Ay 1 – Lecture 11

Neutron Stars, Pulsars, and Black Holes

11.1 Neutron Stars and Pulsars

Crab nebula in X-rays, Chandra

The Origin of Neutron Stars

- Always in SN explosions
- If the collapsing core is more massive than the Chandrasekhar limit (~1.4 $M_\odot$), it cannot become a white dwarf
- Atomic nuclei are dissociated by γ-rays, protons and electrons combine to become neutrons:

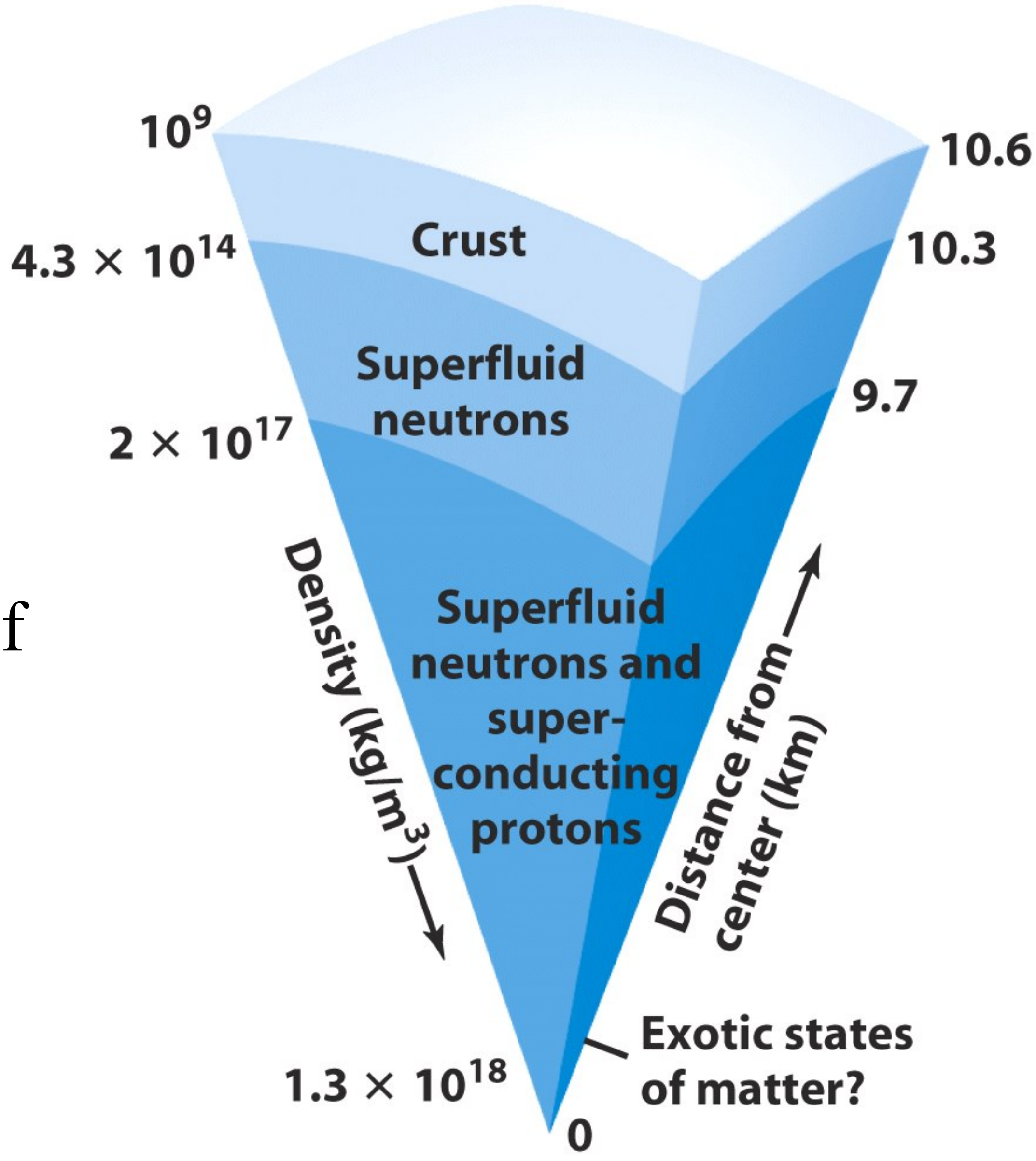
$$e^- + p \rightarrow n + \nu_e$$

- The collapsing core is then a contracting ball of neutrons, becoming a **neutron star**
- A neutron star is supported by a *degeneracy pressure of neutrons*, instead of electrons like in a white dwarf
- Its density is like that of an atomic nucleus, $\rho \sim 10^{15}$ g cm^{-3}, and the radius is ~ 10 km

The Structure of Neutron Stars

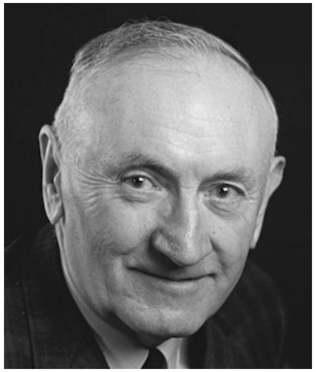
Not quite one gigantic atomic nucleus, but sort of a macroscopic quantum object

A neutron star consists of a *neutron superfluid*, superconducting core surrounded by a superfluid mantle and a thin, brittle crust



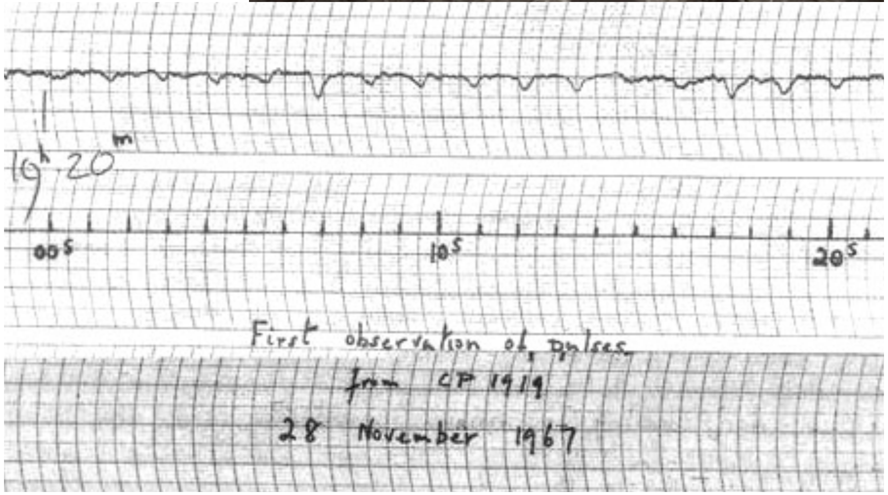
Prediction and Discovery of Neutron Stars

- The neutron was discovered in 1932. Already in 1934 Walter Baade and Fritz Zwicky suggested that supernovae involve a collapse of a massive star, resulting in a neutron star



- In 1967 Jocelyn Bell and Antony Hewish discovered pulsars in the radio (Hewish shared a Nobel prize in 1974)

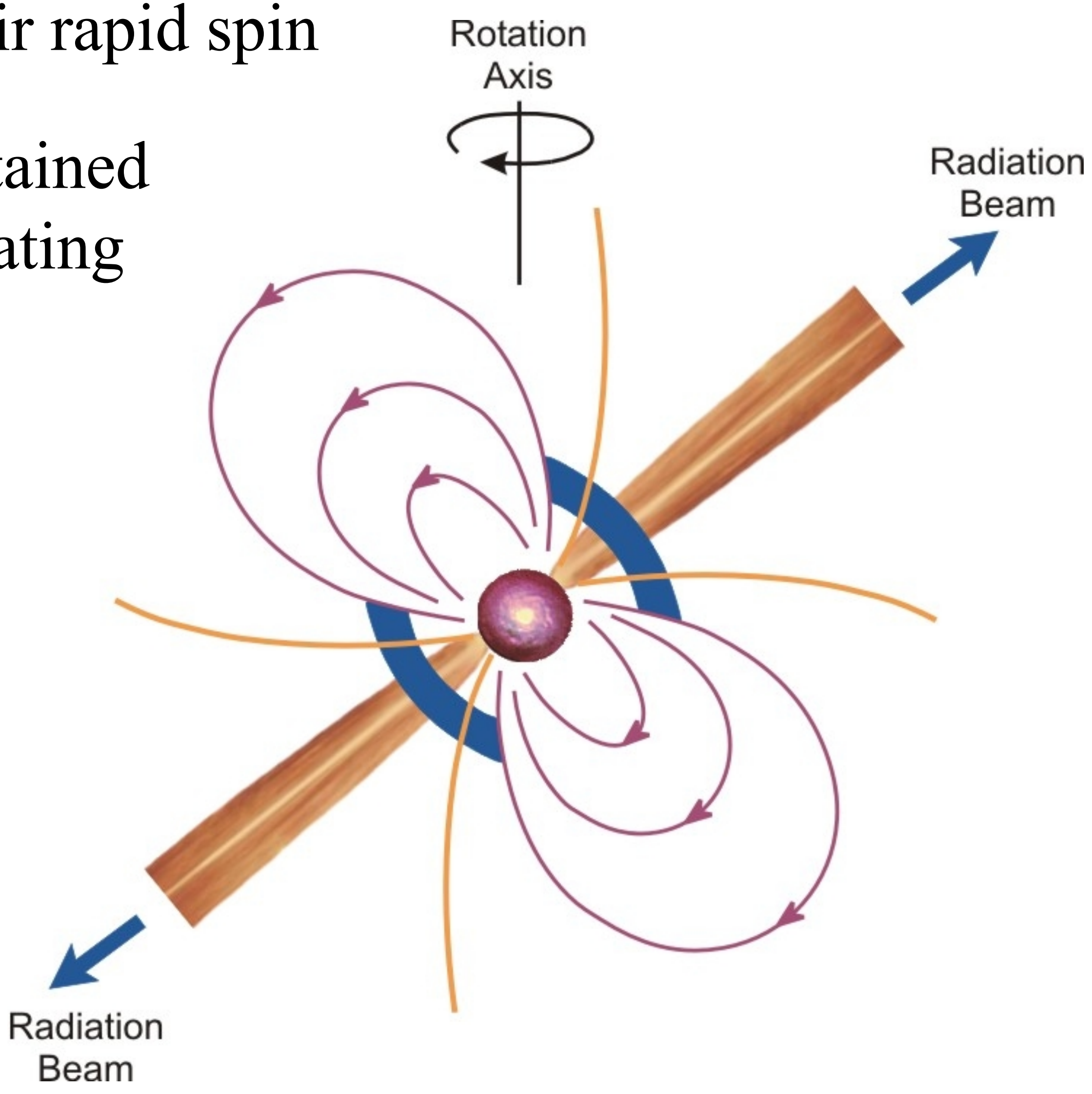
- Fast periods (~ tens of ms) and narrow pulses (~ ms) implied the sizes of the sources of less than a few hundred km (since $R < c\,\Delta t$). That excluded white dwarfs as sources



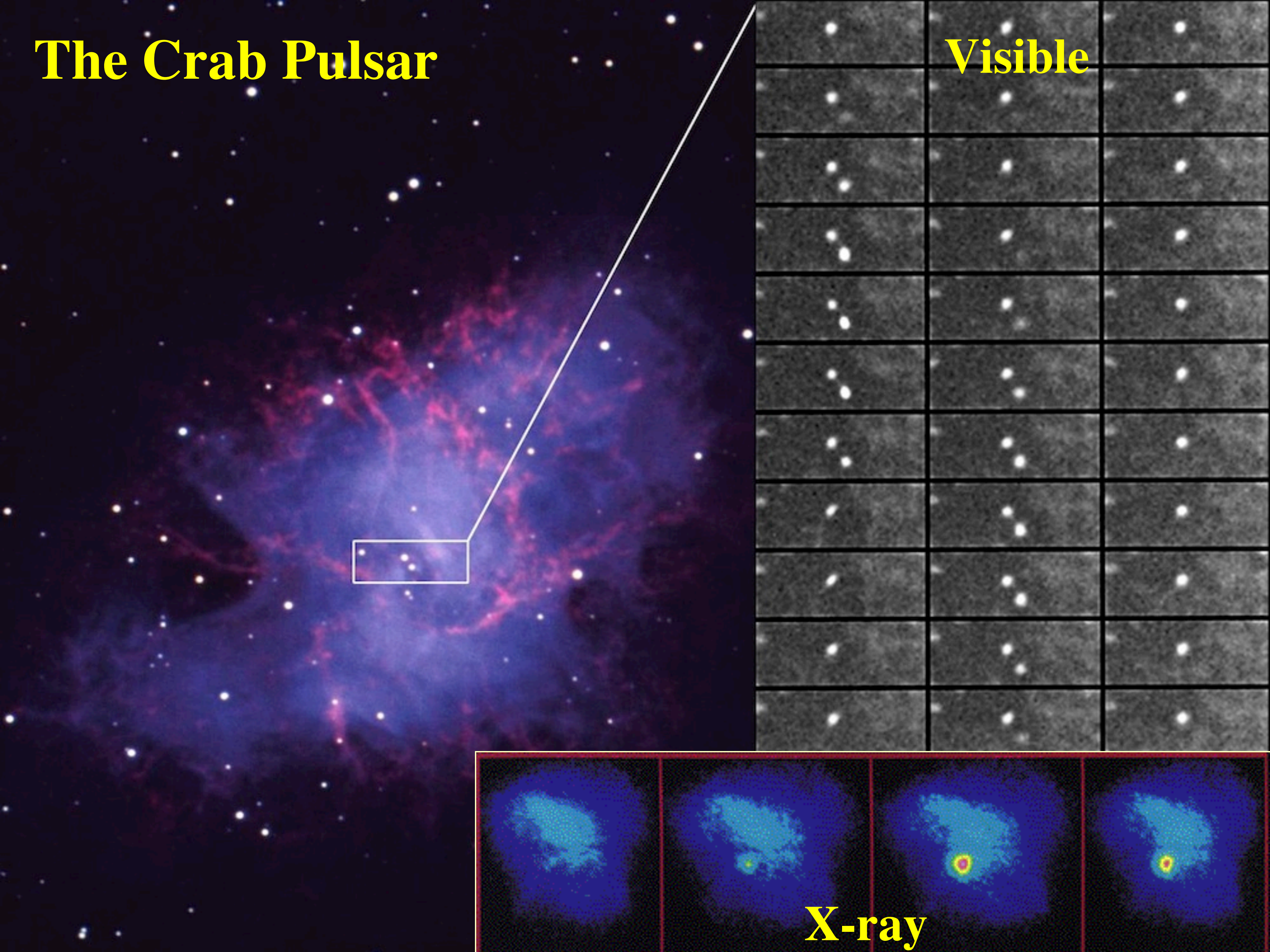
First observation of pulses from CP 1919
28 November 1967

Pulsar: Cosmic Lighthouses

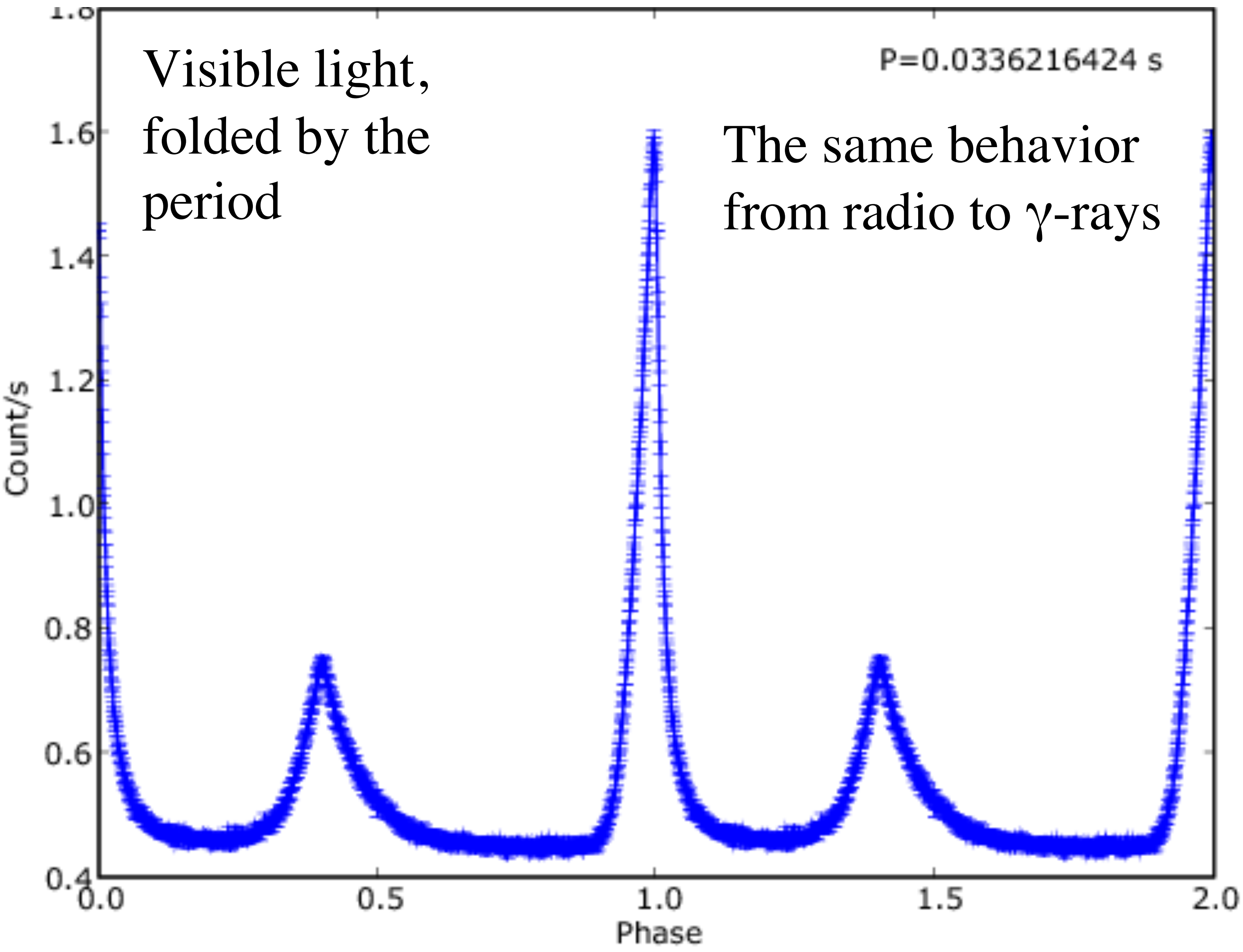
- As a stellar core collapses, in conserves its angular momentum. This gives the pulsar their rapid spin
- Magnetic field is also retained and compressed, accelerating electrons, which emit synchrotron radiation
- Magnetic poles need not be aligned with the rotation axis. Thus, the beams of radiation sweep around as a lighthouse beam



