THE JAMES WEBB SPACE TELESCOPE

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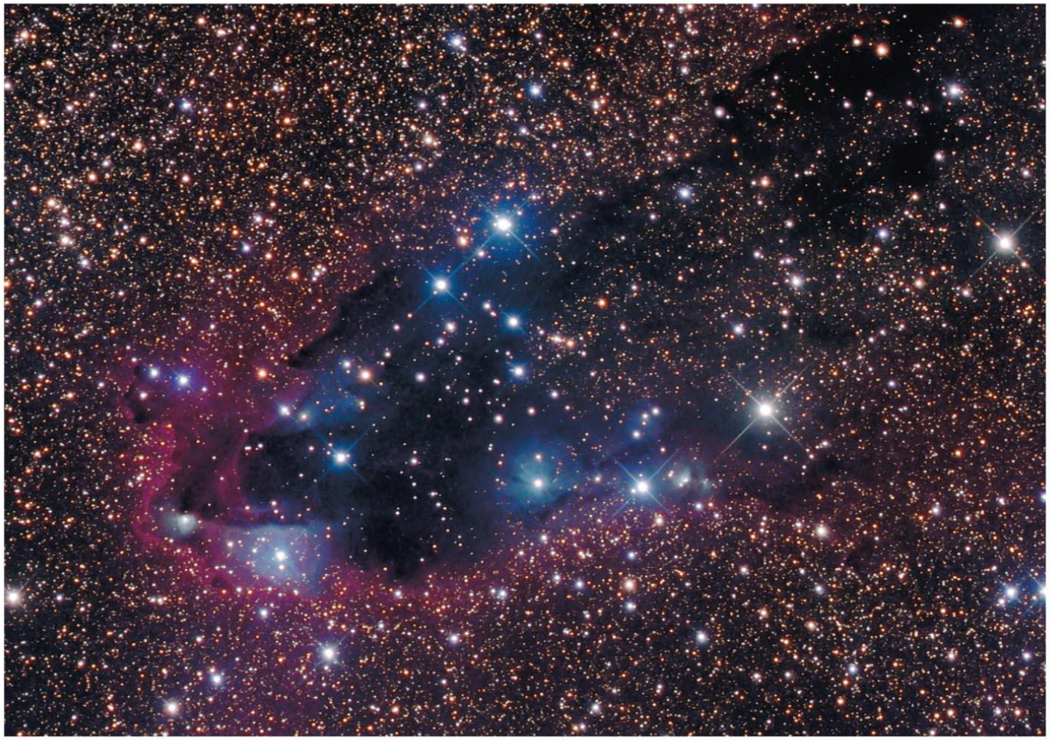
Plan

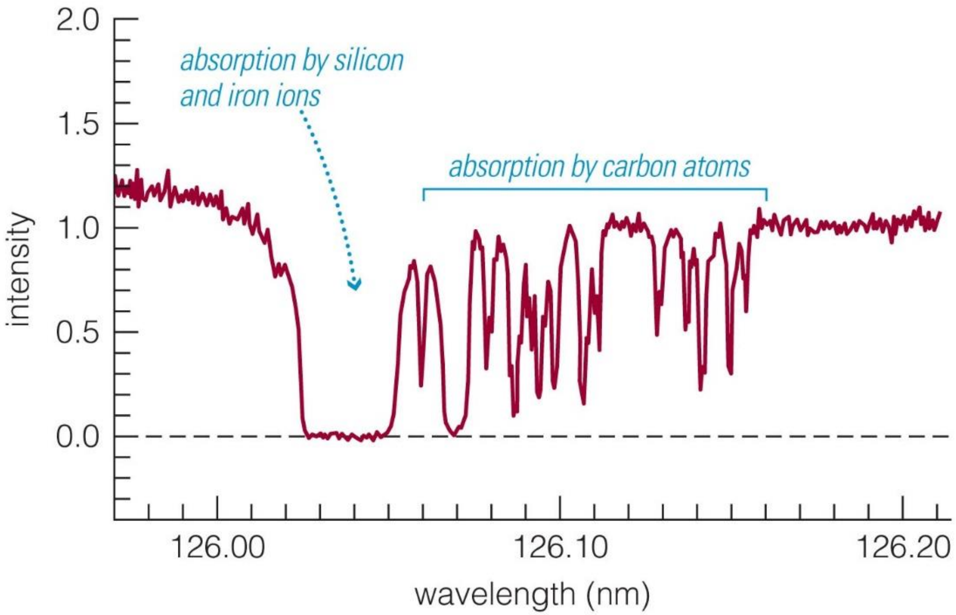
- Day 1:
  - Introduction – motivation
  - Modern astronomical telescopes
  - JWST – history, design and deployment
- **Day 2:**
  - **Star & planet formation – the background**
  - **JWST – new results**
- Day 3:
  - Galaxy formation & cosmology – the background
  - JWST – new results

Star-Forming Clouds



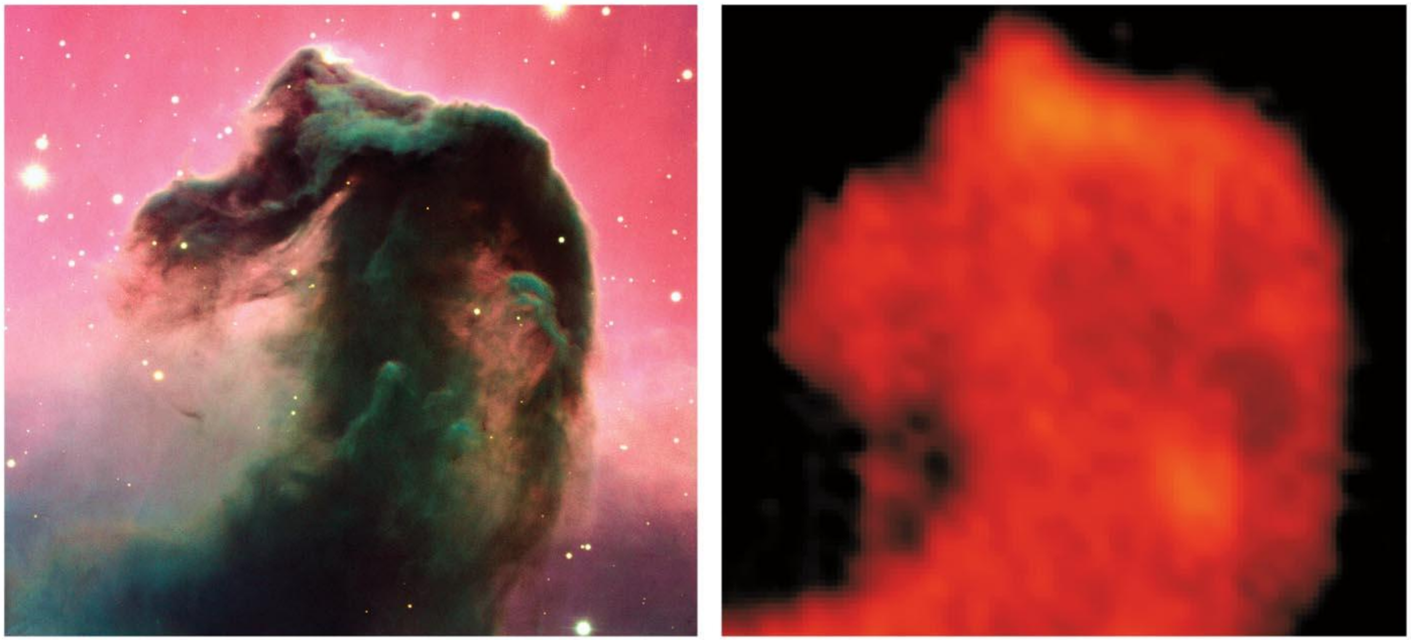
- The matter between the stars is called the **interstellar medium.**
- Stars form in dark clouds of dusty, molecular gas in interstellar space, because there it's cold and dense.

Composition of Clouds



- We were able to determine the composition of interstellar gas from its absorption lines in the spectra of stars, long before modern molecular emission line observations became common.
- 70% H, 28% He, 2% heavier elements: the "stuff" of the Universe.

Molecular Clouds

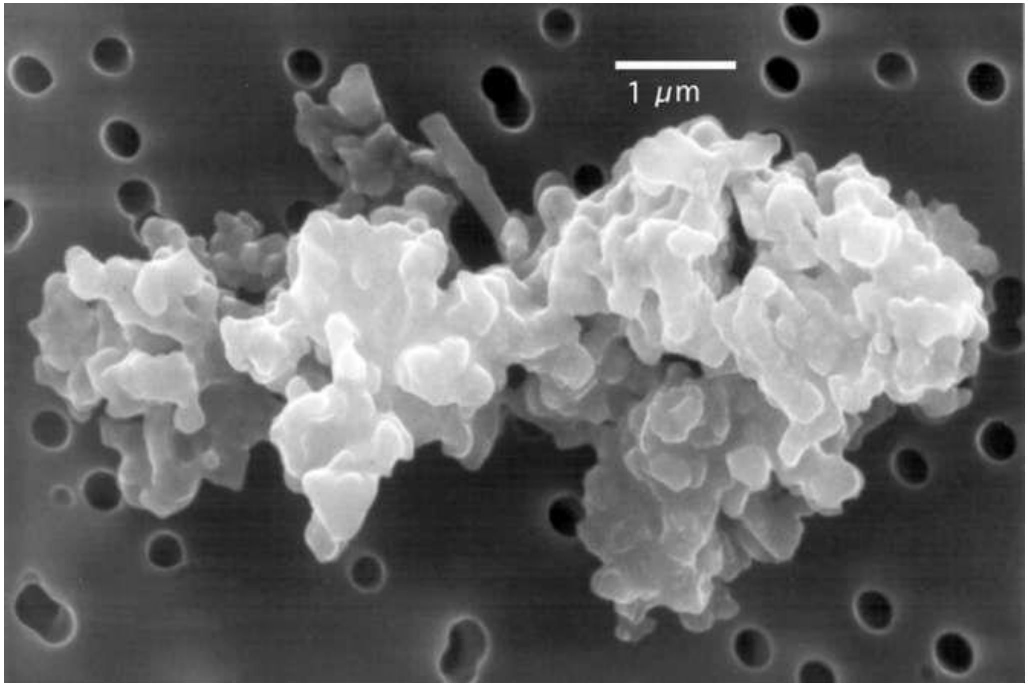


a Visible-light image of the nebula. The dark (horsehead-shaped) region is a molecular cloud.

b Radio-wave image of the nebula showing emission from carbon monoxide (CO) molecules.

- Most of the matter in star-forming clouds is in the form of molecules (H_2, CO, etc.).
- These *molecular clouds* have a temperature of 10–30 K, protected from starlight by dust.

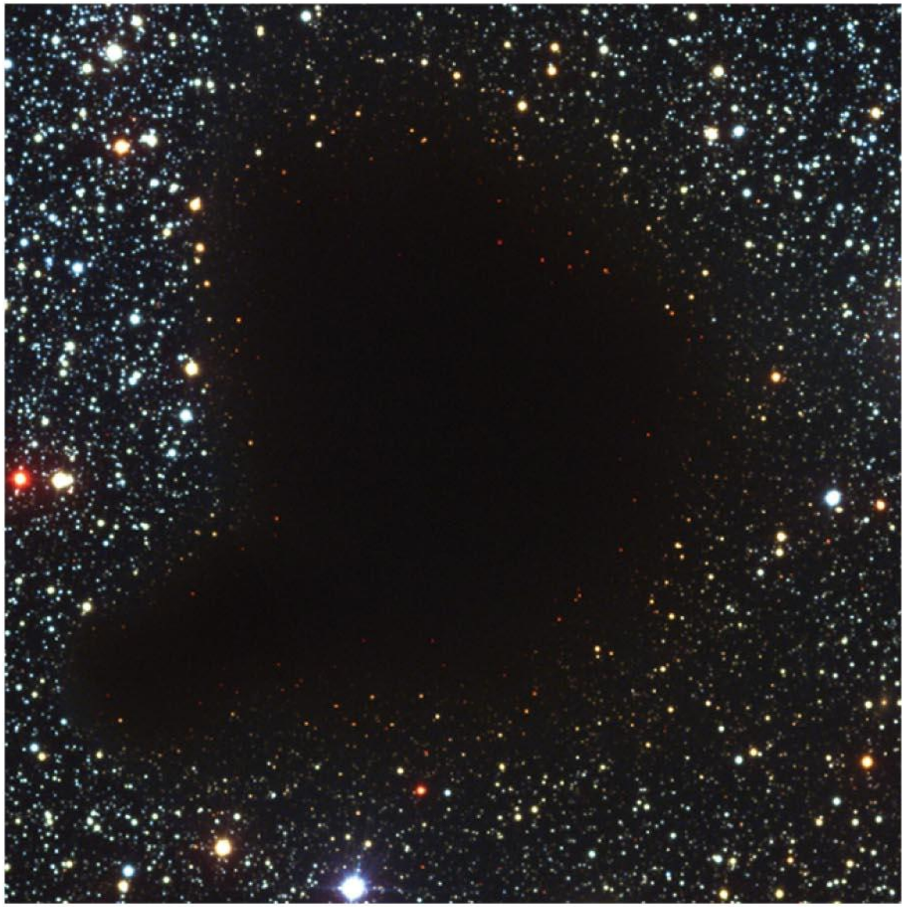
Interstellar Dust



Interplanetary dust – possibly pre-solar nebula

- Particles are < 1 micrometer in size and made of elements like C, O, Si, and Fe.
- *Interstellar dust* is very effective at scattering visible light, and blocks our view of stars within and beyond clouds.

