Star Formation

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Hubble, Eagle Nebula

“STAR” Formation and Evolution in L.A. ?

Picture of Drew Barrymore in E.T. → Picture of Drew Barrymore in movies today

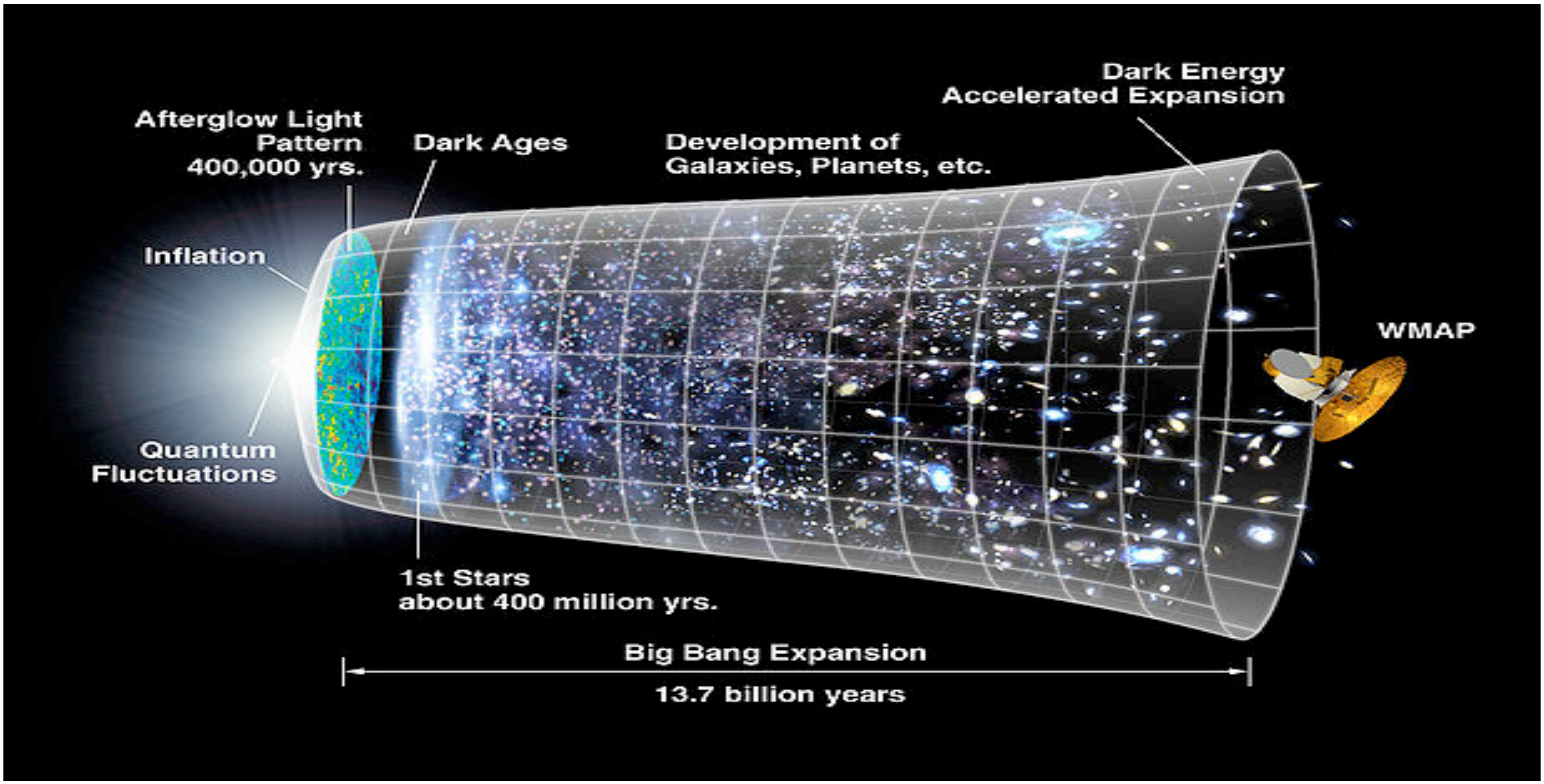
Not the type of “stellar evolution” I’ll be talking about today.

STAR FORMATION: Just the Facts!

- 10 stars forming per year in the Milky Way Galaxy
- Stars like to form in groups or clusters
  - Tend to have similar ages, compositions
- Stars become visible after they have been hidden in their cocoon for about 100,000 years.
- Stars form with a range of masses.
  - 0.1 – 50 M_{sun}
- Planets are a by-product of star formation.

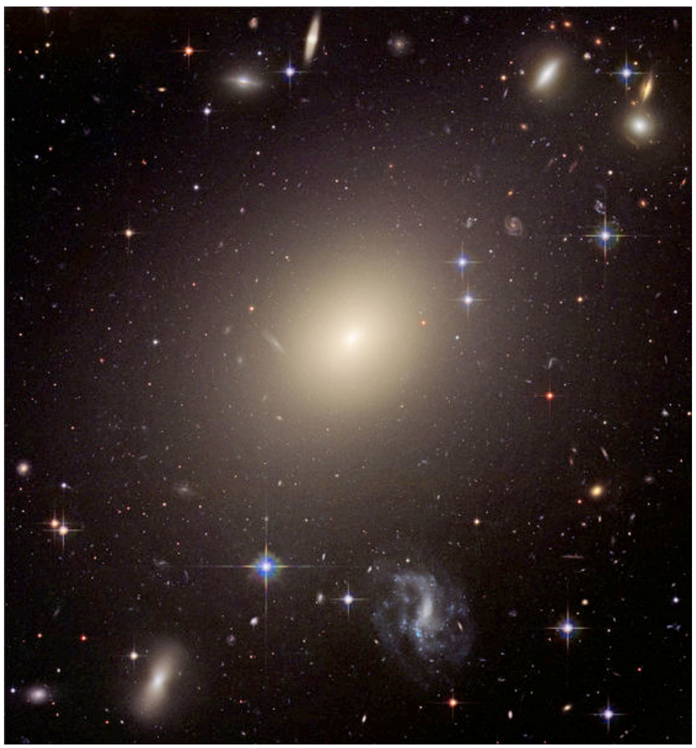
Star Formation – Who Cares?

- Cosmology – Signals end of Dark Ages



Star Formation – Who Cares?

- Galaxy → $>10^{11}$ stars
  - Galaxies composed of stars.



Elliptical

vs.

Spiral

Hubble images

Star Formation – Who Cares?

- Milky Way Galaxy Experts
  - What is the history of the evolution of the galaxy?
  - Did stars form differently in the Milky Way's past?
    - Different conditions, materials
- Planet Hunters/Theorists, Earth/Planetary Scientist
  - Planets and stars form concurrently

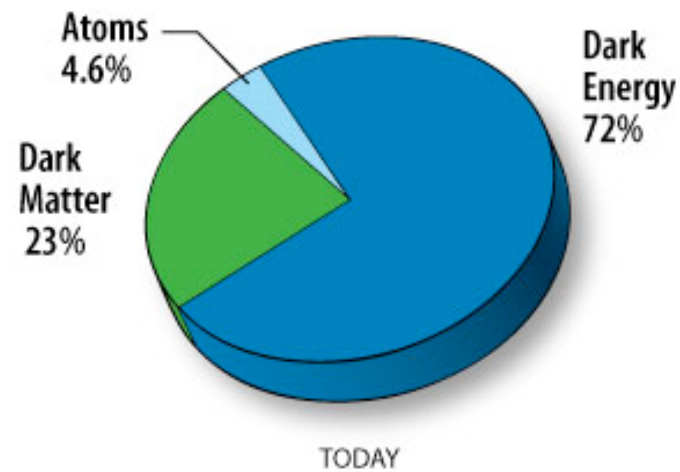
How to Make Stars – A Recipe

- Ingredients – H_2, CO, + a dash of dust
- Physical Conditions – Set oven to 10K
- Process – Stir and let gravity take over

Periodic Table (or Ingredients)

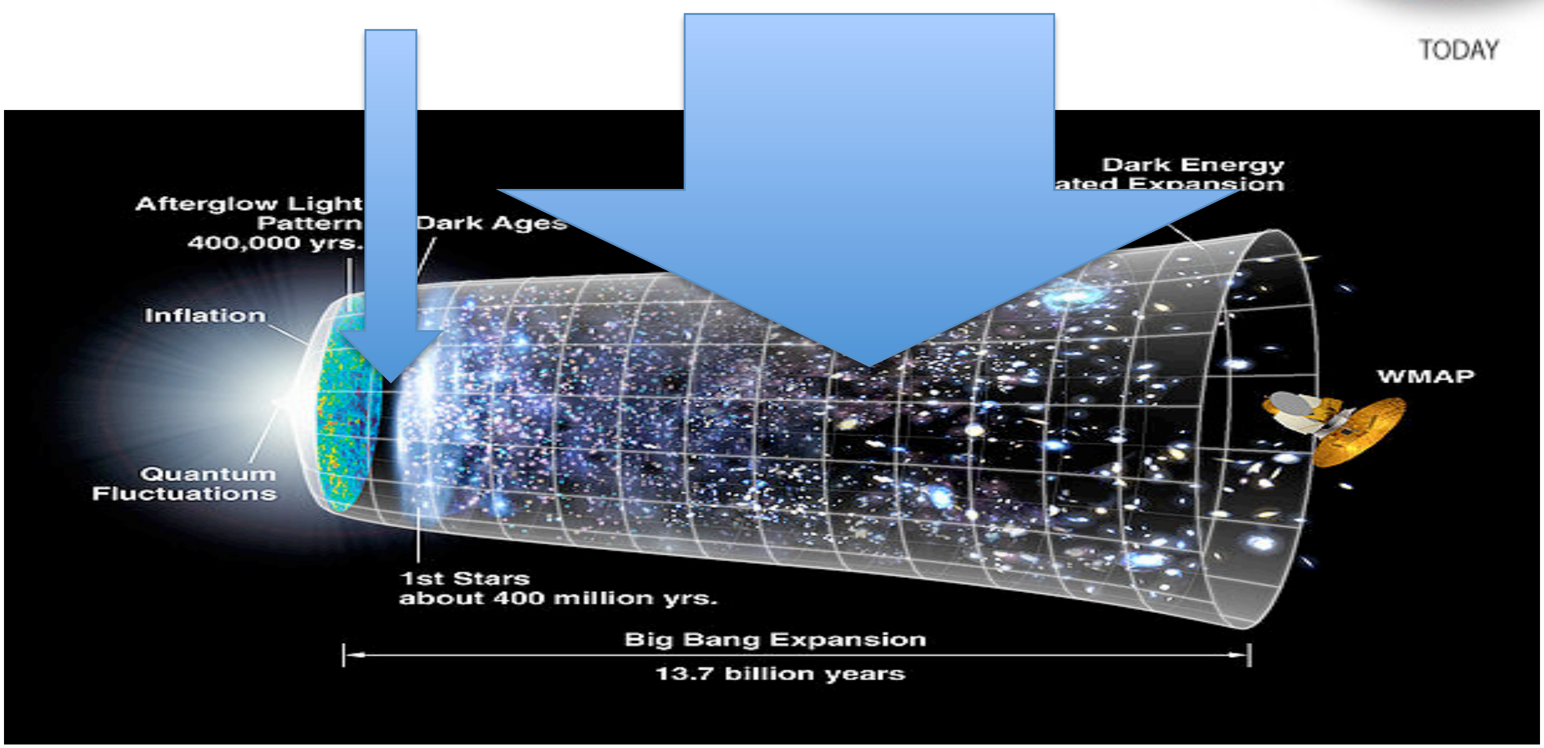
1	1 H																		2 He
2	3 Li	4 Be												5 B	6 C	7 N	8 O	9 F	10 Ne
3	11 Na	12 Mg												13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
4	19 K	20 Ca		21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
5	37 Rb	38 Sr		39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
6	55 Cs	56 Ba	*	71 Lu	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
7	87 Fr	88 Ra	**	103 Lr	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 Uub	113 Uut	114 Uuq	115 Uup	116 Uuh	117 Uus	118 Uuo
*Lanthanoids			*	57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb		
**Actinoids			**	89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No		

Composition of the Universe



Where did the Atoms come from?