The Crab Pulsar



Light Curve of the Crab Pulsar



Visible light, folded by the period

The same behavior from radio to γ-rays

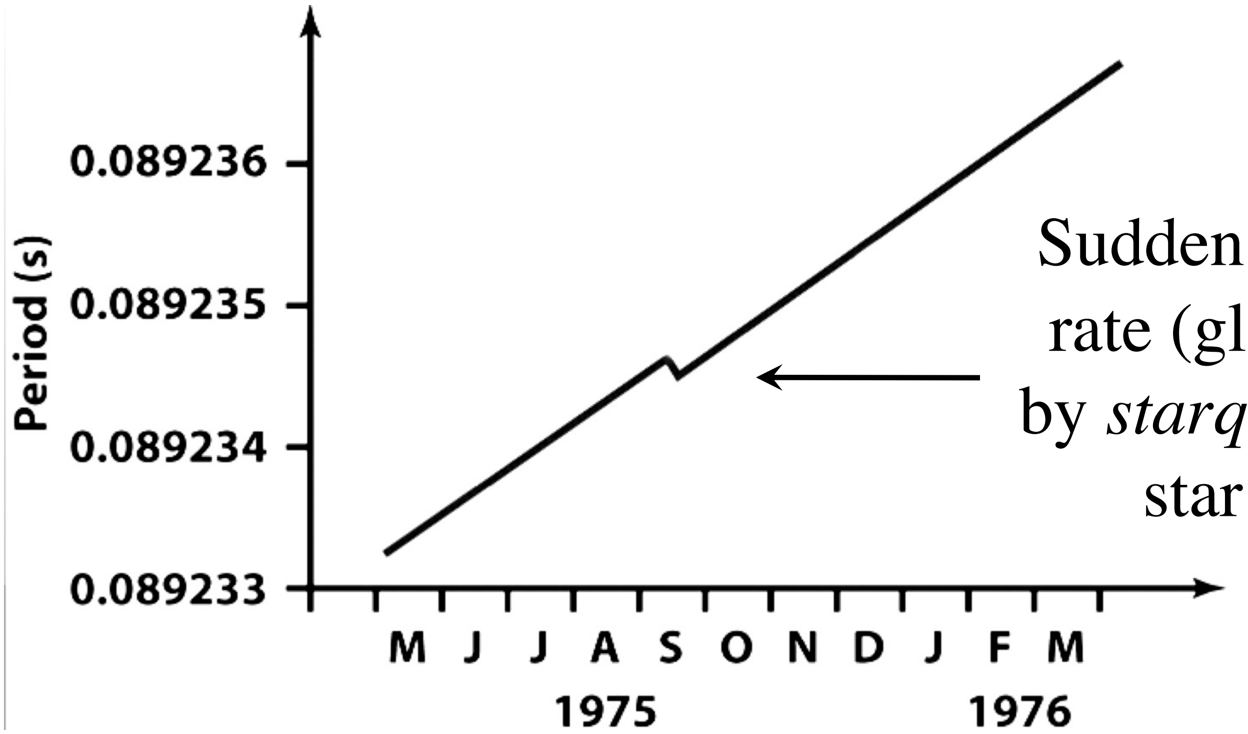
Pulsar Timing and Slowdown

- Because of their huge moments of inertia, most pulsars are *extremely stable*, as steady as (or better than) atomic clocks
- However, the energy they radiate comes at the expense of the rotational kinetic energy, resulting in a gradual slowdown

$E_{rot} = \tfrac{1}{2} I \omega^2 = 2 \pi^2 I P^{-2}$ $L = \mathrm{d}E/\mathrm{d}t = 4 \pi^2 I P^{-3} \dot{P}$

(I = moment of inertia, P = period)

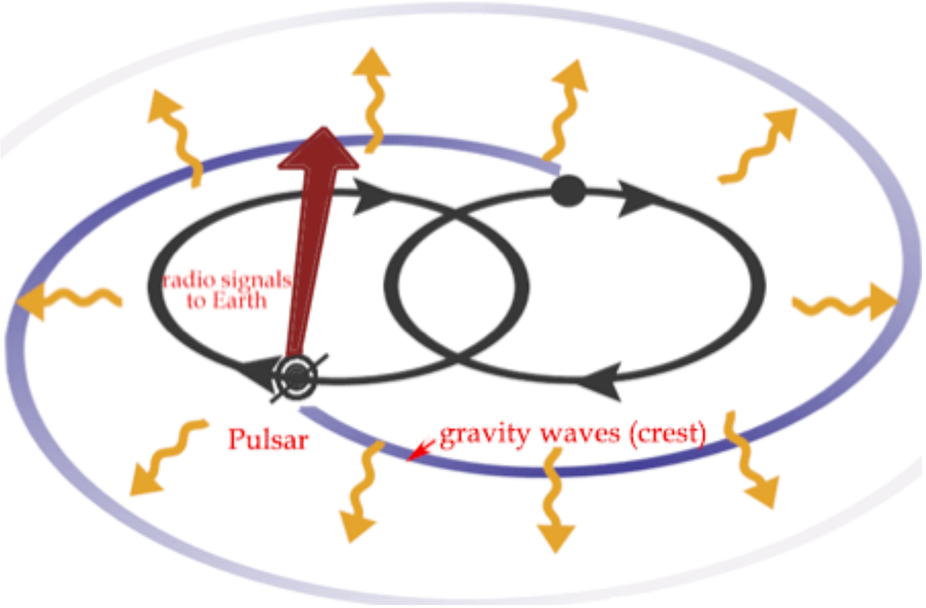
Period derivative

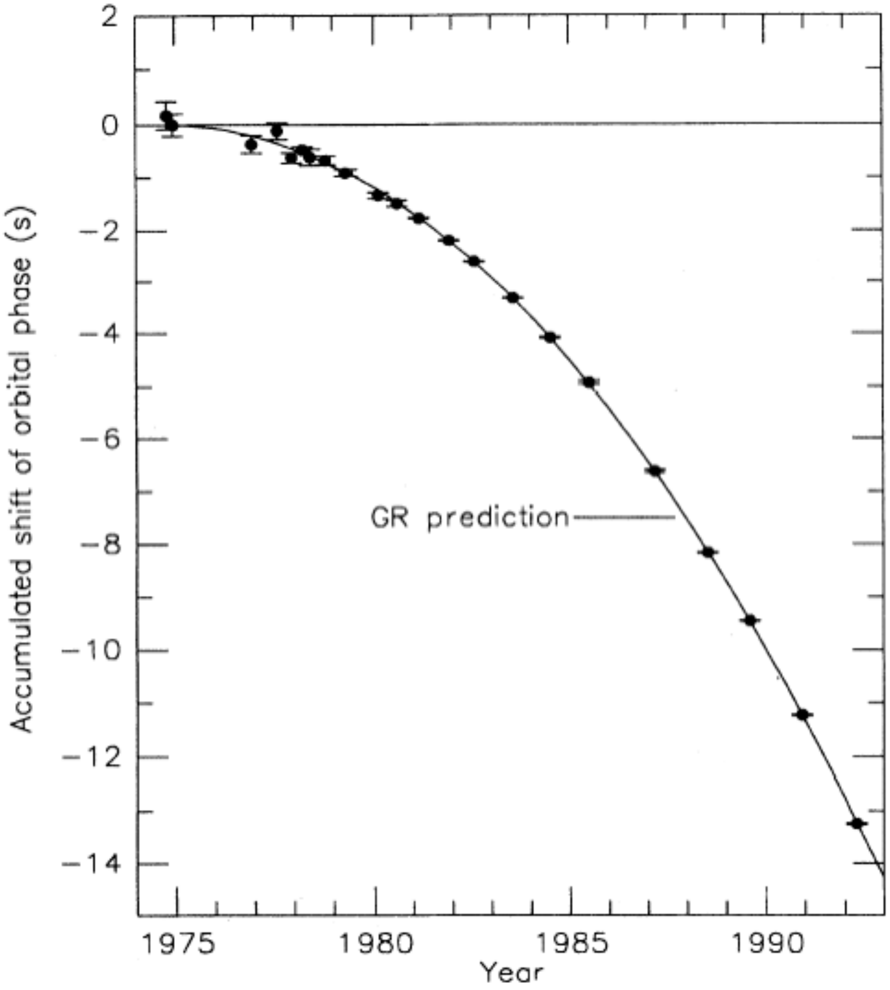


Sudden speedups of the pulse rate (glitches) may be caused by *starquakes* – settling of the star to a lower moment of inertia

Binary Pulsars

- First one discovered in 1974 by Joseph Taylor & Russell Hulse
- This is a *relativistic binary*, and some of the orbital kinetic energy is being radiated away as *gravitational waves*





- The observed rate of energy loss is exactly what the General Relativity predicts!
- Won the Nobel Prize in 1993

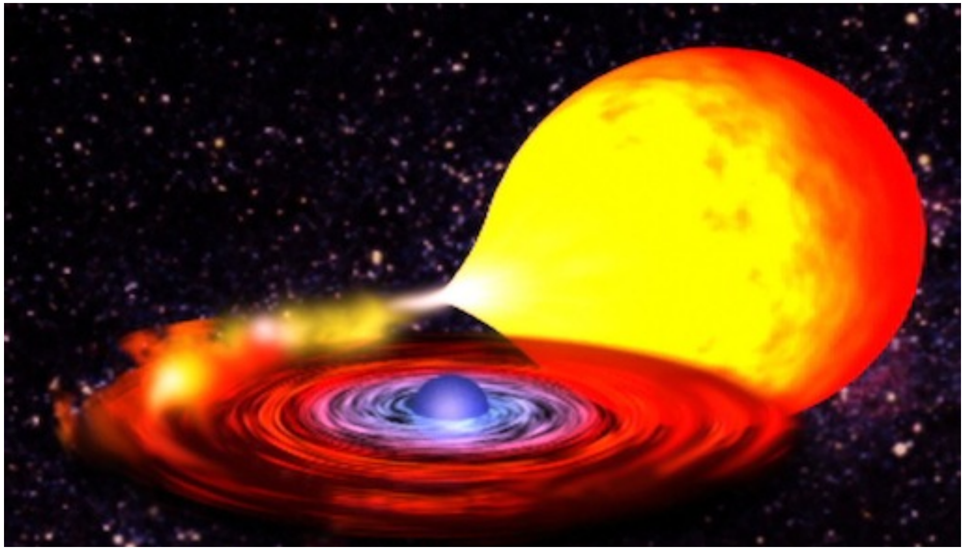
X-Ray Bursters and Millisecond Pulsars

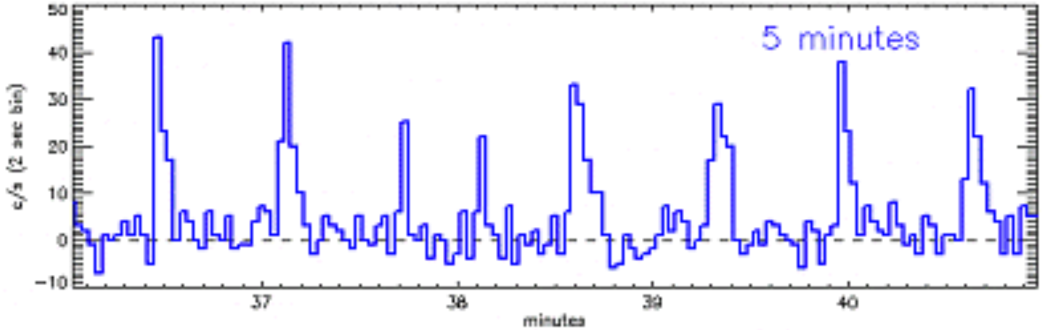
Neutron stars can be in accreting binaries

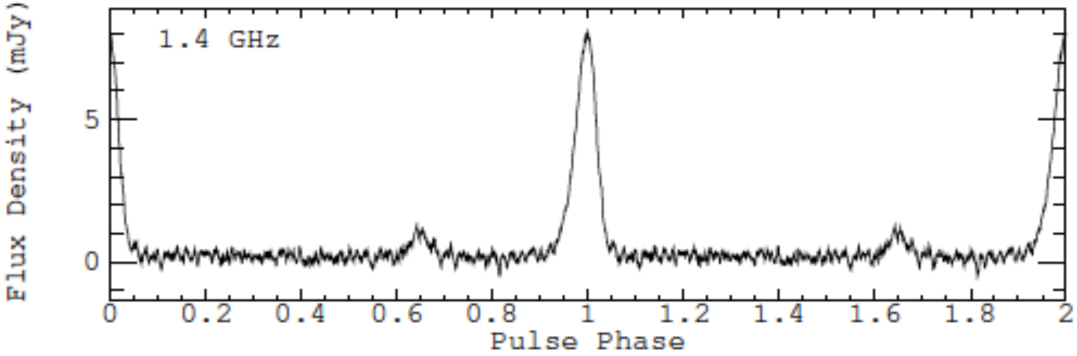
Such systems become *X-ray bursters*

The accretion of the disk material also increases the angular momentum of the neutron stars, and it can spin it up to ~ ms periods

This is the origin of *millisecond pulsars*





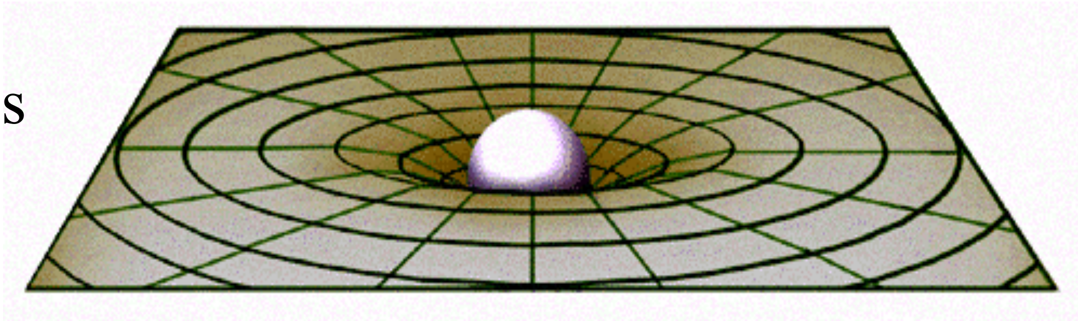


11.2 Stellar Black Holes

Einstein’s General Relativity (1915)

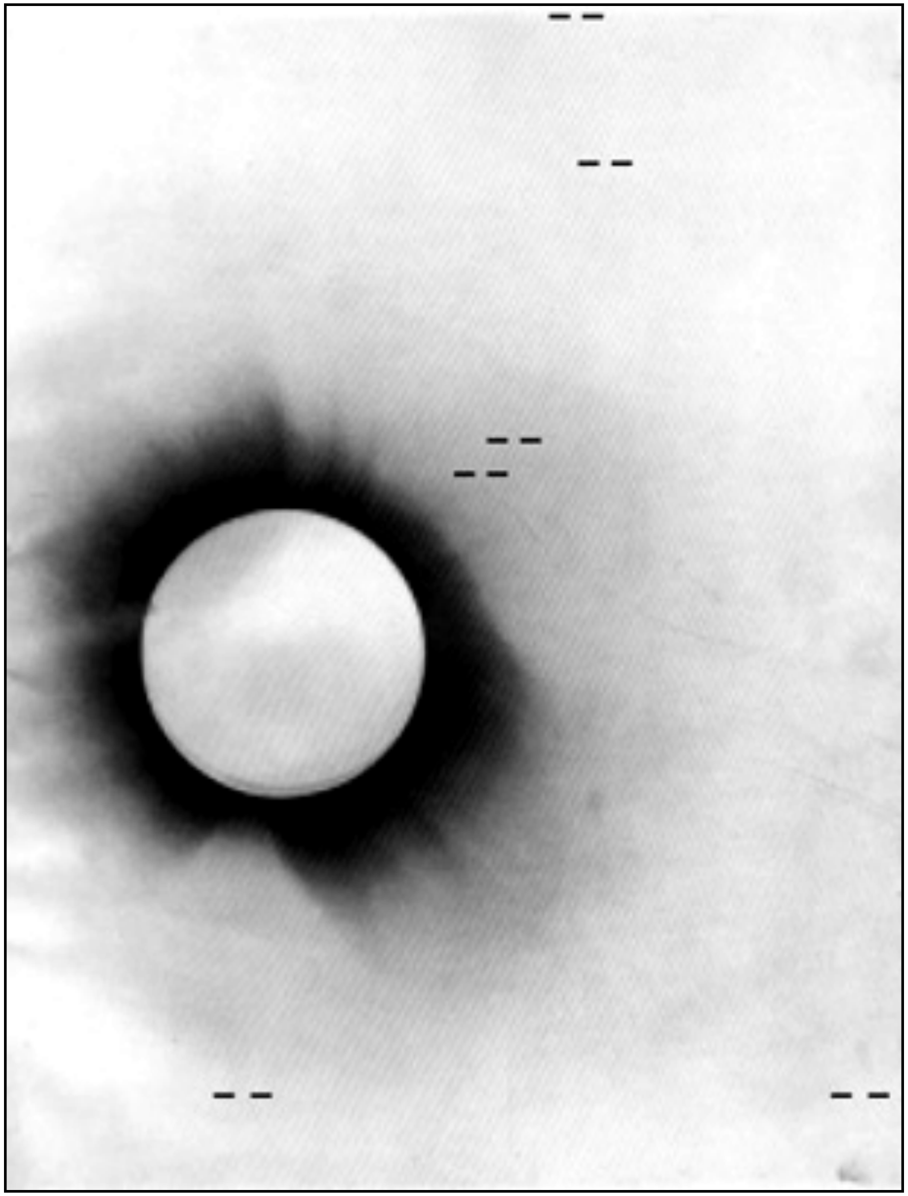
- Following the special relativity, an even more fundamental change in our understanding of the physical space and time, and matter/energy
- Postulates equivalence among **all** frames of reference (including accelerated ones)
- Introduces curvature of space, predicting a number of new effects:
  - Light deflection by masses
  - Gravitational redshift

  etc. etc.