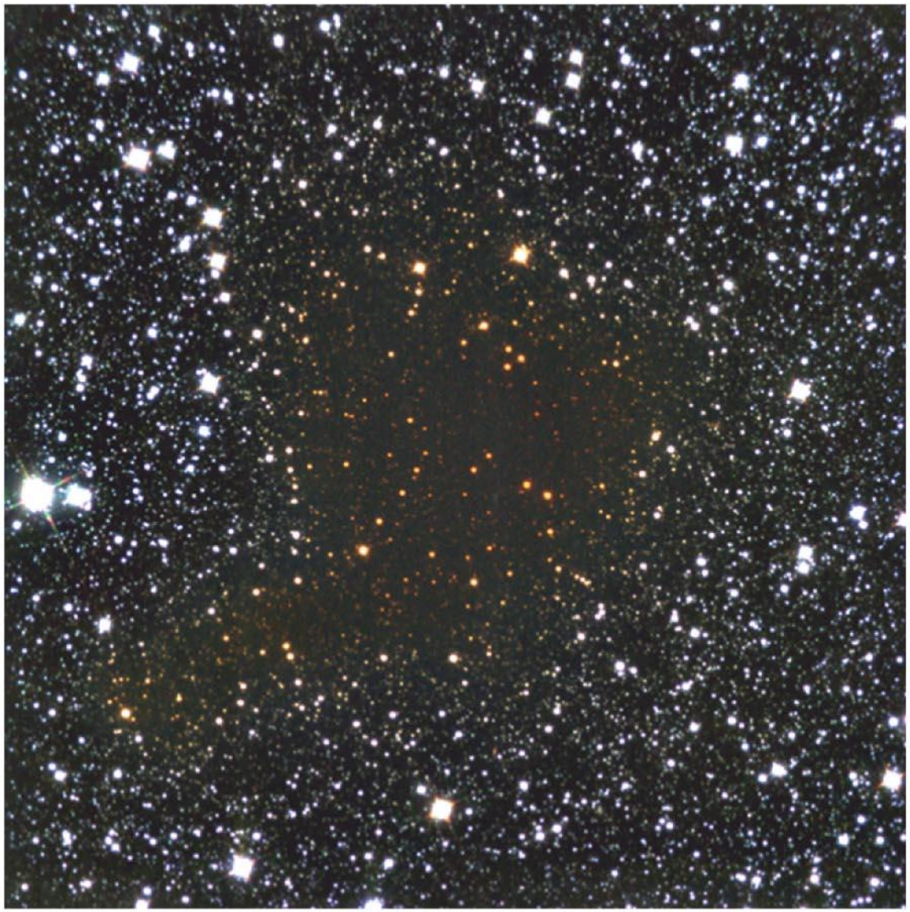
Interstellar Reddening



a A visible-light image of the dark molecular cloud Barnard 68.

- Stars viewed through the edges of the cloud look redder because dust blocks (shorter-wavelength) blue light more effectively than (longer-wavelength) red light.

Interstellar Reddening



b An infrared image of Barnard 68 showing the stars that lie behind the clouc

- Long-wavelength infrared light passes through a cloud more easily than visible light.
- Observations of infrared light reveal stars on the other side of the cloud.

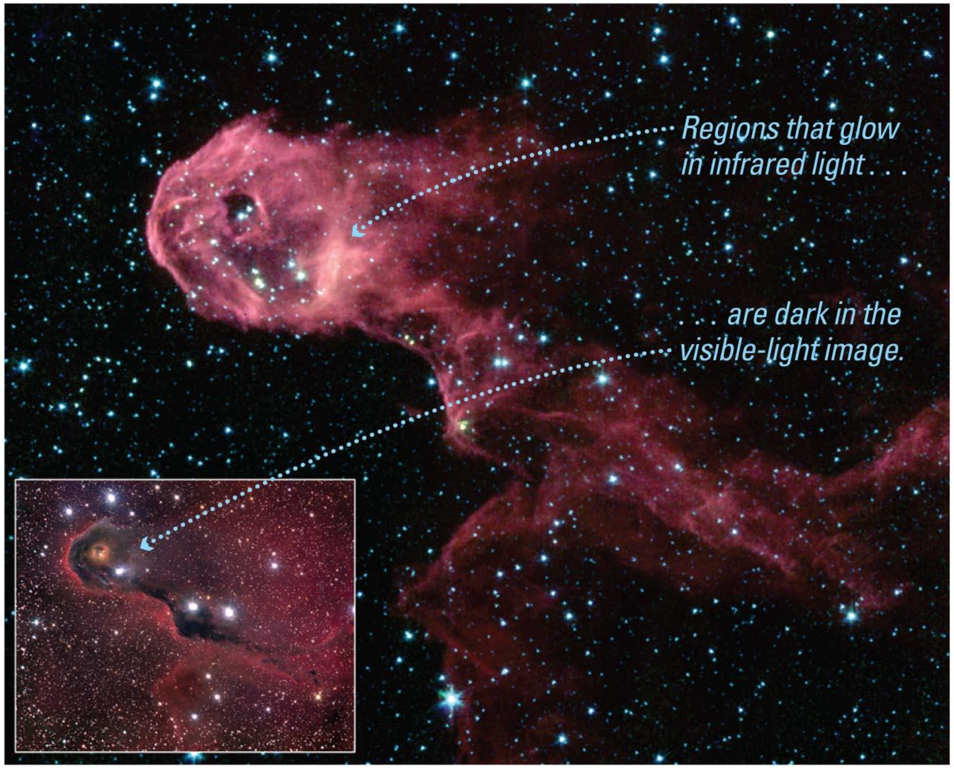
Observing Newborn Stars

- Visible light from a newborn star is often trapped within the dark, dusty gas clouds where the star formed.

Observing Newborn Stars

- Observing the infrared light from a cloud can reveal the newborn star embedded inside it.

Glowing Dust Grains



- Dust grains that absorb visible light heat up and emit infrared light of even longer wavelength.

Gravity versus Pressure

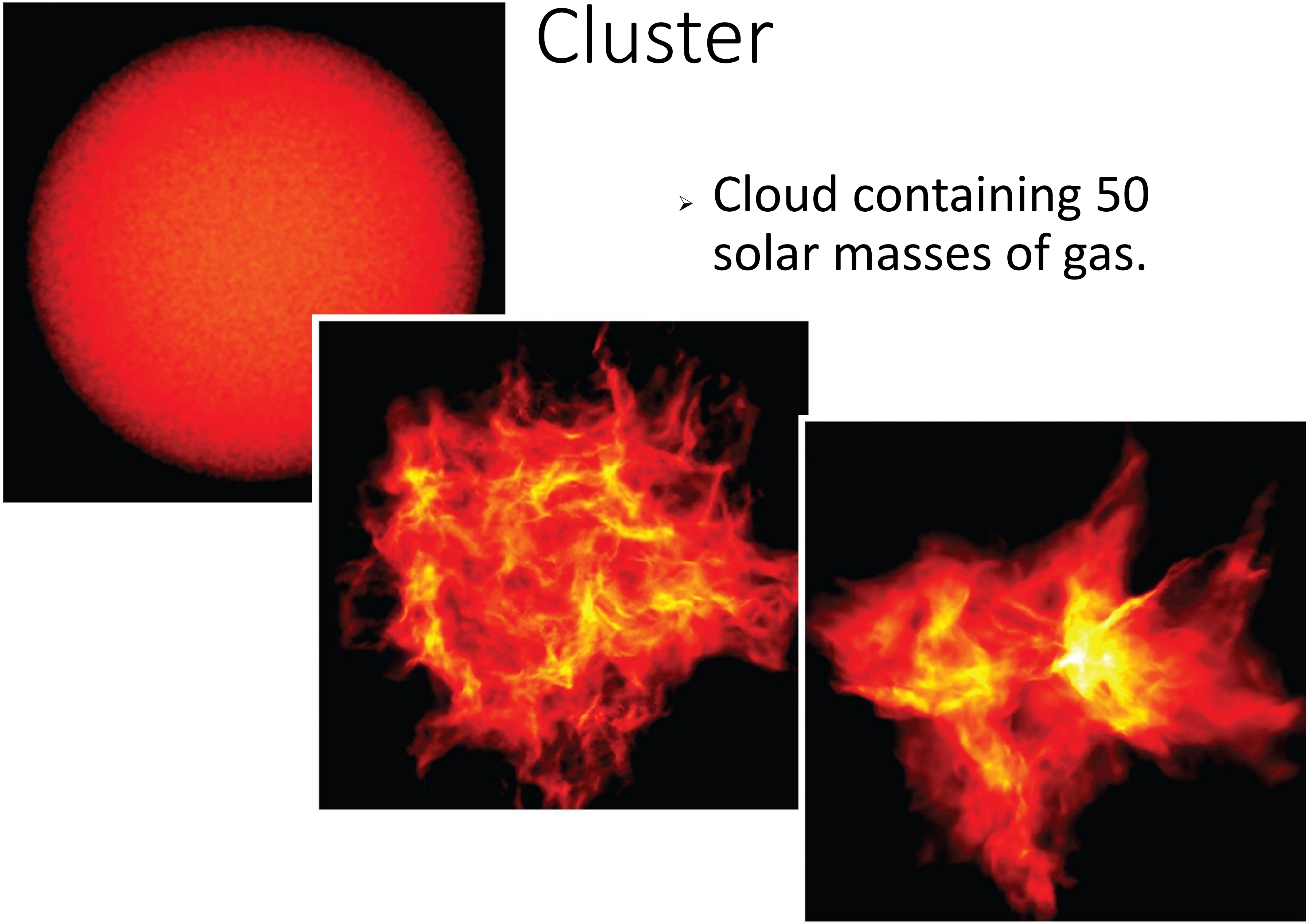
- Gravity can create stars only if it can overcome the force of gas pressure in a cloud.
- A typical molecular cloud ($T \sim 30$ K, $n \sim 300$ particles/cm^3; air has almost 10^{20} molecules/cm^3) must contain at least a few hundred solar masses for gravity to overcome pressure.

Fragmentation of a Cloud

- Gravity within a contracting gas cloud becomes stronger as the gas becomes denser.
- Gravity can therefore overcome pressure in smaller pieces of the cloud, causing it to break apart into multiple fragments, each of which may go on to form a star.

- gravitational force $\propto$ density^2
- pressure force $\propto$ density

Fragmentation of a Cloud: Star Cluster



- Cloud containing 50 solar masses of gas.

Trapping of Energy

- During contraction half the liberated potential energy goes into heat, half is radiated away.
- As contraction packs the molecules and dust particles of a cloud fragment closer together, it becomes harder for infrared and radio photons (from molecular emission lines) to escape.
- Contraction <u>slows down</u>, and the center of the cloud fragment becomes a **protostar.**

Trapping of Energy

- **Gravity always wins, and contraction continues, but at a rate set by the time scale for energy to radiate away.**

- Note balloon analogy.

