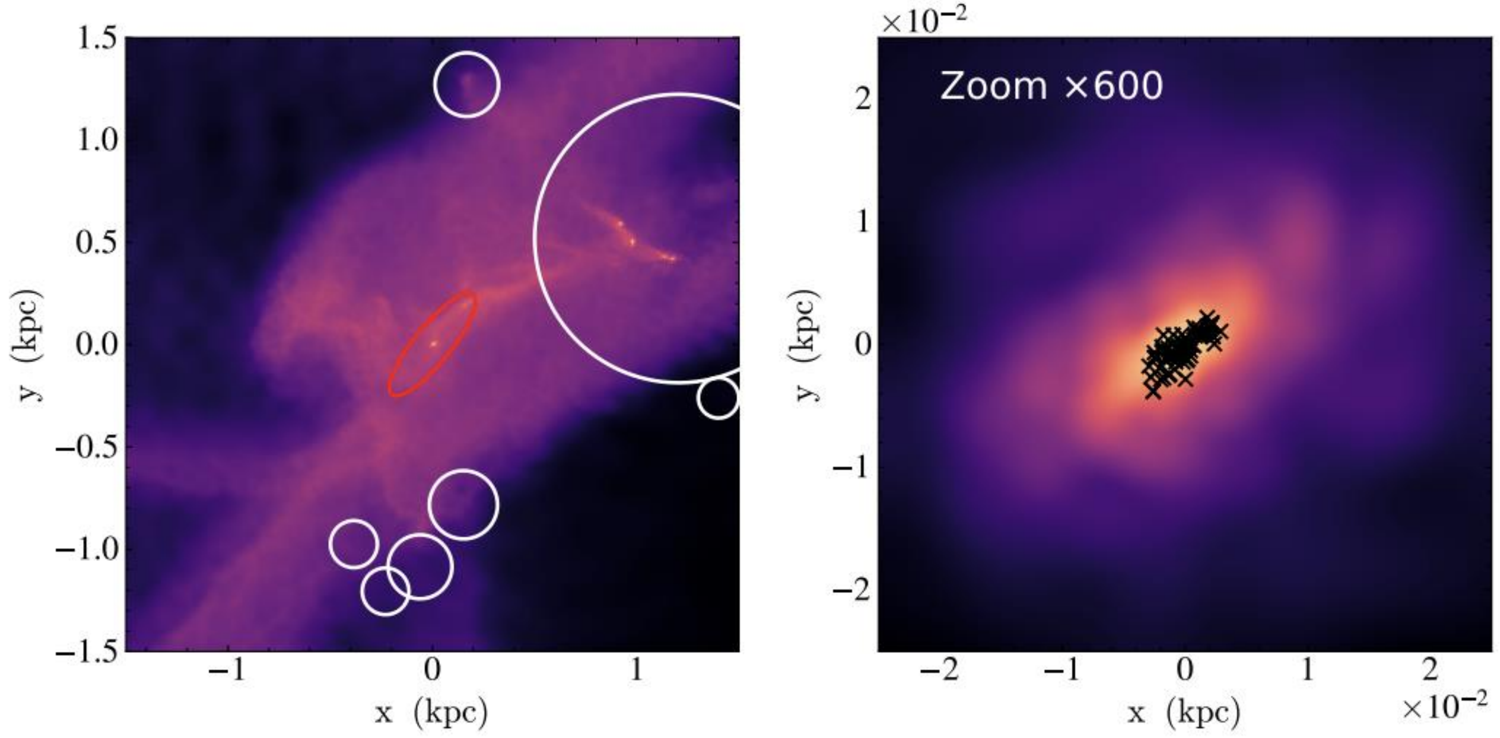
Early Cluster Formation through SIGOs



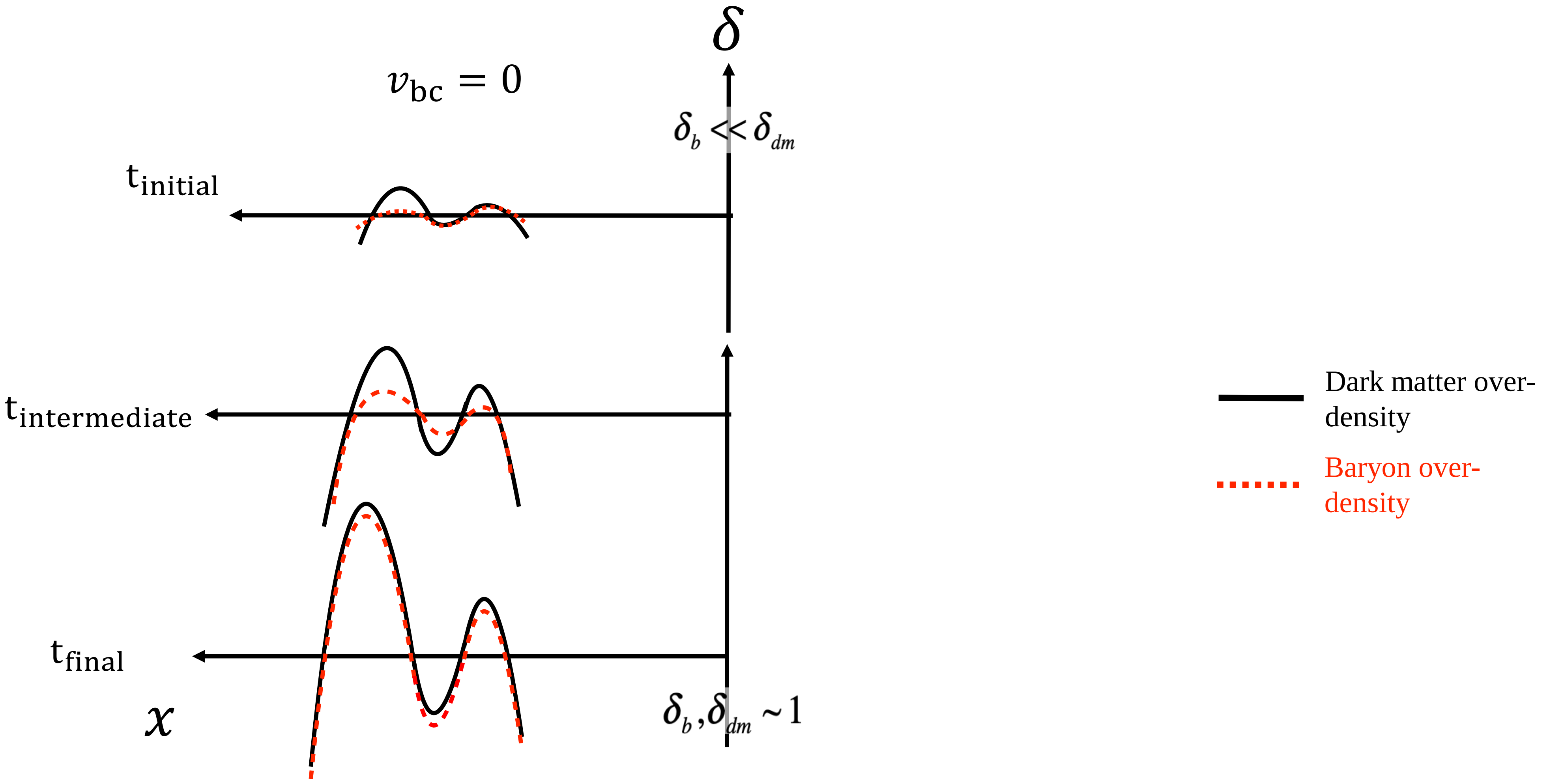
William Lake

Collaborators: Smadar Naoz, Claire Williams, Yeou Chiou, Blakesley Burkhart, Federico Marinacci, Mark Vogelsberger, Naoki Yoshida, Yurina Nakazato, and Gen Chiaki

