Title: Newborn super star clusters at Cosmic Noon seen through gravitational lensing

Speakers: Liang Dai

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Abstract: Super star clusters with masses > 1e6 Msun are thought to be progenitors of globular clusters (GCs). Their births however are seldomly seen in the local Universe. The puzzle of chemically peculiar populations found in most globular clusters implies that much is to be understood about what happens in the immediate environment of these young systems that host a large number of massive stars. I will present a photometric and spectroscopic study of a highly magnified, LyC-leaking super star cluster with a mass ~1e7 Msun and an age ~3-4 Myr, in a lensed Cosmic Noon galaxy. We found dense photoionized clouds at just ~ 10 pc that are highly enriched with nitrogen. We theorize that these dense clouds originate from massive star ejecta and may have implications for the origin of chemically peculiar stars. If time permits, I will discuss another lensed star cluster in the same galaxy that has a lensing anomaly and show intense Fe III fluorescent emissions pumped by Lyman alpha radiation. I will discuss a theory of trapped Lyman alpha radiation to explain this unusual spectral phenomenon, which again hints at an extremely gas-enshrouded environment caused by massive star ejecta inside a compact young super star cluster. These findings call for a better understanding of the interplay between radiation, gravity, gas and massive star evolution in young super star clusters.

Zoom link: https://pitp.zoom.us/j/97462607086?pwd=b0tkVXlTeG5MTnFheEphWXYyOFdhQT09

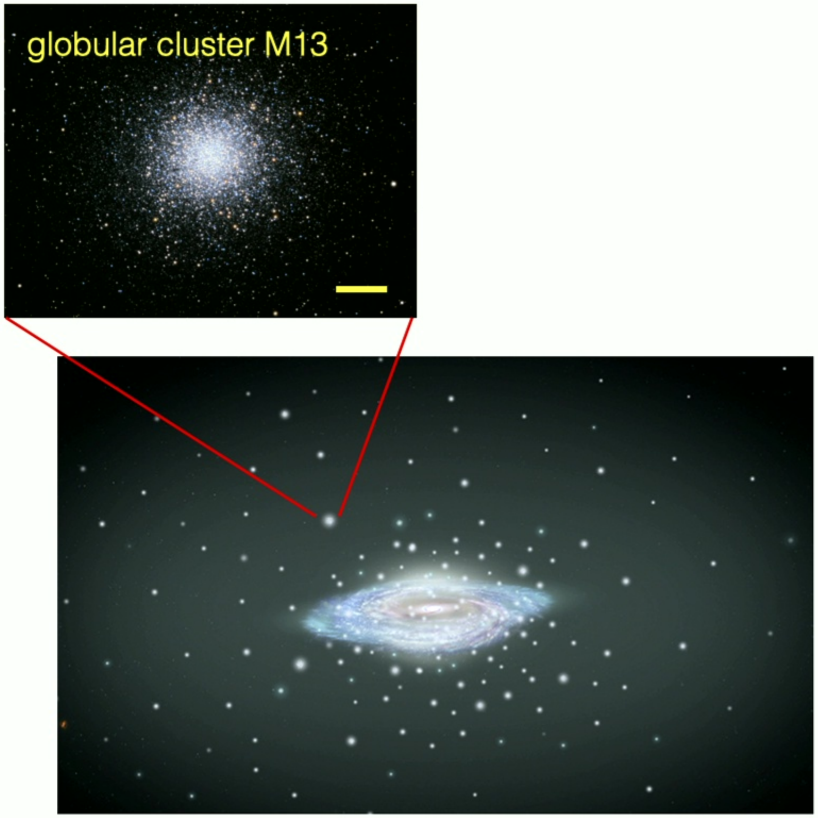
Outline

- *Introduction*:
  Globular clusters (GCs)
  Puzzle of multiple populations
  Super star clusters (SSCs) as GC progenitors

- Photometric and spectral modeling of a gravitationally magnified SSC at Cosmic Noon and its surrounding nebula.

- Physical interpretation of cluster and nebula properties.
  Implication for chemically peculiar stars forming from condensed massive star ejecta?

Globular clusters



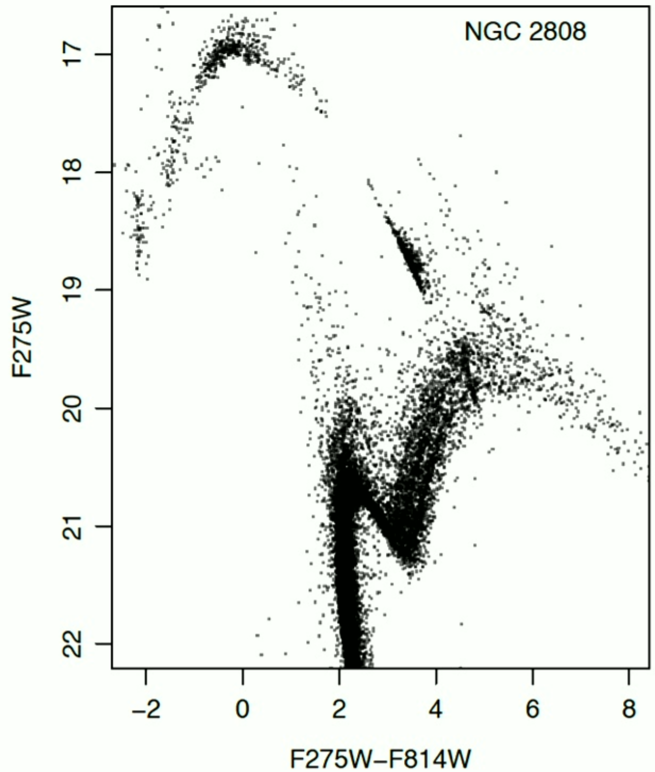
About 200 globular clusters orbit around the Milky Way

Around ~ 10^5-10^6 Msun of stars gravitationally bound within several parsecs

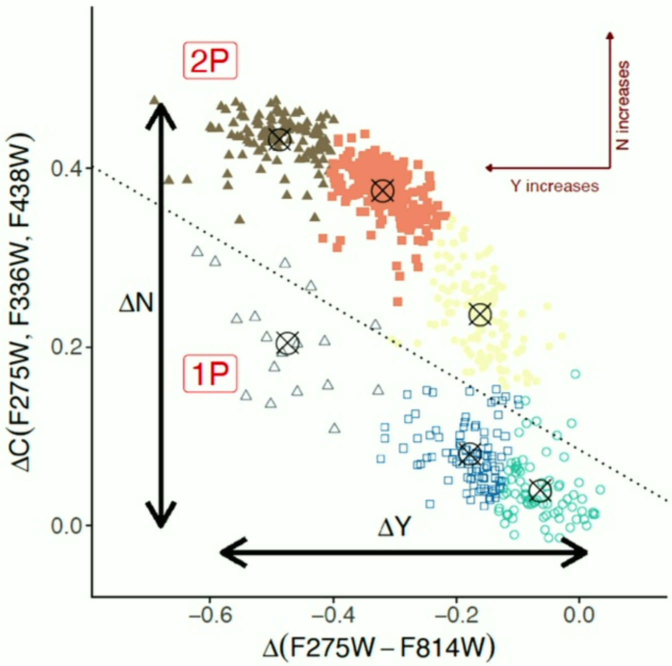
Very old stellar systems.
The progenitor of a GC is likely to be a super star cluster >10^6 Msun

Multiple stellar populations in GCs

Piotto++ (2015)

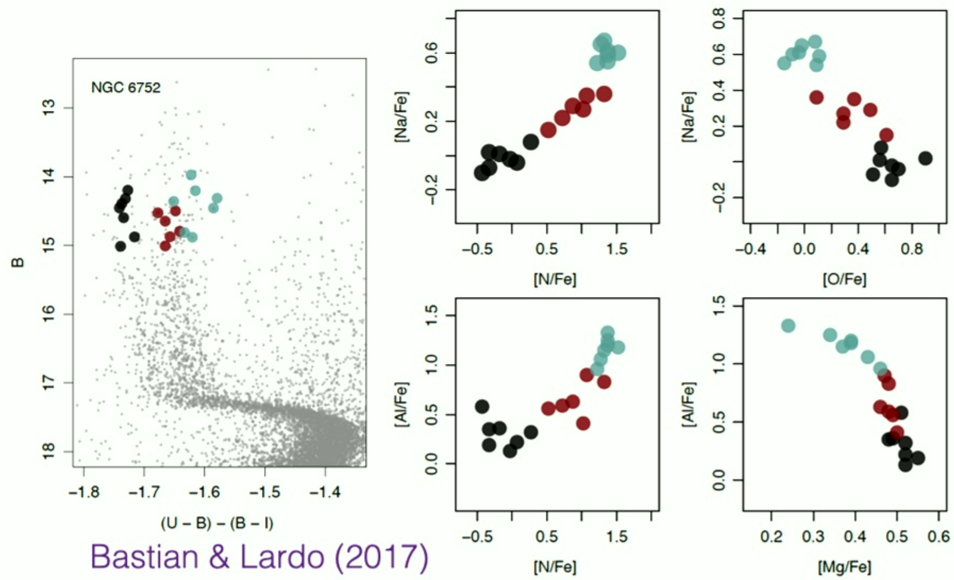


Milone++ (2017)



Discrete isochrones in the color-magnitude diagram
Two or more groups seen in color space.