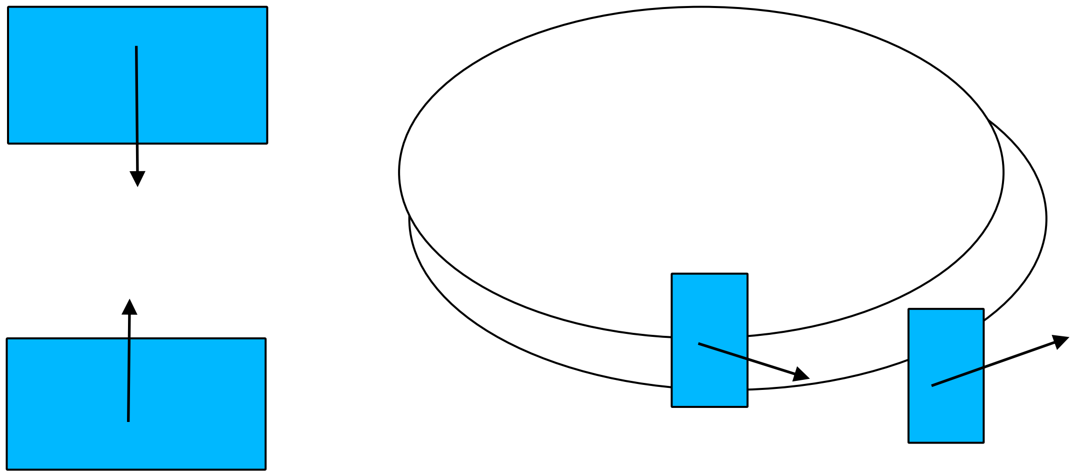
Growth of a Protostar

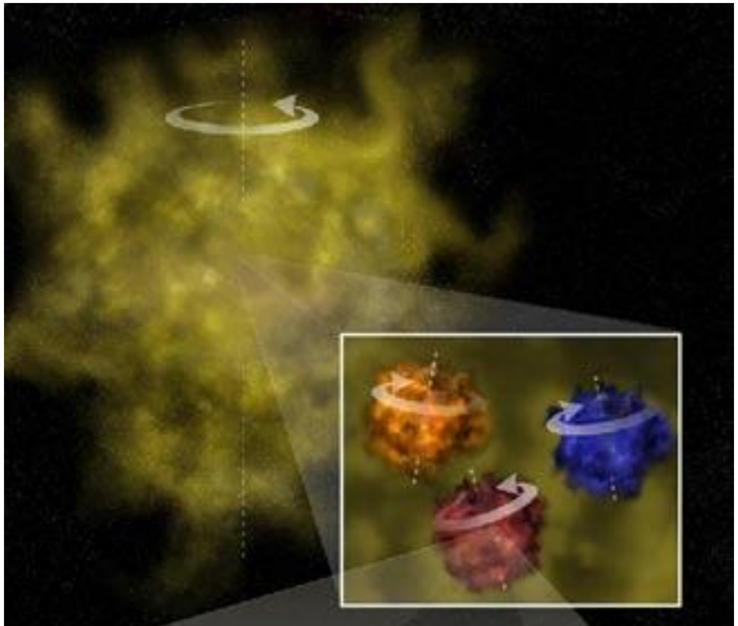
Bow shock in outflow from young star LL Orionis.

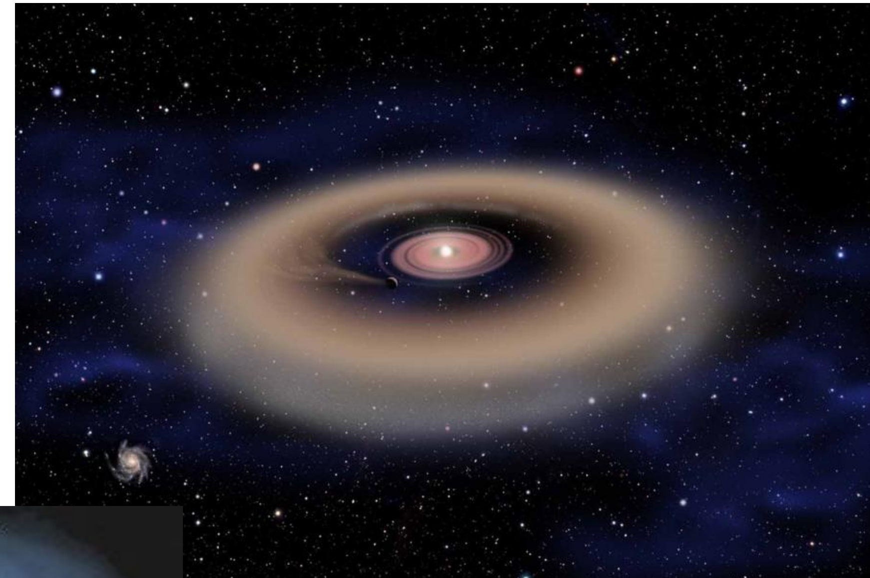
- Matter from the cloud continues to fall onto the protostar until either the protostar or a neighboring star blows the surrounding gas away.

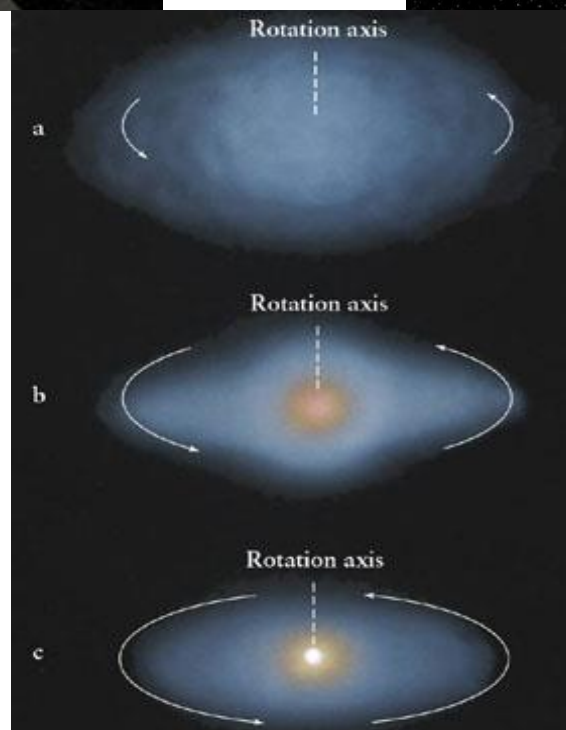
Collapse contd.

- The original nebula had some spin: conservation of angular momentum causes the cloud to **spin up** as it contracts.
- Centripetal force *holds up* the cloud in the 'spin plane', but *not along the axis;* collisions
  - allow collapse to disk;
  - order motions in the disk.



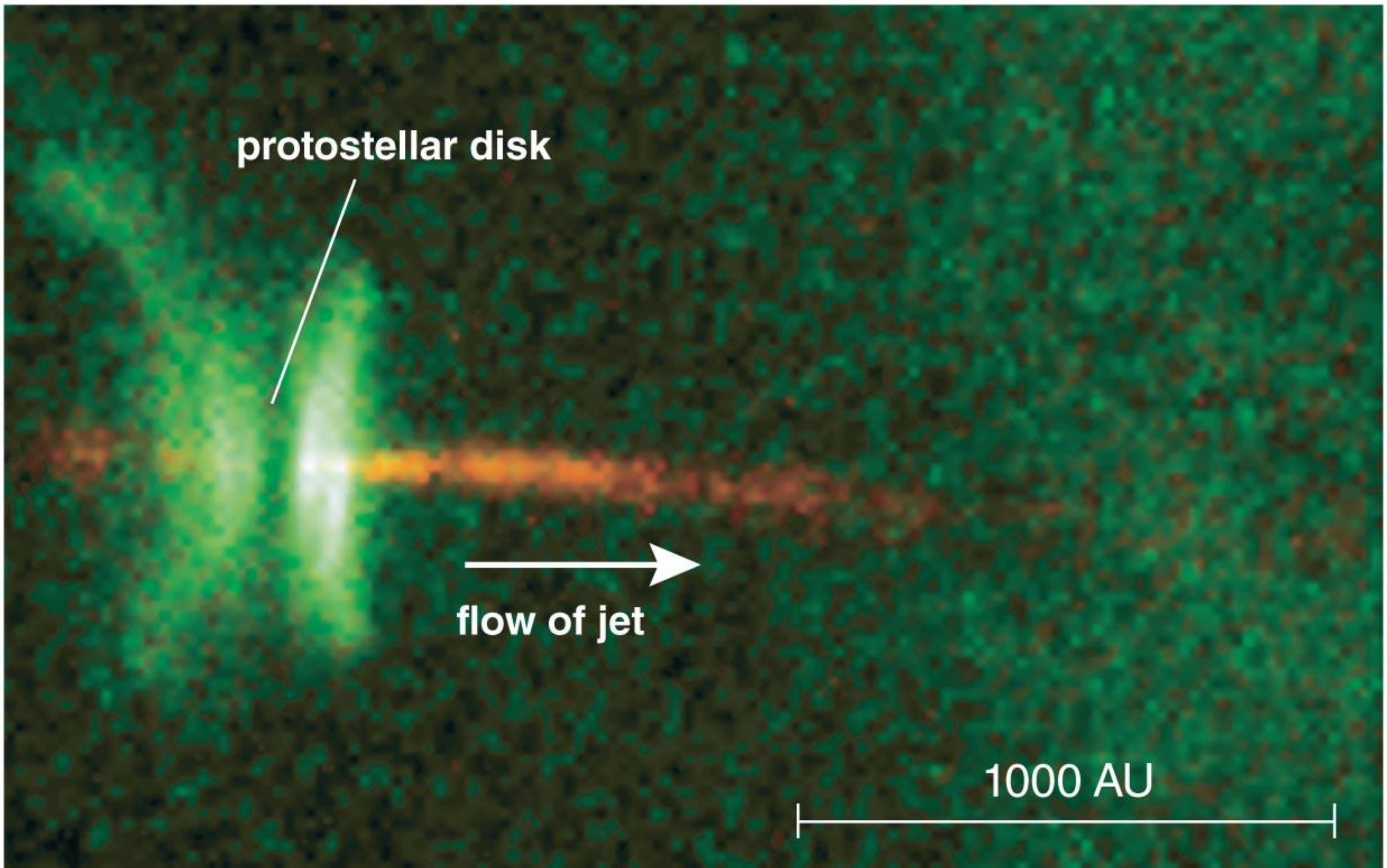


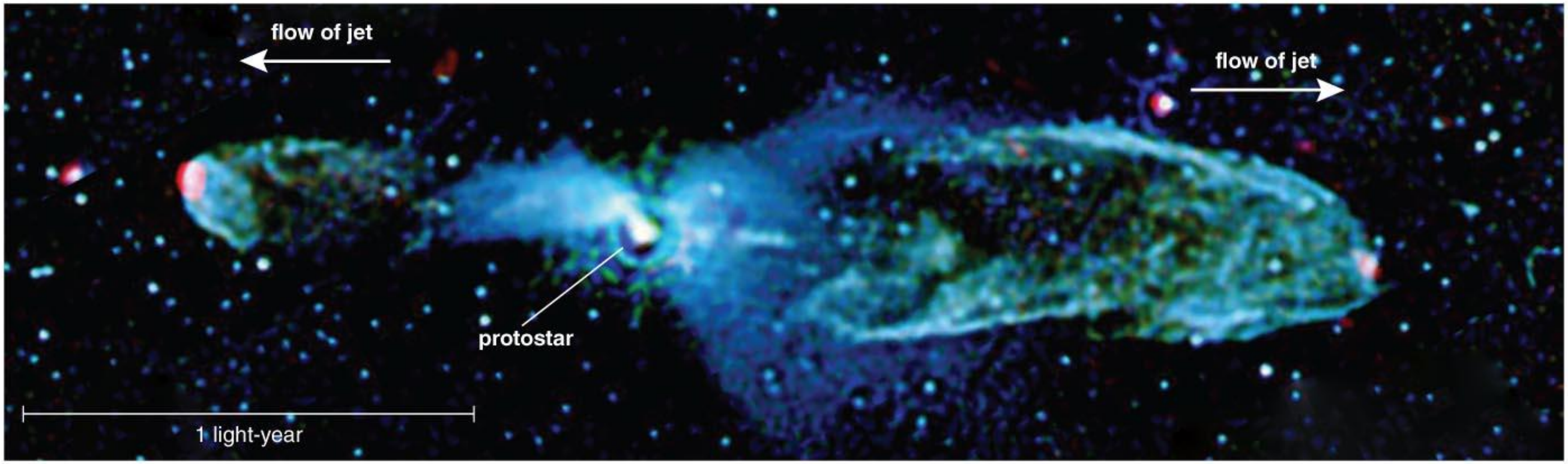



Rotation axis
a
Rotation axis
b
Rotation axis
c

Disk channels released energy

- Jets are observed coming from the centers of disks around protostars.





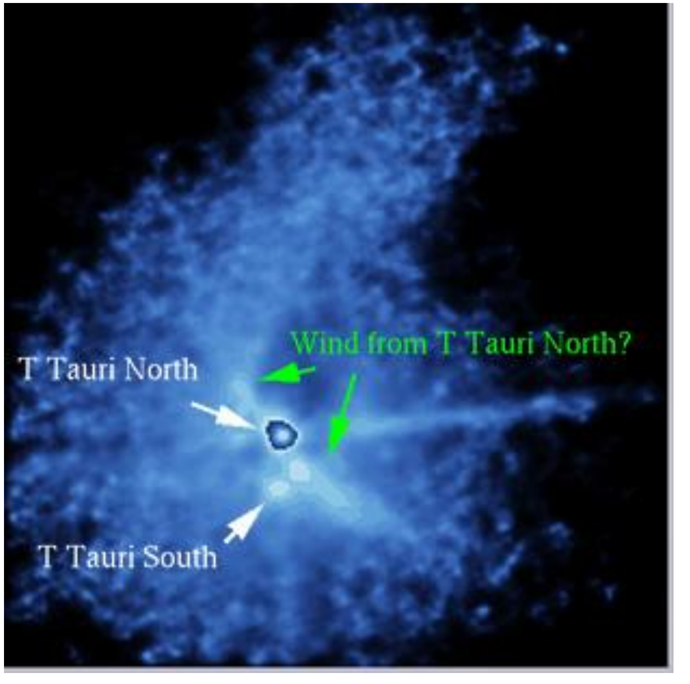
- The jets ram into interstellar gas, heating it and causing it to glow.

