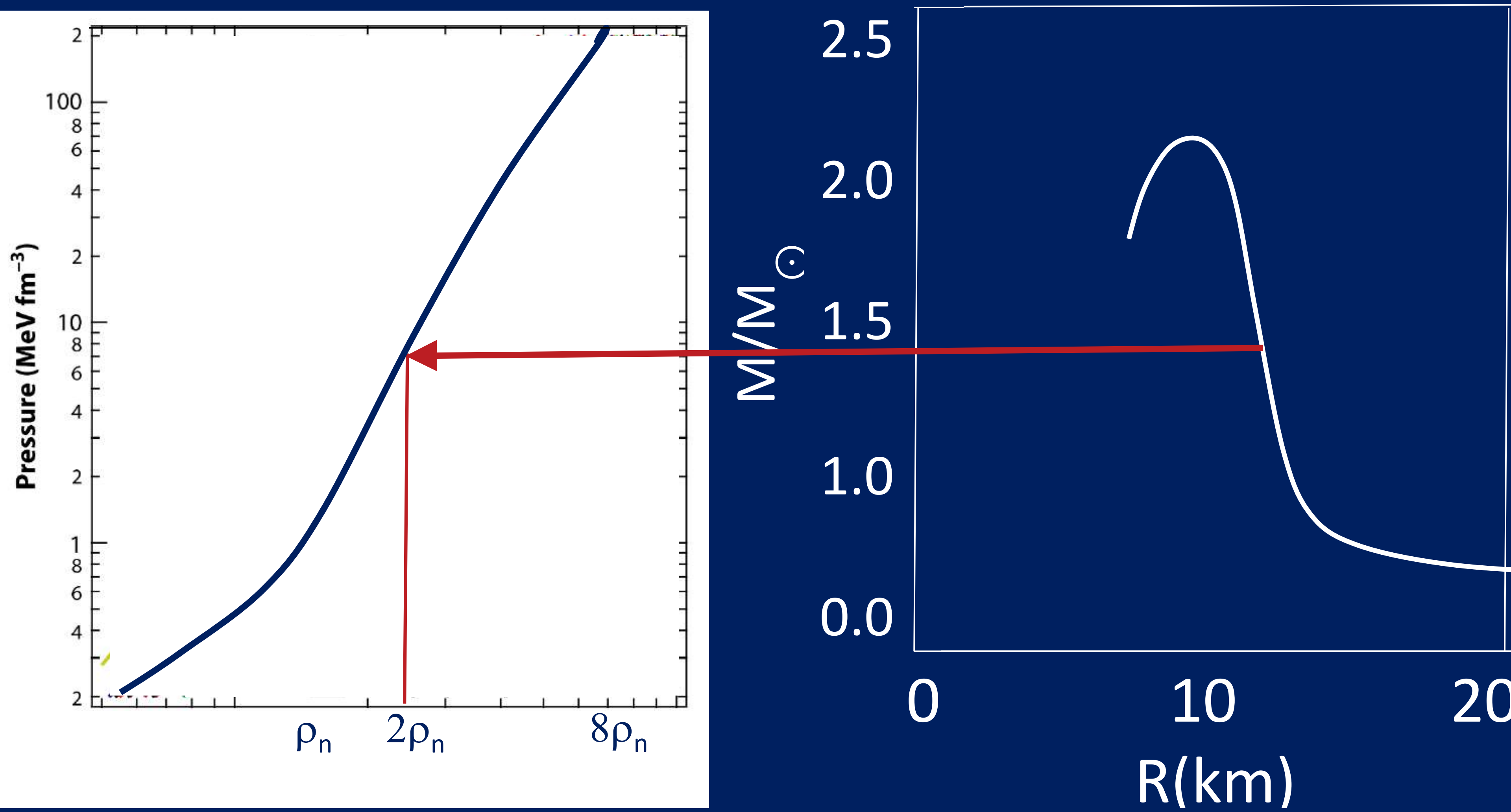



The 1-parameter family of neutron stars portrayed as a curve of mass vs radius

# To each candidate EOS corresponds a M vs R curve.

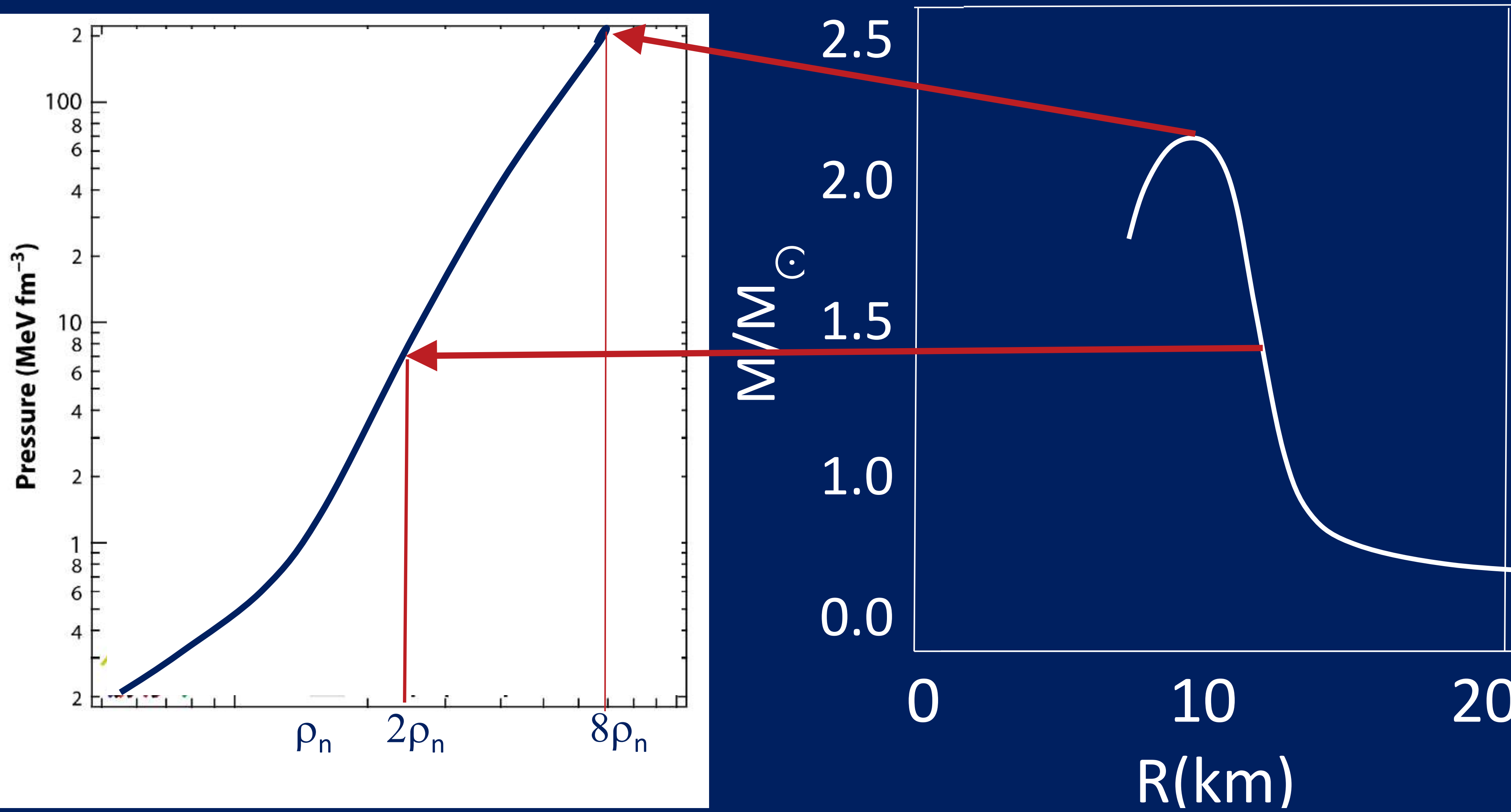


Infer EOS from measurements of mass and radius.
Radius at 1.4 $M_\odot$ gives pressure at $\rho \sim 1.8\ \rho_n$




