Exam 2 Logistics

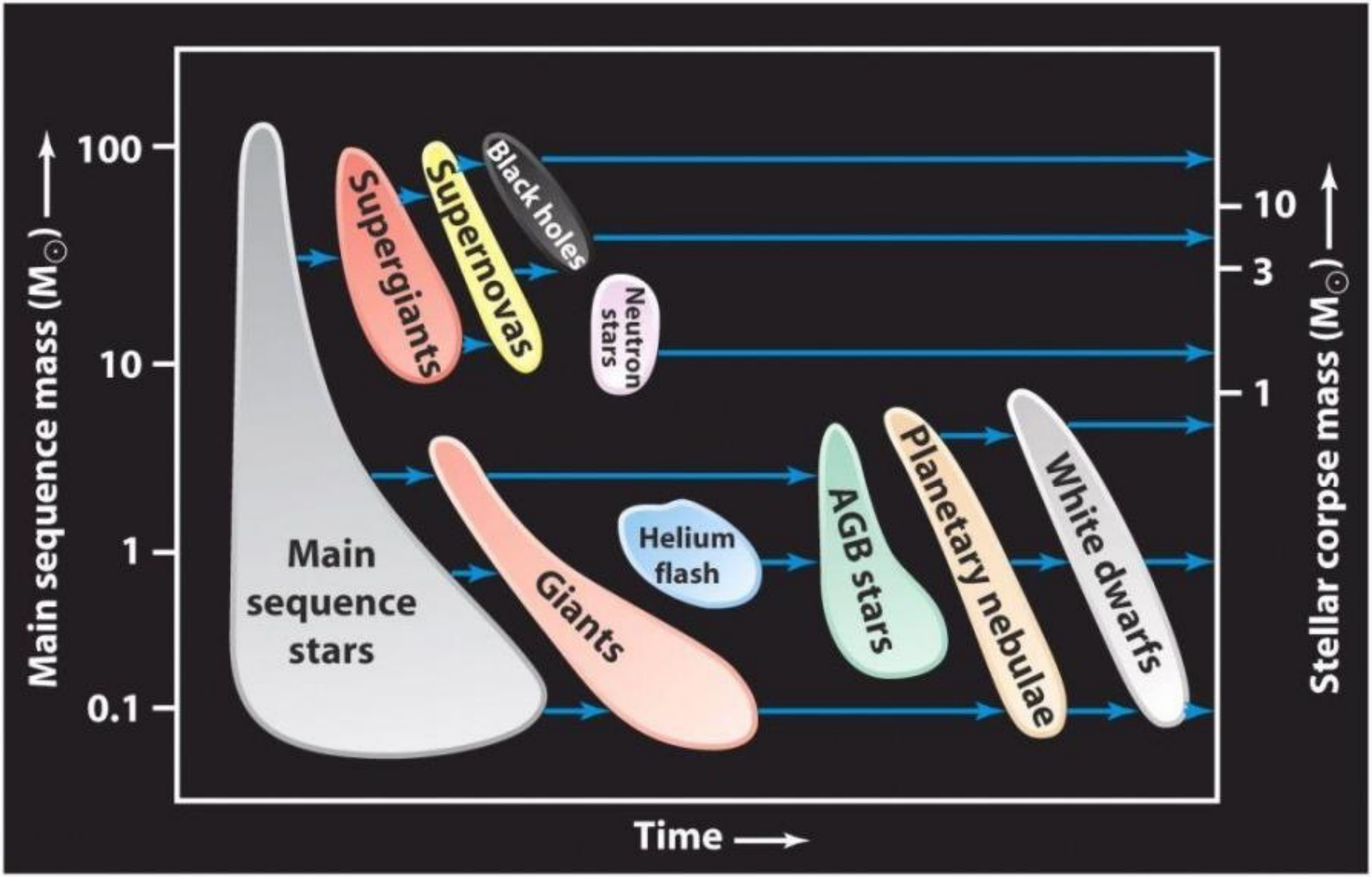
General

- Closed book, closed notes, equation sheet will be provided
- Bring a calculator and two pencils
- Exam will start at 11:00am. Duration 75 minutes.

Advice

- Draw pictures, show your work/reasoning/knowledge
- Make sure you attempt every problem! I give partial credit
- Go over your homeworks
- Go over the worksheets we did in class
- Know the equation sheet
- Read the book (chapters 21-26)
- Review the lecture notes

Summary of star deaths



Escape velocity from a BH

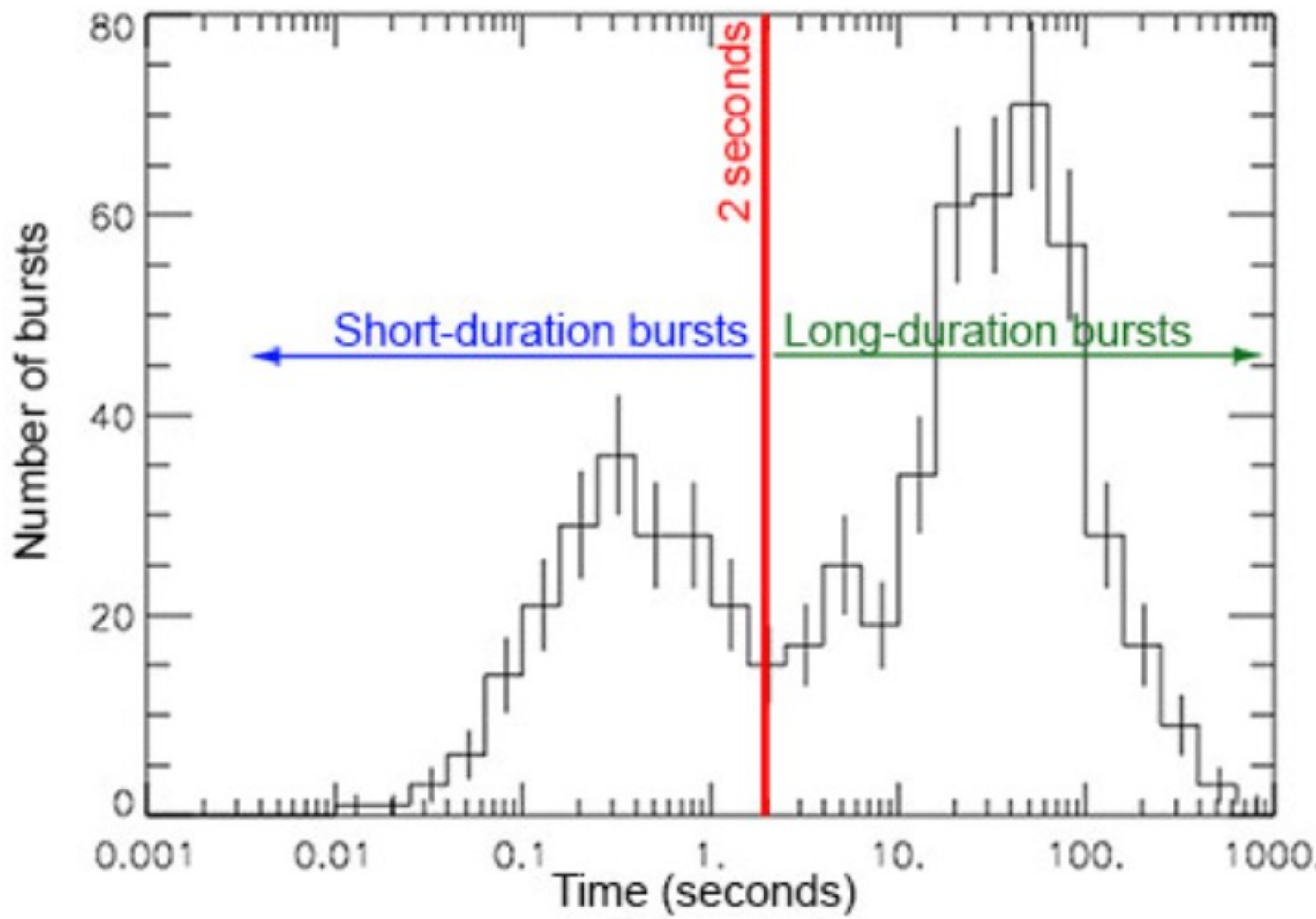
- Another way to look at it is by using the concept of escape velocity. The escape velocity of a black hole is the speed of light (or could even be more) – so nothing escapes, not even light.

$$V_{esc} = \sqrt{\frac{2GM}{R}}$$

- What if escape velocity is equal to the speed of light, c (a black hole)? Solve for R:

$$R_{Vesc=0} = \frac{2GM}{c^2} = R_{Sch}$$: the *Schwarzschild Radius.*

- The surface at the Schwarzschild Radius is called the *event horizon*, and is the boundary between the black hole and the rest of the Universe. Note that it is not a physical surface.

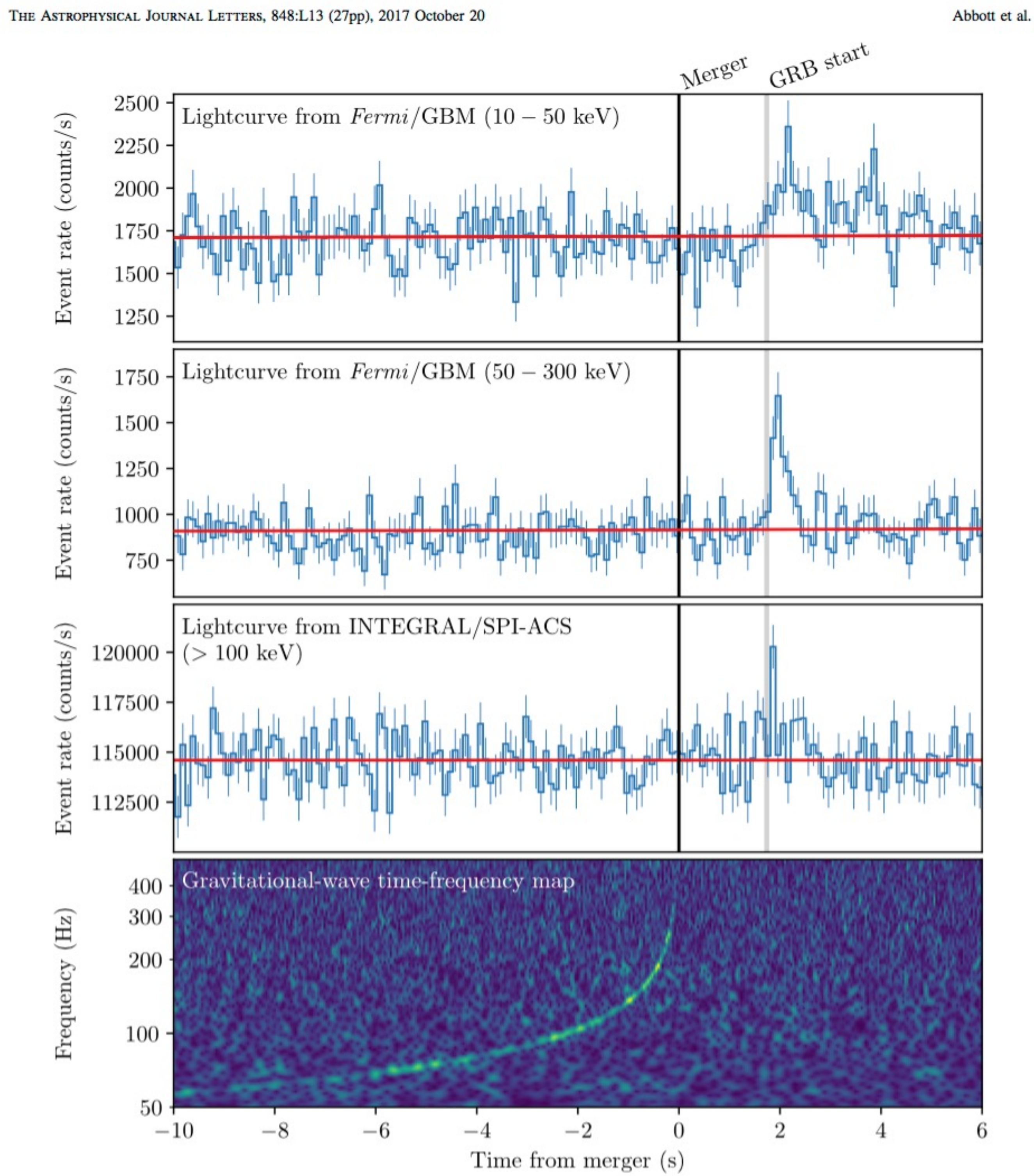


Graph of the time versus number of bursts for the gamma-ray bursts observed by the BATSE instrument on the Compton Gamma-ray Telescope.