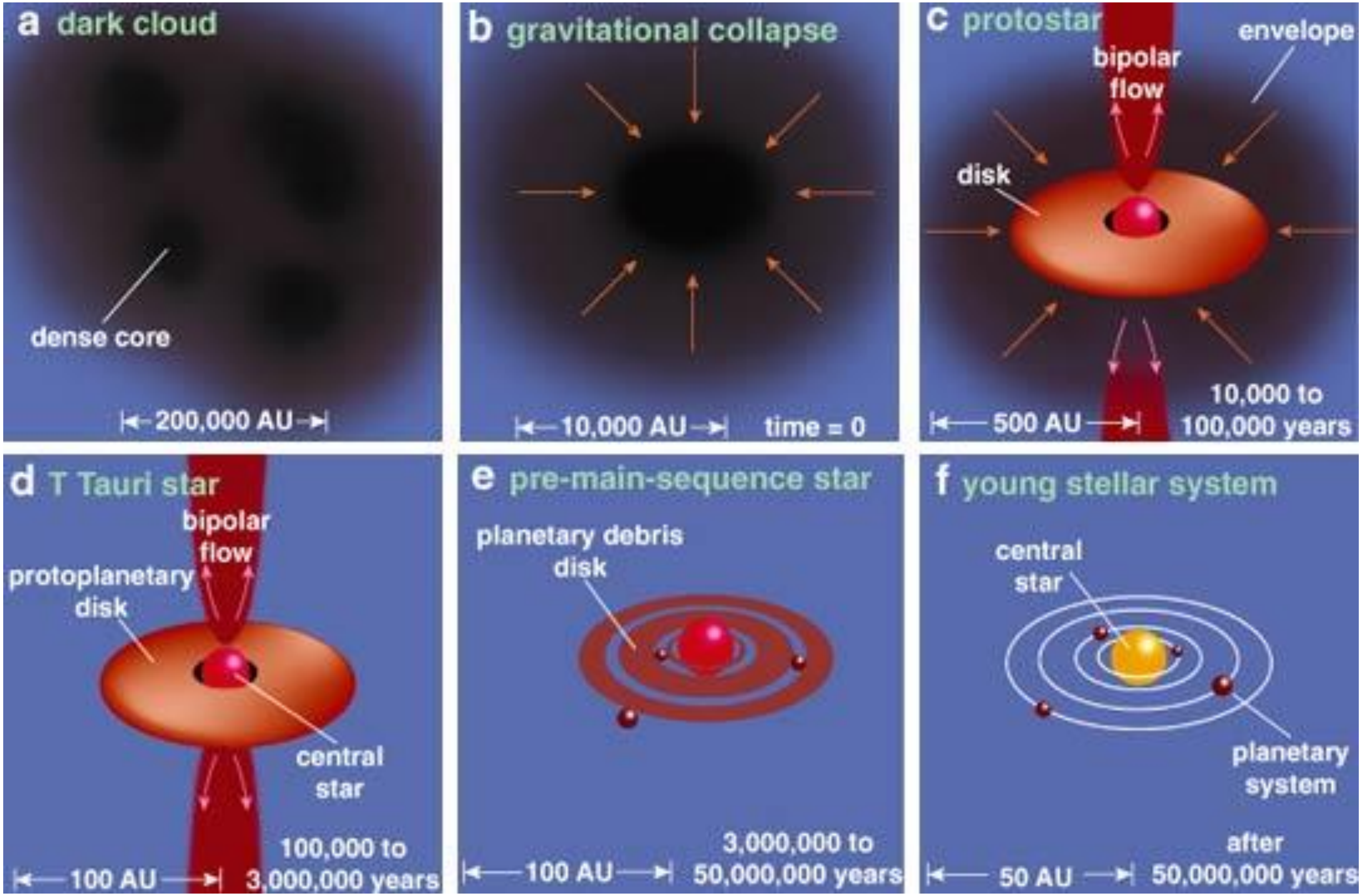
Inside-out collapse of cloud core

- Inner cloud is denser, so free-fall time is less
- This is the **protostellar** phase
- Conservation of angular momentum produces
  - protostar
  - disk
  - infalling envelope (optically thick)

T Tauri phase

- Shrouding envelope disperses – forming star/disk becomes visible
- < 10 million years old
- core too cool for fusion – gravitational potential energy – intermediate between protostar/regular star

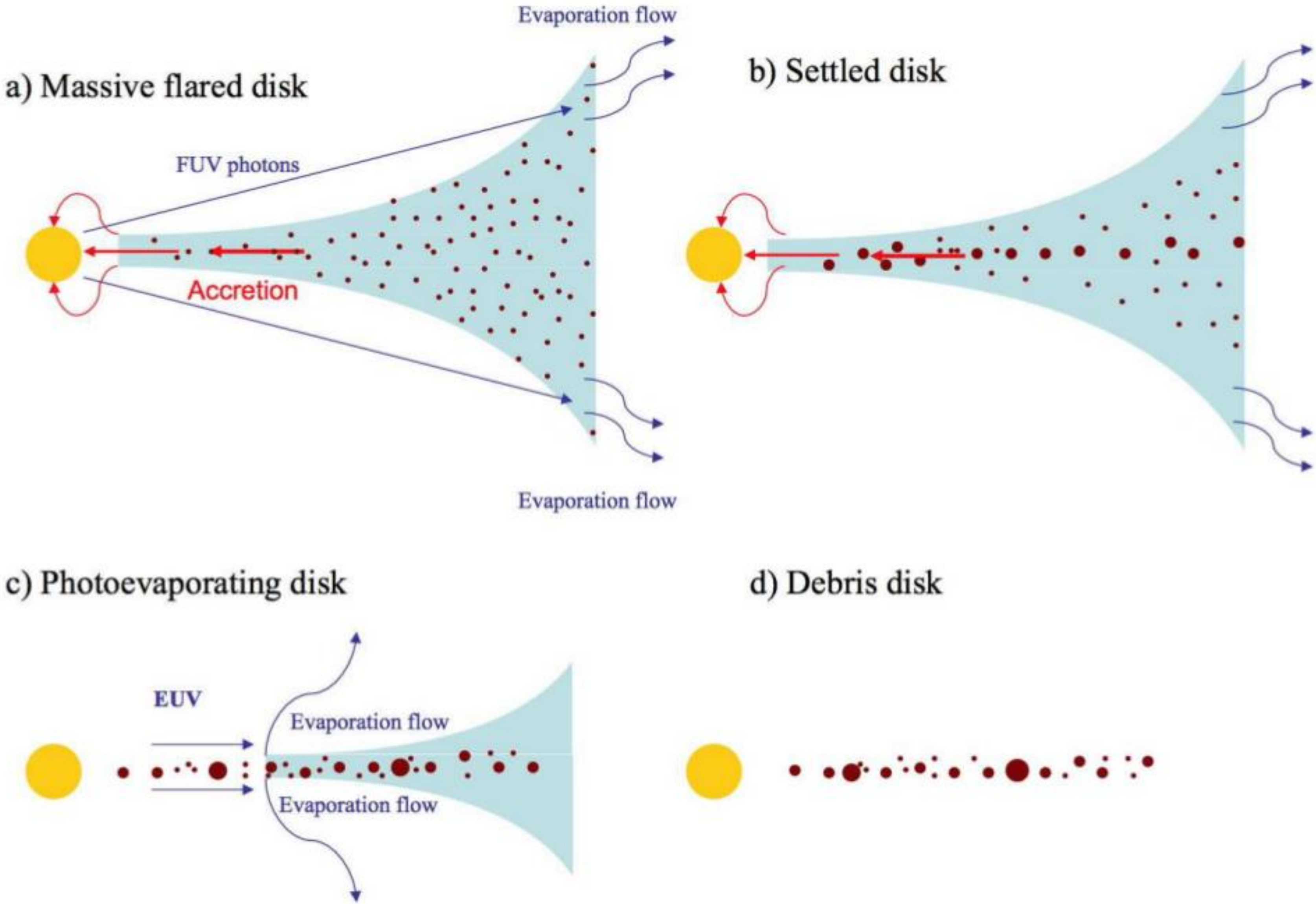



a dark cloud
dense core
200,000 AU
b gravitational collapse
10,000 AU
time = 0
c protostar
bipolar flow
envelope
disk
500 AU
10,000 to 100,000 years
d T Tauri star
bipolar flow
protoplanetary disk
central star
100 AU
100,000 to 3,000,000 years
e pre-main-sequence star
planetary debris disk
100 AU
3,000,000 to 50,000,000 years
f young stellar system
central star
planetary system
50 AU
after 50,000,000 years

Timescales

- The frequency of observed phases tells us the relative time spent in each
- Disks seem to have largely dispersed by 8-10 million years, setting constraints on the time for (and thus mechanism for) giant planet formation

