“Compact Objects and accretion”,

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TA: **Stella Reino**

“Compact Objects and accretion+<u>their merger</u>”

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TA: **Stella Reino** office 560

The course's structure

10 classes: 30 January -- 15 April 2018

- 1st class: Introduction
- 2nd to 6th (or 7th) class: isolated compact objects + merger& gravitational waves
- 6th (or 7th) to 10th class: Accretion

Features

- black board for derivations (to slow down)
- slides for “breaks” and to show plots/figures
- exercises in class

The material

- 1st class: my slides + any book you use in the stellar evolution course
- 2nd-6th classes : "Black Holes, White Dwarfs and Neutron stars", by Shapiro and Teukolsky
- 7th-10th classes : ``Accretion power in Astrophysics", by Frank, King & Raine

..but ALWAYS take notes during classes!

You will be graded upon:

- Your behaviour/interaction level in class
- 3 sets of homework, ``*research*" oriented. Active behaviour/*creativity* together with scientific *precision* on your part. Time : 2 weeks per homework
  - Read, understand and summarise in a written form one or two papers on a given subject. All the main information should be there and clearly reported, length: minimum 4; maximum 5.
  - Complete an associated task: typically reproduce a relevant figure/plot, which require (a bit of) coding
- Written exam: well in advance of exam, you will receive a list of ~30 questions. *Around* 5 (could be 7) of them will form the final written exam.

Grading scheme

- Homework will be graded and contribute to final grade by 20%
- All 3 homework > 6: is the "*conditio sine qua non*" *for being allowed to the final exam*
- Final exam will contribute 80% of the final grade
- Answers to questions in class, active participation to exercise etc…will be registered and will contribute to final grade in rounding grade up or down

TO GET TO KNOW YOU

PLEASE, WRITE THIS PERSONAL INDEX CARD:

- 1) You name (or how you prefer to be addressed) and nationality

- 2) what is your greatest strength as a student and/ or as a person overall?

- 3) is there anything that you would like to share with me, that I need to know about you that I would otherwise not know?

- 4) what do you most want to learn from this class? or what topic are you most curious to know from this course?

- 5)Please, send me a selfie or pic of yourself by email emr@strw.leidenuniv.nl

  with your name on the email subject

Definition of Compact Objects

Compactness

Total Mass M
Size R

$$\boxed{\Xi = \frac{GM}{Rc^2}}$$

Object	Mass M $(M_\odot)$	size R (km)	mean density $(\mathrm{g.cm^{-3}})$	compactness
Earth	3×10^{-6}	6 000	5.4	7×10^{-10}
Sun	1	696 000	1.4	2×10^{-6}
White dwarf	$\sim 0.1 \to 1.4$	$\sim 10\,000$	$\sim 10^6 \to 10^7$	$\sim 10^{-4} \to 10^{-3}$
Neutron star	$\sim 1 \to 3$	~ 10	$\sim 10^{15}$	$\sim 0.2 - 0.4$
stellar black hole	$\gtrsim 3$	$8.9 \left(\frac{M}{3 M_\odot}\right)$	NA	1
Supermassive black hole	$\sim 10^6 \to 10^9$	$20\,\mathrm{AU} \left(\frac{M}{10^9 M_\odot}\right)$	NA	1

by definition

compact objects have $\Xi \gtrsim 10^{-4}$ what is the meaning ?

Gravitational potential

self-gravitating, spherical object has

$$\Phi(r) = -\frac{GM}{r} \quad \text{for} \quad r \geq R .$$

$$\boxed{\Phi(R) = -\Xi c^2}$$

compactness is a measure of the gravitational potential:
compact objects' potential is the largest

binding energy

this is the work that must be done to disassemble an object in parts (bring them to infinity)

for a shell of mass dm

$$\mathrm{d}E_\mathrm{p} = E_\mathrm{p}(r) - E_\mathrm{p}(\infty) = -\frac{Gm(r)}{r}\,\mathrm{d}m$$

m(r)=mass within r

$$\boxed{E_\mathrm{grav} = -\int_0^R \frac{Gm(r)}{r}\,\mathrm{d}m(r) = -\alpha\frac{GM^2}{R} = -\alpha\,\Xi\,Mc^2}$$

<u>Compact Objects have binding energy a fraction of their rest mass</u>

Escape velocity

A particle in radial motion through the gravitational field of a compact object has a mechanical energy per unit mass of

$$e = \frac{1}{2}v^2 + \Phi(r)$$

it can reach infinity only if the (constant) energy is positive :

$$e = \frac{1}{2}v_0^2 + \Phi(R) \geq 0$$

we define $v_{esc} = v_0$ that gives e=0

$$\boxed{\boxed{v_{esc}} = \sqrt{2\,|\Phi(R)|} = \sqrt{\frac{2GM}{R}} = \sqrt{2\Xi}\,c}$$

<u>Compact Objects have escape velocities a fraction of c</u>

note: we will more formally define R_s in next class

Schwarzschild radius

$$R_S = \frac{2GM}{c^2} \simeq 2.95 \left(\frac{M}{M_\odot} \right) \text{ km}$$

from previous slide, light cannot escape for $R<R_s$. therefore R_s is an "horizon"

The compactness measures the relative size of an object with respect to its R_s :

$$\boxed{R = \frac{R_S}{2\Xi}}$$

<u>Compact Objects have the closest size to their R_s</u>

Summary

The larger the compactness, the greater the gravitational filed

$$\boxed{\Xi \sim \frac{|\Phi(R)|}{c^2} \sim \frac{|E_{\rm grav}|}{Mc^2} \sim \left(\frac{v_{\rm esc}}{c}\right)^2 \sim \frac{R_S}{R}}$$

Note: this implies that when describe C.O. (especially NS and BH) <u>one must use a general relativistic framework</u>

Energy reservoir

What said also suggests that there is a very large reservoir of **gravitational energy** that can be liberated and observed.

- how much?..fraction of rest mass energy!

Energy reservoir

- It can be extracted via:

1. **Gravitational collapse**
2. **Accretion**

A mass "m" accreted from infinity to the C.O. surface gain a kinetic energy

$$\Delta E_{\mathrm{k}} = -\phi(R)m = \Theta mc^2$$

A NS may extract ~ 20% of rest mass
BH maximally spinning ~42%

Note: nuclear fusion efficiency is $< 1\%$

Energy reservoir

1. Gravitational collapse (from R_* => R)

$$\Delta E_{\rm collapse} = E_{\rm grav}(R_*) - E_{\rm grav}(R) \simeq -E_{\rm grav}(R) \sim \Theta M c^2$$

The liberated energy is comparable to the rest mass energy of the newly born compact object

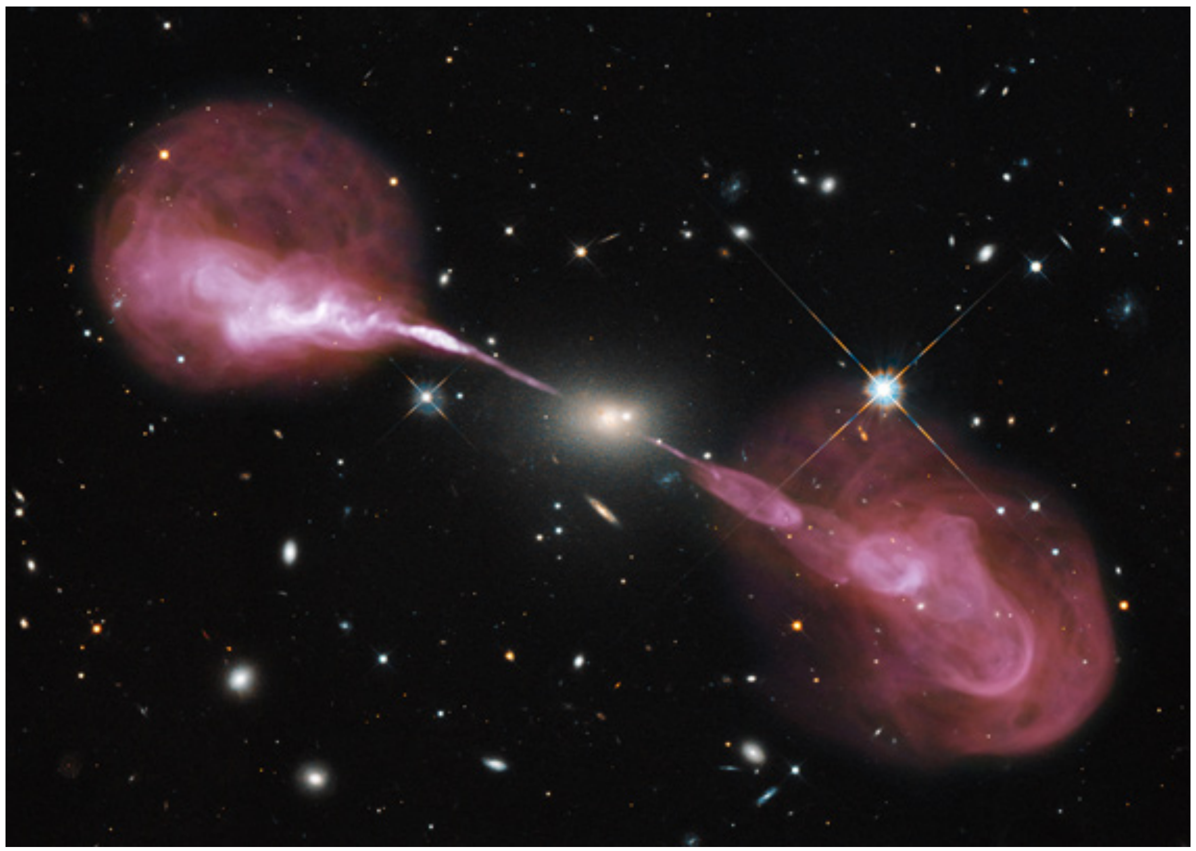
- **Note** their potential energy can also be observed via the motion of a companion satellite

Astrophysical systems

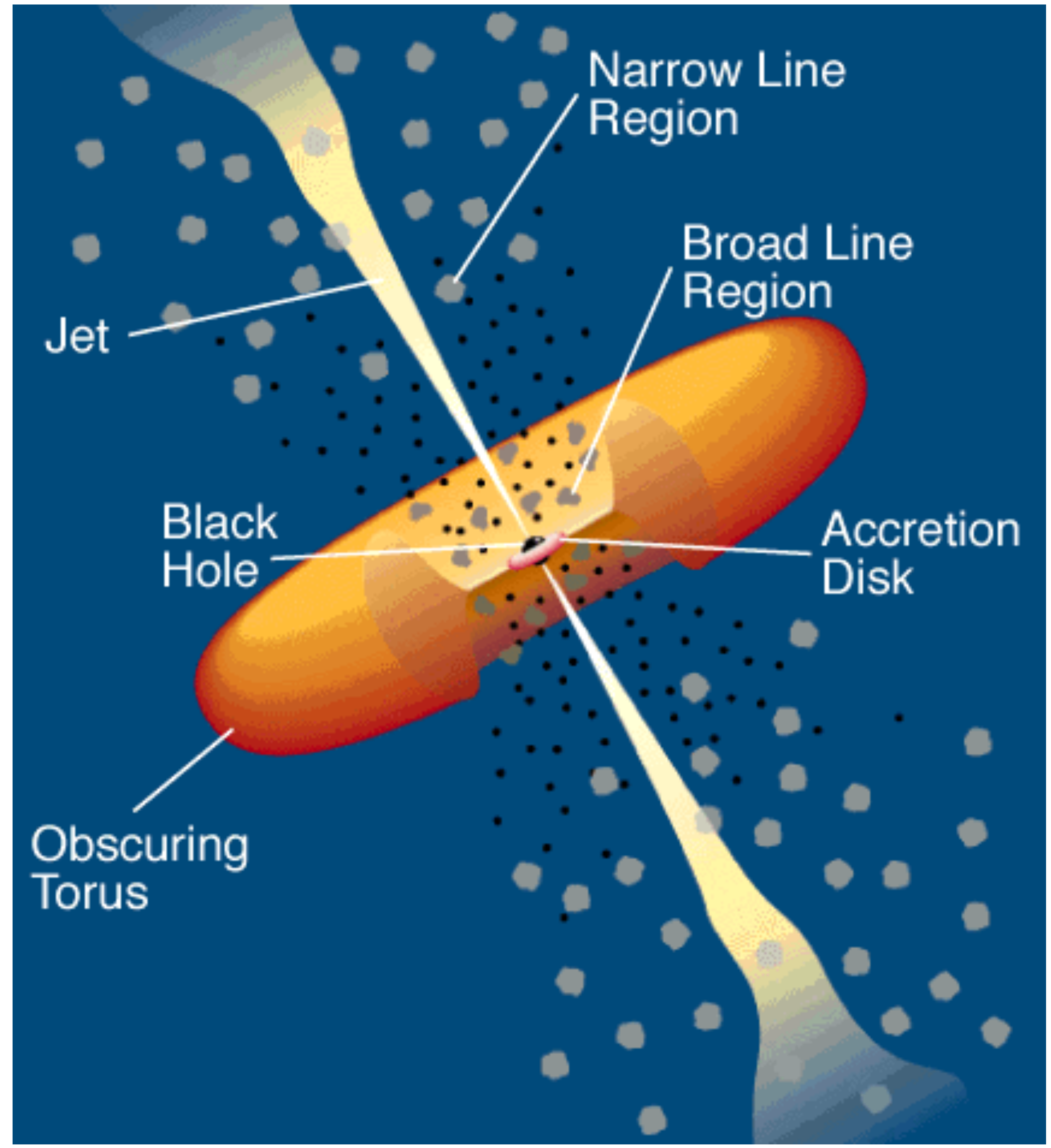
some examples...

