Astrophysics of gravitational waves sources

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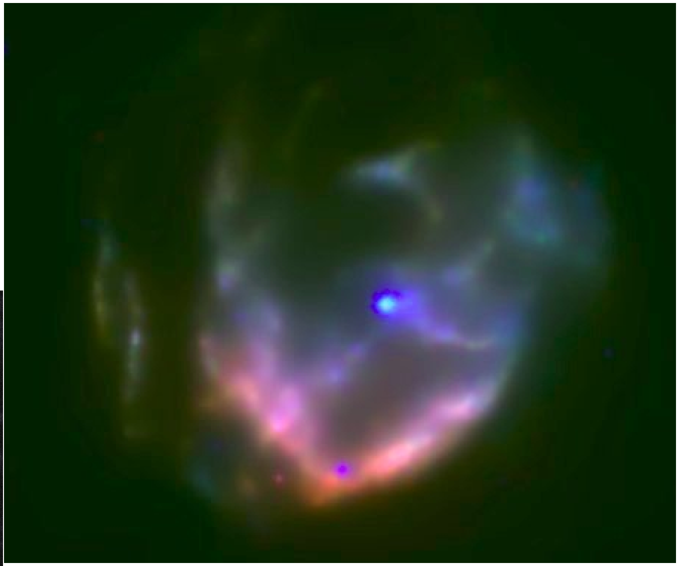
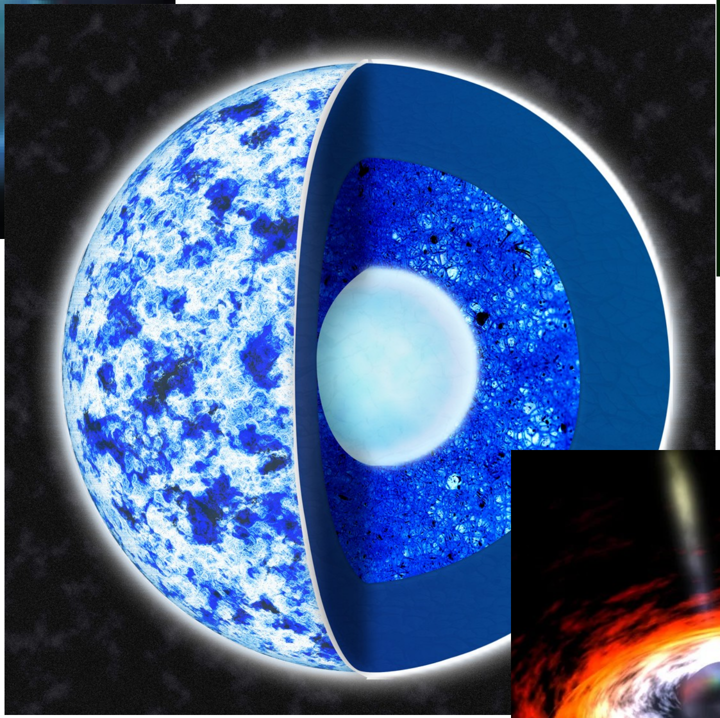
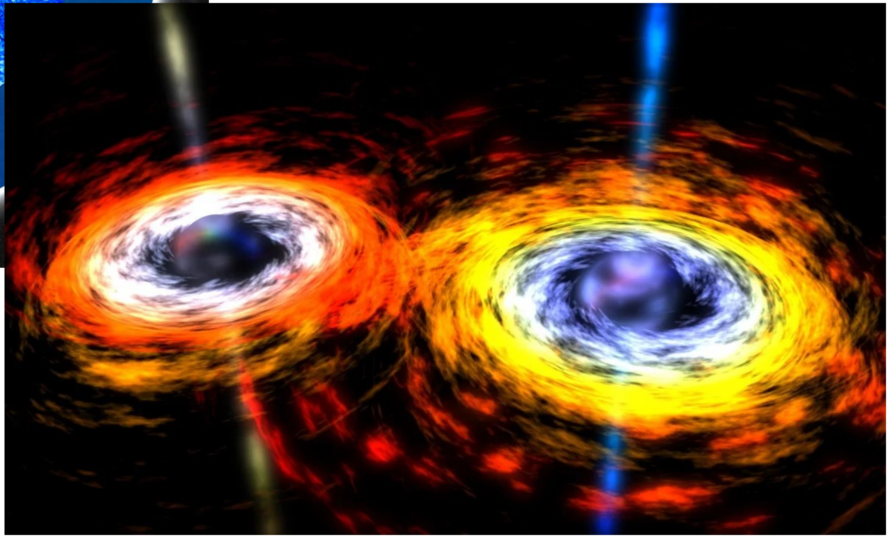
Subjects to discuss

- Stellar mass compact objects and their open questions
  - white dwarfs
  - neutron stars
  - black holes
- Supernovae
- Intermediate/supermassive black holes and structuration of Universe

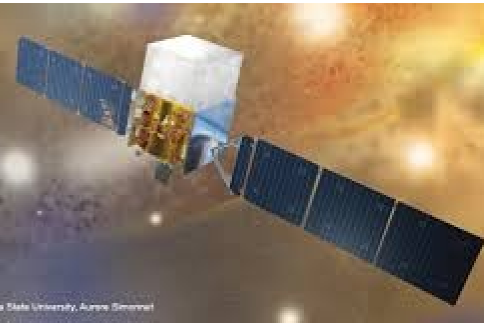
Gravitational wave sources

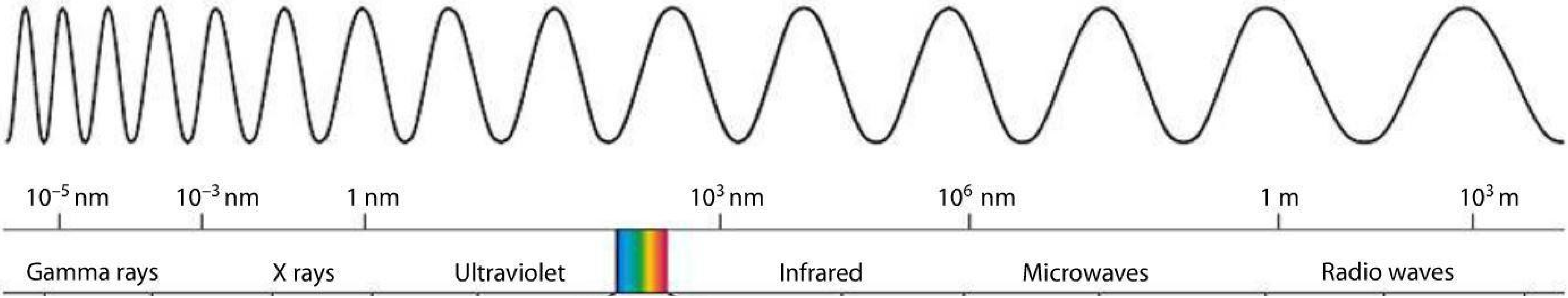




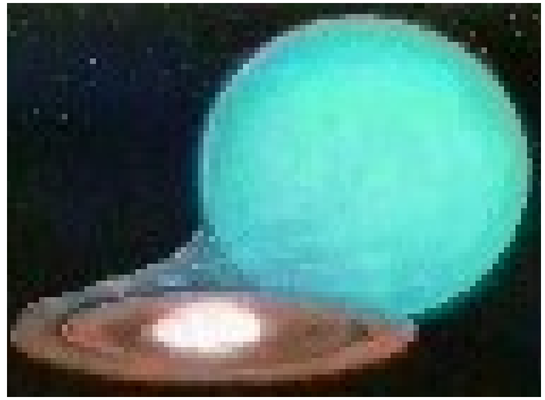


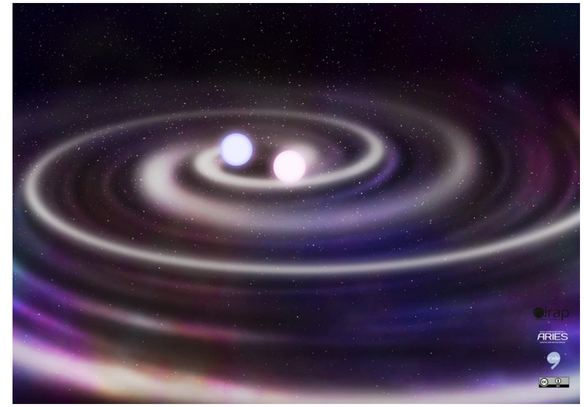
Current understanding largely from electromagnetic radiation





Compact objects



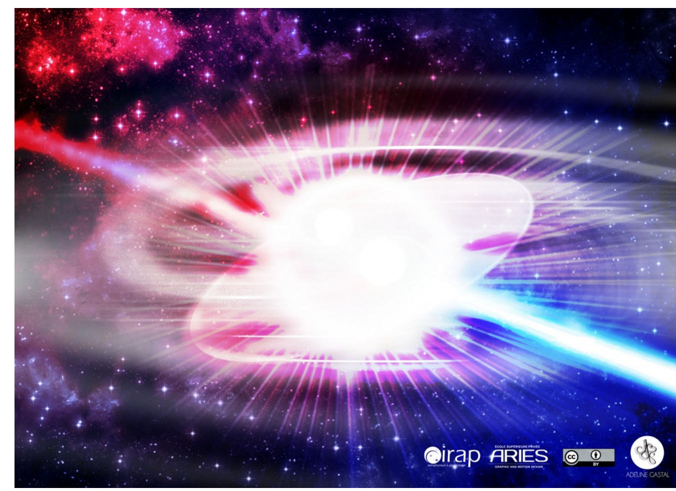


- AM CVns
- Double degenerates

White dwarf
- $< 1.4\ M_\odot$
- $0.002 – 0.02\ R_\odot$
- $\sim 1 \times 10^9$ kg m^{-3}

Neutron star
- $\sim 1.1 - 2.1\ M_\odot$
- ~12 km
- $\sim 5 \times 10^{17}$ kg m^{-3}

Black hole
- $\sim 3 – 80\ M_\odot$ (stellar mass)
- Schwarzschild/Kerr/…. radius



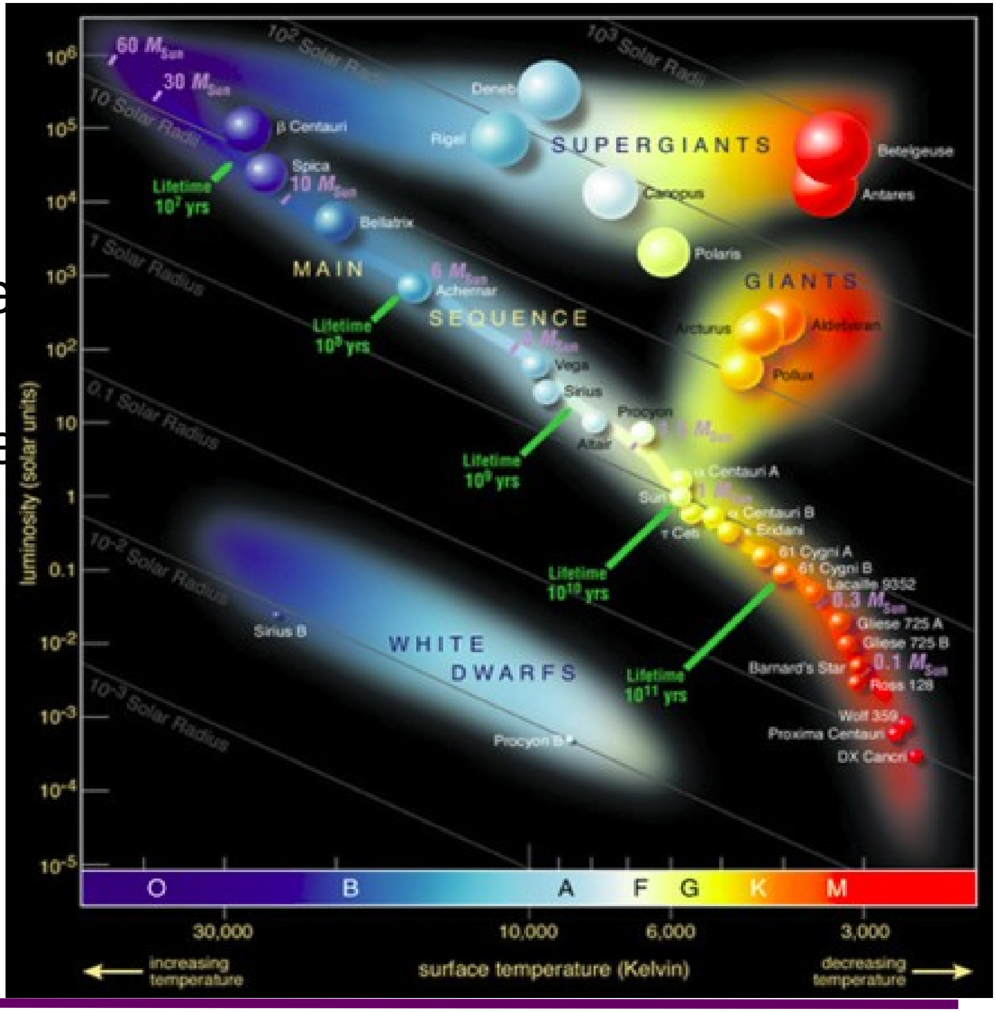
Intermediate mass: $10^2\ M_\odot <$ Mass $< 10^5\ M_\odot$

Supermassive : $10^6\ M_\odot <$ Mass $< 10^{10}\ M_\odot$

White dwarfs

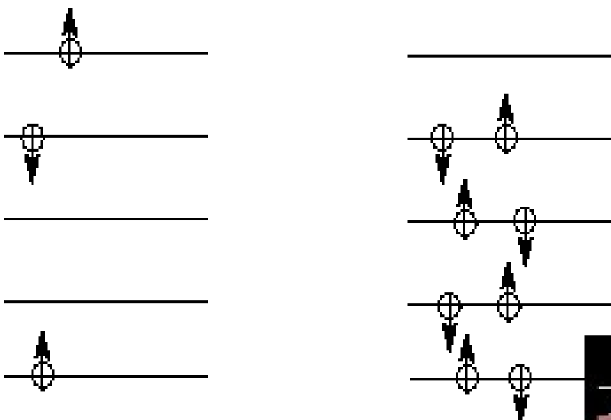
- William Herschel detected first white dwarf, 40 Eridani B (Herschel 1785)
- Adams (1915) showed Sirius' companion was ~1 $M_\odot$ but L ~ L_{40EriB} => small
- ~Flat optical spectrum + small radius led to name *white dwarf* (Luyten 1922)
- 56000 WDs confirmed via spectroscopy (Dufour et al. 2017)

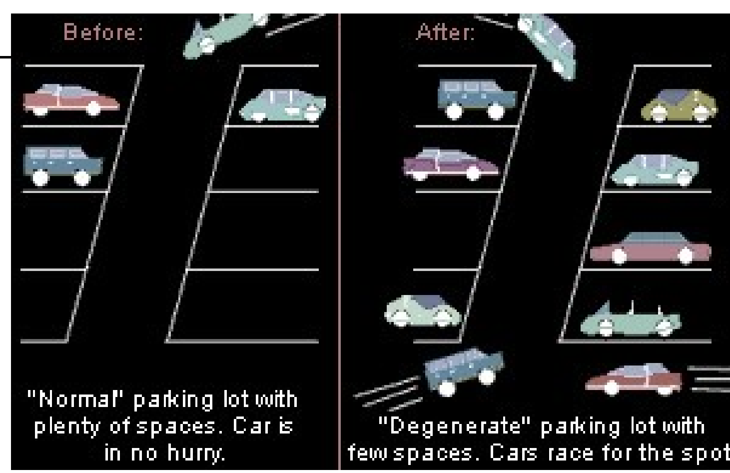
- Fusion ceases when ~10% core H used
- Force due to gravity > radiation pressure
- Star collapses
- Central temperature & pressure increase
- If T ~10^8 K, helium can fuse
- Balance is re-established
- Star becomes a red giant
- He → C, O until fuel exhausted
- Red giant becomes planetary nebula

