Ay1 – Lectures 11 and 12 summary

Neutron Stars, Pulsars, and Black Holes

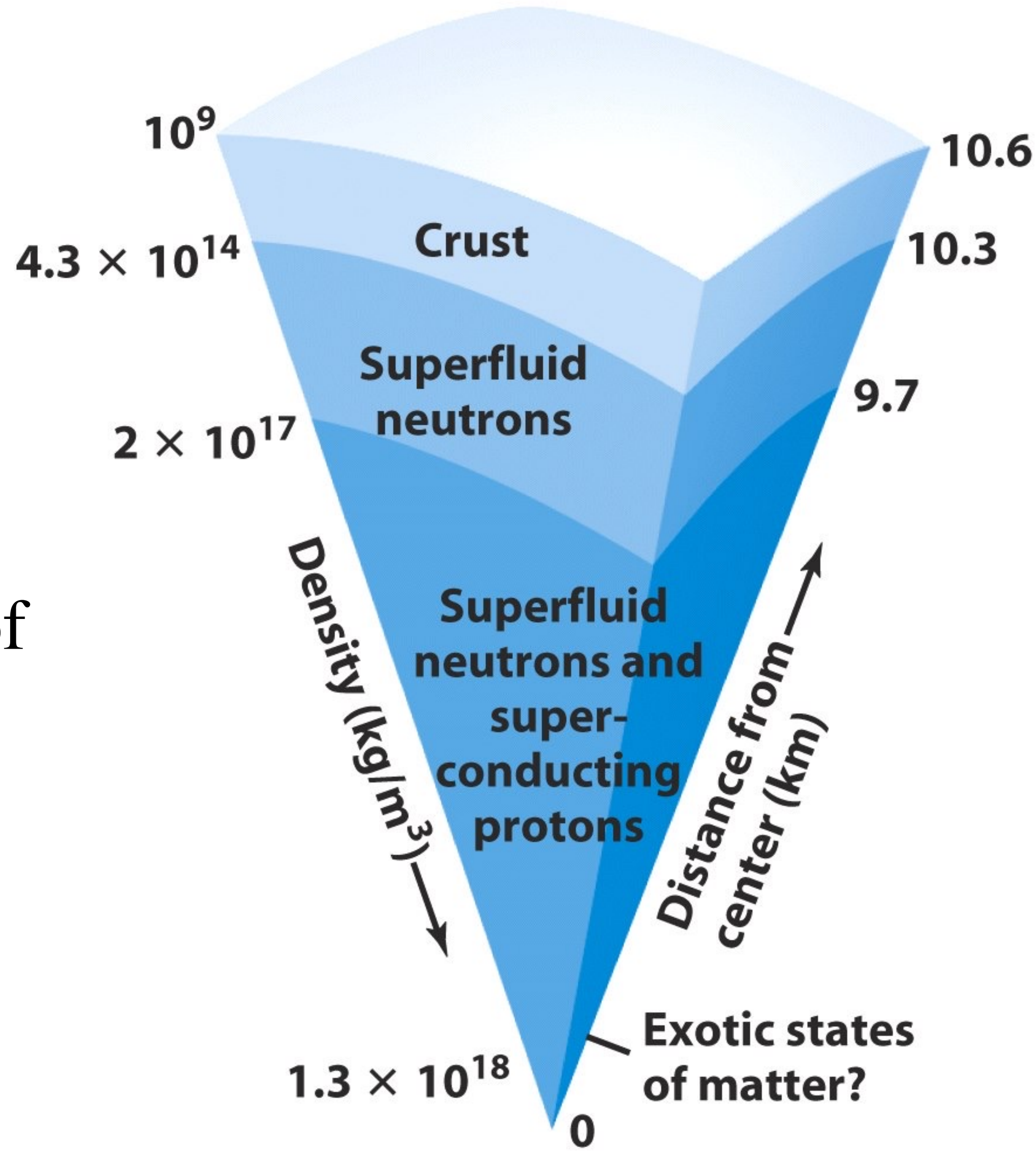
Our Galaxy, The Milky Way

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 neutrinos escape, taking away ~ 10^{54} erg of the thermal energy, which causes the core to collapse under its own gravity
- 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

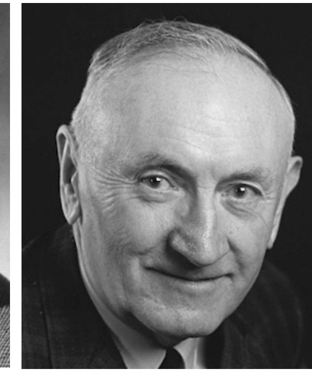
The Structure of Neutron Stars

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



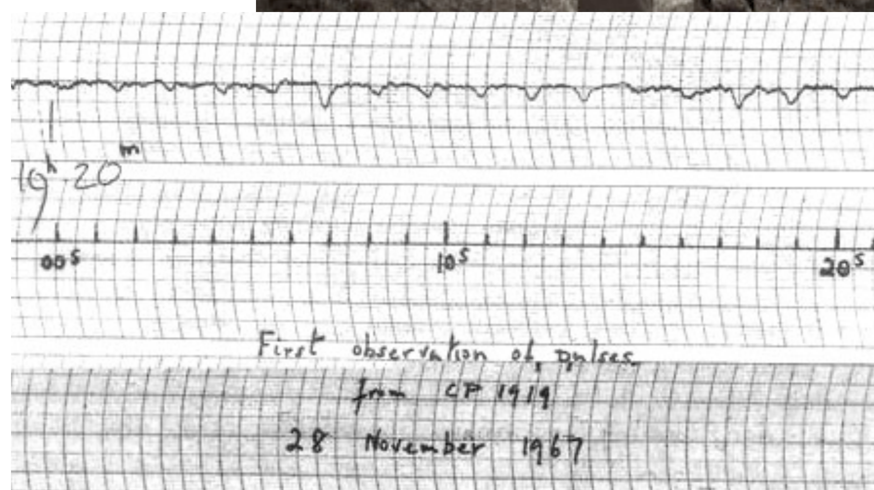
A neutron star consists of a *neutron superfluid*, superconducting core surrounded by a superfluid mantle and a thin, brittle crust

Prediction and Discovery of Neutron Stars



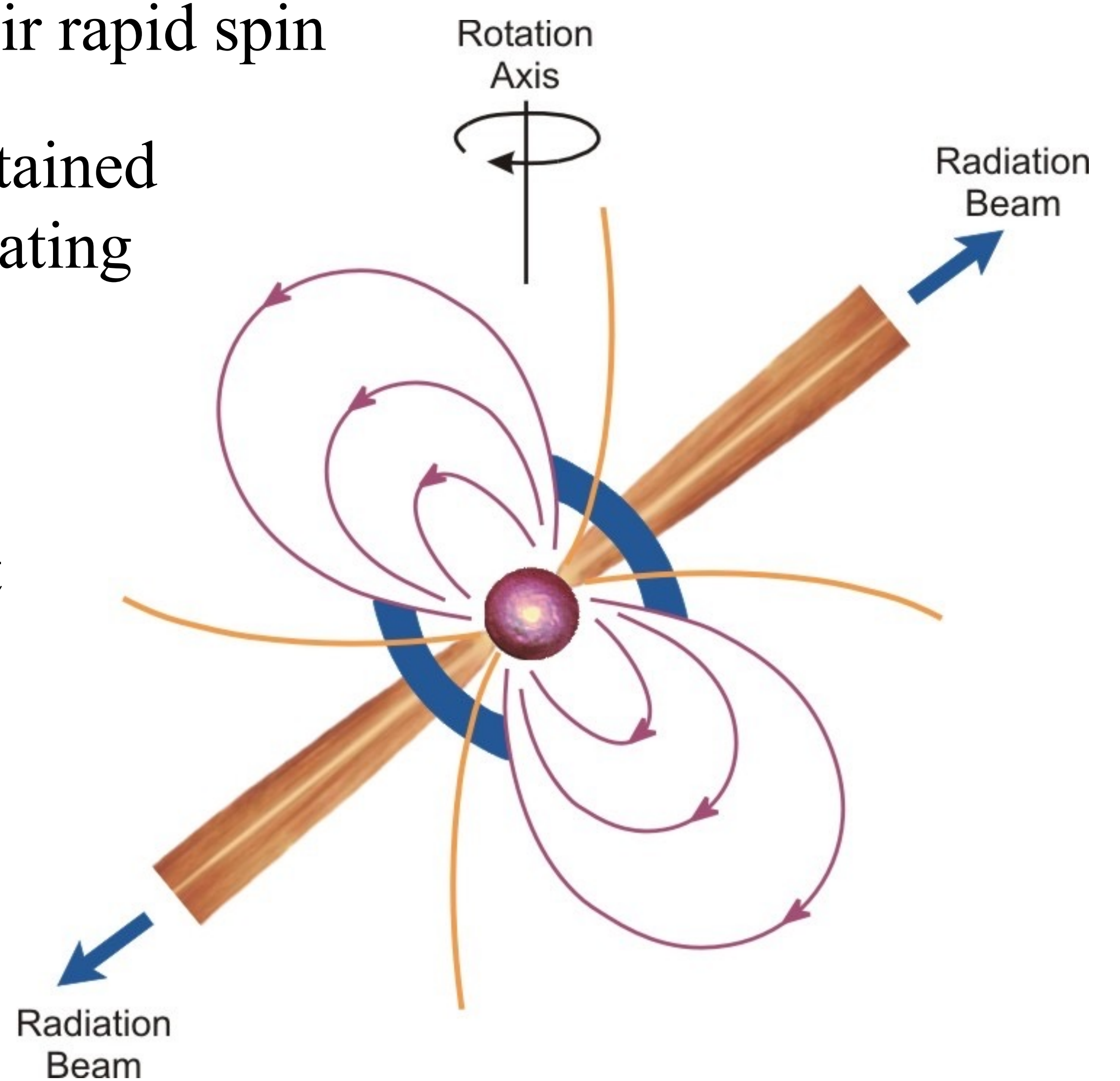
- The neutron was discovered in 1932. Already in 1934 Walter Baade and Fritz Zwicky suggested that supernovae involve a collapse of a massive star, resulting in a neutron star

- 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



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



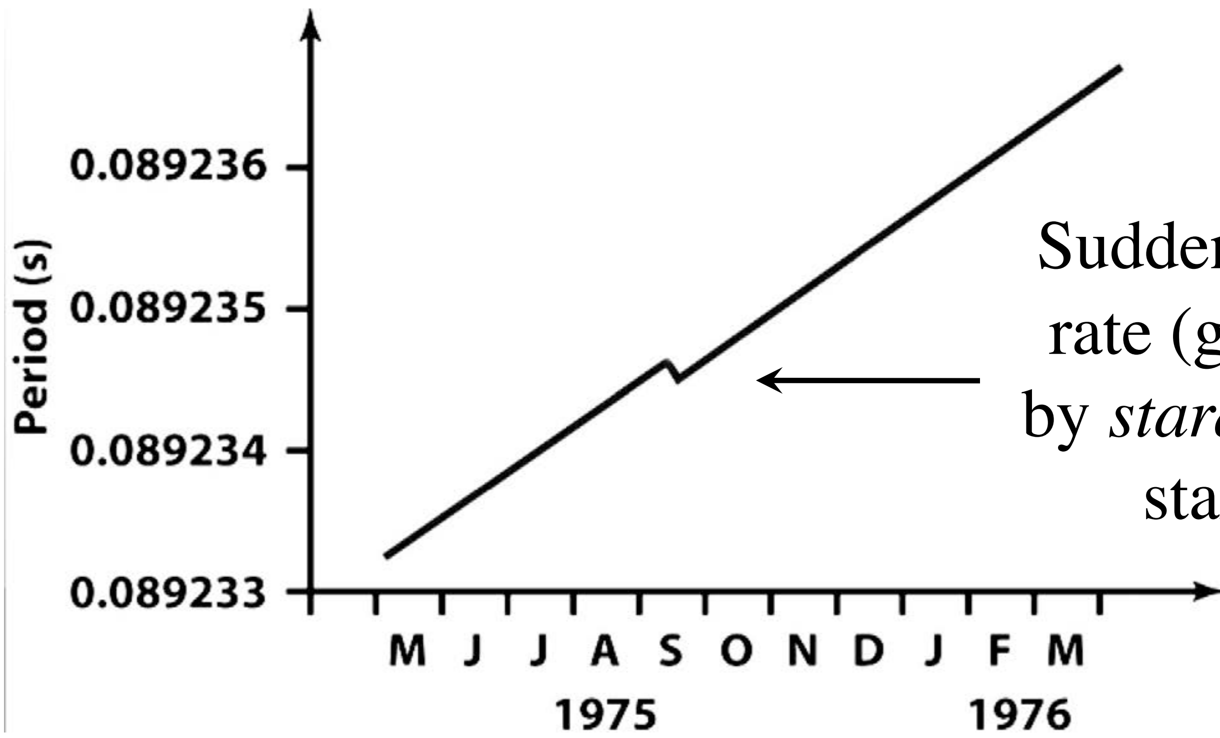
Pulsar Timing and Slowdown

- 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

$$E_{rot} = \tfrac{1}{2} I \omega^2 = 2 \pi^2 I P^{-2} \qquad L = dE/dt = 4 \pi^2 I P^{-3} \dot{P}$$

(I = moment of inertia, P = period)

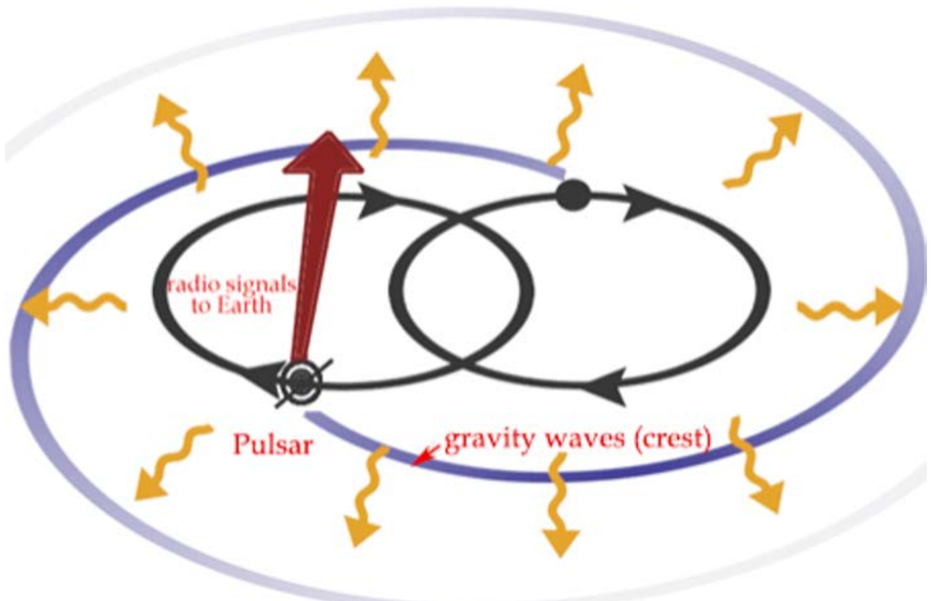
Period derivative

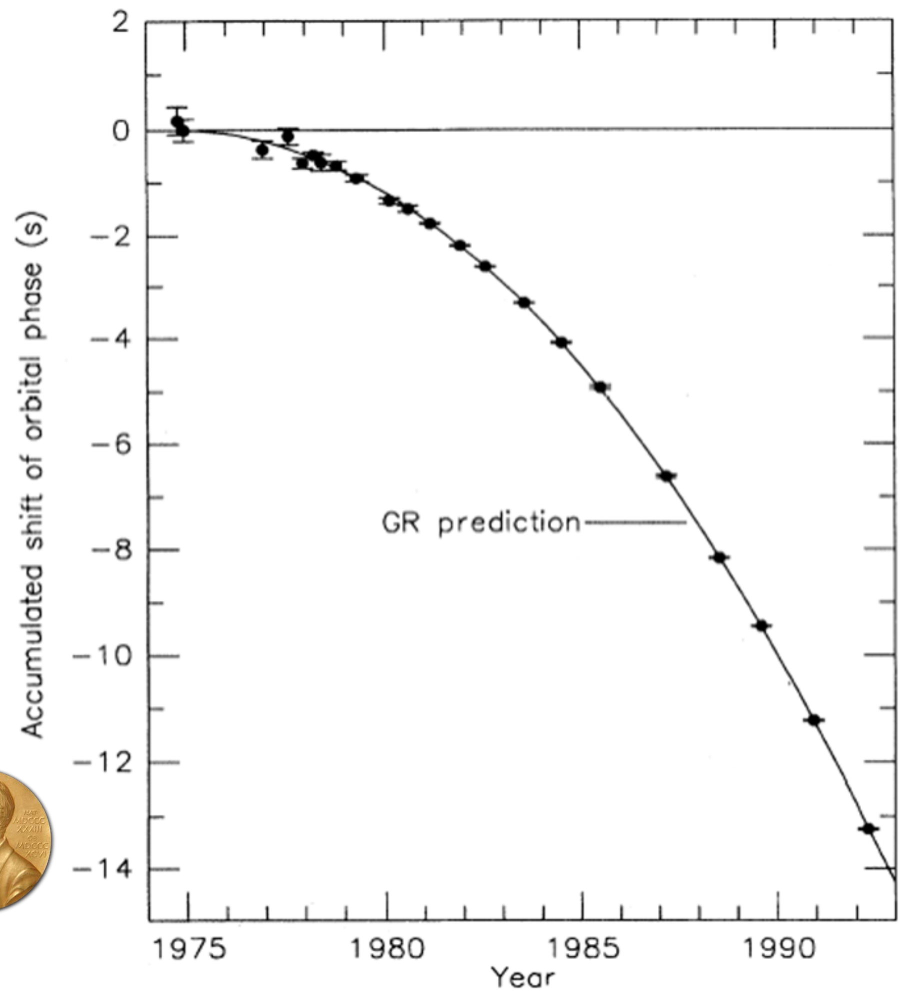


Sudden speedups of the pulse rate (glitches) may be caused by *starquakes* – settling of the star to a lower moment of inertia