The Supersonic Project

UCLA

Structure formation



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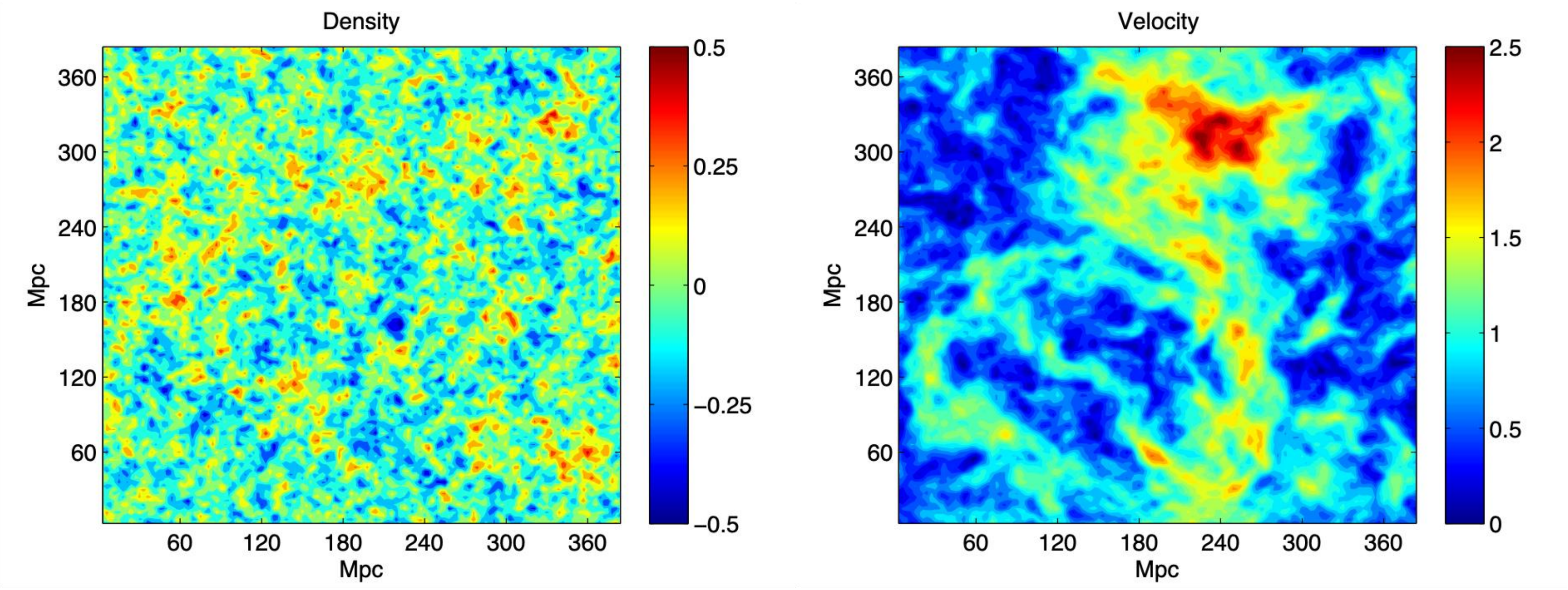
Naoz & Narayan 2014

The Stream Velocity

- Varies spatially and temporally
- Roughly constant on few-Mpc scales
- Exists in ΛCDM but is reduced in some dark matter theories (eg DM-Baryon interactions)



Tseliakhovich & Hirata (2010), Driskell et al. (2022), Figure credit Fialkov et al. (2013)

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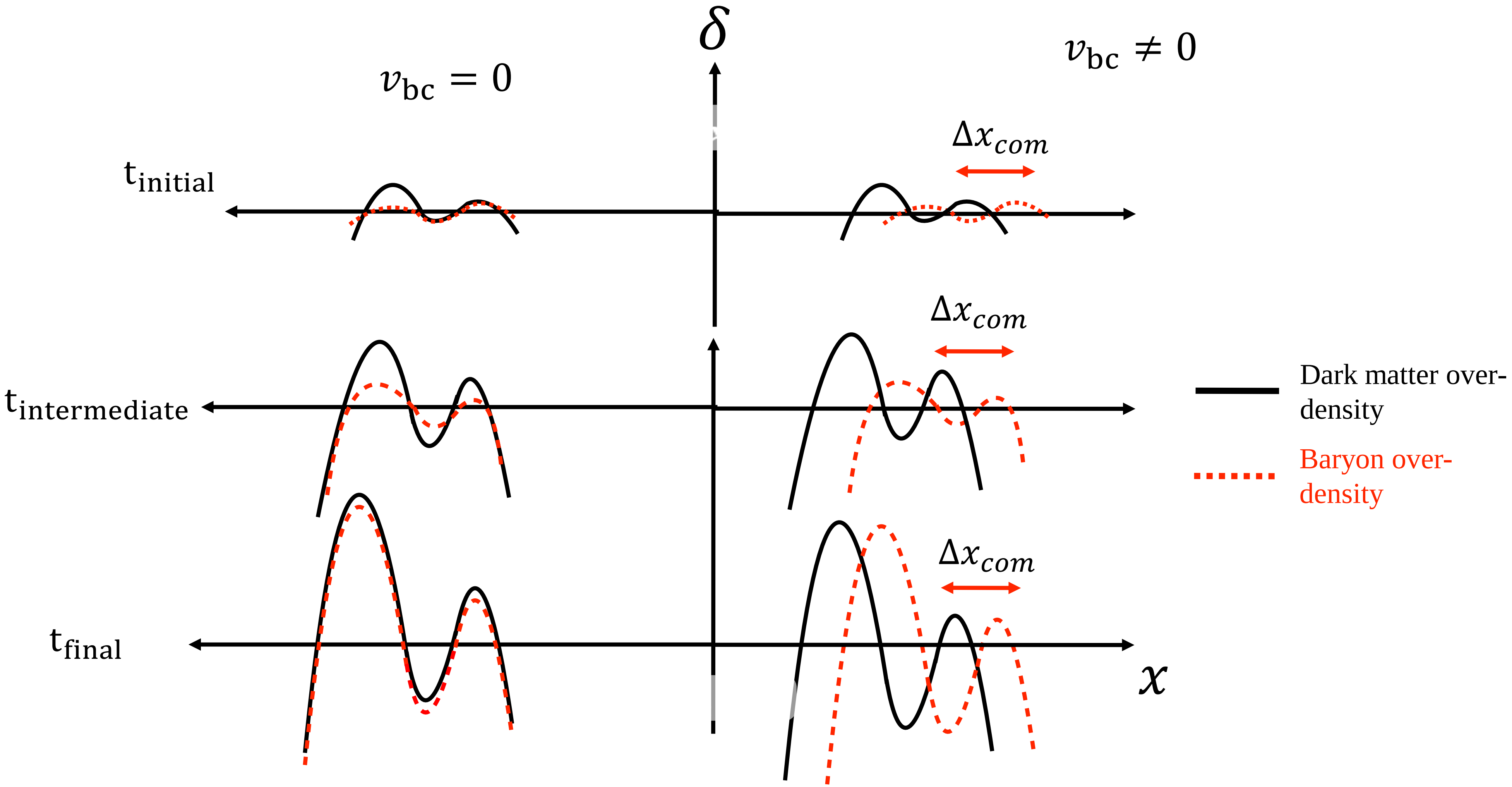
Structure formation



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Naoz & Narayan 2014

What is a SIGO?

Supersonically Induced Gas Object

- Contains relatively little dark matter
- Masses at formation up to a few $\times 10^6\ M_\odot$
- Natural consequence of theories of dark matter that include a significant stream velocity at early times