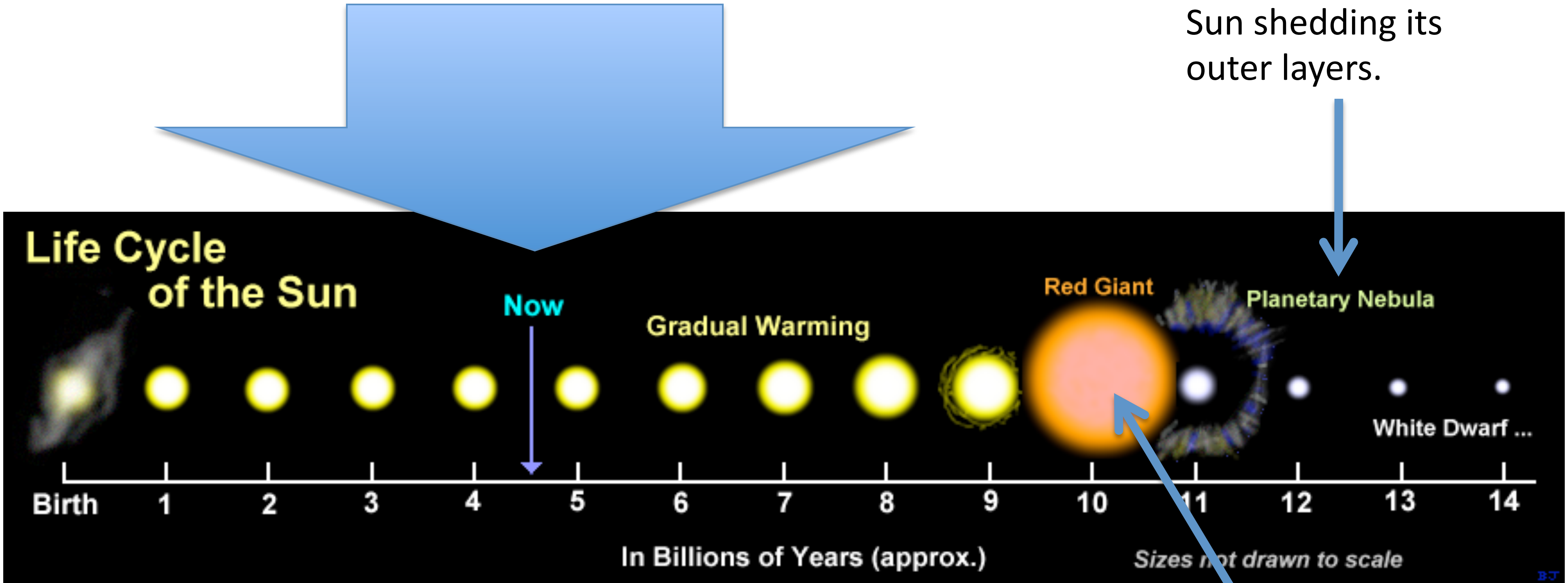
Number of Atoms
90% Hydrogen H, He
10% Helium + everything else



The Sun -- Our Closest Star

- Fusion of H → He

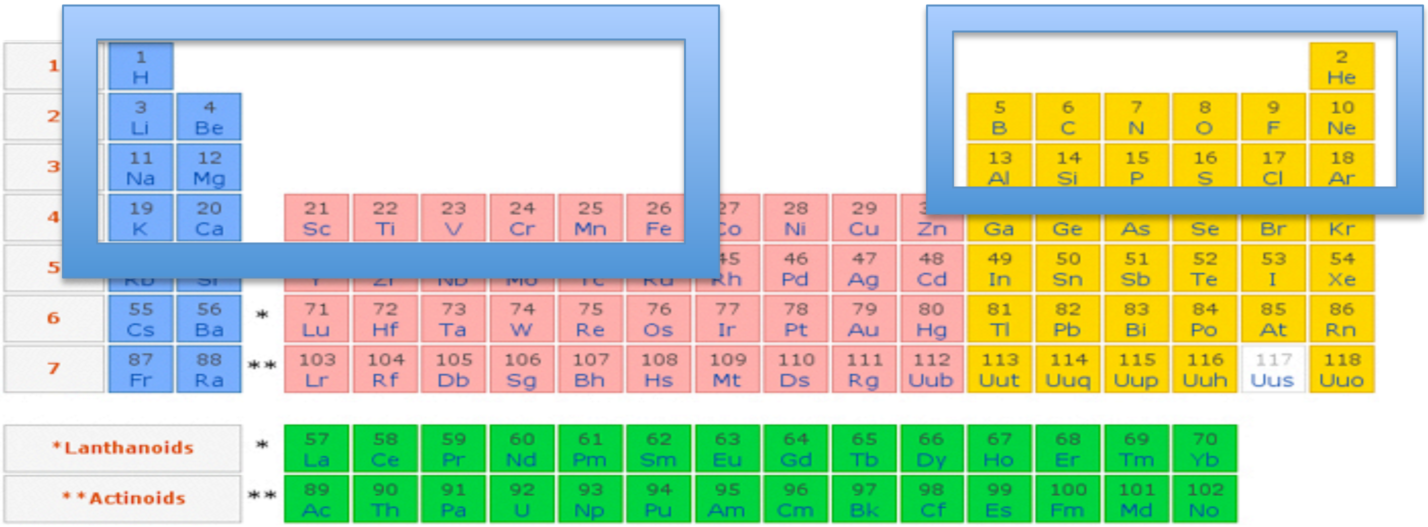
Planetary Nebula:
Nothing to do with planets.
Sun shedding its outer layers.



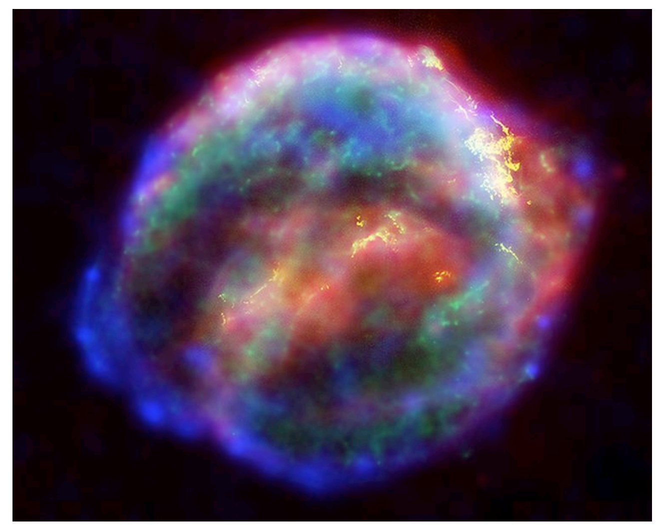
Out to Earth's orbit

Note: "Gradual Warming" not equal to "Global Warming"

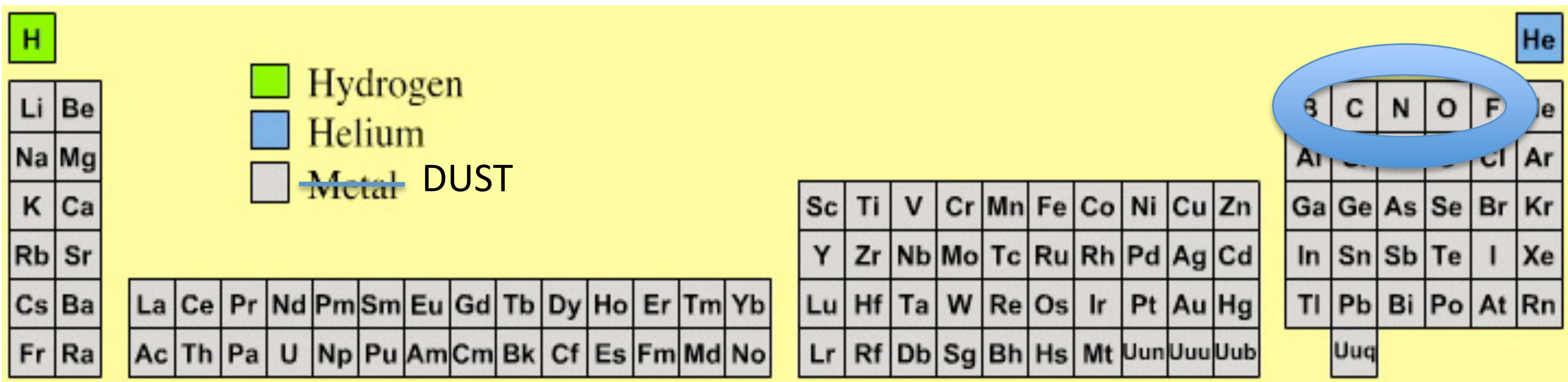
- Stars of different mass produce all of the elements from He to Iron



- Need energy of Supernova to more massive than Iron
  - Kepler Supernova Remnant



Ingredients of Star Formation



Composition:

GAS: 71% in the form of $\mathbf{H_2}$ **,** 27% in He , 1% C, N, O …… , 1% Dust

C, N, O: mostly **CO** Plus other molecules (over 100 detected, alcohol, formaldehyde)

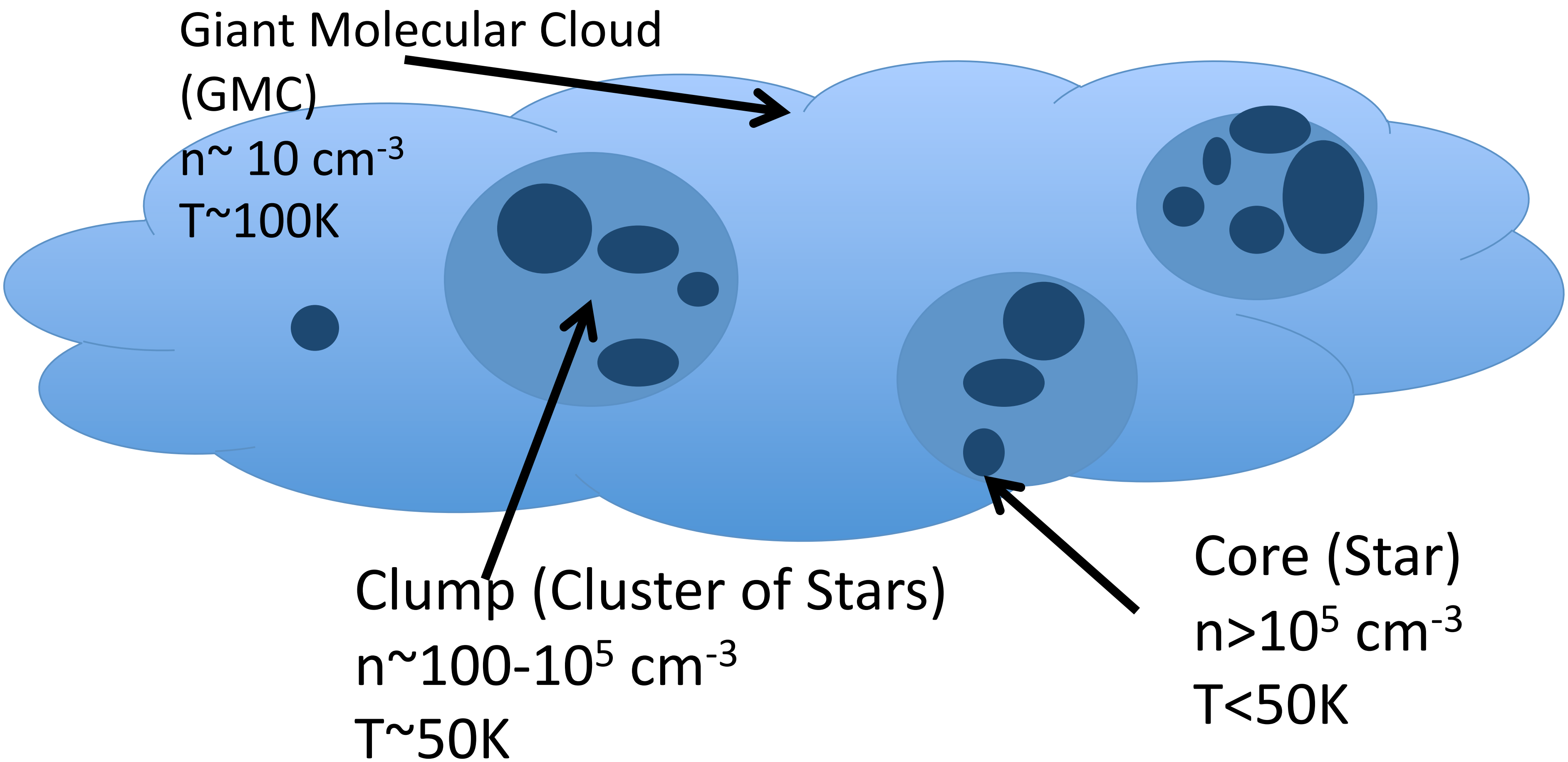
DUST: ~0.1 micron, silicate, carbonaceous grains, some with ice mantles, …