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

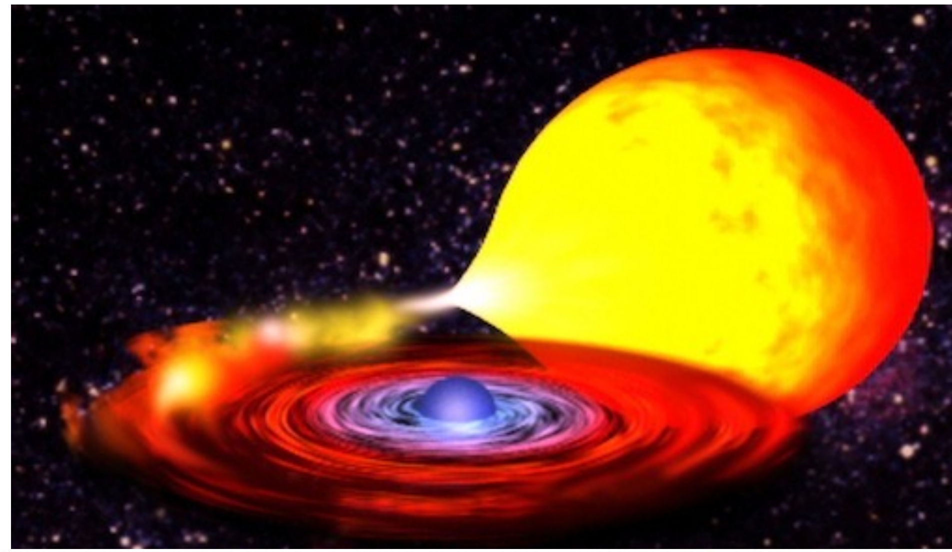
X-Ray Bursters and Millisecond Pulsars

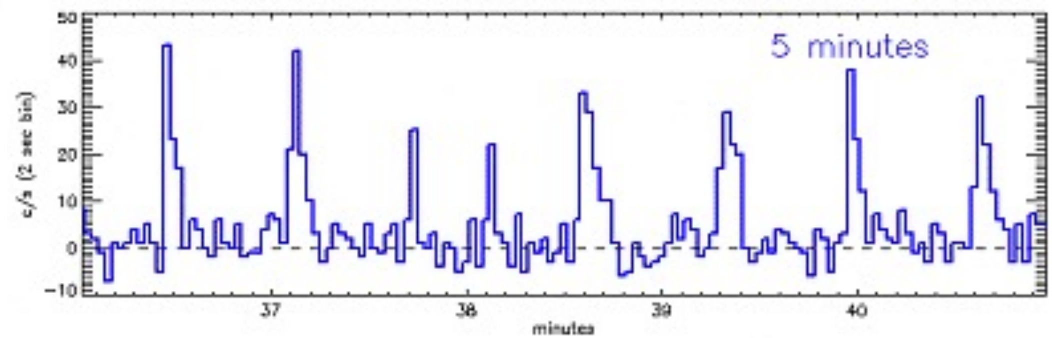
Neutron stars can be in accreting binaries

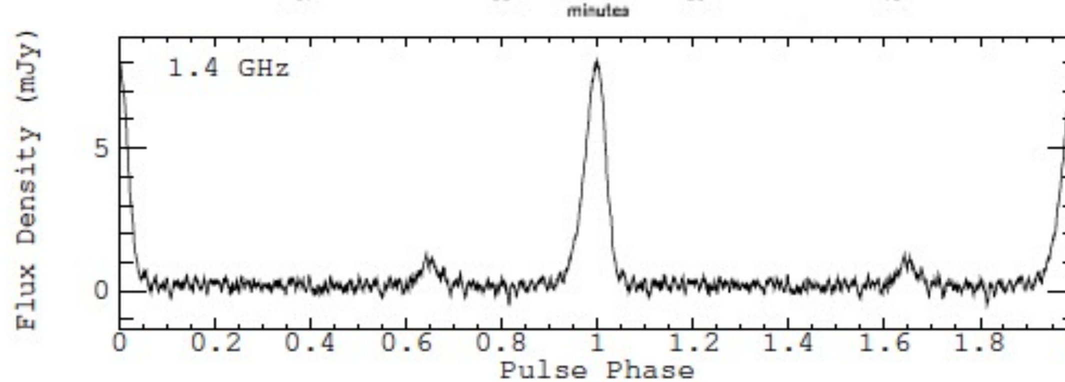
Such systems become *X-ray bursters*

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*



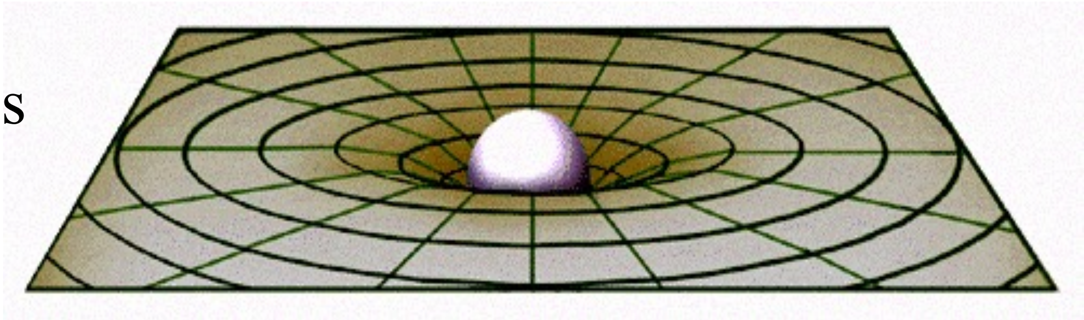




Einstein's General Relativity (1915)

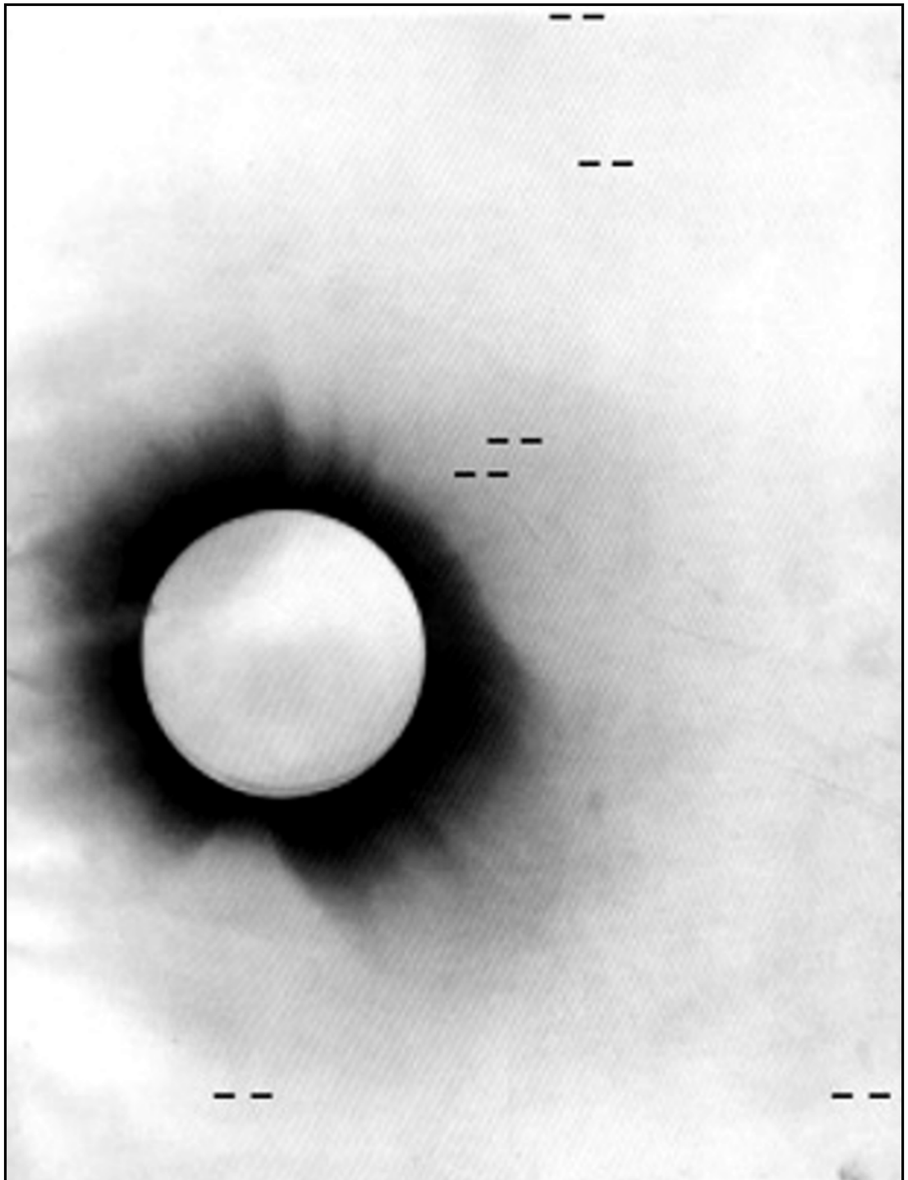
- Following the special relativity, an even more fundamental change in our understanding of the physical space and time, and matter/energy
- Postulates equivalence among **all** frames of reference (including accelerated ones)
- Introduces curvature of space, predicting a number of new effects:
  - Light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

  etc. etc.

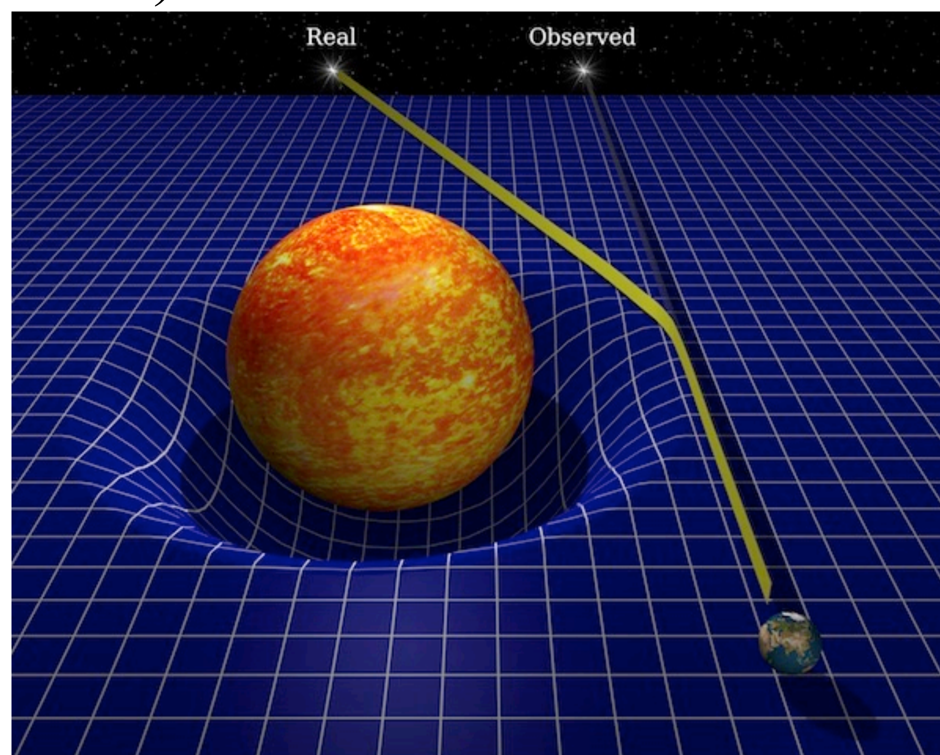


Presence of mass/energy determines the geometry of space
Geometry of space determines the motion of mass/energy

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:

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

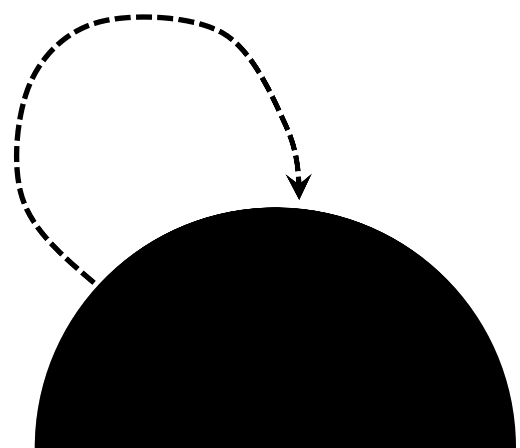
$$m V^2 / 2 > G m M / R$$

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

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

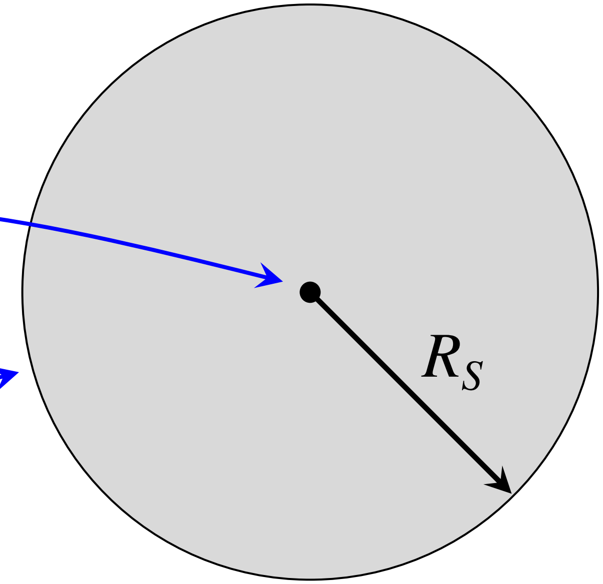
When $V_{esc} > c$, not even light can escape. The enclosed region becomes a **black hole**



(Note: this is a "classical gravity" explanation, and not entirely accurate)

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)

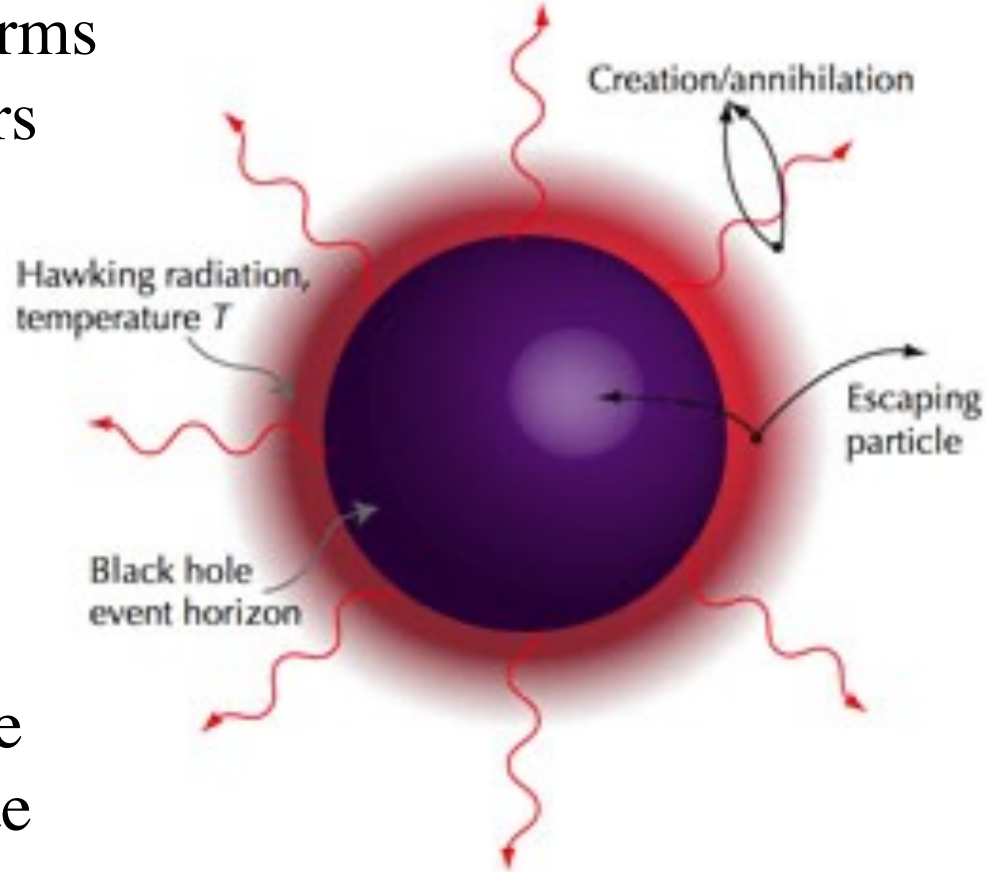
- Things are a bit more complicated for a rotating BH
- The only things we can know about a BH are its mass, spin, and electric charge, regardless of what was the material from which it was made