Light element abundance anomaly



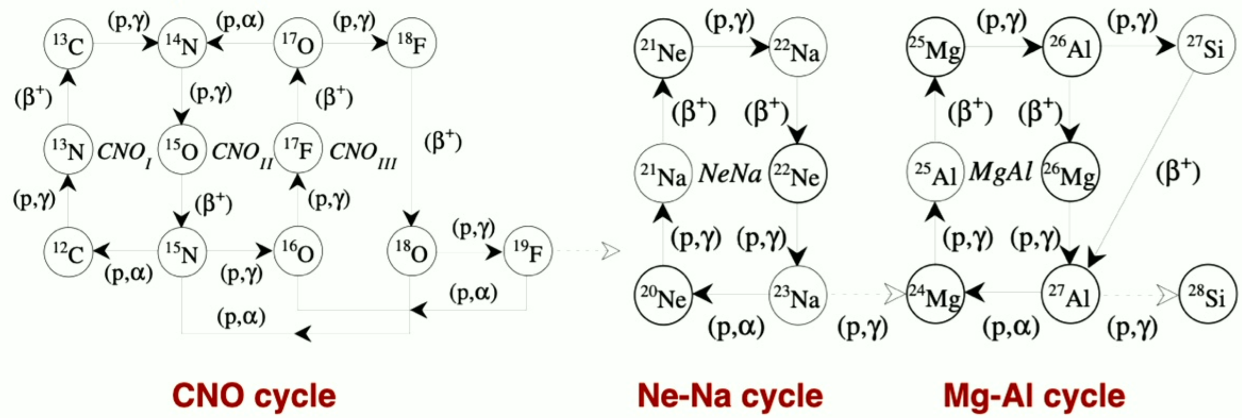
Bastian & Lardo (2017)

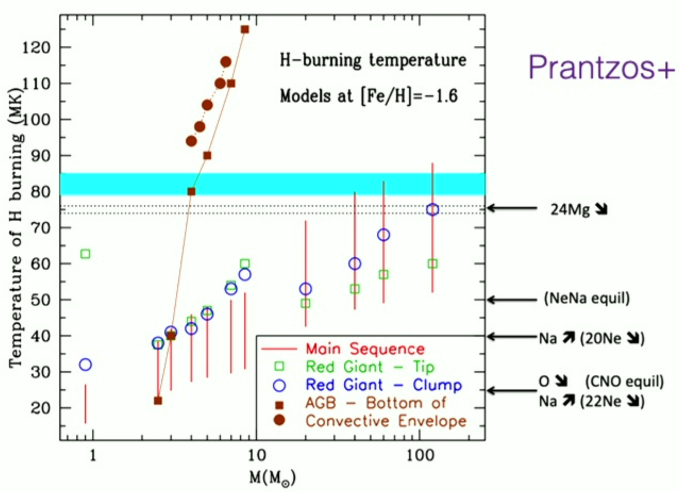
Correlated abundance anomalies:
Elevated N and depleted C and O (C+N+O uniform)
Elevated Na and depleted O
Elevated Al and depleted Mg

However, [Fe/H] is uniform

Hydrogen burning cycles

Arnould++ (1999)



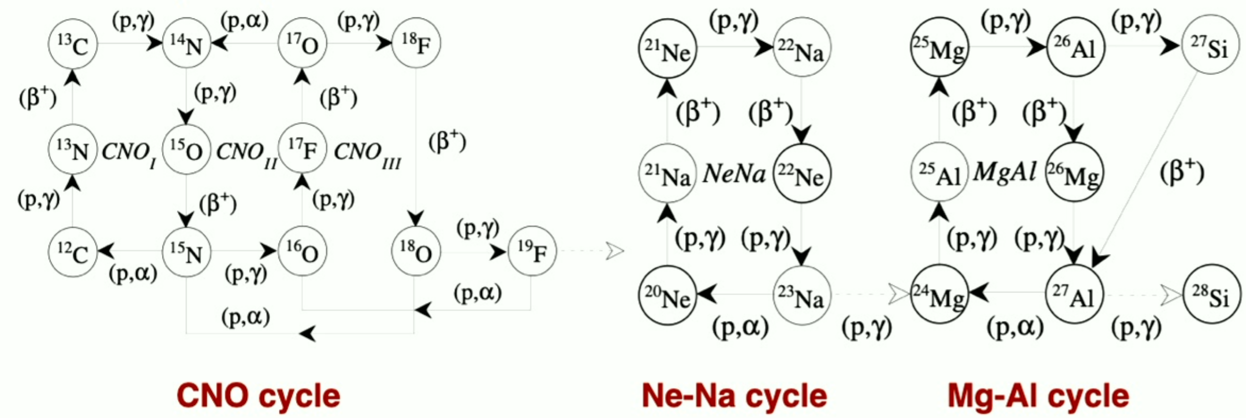


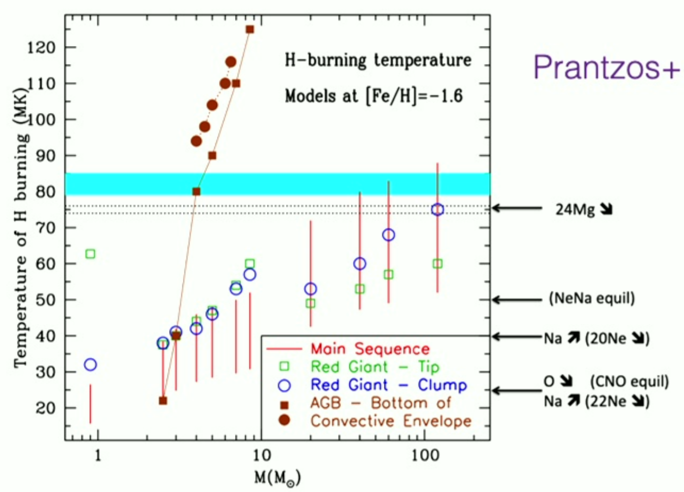
Prantzos++ (2007)

Hint at an origin as H-burning processed material from sufficiently massive stars

Hydrogen burning cycles

Arnould++ (1999)

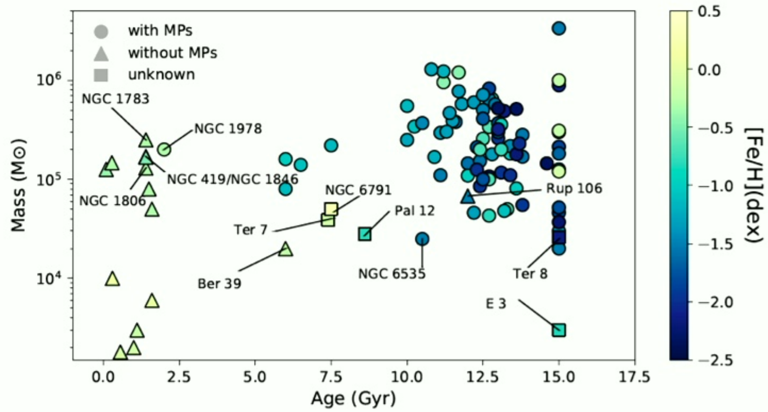


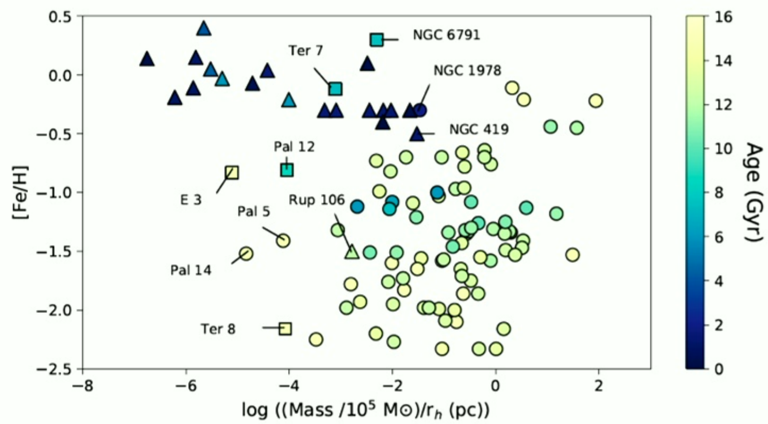


Prantzos++ (2007)

Hint at an origin as H-burning processed material from sufficiently massive stars

MP dependence on cluster mass and age





More 2P population in more massive clusters.
Can even dominate over 1P stars in number.

No multiple populations seen in MW open star clusters (~ 1000 Msun; unbound)

Small fraction (a few %) of chemically anomalous stars in the MW field

No clear detection of age difference between multiple populations

No multiple populations observed in star clusters younger than ~ 2 Gyr

Special IMF for 2P star formation?

What happens when cluster is young?

Some ideas

Turbulent separation of elements during star formation   Hopkins (2014)

Major problem:
[1] Observed element abundance anomaly one-sided but not a symmetric scatter

AGB stars with masses between 6—9 Msun?   e.g. Cottrell & Da Costa (1981); Renzini (2013, 2015);

Chemically enriched slow winds ~ 30 km/s from t = 30—100 Myr

Major problems:
[1] Na-O correlation rather than anti-correlation
[2] Mass budget problem
[3] Onset maybe too late

Very massive stars with masses > 10^3 Msun from runaway merger?

Intense, slow stellar wind pollutes the intracluster medium   e.g. Gieles++ (2018);

Major problem:
[1] VMS still a theoretical speculation; stellar evolution highly uncertain

What happens when the cluster is young?

Fast rotating massive stars with masses > 20 Msun

Slow material ejection from decretion disc near the equatorial plane

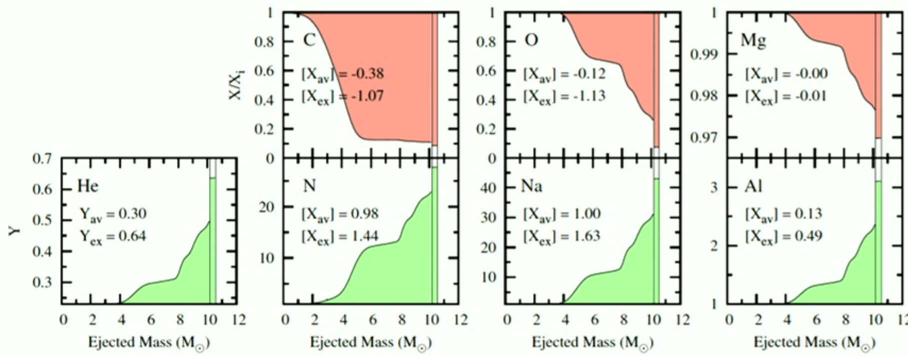
Major challenge:
[1] Mass budget problem
[2] Need to avoid SN gas clearing at ~ 3—8 Myr

e.g. Decressin++ (2007);
Decressin, Charbonnel & Meynet (2007);
Krause++ (2013); Charbonnel++ (2014)

Non-conservative binary mass transfer between massive stars

Slow material ejection from L2 once the donor spins up the companion sufficiently

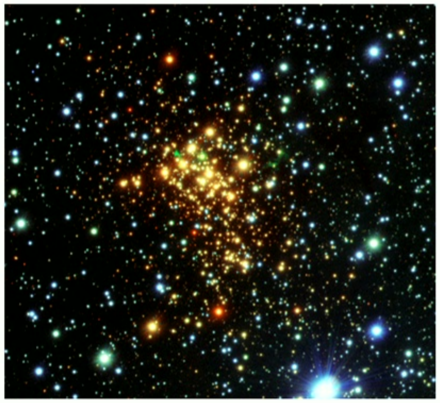
de Mink++ (2009)



