White dwarfs in the GW-era

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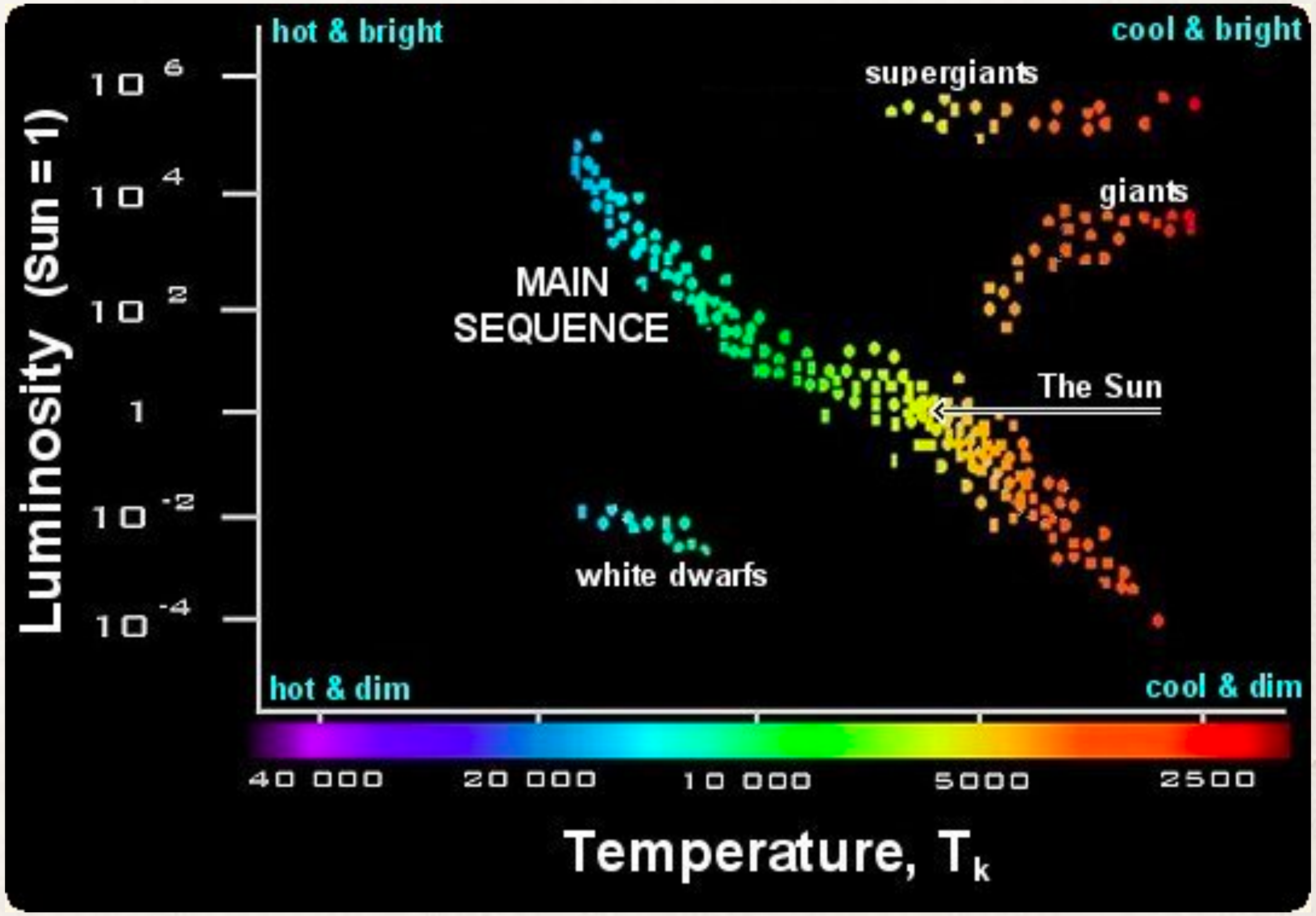
Date 28 October 2019

First detection of a white dwarf

- 40 Eridanus B (part of a triple system)

- Stands out in first HR diagram published by Russell in 1914
- Spectral type (determined by Willamina Flemming)
  - ➡ Too dim for its temperature
  - ➡ Of small size

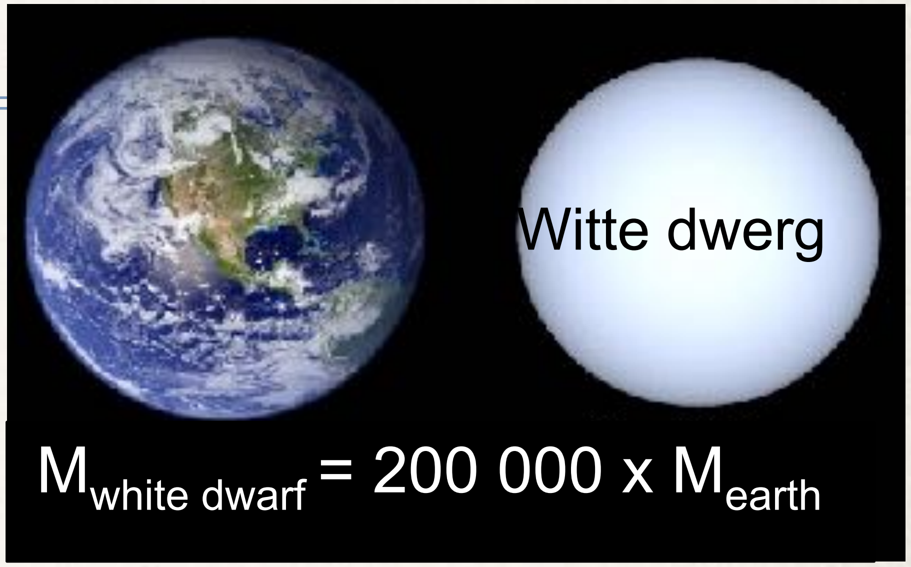


First identification : Sirius B!

Sirius A and B (artist impression)

- Sirius A is brightest star in the sky after the Sun (~2Msun, ~2.7 pc away)
- In binary with Sirius B (discovered by F. Bessel 1844)

First identification : Sirius B!



- Orbital period ~ 50yr
  - Kepler's 3th law: $P=2\pi\ (a^3/GM_{total})^{0.5}$
  - ➡ mass of Sirius B ~0.94 Msun (1910)
- In 1914, W.S. Adams measures the spectrum, and obtains a temperature of ~8000K
  - Stefan-Boltzmann law for black bodies ($L=\sigma R^2 T_{eff}^4$)
    - implies sub-solar radius of 18000 km (Sun ~7e5 km)
    - And ultra dense matter of ~70 kg/m^3 (Sun ~1e-3 kg/m^3)

First compact object was identified!

Equation of state

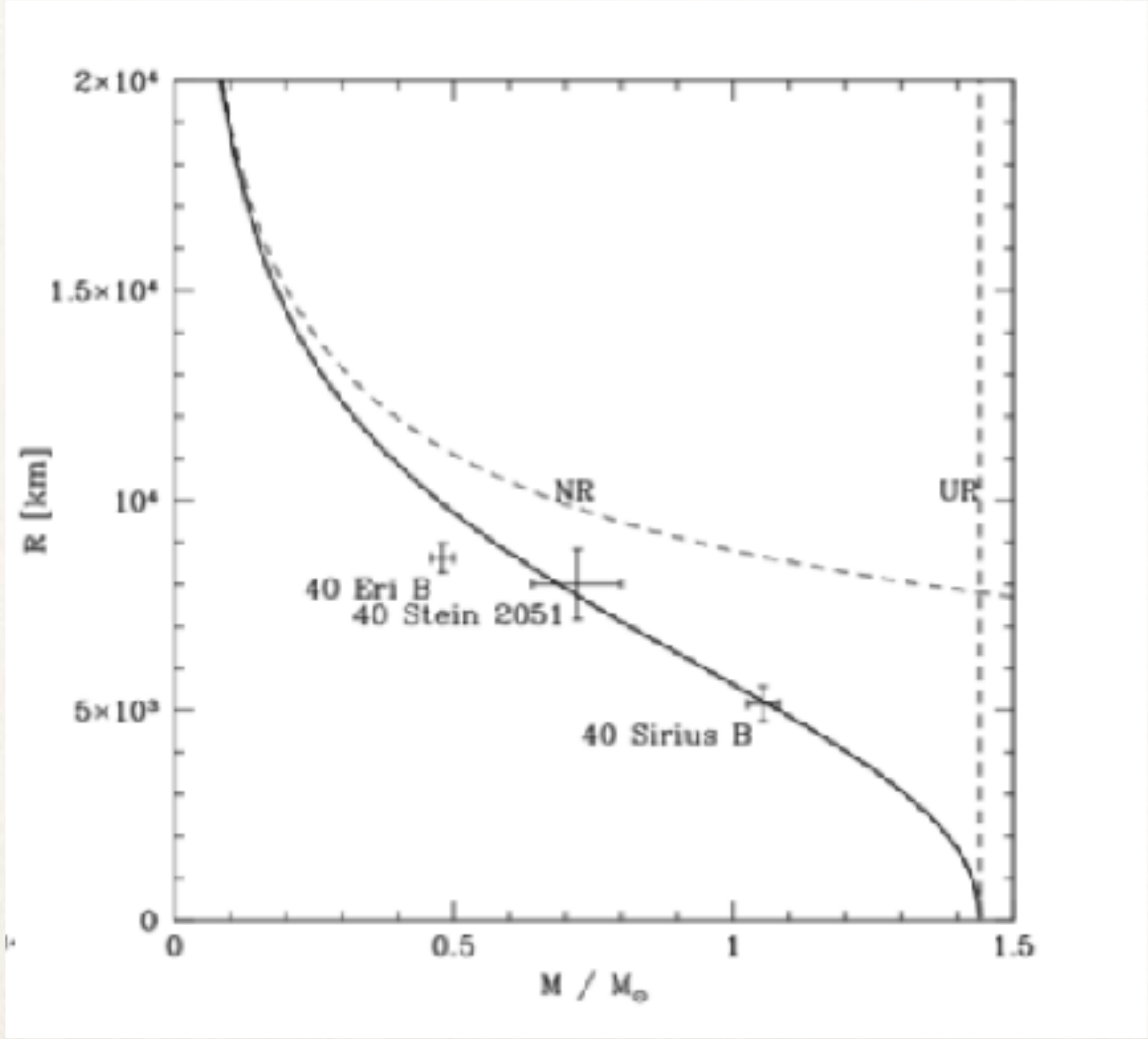
- Pressure support remains a mystery until…
- In 1926 P.A.M. Dirac & E. Fermi independently introduce the quantum mechanical statistical framework
- In the same year, R.H. Fowler (Dirac's supervisor) understands that electron degeneracy pressure can compensate gravity in white dwarfs and ensure equilibrium

WD mass & radius

- Polytropic equation of state $P=k\,\varrho^{\gamma}$
  - Appropriate for zero-temperature degenerate electron gas in two extreme regimes
    - Newtonian regime (p<<mc): $\gamma = 5/3$
    - Ultra-relativistic regime (p>>mc): $\gamma = 4/3$

Hydrostatic equilibrium:

For $\gamma = 5/3$: $M \propto R^{-3}$ (easy to derive!)