Initial Conditions – Interstellar Medium (ISM)

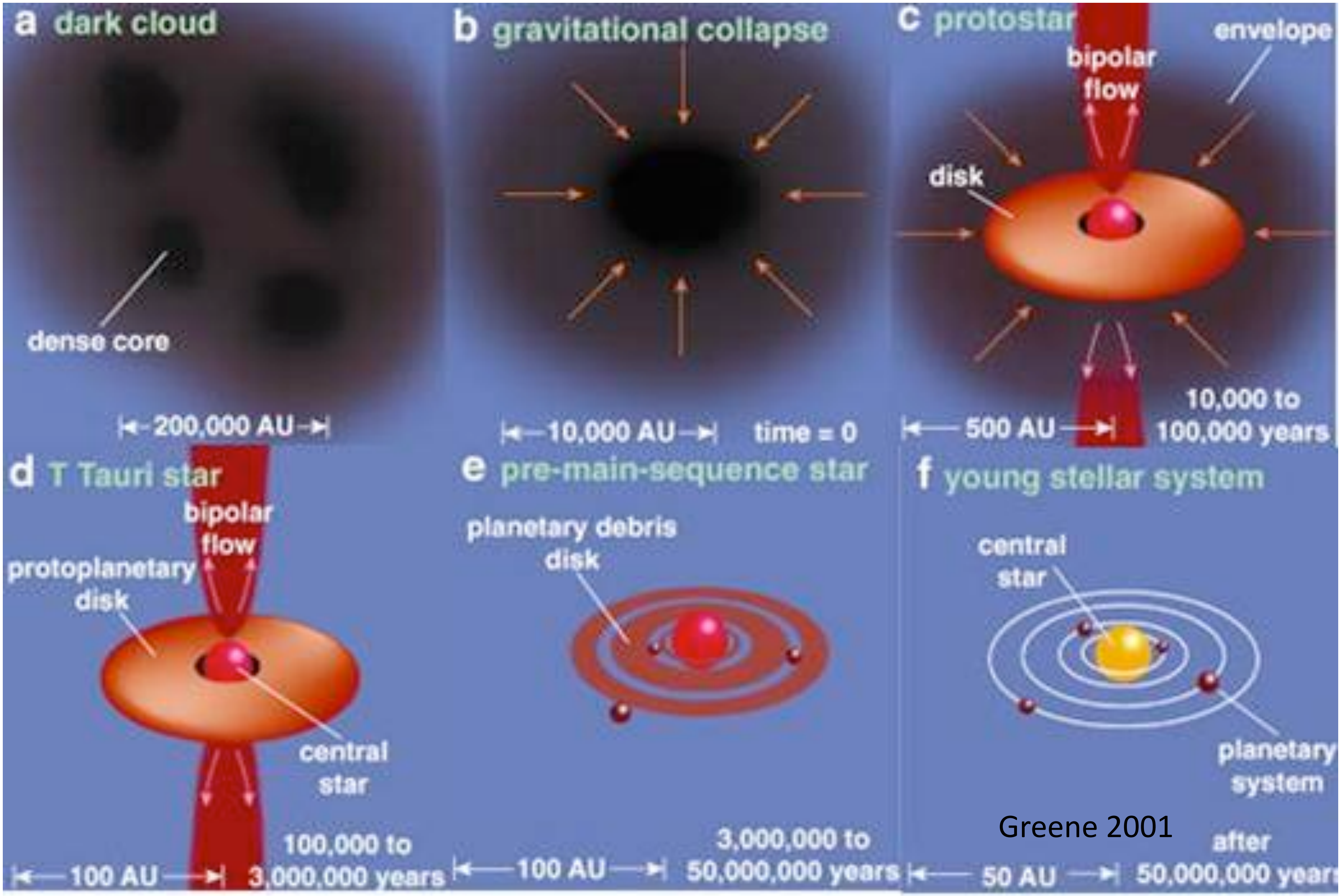
- Temperatures <10K to >1,000,000K
  - 0K = absolute 0
- Densities 0.01 – 1,000,000 particles/cm^3 (and higher)
  - START: VERY LOW DENSITY - ISM
    - Compare with density of air on Earth 1kg/m^3 or 10^{18} particles/cm^3, N_2, O_2
  - FINISH: HIGH DENSITY - STAR
    - To form a star, need to reach about the density of water 1g/cm^3 = 6 x 10^{23} H atoms/cm^3
- How does this compression/collapse happen?
  - In Stages…