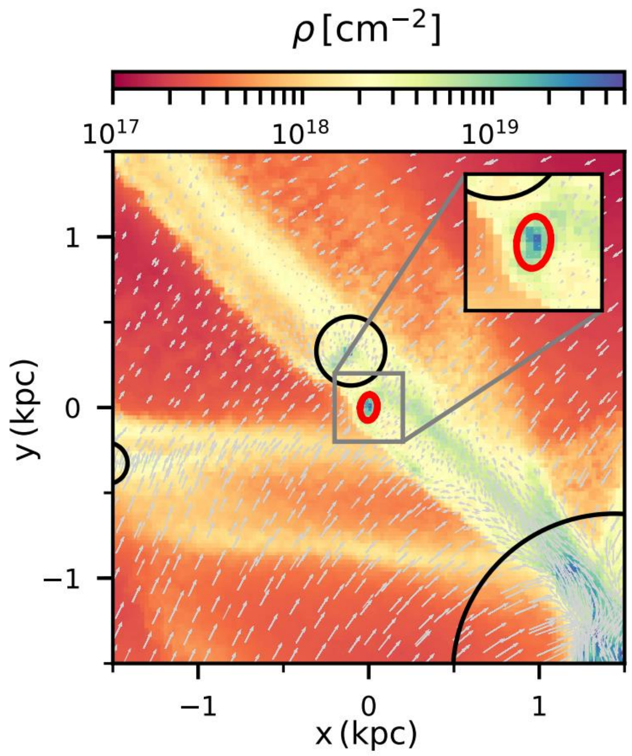


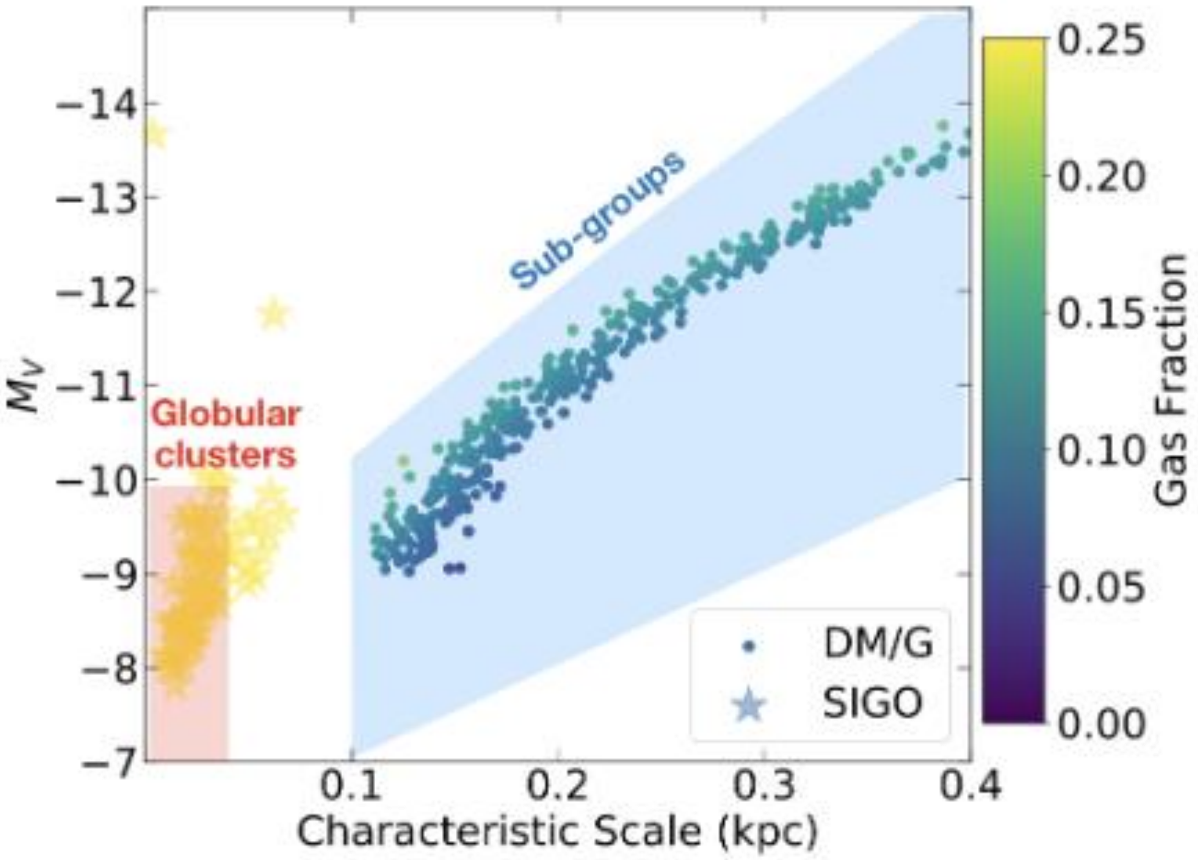
Figure: **Lake** et al. (2022).

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

SIGOs as Globular Cluster Progenitors

GCs also contain relatively little DM

SIGOs form in similar abundance to low-metallicity GCs



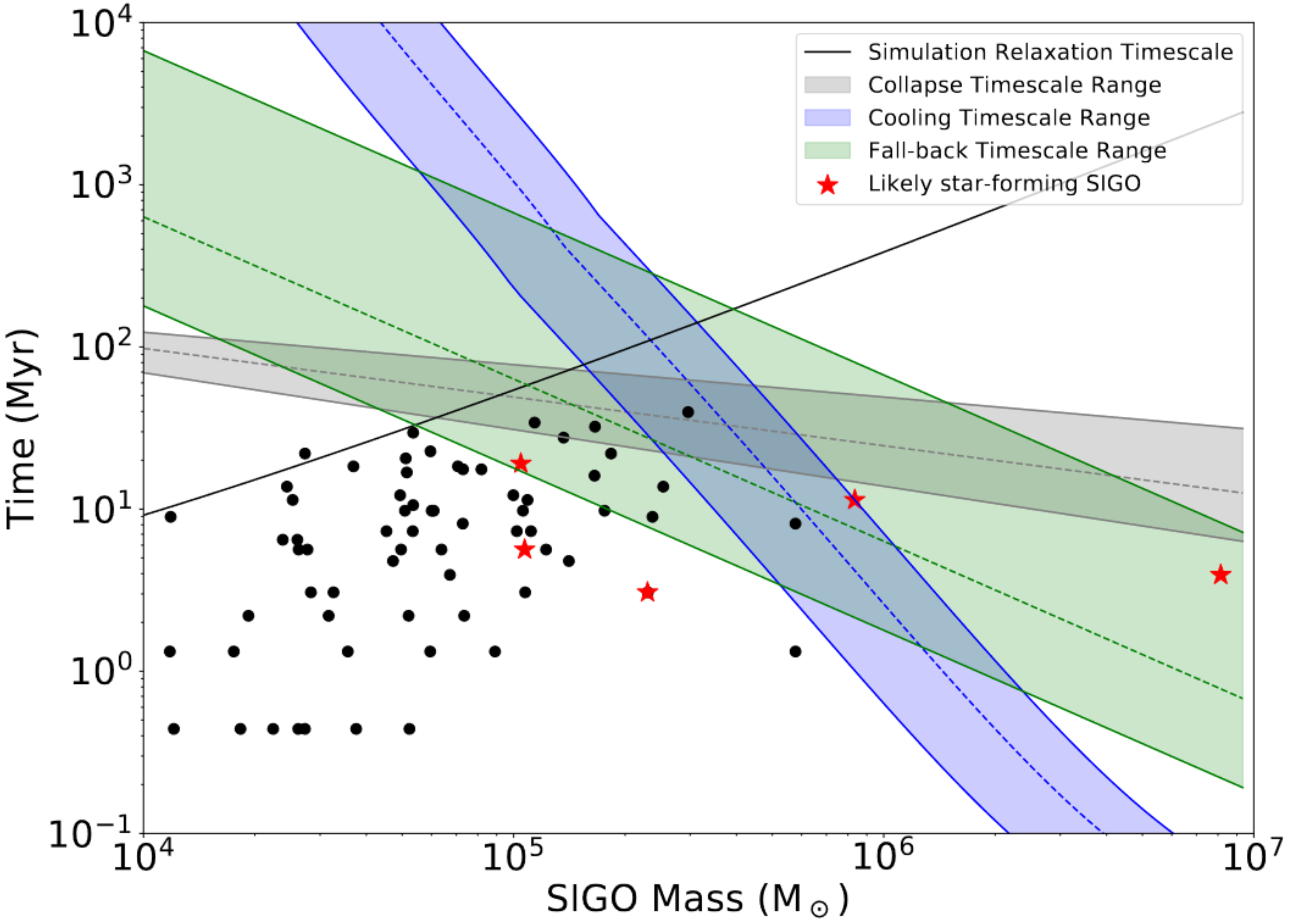
SIGOs occupy a distinctive region in size-visual magnitude space. Chiou et al. (2019) using a Schaerer (2003) starburst model.

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, **Lake** et al. 2021

How Do SIGOs Evolve?

- Gravitational Collapse
  - SIGOs can collapse on themselves gravitationally, forming stars
  - This requires the SIGOs to exceed the Jeans mass
- Cooling
  - SIGOs can cool, mostly through molecular hydrogen cooling
  - This lowers their temperature and Jeans mass
- Fall-back
  - SIGOs can fall back into their parent DM halos, becoming substructure within the halo
- Growth
  - SIGOs can accrete surrounding material and grow

How do these Timescales Compare?



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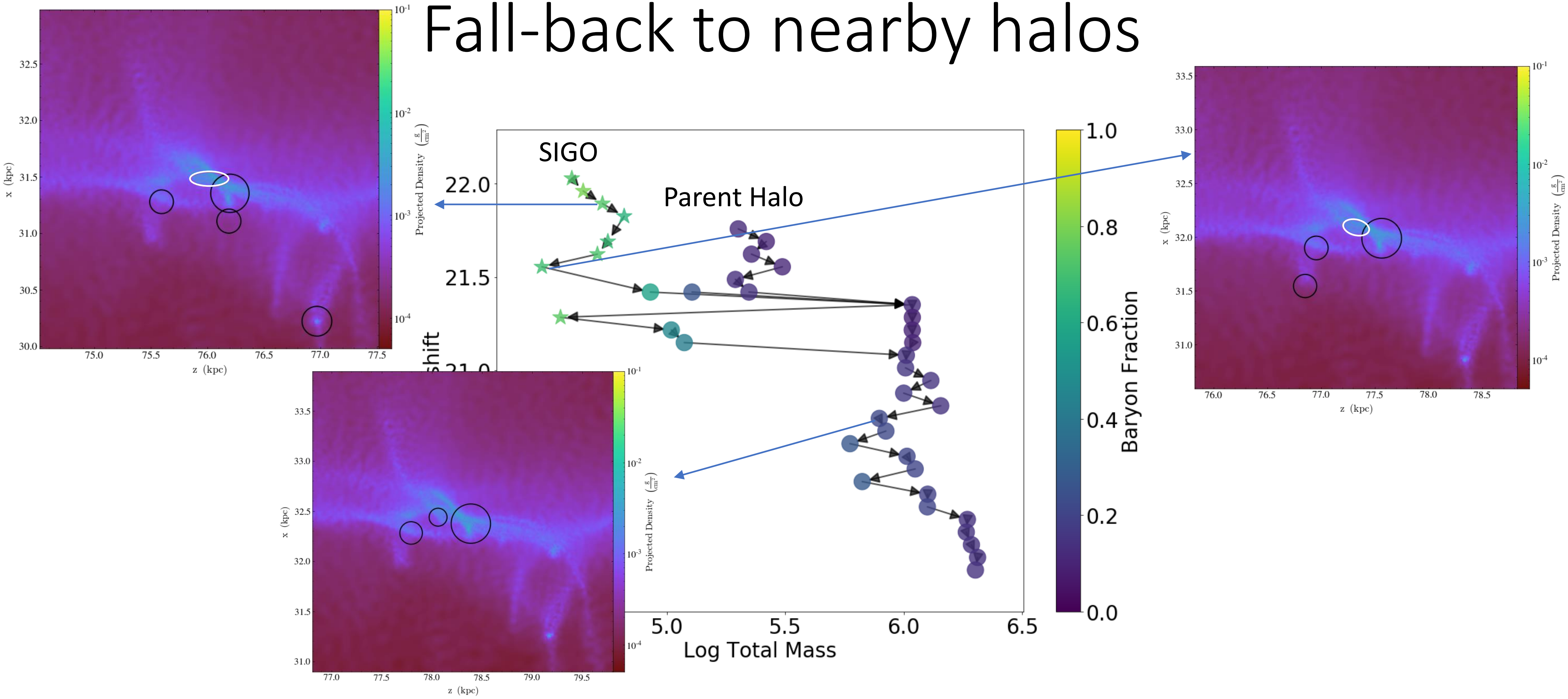
Important timescales for the evolution of SIGOs, and their dependence on mass. **Lake** et al (2022).

