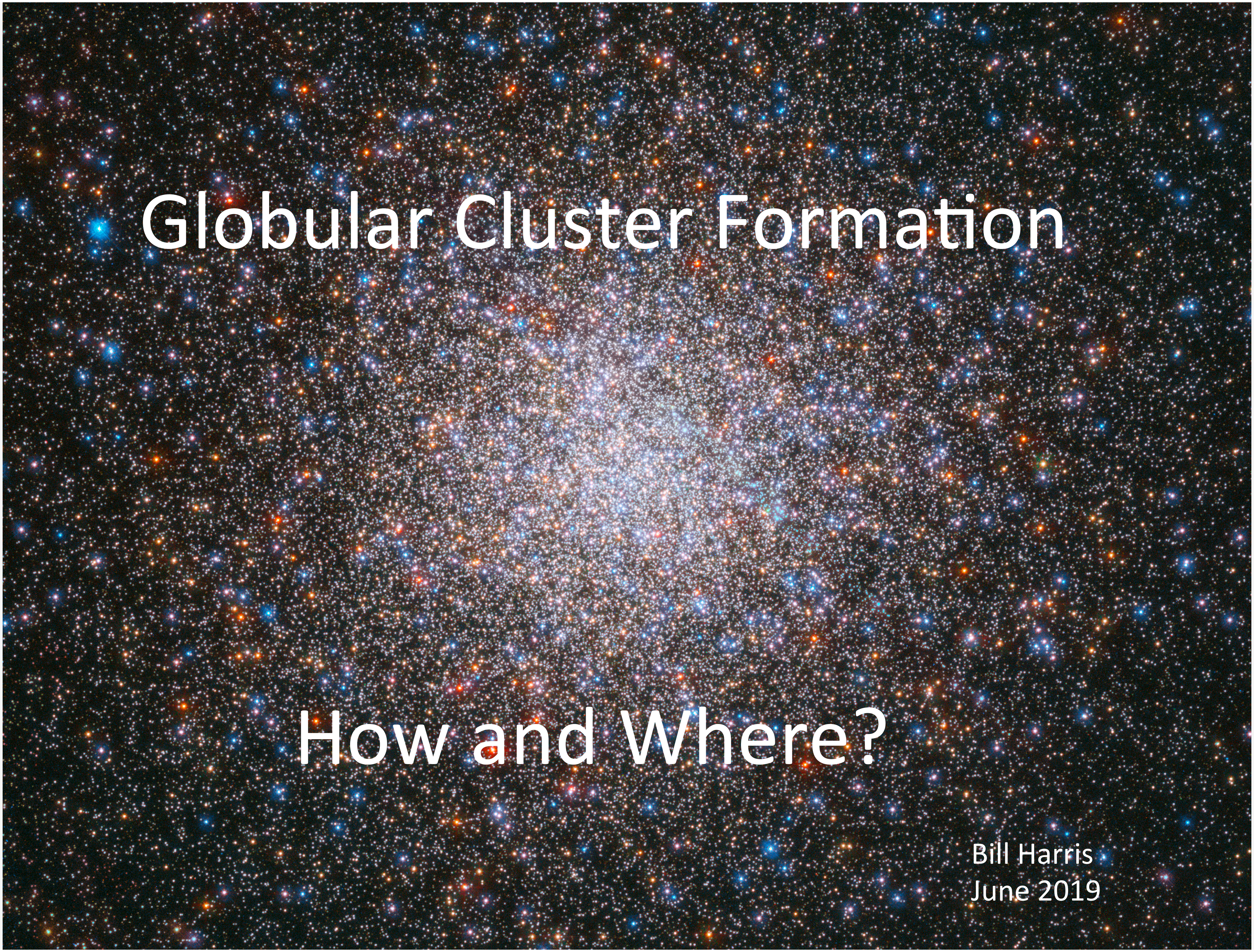

Globular Cluster Formation
How and Where?
Bill Harris
June 2019

Much current GC research now directed toward understanding issues around their ***formation***

Various early concepts based on semi-cosmological scenarios (pre-galactic)

But:

- There's no special mass scale (ICMF has power-law form)
- GC formation epoch(s) range from z ~5-8 down to z~2 or less
- GCs strongly associated with galaxy halos and bulges
- Star clusters don't form out of ***isolated monolithic gas clouds***

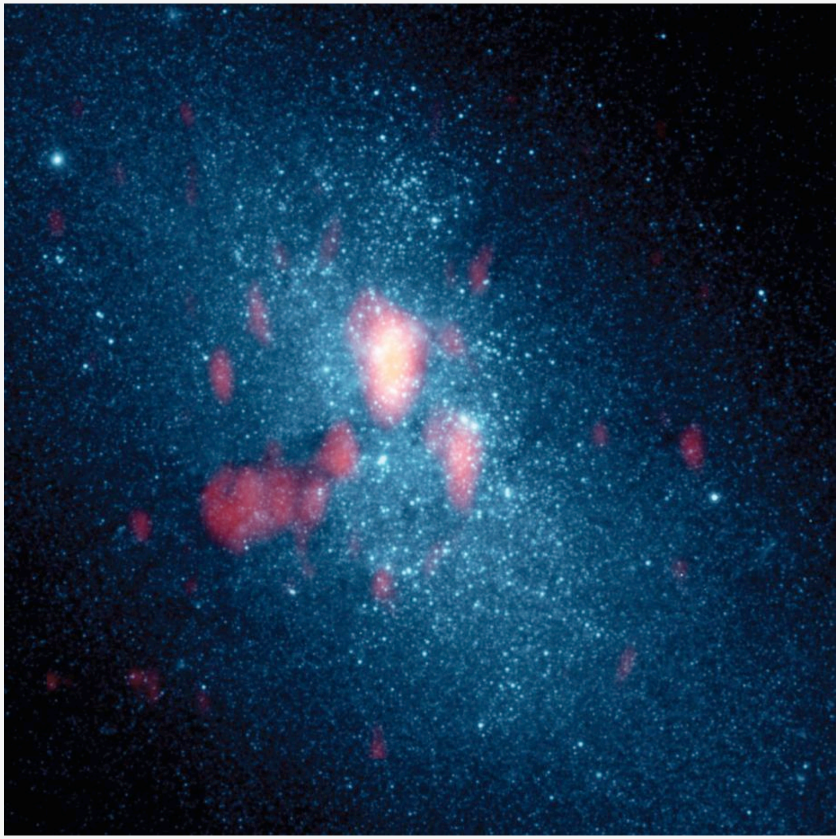
To understand GC formation we need to look into sites like this – GMCs at mass scales 10^7 $M_\odot$ and above

30 Dor complex

ESO

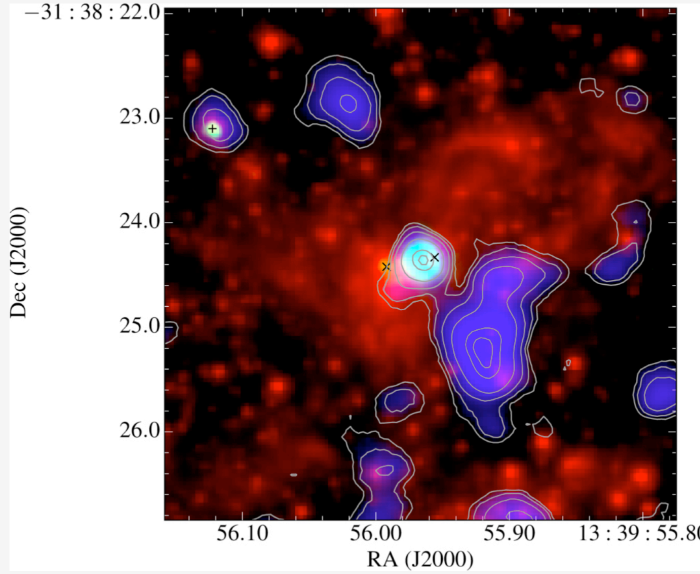
R136

NGC 5253 + proto-YMC
Starlight (blue) + CO(3-> 2) (red)



