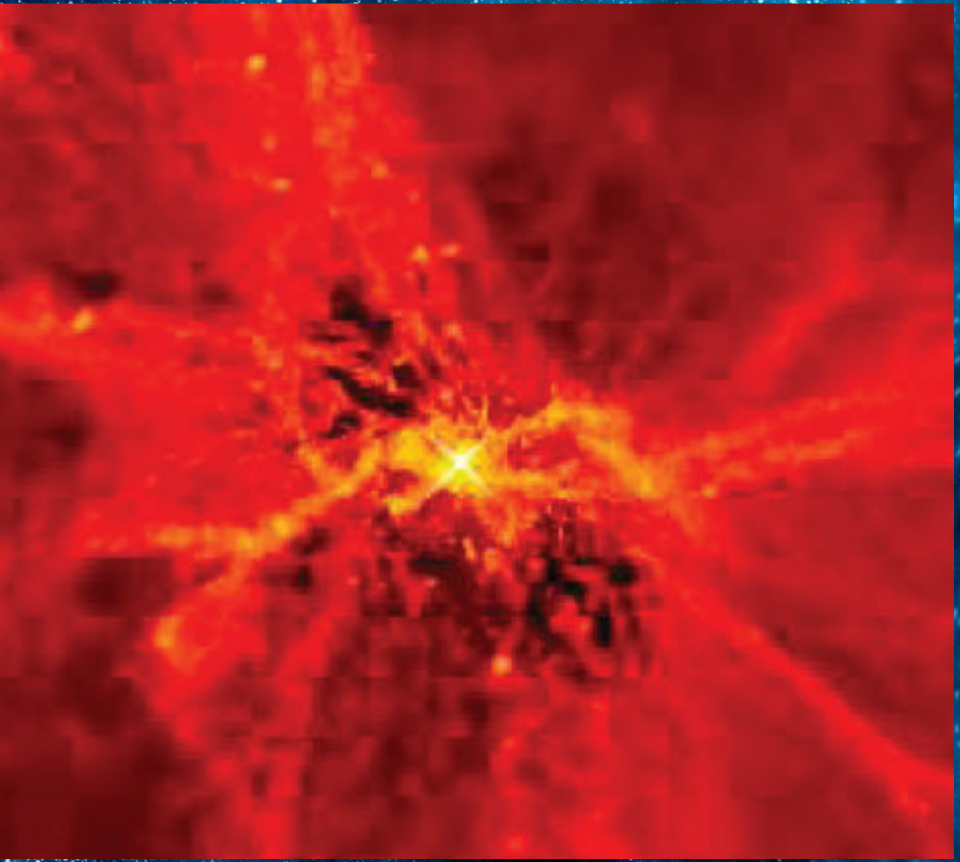
The tale of angular momentum transport in primordial galaxies and the formation of massive BH seeds



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The puzzle of high-z Quasars

Bright Quasars ($L > 10^{47}$ erg/s) < 700 million years after Big Bang ($z > 6$)

$M_{BH} > 10^9$ Mo (see X. Fan's talk - Mortlock et al. 2011; Banados et al. 2016; 2019)

PROBLEM: is there enough time to grow these early SMBHs?

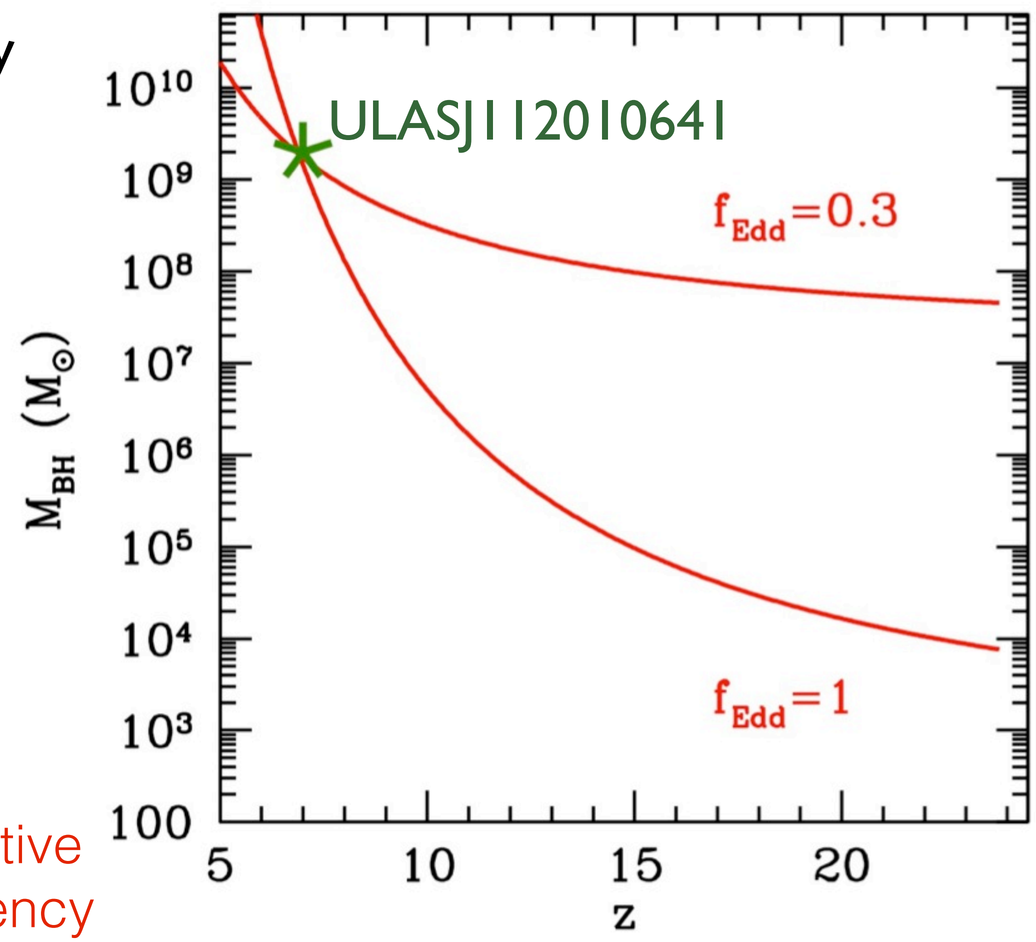
$$\dot{M}_{\rm Edd} = \frac{4\pi G M_\bullet}{\eta \kappa c}$$