Fall-back to nearby halos

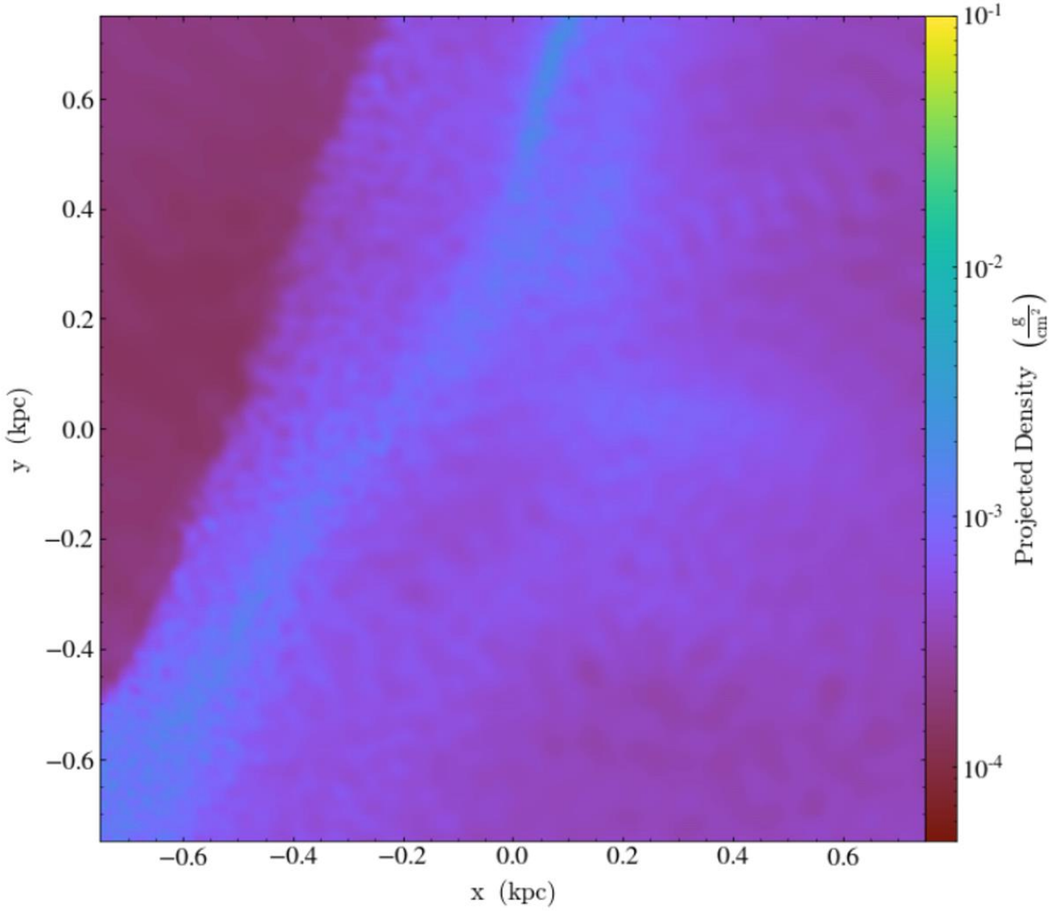


An evolutionary track of a SIGO (left, stars) merging with its parent halo (right). **Lake** et al. (2022)

SIGO Growth

- SIGOs can accrete surrounding material
- This allows their masses and gas fractions to change

SIGO Growth



The formation and growth of a SIGO from $10^{4.8}\ M_\odot$ (z=24) to $10^{5.6}\ M_\odot$ (z=20)
(**Lake** et al. 2022)

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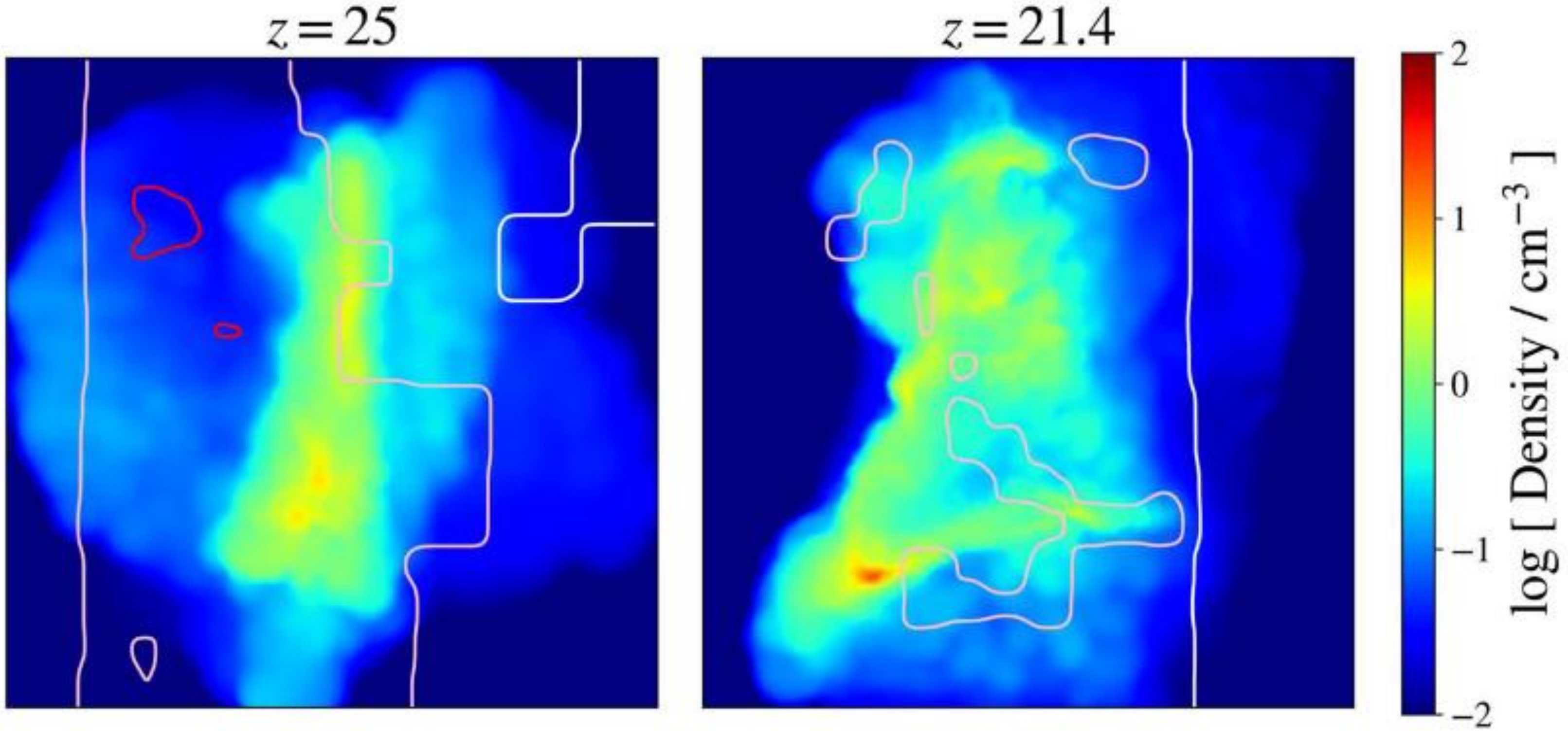
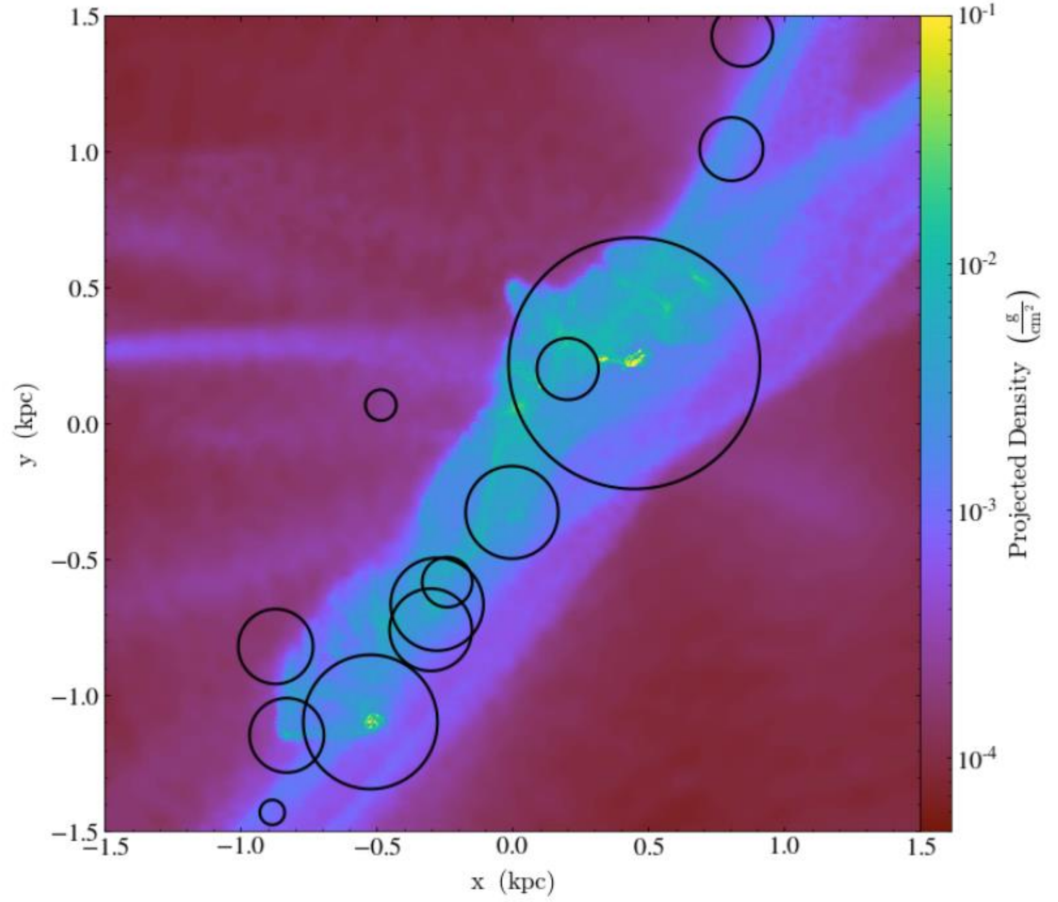
Cooling and Collapse in SIGOs