Turner et al. 2015, Nature 519, 331
2017, ApJ 846

Red: F814W   Blue: CO(3-> 2)



Cohen et al. 2018, ApJ 860, 47

Cluster age ~ 1 Myr, M = 2.5 x 10^5 $M_\odot$

1000's of massive stars, but also accreting molecular gas; outgoing winds damped by radiative cooling

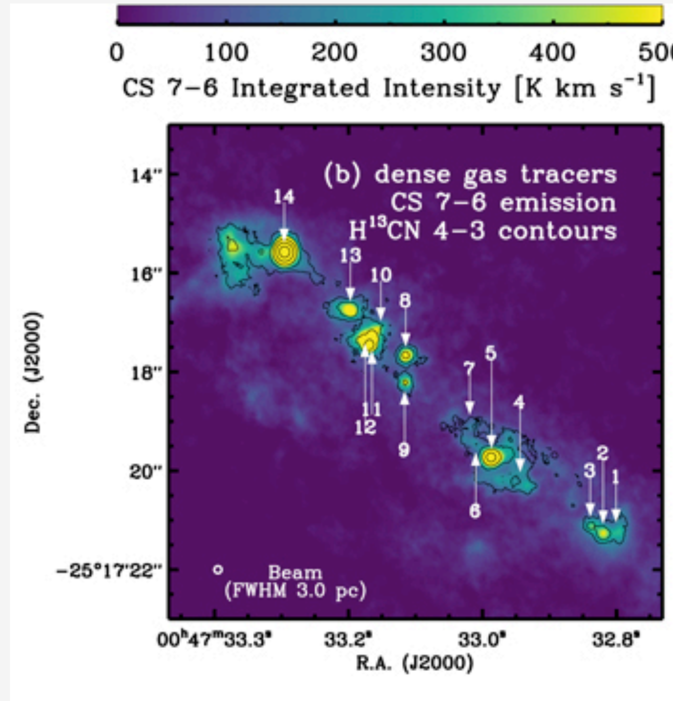
Dense molecular gas coexisting with young stars in ~equal amounts at this stage

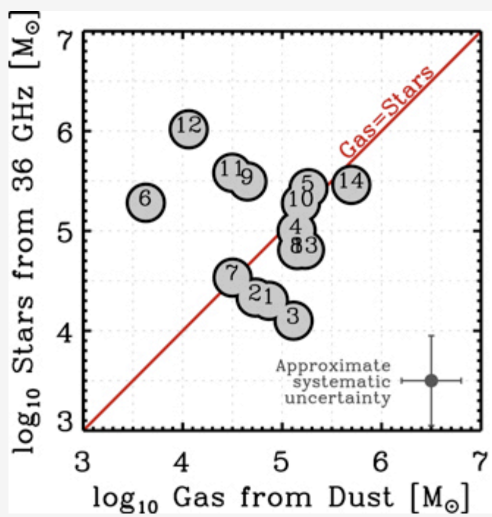
NGC 253 – YMCs in inner region

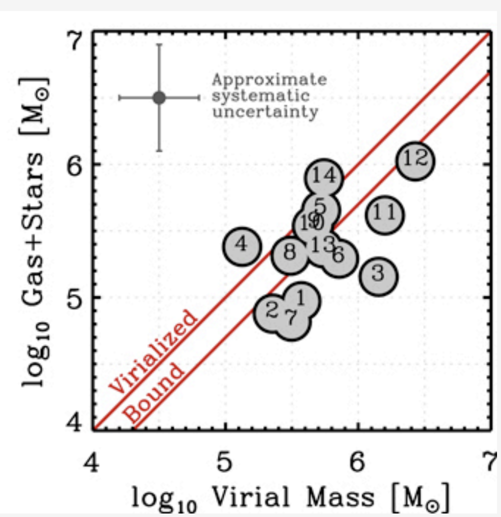
ALMA study (Leroy && 2018, ApJ 869)

Dense gas, dust, radio continuum all present: star formation has started, but ~equal mass of gas still present

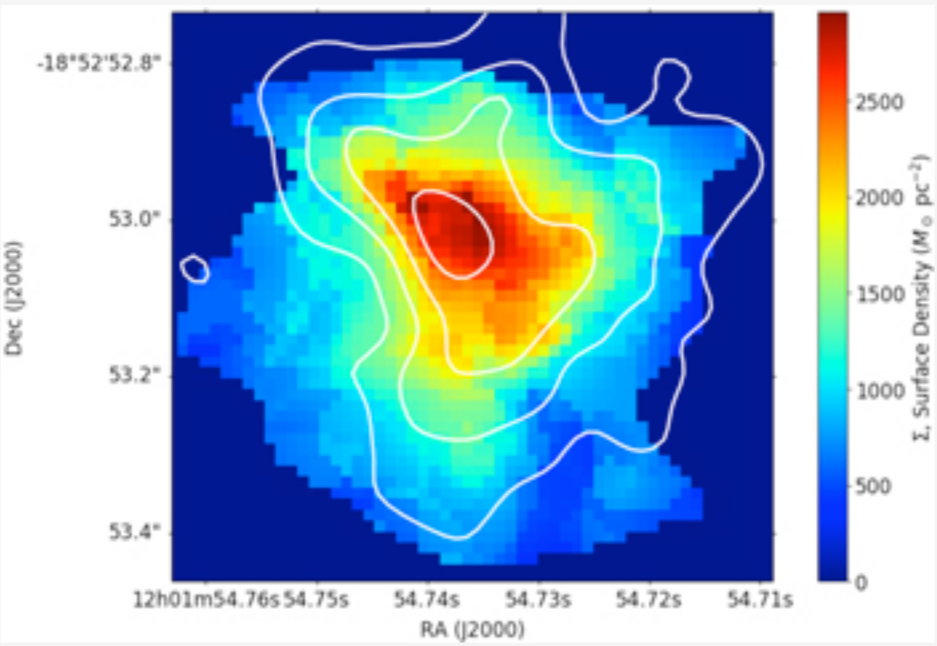
YMC cluster masses $10^4 – 10^6\ M_{\odot}$