Eddington rate: maximum (spherical) accretion rate set by balance between gravity and pressure force of radiation

"Growth equation"

$$M_\bullet(t) = M_\bullet(t_0) e^{(t-t_0)/\tau_{\rm Salp}}$$

$$\tau_{\rm Salp} \approx 4.4 \times 10^7 \left(\frac{f_{\rm Edd}}{1}\right)^{-1} \ {\rm yr}$$ x ($\eta/0.1$) radiative efficiency



(Courtesy of Marta Volonteri)

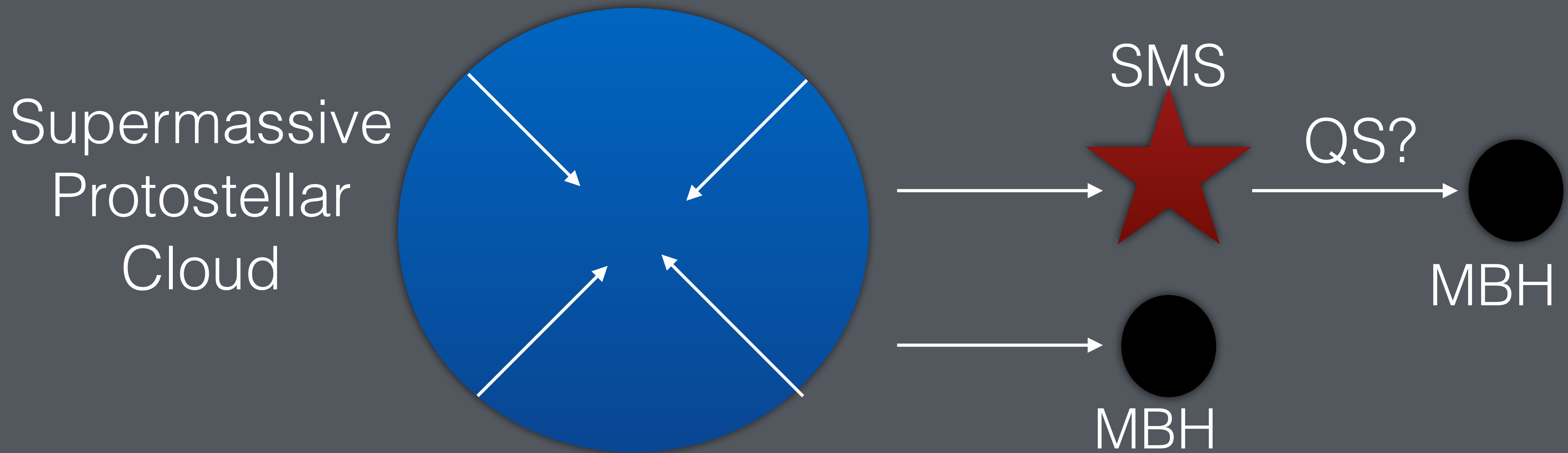
High-z QSO rare (~10^{-8} h^3 Mpc^{-3}), 4 orders of magnitude less abundant than their z=0 counterparts. Abundance and clustering suggest their hosts rare massive halos (M_{halo} >~ 10^{12} Mo — see Volonteri & Rees 2006; Sijacki et al. 2010)

High-z QSOs hardly from Eddington-limited accretion of Pop III BH seeds as seed mass should be >~ 10^4 Mo

Alternative scenarios:

(1) Direct gas collapse into black hole seeds (10^4-10^5 Mo)

(eg Begelman et al. 2006; Lodato & Natarajan 2006; Begelman 2010; Mayer et al. 2010; Latif et al. 2014;2015; Regan & Haenhelt. 2009; 2015; Mayer & Bonoli 2019; Woods et al. 2019; Wyse et al. 2019)



Formation of massive BH from collapse of massive gas cloud, with a prior stage as a supermassive star (SMS) and/or quasi-star (Begelman 2010), or even directly into a BH via GR radial instability ("dark collapse" see Mayer & Bonoli 2019; Hammerle et al. 2019)

(2) Super-Eddington accretion onto Pop III seeds (eg Madau et al. 2014; Lupi et al (2016); Inayoshi et al. 2016; Regan et al. 2019, see review in Mayer 2018, 2018arXiv180706243M)

Regime: *radiatively inefficient accretion* in large optical depth medium (**τ >~ 10^3**) with highly viscous-driven accretion flow

t_{diff} >> $t_{advection}$

Prototypical model is SLIM disk by Sadowski et al. (2011;2013).