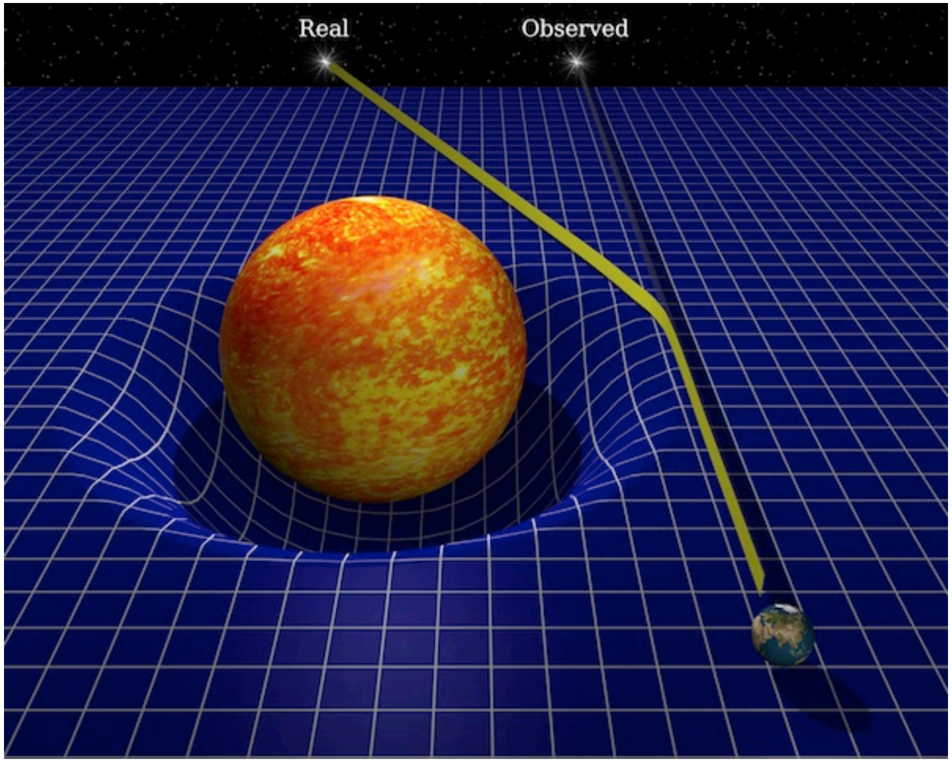


Presence of mass/energy determines the geometry of space
Geometry of space determines the motion of mass/energy

Confirmation of the GR



Eddington's 1919 Solar eclipse observations "confirmed" Einstein's relativistic prediction of $\alpha = 1.78$ arcsec (confirmed by more accurate observations later)



Escape Velocity

An object with a mass *m* can escape from the gravitational potential well of a mass *M* from a radius *R* if:

$$E_{kin} > |E_{pot}|$$

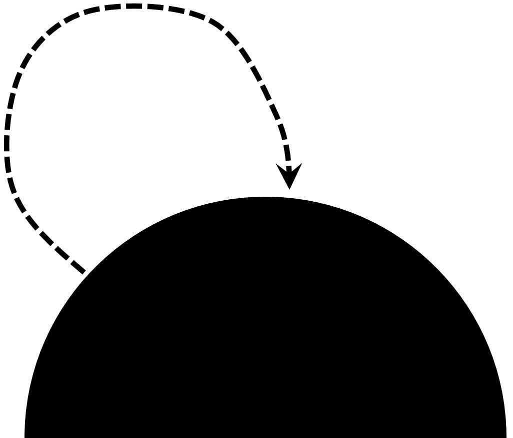
$$m\,V^2 / 2 > G\,m\,M / R$$

$$V > V_{esc} = [2\,G\,M / R]^{1/2}$$

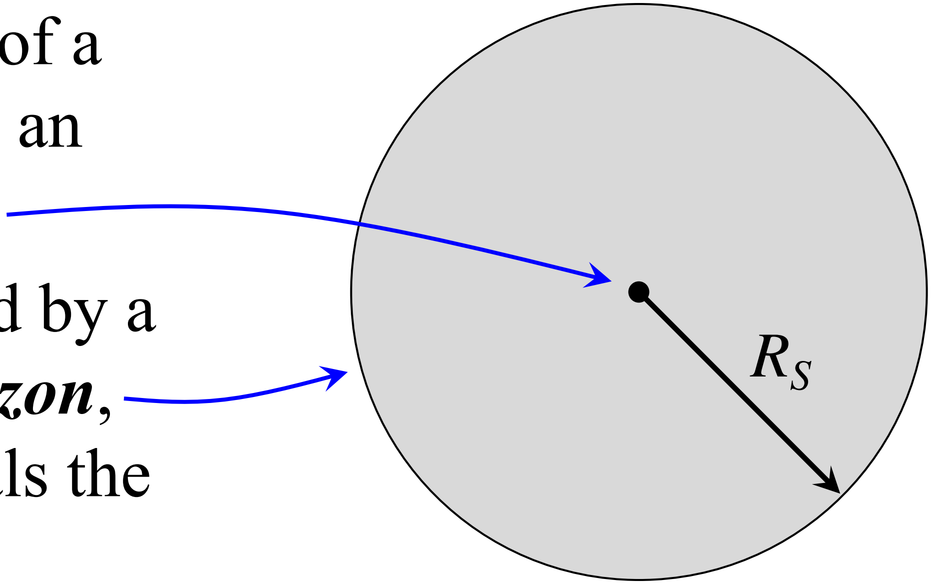
For the Earth, $V_{esc} = 11.2$ km/s

You can increase V_{esc} either by increasing the mass within a given radius, or by decreasing the radius for a given mass

When $V_{esc} > c$, not even light can escape. The enclosed region becomes a **black hole**

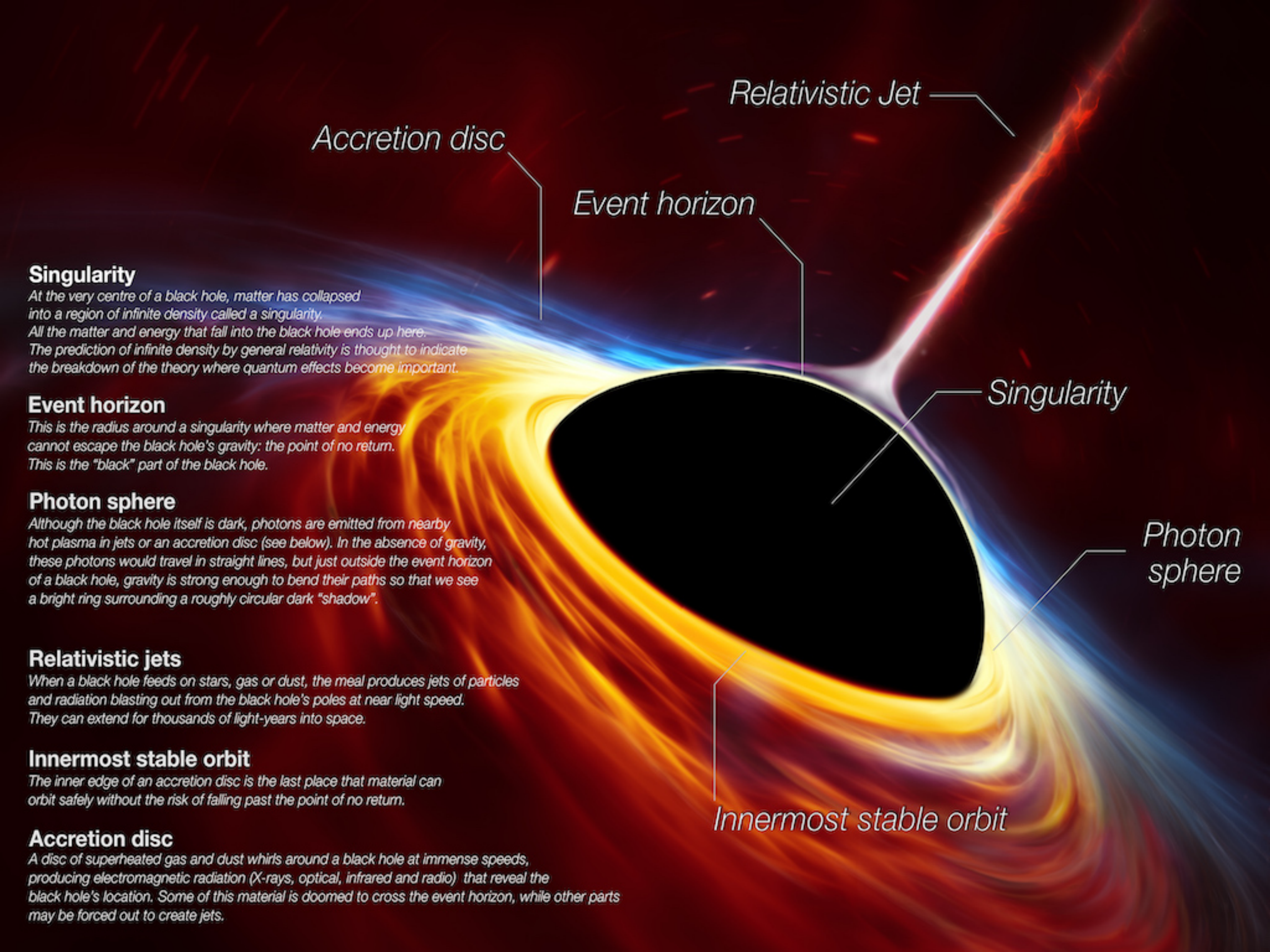


The Structure of a Black Hole



- In principle, the entire mass of a black hole is concentrated in an infinitely dense ***singularity***
- The singularity is surrounded by a surface called the ***event horizon***, where the escape speed equals the speed of light
- For a non-rotating BH, the radius of the event horizon is the ***Schwarzschild radius***: $R_S = 2GM/c^2$

  (For our Sun, $R_S = 3$ km, for the Earth, $R_S = 9$ mm)
- Things are a bit more complicated for a rotating BH
- The only things we can know about a BH are its mass, spin, and electric charge, regardless of what was the material from which it was made



Singularity

At the very centre of a black hole, matter has collapsed into a region of infinite density called a singularity. All the matter and energy that fall into the black hole ends up here. The prediction of infinite density by general relativity is thought to indicate the breakdown of the theory where quantum effects become important.

Event horizon

This is the radius around a singularity where matter and energy cannot escape the black hole's gravity: the point of no return. This is the "black" part of the black hole.

Photon sphere

Although the black hole itself is dark, photons are emitted from nearby hot plasma in jets or an accretion disc (see below). In the absence of gravity, these photons would travel in straight lines, but just outside the event horizon of a black hole, gravity is strong enough to bend their paths so that we see a bright ring surrounding a roughly circular dark "shadow".

Relativistic jets

When a black hole feeds on stars, gas or dust, the meal produces jets of particles and radiation blasting out from the black hole's poles at near light speed. They can extend for thousands of light-years into space.

Innermost stable orbit

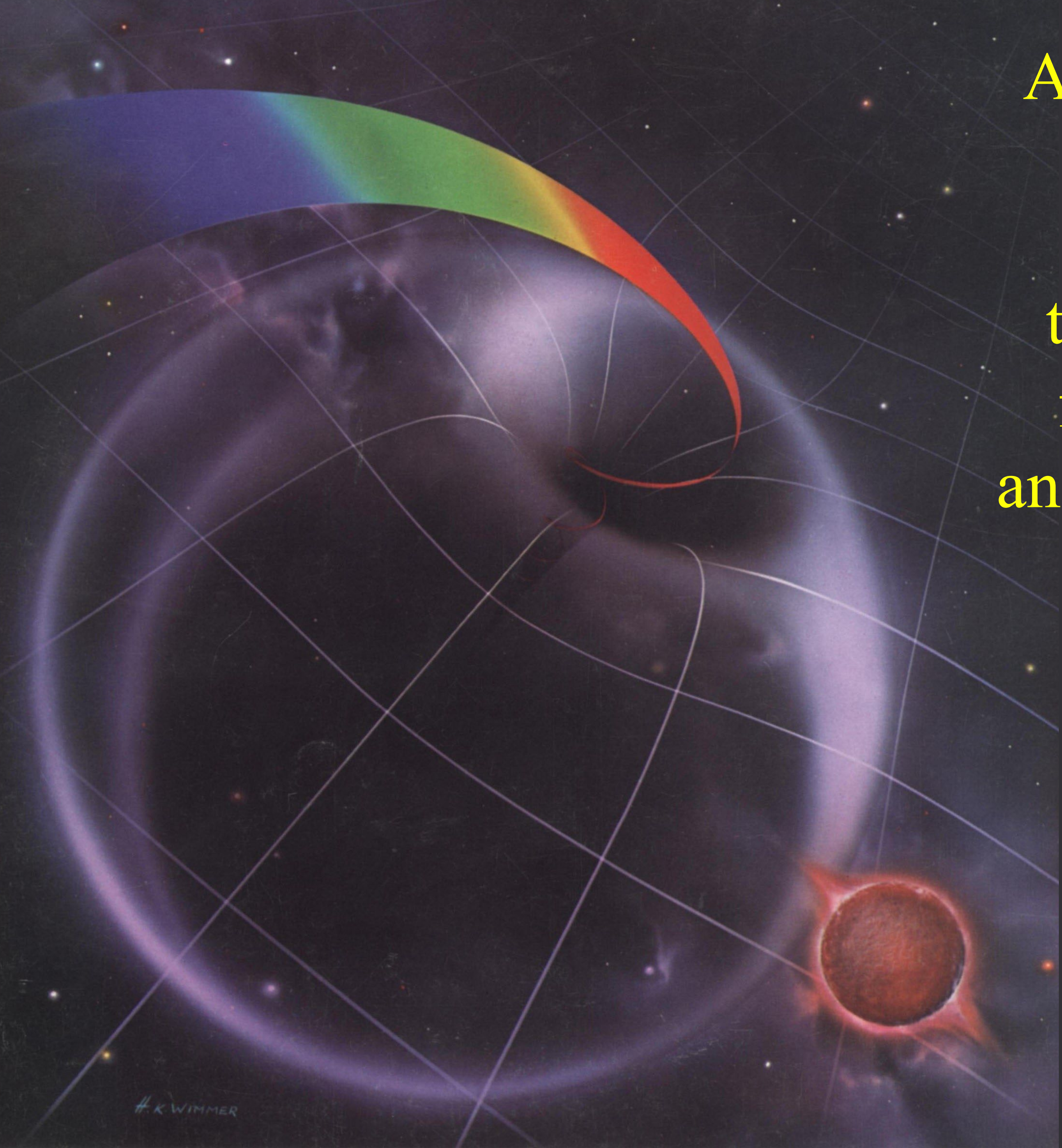
The inner edge of an accretion disc is the last place that material can orbit safely without the risk of falling past the point of no return.

Accretion disc

A disc of superheated gas and dust whirls around a black hole at immense speeds, producing electromagnetic radiation (X-rays, optical, infrared and radio) that reveal the black hole's location. Some of this material is doomed to cross the event horizon, while other parts may be forced out to create jets.