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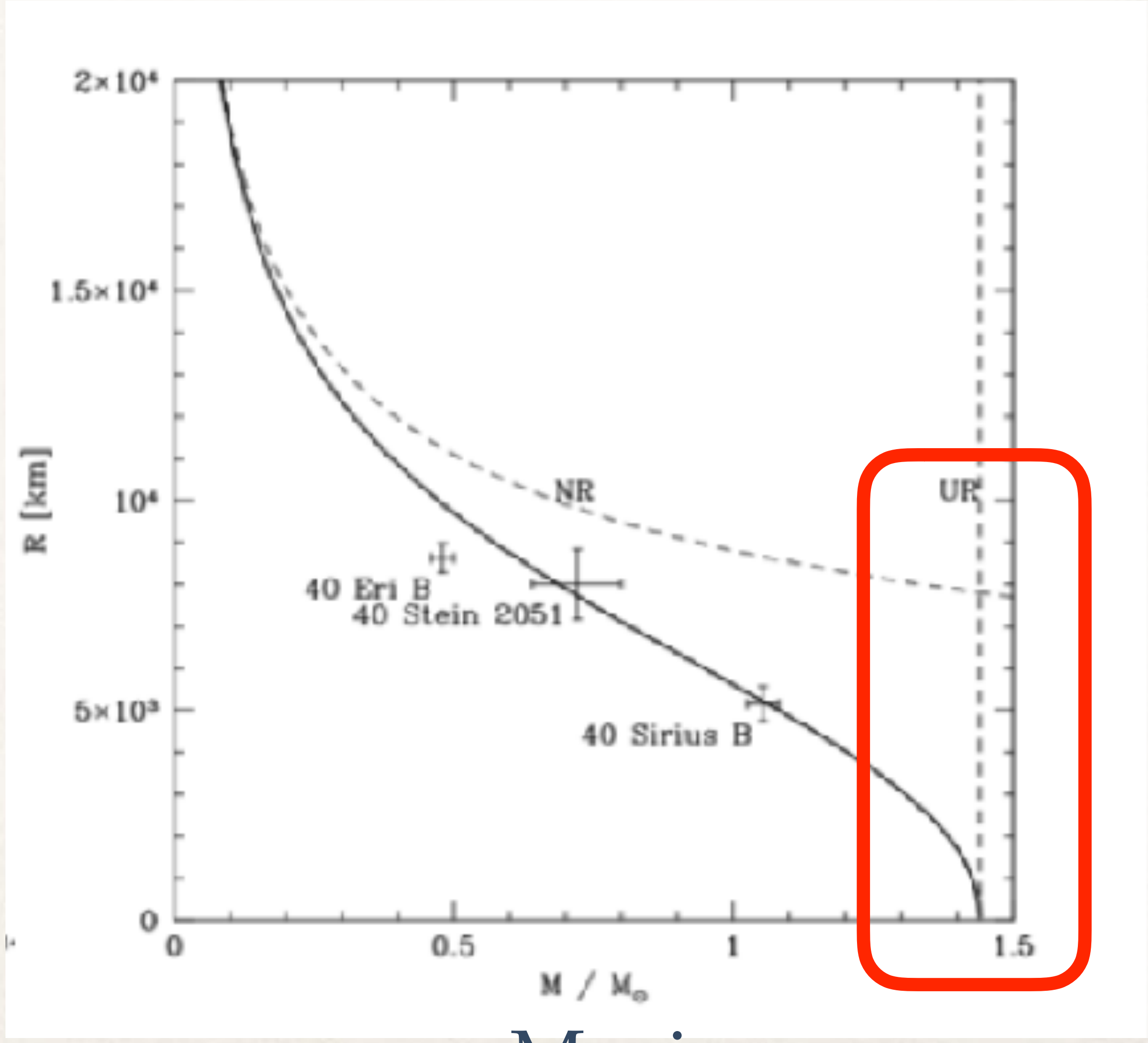
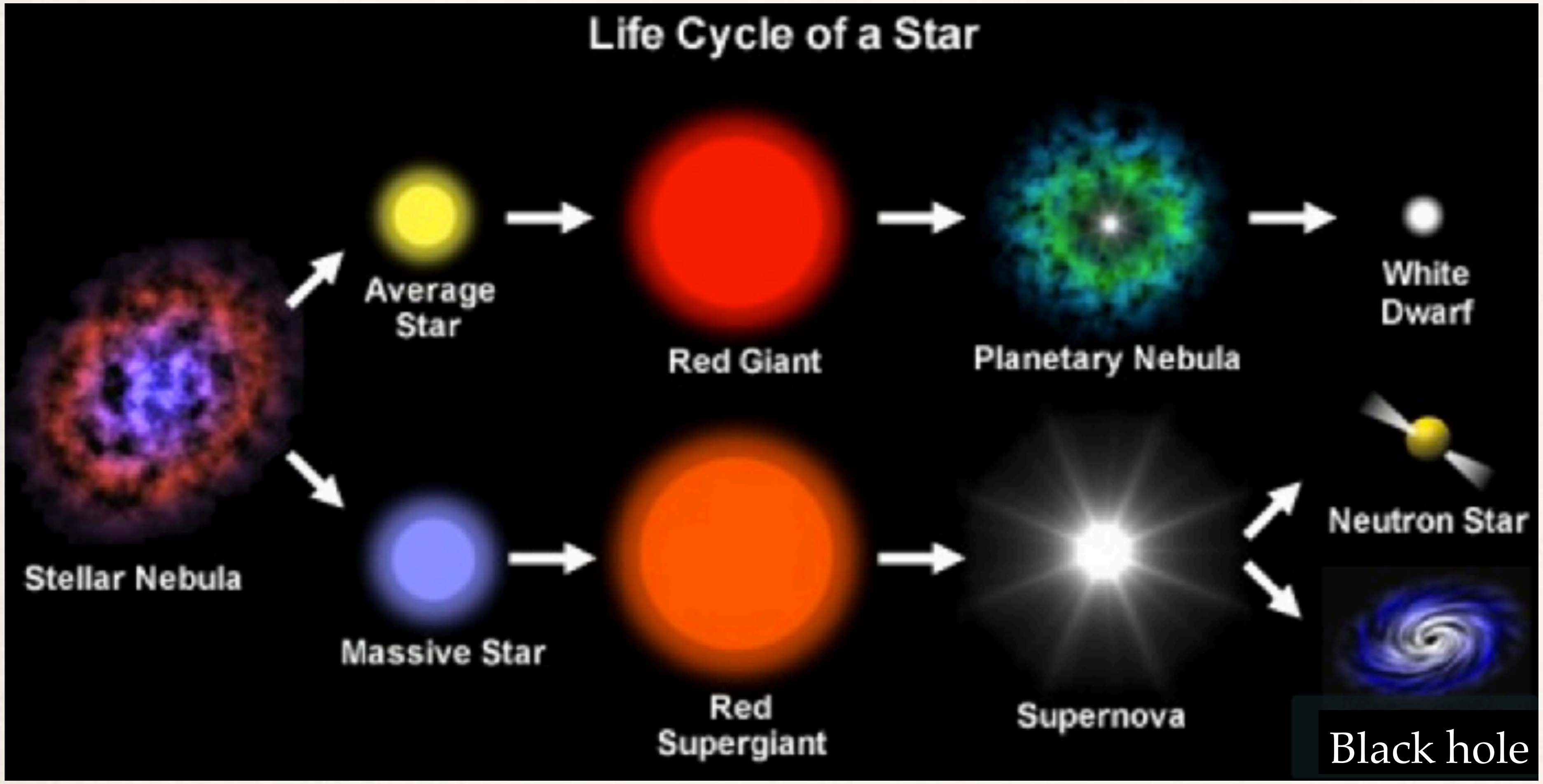


Maximum mass: Chandrasekhar limit

Compact objects as endpoints of stellar evolution

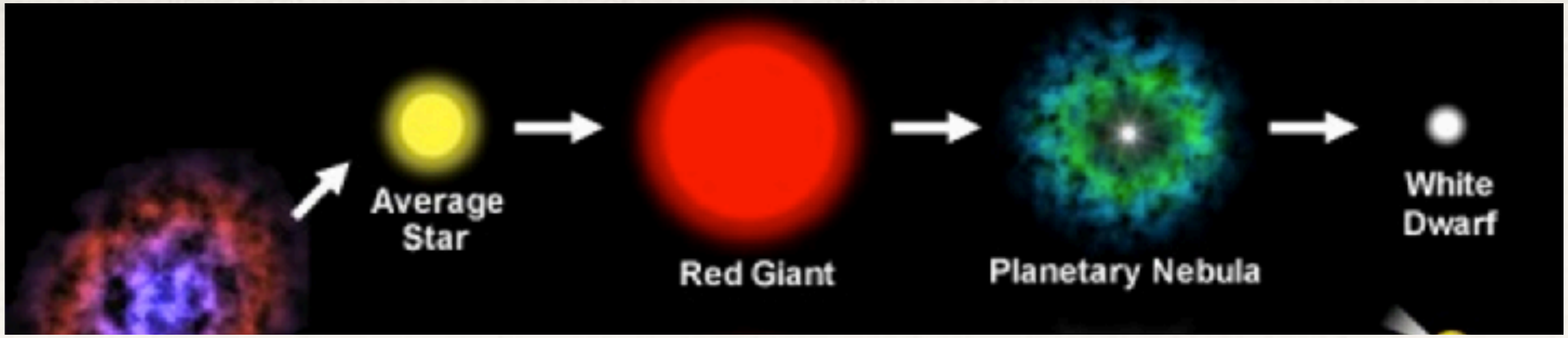


For 0.95-8Msun

For ~8-25Msun

For >~25Msun

- WDs are common
- ~90% of stars become WDs

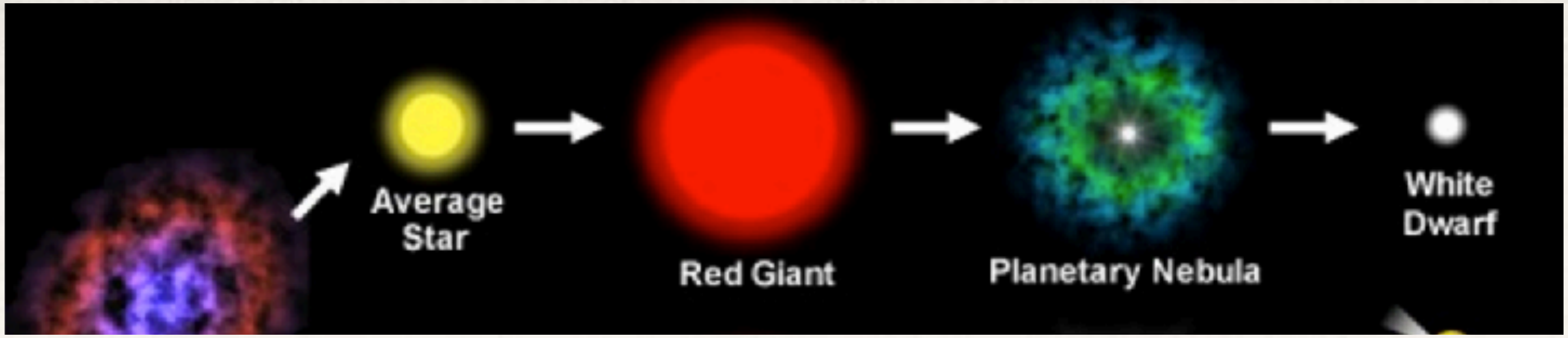


If M<~0.95Msun:

- $t_{\text{H-core burning}} \sim \varepsilon Mc^2/L = 10\text{Gyr } M/L \;\; > $ Age universe

Else: successive stages of nuclear burning

- If ~0.95 - 7Msun: core H & He burning -> CO core
  - CO WD of mass ~ 0.55-1.1Msun
- If ~7-8 Msun: core H, He & CO burning -> ONe core
  - ONe WD of mass >~1.1Msun



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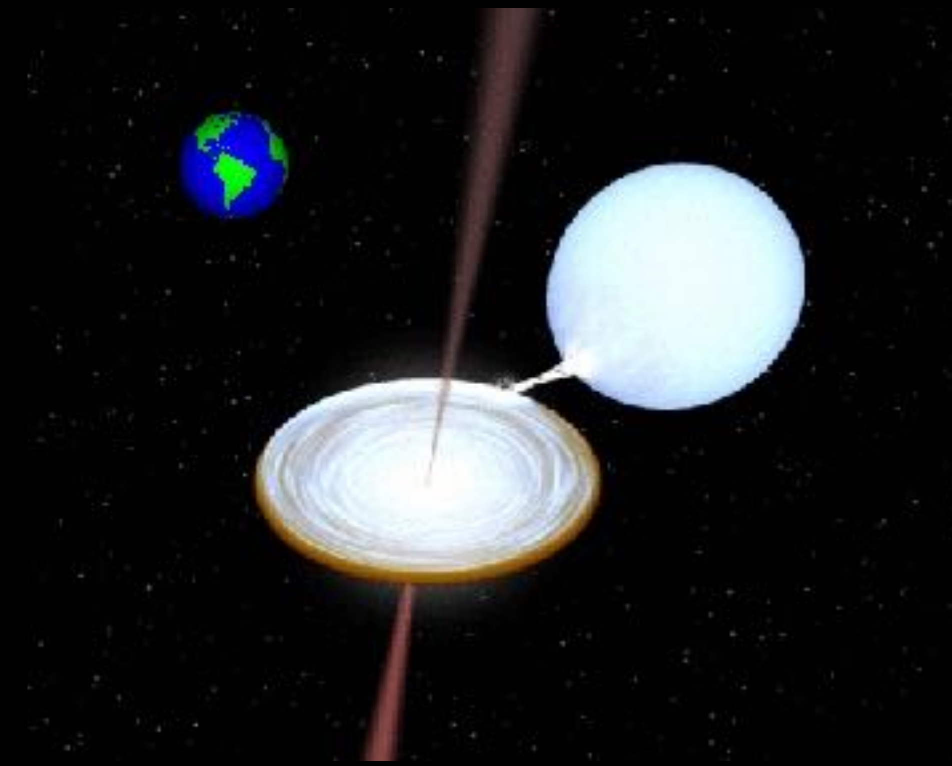
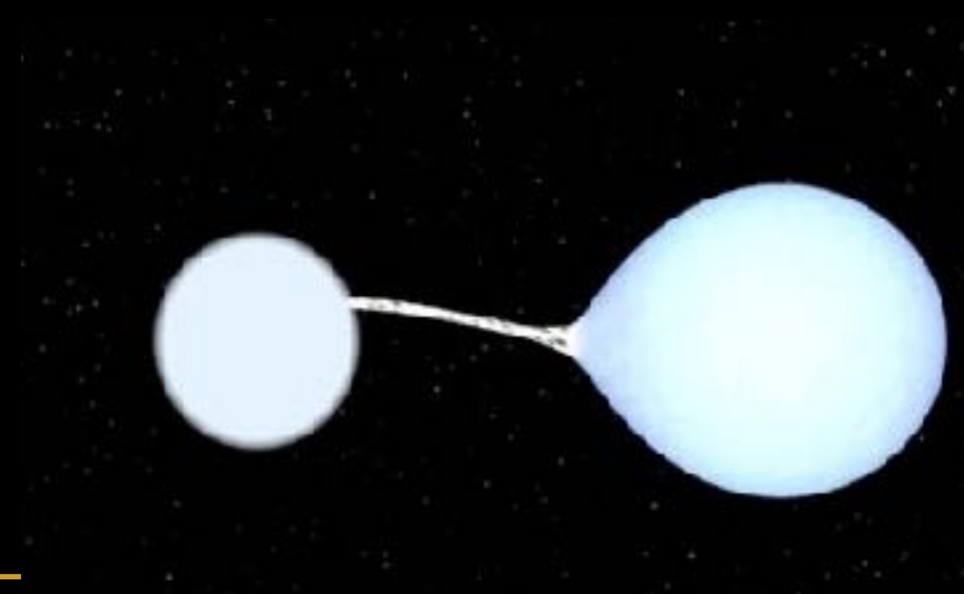
- If ~7-8 Msun: core H, He & CO burning -> ONe core
  - ONe WD of mass >~1.1Msun
- He WD of mass ~0.2-0.5 Msun
  - if stellar envelope removed / binary interaction

White dwarfs in binaries

Most extreme binaries

- Orbits are extremely small
  - Days to minutes!
- Compact stars
  - White dwarfs
  - Neutron stars
  - Black holes
- *Extremely bright through mass transfer or mergers!*





Why study double white dwarfs?

