Today

- Neutron stars & Black Holes

Homework 5 due in one week

Extra credit
(2 points)

- What supports a neutron star against gravity?

- Be sure to include your name and section number

- You may consult your notes, but do not communicate with anyone else

Neutron stars detected as pulsars

The radiation beams sweep through space like lighthouse beams as the neutron star rotates.

Why Pulsars Must Be Neutron Stars

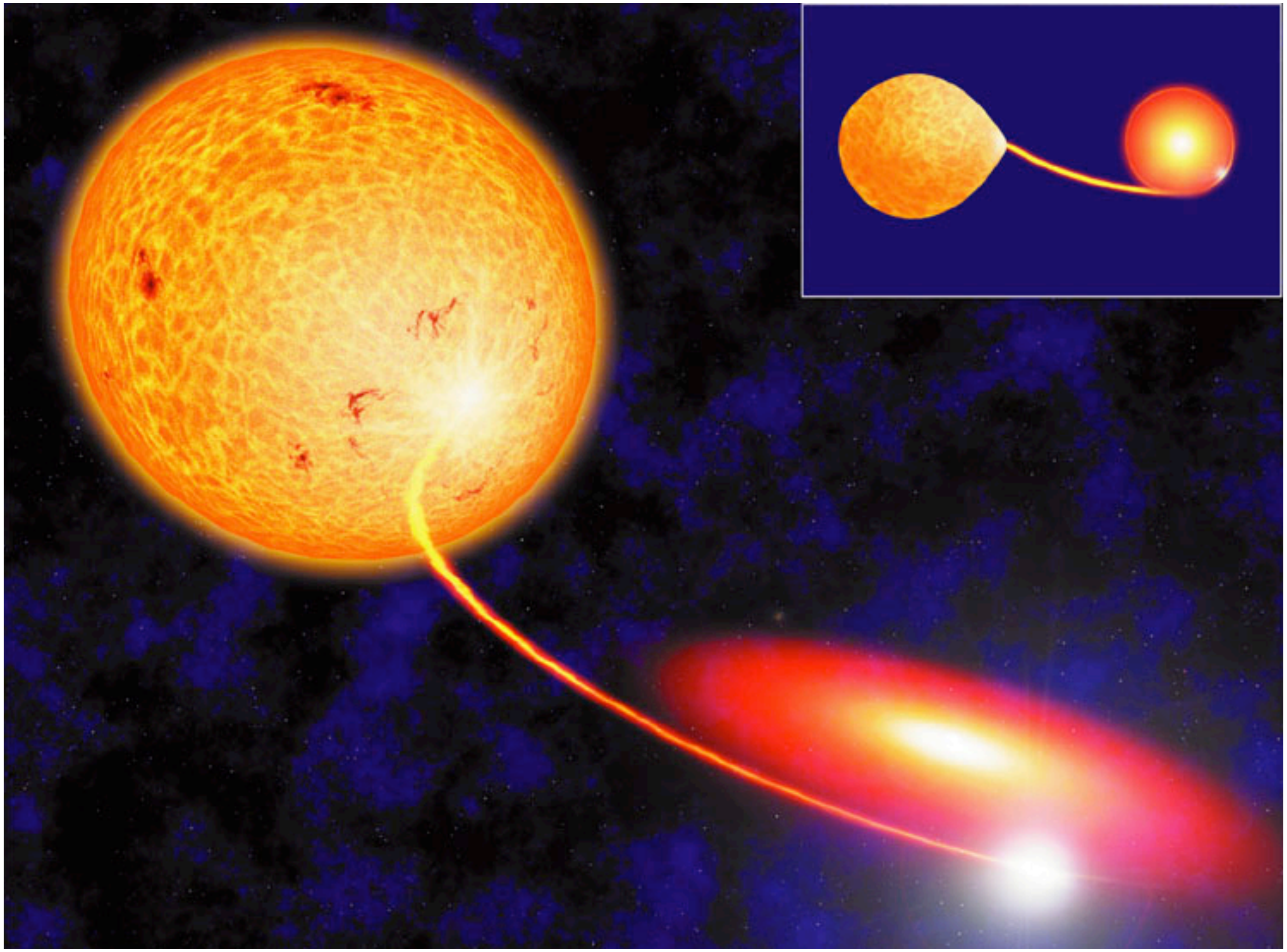
Circumference of Neutron Star = 2π (radius) ~ 60 km

Spin Rate of Fast Pulsars ~ 700 cycles per second

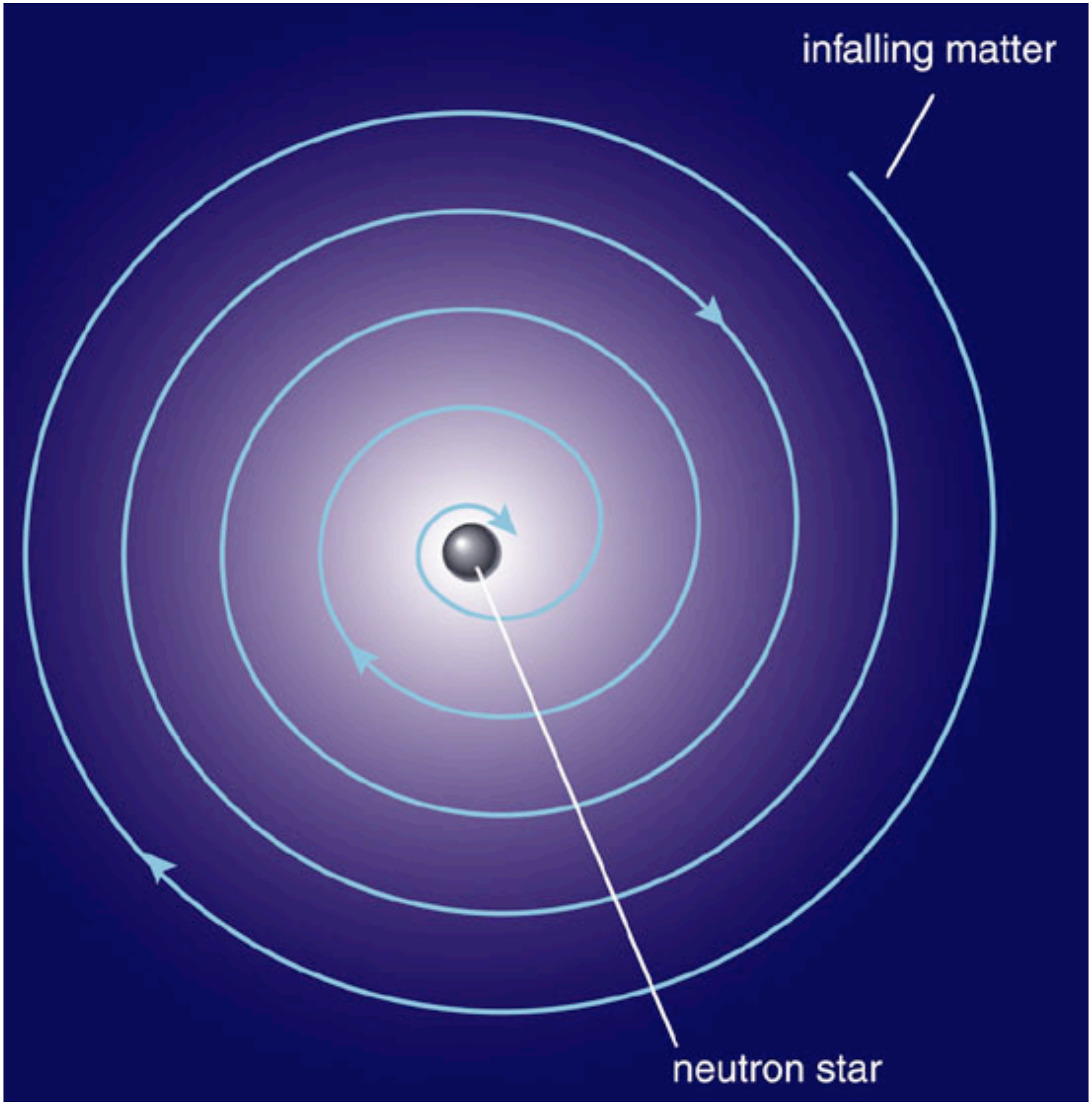
Surface Rotation Speed ~ 40,000 km/s
~ 13% speed of light
~ escape velocity from NS

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

Anything else would be torn to pieces!



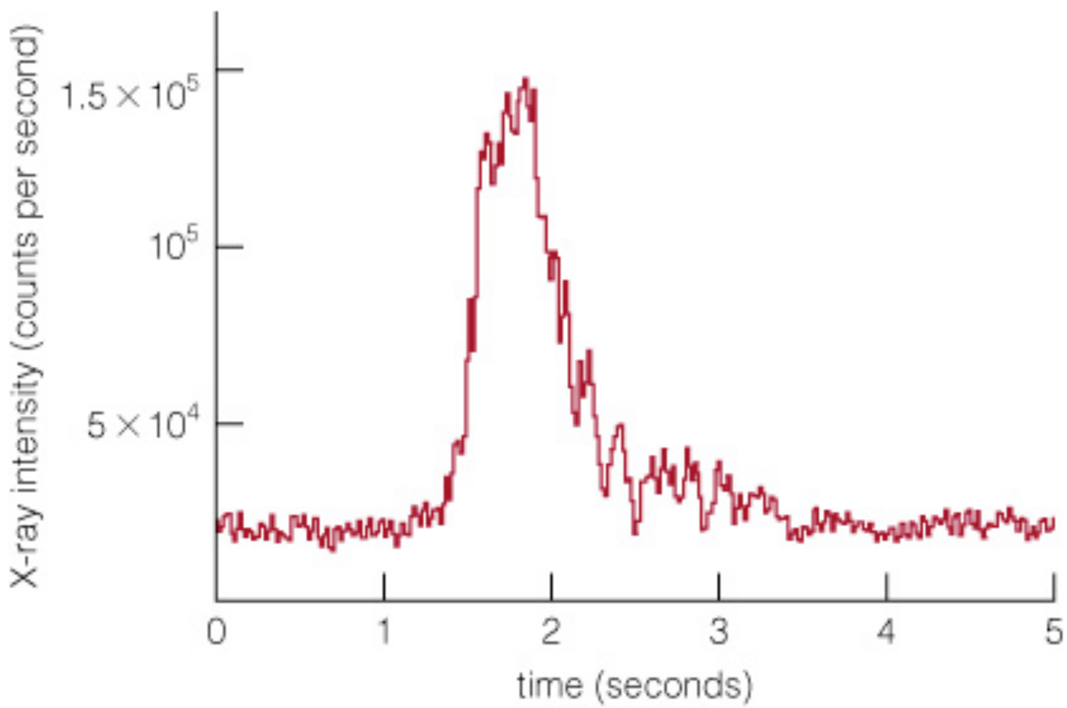
Matter falling toward a neutron star forms an accretion disk, just as in a white-dwarf binary.



Accreting matter adds angular momentum to a neutron star, increasing its spin.

Episodes of fusion on the surface lead to X-ray bursts.

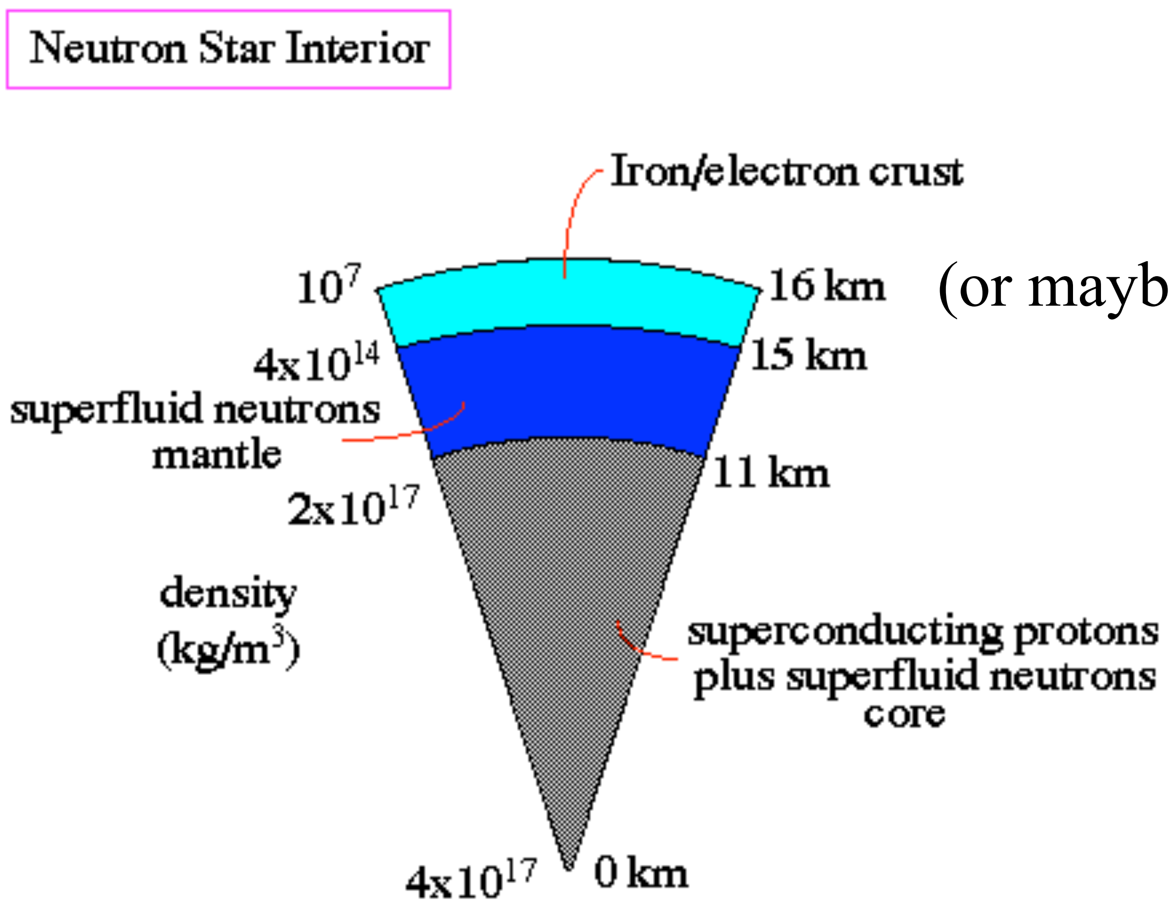
X-Ray Bursts



- Matter accreting onto a neutron star can eventually become hot enough for helium to fuse.
- The sudden onset of fusion produces a burst of X-rays.

Neutron Star Limit

- Neutron degeneracy pressure can no longer support a neutron star against gravity if its mass exceeds about 2-3 M_{Sun}.



(or maybe 10 km)

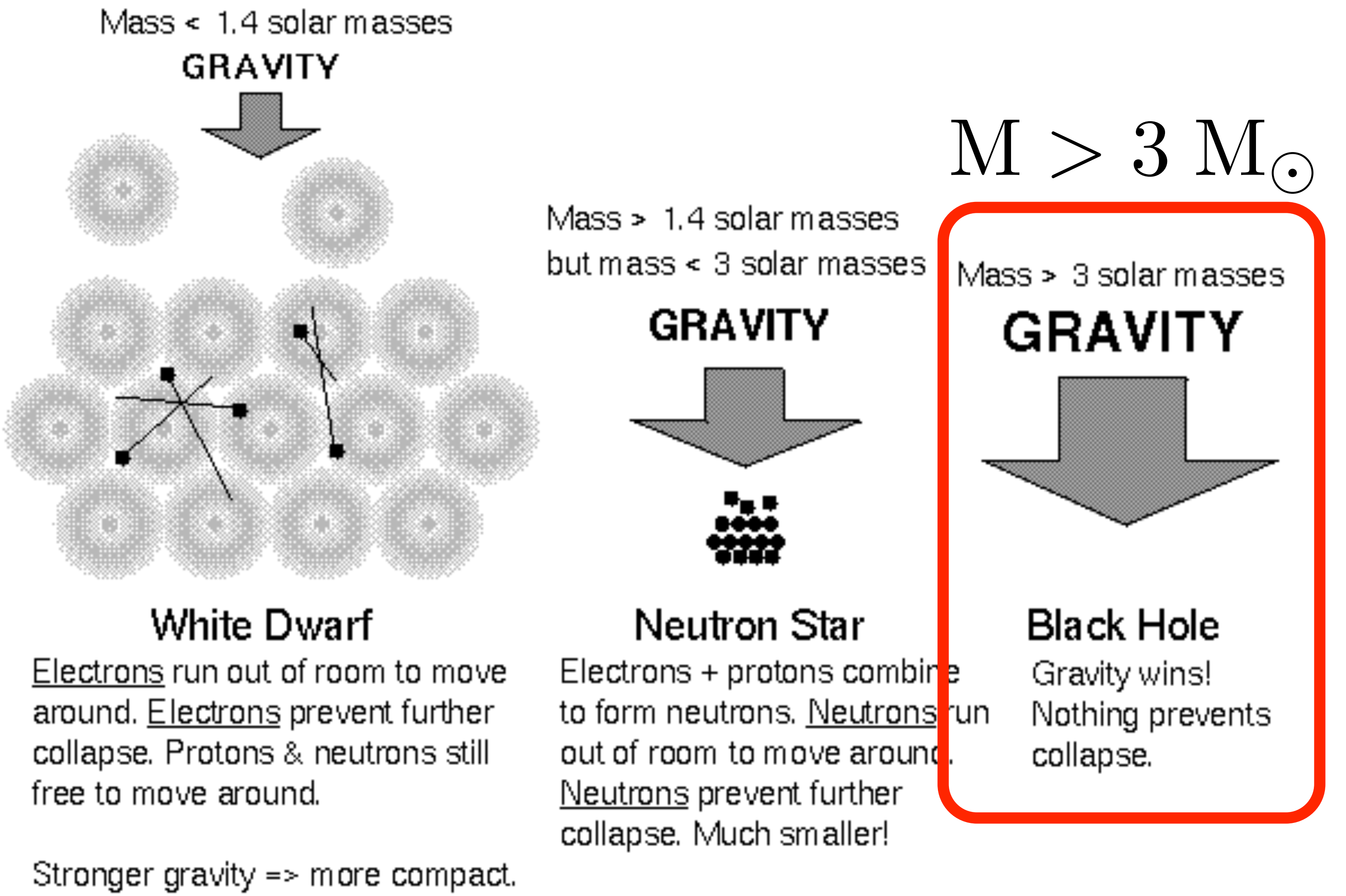
TBH

Black Holes

A ***black hole*** is an object whose gravity is so powerful that not even light can escape it.