Star Forming Regions

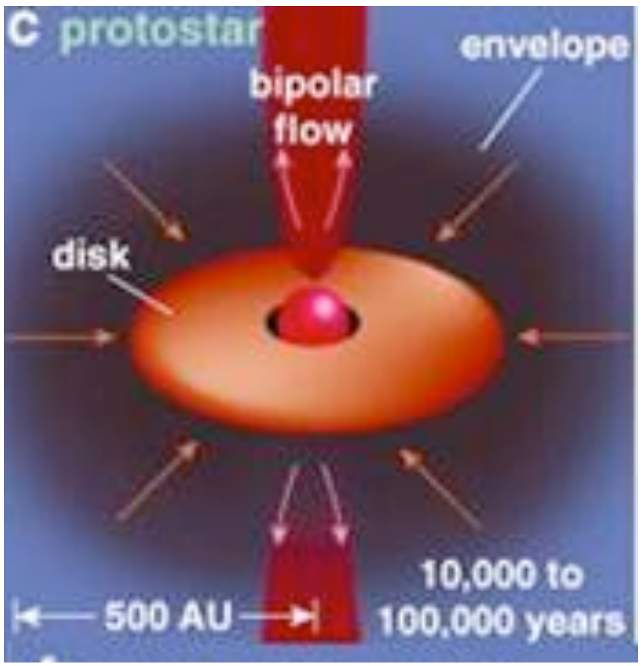
- Levels of Fragmentation

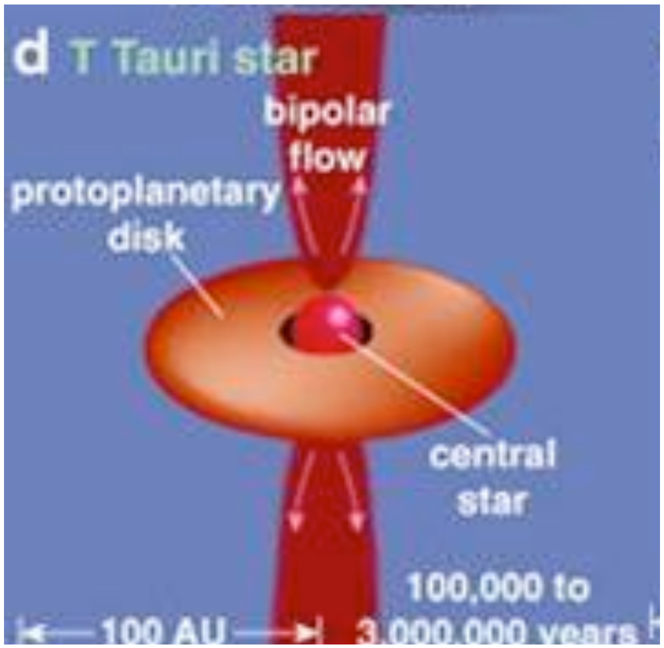


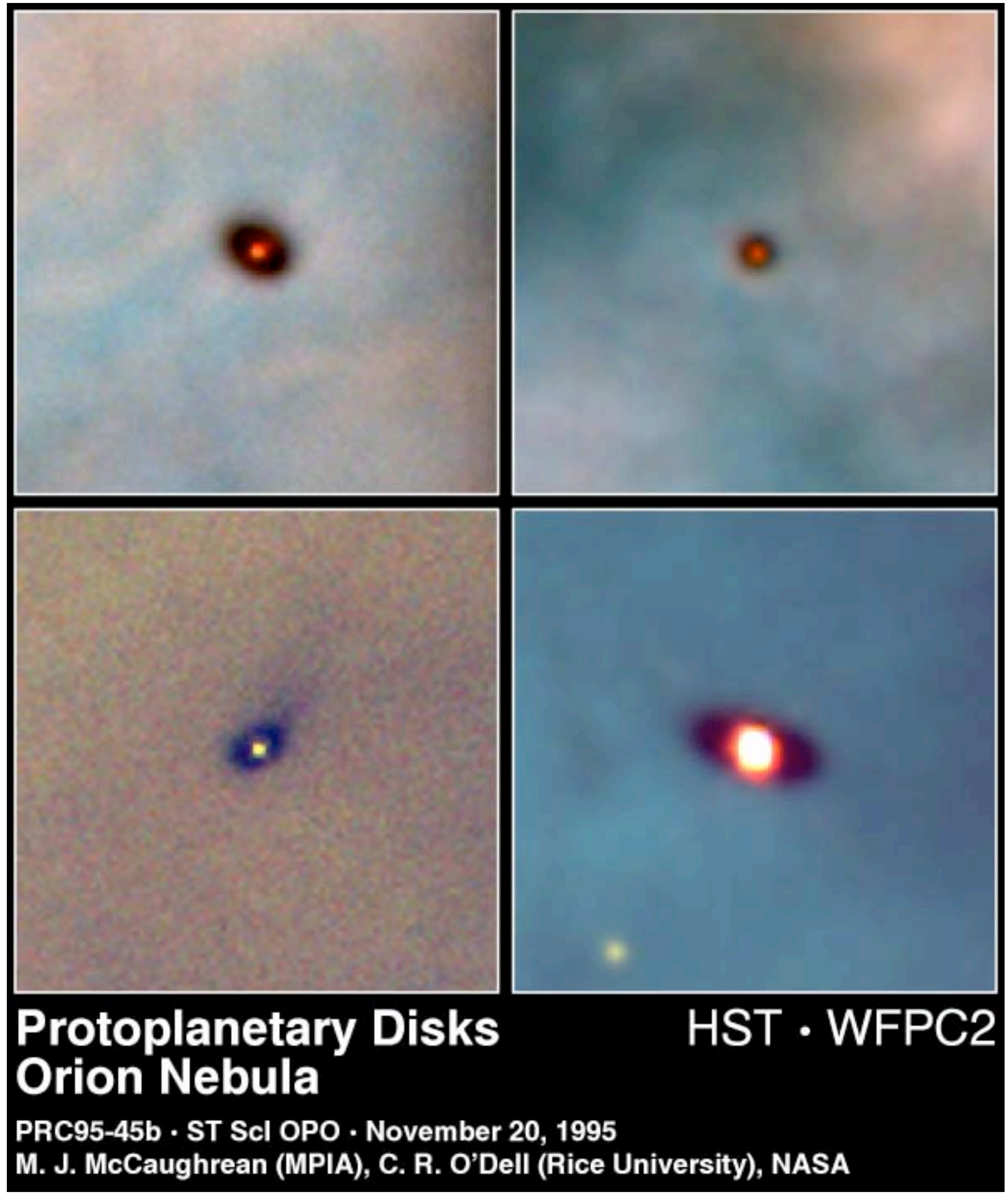
Star Formation Stages



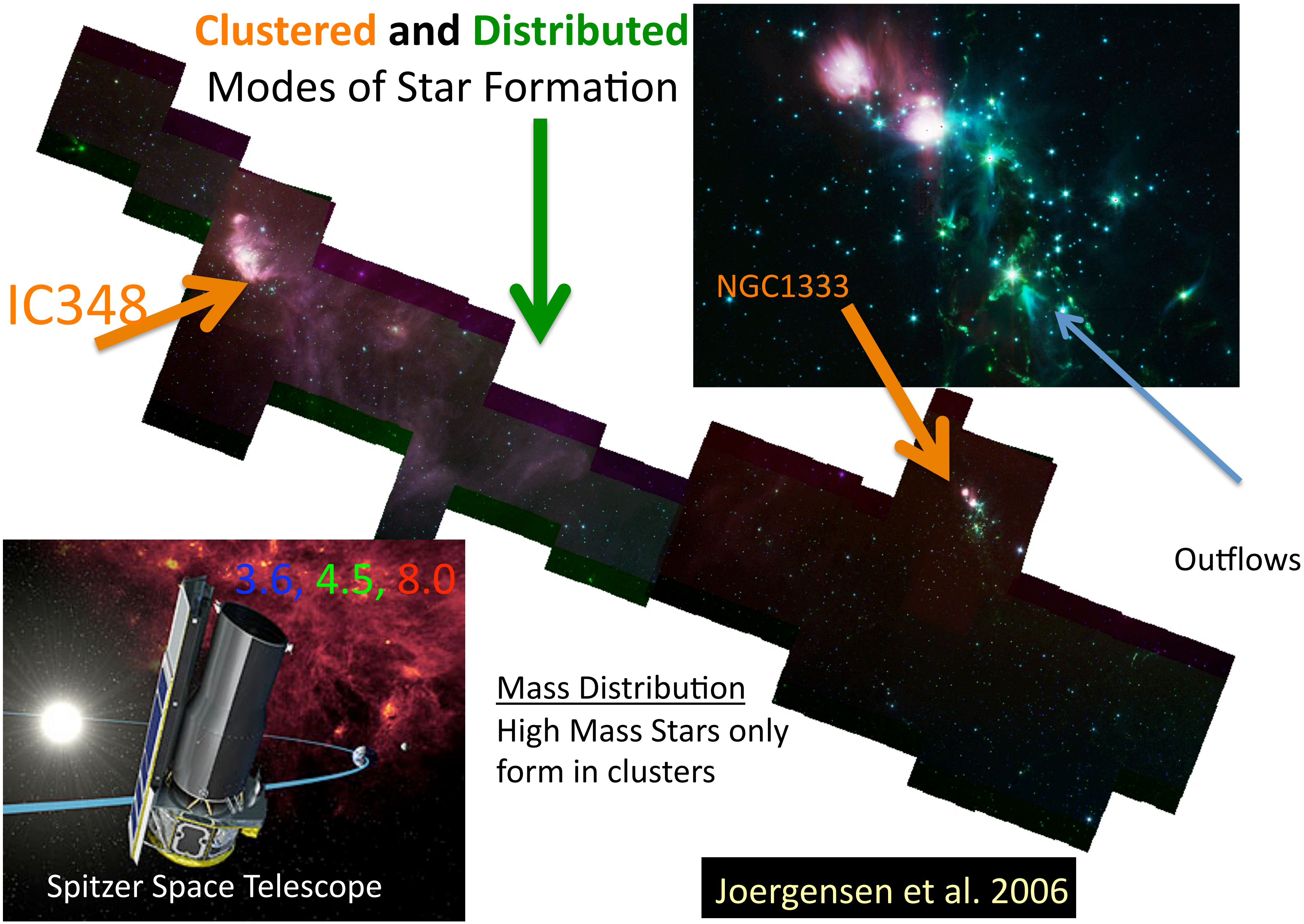
Outflow: HH 46/47

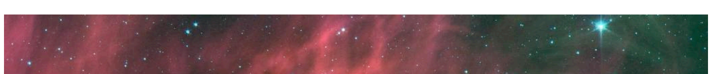



d T Tauri star
bipolar flow
protoplanetary disk
central star
100,000 to 3,000,000 years
100 AU


Protoplanetary Disks
Orion Nebula
HST • WFPC2
PRC95-45b • ST ScI OPO • November 20, 1995
M. J. McCaughrean (MPIA), C. R. O'Dell (Rice University), NASA

GMC: Perseus as seen by IRAC





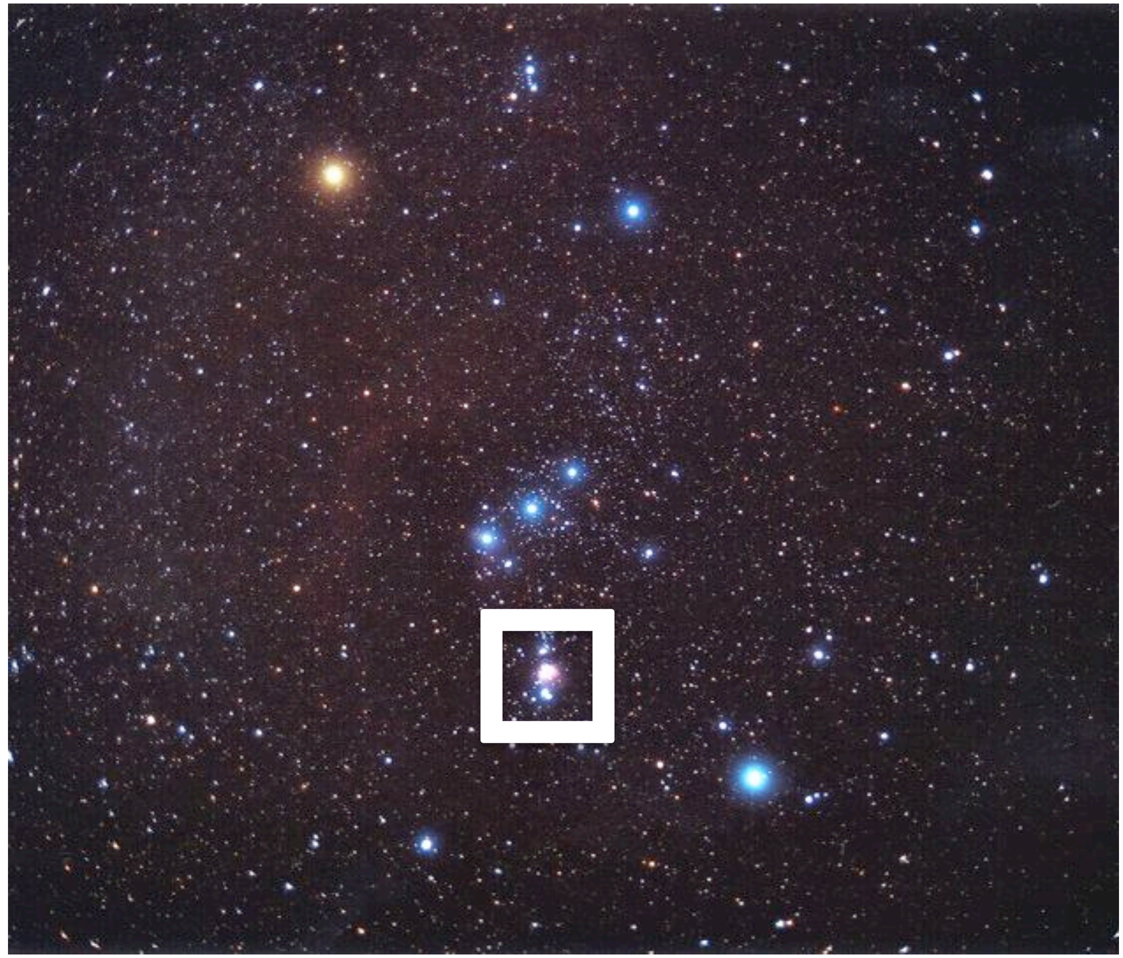
Orion – Clustered Star Formation

Nearest Example of Massive Star Formation

Diameter:
4 pc = 825,000 AU
Age of Stars:
100,000 - 1 million years old

Trapezium: Ionizing Sources

Hubble and Spitzer composite image



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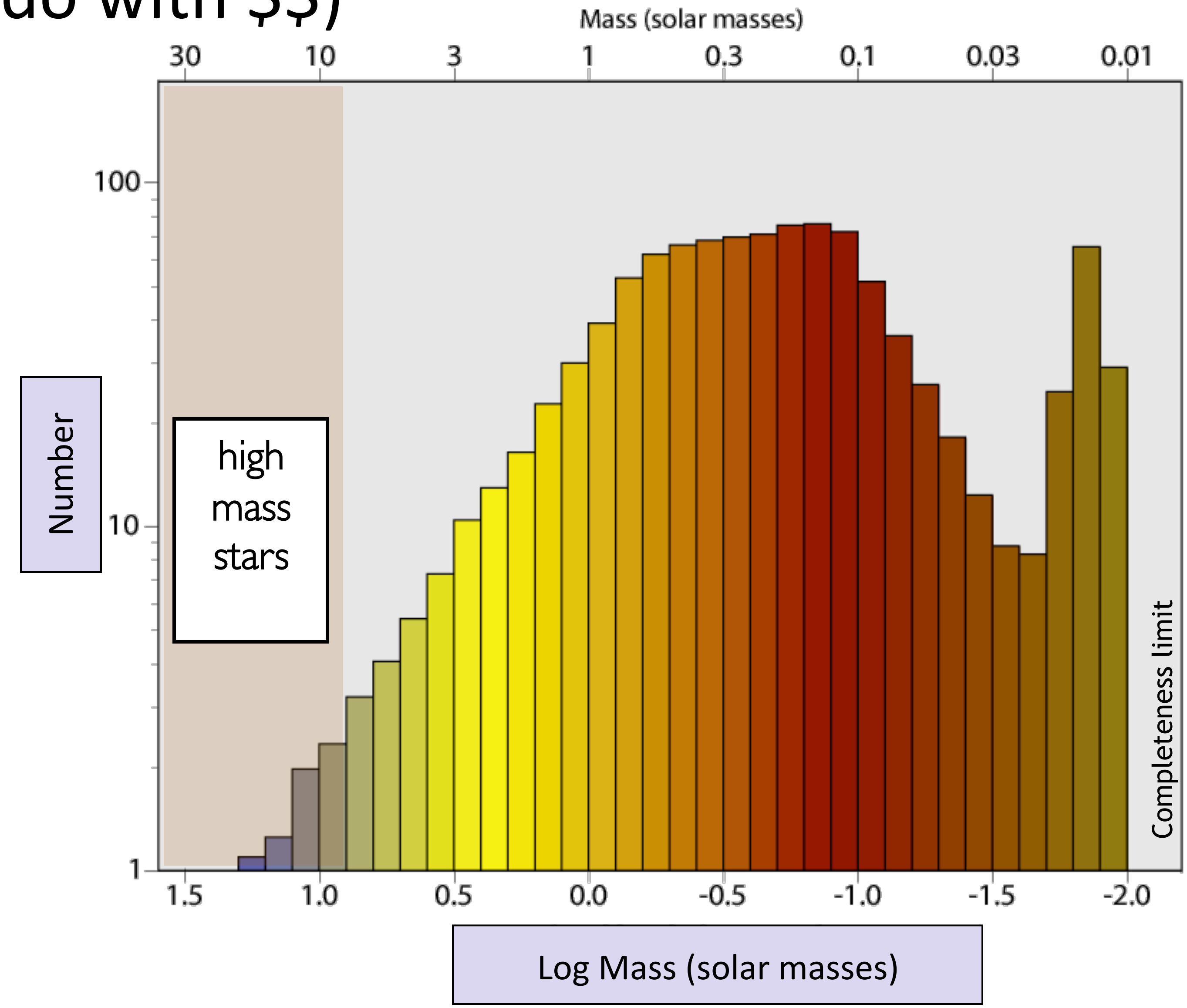
<u>**Initial**</u> Mass Function -- <u>**IMF**</u>