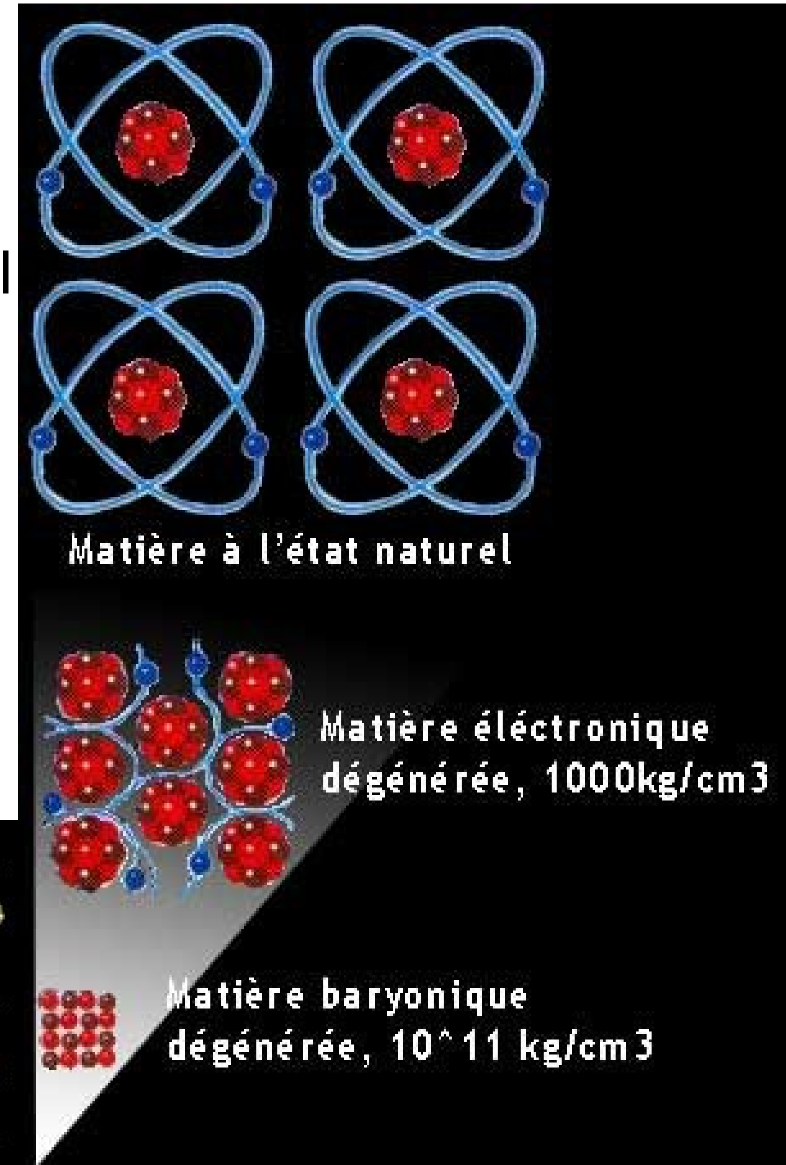


White dwarfs

- Pauli exclusion principal states two electrons (2 fermions) can not be in same quantum state
- Electrons obey Heisenberg uncertainty principal $\Delta p \, \Delta x \geq \hbar$
- Momentum for each electron is $p \sim \Delta p \sim \hbar / \Delta x$







Simplified description of degenerate electrons

If the electron density is n_e , the electron separation is $x \sim n_e^{-1/3}$, so the momentum for each electron is :

$$p \sim \hbar n_e^{1/3}$$

Rewriting pressure as a function of momentum (p), and using the fact that kinetic energy is :

$0.5mv^2 = 1.5\ NkT$ for an ideal gas

⇒ $0.333\ mv^2 = NkT$ and $P = NkT/V$ et $p=mv$
⇒ $0.333\ pv/V = P$ and $n_e \sim V^{-1}$
⇒ $0.333\ n_e pv = P$

where

$$P = \frac{1}{3} n_e p v = \frac{1}{3} n_e p \left(\frac{p}{m_e} \right)$$

White dwarf pressure

So the pressure is given by :

$$P = \frac{1}{3} n_e p v = \frac{1}{3} n_e p \left(\frac{p}{m_e} \right)$$

Using $p \sim \hbar n_e^{1/3}$

$$\longrightarrow P = \frac{1}{3} n_e \left(\hbar n_e^{1/3} \right) \left(\frac{\hbar n_e^{1/3}}{m_e} \right) \sim n_e^{5/3} \sim \rho^{5/3}$$

So for a degenerate gas,

$$P \sim \rho^{5/3}$$

Chandrasekhar mass

If the electron speed approaches the speed of light : $P = \frac{1}{3} n_e \left(\hbar n_e^{1/3}\right) c \sim n_e^{4/3} \sim \rho^{4/3}$

The relativistic case is then :

$$P_c \simeq P_{e,rel}$$

$$\rho^2 R^2 \sim \rho^{4/3}$$

$$R^2 \sim \rho^{-2/3}$$

$$R^2 \sim \frac{M^{-2/3}}{R^{-2}}$$

$$1 \sim M^{-1/3}$$

Hydrostatic equilibrium :

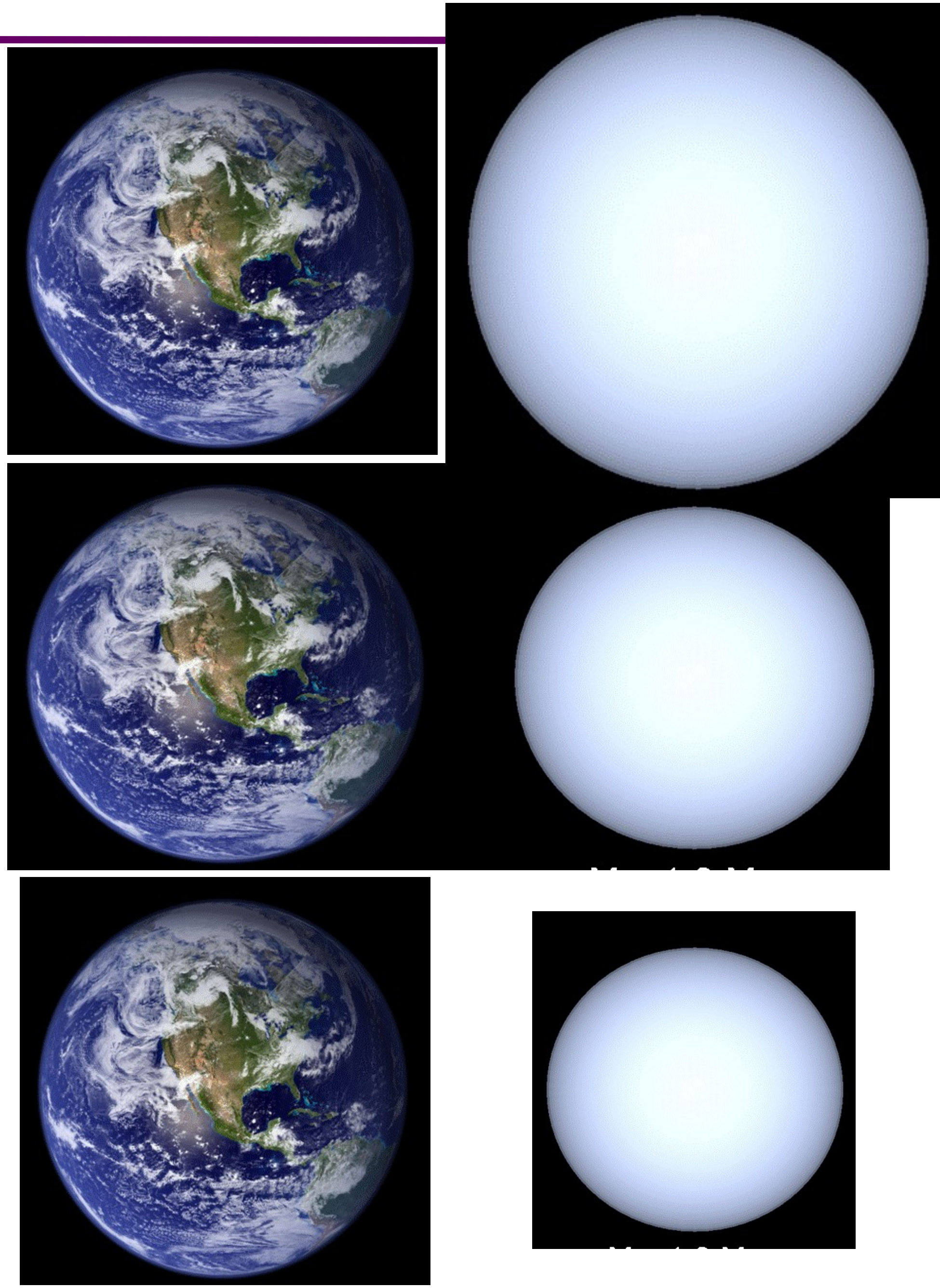
$$\frac{dP}{dr} = -\frac{GM\rho}{r^2} = -\frac{G\,(4/3\,\pi\, r^3\rho)\rho}{r^2} = -G\, 4/3\,\pi\, r\,\rho^2$$

$$P_c = \int_0^R -4/3\, G\,\pi\, r\,\rho^2\, dr$$

$$= -2/3\, G\,\pi\, R^2\,\rho^2$$

- The nucleus has a maximum mass of 1.4 M_{solar} the *Chandrasekhar mass* after Subrahmanyan Chandrasekhar (Chandrasekhar, 1934)

White dwarf size (for diff. masses) compared to Earth

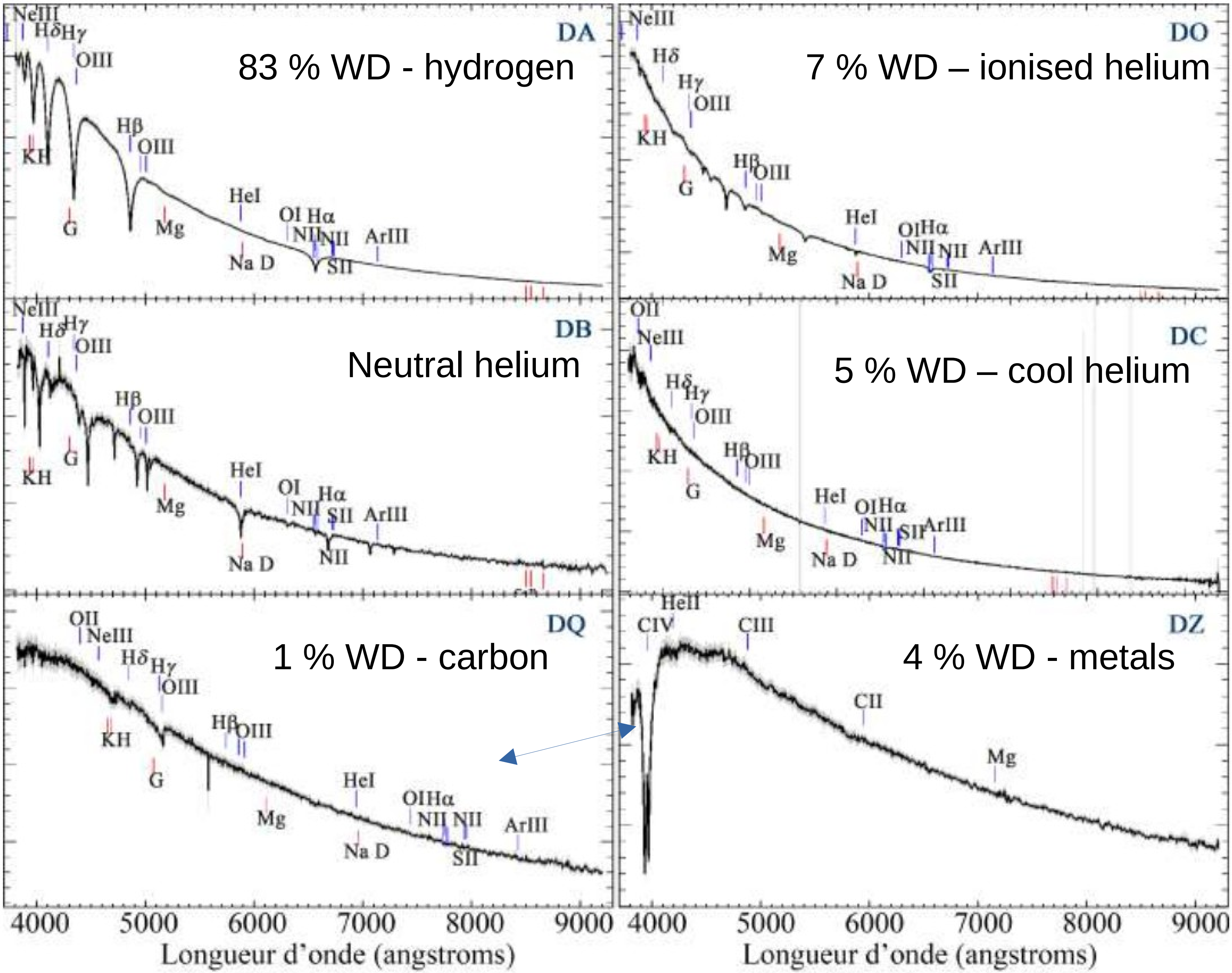


~0.5 $M_\odot$

~1.0 $M_\odot$

~1.3 $M_\odot$

Types of white dwarf (WD) – strongly stratified atmospheres

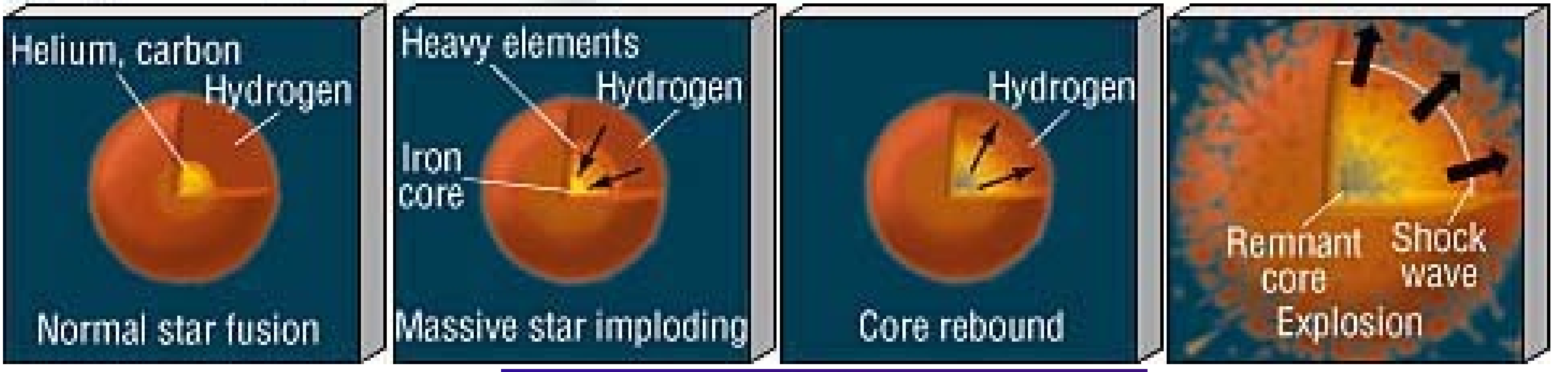


Why study white dwarfs ?