Largest population of ultracompact binaries in the Milky Way

Gravitational waves:
Dominant sources at
milli- and decihertz frequencies

Progenitors of supernova Type Ia:
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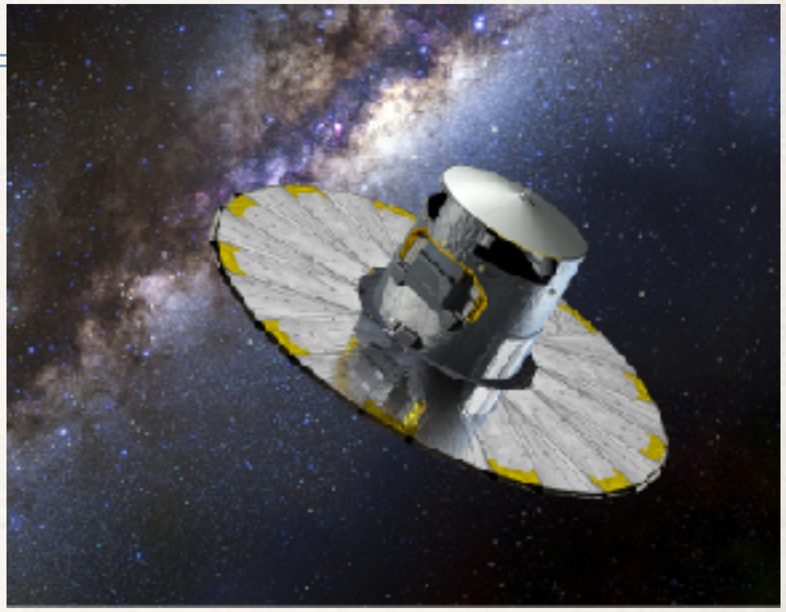
Mass transfer

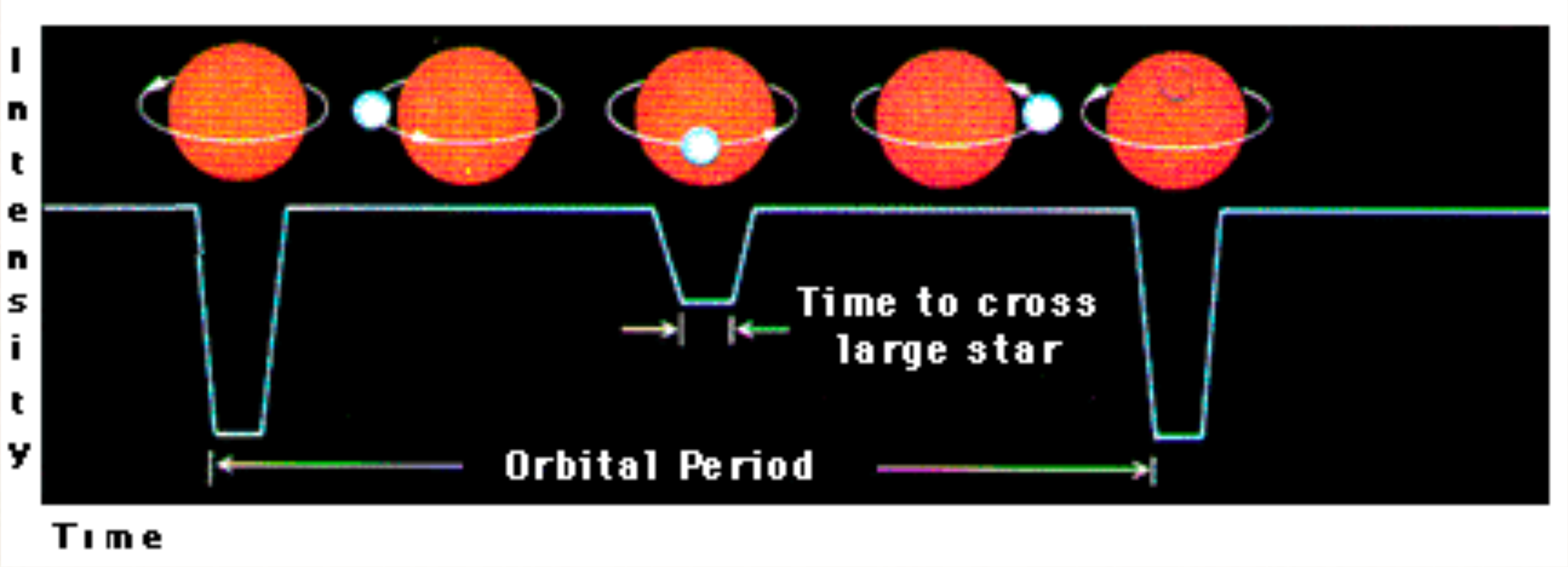
Observations so far

Gaia satellite
(1st data release: sep 2016,
2nd: apr 2018, 3th: 2020)



- ~10 yrs ago : ~50 double WDs known
  - detected with variety of methods
- Now: ~100 double WDs
  - SDSS ELM survey: Extremely-Low Mass WDs
- Next few years: Gaia
  - 5-10% double WDs in several 100,000 WDs
  - Needs follow-up for confirmation of binarity

Eclipsing binaries



- Expectations:
  - Gaia satellite: ~200 double WDs
  - LSST (>2020-2022): ~1000-1500 double WDs

Korol+ 17

Optical observations

- WDs are dim objects (<300 pc)
- Sensitive to cooling physics & dust extinction
- Selection effects hard to model

Gravitational waves can be a game changer!

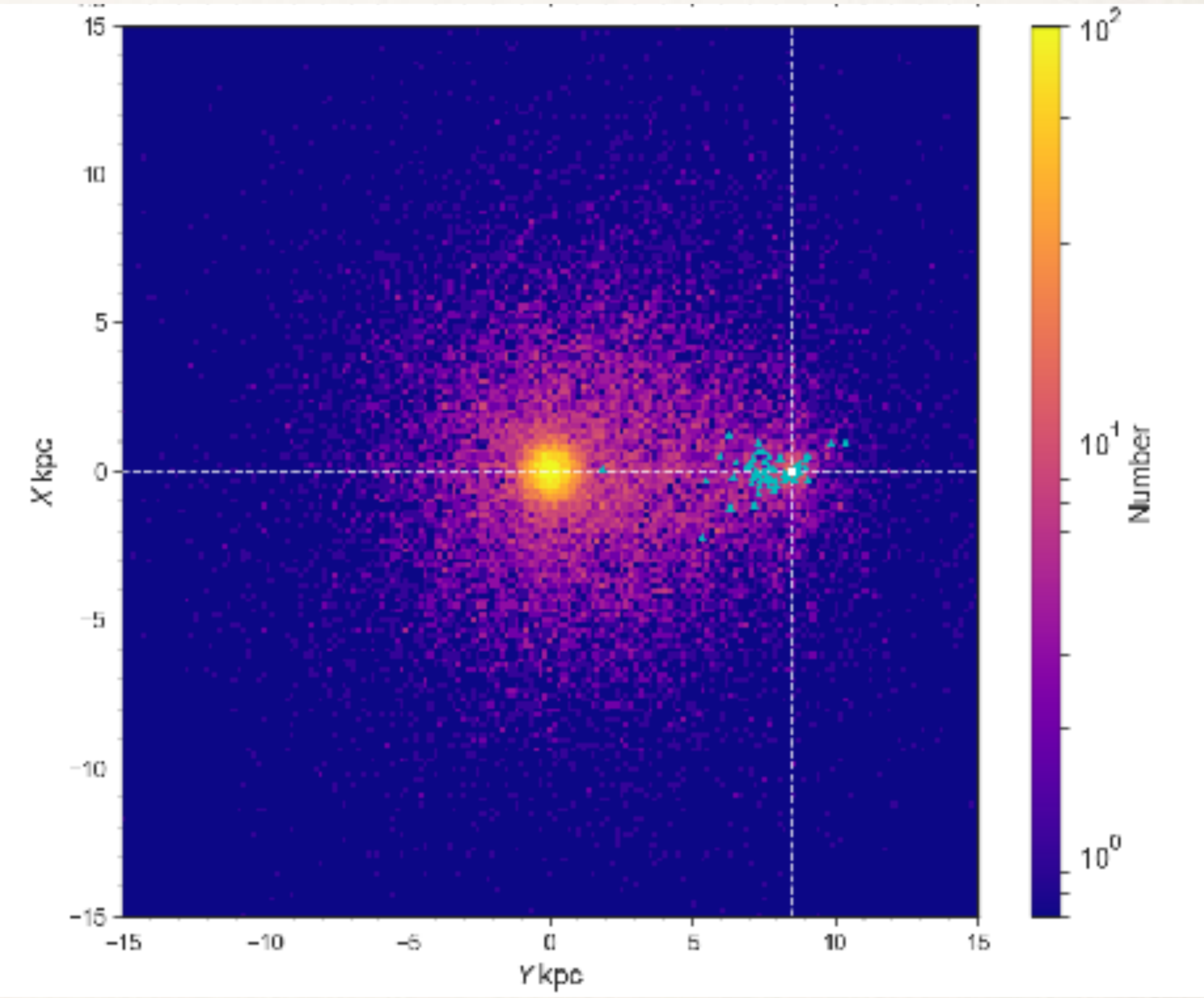
GW observations

GW amplitude:

$$A = \frac{2G^{5/3}\pi^{2/3}}{c^4} M_{\rm chirp}^{5/3} f^{2/3} D^{-1}$$

Chirp mass:

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



Korol+ 19

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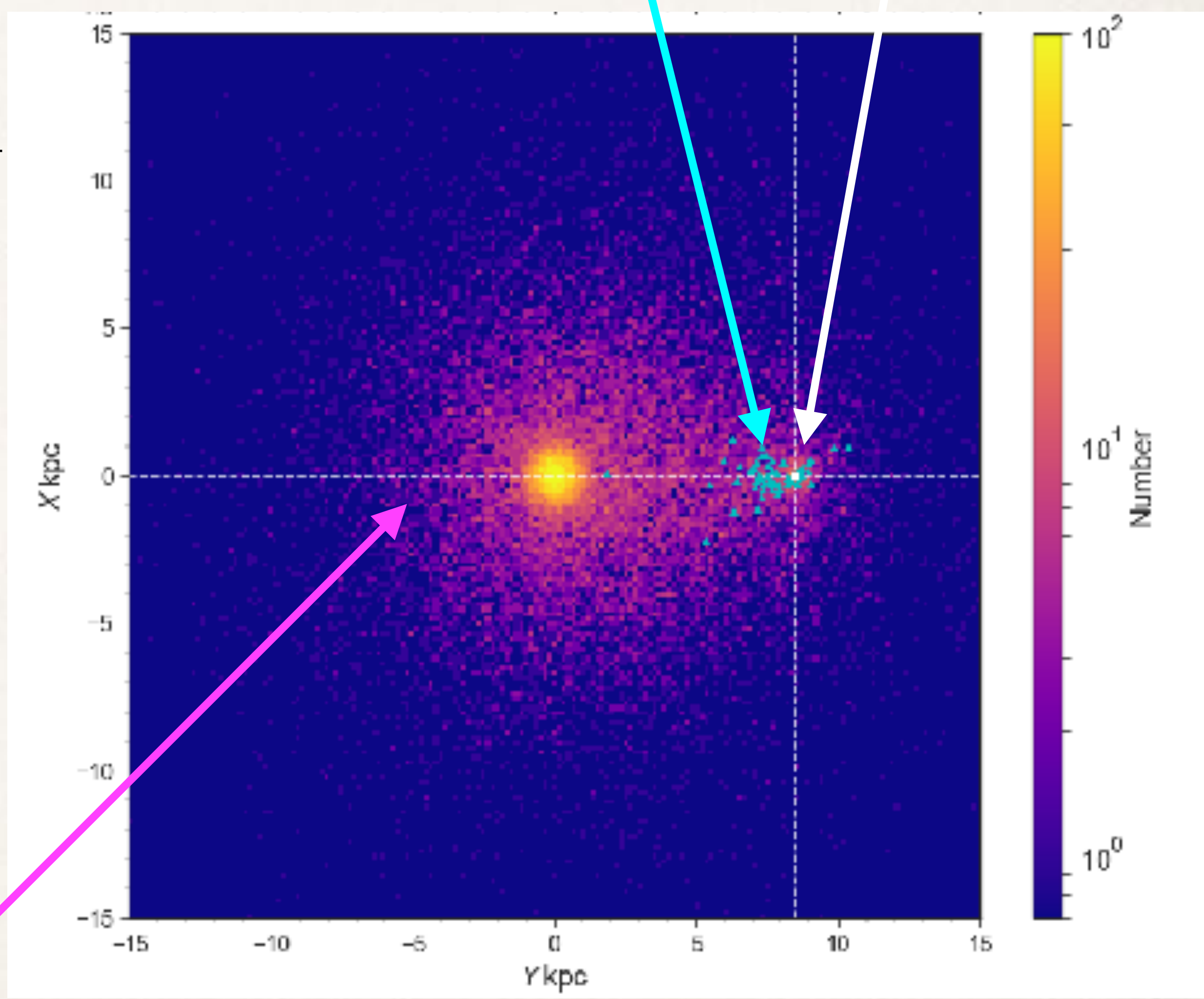
Optical Dwds

Sun



Opposite side of Milky Way!