Active supermassive black holes within galaxies : a.k.a Active Galactic Nuclei: AGNs

Jets +lobes ~ 1 Mpc ! 4×10^9 M_{sun} BH

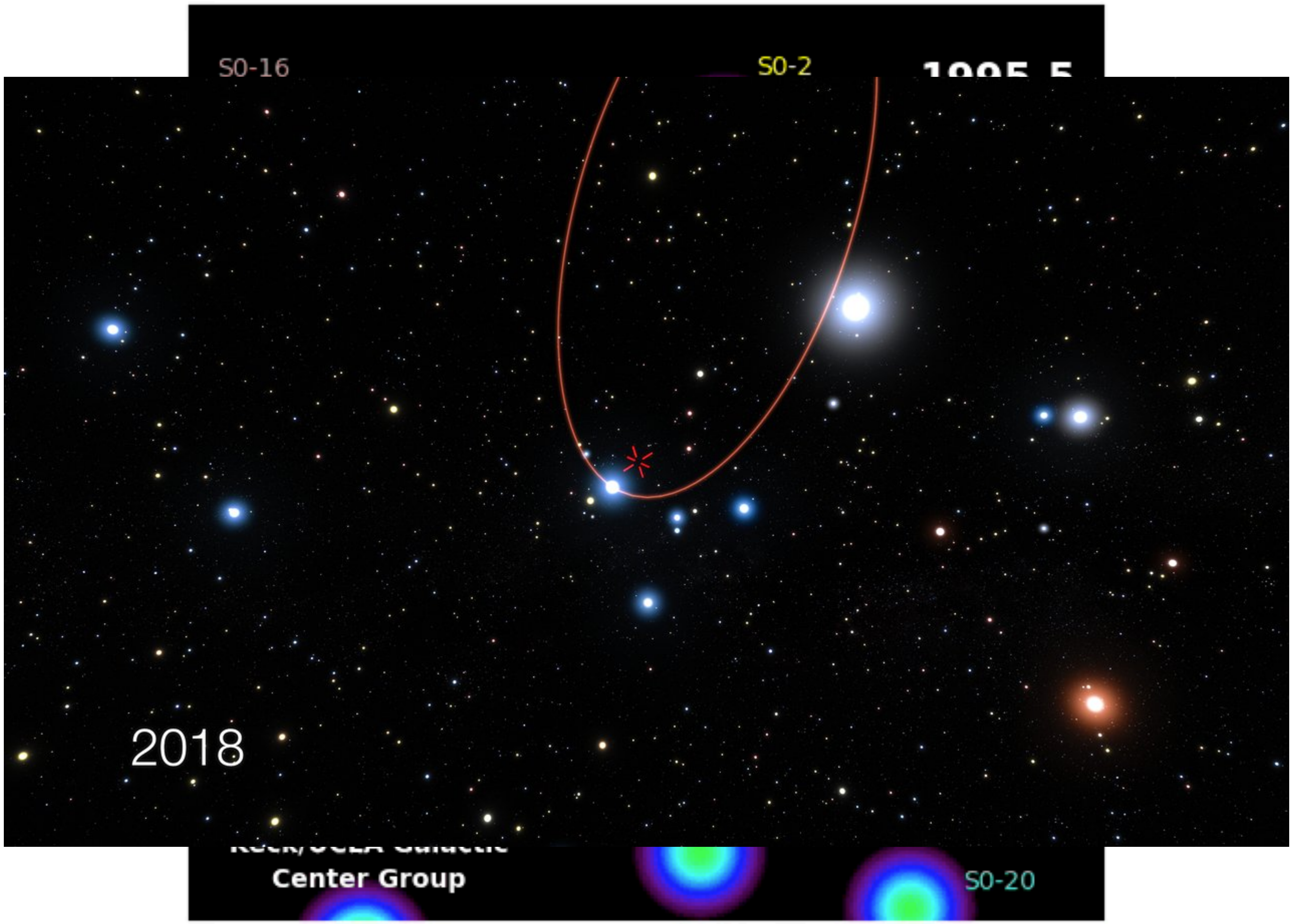


Radio galaxy, Hercules A, z~0.15



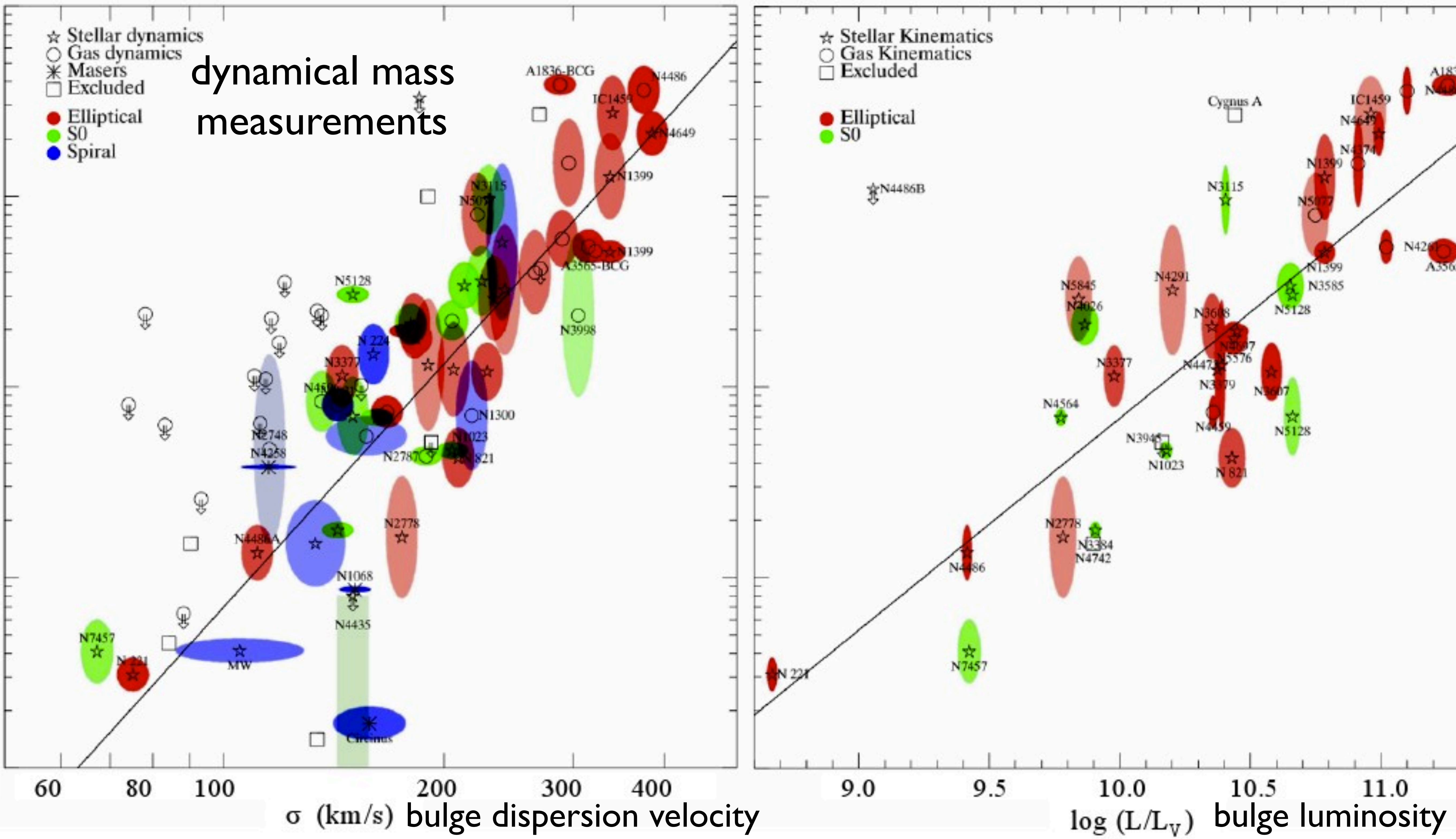
the are "rare"~1%; observed > = 7, Masse > 10^9 Msun

Quiescent supermassive black holes: e.g. Sgr A*



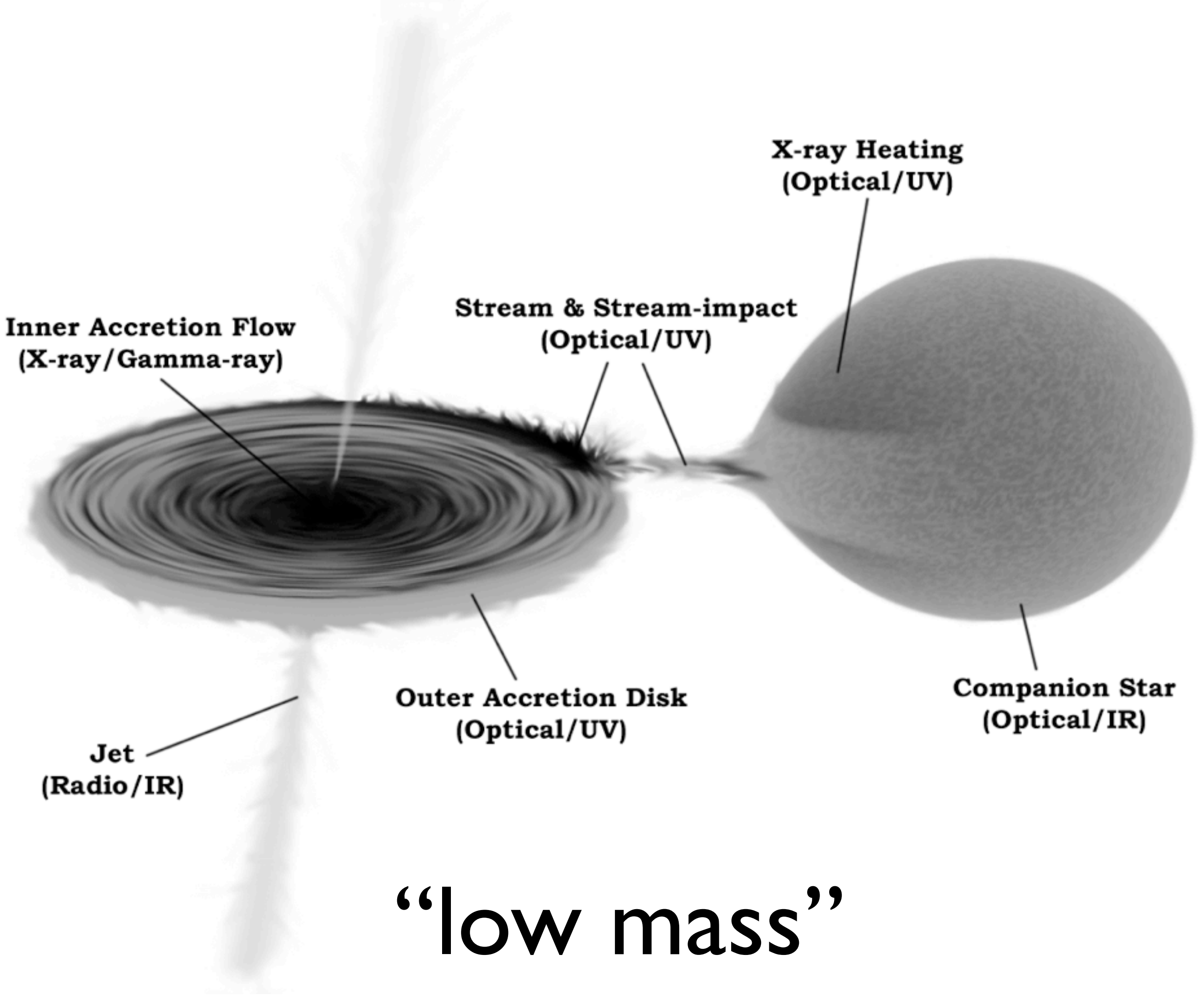
when will S2 have his next closest approach again?
believed to hosted by the vast majority of galaxies

Deep relation with host galaxy



Reference K. Gültekin et al. 2009, ApJ 698, 198

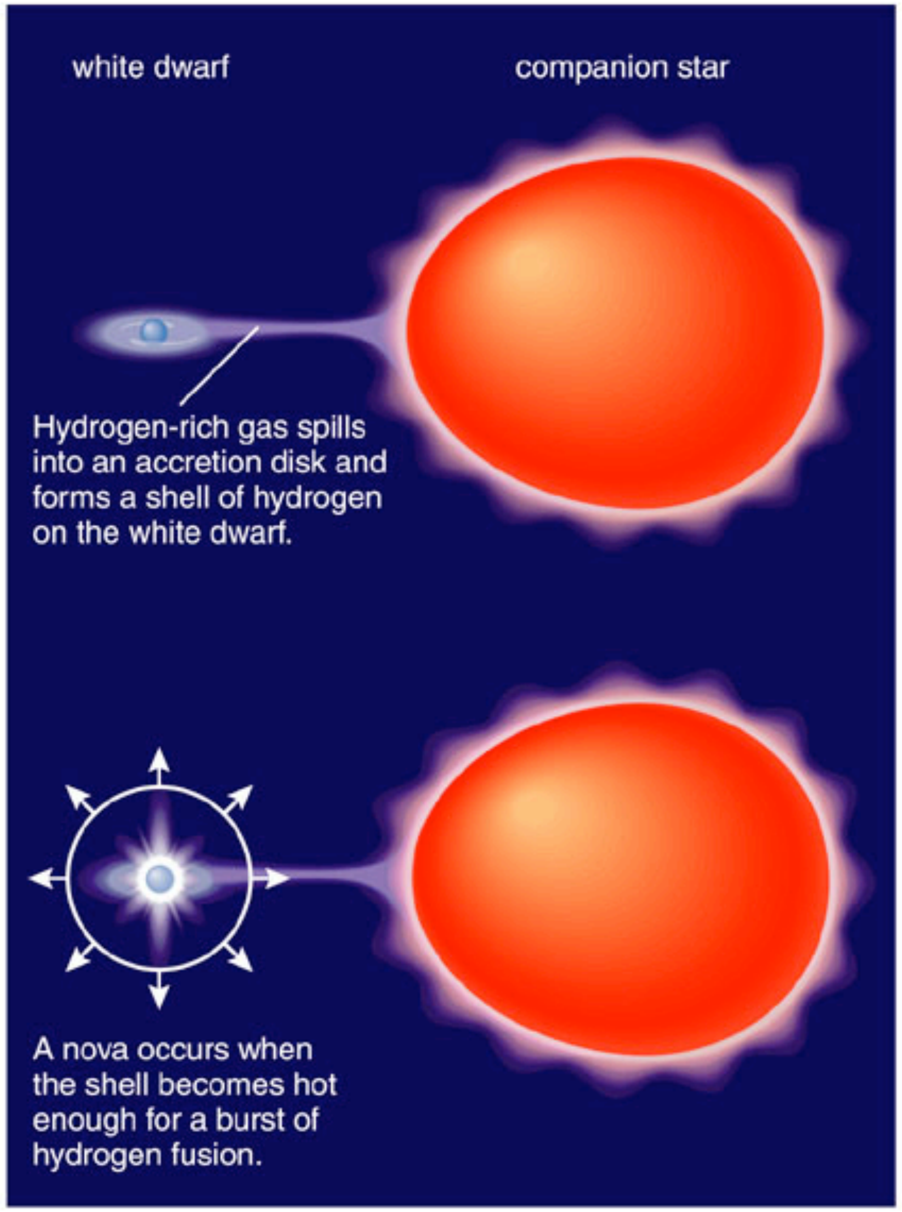
X-ray binaries: binaries with a (solar) BH or neutron star, accreting from a companion star

