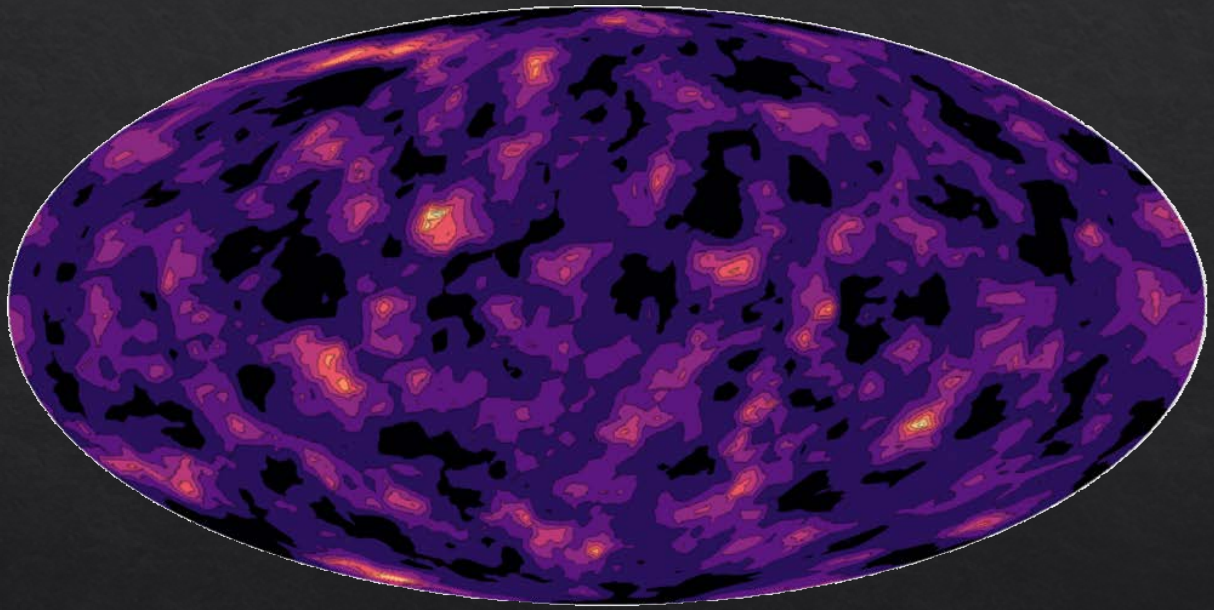
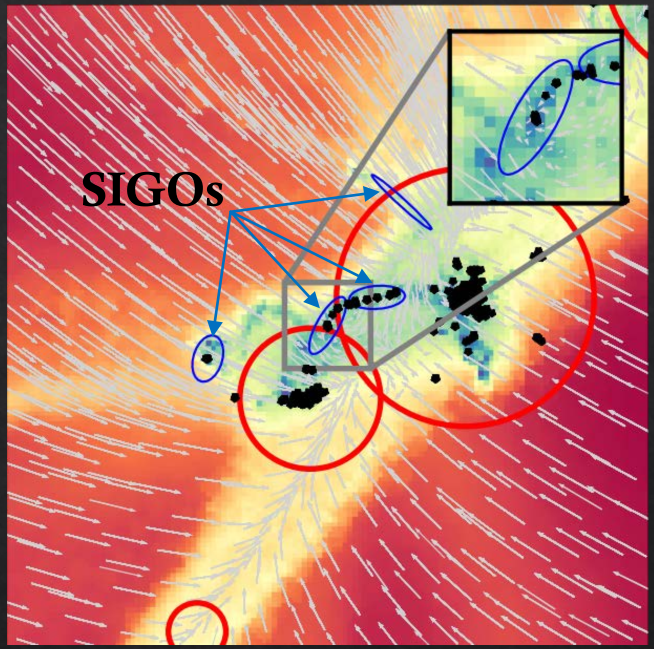
Supersonically Induced Gas Objects (SIGOs): a Potential New Formation Route for Globular Clusters

William Lake





Collaborators: Smadar Naoz, Yeou Chiou, Blakesley Burkhart, Federico Marinacci, Mark Vogelsberger, Kyle Kremer

UCLA

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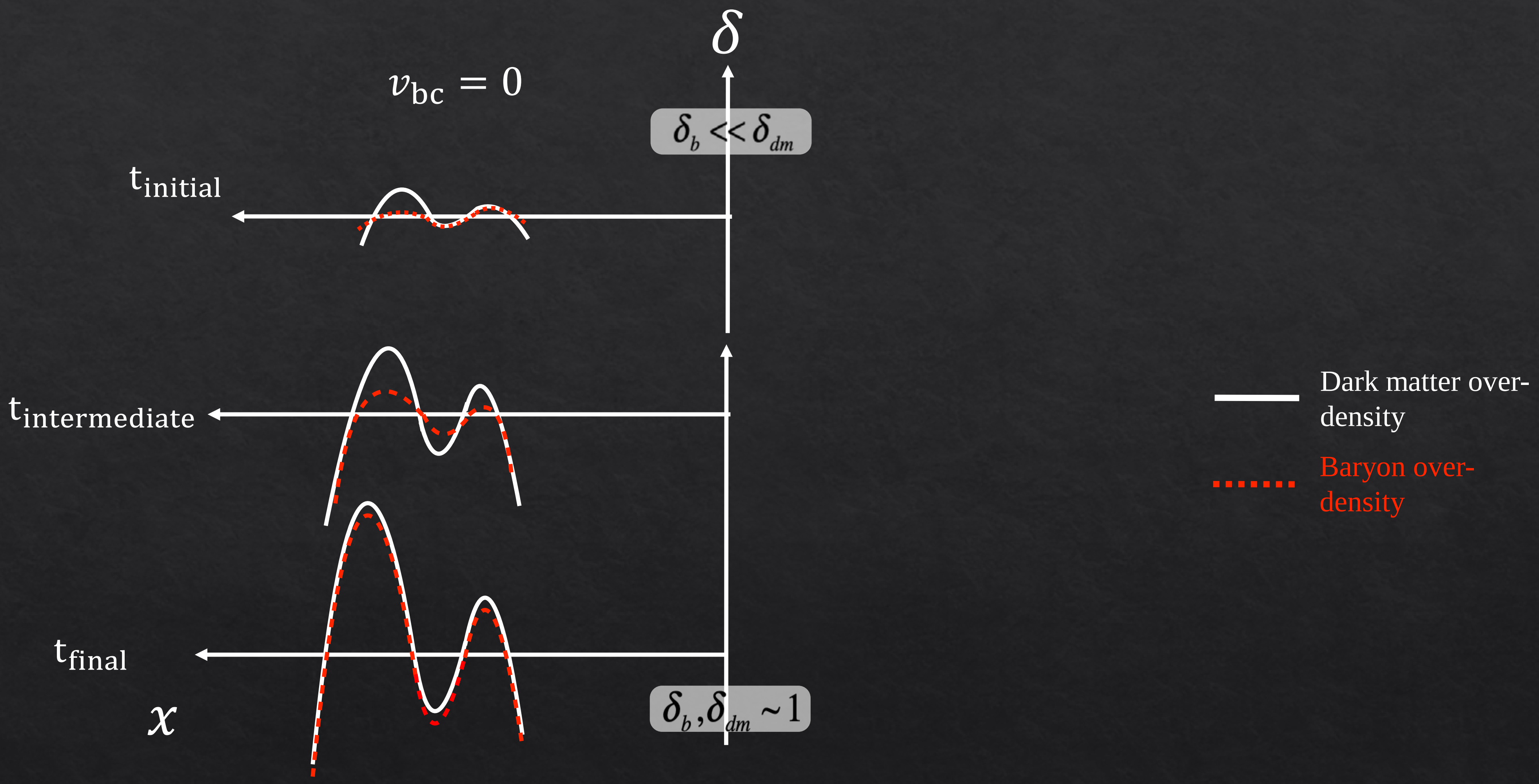
Structure formation