(nothing to do with $$)

IMF = distribution of stellar masses



Center of Orion Trapezium cluster

(Muench et al. 2001)

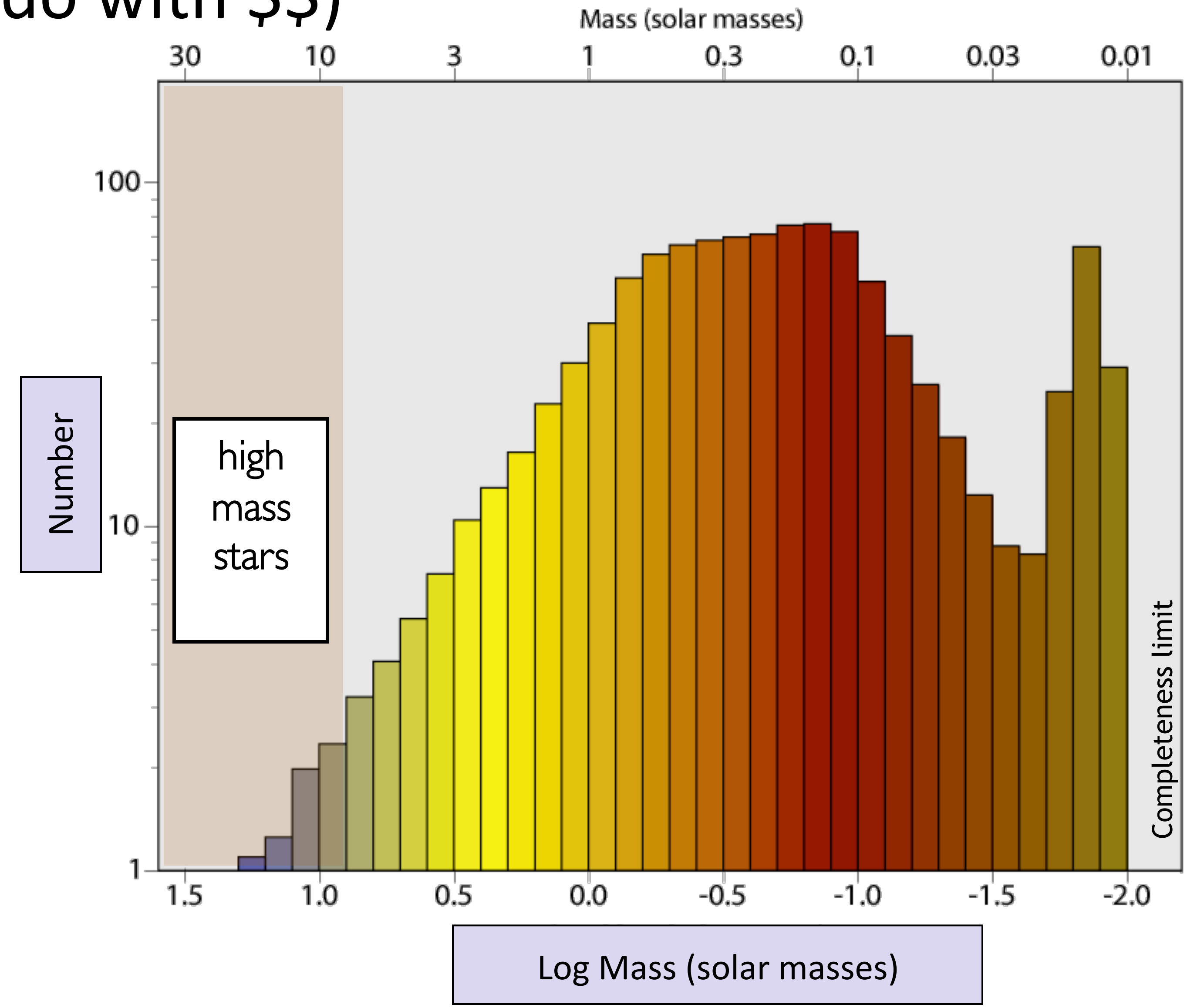
<u>Initial</u> Mass Function -- **<u>IMF</u>**

(nothing to do with $$)

1. Why does is behave like this?

2. Why is the shape similar in very different regions?

Distributed and
Clustered SF
Field



Center of Orion Trapezium cluster
(Muench et al. 2001)

Use **<u>Simulations</u>** to Understand IMF in Clustered Regions

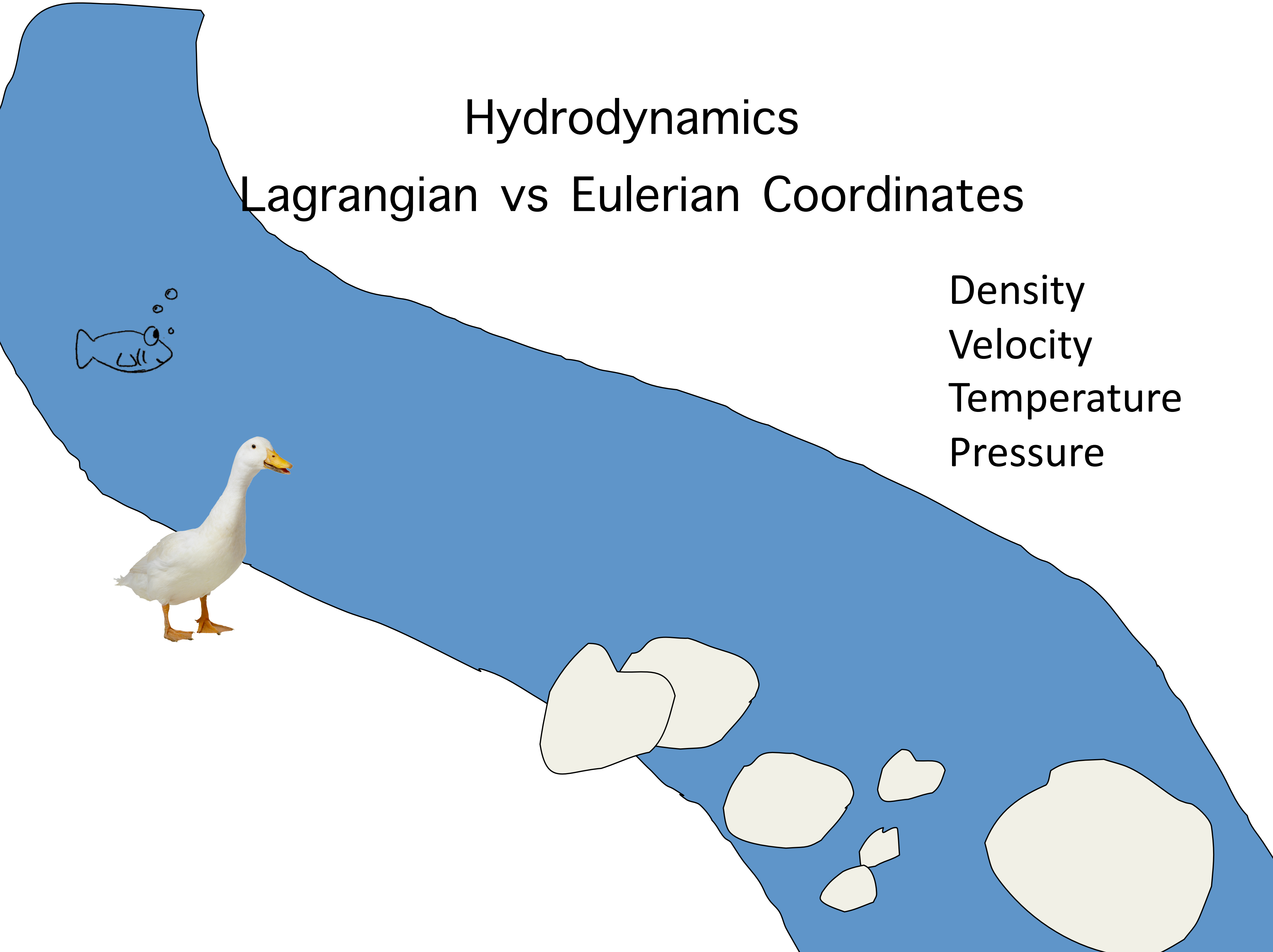
- Impossible to watch formation of star
  - birth is about 100,000 years
  - Changes occur very very slowly

    (on timescales > lifetime of an astronomer)
- Observations only provide snapshots of different objects at different times → incomplete
- Theory connects dots between observations.
- Simulations: a complementary method of studying star formation using SUPERCOMPUTERS.