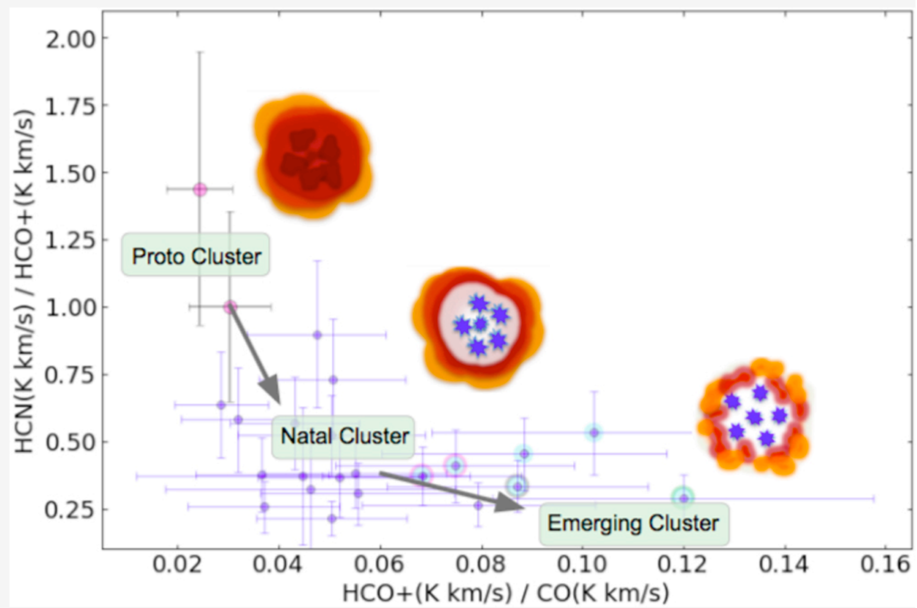




Finn et al. 2019, ApJ 874 -- *ALMA* measurements of GMC in the Antennae (the "Firecracker")
Appears to be a ***proto***-YMC (star formation not yet underway)



GMC diameter ~ 40 pc
Stable, pressure confined
cloud mass = few x 10^6 $M_{\odot}$



Behaviors of HCN, HCO with protocluster age

- ***Star clusters are seen to form within GMCs.***
- → To explore the mechanisms needed, we should carry out full hydro modelling of GMCs specifically directed at generating star clusters
- Must also cover large range of masses: can we get "young GCs" just by scaling up host GMC mass? (Harris & Pudritz 1994)

“We need models!”

Francesca D’Antona

IAU351, Bologna, May 2019

Timeline

T = 0, formation

12 Gyr

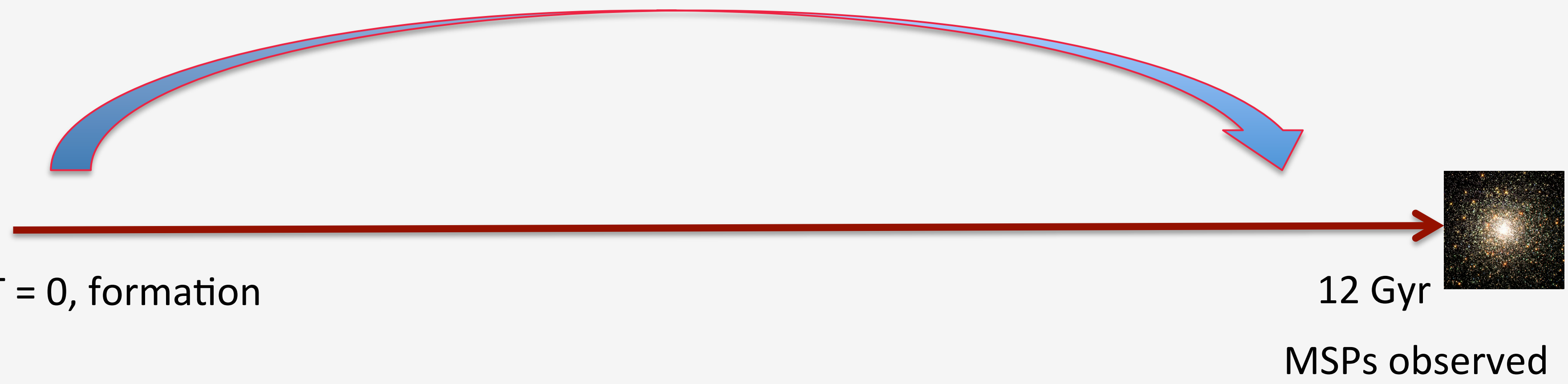
MSPs observed

Reconstruct formation events?

Must work backward through –
- Secular dynamical evolution
- Early rapid mass loss era
- SNe era and removal of gas
- Pre-SN era of star formation and stellar winds

Much information on the original conditions has been erased

Timeline

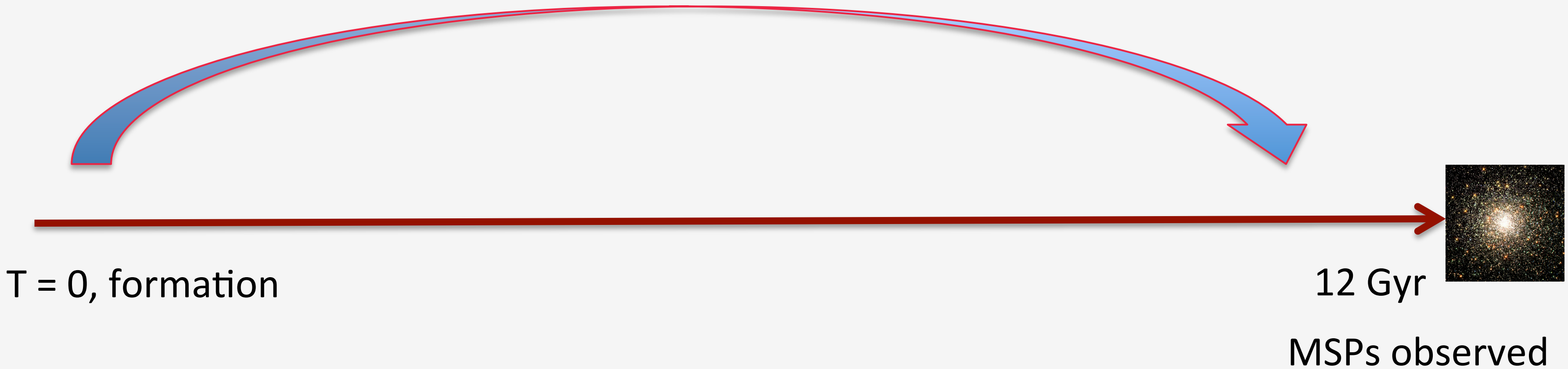


Make a cluster and evolve ***forward*** in time.

Do MSPs emerge in a natural way?

How do we make MSPs?

Timeline



Make a cluster and evolve ***forward*** in time.

Do MSPs emerge in a natural way?

How do we make a massive star cluster?

Major assumptions:

All star clusters form within GMCs, regardless of mass or metallicity.

All clusters must form in a "normal" way regardless of mass.