- Understand stellar evolution for the lower mass stars
- Determine the initial mass function of stars (in our Galaxy, elsewhere, …)
- Study degenerate matter, may help to better understand their tidal disruption
- Deduce the origin of the magnetic field
- Comprehend their rôle in the evolution of globular clusters
- By understanding their cooling, we can constrain the age of the Universe
- Improve understanding of type Ia supernova (for cosmological distances)

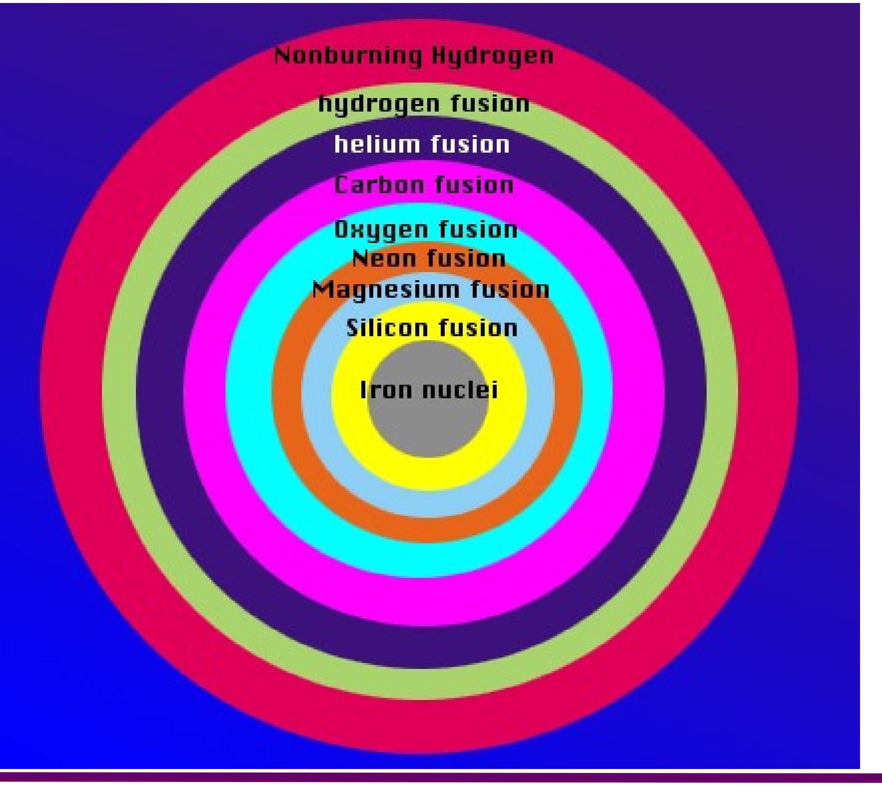
- Essential to find the double degenerates to improve LISA background model
- Also use brightest gravitational wave sources as verification binaries
- Vera Rubin Observatory (LSST) should find 2000 - >12000 expected with LISA (Lamberts et al. 2019)

Forming neutron stars from stars ≥ 8 $M_\odot$

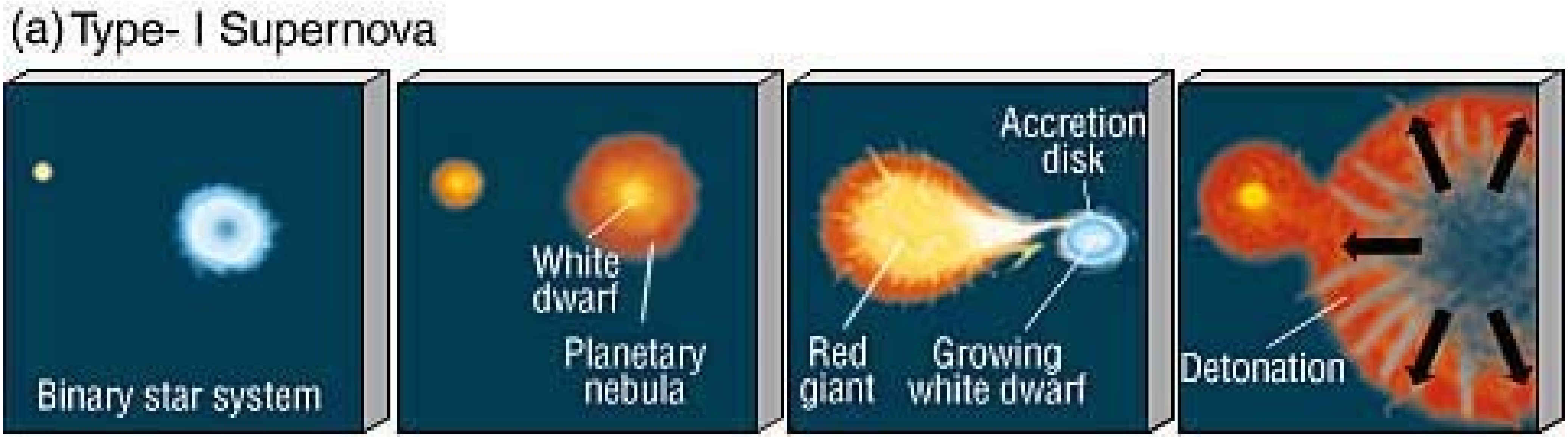


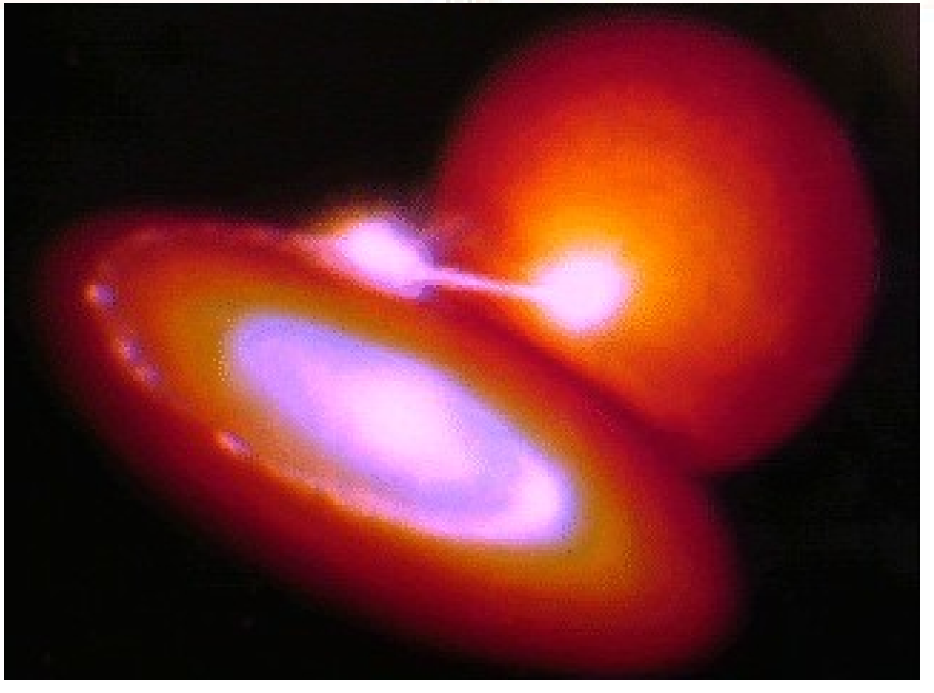
Supernovae type II

- Many different types
- Study lightcurve to understand
- Further observations required to understand explosion mechanism

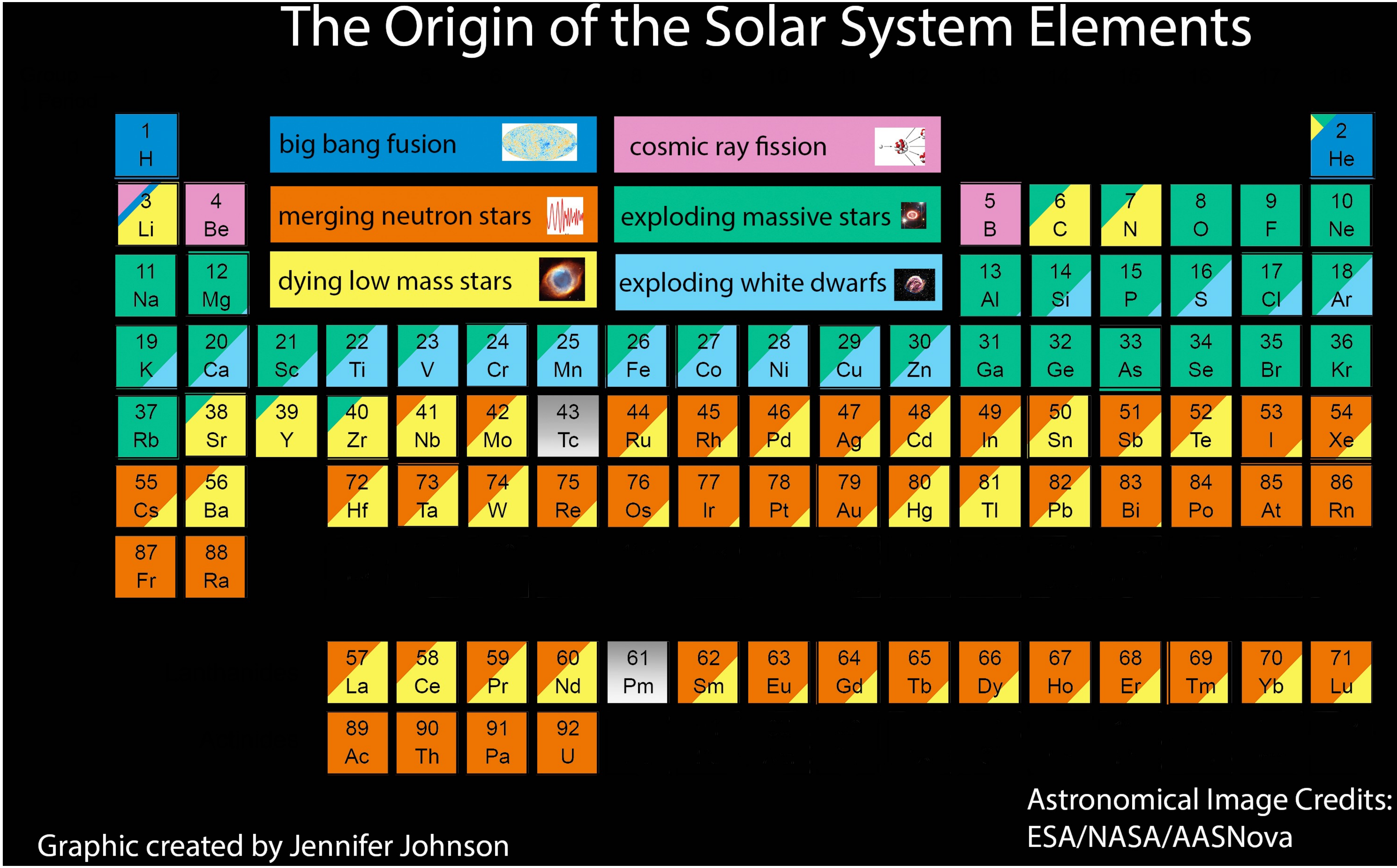


Forming neutron stars from white dwarfs





Understanding the creation of the elements



Neutron stars

- Neutron stars first proposed by Baade & Zwicky (1934)
- First detected (Sco X-1) by Giacconi et al. (1962) and identified by Shklovskii (1967). First pulsar found same year (Hewish et al. 1968).
- Stars of M $\gtrsim$9 M$_\odot$ can evolve to form neutron stars (e.g. Heger et al. 2003)
- For ρ>10^7 g cm^{-3} electrons have energies > $\mathrm{m}_n\mathrm{c}^2$ - $\mathrm{m}_p\mathrm{c}^2 = 1.294$ MeV
- Electrons are forced into the atomic nucleus,combine with protons (inverse β decay) and the neutron star cools via ν loss $e^- + p \rightarrow n + \nu_e$
- At densities of 3 x 10^{11} g cm^{-3} neutrons are forced out of the core and stabilise the neutron star (baryonic degeneracy)
- If the chemical potential of the electrons > the muon rest mass, electrons can disintegrate into muons producing ν_e and $\nu_{\bar{\mu}}$ in the general β-decay
- If the density reaches 2-3 times the nuclear density (ρ∼ 2.3 × 10^{14} g cm^{-3}), the strong force between nucleons can provoke apparition of new particles, e.g. hyperons (baryons with three quarks and ≥ 1 is a strange quark)
- The Einstein equation can be rewritten as a system of 1st order differential equations called *TOV* (Tolman, 1939; Oppenheimer et Volkoff, 1939)
- Resolving these equations provides the neutron star equation of state

Neutron stars

White dwarfs to neutron stars:

ρ_{labo} — 10^4 — 10^7 — 3.2×10^{11} — ρ (g/cm³)

No neutronisation | Neutronisation of the nucleii | Neutron drip

$$M(A,Z) + e^- \rightarrow M(A,Z-1) + \text{neut}$$

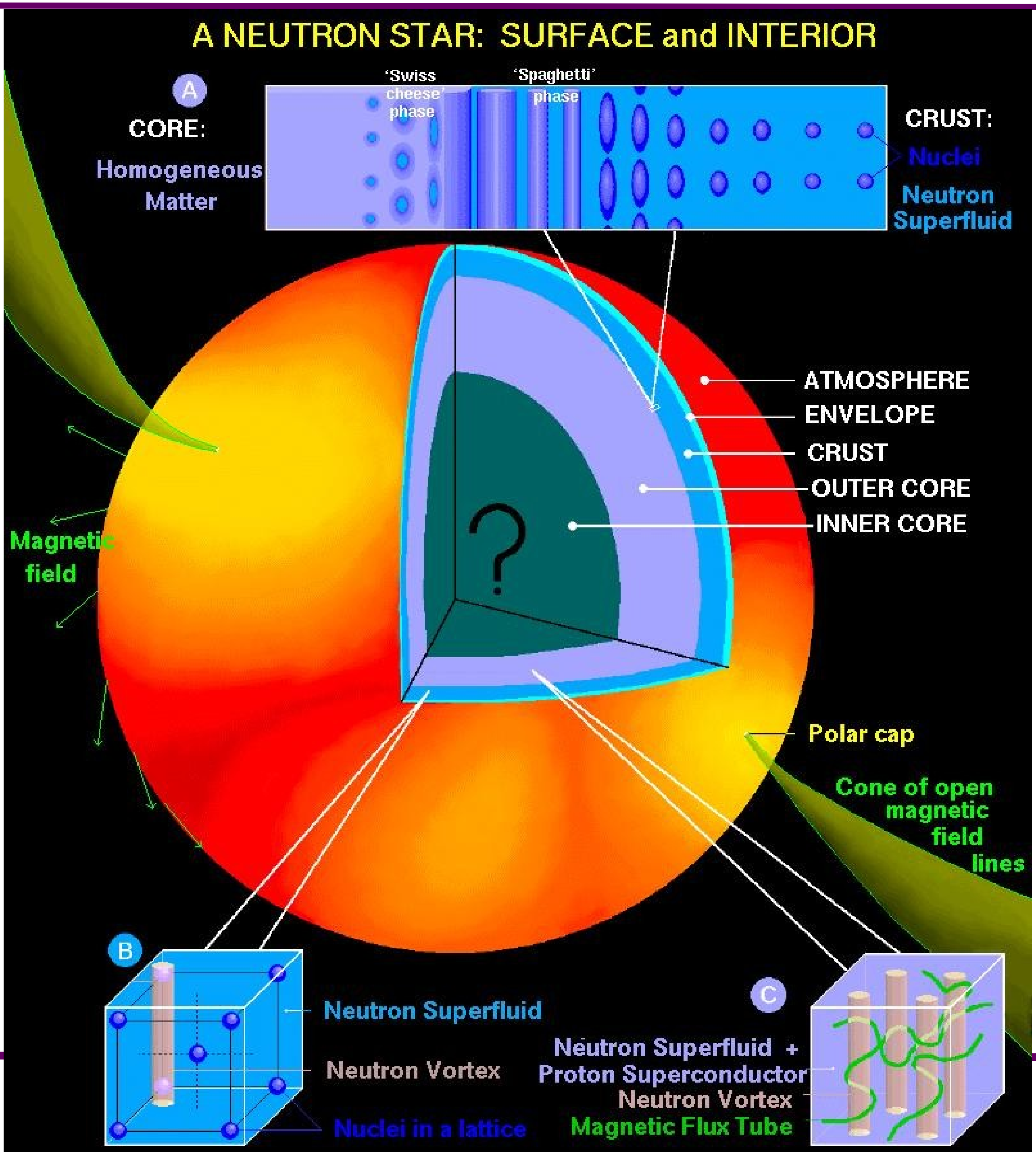
$$p^+ + e^- \rightarrow n + \text{neut}$$

$$M(A,Z) \rightarrow M(A-1,Z) + n$$

- Provokes catastrophic energy loss from system (absorption and emission of neutrinos)
- Collapse of matter in this regime