Some massive star supernovae can make a black hole if enough mass falls onto the core.

$$M > 3\ M_{\odot}$$


Mass < 1.4 solar masses
GRAVITY
White Dwarf
Electrons run out of room to move around. Electrons prevent further collapse. Protons & neutrons still free to move around.
Stronger gravity => more compact.
Mass > 1.4 solar masses
but mass < 3 solar masses
GRAVITY
Neutron Star
Electrons + protons combine to form neutrons. Neutrons run out of room to move around. Neutrons prevent further collapse. Much smaller!
Mass > 3 solar masses
GRAVITY
Black Hole
Gravity wins! Nothing prevents collapse.

Escape Velocity

A black hole is an object so compact that its escape speed exceeds the speed of light.

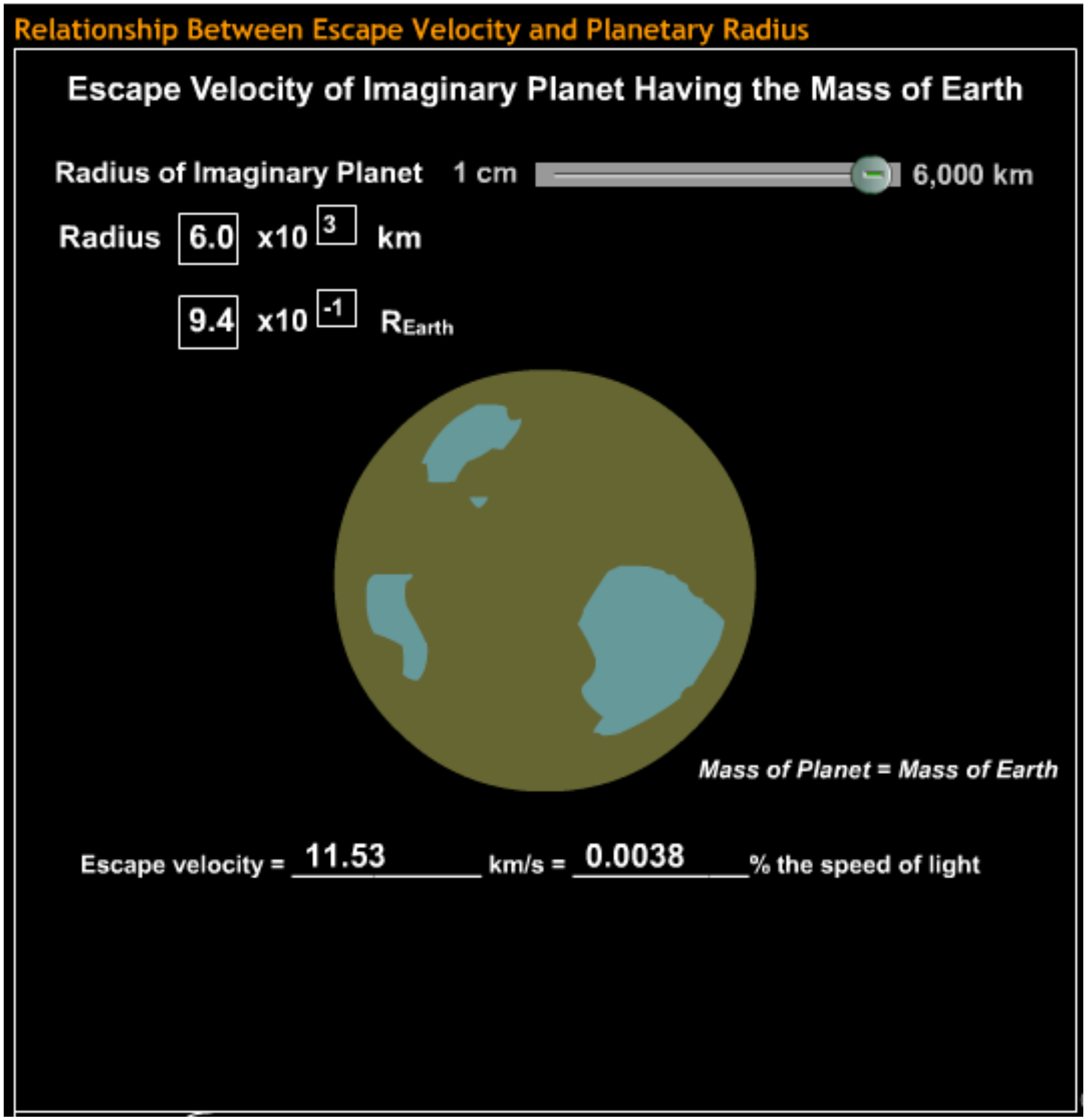
$$V_{esc} = \sqrt{\frac{2GM}{R}}$$

The key is size as much as mass.

$$V_{esc} = c$$

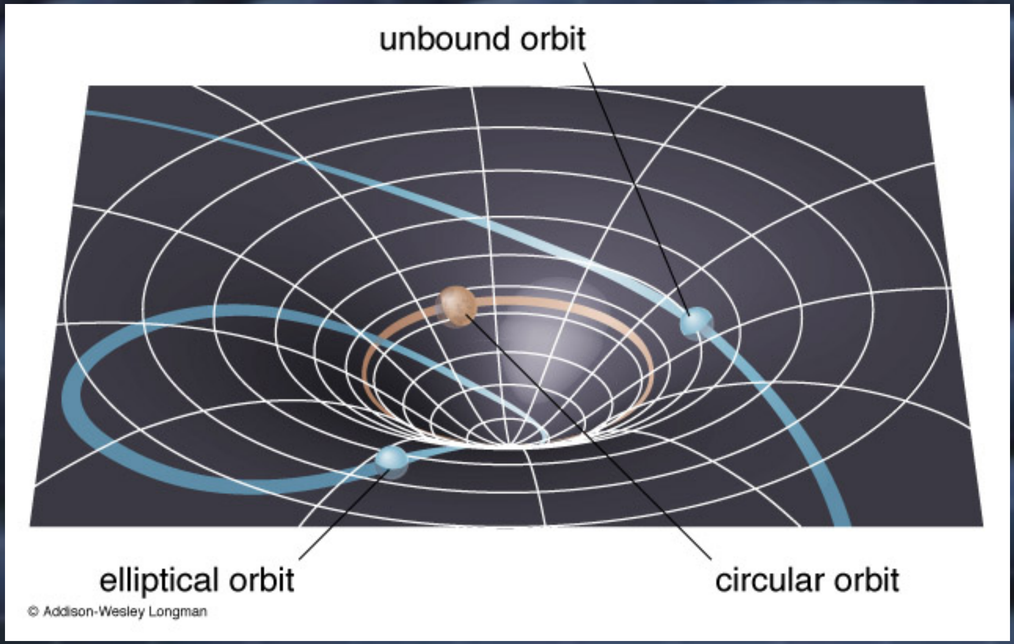
The "Event Horizon" is the radius of no return, from which even light cannot escape.

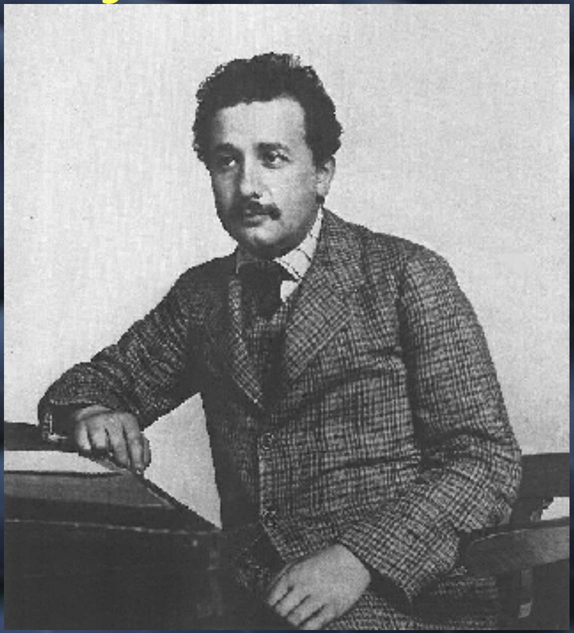
$$R_{EH} = \frac{2GM}{c^2}$$



Light would not be able to escape Earth's surface if you could shrink it to <1 cm.

General Relativity

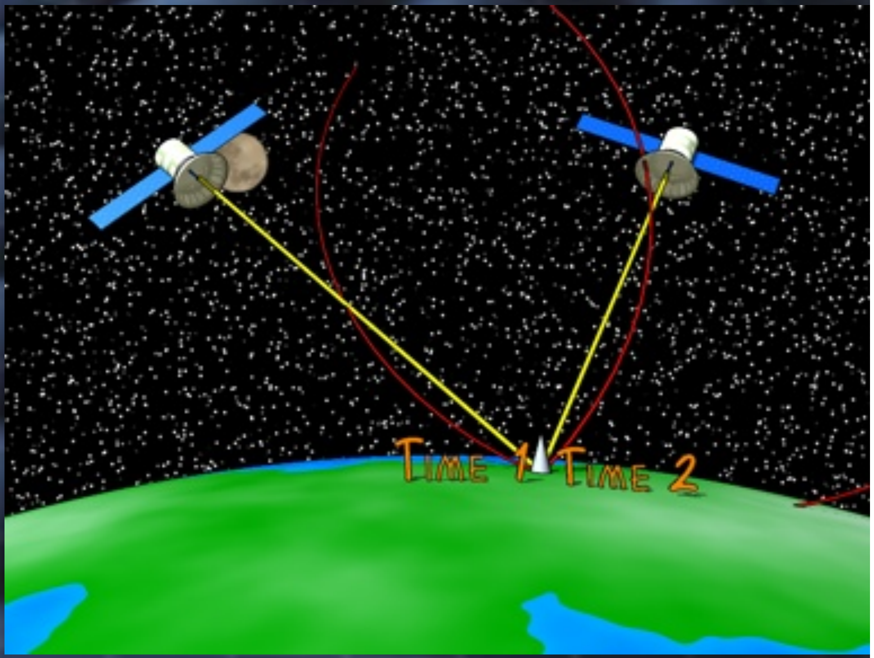




- Einstein's theory of gravity (1915)
- Free-fall is the "natural" state of motion
- Space+time (spacetime) is warped by gravity
- Reduces to Newton's laws in weak gravity

Practical Effects of GR?

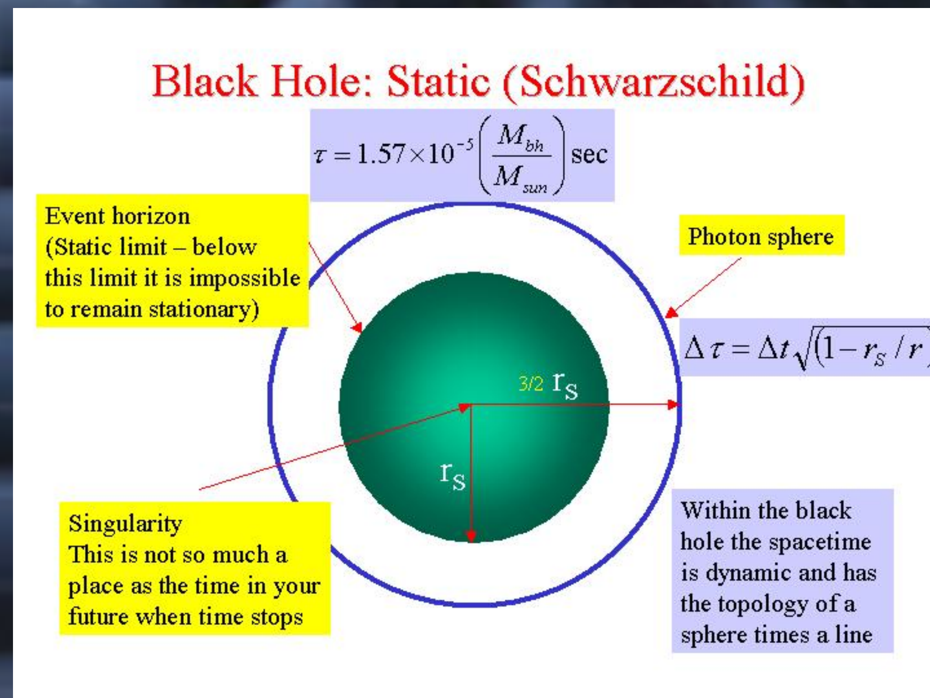
- Global positioning system
- Must account for GR time dilation effect
- Otherwise, would drift rapidly out of alignment
- You never know the benefits of research!



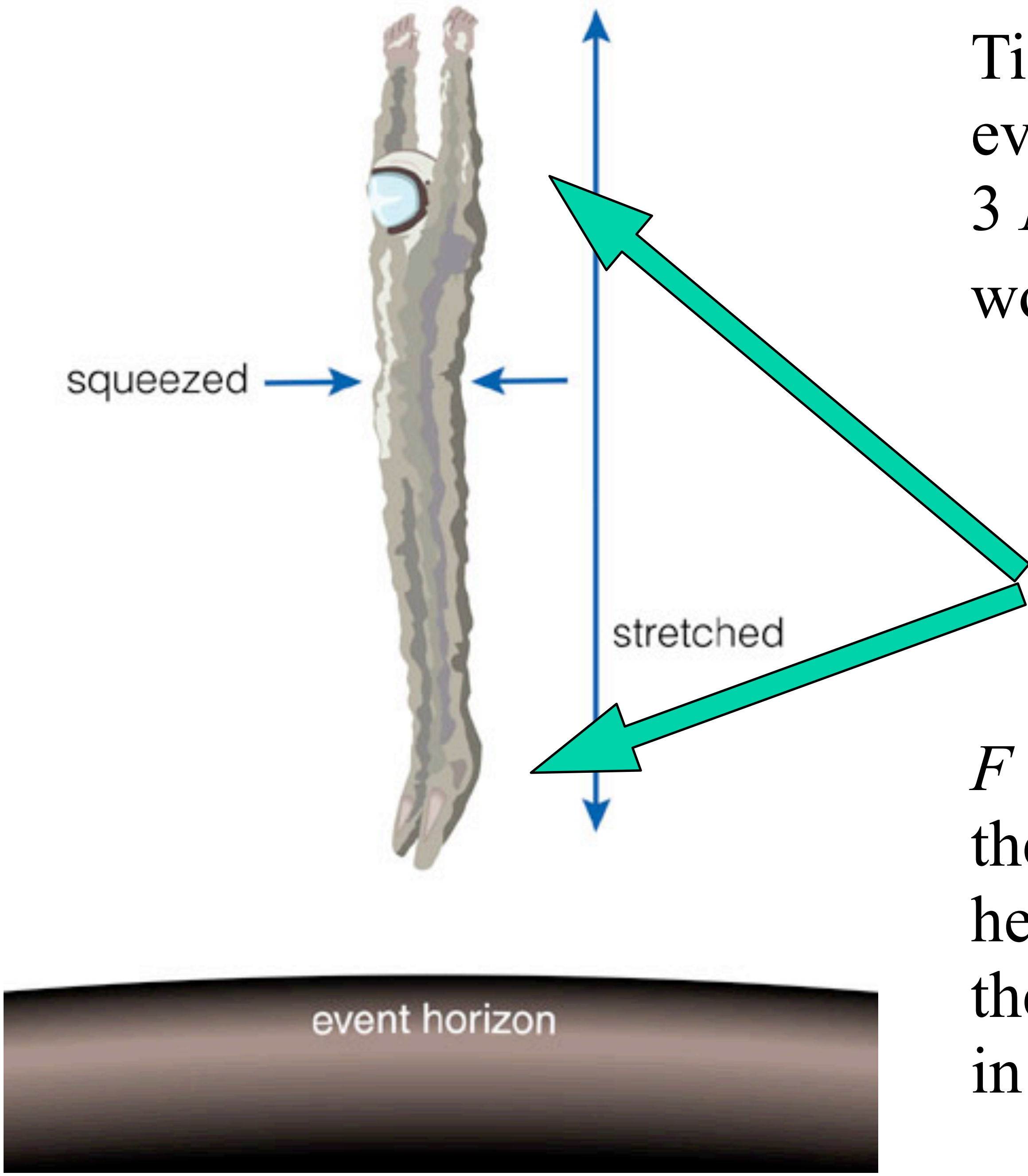
http://www.whylearnthat.co.uk/GPSPic.jpg