A SIGO that has reached the Jeans density in a simulation with molecular cooling. From Nakazato,…, **Lake,** et al. (2022).

Star Cluster Formation Movie



The formation and star cluster formation of a $10^{5.5}\ M_\odot$ SIGO between z=20 and z=15. (**Lake** et al. in prep)

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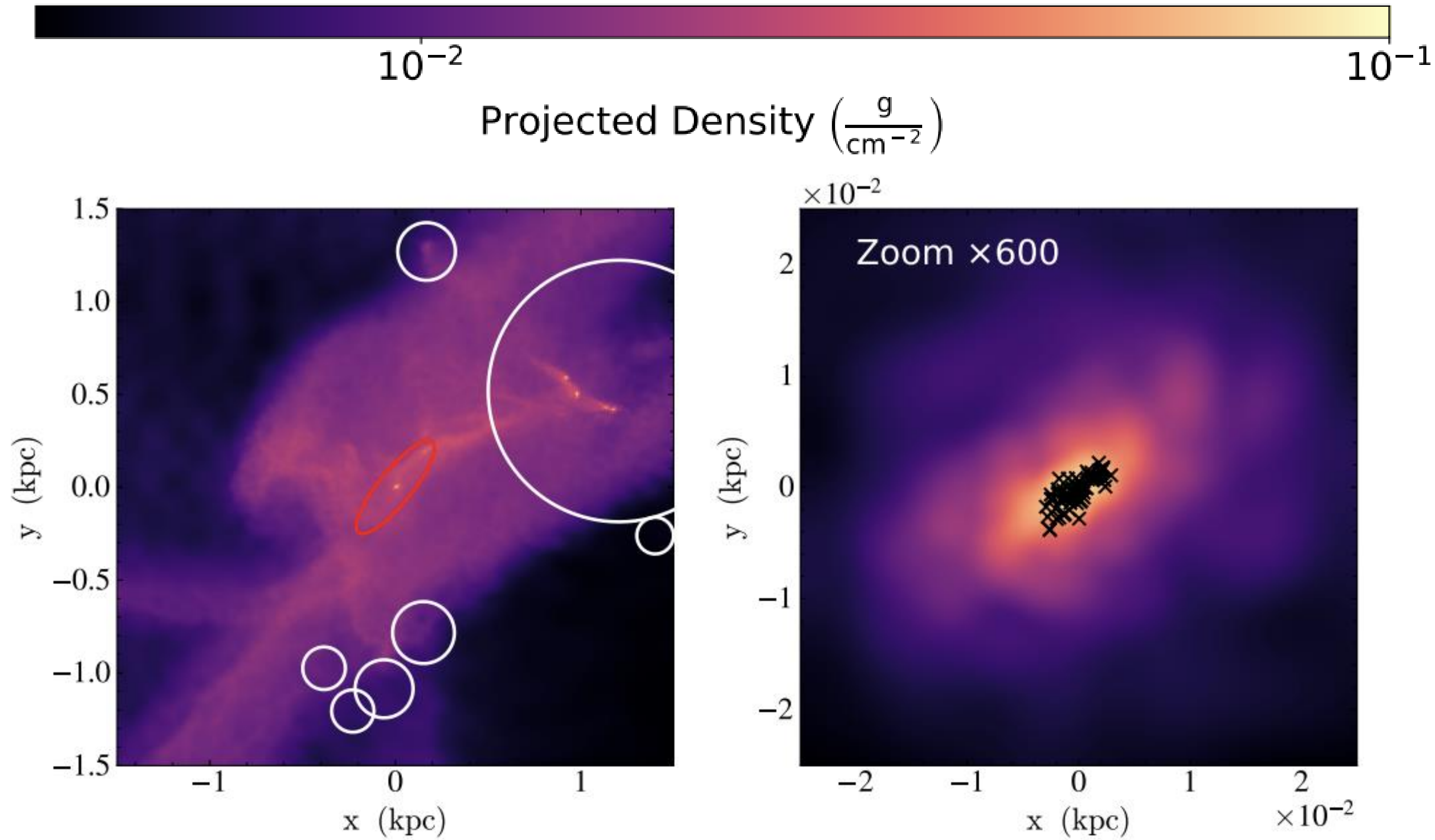
SIGO Star Cluster Formation



A SIGO undergoing star formation at z=15 (red, left) and a zoomed in view of the star formation region (right). Preliminary results.

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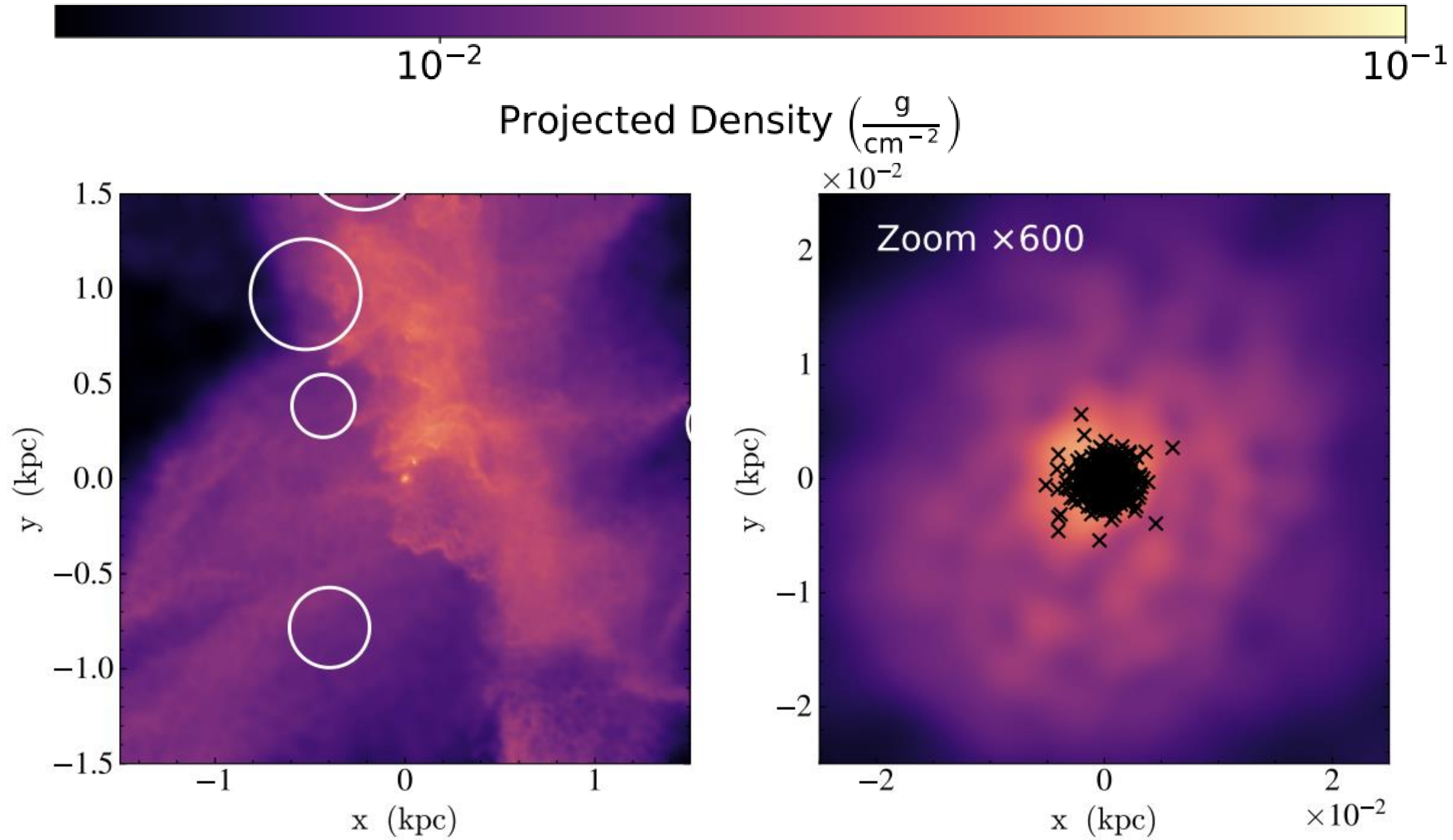
SIGO Star Cluster Formation



A SIGO after star formation at z=12 (left) and a zoomed in view of the resulting star cluster (right). Preliminary results.