Massive compact young star clusters in MW

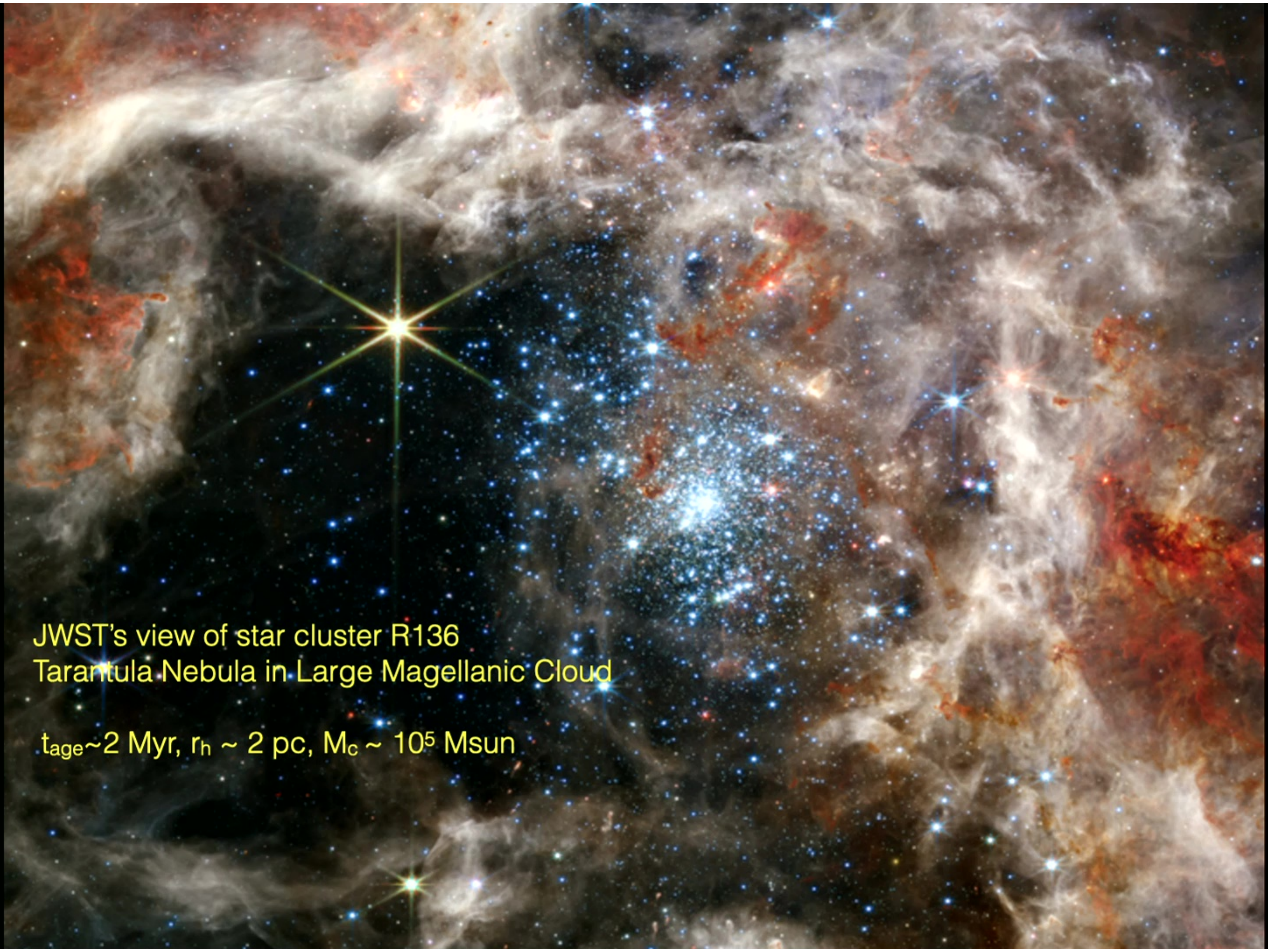
Arches cluster
t_{age}~2.5 Myr, r_h ~ 0.5 pc, M_c ~ 10^4 Msun

Quintuplet cluster
t_{age}~5 Myr, r_h ~ 1 pc, M_c ~ 10^4 Msun



Westerlund 1
t_{age}~3.5 Myr, r_h ~ 1 pc, M_c ~ $6x10^4$ Msun

Westerlund 2
t_{age}~1—2 Myr, r_h ~ 2 pc, M_c ~ $4x10^4$ Msun

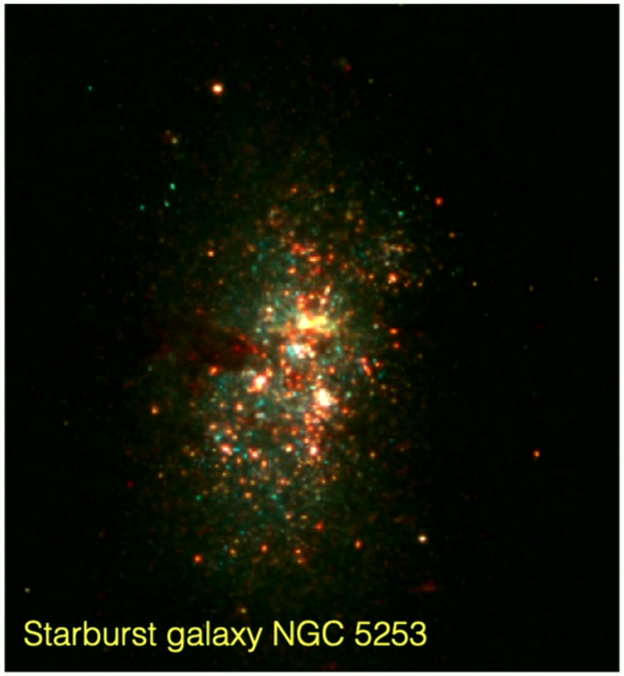

JWST's view of star cluster R136
Tarantula Nebula in Large Magellanic Cloud
t_{age}~2 Myr, r_h ~ 2 pc, M_c ~ 10^5 Msun

More massive star clusters in more distant galaxies

Two compact super star clusters

One super star cluster at only a few Myr old, and with a mass ~ $3x10^5$ Msun

Ho & Filippenko (1996)



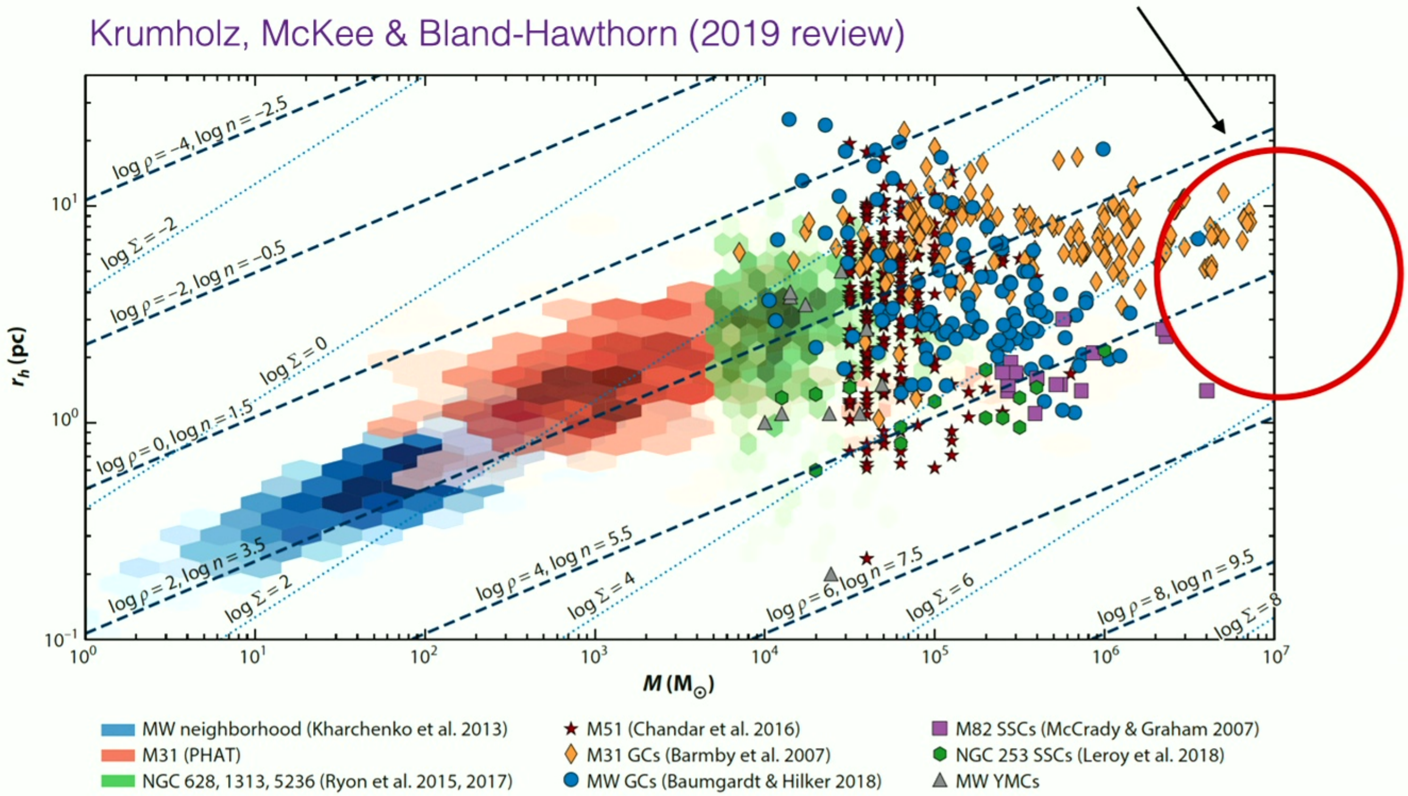
A few newborn super star clusters < 10^6 Msun
embedded in molecular clouds
More exposed but less massive young star clusters

Turner++ (2000; 2015)