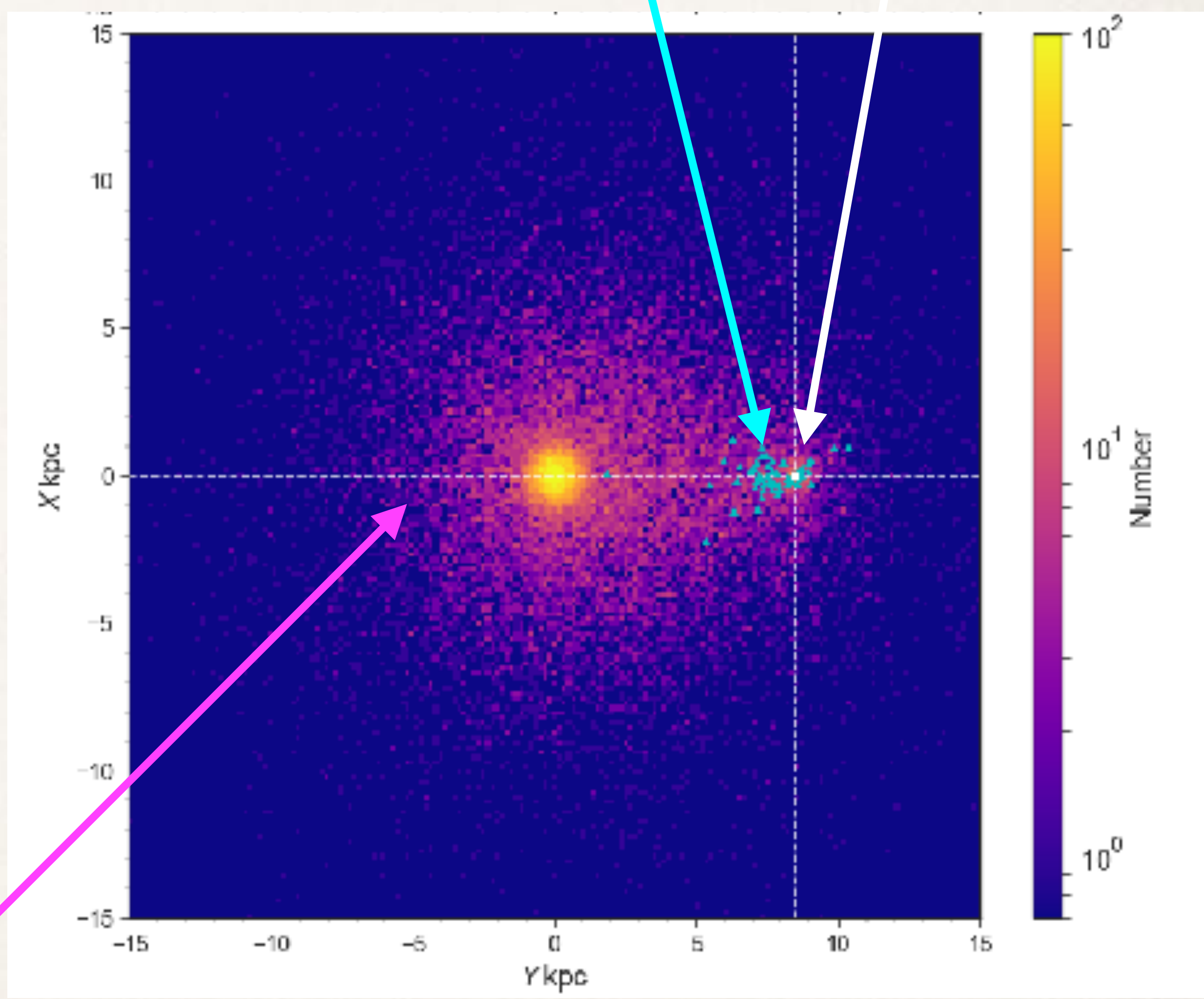
Korol+ 19

GW observations

- New era for double WDs:
  - LISA: ~25000 DWDs
  - Tracer of Galactic structure
  - Even the Local group (Korol +18)

Optical Dwds

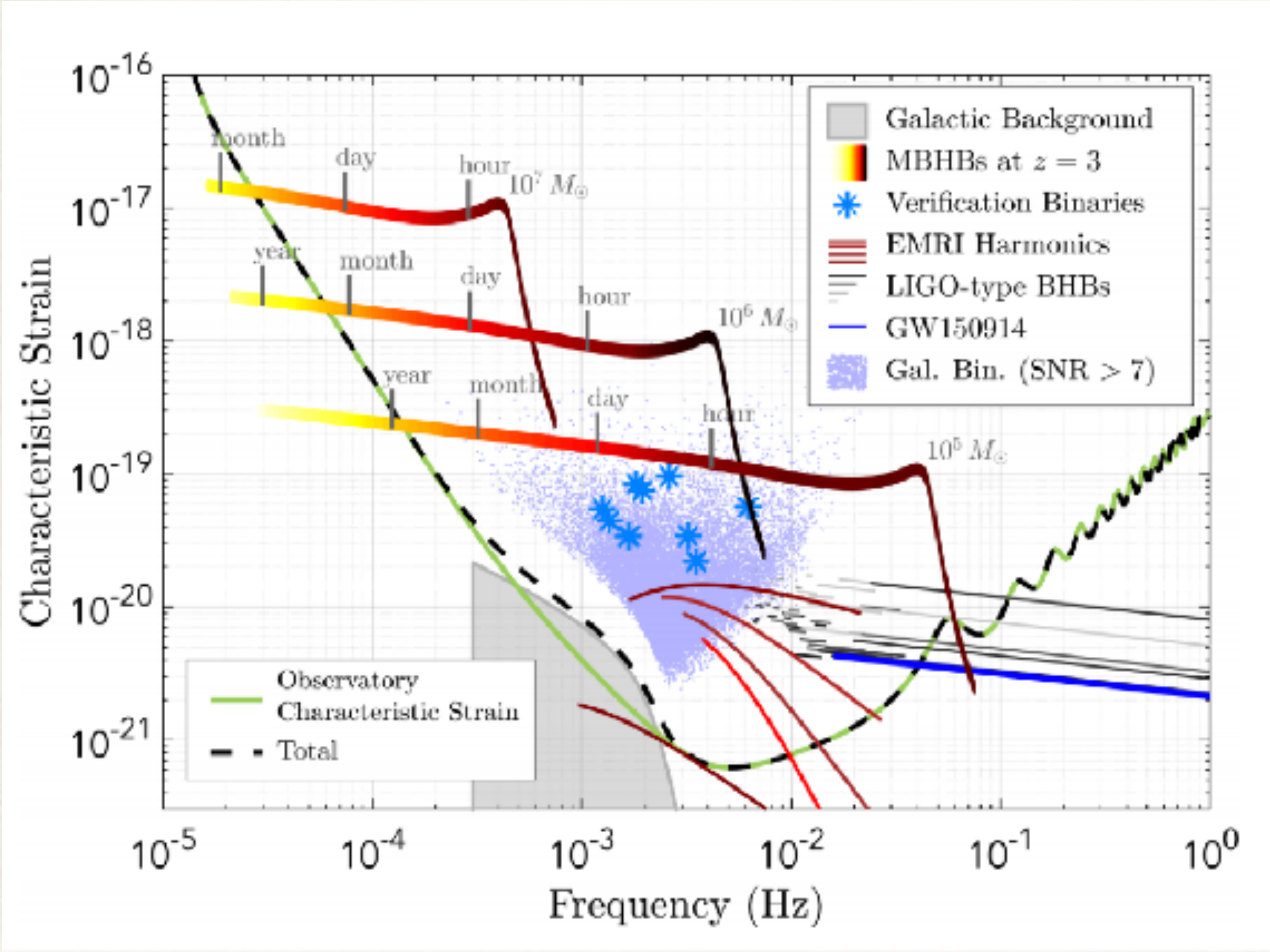
Sun



Opposite side of Milky Way!

Korol+ 19

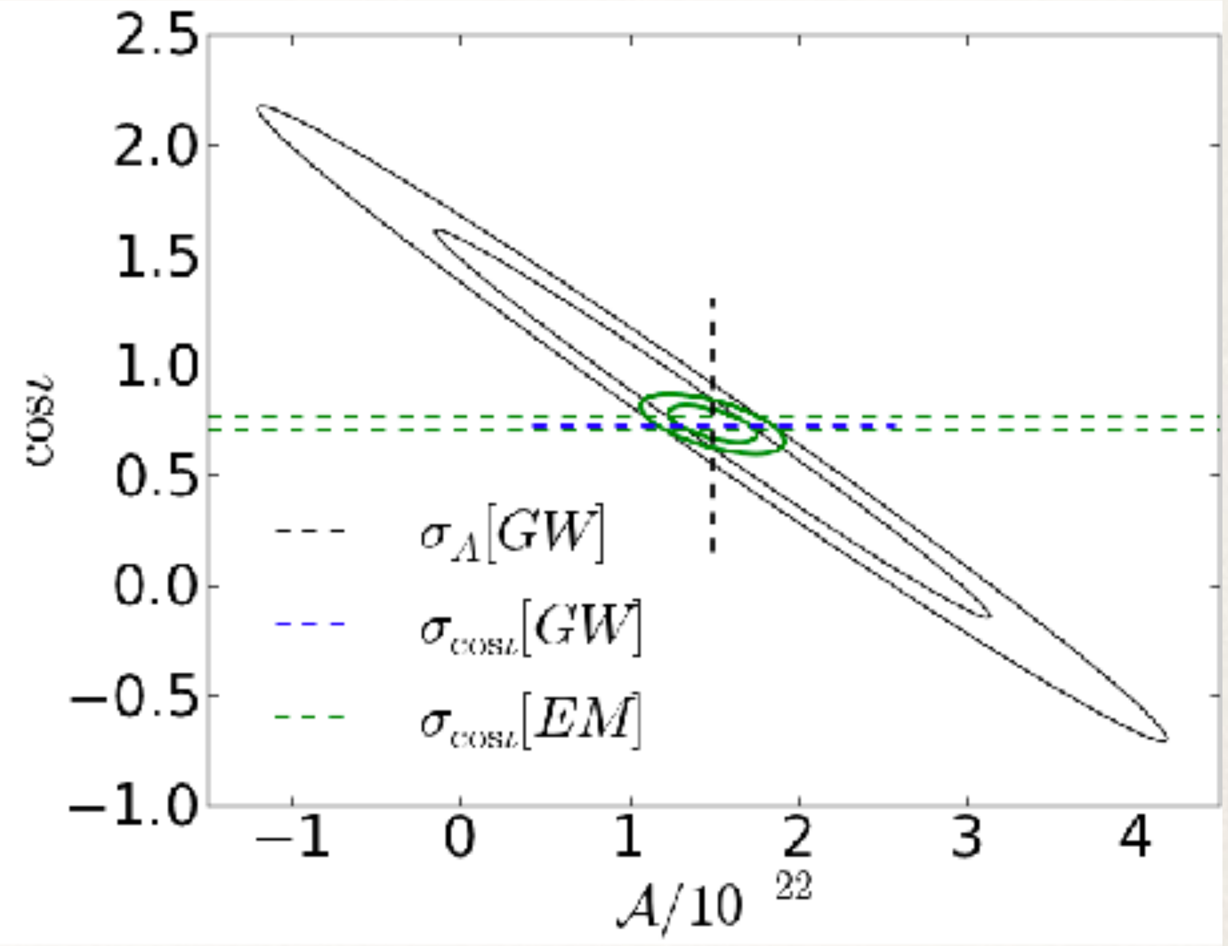
GW foreground



- Resolved vs unresolved
- $\Delta f_{lisa} = 1/T_{obs}$ ~8e-9Hz

Multimessenger binaries

- Observed in GW and Electromagnetic radiation
  - Improves parameter estimations (Shah+ 12,13,14)
  - From EM: inclination, sky position, distance



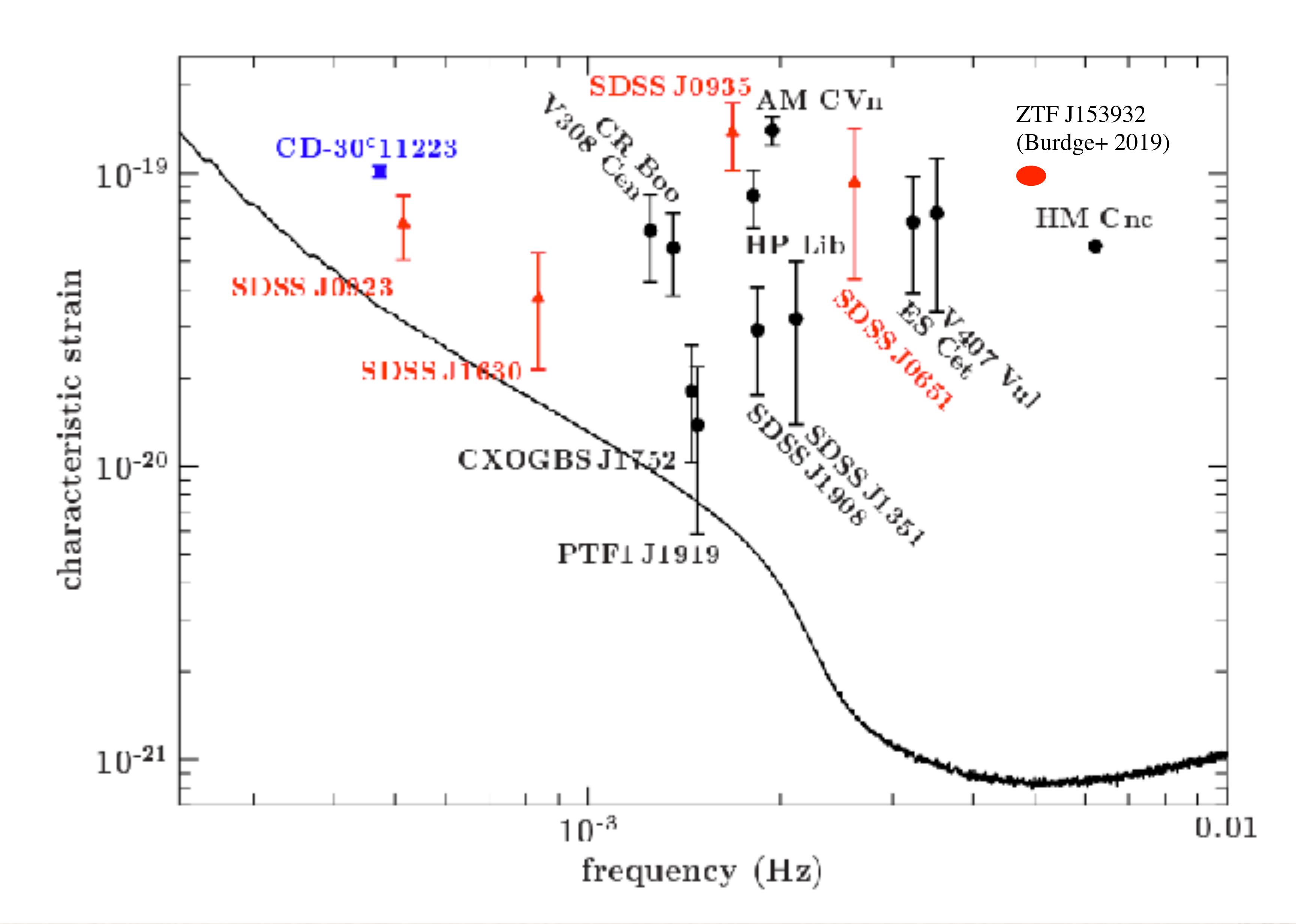
Verification binaries

Detached DWDs

DWDs undergoing mass transfer (AM CVn)