Long duration GRBs are a type of Supernova “Hypernova”

- Peak toward low end of gamma-ray, complex gamma-ray light curves
- Often have bright afterglows
- Evidence for a relativistic explosion
- Energy required of ~ 10^{53} ergs (isotropic)
- Associated with regions of star formation in distant galaxies (out to edge of observable universe)
- Sometimes obscured by dust
- → progenitor is a massive star (over 25 solar masses)

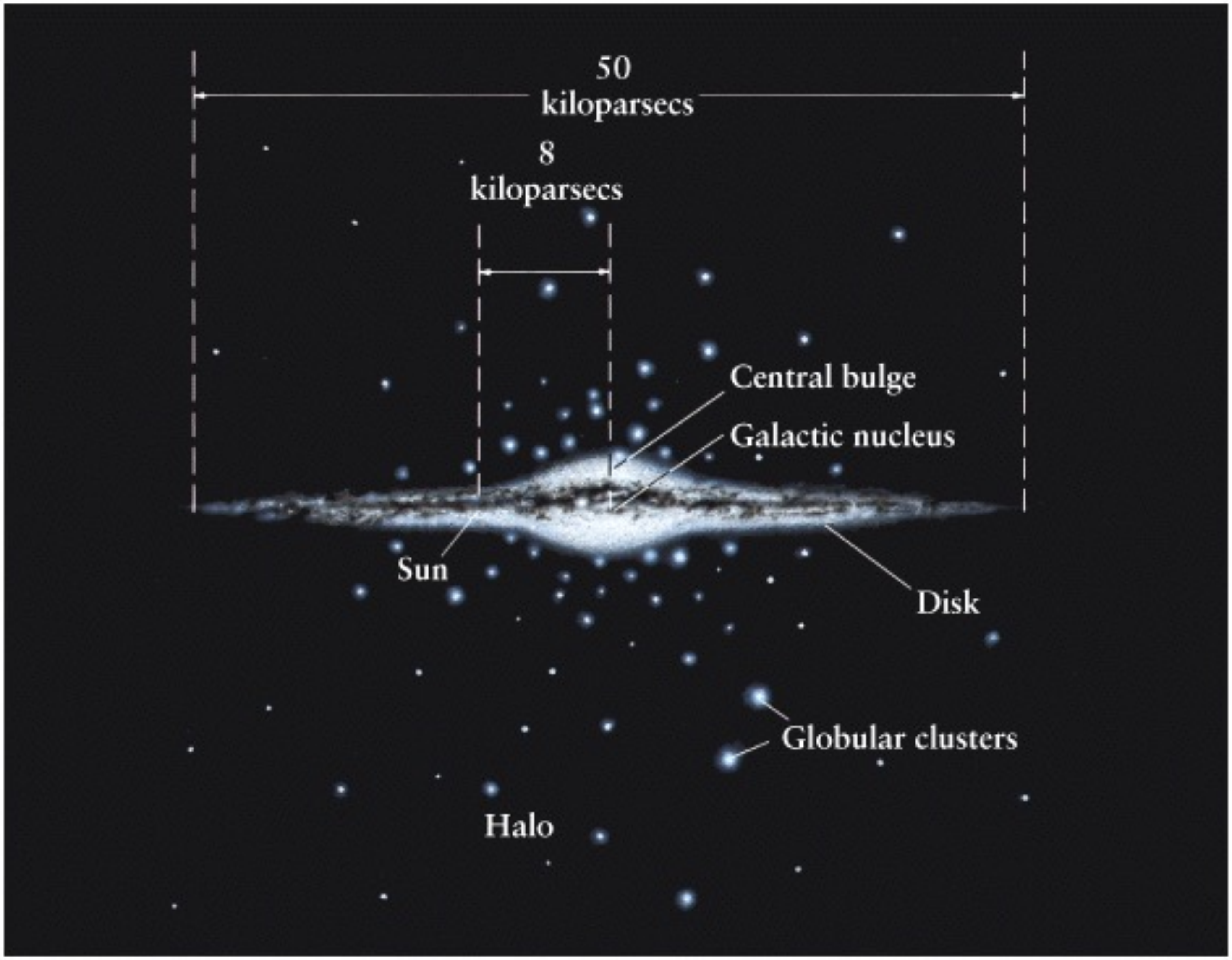

LIGO sees binary neutron star merger on August 17, 2017

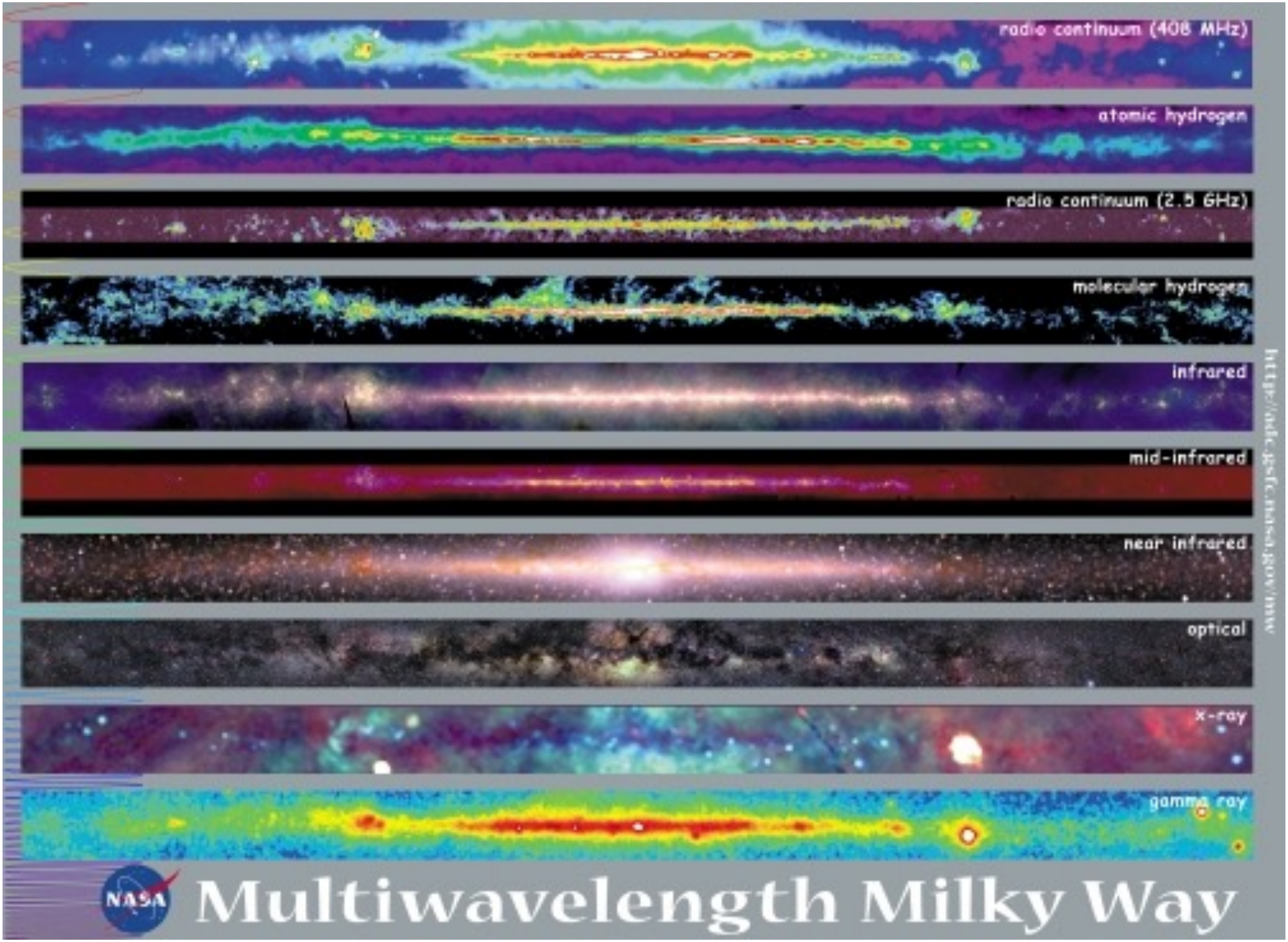


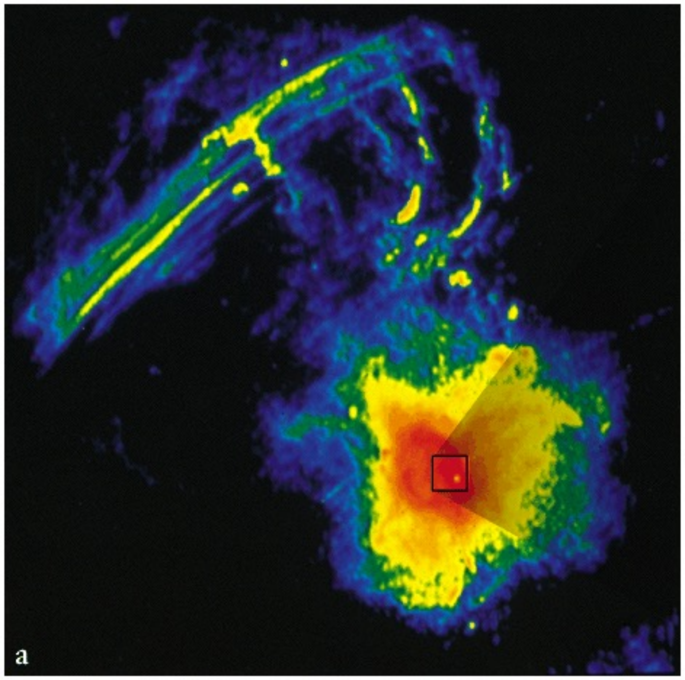
Gamma-rays look like a short GRB

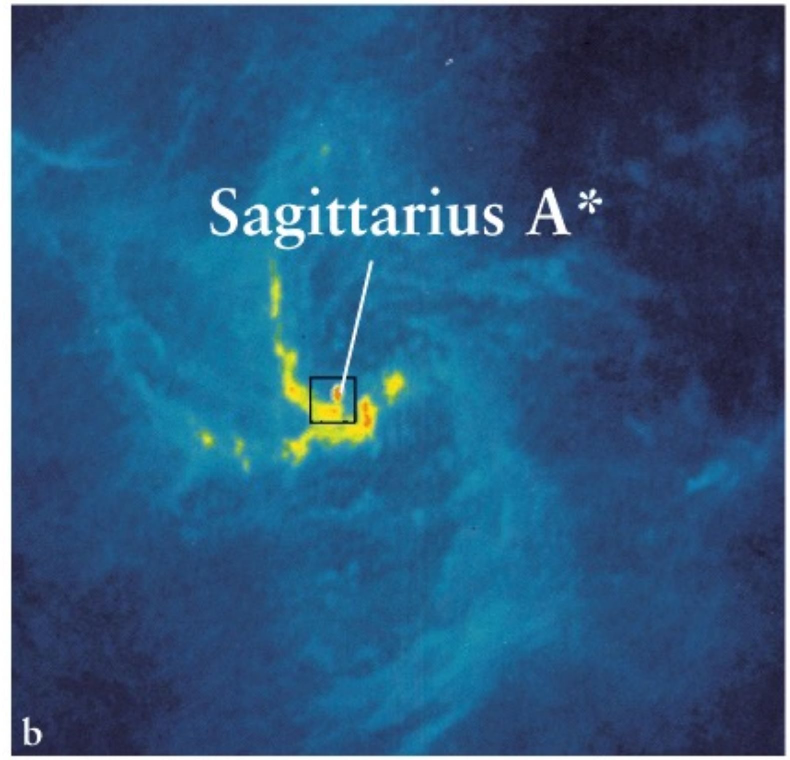
Little or no delay between arrival of photons and GWs over 100 Ml-y