Black Holes

- John Michell, 1783: would most massive things be dark?
- Modern view based on general relativity
- Event horizon: point of no return
- Near BH, strong distortions of spacetime



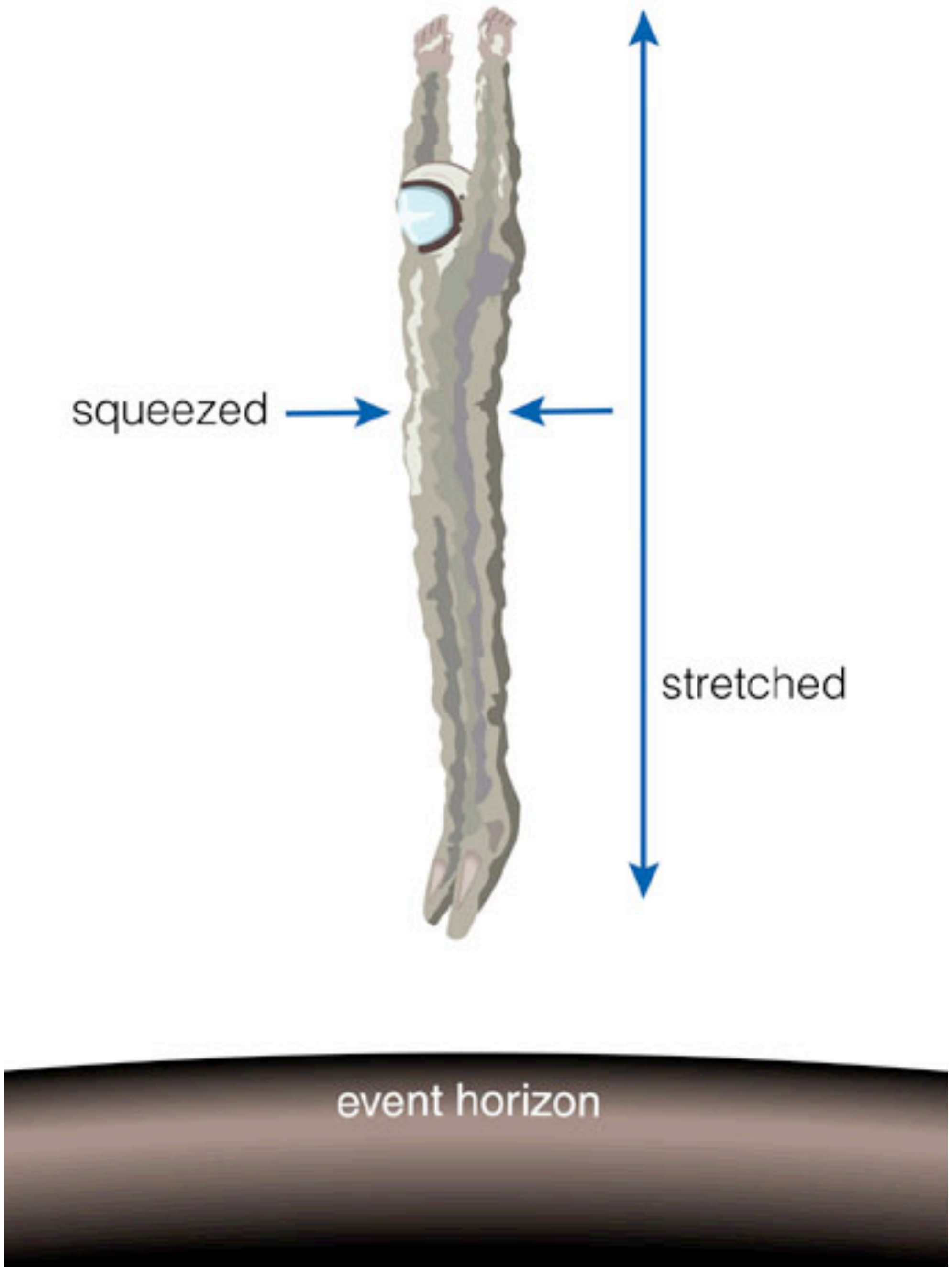
Simplest big things in the universe!
But not large: R=3 km (M/M_{sun})



Tidal forces near the event horizon of a 3 M_{Sun} black hole would be lethal.

$$F = \frac{GMm}{r^2}$$

F much stronger on the feet than on the head just because of the small difference in r.



Tidal forces near the event horizon of a $3\ M_{\text{Sun}}$ black hole would be lethal.

Tidal forces would be gentler near a supermassive black hole because its radius is much bigger.

“Spaghettification”

Gravitational Light Deflection

DW

BH Effect at a Distance

My boy Lord Voldemort turns our Sun into a black hole with the same mass as the Sun. What happens to the Earth as a result?

A. The Earth is flung out into space

B. The Earth is sucked into the BH, confirming LV's evil

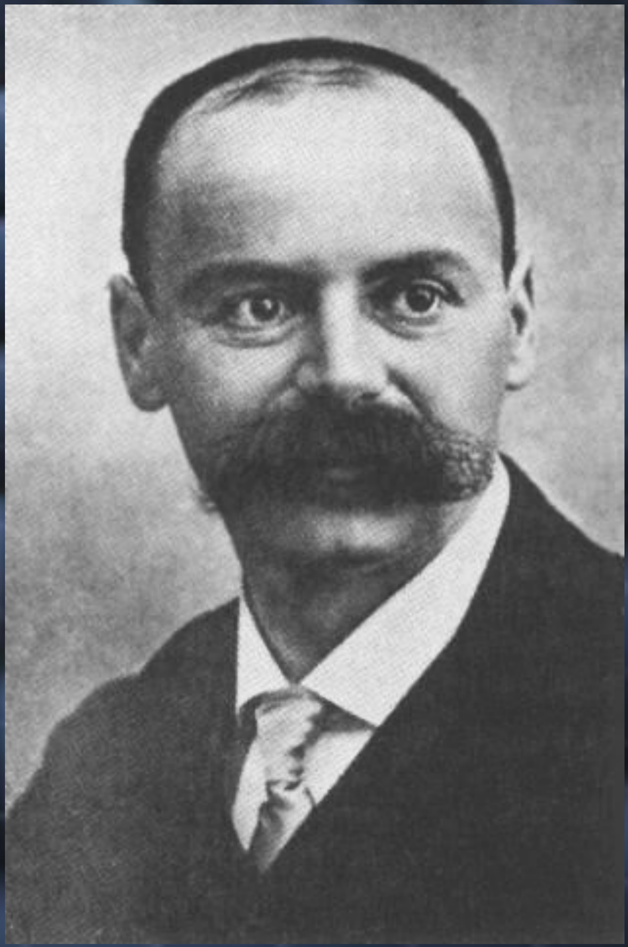
C. The Earth's orbit is unchanged

D. The Earth is destroyed by radiation

E. I don't know

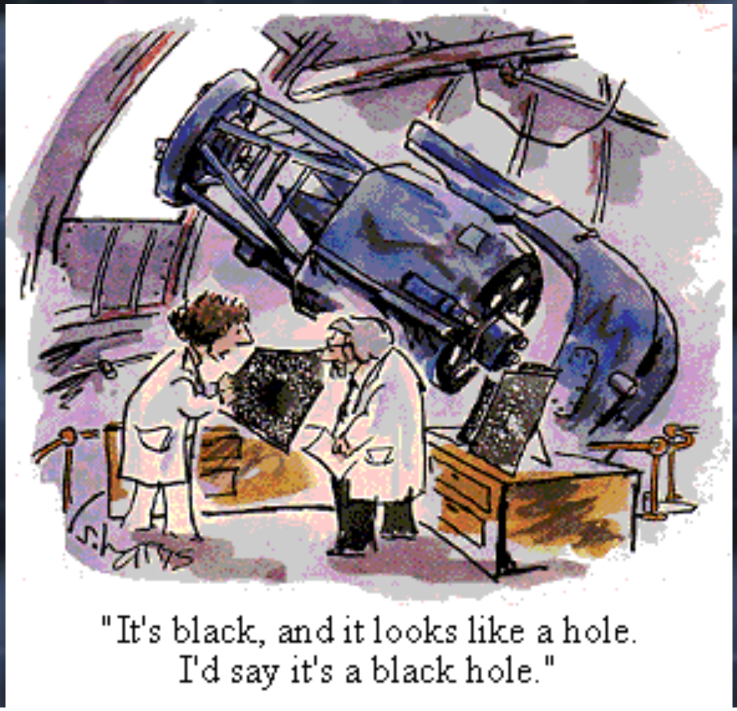
But Do Black Holes Exist?

- First hint was solution of Einstein's equations by Karl Schwarzschild in 1916
  From Russian front in WW I
- But do BH actually exist? How would we detect them?



Detecting Black Holes

- Problem: what goes down doesn’t come back up
- Seems like they would be invisible...



How Do We Detect BH?

- By their effects on other things!
- Could see star (or stars) orbiting around something that we can’t see
- Or, rapidly spiraling gas that is therefore hot
- But do we actually see these things?

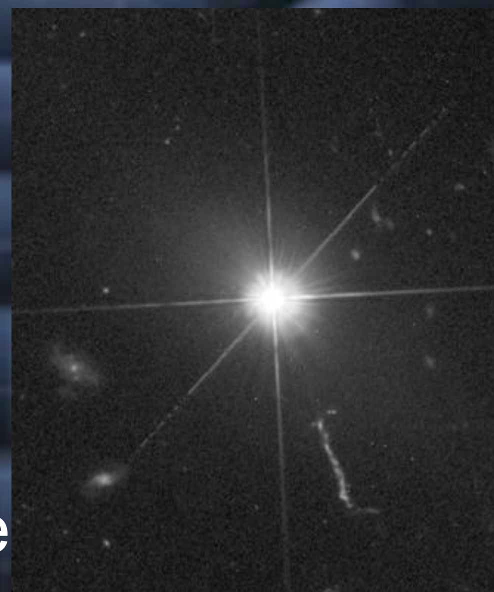
BH video

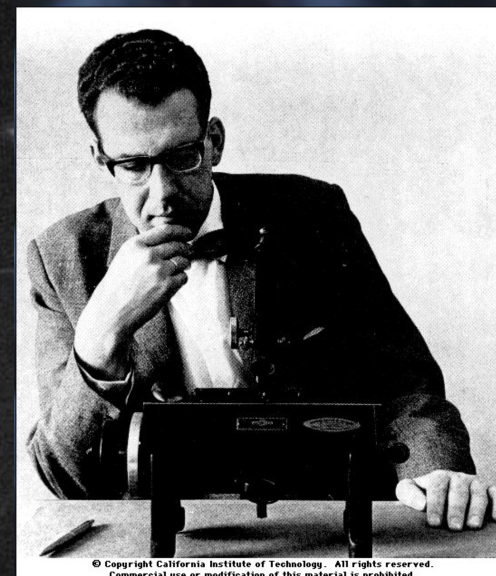
Stellar-Mass Black Holes

- First example: Cyg X-1
- Now >20 definite cases
  Mass 3-30 M_{sun}
- Still a small number!
  Hundreds of billions of stars in our galaxy
- Probable number of BH in our galaxy: >100 million
- Most stellar-mass BH are quiet!

Quasars

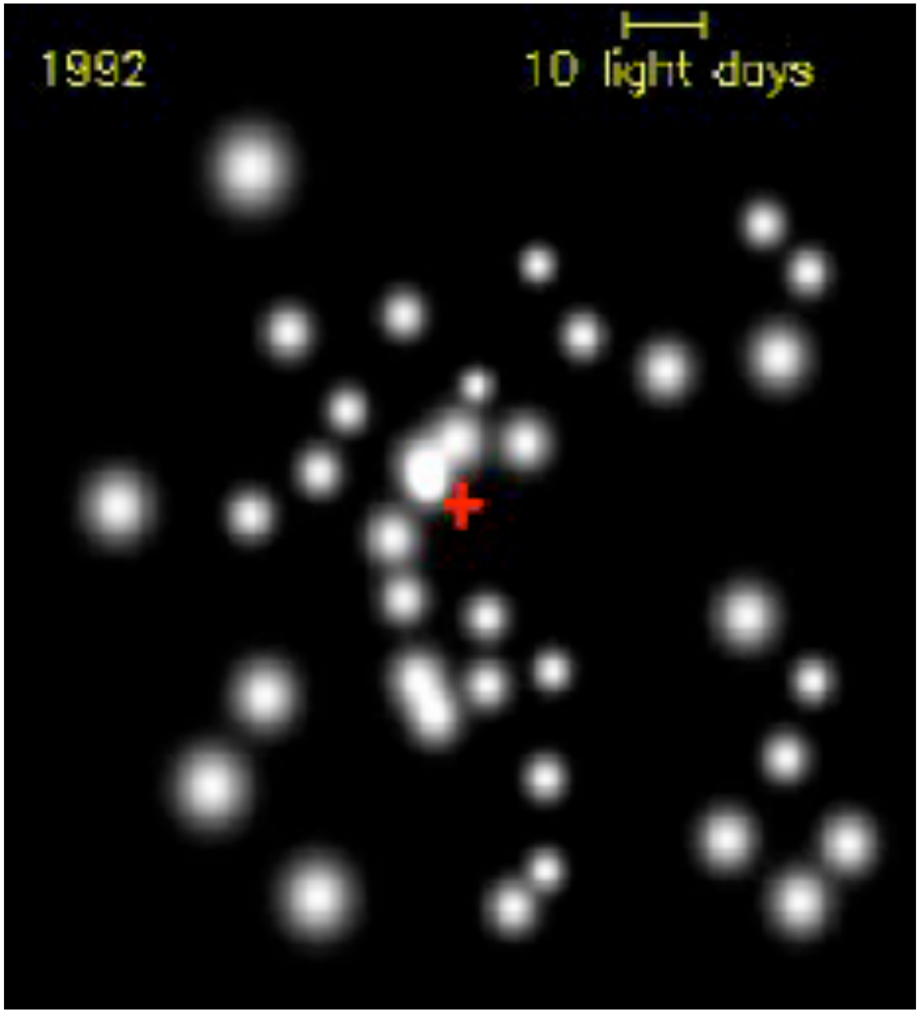
- Quasi-stellar (i.e., pointlike) sources
  Smaller than Solar System, brighter than galaxies!
- Strange spectra
- In 1963, Maarten Schmidt realized these are extremely distant
- Powered by $10^{6\text{-}10}$ M_{sun} supermassive BH!
  Gas spirals in, heats up