Star cluster mass versus size

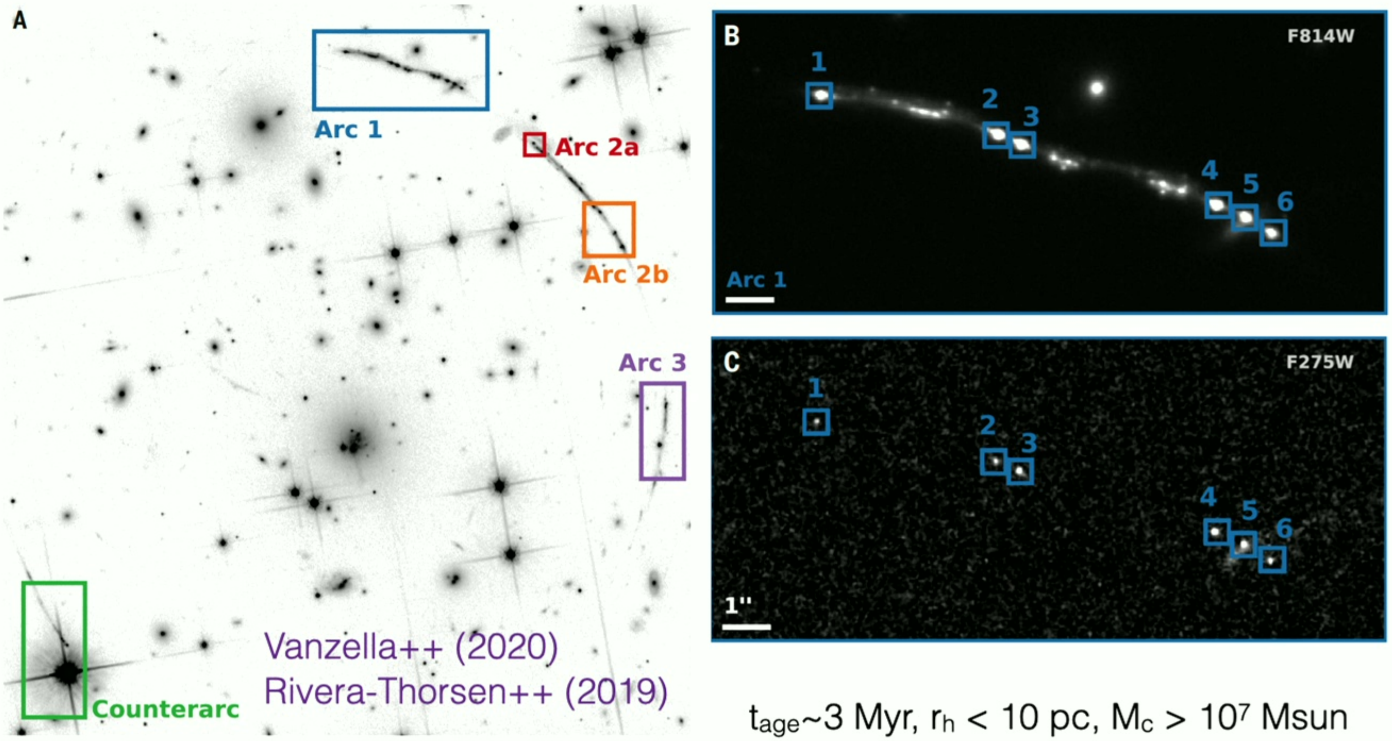
Hint of such massive, compact star clusters in the high-z universe (?!)

Krumholz, McKee & Bland-Hawthorn (2019 review)



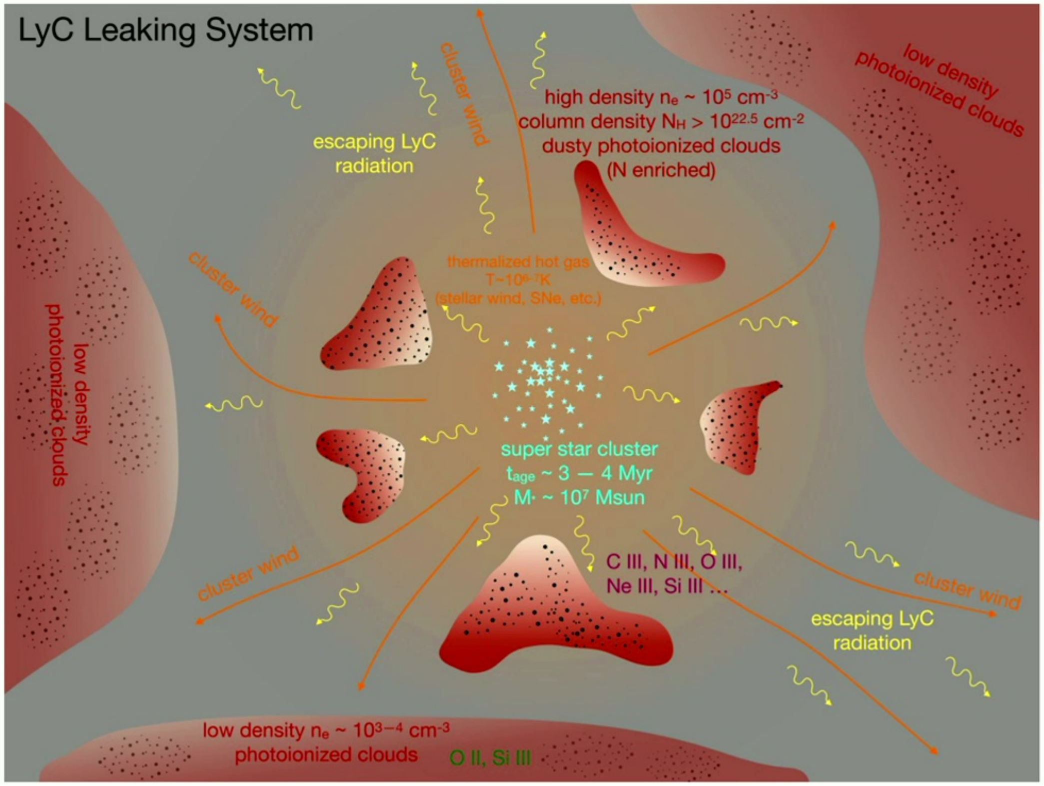
Super Star Cluster at Cosmic Noon (z=2.37)

A SSC candidate is the strongly lensed Sunburst galaxy.
Shows 12 highly magnified ($\mu \sim 10$—100), lensed images.



t_{age}~3 Myr, r_h < 10 pc, M_c > 10^7 Msun

Spectral modeling of the LyC cluster



Massimo Pascale

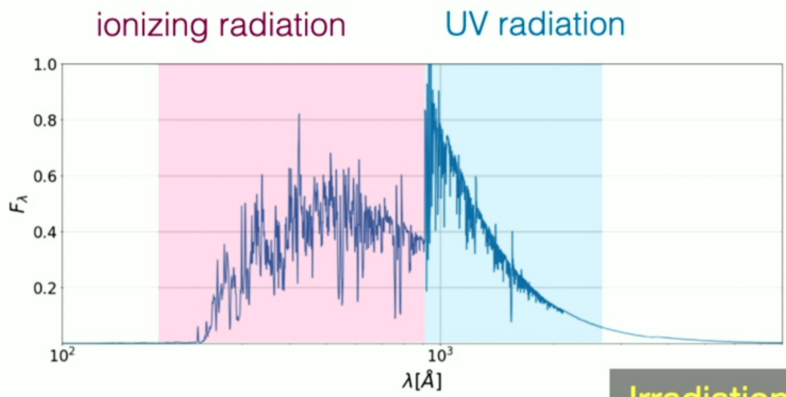
***Data*:** magnitudes in a dozen HST filters; (rest-frame) UV and optical emission lines

***Physical model*:** direct star light + nebular continuum + nebular emission lines

Spectral calculations

Cluster integrated stellar radiation output (BPASS with binary stars)

Metallicity: **Z**
Age: $\mathbf{t_{age}}$

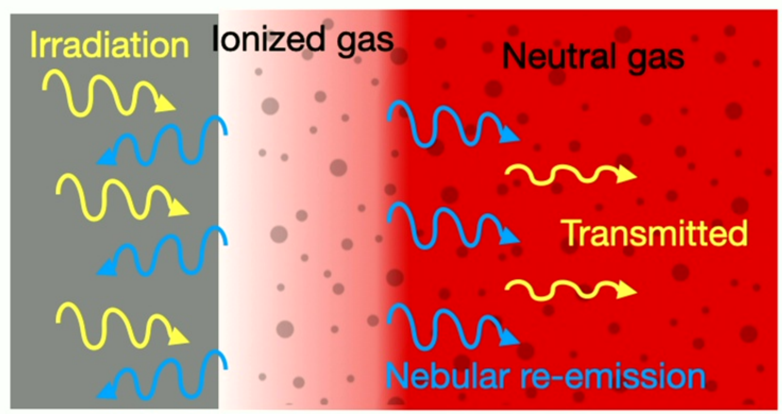


ionization parameter: **U**
(radiation-gas ratio)

(Total) pressure: **P**

Photoionization of surrounding clouds (CLOUDY)

Ferland++ (2017)



Host ISM dust reddening: **E(B-V)**

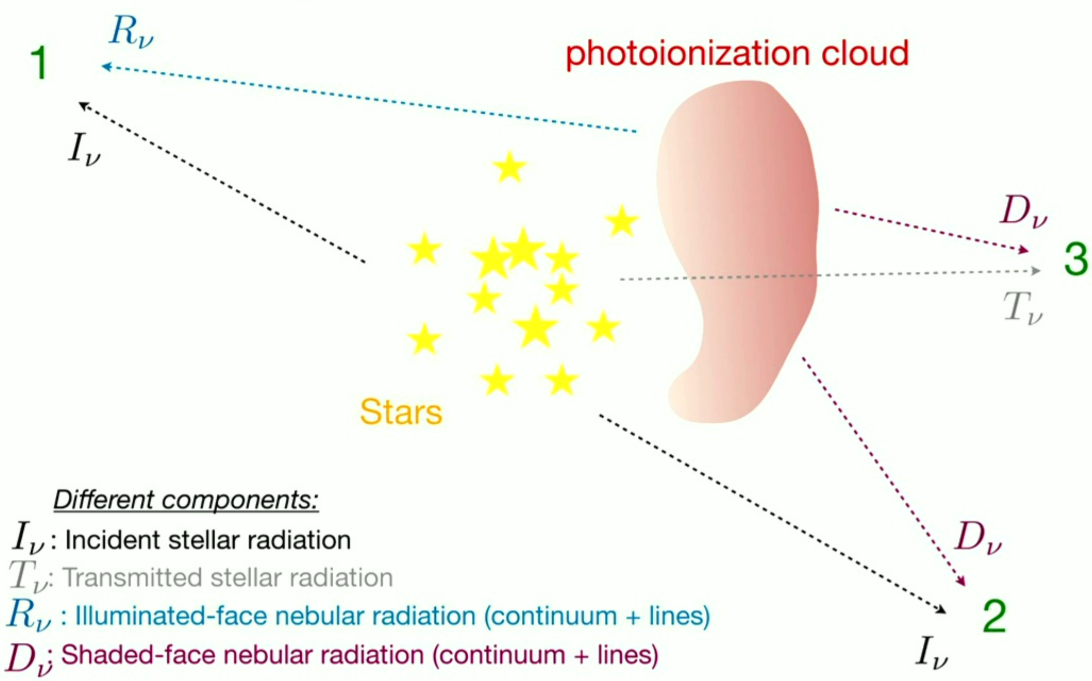
Observed spectrum

Spectrum dependent on line of sight

Covering factor around the cluster:
0 <= x <= 1

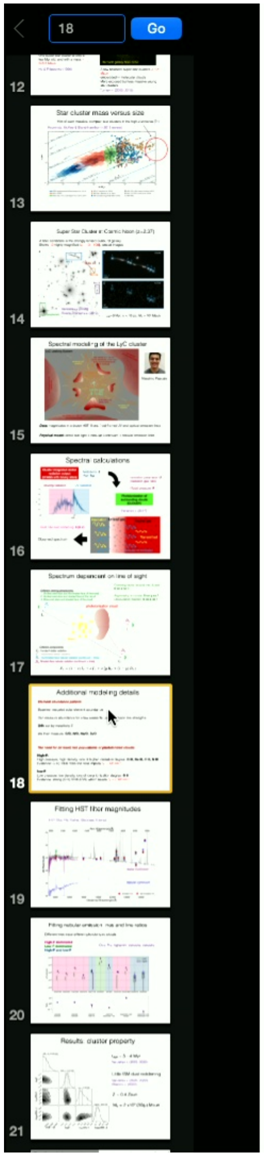
Asymmetry of clouds: **0 <= y <= 1**
Obscuration fraction: **0 <= z <= 1**