(inverse construction by Lindblom; Fig. idea from Lattimer)

# Maximum mass gives pressure at $\rho \sim 8\ \rho_n$




(inverse construction by Lindblom; Fig. idea from Lattimer)

If the EOS of cold matter above nuclear density is soft the radius of a 1.4 $M_\odot$ neutron star will be small

Soft EOS: $p$ small for $\rho \sim 2\rho_{\text{nuclear}}$ implies star more centrally condensed, $R$ small

If the EOS of cold matter above nuclear density is stiff the radius of a 1.4 $M_{\odot}$ neutron star will be large

Stiff EOS: $p$ large for $\rho \sim 2\rho_{\text{nuclear}}$ implies star less centrally condensed, $R$ large

# IV. Tidal imprint on the inspiral waveform

With no tide, distance *d* between stars decreases at rate determined by energy loss to gravitational waves.

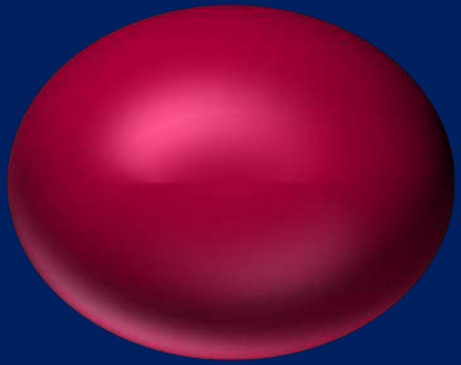
$$E_{\rm orbit} = -\frac{M^2}{d} \Rightarrow \frac{\dot{E}_{\rm orbit}}{E_{\rm orbit}} = \frac{\dot{d}}{d}$$

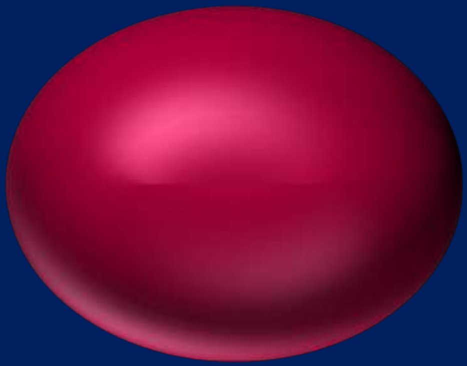
# Tidal imprint on the inspiral waveform

As *d* decreases, the height of the tides increases

# Tidal imprint on the inspiral waveform

As *d* decreases, the height of the tides increases





# Tidal imprint on the inspiral waveform

The tidal distortion of each star increases the total quadrupole moment *Q* of the orbiting stars

Tides increase the rate at which the orbit loses energy in two ways:

orbital energy → stellar deformation
orbital energy → enhanced GW from larger Q

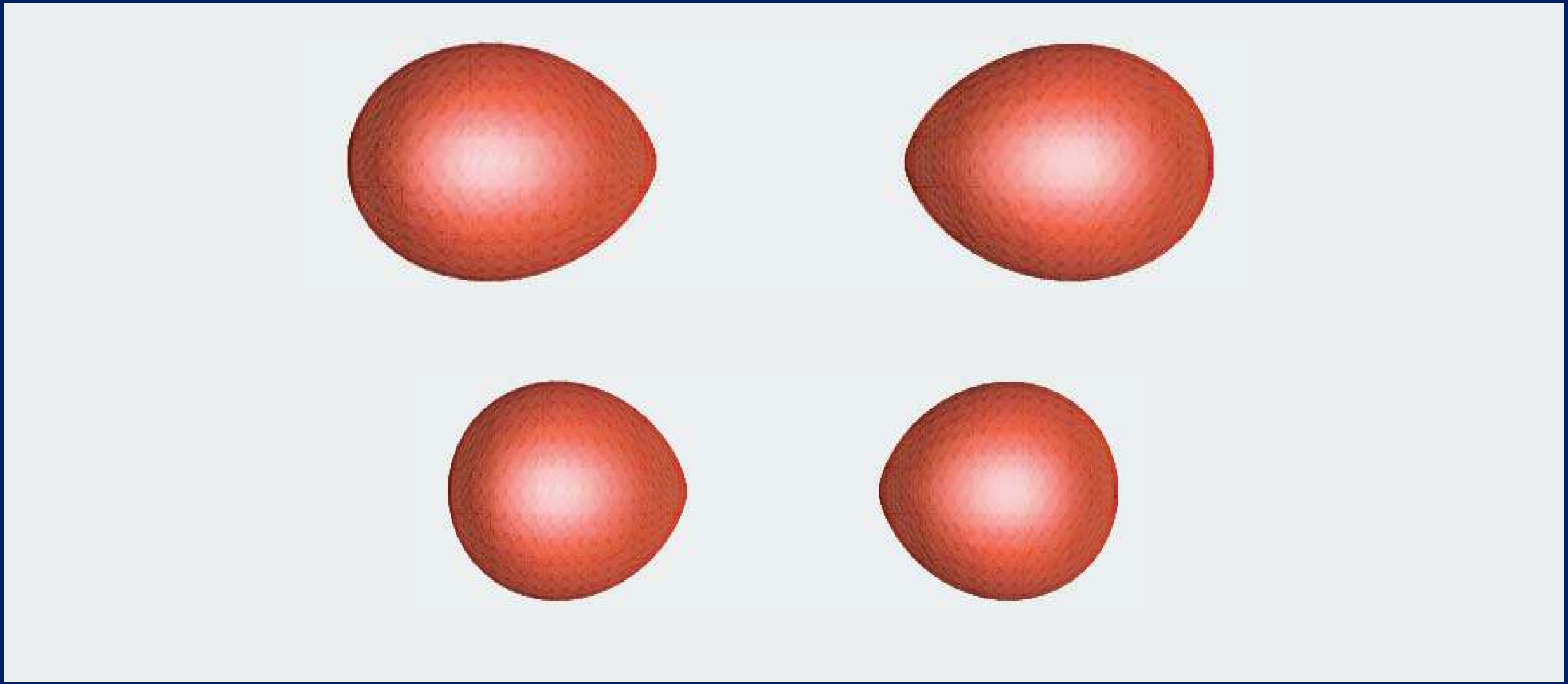
the orbit shrinks faster

the frequency *f* increases more quickly.

and tidal disruption ends the inspiral sooner – the cutoff frequency is lower.