But computation of cluster formation ***in its full context*** faces 3 big challenges:

(1) It's hard. (radiative-hydro gas dynamics; needs HPC)

(2) It's messy. (Ditto)

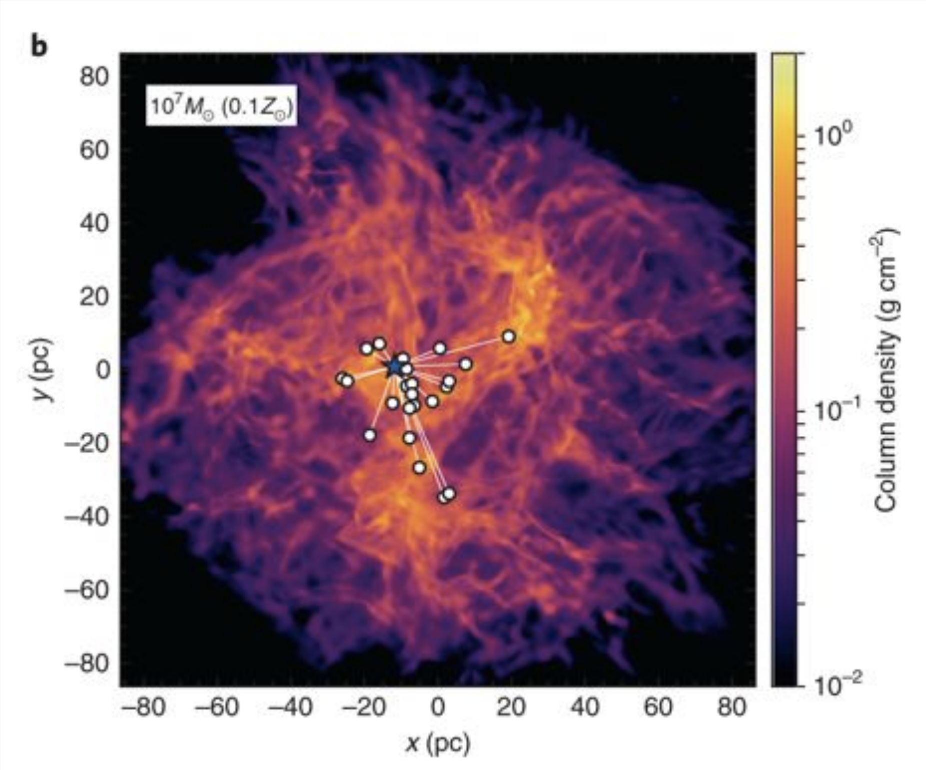
(3) It's messy at every level:

- ~1 AU (protostellar)
- ~0.1 parsec (protocluster)
- ~50 parsecs (surrounding GMC)

Howard, Pudritz, & Harris 2017, MNRAS 470, 3346
Howard, Pudritz, & Harris 2018, Nature Astronomy 2, 725
Howard, Pudritz, Sills, & Harris 2019, MNRAS 486, 1146

Radiative hydrodynamic (RHD) realizations of turbulent GMCs with AMR code FLASH2.5: suite of simulations

- Covers first ~5 My of GMC's history (before SNe)
- Traces radiative and ionizing feedback from SF on the surrounding GMC



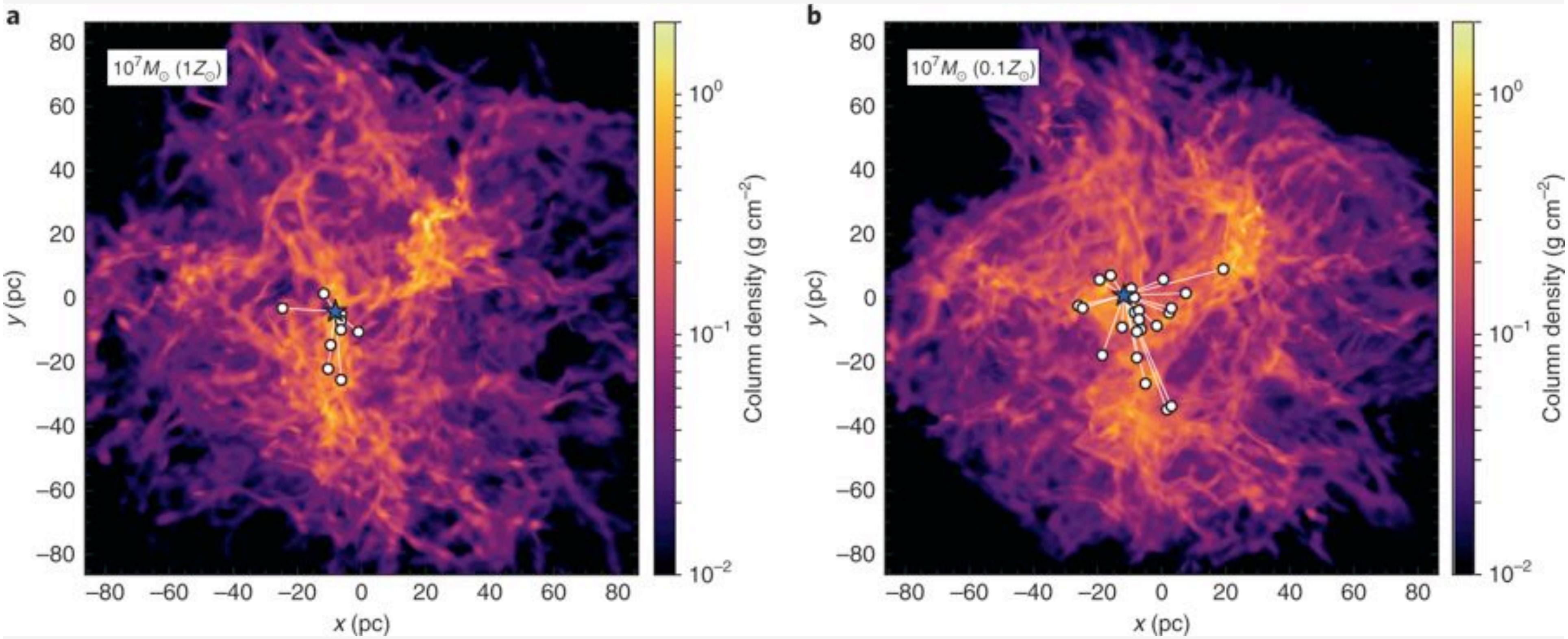
Young star clusters represented by high-density, gravitationally bound spots along the gaseous filaments

Features of the set of simulations:

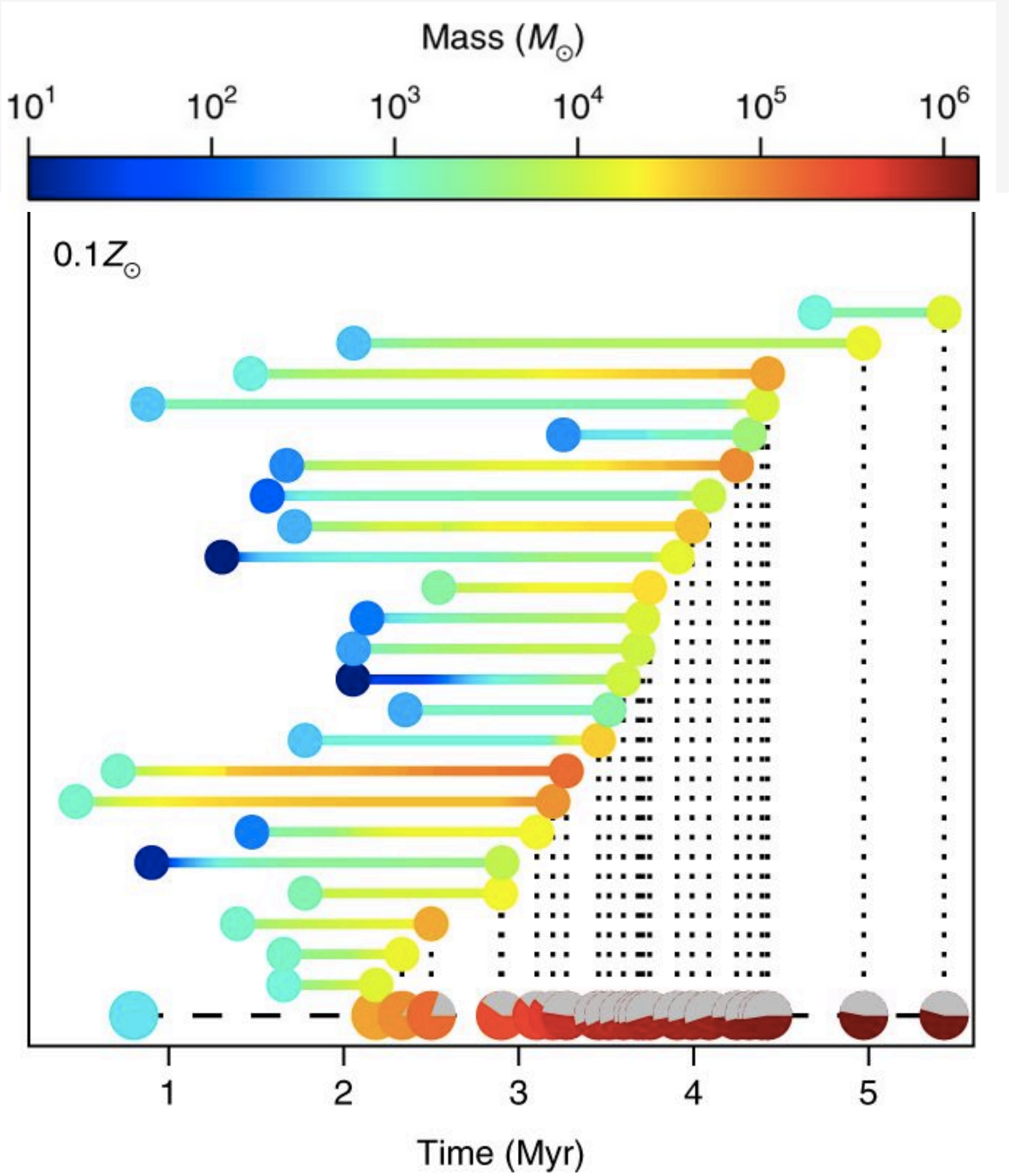
- GMC masses $10^4 - 10^7\ M_\odot$
- **Turbulence spectrum** (Burgers) imposed initially
- Heavy-element abundances: **$Z = Z_\odot$ and $0.1\ Z_\odot$**
- 5 values of initial v**irial parameter** ($2\ E_{kin}/E_{grav}$) ranging from very bound to very unbound
- Initial d**ensity profile**: $\rho \sim r^{-3/2}$ power-law falloff, but with flat core
- Mass is not conserved; gas flow can leave the volume of the simulation
- Formation of cluster happens wherever density rises above an assumed **threshold density**, at local potential minimum, Jeans unstable … (several stringent conditions). Calculated for thresholds 10^4, 10^5, 10^6 /cm^3
- Gas forms stars at 20% efficiency per t_{ff} with random sampling of **Chabrier IMF**
- **Feedback** from young clusters includes ionizing radiation, radiative heating, radiation pressure
- **Stellar winds** from young stars stay within the protoclusters
- Highest resolution = 0.6 pc → 10^7 cells covering largest GMC in the suite

Snapshot at the formation time of the most massive cluster (10^7 $M_\odot$ GMC).

Other small clusters that will eventually merge with it are marked by white dots.



The YMC can merge with other protoclusters up to 20-30 pc distant



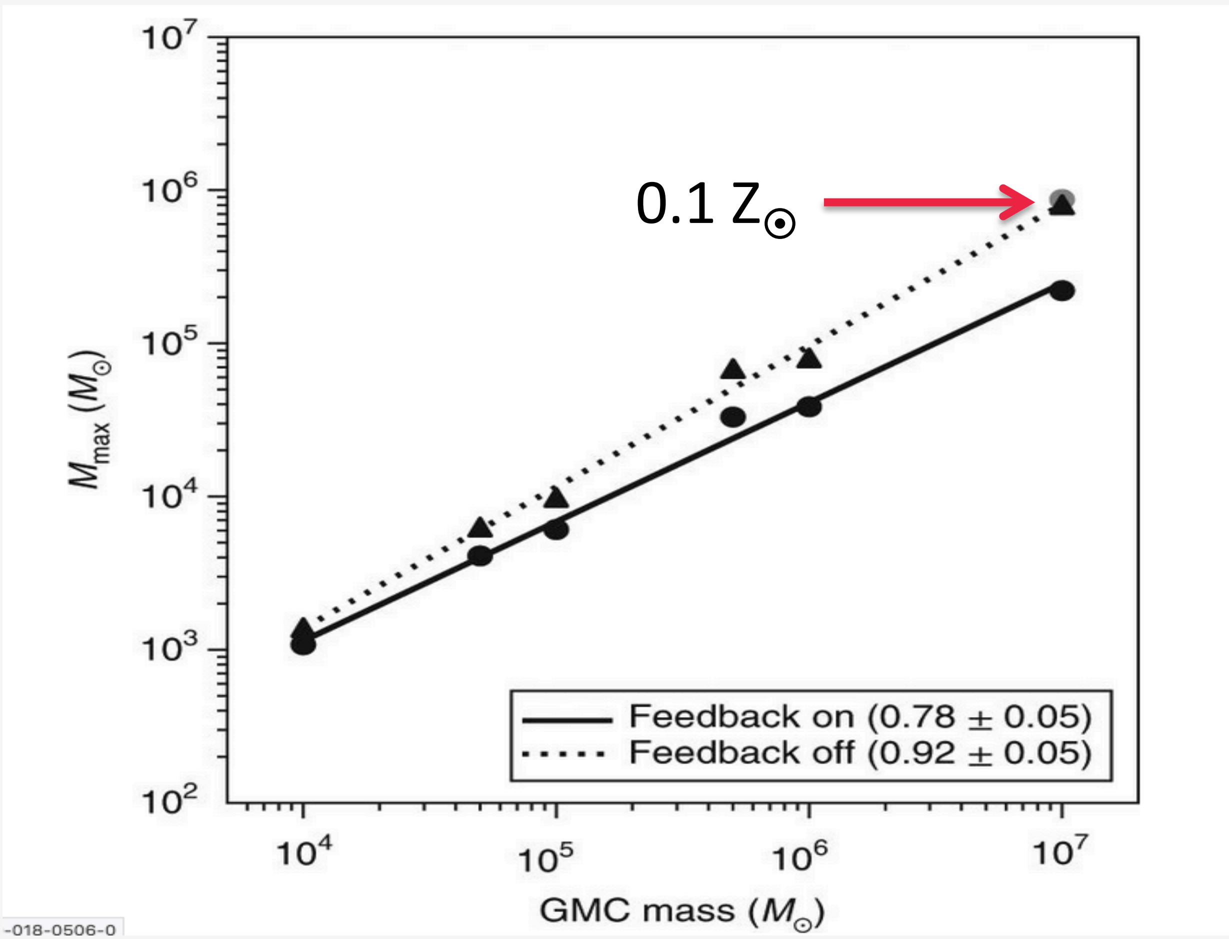
$10^7\ M_\odot$ GMC at $0.1\ Z_\odot$

YMC growth history

Grey = mass fraction gained from direct mergers

Gas inflow, and mergers with smaller clusters, are equally important!