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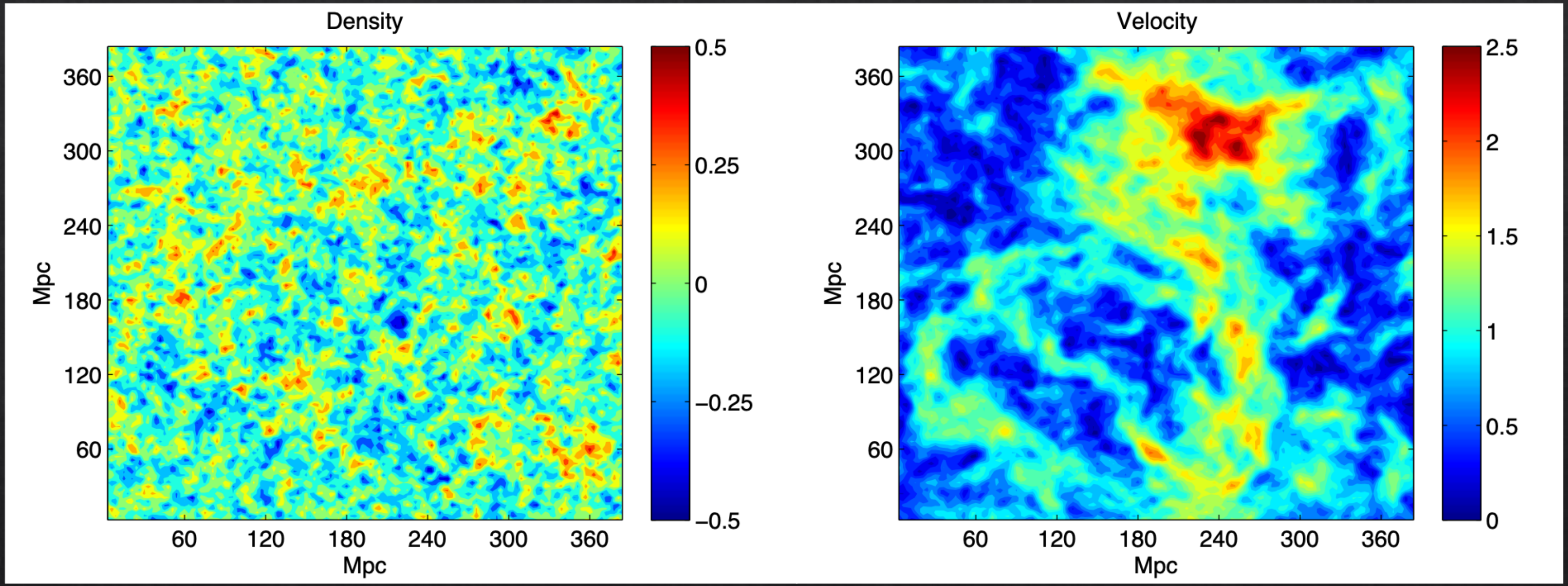
Naoz & Narayan 2014

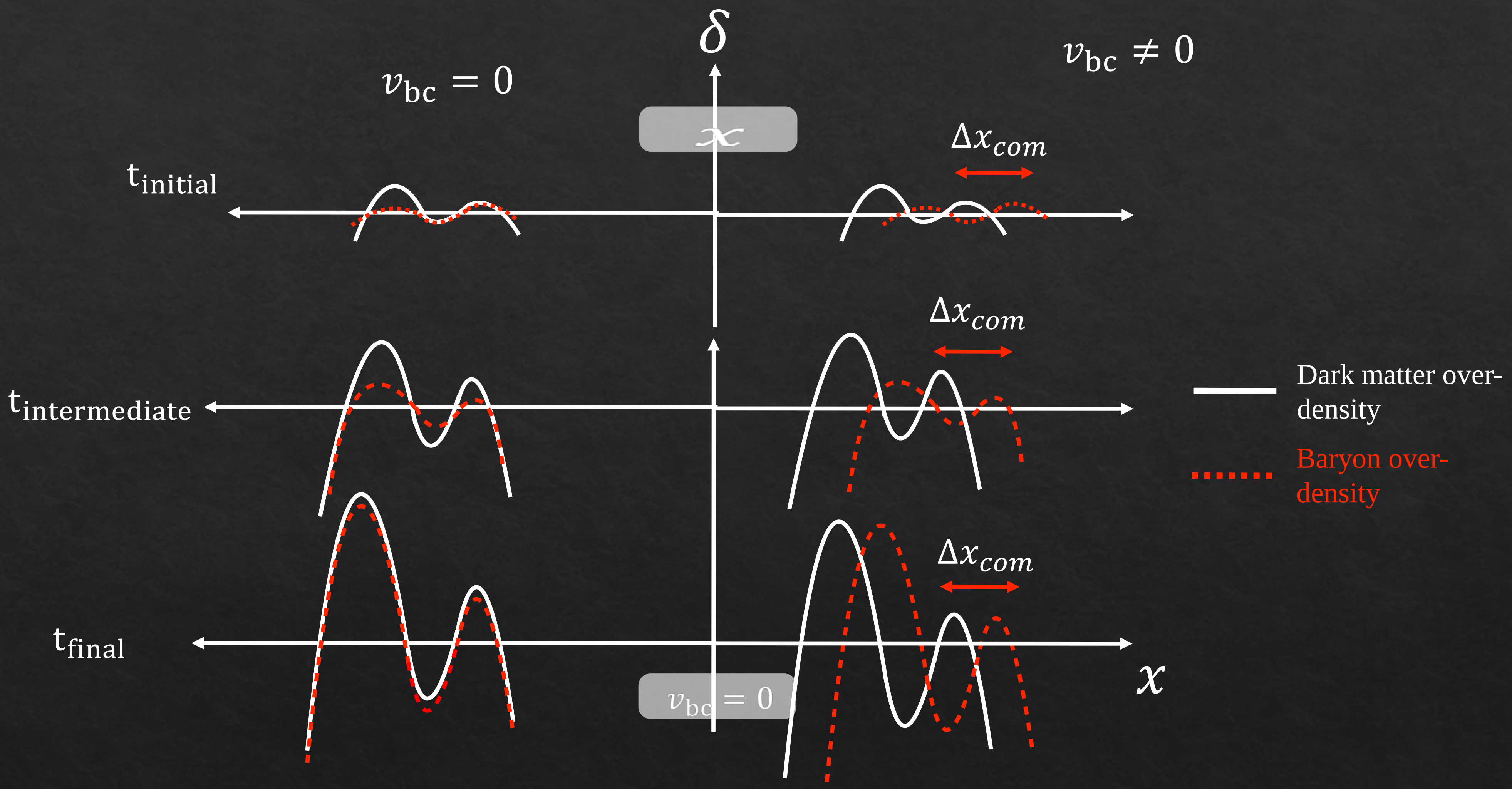
The Stream Velocity

- Varies spatially and temporally
- Coherent on few-Mpc scales



Tseliakhovich & Hirata (2010), Figure credit Fialkov et al. (2013)

Structure formation



Naoz & Narayan 2014

What is a SIGO?

Supersonically Induced Gas Object

- Contains relatively little dark matter
- Mass between $10^4 - few * 10^6\ M_\odot$