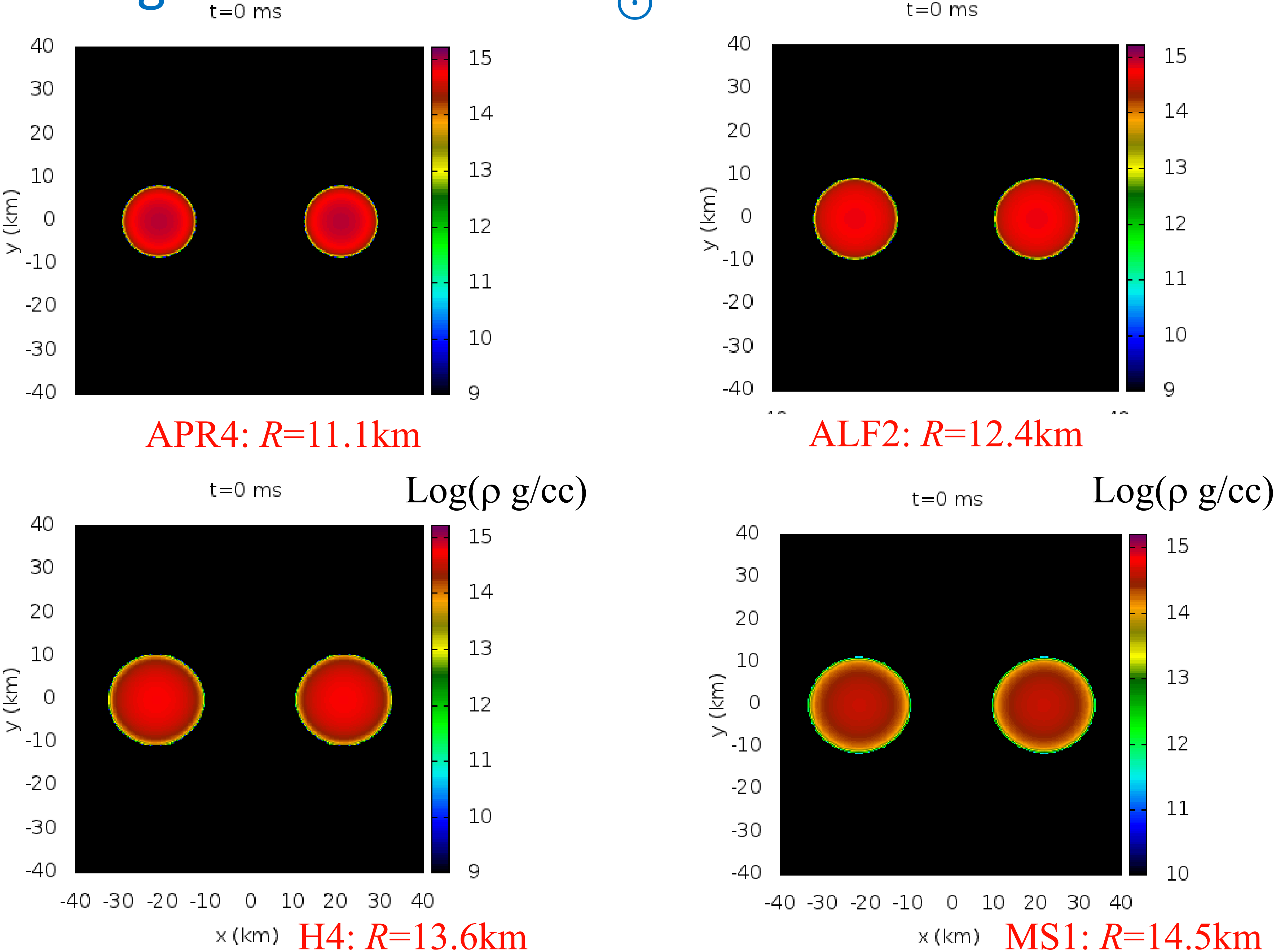
In a binary system, the tides raised on each star depend on the deformability of that star:

Tides are larger for large radii
and so larger for stiffer EOS.



# Merger of 1.35-1.35$M_\odot$ NS with four EOSs

By hotokezaka + 2013



# Formally, define deformability $\lambda$

For an imposed external quadrupole field $E$, a star acquires a quadrupole moment $Q$

$$Q = \Lambda E$$

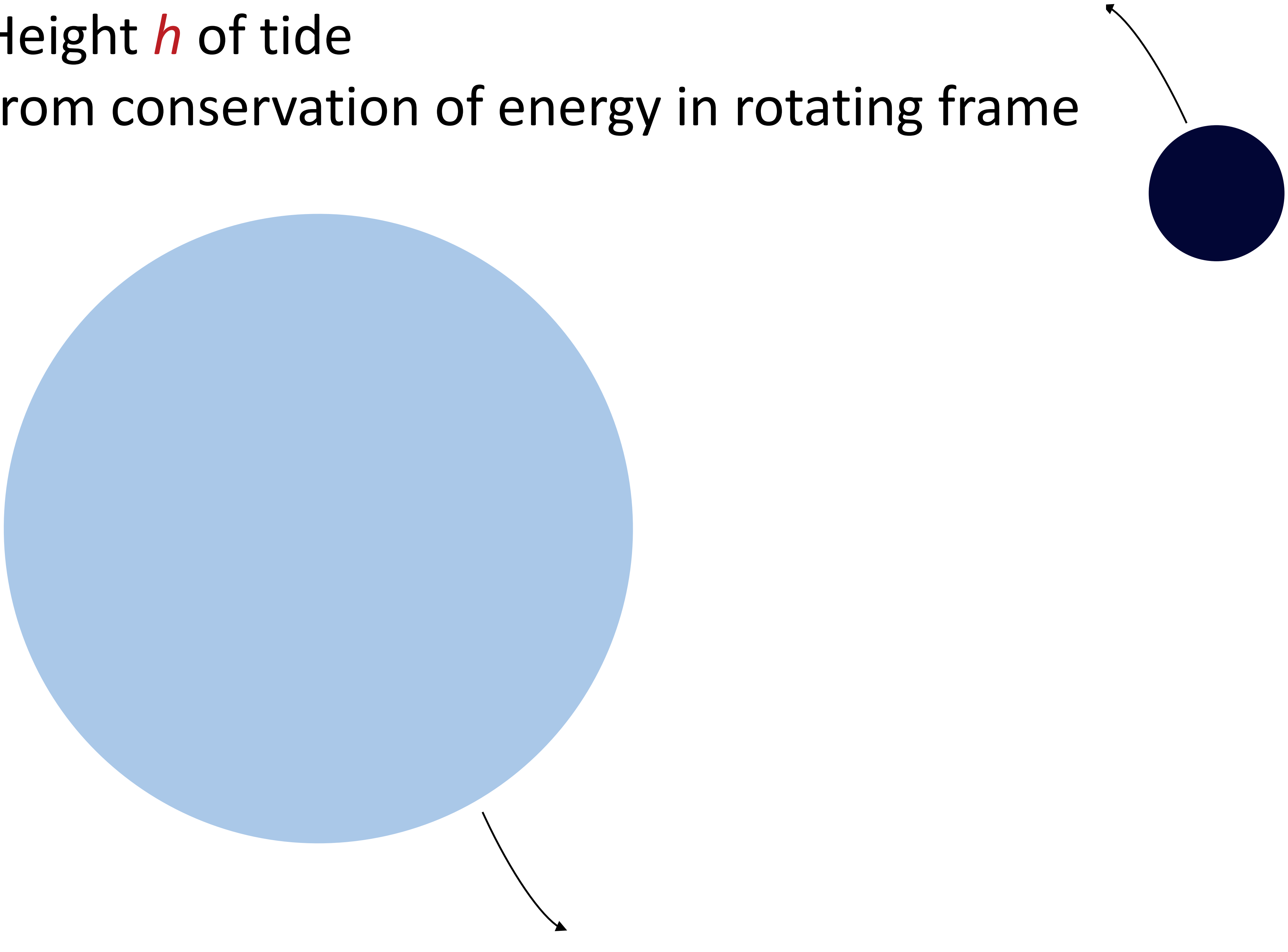
We'll see that $\Lambda$ is roughly proportional to $R^5$

