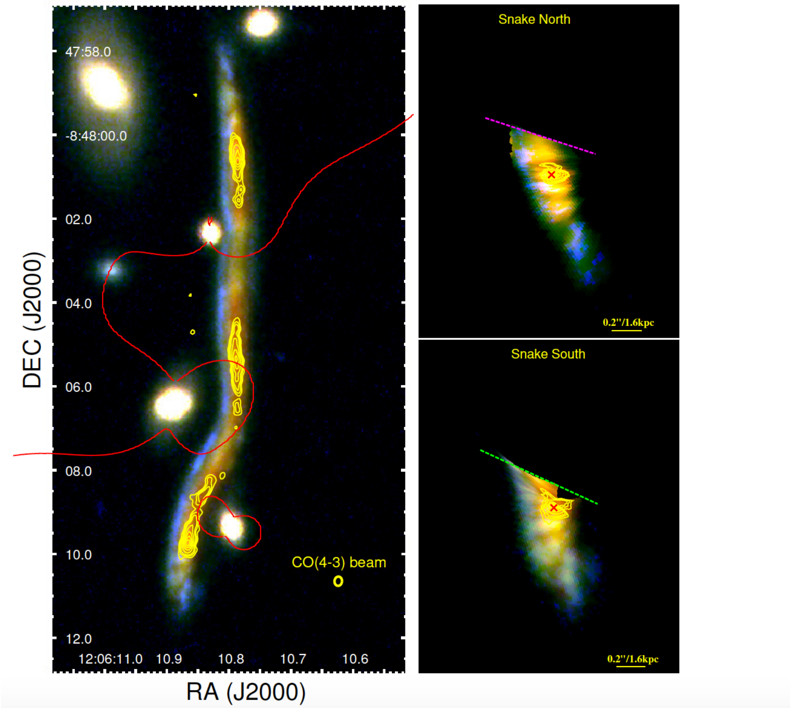
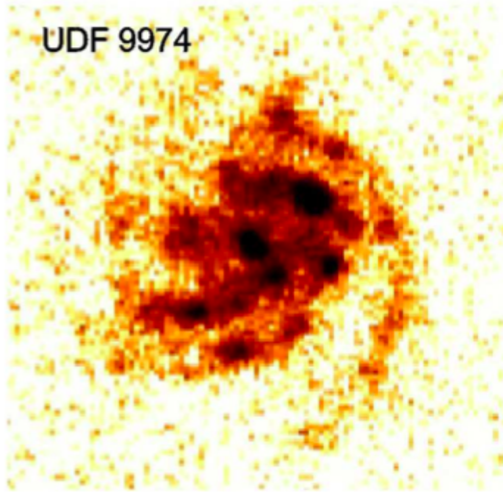
# Fragmenting galactic disk simulations with SPH-EXA

Noah Kubli




**Dessauges-Zavadsky et al. 2018**




**Elmegreen et al. 2007**

# Theory of disk instability

**Toomre dispersion relation:**

$$\omega^2 = \kappa^2 - 2\pi G\Sigma_0|k| + c_s^2k^2$$

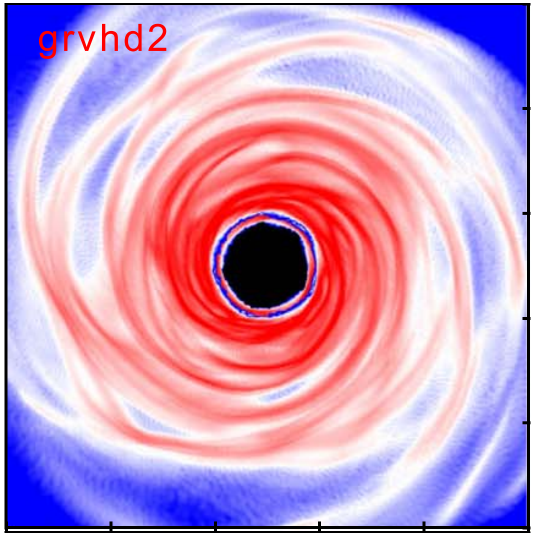
Criterion for instability:

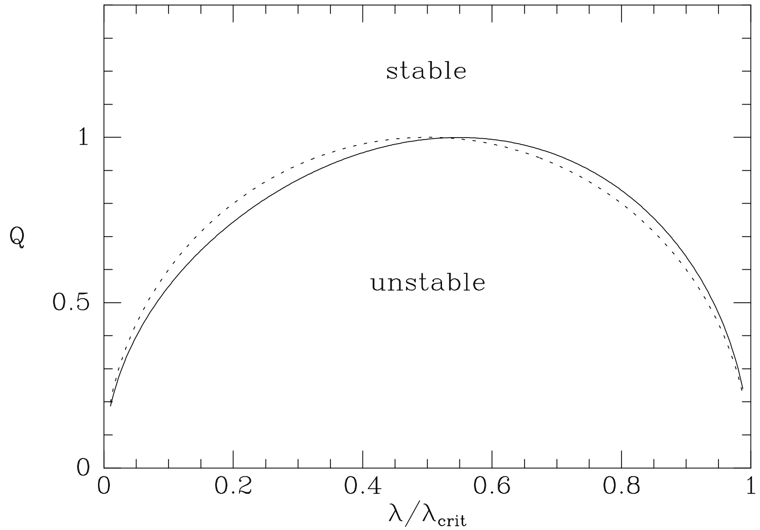
$$Q = \frac{c_s\kappa}{G\pi\Sigma} < 1$$

Most unstable wavenumber:

$$k_{mu} := \frac{\pi G\Sigma}{c_s^2} \underbrace{=}_{Q=1} \frac{\kappa^2}{\pi G\Sigma}$$

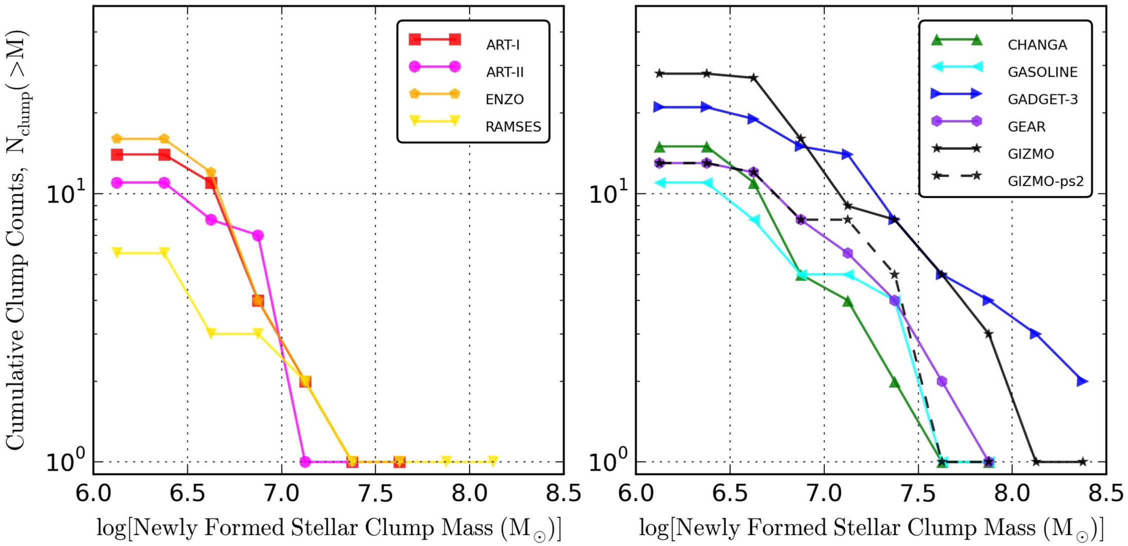
Emergence of a spiral structure in a gravitationally unstable protoplanetary disk (Deng et al. 2020)