Low radiative efficiency (~ 0.1%, as opposed to >~10% in standard α-disk accretion), no energy loss via winds

More recent 3D MHD-RT accretion disk simulations by Jiang et al. (2015;2018) using VET method for RT show enhanced radiative losses in turbulent non-axisymmetric flow with **radiative efficiency of 1-5%, sustaining M_{dot} ~ 25-150 $M_{dot, edd.}$ (+winds)**

In both direct gas collapse and Super-Eddington accretion a **challenge is to supply the gas at sufficiently high rates to sub-nuclear scales (< 10^{-2} - 1 pc** — scales of supermassive protostellar cloud in direct collapse scenarios or the accretion disk in super-Eddington scenarios)

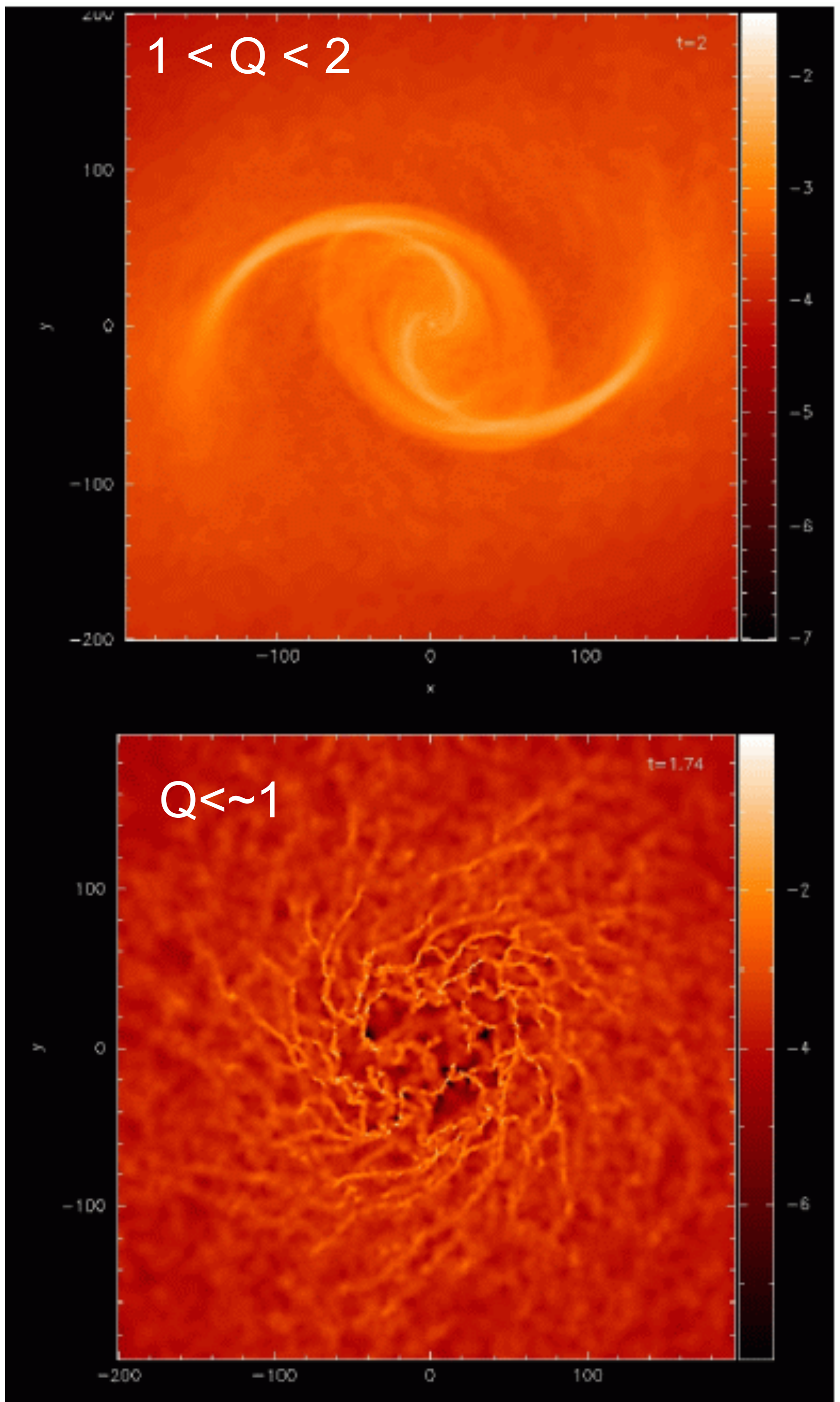
For example, for SMS formation (M* > 10^4 Mo) **M_{dot} > 0.1-1 Mo/yr** is required (Hosokawa et al. 2014; Woods et al. 2019).
For Super-Eddington accretion onto light Pop III BH seeds (<1000 Mo) (Madau & Rees 2000) smaller M_{dot} required at the beginning then larger as seed grows (Regan et al. 2019)
For dark collapse into a massive BH even larger **M_{dot} >~ 100 Mo/yr** is required (Hammerle, Meynet, Mayer et al. 2019).

Need to feed from gas reservoir in galactic-scale disk
Which angular momentum transport mechanism(s) can feed the sub-nuclear galactic region efficiently enough?

A GENERAL MECHANISM FOR ANGULAR MOMENTUM TRANSPORT: GRAVITATIONAL TORQUES

Toomre parameter $Q = \kappa c_s / \pi G \Sigma$

(balance centrifugal force, pressure and gravity)



THREE REGIMES

(a) Q <~ 1 locally unstable to collapse, fragmentation (eg star formation) on a dynamical timescale (t_{dyn})