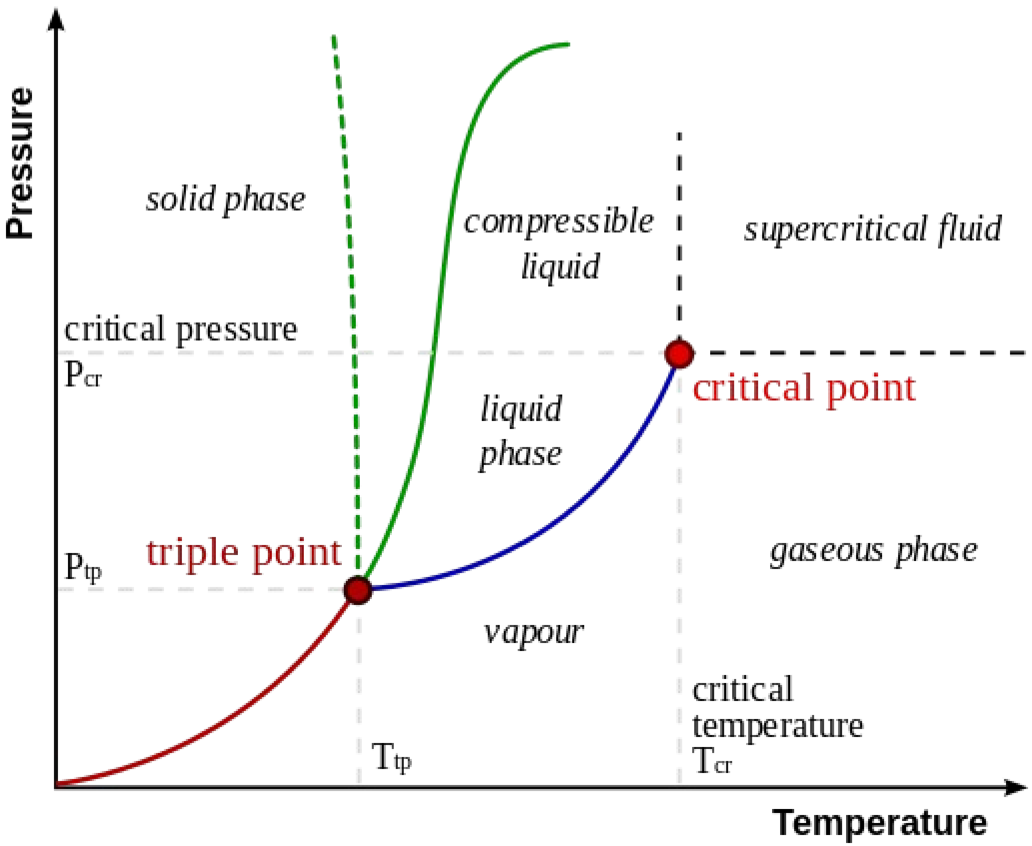
- Allows free and stable neutrons
- Stops further collapse

Neutron star structure

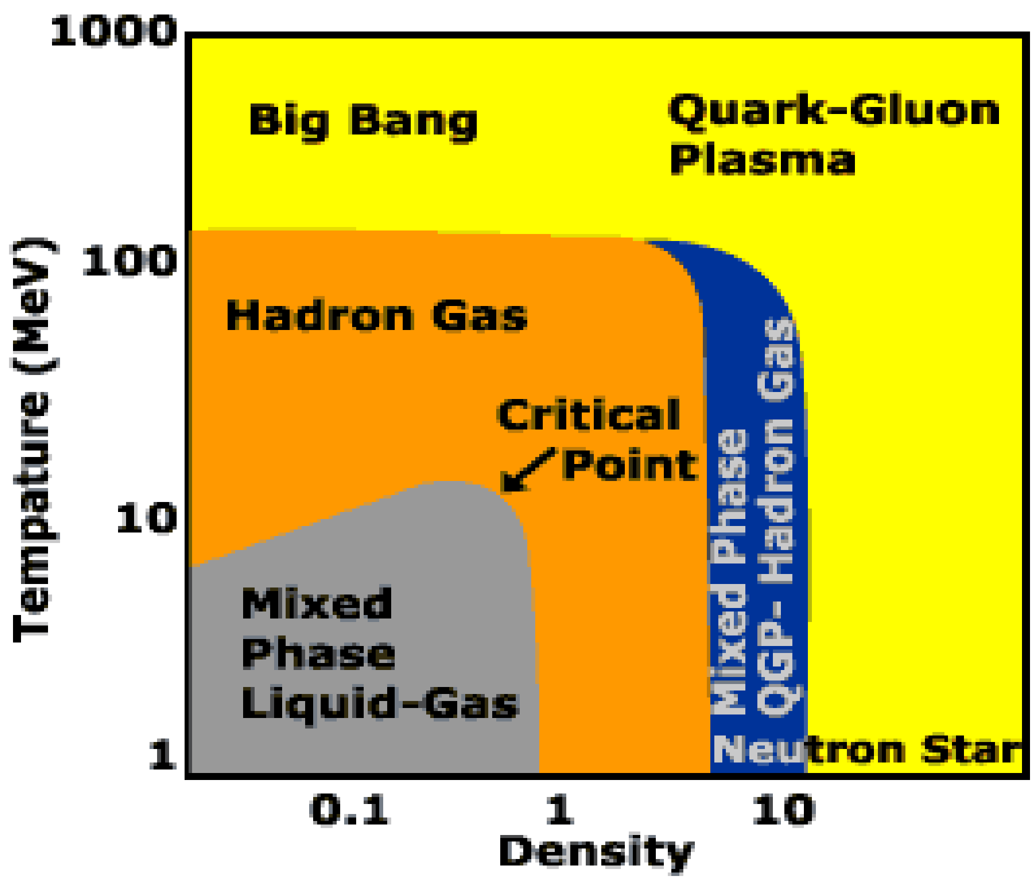


The equation of state

Equation of state of e.g. water



To determine the equation of state of nucleii we need to explore all temperatures and pressures /densities



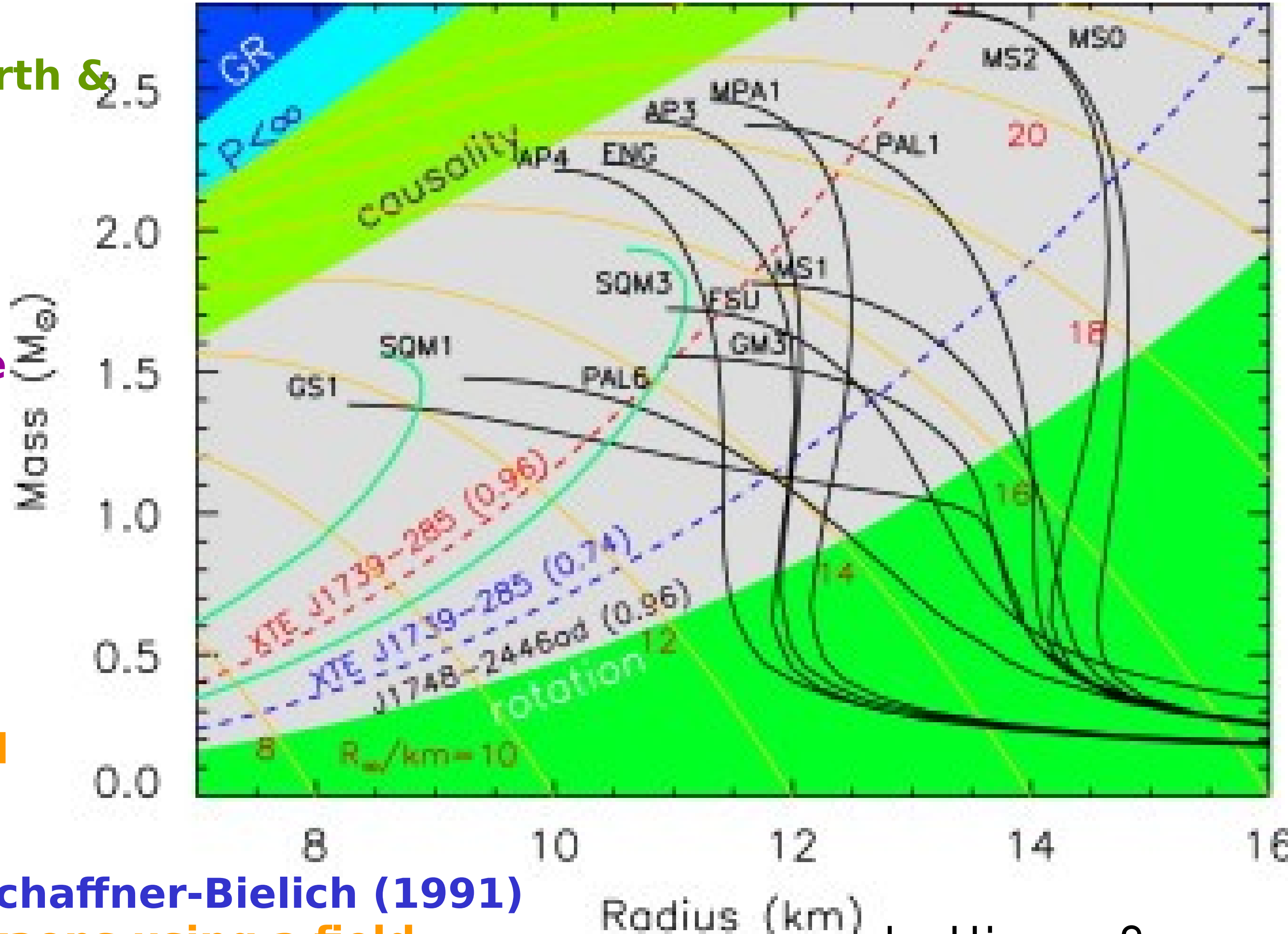
The neutron star equation of state

PAL -Prakash, Ainsworth & Lattimer (1988)
Neutrons + protons using a schematic potential

SQM – Prakash, Cooke & Lattimer (1995)
Strange Quark Matter model

GM – Glendenning & Moszkowski (1991)
Neutrons, protons + hyperons using a field theoretical approach

GS – Glendenning & Schaffner-Bielich (1991)
Neutrons, protons + kaons using a field theoretical approach



Lattimer & Prakash (2007)

Question

To determine the neutron star equation of state, we need to know its mass and radius.

Mesuring the radius of a neutron star locally in our galaxy is comparable to measuring :

A) the height of the Eiffel Tower from London

B) the height of a house in the USA from France

C) the width of a hair on the moon

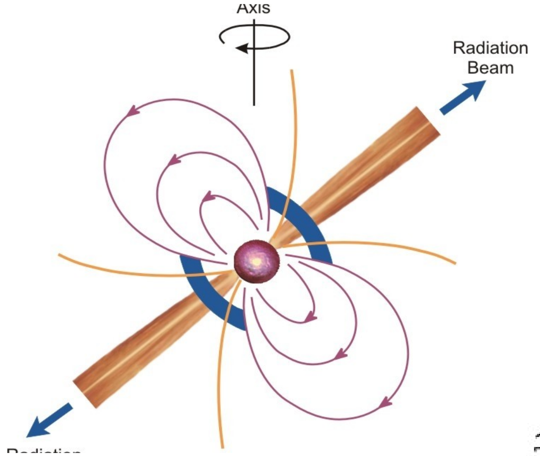
Question

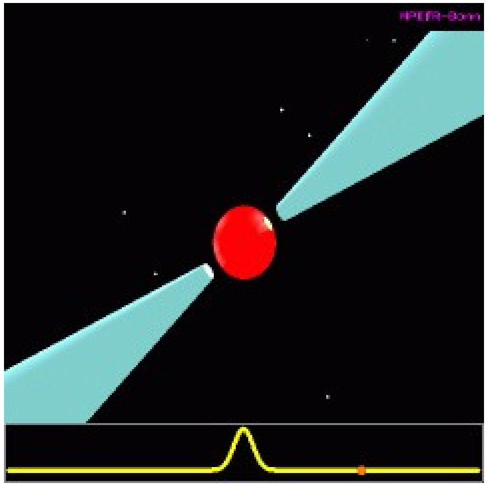
To determine the neutron star equation of state, we need to know its mass and radius.

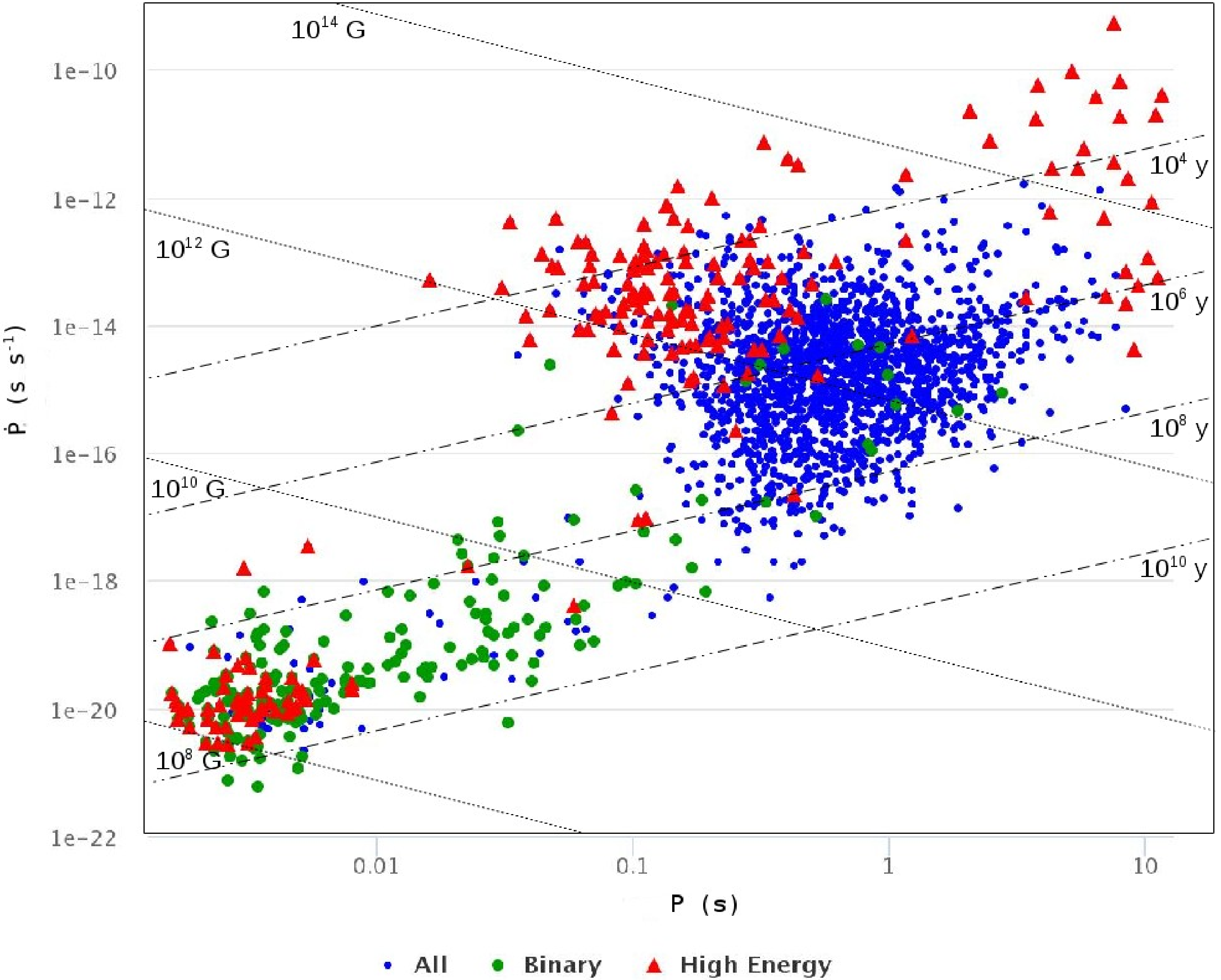
Mesuring the radius of a neutron star locally in our galaxy is comparable to measuring :