Different viewing perspectives:
1: Unobscured stars and illuminated face of the cloud
2: Unobscured stars and shaded face of the cloud
3: Obscured stars and shaded face of the cloud



Different components:
I_ν : Incident stellar radiation
T_ν: Transmitted stellar radiation
R_ν : Illuminated-face nebular radiation (continuum + lines)
D_ν: Shaded-face nebular radiation (continuum + lines)

$$F_\nu = (1-z)\, I_\nu + z\, T_\nu + x\,(y\, R_\nu + (1-y)\, D_\nu)$$



Additional modeling details

Element abundance pattern:

Baseline: rescaled solar element abundance

Can measure abundance for a few elements using emission line strengths:

O/H: set by metallicity Z

We then measure: **C/O, N/O, Ne/O, Si/O**

The need for (at least) two populations of photoionized clouds:

High-P:
High pressure, high density, ions of higher ionization degree: **O III, Ne III, C III, N III**
Evidence: C III] 1908,1906 line ratio implies $n_e \sim 10^5$ cm^{-3}

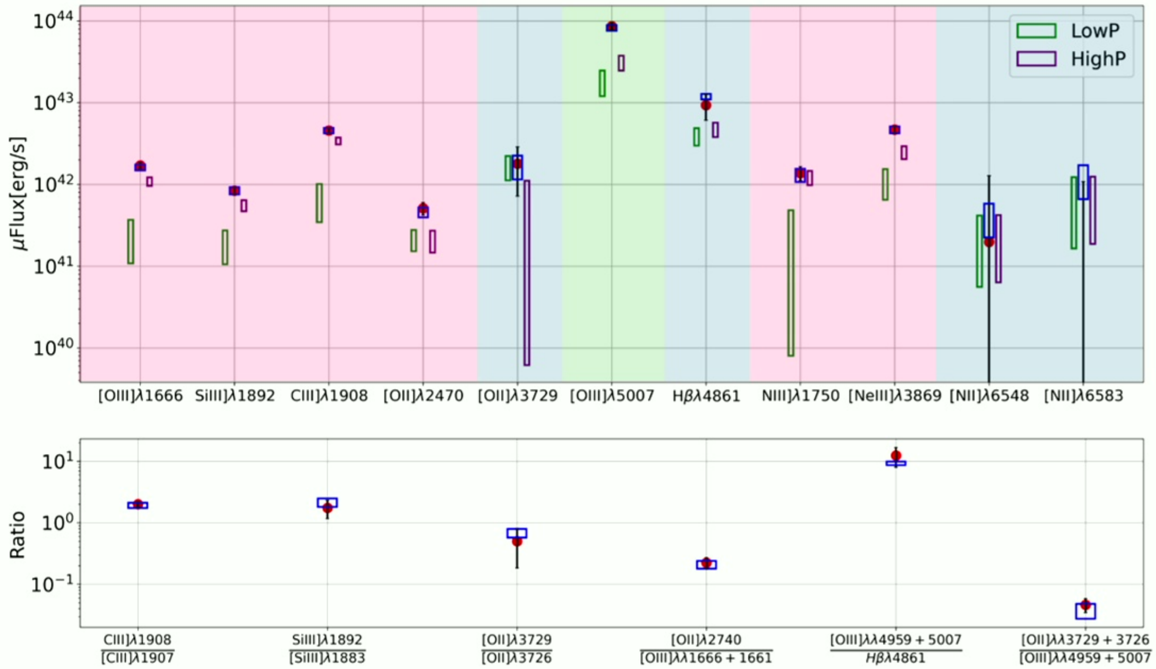
low-P:
Low pressure, low density, ions of lower ionization degree: **O II**
Evidence: strong [O II] 3726,3729, which needs $n_e <\sim 10^4$ cm^{-3}

Fitting nebular emission lines and line ratios

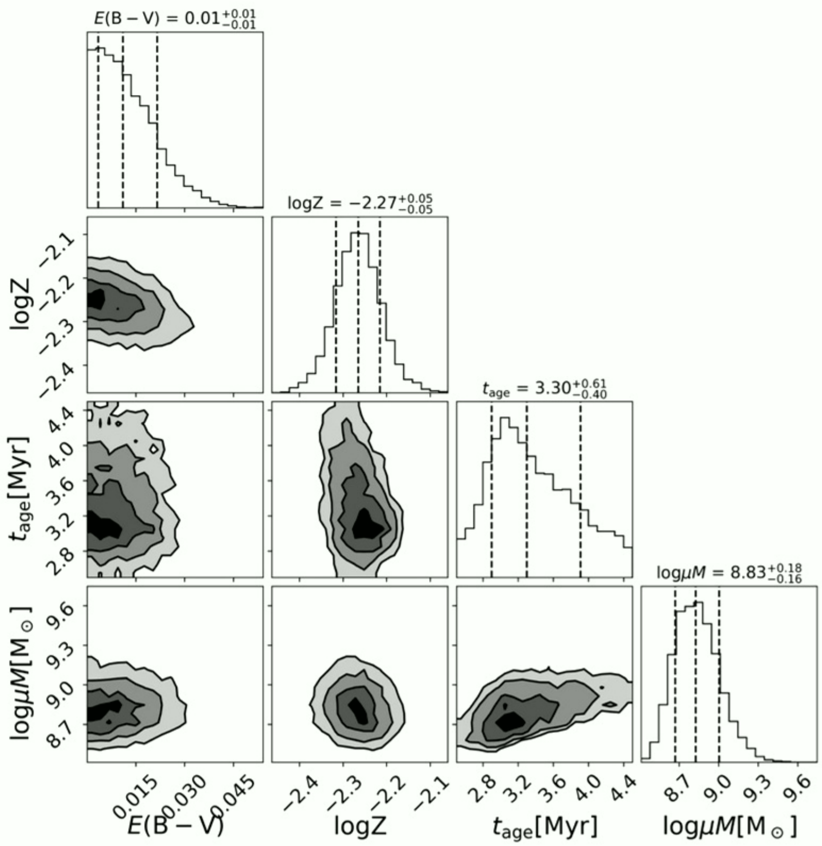
Different lines trace different photoionized clouds

High-P dominated
Low-P dominated
High-P and low-P

Obs. PIs: Aghanim, Vanzella, Vanzella



Results: cluster property



t_{age} ~ 3—4 Myr

Vanzella++ (2020, 2022)

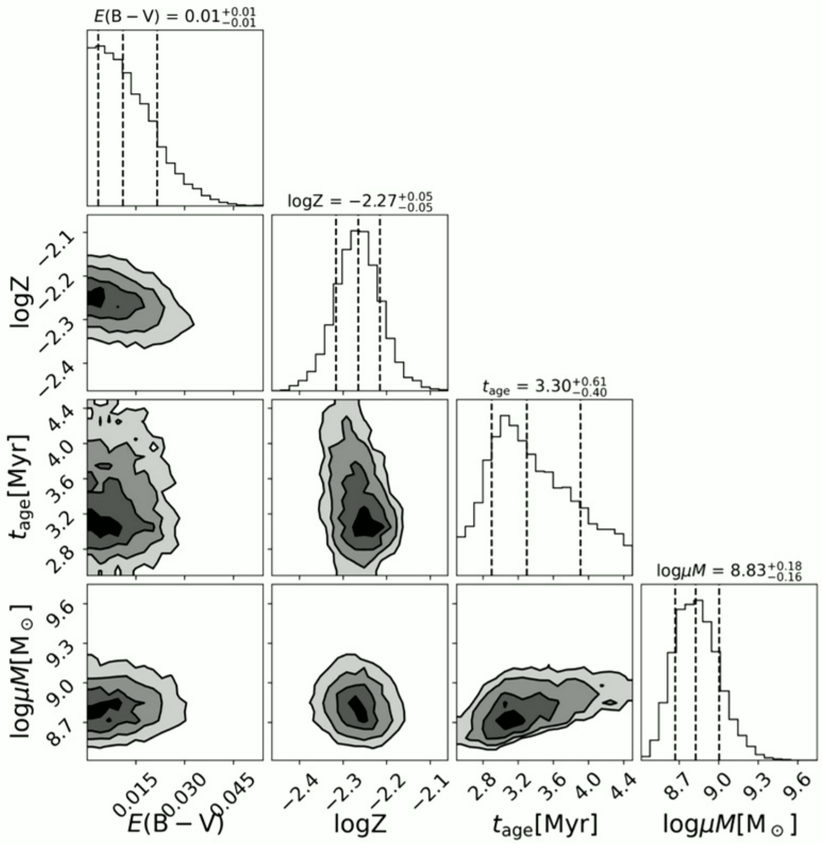
Little ISM dust reddening

Vanzella++ (2020, 2022);
Sharon++ (2022)