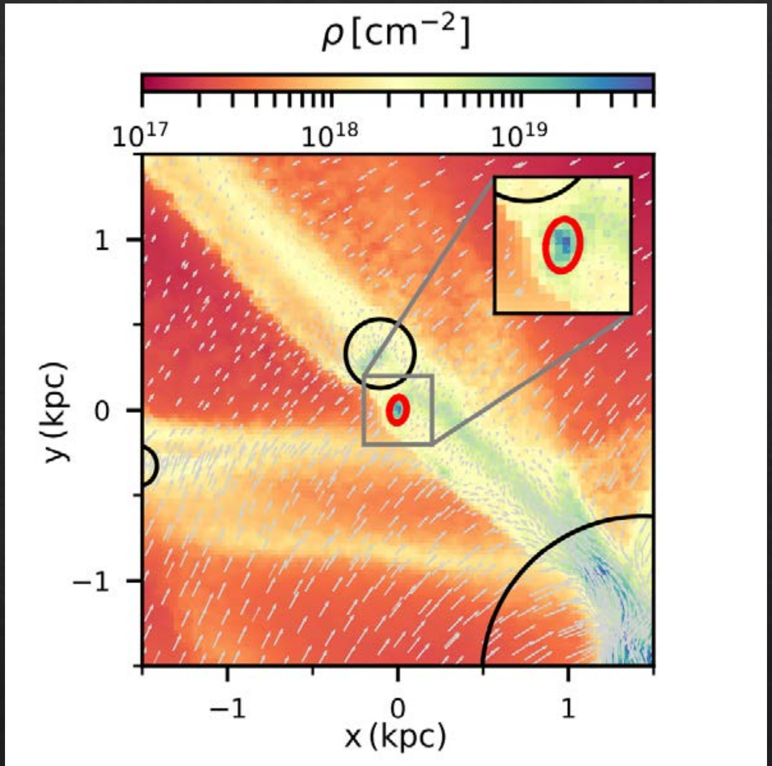
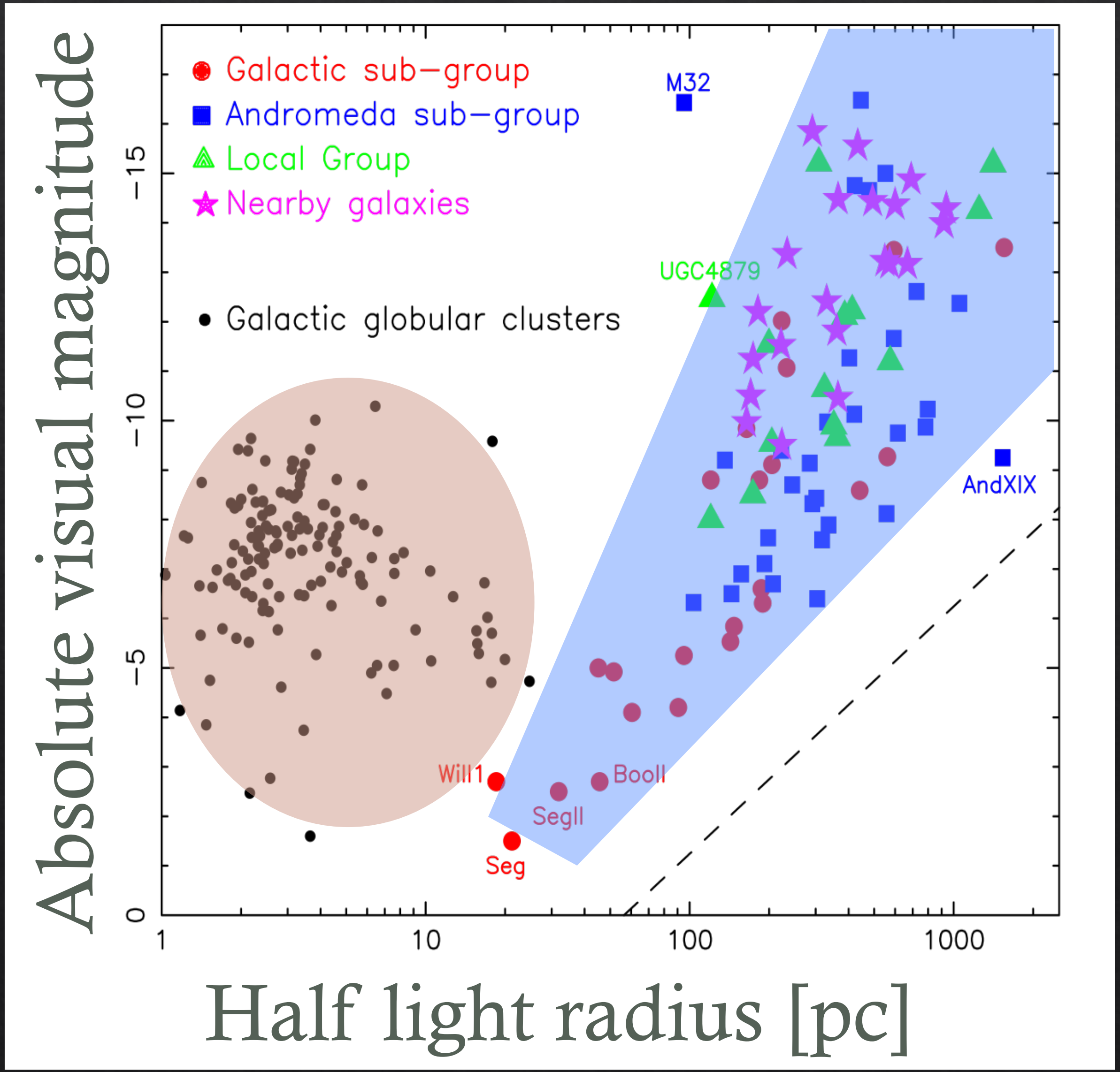


Figure: Lake et al. (in prep).

Sources: Naoz & Narayan 2014, Popa et al. 2016, Lake et al. 2021

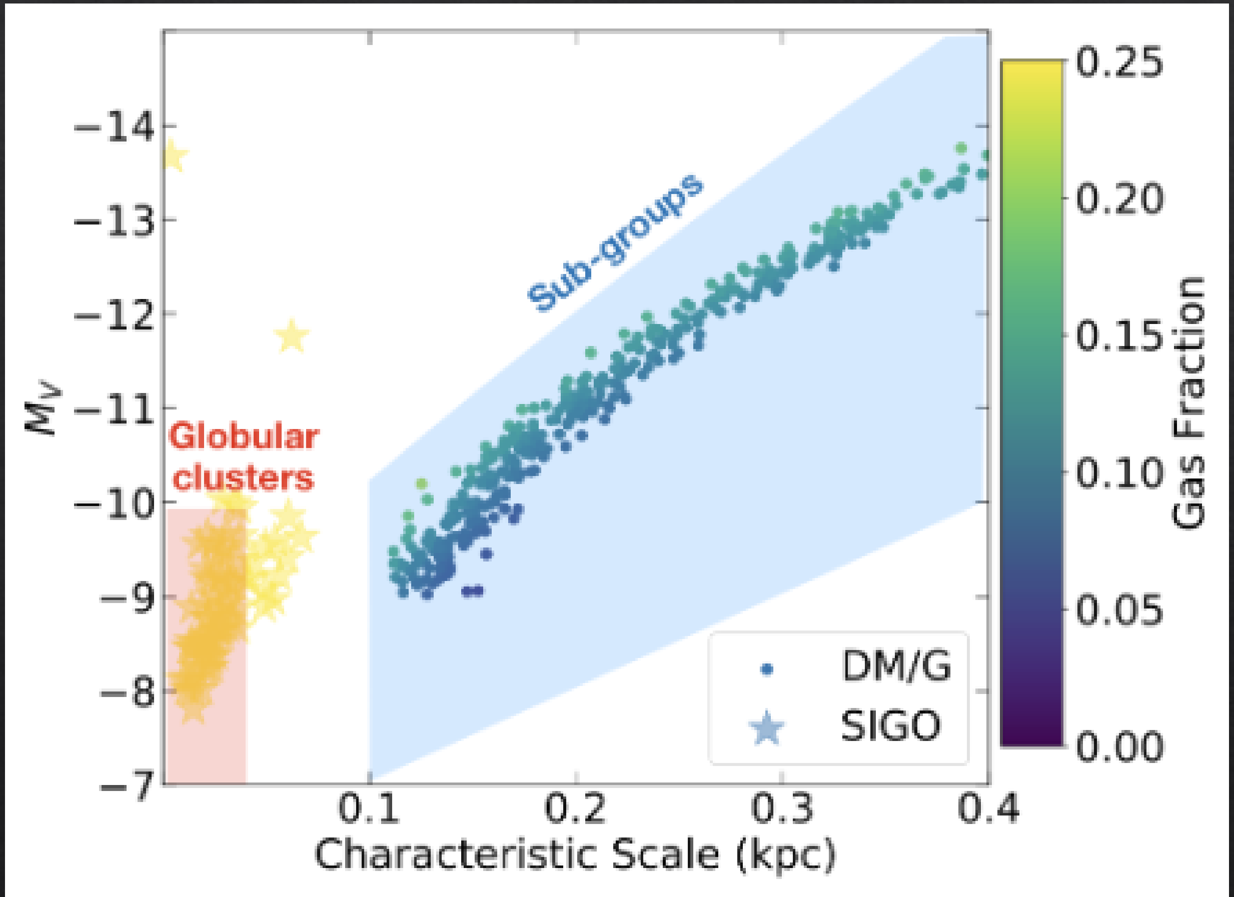
Globular Clusters and Small Satellites



Globular clusters occupy a distinctive region in size-luminosity space.
From McConnachie (2012)

SIGOs as Globular Cluster Progenitors

GCs also contain relatively little DM



SIGOs occupy a distinctive region in size-luminosity space. Chiou et al. (2019).

Sources: Naoz & Narayan 2014, Heggie & Hut 1996, Bradford et al. 2011, Portegies Zwart & McMillan 2000, O'Leary et al. 2006, Rodriguez et al. 2015, 2016, 2021, Chaterjee et al. 2017, Chiou et al. 2019

Investigating SIGO Abundances and their link to GCs

- What is the large-scale distribution and abundance of SIGOs?
- Can SIGOs form stars?