Black Holes May 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**

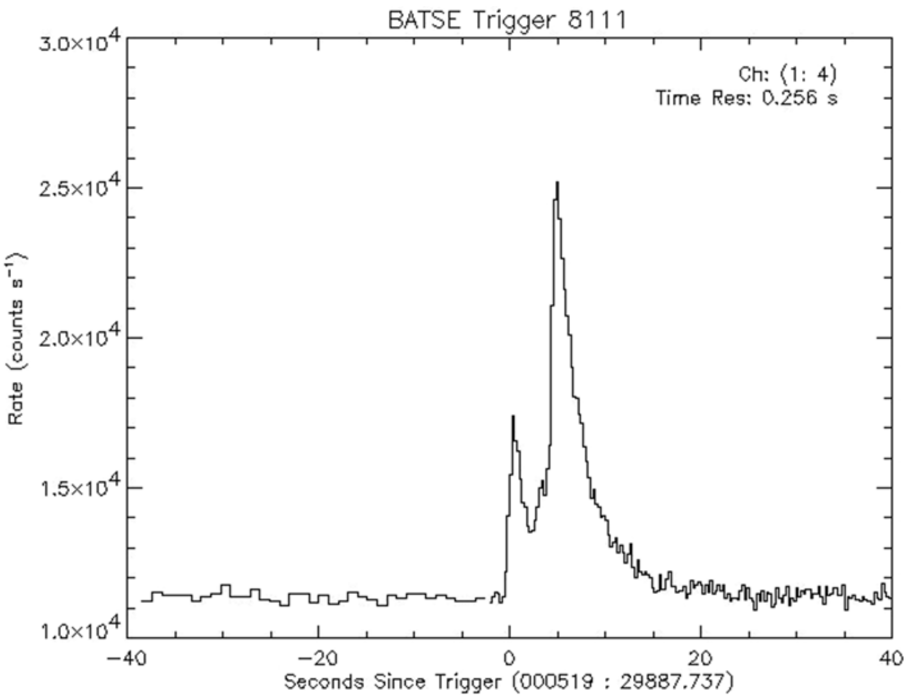
The energy comes at the expense of the BH's rest mass energy

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*** (although we expect that this classical extrapolation breaks down at some point)
- 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**

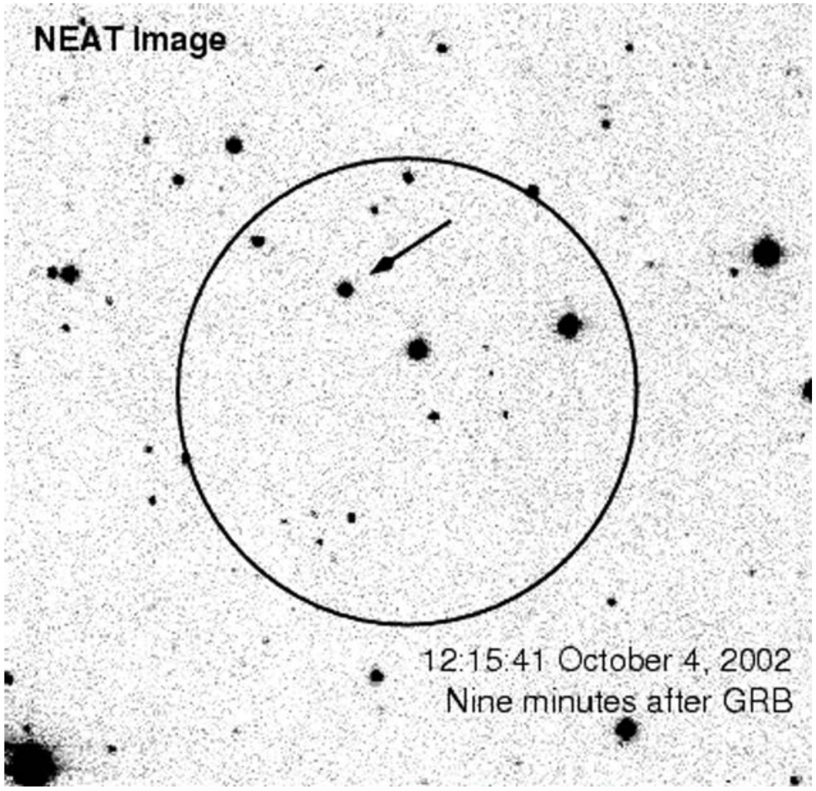
Gamma Ray Bursts: The Birth of Stellar Black Holes

Typical γ-ray light curve



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

Optical (and X-ray, and radio) afterglows of GRBs



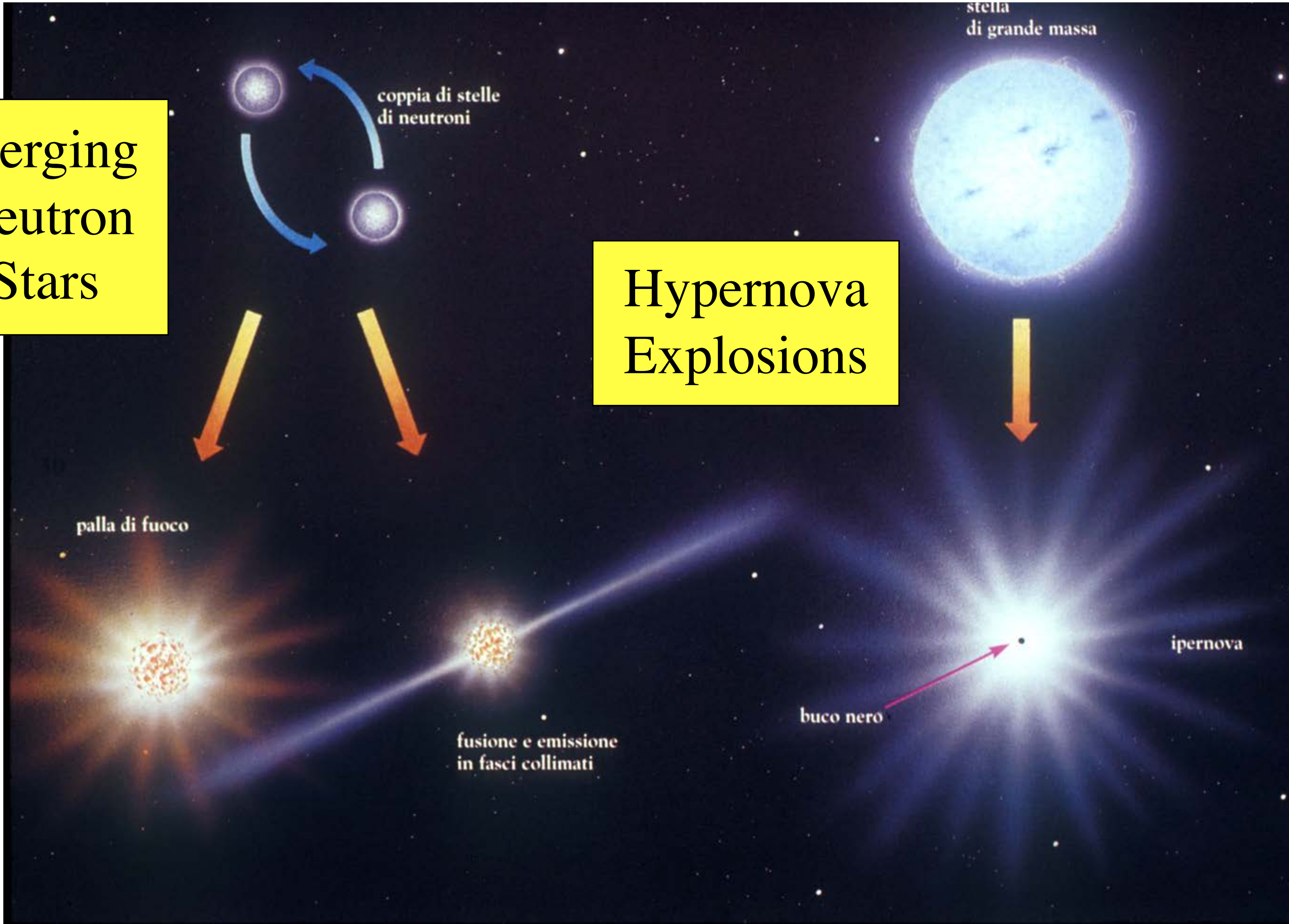
Typically fade as ~ t^{-1}

Enabled the understanding of GRBs

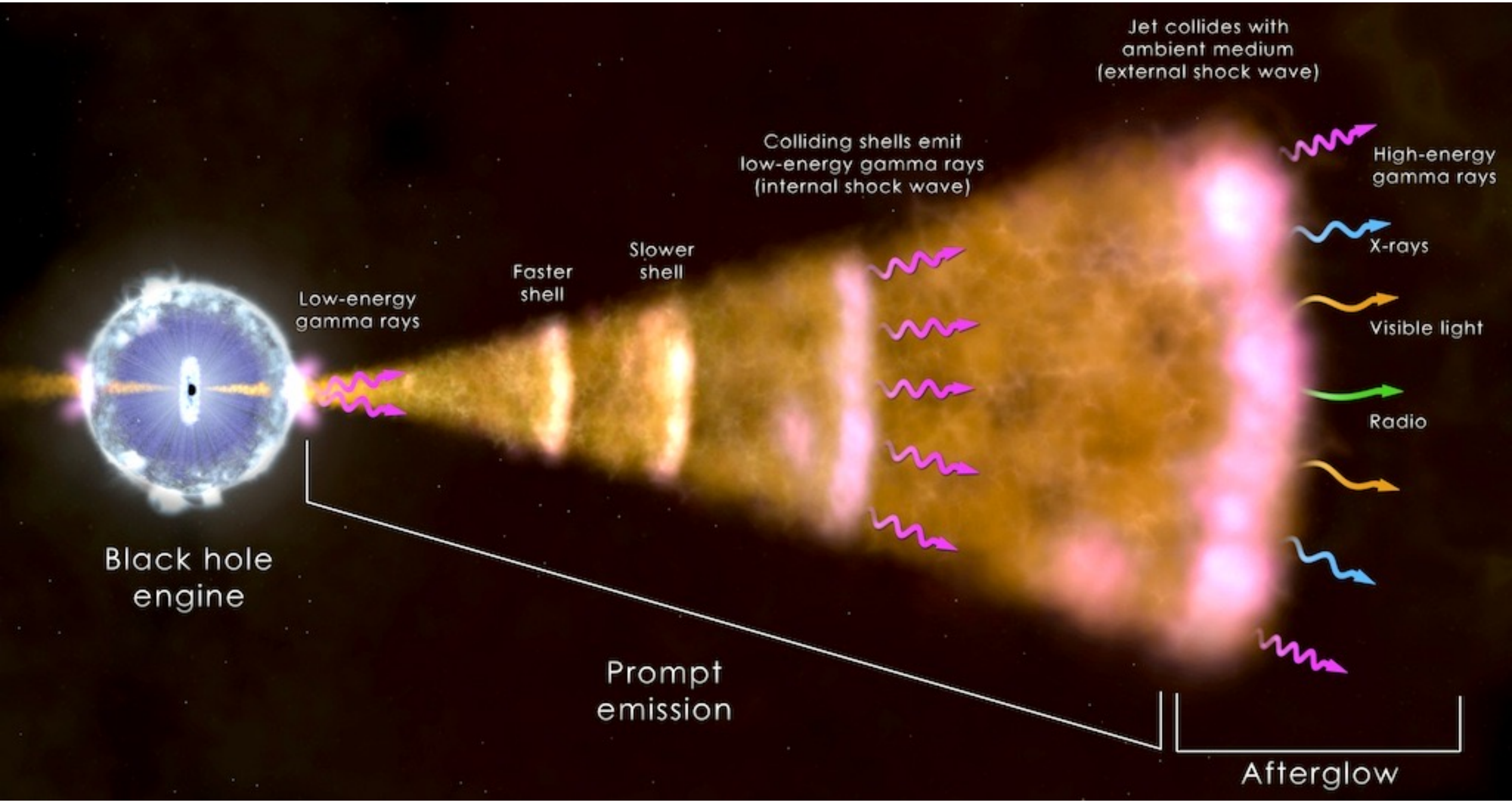
Popular Models for GRB Origins

Merging Neutron Stars

Hypernova Explosions

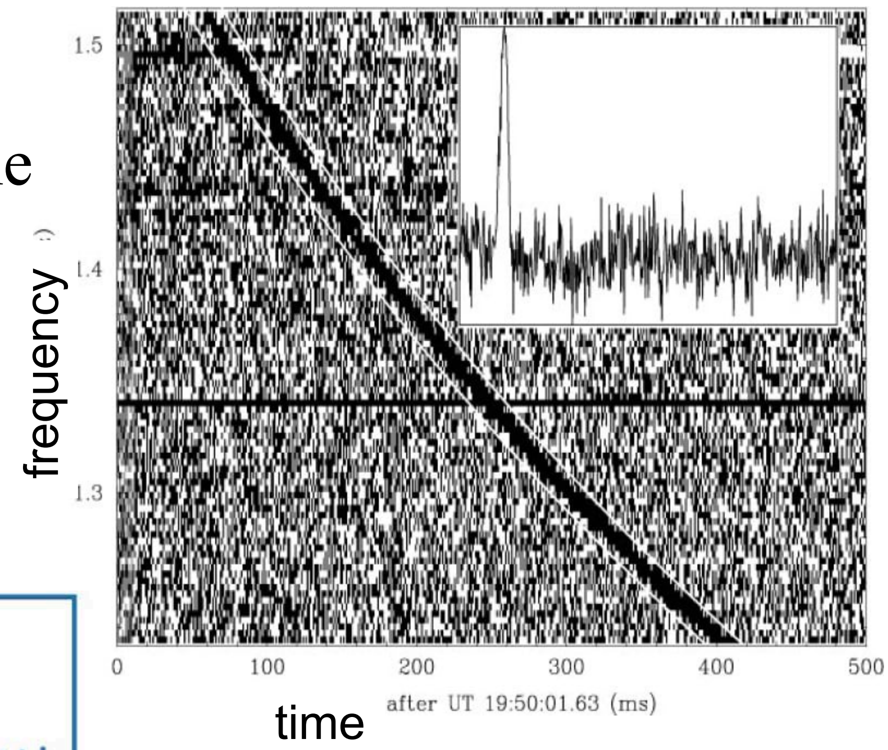


The Collapsar Model for GRBs

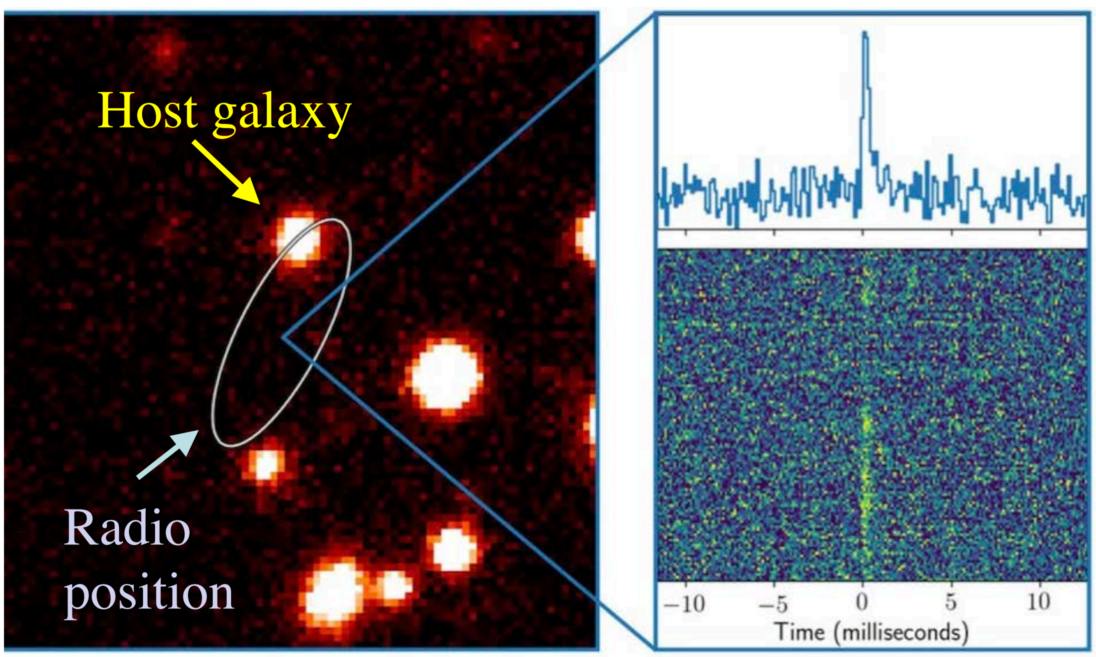


Fast Radio Bursts (FRBs)