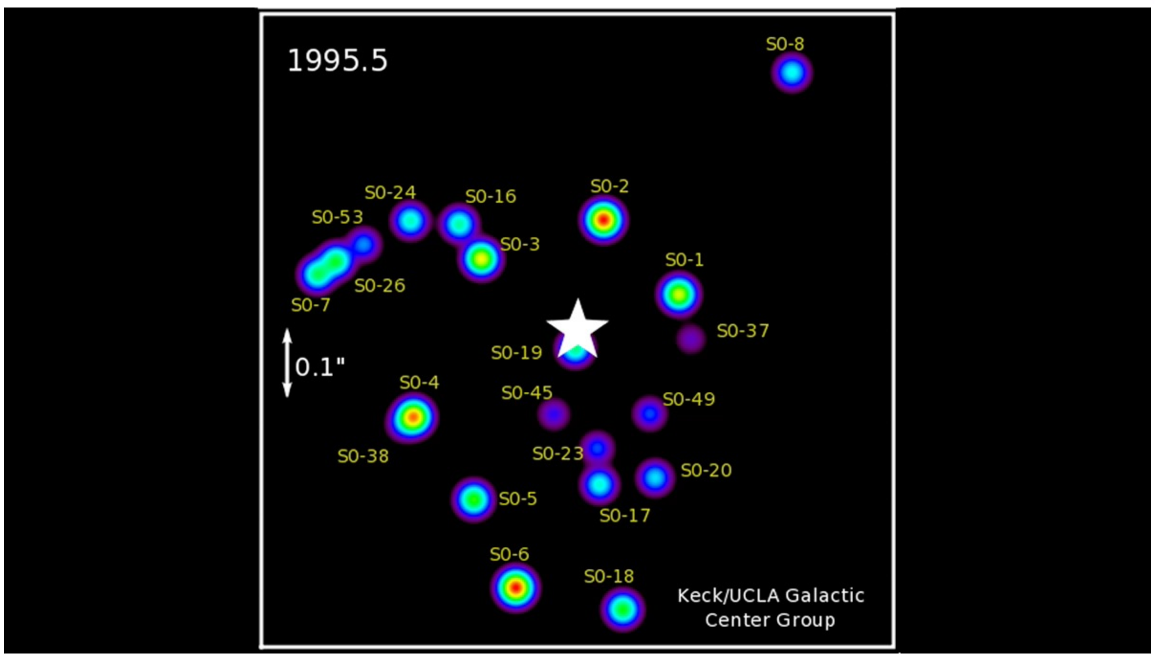
Modern “Artist’s conception” of the Milky Way (edge-on view)
Overall structure: disk, central bulge, halo.




radio continuum (408 MHz)
atomic hydrogen
radio continuum (2.5 GHz)
molecular hydrogen
infrared
mid-infrared
near infrared
optical
x-ray
gamma ray
http://adc.gsfc.nasa.gov/mw
NASA
Multiwavelength Milky Way







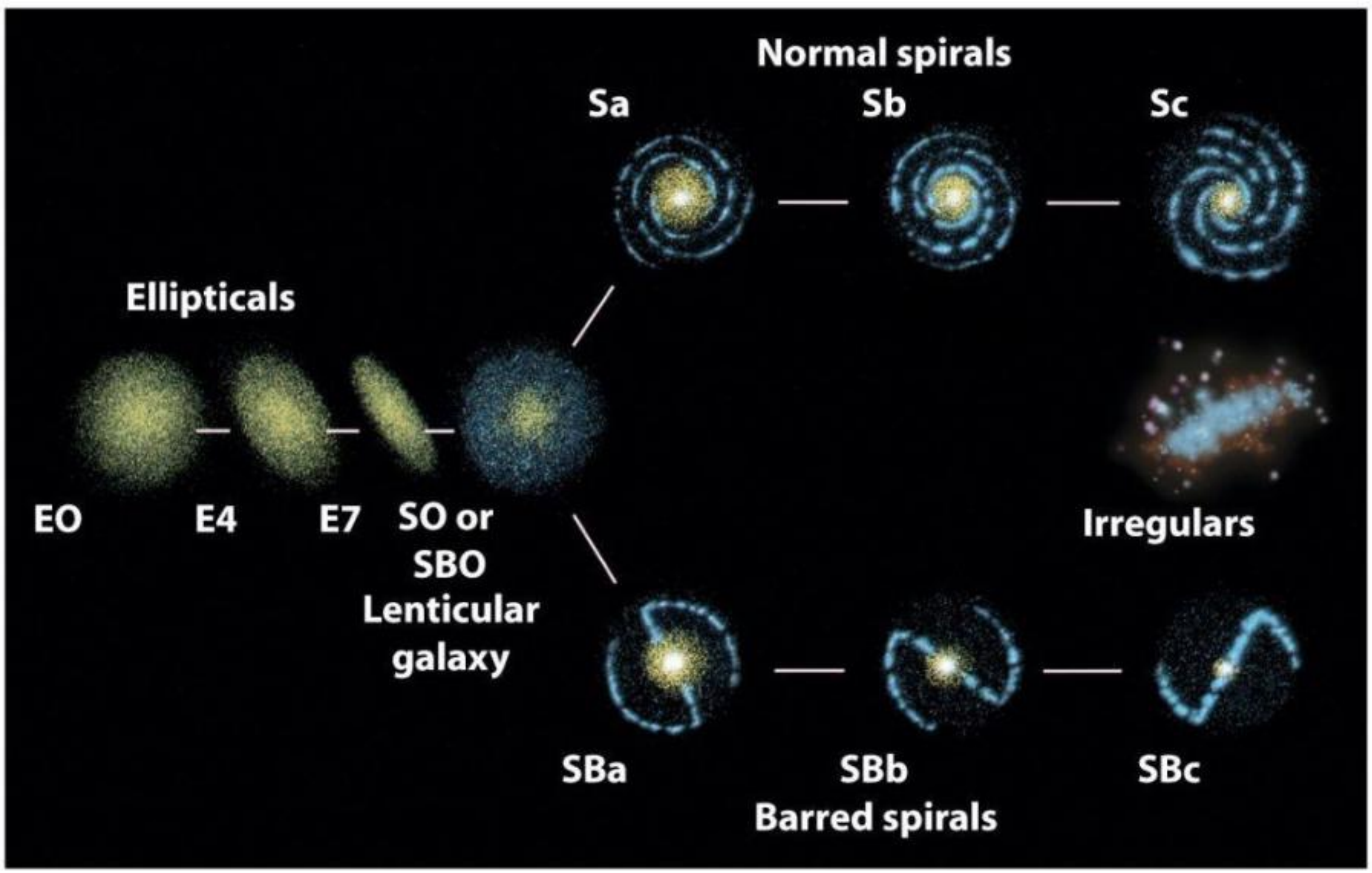
Pinwheel of material is orbiting strong radio source Sgr A*

3.7 Million solar mass black hole

Galaxy classification: morphology

- All bright galaxies fall into one of three main classes according to their shape:
- Spirals (77%), ellipticals (20%), irregulars (3%).