Forming a Stellar Black Hole

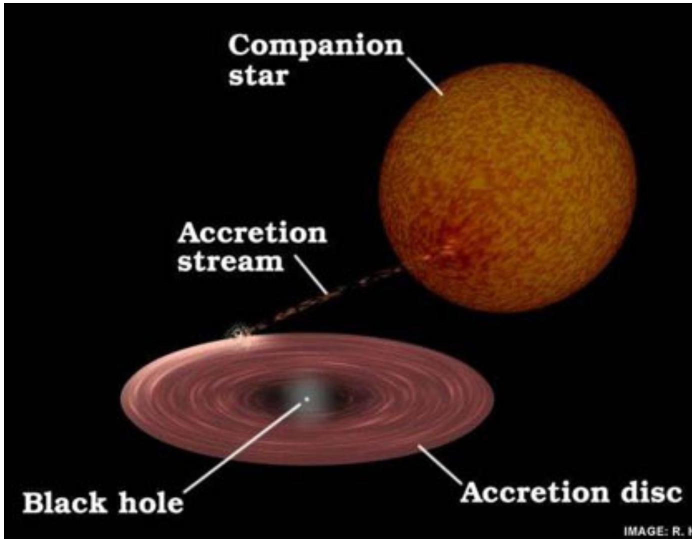
- If the core of a star collapses and it has more than 3 solar masses, no known force can stop the collapse.
- The electron degeneracy cannot stop the gravitational force
- The neutron degeneracy cannot stop the gravitational force of collapse
- The star collapses to a radius of "zero"
- Now the star has infinite density and gravity—called a ***Singularity***
- We call the region where the contracting core of a star becomes small enough that the escape velocity is so large that even light cannot escape a **black hole**

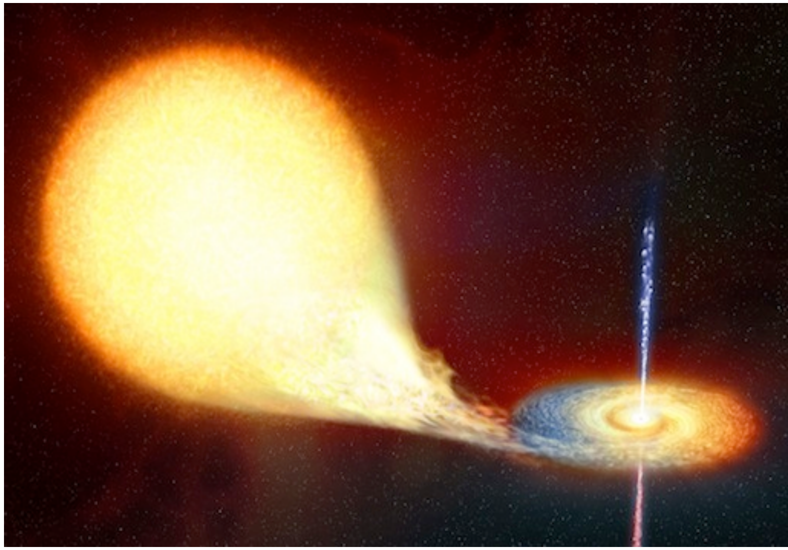


At the black hole boundary (the event horizon), the gravitational force is infinite, and the time stops

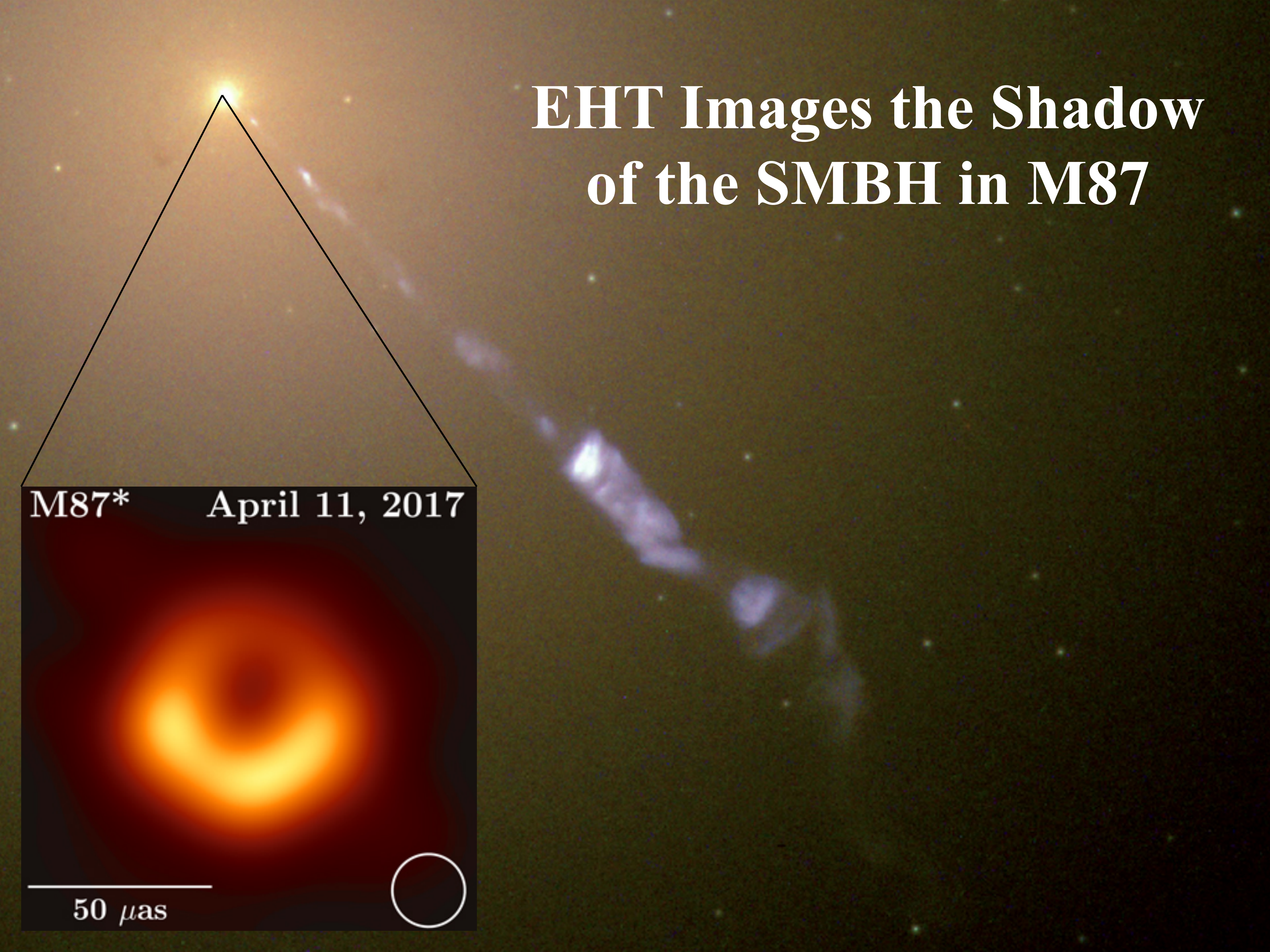
Evidence for Black Holes

- A black hole alone is totally invisible
- But a matter is falling into the potential well of a BH would radiate away its binding energy, e.g., in X-rays
- So we can search for black holes by searching among X-ray binaries (example: Cygnus X-1)
- If the object pulses, we know it is a neutron star binary
- Sometimes BH binaries form jets – they are *microquasars*
- But the really spectacular are the supermassive black holes in galactic nuclei





EHT Images the Shadow of the SMBH in M87

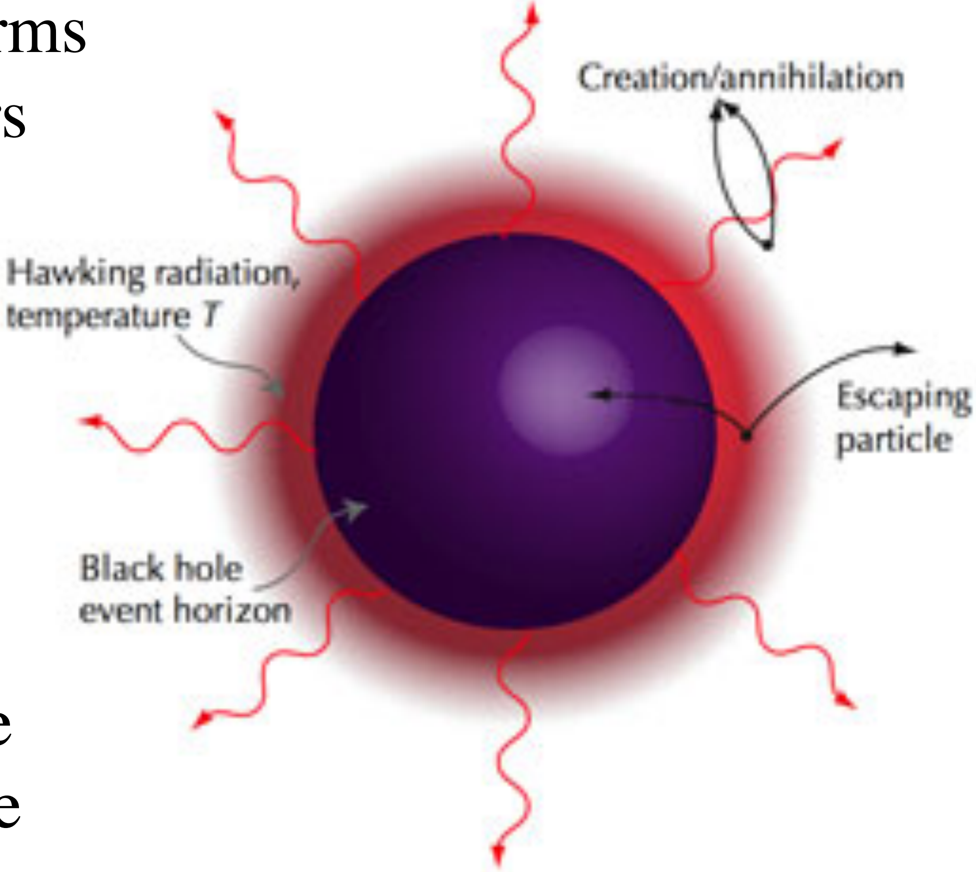


Black Holes Evaporate

Physical vacuum constantly forms virtual particle-antiparticle pairs

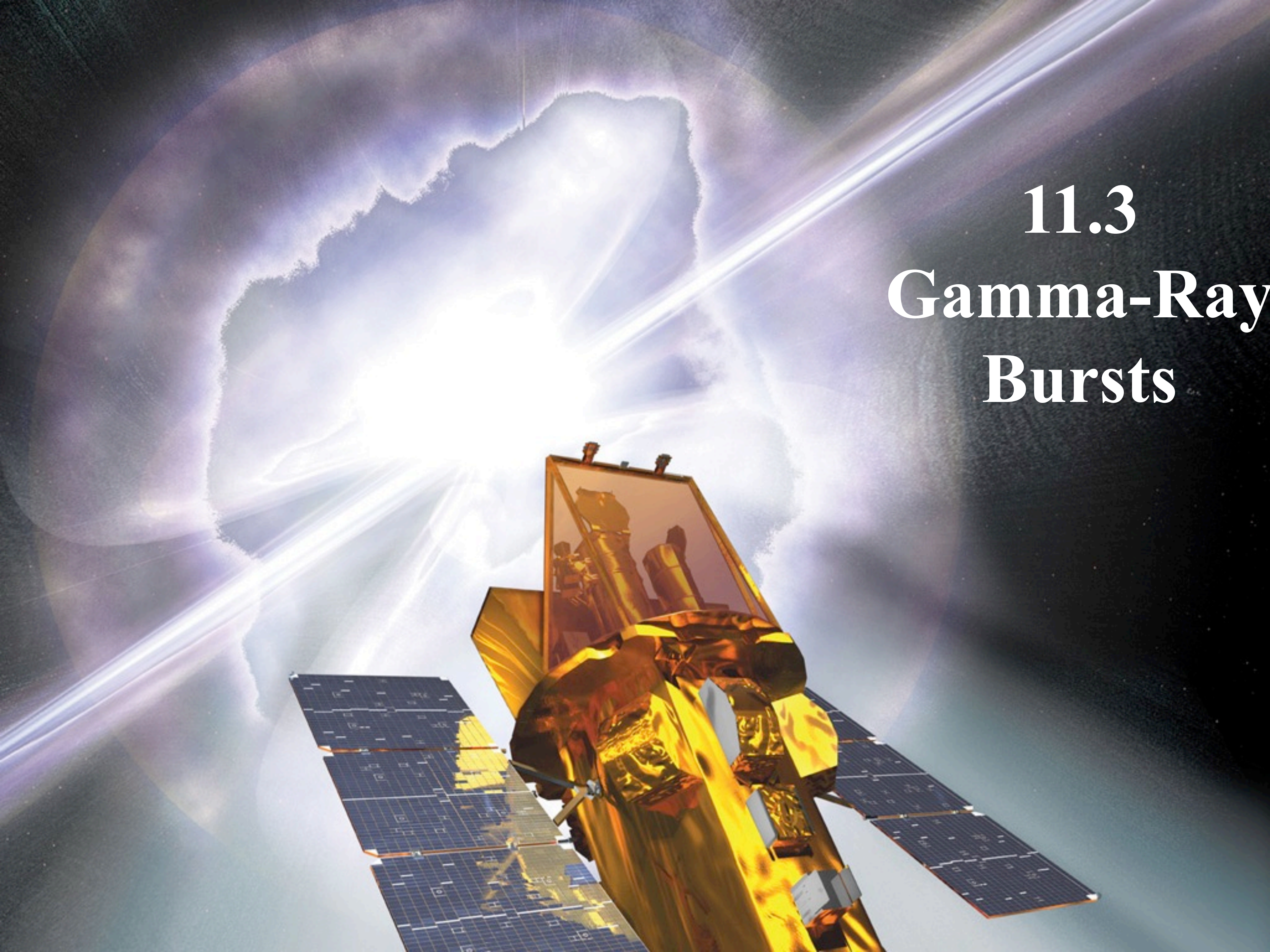
Normally they annihilate within the time interval given by the Heisenberg's uncertainty principle

But near the event horizon, some of them will fall in before they have a chance to annihilate



Their leftover partners *do* annihilate – *outside the BH*, and that radiation escapes: the **Hawking radiation**

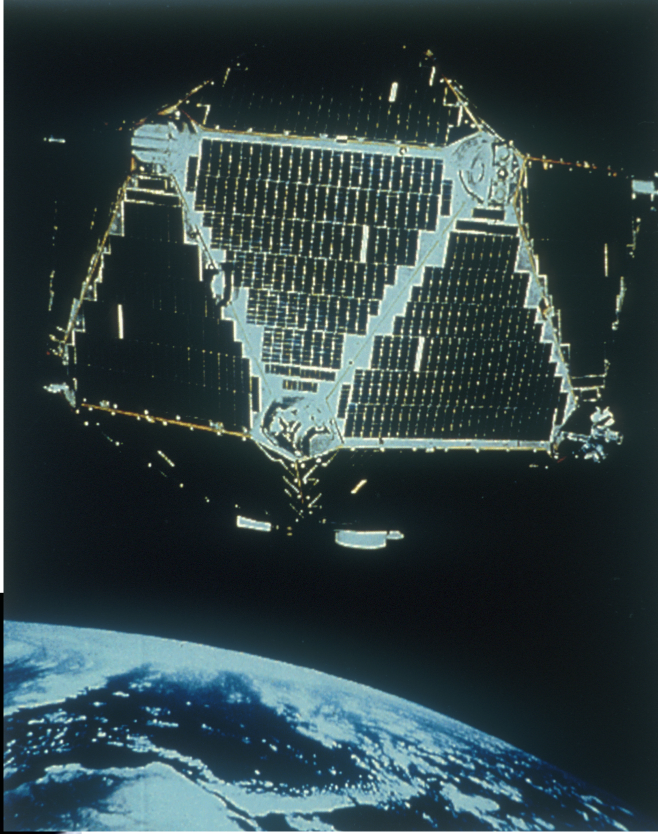
The energy comes at the expense of the BH's rest mass energy



11.3
Gamma-Ray Bursts

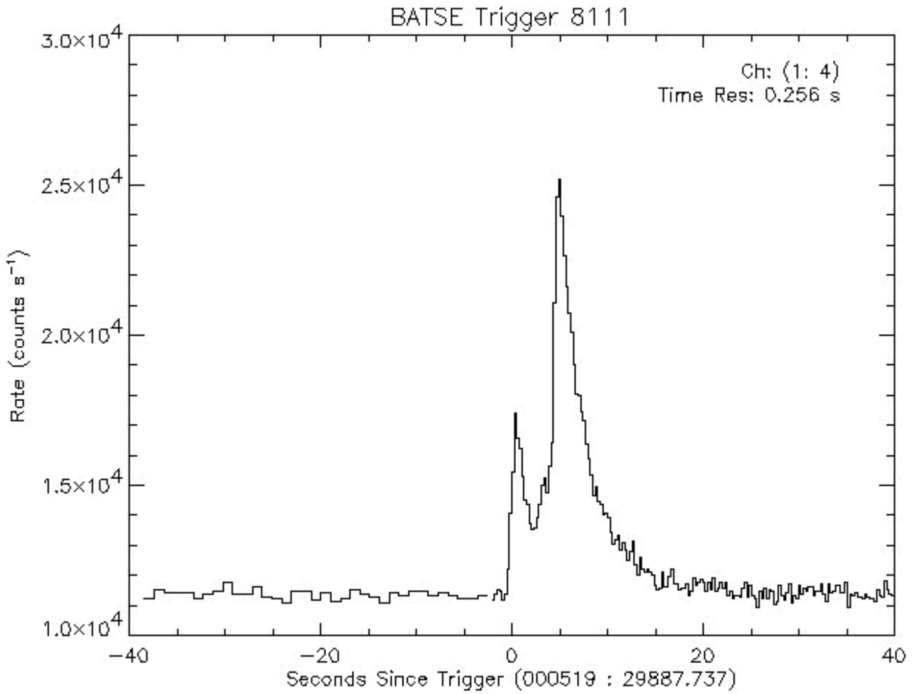
Discovered by the Vela Satellites, circa 1970