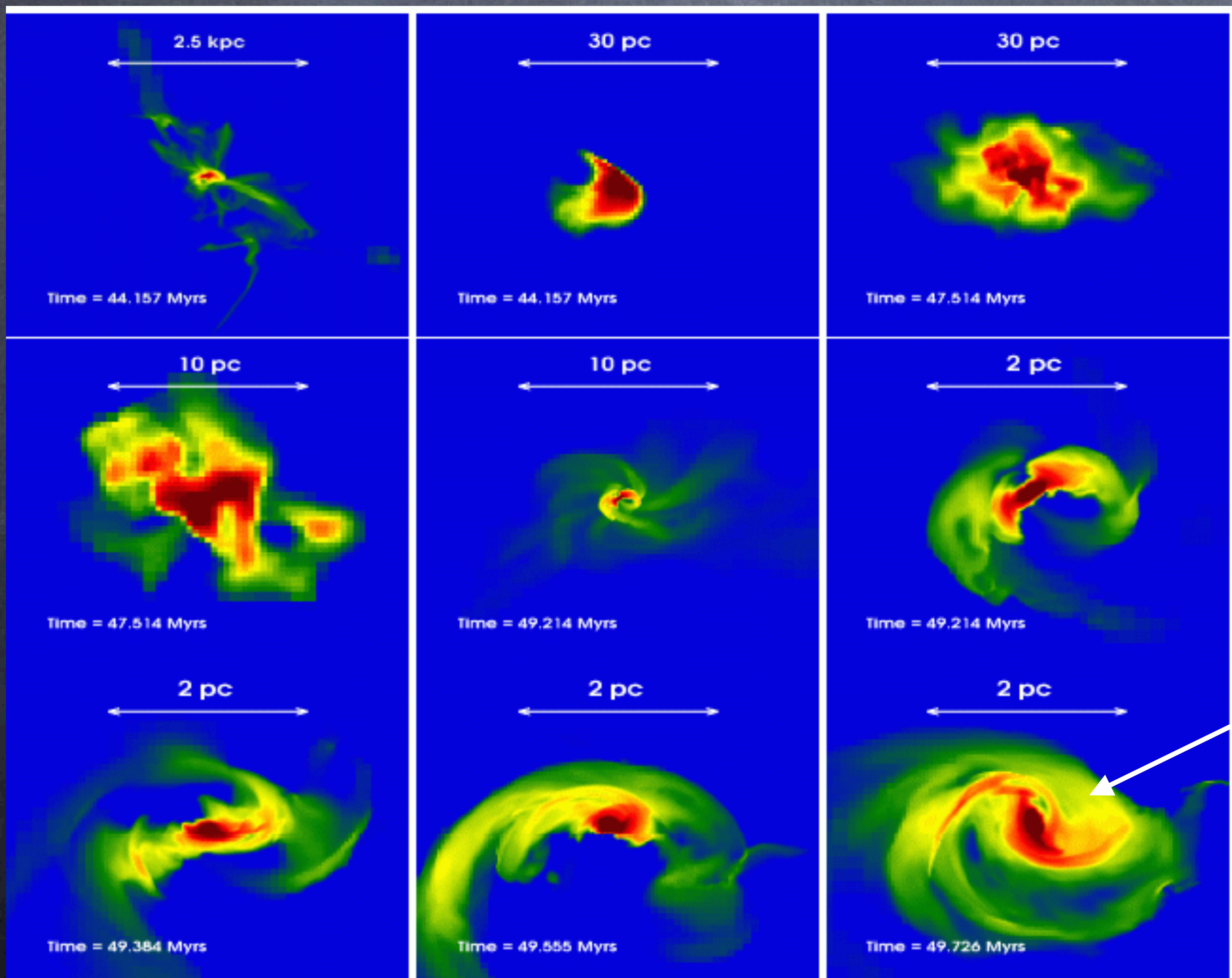
(b) 1 < Q < 2 locally stable, globally unstable to non-axisymmetric disturbances (spiral modes, bar-like modes)
Angular momentum transport (on ~ t_{orb} timescale) via spiral density waves (Lynden Bell & Pringle1979; Lin & Pringle 1987; Laughlin & Adams 2000)
Mass/angular momentum transport can be parametrized with (local) 'alpha disk" (effective "alpha" large <~ 0.1).
——> Nonlinear regime, hydro simulations needed

(c) Q > 2 locally and globally stable - dynamically uninteresting (remains close to axisymmetric)

1 < Q < 2 is the "useful" regime for sustained angular momentum transport

The cooling timescale controls in which Q regime the disk will settle.
IF $t_{cool} < t_{orb}$ —> Q < 1 —-> **fragmentation** (Gammie 2001;Rice et al. 2004; Deng et al. 2017)

How can one enforce $t_{cool} > t_{orb}$?
Conventional route: inefficient radiative cooling *by ansatz* — metal-free gas plus dissociation of H_2 byLyman-Werner ionising radiation field from nearby star forming galaxies—-> atomic cooling halos at z ~ 15-20 (eg Wyse et al. 2019)



