STAR CLUSTERS

Lecture 2

Formation and Multiple Stellar Populations

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LECTURE 1

1. **Star Clusters:**
   - ➡ Collection of stars roughly born at the same time (sometimes gravitationally bound)

100 -1000	1e4-1e6	1e4-1e5	1e5-1e7	1e6-1e8
				
OB Associations	Embedded Clusters	Open Clusters	Globular Clusters	Nuclear Clusters
- in the disk - gravitationally unbound	- in the disk - still gas left	- in the disk - gravitationally bound	- in the halo/ bulge - oldest objects in the universe	- at the center of the galaxy - densest objects in the universe

Outline

1. Formation
   a. Star formation
   b. Initial Mass Function
2. Multiple Stellar Populations
   a. What, Where, Why?
   b. Historical Picture
   c. Observations
   d. Explanations

Outline

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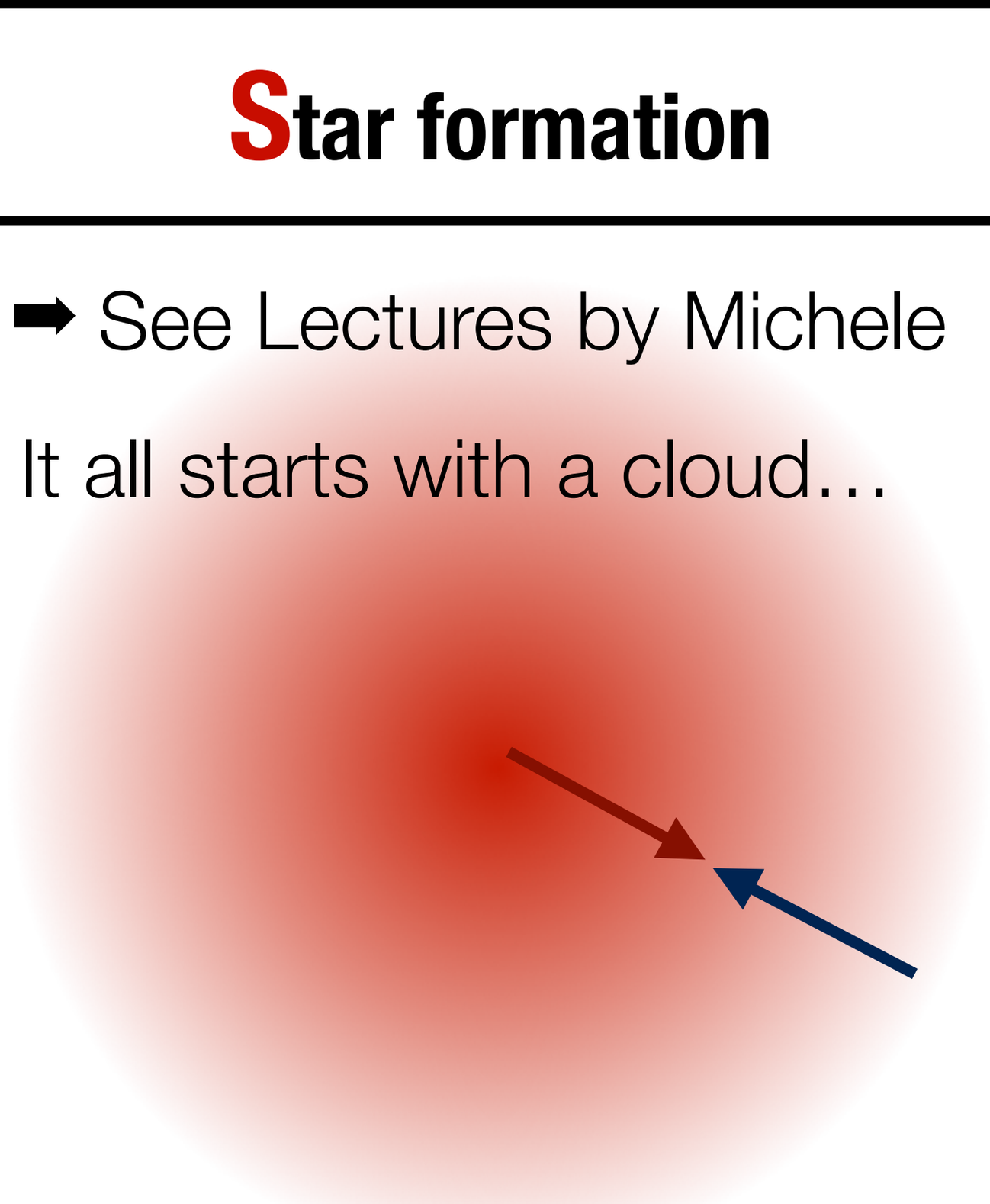
Star formation

➡ See Lectures by Michele

It all starts with a cloud…



Gas Pressure = Gravitational Attraction

Excursion: Jeans Radius

Radius where
THERMAL ENERGY = GRAVITATIONAL ENERGY

$$R_J \sim \sqrt{\frac{T}{\rho}}$$

Temperature

Density

Excursion: Jeans Mass

Mass of the cloud where
THERMAL ENERGY = GRAVITATIONAL ENERGY

$$M_J = \rho R_J^3 \sim \sqrt{\frac{T^3}{\rho}}$$

Temperature

Density

Star formation

Gas cools → Pressure decreases

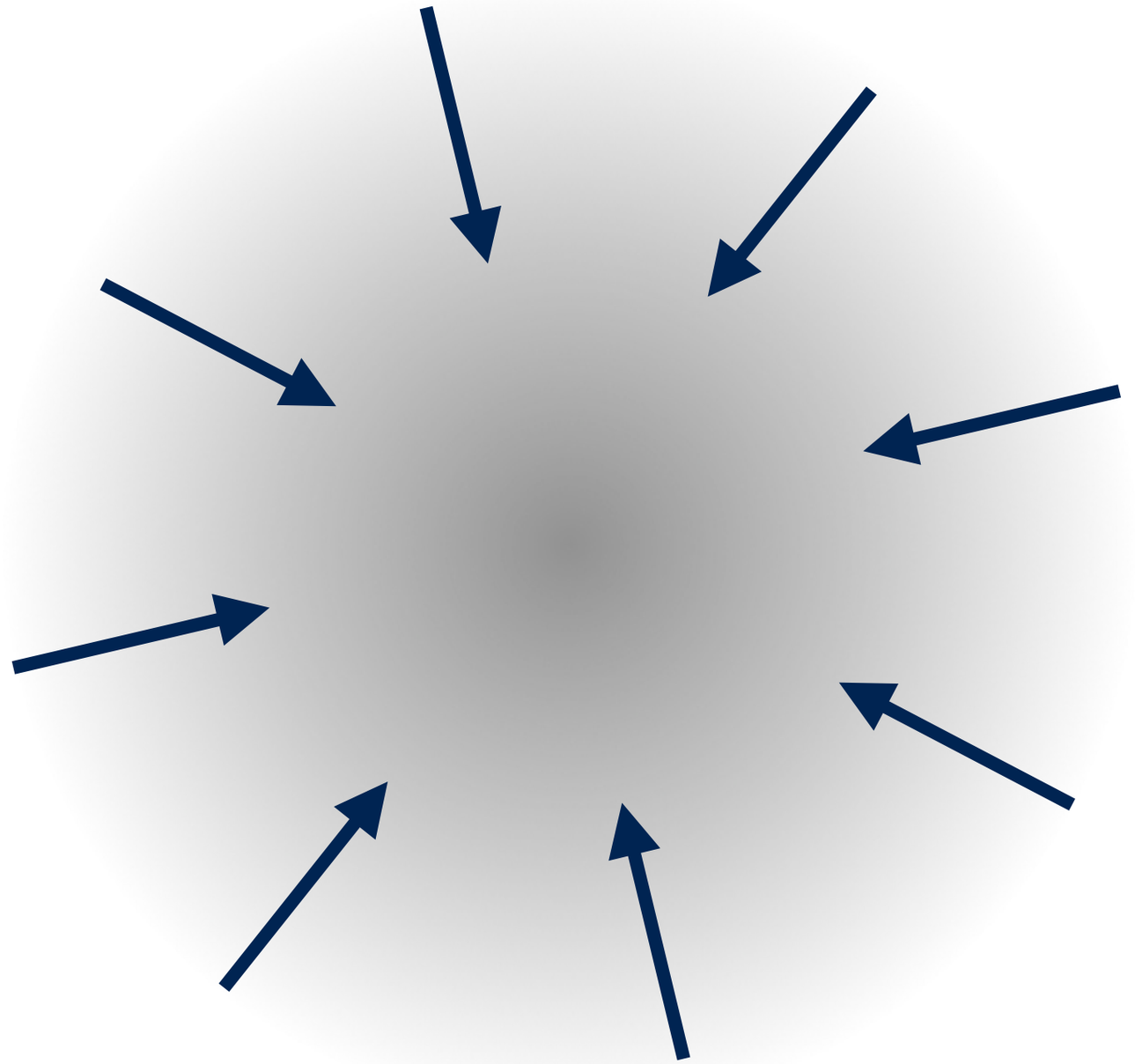
$$M_J \sim \sqrt{\frac{T^3}{\rho}}$$

or…

Instability

Gas Pressure < Gravitational Attraction

Star formation



Gravitational Collapse

Star formation

$$M_J \sim \sqrt{\frac{T^3}{\rho}}$$

Higher Density!

Star formation

Fragmentation!!

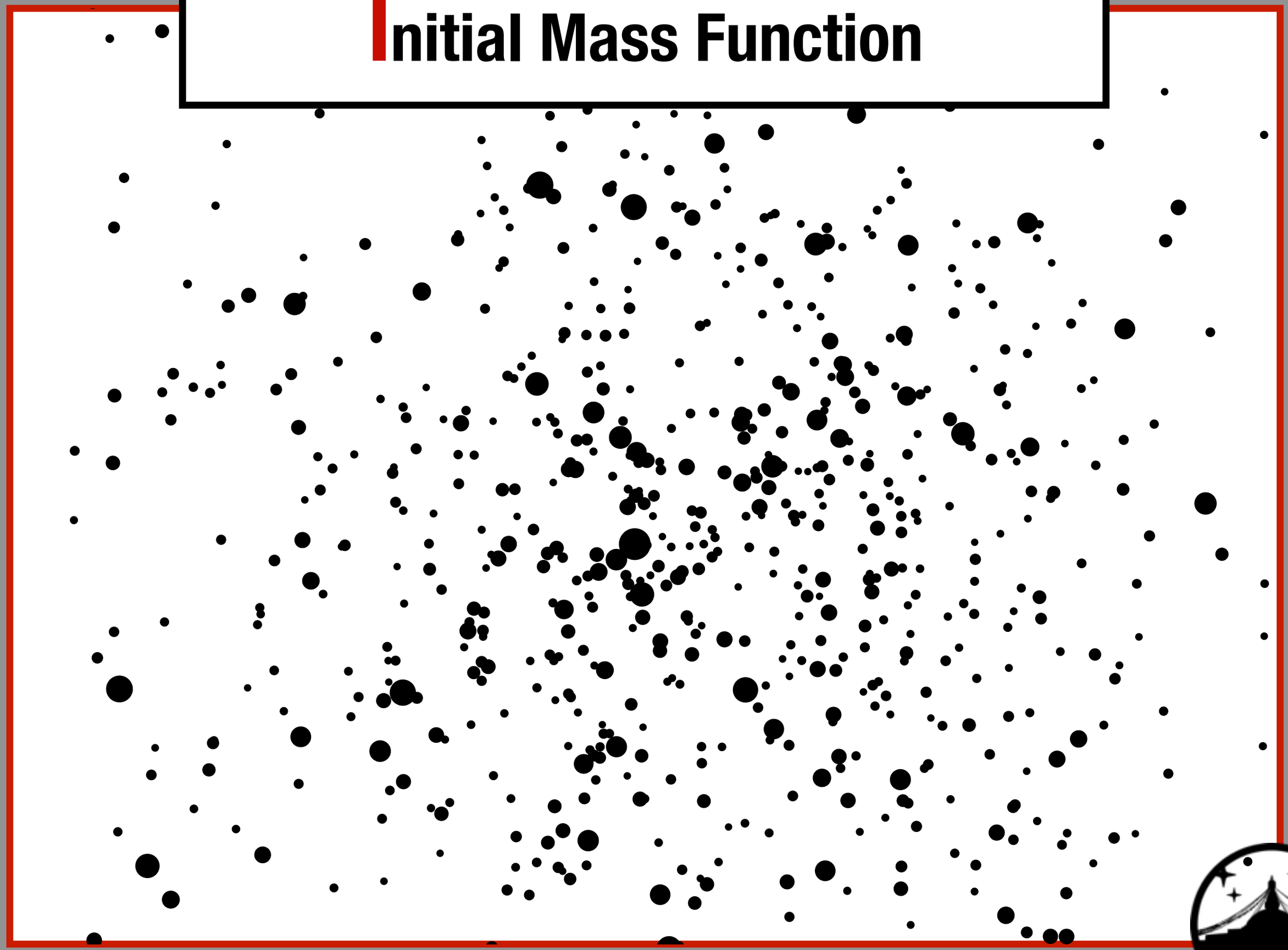
Star formation

"Most stars form in clusters"