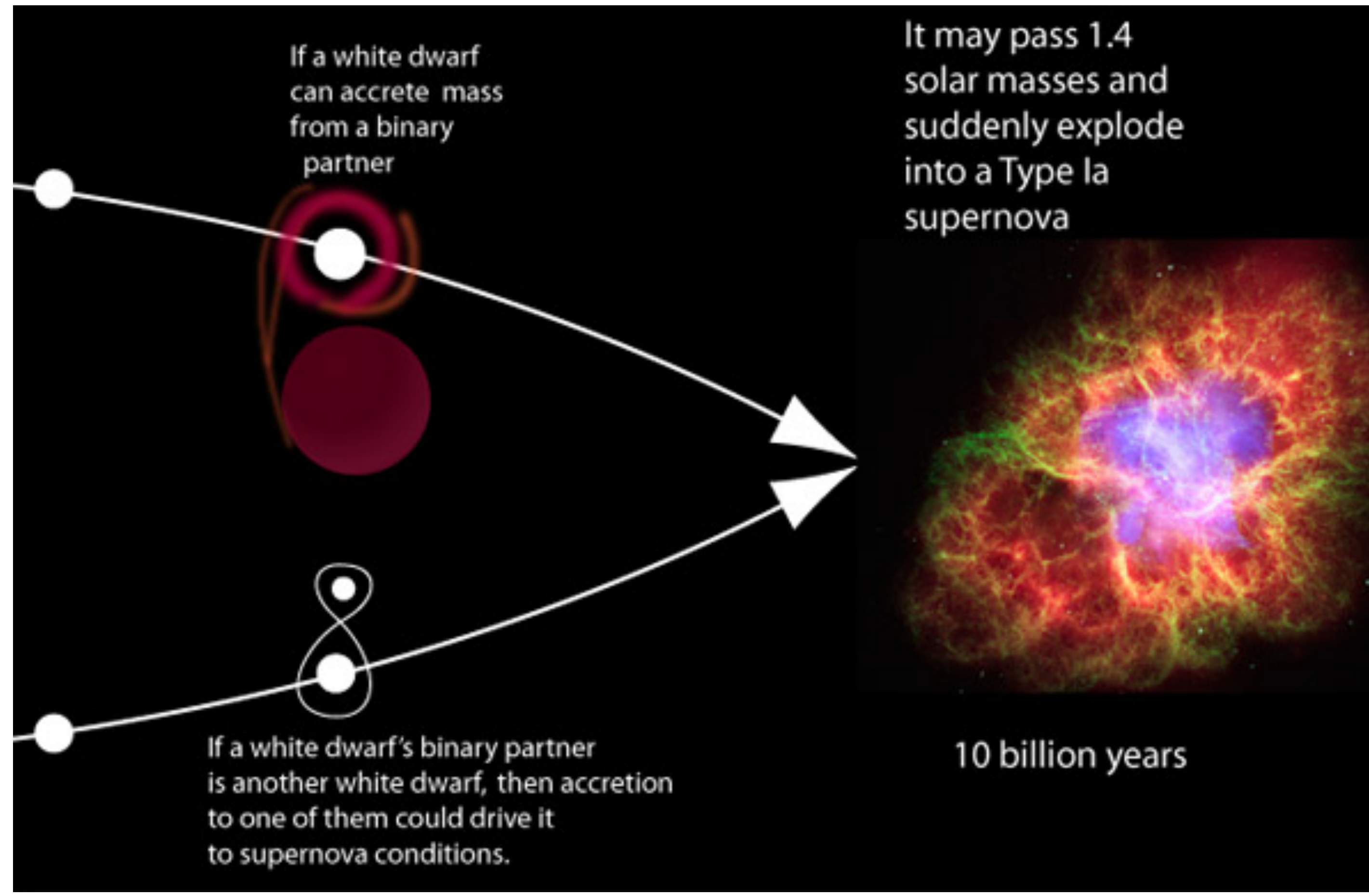


"low mass"

"high mass"

white dwarf in binaries



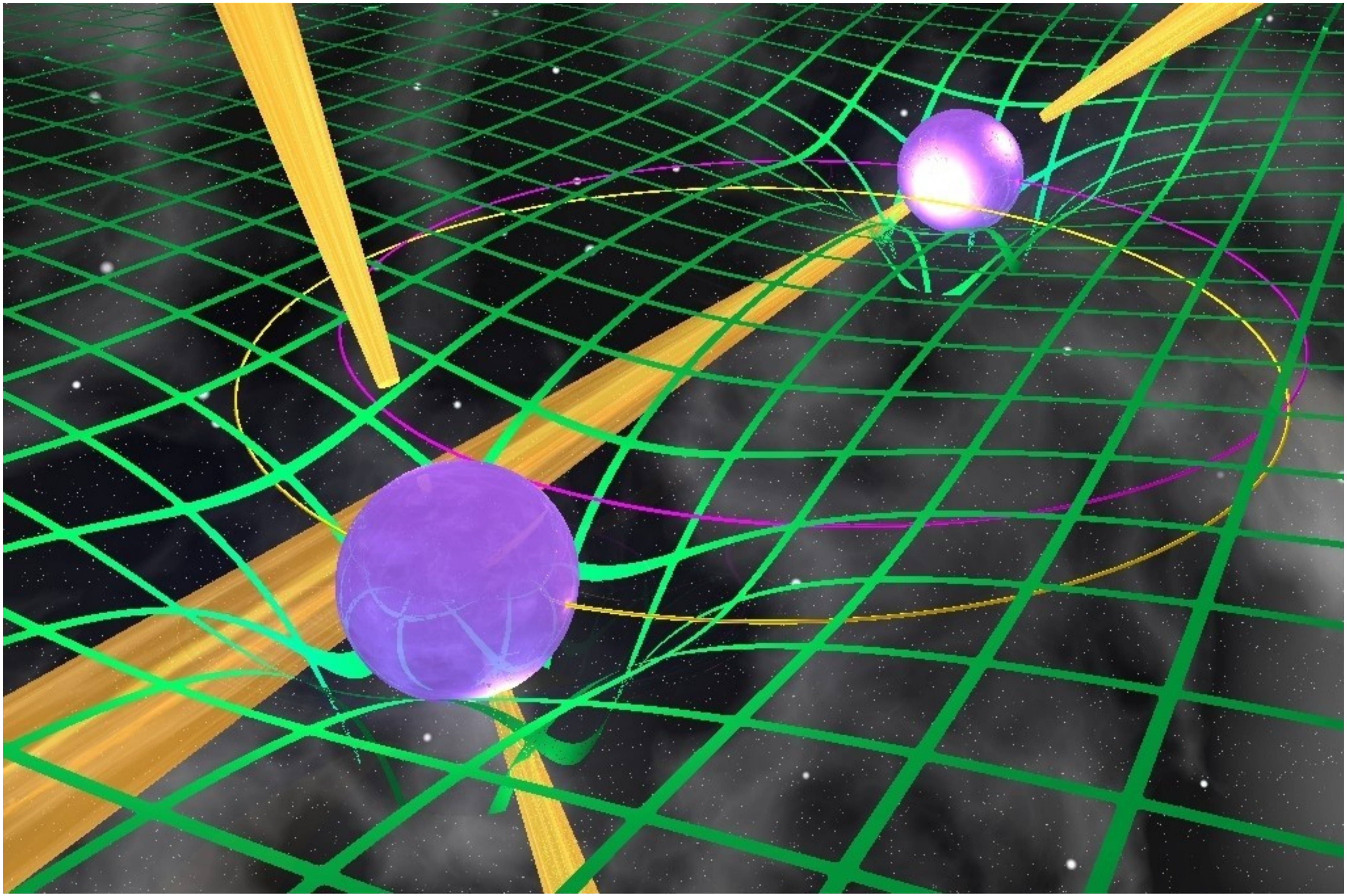


Supernova Ia progenitor and gravitational wave emitter

Cataclysmic variables (CVs):

PSR J0737-3039

radio beams of light



Why compact objects are *cool* ;-)

Compact Objects have in common a certain numbers of features that made them important for several fields in <u>astrophysics, cosmology and physics</u>

Stellar physics

Final stage of stellar evolution (with the exception of supermassive black holes), where nuclear reaction are no longer present

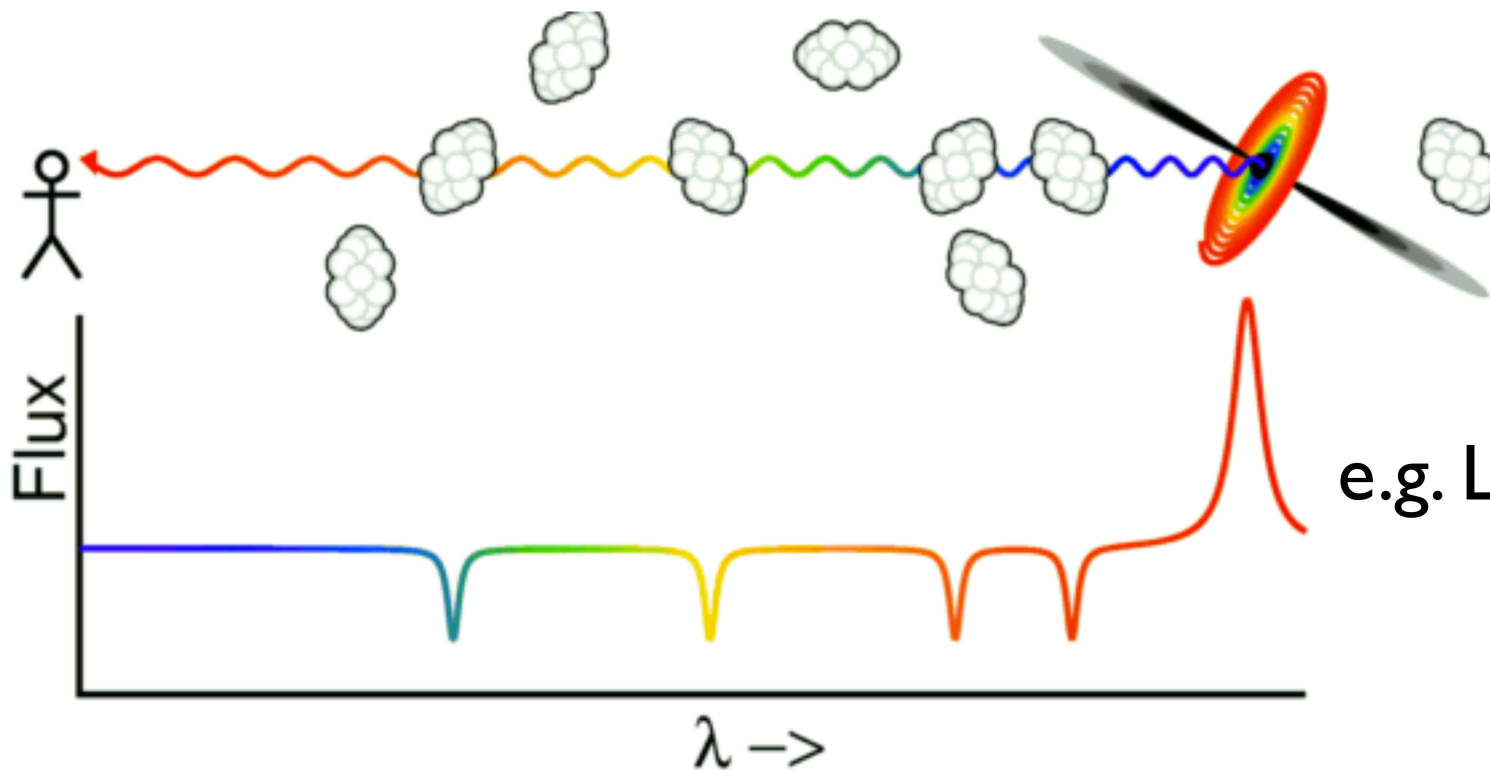
more details later today...

Cosmology

- **Very luminous** (when accreting or the forming phase, as their huge gravitational energy is liberated), therefore detectable at large distances

a few examples...

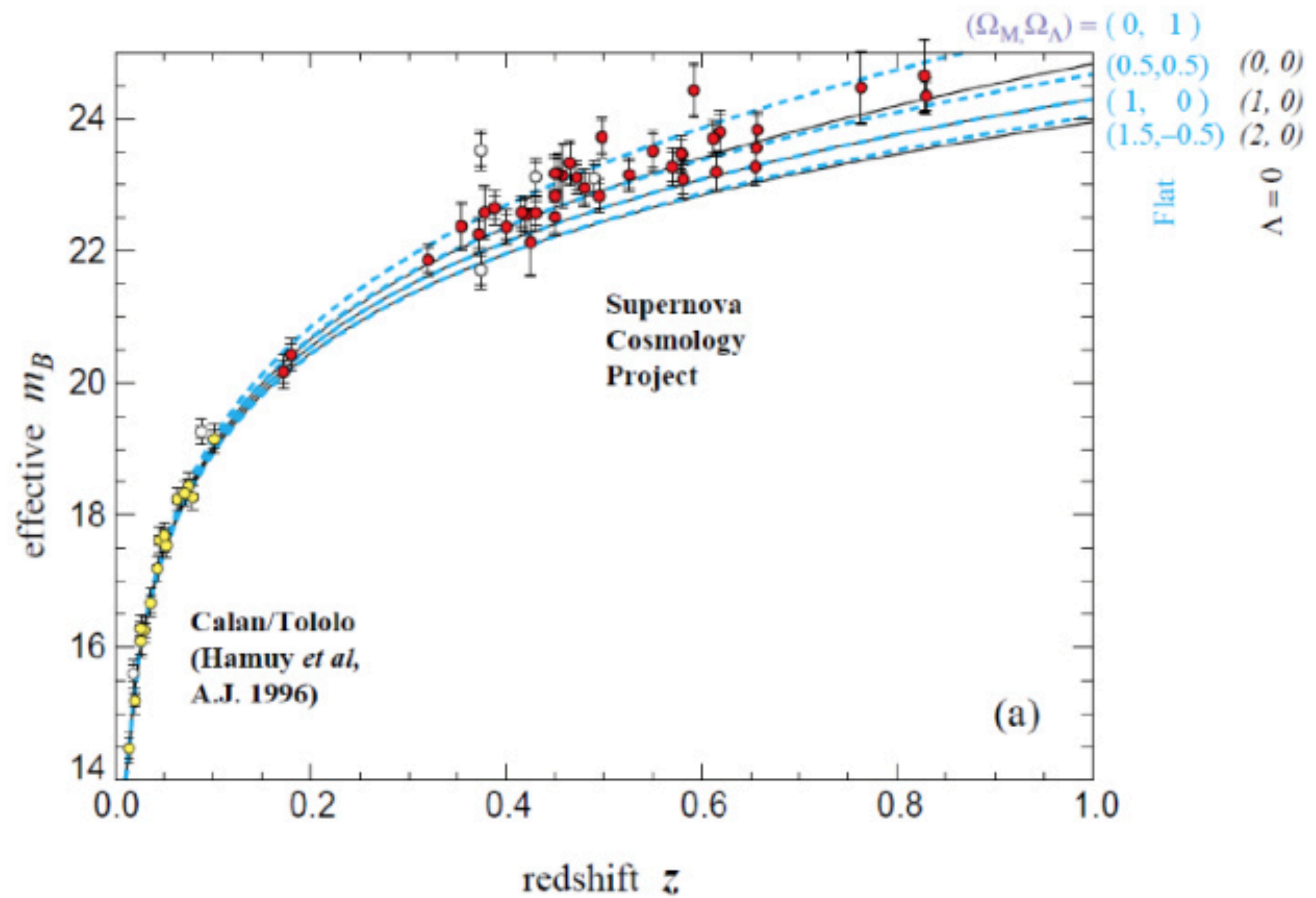
Quasars and GRBs as "beacons" for interstellar medium studies



mapping distribution of gas and metals around galaxies
constrain Epoch of Reionization