Hubble types: the *tuning fork* diagram



Measuring Galaxy Masses

- Gravitational Lensing
- Virial Theorem

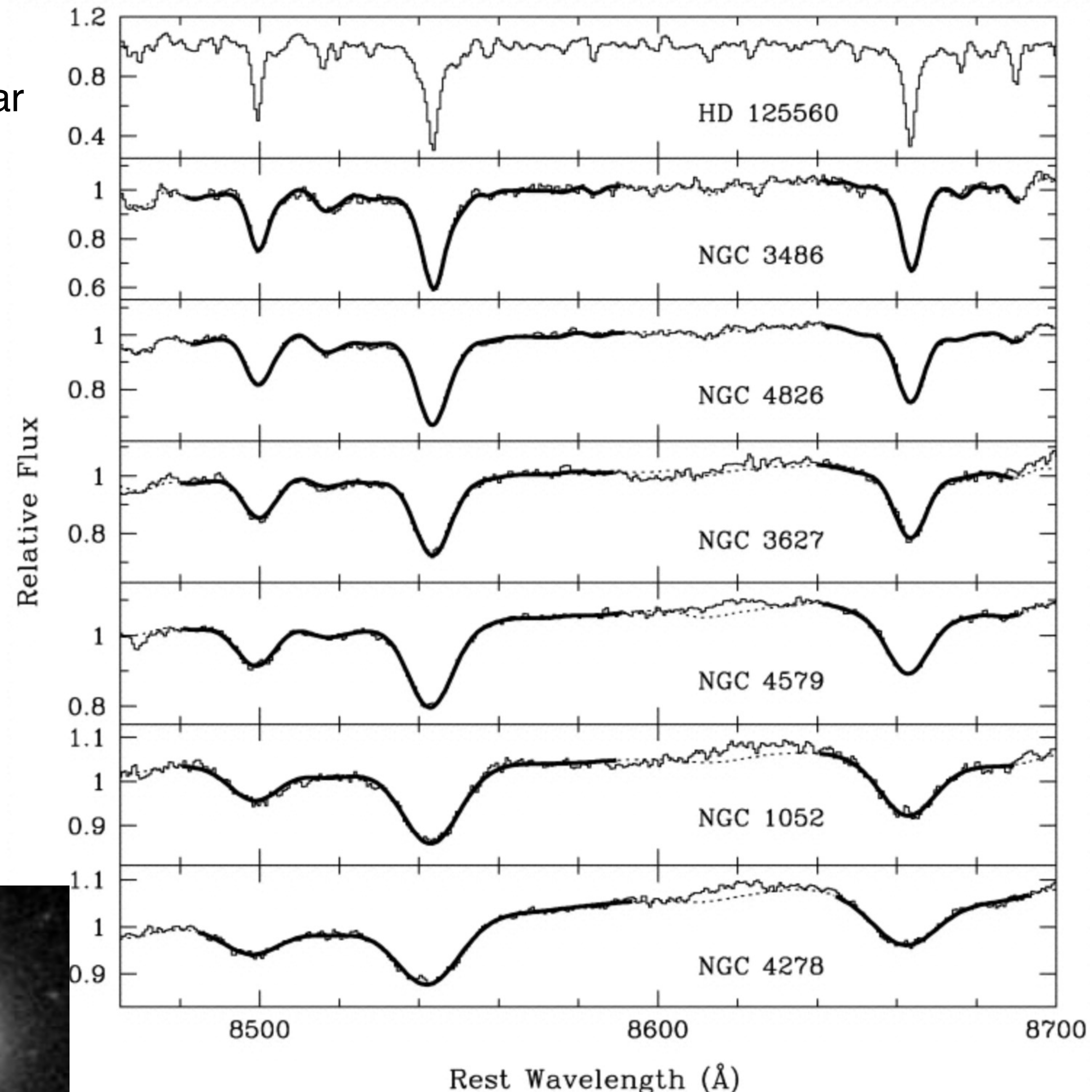
K.E. = P.E./2

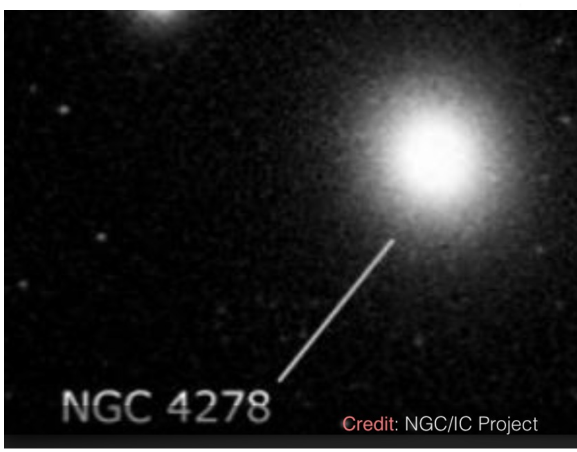
$mv^2/2 = GMm/2R$

$v^2 = GM/R$

$M = v^2R/G$

star





V = 261 +/- 8 km/s

R = 8 kpc

M = 1.2×10^{11} M_sun

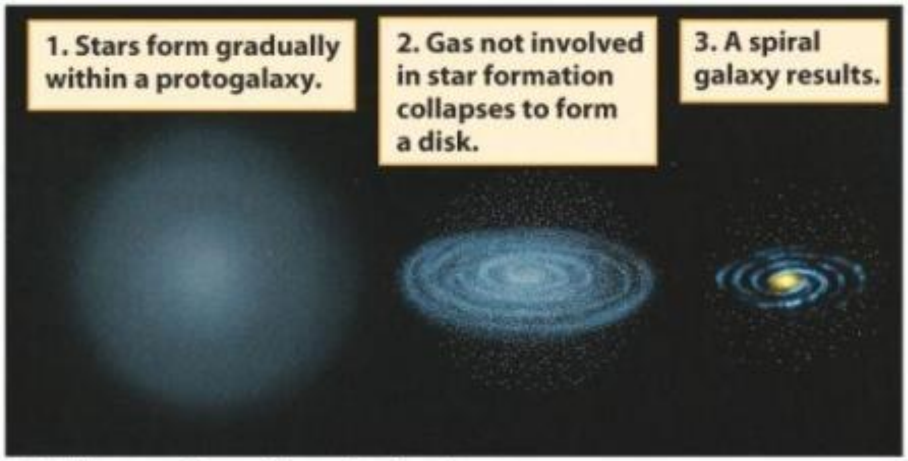
Barth et al. 2002

Dwarf galaxies

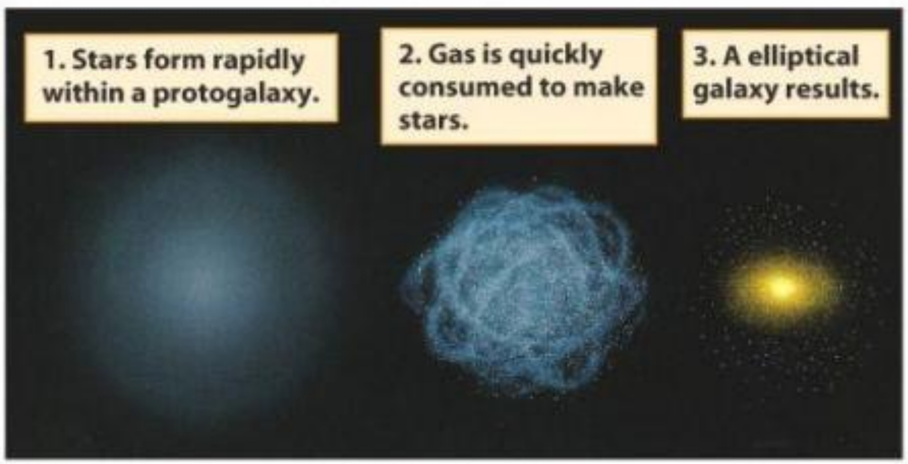
- The most common type: only a few 10^6 stars

The Leo I dwarf system, dE – a satellite of the Milky Way.

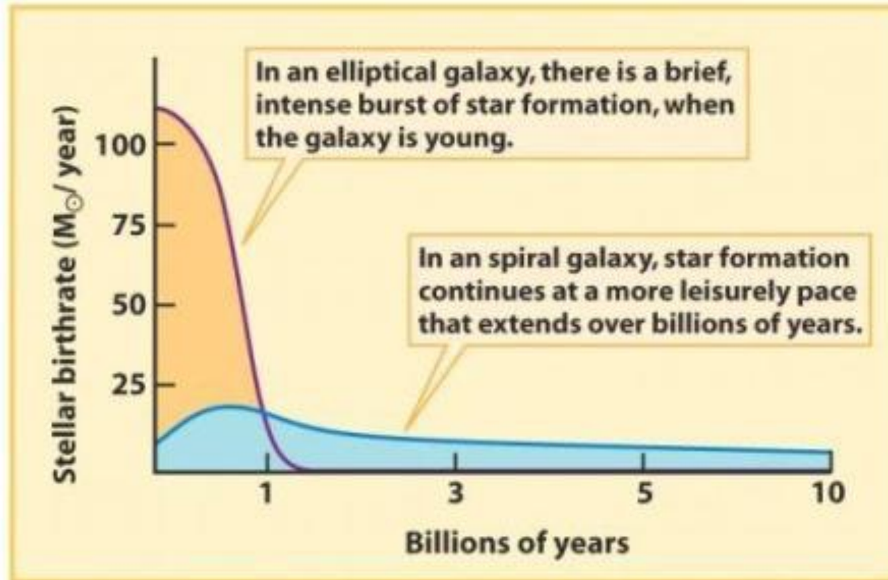
- Note that both E and S galaxies have similar ages – they both have old stars, but only the S have young stars and *current* star formation.



(a) Formation of a spiral galaxy



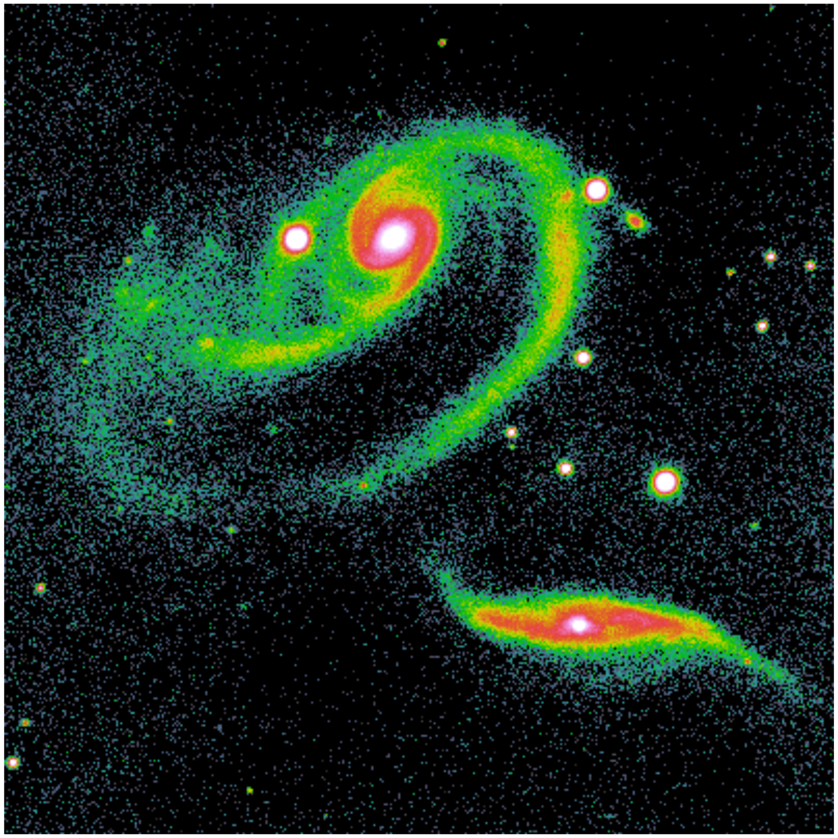
(b) Formation of an elliptical galaxy



(c) The stellar birthrate in galaxies

Colliding galaxies

- Collisions might distort shapes of galaxies involved in the collision, and thus impact the evolution of the galaxies



Arp273

Major Mergers

1. Two spiral galaxies on a collision course …

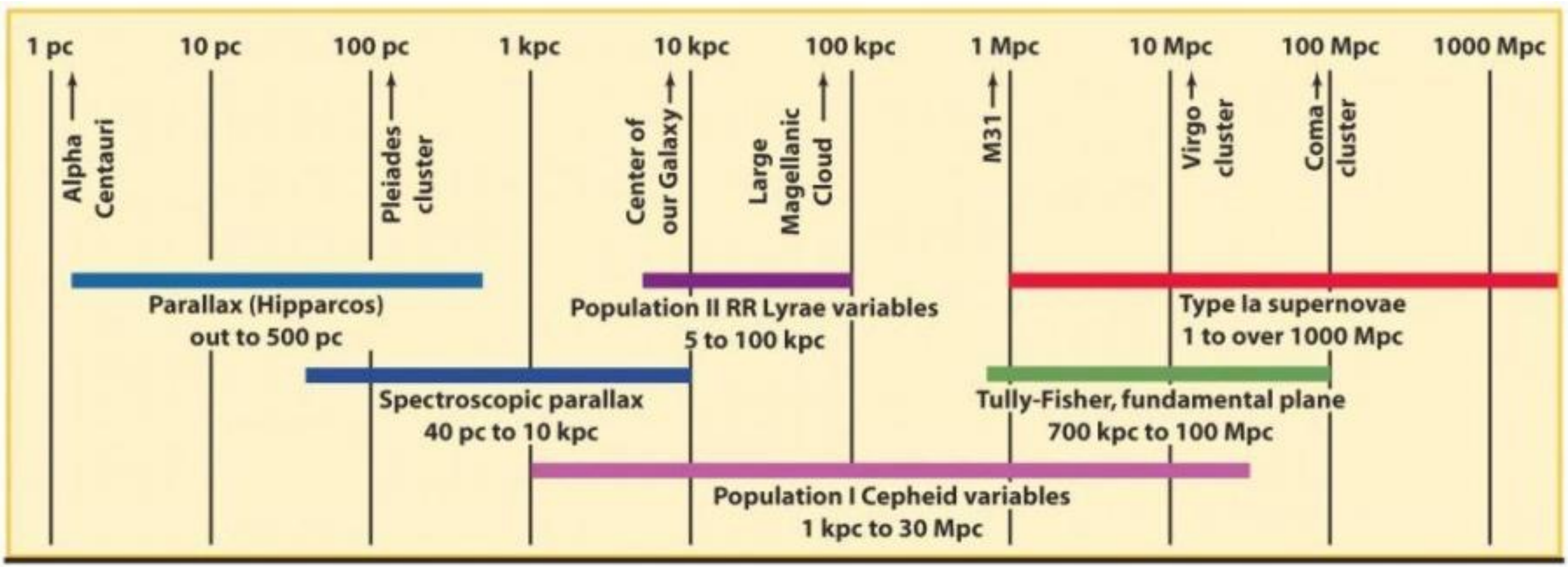
2. Gravitational forces throw out stars and gas along two extended tails. The length of the two tails reflects the rotation of the two initial galaxies.