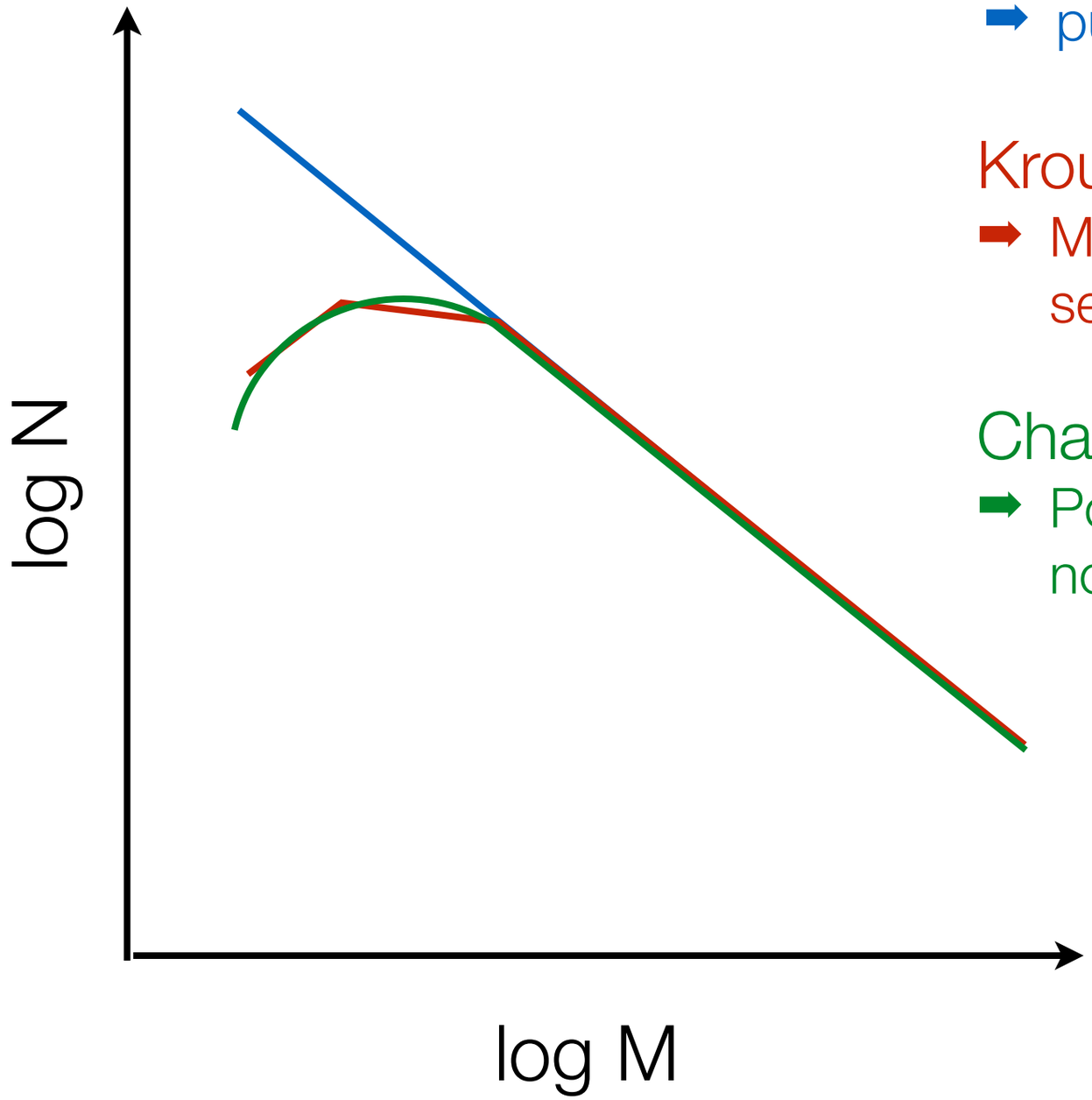
- Lada & Lada (2003)

Star formation

Initial Mass Function



Initial Mass Function



Salpeter (1955)

➡ pure power law

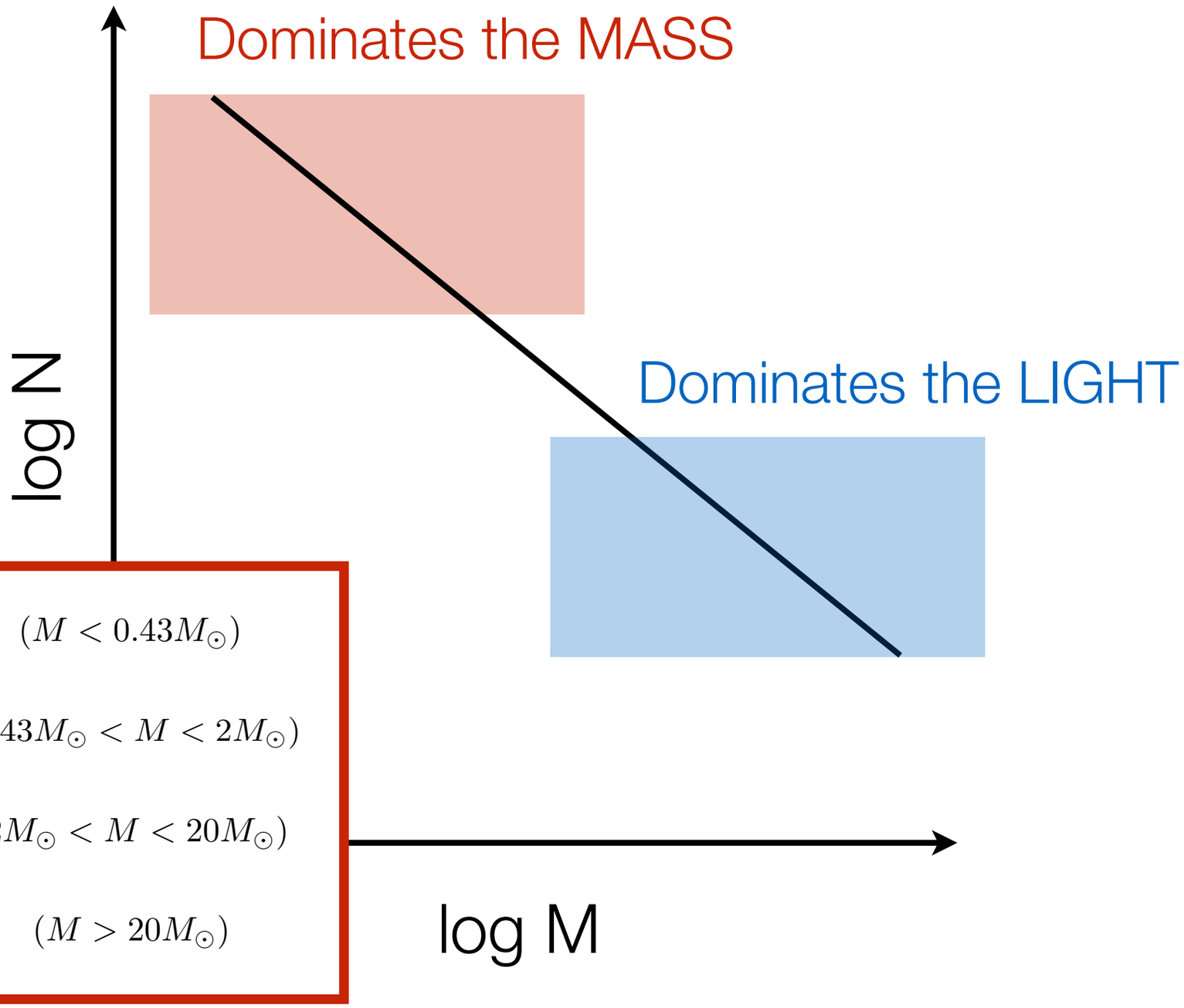
Kroupa (2001)

➡ Multiple power law segments

Charbier (2003)

➡ Power law + log normal

Initial Mass Function



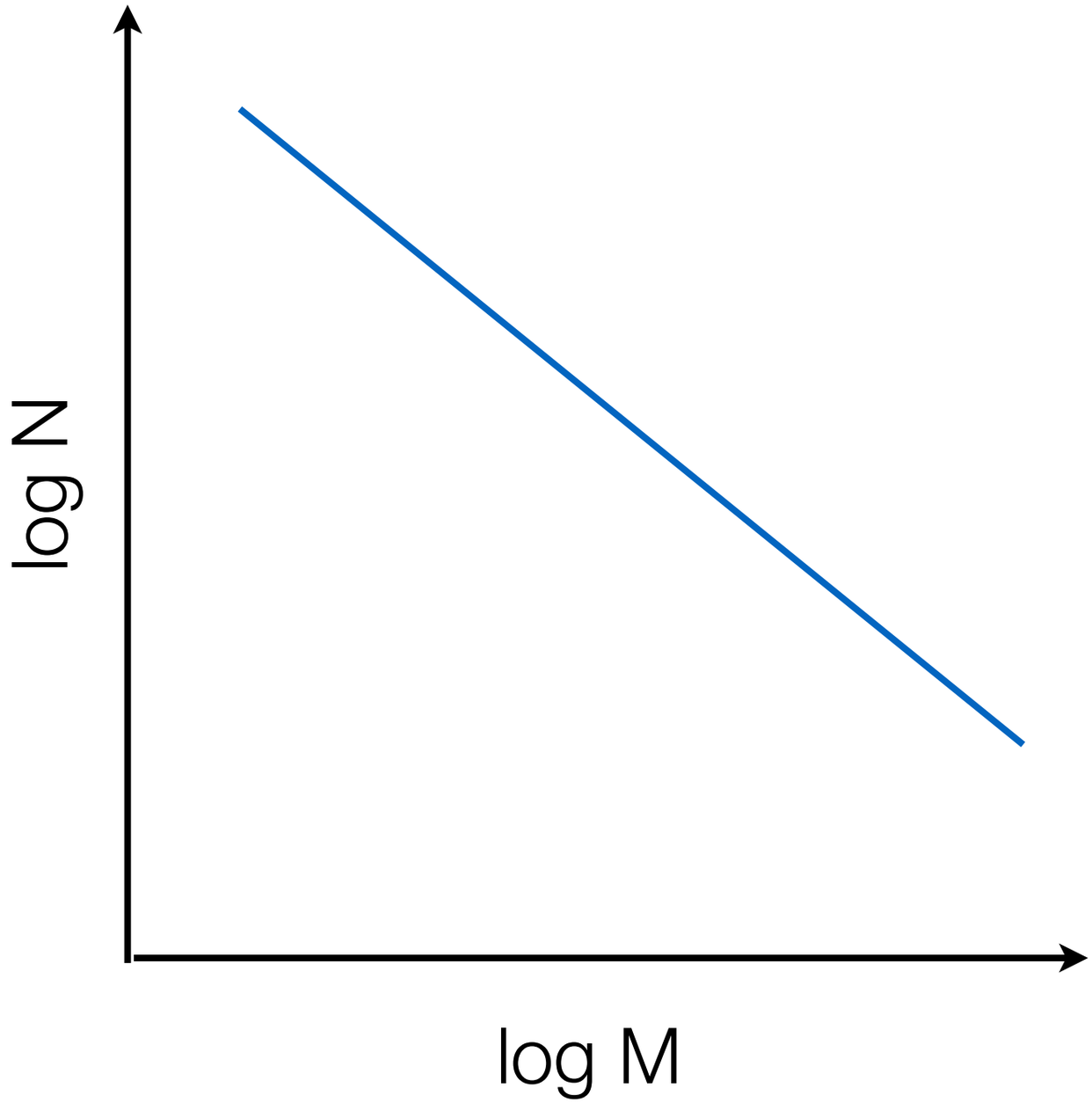
$$\frac{L}{L_\odot} \approx 0.23 \left(\frac{M}{M_\odot}\right)^{2.3} \quad (M < 0.43 M_\odot)$$

$$\frac{L}{L_\odot} \approx \left(\frac{M}{M_\odot}\right)^{4} \quad (0.43 M_\odot < M < 2 M_\odot)$$