Image: NASA/HST

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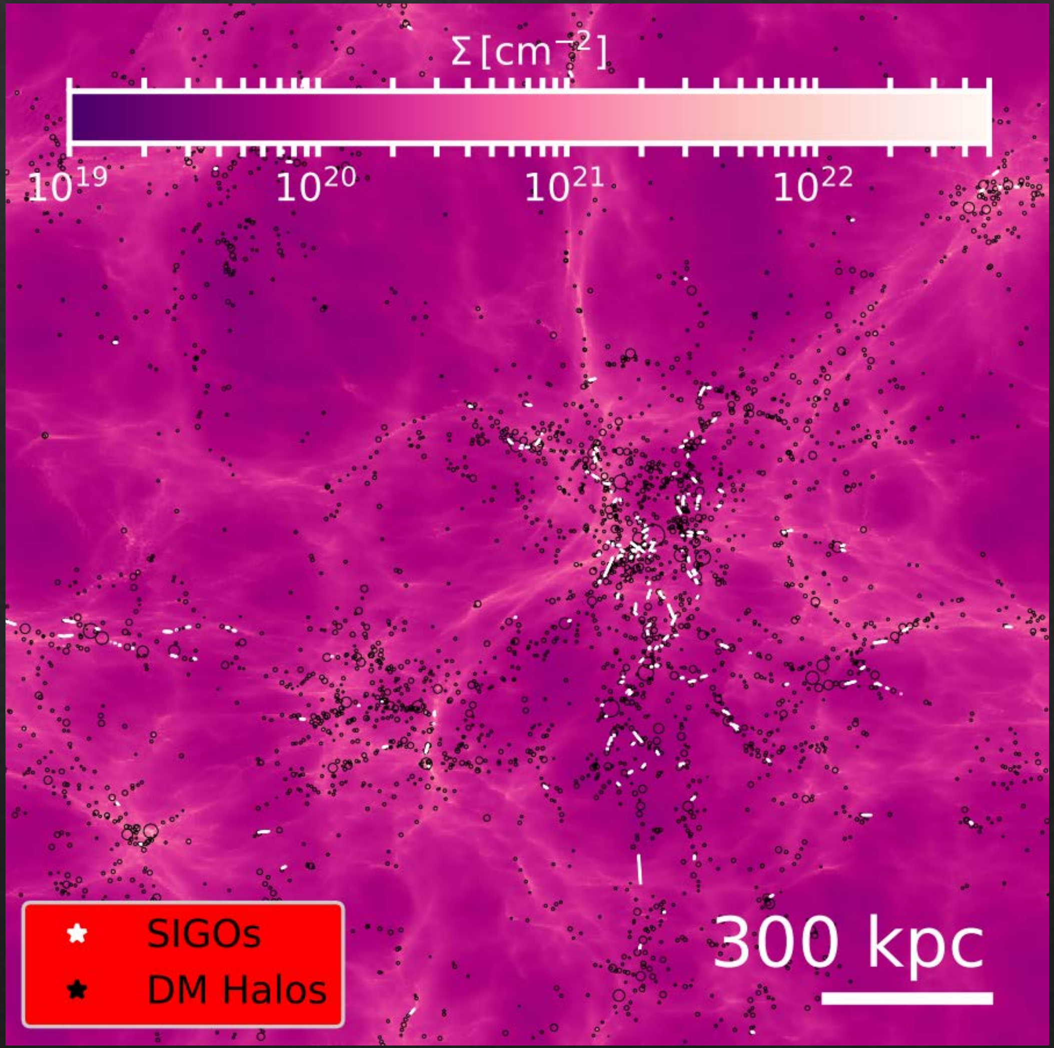
Small-scale Variation in SIGO Abundances



2D Projection of our 2 cMpc simulation box.
From Lake et al. (in prep).

Note that SIGOs trace halo abundances on these scales.

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The connection between DM halos and SIGOs

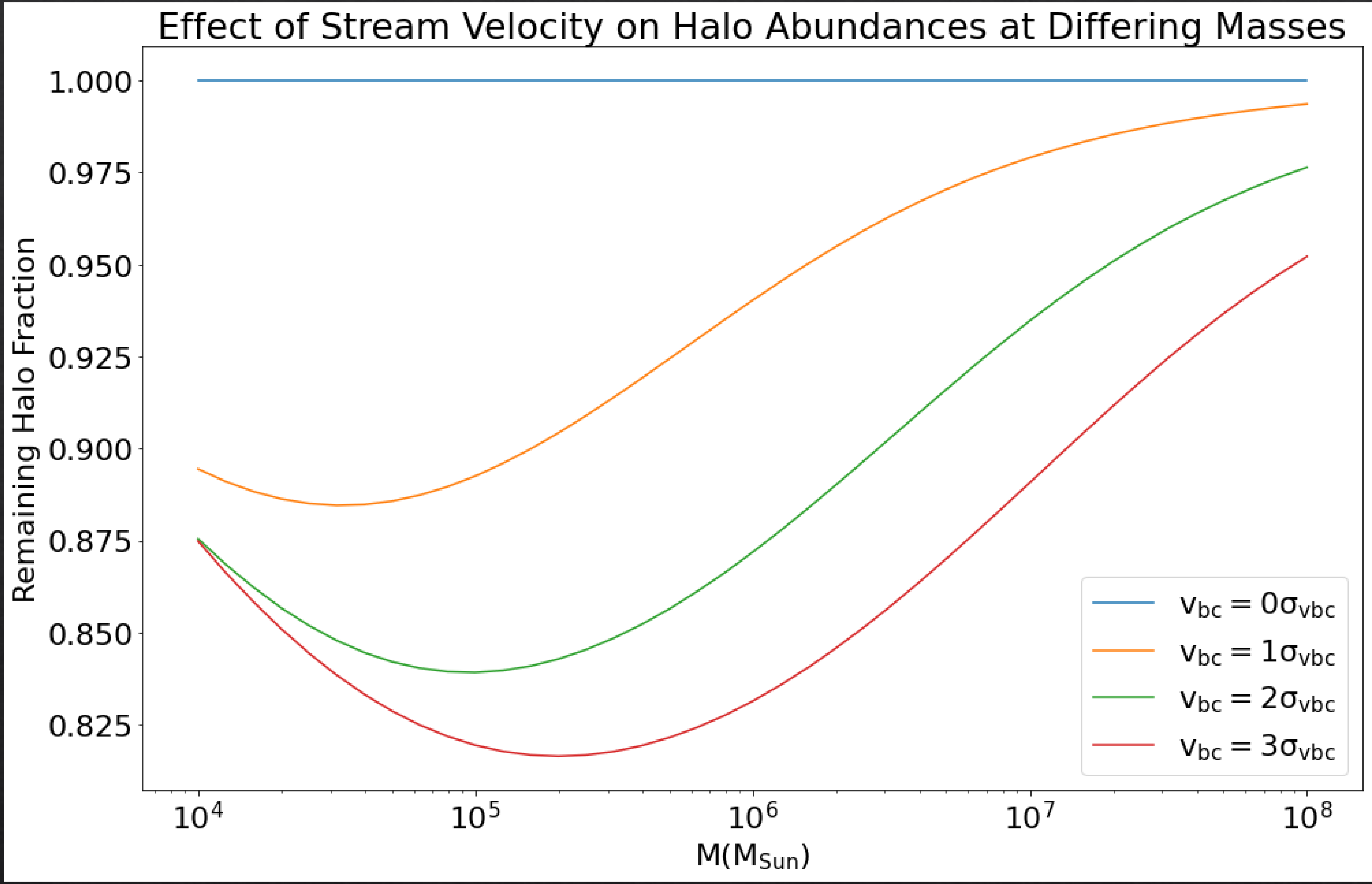
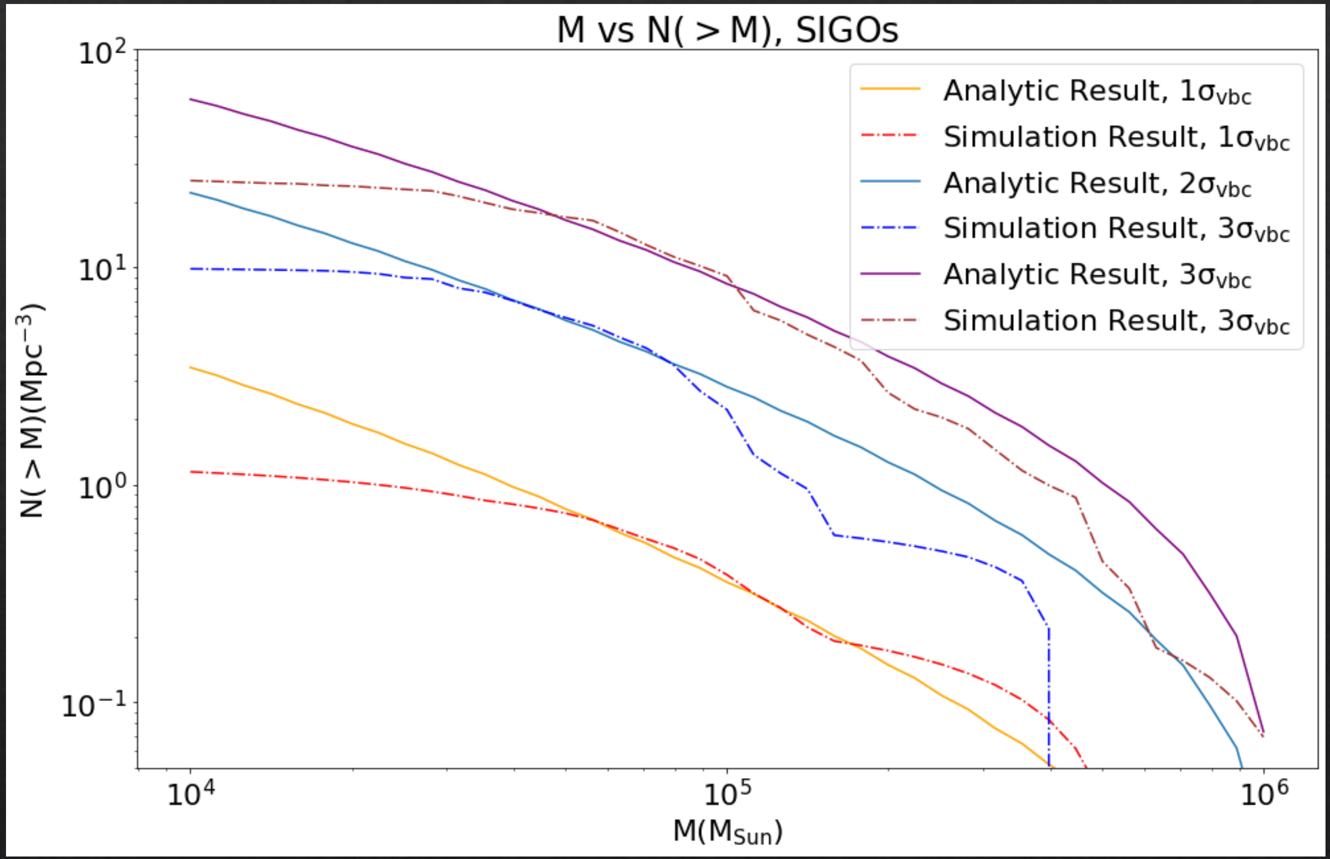