- 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 (magnetars)

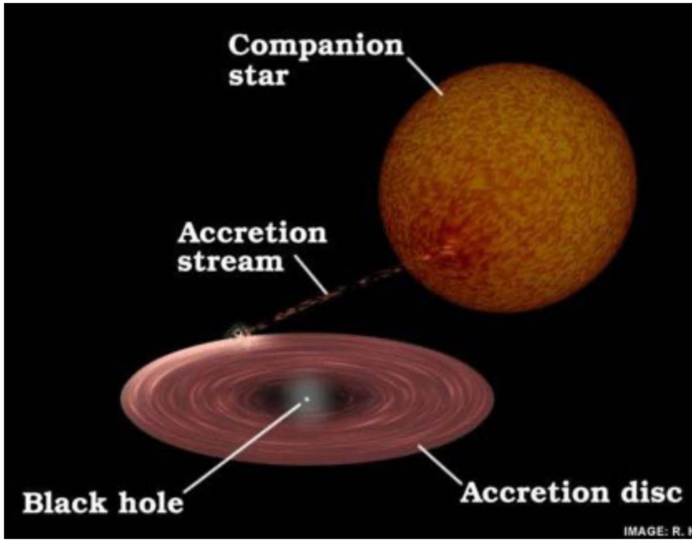


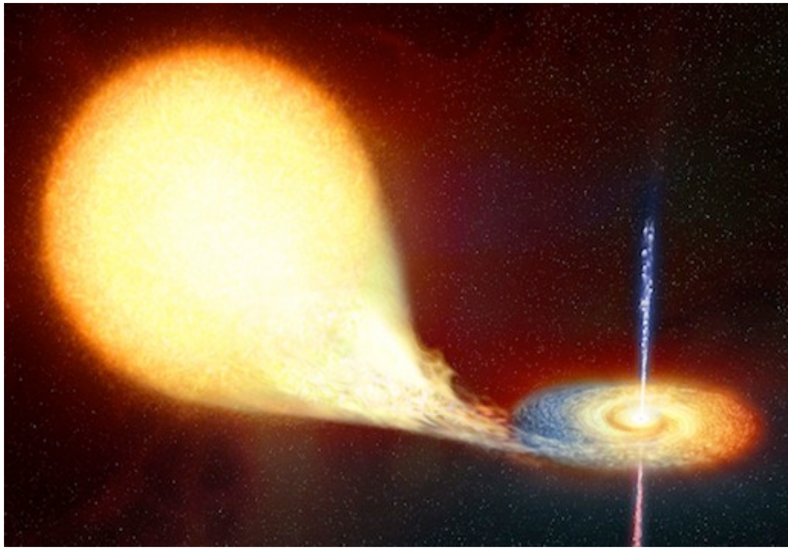
Intensity as a function of time and frequency for the first detected ("Lorimer") FRB. The peak frequency drifts as the time goes on.

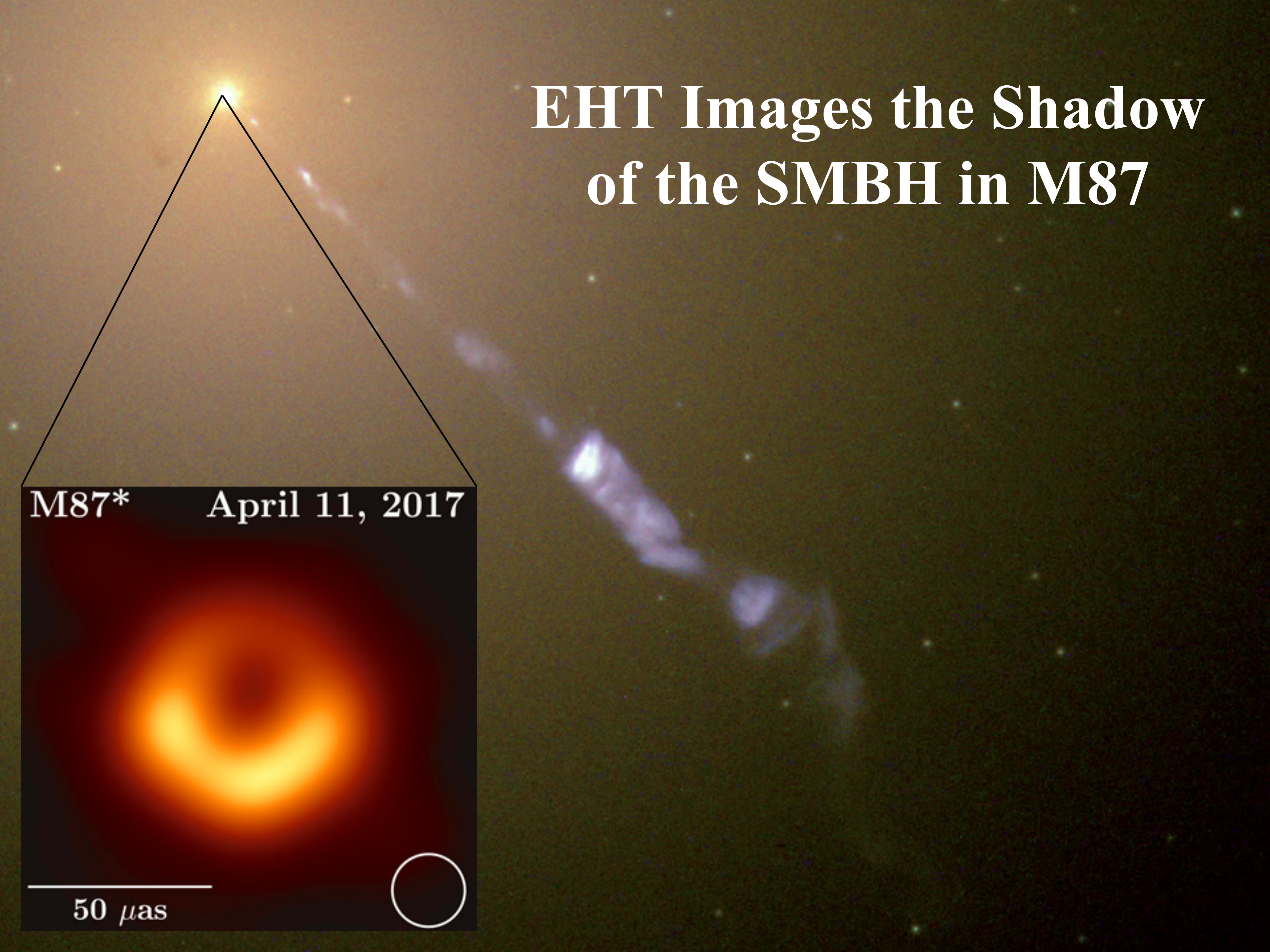


Evidence for Black Holes

- 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



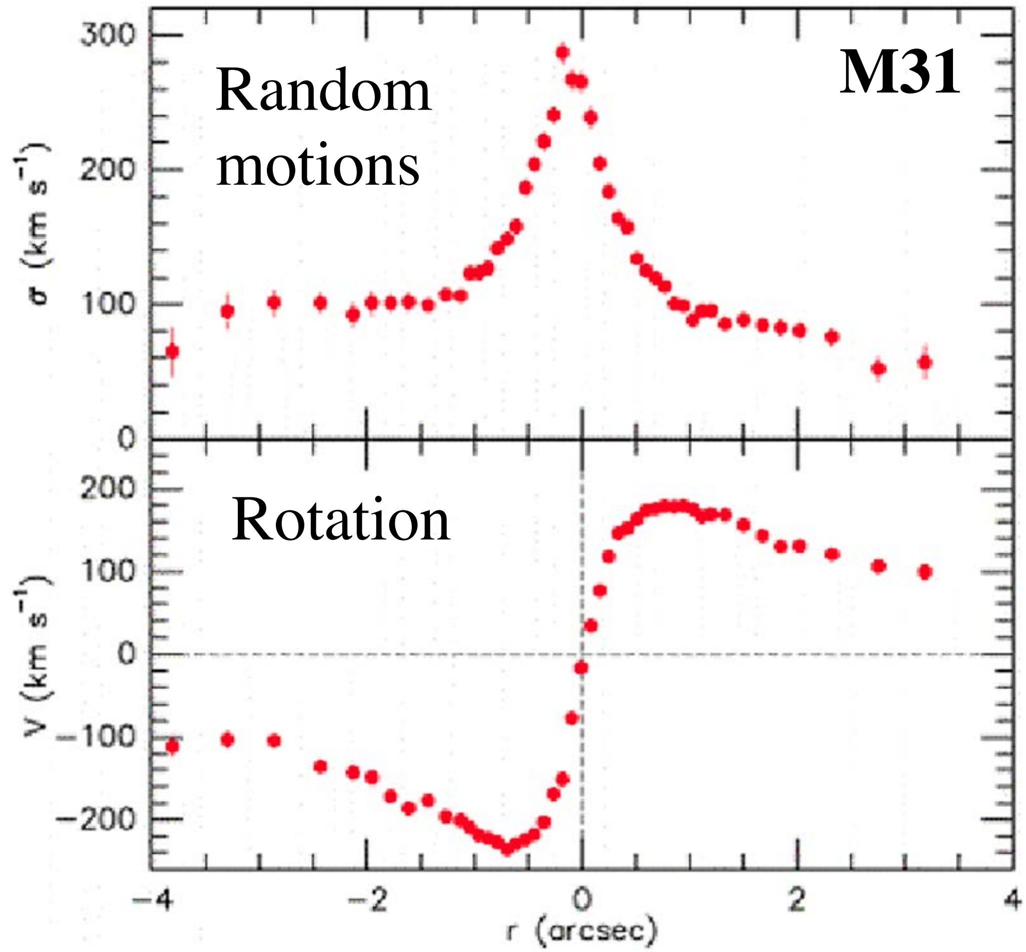



EHT Images the Shadow of the SMBH in M87
M87*
April 11, 2017
50 μas

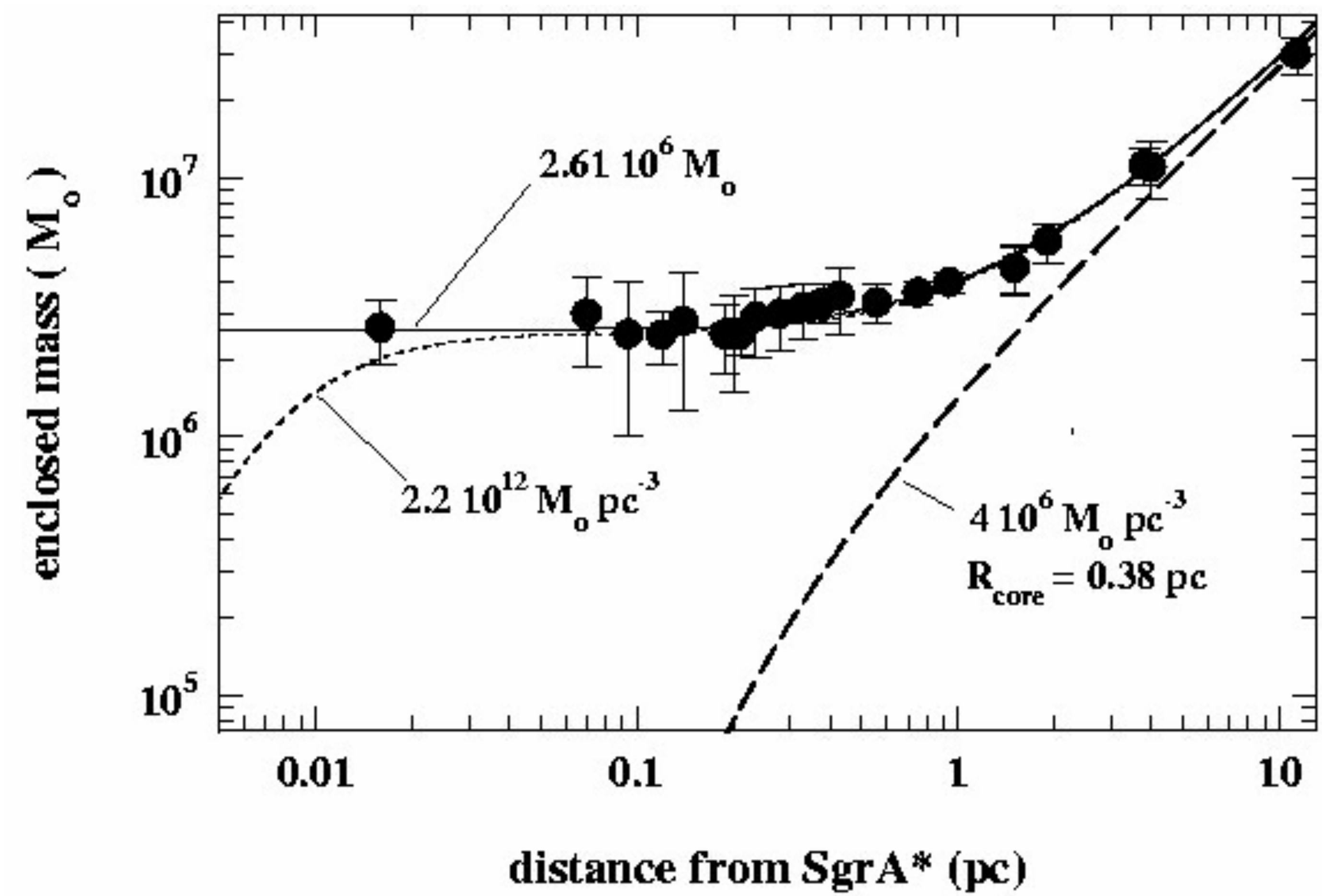
Massive Black Holes in Galactic Nuclei

- 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



Dynamical Evidence for a Supermassive Black Hole at the Galactic Center



Reihard Genzel et al., Andrea Ghez et al.