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Summary

- SIGOs arise as a natural consequence of ΛCDM

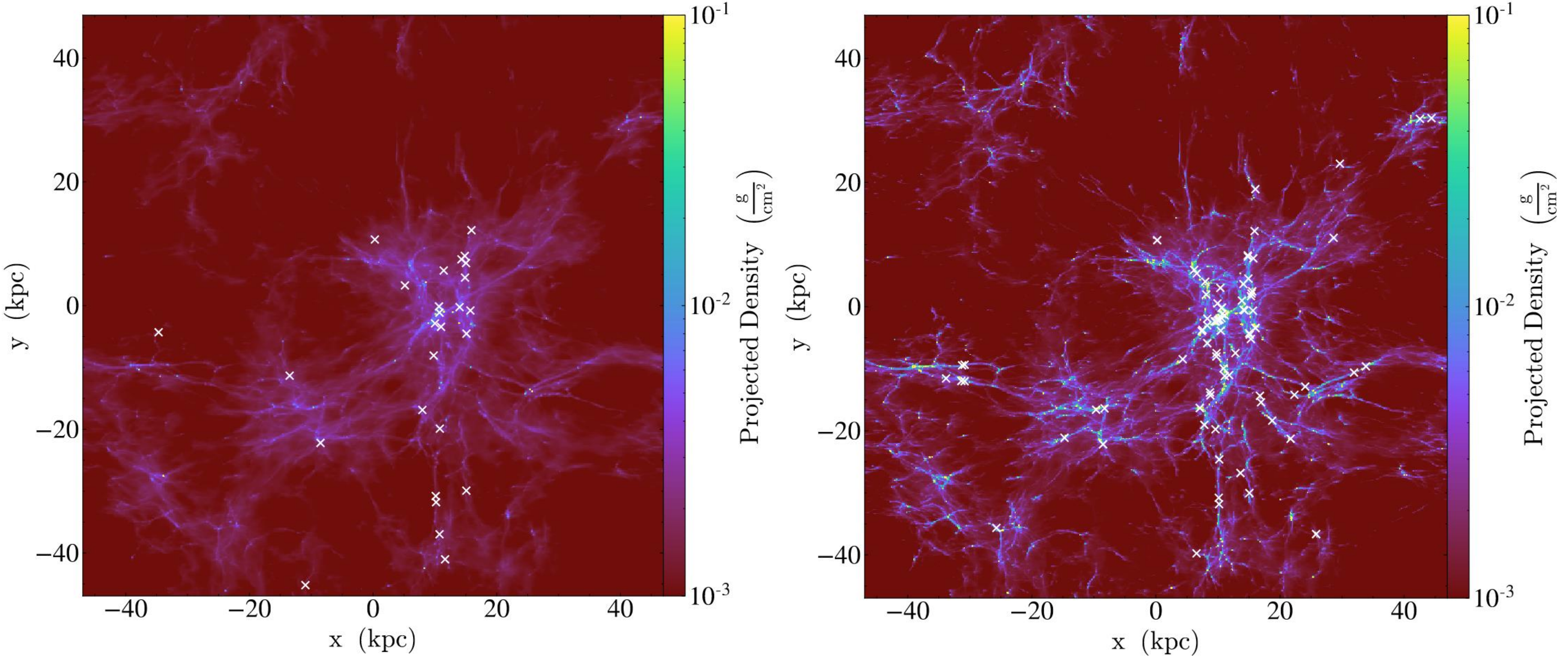
- Some SIGOs form stars without dark matter, potentially permitting detection

- This is not a given, the SIGO must be massive enough to collapse

- Detection of SIGOs at early times may provide constraints on theories that include a reduced stream velocity

Questions?

Molecular Hydrogen Cooling



Without molecular hydrogen cooling

With molecular hydrogen cooling

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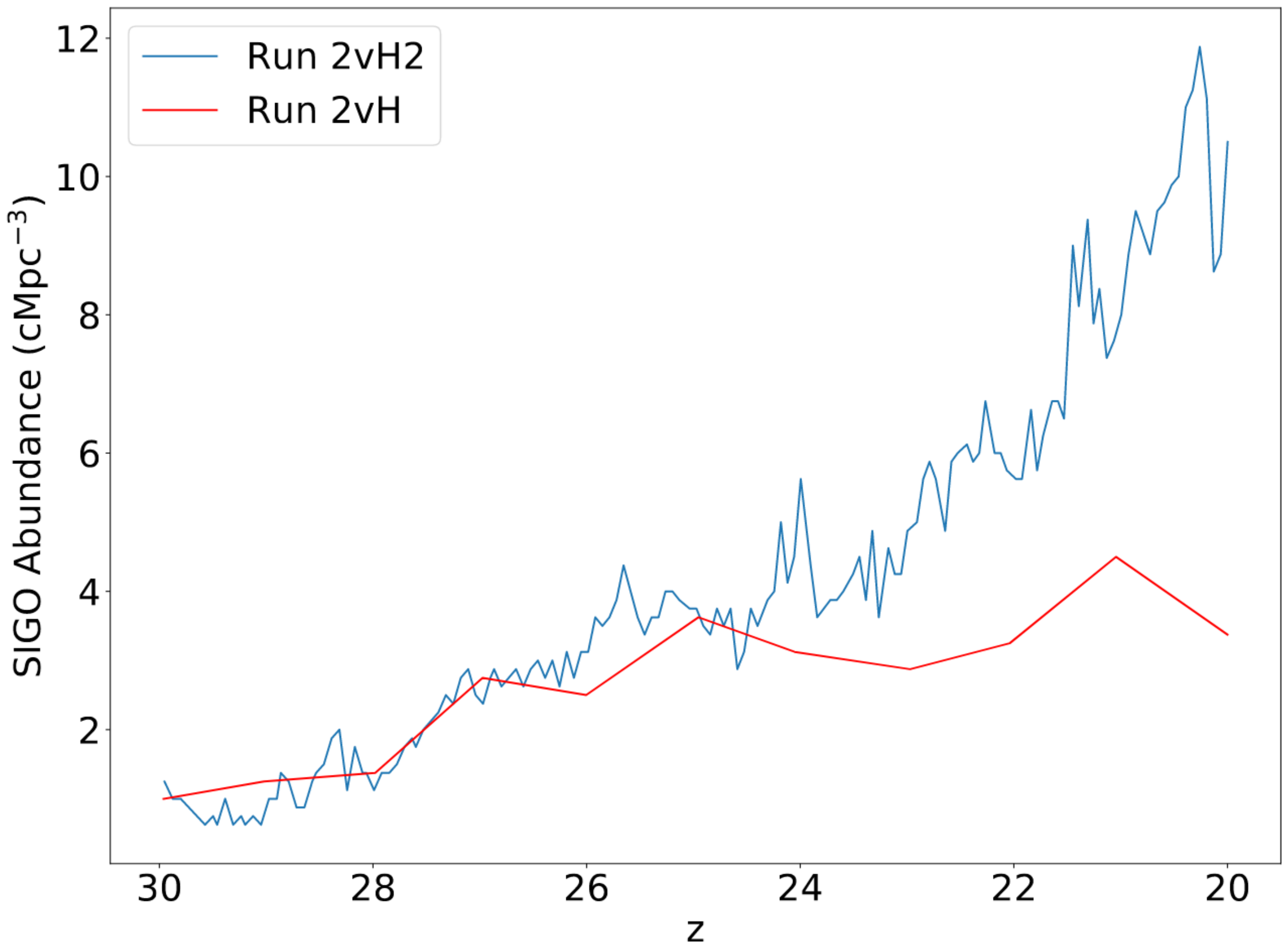
(**Lake** et al. 2022)



The abundance of SIGOs over time with and without molecular hydrogen cooling. **Lake** et al. (2022)