Studied by many missions since,
but the origins remained mysterious

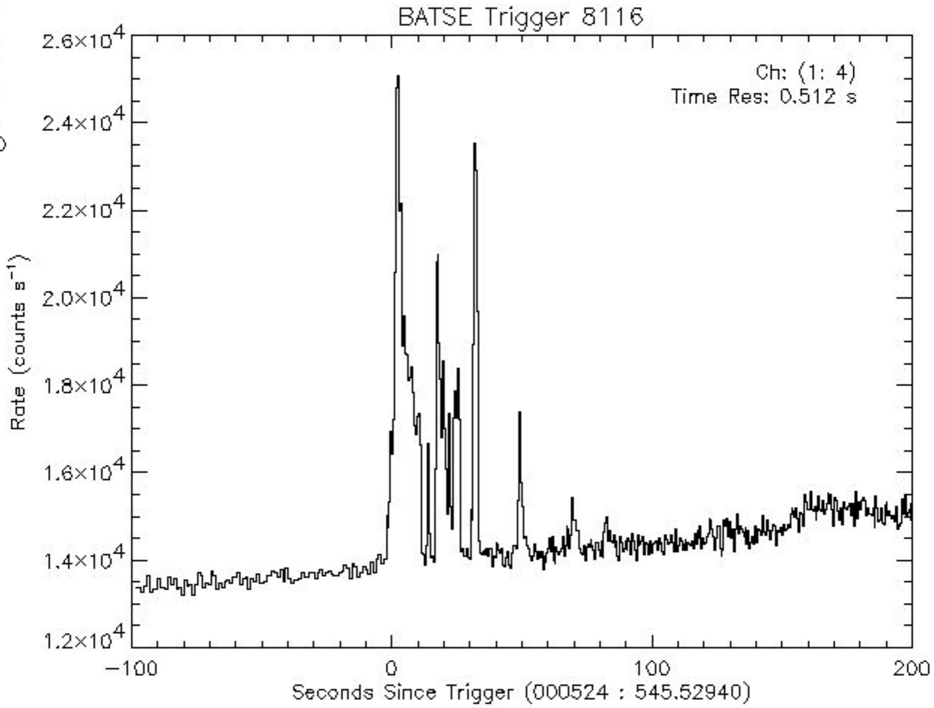


< --Compton
Gamma-Ray
Observatory
(CGRO)

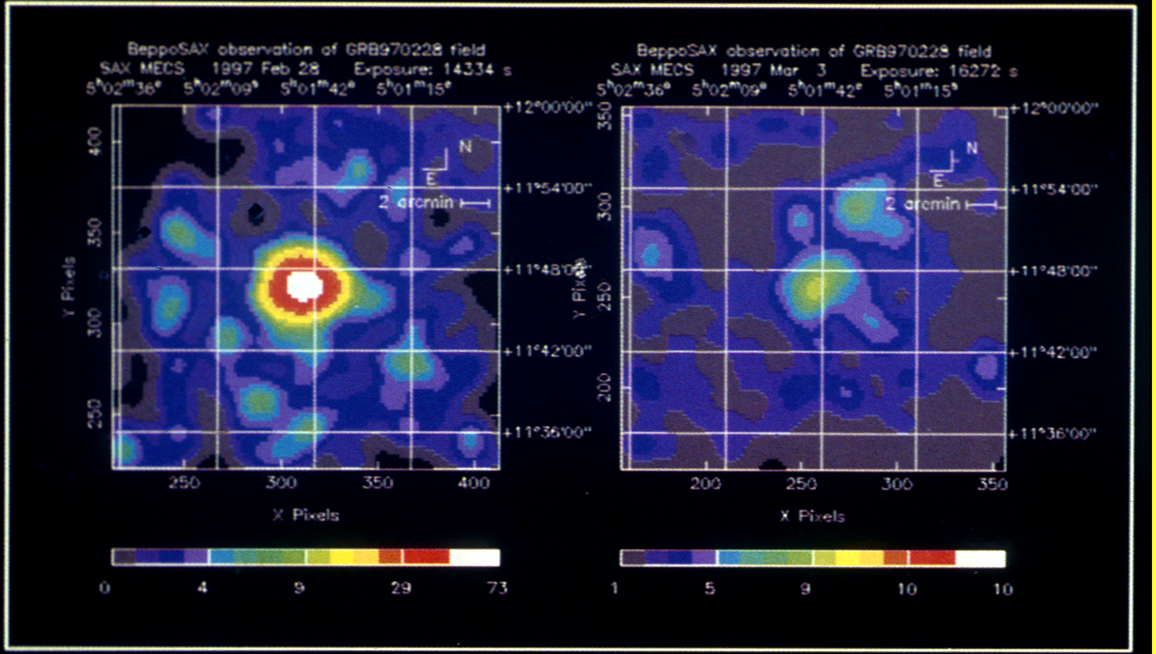
Typical GRB Light Curves



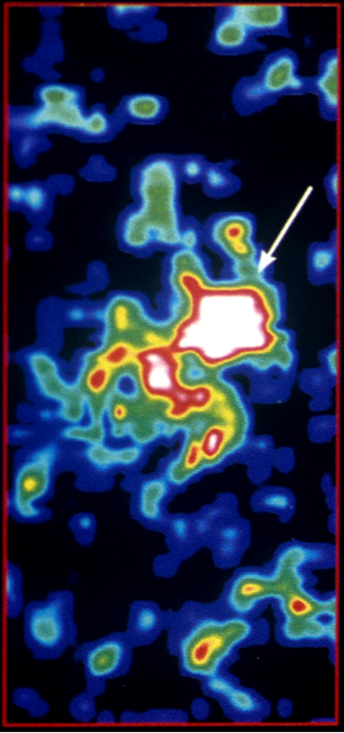
Typical detected fluences are ~ 10^{-5} - 10^{-6} erg/cm^2 So, if GRBs are at cosmological distances, ~ 10^{29} cm, then the energies are ~ 10^{52} - 10^{54} erg !

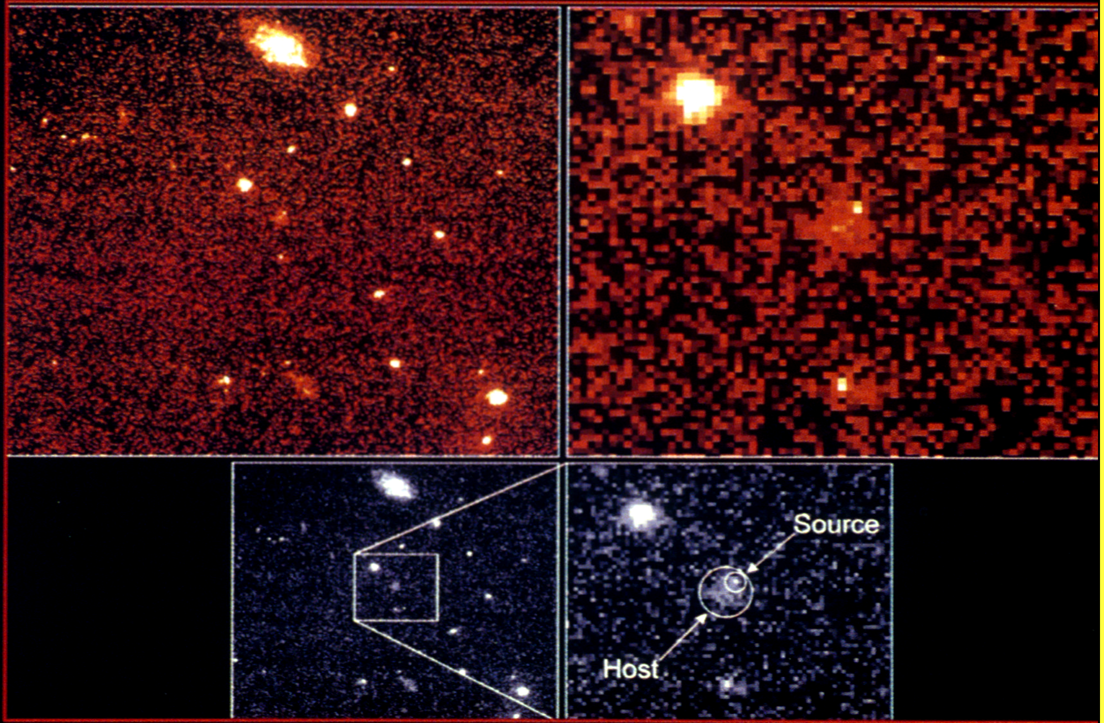


Rapid (~ ms) variability time scales imply small sizes, ~ 100 km. Thus, the source of the emisison must be nonthermal



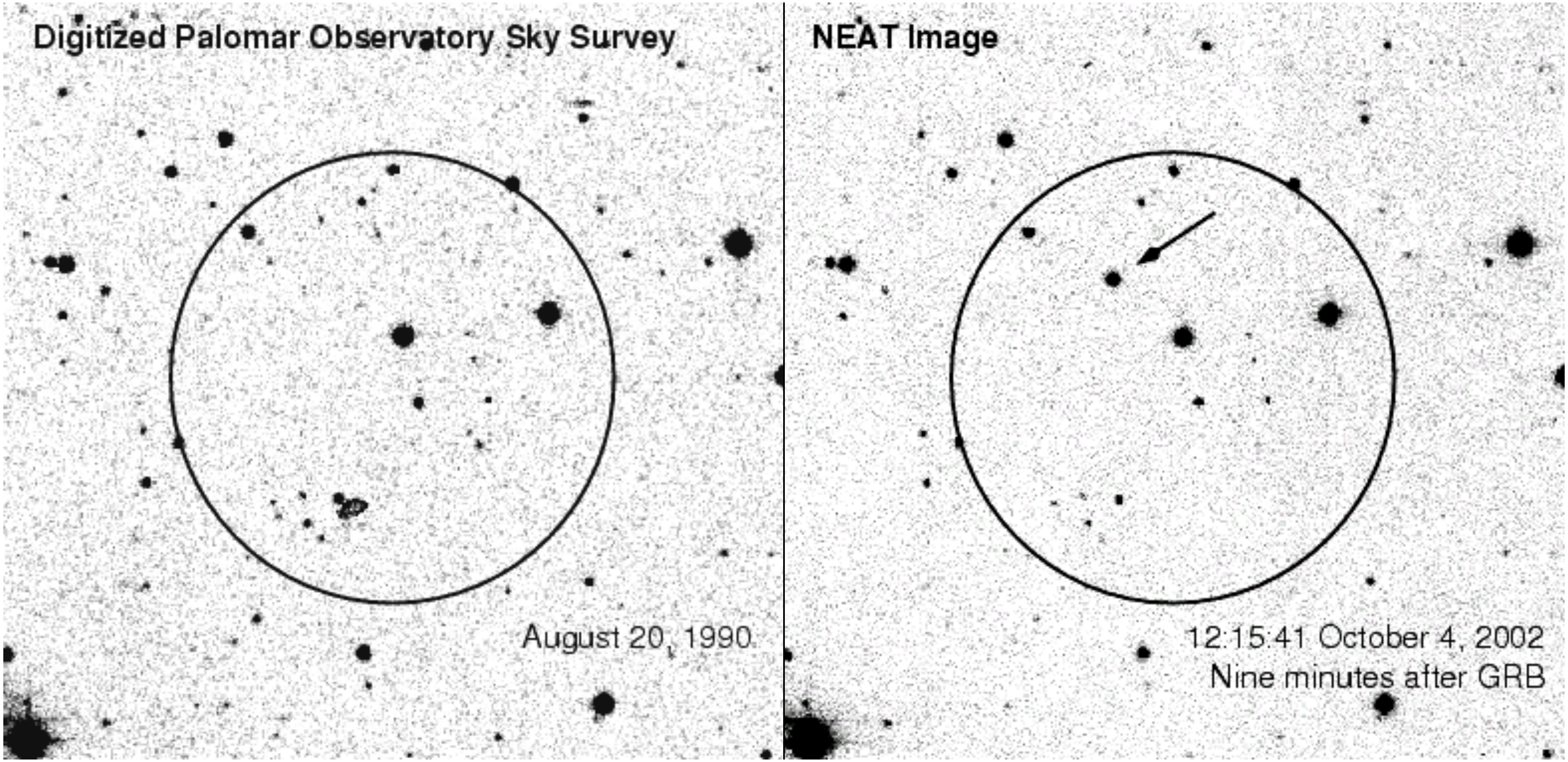
It all changed with the precise (~ arcmin) X-ray localizations of GRB afterglows by the BeppoSAX satellite …