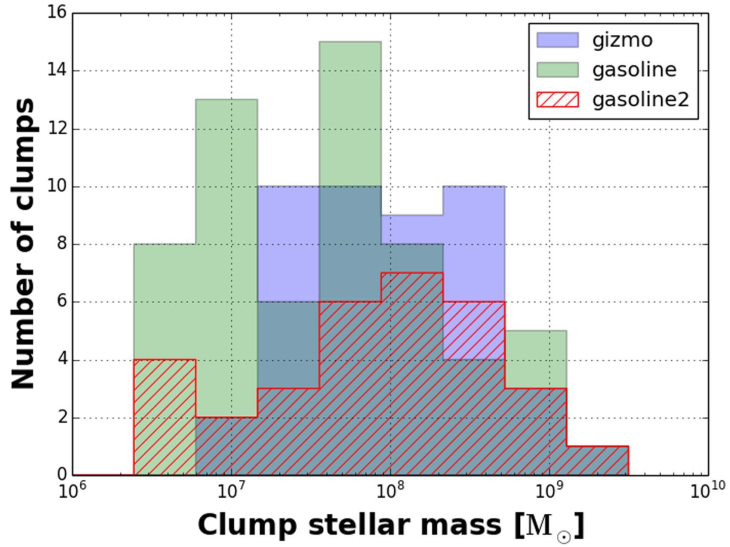




**Binney and Tremaine 2008**

# Clumps in galactic simulations



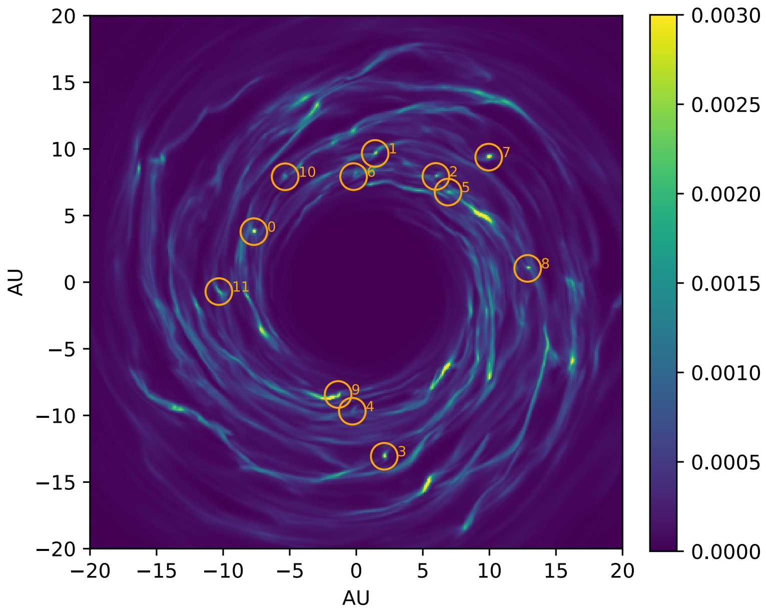

Stellar clump mass distribution from AGORA project (Kim et al. 2016) for 20% gas fraction (z < 1)



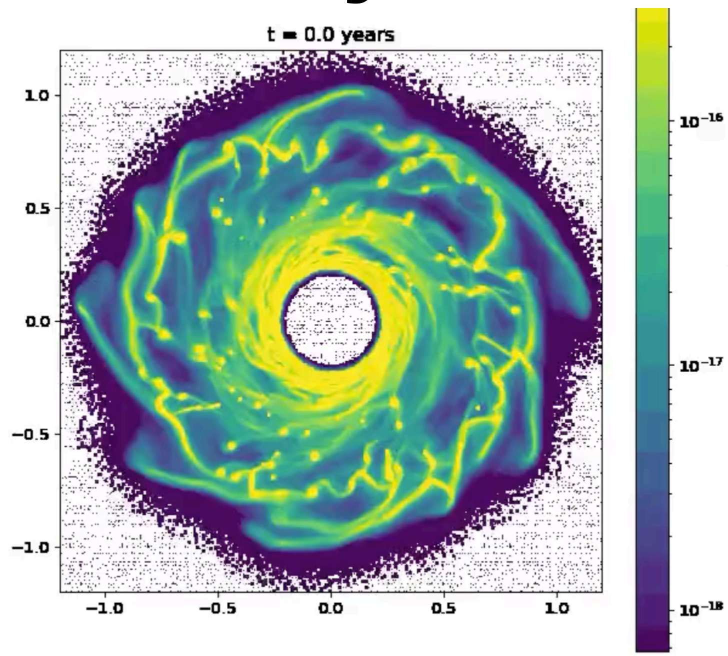

Stellar clump mass distribution in Mayer et al. 2016 for a massive gas disk (50% gas fraction), as observable at z~2-3.