Supernova Ia to measure expansion of universe

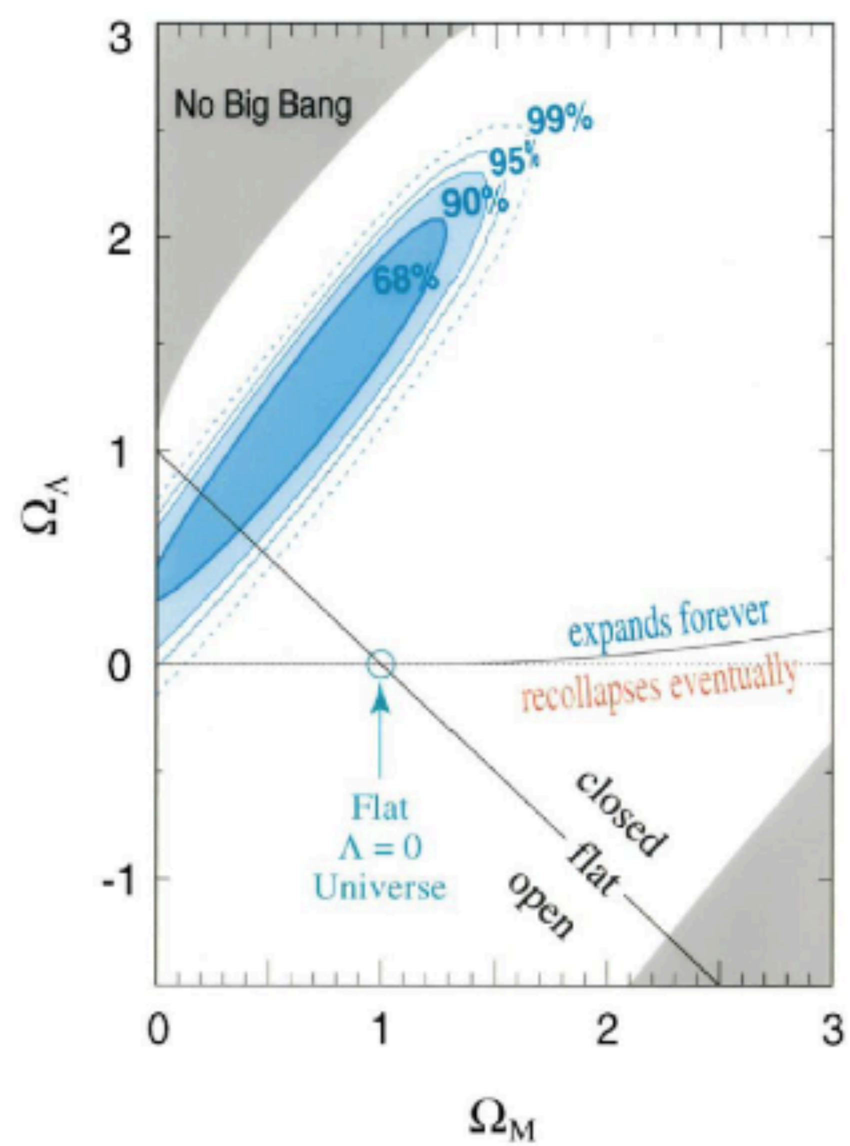
- standard candles to measure distances ==> Hubble diagram

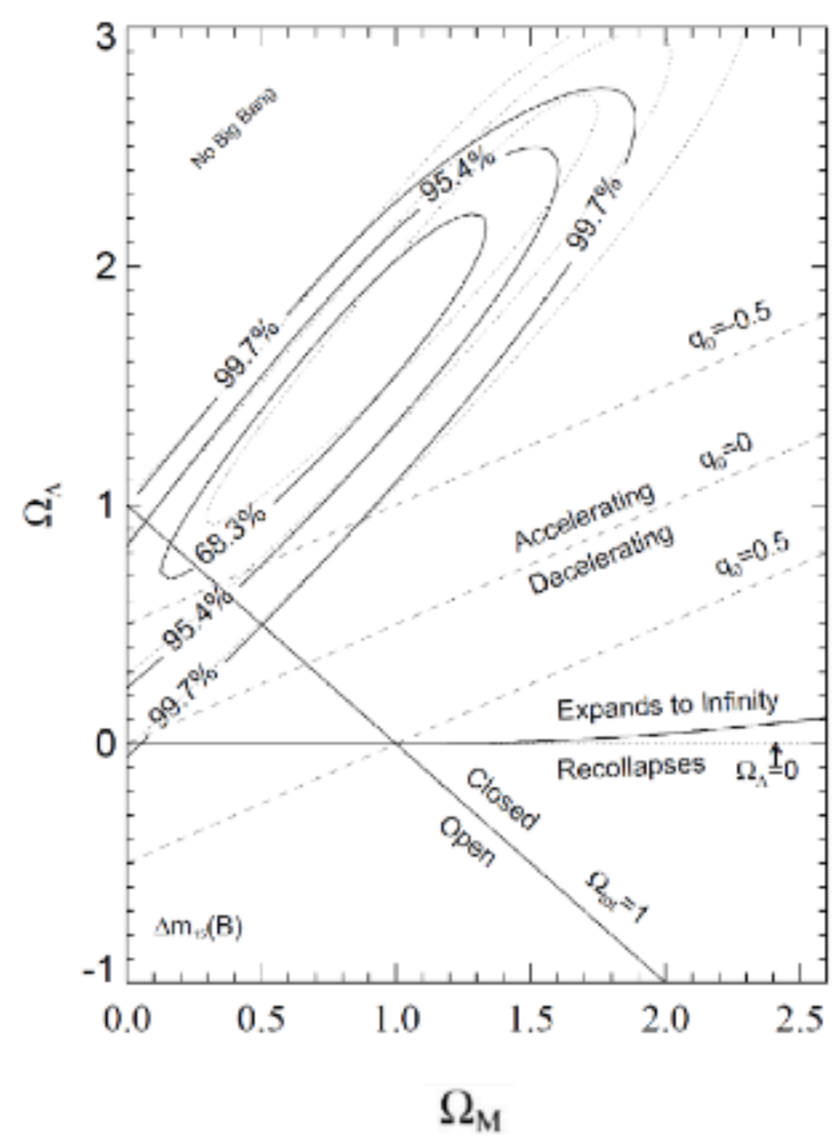


Nobel prize 2011 to Perlmutter, Schmidt, Riess

Flat Universe with no dark energy excluded at high significance

Accelerated expansion of Universe





Supernova Ia to measure expansion of universe

Systematics is becoming the limiting factor: need a better understanding of the progenitor system and explosion mechanism

Cosmology

- **Existence of supermassive black holes** at any z but particularly at z>6 + empirical correlations with hosts

How do supermassive black holes form? what is their relation with galaxy formation and in general with structure formation in the Universe?

Fundamental physics

- *Stellar* C.O. the densest structure in Universe (no parallel on Earth) => test physics of ultra-dense matter

$$\bar{\rho} = \frac{3M}{4\pi R^3} = 1.5 \times 10^{17} \Theta^3 \left(\frac{M}{M_\odot}\right)^{-2} \ \mathrm{g\ cm}^{-3}$$

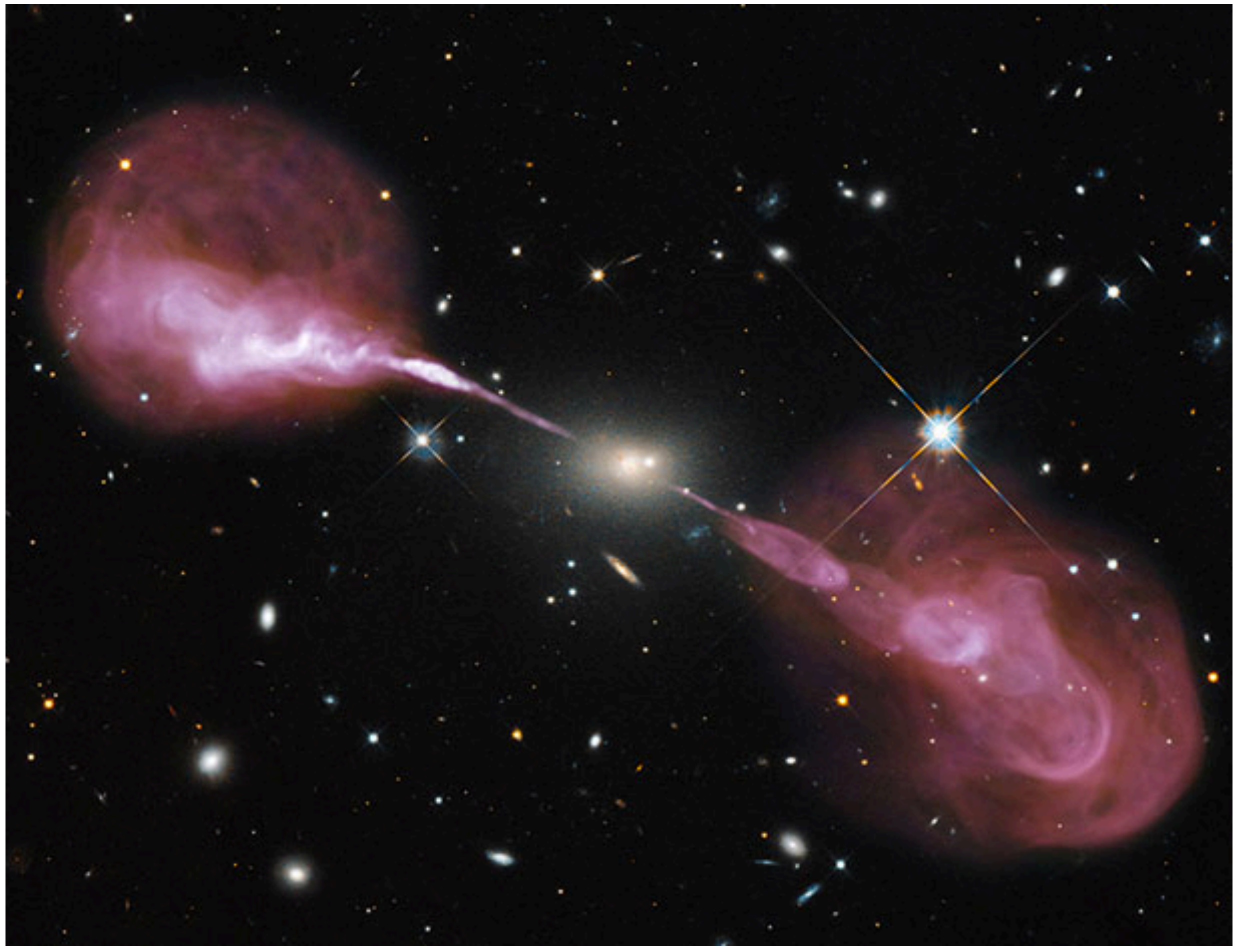
Fundamental physics

- **Tests strong-field gravity**: e.g. binary pulsars, gravitational waves,
- **Physics of neutrinos**: from supernova SN1987 i) constrain on superluminal neutrino: (v-$c/c < 10^{-9}$), ii) constraints on neutrino flavours, iii) upper bound on mass and charge (see Volpe 16 for a review)
- **Lorentz invariance**: using Blazars and GRBs flares, to compare the arrival times of high and low energy photons : are the same?

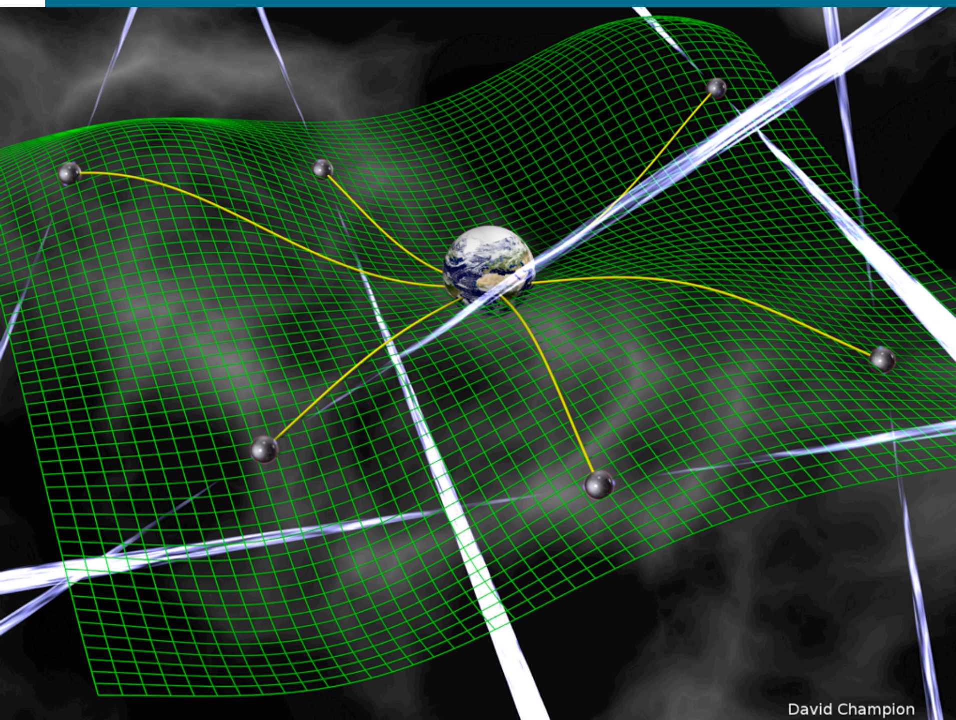
not only photons...

This gravitational energy may also be in

- neutrinos (99% in supernovae)
- winds and jets (conversion into kinetic energy of matter)
- and...