The tidal effect on the inspiral waveform measures the neutron-star radius

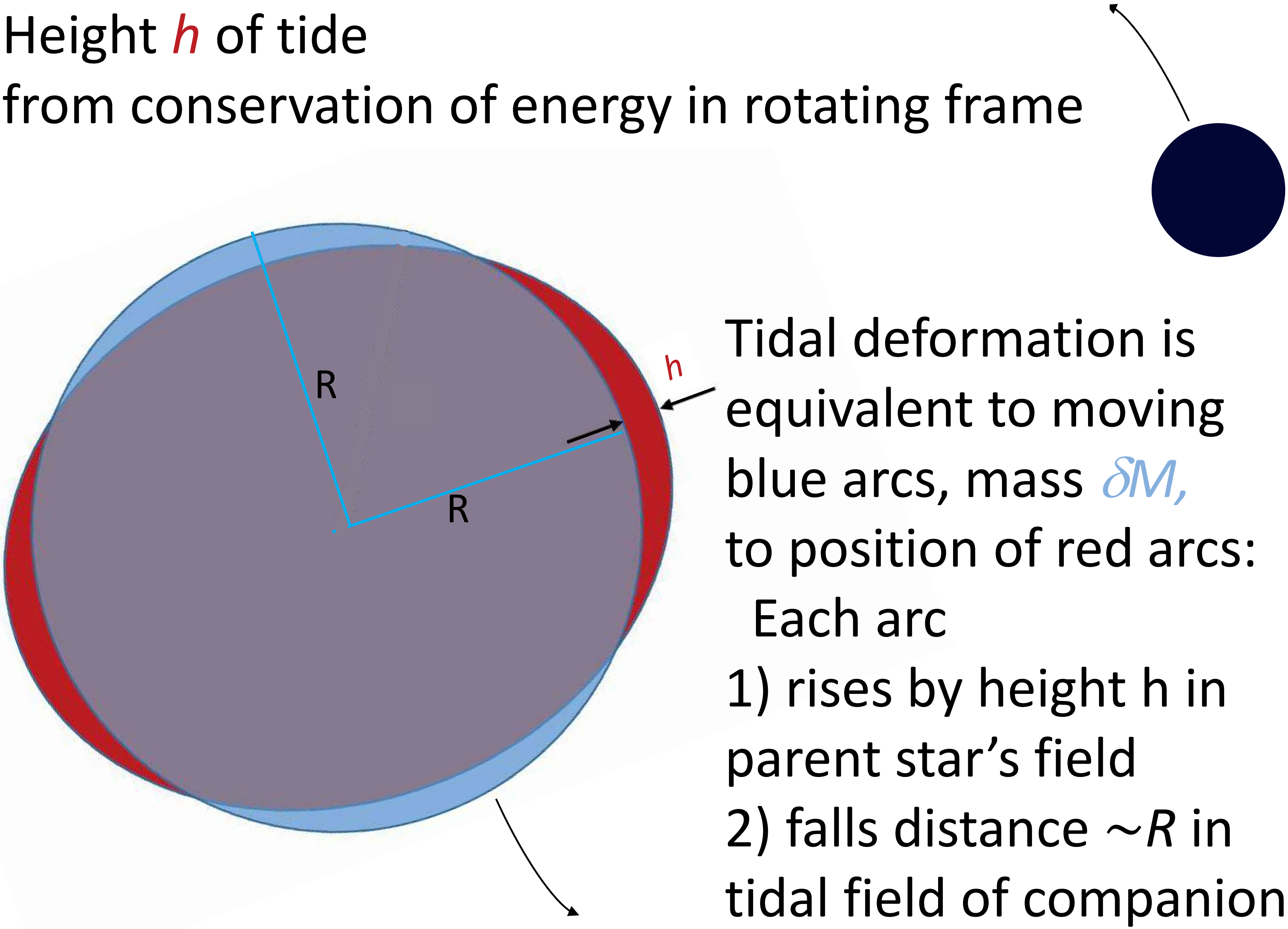
# Estimating the tidal imprint

- Height of the tide
- $$\frac{\delta \dot{E}_{\mathrm{GW}}}{\dot{E}_{\mathrm{GW}}} \sim \frac{R^5}{d^5}$$ (change in radiated power due to increased quadrupole moment)
- $$\frac{\dot{E} \text{ to raise tides}}{\dot{E}_{\mathrm{GW}}} \sim \frac{R^5}{d^5}$$

# Height $h$ of tide
# from conservation of energy in rotating frame



# Height *h* of tide
# from conservation of energy in rotating frame




Tidal deformation is equivalent to moving blue arcs, mass $\delta M$, to position of red arcs:

Each arc

1) rises by height h in parent star's field
2) falls distance $\sim R$ in tidal field of companion