… which led to optical IDs, and then redshifts

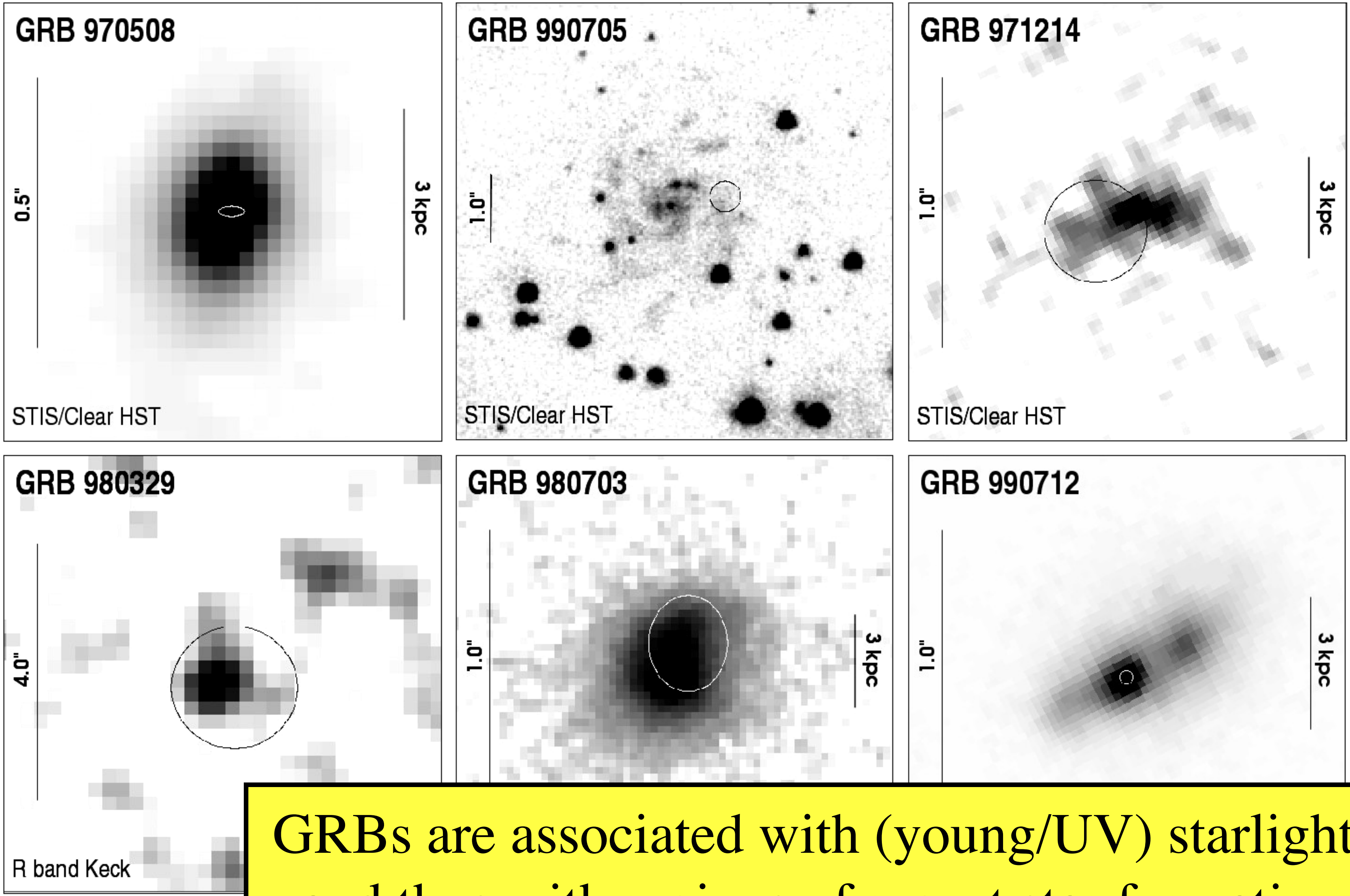
Optical Transients Associated With GRBs



Typically fade as ~ t^{-1}

Explained (and predicted) as afterglows of GRBs

Location of GRBs Within Their Host Galaxies

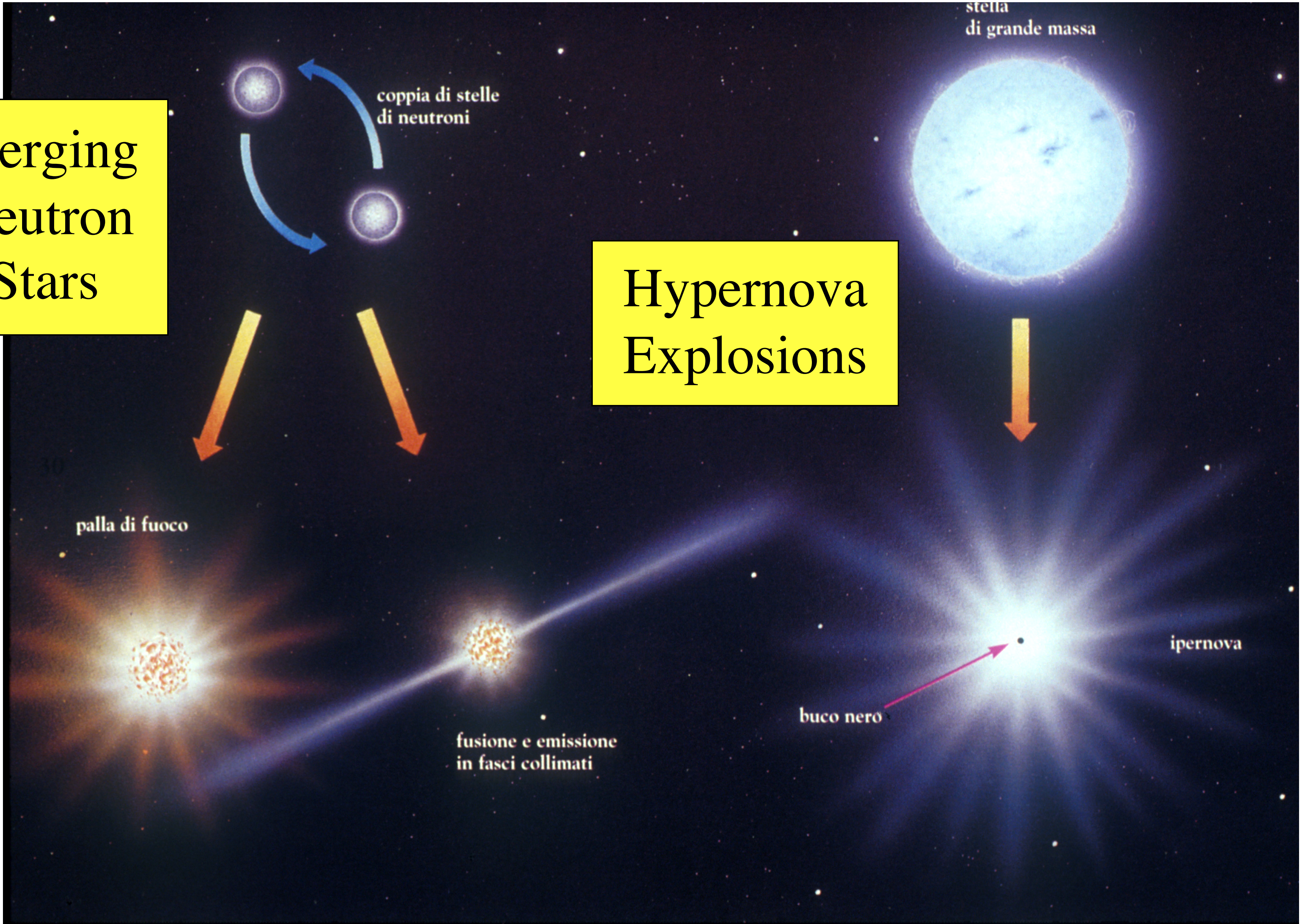


GRBs are associated with (young/UV) starlight, and thus with regions of recent star formation

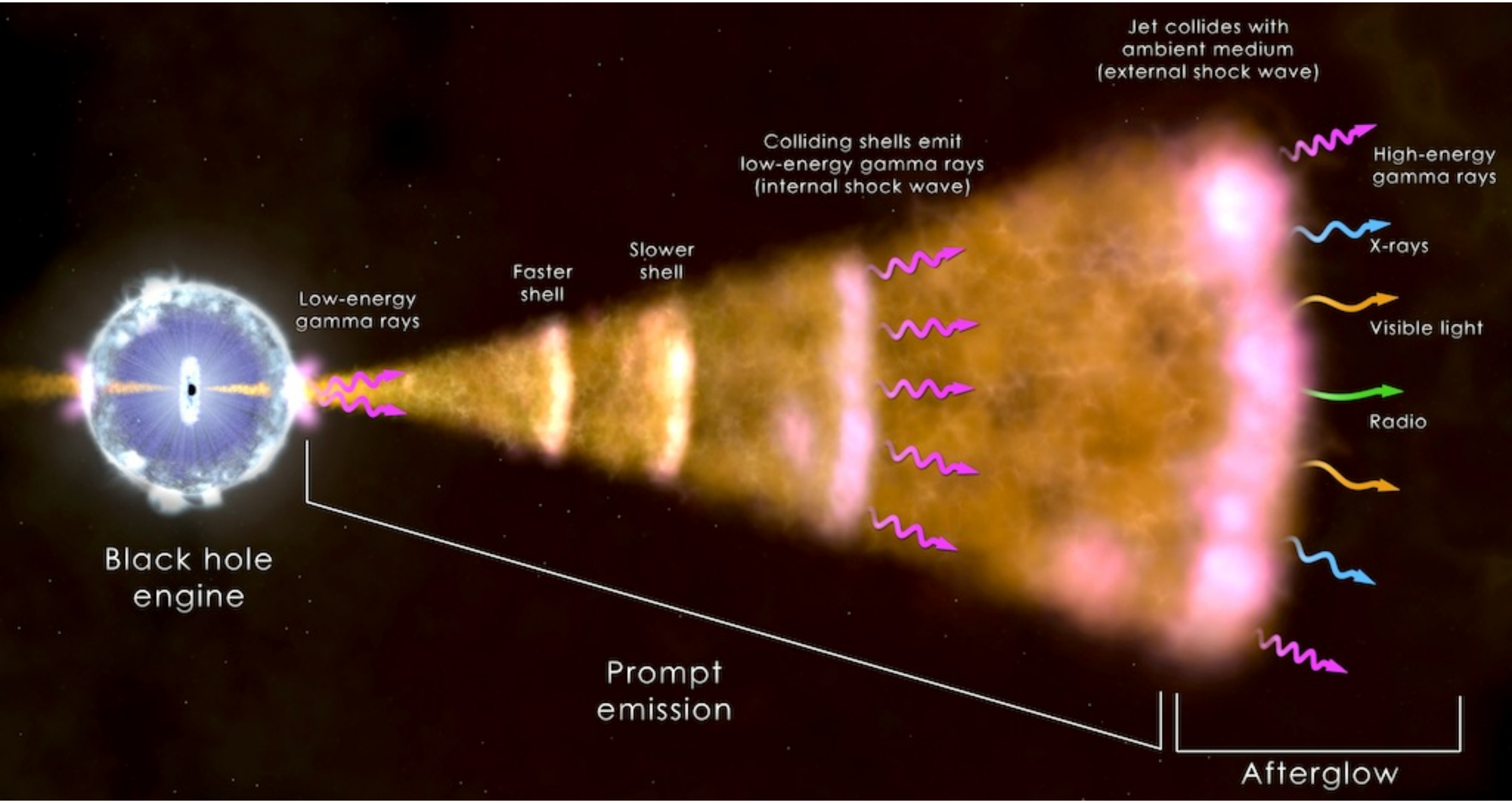
Popular Models for GRB Origins

Merging Neutron Stars

Hypernova Explosions

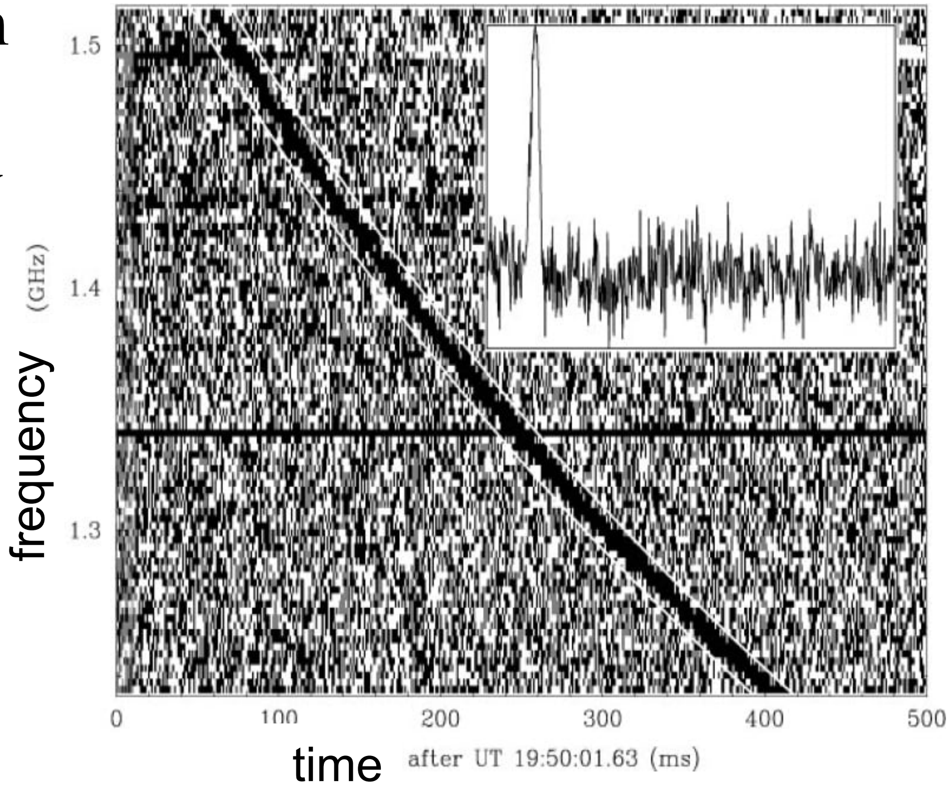


The Collapsar Model for GRBs



Fast Radio Bursts (FRBs)

- Duration in milliseconds, a high dispersion measure (delay at different frequencies, caused by the passage through a plasma)
- Believed to be extragalactic
- Believed to be related to neutron stars, but still not really understood



⬆️ Intensity as a function of time and frequency for the first detected ("Lorimer") FRB. The peak frequency drifts as the time goes on.

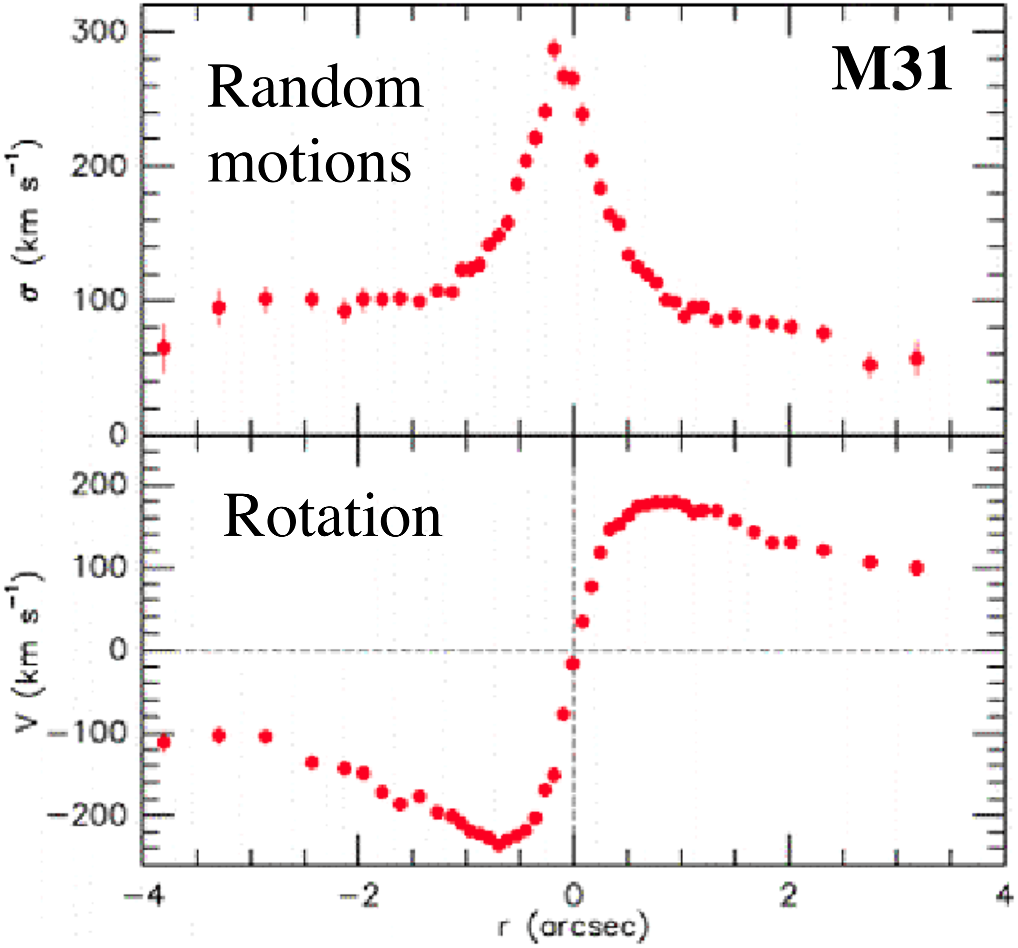
11.4 SuperMassive Black Holes in Galactic Nuclei

Massive Black Holes in Galactic Nuclei

- They are ***ubiquitous***, even though only a small fraction are active today; but these SMBHs are just ***dormant quasars***, which were once active - this is where their mass comes from!

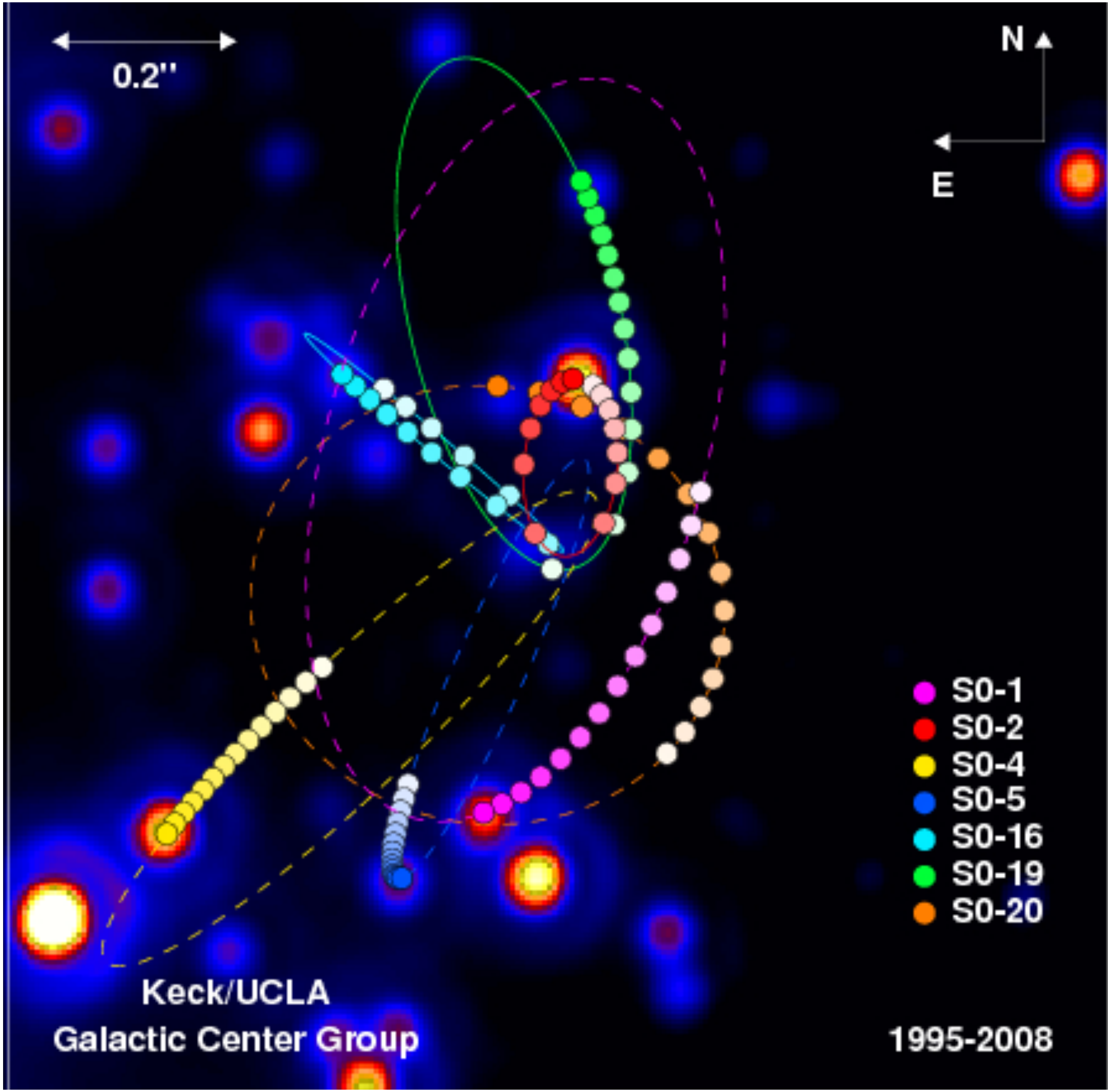
- They are detected through kinematics of stars or gas near the galactic centers:

  These are test particles probing the gravitational potential of the central mass – whether you can see it or not