- Mass distribution has not converged between codes
- Low-mass end of the distribution truncated by resolution
- Gas clumps determine mass range of stellar clusters

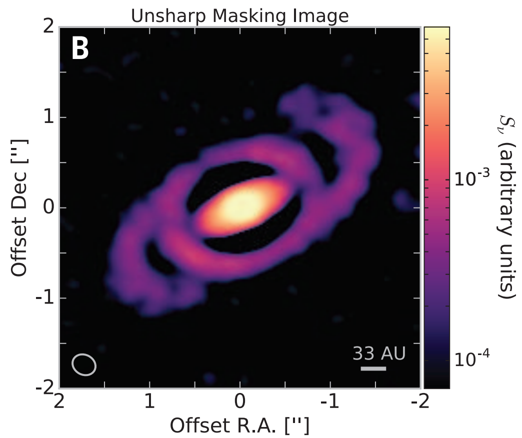
# Disk instability in different systems




Formation of protoplanets in a magnetized, gravitationally unstable disk (simulations by Deng et al. 2021)

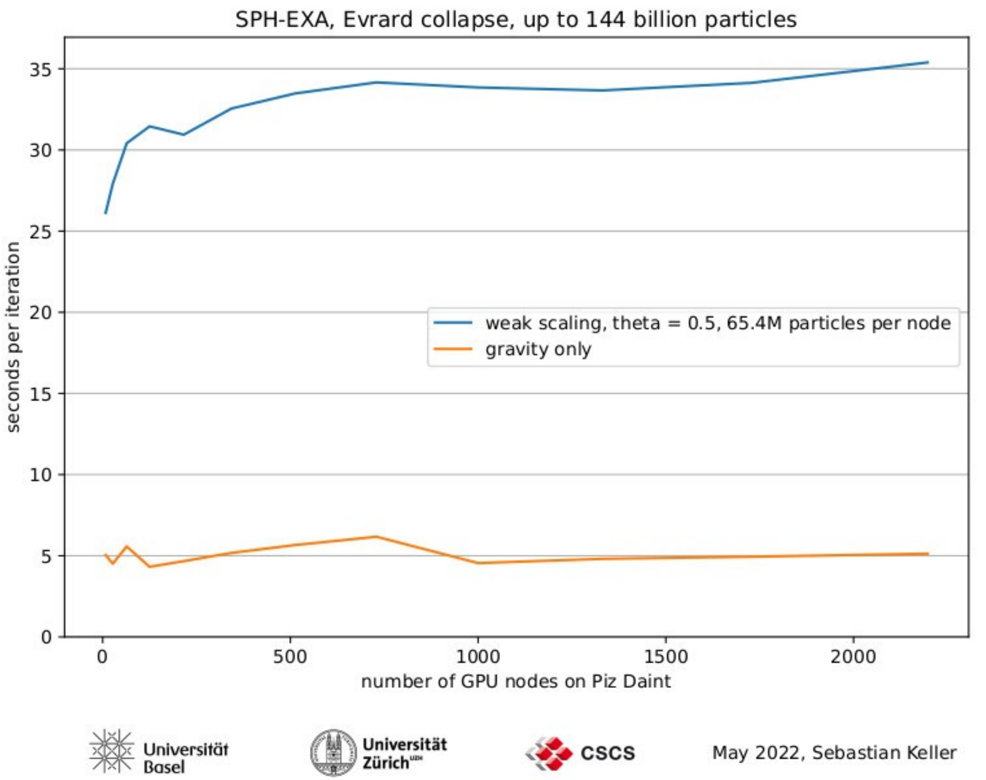