WD + stripped-envelope star

- Multimessenger sources
- 17 known to date (Many more to come e.g. Gaia, LSST, SDSS-V)
- Crucial for testing of space-based GW interferometers



Kupfer+ 15

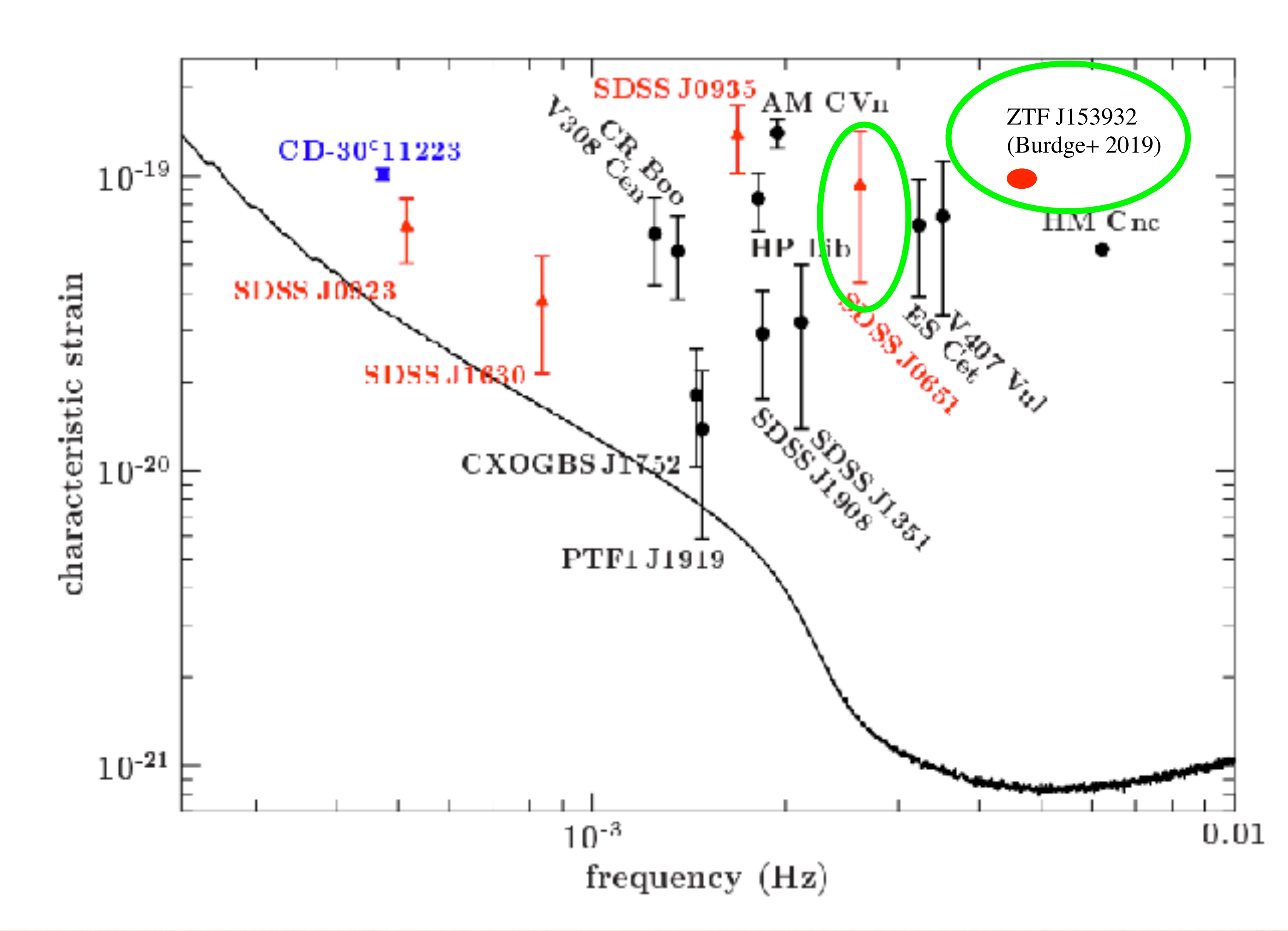
Verification binaries

Detached DWDs

DWDs undergoing mass transfer (AM CVn)

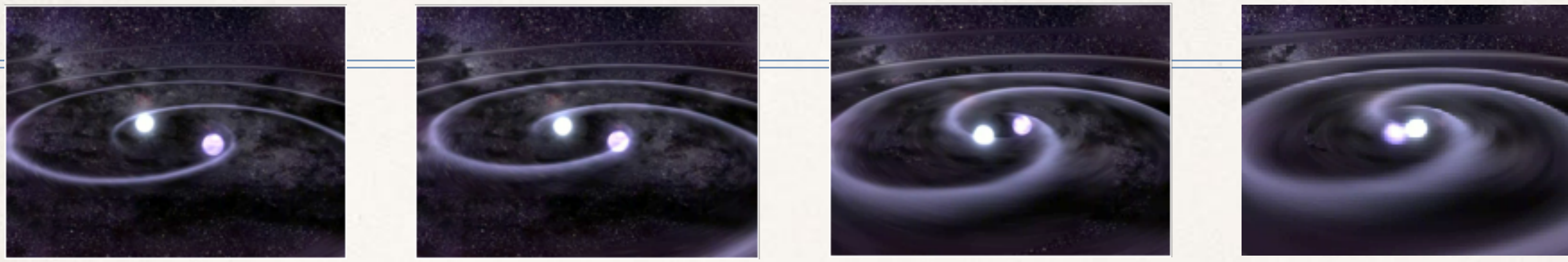
WD + stripped-envelope star

- Periods of 12.7 & 6.9 min!
- Visible with LISA within weeks!
- Eclipsing -> mass ratio, inclination



Kupfer+ 15

Orbital shrinkage



- Monochromatic vs chirping sources

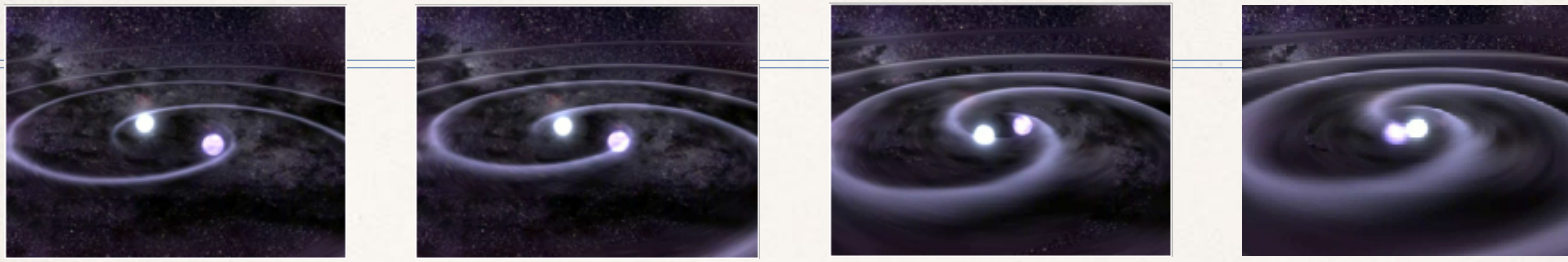
GW: $$\left\langle \frac{da}{dt} \right\rangle = -\frac{64}{5}\frac{G^3 \mu M^2}{c^5 a^3 (1-e^2)^{7/2}}\left(1+\frac{73}{24}e^2+\frac{37}{96}e^4\right)$$

$M = m_1 + m_2$

$\mu = m_1 m_2 / M$

Mass transfer: $\left\langle \frac{da}{dt} \right\rangle < 0$ & $\left\langle \frac{da}{dt} \right\rangle > 0$