Hydrodynamics

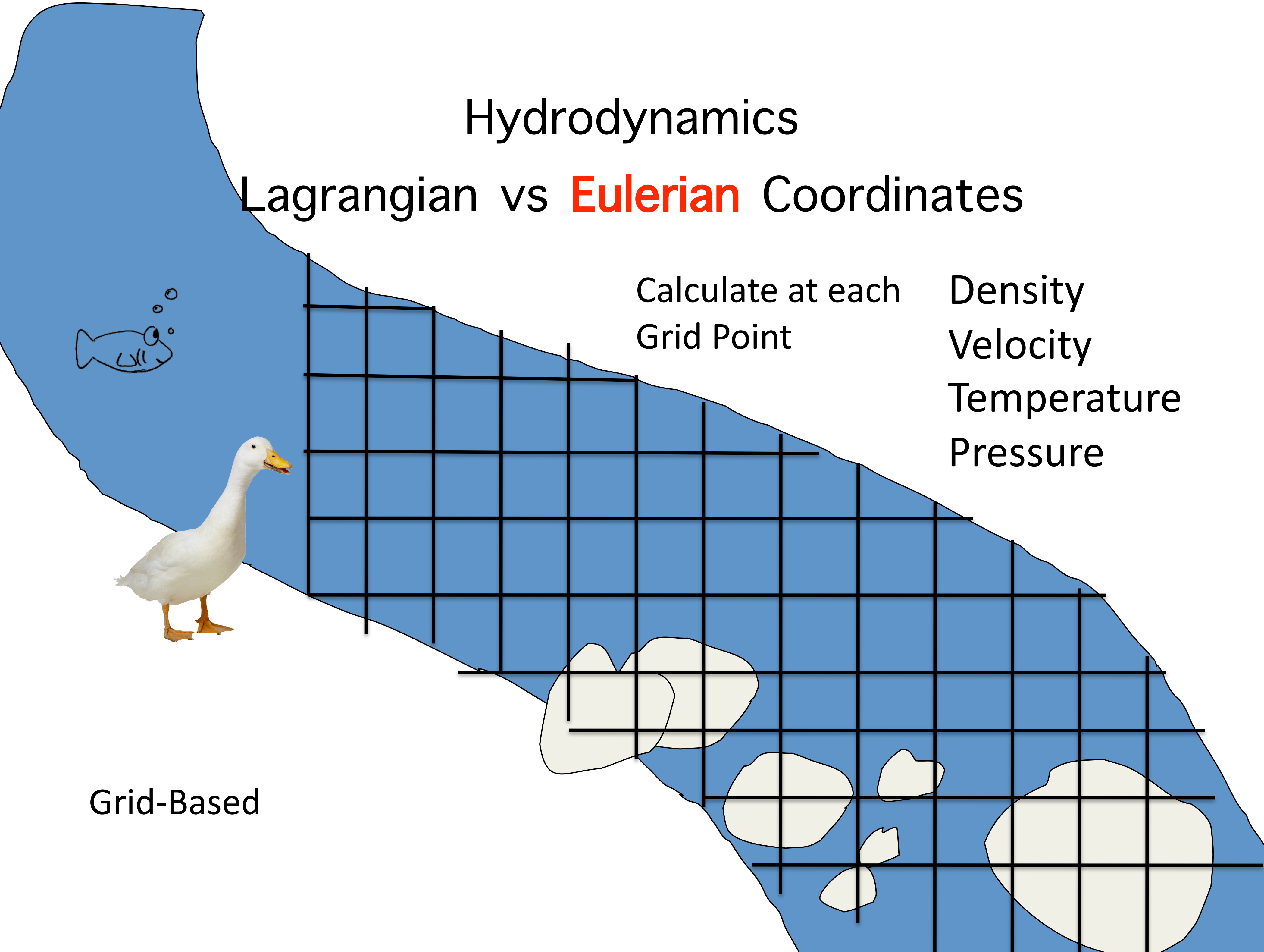
Lagrangian vs Eulerian Coordinates

Density
Velocity
Temperature
Pressure



Hydrodynamics

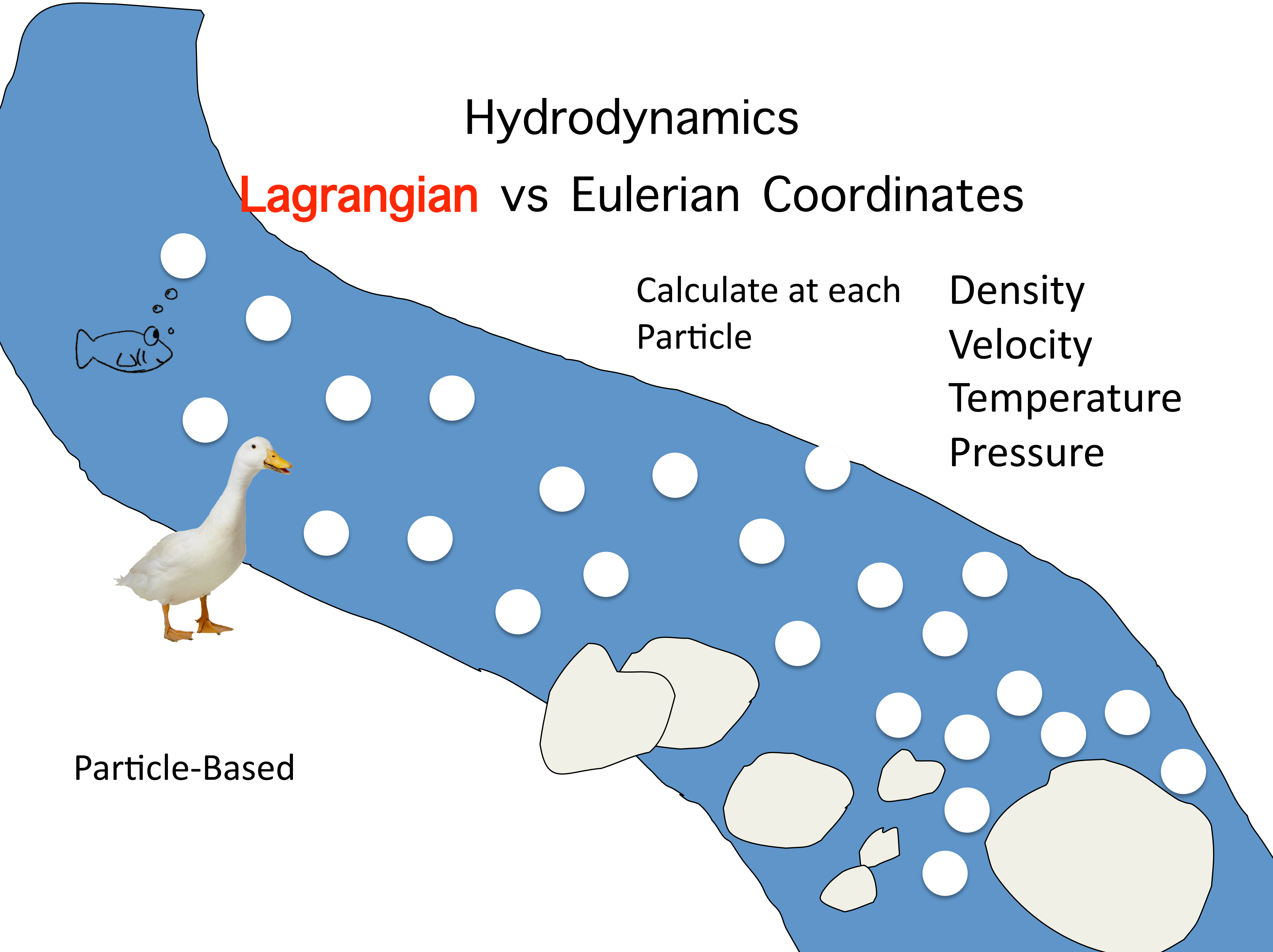
Lagrangian vs Eulerian Coordinates

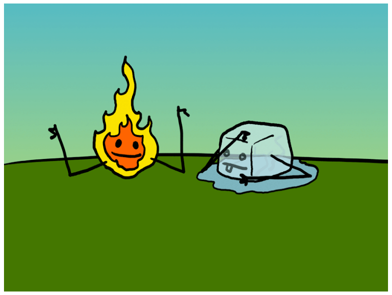


Calculate at each Grid Point

Density
Velocity
Temperature
Pressure

Grid-Based

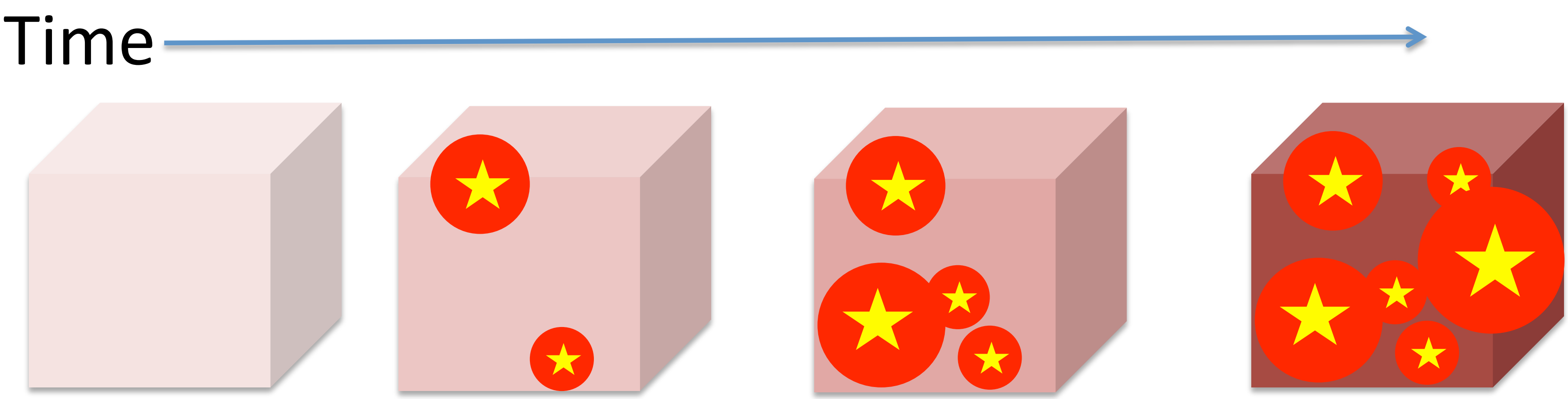

Hydrodynamics
Lagrangian vs Eulerian Coordinates
Calculate at each Particle
Density
Velocity
Temperature
Pressure
Particle-Based



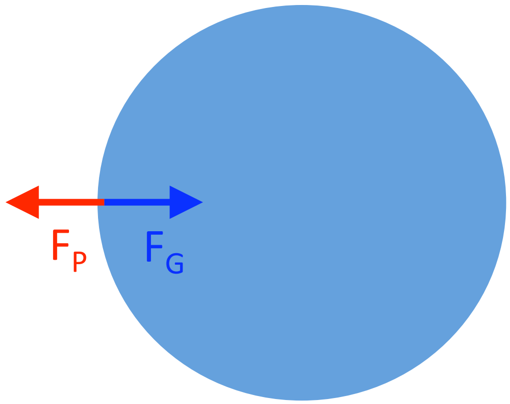
Modeling Clustered Star Formation

HOW DOES HEATING & COOLING AFFECT THE MASS FUNCTION (IMF) AND CLUSTERED STAR FORMATION ?

- Gas Dynamics
- Gravity
- Radiative Heating from Stars – MAIN HEATING SOURCE
- Radiative De-Excitation from Molecules and Atoms – MAIN COOLING SOURCE



How will Temperature affect Star Formation?