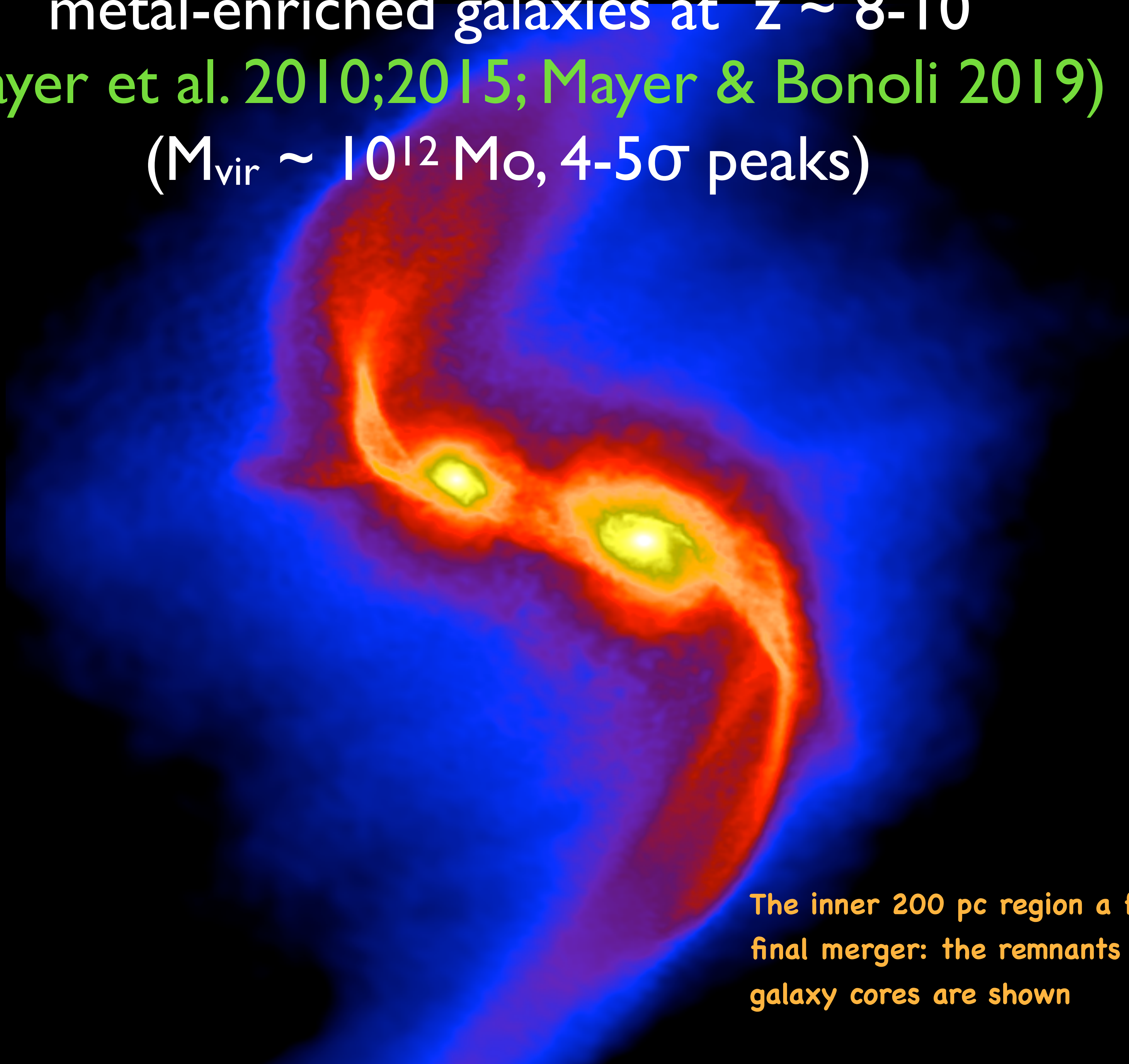
Example of protogalactic disk simulation in metal-free stomic cooling halo
Latif et al. (2013)

Jeans unstable clump (M >~ 10^4 Mo)
M_{dot} <~ 1 Mo/yr
Mclump >~ 10^{3-4} Mo
(still too small BH seed?)

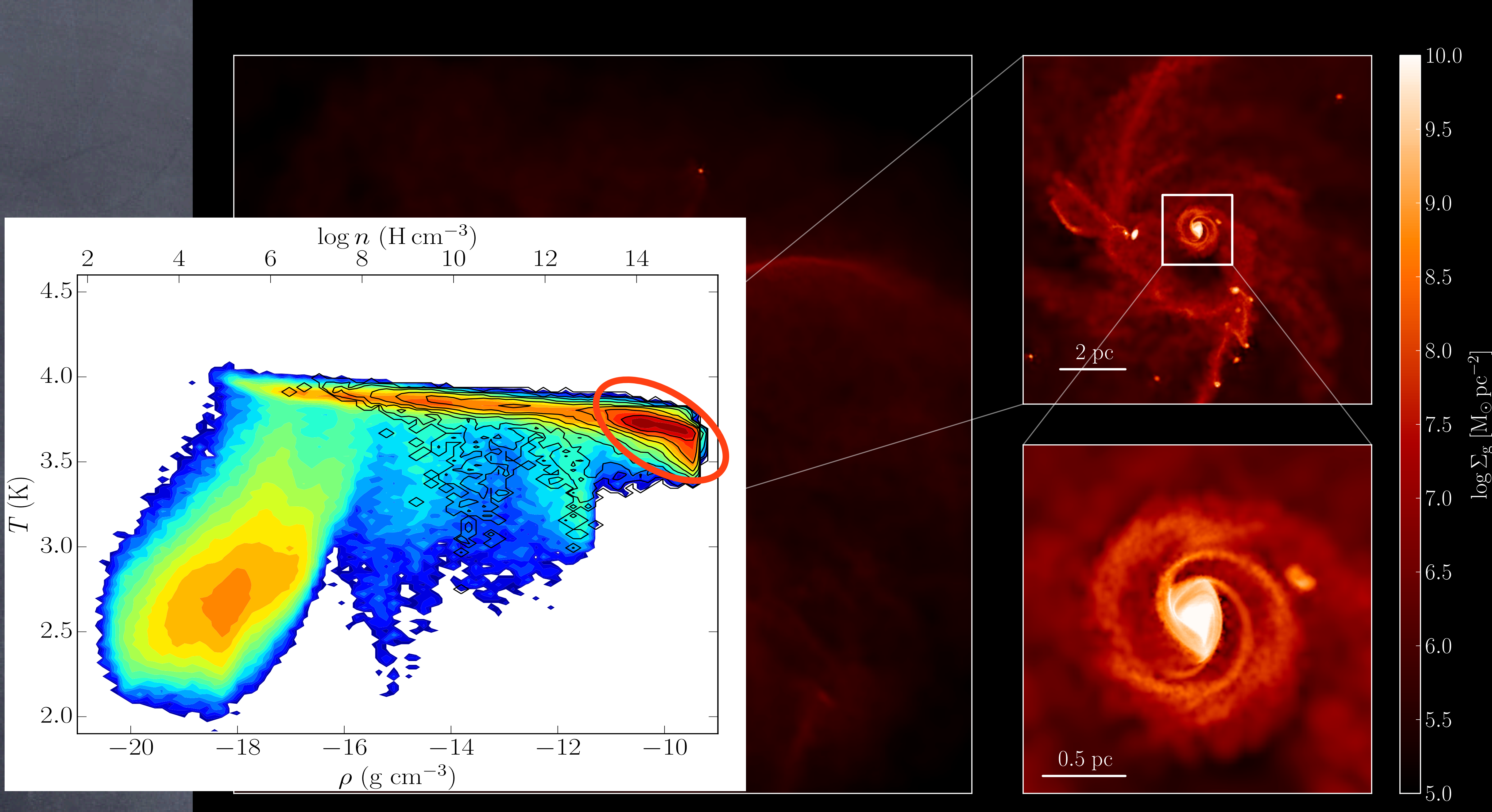
Alternative route direct collapse route: nuclear inflows in mergers of massive metal-enriched galaxies at $z \sim 8$-10