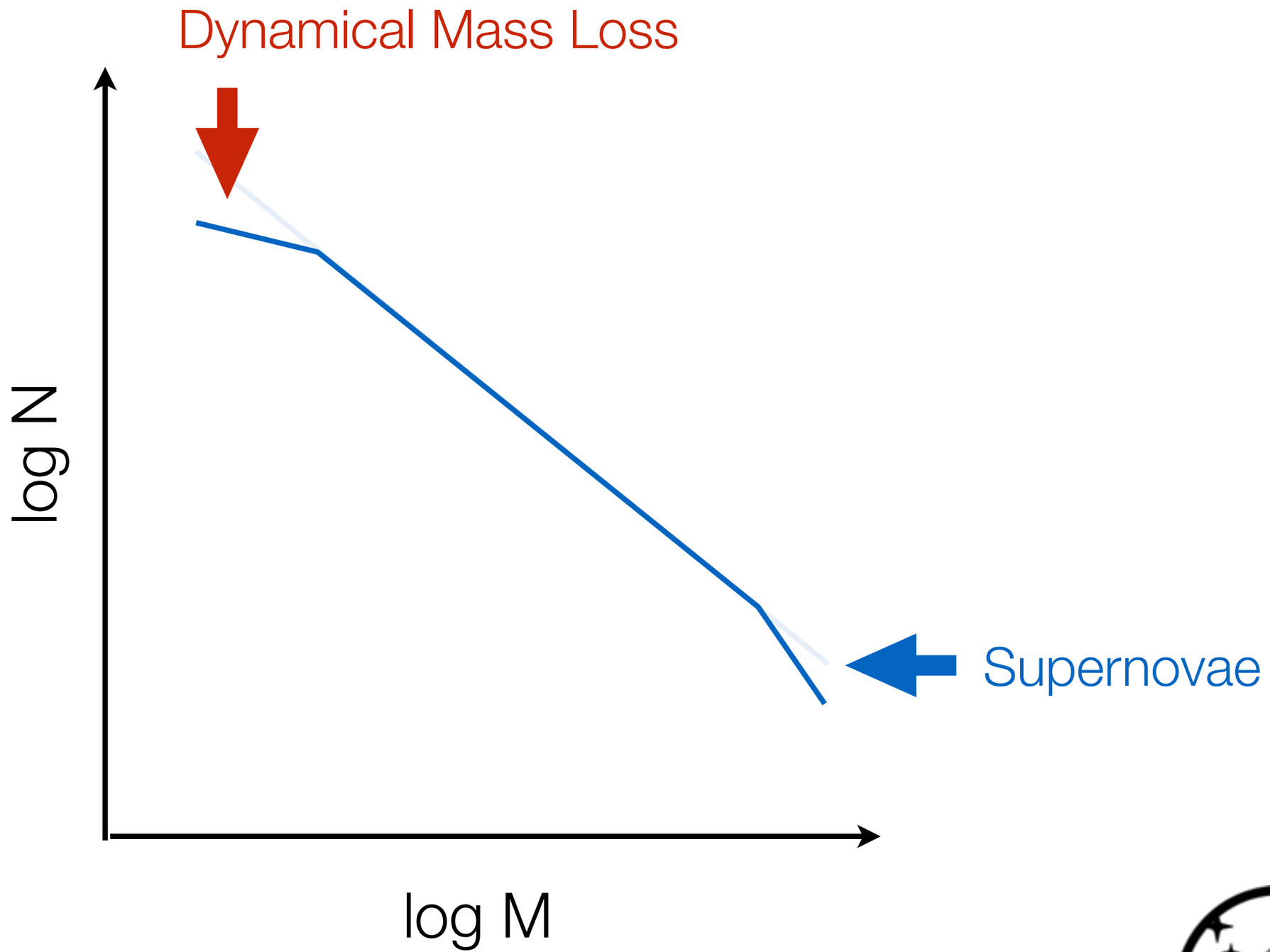
$$\frac{L}{L_\odot} \approx 1.5 \left(\frac{M}{M_\odot}\right)^{3.5} \quad (2 M_\odot < M < 20 M_\odot)$$

$$\frac{L}{L_\odot} \approx 3200 \frac{M}{M_\odot} \quad (M > 20 M_\odot)$$

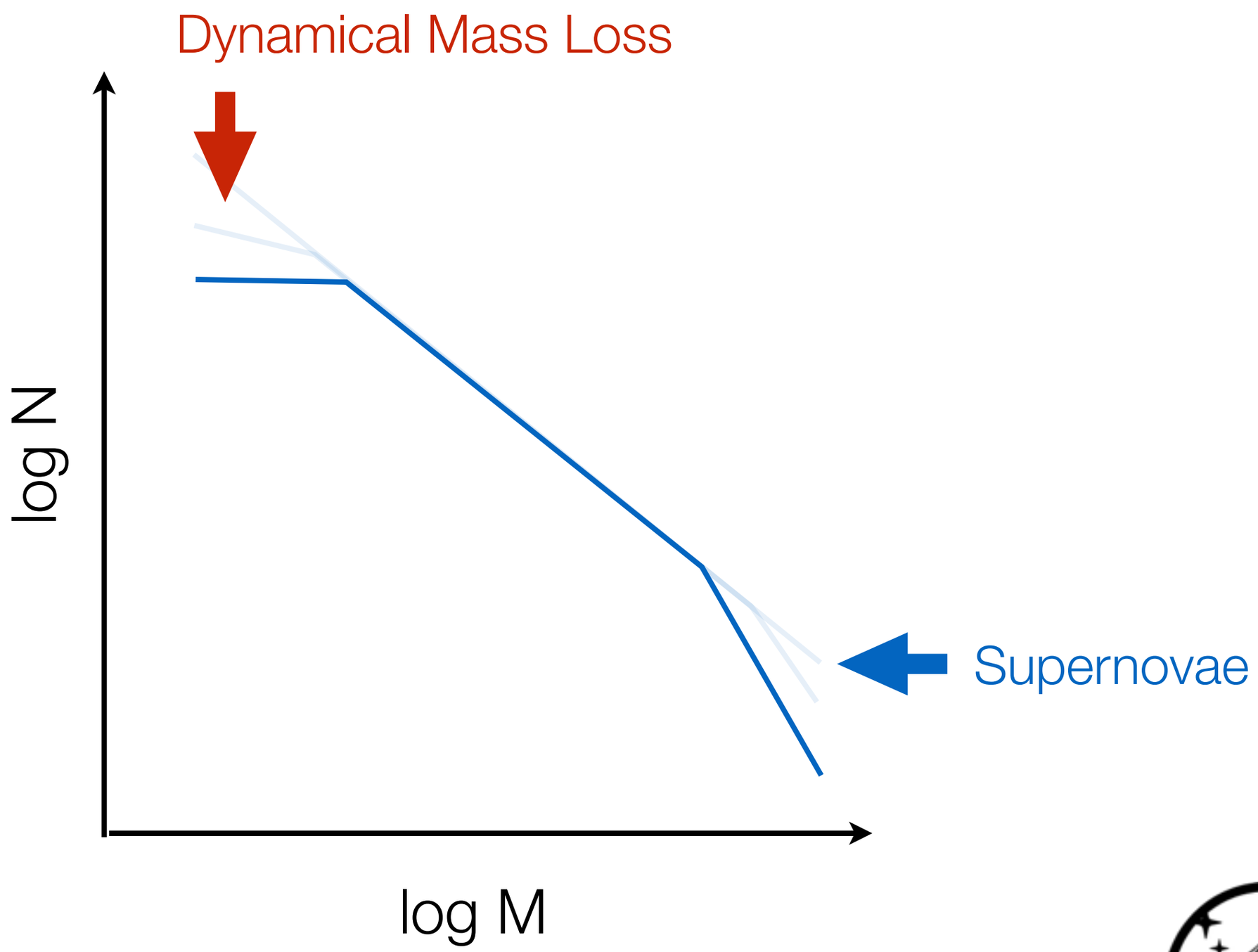
Initial Mass Function



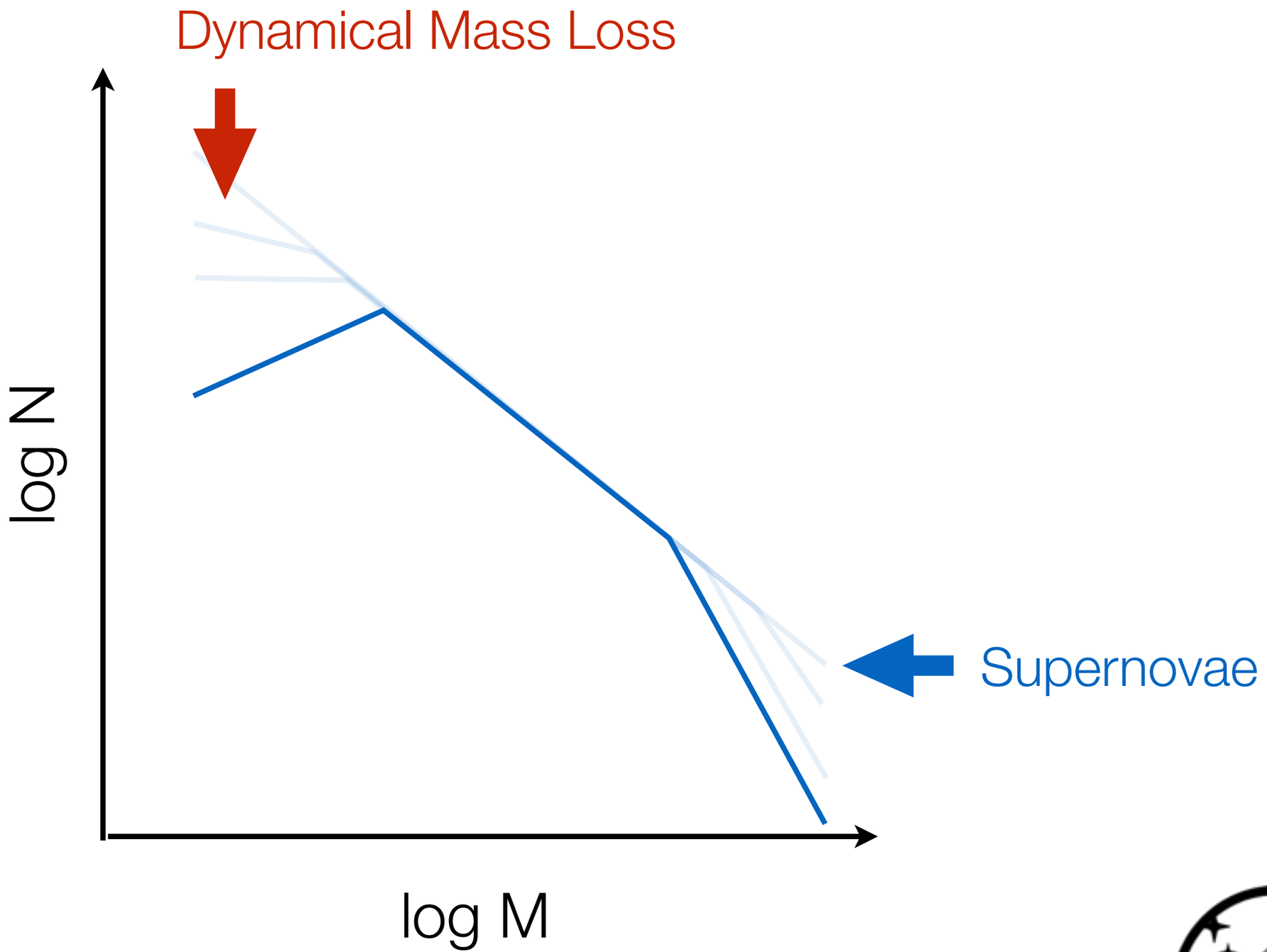
Initial Mass Function



Initial Mass Function



Initial Mass Function



Outline

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   a. What, Where, Why?
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What? Where? Why?

1. WHAT?

   ➡ Globular Clusters show spectroscopic and photometric evidence of “abundance anomalies”

2. WHERE?

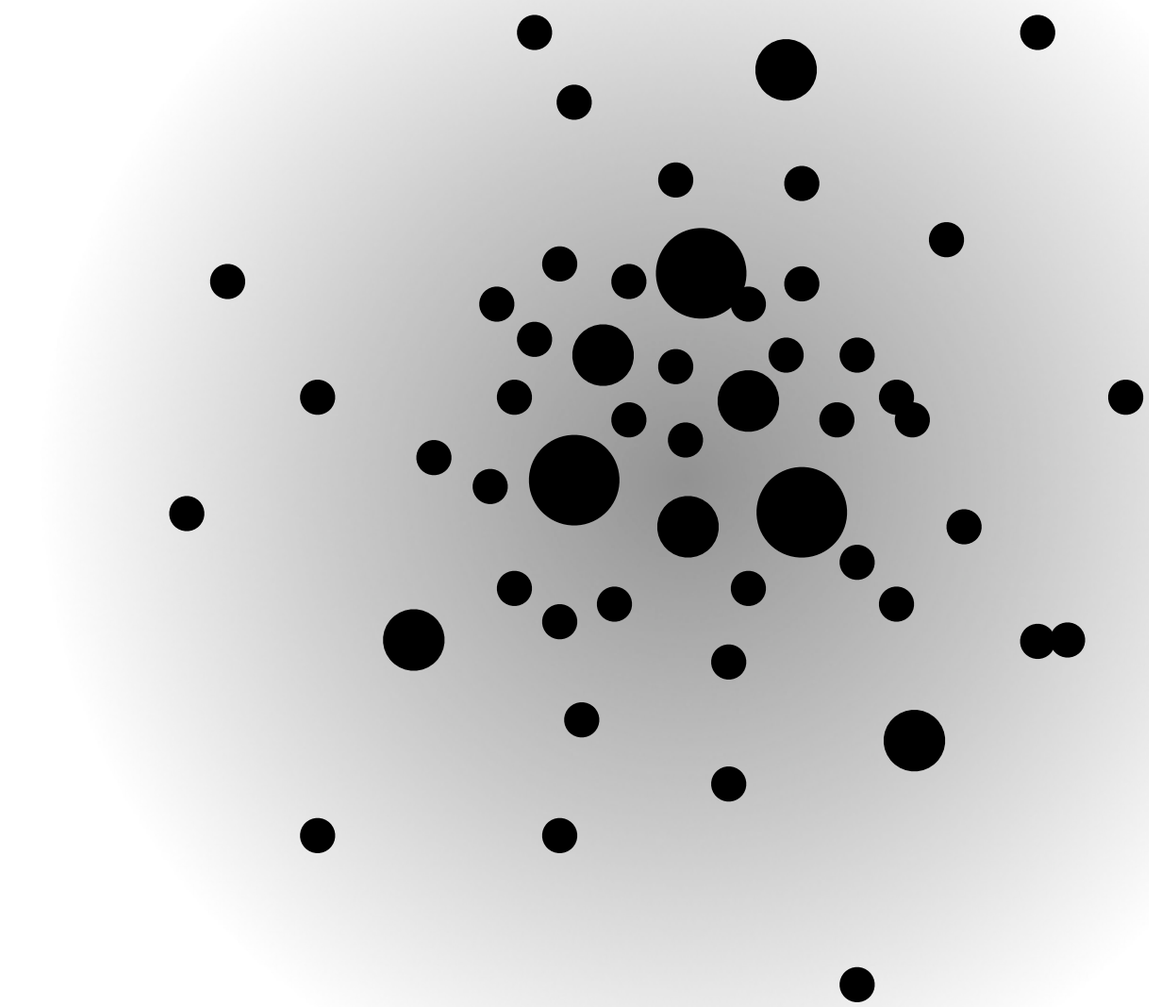
   ➡ Multiple populations are found in almost all clusters, “anomalous” stars are the majority in the cluster.