Z ~ 0.4 Zsun

M_c = 2 x10[7] (30/μ) Msun

Results: cluster property



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Little ISM dust reddening

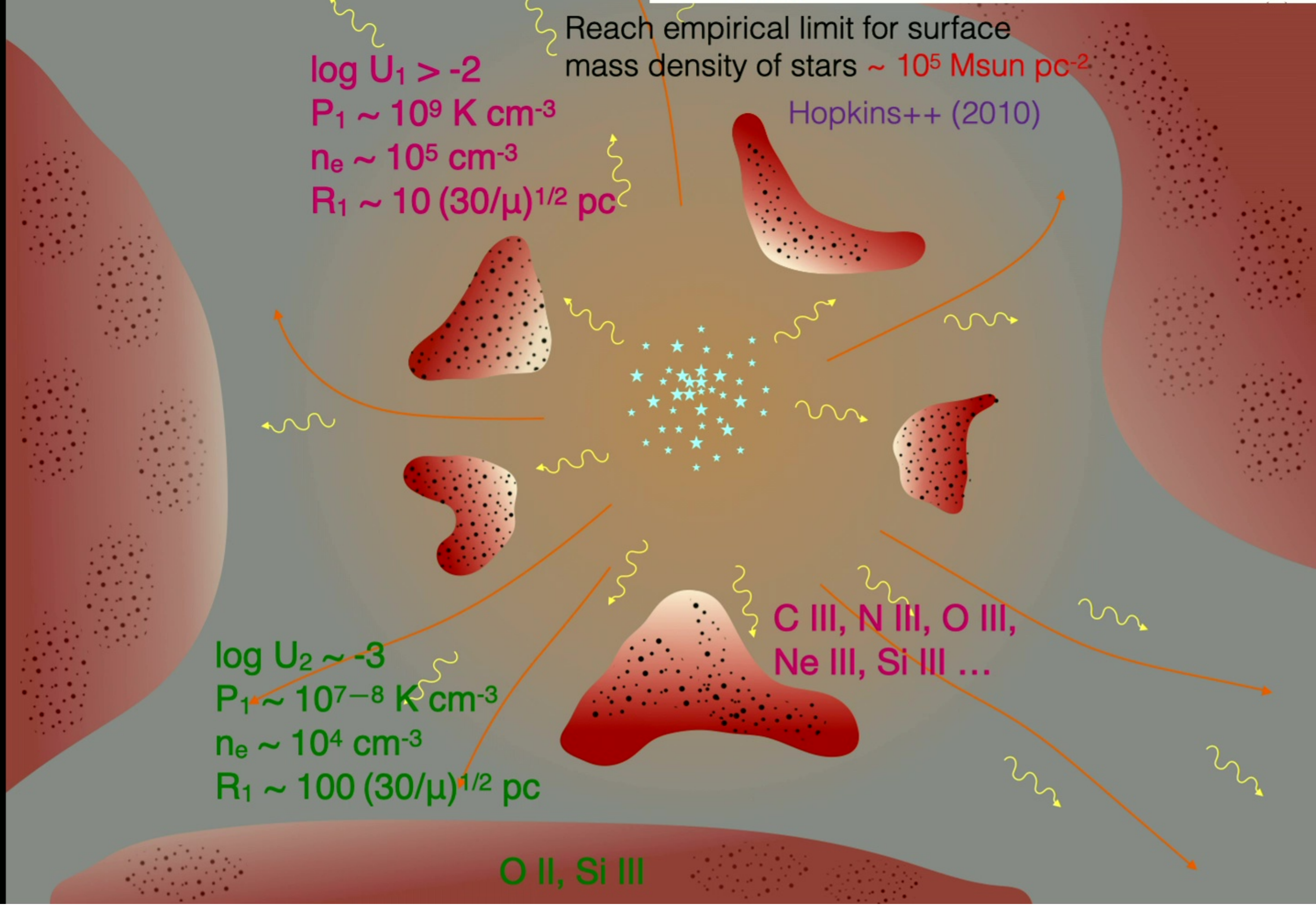
Vanzella++ (2020, 2022);
Sharon++ (2022)

Z ~ 0.4 Zsun

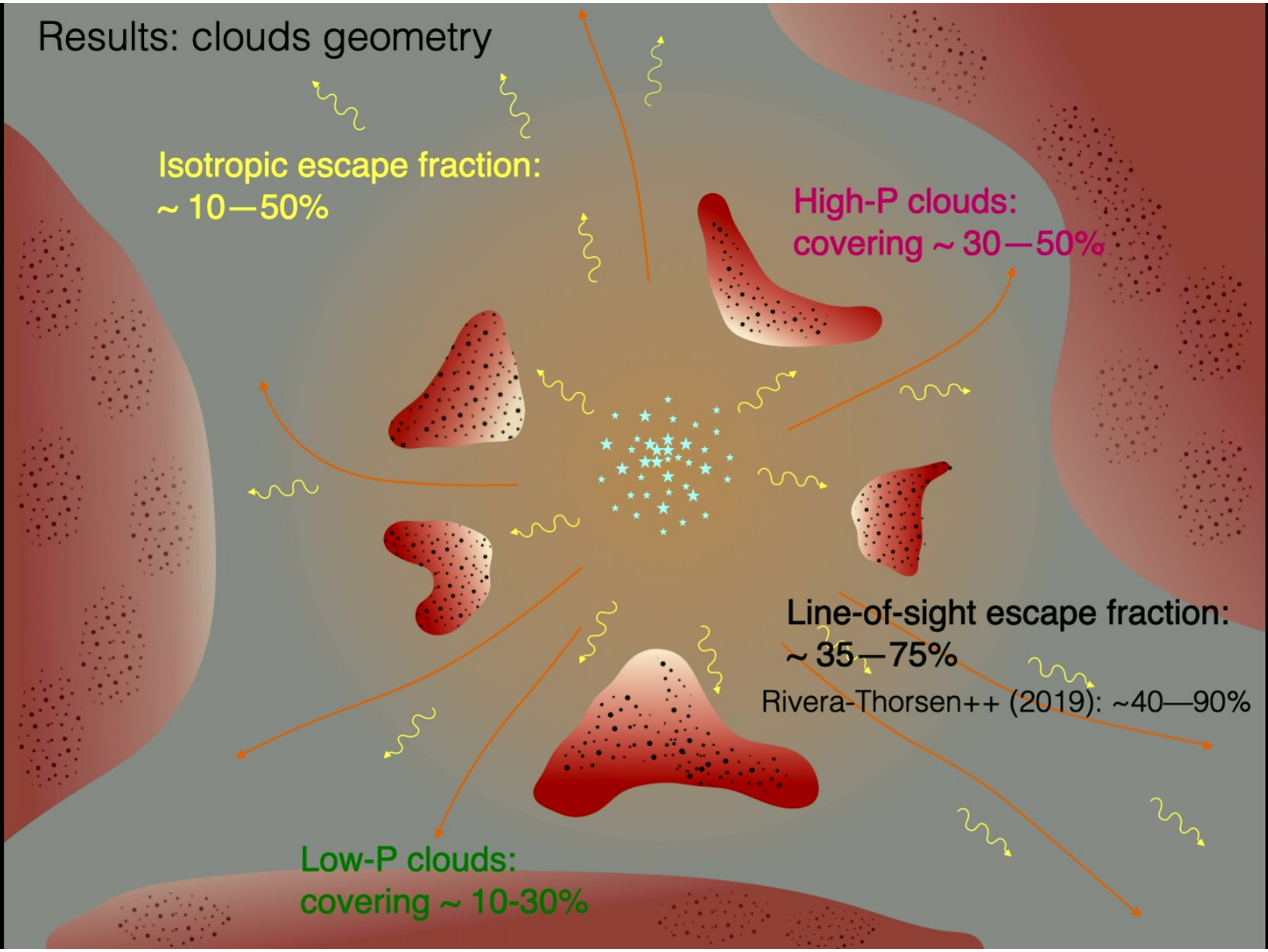
M_c = 2 x10^7 (30/μ) Msun

Results: nebular property

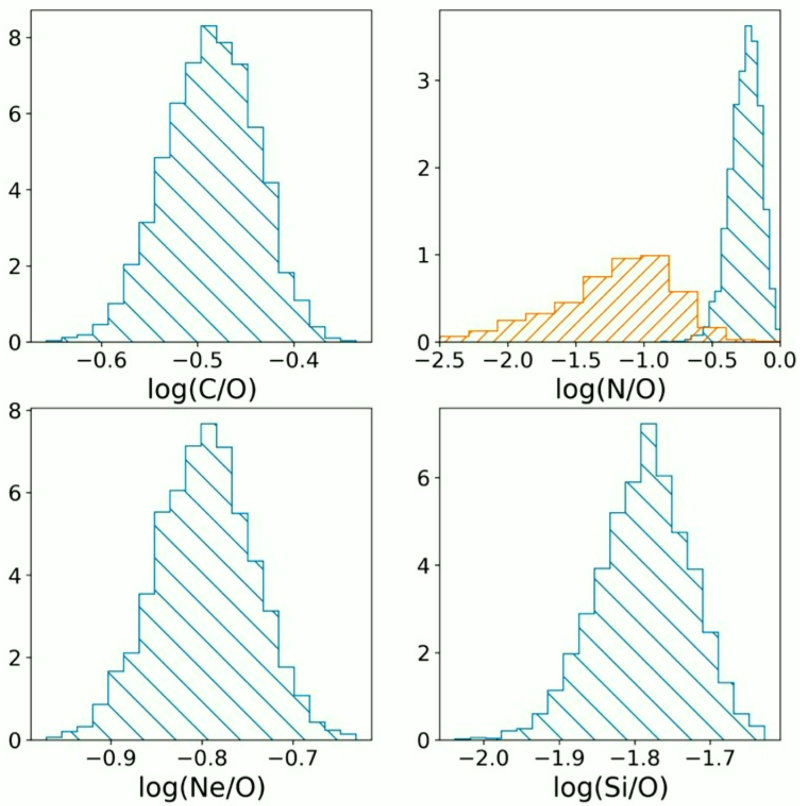
$$\Sigma_\star = \frac{1}{2}\frac{M_\star}{\pi R_1^2} = 6\times 10^4\,\frac{M_\odot}{\mathrm{pc}^2}\left(\frac{\mu_9\, M_\star}{10^{8.8}\, M_\odot}\right)\left(\frac{R_1\sqrt{\mu_9}}{10^{20.1}\,\mathrm{cm}}\right)^{-2}$$