Orbital shrinkage



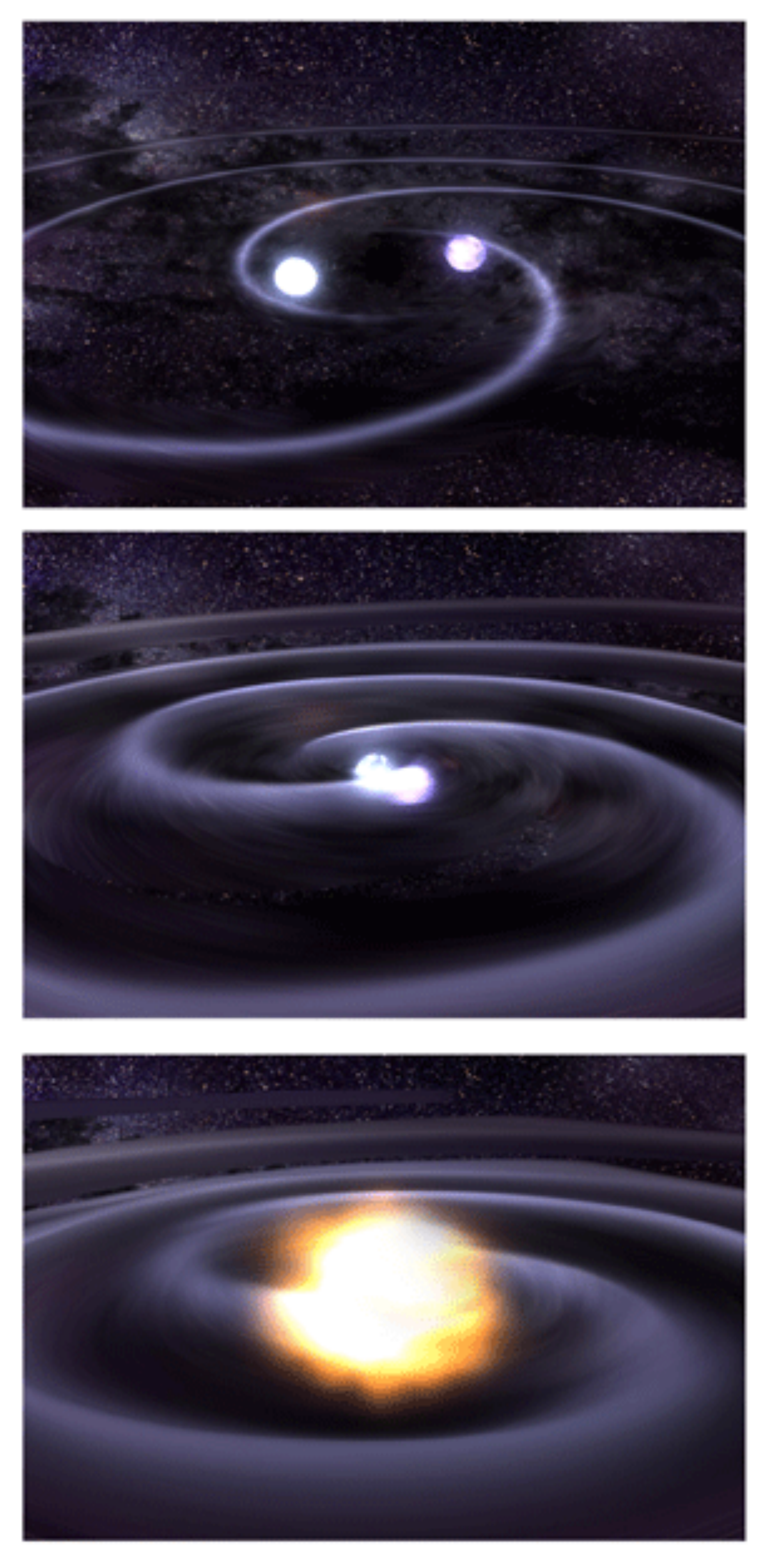
SDSS J0651

Hermes+ 19

Mergers with WDs

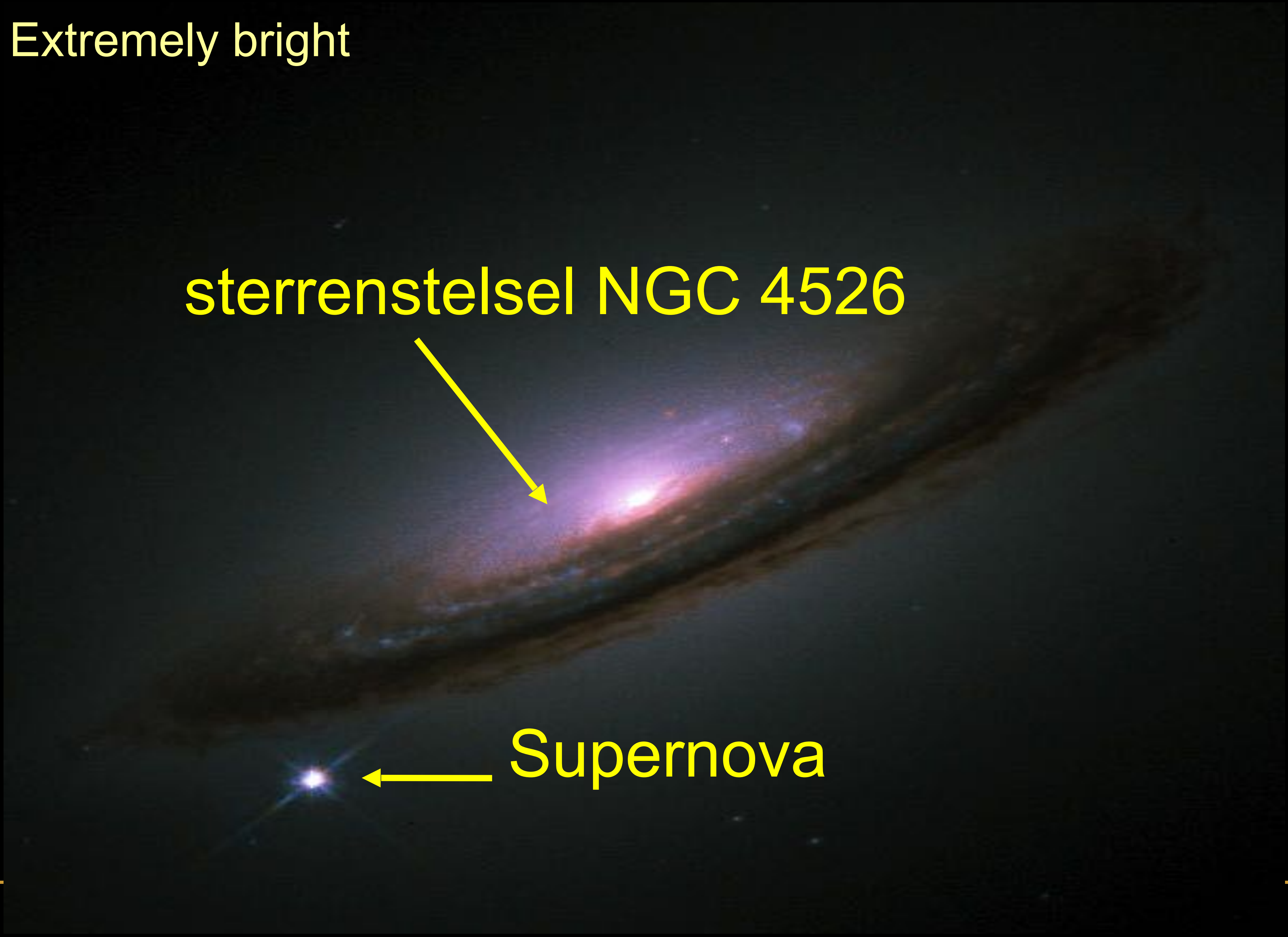
Transient events:

- Supernova type Ia
- Calcium-rich transients
- Birth of a RCrB star

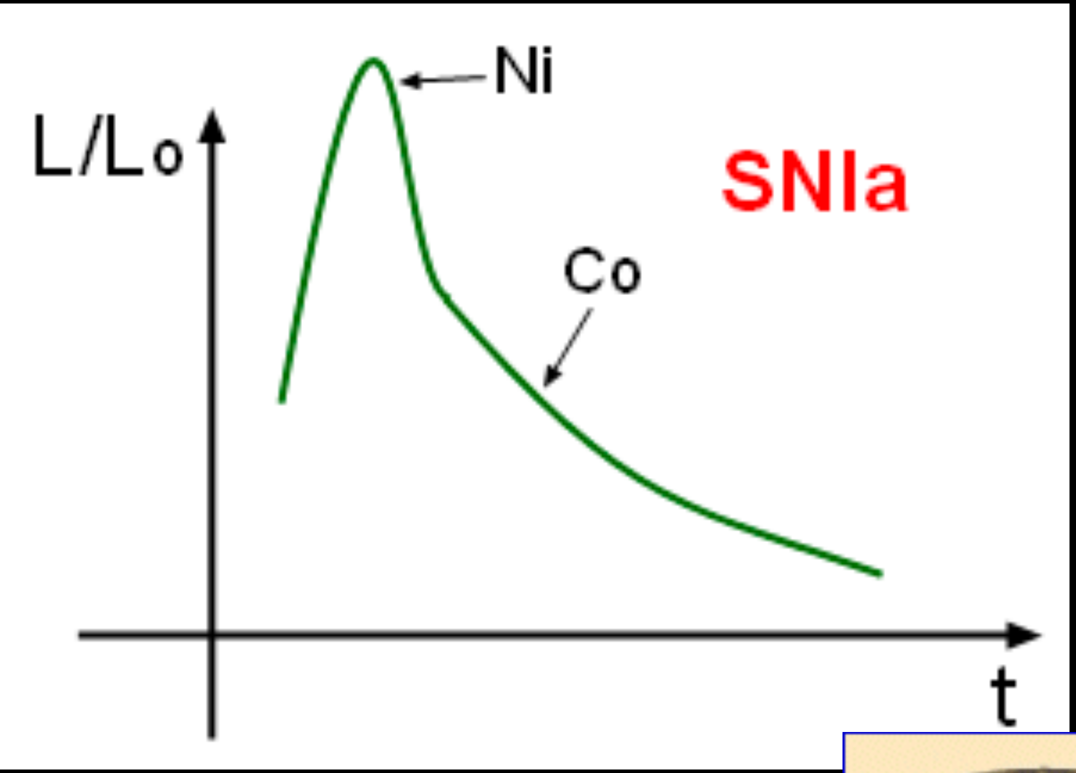


Supernovae Type Ia

Extremely bright

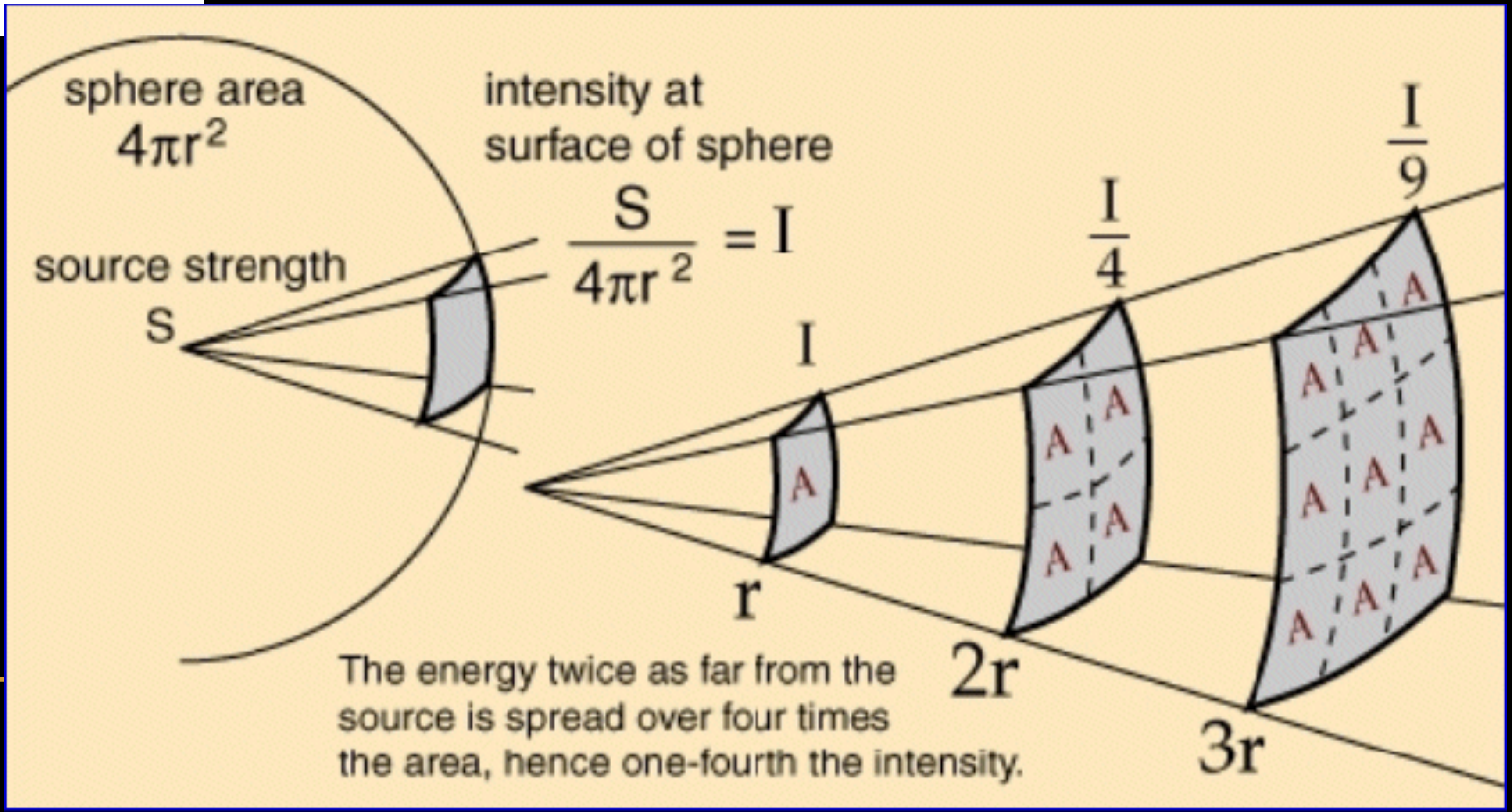


Distance measurement on cosmological scales



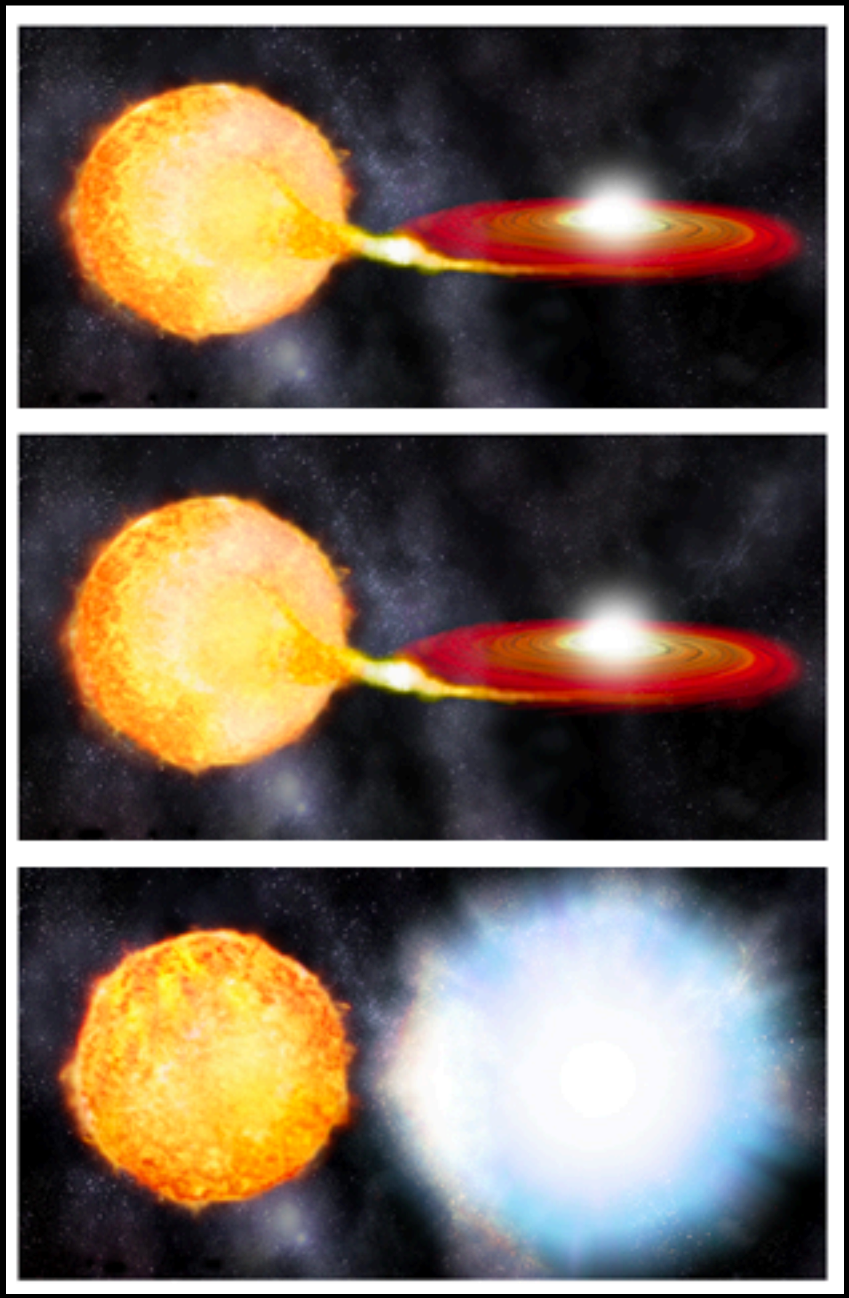
Standard(izable) candles

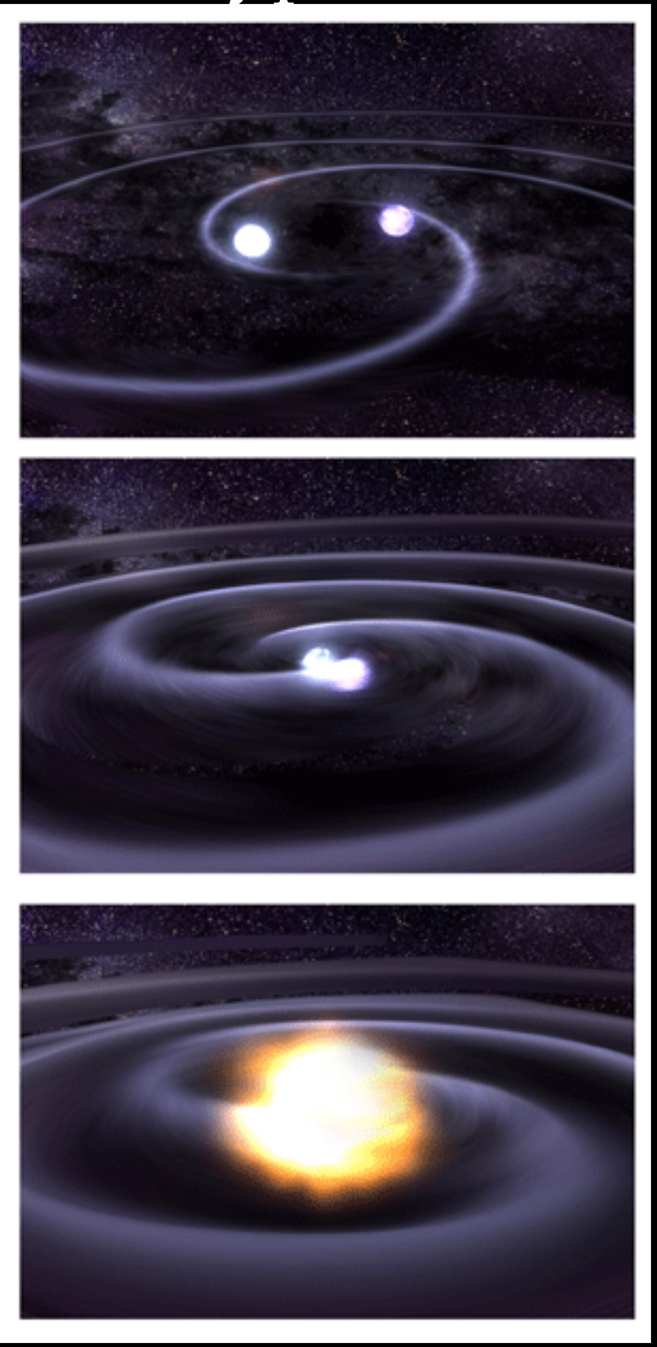
- Relation between peak brightness and light curve width
- First realised by: Bert Woodard Rust & Yury Pavlovich Pskovskii in 1970s
- Revised by Mark Phillips in 1993