Mass of biggest central YMC is nearly proportional to the host GMC mass



Biggest YMC takes up several percent of total GMC mass

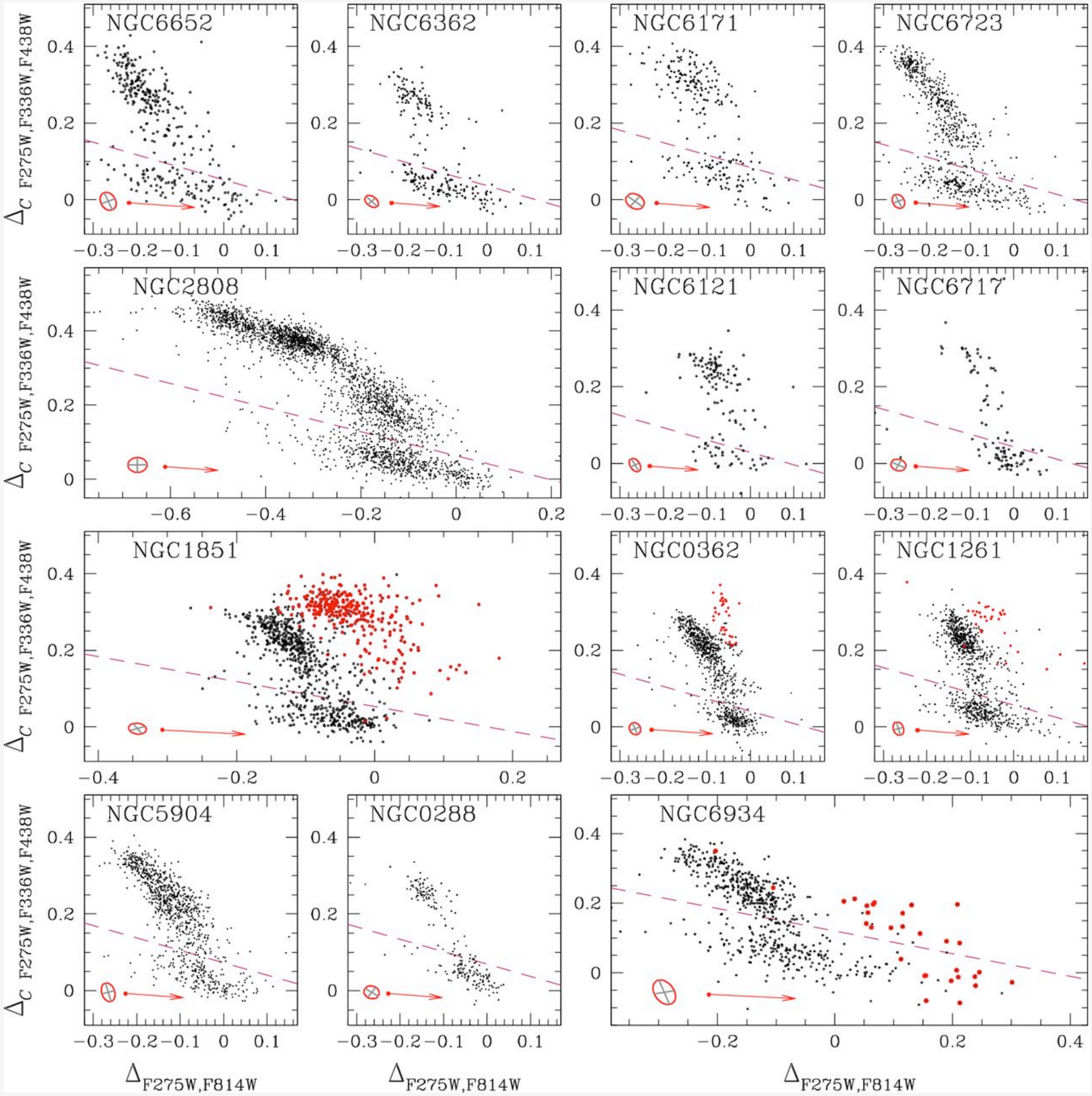
Lessons learned so far:

- At low mass, cluster formation is simple (single-epoch, little merging)
- At higher mass, growth history becomes more complex. **Direct gas inflow along filaments**, and growth by **numerous mergers**, are of major importance → more extended period of star formation and growth
- At low metallicity, feedback is not very important – growth to larger masses is easier
- Gas flows (in + out) are highly **anisotropic, time-variable**, but slow down after ~5 Myr
- Strongly contingent i**ndividual histories**!

Can production of MSP's fit within this framework?

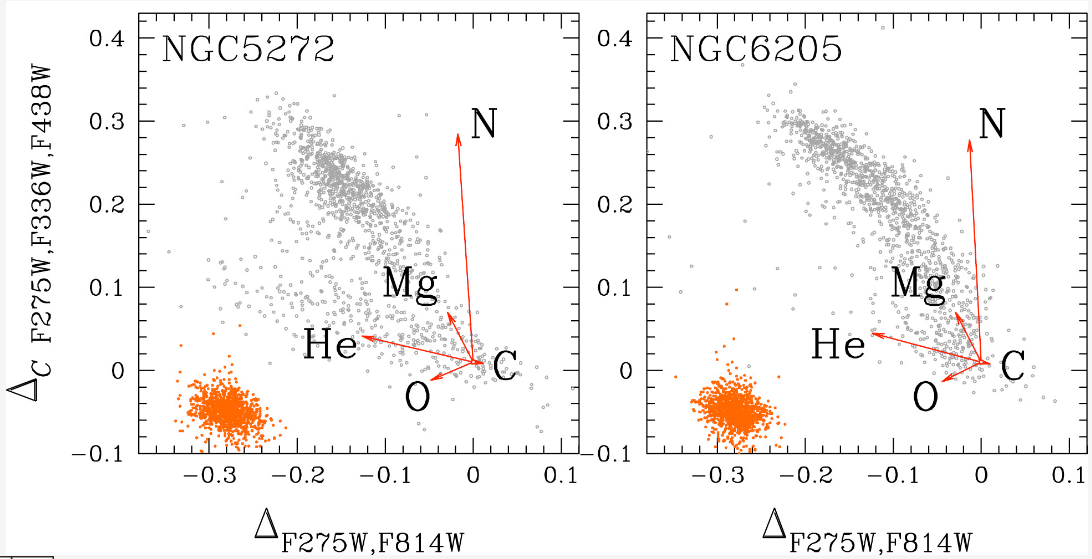
Milone et al. 2017, MNRAS 464, 3636

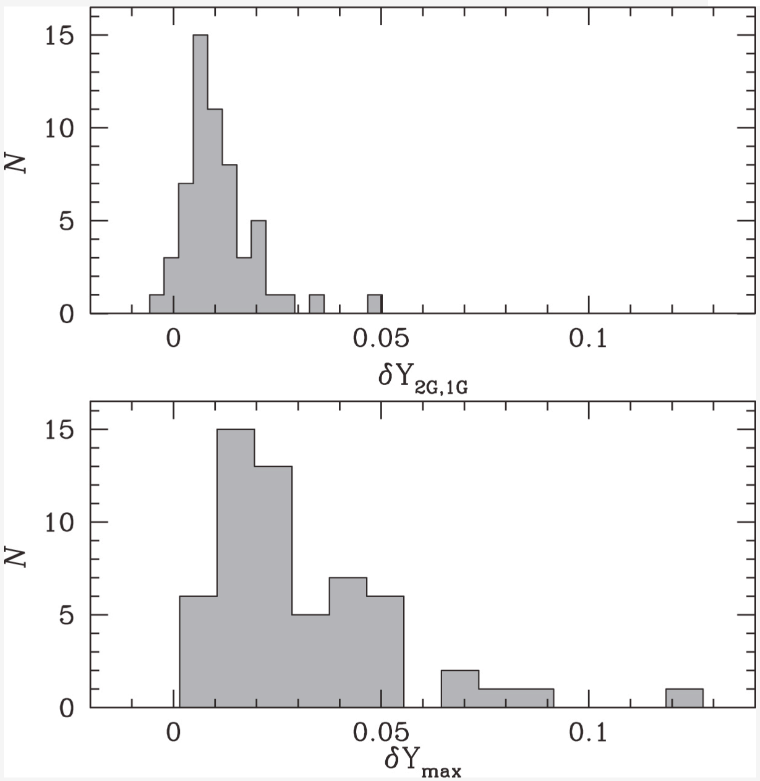
Sample chromosome maps for moderately metal-poor GCs