3. The stars in the tail fade away, but gas in the tails falls back into the galaxies to form stars.

4. The disks are destroyed via violent relaxation.

5. The end product is an elliptical galaxy.

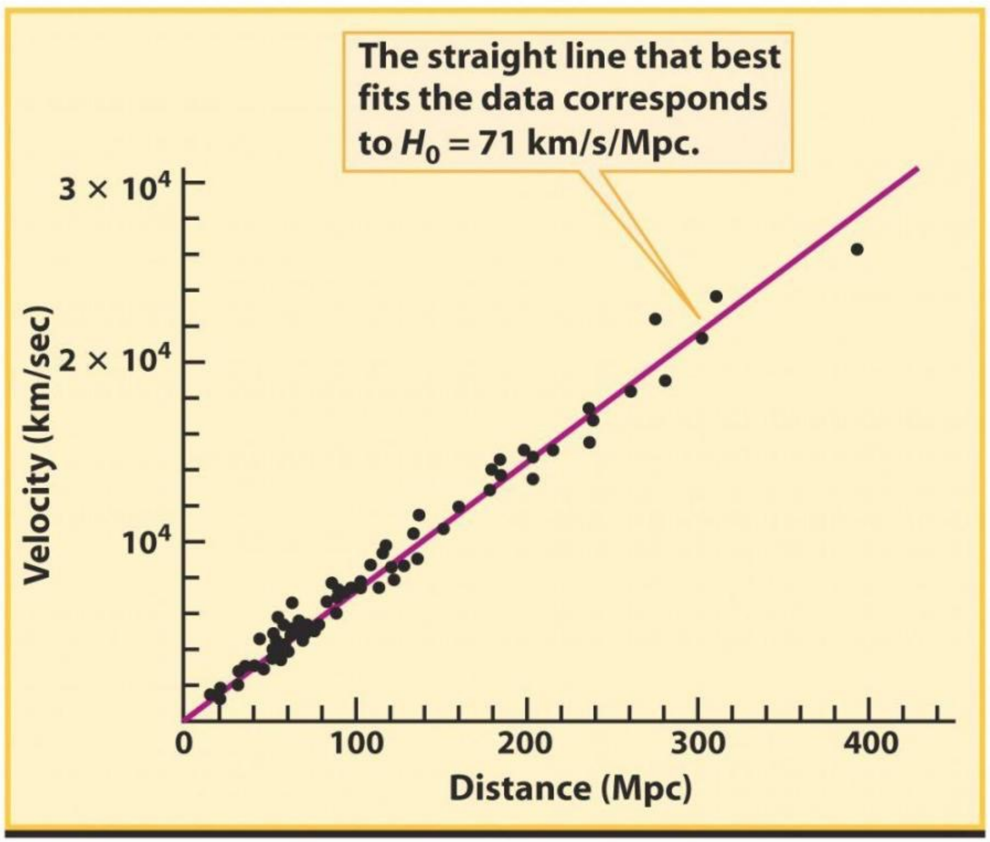
The "Distance Ladder"



The Hubble Law

- Plotting recession velocity *V*, versus distance *d*:

$V = H_0 d$ where the slope H_0 is Hubble's constant.



Starbursts

- Interacting galaxies tend to be bluer, with high far-IR luminosities due to triggered star formation.
  - Both direct mergers and more indirect interactions can trigger star formation

- Caused by gas agglomerating, causing shocks triggering collapse
  - Starbursts often occur at galaxy center, due to gas cloud orbits being disrupted by encounter.
  - Example M82 a few $M_{\odot}$/yr in a nuclear area of 100 pc (similar to a large spiral!)

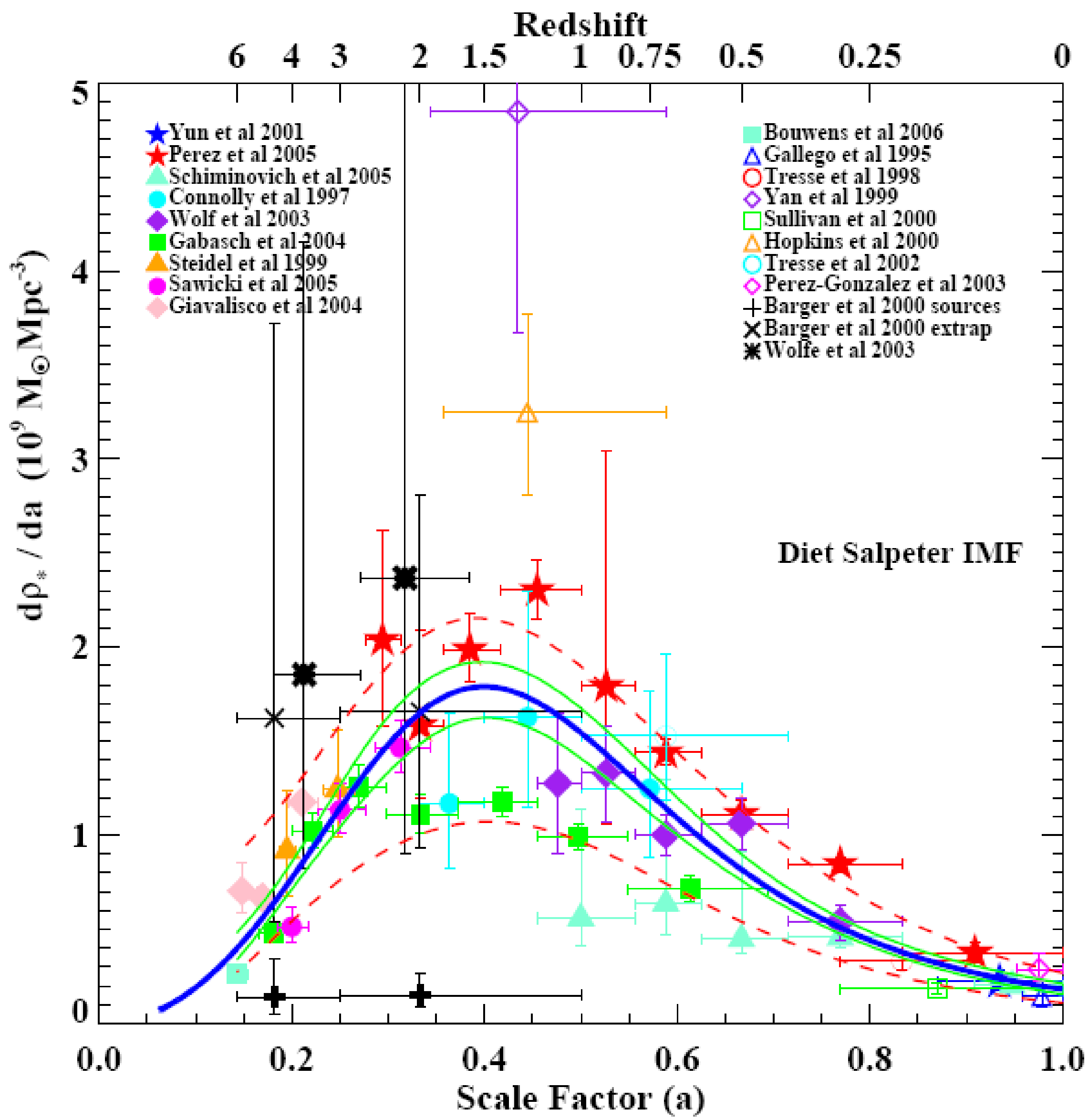
- May last 20Myrs (theoretically 10^8-10^9 yrs). Why so short?

- We observe *ultra luminous infrared galaxies (ULIRGS)* which have very high star formation rates (100-1000 x MW value)

Lilly-Madau Plot

- Fair amount of scatter, but for z>1 it is at the ~50% level now.
- Half the stars formed by z~1.7.
- Many issues: Dust? IMF? Sample overlap?

Fardal et al 2006



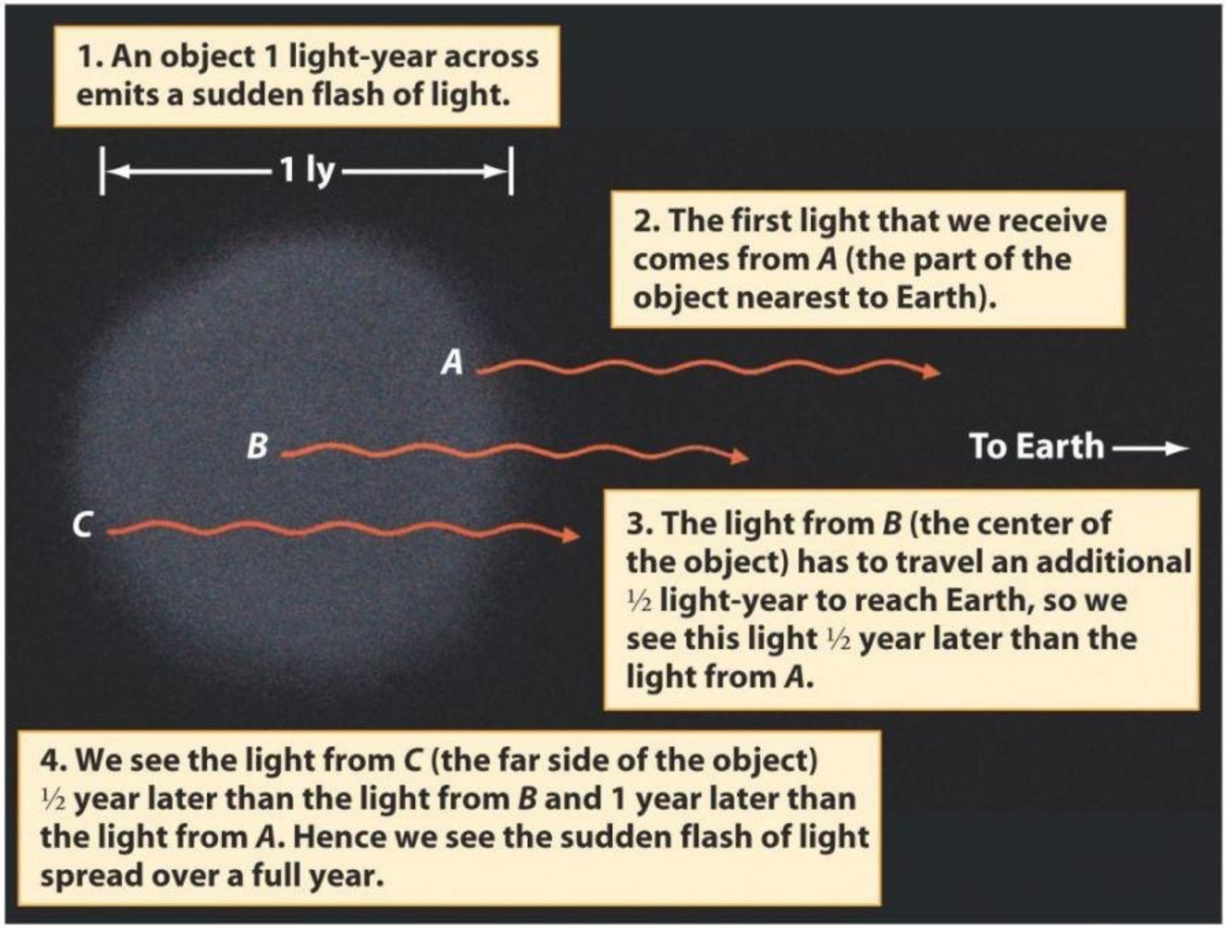
Active Galactic Nuclei: Ch 25

Key points:

- Active Galactic Nuclei: powerful energy sources in nuclei of some galaxies
- Types: Seyferts, quasars and radio galaxies.
- Power source: accretion of matter onto a supermassive black hole.