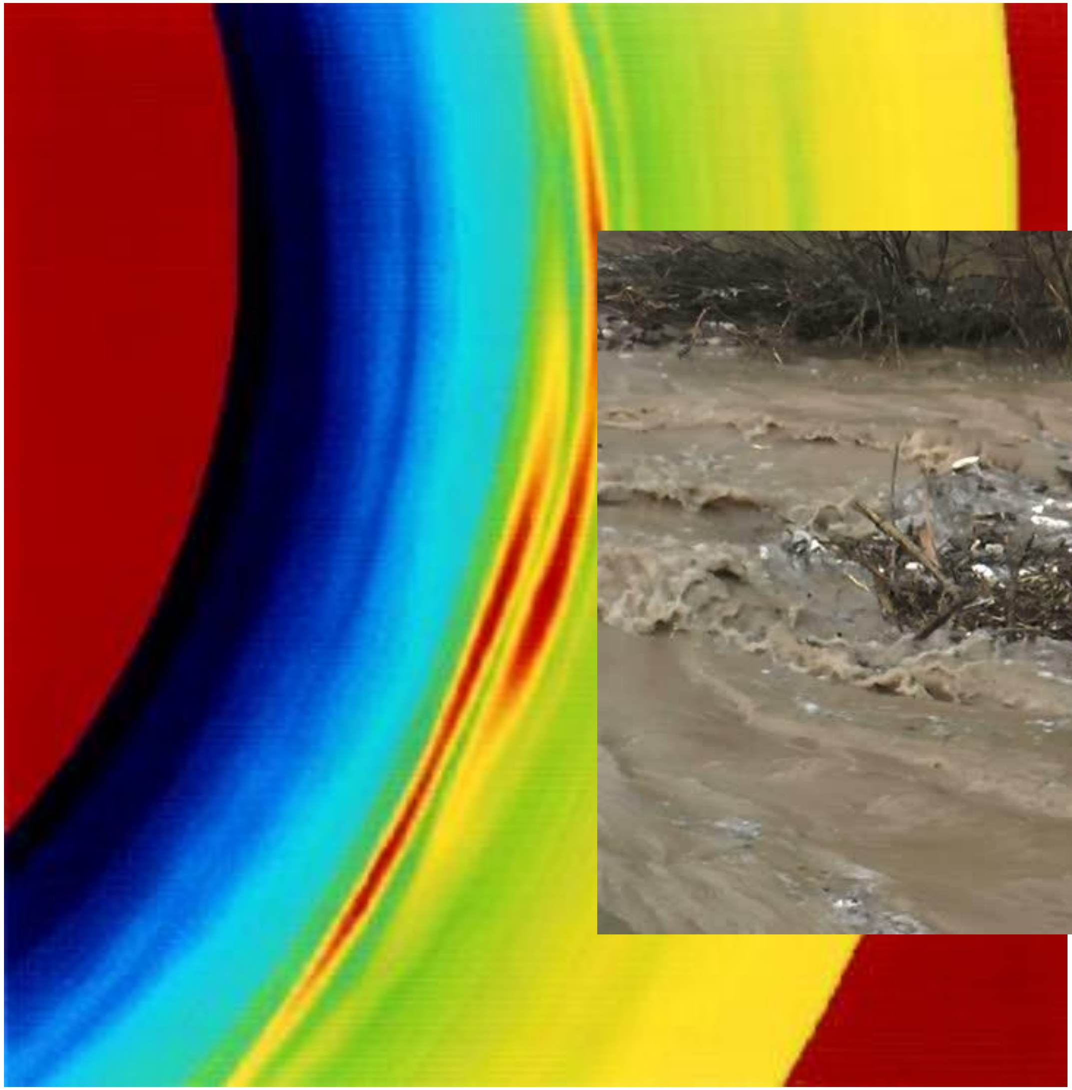
Gas & Grains In Disk



Major Issues: Growth Of Planets

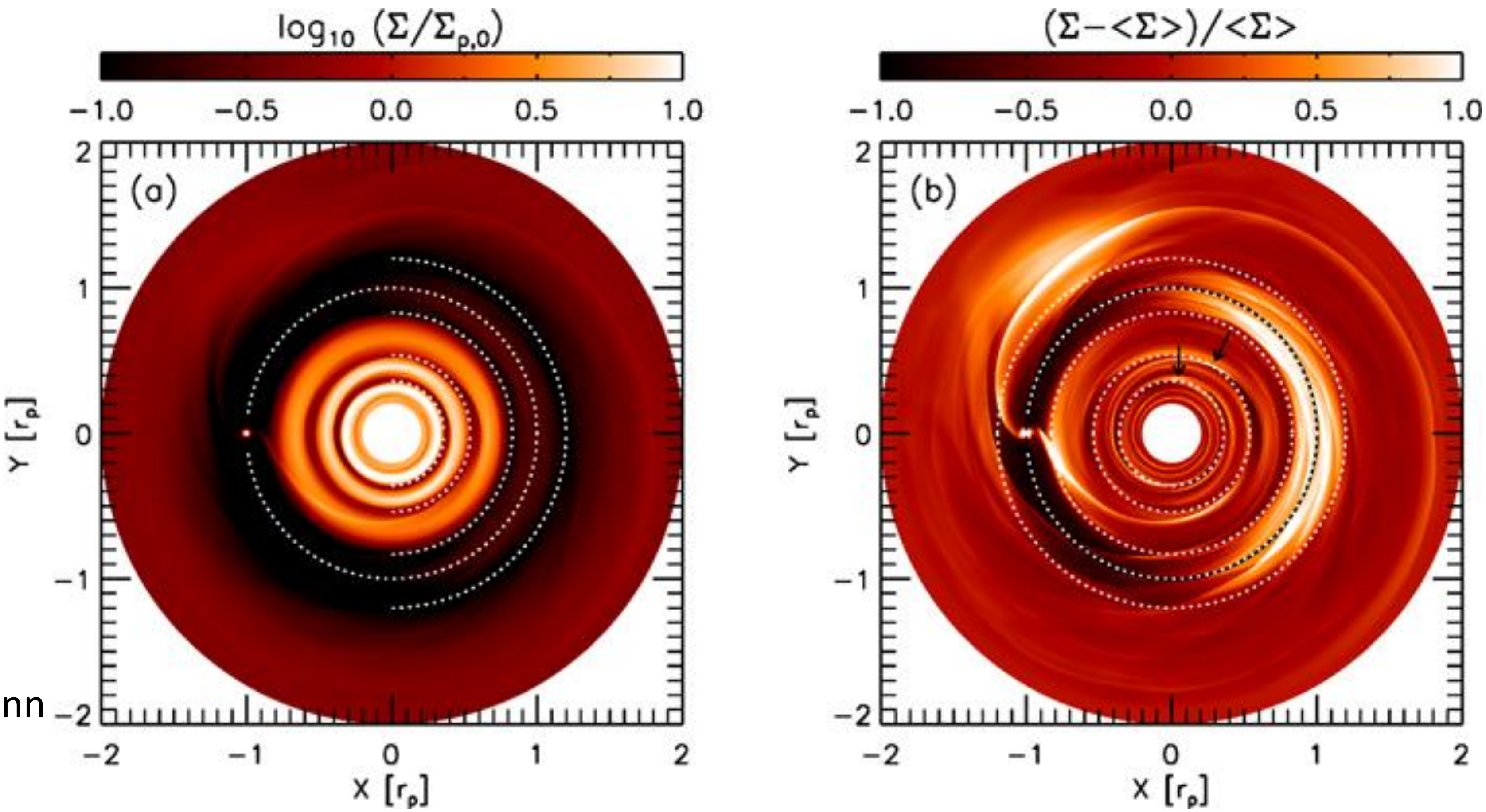
- By x 10^{13} in scale!
- Electrostatic sticking
- Collisional melding – tricky:
  - shatter wins over sticking
  - meter size barrier
  - do big things even stick?
  - **maybe vortices pull stuff together**
- Gravitational accretion

Disk Vortices To The Rescue?



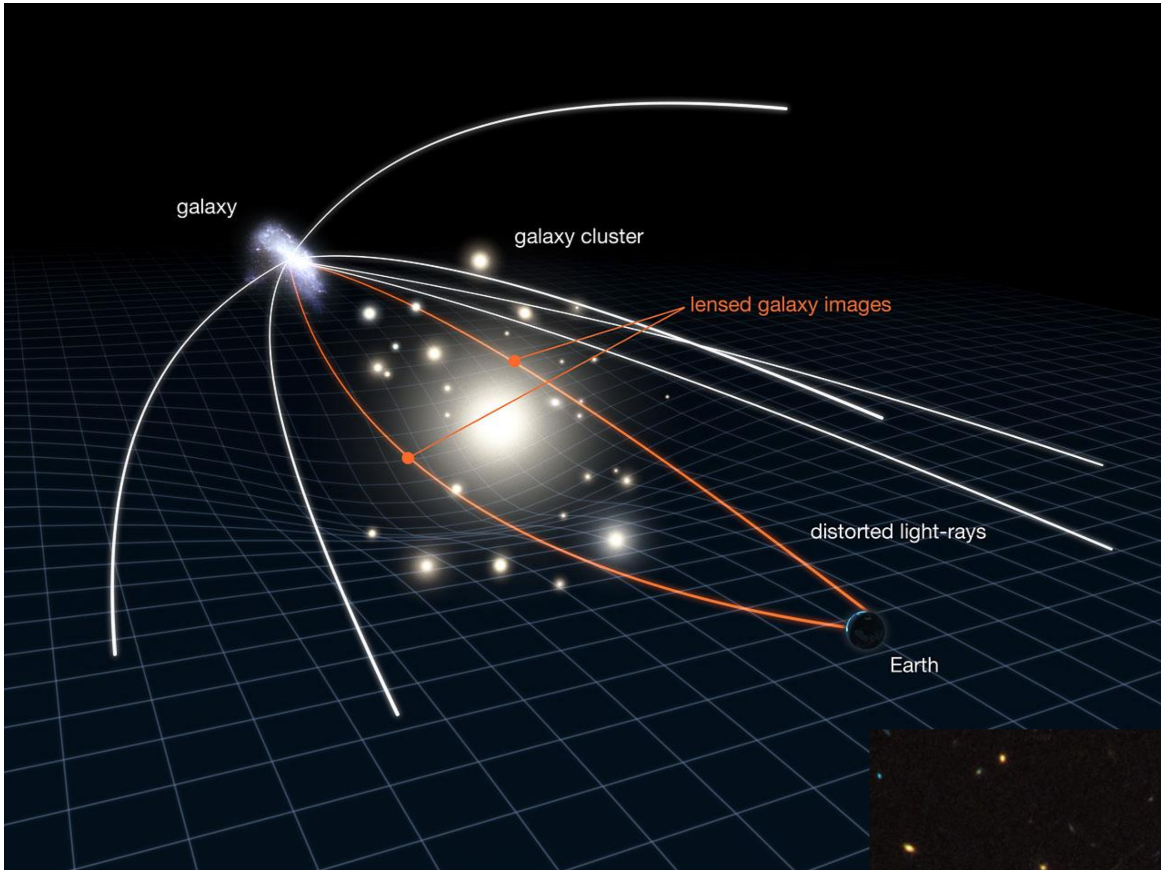
Major Issues: Gaps

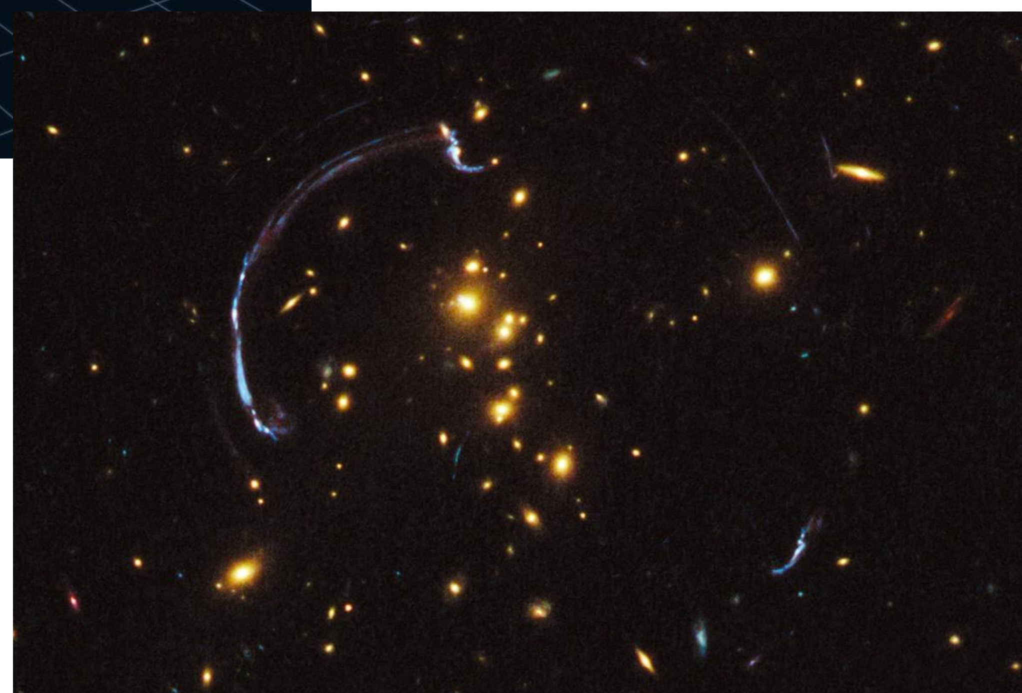
- Planets open gaps
- **One planet can open multiple gaps** – interior and exterior to orbit



Bae, Zhu, & Hartmann

Earendel


galaxy
galaxy cluster
lensed galaxy images
distorted light-rays
Earth



Earendel

- NIRCam image reveals “Sunrise arc”, a gravitationally lensed image of a galaxy
- Contains a B star (twice as hot as Sun, million times more luminous) from within 1 billion years of Big Bang [brightened by x4000 due to lensing]: most distant star ever detected
- **Originally found by HST, but JWST data suggests a companion red star, consistent with massive stars often being binary**
- **Patches of light on either side of Earendel are two images of one star cluster 10 million years old; we are probing the earliest stars to form in the Universe**