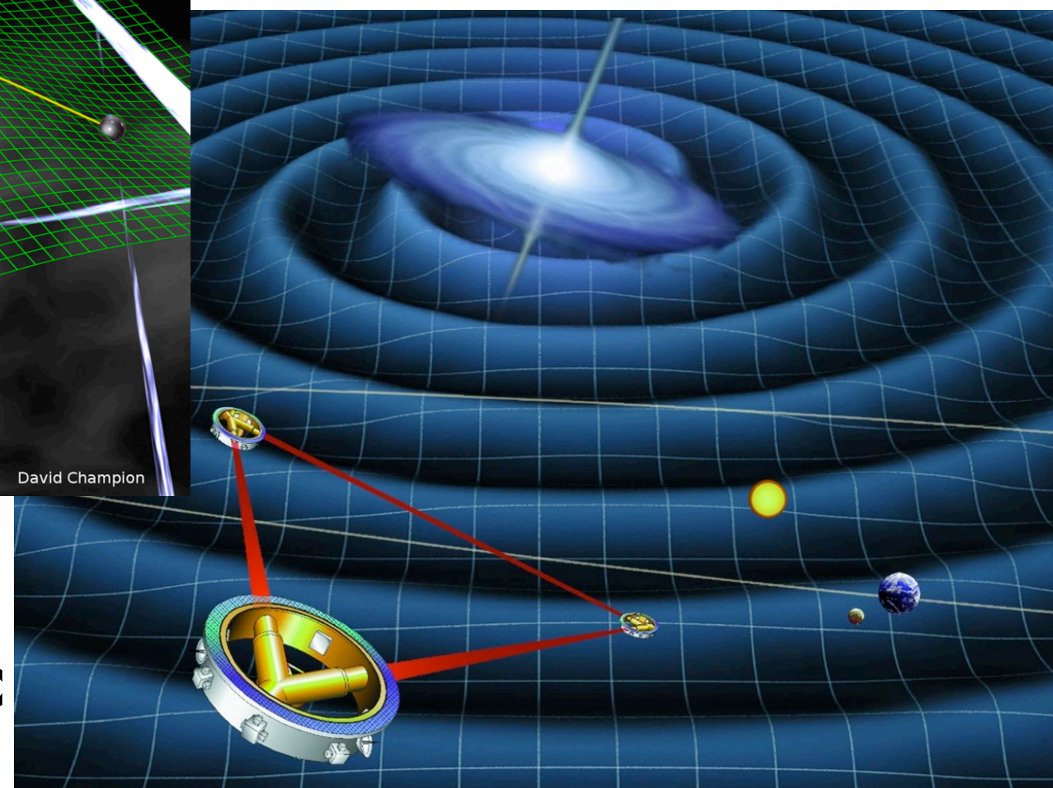


Gravitational Waves



Pulsar Timing Array

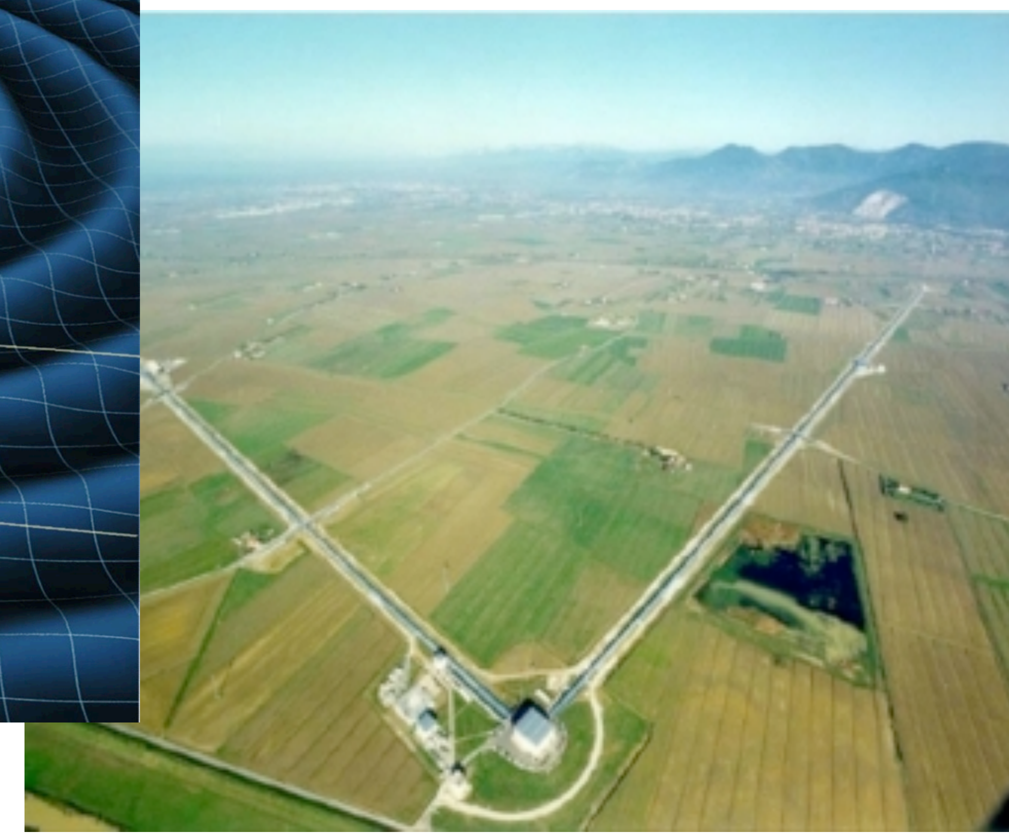
10^9 M_{sun} BH @1 Gpc



eLISA space mission

10^6 M_{sun} BH @100 Gpc

Galactic binaries



Advanced L-Virgo

WD-WD WD-BH

$<10^{-5}$ 10^{-3}-10^{-2} 10^2-10^3

observed frequency [Hz]

Exercise time

1) Stellar magnetic field

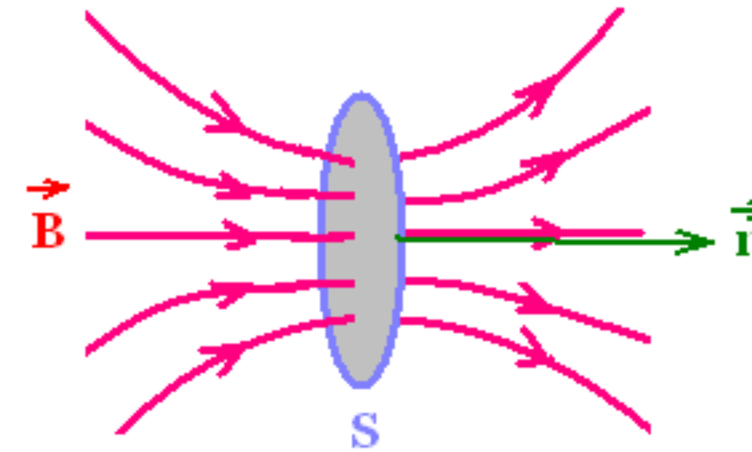
- How would you estimate the magnetic field of a white dwarf or a neutron star?
- If the progenitor star has a magnetic field of 100 Gauss, what would you predict their magnetic field to be ?

2) Stellar rotation

- Estimate the relative enhancement of the angular frequency at the surface of a NS and WD w.r.t. that of the stellar progenitor

Solution

1) Stellar magnetic field



- magnetic flux $\phi_{\rm B} \propto BR^2$ conservation:

$\vec{S} = S\,\vec{n}$

$\Phi_B = \oint \vec{B}.d\vec{S}$

$$\frac{B}{B_*} = \left(\frac{R_*}{R}\right)^2 \begin{array}{l} \sim 5\times 10^3 \text{ for WD} \\ \sim 5\times 10^{11} \text{ for NS} \end{array}$$

(Sun —-> WD)
(10xSun —-> NS)

- NS & WD are born with large magnetic field.

$B \sim 5\times 10^5$ Gauss for WD

$B \sim 5\times 10^{13}$ Gauss for NS

The observed magnetic field ranges between 10^3 Gauss and 10^9 Gauss

For NS B~10^{12-15} G

``Magnetars" are the most extreme in the universe ~10^{15} G

: no life possible! magnetic field on Earth ~0.25 G

Solution

2) Stellar rotation

- From angular momentum ΩR^2 conservation:

$$\frac{\Omega}{\Omega_*} = \left(\frac{R}{R_*}\right)^2 \sim 5\times 10^3 \text{ for WD} \quad \text{(Sun —-> WD)}$$
$$\sim 5\times 10^{11} \text{ for NS} \quad \text{(10xSun —-> NS)}$$

Observed period for WDs ranges ~hours to days

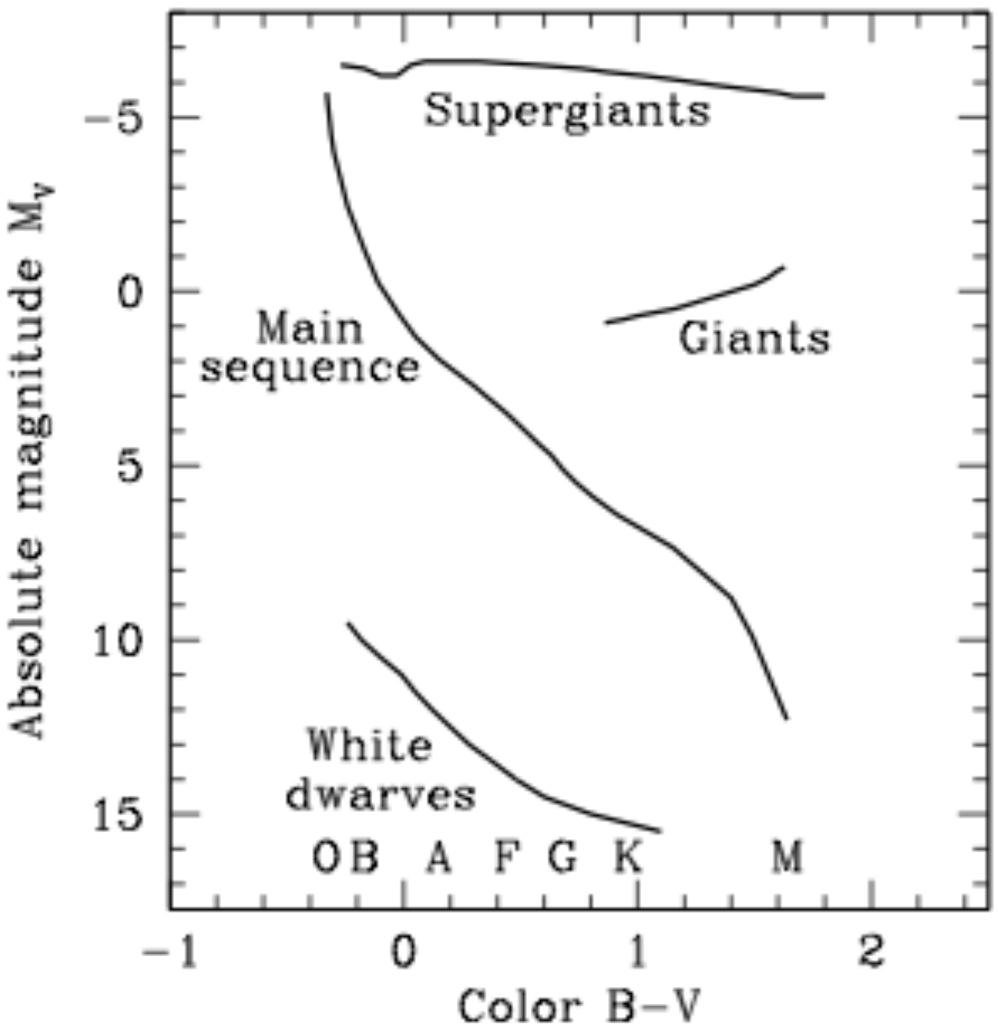
Observed period for NSs ranges ~1.5ms to 30 s

==> NS & WD are born fast rotator

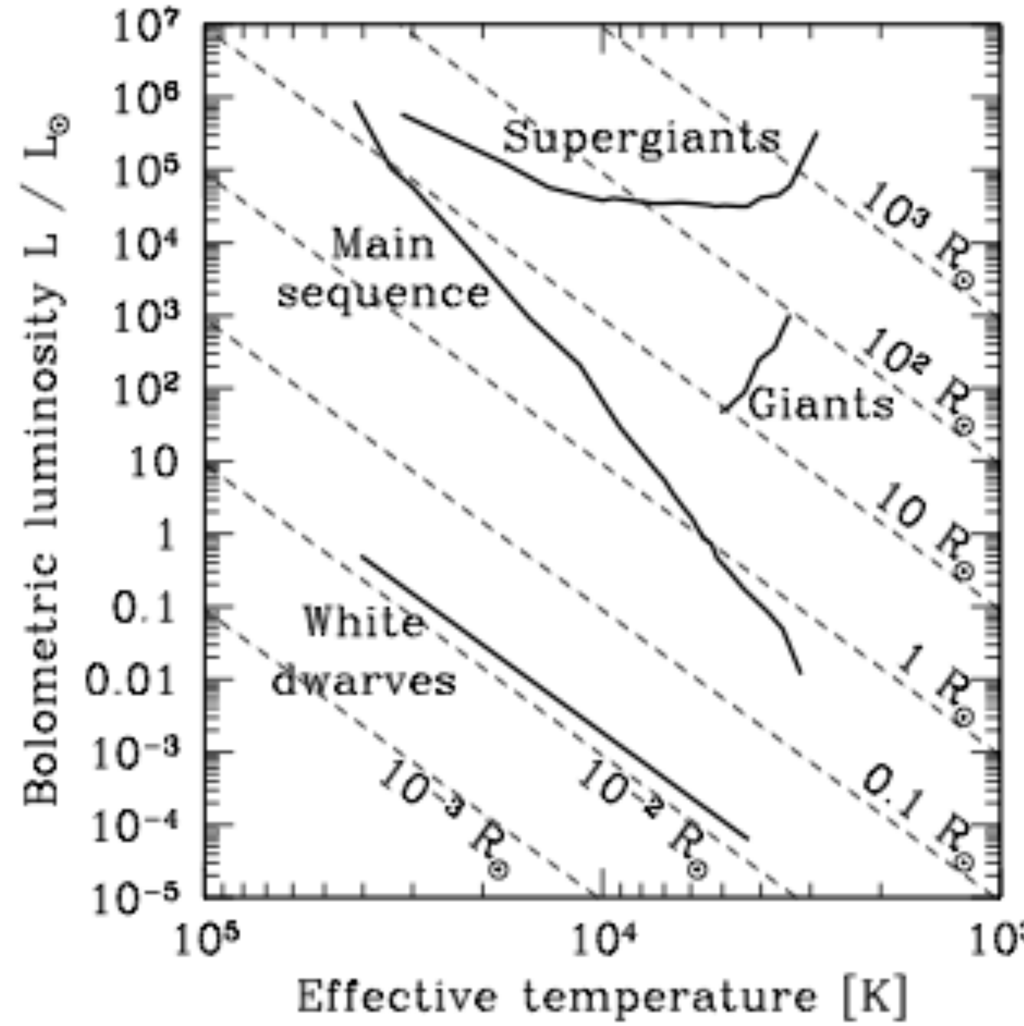
Stellar Origin of Compact Objects

Herzsprung-Russel (HR) diagram (1914)