NOTE: no light comes from BH itself, just orbiting gas heated up by friction

Stars at the Galactic Center



From Reinhard Genzel's group

Black Holes Critical in Galaxy, Star Formation

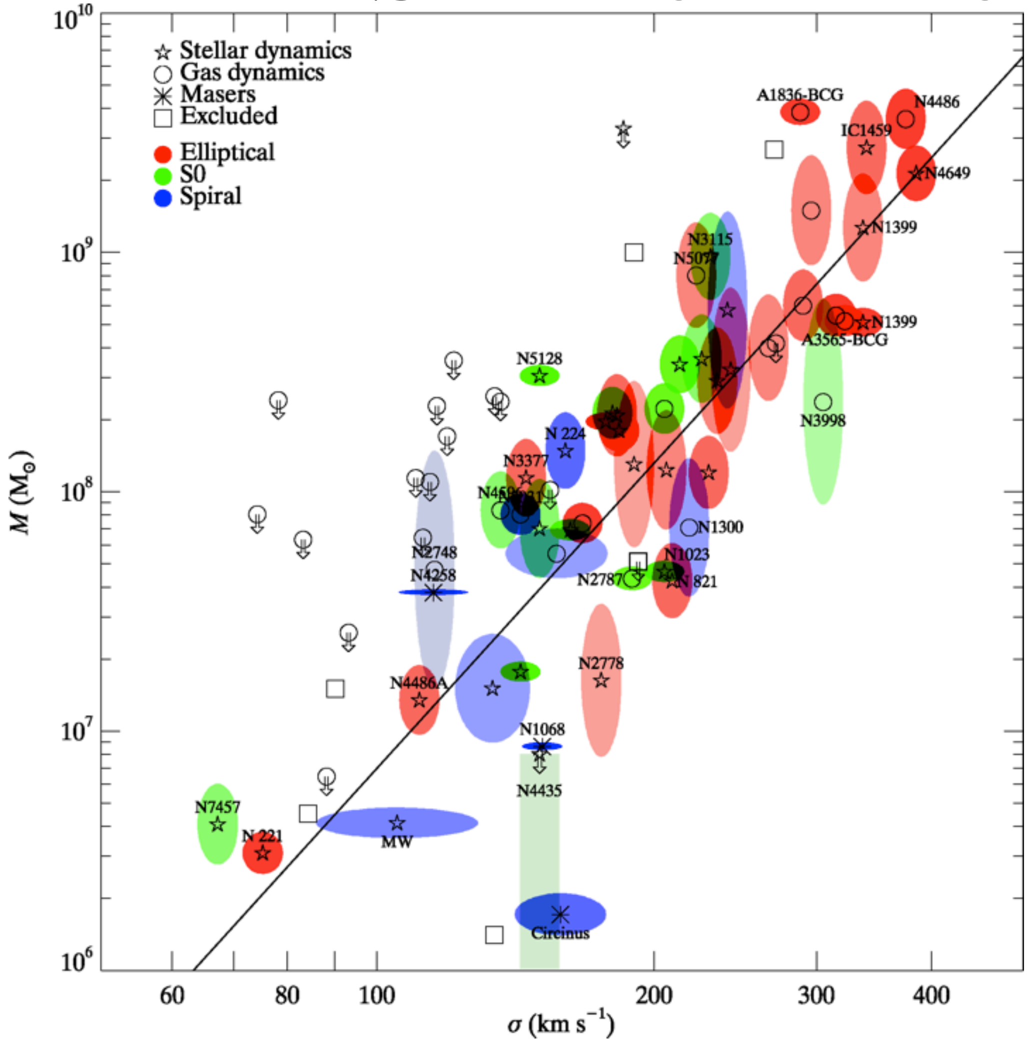
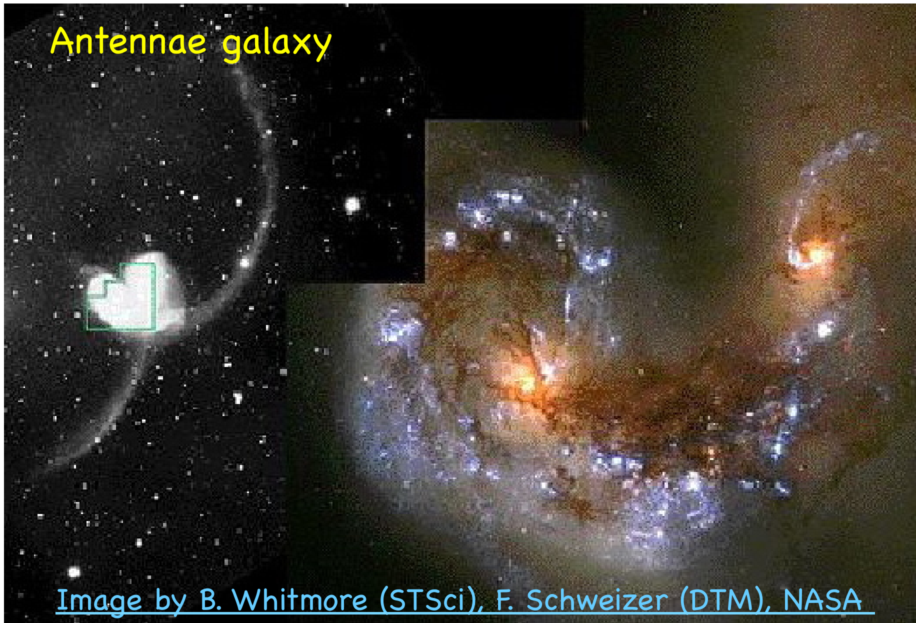
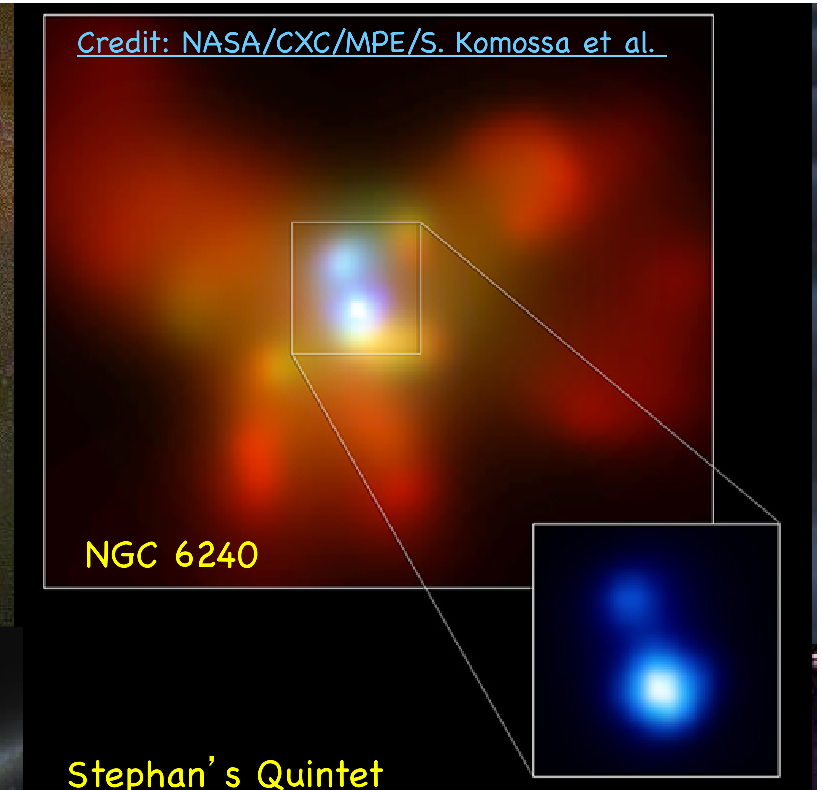


Figure produced by my former student Kayhan Gultekin


Antennae galaxy
Image by B. Whitmore (STScI), F. Schweizer (DTM), NASA


Credit: NASA/CXC/MPE/S. Komossa et al.
NGC 6240

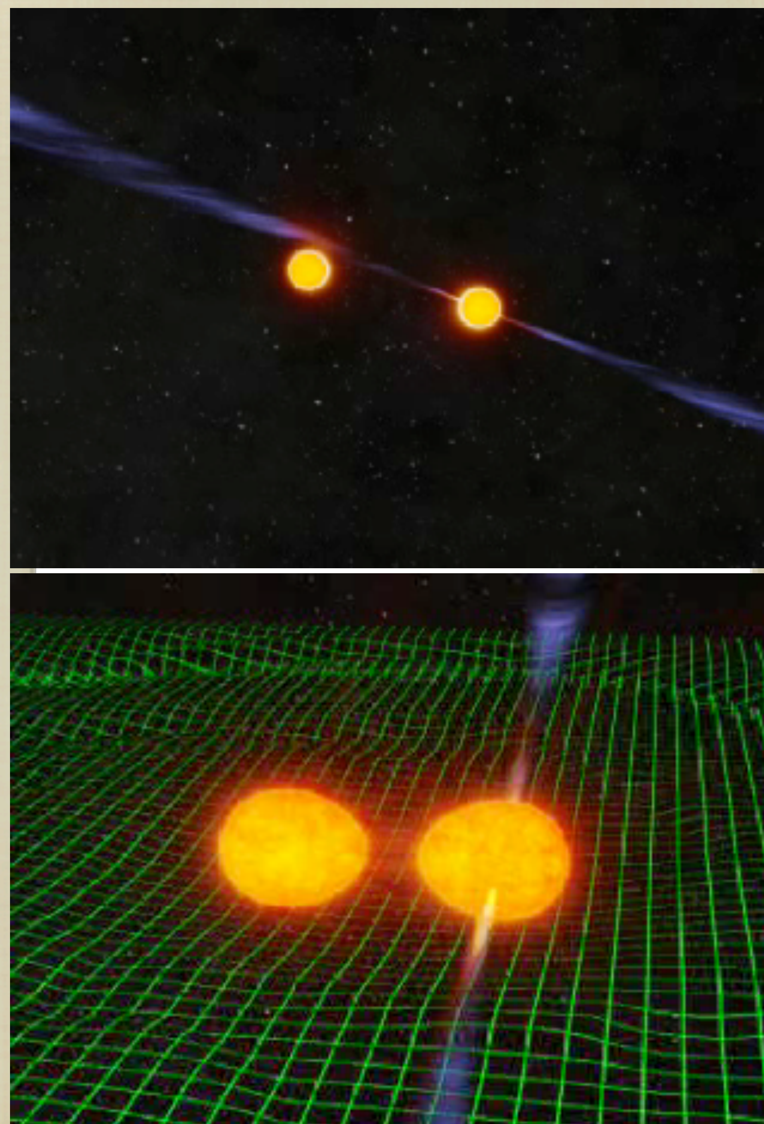

Mice galaxy
Credit: NASA/ESA-ACS Science Team


Stephan's Quintet
Credit: NASA/JPL-Caltech/Max-Planck Institute/SSC

NGC 6240: Galaxy With Two BH

Gravitational Waves

John Rowe Animation



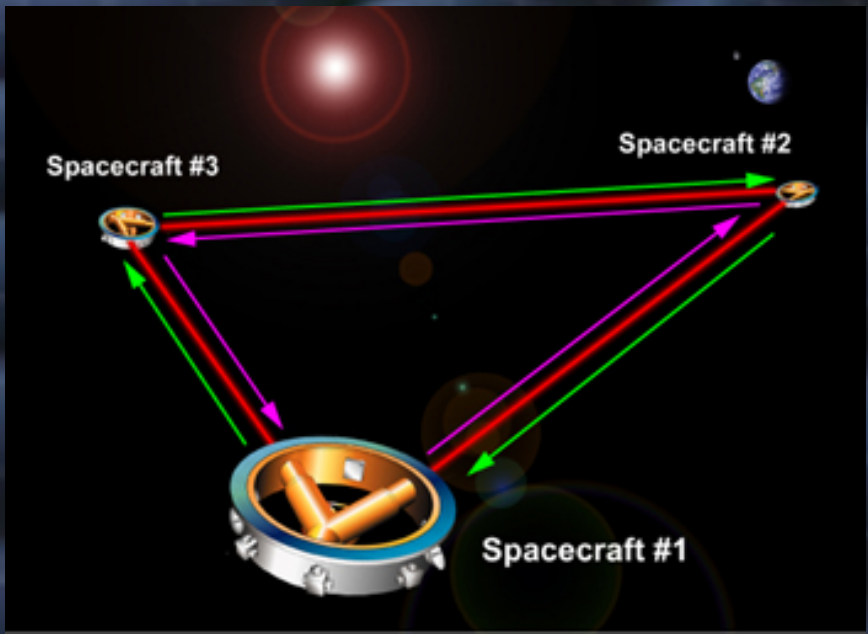
- Back to rubber sheet
- Moving objects produce ripples in spacetime
- E.g., close binary black hole or neutron star
- Very weak!
- How can we detect these?

Gravitational Wave Detectors

LIGO

Program Advisory Committee

LISA

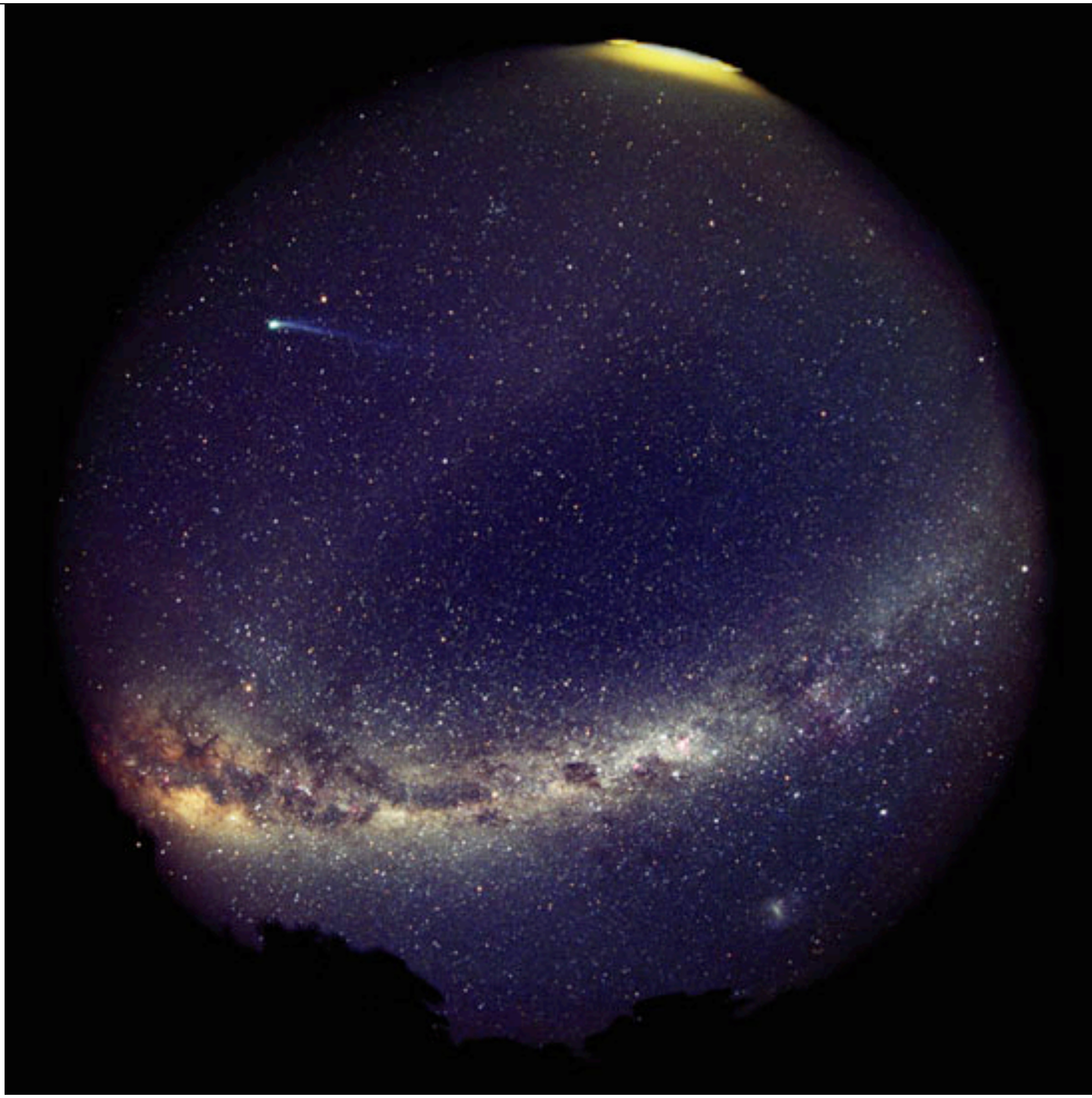


Science Team

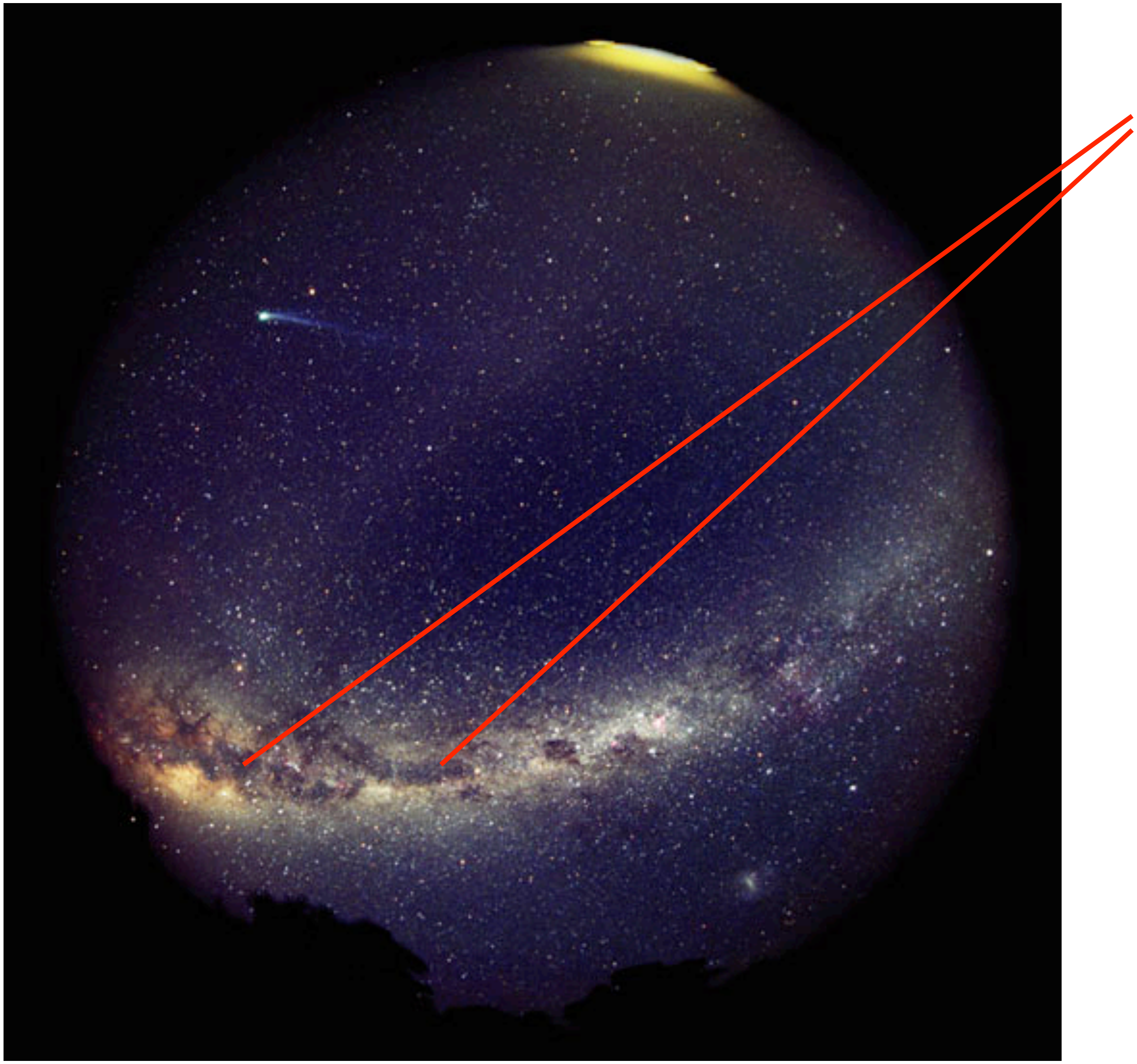
What Lies Ahead

- The field of black holes involves physics, astrophysics, astronomy, and computation
- Detections of gravitational waves with LIGO expected in less than a decade
- In space: LISA, focusing on bigger BH
  Assembly of structure in early universe?
  New window on cosmology