Milone et al. 2018, MNRAS 481, 5098

Reading the chromosome maps





Mean and maximum spreads in Helium abundance ΔY (2P – 1P)

We add ONE additional feature to our GMC simulations:

Hypothesis: MSPs are an automatic result of rapid self-enrichment during star formation in ***some*** YMCs (maybe not all), produced by massive young stars in the cluster

Try two opposite extremes:

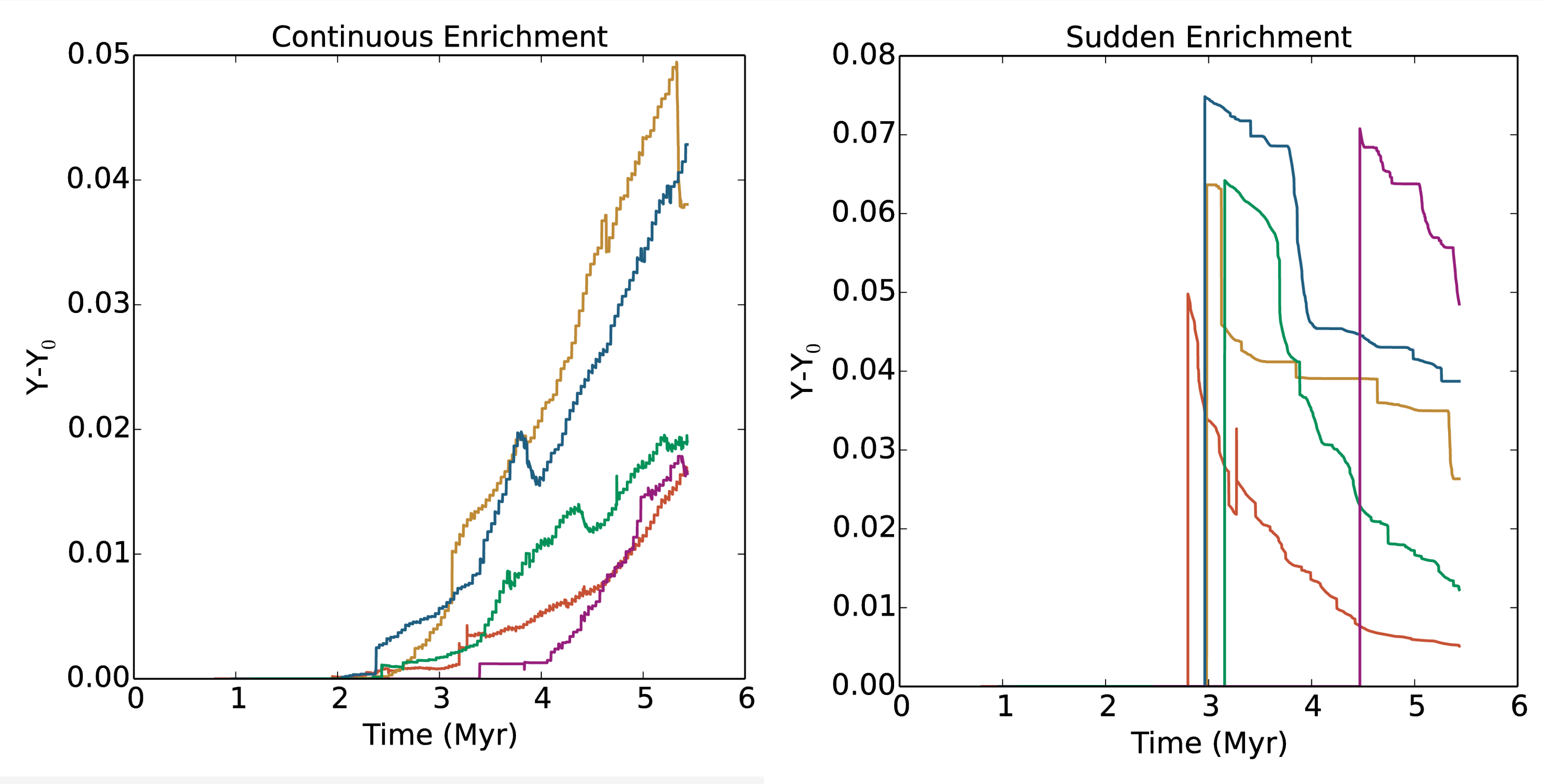
- Internal enrichment tracks the star formation rate

or

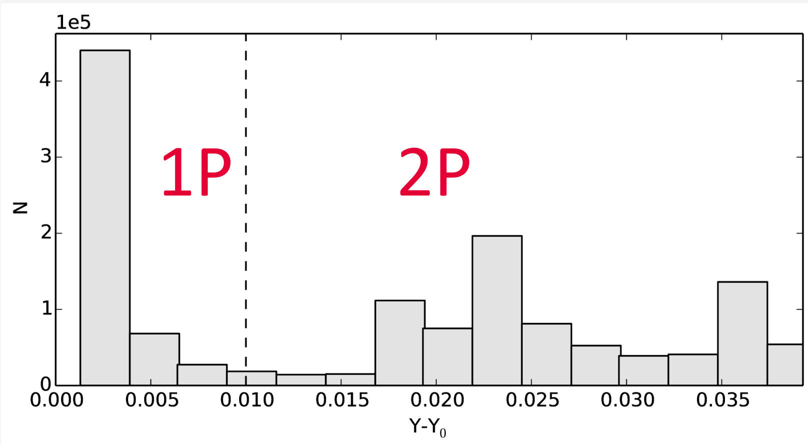
- Internal enrichment is a sudden, one-time event

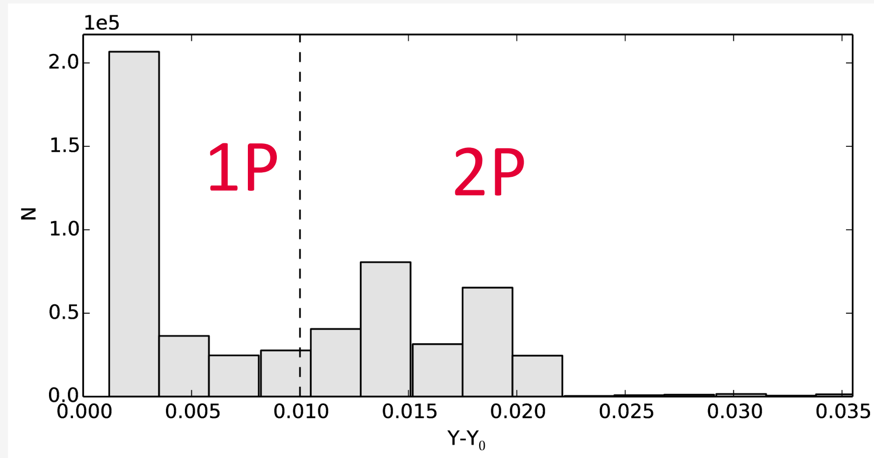
What do we get? Use Helium abundance of the gas inside the YMC as a tracer