C) the width of a hair on the moon

Neutron star characteristics

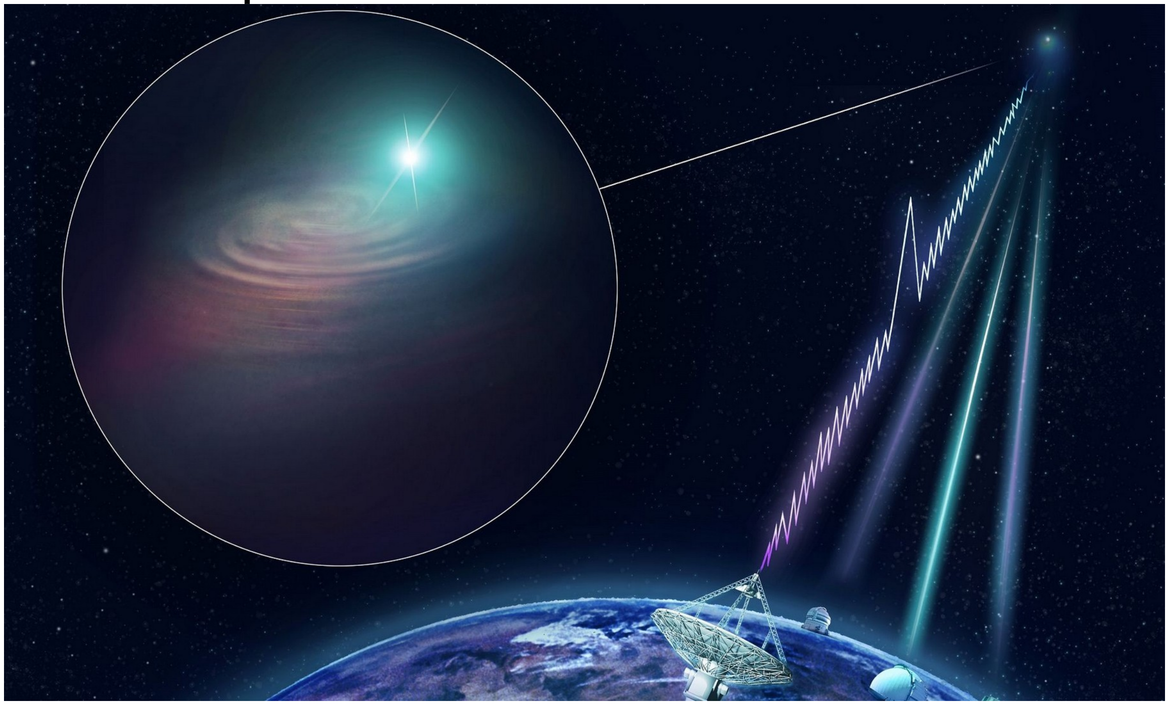






...and the unknown ?

- Fast radio bursts (FRBs), first discovered ~20 years ago
- Rapid (~1 ms) extra-galactic radio bursts
- Burst energies < 10^{42} erg s^{-1}
- Some repeat (periodically) – non catastrophic event
- Several thousand discovered through dedicated searches
- Expected to be related to neutron stars, although nature still unknown
- Gravitational wave observations could help elucidate their nature ??



Black hole concept

John Michell (1724-1793)
Proposed that massive 'dark stars' could exist (1783)

Pierre-Simon Laplace (1749-1827)
Provided a mathematical description of a 'dark star' (1799)

Consequence of Einstein Equations

The no-hair theorum
(only three parameters : mass, electric charge & angular momentum)

(1) The Schwarzschild solution (Schwarzschild 1916)
Black hole has mass i.e. is static & spherically symmetric

(2) The Reissner-Nordström solution (Reissner 1916, Nordström 1918)
Black hole has mass + electric charge i.e. is static & spherically sym.

(3) The Kerr solution (Kerr 1963)
Black hole has mass + angular momentum i.e. is stationary & axisym.

(4) The Kerr-Newman solution (Newman and Janis 1965)
Black hole has mass, electric charge + angular momentum

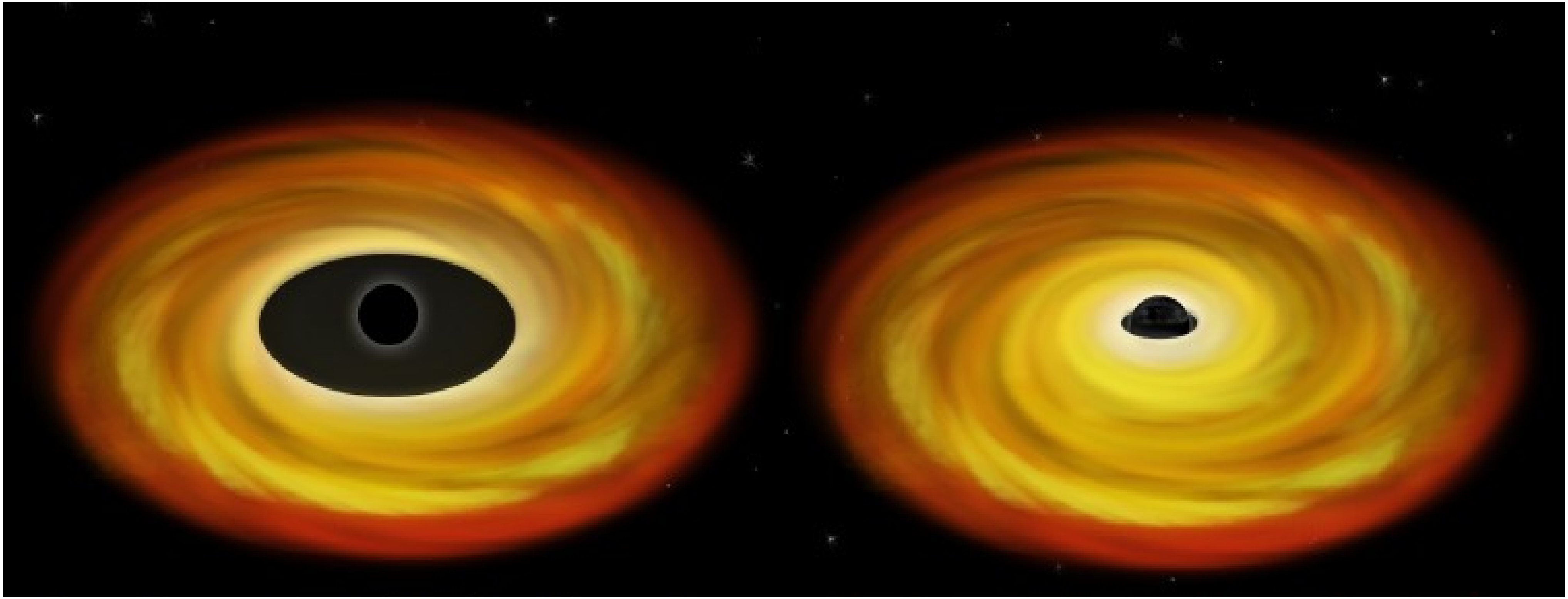
Note : the term « black hole » was adopted in 1967 during a talk by John Wheeler

But what are the spins and masses of black holes ?