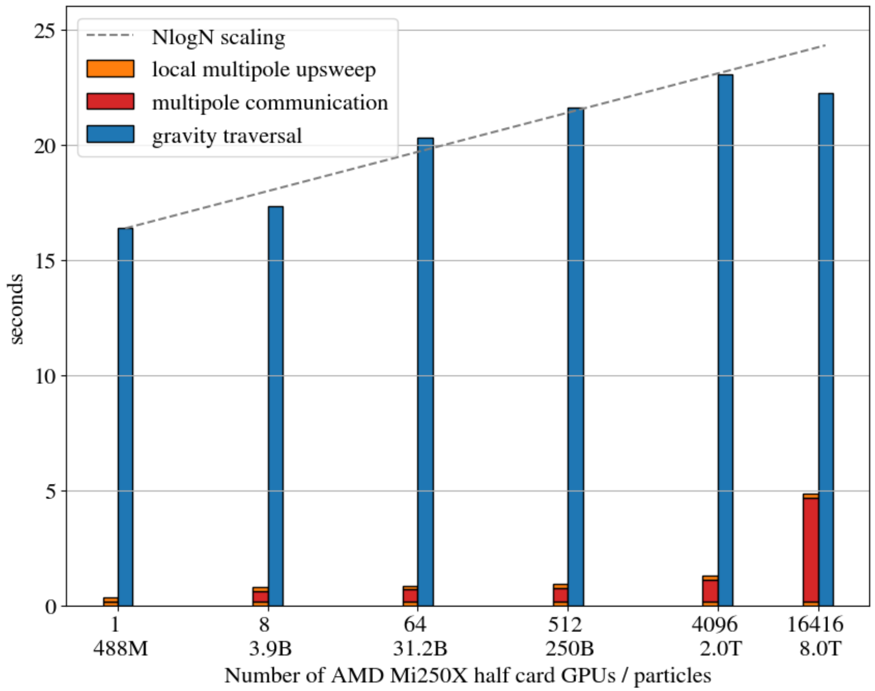

Fragmenting AGN disk, forming massive stars (Pacuraru et al. 2022)




Elias 2-27, first observed gravitationally unstable protoplanetary disk (Pérez et al. 2016)

# SPH-EXA

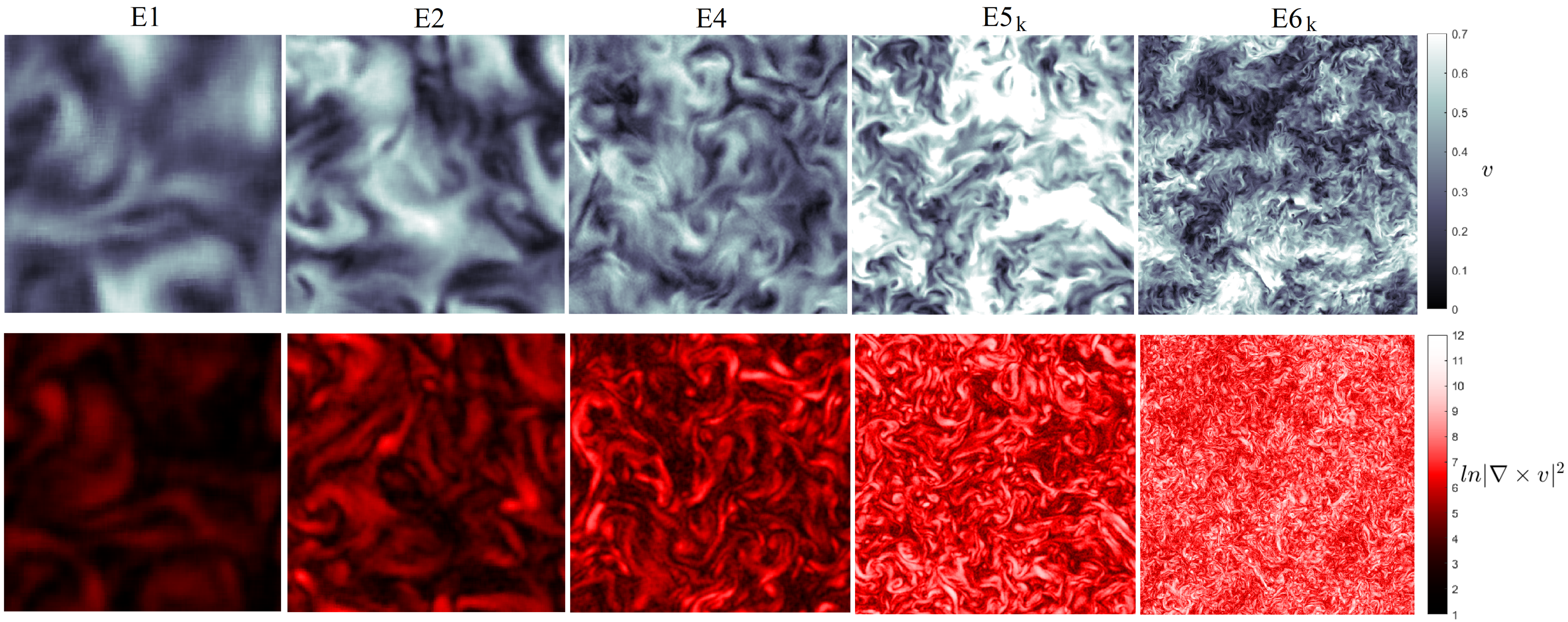



Weak scaling of SPH-EXA. Left: Evrard collapse, right: gravity-only (N-body) test up to 8 T particles