Active Galactic Nuclei (AGN)

- ~1% of galaxies have an *active nucleus*
- Nucleus is compact and bright, sometimes outshining the whole galaxy
- Display strong, broad emission lines from hot, dense, highly excited gas
- Highly variable => small, only a few light days across

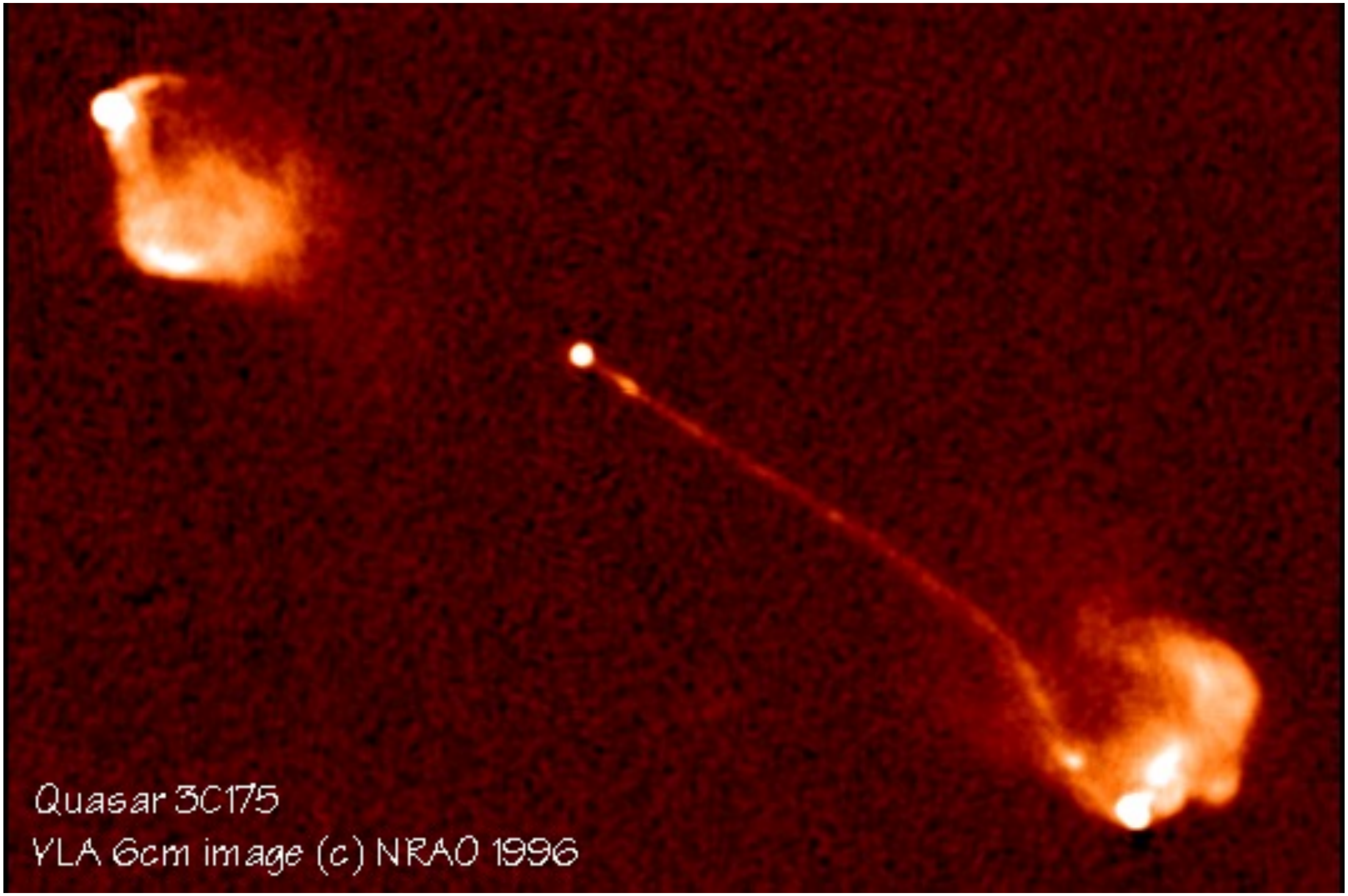


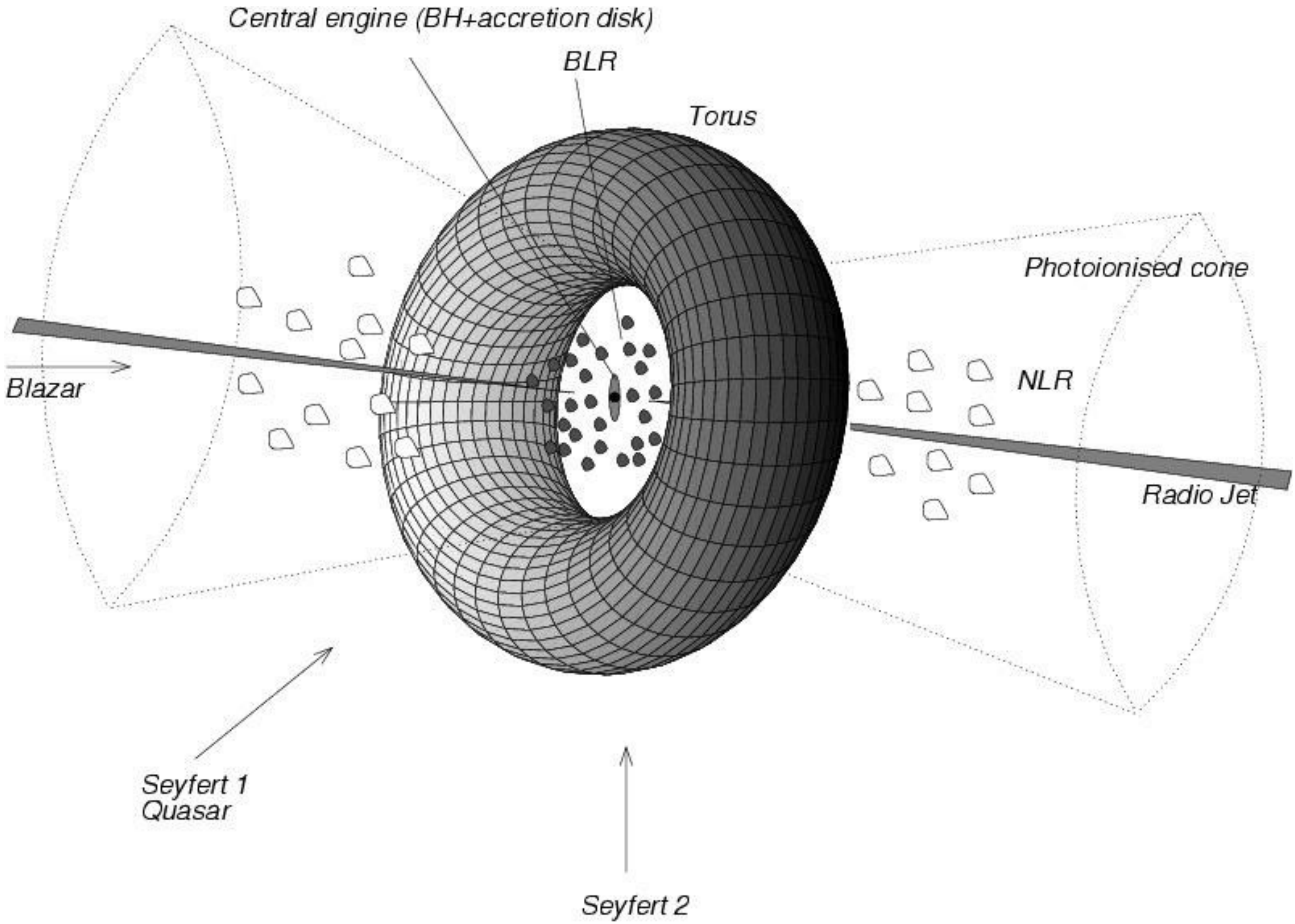
Rapid variability

A way of measuring *size* of the object. Big things can't vary rapidly.

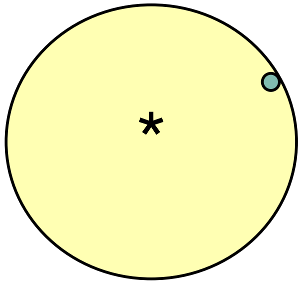
Example: an object 1 ly across can't change its brightness in less than a year

Quasars resemble High Power (FR II) radio galaxies




Central engine (BH+accretion disk)
BLR
Torus
Photoionised cone
NLR
Radio Jet
Blazar
Seyfert 1
Quasar
Seyfert 2

Bondi Accretion



$v = (2GM/R)^{1/2}$

$\quad = c\,(R_g/R)^{1/2}$

$L = 0.5\,\dot{M}\,c^2\,(R_g/R)$

$L = \varepsilon\,\dot{M}\,c^2$

c = speed of light
v = velocity
R = object radius
Rg = gravitational radius
ε = efficiency

$\varepsilon = 3 \times 10^{-4}$ for a white dwarf, 0.15 for a neutron star
ε up to 0.5 for a rotating black hole

Compared to 7×10^{-3} for hydrogen fusion, or 10^{-9} for chemical reactions

Accretion is a very efficient energy source

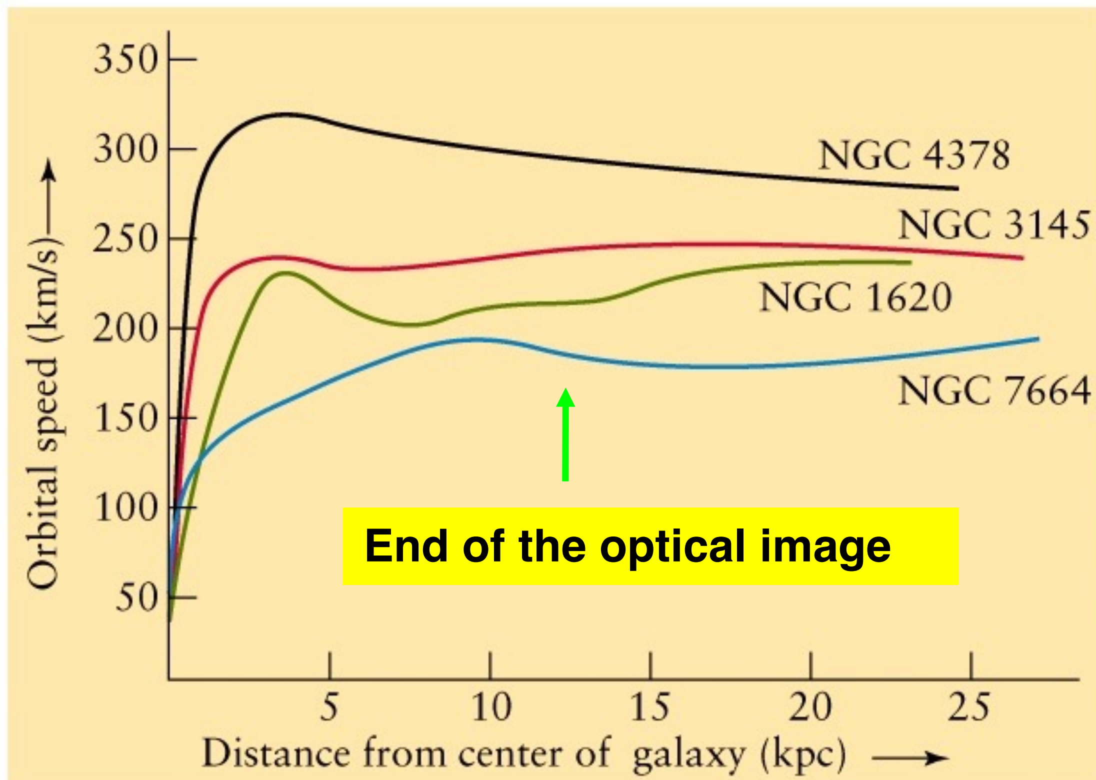
Mass in clusters

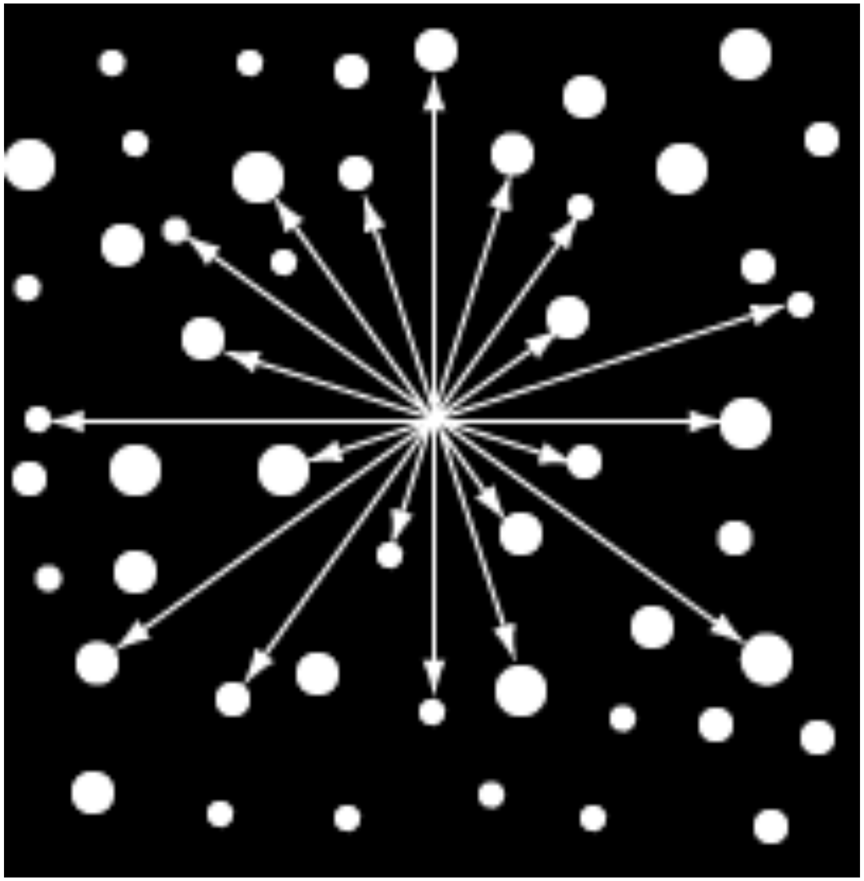
- The mass of a cluster can be estimated using the virial theorem:

$$M \approx \frac{RV^2}{G}$$

- The mass of the individual galaxies can be estimated using their rotation curves:

- Note that not only are the rotation curves flat, but they extend far farther (in radio) than the optical image.