Our Galaxy - the Milky Way



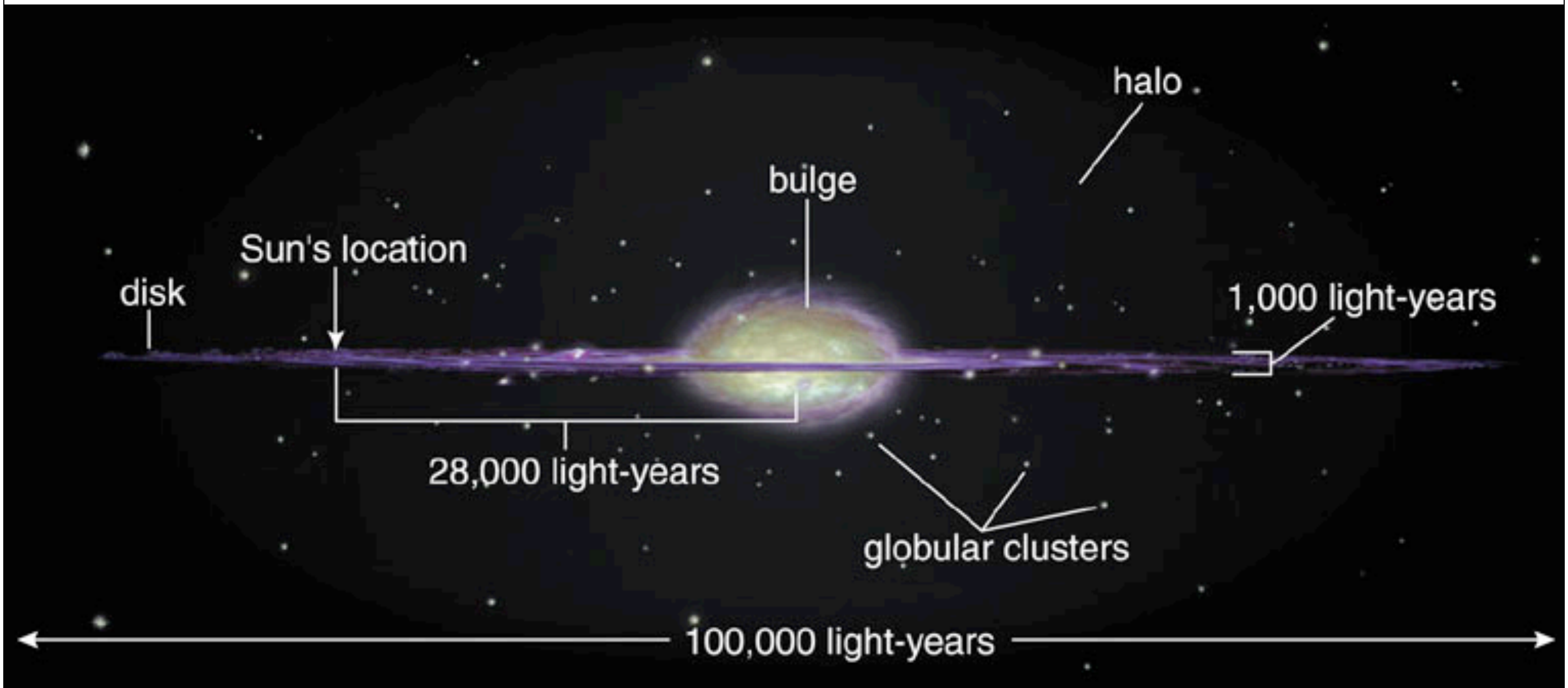
The Milky Way galaxy appears in our sky as a faint band of light - the light from many unresolved stars.



Dusty gas clouds obscure our view because they absorb visible light.

This is the ***interstellar medium*** that makes new star systems.

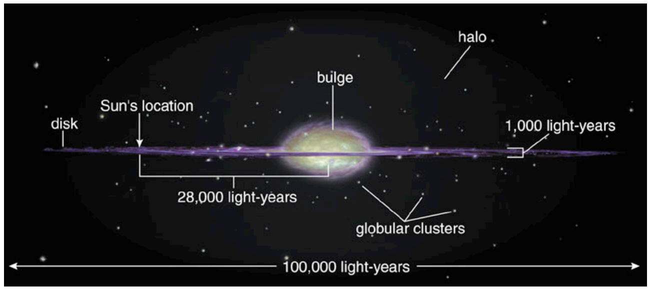
Milky Way schematic, seen edge-on

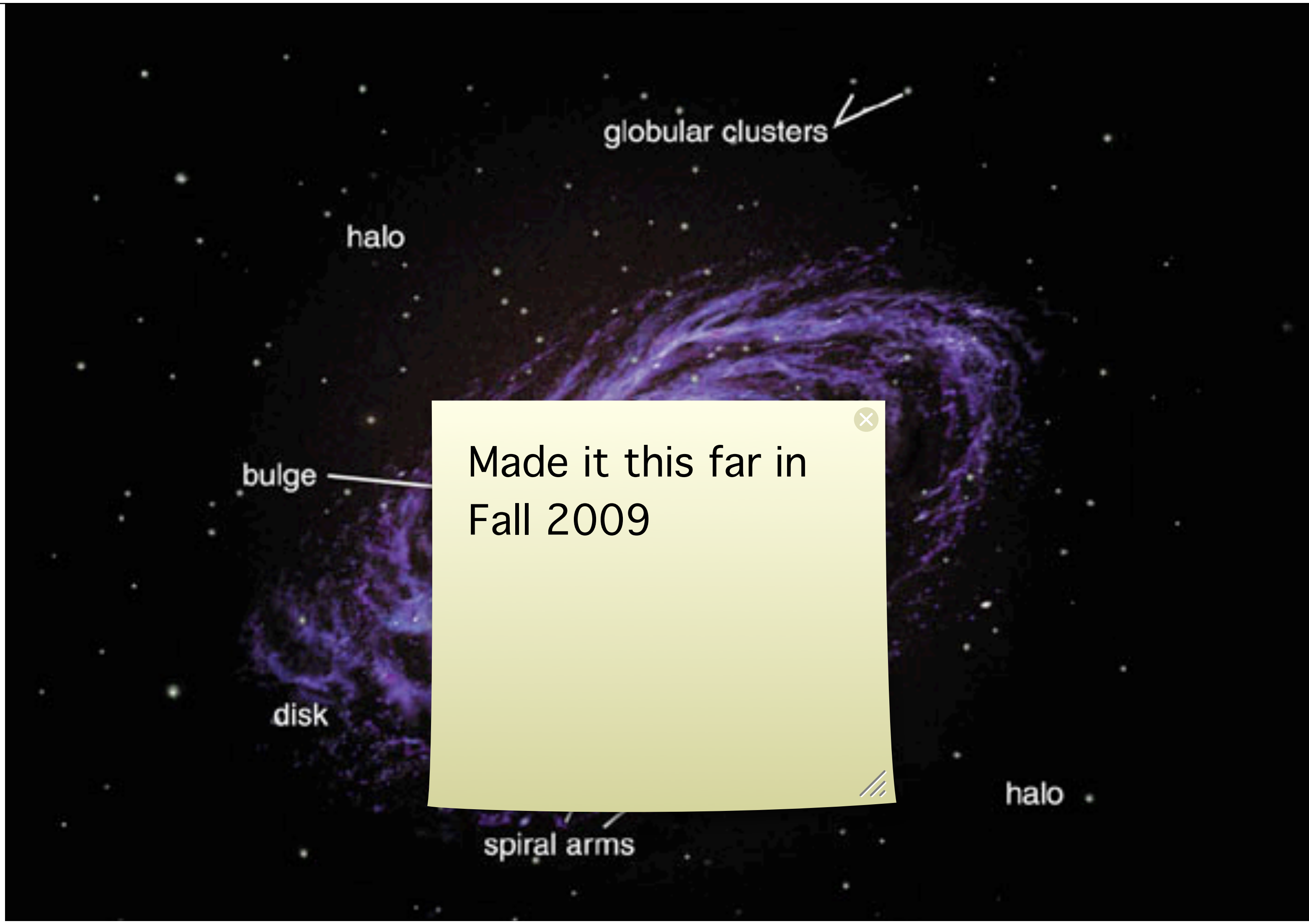


Primary features: disk, bulge, halo.
Globular clusters are part of the halo.
The sun (like most stars) is in the disk.

Galactic Structure

- Stars
  - DISK - individual stars; open clusters
  - BULGE - individual stars; globular clusters
- Gas (mostly in disk)
  - atomic gas ("H I")
  - molecular gas (H_2, CO, many other molecules)
  - hot, ionized gas ("H II")
- Dust (mostly in disk)
  - between stars
  - mostly in spiral arms & molecular clouds



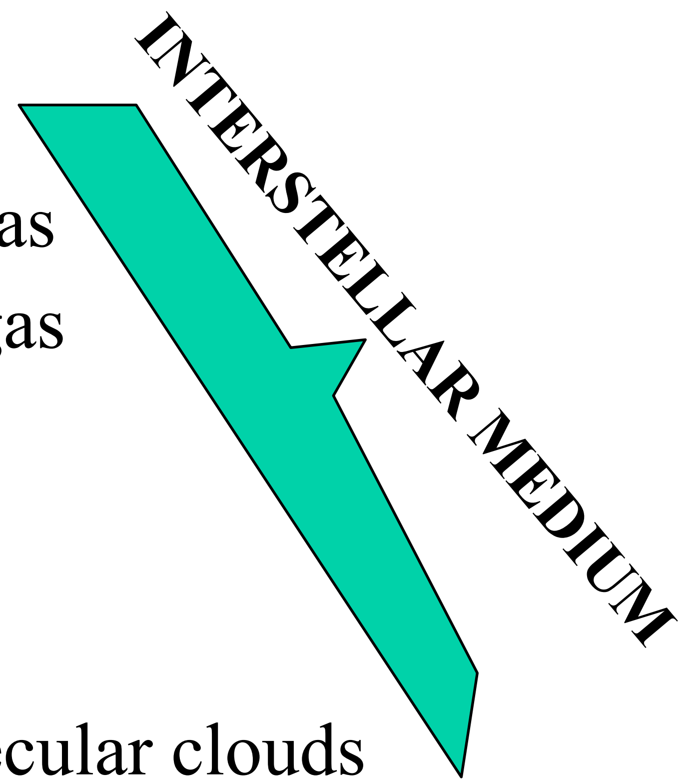


If we could view the Milky Way from above the disk, we would see its spiral arms.

14_01ViewSpiralGalx

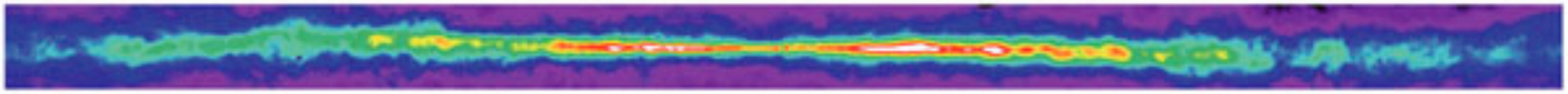
Galactic Structure

- Stars ~80% of mass
  - DISK ~80% of stars
  - BULGE ~20% of stars
- Gas ~20% of mass
  - atomic gas ("H I") ~2/3 of gas
  - molecular gas (H_2) ~1/3 of gas
  - hot, ionized gas ("H II")
- Dust
  - between stars
  - mostly in spiral arms & molecular clouds



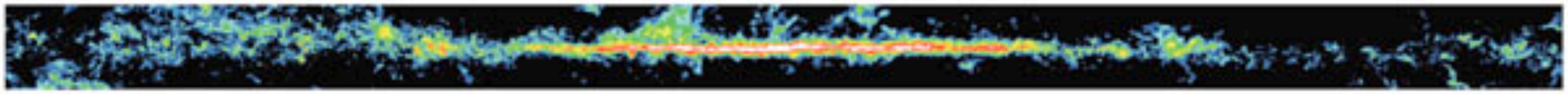
Multi-wavelength Milky Way

radio (21 cm)
HI gas



a 21-cm radio emission from atomic hydrogen gas.

radio (CO)
molecular gas



b Radio emission from carbon monoxide reveals molecular clouds.

far-IR
dust

c Infrared (60–100 μm) emission from interstellar dust.

near-IR
stars

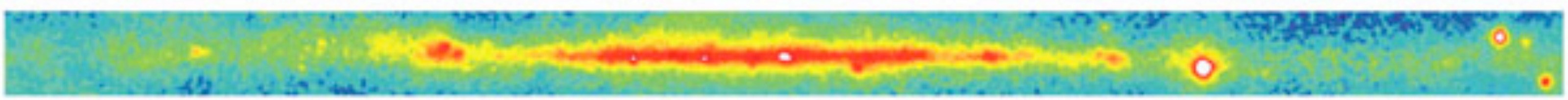
d Infrared (1–4 μm) emission from stars that penetrates most interstellar material.

Optical
stars & dust

e Visible light emitted by stars is scattered and absorbed by dust.

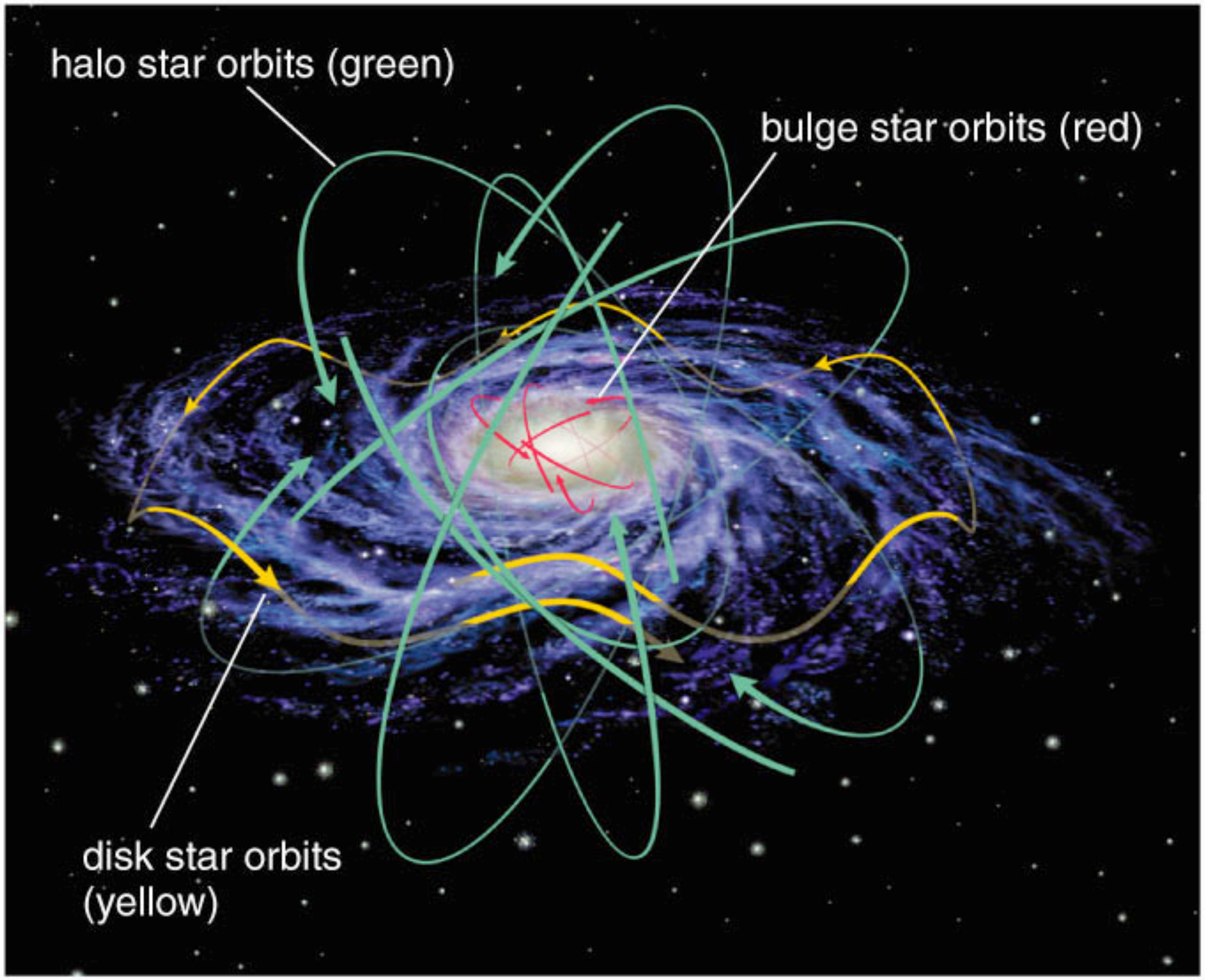
X-ray
hot gas

f X-ray emission from hot gas bubbles (diffuse blobs) and X-ray binaries (pointlike sources).