Mystery…

What are the progenitors of supernova type Ia ?





Accretion

Mergers

Why study double white dwarfs?

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Gravitational waves:
Dominant sources at
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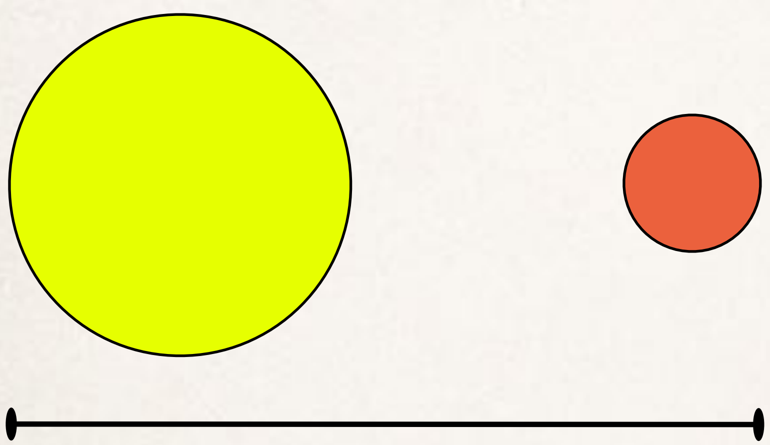
Stellar interaction:
Stellar and binary evolution
Mass transfer

Evolution towards compact orbit

Evolution towards compact orbit

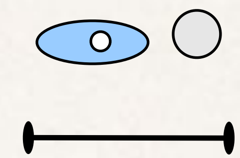
Normal stars



Few 1-1e6 Rsun

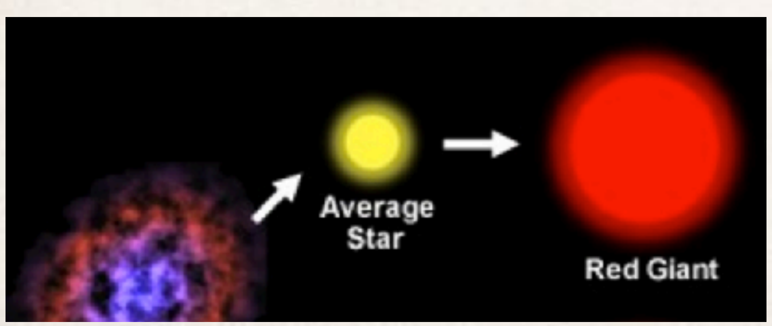
Ultracompacte

Binary



<0.5Rsun

Stellar evolution important!



Evolution towards compact orbit

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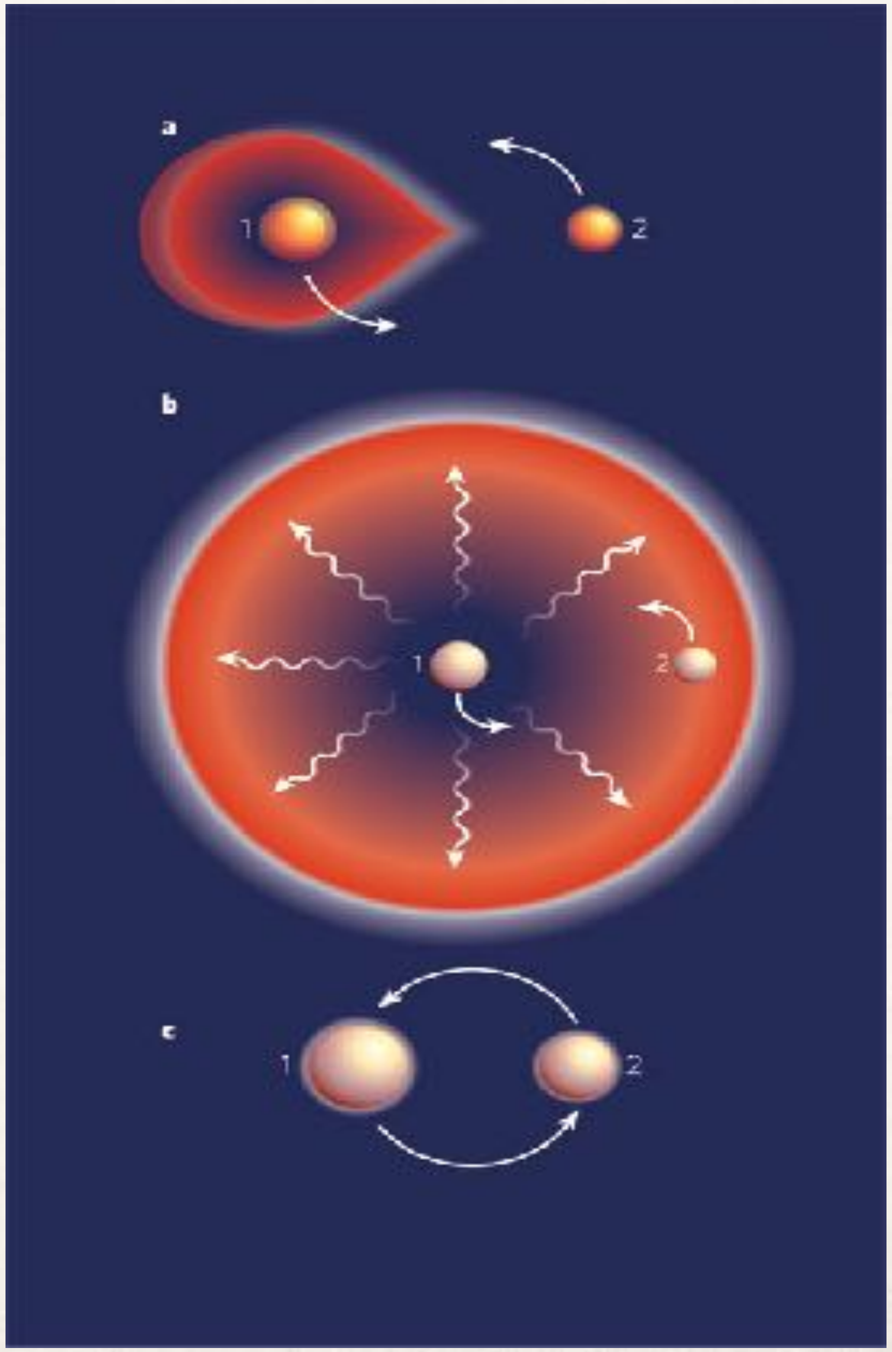
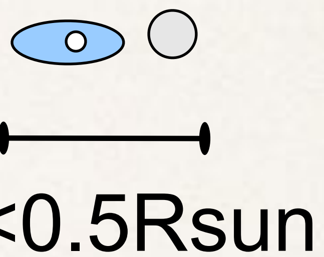