energy gained by rising a height *h* in parent star's field

=

energy lost falling distance *R* in other star's tidal field

force of parent star x *h* $\sim$ tidal force x *R*

$$\frac{M\delta M}{R^2} h \sim \frac{M\,\delta M\,R}{d^3} R$$

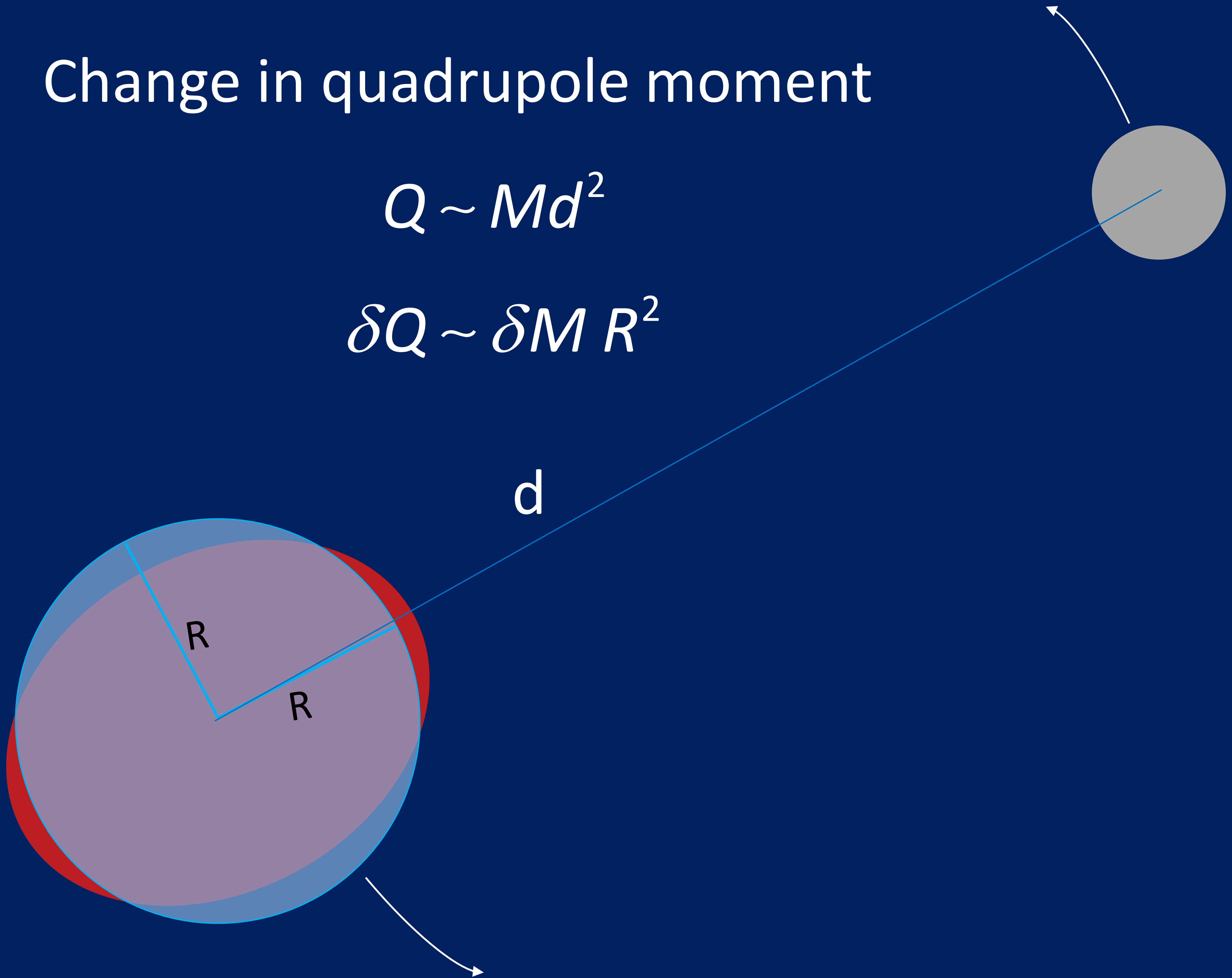
Then

$$h \sim \frac{R^4}{d^3} \qquad \delta M \sim M \frac{h}{R} \sim M \frac{R^3}{d^3}$$

# Change in quadrupole moment

$$Q \sim Md^2$$

$$\delta Q \sim \delta M\, R^2$$



# Enhanced gravitational waves from larger Q

$$\delta Q \sim \delta M\, R^2$$

$$\frac{\delta Q}{Q} \sim \frac{\delta M}{M}\frac{R^2}{d^2} \sim \frac{R^5}{d^5}$$

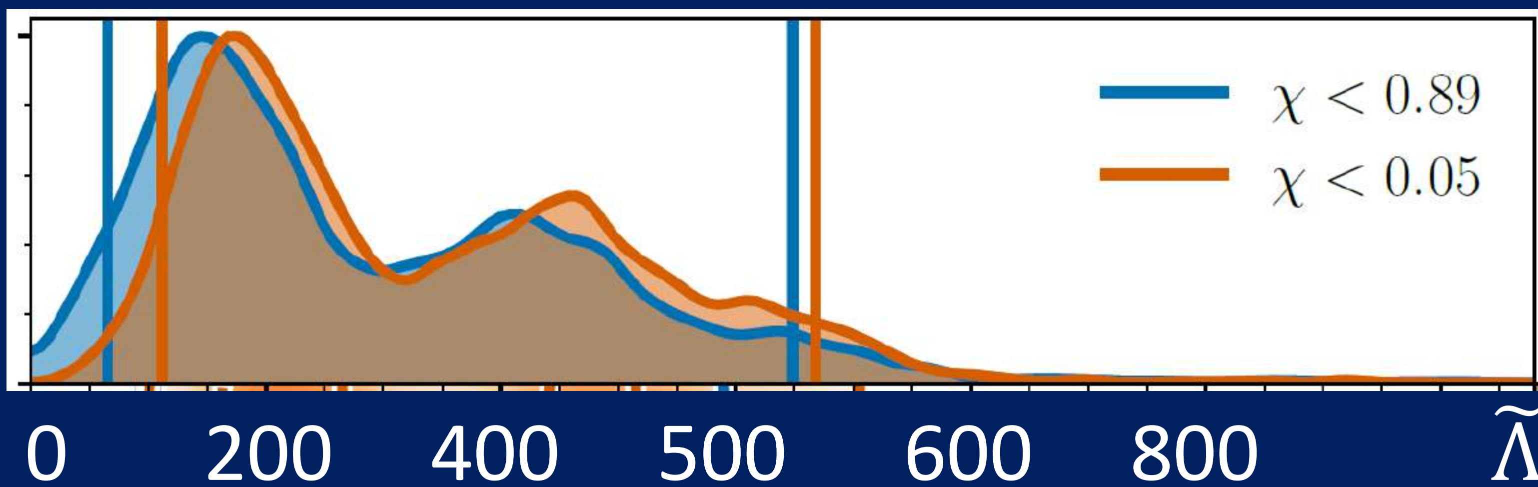
$$\frac{\delta M}{M} \sim \frac{R^3}{d^3}$$

$$\frac{\delta \dot{E}_{\mathrm{GW}}}{\dot{E}_{\mathrm{GW}}} \sim \frac{\delta Q}{Q} \sim \frac{R^5}{d^5}$$

Measuring tidal deformability is equivalent to measuring *R* within current GW observational error.

# LIGO/VIRGO analysis of GW170817

Probability density of an average value $\widetilde{\Lambda}$ of the two stars' deformability




9 km

14 km

At 90% probability, neutron stars' radii in the range

8.7 km ≤ $R$ ≤ 14.1 km

Bonus:
Ejected mass is roughly $\delta M$ near merger, say $d \sim 3R$ $\delta M \sim M/3^3$ , a few percent.

For NS-NS mergers, ejecta from shock after merger give a somewhat larger contribution, but of the same magnitude.