Observational



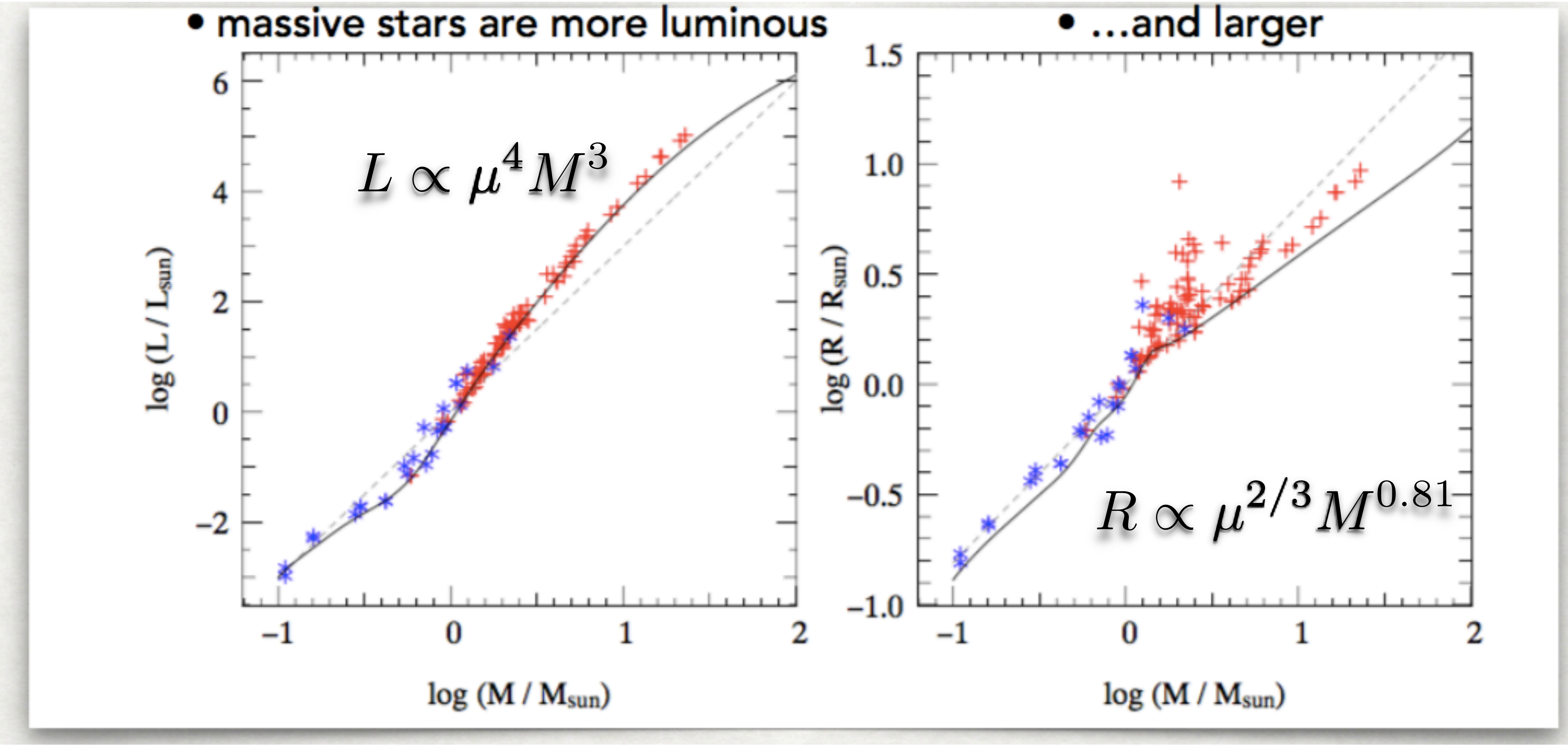
theoretical



$$L = 4\pi R^2 \sigma T_{\text{eff}}^4$$

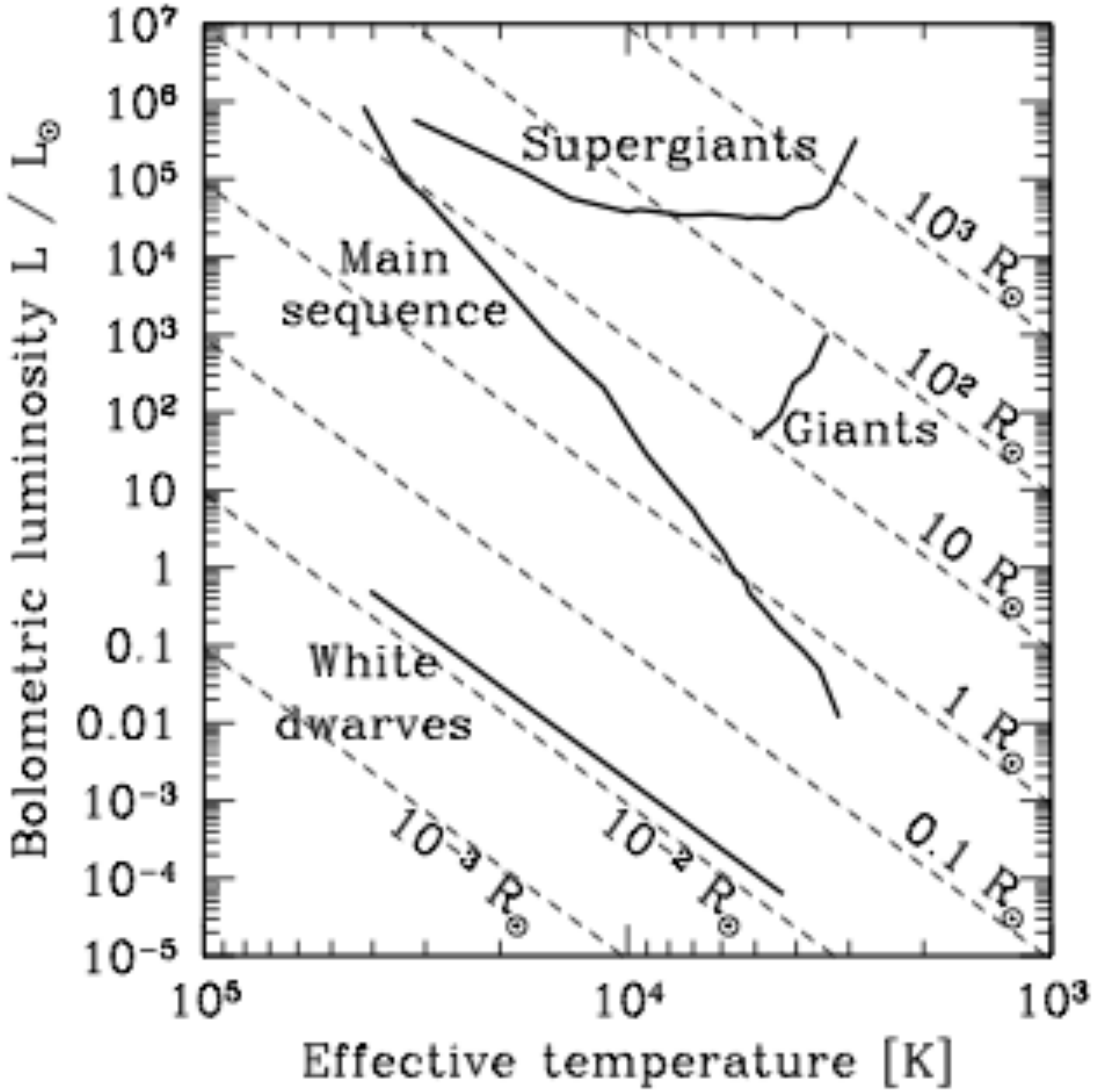
Main sequence

- Stars in hydrostatic and thermal equilibrium, powered by H burning



Main sequence

=>Main sequence is a mass sequence



Main sequence

- lifetime:

mass fraction in H

H fusion efficiency

$$t_{\rm nucl.} \simeq f\epsilon \frac{Mc^2}{L} \simeq 10\ {\rm Gyr}\ \left(\frac{f}{0.1}\right)\left(\frac{\epsilon}{7\times10^{-3}}\right)\left(\frac{M}{M_\odot}\right)\left(\frac{L}{L_\odot}\right)^{-1} .$$

==>

- lifetime decreases with mass
- + initial mass fun. => massive stars are rare
- < 0.5 M_{sun} t_{nucl} > age universe

BINDING ENERGY

NOT EQUAL TO SUM OF MASSES X C²; USUALLY IN MEV

For nucleus "i":

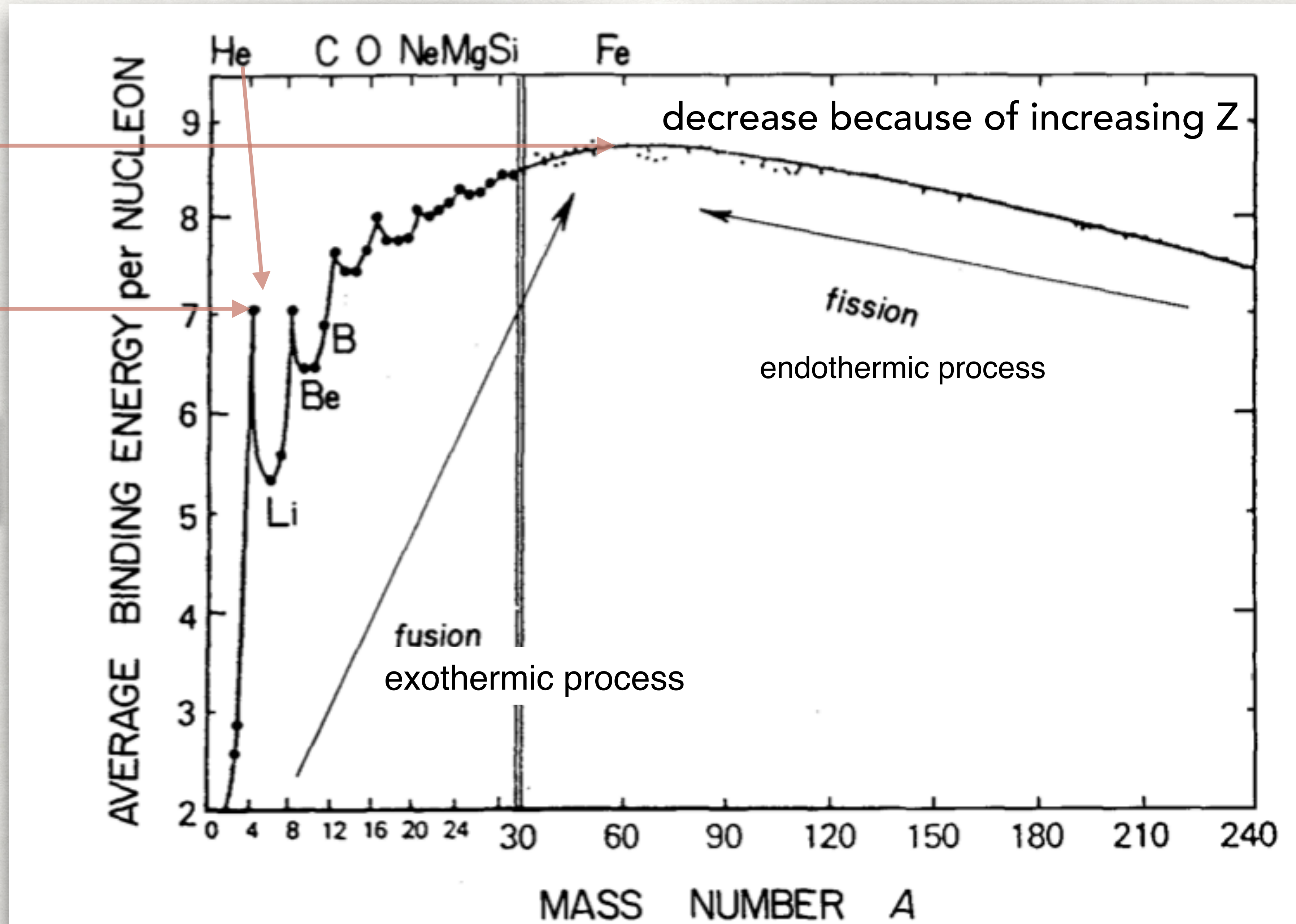
$$E_{B,i} = [(A_i - Z_i)m_\mathrm{n} + Z_i m_\mathrm{p} - m_i]\, c^2,$$

m_p, m_n = free proton/neutron mass

8.79 MeV

~7 MeV

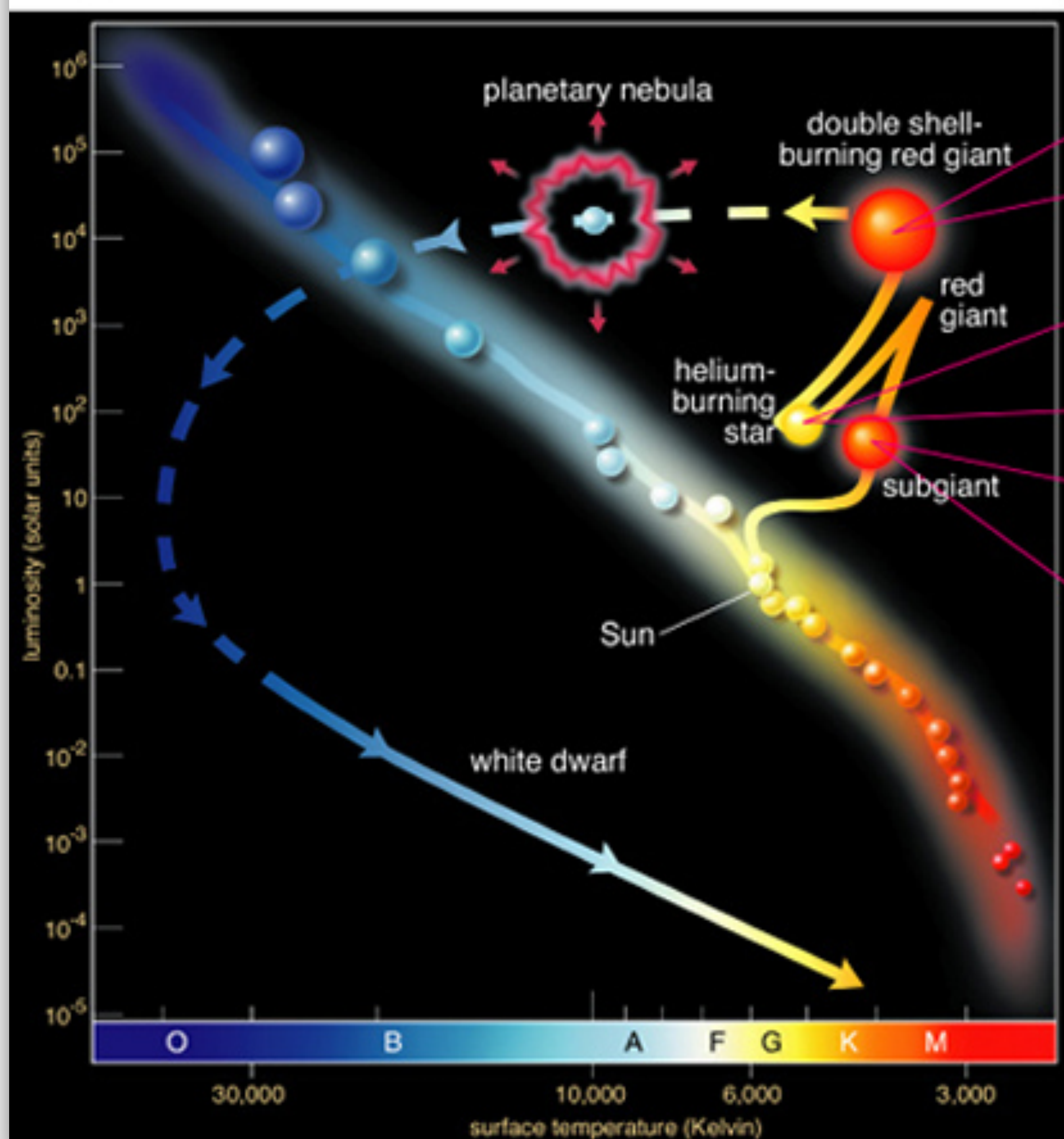
E_b/A



White Dwarfs & Planetary nebulae

M< ~8 M_{sun}

cat's eye nebula



For M> 2 stable He burning to CO degenerate core.

In low- and intermediate-mass stars, up to about 8 M⊙, the C-O core becomes degenerate and their late evolution is qualitatively similar. These stars evolve along the so-called asymptotic giant branch (AGB) in the H-R diagram. The AGB is a brief but interesting and important phase of evolution, among other things because it is the site of rich nucleosynthesis. AGB stars also suffer from strong mass loss, which eventually removes their envelope and leaves the degenerate C-O core, which after a brief transition stage as the central star of a planetary nebula, becomes a long-lived cooling white dwarf.