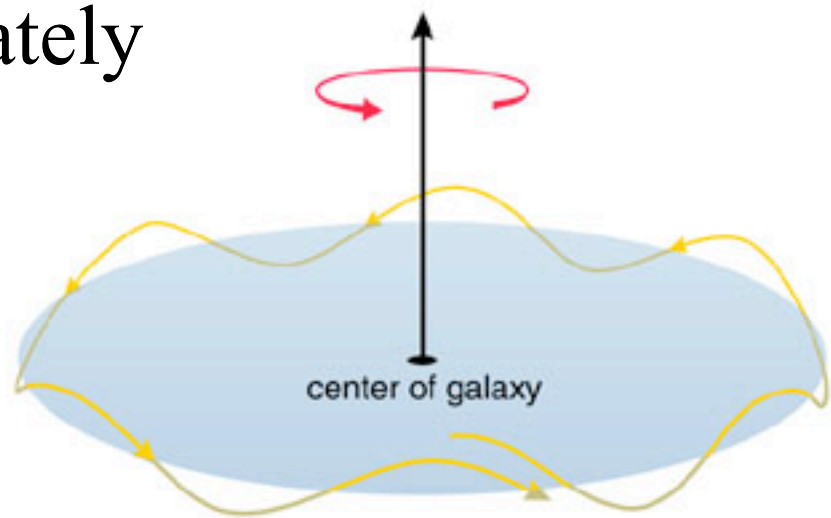
g Gamma-ray emission from collisions of cosmic rays with atomic nuclei in interstellar clouds.

Stellar orbits

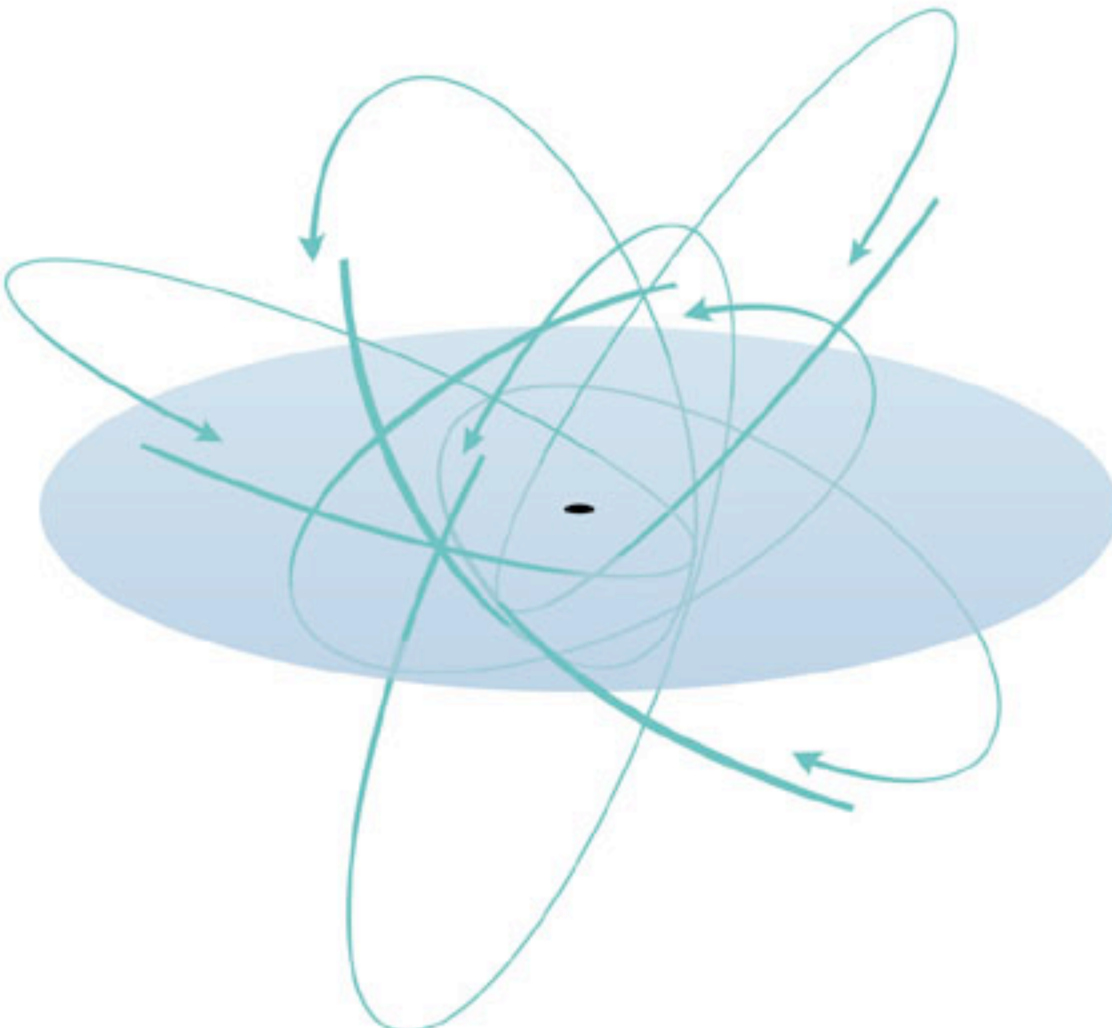


Disk

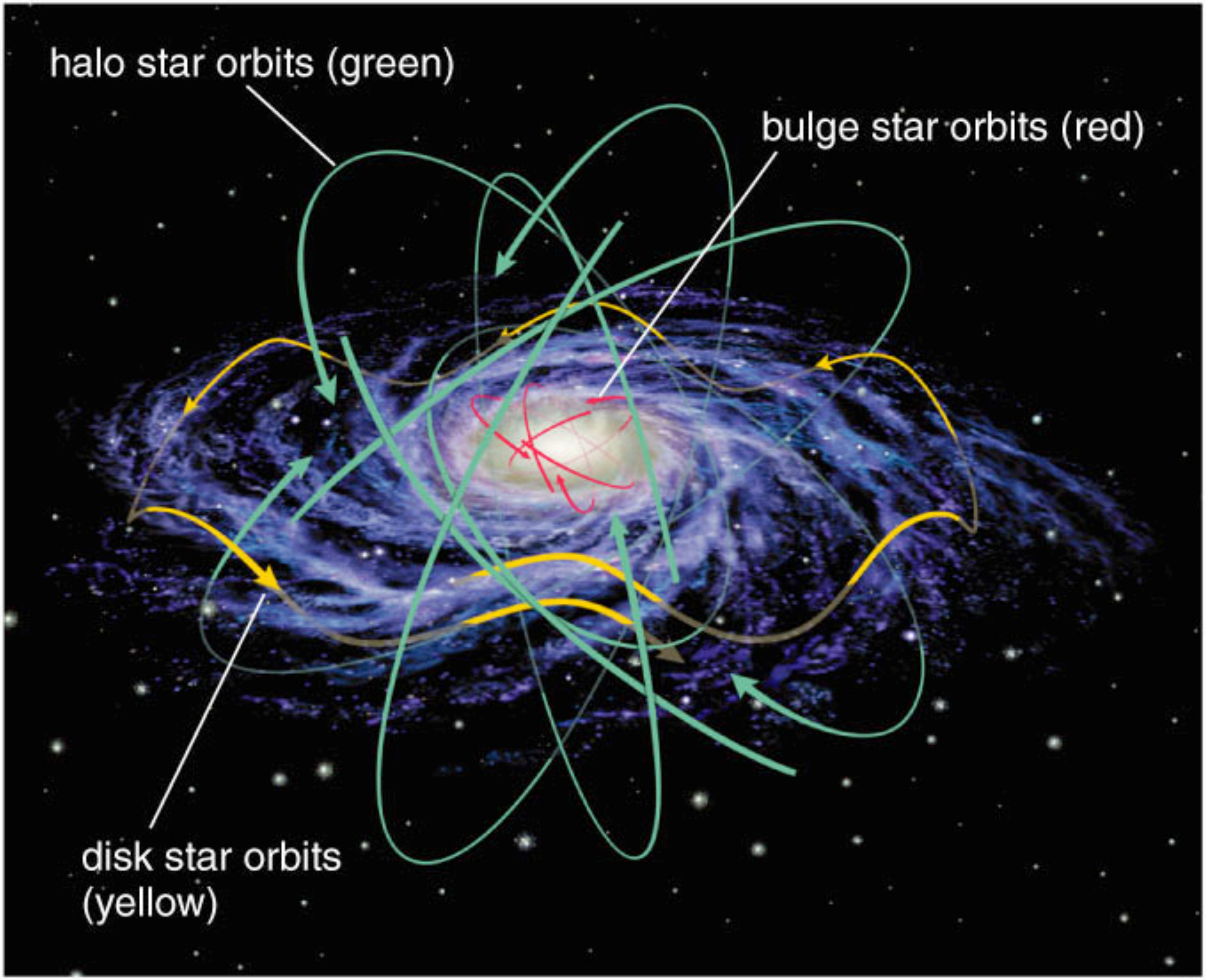
- Most stars are in the disk (2D)
- Disk stars have approximately circular orbits
- Disk stars orbit in same direction
- Individual stars oscillate slightly in the vertical direction (perpendicular to the disk), giving the disk a finite thickness

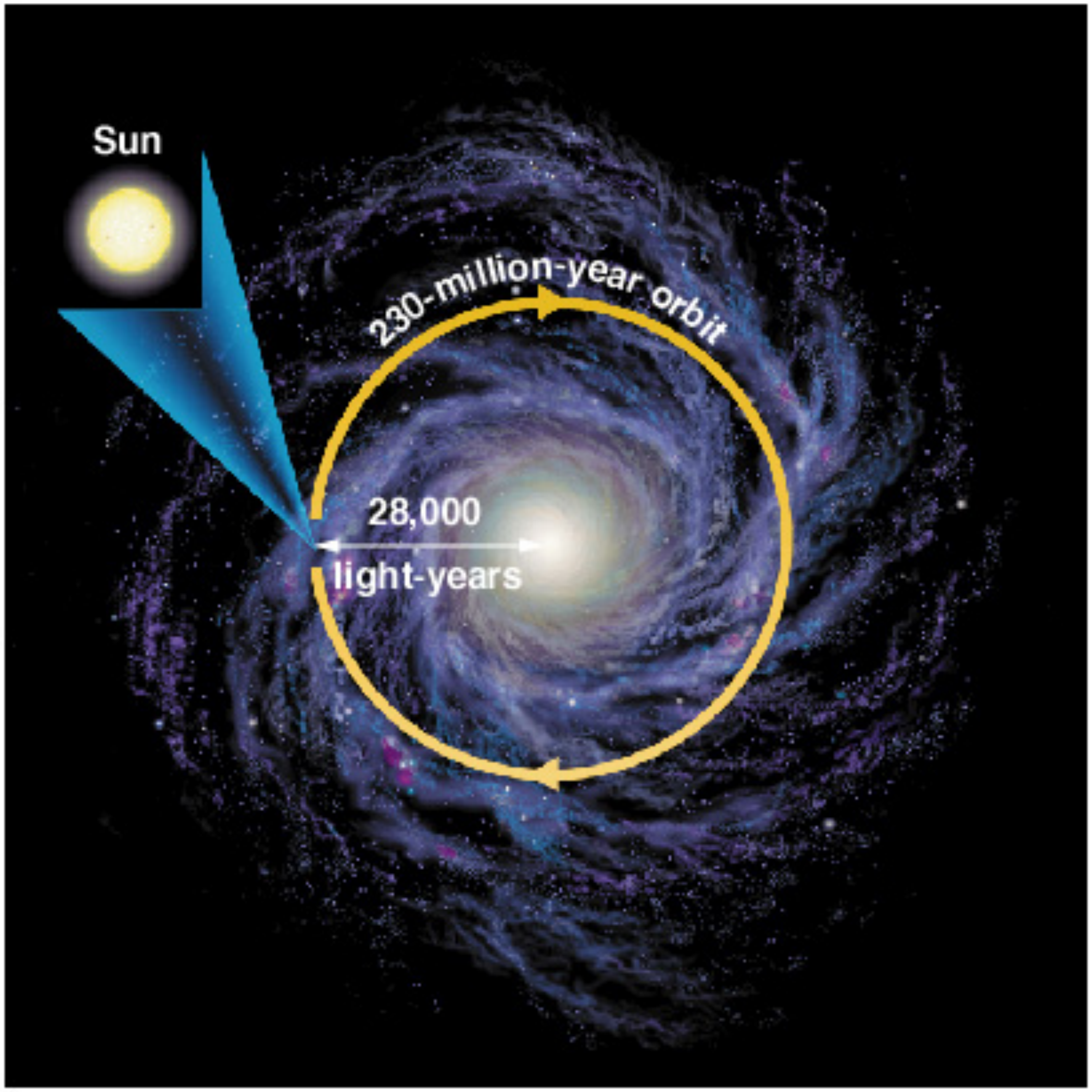


Bulge & Halo



- Bulge mass < 20% of disk
- Halo fraction small ~2%
- Bulge & halo stars have elliptical orbits
- Bulge & halo stars orbit with random orientations; fill out 3D structure


halo star orbits (green)
bulge star orbits (red)
disk star orbits
(yellow)



Sun's orbital motion (radius and velocity) tells us mass within Sun's orbit:

$$1.0 \times 10^{11} M_{\mathrm{Sun}}$$

Orbital Velocity Law

$$V^2 = \frac{GM}{R}$$ measure circular velocity and radius

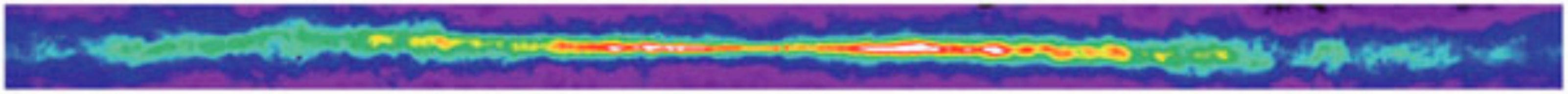
solve for mass: $$M = \frac{V^2 R}{G}$$

- The orbital speed (*V*) and radius (*R*) of an object on a circular orbit around the galaxy tell us the mass (*M*) enclosed within that orbit.

stars and gas: $$M \approx 6 \times 10^{10}\ M_{sun}$$

Relation of Milky Way components

radio (21 cm)
HI gas



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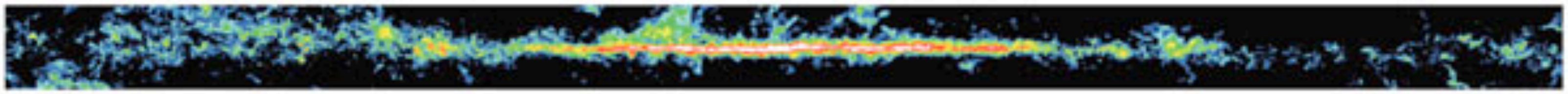

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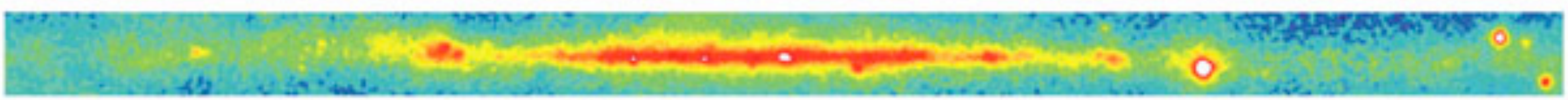