Increases in Helium abundance with time, for the two extreme cases



Final Y distributions: examples for continuous enrichment





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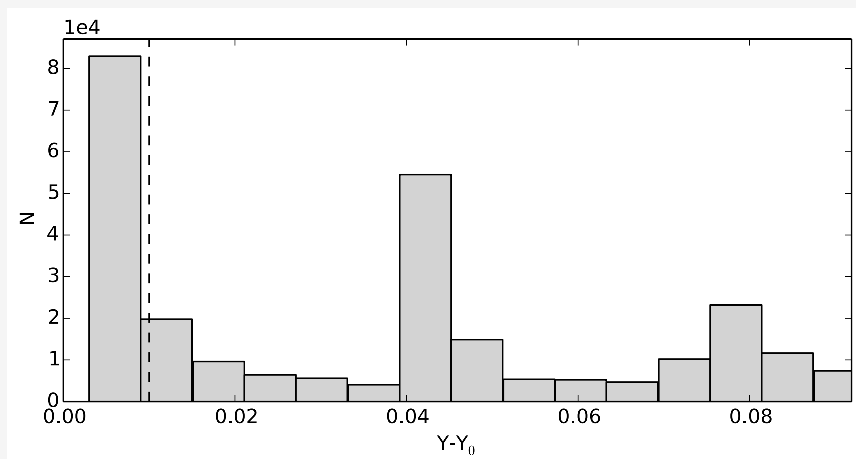
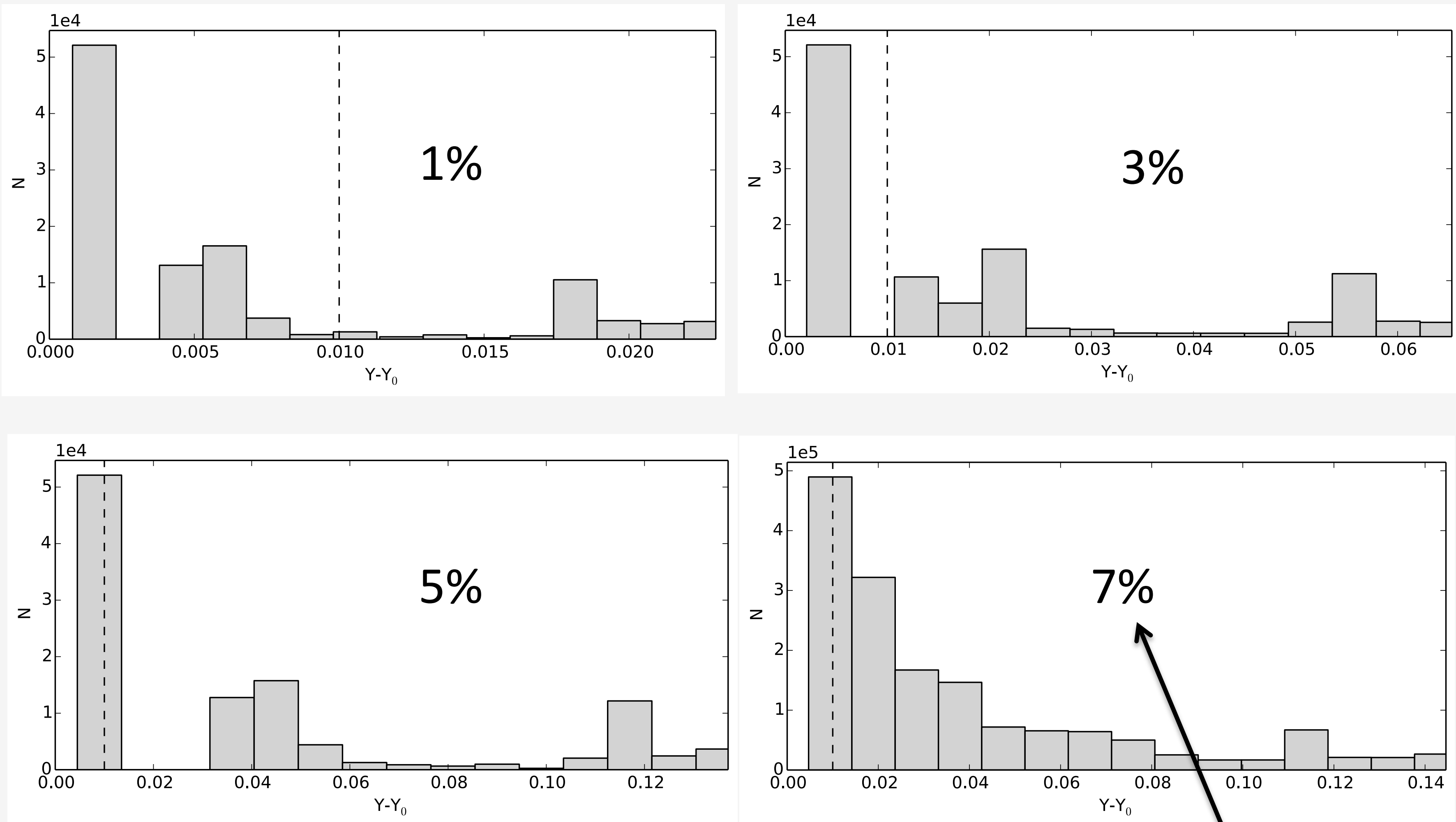


50%

Mass fraction of massive stars injected as Y

Final Y distributions: examples for instantaneous enrichment



Mass fraction of cluster injected as Y

These models essentially tell us how much mass in newly made Helium we must add to the protocluster, to get realistic spreads in abundance.

Bottom line: a few percent of the cluster mass must be enriched – this newly made Helium is added to the gas reservoir inside the protocluster.

Some strategic advantages:

- Built on a quantitative, rigorous RHD model for cluster formation within GMCs
- Both original and enriched populations form within ~5 Myr interval → little age difference. (i.e: there are no "first" and "second" generations: they all belong to the *same* generation, with a range of abundances}
- Stochasticity is built in automatically → different outcomes for the abundance distributions in different YMCs
- No "mass budget" problem (the host GMC provides the big reservoir of gas needed)
- MSPs should be more prominent in more massive clusters (deeper potential wells)

What stars would be responsible for the internal enrichment?

Continuous enrichment: O-star close binaries?

Sudden enrichment: central supermassive star?

See also:

Elmegreen 2017, ApJ 836, 80
Denissenkov & Hartwick 2014, MNRAS 437, L1
Prantzos & Charbonnel 2006, AAp 458, 135
De Mink et al. 2009, AAp 507, L1
Gieles et al. 2018, MNRAS 478, 2461
Kim & Lee 2018, ApJ 869, 35
Naiman et al. 2018, MNRAS 478, 2794
Cohen et al. 2018, ApJ 860, 47

Lots to be done:

- Set initial conditions for GMC from galaxy-scale models
- Use the current models to set the initial conditions for the YMC protocluster; do subgrid model fully resolved
- Track what's happening to the gas reservoir inside the YMC
- Extend integrations beyond ~5 Myr and add SNe
- More complete calculation of self-enrichment (abundance ratios of heavier elements)

Work in progress!

What is our state of progress on modelling cluster formation?