Nobel Prize in Physics 2020

Note: R_S ($M_\bullet \sim 4 \times 10^6 M_\odot$) $\sim 1.2 \times 10^7$ km $\sim 10^{-5}$ arcsec

→ Barely resolvable by the EHT

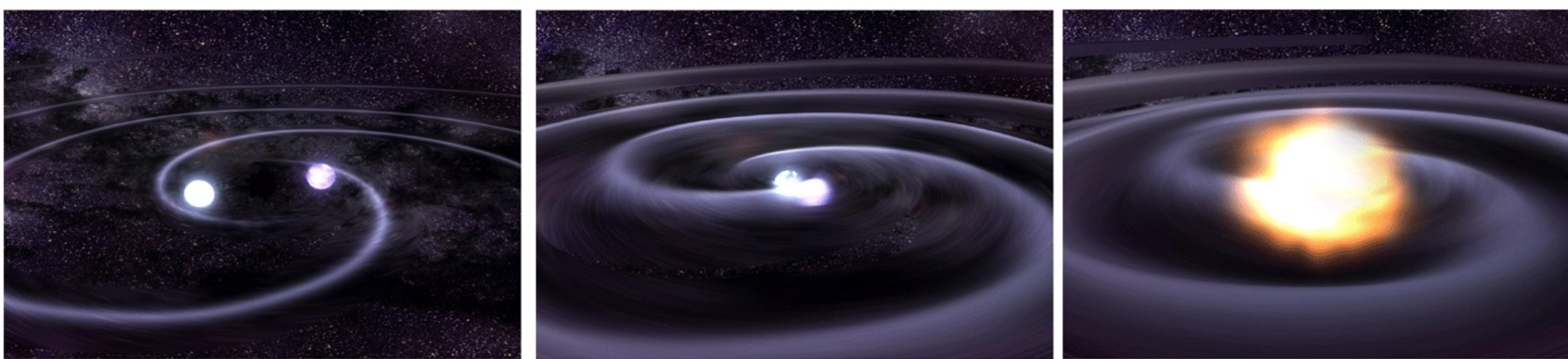
Merging Compact Binaries

- 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

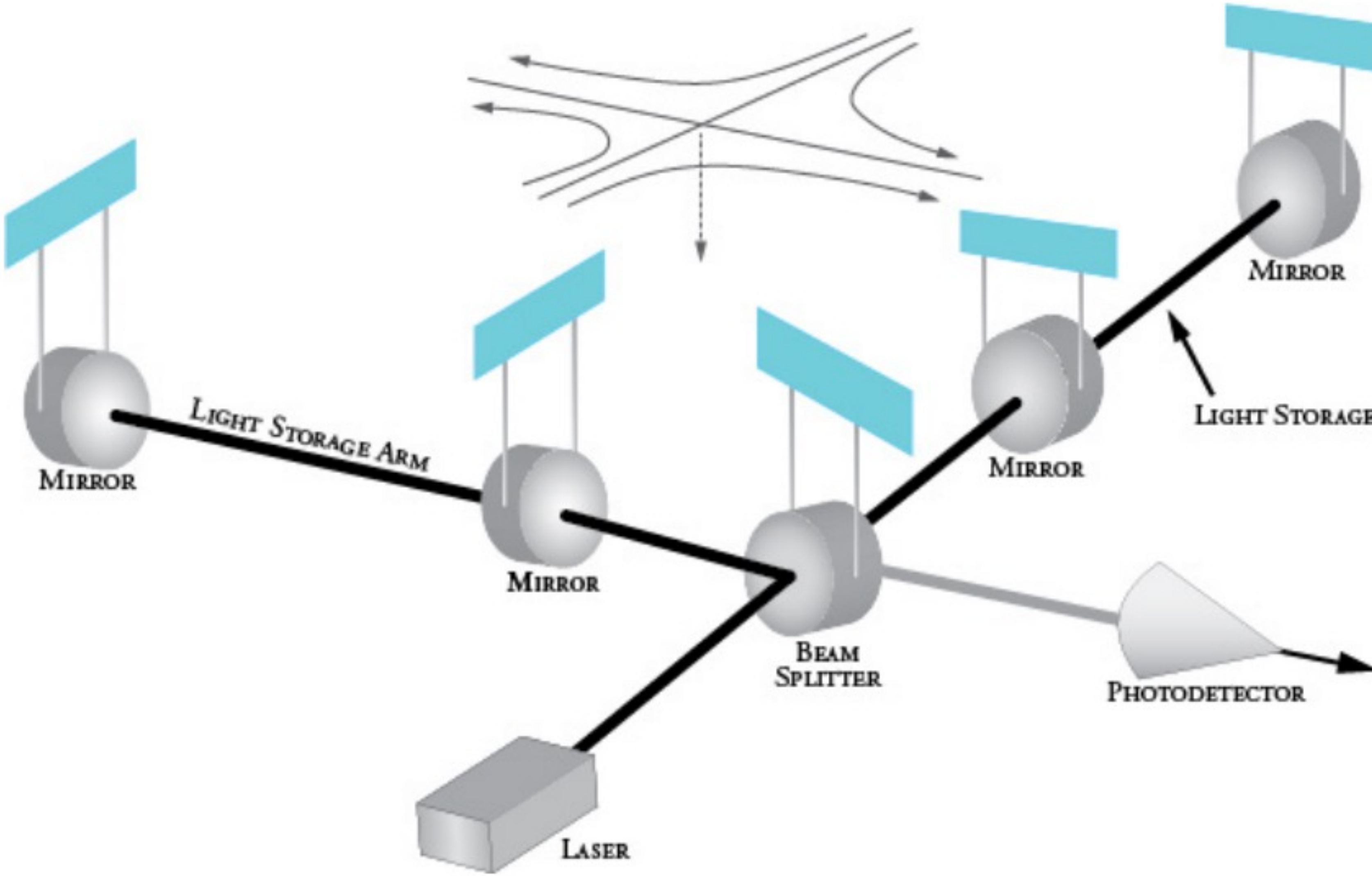
White dwarf mergers ⟶ SN Ia explosion ⟶ neutron star

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

Black hole mergers ⟶ GW burst ⟶ black hole

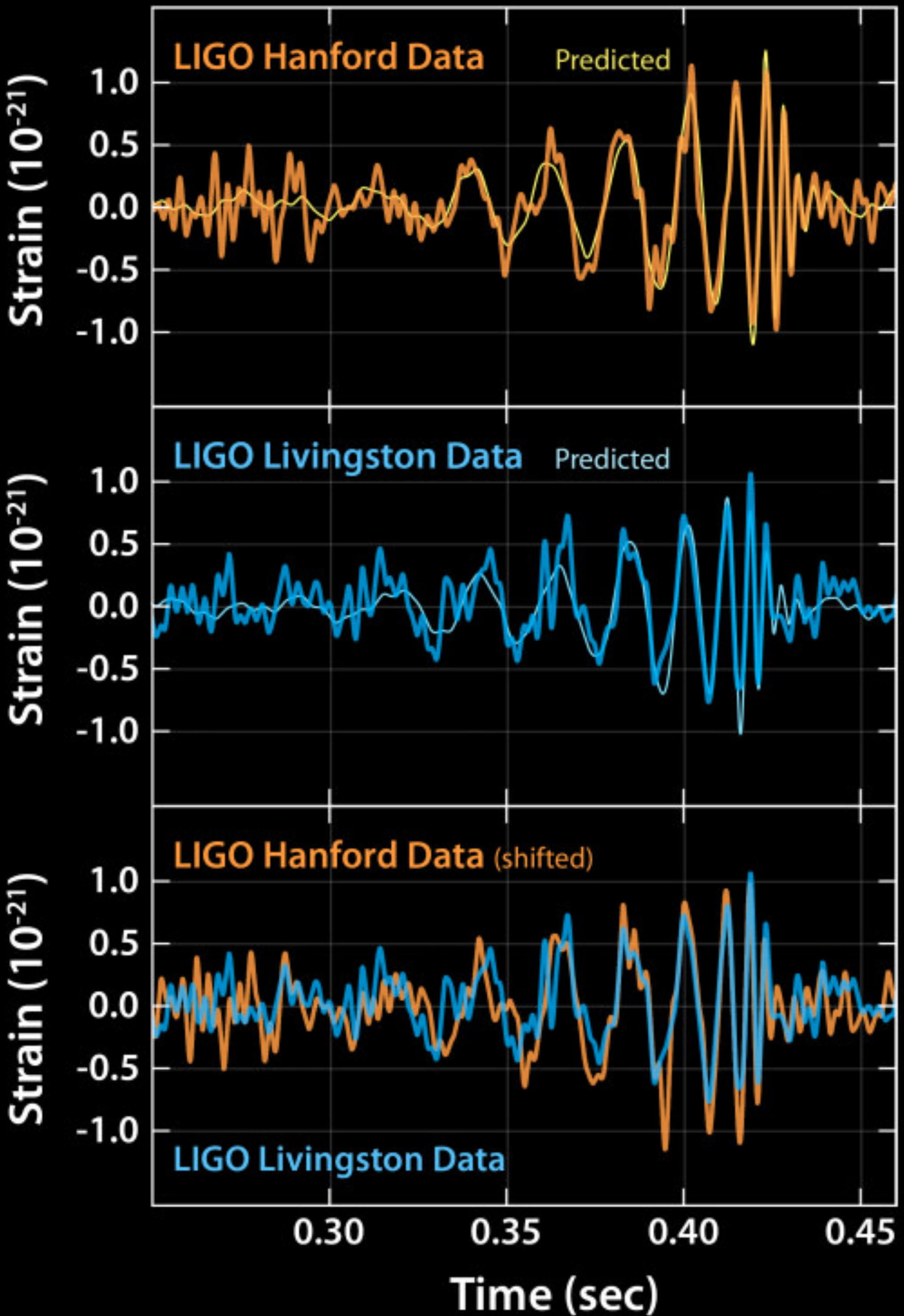


How LIGO works: a laser interferometer

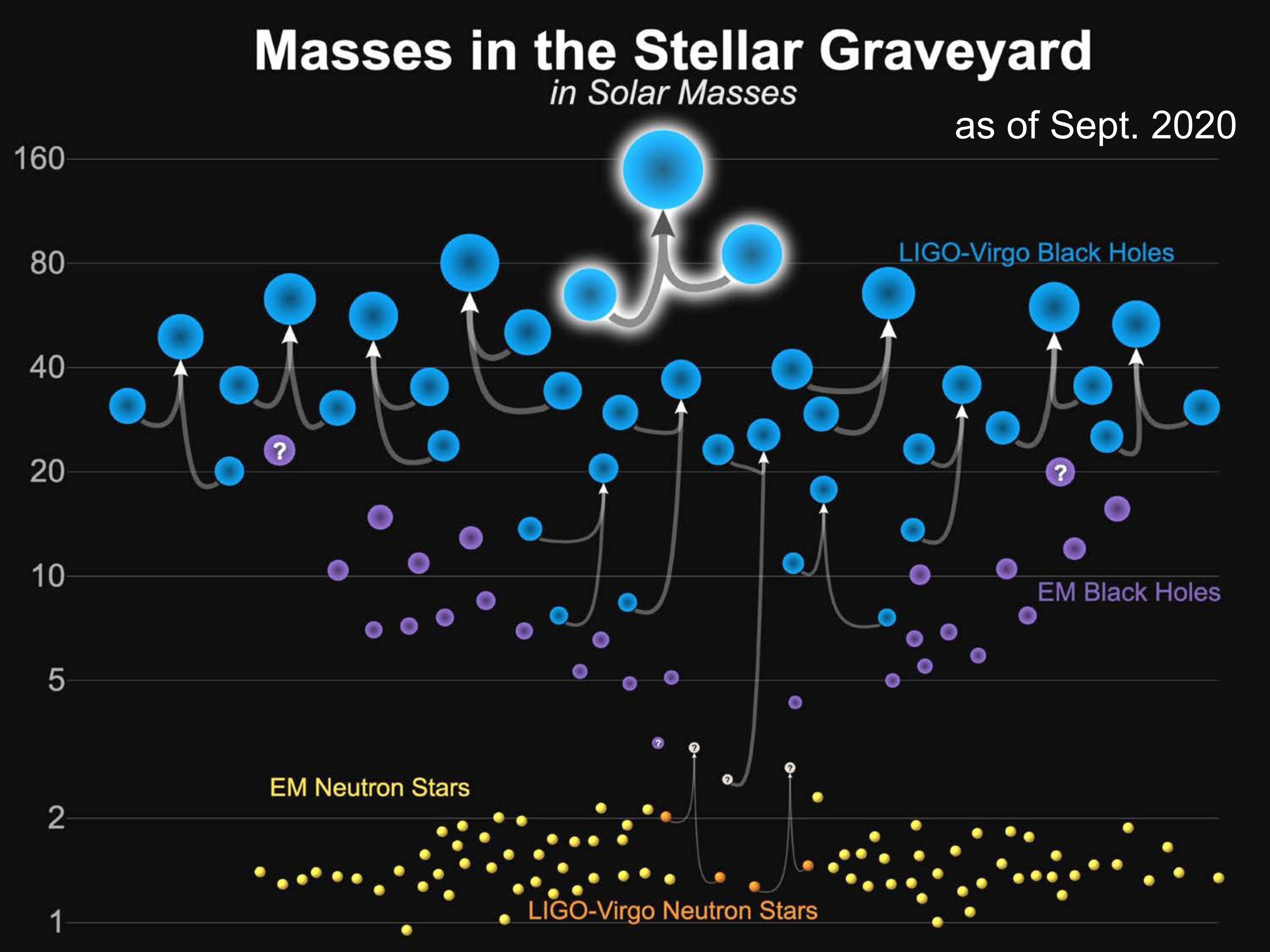


Measurement precision: 1 / 1,000,000,000,000,000,000,000

The First LIGO Detection September 2015



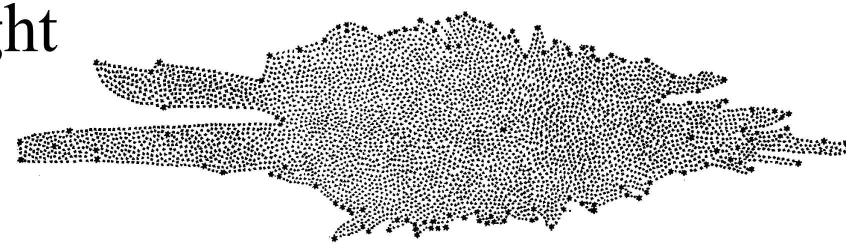
Kip Thorne, Bary Barish, Reiner Weiss, Nobel Prize 2017



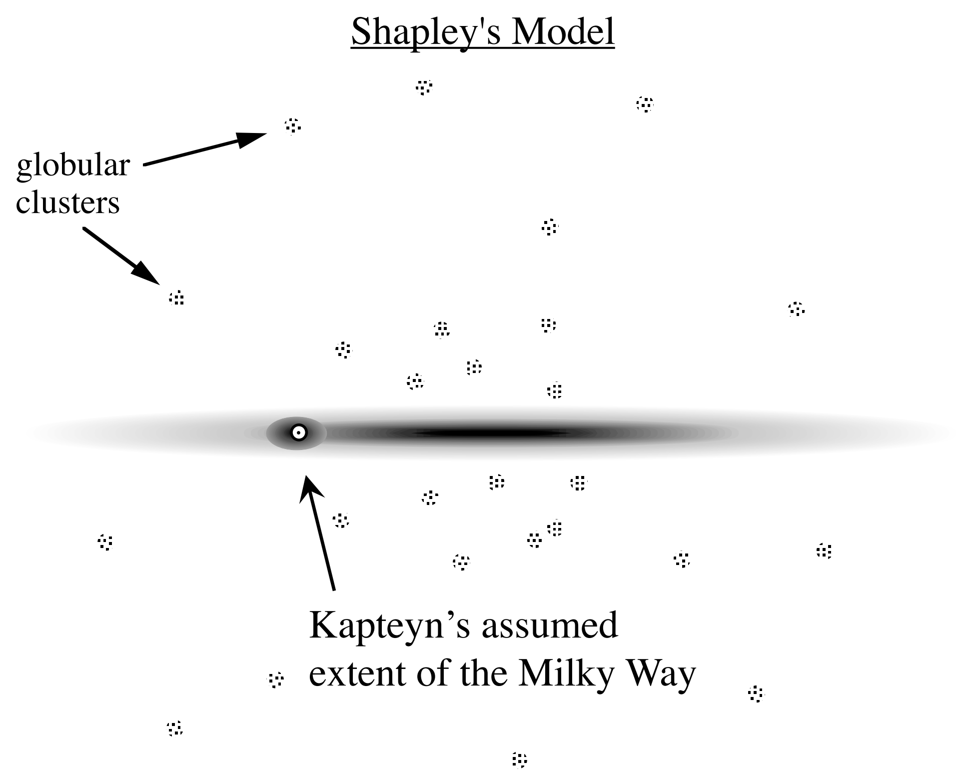
Masses in the Stellar Graveyard
in Solar Masses
as of Sept. 2020
160
80
40
20
10
5
2
1
LIGO-Virgo Black Holes
EM Black Holes
EM Neutron Stars
LIGO-Virgo Neutron Stars

The Discovery of Galaxies

- At first, the Milky Way was thought to be *the universe*, not as one of many galaxies

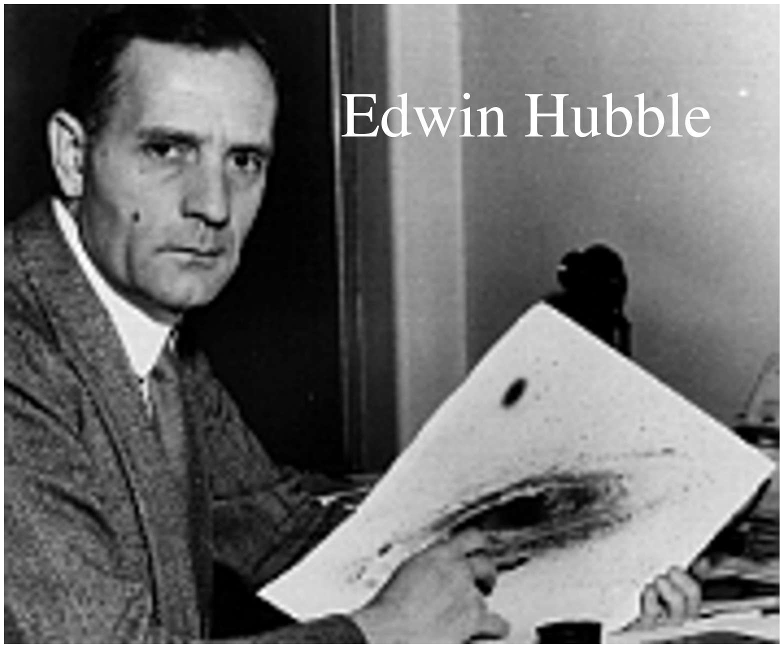


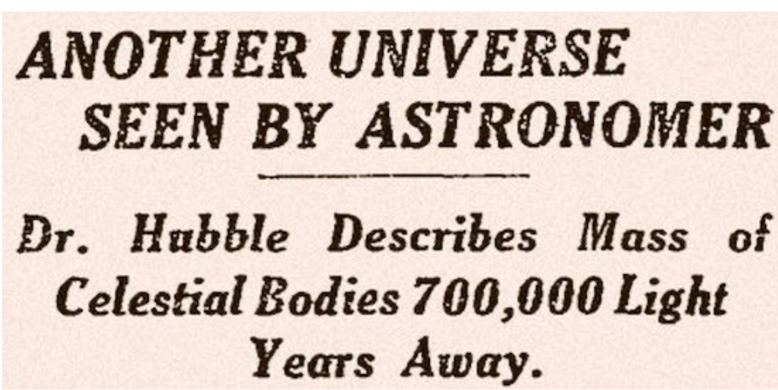
- Hypothetical "Island universes": Thomas Wright, Immanuel Kant, William Herschel …
- 19th/20th century: star counts an the Galactic structure (Jakobus Kapteyn, Harlow Shapley)
- Discovery of the interstellar extinction circa ~ 1920's (Trumpler, Shapley) greatly expanded the scale of the Milky Way, and displaced the Sun from its center