3. WHY?

   ➡ ??? - We need models and more observations to understand

Historical picture

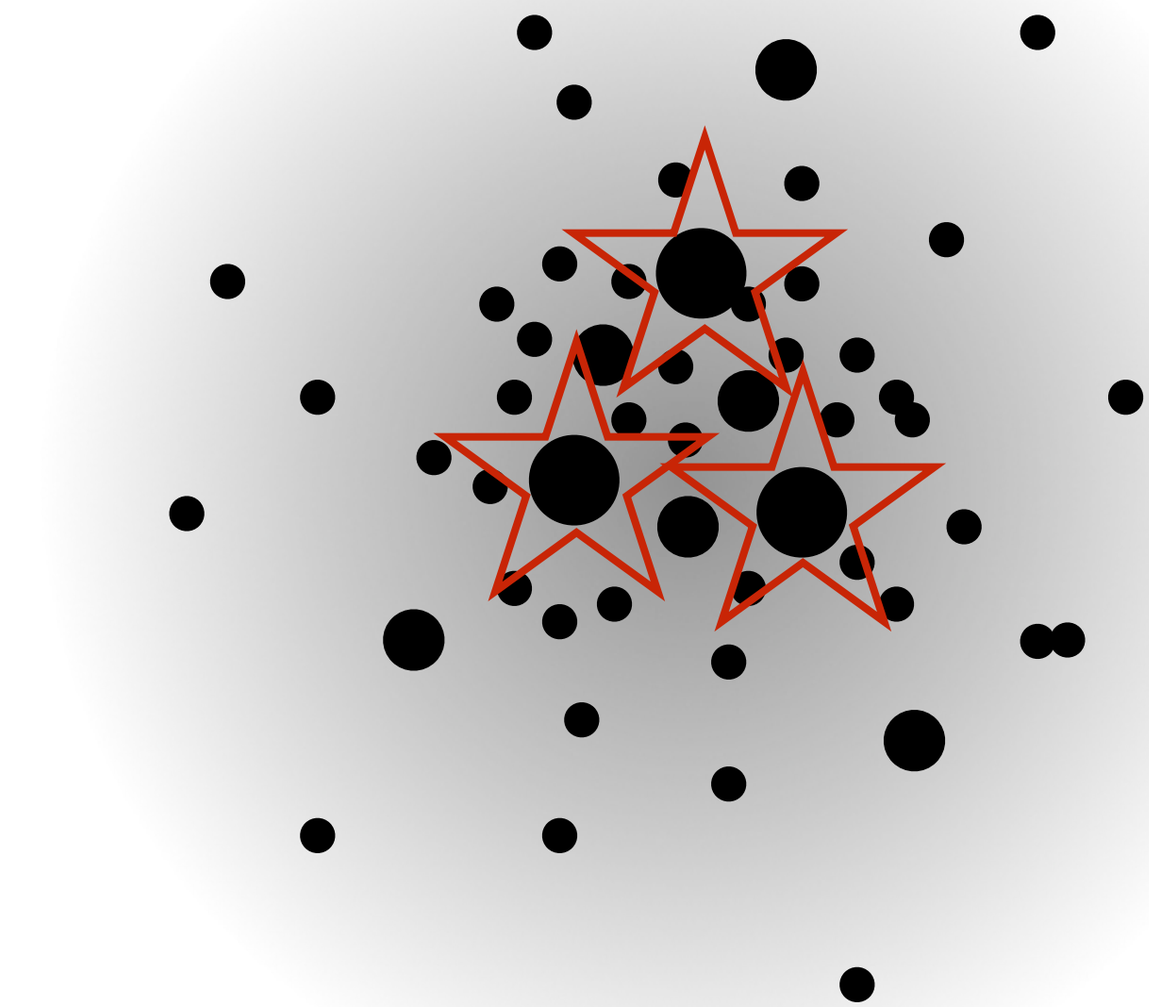
T = 0



Stars born in gas cloud, Gas still present

Historical picture

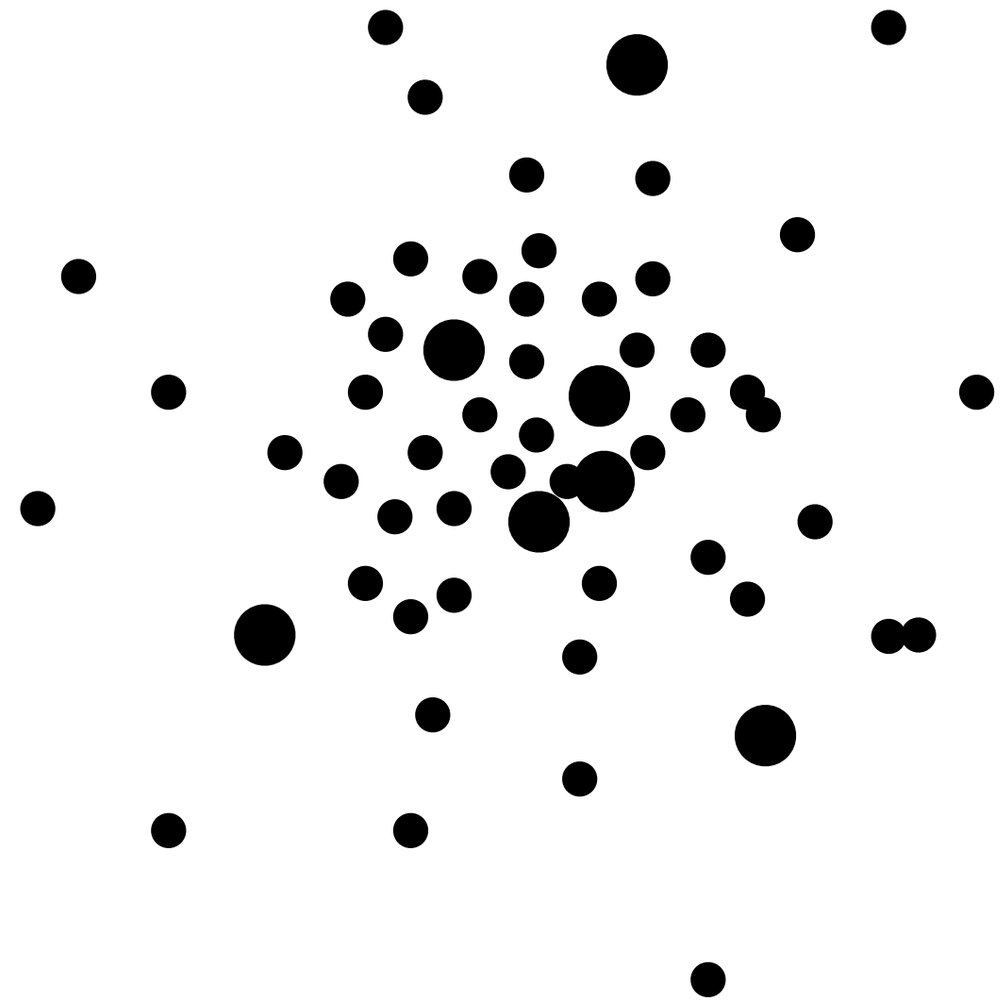
T = 2-3 10^6 yr



Supernova explosion → expel primordial gas

Historical picture

$T > 2\text{-}3\ 10^6$ yr



Star formation stops → Singel population evolves

Historical picture - Evidence

1. Spectroscopically

   ➡ All stars have the same iron content!

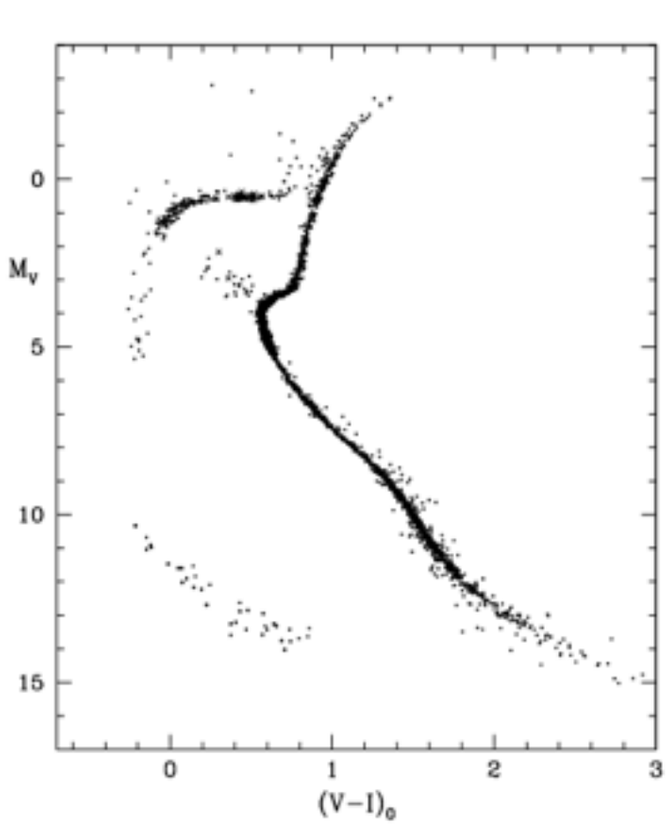
2. Photometrically

   ➡ Narrow Color-Magnitude Diagram

   ➡ Only one population!

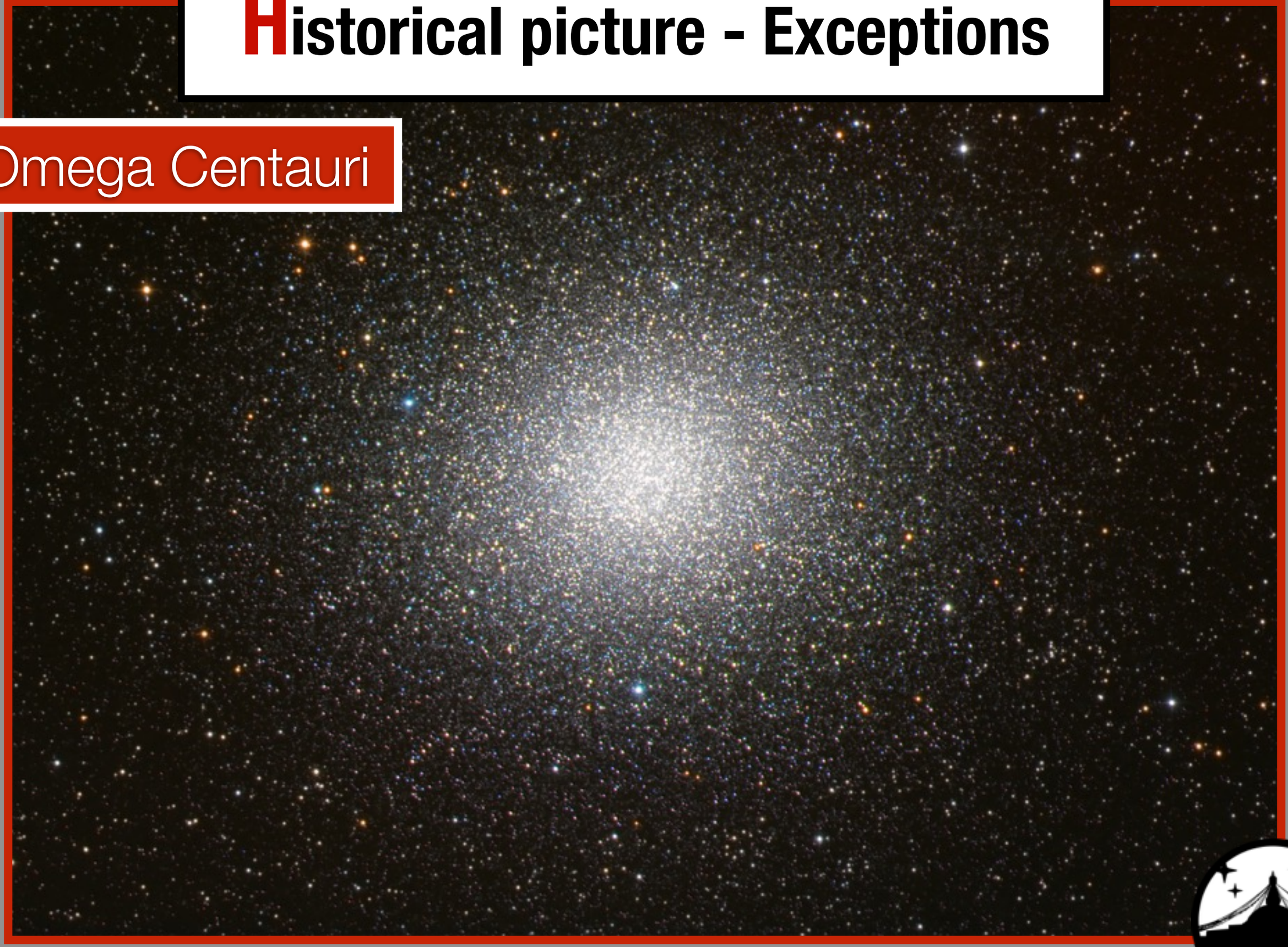
   ➡ Best Example:

   - NGC 6397



Historical picture - Exceptions

Omega Centauri



Historical picture - Exceptions

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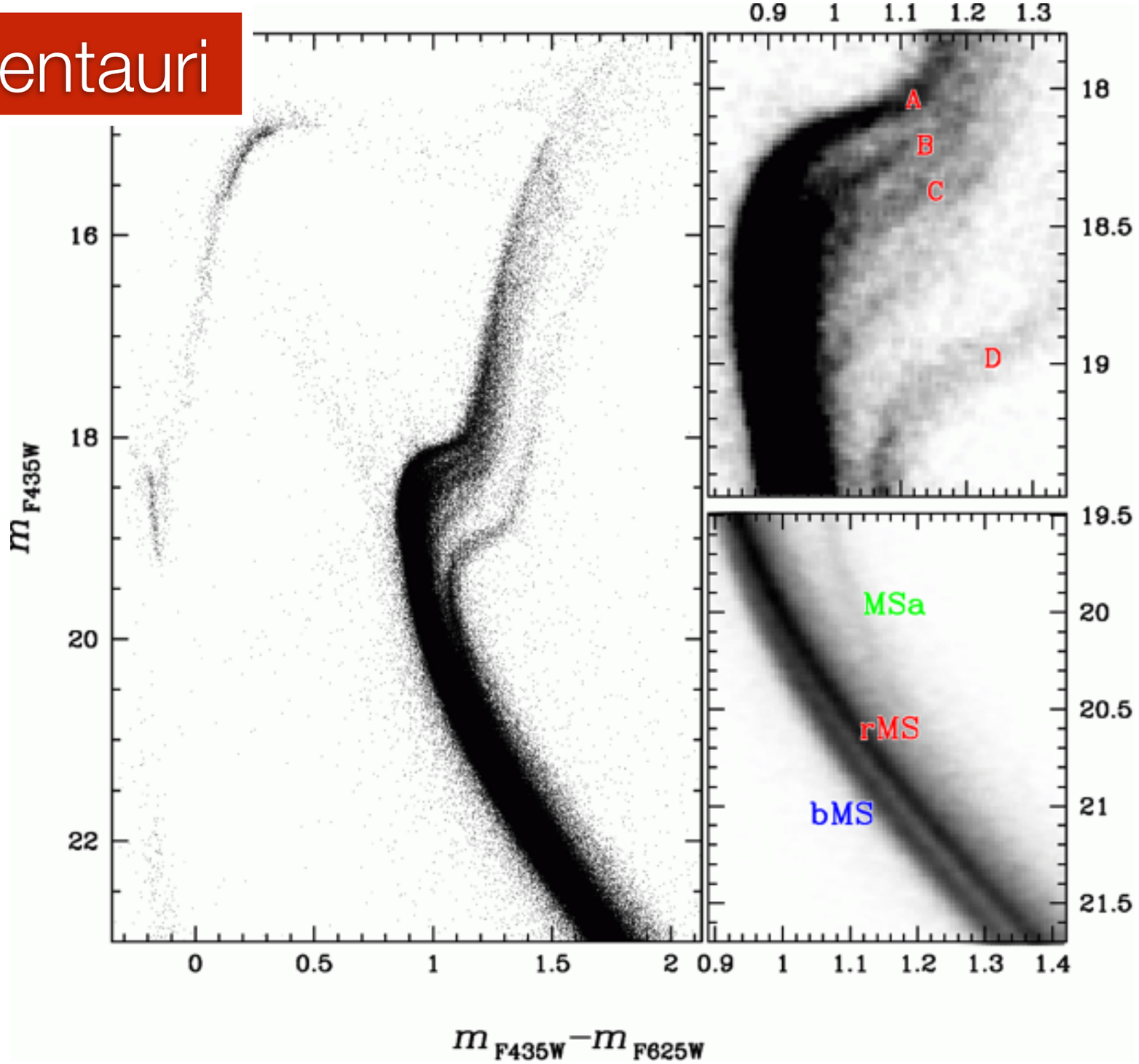
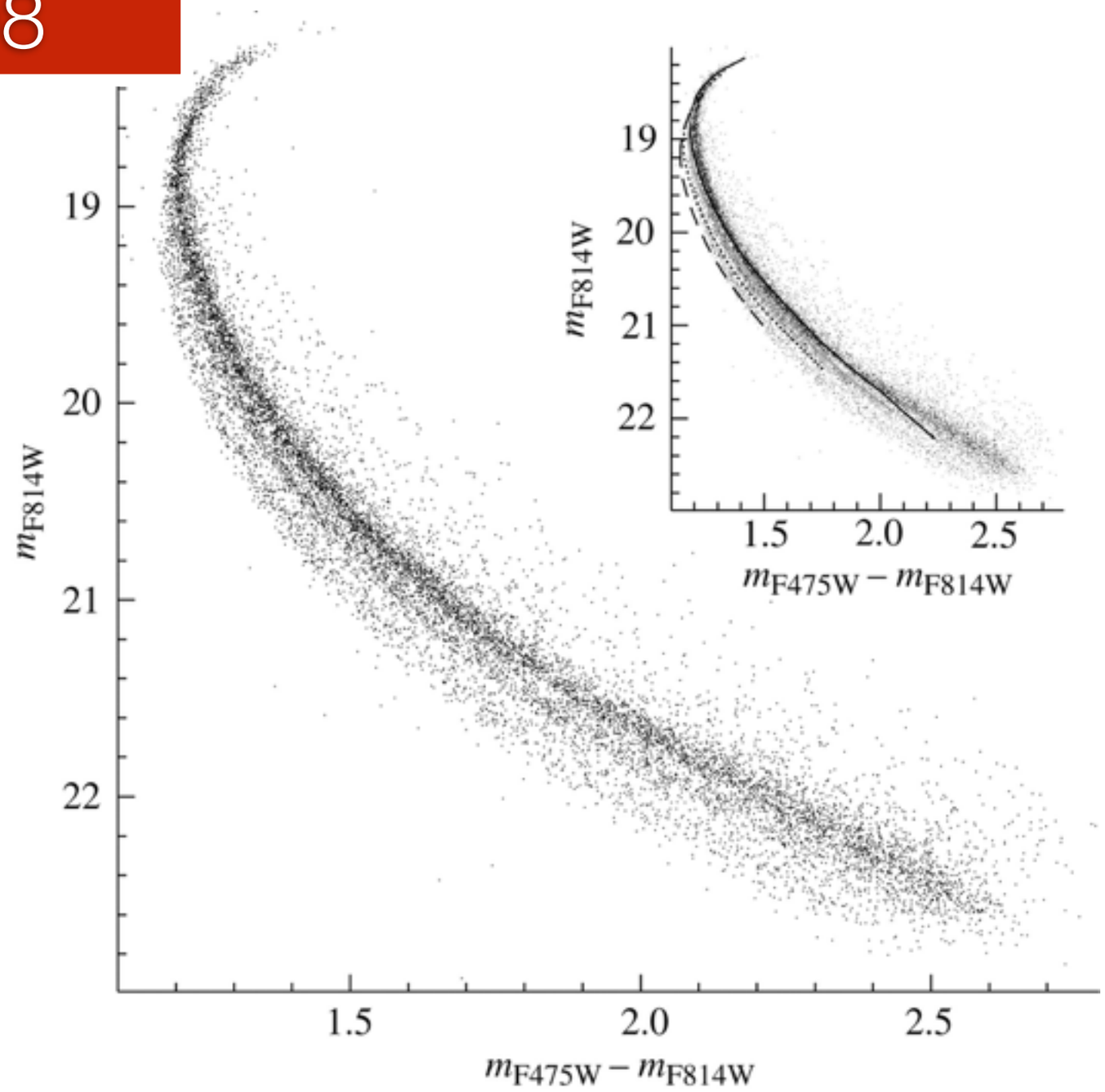
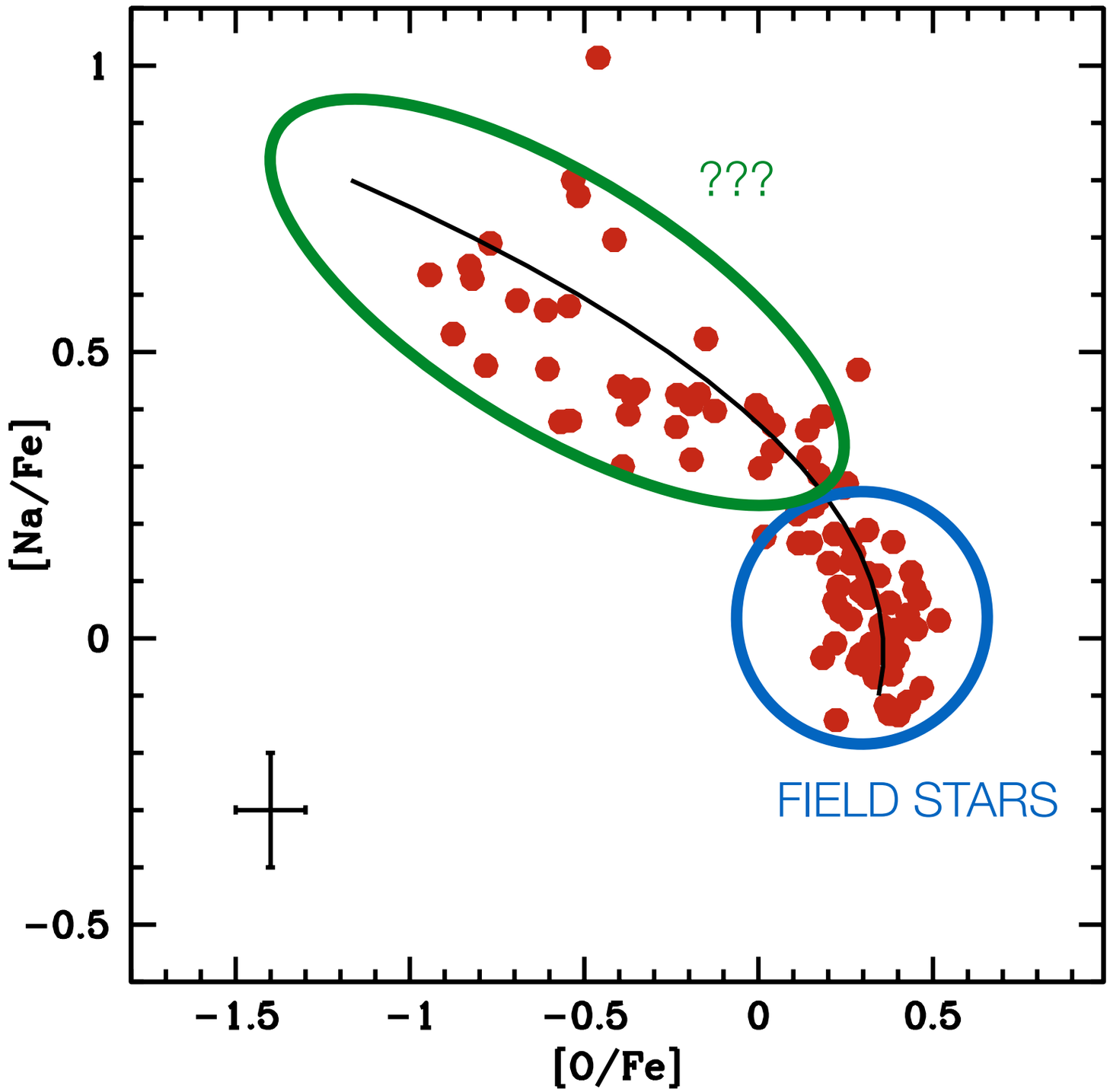