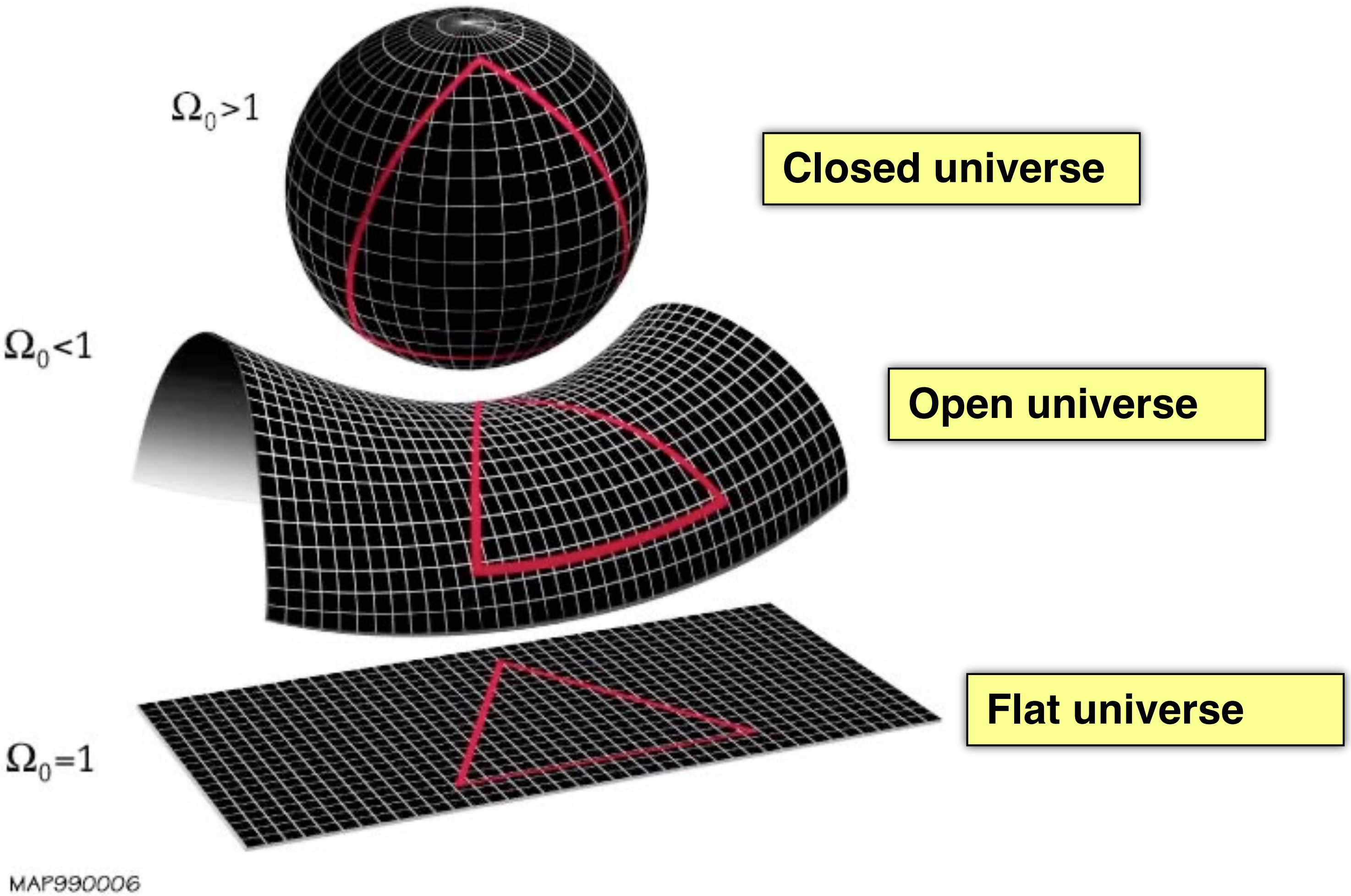


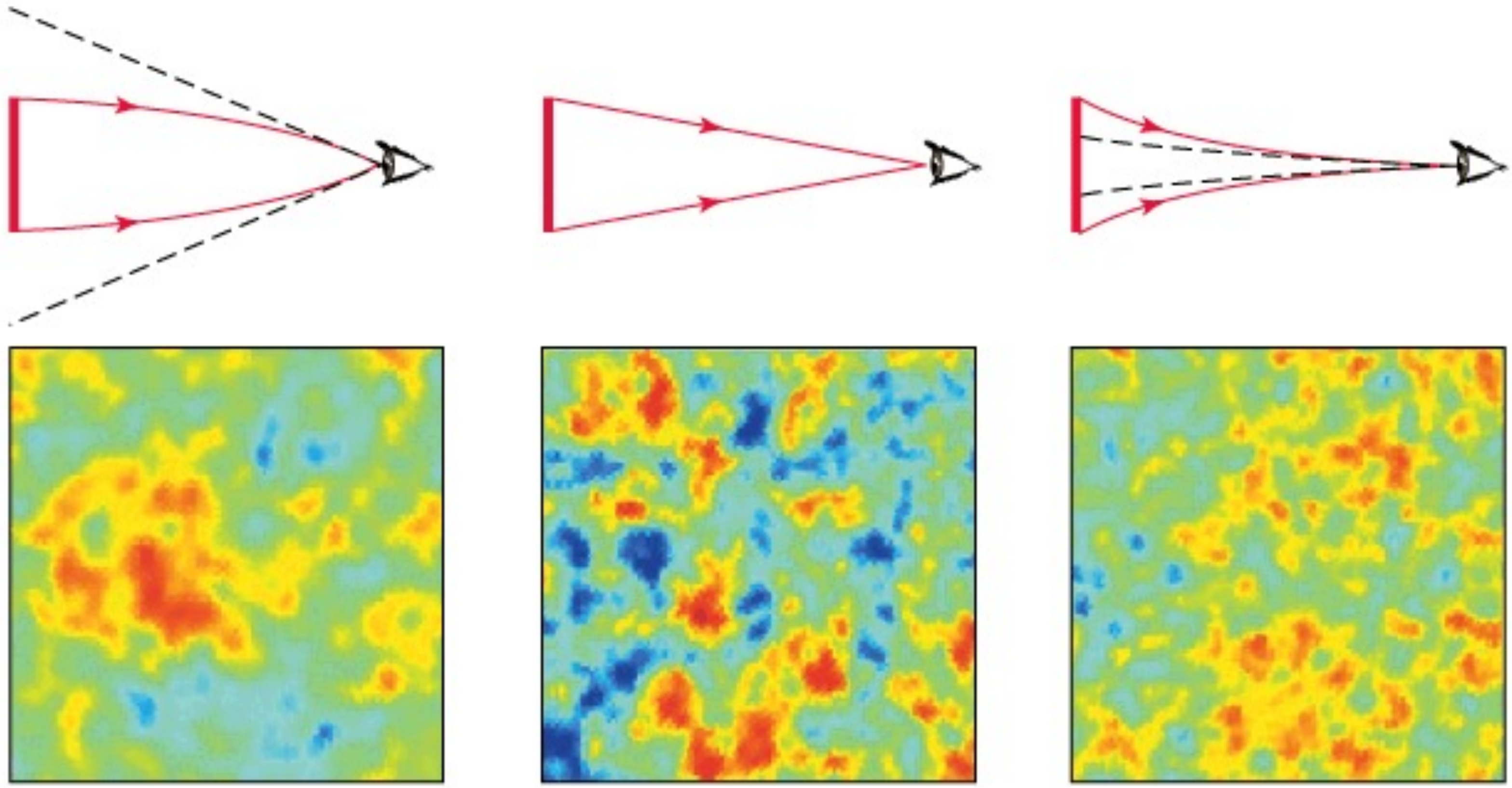


Olber's paradox

- Why is the sky dark at night? The cosmological principle would imply that the line of sight will always intersect at least one object?
- The sky is dark because the Universe has a finite age, and the expansion is reducing the energy radiated from distant stars. And there is dust.