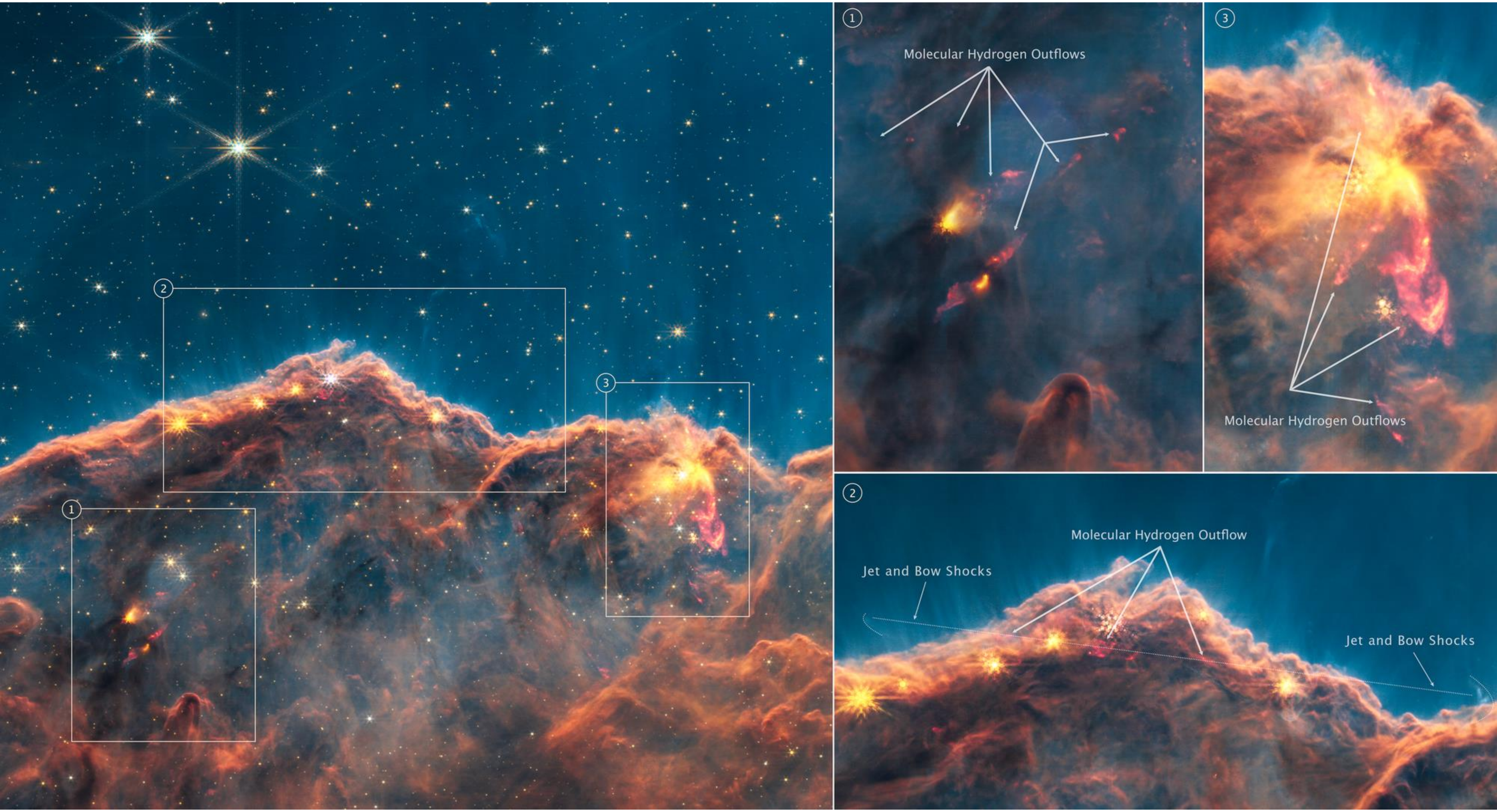

NGC 346

NGC 346

- MIRI image of cool gas and dust in a star forming region in SMC
- Blue* is emission from silicates and PAHs; red* is warmer dust heated by stars
- Filaments are regions with a high density of protostars (over 1000 identified)
- **Widely thought the SMC is less evolved than Milky Way – fewer heavy elements – less dust – this will cause a rethink!**
- **Will help us understand "cosmic noon" when there was less dust around, but star formation peaked**

* "false colors"

Cosmic Cliffs



Cosmic Cliffs

- NIRCam observation of “Cosmic Cliffs”, a large gaseous cavity within star cluster NGC 3324 (NW of the Carina nebula, at about 9,000 ly)
- Reveals several dozen jets and outflows from stars in formation within the “cliffs”, interpreted using detailed exploration with multiple filters
- **Gives new insight into just how active star forming regions are, and the demographics of young star systems**

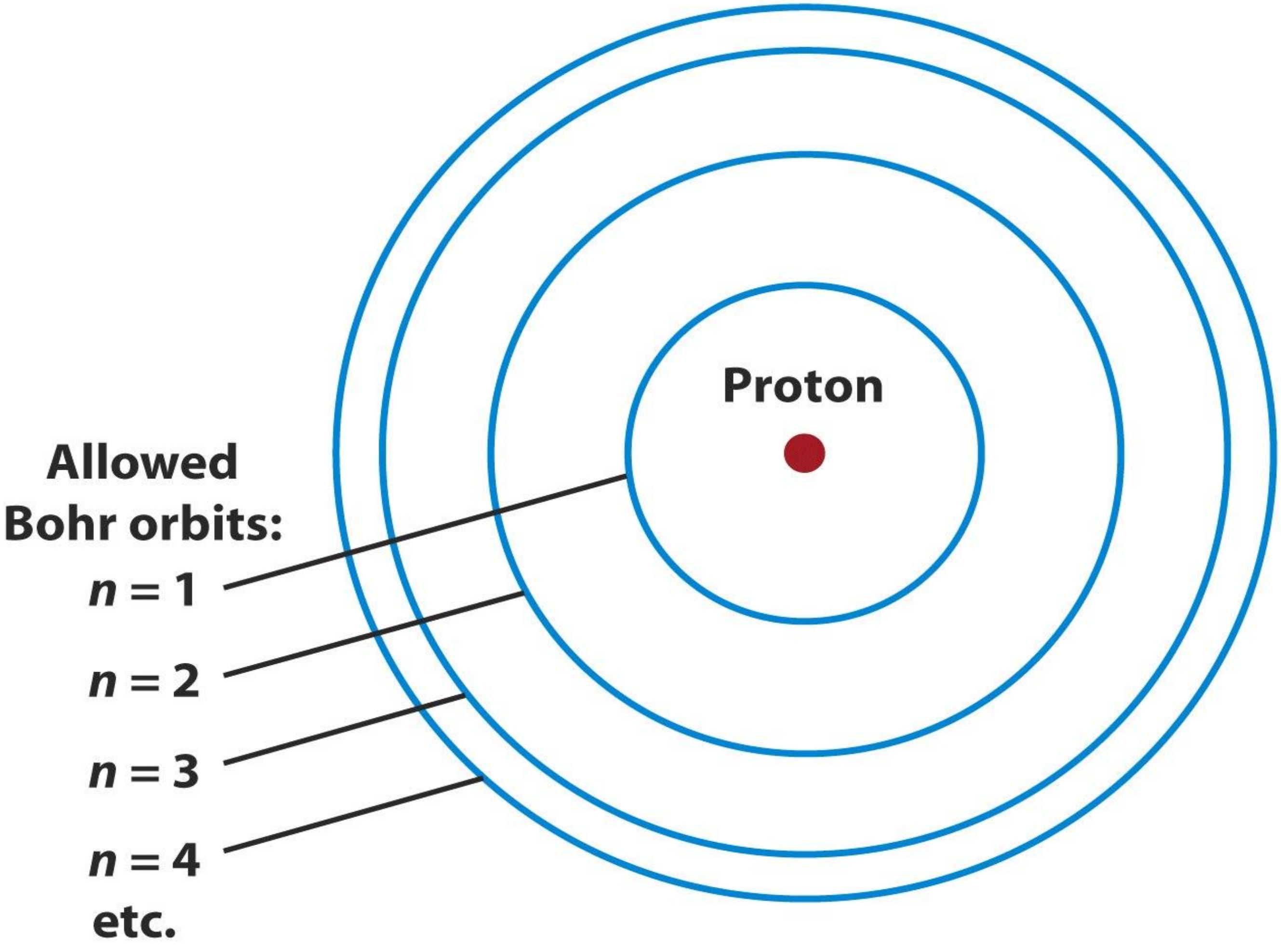

Orion Disk
MIRI Mid-Infrared
NIRCam Near Infrared
MIRI and NIRCam

Orion Disk

- NIRCam & MIRI observations of a protoplanetary disk in the Orion star forming region, 1350 ly away
- Detect the methyl cation (CH_3^+) molecule
- Initiates the growth of carbon-based molecules
- **Major impact on our understanding of interstellar chemistry (in particular in the presence of UV radiation from hot stars) and the origins of life**
- Study by Felipe Alarcón and Ted Bergin

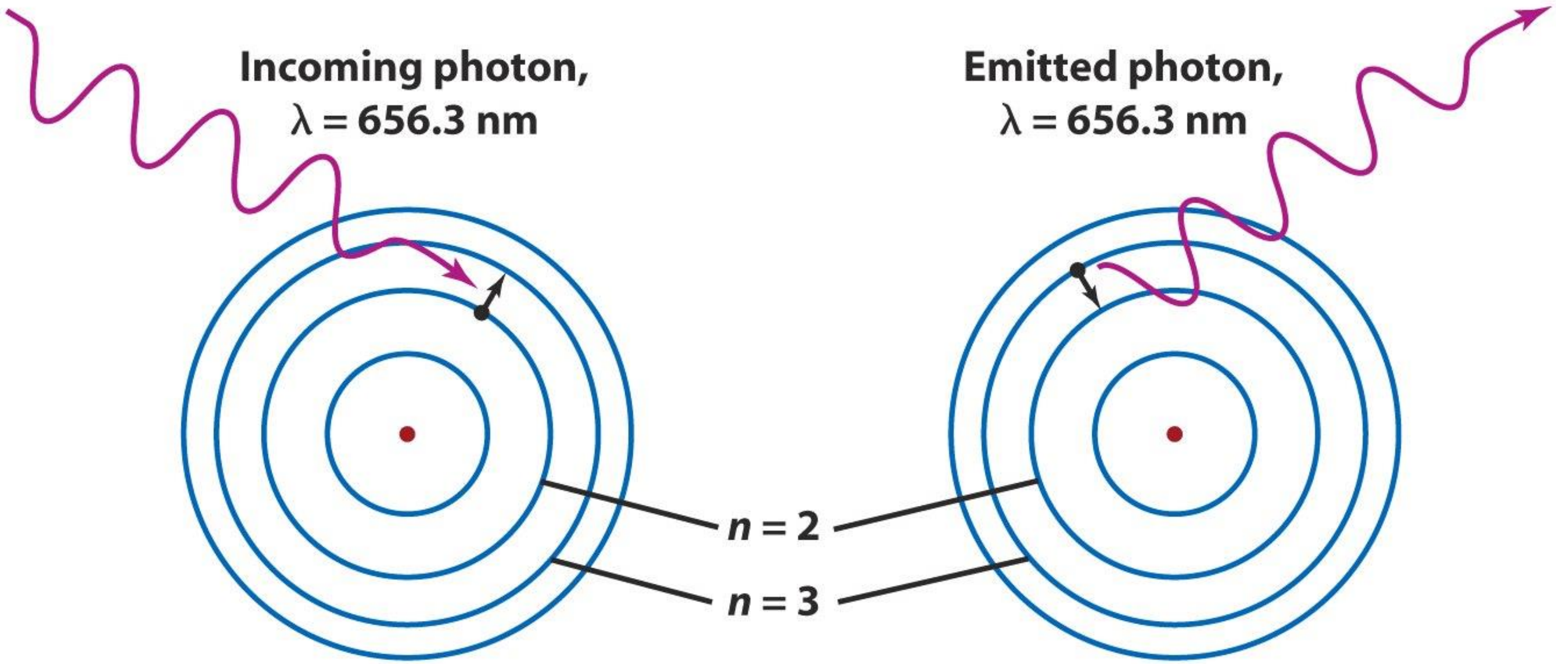
  (UM Astronomy)

Background: Spectra



Atom is quantized!