# V. Implications of post-merger observations:

Maximum mass of neutron star and constraints on the highest-density part of the EOS

# Neutron star masses

## Largest seen electromagnetically:

Ozel, Freire, '16

$1.97 \pm 0.04\ M_\odot$

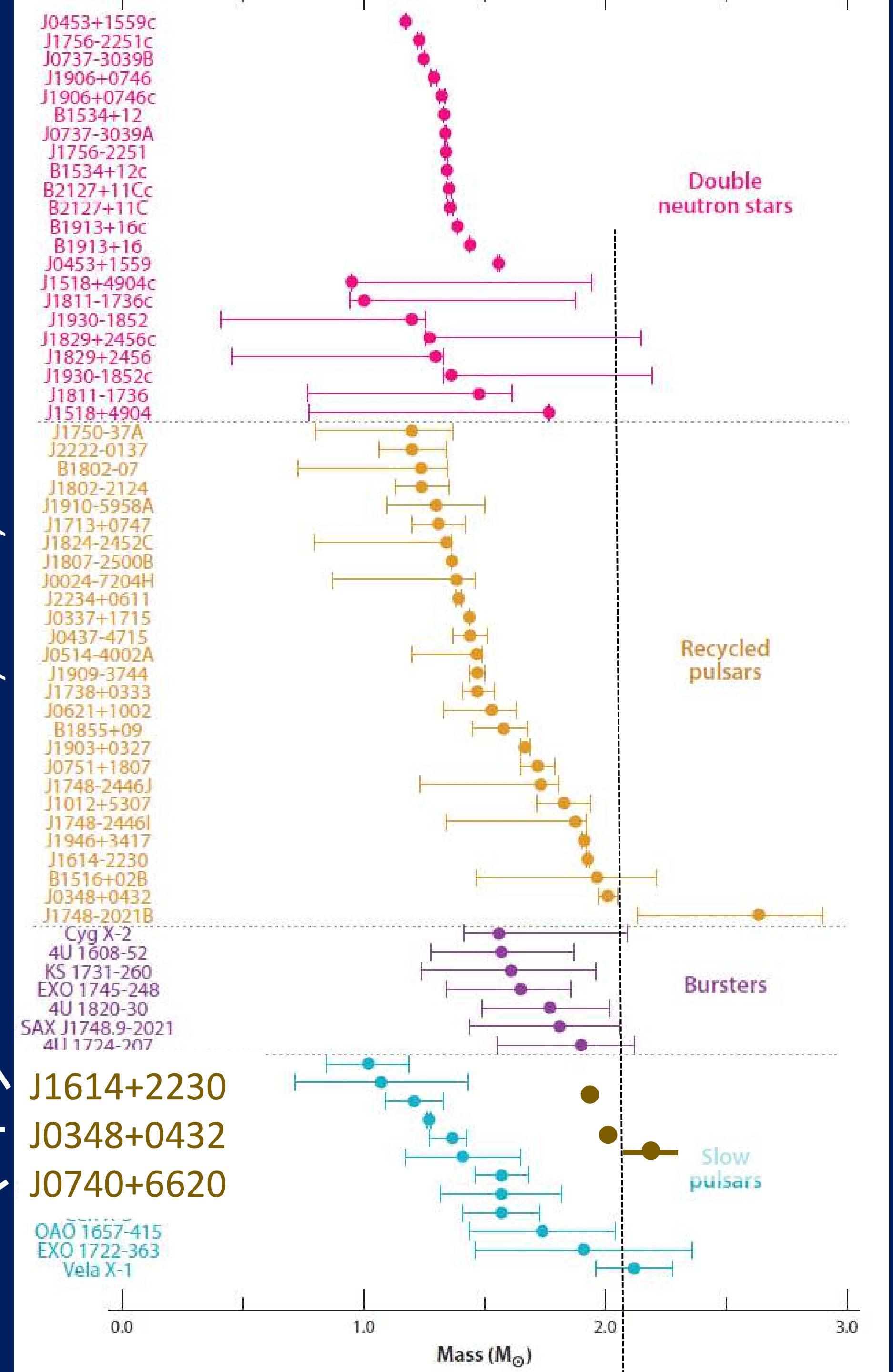
Demorest *et al.* '10

$2.01 \pm 0.04\ M_\odot$

Antoniadis *et al.* '13

$2.14 \pm 0.1\ M_\odot$

Cromatie *et al.* '19



# Maximum mass from post-merger observations

Prompt collapse: Mass above upper limit for hot, differentially rotating star

$M > M_{\text{max, hot, differential rotation}}$

Delayed collapse:

$M_{\text{max, hot, differential rotation}} > M > M_{\text{max, uniform rotation}}$

No collapse : $M < M_{\text{max, uniform rotation}}$

# Maximum mass from post-merger observations

Total mass $\geq 2.73\ M_\odot$ (LIGO observation)

Mass of ejected material $\leq 0.08\ M_\odot$
(e-m observations+simulations)

No prompt collapse implies
$M_{\text{max, hot, differential rotation}} \geq 2.73 - 0.08 = 2.65\ M_\odot$

Rotating stellar models with a threshold mass this large have

$M_{\text{max, spherical}} > 2.15\ M_\odot$

# Maximum mass from post-merger observations

Initially remnant differentially rotating and hot.
It collapsed before the differential rotation ended and it reached uniform rotation. The maximum mass of a uniformly rotating cold neutron star is

$$M_{\text{max, uiform rotation}} = 1.2\ M_{\text{max,spherical}}$$

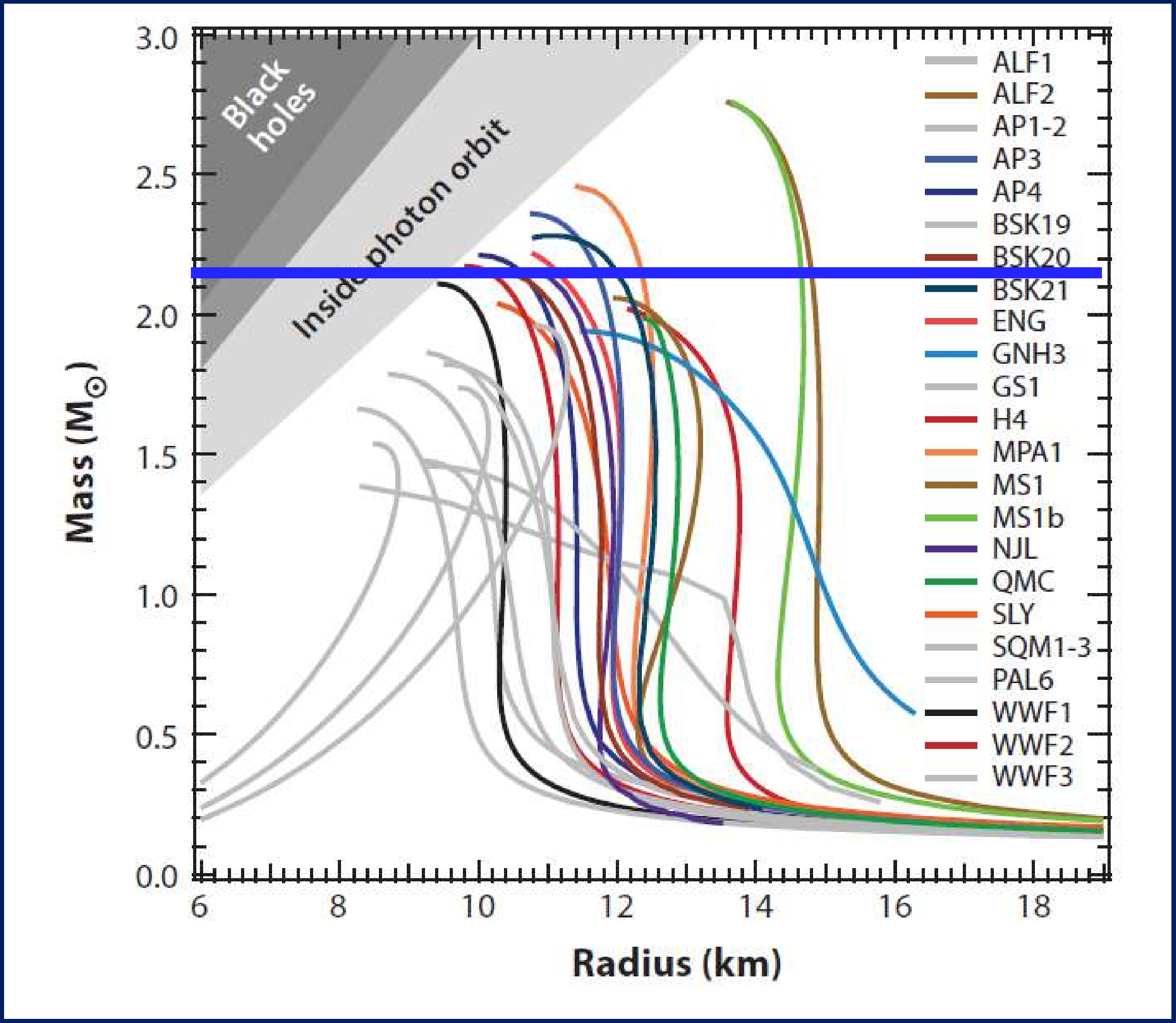
$$M_{\text{max,spherical}} < 2.73\ M_{\odot}/1.2 = 2.28\ M_{\odot}.$$