Figure: Lake et al. (2021)

Supersonically Induced Gas Object (SIGO) large-scale abundances

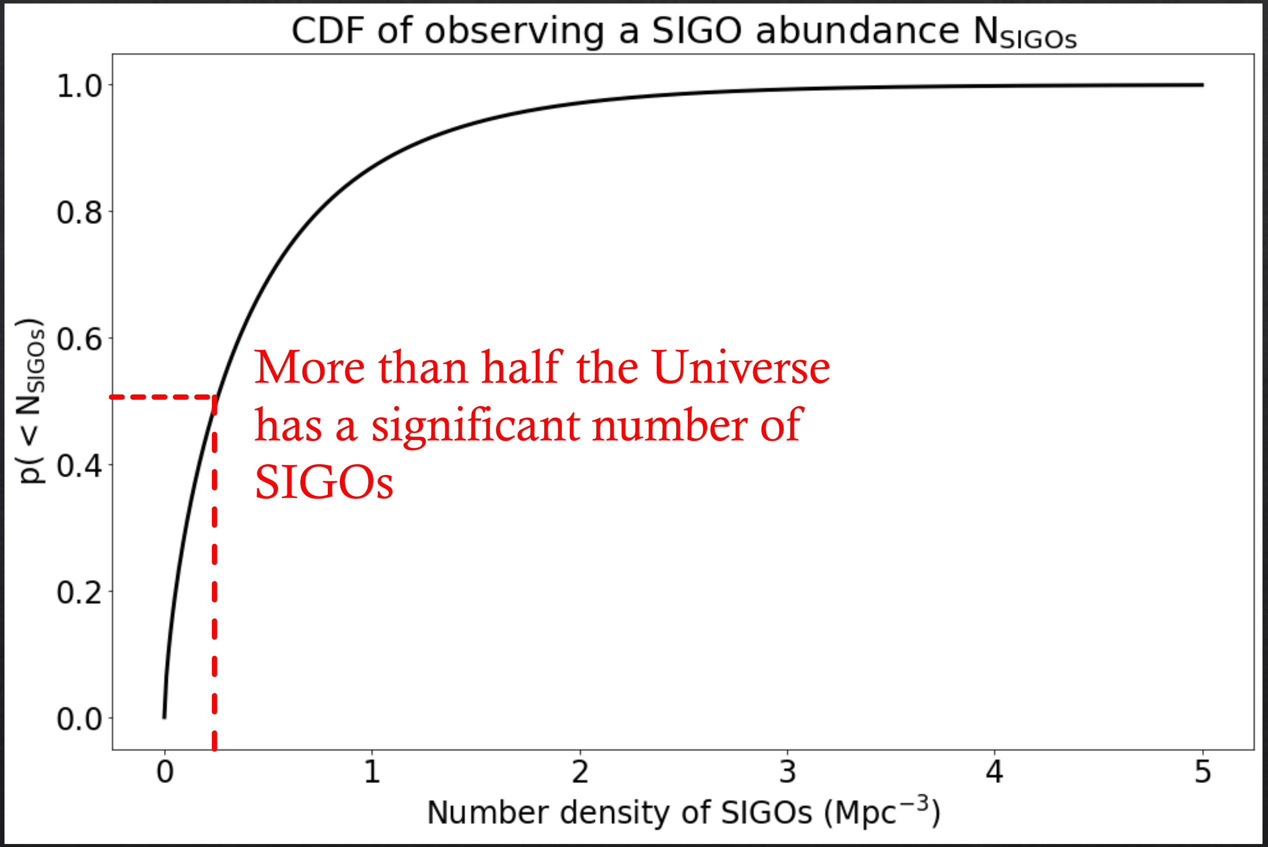
- Related to reductions in halo abundances through the stream velocity
  - Related to the chance of a gas clump to escape its parent halo (a function of stream velocity)



Abundance of SIGOs over a range of masses and stream velocities.
Lake et al. (2021).