- We define the *density parameter* $$\Omega_0 = \frac{\rho_0}{\rho_c}$$



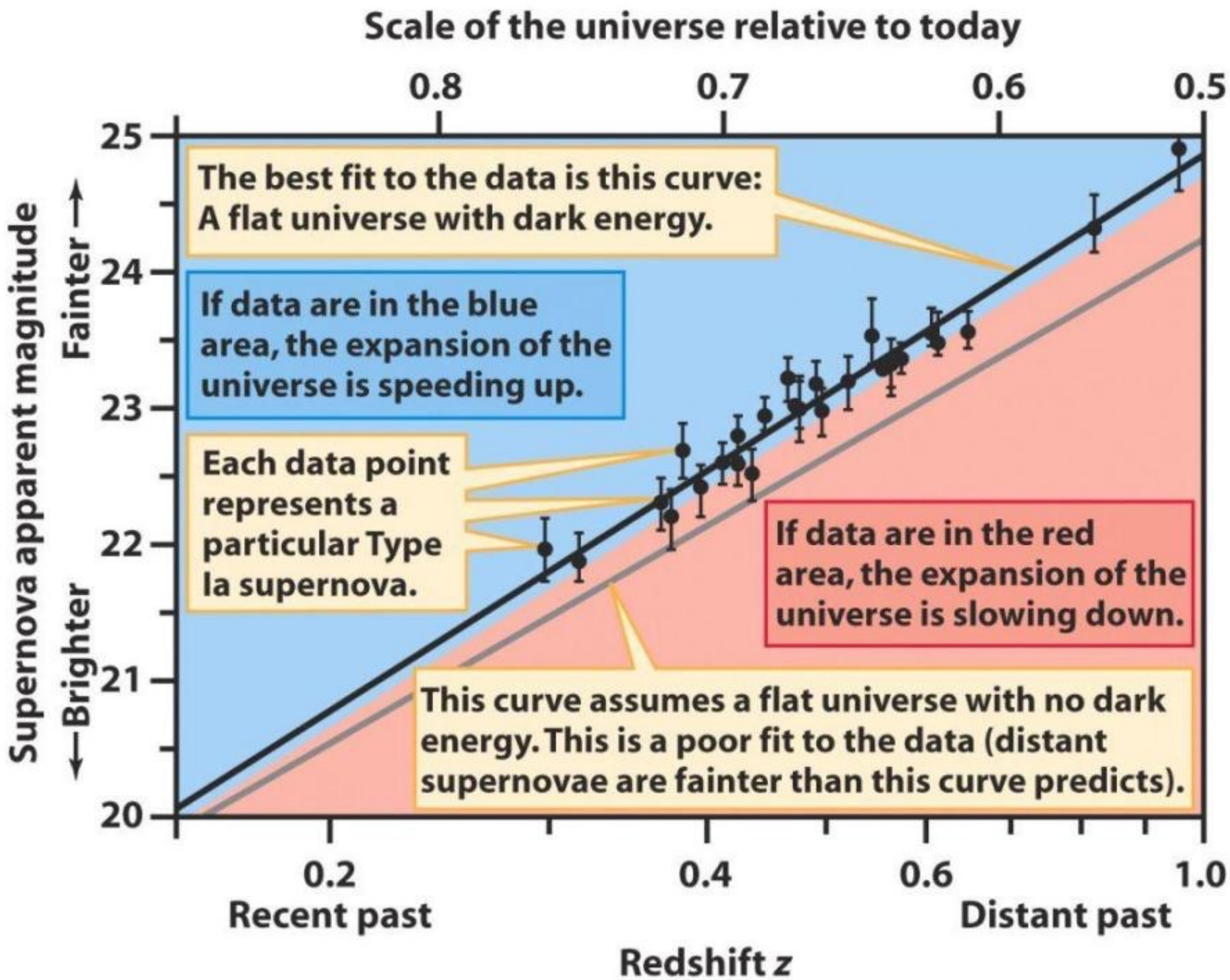


a If universe is closed, "hot spots" appear larger than actual size

b If universe is flat, "hot spots" appear actual size

c If universe is open, "hot spots" appear smaller than actual size

Apparent size of spots depends on curvature of space.



- Using SNe Ia as standard candles, we have found that the expansion of universe is speeding up.

Summary of problems with the Hot Big Bang model:

- Horizon problem
  - how could the CMB acquire a single temperature across the sky?
  - causality: how can structures in the CMB know about each other?

- Flatness problem
  - how could the density parameter be fine-tuned such that

$$\Omega_{tot} \sim 1$$

- The relic problem
  - where are all the magnetic monopoles predicted?

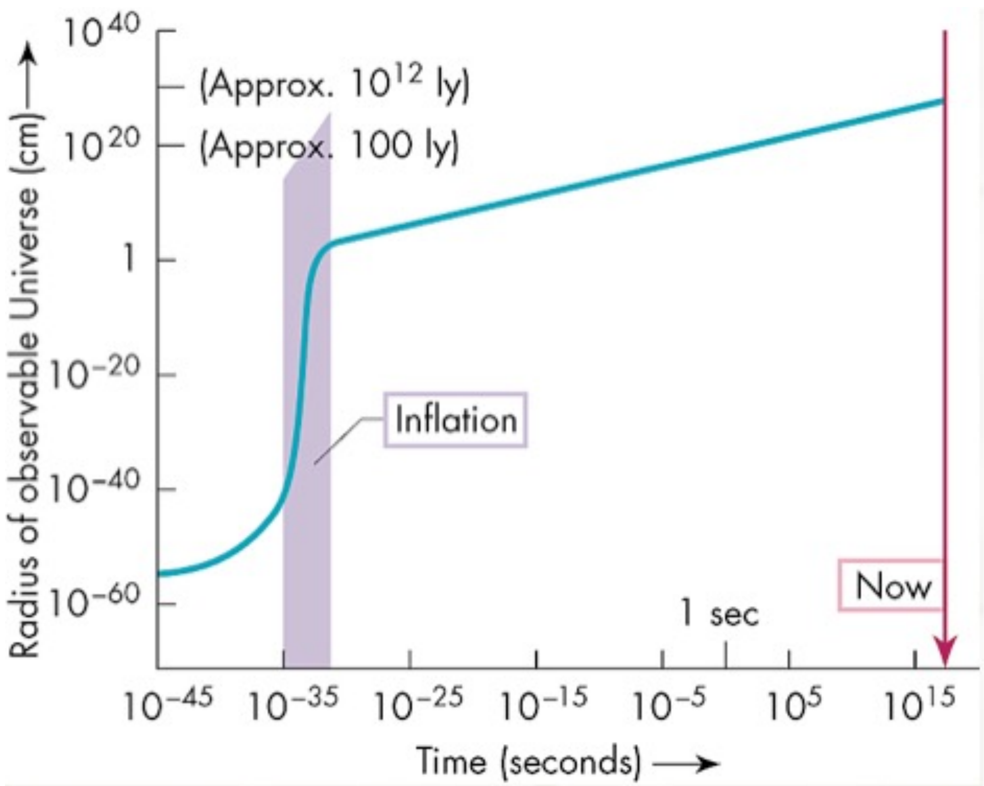
- Origin of structure
  - How could structure arise in this very smooth universe

In principle, the purpose of *inflation* is to create a large, flat, homogenous universe.

- Theory of cosmic inflation was first suggested by Alan Guth in 1982

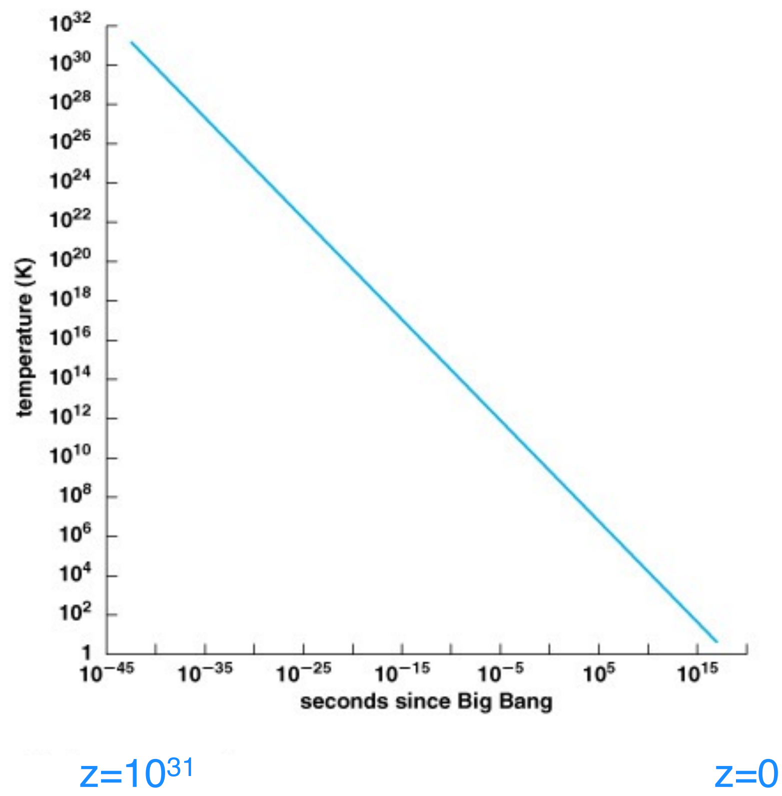
- He postulated an *inflationary epoch*
  - very rapid, exponential expansion of the universe
  - occurs during the first 10^{-37}-10^{-32} sec
  - During this time, the universe expanded by a factor of 10^{40}-10^{100}

- **Inflation and the radius of the observable universe**

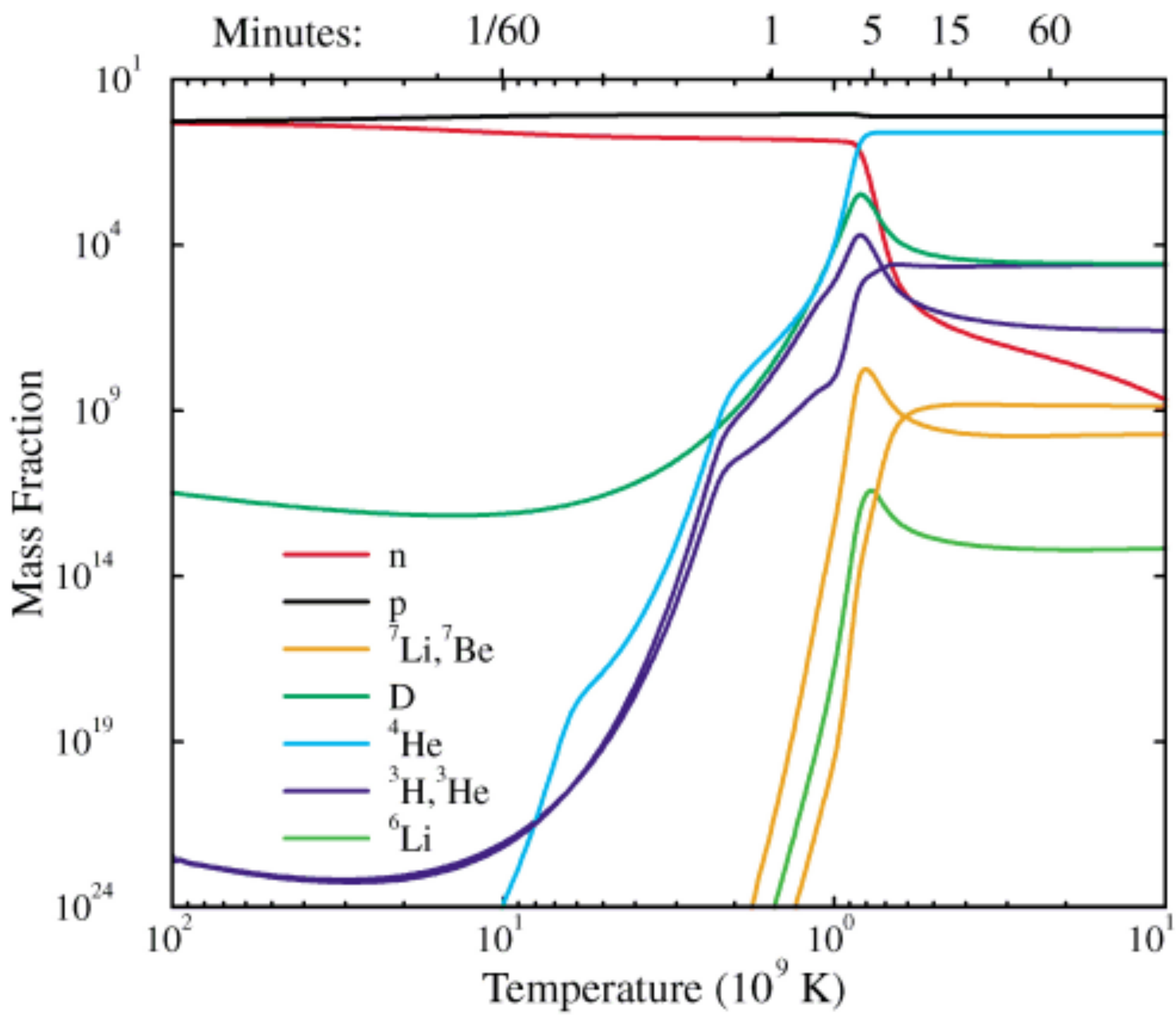


The Early Universe: conditions

- We know the the conditions & expansion rate of the universe today.
- If we run the expansion backwards we can predict the temperature & density of the Universe at anytime in its history using basic physics
  - we can study how matter behaves at high temperatures & densities in laboratory experiments
- Current experimental evidence provides information on conditions as early as 10^{-10} s after the Big Bang. Theories take us back to as little as as 10^{-43} s.



Big Bang Nucleosynthesis



Finally, relative abundances are sensitive to density of normal (baryonic matter)

Thus $\Omega_{b,0} \sim 4\%$. So our universe $\Omega_{total} \sim 1$ with 74% in Dark Energy, 26% in matter but only 4% baryonic!