Combined,

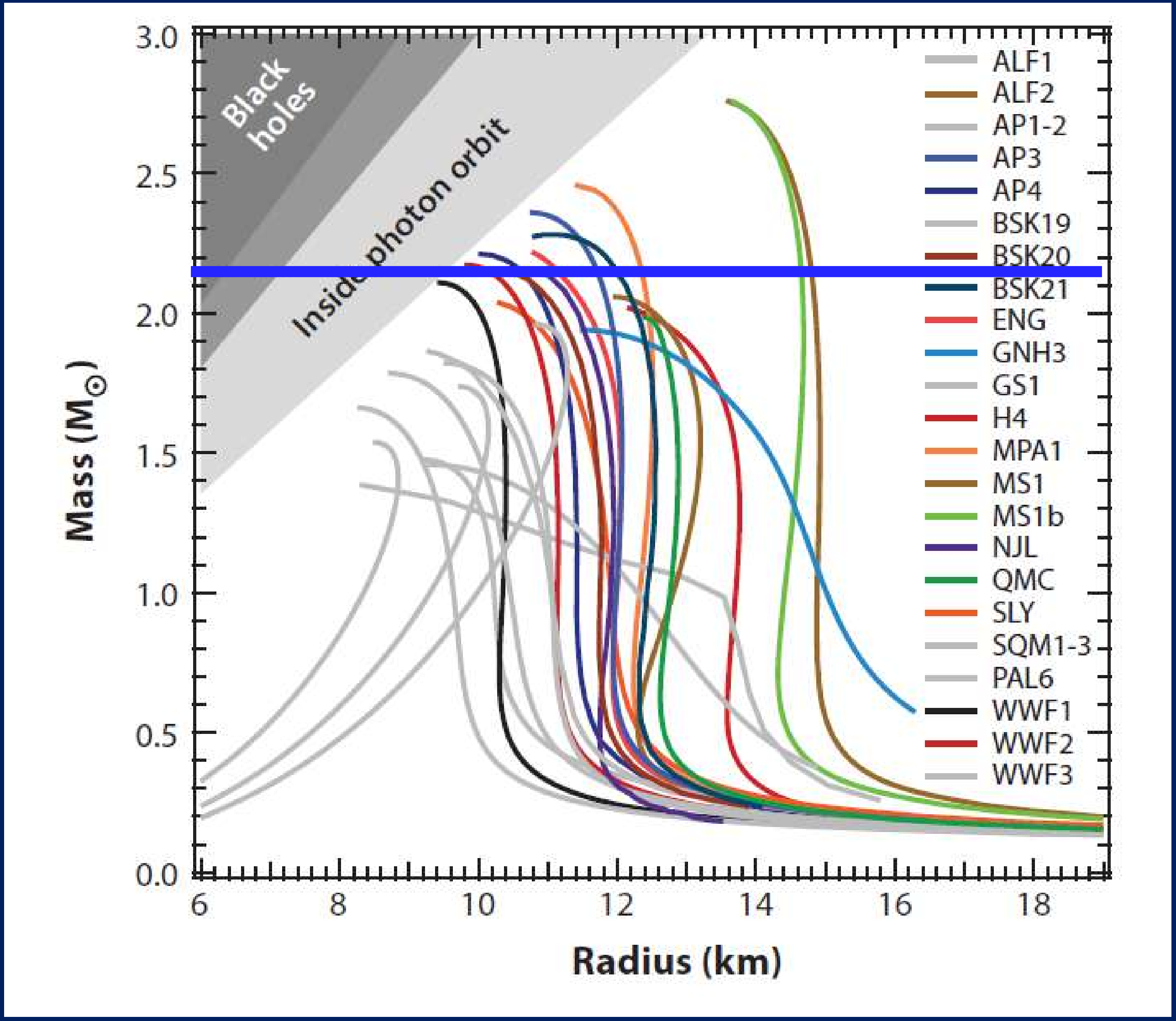
$$2.15\ M_{\odot} < M_{\text{max,spherical}} < 2.28\ M_{\odot}$$

More stringent claims by various authors:
e.g., Margalit & Metzger find Mmax < 2.17 $M_{sun.}$
These rely on modeling the ejecta and so have more systematic uncertainty.

# Equations of state that are soft at high density are ruled out by a 2.15 $M_\odot$ neutron star



# Cores with hyperons, quark cores, pion or kaon condensates (gray curves) all increasingly unlikely.



# VI. The Hubble Constant

The Hubble constant $H_0$ relates the velocity at which galaxies recede from us to their distance.

$$H_0 = \frac{v}{d}, \qquad d = \text{proper distance to galaxy}$$

If can identify the galaxy of an observed binary inspiral, have $v$ from the galaxy's redshift.
Find the distance $d$ from the inspiral waveform as follows

For quadrupole radiation,
GW frequency = 2 x orbital frequency

$$\omega = 2\,\Omega$$

$$E = \text{Newtonian energy of binary } \propto -\mu a^2 \Omega^2$$

$$\propto \omega^{3/2}, \quad \text{(by Kepler's law } a \propto \Omega^{-2/3}) \Rightarrow$$

$$\frac{\dot{E}}{E} = \frac{3}{2}\frac{\dot{\omega}}{\omega}$$

For quadrupole radiation,

Amplitude $$h \propto \frac{\ddot{Q}}{D} \propto \frac{\mu a^2 \Omega^2}{D} \propto \frac{E}{D}$$

D $=$ luminosity distance

= d (1+z)

Finally,

$$\dot{E} \propto \dot{h}^2 D^2 = \omega^2 h^2 D^2$$

Then $$\frac{\dot{\omega}}{\omega} = \frac{3}{2}\frac{\dot{E}}{E} \propto \frac{\omega^2 h^2 D^2}{hD}$$