SIGO large-scale abundances

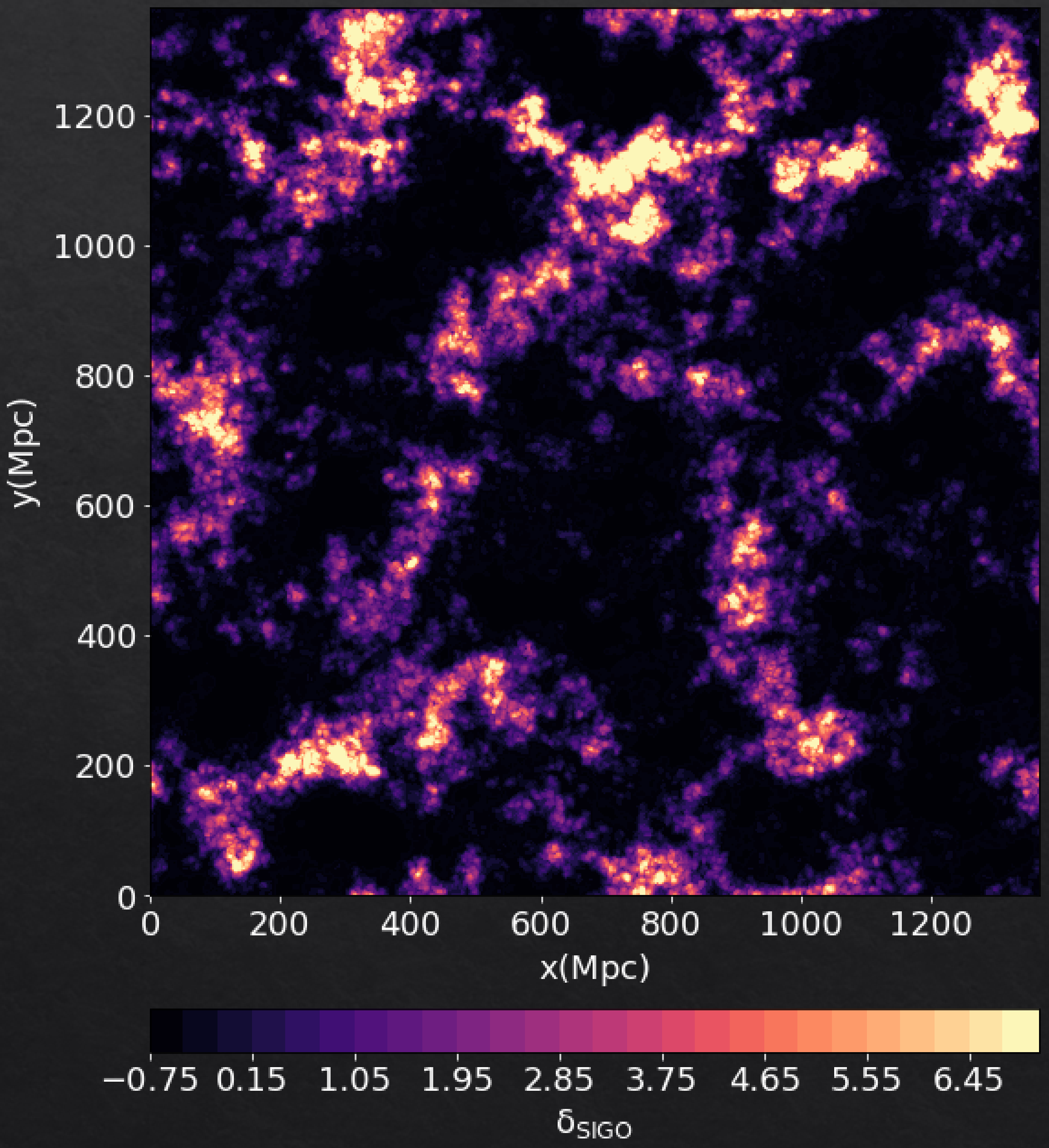
- 50% of the Universe has more than 0.25 SIGOs per comoving Mpc^3
- There are an average of 0.5 SIGOs per comoving Mpc^3 in our model
- This is consistent with the observed local density of GCs (order unity per Mpc^3)
- This is almost equal to the estimated local density of low metallicity GCs (0.44 Mpc^{-3})



Cumulative probability density of various SIGO abundances. From Lake et al. (2021).

Sources: Lake et al. (2021), Rodriguez et al. (2015)

Large-scale Spatial Variation in SIGO Abundances



SIGO abundances vary with the stream velocity on large scales

Shows $\delta_{\mathrm{SIGO}} = \frac{N_{\mathrm{SIGO}} - \bar{N}_{\mathrm{SIGO}}}{\bar{N}_{\mathrm{SIGO}}}$ for $M > 10^5\ M_\odot$

Lake et al. (2021)

Implications to BBH mergers

- GCs have been suggested as the primary source of BBH merger events
- We assume a BBH merger rate of 10^{-8} yr^{-1} for GCs above 10^5 $M_{\odot}$
- We can predict an anisotropy in BBH merger abundances

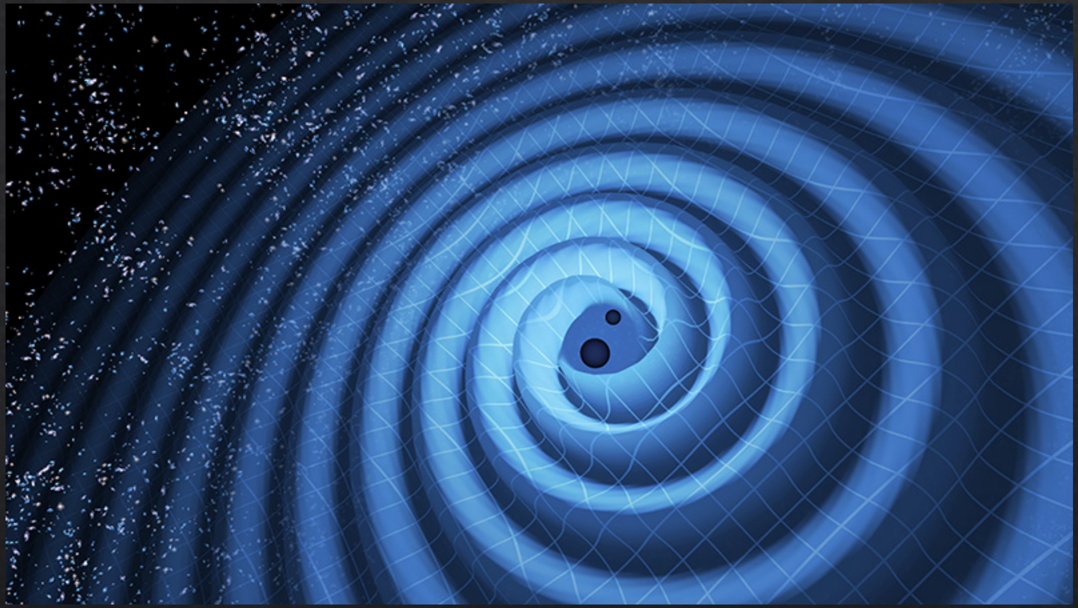
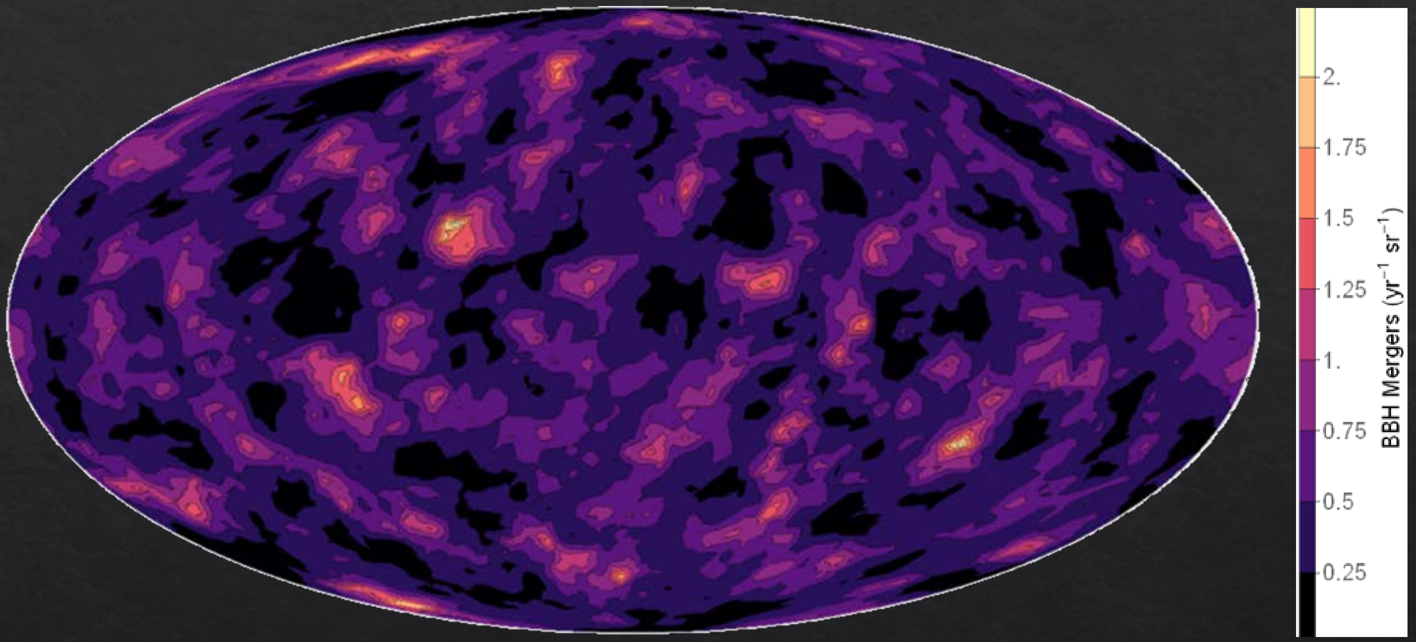


Image credit: LIGO/T Pyle

Sources: Portegies Zwart & McMillan 2000, O'Leary et al. 2006, Rodriguez et al. 2015, 2016, 2021, Chaterjee et al. 2017, Kremer et al. 2020

Implications to BBH mergers

- We find a mean merger abundance of 0.5 $\mathrm{sr}^{-1}\mathrm{yr}^{-1}$ with a standard deviation of 0.3 $\mathrm{sr}^{-1}\mathrm{yr}^{-1}$ on the sky, to a depth of 675 Mpc
- The abundance varies over scales of a few degrees
- This signal is at early redshifts, in the present day it will be more distant