Results: clouds geometry



Results: chemical abundance



C/O and Ne/O unremarkable

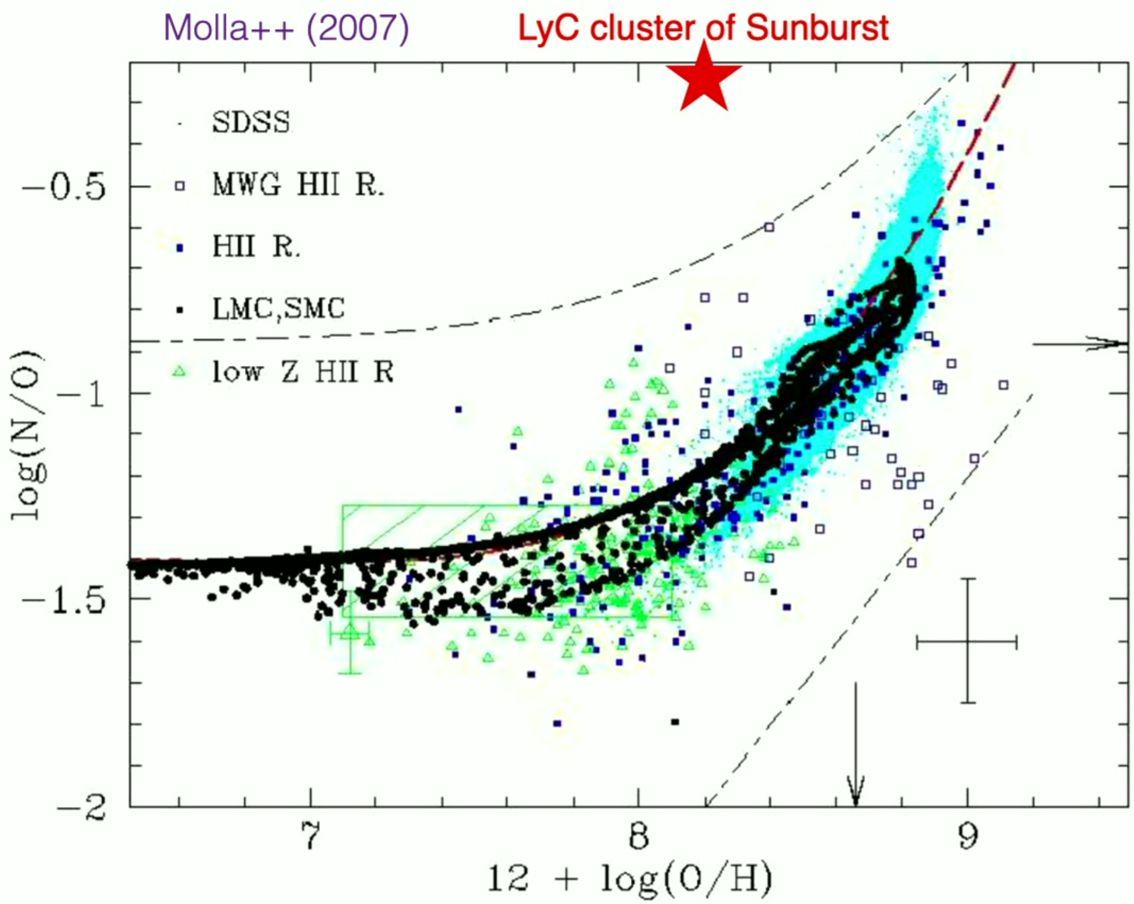
Si depleted by ~ 6x
weak Mg II 2795,2803
No Fe IV 2829,2835
Internal dust grain formation

High-P clouds:
N enriched by ~ 8—10x
N III] 1750,1752 strong

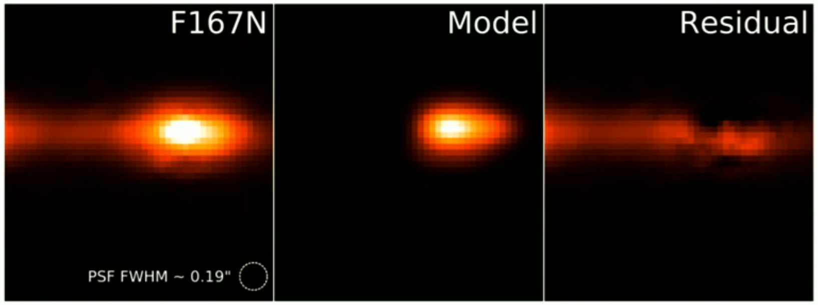
Massive star ejecta?

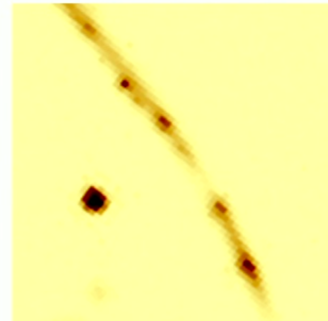
Low-P clouds:
No evidence for N enrichment
[N II] 6548,6583 upper limits

Localized nitrogen enrichment



Astrometric evidence for two nebulae?

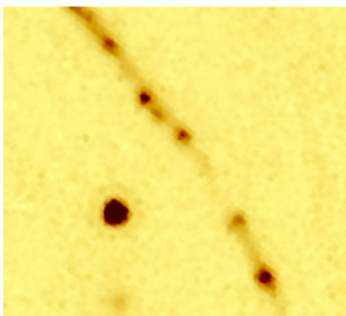




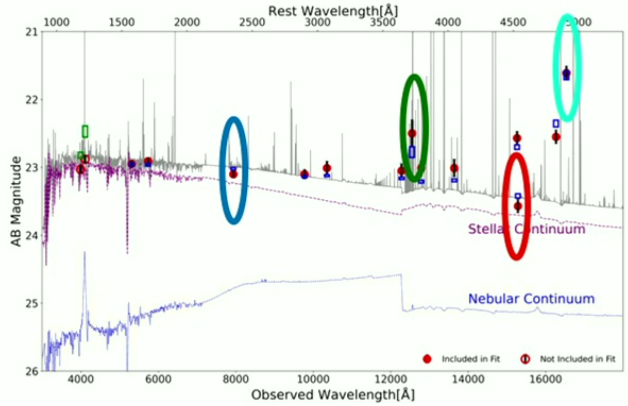
F126N

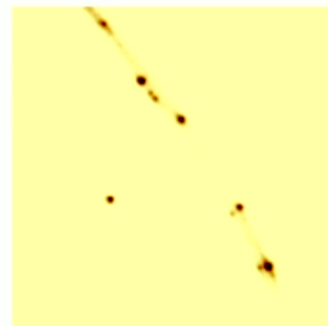
(Enhanced by [O II] 3726,3729)

Narrow filter **F167N**
Flux dominated by strong emission line
[O III] 4959



F153M
(continuum only)





F814W
(stellar+nebular continuum)

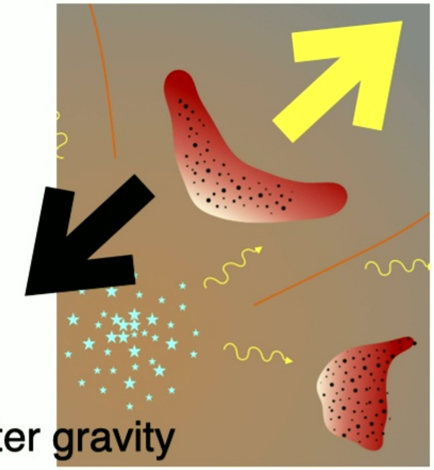
Checks for robustness of results

Table 6. Physical parameters derived for the two-population ("Two-Comp."), top-heavy IMF ("Top-heavy"), single-population ("One-Comp."), and continous star-formation ("Cont. SF") models. The "Two-Comp." model is the default model of this work. Pressures are in units of $\mathrm{K\,cm^{-3}}$, photon fluxes in units of $\mathrm{cm^{-2}\,s^{-1}}$, and radii in units of cm. μ_9 is the magnification of Image 9.

Parameter	Meaning	Two-Comp.	Top-heavy	One-Comp.[a]	Cont. SF
χ^2_ν	Reduced chi square	2.31	2.33	1.97	2.43
χ^2	Chi square	25.41	25.63	21.67	26.73
$E(\mathrm{B-V})$	Host ISM dust reddening	$0.01^{+0.01}_{-0.01}$	$0.01^{+0.01}_{-0.01}$	$0.01^{+0.01}_{-0.01}$	$0.03^{+0.02}_{-0.01}$
$\log Z$	Metallicity	$-2.27^{+0.05}_{-0.05}$	$-2.24^{+0.05}_{-0.05}$	$-2.26^{+0.05}_{-0.06}$	$-2.27^{+0.06}_{-0.06}$
$t_{\rm age}$	Cluster age [Myr]	$3.30^{+0.61}_{-0.40}$	$3.34^{+0.63}_{-0.40}$	$3.35^{+0.65}_{-0.51}$	$5.21^{+1.17}_{-1.32}$
$\log U_1$	Ionization parameter of high-pressure clouds	$-0.92^{+0.31}_{-0.43}$	$-0.96^{+0.34}_{-0.42}$	$-1.55^{+0.55}_{-0.29}$	$-0.96^{+0.32}_{-0.40}$
$\log U_2$	Ionization parameter of low-pressure clouds	$-2.69^{+0.39}_{-0.40}$	$-2.65^{+0.37}_{-0.40}$	—	$-2.51^{+0.36}_{-0.39}$
$\log P_1$	Total pressure of high-pressure clouds $[\mathrm{K\,cm^{-3}}]$	$9.24^{+0.38}_{-0.18}$	$9.30^{+0.48}_{-0.21}$	$9.08^{+0.10}_{-0.10}$	$9.46^{+0.60}_{-0.26}$
$\log P_2$	Total pressure of low-pressure clouds $[\mathrm{K\,cm^{-3}}]$	$7.69^{+0.28}_{-0.33}$	$7.72^{+0.27}_{-0.32}$	—	$7.81^{+0.25}_{-0.29}$
$\log(\mu_9\,M_\star)$	(Magnified) cluster stellar mass $[\mathrm{M_\odot}]$	$8.83^{+0.18}_{-0.16}$	$8.47^{+0.19}_{-0.18}$	$8.75^{+0.19}_{-0.15}$	—
$\log(\mu_9\,\mathrm{SFR})$	(Magnified) cluster SFR $[\mathrm{M_\odot/yr}]$	—	—	—	$2.13^{+0.18}_{-0.15}$
$\log(\mu_9 Q(\mathrm{H^0}))$	(Magnified) cluster ionizing photon rate $[\mathrm{s^{-1}}]$	$55.37^{+0.17}_{-0.13}$	$55.38^{+0.18}_{-0.13}$	$55.28^{+0.19}_{-0.12}$	$55.61^{+0.16}_{-0.15}$
$\log\Phi_1(\mathrm{H^0})$	Ionizing flux incident on high-pressure clouds $[\mathrm{s^{-1}\,cm^{-2}}]$	$14.10^{+0.36}_{-0.20}$	$14.15^{+0.42}_{-0.22}$	$13.66^{+0.16}_{-0.17}$	$14.30^{+0.56}_{-0.25}$
$\log\Phi_2(\mathrm{H^0})$	Ionizing flux incident on low-pressure clouds $[\mathrm{s^{-1}\,cm^{-2}}]$	$11.25^{+0.53}_{-0.54}$	$11.32^{+0.54}_{-0.51}$	—	$11.54^{+0.48}_{-0.50}$
$\log(R_1\mu_9^{1/2})$	Radius of high-pressure nebula [cm] multiplying $\sqrt{\mu_9}$	$20.08^{+0.13}_{-0.18}$	$20.07^{+0.14}_{-0.22}$	$20.27^{+0.12}_{-0.11}$	$20.11^{+0.15}_{-0.31}$
$\log(R_2\mu_9^{1/2})$	Radius of low-pressure nebula [cm] multiplying $\sqrt{\mu_9}$	$21.52^{+0.28}_{-0.28}$	$21.50^{+0.26}_{-0.29}$	—	$21.50^{+0.26}_{-0.27}$
x_1	Fraction of radiation processed by high-pressure clouds	$0.44^{+0.22}_{-0.18}$	$0.40^{+0.22}_{-0.18}$	$0.63^{+0.23}_{-0.22}$	$0.31^{+0.22}_{-0.15}$
y_1	Asymmetry of high-pressure cloud distribution	$0.61^{+0.24}_{-0.24}$	$0.56^{+0.27}_{-0.23}$	$0.67^{+0.21}_{-0.22}$	$0.44^{+0.28}_{-0.22}$
x_2	Fraction of radiation processed by low-pressure clouds	$0.18^{+0.18}_{-0.10}$	$0.20^{+0.20}_{-0.11}$	—	$0.18^{+0.18}_{-0.10}$
y_2	Asymmetry of low-pressure cloud distribution	$0.45^{+0.30}_{-0.26}$	$0.48^{+0.30}_{-0.25}$	—	$0.44^{+0.28}_{-0.22}$
z_1	Line-of-sight obscuration fraction by high-pressure clouds	$0.19^{+0.20}_{-0.13}$	$0.19^{+0.20}_{-0.13}$	$0.33^{+0.25}_{-0.21}$	$0.17^{+0.19}_{-0.12}$
z_2	Line-of-sight obscuration fraction by low-pressure clouds	$0.19^{+0.19}_{-0.13}$	$0.19^{+0.20}_{-0.13}$	—	$0.17^{+0.18}_{-0.12}$
$1-x_1-x_2$	Isotropic escape fraction of ionizing radiation	$0.32^{+0.21}_{-0.20}$	$0.33^{+0.21}_{-0.20}$	$0.37^{+0.22}_{-0.23}$	$0.45^{+0.20}_{-0.22}$
$1-z_1-z_2$	Line-of-sight escape fraction of ionizing radiation	$0.55^{+0.19}_{-0.19}$	$0.56^{+0.19}_{-0.19}$	$0.67^{+0.21}_{-0.25}$	$0.60^{+0.18}_{-0.19}$
$\log(\mathrm{C/O})$	Carbon abundance	$-0.48^{+0.05}_{-0.05}$	$-0.48^{+0.05}_{-0.05}$	$-0.47^{+0.04}_{-0.04}$	$-0.48^{+0.05}_{-0.05}$
$\log(\mathrm{N/O})_1$	Nitrogen abundance of high-pressure clouds	$-0.25^{+0.10}_{-0.12}$	$-0.25^{+0.11}_{-0.11}$	$-0.36^{+0.07}_{-0.09}$	$-0.23^{+0.10}_{-0.11}$
$\log(\mathrm{N/O})_2$	Nitrogen abundance of low-pressure clouds	$-1.16^{+0.34}_{-0.55}$	$-1.15^{+0.36}_{-0.52}$	—	$-1.18^{+0.36}_{-0.52}$
$\log(\mathrm{Ne/O})$	Neon abundance	$-0.79^{+0.05}_{-0.05}$	$-0.80^{+0.05}_{-0.05}$	$-0.80^{+0.05}_{-0.05}$	$-0.80^{+0.05}_{-0.05}$
$\log(\mathrm{Si/O})$	Silicon abundance	$-1.77^{+0.06}_{-0.07}$	$-1.78^{+0.06}_{-0.06}$	$-1.80^{+0.06}_{-0.07}$	$-1.78^{+0.06}_{-0.07}$