(Mayer et al. 2010;2015; Mayer & Bonoli 2019)

($M_{vir} \sim 10^{12}$ Mo, 4-5σ peaks)



The inner 200 pc region a few Myr before final merger: the remnants of the two galaxy cores are shown

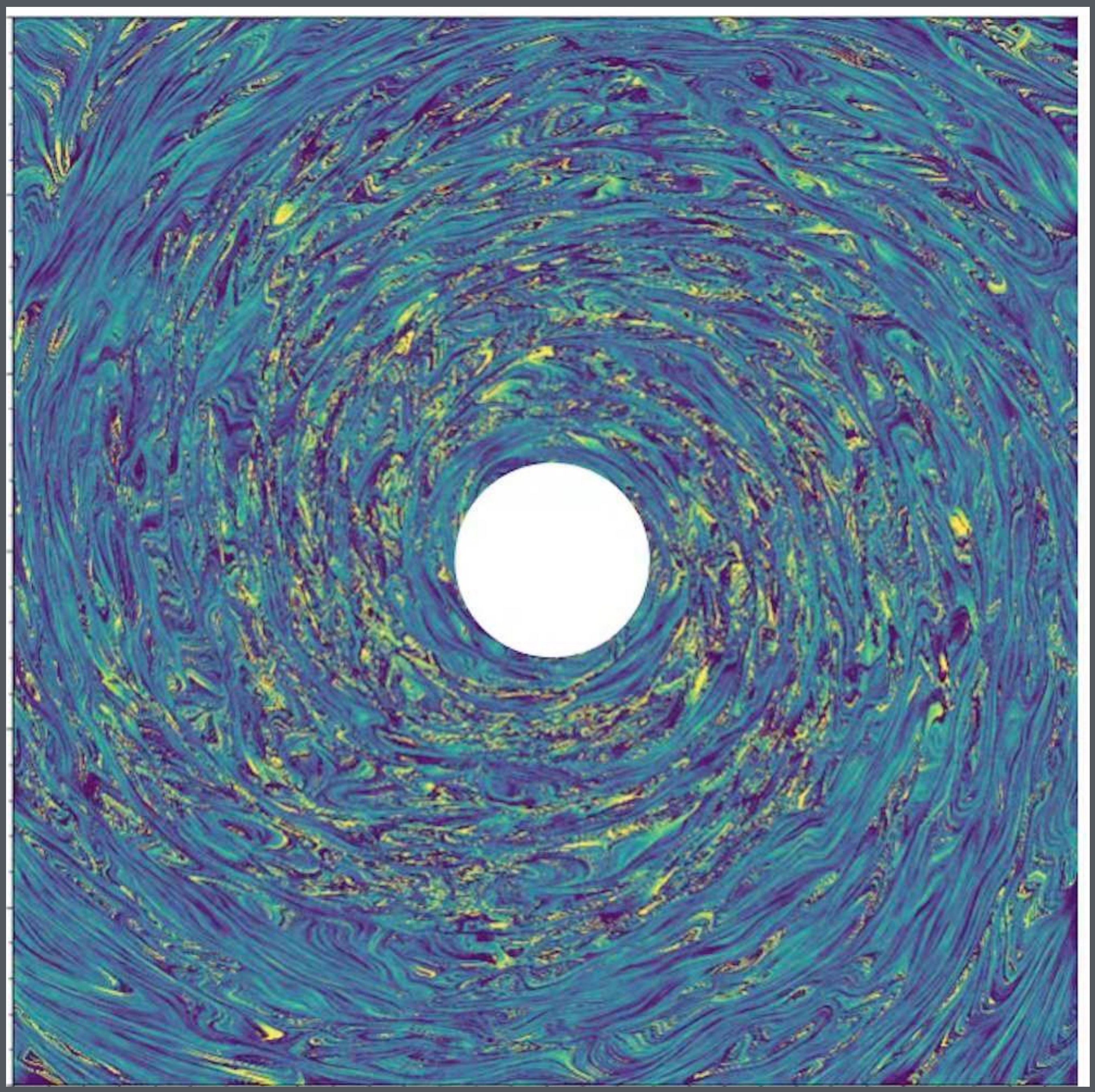


Parsec- scale dense nuclear disk forms which keeps accreting matter infalling supersonically (Mdot > 1000 Mo/yr).
Disk core is warm and stable to fragmentation due to dynamical heating by shocks in accretion flow and disk (Mayer et al. 2015)

>~10⁹ Mo inside ~2 pc in only ~ 10⁴ yr after galaxy merger
Any direct collapse pathway possible, including "dark collapse"
(Hammerle et al. 2019)

A novel regime: Magnetised Gravitoturbulent Nuclear Disk

Increased stability against fragmentation? New pathway for enhanced angular momentum transport?