The Resolution: Nebulae are Extragalactic

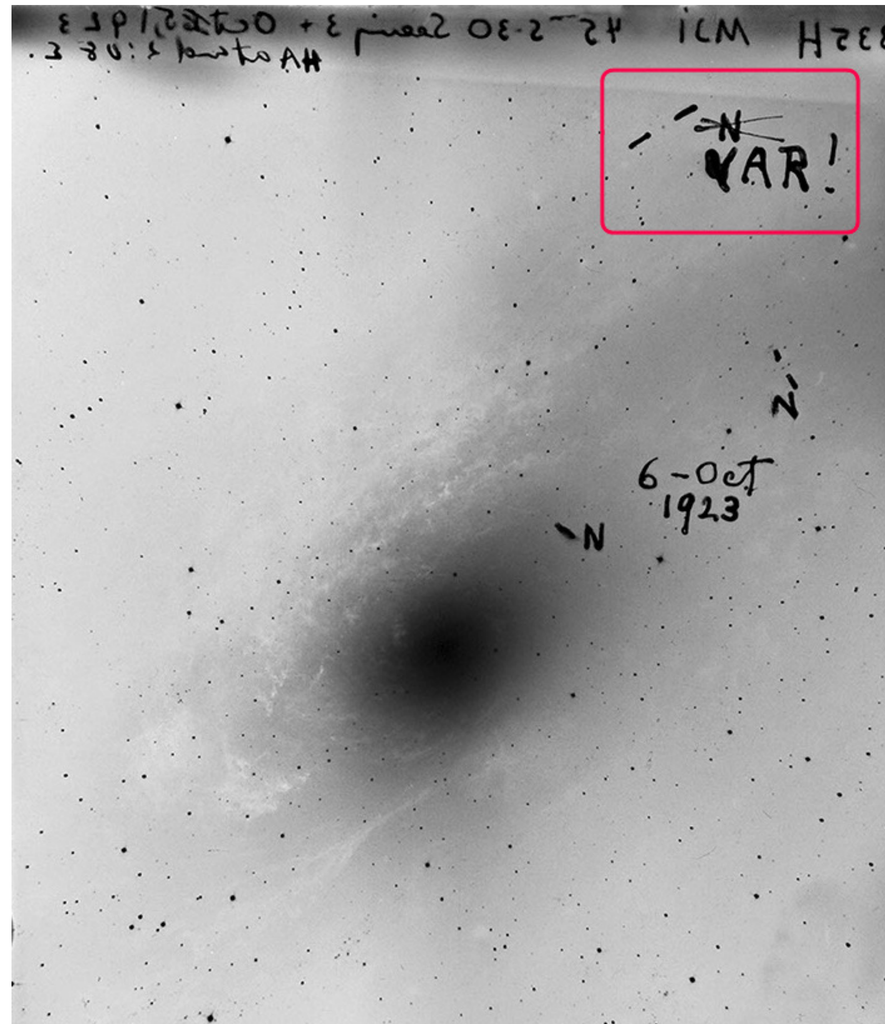
- In 1923 Hubble resolved Cepheids in M31 (Andromeda)
- A profound shift in the understanding of the scale of the universe





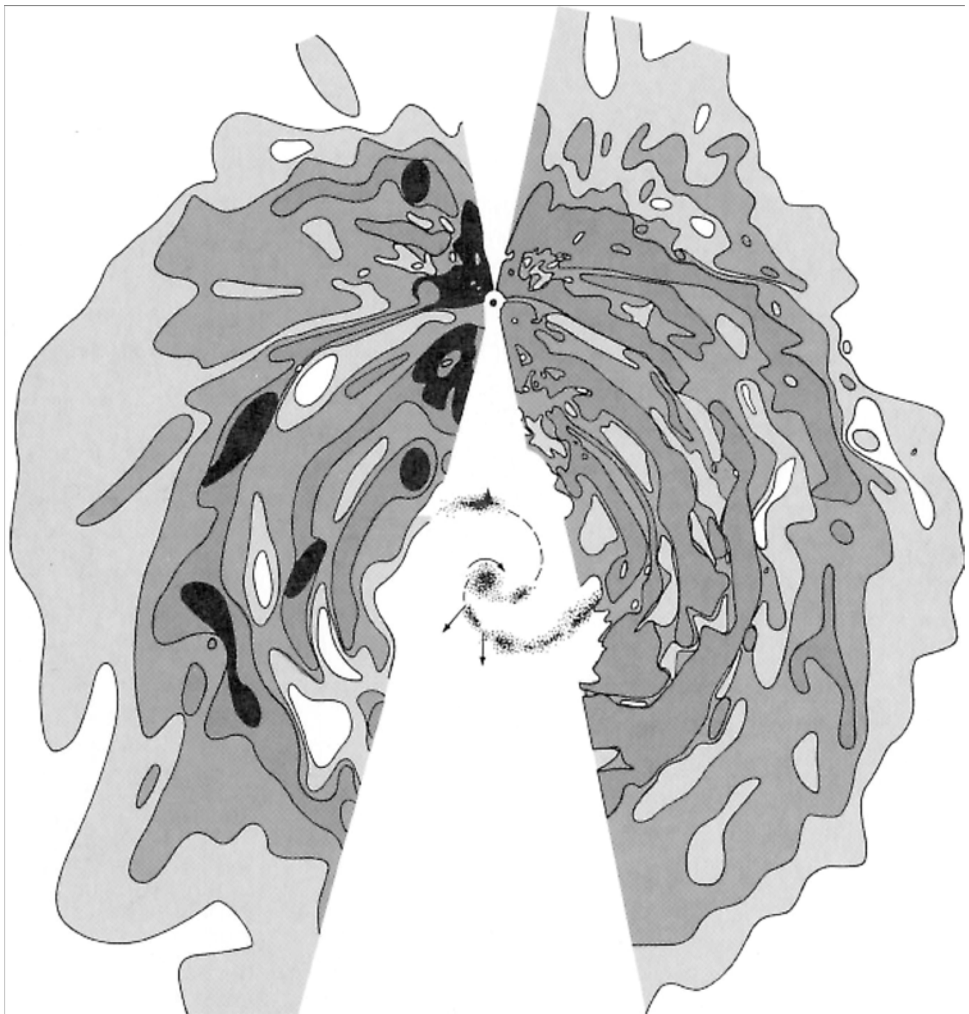
ANOTHER UNIVERSE SEEN BY ASTRONOMER

Dr. Hubble Describes Mass of Celestial Bodies 700,000 Light Years Away.



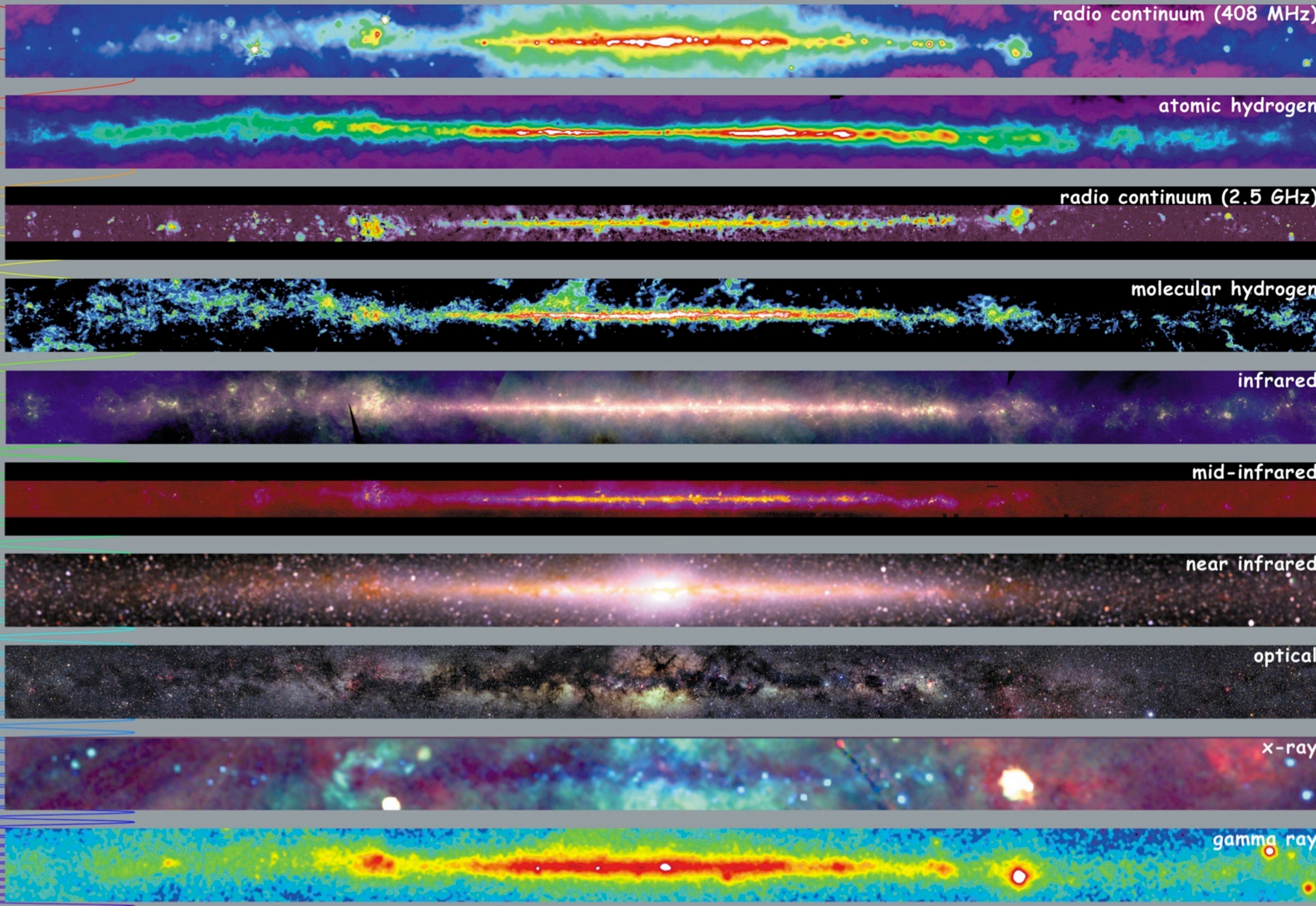
Mapping the Milky Way and Its Kinematics

The development of radio astronomy after the WW2, and the discovery of the 21 cm line of H I, enabled the mapping of the Milky Way independent of the optical extinction.



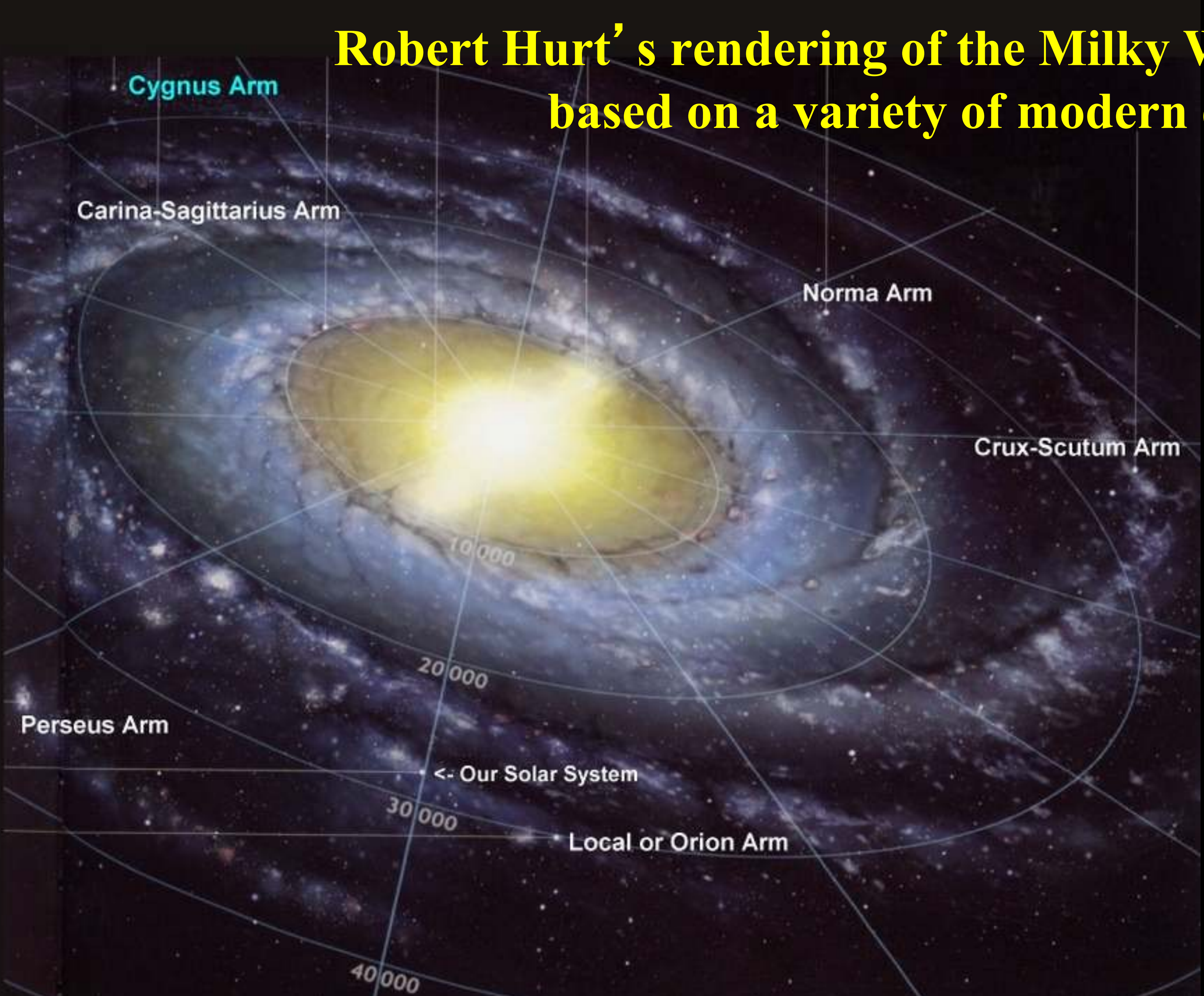
That also opened the enabled the measurements of the global kinematics and rotation of the Milky Way (Jan Oort et al. 1958).

Until then, only the ~ local kinematic of stars could be measured.