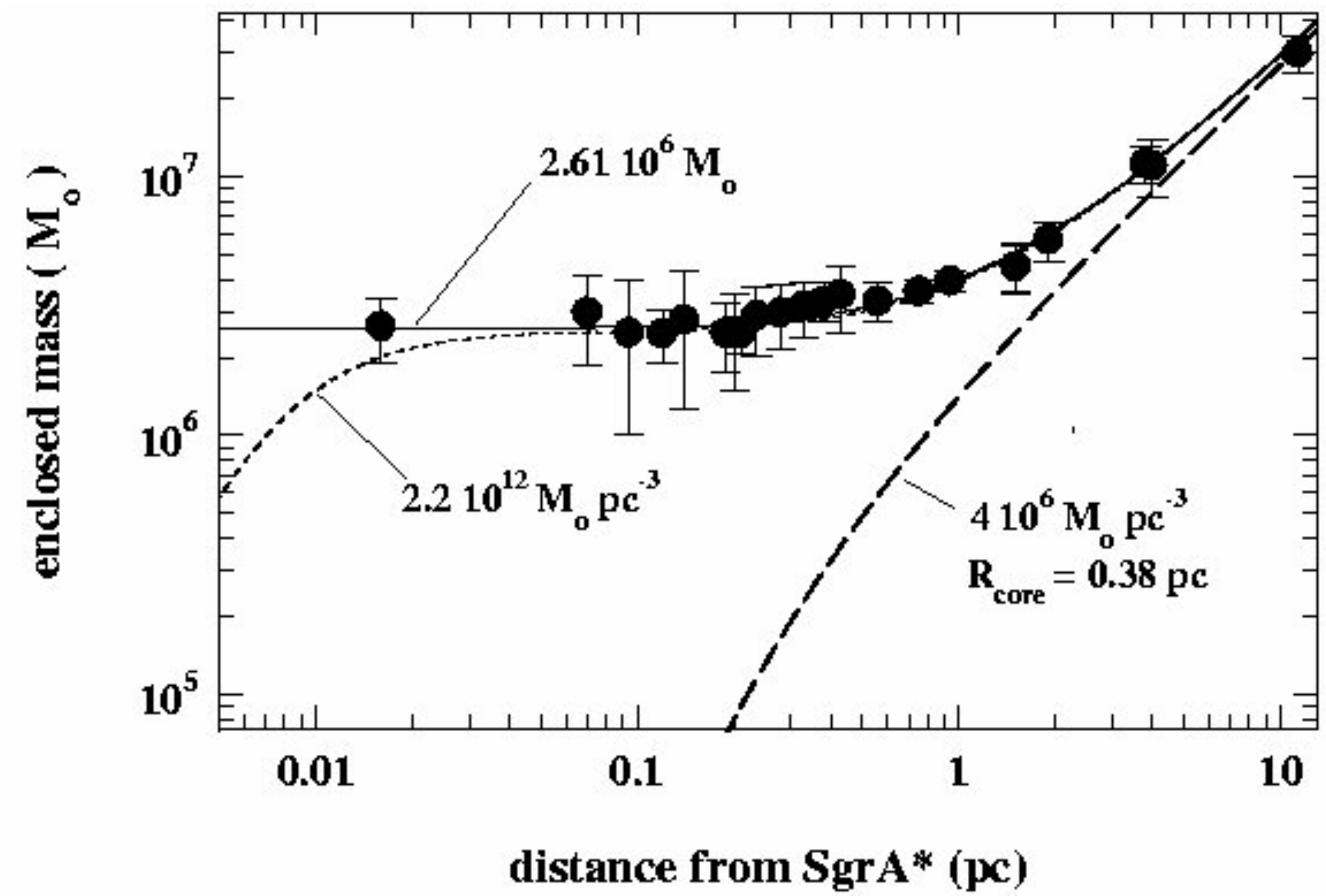


Keck measured proper motions of stars near the Galactic center

(A. Ghez et al., UCLA)



Dynamical Evidence for a Supermassive Black Hole at the Galactic Center



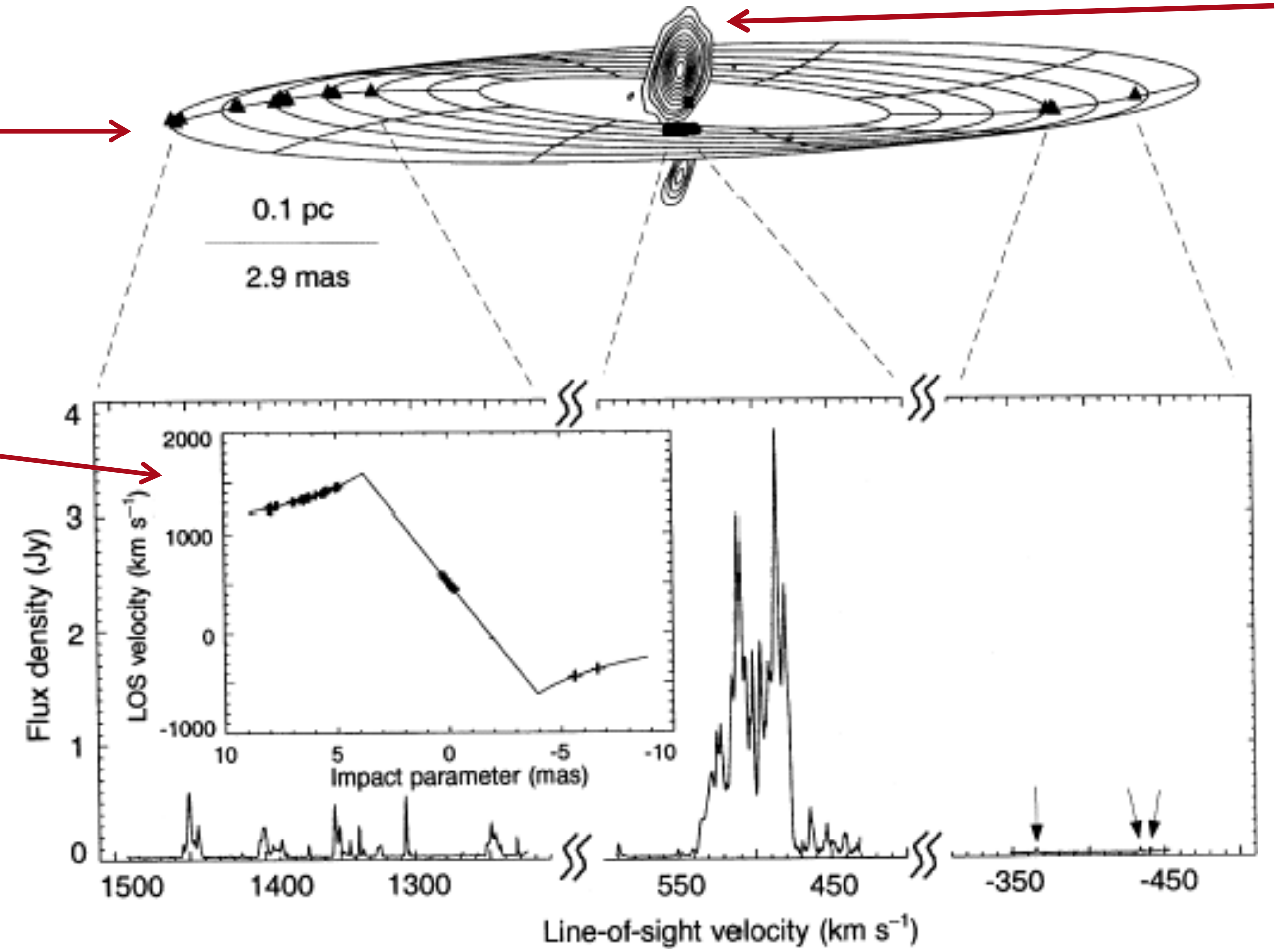
(Genzel et al., Ghez et al.)

Note: $R_S\ (M_\bullet = 2.6 \times 10^6\ M_\odot) = 7.8 \times 10^8$ cm $= 6.5 \times 10^{-8}$ arcsec

→ Unresolvable by any technology we have now

Black Hole in NGC4258

Observe the positions and velocities of **water masers** in a thin gas disk orbiting the black hole; their Keplerian motions provide a measurement of the central point mass



Radio jet

Thin disk

Rotation curve

But the really spectacular ones are quasars:
supermassive black goles accreting at prodigious rates

They are the most luminous objects in the universe, 100 or 1000 times brighter than the entire galaxy of stars

Where Does the Energy Come From?

- Accretion onto the central supermassive black holes provides the only known viable answer
- The fuel comes from ~ kpc scales (or larger) and ends near the ***Schwarzschild radius***,

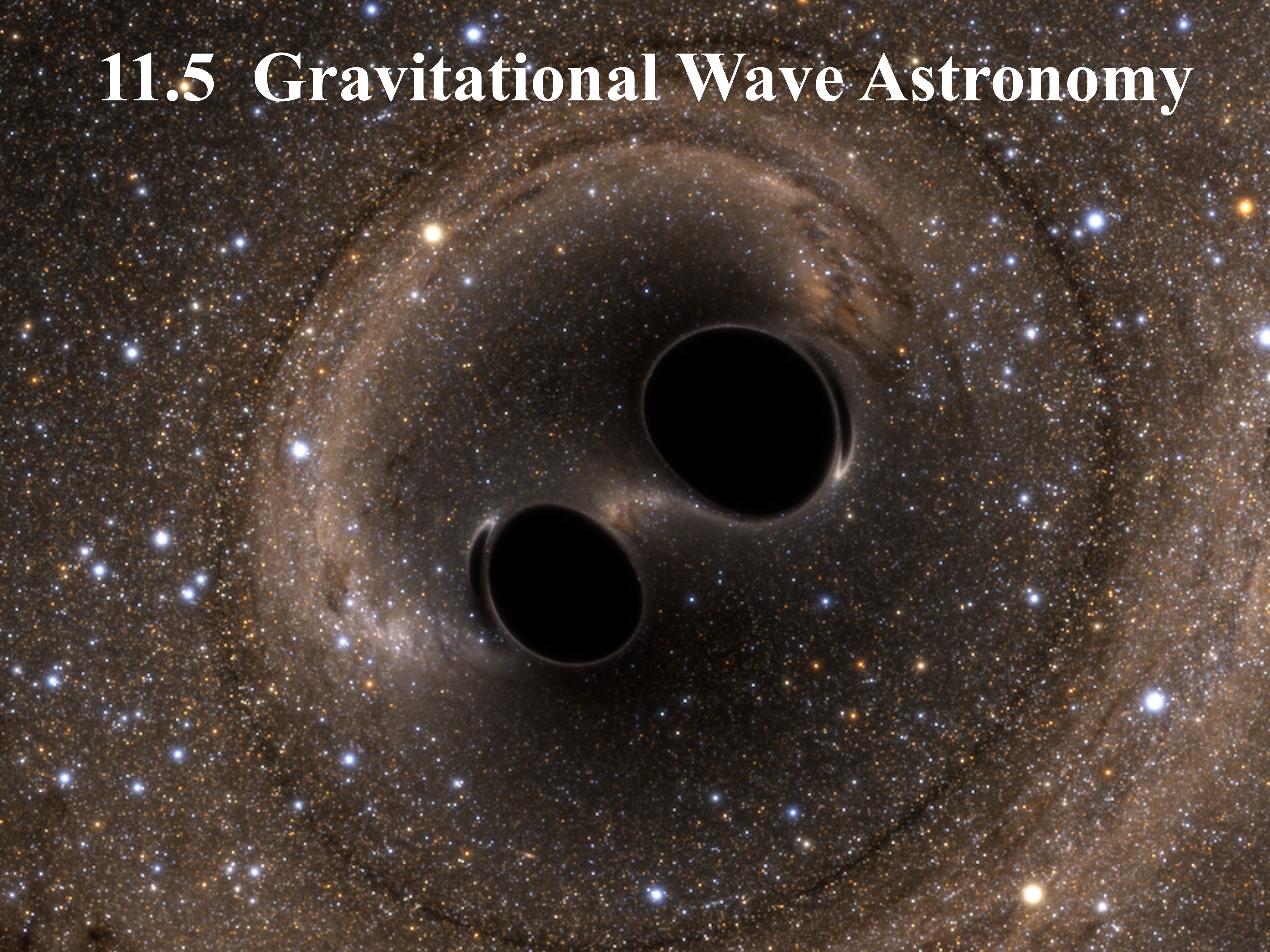
$$R_s = \frac{2GM}{c^2}$$

(actually, the relevant radius is the smallest stable orbit, at a few R_s)
For a $M_\bullet \sim 10^8 M_\odot$, $R_\mathrm{s} \sim 3 \times 10^8$ km ~ 10^{-5} pc

- The binding energy for a mass m is: $E_b(R) = G\, m\, M_\bullet / R$
- In order for it to be accreted over many orders of magnitude in radius, it has to release the amount of energy comparable to E_b namely $G\, m\, M_\bullet / R_{min} = m\, c^2 / 2$, where $R_{min} \sim$ a few R_s

➡ ***Accretion to black holes can result in the energy release comparable to the rest mass energy!*** Usually a ~ 10% net efficiency is assumed, still much larger than the 0.1% energy conversion efficiency of thermonuclear reactions.

11.5 Gravitational Wave Astronomy



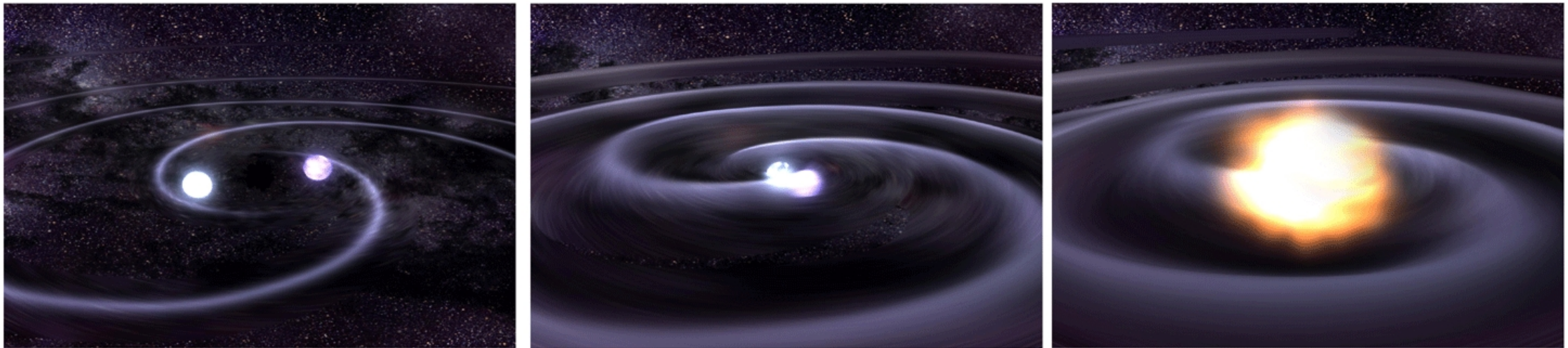
Merging Compact Binaries

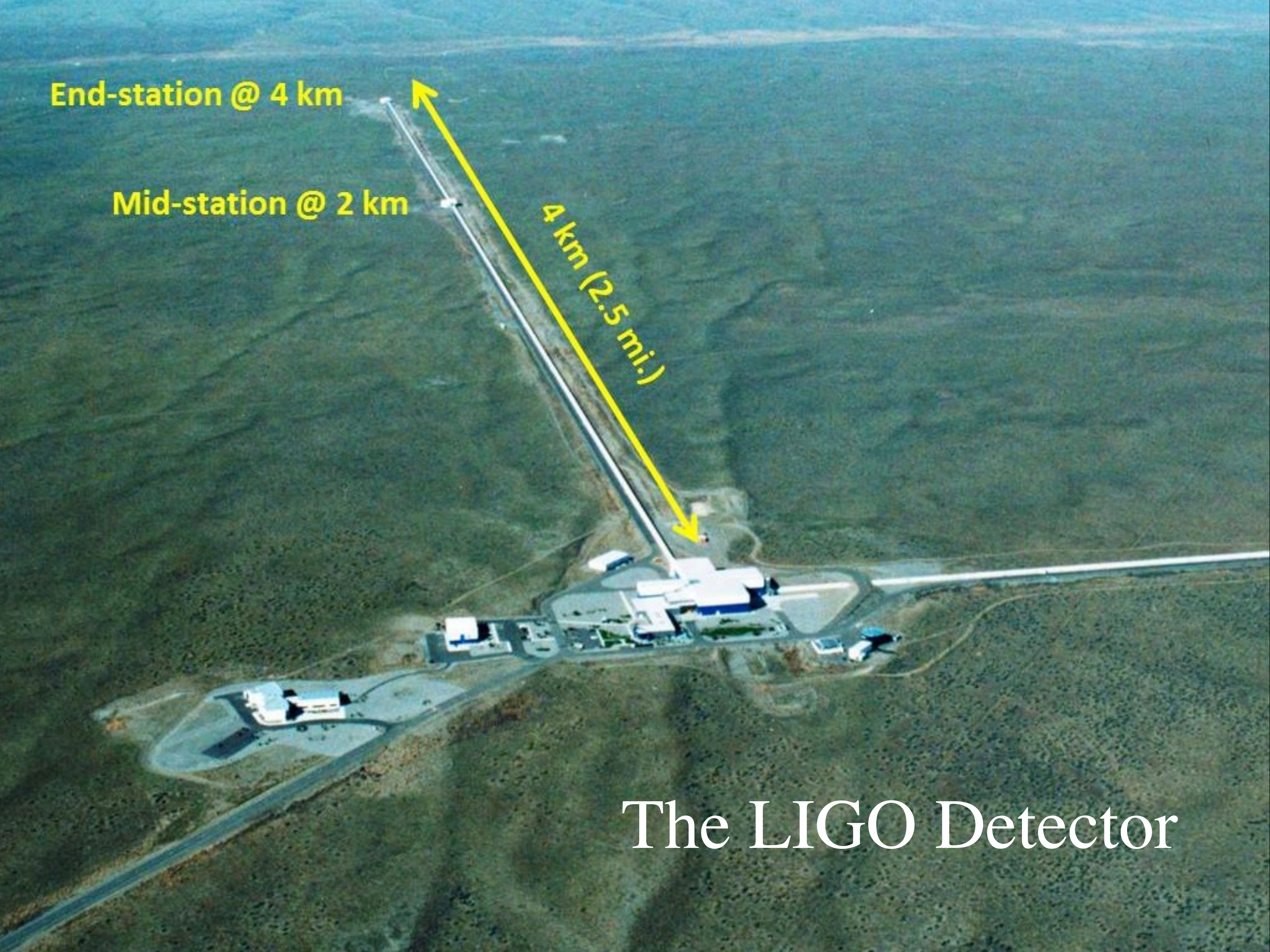
- Compact binaries initially loose energy due to the mutual tides, and become more compact (closer)
- Eventually they start loosing the orbital energy to the emission of gravitational waves, and get even closer, until they finally merge, with a massive release of the binding energy