Star formation is a balancing act between
Gravity and Pressure

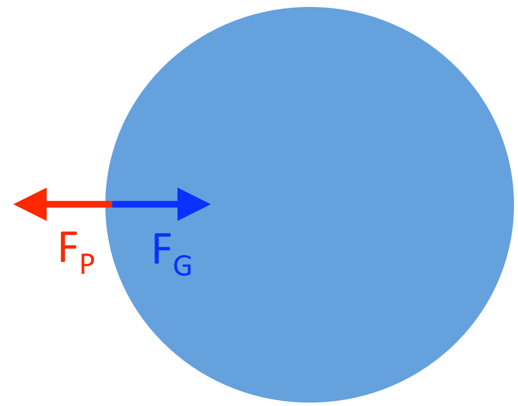
Pressure force controlled by Temperature
Higher Temperatures →
Higher Pressure Forces →
Expansion and more mass/gravity needed to balance pressure

Mass at which pressure and gravity are balanced is called the Jeans Mass

For Star Forming Region Conditions, T = 10K, n = 10^5cm^{-3},

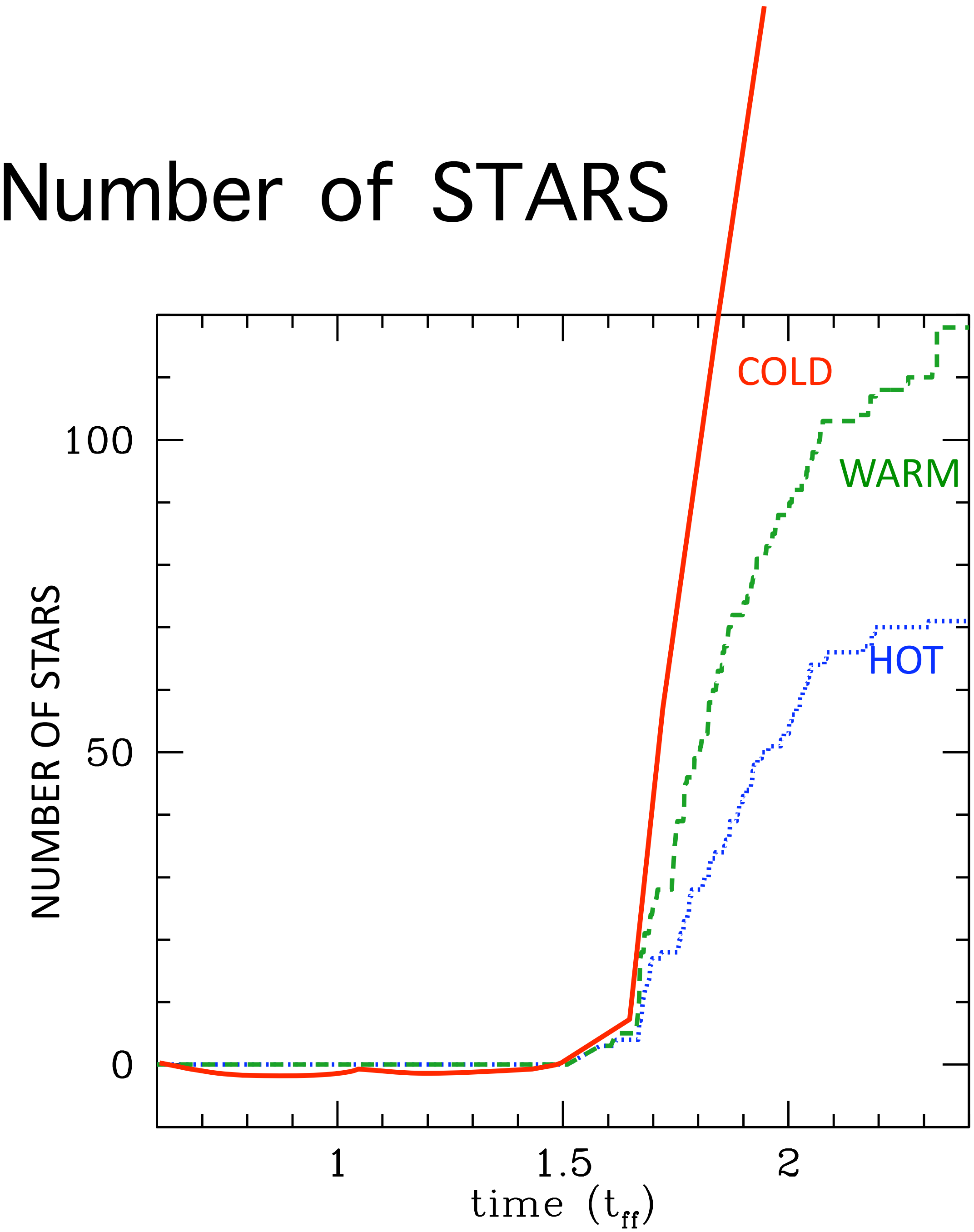
$$M_{Jeans} = 18 M_{sun} n^{-0.5} T^{1.5}$$

3 different tests



1. Assume Gas Temperature is fixed – VERY COLD
   - Material will collapse/fragment immediately because Temperature is low and pressure force is low leading to many stars forming
   - Only differences in mass will be due to subsequent accretion of remaining material after formation.
2. Assume Gas is only able to get HOT
   - Since Temperature is able to vary, the Jeans mass will also vary
   - At high temperatures, higher mass stars will be able to form
3. Gas gets HOT and is able to COOL DOWN
   - Expect Variable Jeans mass as well, but lower masses in general than Heating-Only Case
   - Intermediate Case

Number of STARS



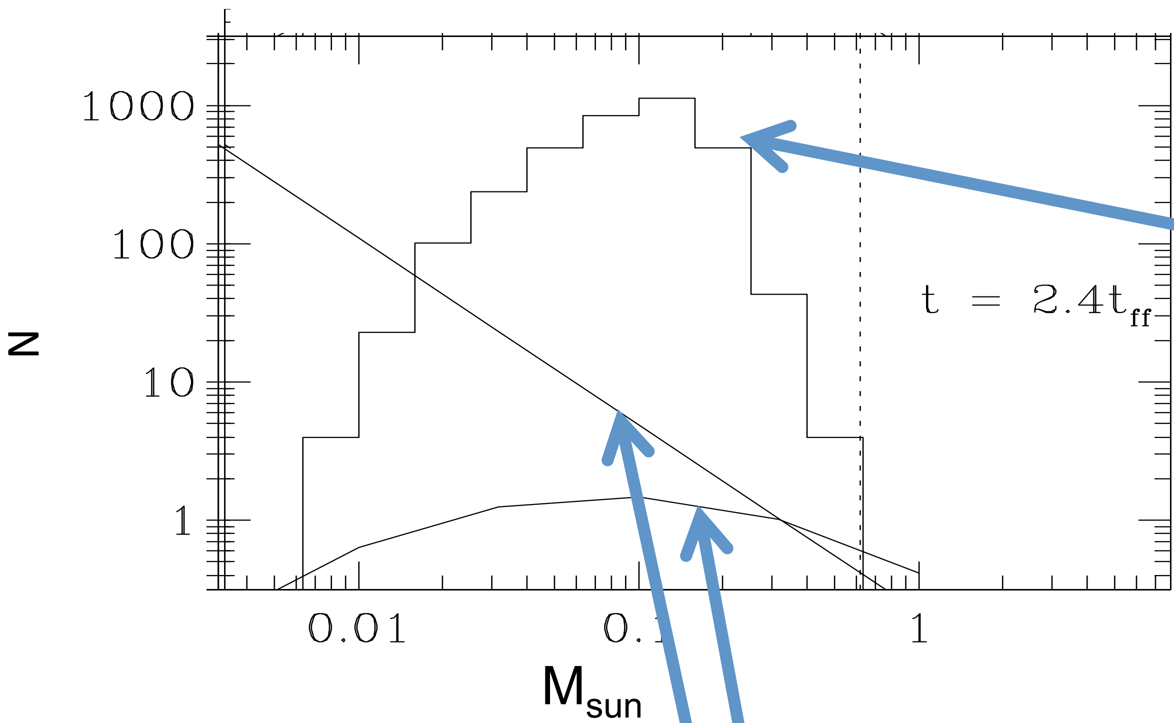
- Assume Gas Temperature is fixed – VERY COLD
- Assume Gas is only able to get HOT
- Gas gets HOT and is able to COOL DOWN

HEATING AND COOLING
-affects how many stars form

But does it affect the Mass Distribution (IMF) ??

Mass Distribution (IMF) at End of Simulation.

- Assume Gas Temperature is fixed – VERY COLD



Simulation Results

Observed Shapes of IMF

1000's of stars formed

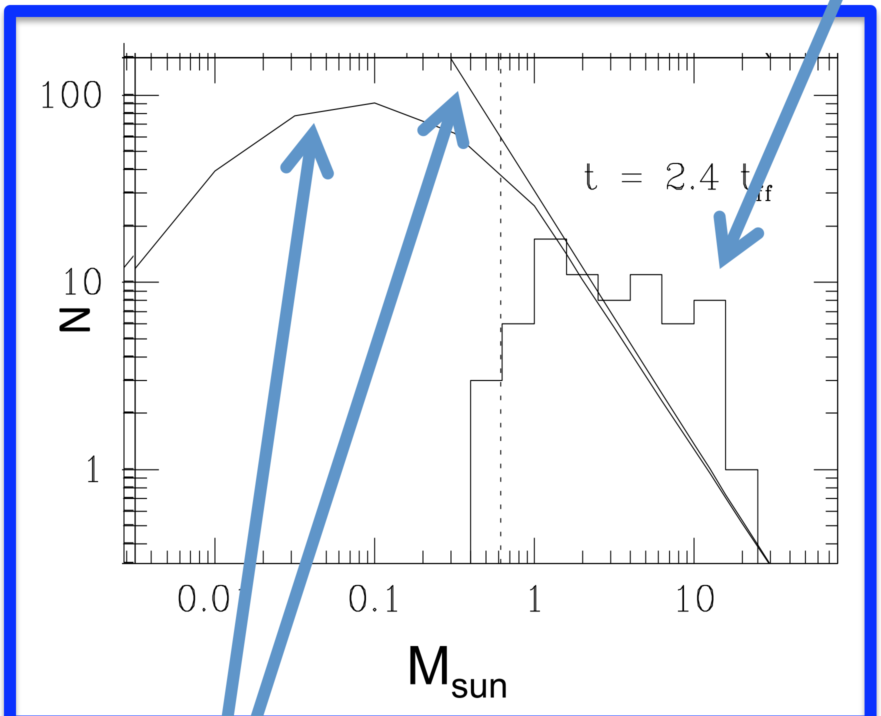
**Over-Predicting Number of Low Mass Objects

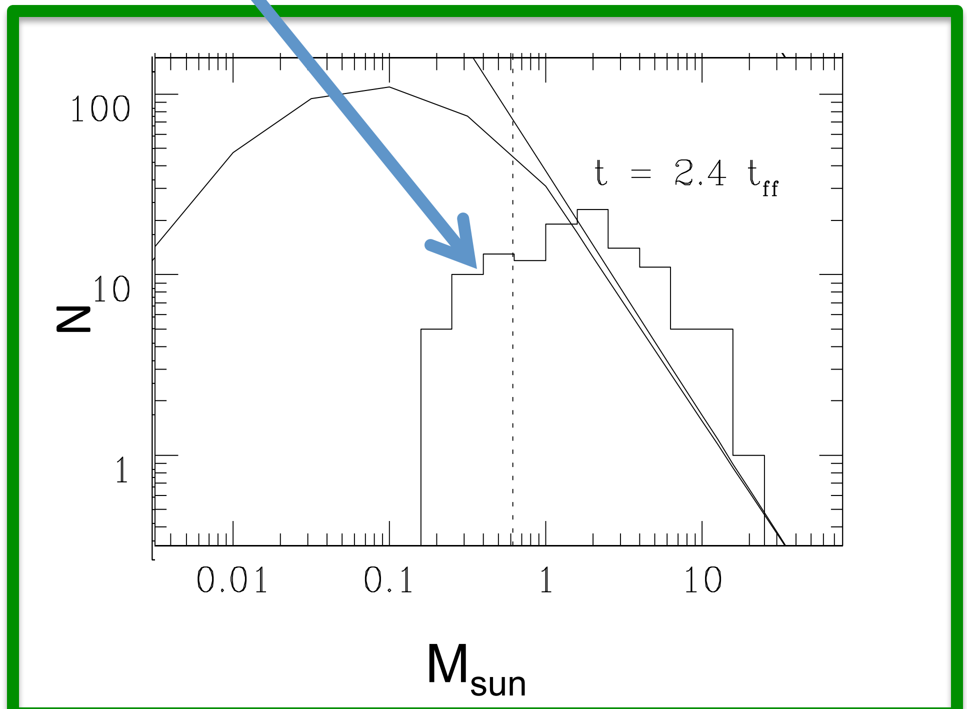
Not realistic compared to observations

Mass Distribution (IMF) at End of Simulation.

- Assume Gas is only able to get HOT
- Gas gets HOT and is able to COOL DOWN

Simulation Results





Observed Shapes of IMF

Both Simulations miss Very Low Mass Objects
Simulation with Heating and Cooling is best:
better fit to high-mass slope
more low-mass objects

Why is the Initial Mass Function So Important?