Observations - Photometry

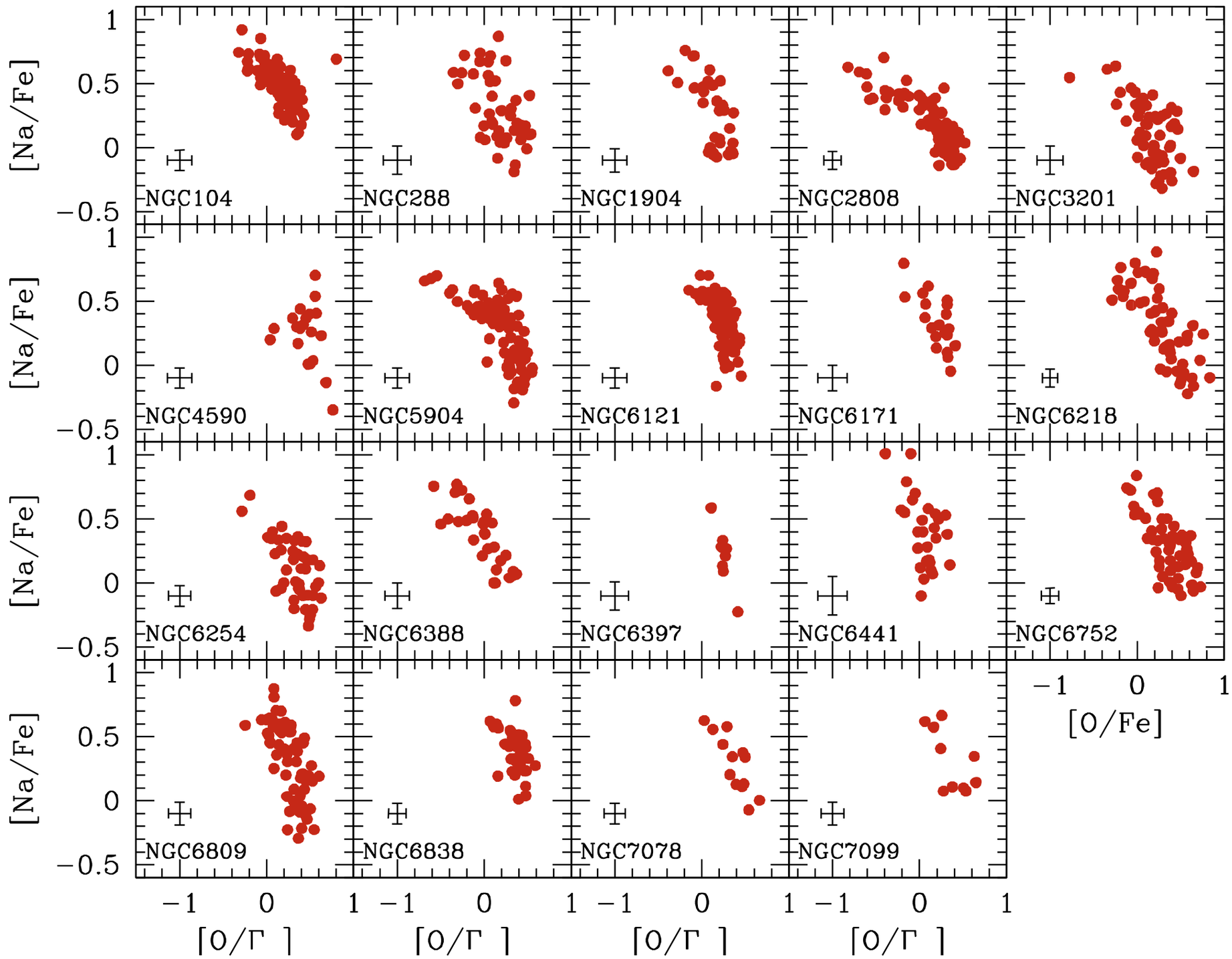
NGC 2808



Observations - Na-O Anti Correlation



Observations - Na-O Anti Correlation



Explanations

1. Multiple generations of stars?
2. Pollution of stars?
3. Both?

Explanations

POLLUTERS + 2ND GENERATION

1. AGB Stars

   ➡ Pollution of gas from AGB stars winds

2. Fast Rotating Massive Stars

   ➡ Pollution of gas from fast rotating stars

3. Very Massive Stars

   ➡ Pollution of gas from stars with $M > 10^4\ M_{SUN}$

POLLUTERS

4. Early Disc Accretion

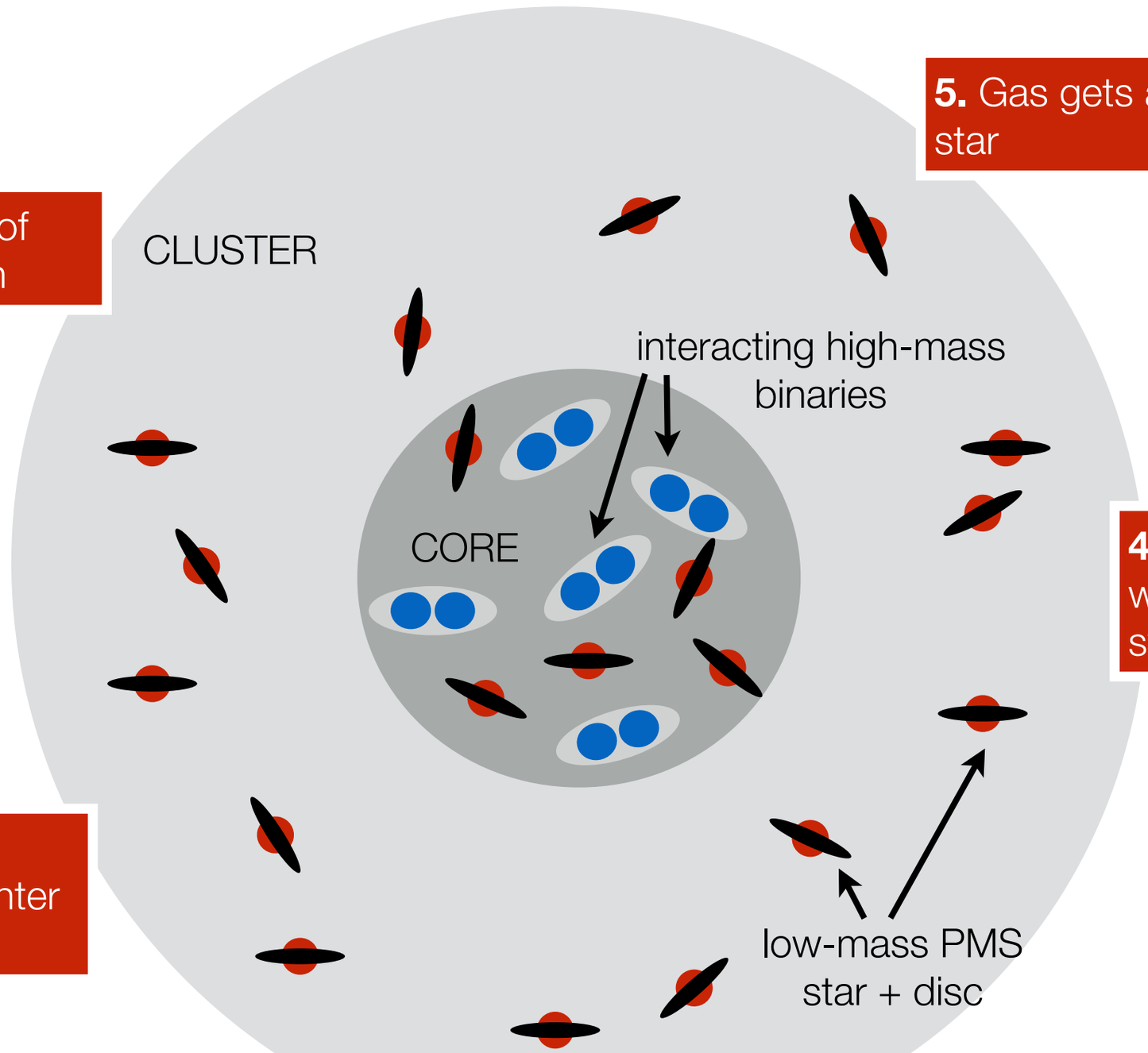
   ➡ Only one generation of stars

   ➡ Low-mass stars swipe gas from protoplanetary disks

Explanations - Polluters

1. One burst of star formation

5. Gas gets accreted to star



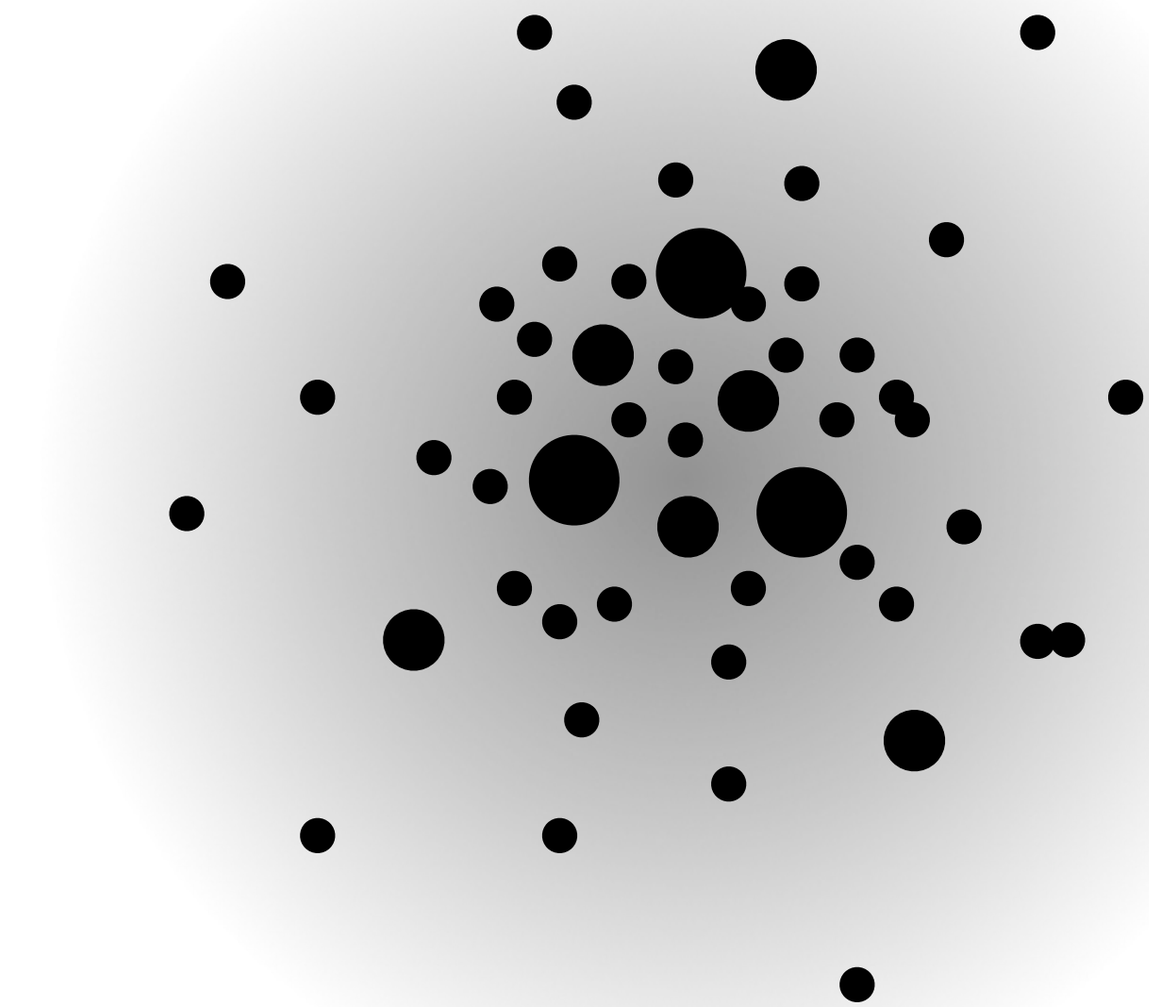
4. Low-mass stars with discs (5-10 Myr) swipe up the gas