Multiwavelength Milky Way

Robert Hurt's rendering of the Milky Way, based on a variety of modern data



The Concept of Stellar Populations

- Originally discovered by Walter Baade, who came up with 2 populations:

  Pop. I: *young stars in the (thin) disk, open clusters*

  Pop. II: *old stars in the bulge, halo, and globular clusters*

  - Today, we distinguish between the old, metal-rich stars in the bulge, and old, metal-poor stars in the halo
  - Not clear whether the Pop. I is homogeneous: young thin disk, vs. intermediate-age thick disk
- A good modern definition of stellar populations:

  Stellar sub-systems within the Galaxy, distinguished by density distributions, kinematics, chemical abundances, and presumably formation histories. Could be co-spatial

Major Components of the Galaxy

The disk: thin, roughly circular disk of stars with a coherent rotation about the Galactic center

$$L_{disk} \approx 15 - 20 \times 10^9 L_{sun}$$

$$M_{disk} \approx 6 \times 10^{10} M_{sun}$$

Disk extends to at least 20 kpc from the Galactic center. Density of stars falls off exponentially, both radially and vertically:

disk scale length $h_R \sim 3$ kpc

$$n(R) \propto e^{-R/h_R}$$

Most of the stars (95%) lie in a young, **thin disk,** with a vertical scale height ~ 300 pc. Rest form an older, **thick disk** with a vertical scale height ~ 1 kpc

A thin gas disk (mostly H I, also H II, dust)

Major Components of the Galaxy

- **The bulge**: central, mostly old spheroidal stellar component

$$L_{bulge} \approx 5 \times 10^9 L_{sun}$$

$$M_{bulge} \approx 2 \times 10^{10} M_{sun}$$

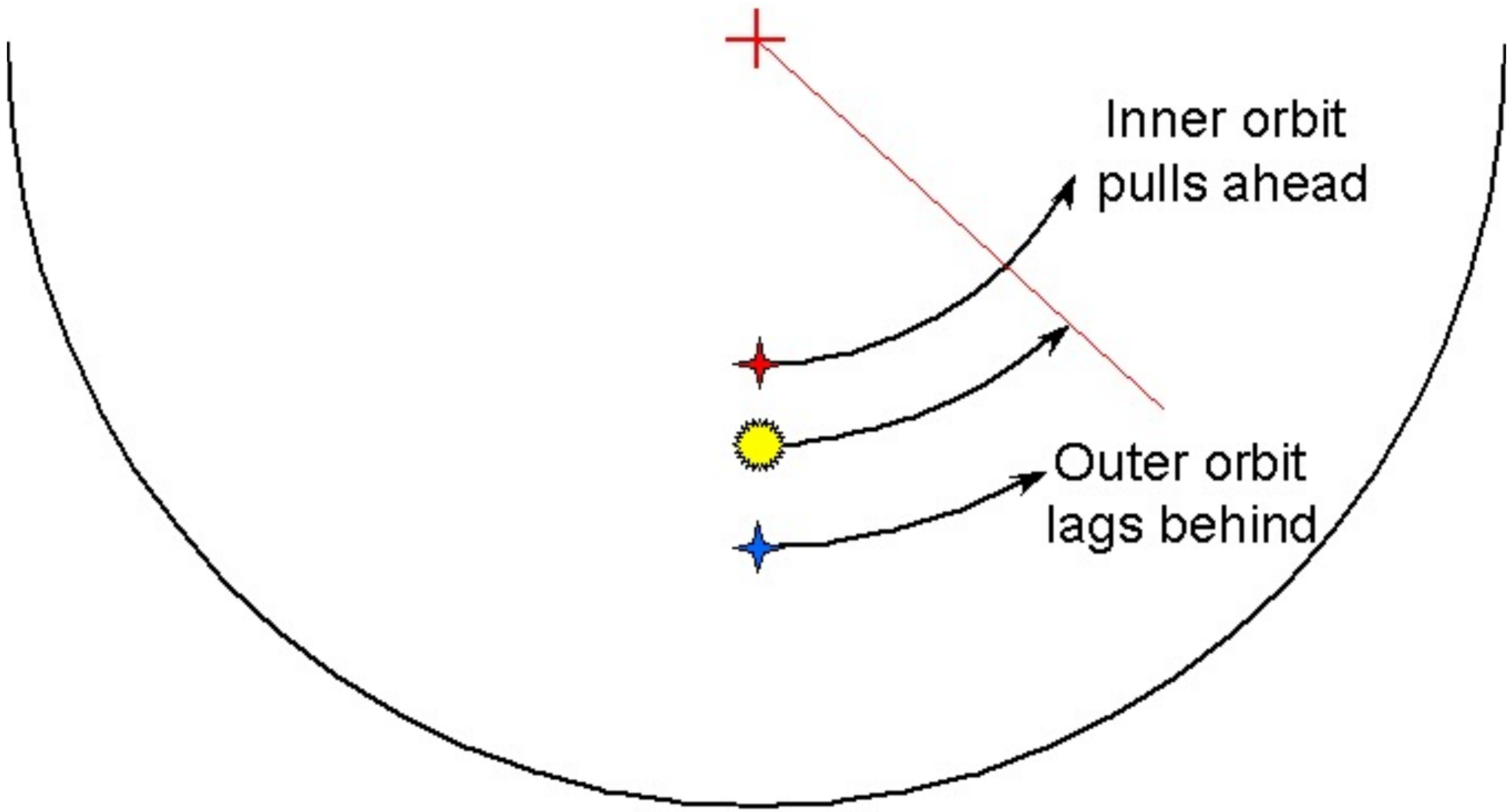
Galactic center is about 8 kpc from the Sun, the bulge is a few kpc in radius

- **The bar**, an ellipsoidal component superposed on the bulge
- **The halo**, containing:
  - ★ Stellar halo (field stars): low density, old, metal poor, random motions; total mass ~10^9 M_{sun}
  - ★ Globular clusters. A few % of the total halo stellar content
  - ★ Gas with T ~ 10^5 - 10^6 K. Total mass unknown
  - ★ Dark matter. Physical nature unknown. About 90% of the total mass

Where Do They Come From?

- **The thin disk**: stars formed out of the thin gas disk, it gets gradually puffed up (thicker) due to dynamical effects
- **The thick disk**: it could be a thin disk that was dynamically heated by minor mergers with other galaxies
- **The bulge**: the original, self-enriched stellar population that formed at the bottom of the galaxy's potential well
- **The bar**: formed from the disk material due to a dynamical instability, that funnels out the gas, and ceases the star formation
- **The stellar halo**: debris from the tidal disruptions of dwarf galaxies and globular clusters
- **The halo gas:** ejected by supernovae ("Galactic fountain")
- **The dark halo:** collapse of density fluctuations in the early universe, the original "container" for galaxy building

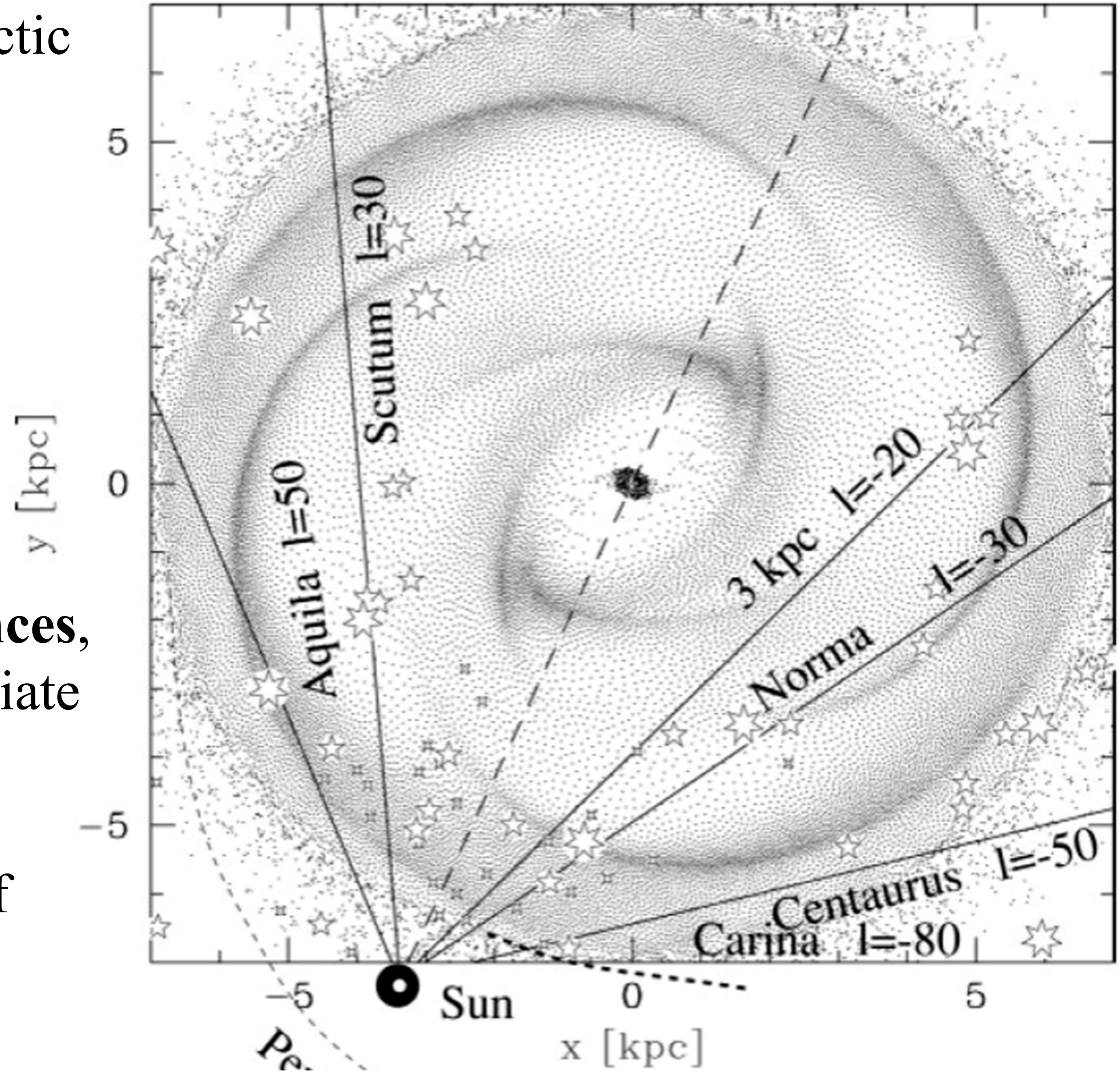
Galaxy Has a Differential Rotation: Angular Velocity Declines Outwards



Locally, we can use stellar velocities, but to measure the ***global kinematics*** of the Galaxy, and thus map its rotation, we use the H I 21 cm line, as it penetrates through the dust

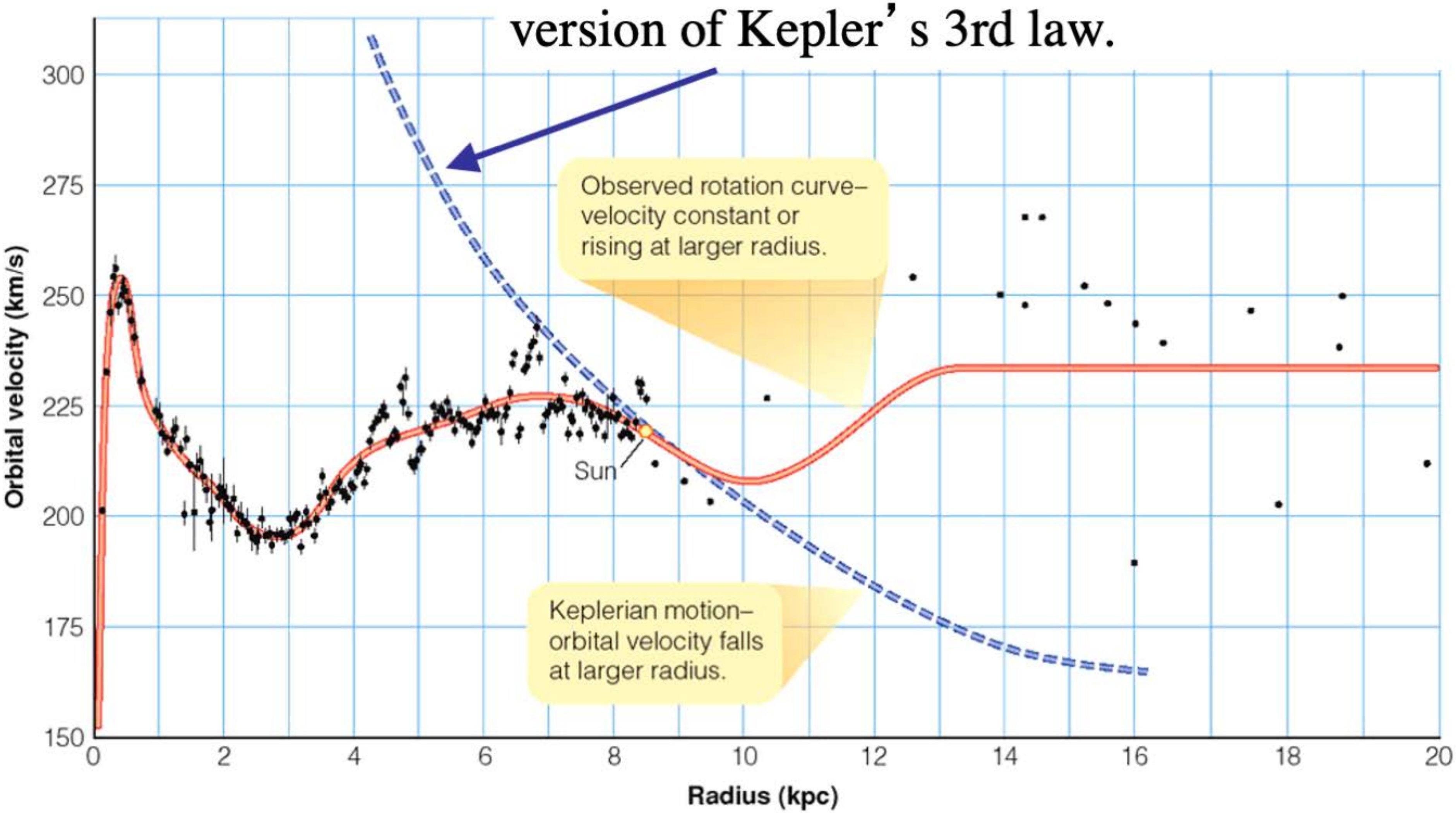
Along every line of sight in the Galactic plane, we can measure the H I intensity as a function of the **radial velocity**

To get the **distances**, we have to associate objects like star clusters with the concentrations of the gas



The Observed Rotation Curve of the Milky Way

If all mass was concentrated in the center, rotation curve would follow a modified version of Kepler's 3rd law.



Interpreting the Rotation Curve

Motions of the stars and gas in the disk of a spiral galaxy are mostly circular (V_R and $V_Z << V_R$). If $V(r)$ = the circular velocity at radius *r*, the centrifugal force must be balanced by gravitational force:

$$\frac{V^2(r)}{r} = -F_r(r)$$

If the mass enclosed within radius *r* is $M(r)$, gravitational force is:

$$F_r = -\frac{GM(r)}{r^2}$$

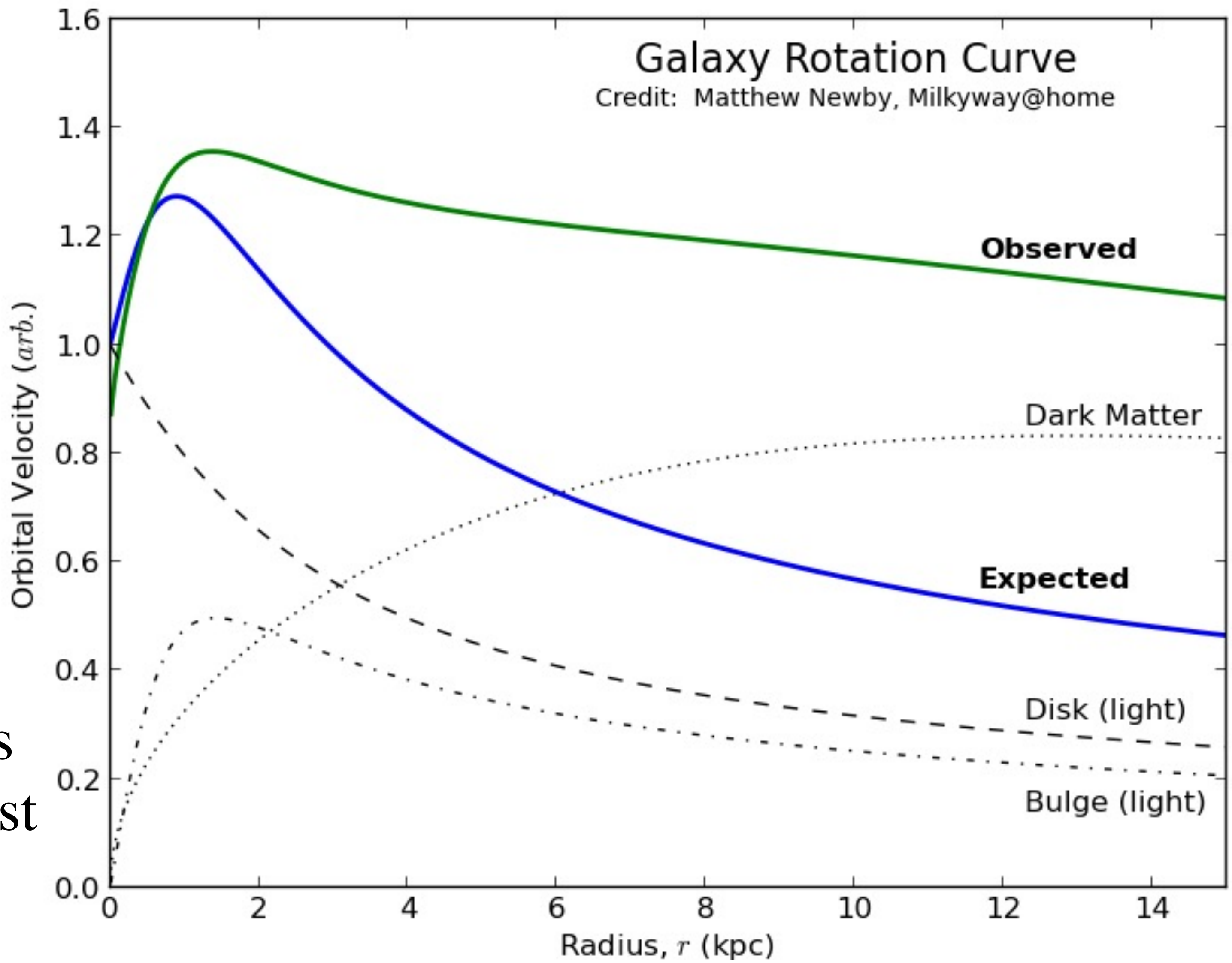
Thus, from observed $V(r)$, we can infer $M(r)$

A flat rotation curve, $V(r) \sim const.$ implies $M(r)/r \sim const.$, *i.e.*, $M(r) \sim r$ (but it must cut off at some point) and thus $dM/dr \sim const.$

For a spherical distribution, $dM(r) = 4\pi r^2 \rho(r)\, dr$, and thus $\rho(r) \sim r^{-2}$. This profile is called a *singular isothermal sphere*, as it implies an infinite density at the center. However, the observed rotation curves $V(r) \rightarrow 0$ as $r \rightarrow 0$, so the density profile must flatten near the center.