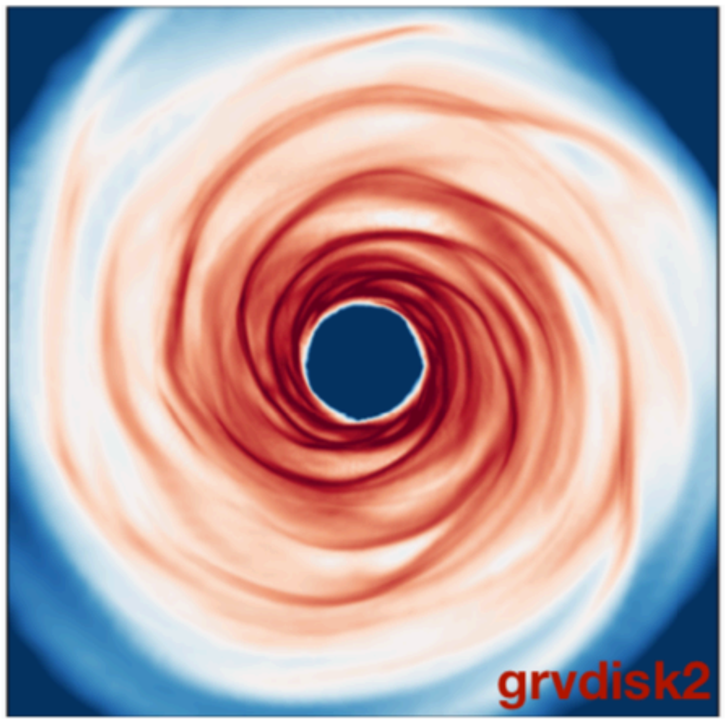
Test case: self-gravitating protoplanetary disk

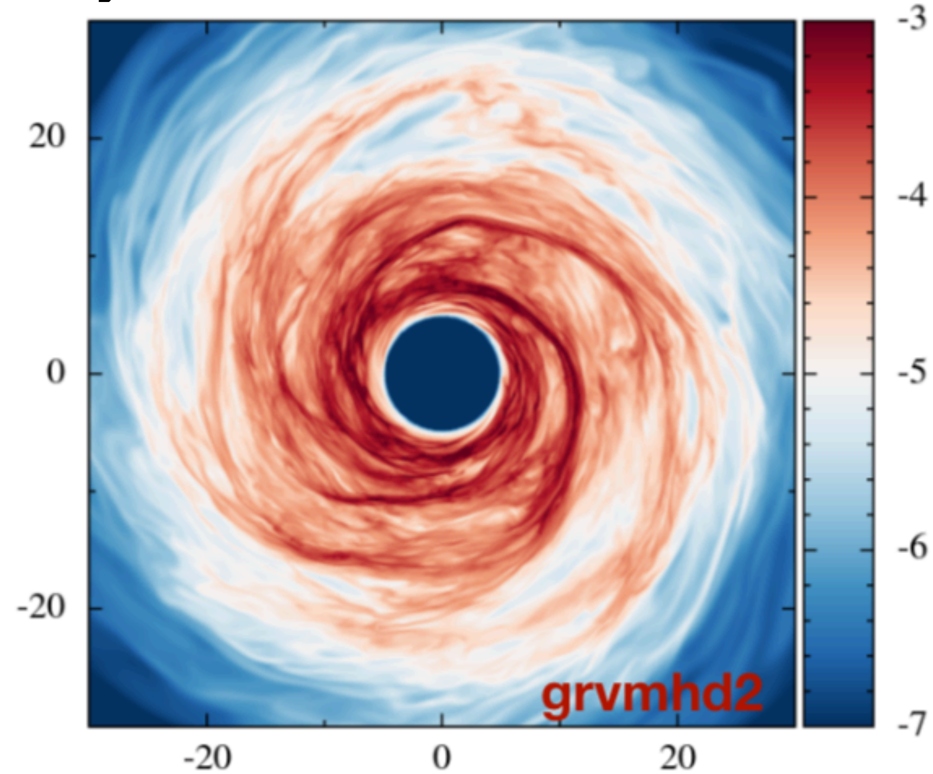
Assume some prior amplification of B field by turbulent dynamo during gravitational collapse or merger (eg Schober et al. 2013; Grete et al. 2019) —> Initial seed B_z field in the range 0.1-1 Gauss