2. High-mass stars (binaries) sink to the center (Lecture 3)

3. Eject polluted material

Explanations - Polluters + 2nd generation

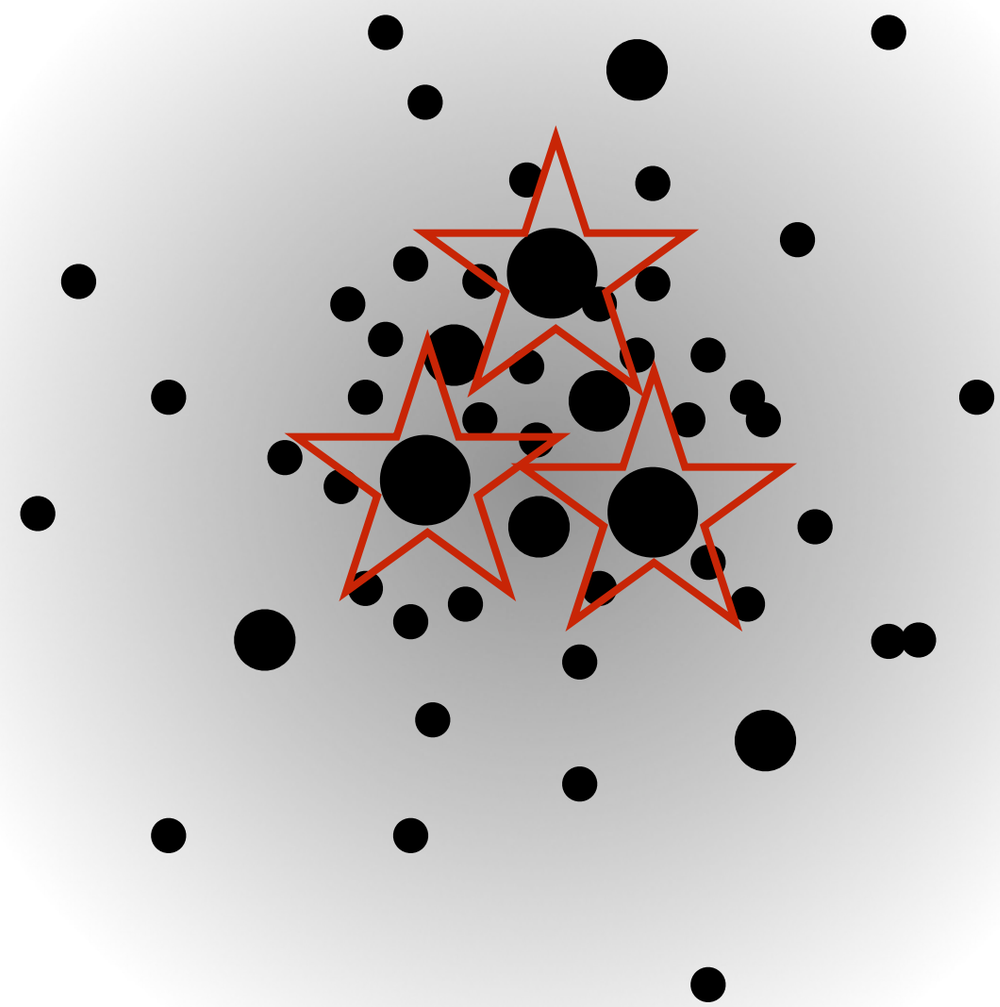
T = 0



Stars born in gas cloud, Gas still present

Explanations - Polluters + 2nd generation

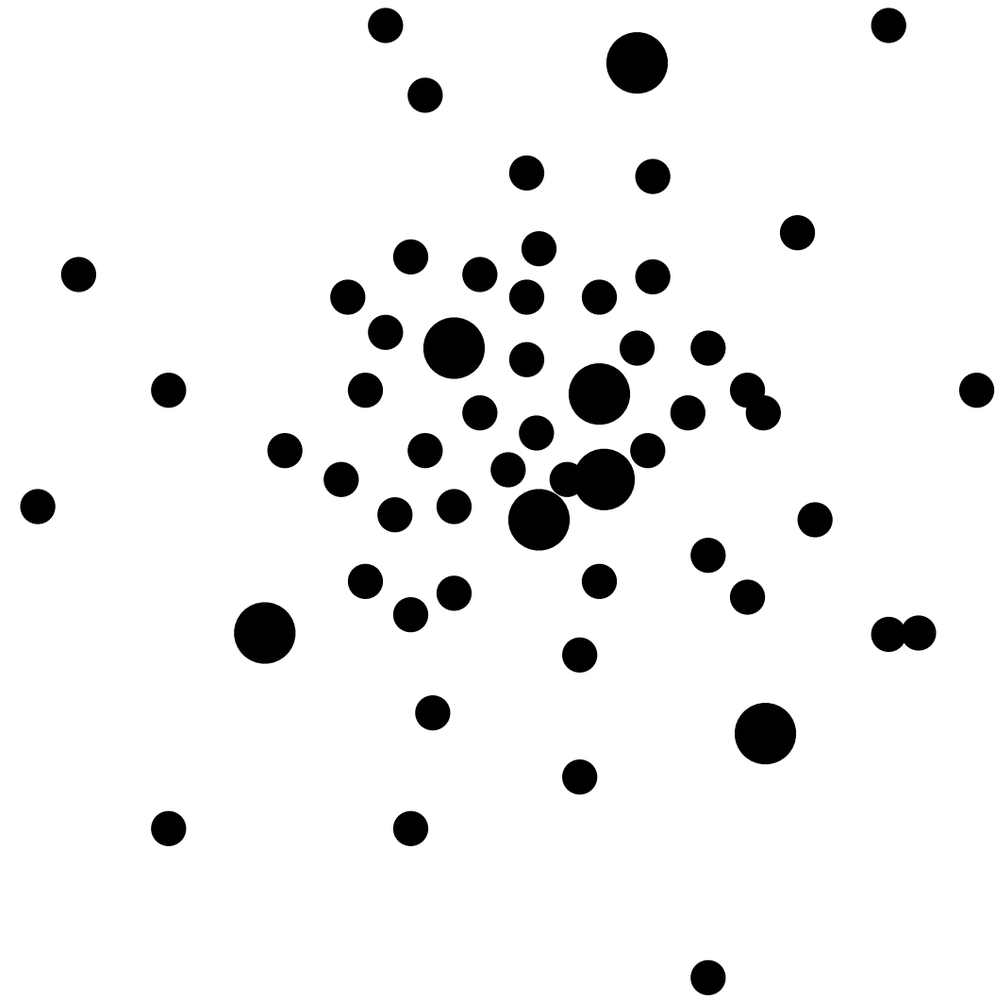
T = 2-3 x10^6 yr



Supernova explosion → expel primordial gas

Explanations - Polluters + 2nd generation

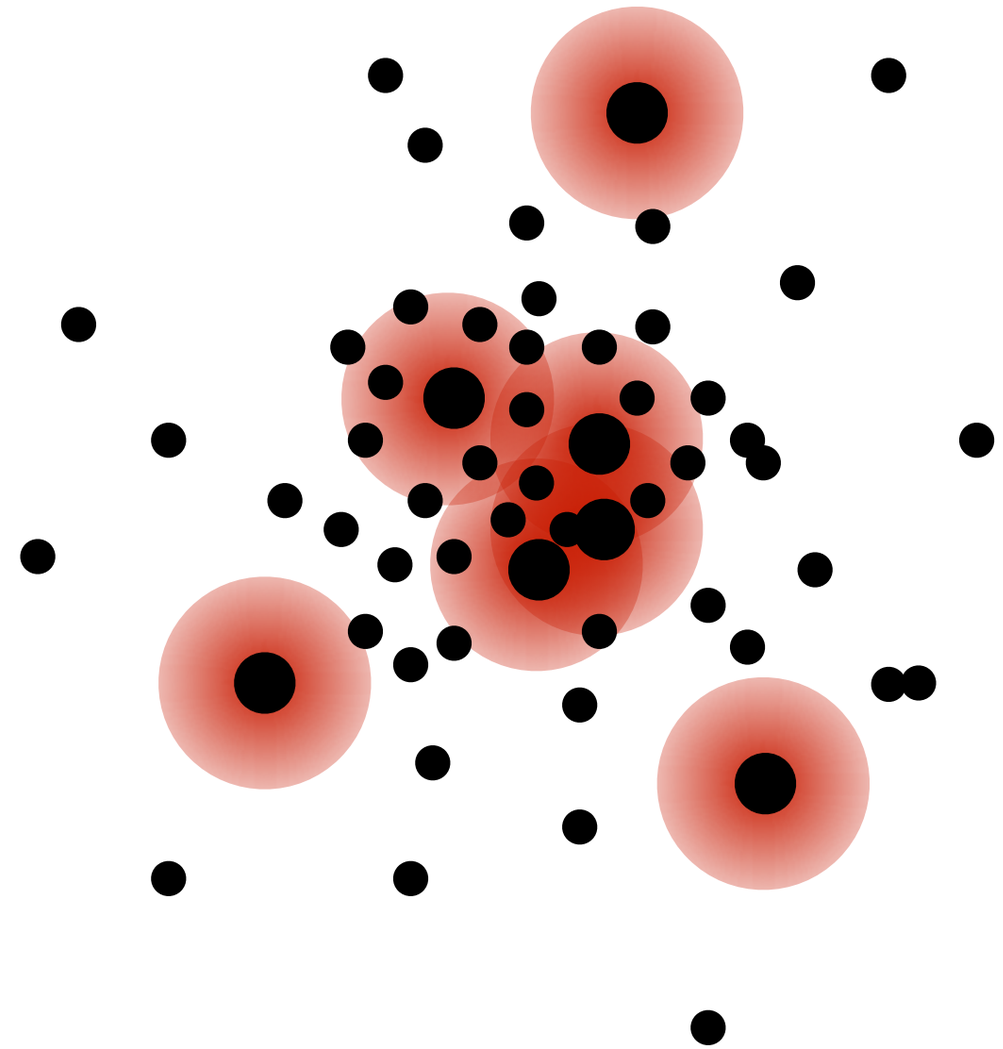
T > 2-3 x10^6 yr



Star formation stops → Singel population evolves

Explanations - Polluters + 2nd generation

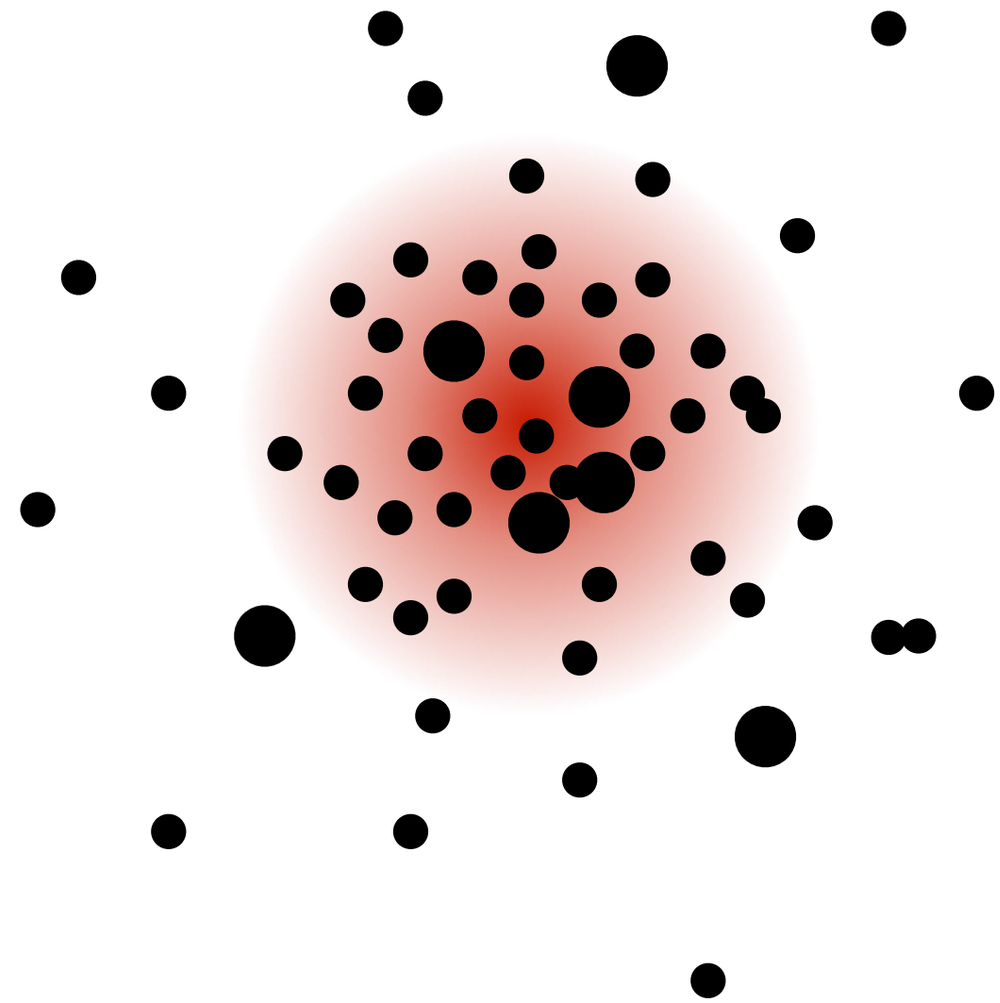
$T > 30 \times 10^6$ yr



Polluters (AGB, FRMS, VMS) start expelling material

Explanations - Polluters + 2nd generation

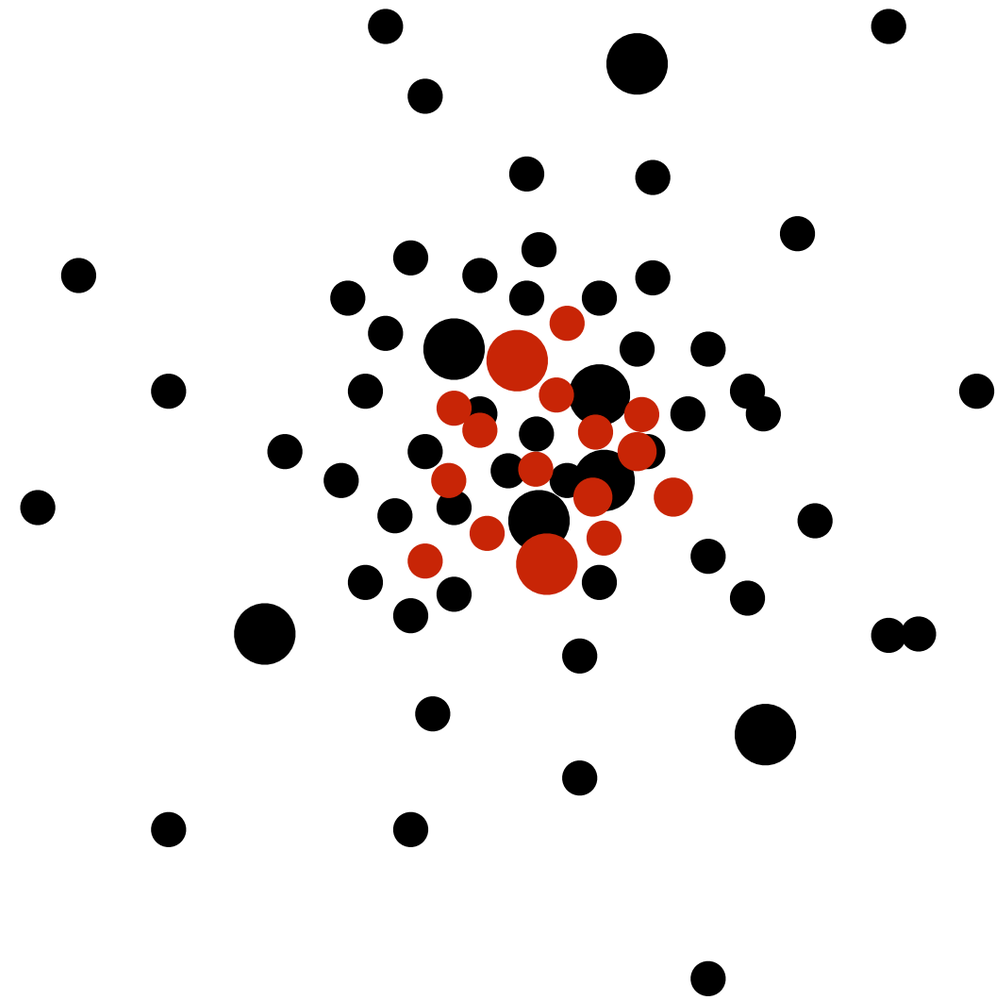
$T > 30 \times 10^6$ yr



(polluted) Gas collects in the center of the cluster

Explanations - Polluters + 2nd generation

$T < 100 \times 10^6$ yr



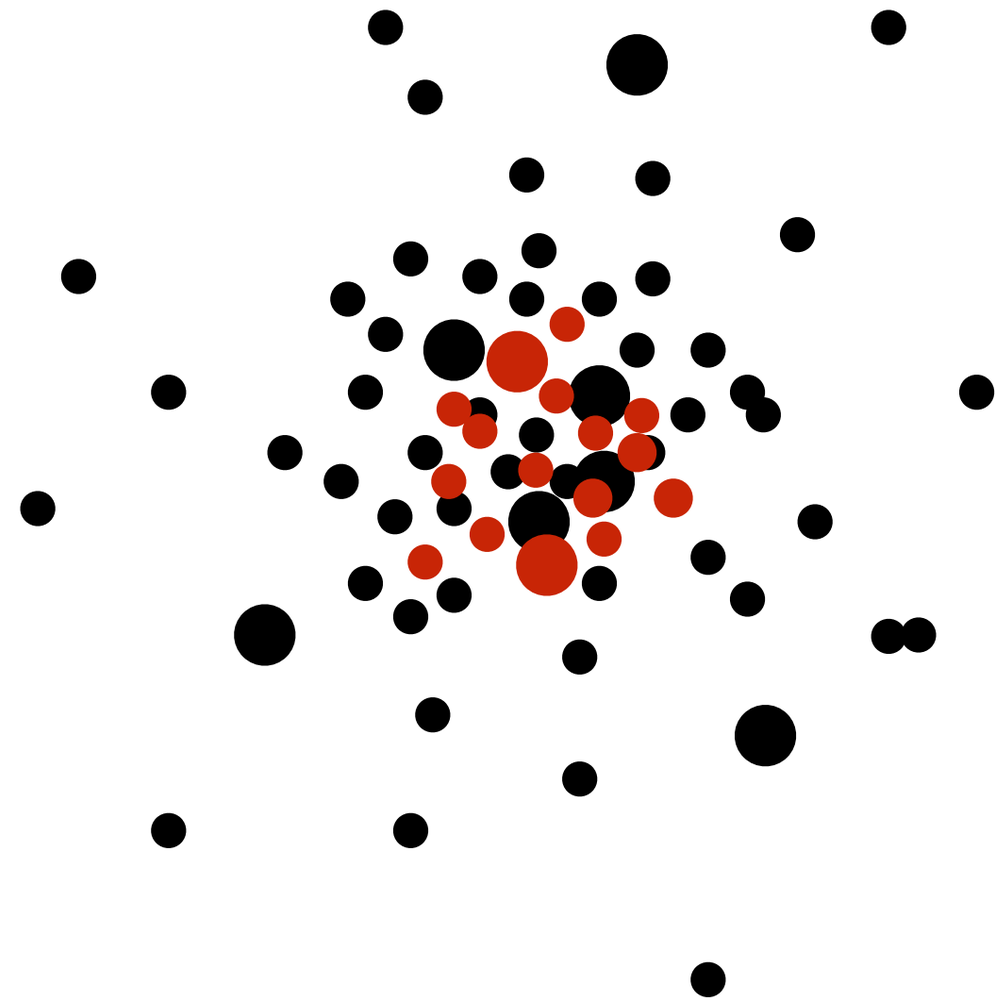
2nd Generation is forming

Explanations - Problems

THIS IS ALL GREAT, BUT…

Explanations

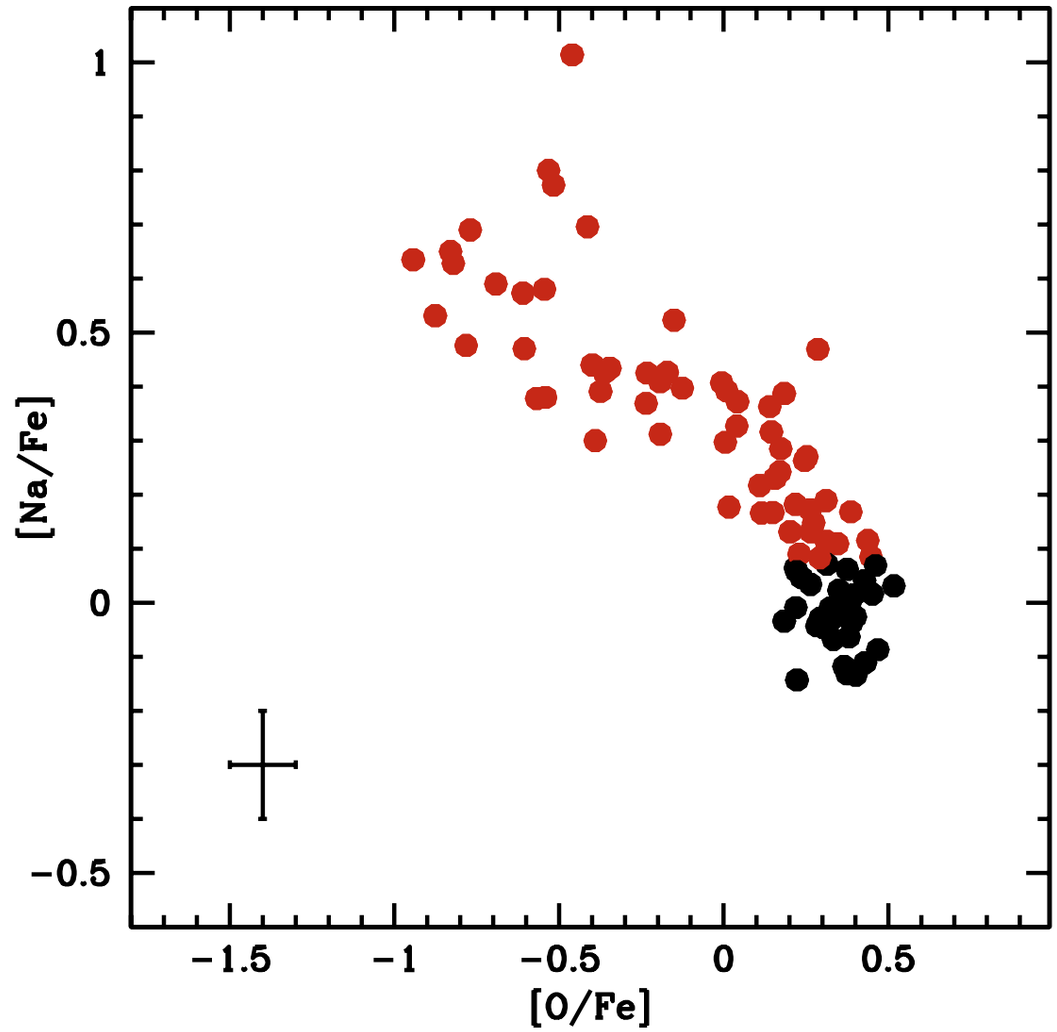
THEORY: Mass of First Generation (FG) > Mass of Second Generation (SG)



Explanations

THEORY: Mass of First Generation (FG) > Mass of Second Generation (SG)

OBS: Mass of First Generation (FG) < Mass of Second Generation (SG)



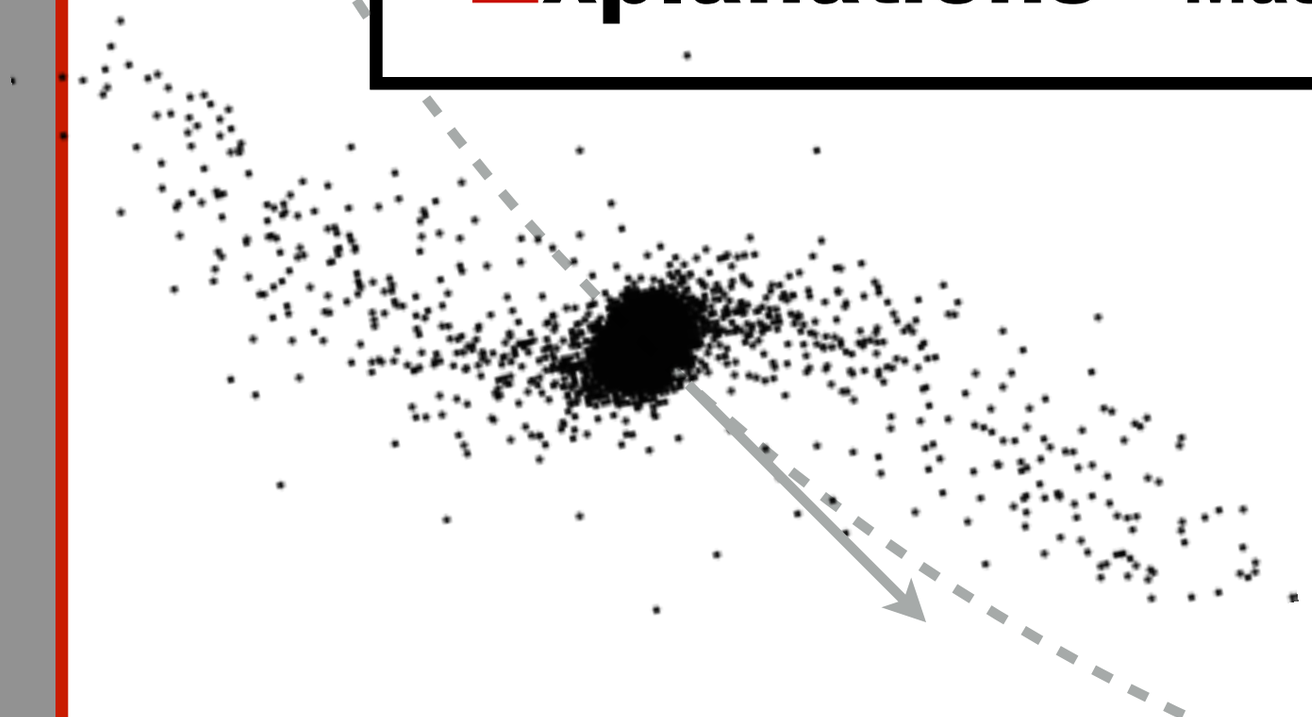