**Credits to S. Keller**

# SPH-EXA




Turbulent box simulations at various resolutions with SPH-EXA.
From left to right: N = $50^3$, $100^3$, $200^3$, $400^3$, $1000^3$

**Sanz et al. 2022**

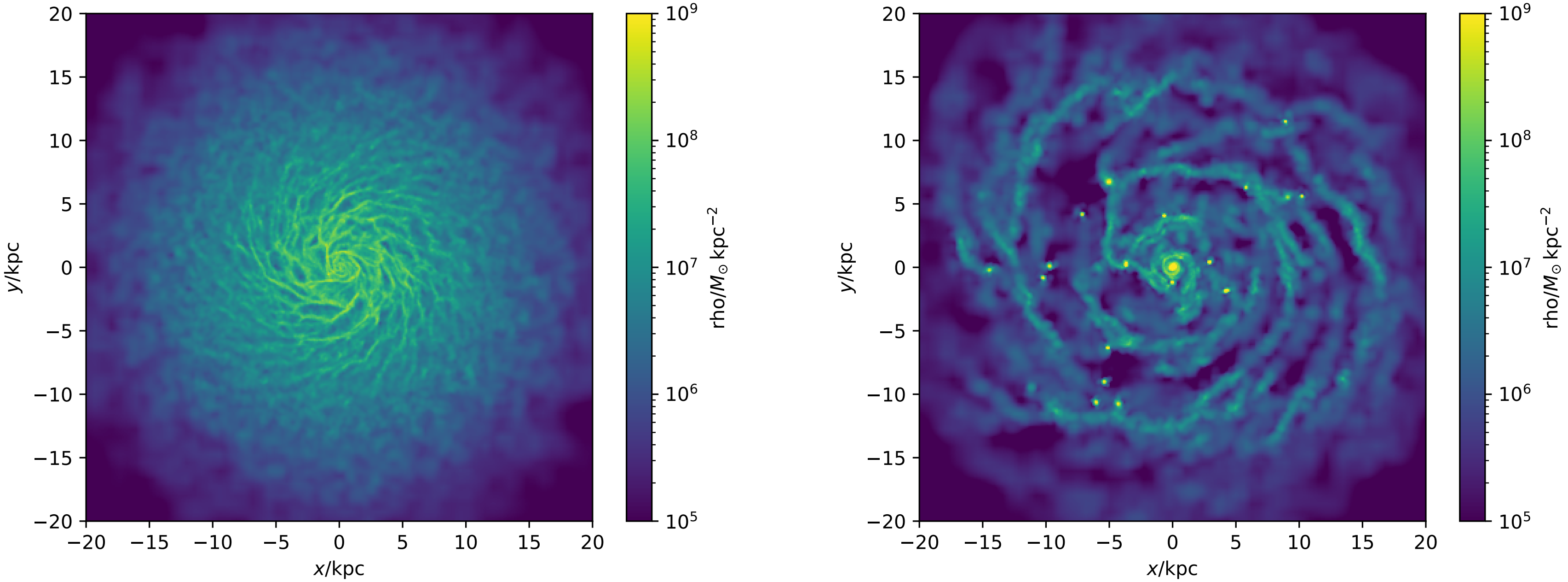
# SPH-EXA

- Excellent scalability demonstrated for hydro and gravity
- GRACKLE[1] chemistry and cooling library included
- Use SPH-EXA for simulations at much higher resolution and to probe the low-mass end of the clump distribution

[1]Smith et al. 2017

# Simulation setup

- Use initial conditions from AGORA code comparison project
- Preliminary low-res and med-res runs ($10^5$ and $10^6$ particles) with ChaNGa and SPH-EXA
- Cross-validation of GRACKLE implementation (GRACKLE is default for AGORA)
- Then high-res ($10^8$) runs with SPH-EXA and benefit from efficient scaling:
  This would allow to resolve even the low-mass clouds down to $10^3$ $M_{sun}$
- Goal: develop general predictions for SKA observation by resolving the full mass-spectrum of clouds