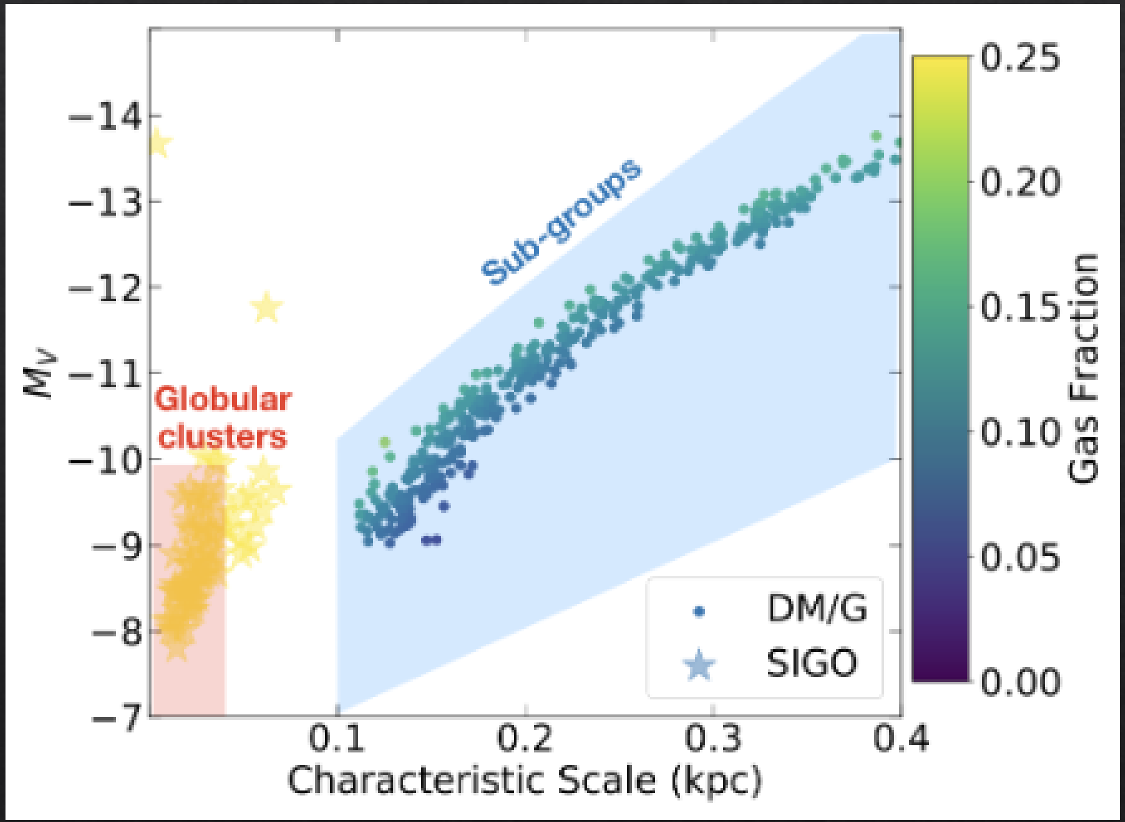


Map of integrated merger abundances: Lake et al. (2021)

The Role of Molecular Cooling in SIGO Formation

- Prior studies used adiabatic cooling

- Molecular hydrogen cooling is important for reaching the densities needed for star formation (Nakazoto et al. 2022)



From Chiou et al. (2019)

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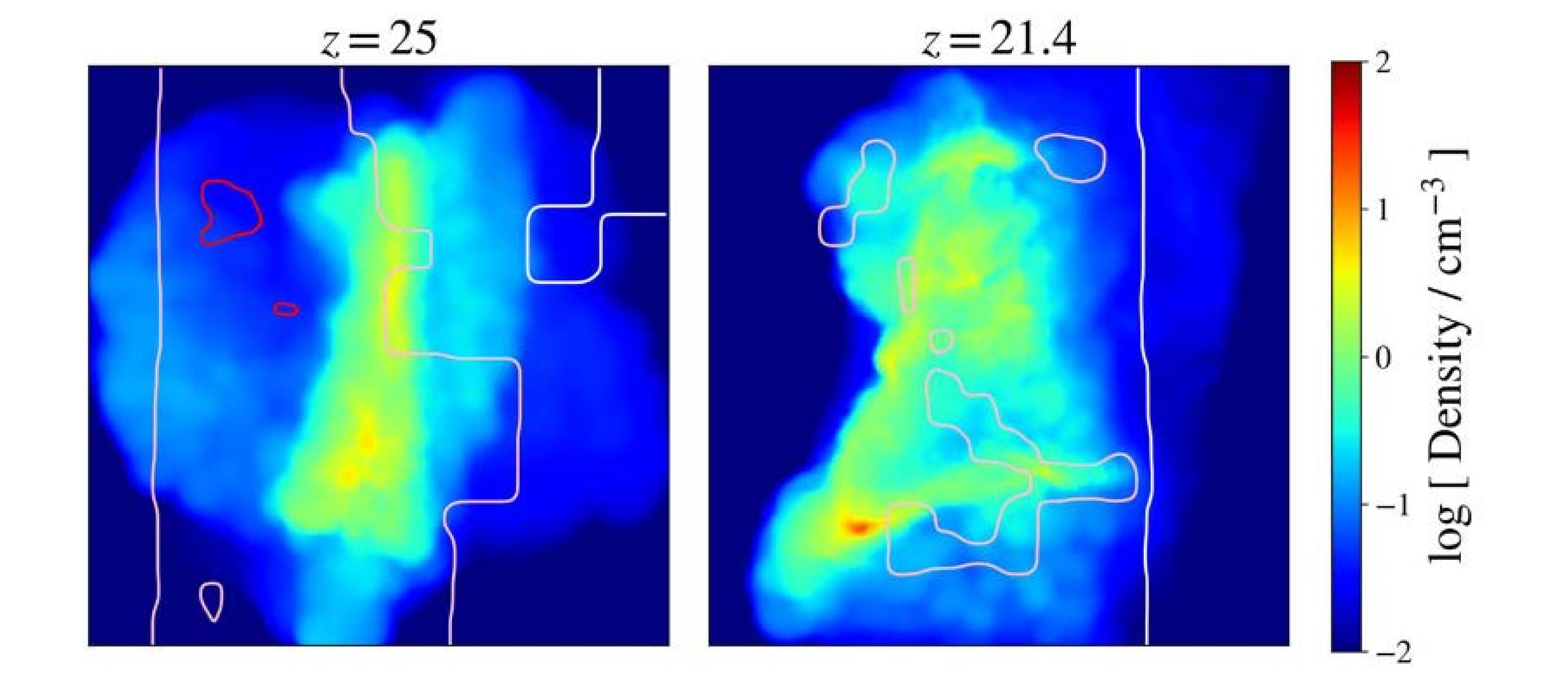
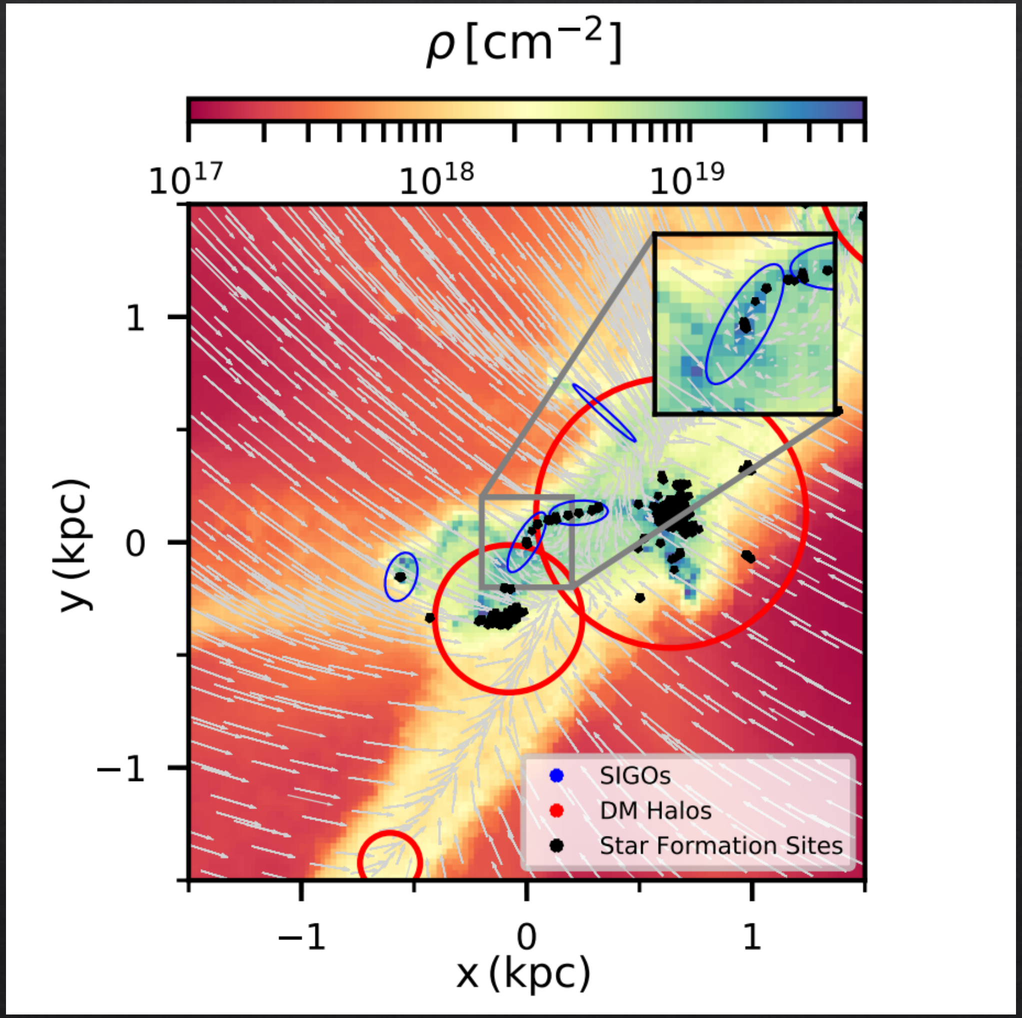
The Role of Molecular Cooling in SIGO Formation