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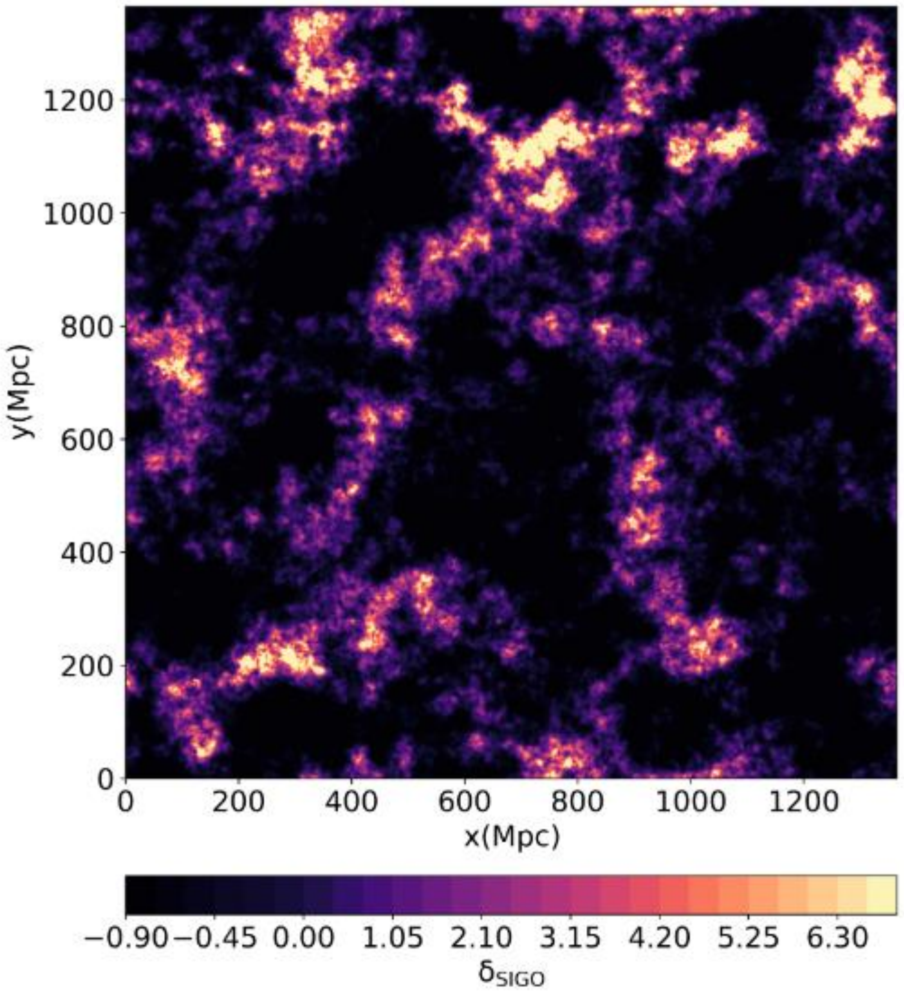
The Abundance of SIGOs Varies Spatially



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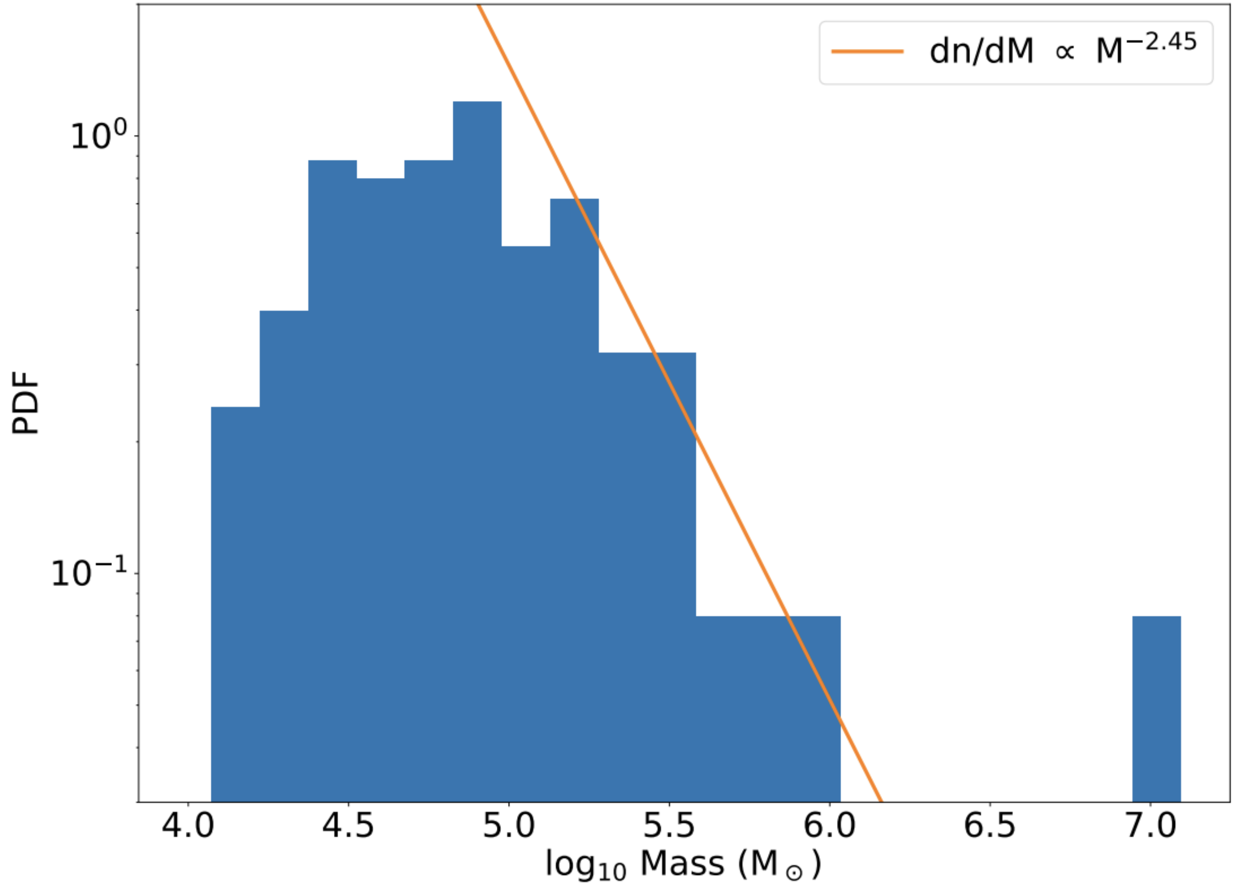
The spatial variation in SIGO abundances. **Lake** et al. (2021)

SIGOs Follow a Power-Law Mass Function

- SIGOs follow a power-law mass distribution in simulations
- This mass distribution resembles the empirically determined mass distributions of GMCs (spectral index of -2.1 in the outer Milky Way, -2.9 in M33)

Rosolowsky 2005, **Lake** et al. 2022



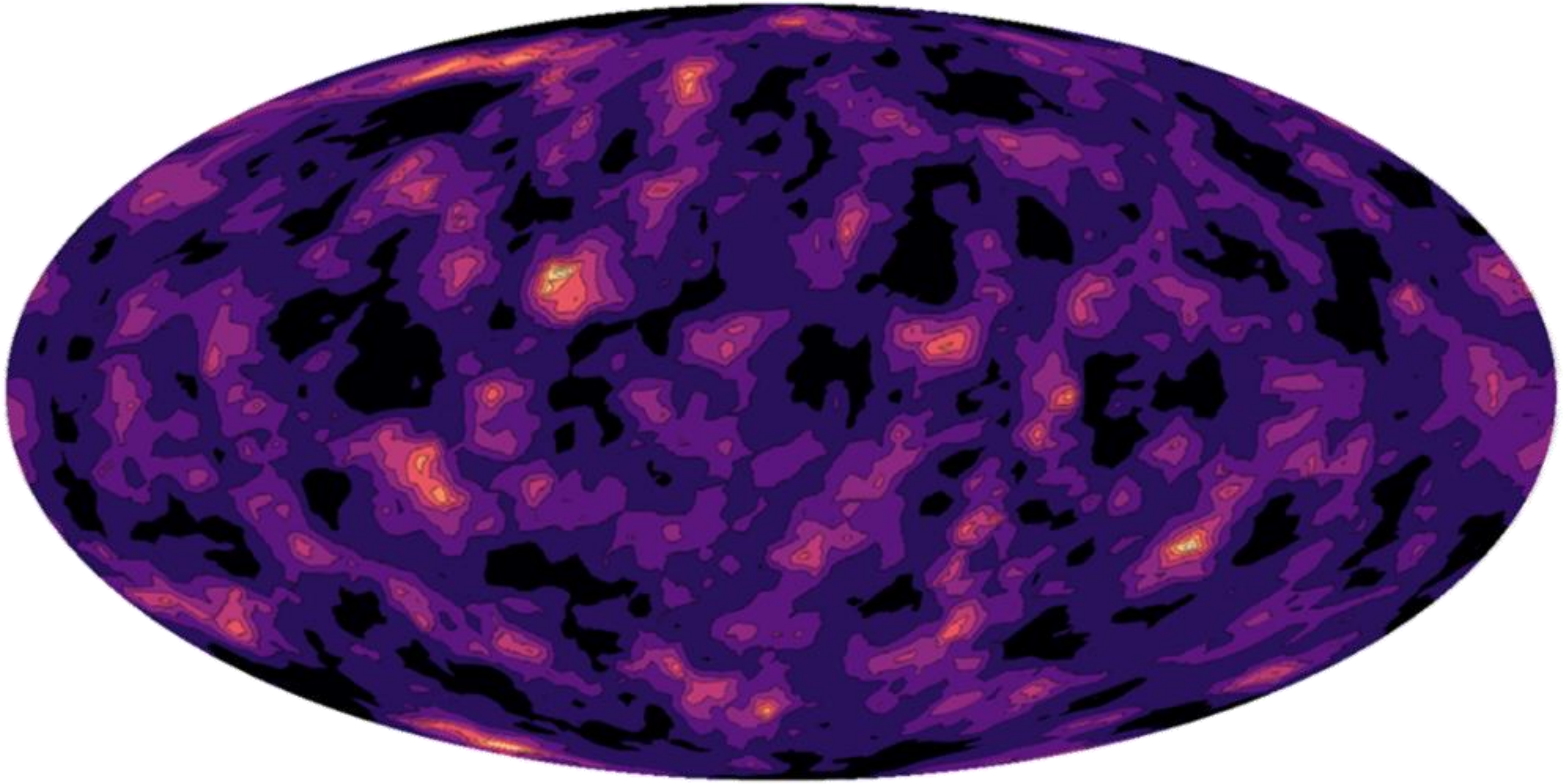
The mass spectrum of SIGOs follows a power-law PDF with spectral index -2.45. **Lake** et al. (2022).