Galactic disk simulation using ChaNGa with Grackle cooling (no metals).
left: after 50 Myr, right: after 500 Myr; showing full gas density distribution

# Subgrid models: star formation and feedback (to be implemented in SPH-EXA)

- Star formation (Stinson et al. 2006): $$p = \frac{m_{\rm gas}}{m_{\rm star}}(1 - e^{-c^{\star}\Delta t/t_{\rm form}})$$
- SN feedback (Stinson et al. 2006): Cooling shut-off leads to blastwave
- Results depend on choice of subgrid model (see plots below)

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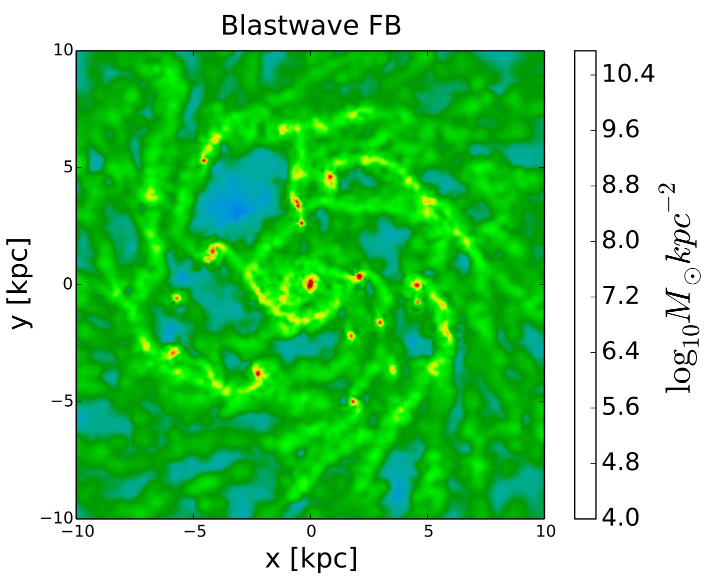
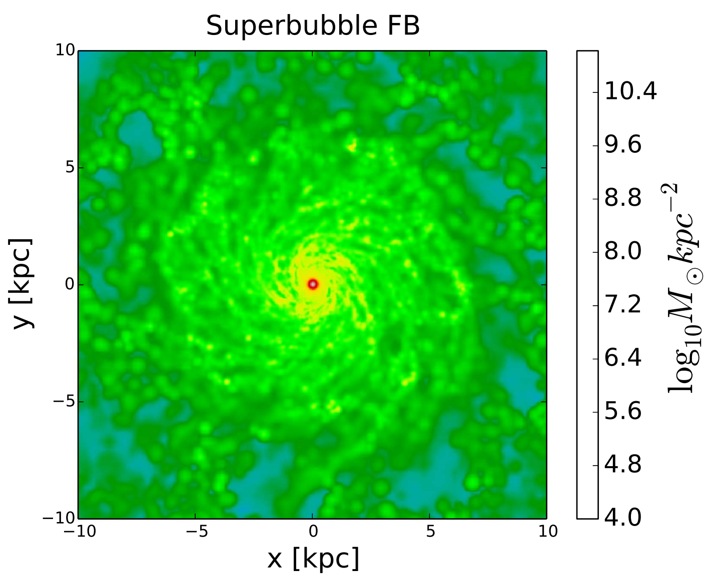
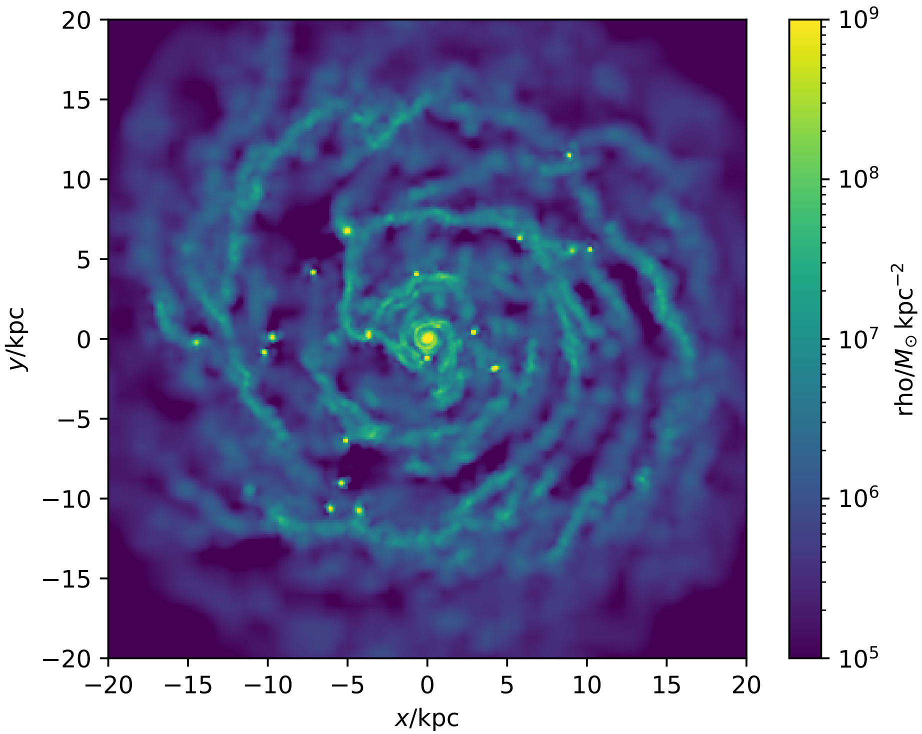