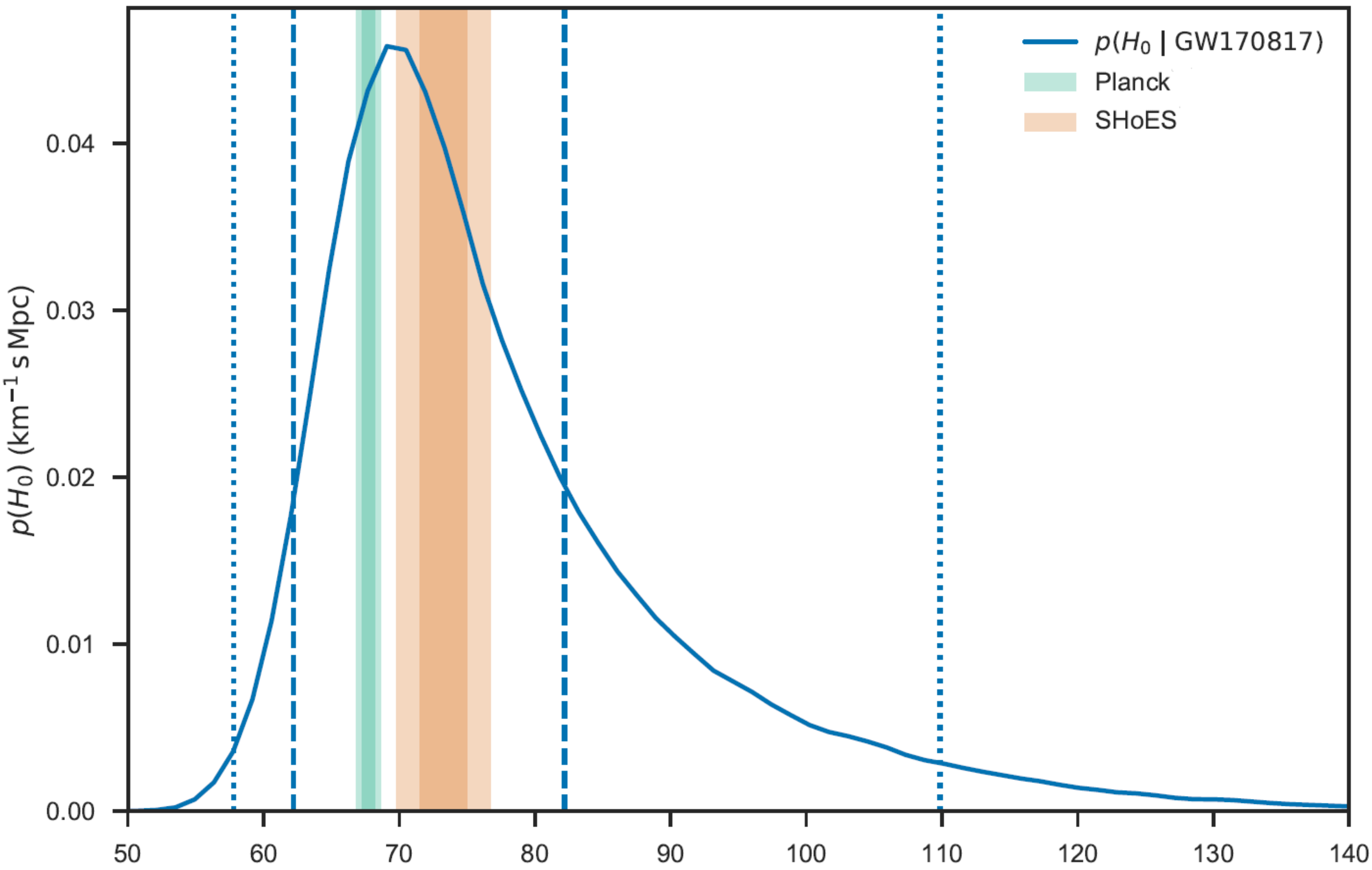
implying $$D \propto \frac{\dot{\omega}}{\omega^3 h}$$

With numerical constants kept,

$$D \propto 780 \frac{\dot{f}_{100}}{f_{100}^3 (h/10^{-23})} \text{Mpc}, \quad f_{100} := \frac{f}{100\text{Hz}}$$

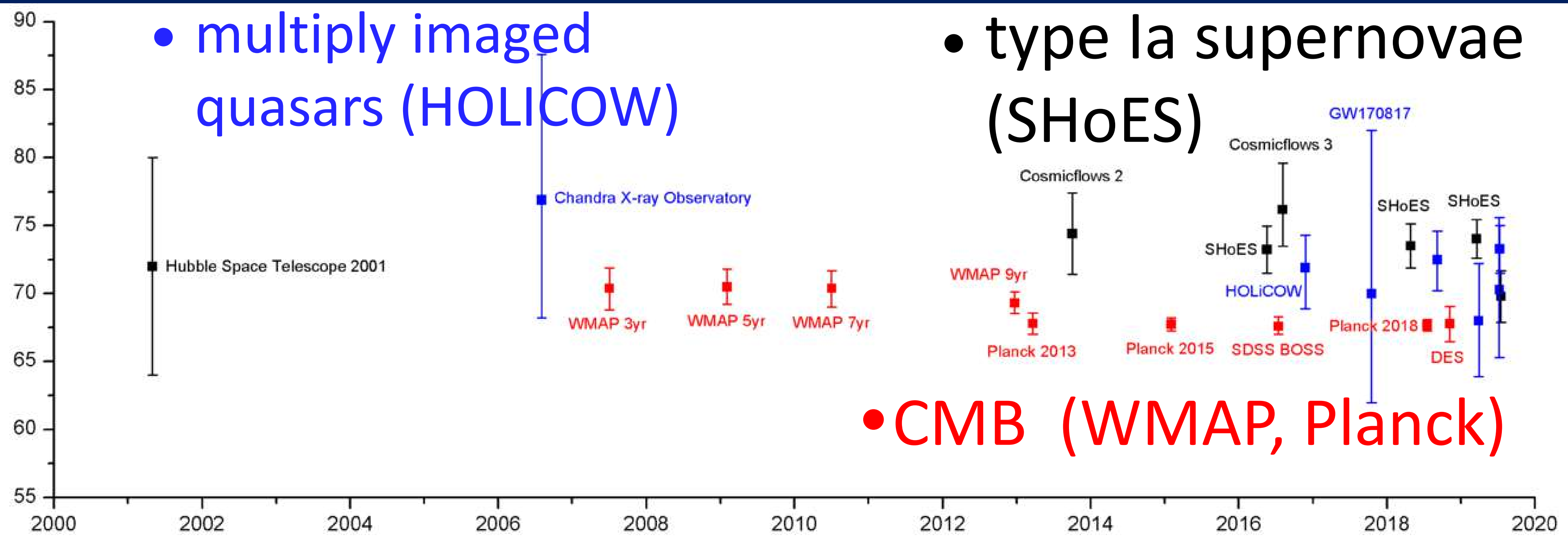
Schutz '86

# GW710817:




$H_0$ (km $s^{-1}$Mpc$^{-1}$) LIGO/Virgo, Nature ‘17

# Need ~ 50 similar detections to resolve the issue




Wikpedia compendium

Postdocs, faculty, and research scientists at UWM in gravitational wave astronomy and at the Leonard Parker Center for Gravitation, Cosmology and Astrophysics

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