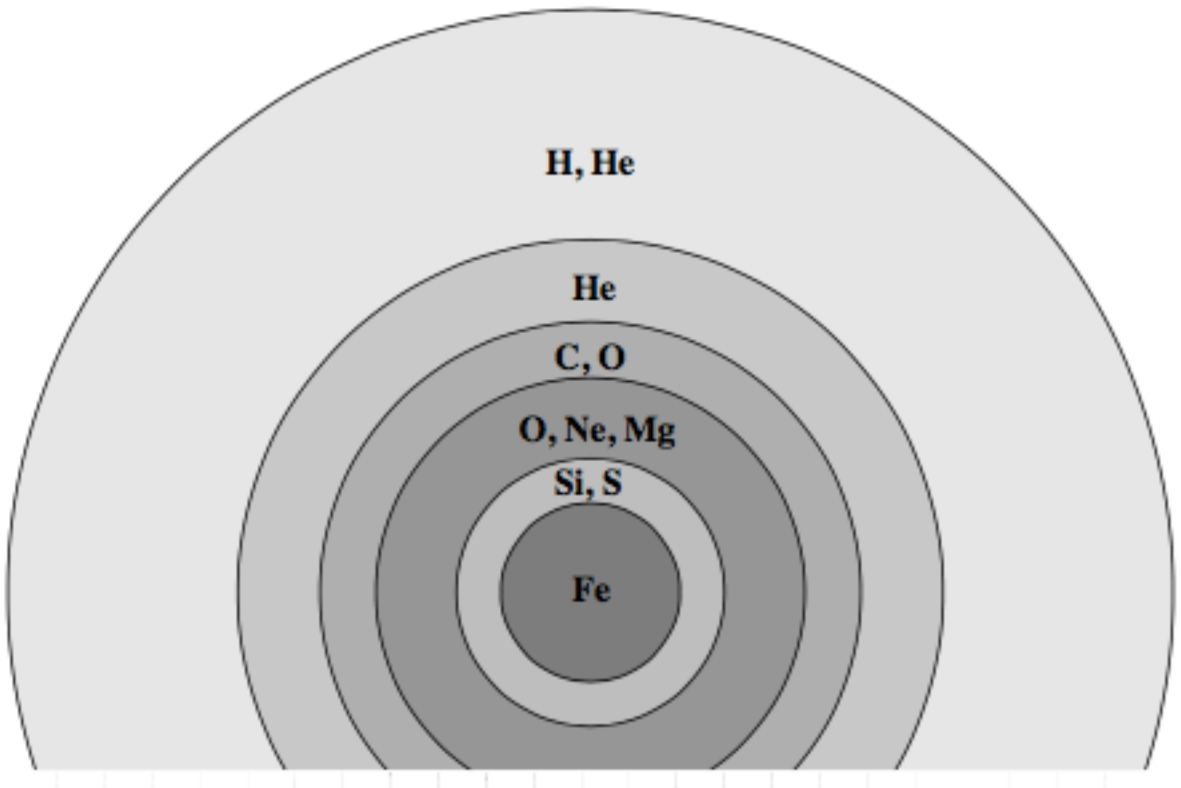
low-mass stars are those that develop a degenerate helium core after the main sequence, leading to a relatively long-lived red giant branch phase. The ignition of He is unstable and occurs in a so-called helium flash. This occurs for masses between 0.8 M⊙ and ≈ 2 M⊙ (this upper limit is sometimes denoted as MHeF).
intermediate-massstars developaheliumcorethatremainsnon-degenerate,andtheyignitehelium in a stable manner. After the central He burning phase they form a carbon-oxygen core that becomes degenerate. Intermediate-mass stars have masses between MHeF and Mup ≈ 8 M⊙. Both low-mass and intermediate-mass stars shed their envelopes by a strong stellar wind at the end of their evolution and their remnants are CO white dwarfs.

fusion of H & He —> CO/NeO degenerate core
=> CO or NeO White Dwarfs

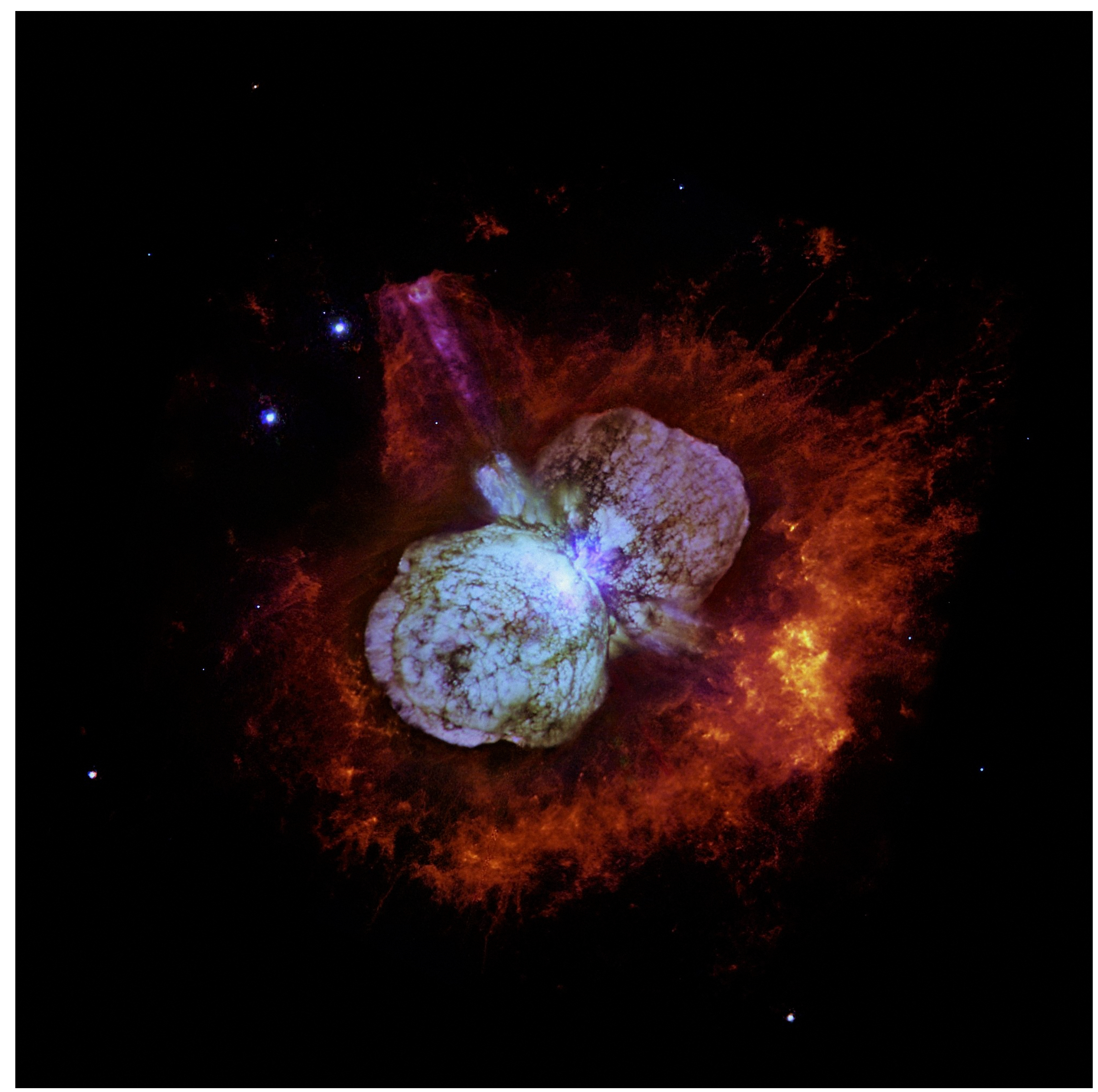
Dumbbell nebula

late evolution of Massive stars M> ~8 M_{sun}

1) Core nucleosynthesis up to iron



2) Very powerful winds, difficult to model



Core Collapse

$8 < M_{sun} < 30$

photodisintegration of iron nuclei
($T \sim 10^9$ K)

neutralisation (inverse beta-decay)

$$p^+ + e^- + 1.36\mathrm{MeV} \rightarrow n + \bar{\nu_e}$$

$$^{56}Fe + 3.7\mathrm{MeV} \rightarrow ^{56}Mn + \bar{\nu_e}$$

strong force halts collapse =>
Neutron star

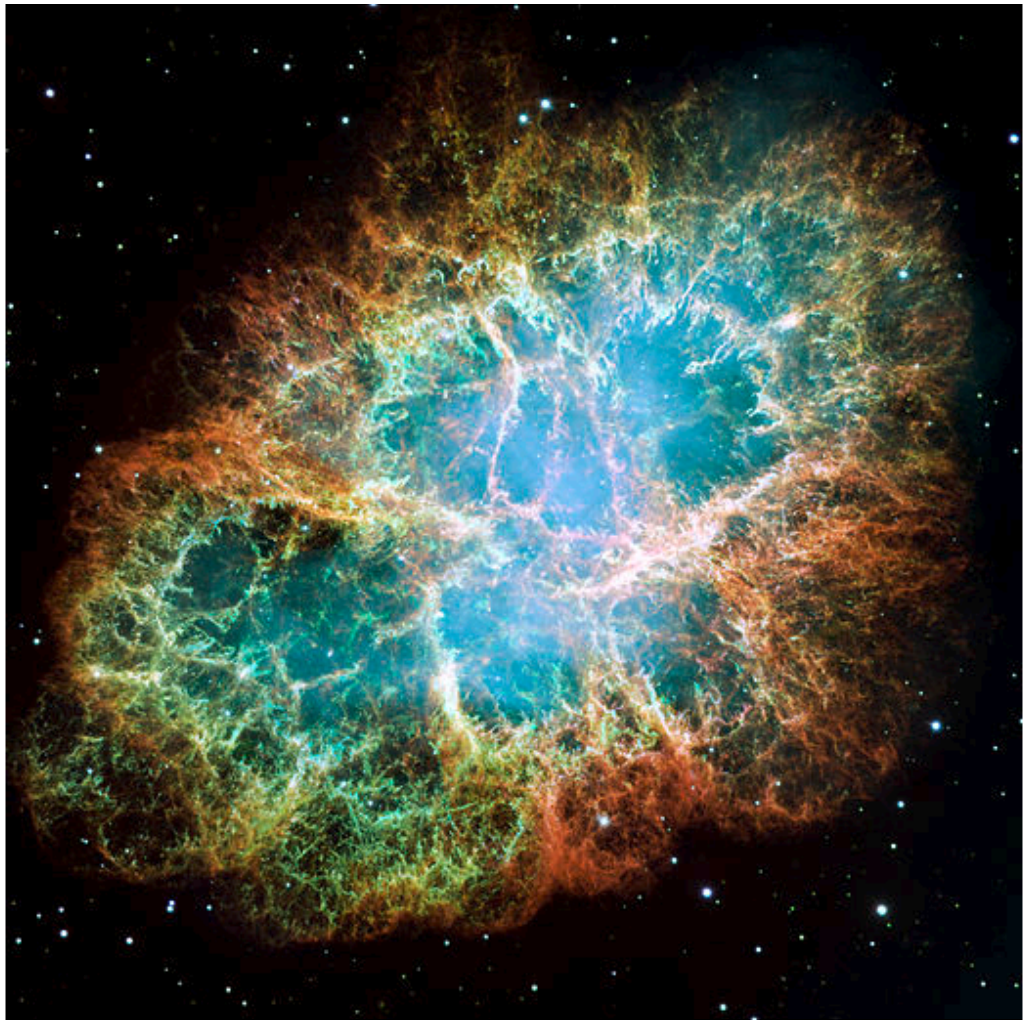
$M_{sun} > 30$ (appox)

Strong interaction between
nucleon not enough

Black hole

Supernovae

Core collapse is accompanied by rebound of the falling matter

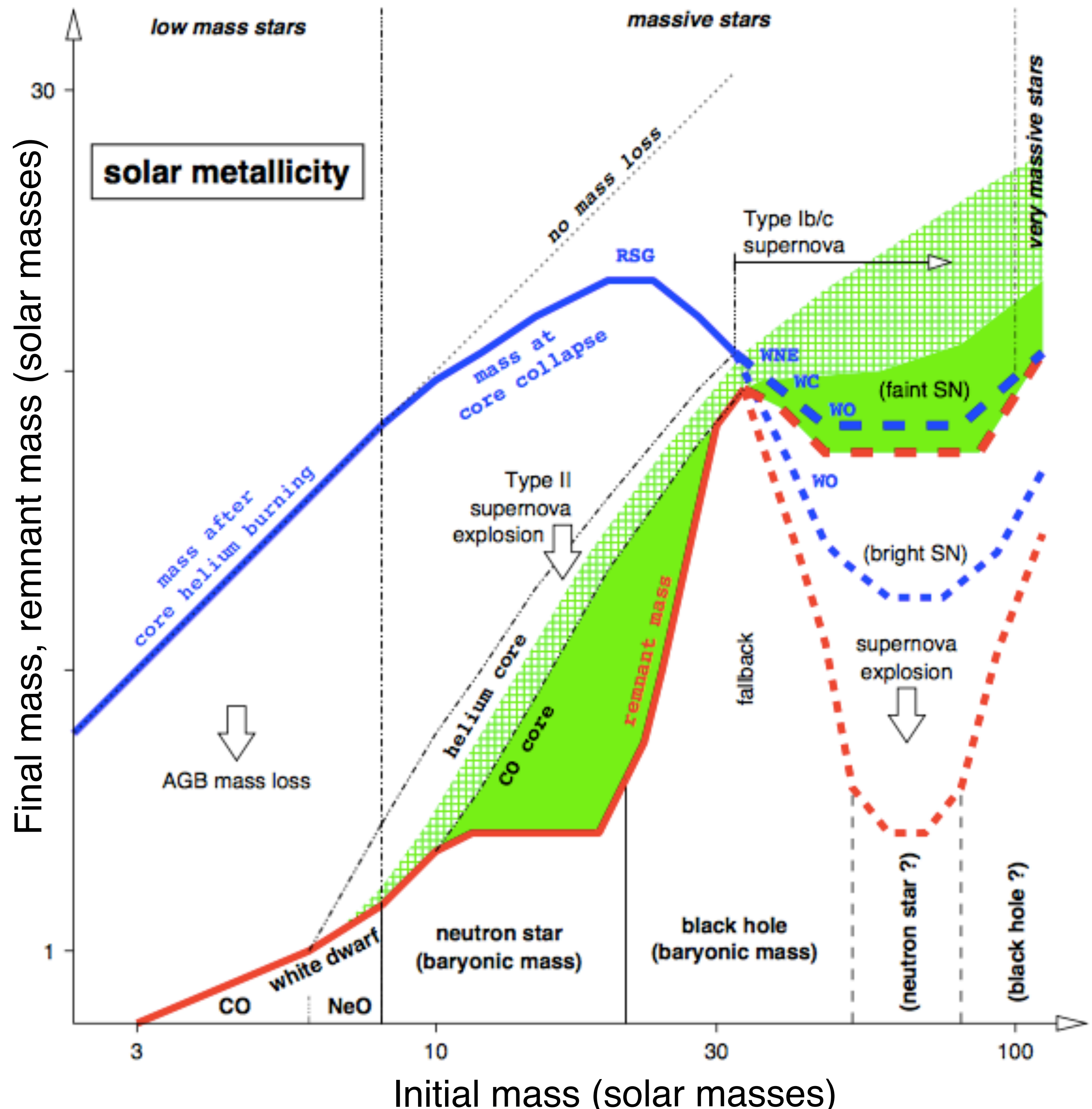


Crab view from HST

Crab view from Chandra (white)+Hubble (red)

which is the progenitor mass ?