White dwarf mergers ⟶ SN Ia explosion ⟶ neutron star

Neutron star mergers ⟶ short GRB + GW burst ⟶ black hole

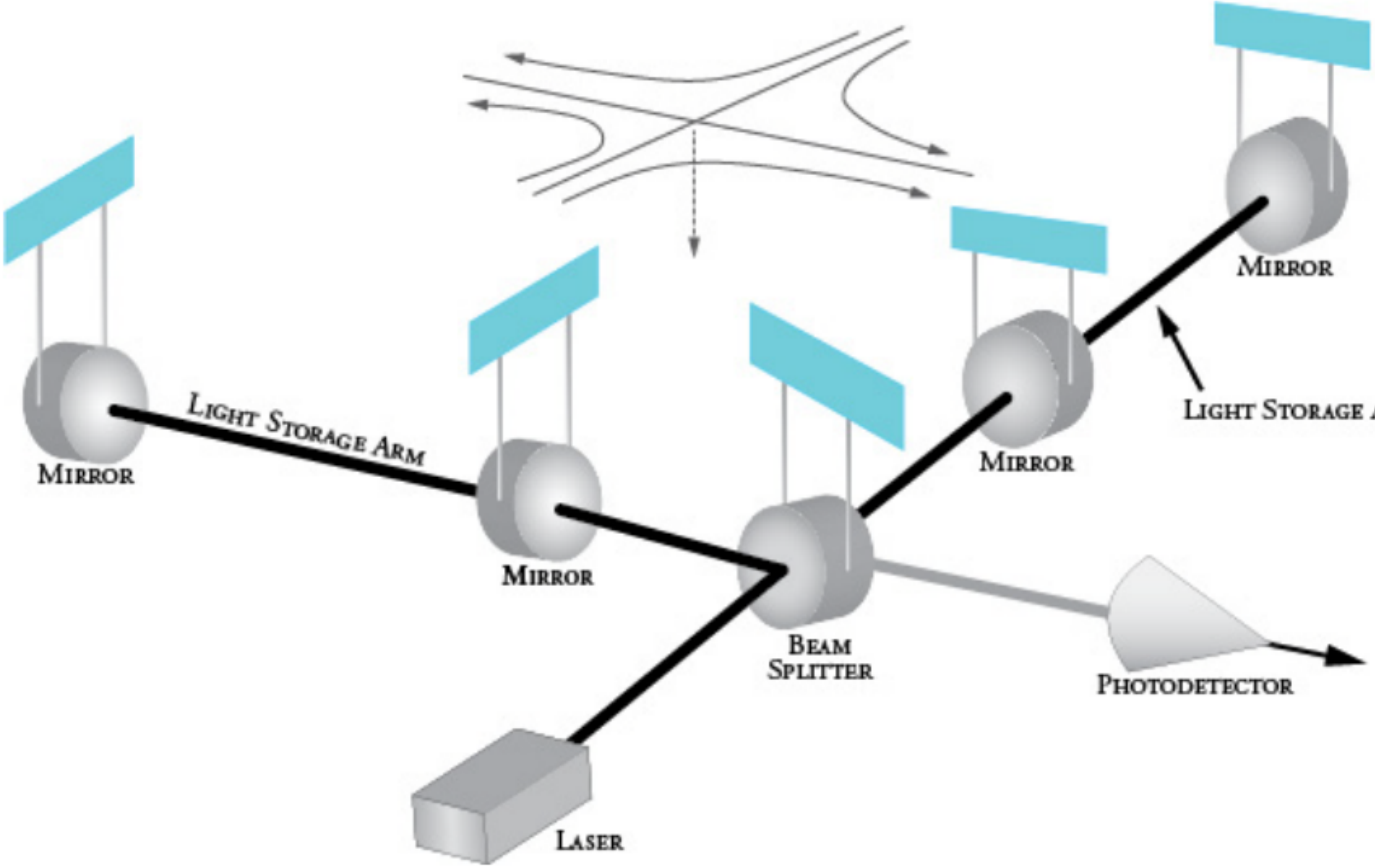
Black hole mergers ⟶ GW burst ⟶ black hole



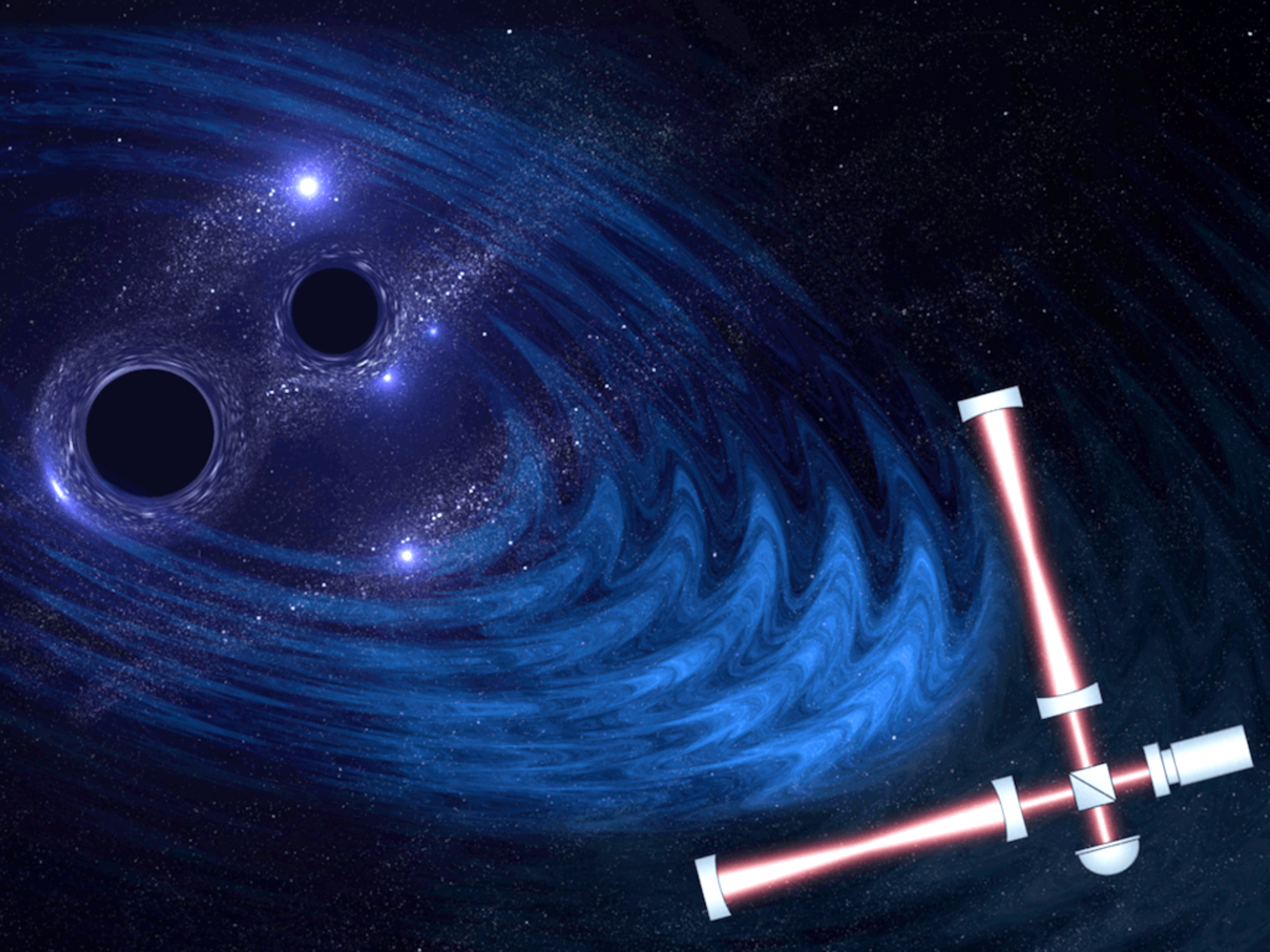


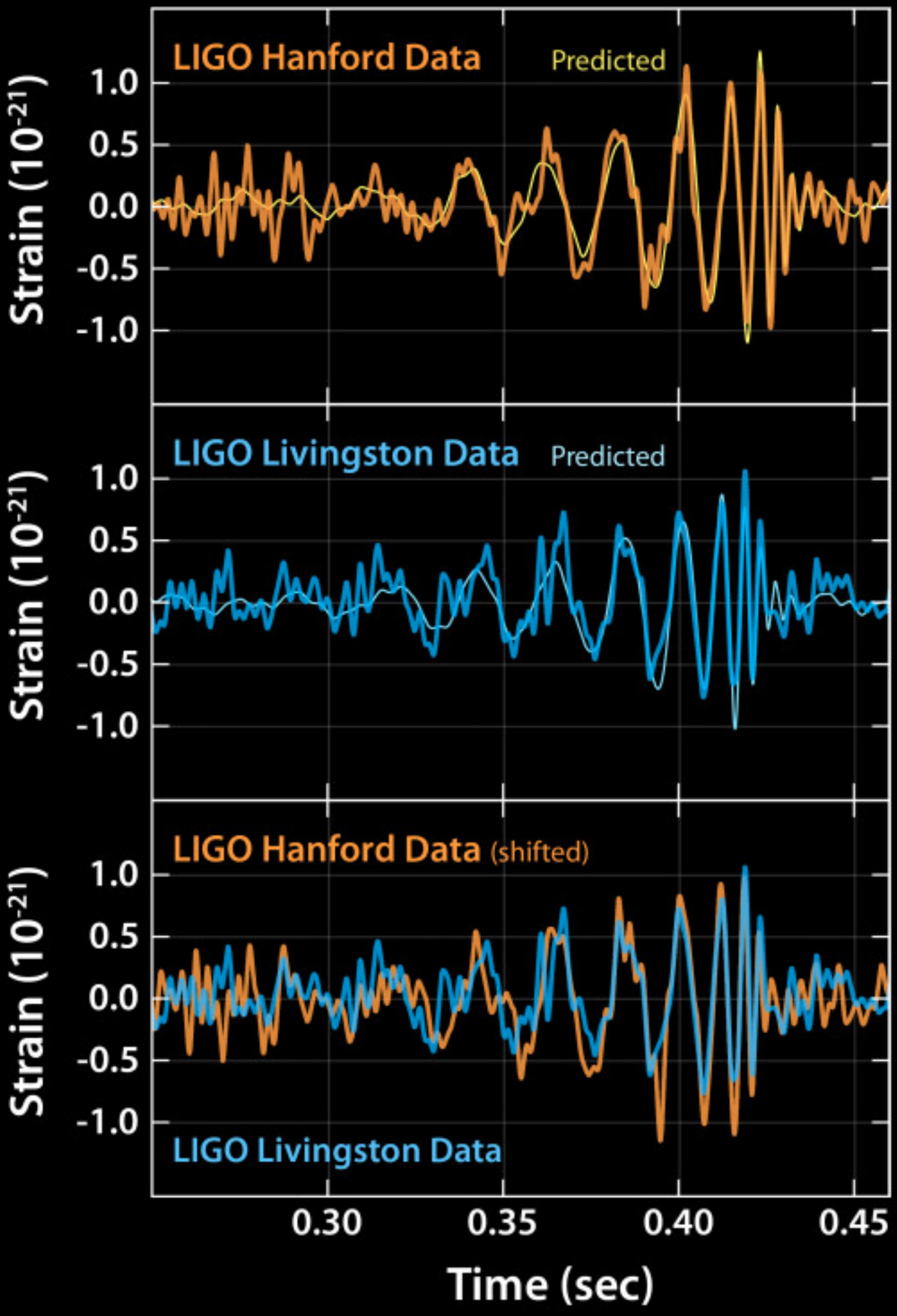
The LIGO Detector

How LIGO works: a laser interferometer



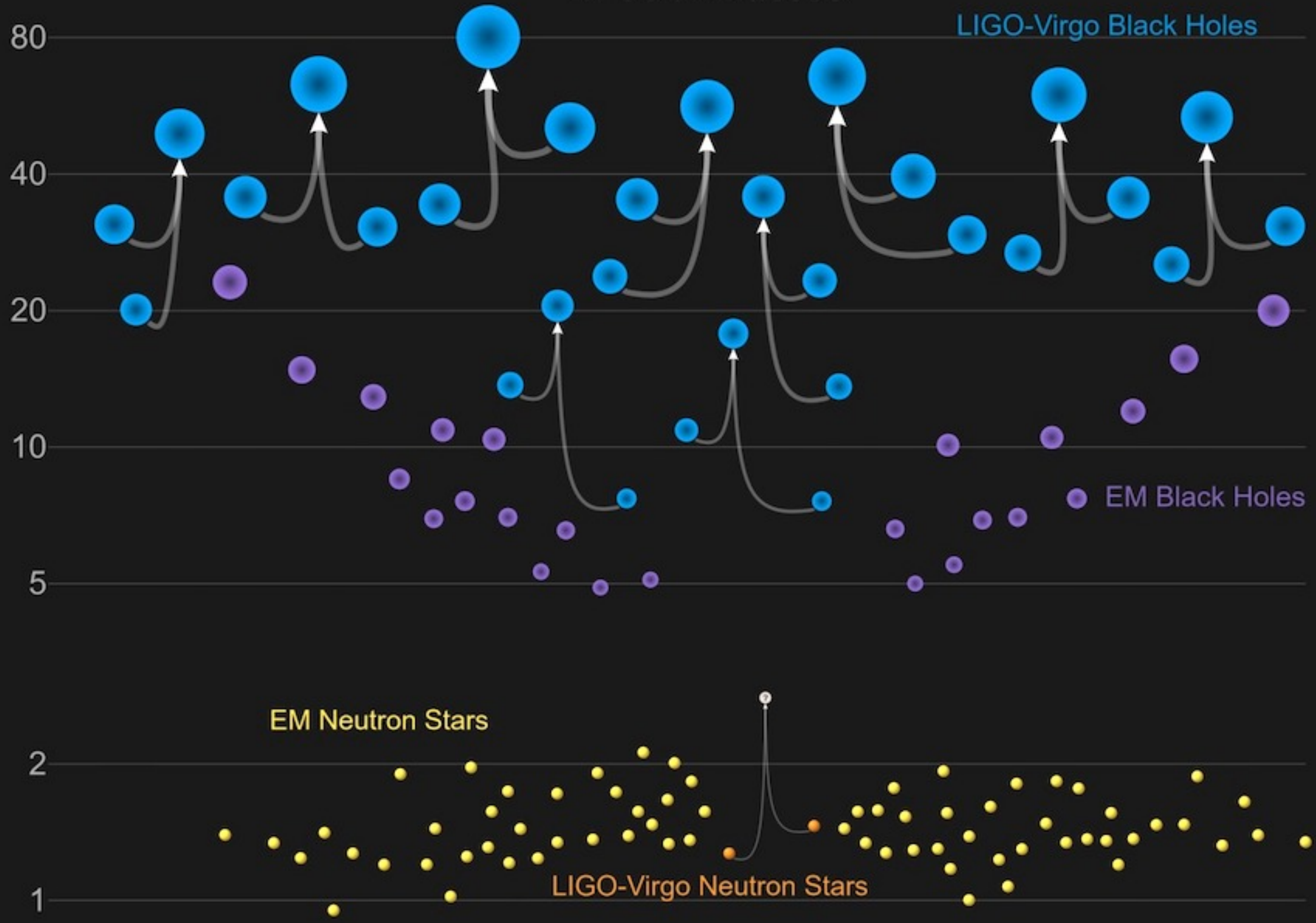
Measurement precision: 1 / 1,000,000,000,000,000,000,000




LIGO Hanford Data
Predicted
LIGO Livingston Data
Predicted
LIGO Hanford Data (shifted)
LIGO Livingston Data
Strain (10^{-21})
1.0
0.5
0.0
-0.5
-1.0
0.30
0.35
0.40
0.45
Time (sec)

Masses in the Stellar Graveyard

in Solar Masses



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