The event horizon for static and spinning black holes

Schwarzschild black hole
Spin (a_*) = 0

Kerr black hole
Maximum spin (a_*) = 1



Credit : NASA

Radius = $(1+(1-a_*^2)^{0.5})\ GM/c^2$

Radius = $2GM/c^2$

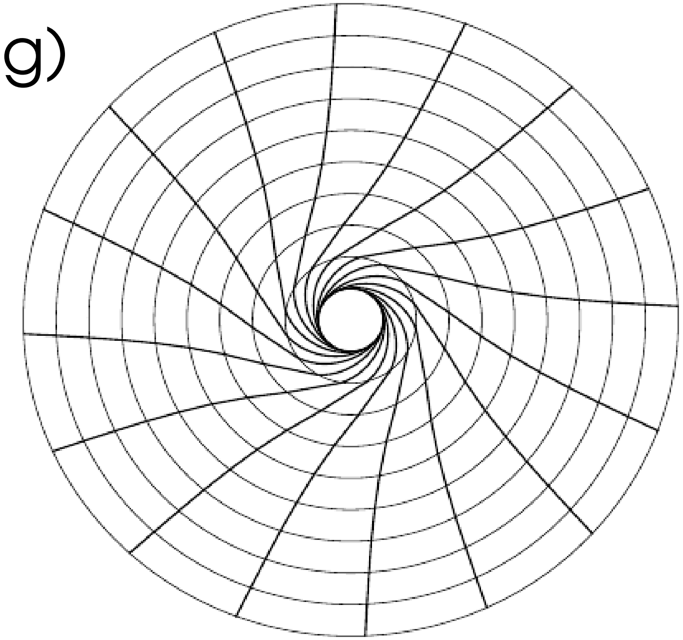
Radius = GM/c^2

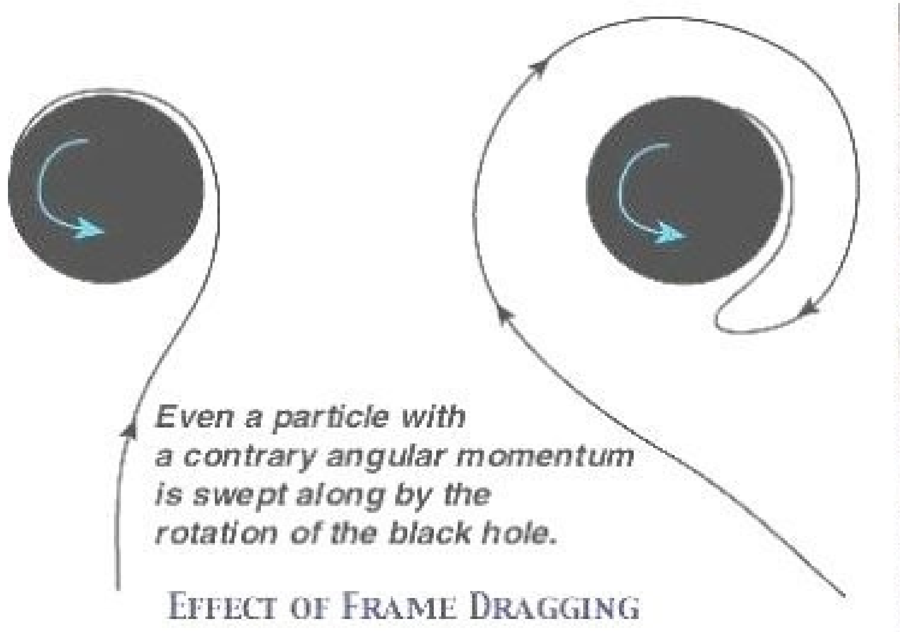
ISCO = $6GM/c^2$

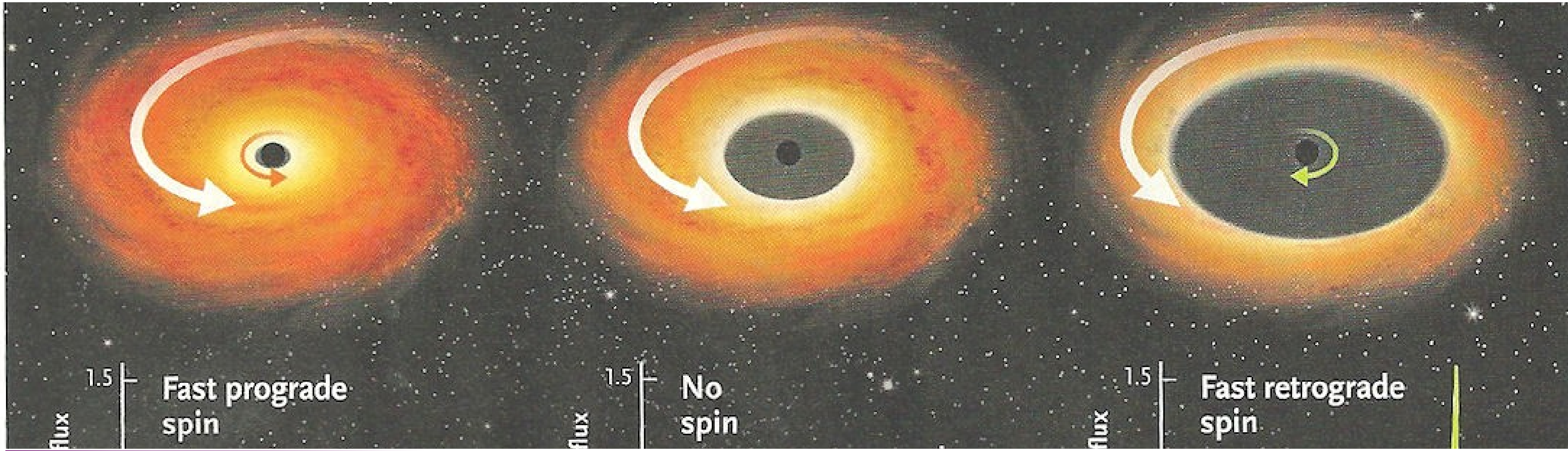
ISCO (for $a_*=1$) = GM/c^2

Frame dragging and the innermost stable circular orbit

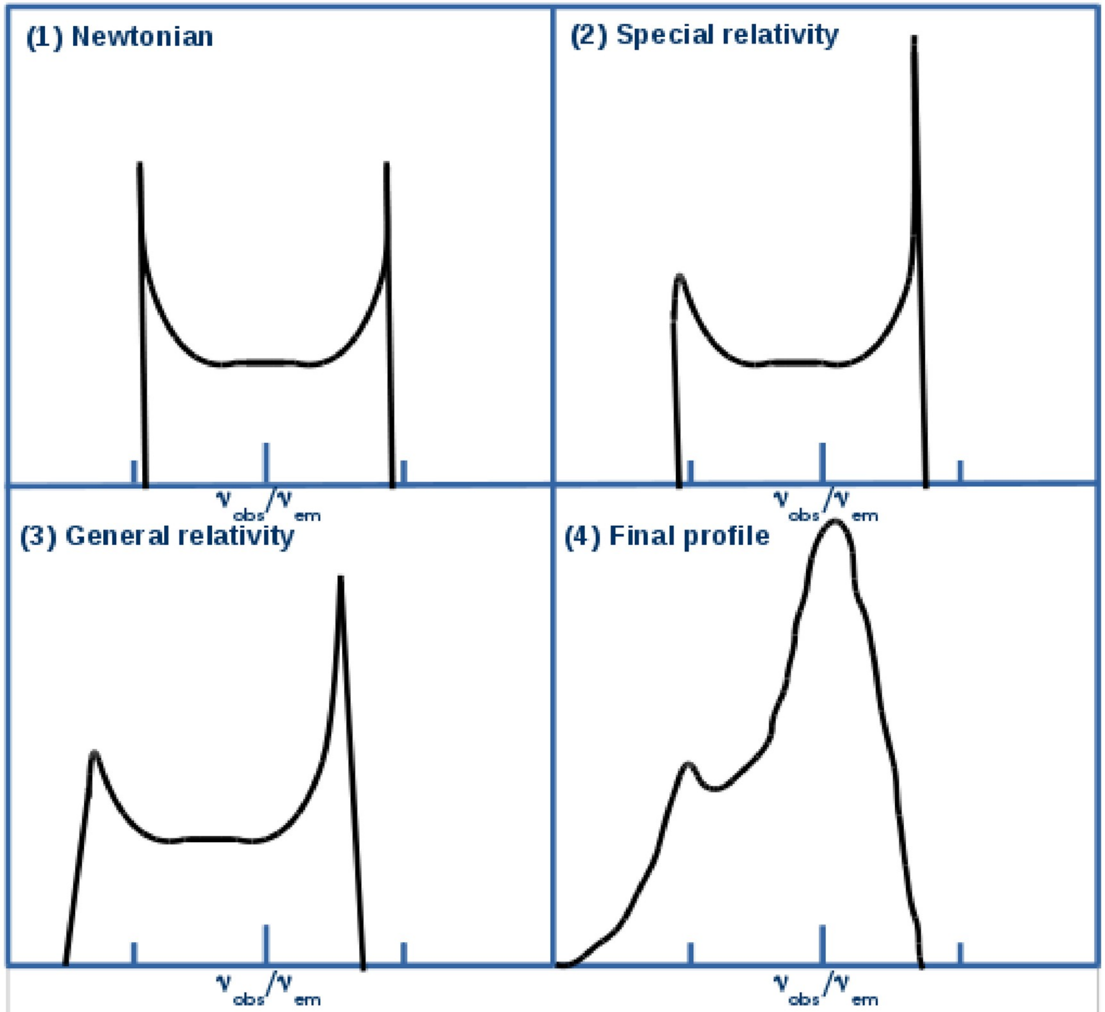
Kerr (spinning) black holes

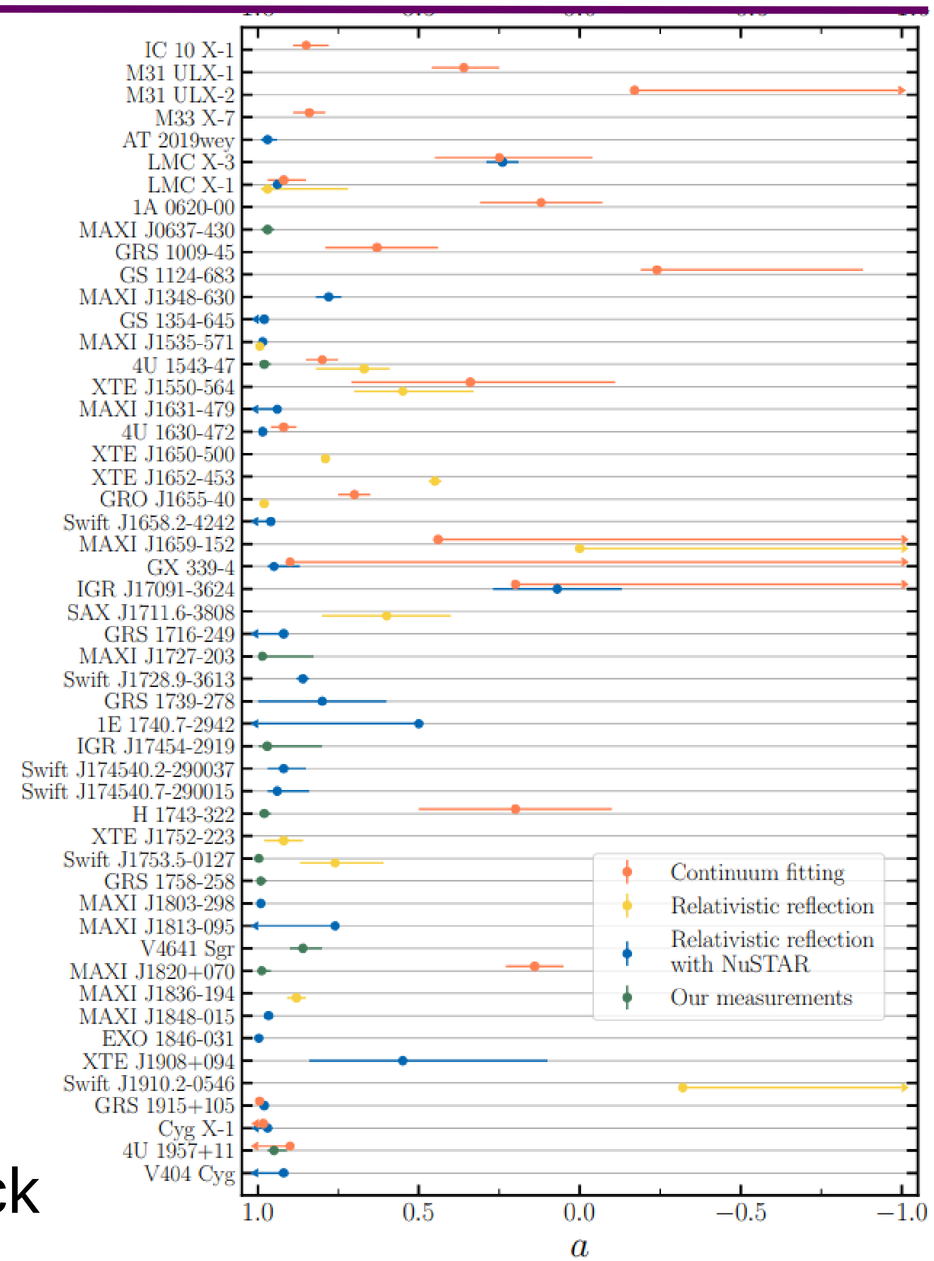






Probing strong gravity



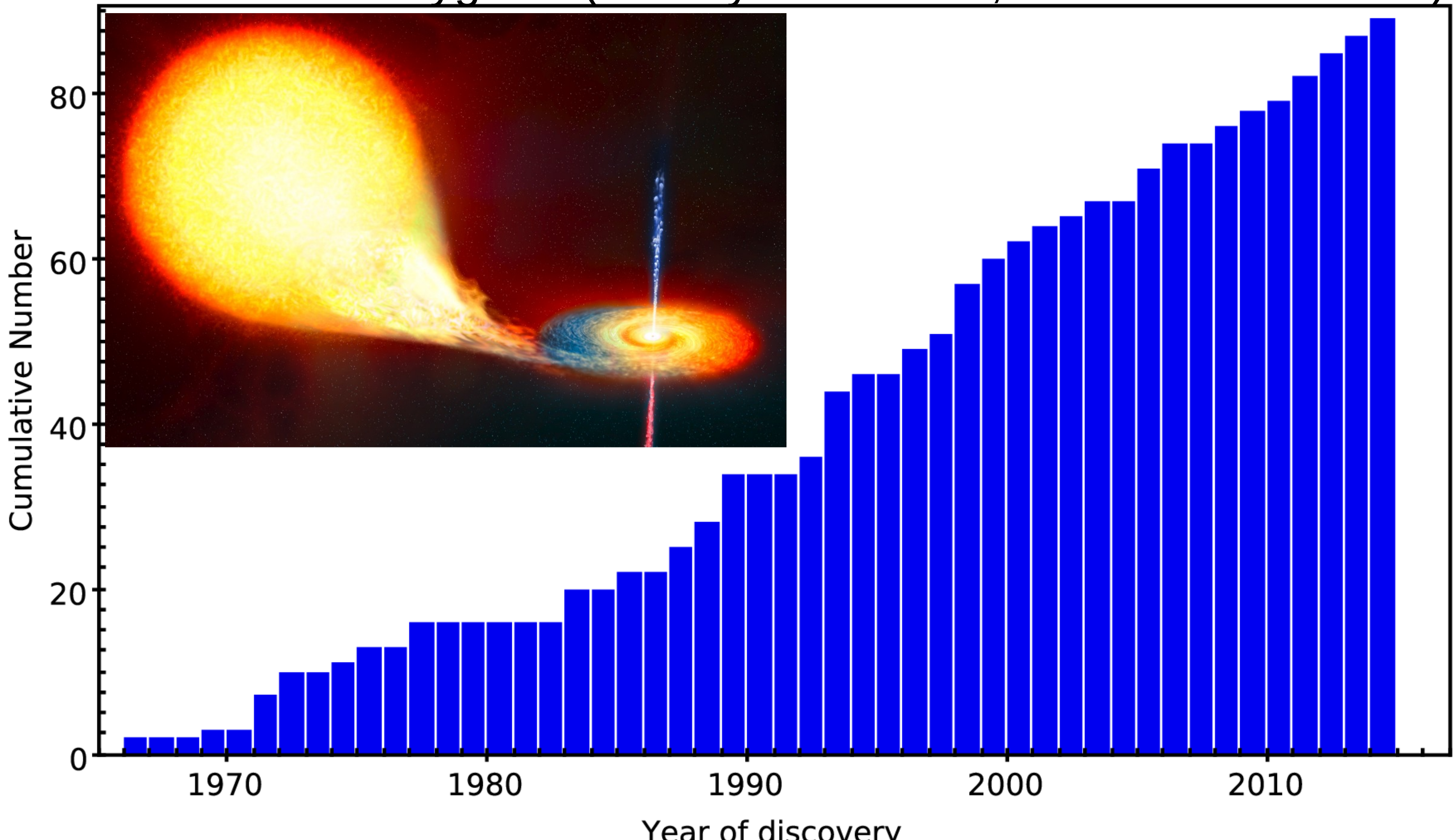


- Relate to the supernova mechanism
- Study accretion history in massive black holes (distinguish mergers/acc.)

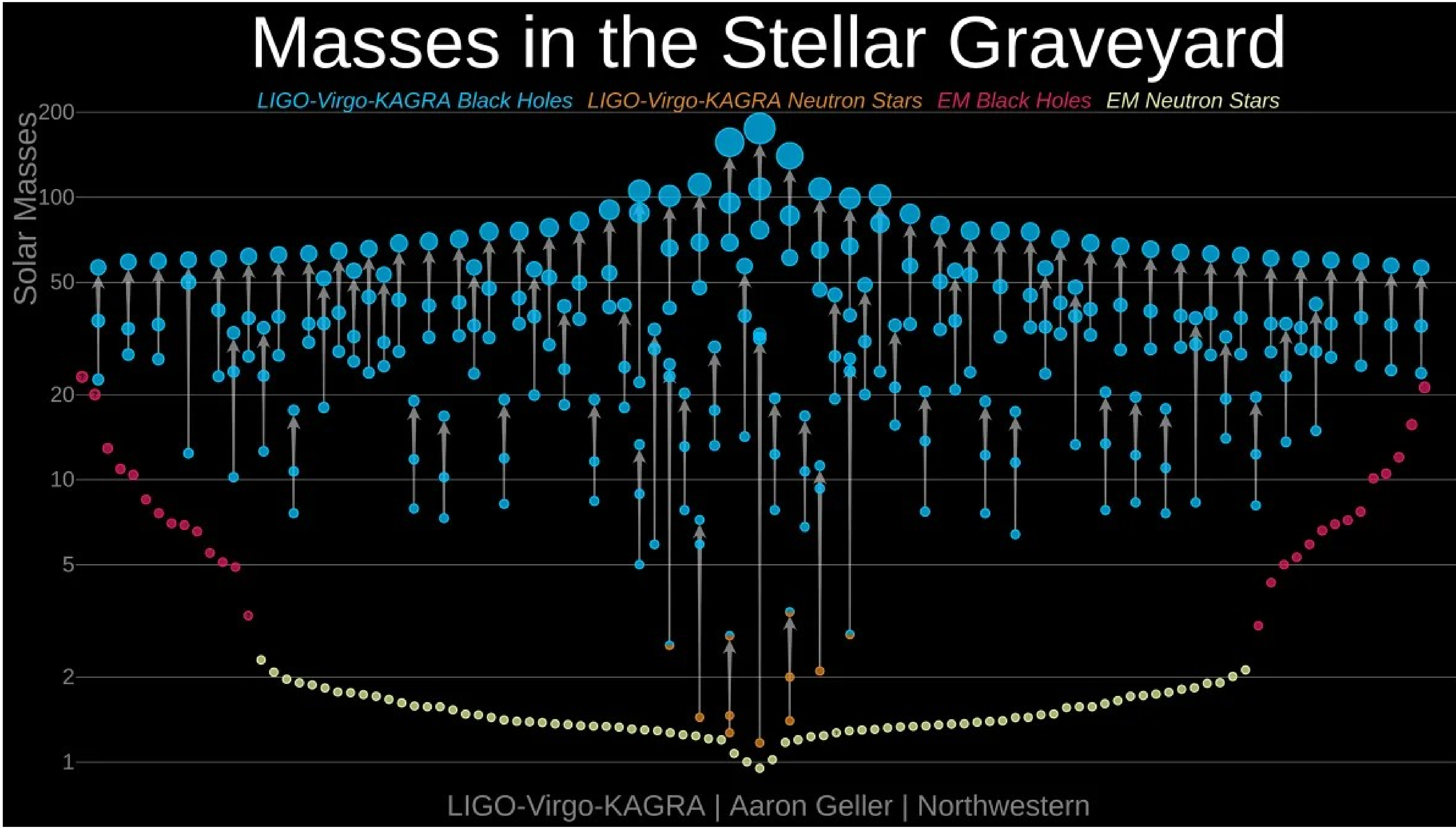
Current BH spin measurements (Draghis et al. 2022)

Stellar mass black hole formation & Galactic discoveries

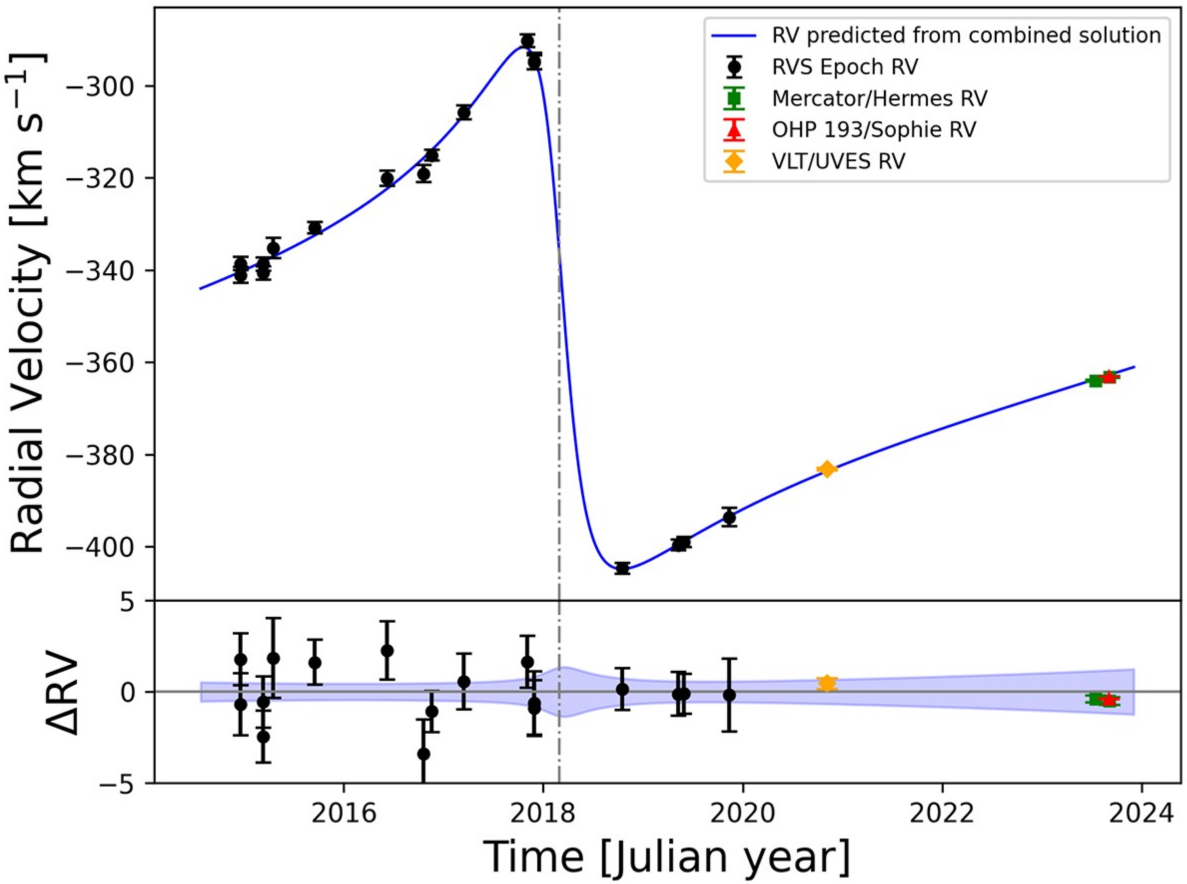
- From stars with mass ≥ 20 $M_\odot$
- From neutron star-neutron star mergers
- Overdense regions in the primordial Universe that collapsed
- First black hole : Cyg X-1 (Gursky et al. 1963, Giacconi et al.1967)



Why are the electromagnetic black holes less massive ?