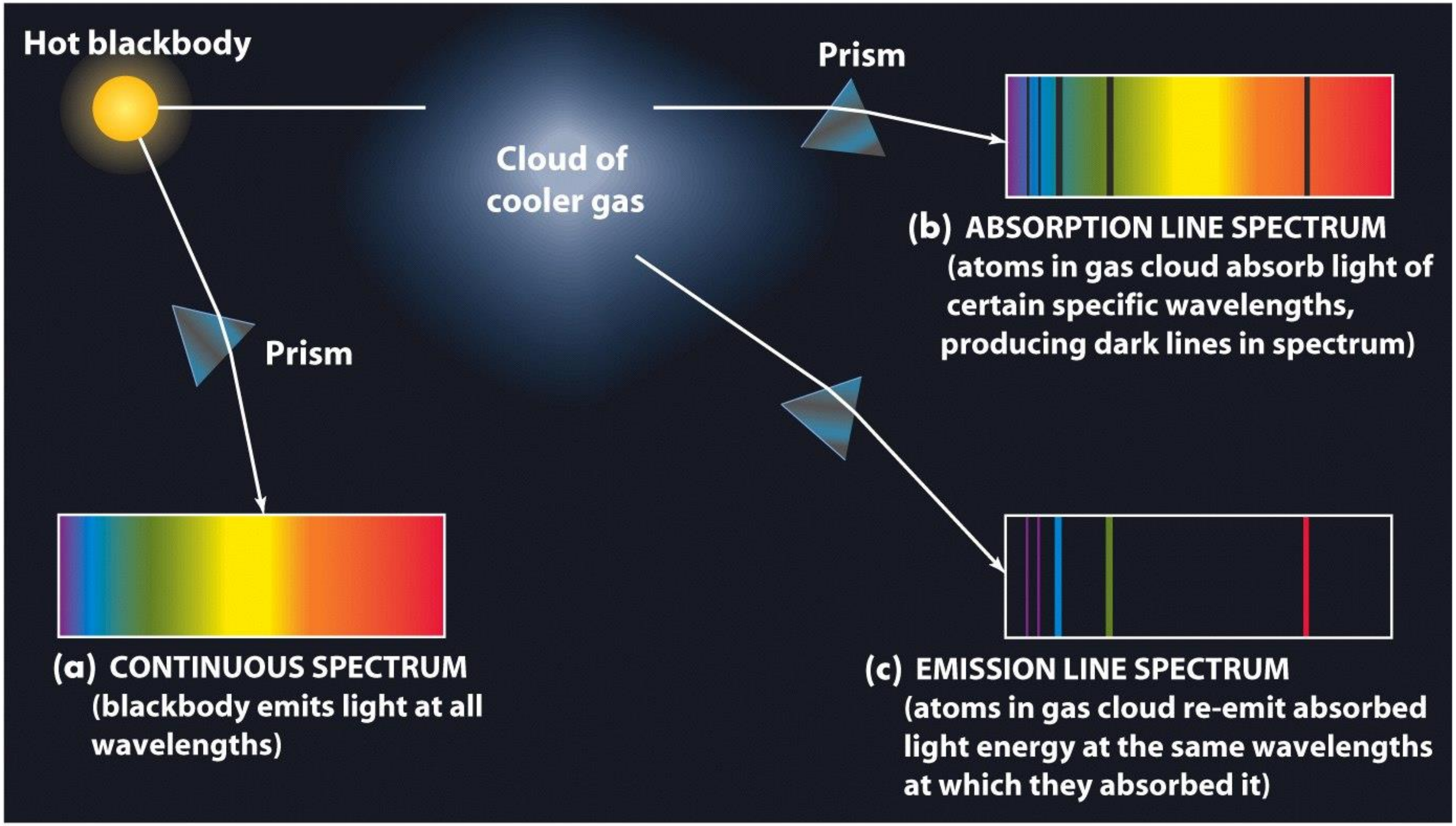
Background: Spectra



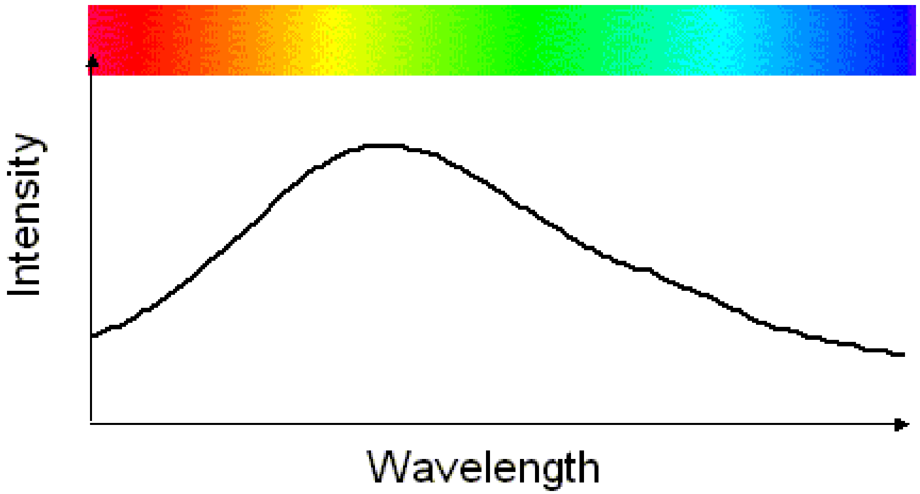
(a) Atom absorbs a 656.3-nm photon; absorbed energy causes electron to jump from the $n = 2$ orbit up to the $n = 3$ orbit

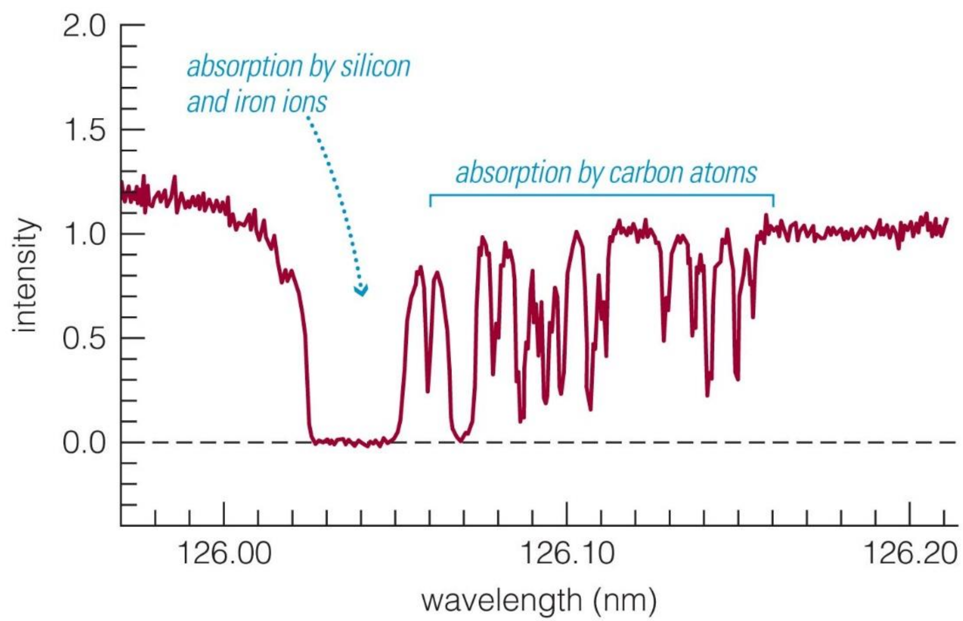
(b) Electron falls from the $n = 3$ orbit to the $n = 2$ orbit; energy lost by atom goes into emitting a 656.3-nm photon

Background: Spectra

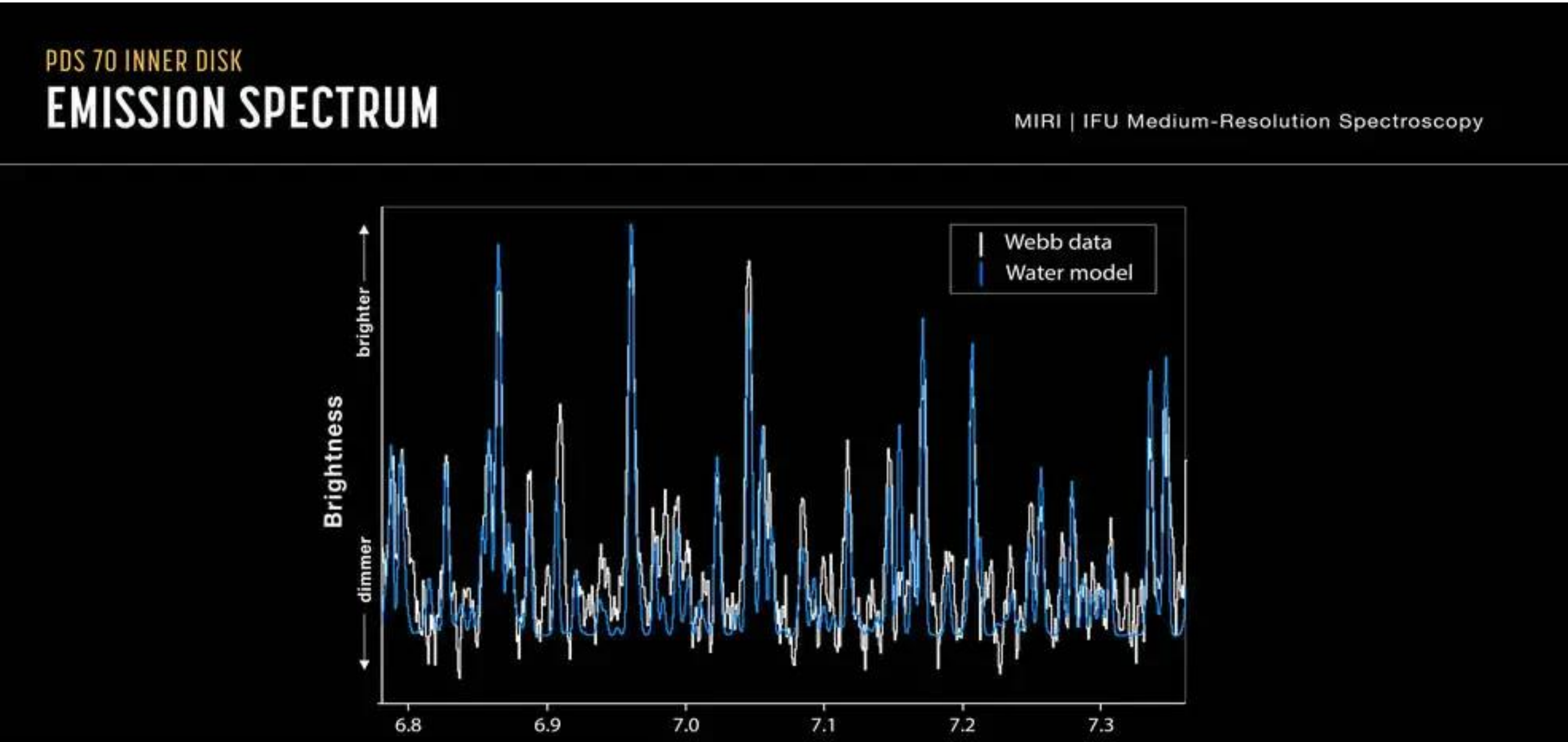


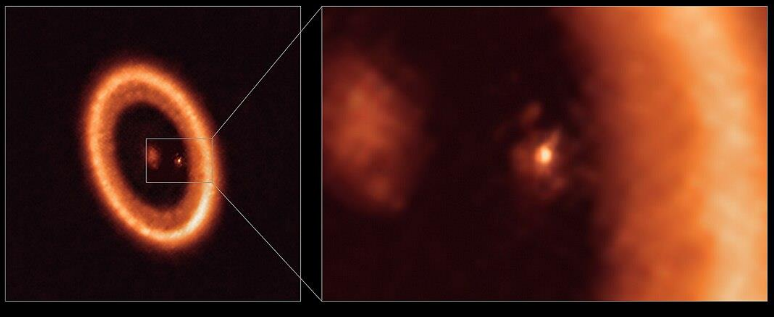
Background: Spectra





PDS 70


PDS 70 INNER DISK
EMISSION SPECTRUM
MIRI | IFU Medium-Resolution Spectroscopy
Webb data
Water model
Brightness
brighter
dimmer
6.8
6.9
7.0
7.1
7.2
7.3
Wavelength of Light
microns
WEBB
SPACE TELESCOPE



ALMA

PDS 70

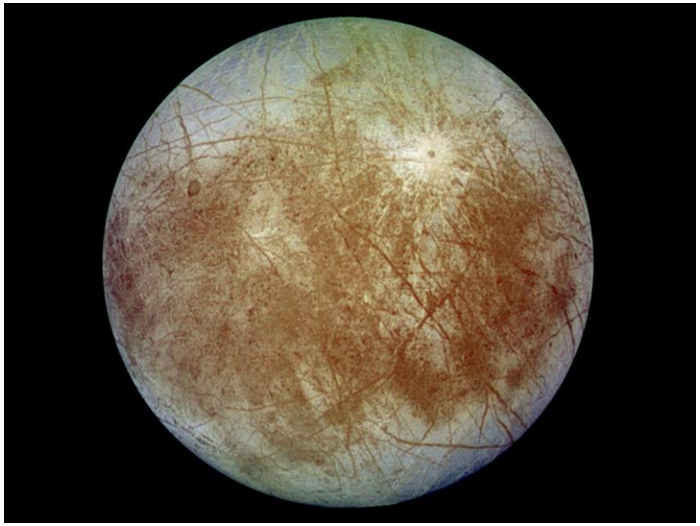
- MIRI observations of a young star with gapped disk with two giant planets, 370 ly away
- Detects water vapor in inner disk, where terrestrial type planets might be forming
- **Motivates new lines of thought: did the water form in place, or get carried in on ice-coated particles; does dust help it survive UV radiation from star?**
- **Maybe terrestrial planets have access to water from their formation**