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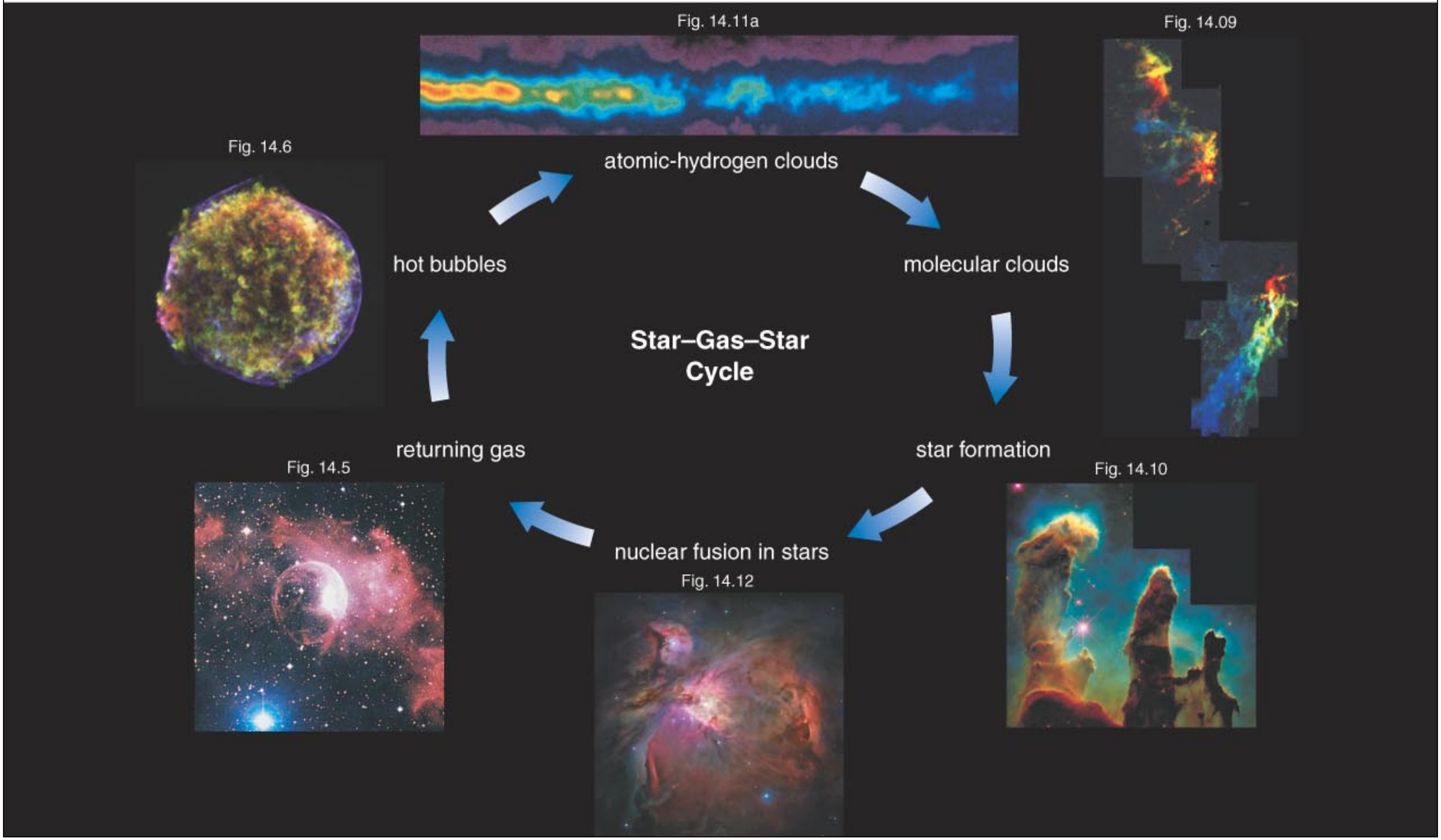
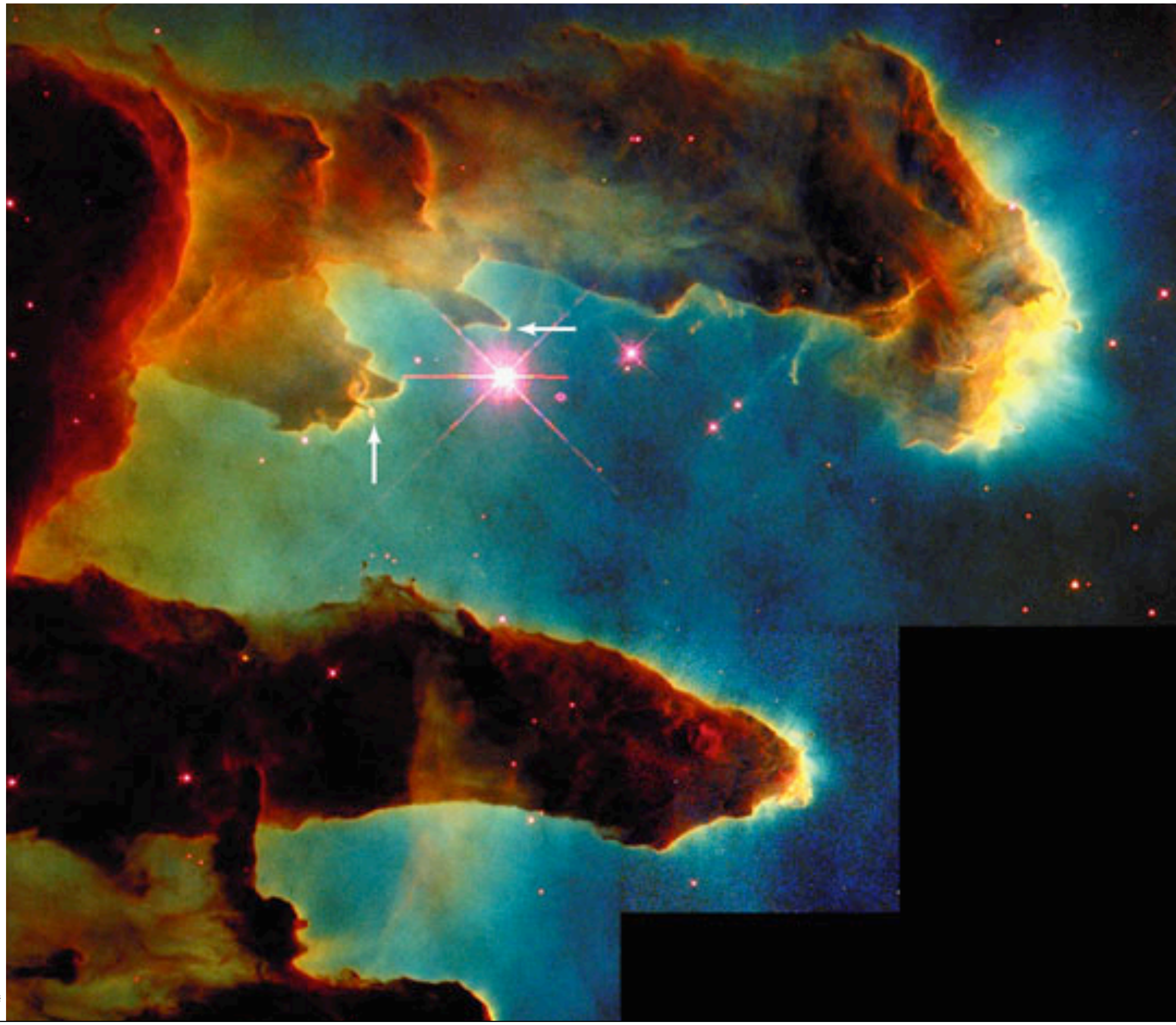
Gas recycling in our galaxy



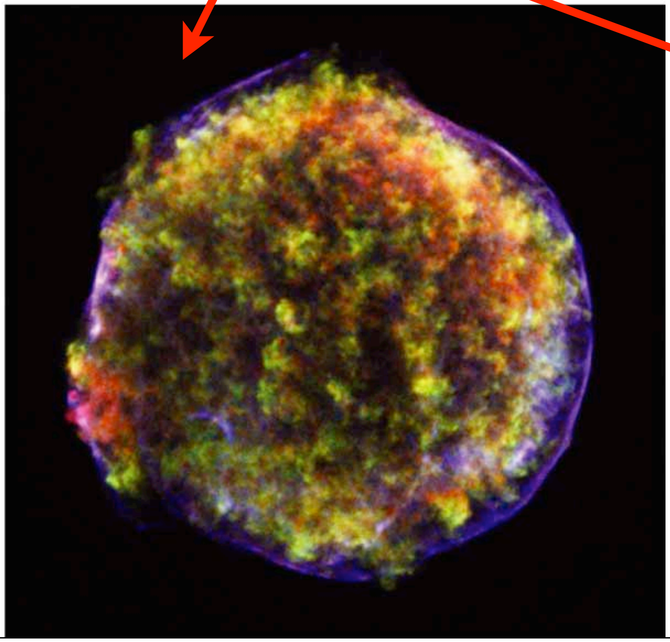
Gas recycling

- Stars form in cold molecular gas clouds



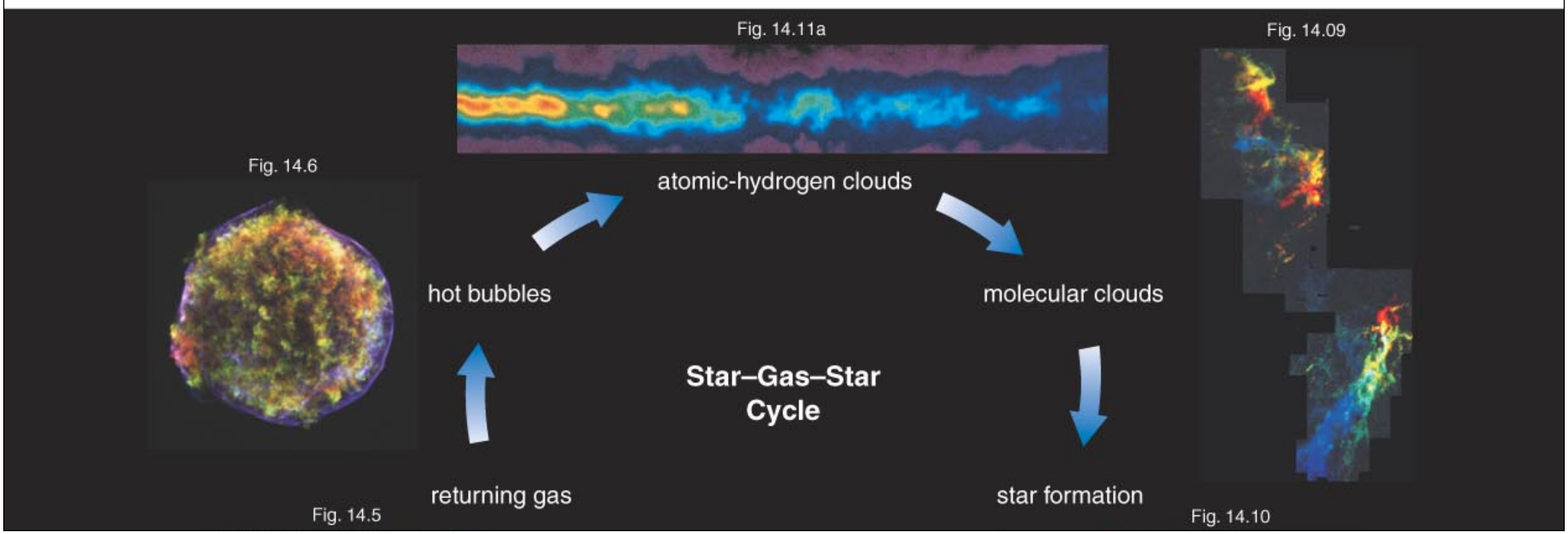
Gas recycling

- Stars form in cold molecular gas clouds
- High mass stars explode
  - return processed gas to interstellar medium
  - heat surrounding gas
    - Supernova bubbles
    - Ionized gas (H II regions) [hot stars emit UV radiation]



Gas recycling

- Stars form in cold molecular gas clouds
- High mass stars explode
- Hot gas cools
  - First into "warm" atomic gas (H I), then
  - into "cold" molecular gas (H_2) in dusty places (~30 K)



Gas recycling

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- Hot gas cools
  - First into “warm” atomic gas (H I), then
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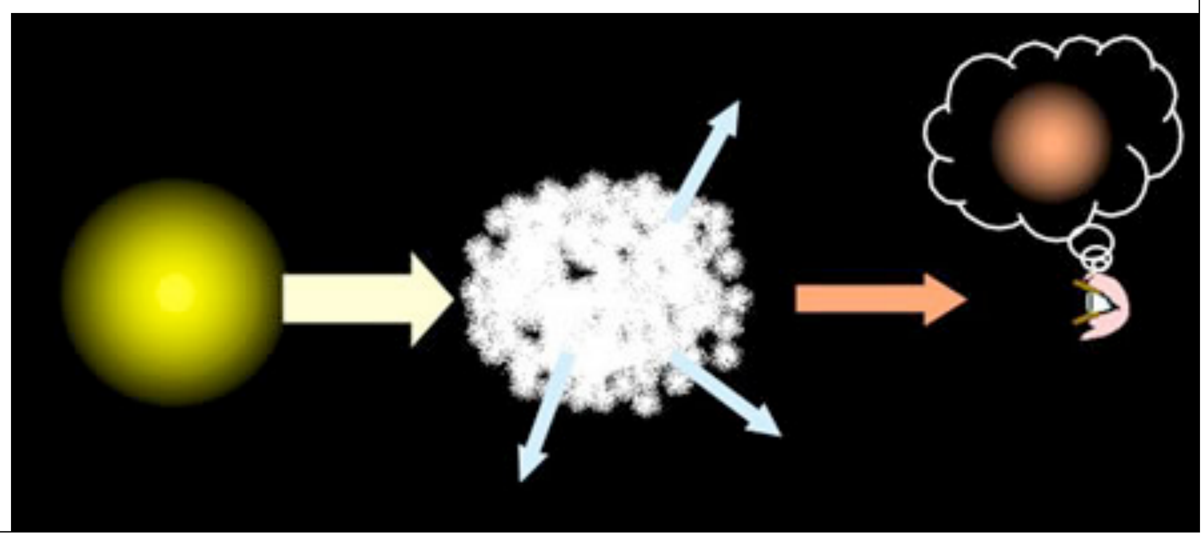
- Stars form in cold molecular gas clouds

Note: recycling is inefficient. Some mass locked up in remnants.

The Effects of Dust

- Interstellar dust
  - small grains in space
  - scatters star light passing through it
- Dims light
- Reddens it



The Effects of Dust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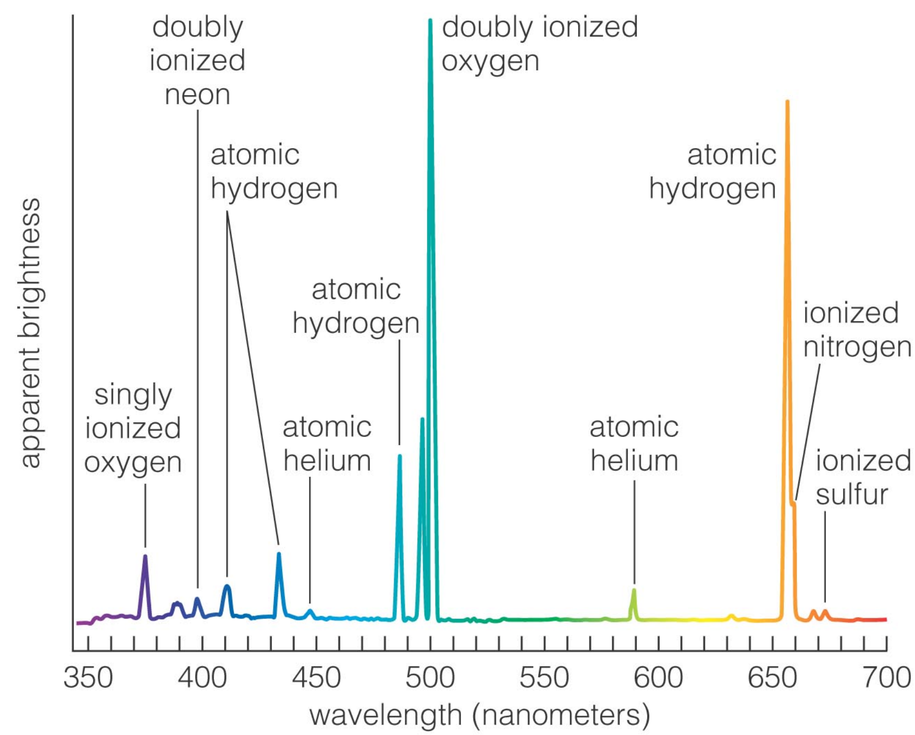
- Interstellar dust
  - small grains in space
  - scatters star light passing through it
- Dims light
  - blocks some light
  - stars appear fainter than they otherwise would
- Reddens
  - preferentially scatters blue light
  - light that gets through is redder than it started

Various Nebulae

H II Regions

Ionization nebulae are found around short-lived high-mass stars, signifying active star formation.



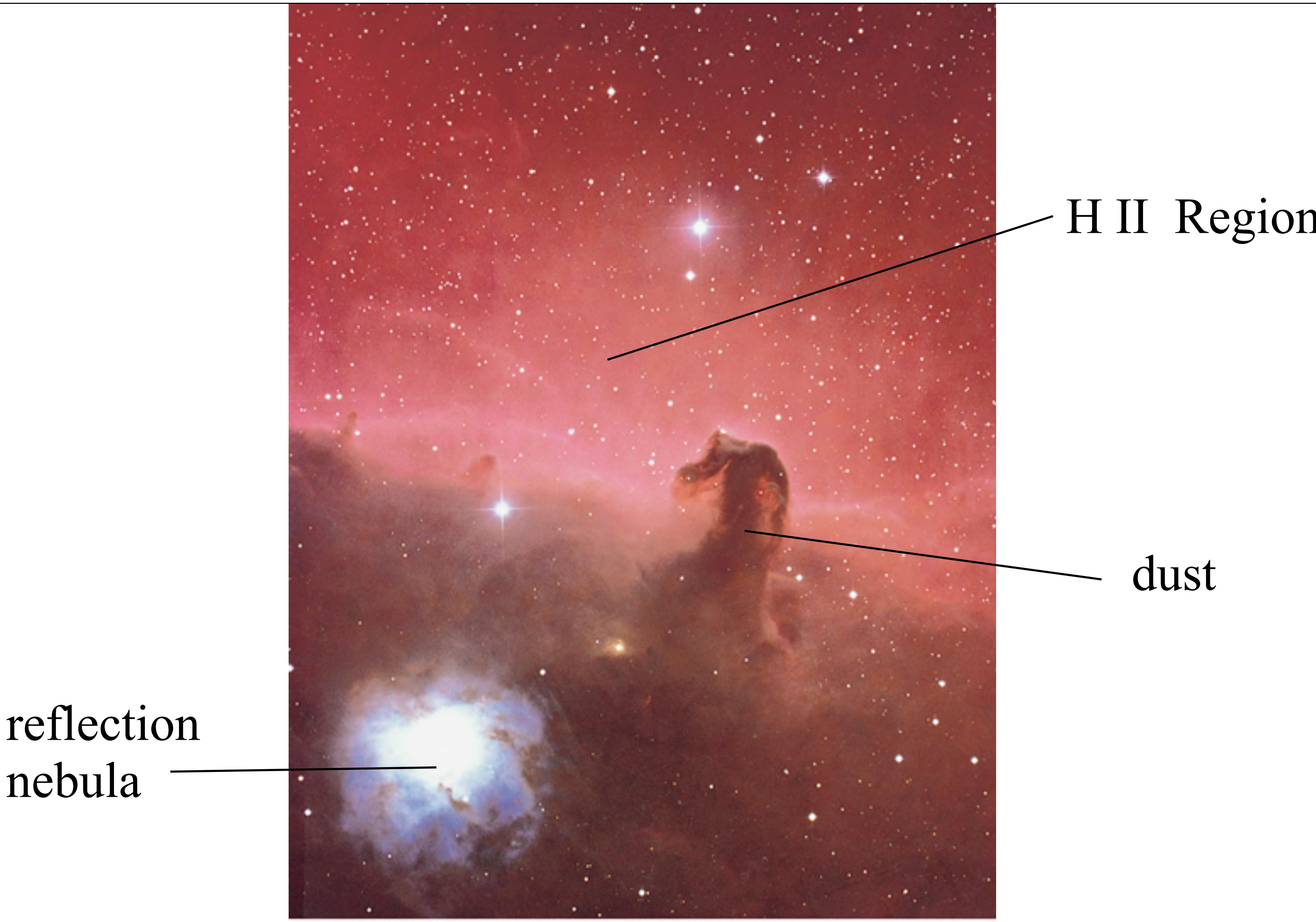
Reflection nebulae scatter the light from stars.