Breaking news, Panuzzo et al. 2024 (27 May), A&A



- Gaia BH-3
- 590 pc
- Period ~ 11.6 years
- 32.70 ± 0.82 $M_\odot$ BH
- Companion, very old & metal poor
- $M_\star$ = 0.76 ± 0.05 $M_\odot$
- Possibly from a globular cluster disrupted by the Milky Way

..and how did the >50 solar mass black holes form ?

- Stars with a main-sequence mass ~150-260$M_\odot$ very hot
- Conversion of photons to e^+/e^- pairs in hot dense core drives runaway collapse
- When collapse halted by oxygen burning, powerful explosion destroys remnant
- There should be no black holes with masses in the range 50-140$M_\odot$
- Either black holes created through mergers
- Or, some new development indicates pair-instabilities can be overcome in some circumstances
- Need to study final evolutionary stages of stellar evolution & supernovae

How do supermassive black holes (SMBH) form ?

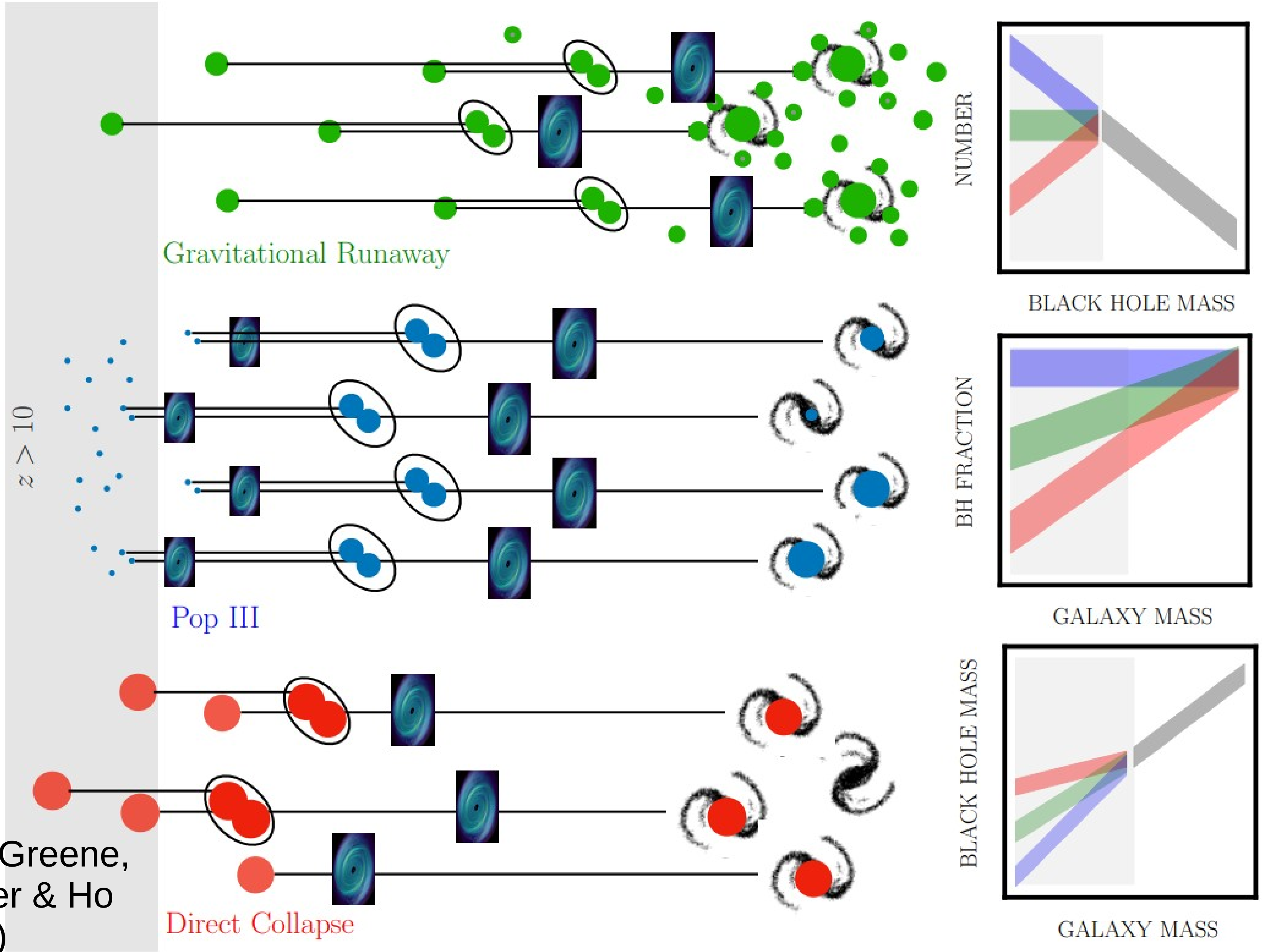
Stellar mass black holes (~3-100 $M_\odot$) form at the end of the lives of massive stars or from the coalescence of neutron stars

But supermassive black holes (~10^{6-10} $M_\odot$) can not form in the same way

Accretion onto a stellar mass black hole, even at maximal rate (Eddington limit), difficult to explain a population of black holes of ~10^9 $M_\odot$ at z>7 (e.g. z~7.1 e.g. Mortlock et al. 2011, or 8×10^8 $M_\odot$ at z=7.54 Bañados et al. 2018)

Requires high merger rates and/or more massive « seeds » (~10^{2-5} $M_\odot$) and/or super-Eddington accretion to form supermassive black holes (SMBH, e.g. Volonteri, 2012; Volonteri, Silk & Dubus, 2015)

Evolution from seeds to supermassive black holes

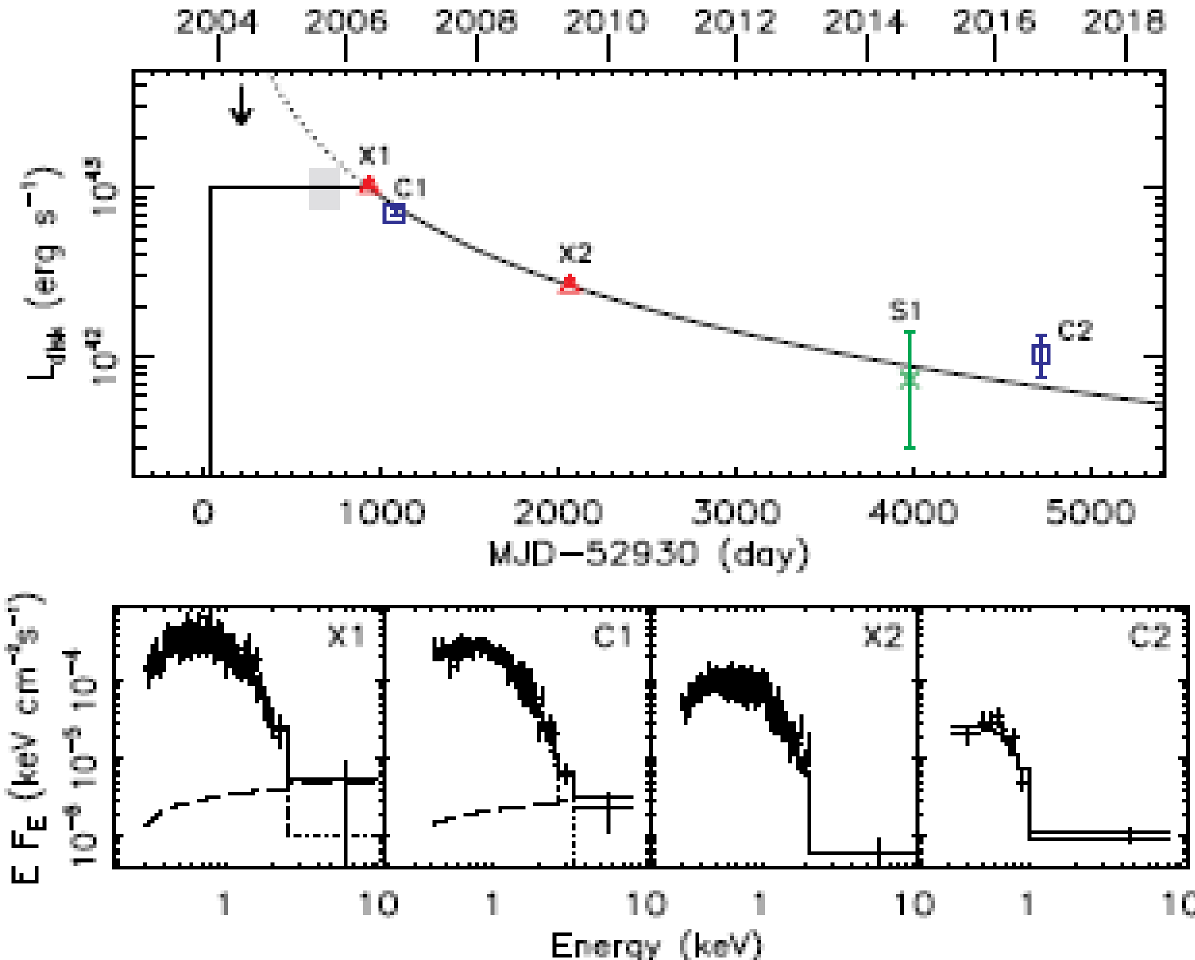


LISA data will help to answer these questions

From Greene, Strader & Ho (2020)

(Super-Eddington) accretion onto massive black holes

Tidal disruption events (TDE) ~ a hundred known – LISA can find more (e.g. Toscani et al. 2020)!

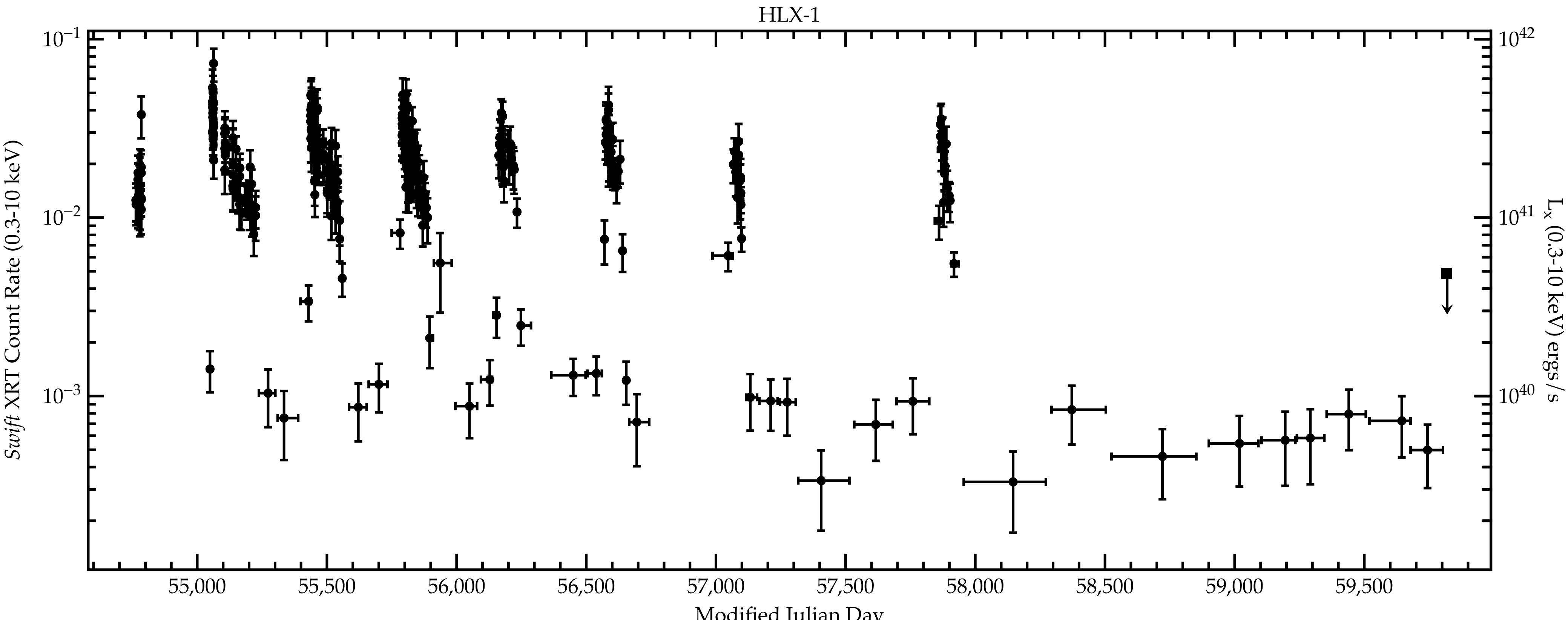


Lin et al. Nature Astronomy (2018)

$5.3 \times 10^4 M_\odot < \text{mass} < 1.2 \times 10^5 M_\odot$

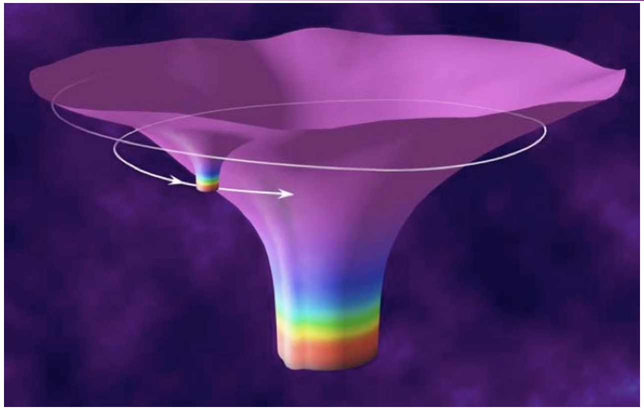
Repeated accretion onto massive black holes