Explanations

THEORY: Mass of First Generation (FG) > Mass of Second Generation (SG)

OBS: Mass of First Generation (FG) < Mass of Second Generation (SG)

GCs must have lost 90% of their mass?

Explanations - Mass-Budget Problem



➡ GCs **do** loose 50% - 60% of their mass during their lifetime

BUT

> 60% is dynamically not possible

Explanations - More problems

AND THERE IS MORE…

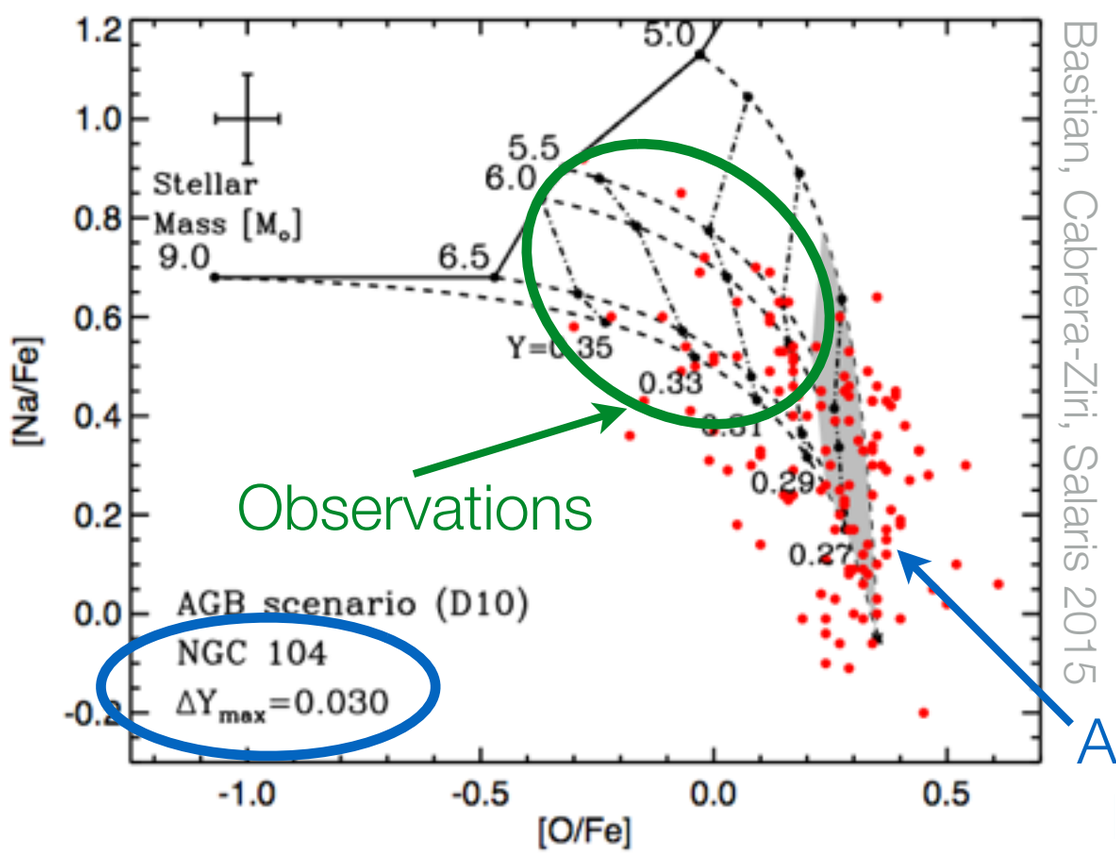
Explanations - More problems

1. Young Massive Clusters

   ➡ Don’t see any sign of 2nd star formation

2. Abundance patterns

   ➡ Models over-predict He abundance



Explanations - More problems

	YOUNG MASSIVE CLUSTERS	ABUNDANCE PATTERNS	MASS BUDGET	…
POLLUTERS + 2ND GENERATION: AGB	✗	✗	✗	
POLLUTERS + 2ND GENERATION: FRMS — Fast rotating massive stars	✗	✗	✗	
POLLUTERS + 2ND GENERATION: VMS — Very massive stars	✓	✗	✗	
POLLUTERS: EDA — Early Disc Accretion	✓	✗	✗	

Summary

1. **Star Formation**
   - from gas clouds, fragmentation
   - Initial mass function (IMF): multiple power laws, changes with time
2. **Multiple Stellar populations**
   - Photometric evidence: Multiple sequences in CMD
   - Spectroscopic evidence: Na-O anti-correlation
   - Explanations:
     1. Polluters + 2nd Generation
     2. Polluters
   - Problems: Mass budget problem (must have lost 90% of their mass??…), and many more…