[a] $[\mathrm{OII}]\lambda\lambda3726,3729$ line measurements are excluded from analysis.

Dynamic considerations



Gas mass of high-P clouds

$$M_c \simeq 1.4 \times 4\pi R_1^2 N_{\rm H} m_p x_1 = 3\times10^5 M_\odot \left(\frac{N_{\rm H}}{10^{23}\,{\rm cm^{-2}}}\right)\left(\frac{\mu_9^{1/2} R_1}{10^{20.1}\,{\rm cm}}\right)^2 \times \left(\frac{\mu_9}{30}\right)^{-1}\left(\frac{x_1}{0.4}\right),$$

Column density N_H not directly constrained by data
More likely $\log N_H \sim 23$

If clouds retained in the cluster potential for much longer than 0.1 Myr
We require $\log N_H > 22.5$

$$M_N \approx 200\, M_\odot \left(\frac{N_{\rm H}}{10^{23}\,{\rm cm^{-2}}}\right)\left(\frac{\mu_9^{1/2} R_1}{10^{20.1}\,{\rm cm}}\right)^2 \times \left(\frac{\mu_9}{30}\right)^{-1}\left(\frac{x_1}{0.4}\right)\left(\frac{\rm N/O}{0.6}\right)\left(\frac{Z}{0.27\,Z_\odot}\right)$$

If $\log N_H > 24$, then:
[1] not enough massive star ejecta
[2] not enough nitrogen yield
[3] star formation in the shielded interior

Implications & Questions

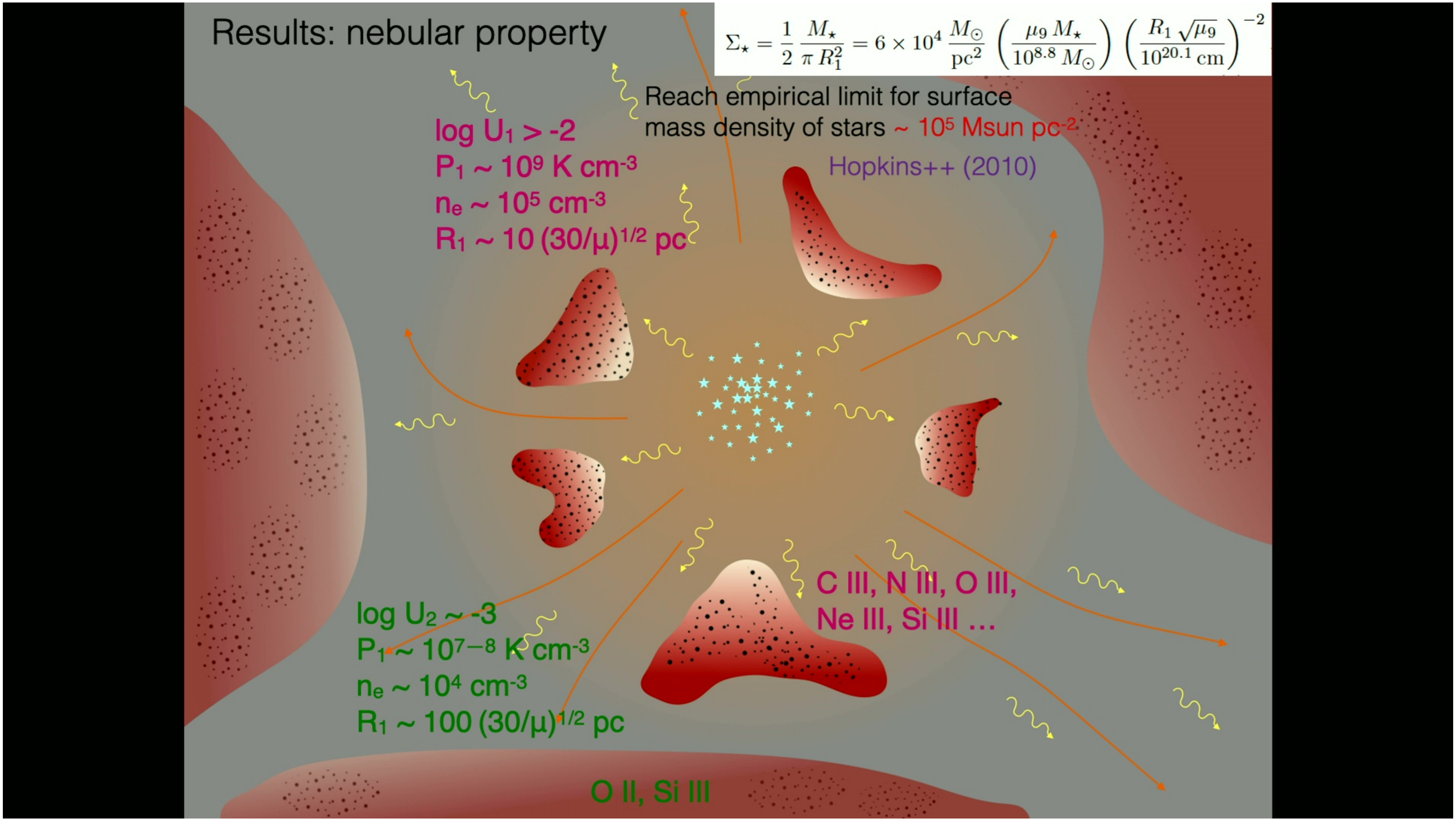
- Detailed spectral modeling of highly-magnified Cosmic Noon systems can yield a lot of information!

- Localized nitrogen pollution may be very common in the proximity of newborn (t < 10 Myr) super star clusters.

    N enrichment x3 from a few SSCs in NGC 5253; (Kobulnicky++ 2004)

- Winds from main-sequence massive stars?
  Wolf-Rayet winds?
  First batch of SNe from M > 60 Msun stars?
  Slow H-burning ejecta from **fast rotating massive stars** or **binary mass transfer** seems favored.   De Mink++ (2009)

- How is ejecta retained in the cluster potential?
  Does catastrophic cooling happen?
  Do clouds survive radiation ablation?
  A radiation-hydrodynamics problem



Results: nebular property
$\Sigma_\star = \frac{1}{2}\frac{M_\star}{\pi R_1^2} = 6\times10^4 \frac{M_\odot}{\mathrm{pc}^2}\left(\frac{\mu_9 M_\star}{10^{8.8} M_\odot}\right)\left(\frac{R_1\sqrt{\mu_9}}{10^{20.1}\,\mathrm{cm}}\right)^{-2}$
Reach empirical limit for surface mass density of stars ~ 10^5 Msun pc^{-2}
Hopkins++ (2010)
log U_1 > -2
$P_1 \sim 10^9$ K cm^{-3}
$n_e \sim 10^5$ cm^{-3}
$R_1 \sim 10\,(30/\mu)^{1/2}$ pc
C III, N III, O III,
Ne III, Si III ...
log $U_2 \sim -3$
$P_1 \sim 10^{7-8}$ K cm^{-3}
$n_e \sim 10^4$ cm^{-3}
$R_1 \sim 100\,(30/\mu)^{1/2}$ pc
O II, Si III