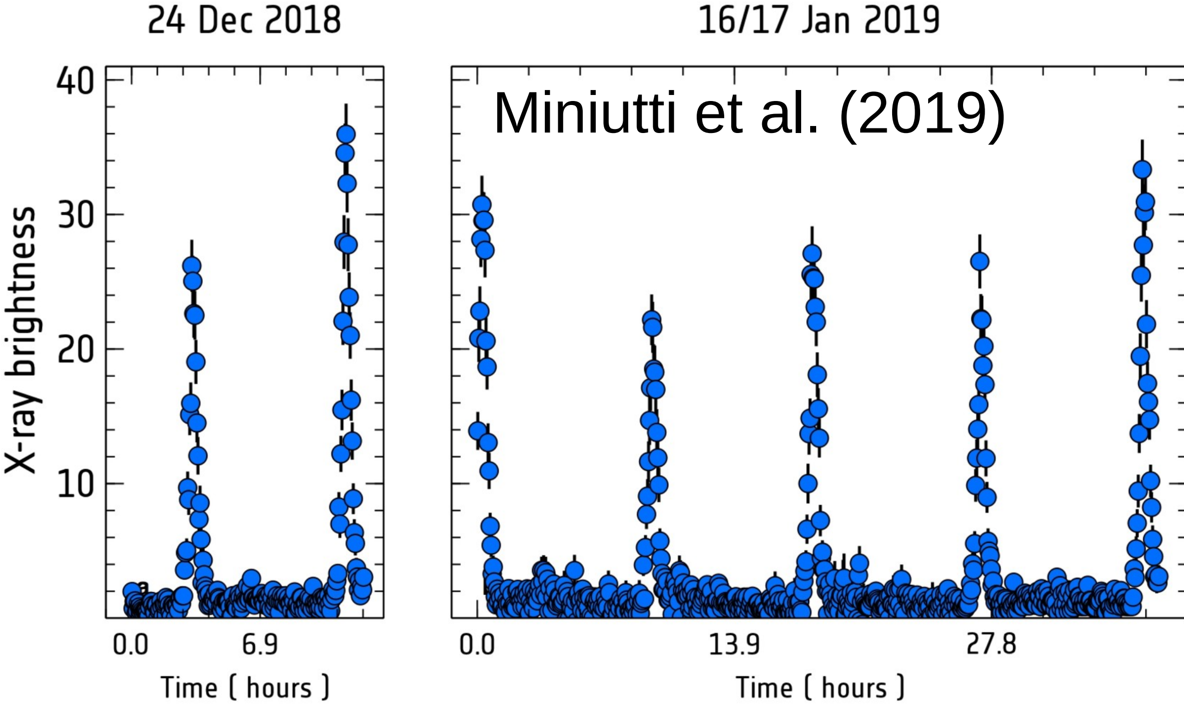
- Partial tidal disruption events (TDE) ~ a handful known – LISA can find more !
- How often do they occur ?
- What are the properties of the accretor and the star ?
- How much matter is accreted ?

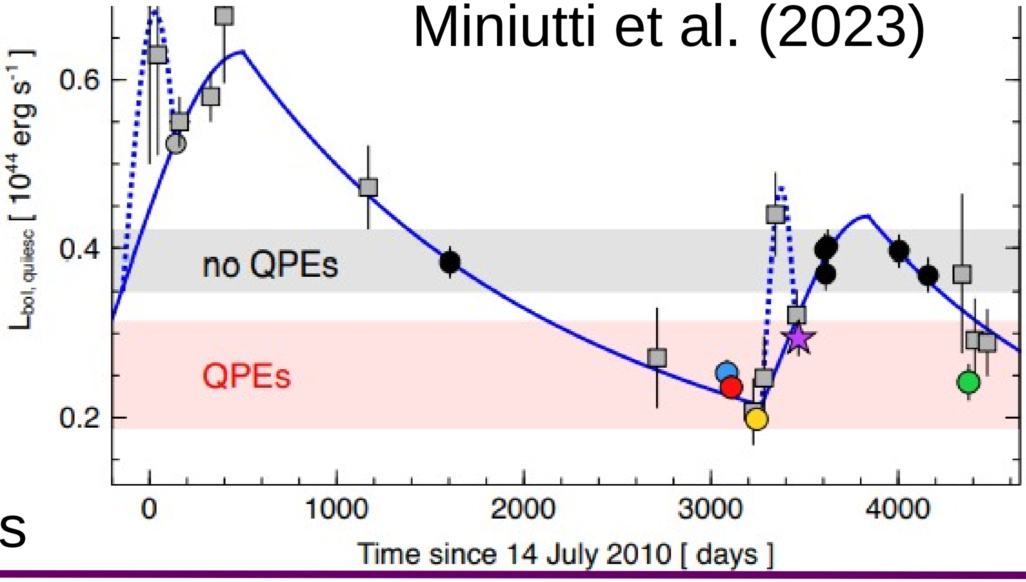


ESO 243-49 HLX-1, Webb et al. (2023)

Are Quasi Periodic Eruptions (QPEs) evidence for Extreme Mass Ratio Inspirals (EMRIs) ?







- Regular bursts from centres of 7 galaxies
- Probably associated with TDEs (Quintin et al., 2023)
- Varying phenomena turning on/off
- Variety of different examples
- **LISA** :
- Pinpoint EMRIs
- Measure general-relativistic and Lense–Thirring precession
- Constrain compact object parameters

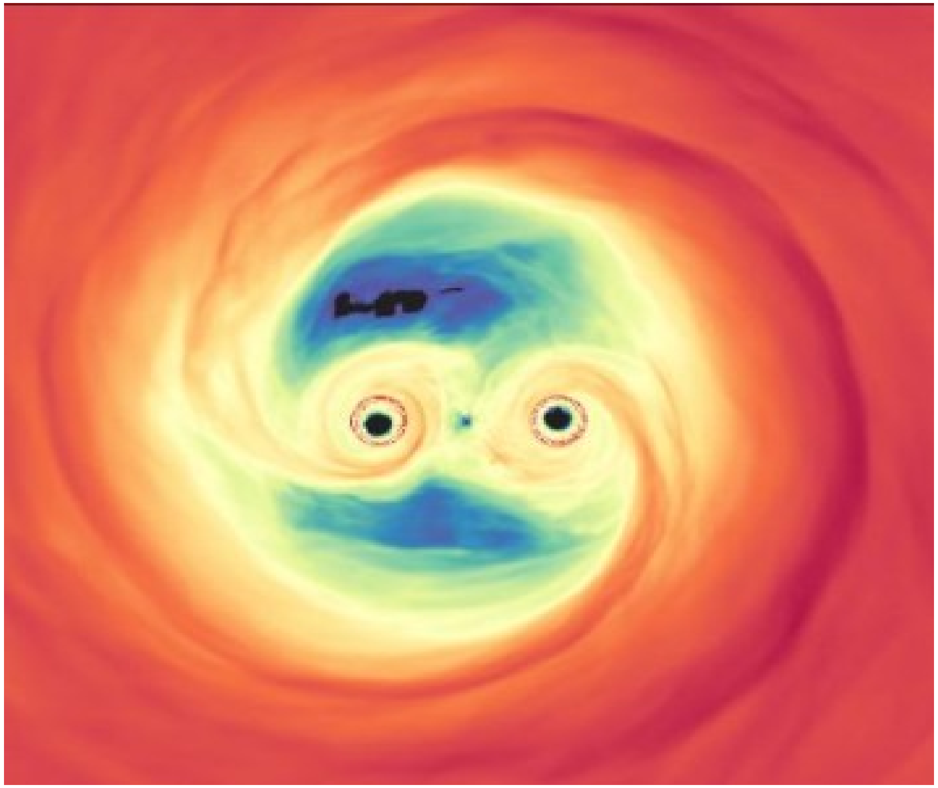
Merging massive black holes

- Binary SMBH can show (sinusoidal) modulation in long-term light-curves
- Origin unclear could be from

  - Doppler boosting mini-discs

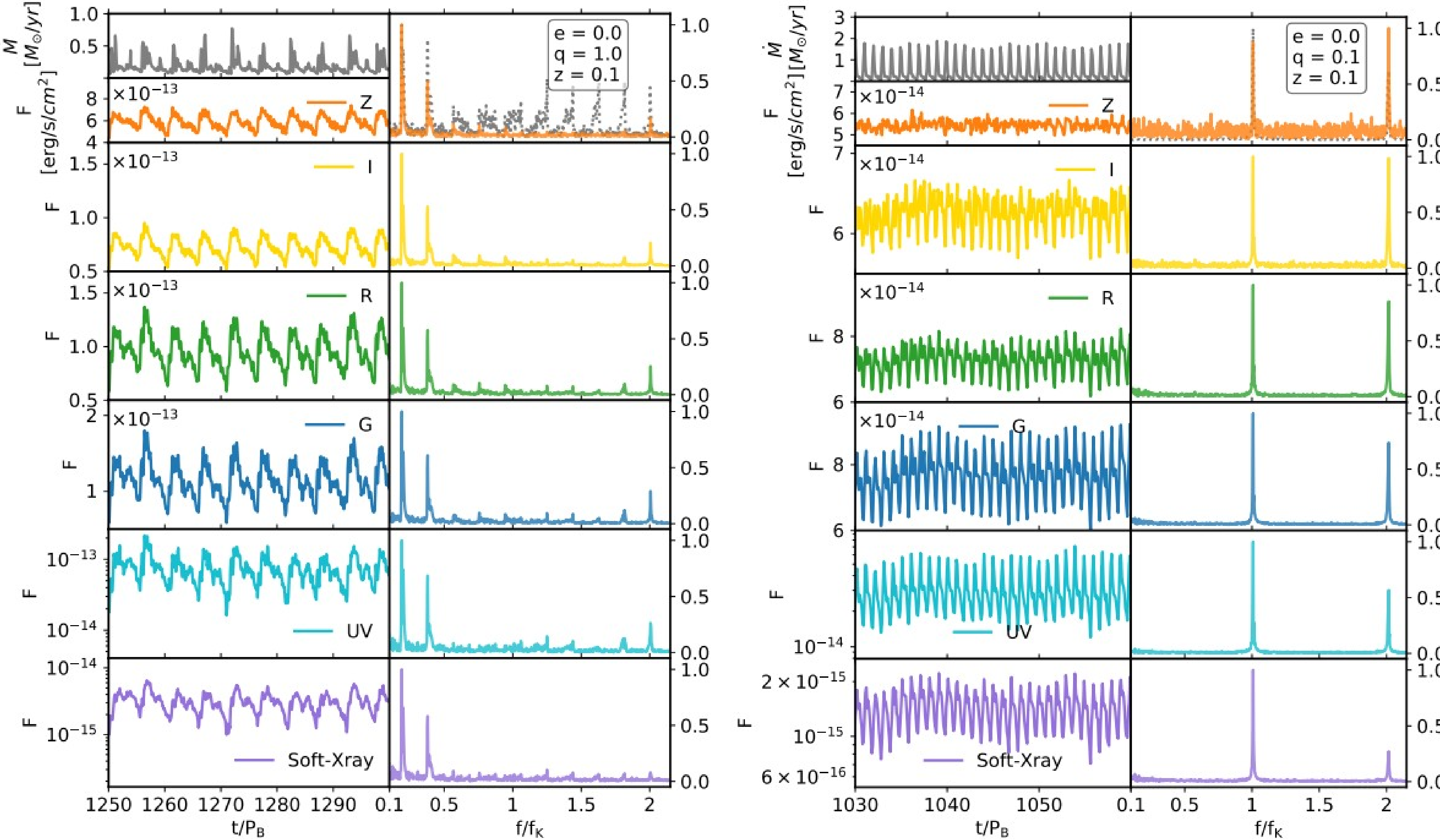
  - Asymetric accretion streams

  - Lump (blob) in circumbinary disc
- Difficult to verify if due to binary black holes or red-noise (Vaughan et al. 2016)
- Can help to understand when and where mergers were important in the formation/evolution supermassive black holes and find intermediate mass black holes



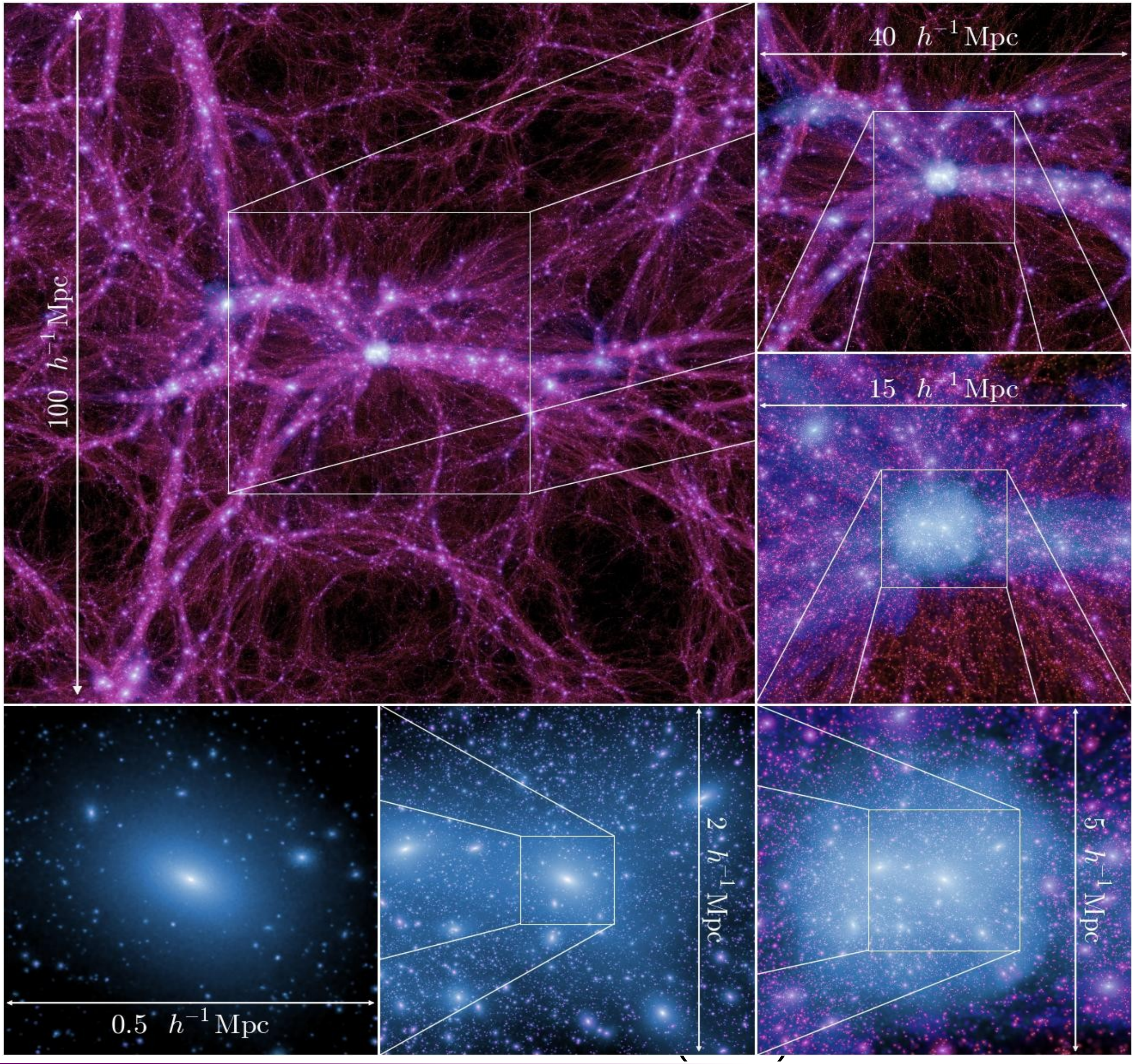
D'Ascoli et al. 2018

Expected emisison from merging massive black holes



Cocchiararo et al. (2024)

The rôle of supermassive black holes in the Universe



Boylan-Kolchin et al. (2009)

Summary

- Much of our knowledge of observational astrophysics from electromag. data
- Compact objects + associated phenomena also radiate in gravitational waves
- Finding and studying stellar mass compact objects constrains stellar evol.
- Studying black holes helps understand how the Universe is structured
- Complementary gravitational wave and electromagnetic observations can constrain physics, astrophysics and cosmology