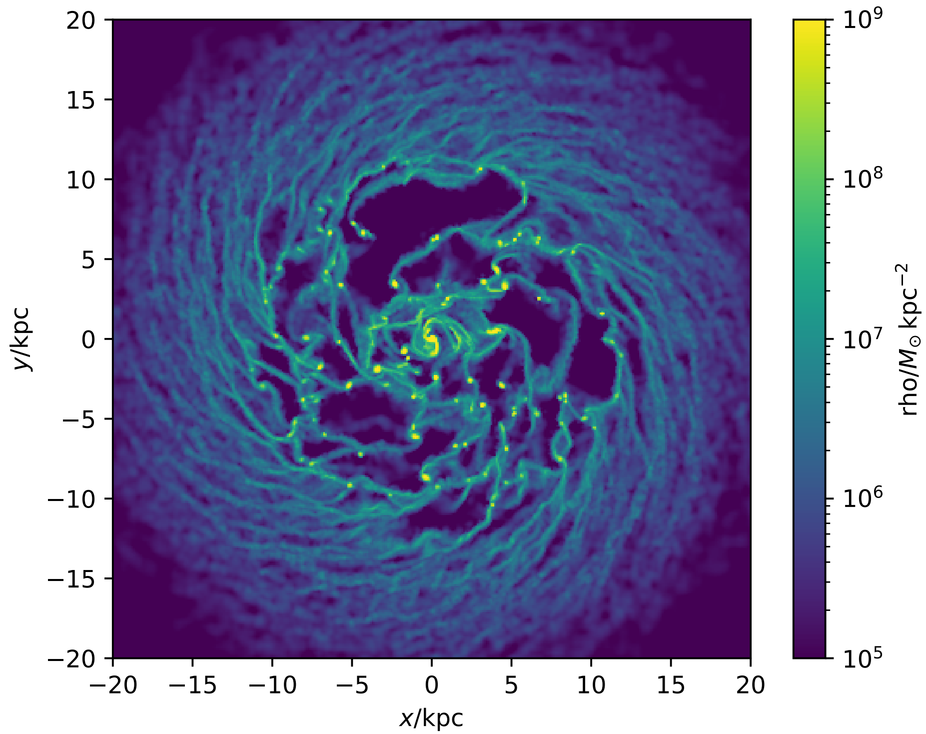

Fragmenting galactic disk simulations using Blastwave feedback (left) vs. Superbubble (right) (Mayer et al. 2016)

# Physics to be implemented in SPH-EXA

- Star formation and SN feedback
- Ewald summation for cosmological runs
- Thermal and metal diffusion
- Stellar feedback and newer, advanced models of star formation and SN feedback
- Black holes




**10⁵ particles**




**$10^6$ particles**