The Sonic Scale

- Scale at which 1d velocity dispersions are Mach 1

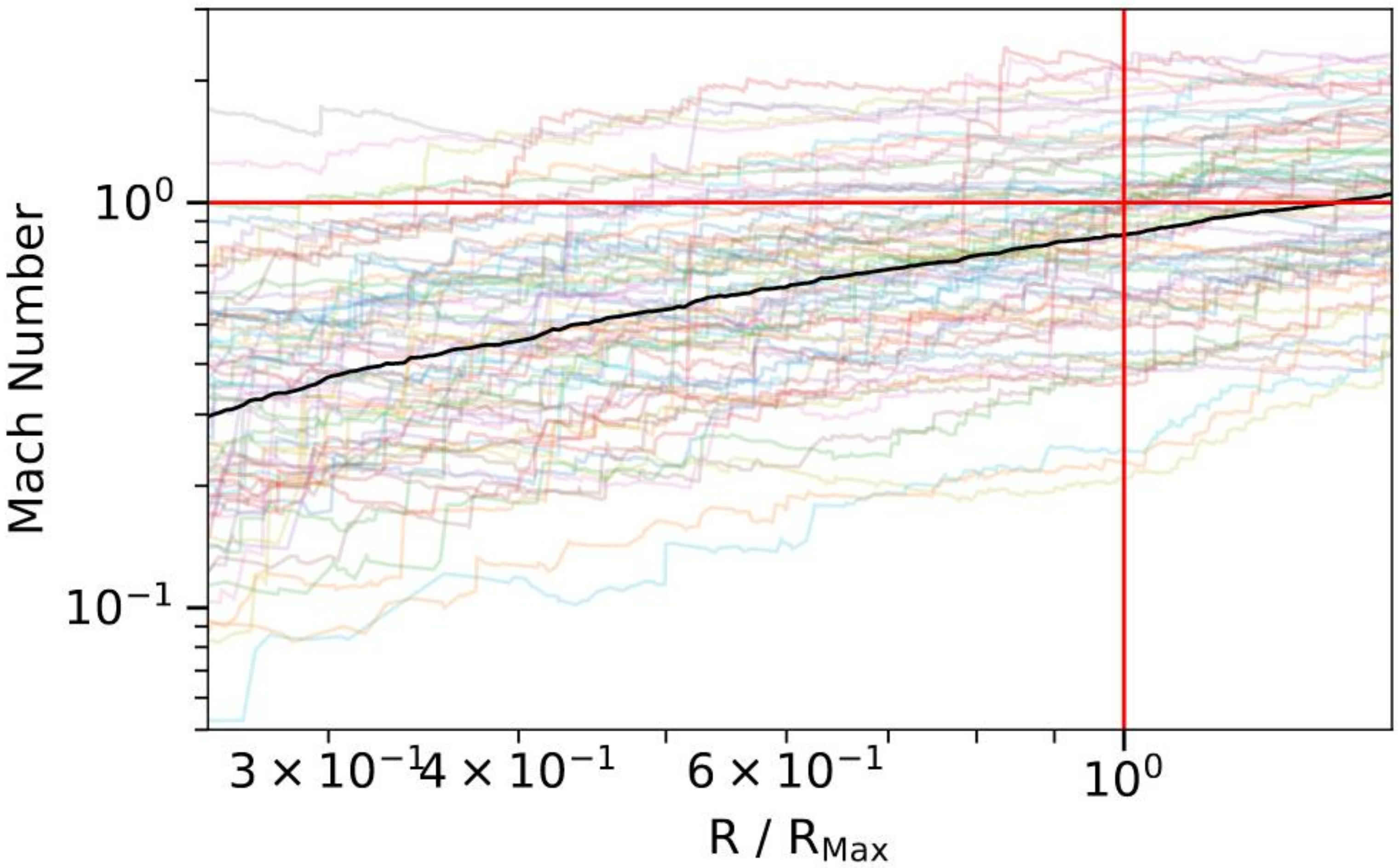
- $\lambda_S = \frac{\mathrm{L_{drive}}}{\mathcal{M}^2}$

The Gravitational Wave Background at High z could Vary Spatially with the Stream Velocity



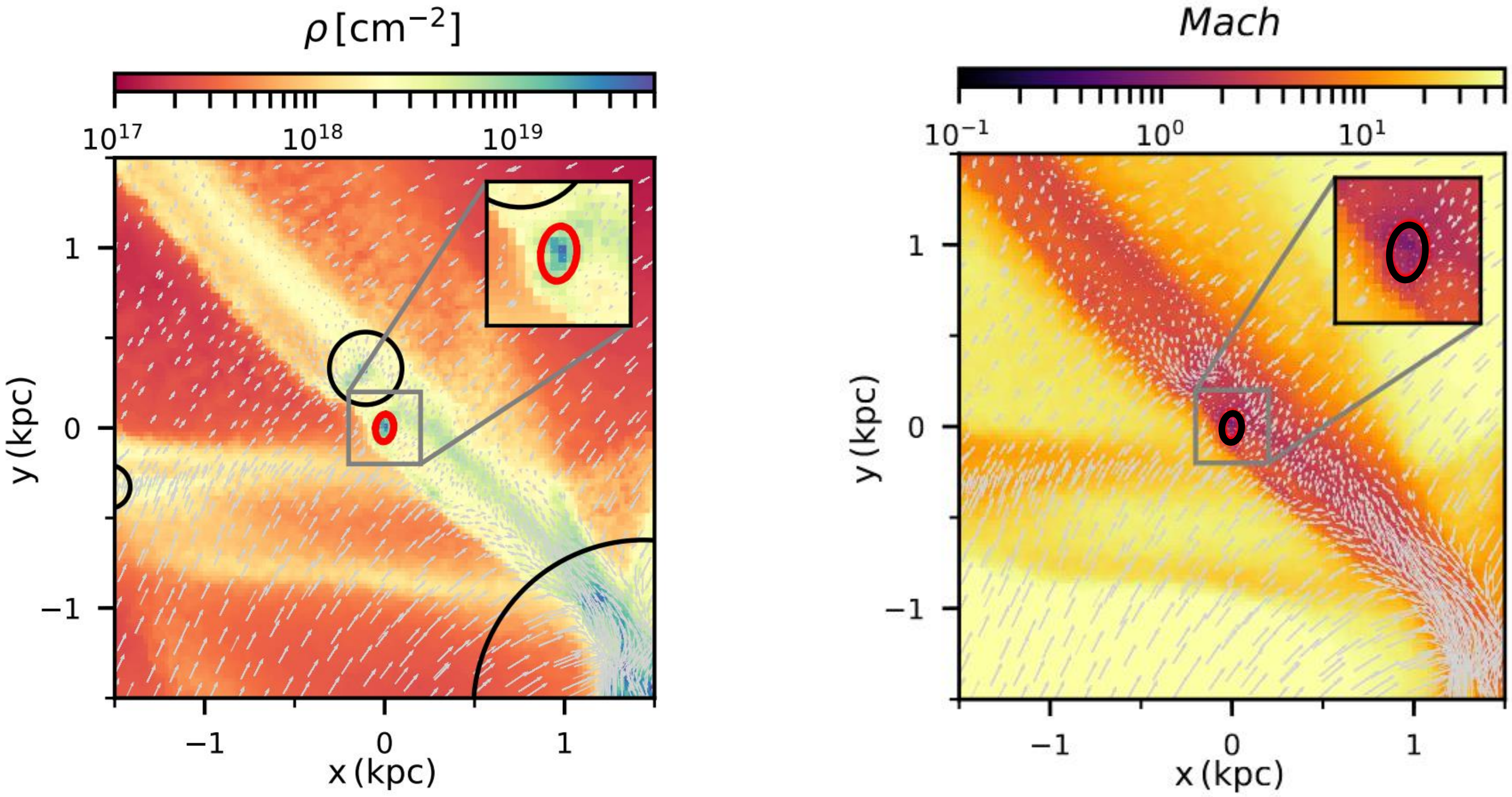
Map of integrated SIGO abundances. **Lake** et al. (2021)

The Turbulent Energy Inside SIGOs



The Mach number dispersion within SIGOs. **Lake** et al. (2022).

SIGOs Form in a Turbulent Environment



The Mach number dispersion of a SIGO and its environment.
Lake et al (2022).