Rotation Curve and the Dark Halo

Gravity from the visible mass is insufficient to account for the observed rotation speeds



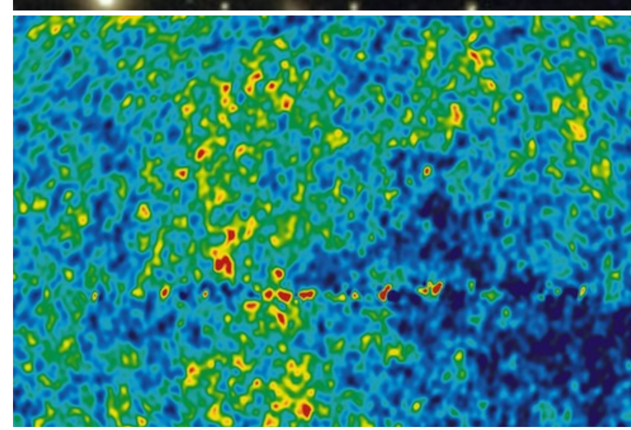
Therefore, an additional mass component must be present: **the dark halo**

Other Evidence for the Dark Matter

X-ray gas in galaxy clusters: too hot to be explained by the gravity of the visible matter alone

Gravitational lensing: implies the existence of an unseen mass component

Cosmic Microwave Background fluctuations: also require a substantial non-baryonic dark matter component

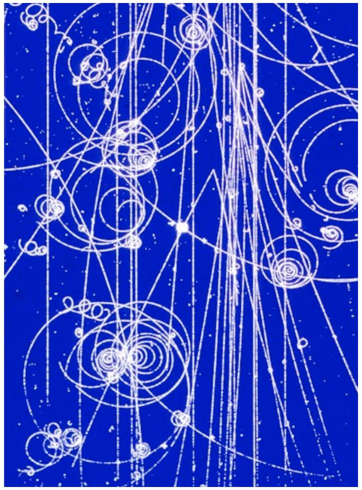


Large-scale structure formation and evolution needs a substantial amount of dark matter

… and they all agree!

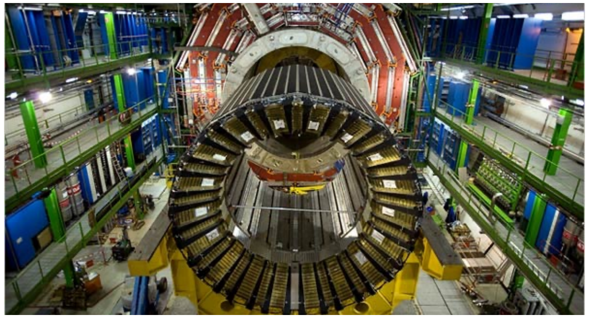
The Physical Nature of the DM

We know that ***some of it*** is regular matter, H and He atoms and ions, just hidden; and some is in massive cosmological neutrinos



But we also know that ***most of it*** is composed of some as yet unknown type of particles, or represents some new physics

The proposed possible constituents range from unknown ultra-light particles, to massive black holes and cosmic strings, but the favorite DM particles are WIMPs, or axions



These particles could be detected in laboratory experiments, or with accelerators like the LHC

Spiral Arms

Defining feature of spiral galaxies - what causes them?

Observational clues:

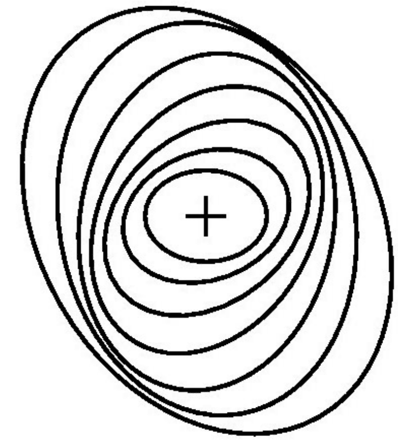
Seen in disks that contain gas, but not in gas poor S0 galaxy disks.

Defined mainly by blue light from hot massive stars, thus lifetime is << galactic rotation period

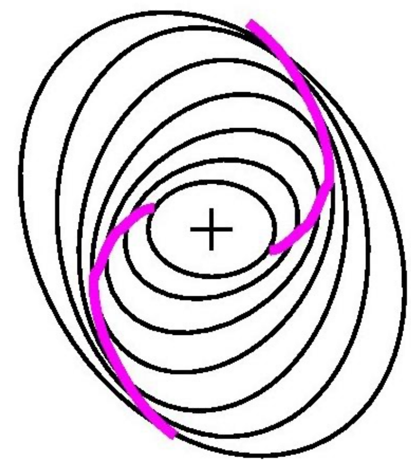
When the sense of the galactic rotation is known, the spiral arms almost always trail the rotation

Spiral Density Waves

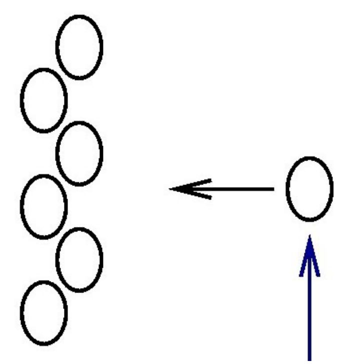
- The orbits in spiral galaxies are not quite circles – they are ellipses. These ellipses are slightly tilted with respect to each other



- Thus there are regions of slightly higher density than their surroundings. The higher density means higher gravity.

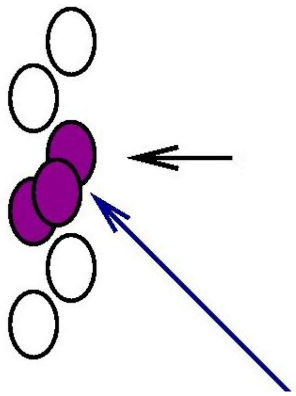


- Objects (such as a gas cloud) will be attracted to these regions and will drift towards them.

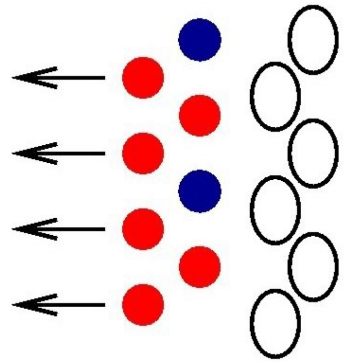


Spiral Density Waves and Star Formation

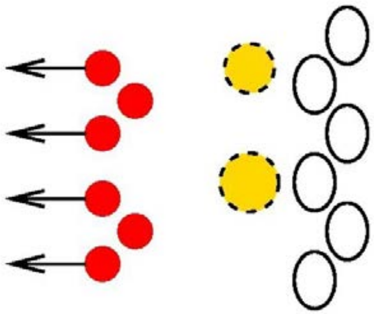
- When the gas cloud collides with other gas clouds, stars will be formed. This is where most of the star formation takes place

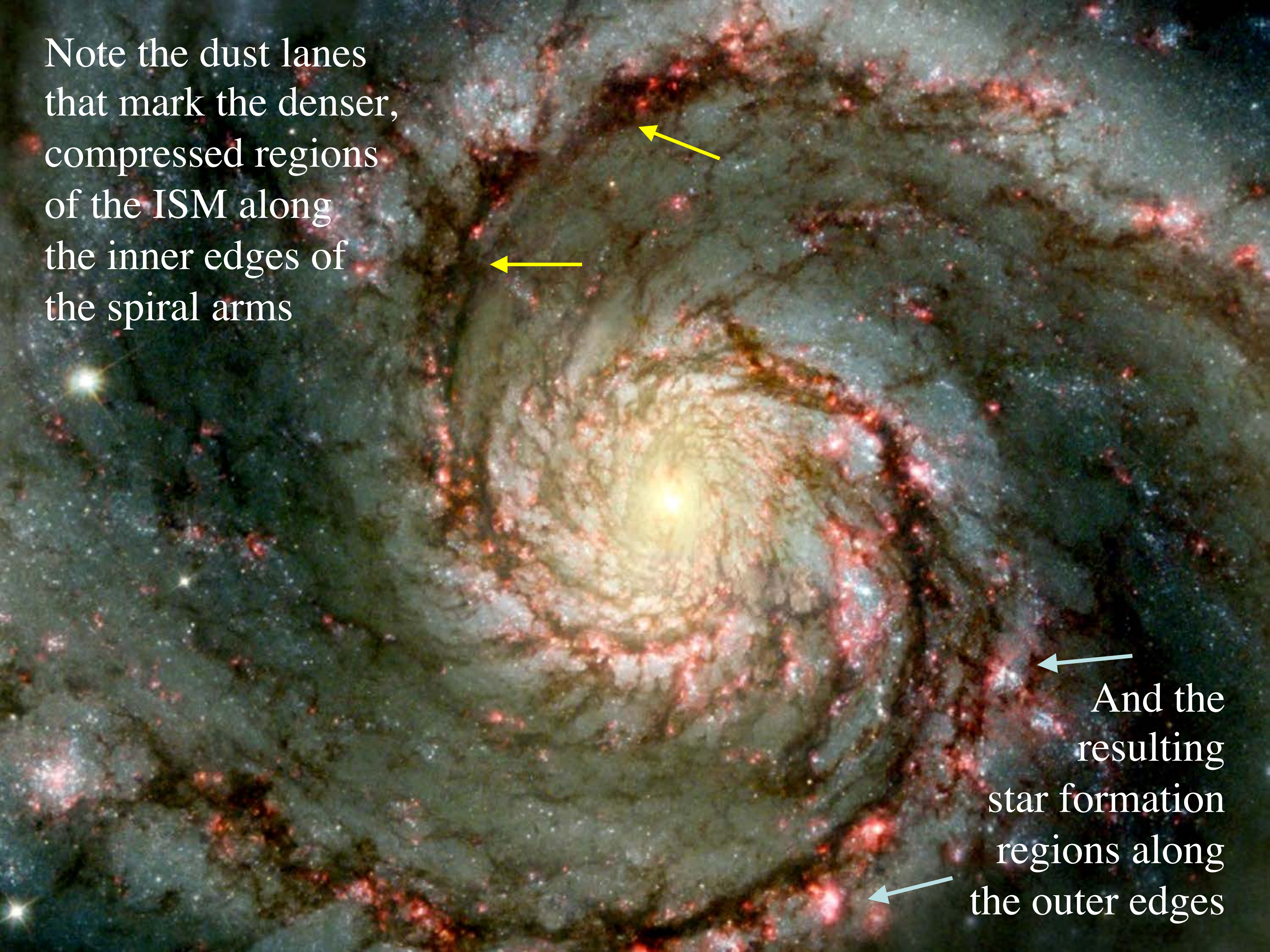


- Newly formed stars, including the luminous OB stars will continue to drift through the region



- The brightest and bluest, OB stars explode within a few million years, and thus don't go far from the spiral arm where they were born




Note the dust lanes that mark the denser, compressed regions of the ISM along the inner edges of the spiral arms
And the resulting star formation regions along the outer edges

Star Formation in Spiral Arms

- Spiral density wave creates spiral arms by the gravitational attraction of the stars and gas flowing through the arms
- Even if there was no star formation, there would be spiral arms - but star formation makes them more prominent
- This can explain the so-called ***"grand design"*** ***spirals***
- Star formation can ***self-propagate*** in a differentially rotating disk, e.g., as supernova shocks compress neighboring molecular clouds
- This may be responsible for the branches and spurs in the spiral arms, or disks without evident spiral density waves (the so-called ***flocculent spirals***)

Galaxy Bars

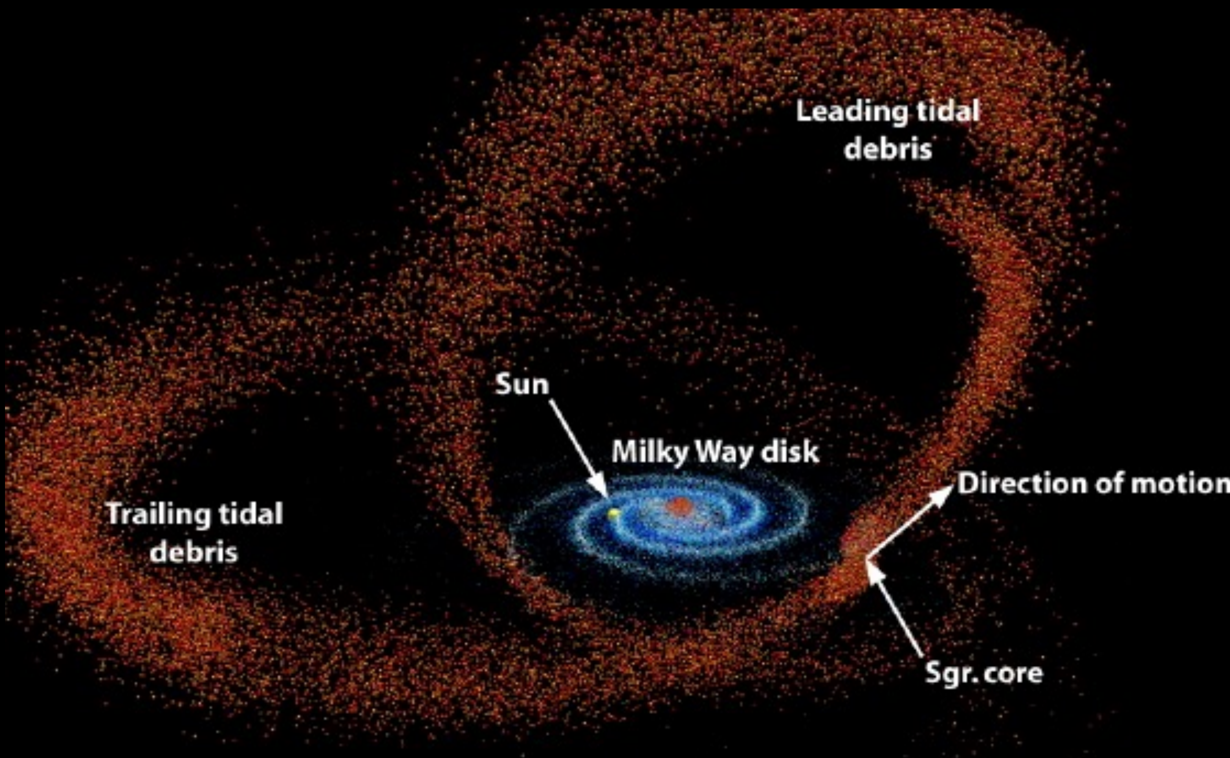
- Very common: occur in ~50% of all spirals (MW included)
- Isophotes not fit by ellipses; more **rectangular**, probably **flat** in disk plane
- Bars are **straight**, and stars **stay in the bar** rigid rotation of pattern
- Bars are **not** density waves: Stars **move along the bar** on closed orbits in frame rotating at a constant angular speed

- They can *drive a density wave in disk* and help maintain spiral structure, and also funnel gas to the center, where it could feed an active nucleus, if one is present

The Local Group of Galaxies

- A collection of nearby galaxies, consisting of:
  - 2 large spirals (the Milky Way and Andromeda)
  - 1 small spiral (M33)
  - 1 small elliptical (M32)
  - A lot of dwarf galaxies of different kinds: Magellanic Clouds, other dwarf irregulars, dwarf spheroidals, …
- About 1 Mpc in size (M31 is 700 kpc away)
- Not gravitationally bound (some parts are)
- Part of the Local Supercluster
- Most galaxies are found in groups

Tidal Tails and Shredding of Dwarf Galaxies



Dwarf galaxies are disrupted by their massive neighbors, leaving "tidal tails" of stars in the process

All halo stars probably come from disrupted/evaporated dwarf galaxies

An example is the Sagittarius dwarf >