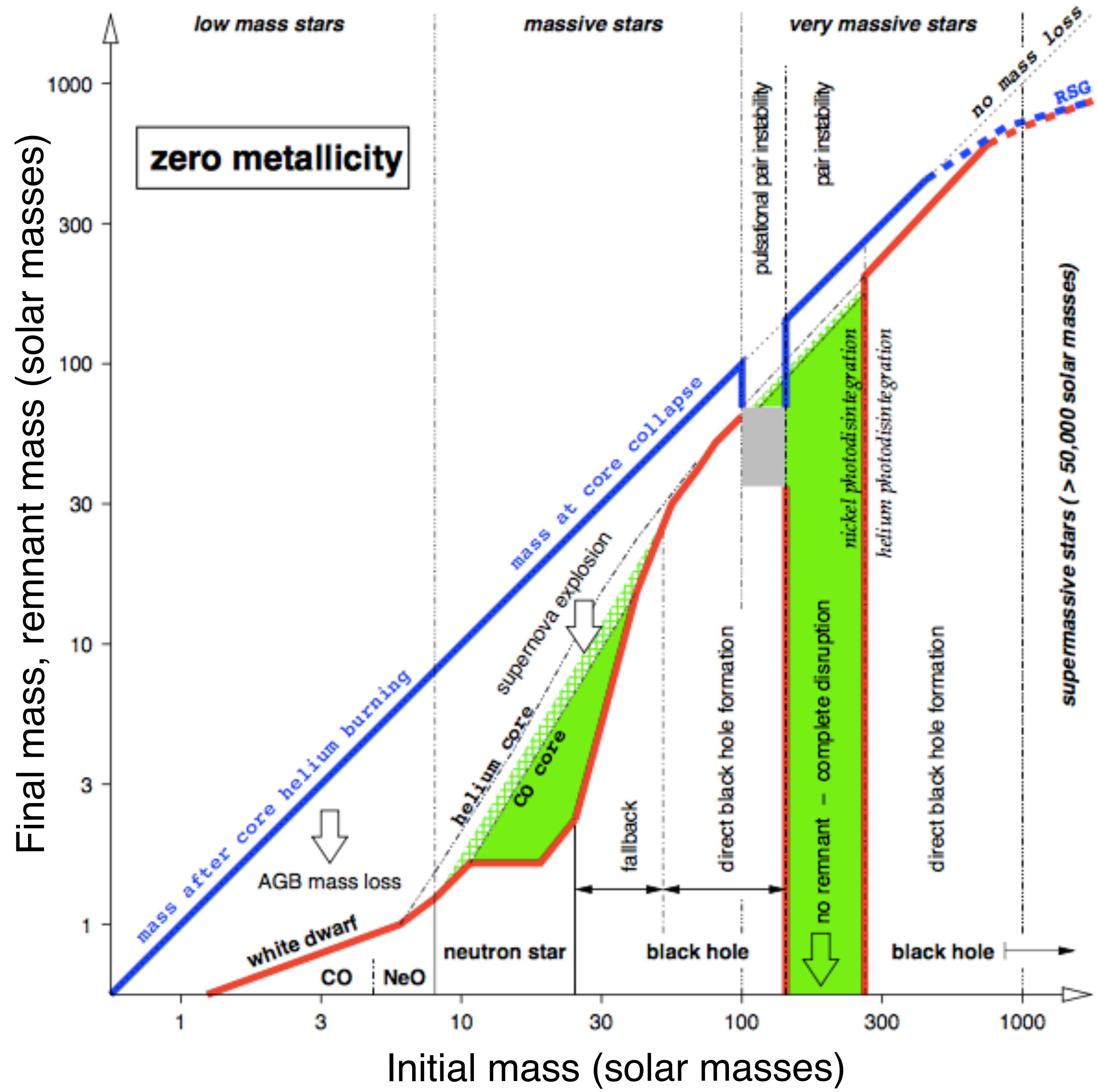
Maximum BH mass ~25 M_{sun}!



Heger+03

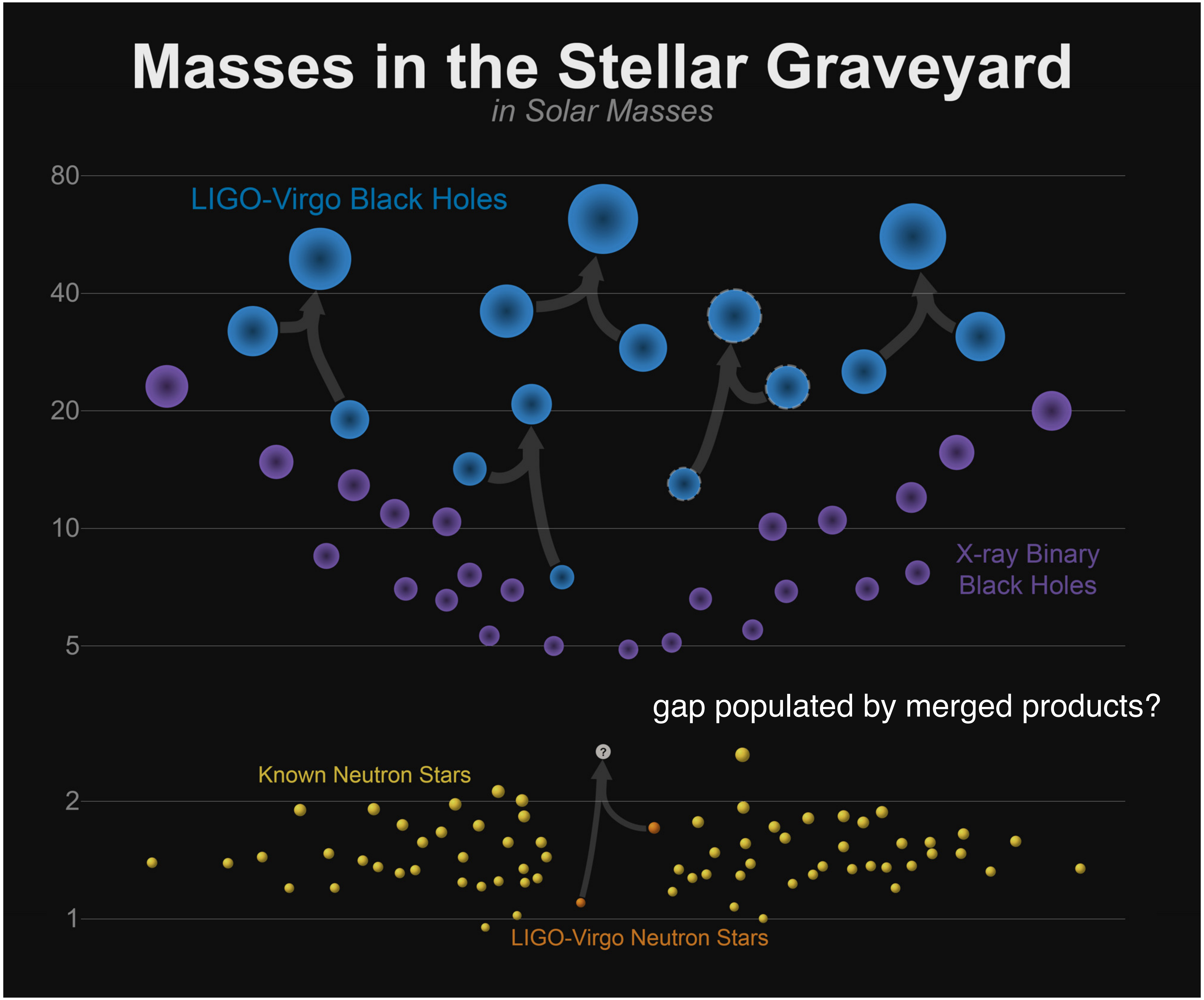
which is the progenitor mass ?

Maximum BH mass just depends on the maximum possible mass for stars!



Heger+03

Observed masses : black hole +NS



dynamical mass measurements

In binary systems, the signal is modulated by the orbital period T. The Doppler effect measured with lines gives a_1 sin(i) (the distance form the centre of mass of primary projected perp. to line of sight)

These parameters allow to determines a combination of primary and secondary masses M_1 and M_2:

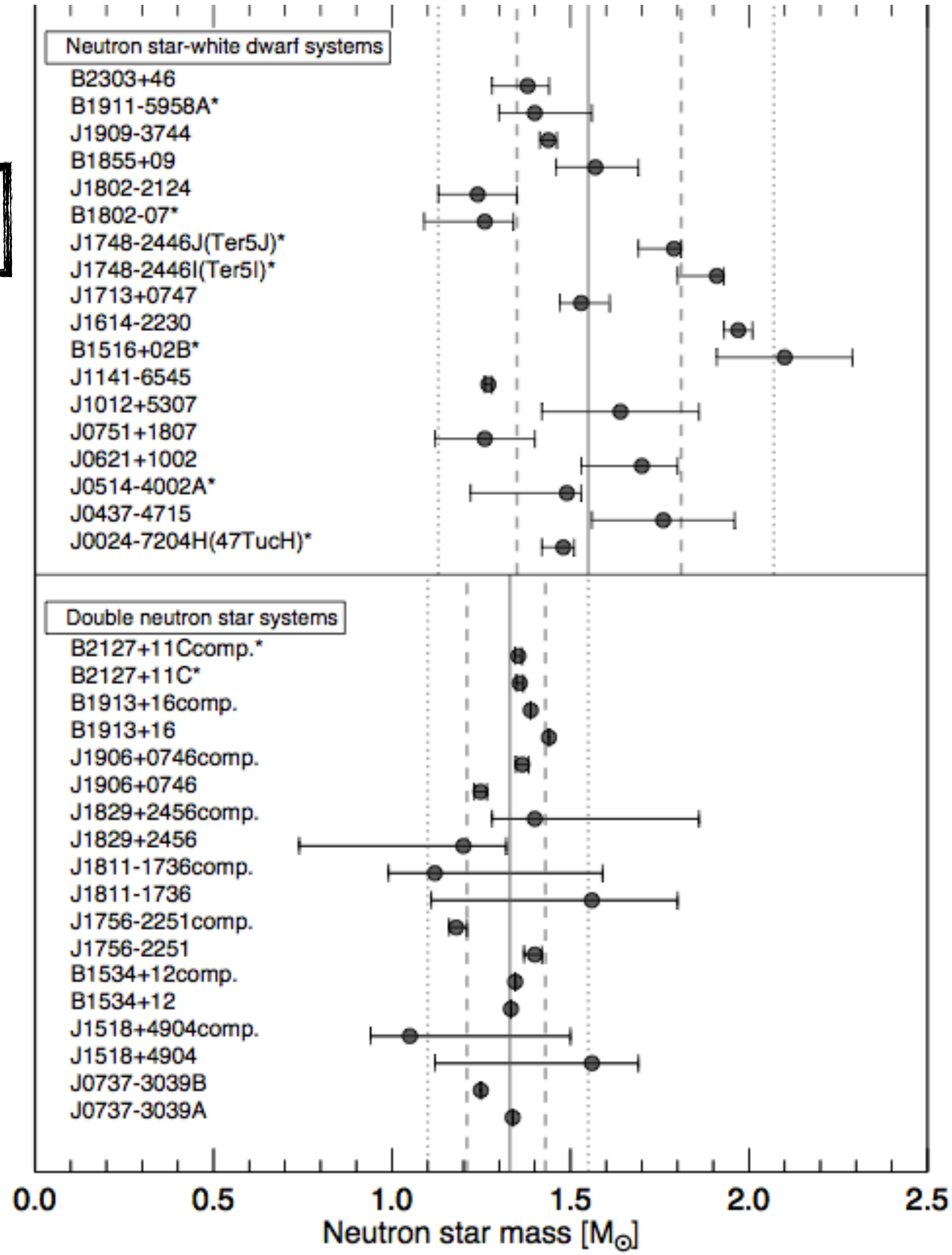
$$f = \frac{(M_2 \sin i)^3}{(M1 + M_2)^2} = \frac{4\pi^2}{G} \frac{(a_1 \sin i)^3}{T^2} .$$

If the mass function can be also constructed for the secondary, both mass can be determined, otherwise not. Additional uncertainty in "i". This is also true for WDs

Observed masses : neutron stars

NS + WD

Double NSs



smaller errors

Kiziltan et al. (2013)

Mass measurements

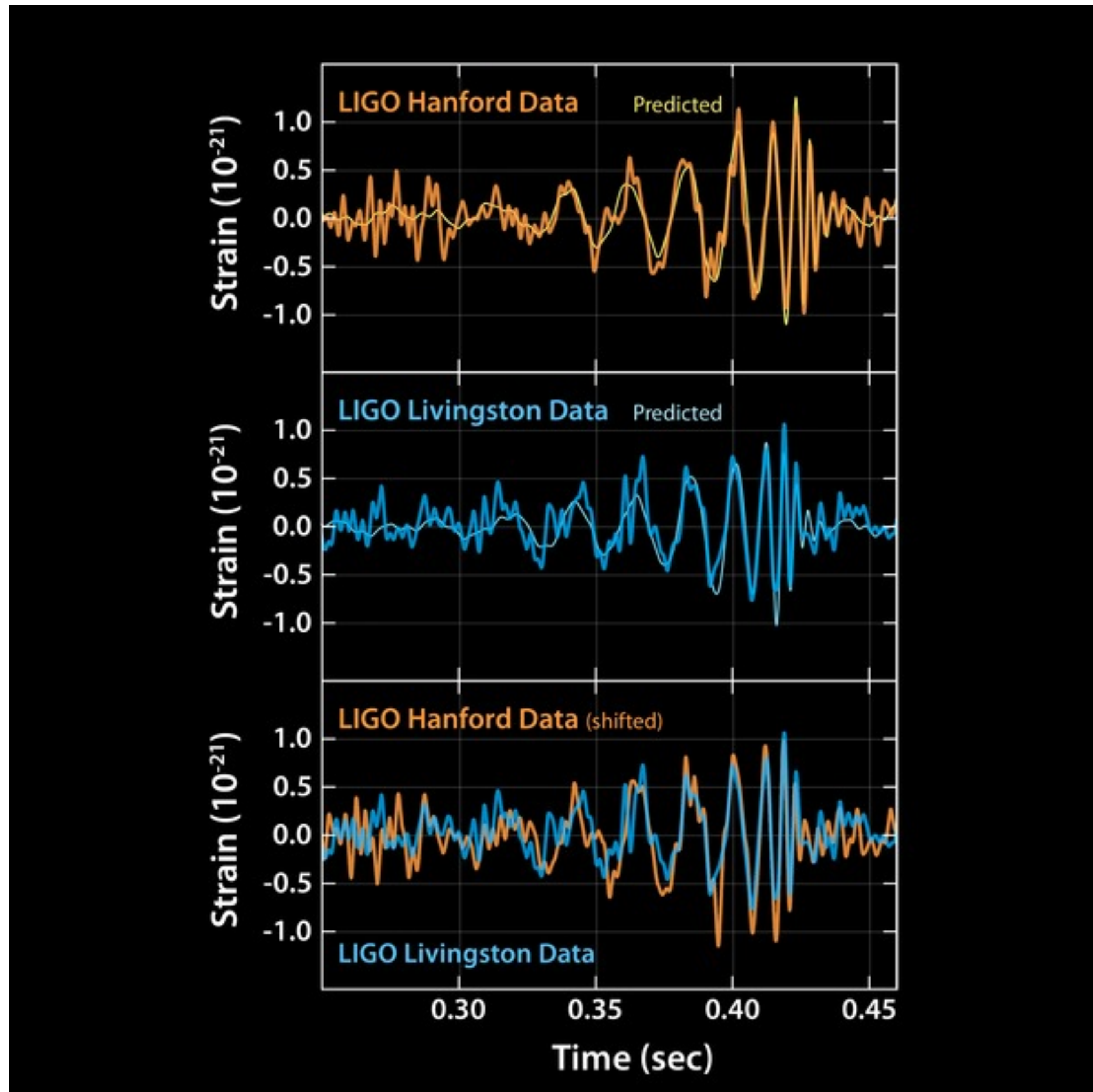
For binaries with two NSs, general relativistic effects help constraining mass precisely, since effects depend on mass. E.g. pericenter precession of orbital motion, that "advances" at a rate:

$$\dot{\omega} = \frac{3}{1-e^2}\left(\frac{2\pi}{T}\right)^{5/3}\frac{G^{2/3}}{c^2}(M_1+M_2)^{2/3}$$

if also other effects like, Einstein's redshifts, period's change due to gravitational wave etc... can be measured, then the mass and orbital parameter measurements become very precise, allowing for orbital evolution predictions (e.g. Hulse & Taylor's work)

mass measurement from GW

Extracting parameter from the GW signal itself



credit: LIGO collaboration