Ultracompacte

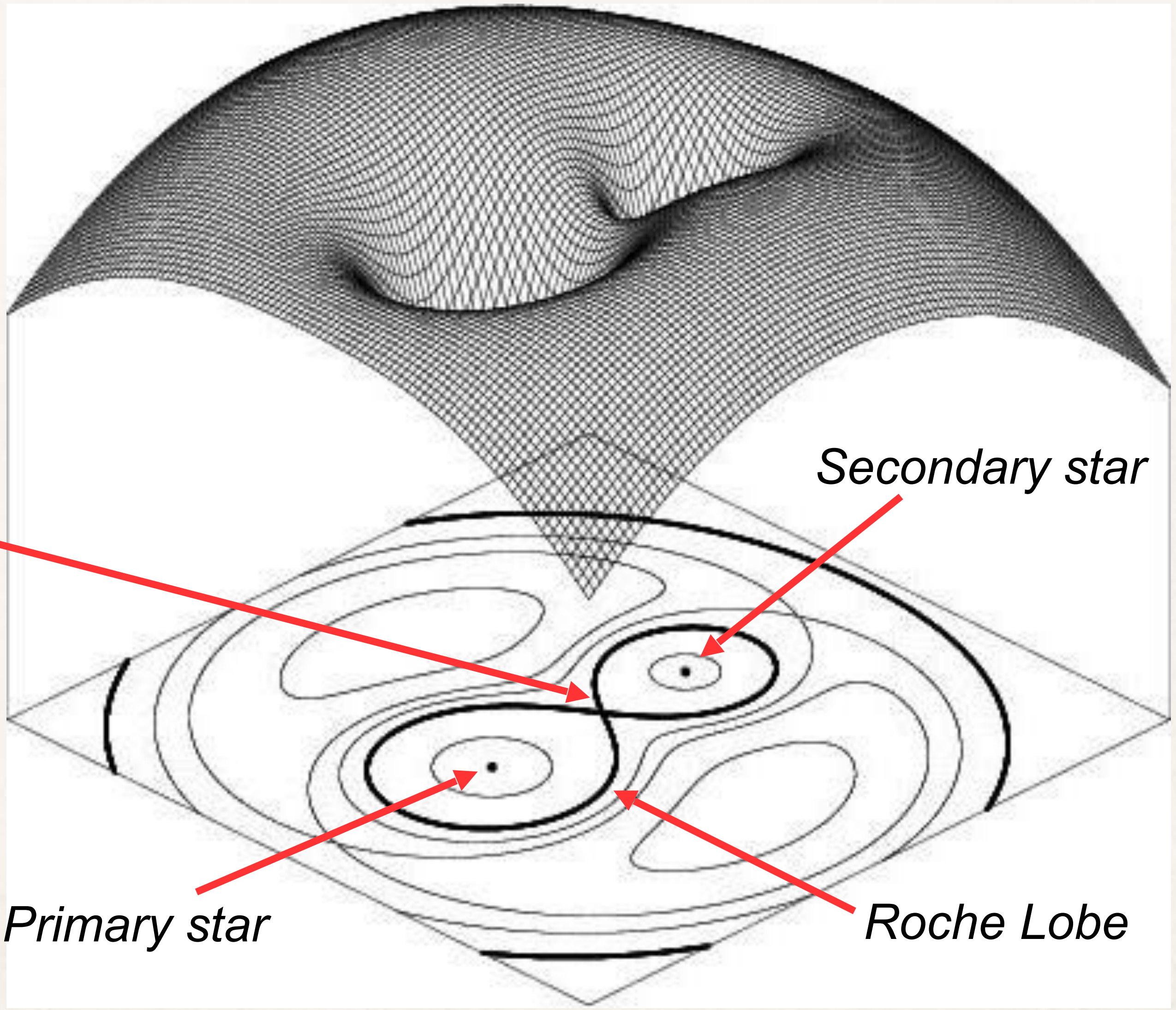
Binary



Roche geometry

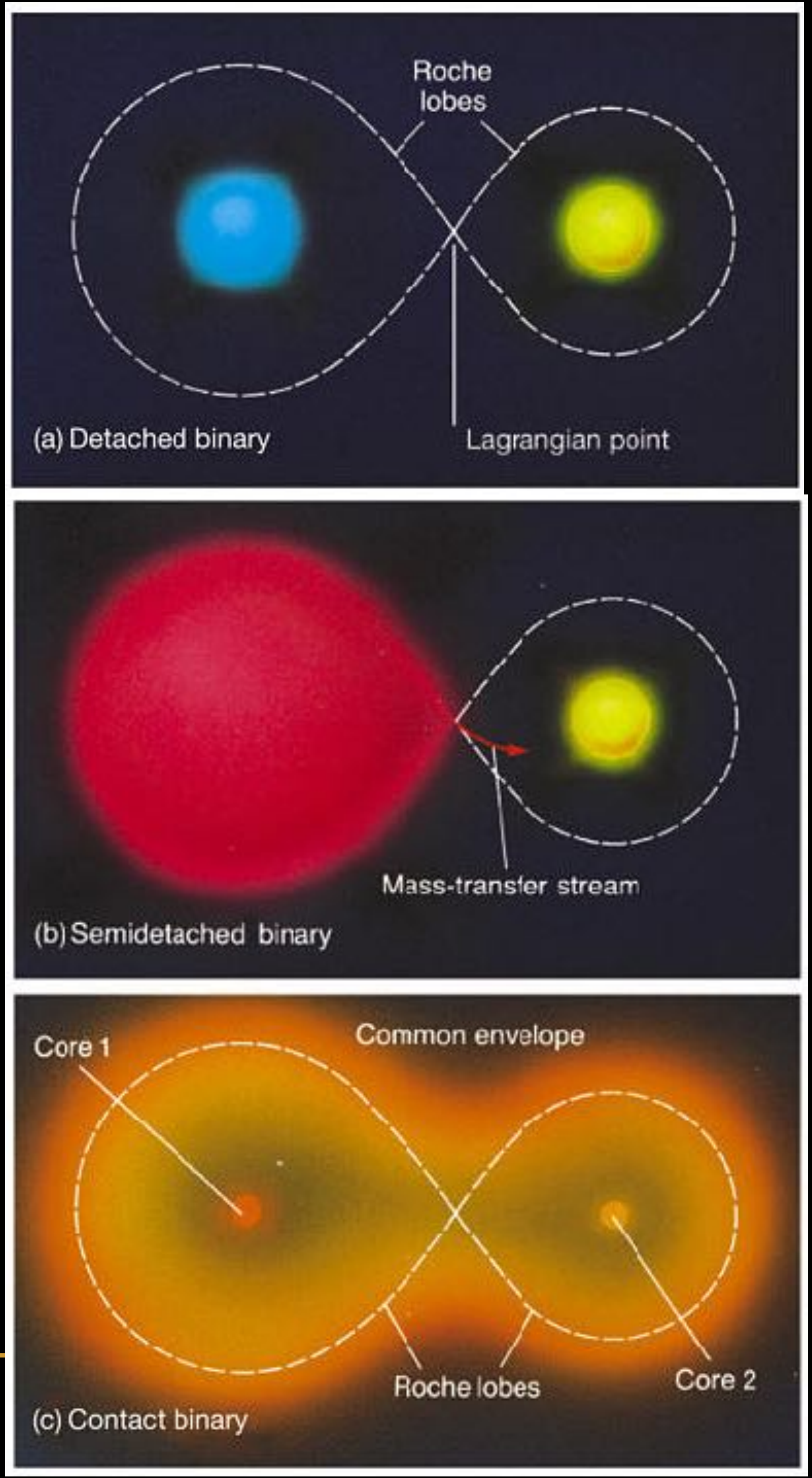
Lines = equal Gravitational pull

Potential surface

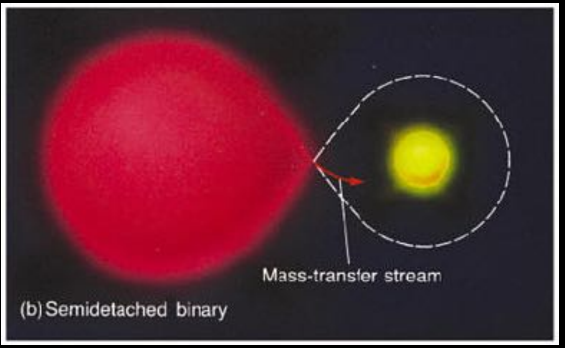


Types of binaries

- Depends on ratio of stellar radius to Roche lobe radius
  - Detached (Both within RL)
  - Semi-detached (one fills RL)
  - Contact (both fill RL)
- Limited volume in Roche lobe leads to mass transfer!



Semi-detached: Mass transfer



Angular momentum: $J^2 = \frac{G M_1^2 M_2^2}{M_1+M_2} a$

Conservative mass transfer:

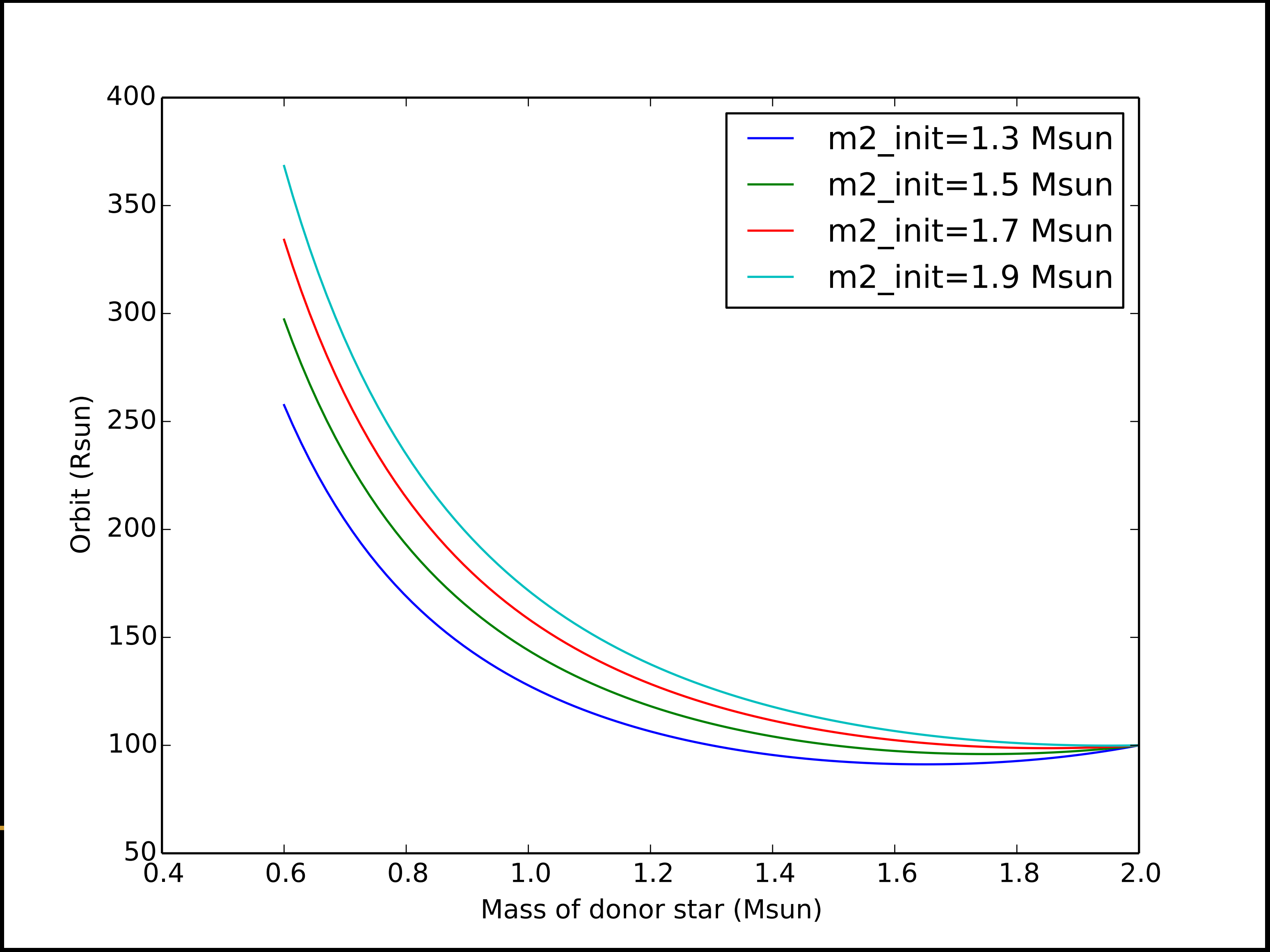
J conserved,

M_1+M_2 conserved

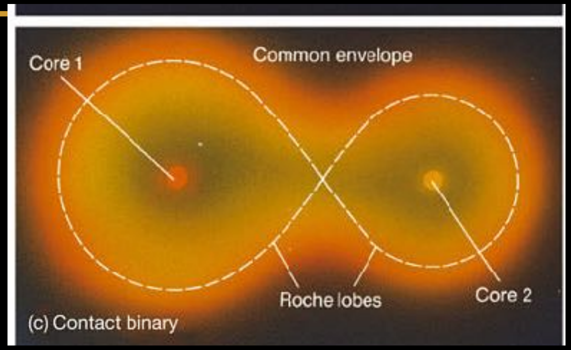
=>

$M_1^2 M_2^2 a$ = constant

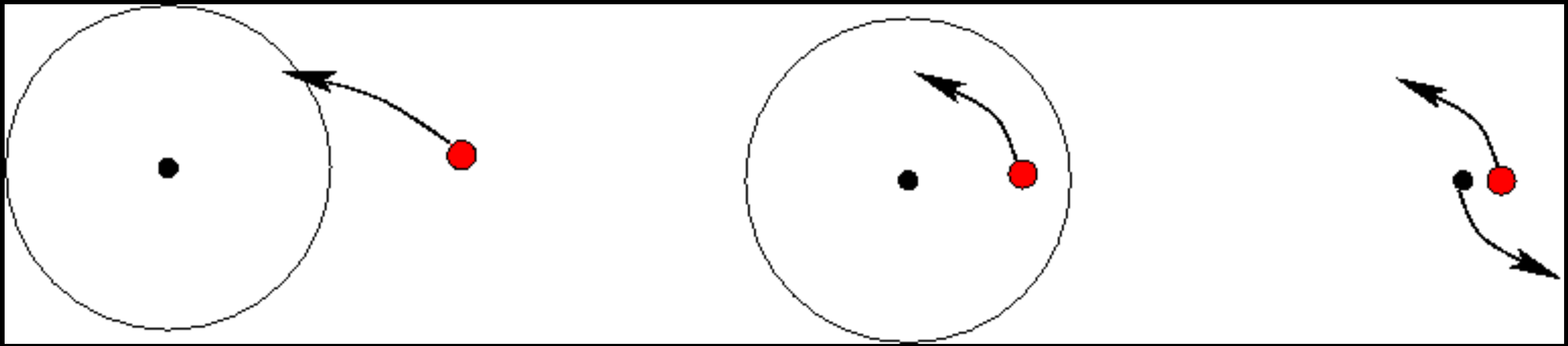
(Trivial to show!)



“Common-envelope”



- Sometimes the donor star enters into the envelope of the giant and spirals into the centre of the star



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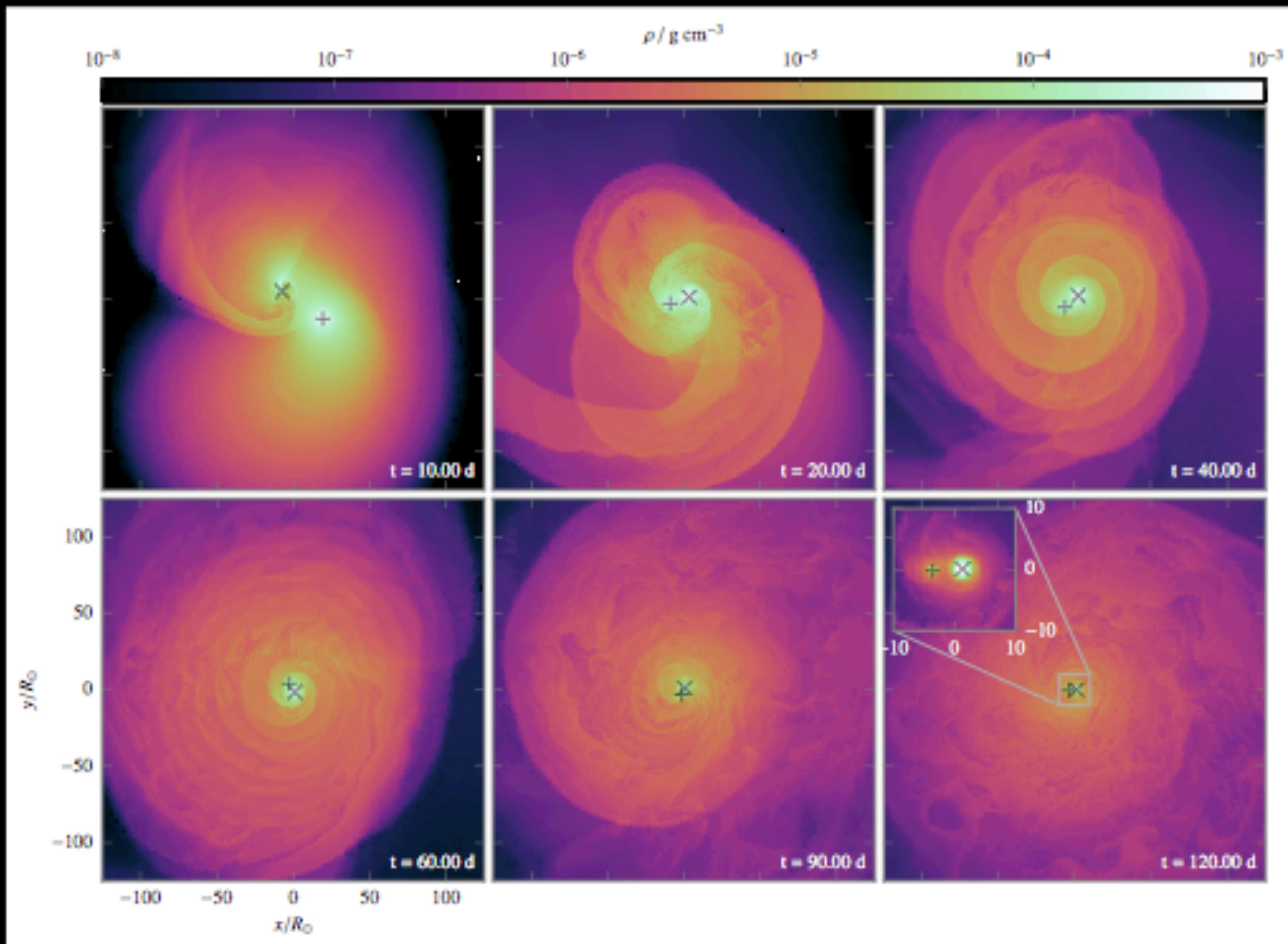

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