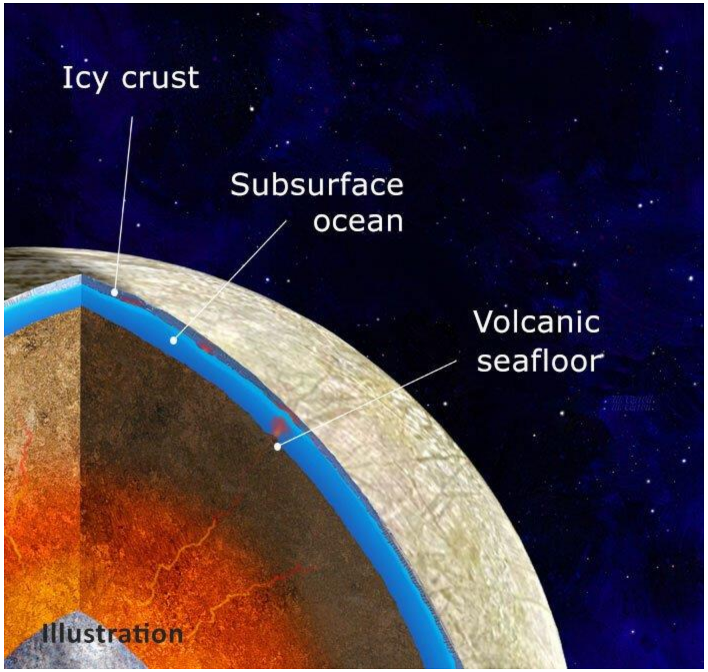
HH 211

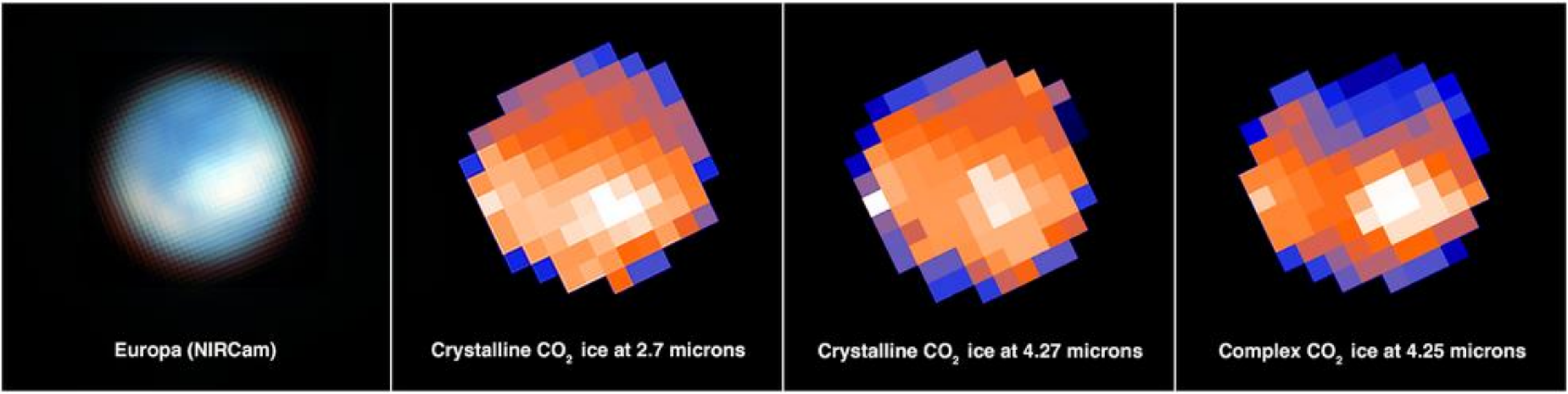
HH 211

- NIRCam image of Herbig-Haro 211
- Reveals bow shocks with unprecedented detail from an infant star; <10% solar mass, 10,000s years old
- Note knotty, wiggling supersonic core flow (cf. water jet); binary star?
- Innermost flow is ~100 km/s; not enough energy to break apart molecules, so we now know these are molecular flows
- **Such observations are better-defining composition and dynamics of these bipolar flows**

Europa



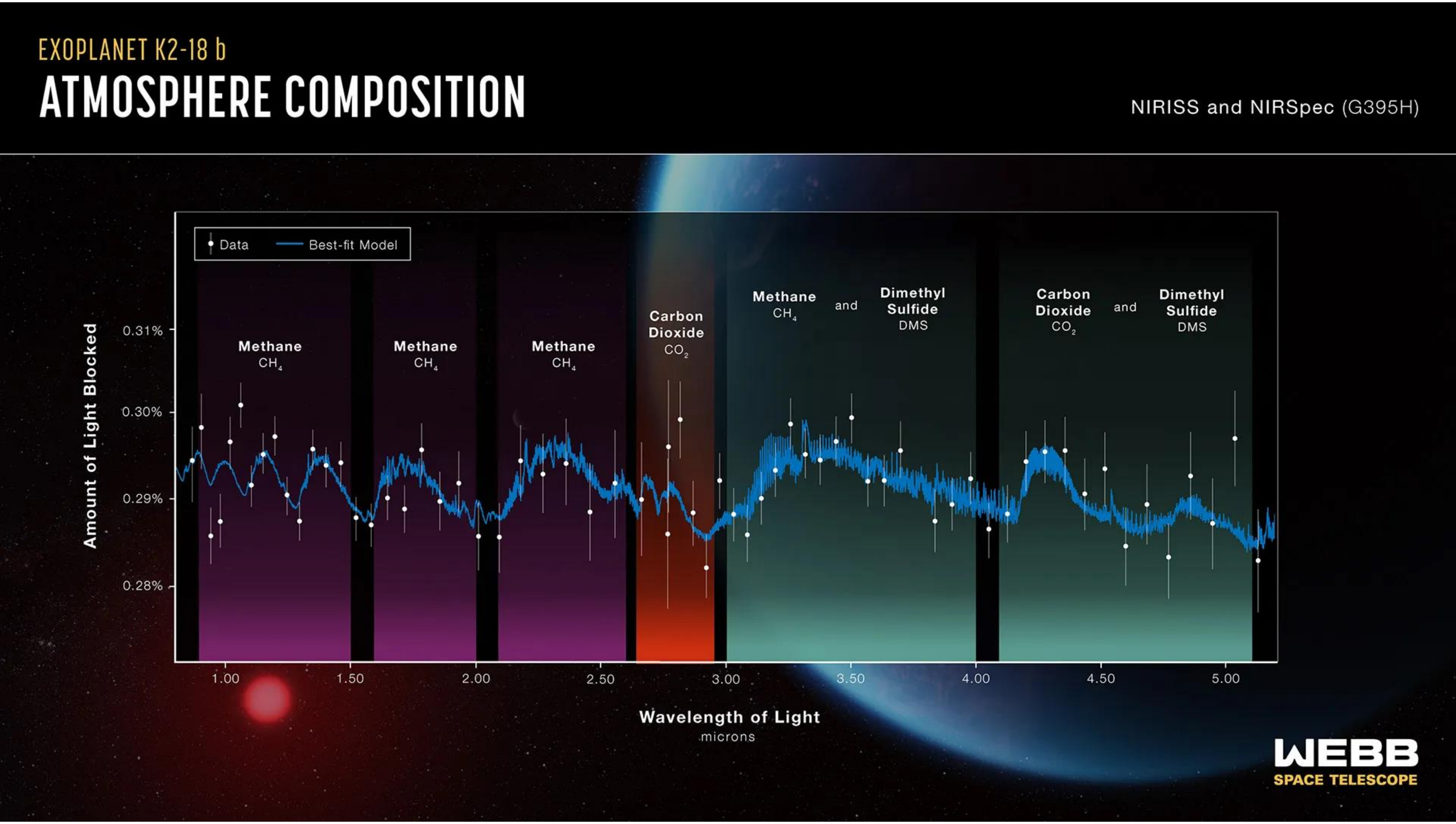

Icy crust
Subsurface ocean
Volcanic seafloor
Illustration


Europa (NIRCam)
Crystalline CO_2 ice at 2.7 microns
Crystalline CO_2 ice at 4.27 microns
Complex CO_2 ice at 4.25 microns

Europa

- Image from NIRCam, composition from NIRSpec
- Crystalline or amorphous CO_2 in chaos terrain
- From subsurface ocean, not delivered by meteorites! (Most abundant in disrupted chaos terrain area where an exchange between ocean and surface is likely)
- Recent! (CO_2 not stable on surface)
- **Bolsters the argument for life in Europa's ocean**

K2-18 b

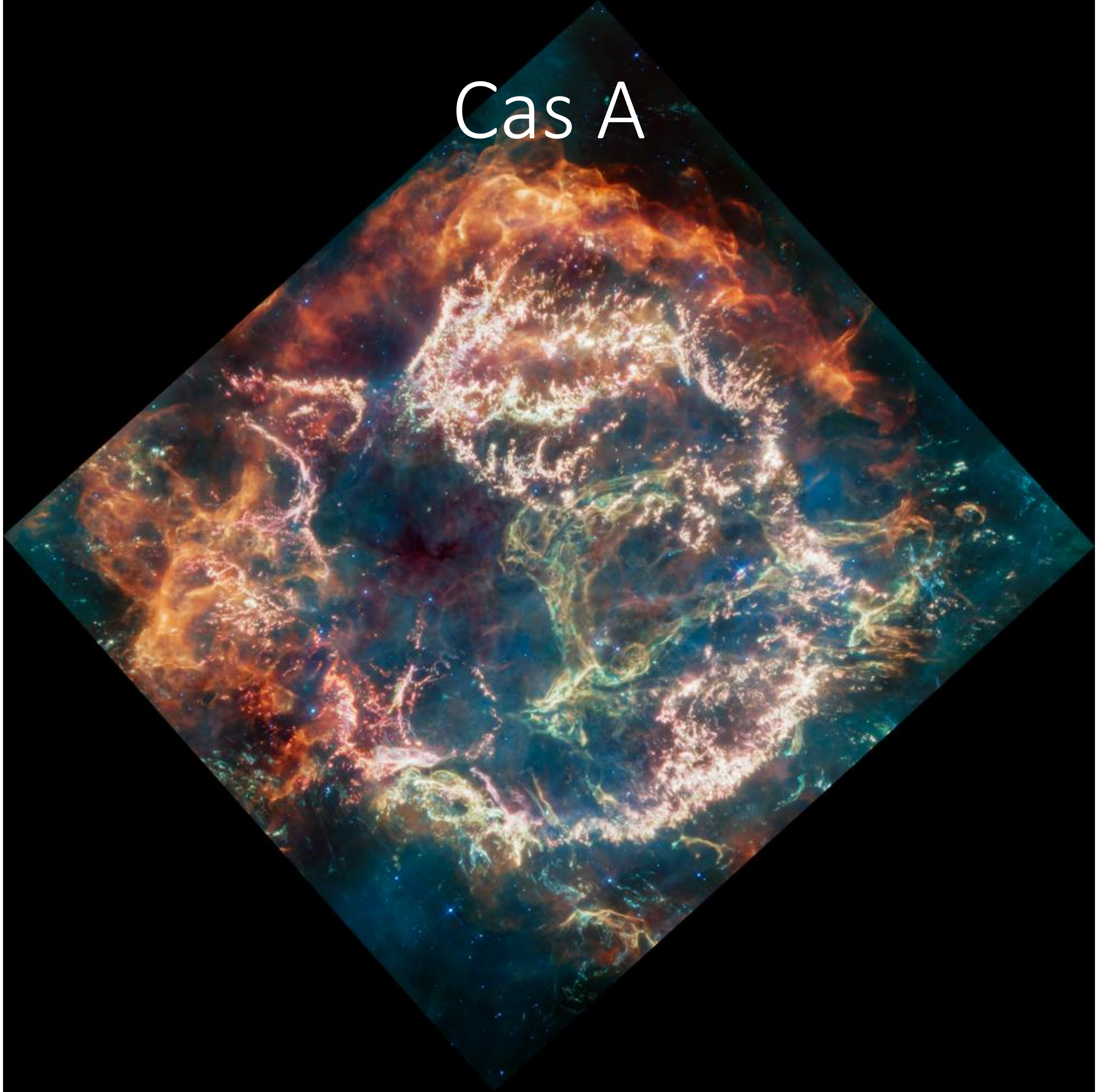

EXOPLANET K2-18 b
ATMOSPHERE COMPOSITION
NIRISS and NIRSpec (G395H)
Data
Best-fit Model
Methane
CH_4
Methane
CH_4
Methane
CH_4
Carbon Dioxide
CO_2
Methane
CH_4
and
Dimethyl Sulfide
DMS
Carbon Dioxide
CO_2
and
Dimethyl Sulfide
DMS
Amount of Light Blocked
0.31%
0.30%
0.29%
0.28%
1.00
1.50
2.00
2.50
3.00
3.50
4.00
4.50
5.00
Wavelength of Light
microns
WEBB
SPACE TELESCOPE

K2-18 b

- NIRSpec study of atmosphere of exoplanet K2-18 b
- Planet is about 8 M_{earth}, about 120 ly from Earth, and in habitable zone of its star
- Complements studies suggesting Hydrogen rich atmosphere above water ocean surface
- Tentative identification of dimethyl sulfide – found on Earth only due to life: mostly phytoplankton
- **Large planet mass suggests ocean might be too hot for life – but DMS is intriguing and shows how much exoplanet atmosphere studies have advanced**

1.5 sigma result – shameless self-promotion

Cas A



Cas A

- MIRI image of supernova remnant Cas A, 1100 ly away; image is about 10 ly across

(Massive stars end their life as a supernova + neutron star, black hole, or "nothing")

- Youngest known remnant in Milky Way: 340 years ago from Earth's perspective
- Unprecedented resolution and wavelength coverage

Cas A

- Different colors depict emission from different elements:
- Exterior orange/red is emission from warm dust where stellar stuff is ramming into circumstellar medium
- Interior clumps and knots (pink & white) is stellar material with oxygen, argon, neon, etc. made in the explosion
- **Allows "stellar autopsy" to find out about original star, how it exploded, and origin of elements/dust**

Next Week….

More science: galaxy formation & cosmology