Why do reflection nebulae look bluer than the nearby stars?

Reflection nebulae scatter the light from stars.

Why do reflection nebulae look bluer than the nearby stars?

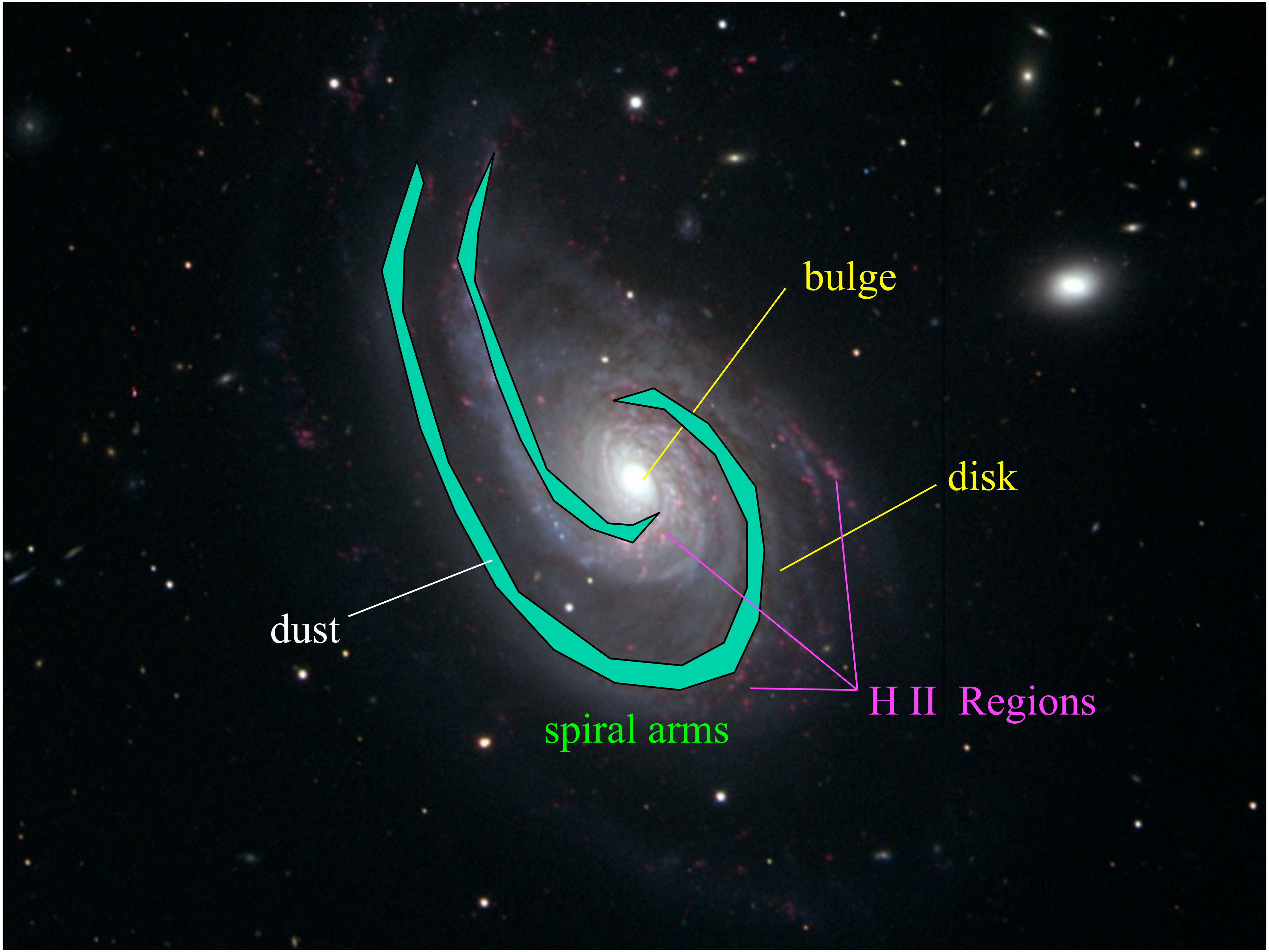
For the same reason that our sky is blue!



What kinds of nebulae do you see?

Star formation

- Stars form in molecular clouds
- Molecular clouds contain a lot of dust
- Most star formation occurs in spiral arms

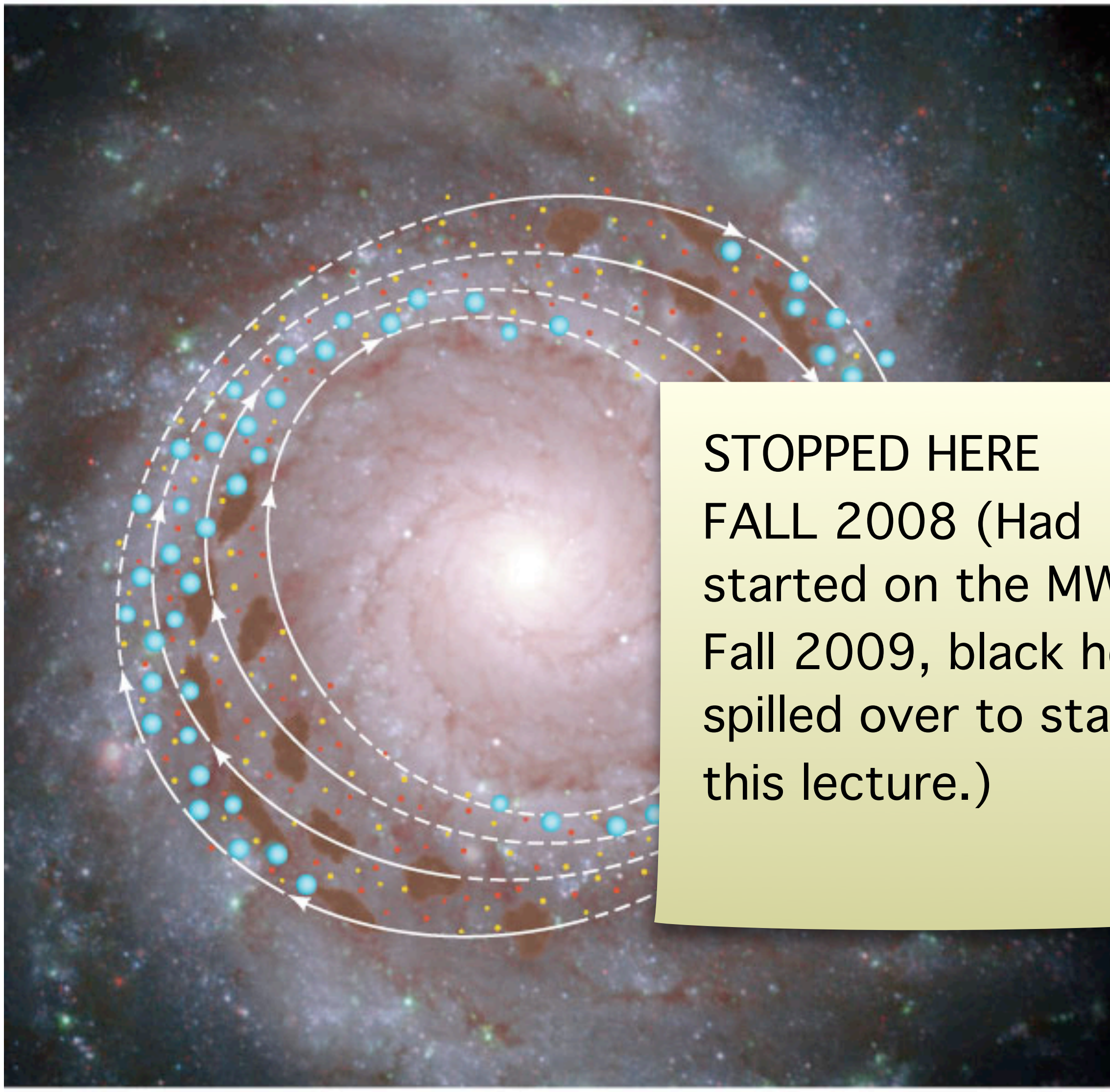

bulge
disk
dust
H II Regions
spiral arms

Spiral arms are waves of star formation:

1. Gas clouds get squeezed as they move into spiral arms.

The squeezing of clouds triggers star formation.

3. Young stars flow out of spiral arms.

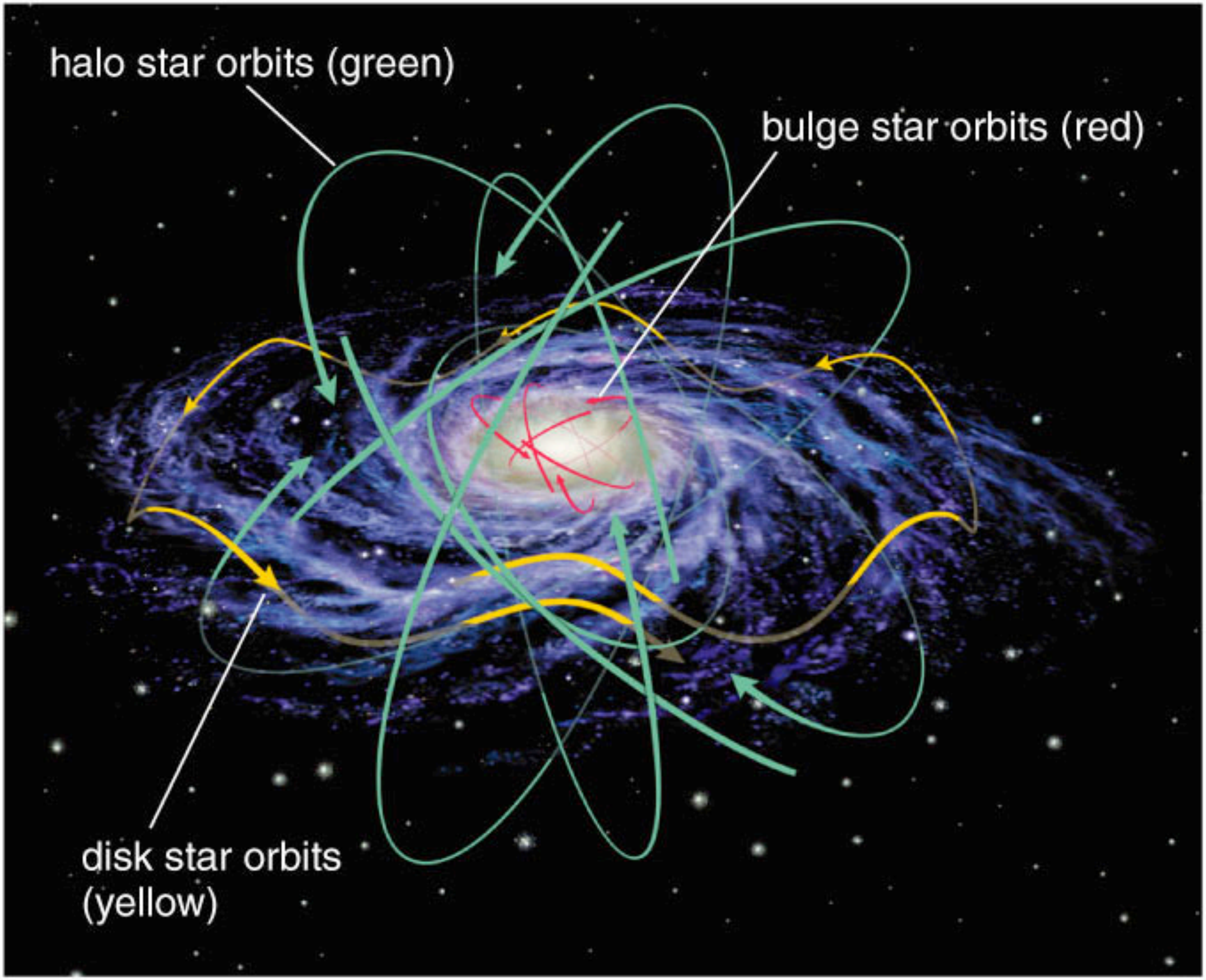


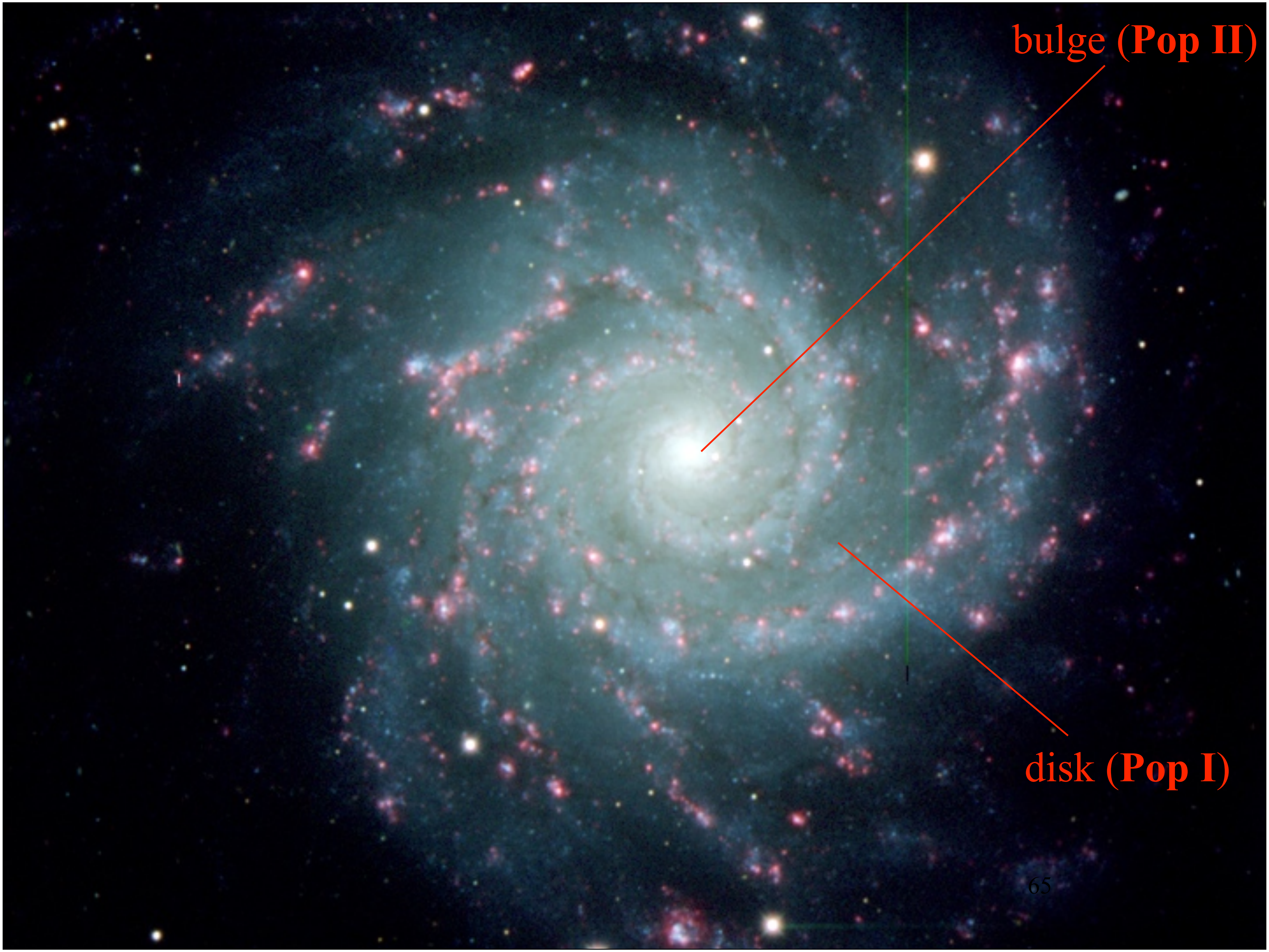
STOPPED HERE FALL 2008 (Had started on the MW. In Fall 2009, black holes spilled over to start of this lecture.)

14_17SpiralArmPattern

Stellar Populations

- **Population I**
  - – circular orbits in plane of disk
  - – mix of ages
    - young, newly formed OB stars
    - old stars (& everything in between)
  - – metal rich, like sun (~2% mass in “metals”)
- **Population II**
  - – elliptical orbits of all orientations
  - – old stars only
  - – metal poor in halo (~0.2% metals)
    - but metal rich in bulge


halo star orbits (green)
bulge star orbits (red)
disk star orbits
(yellow)


bulge (**Pop II**)
disk (**Pop I**)