A SIGO that has reached the Jeans density in a simulation with molecular cooling. From Nakazoto et al. (2022). See also Schauer et al. (2021).

Star Formation in SIGOs



Lake et al. (in prep)

Some SIGOs form stars

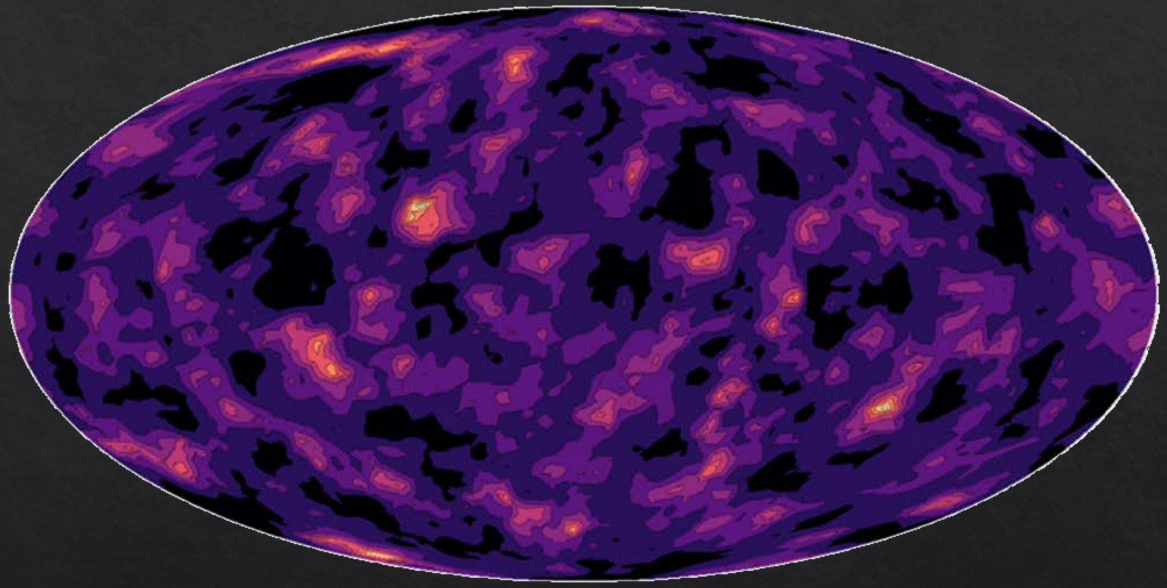
Stellar masses with molecular hydrogen cooling reach $10^5\ M_{\odot}$

There is still a ways to go

- Feedback needs to be incorporated into star formation models in SIGOs
- The role of metal line cooling in SIGOs needs to be explored (e.g. Schauer et al 2021)
- The next big step is a zoom-in simulation that incorporates all of this to follow a SIGO's evolution to the present day

Summary

- The abundance of SIGOs is consistent with that of GCs in the present day
- This abundance varies spatially
    - This may cause an anisotropy in the abundance of SIGOs on the sky
- SIGOs form stars
- There is still a lot of work left to do: SIGOs have never been simulated all the way to the present day



Map of SIGO abundances: Lake et al. (2021)

Questions?

Power Spectrum of Density Fluctuations

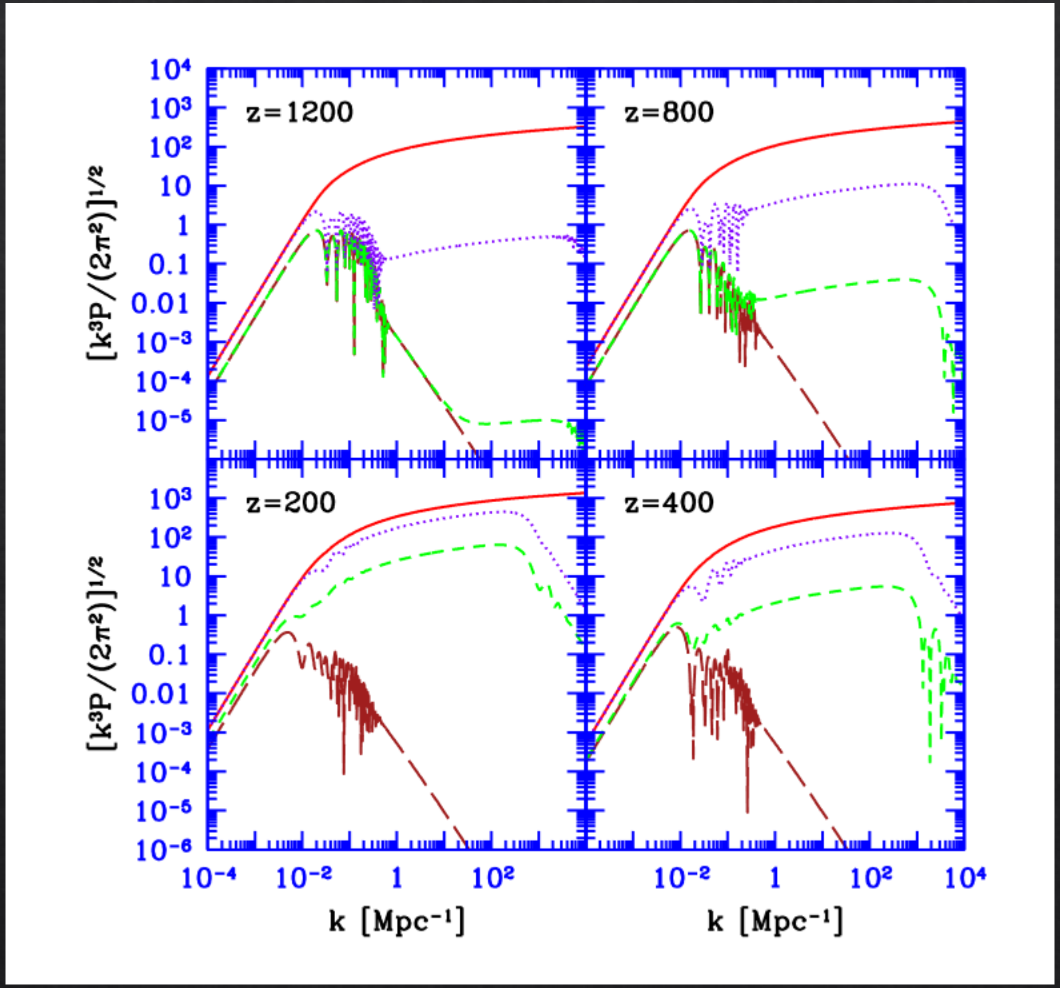


Figure: Naoz & Barkana (2005). DM density fluctuations in red, gas density fluctuations in purple.

SIGO Formation