- Heating and Cooling are important effects to consider when modeling the mass function in a clustered environment.
- Observations suggest that stars forming in different environments (i.e. clustered vs. distributed, high vs. low metallicity) have similar mass functions. Why? More work needs to be done…
- Environment doesn't seem to affect the mass distribution of stars, but what about planets???

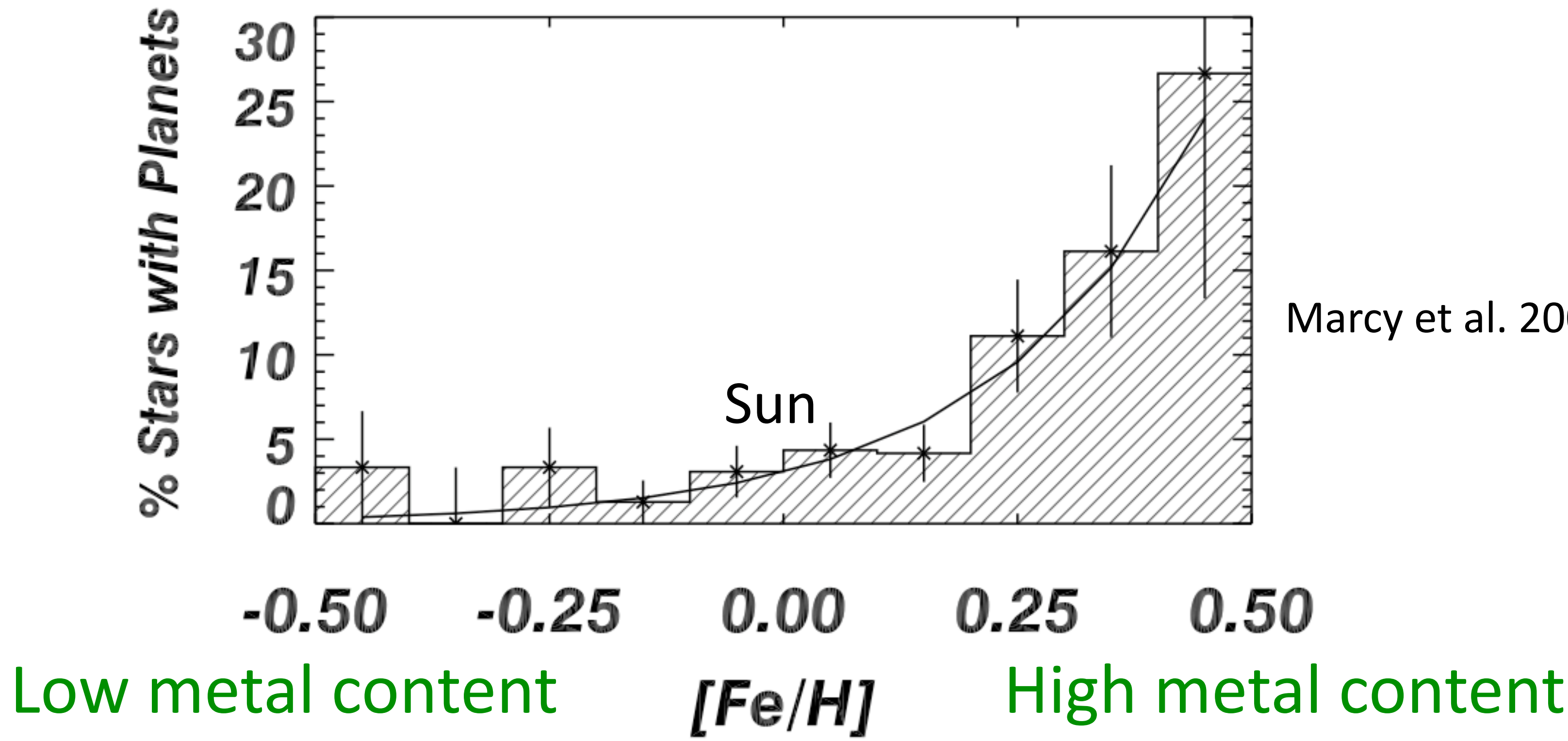
Planet Properties

- 346 known planets (not including Pluto) as of this morning.

<u>EXO-PLANET PROPERTIES</u>

- What type of stars do planets form around?
  - Hard to tell because we've only really looked around Sun-like stars
- Interesting relationship to metallicity

Link Between Metallicity (Amount of planet-building material) of Host Star and its Orbiting Planet

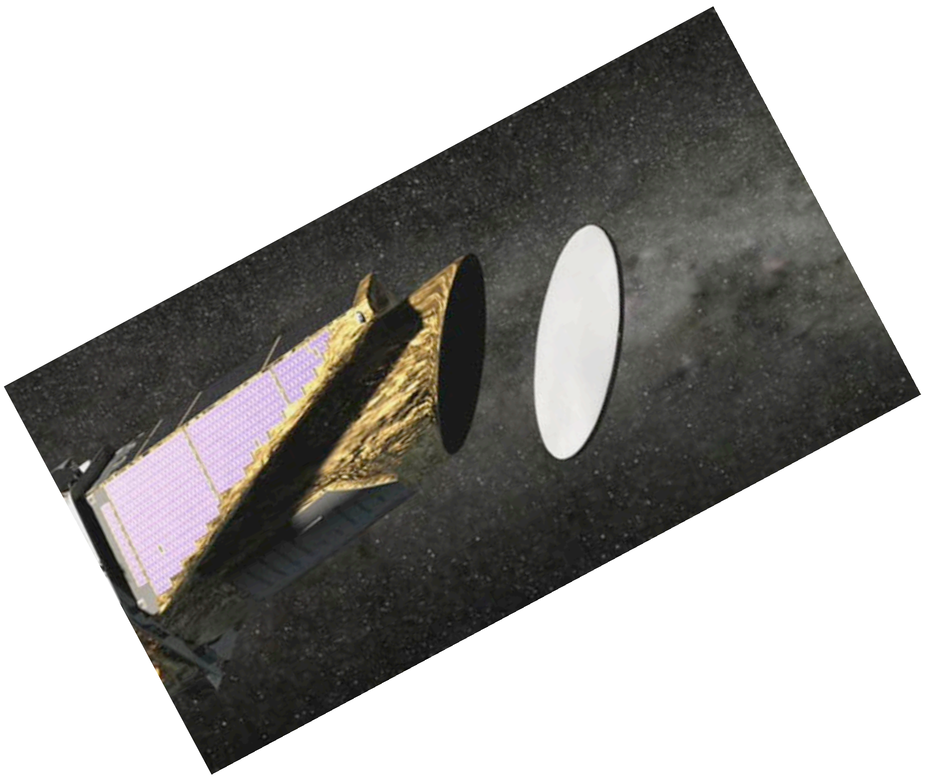


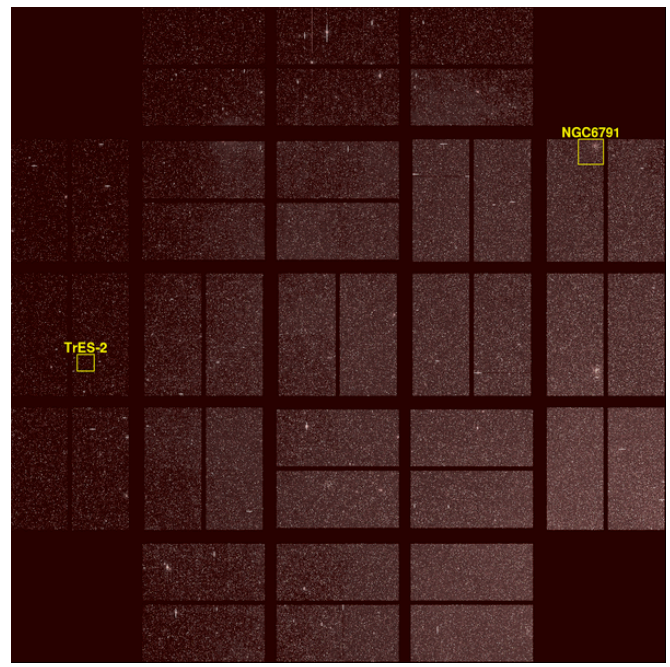
Marcy et al. 2005

Nature: Do high metallicity stars preferentially form planets? (Winner so far)
Or
Nurture: Do stars with planets become polluted by planets being absorbed by the star?

Kepler: Searching for Planets

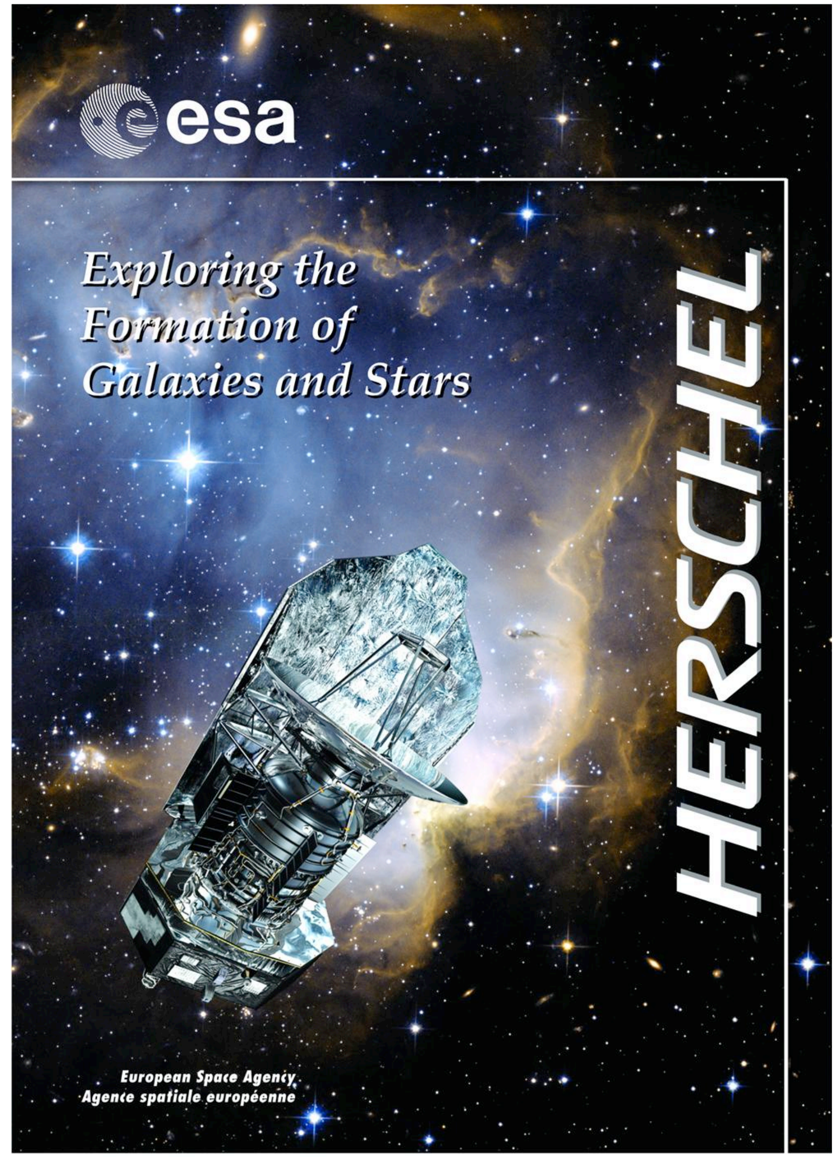
- Goal: Find Planetary Systems.
- Kepler takes first picture





Herschel

- Launch May 14, 2009
- Far-Infrared/Sub-mm Telescope
- Largest Telescope in Space.
- Will expand on the results of the Spitzer Space Telescope.



Thank you

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  - Steven Doty (Denison University)

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END