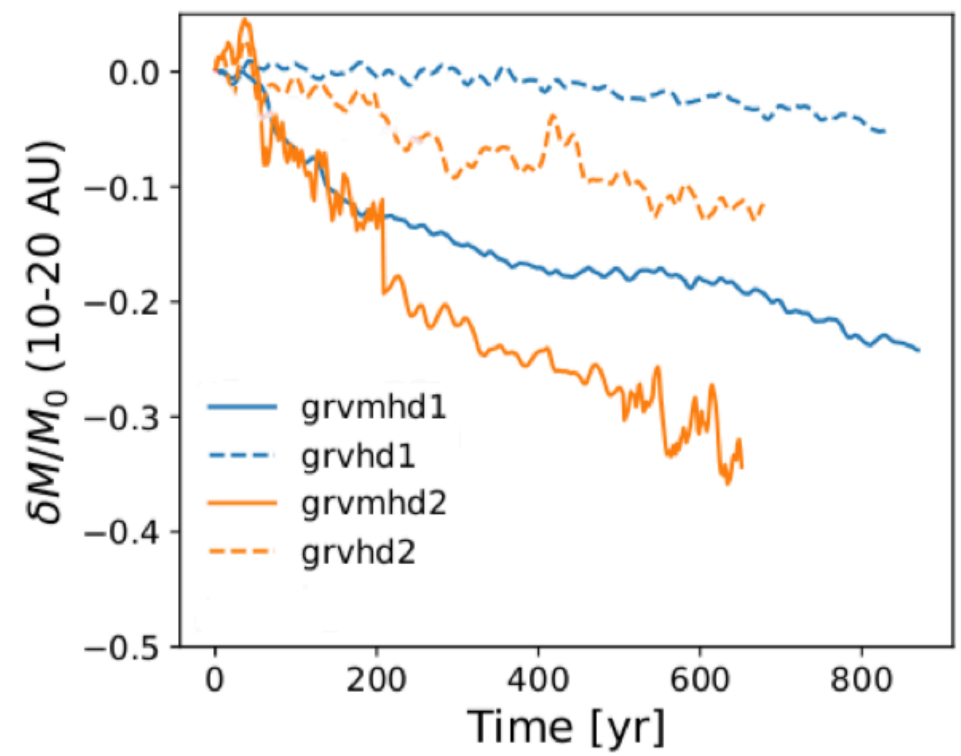
Regime initially studied in 3D magnetised self-gravitating protoplanetary disk simulations (Deng, Mayer et al. 2019)

Gravitational instability with magnetic dynamo: stabilising effect (Q rises) PLUS enhanced turbulent mass transport

Density







Hydro **MHD**

Disk models with a range of cooling rates, from a few to 10 orbital times

$$\alpha \sim \langle H_{r\phi} + M_{r\phi} + G_{r\phi} \rangle / \langle P \rangle$$

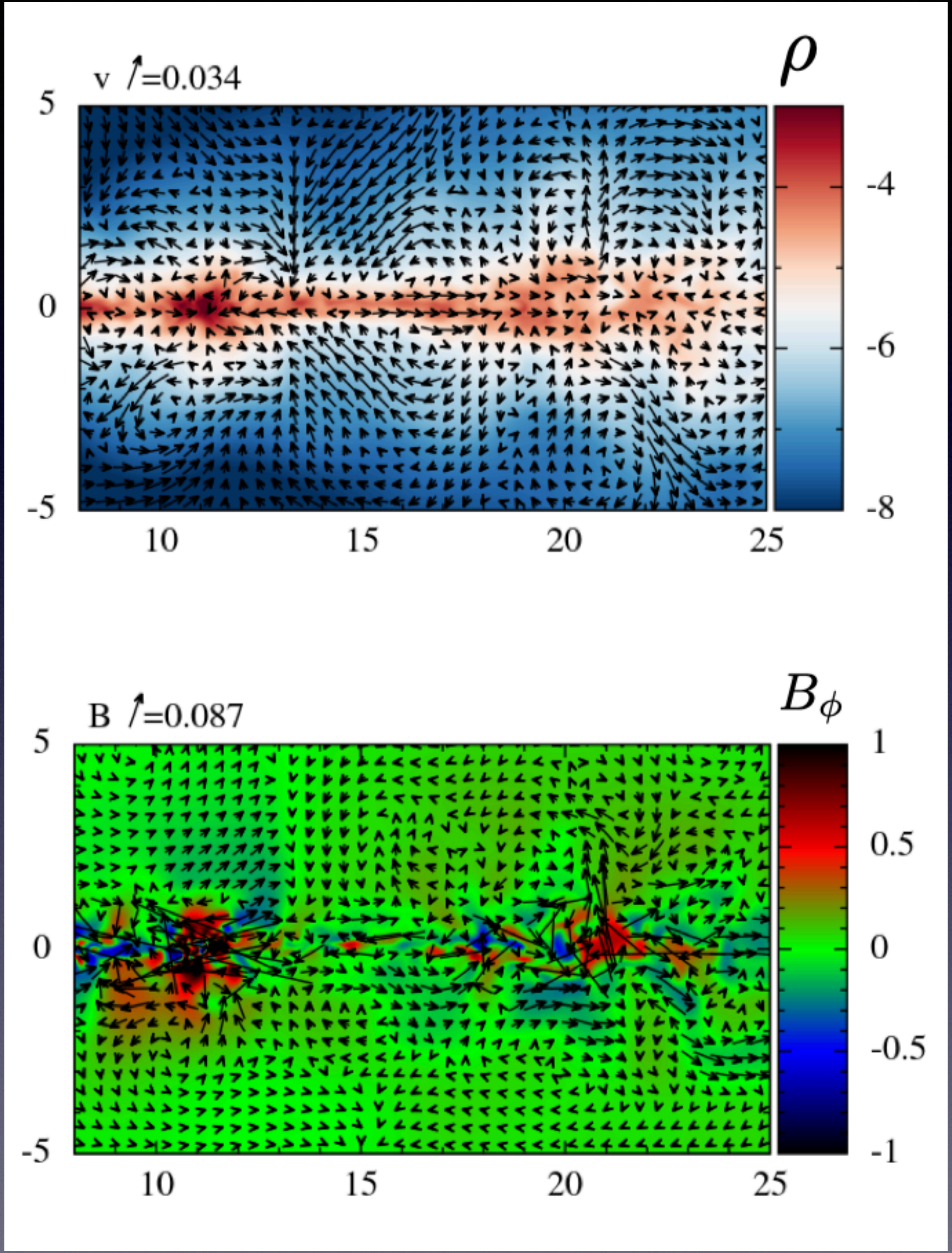
Stresses (hydro, magnetic and gravitational)

Turbulent viscosity **α ~0.2-0.3**
In non-magnetised self-gravitating disks **α <~ 0.1**

Shown is vertical slice through disk

Field amplification driven by dynamo mechanism

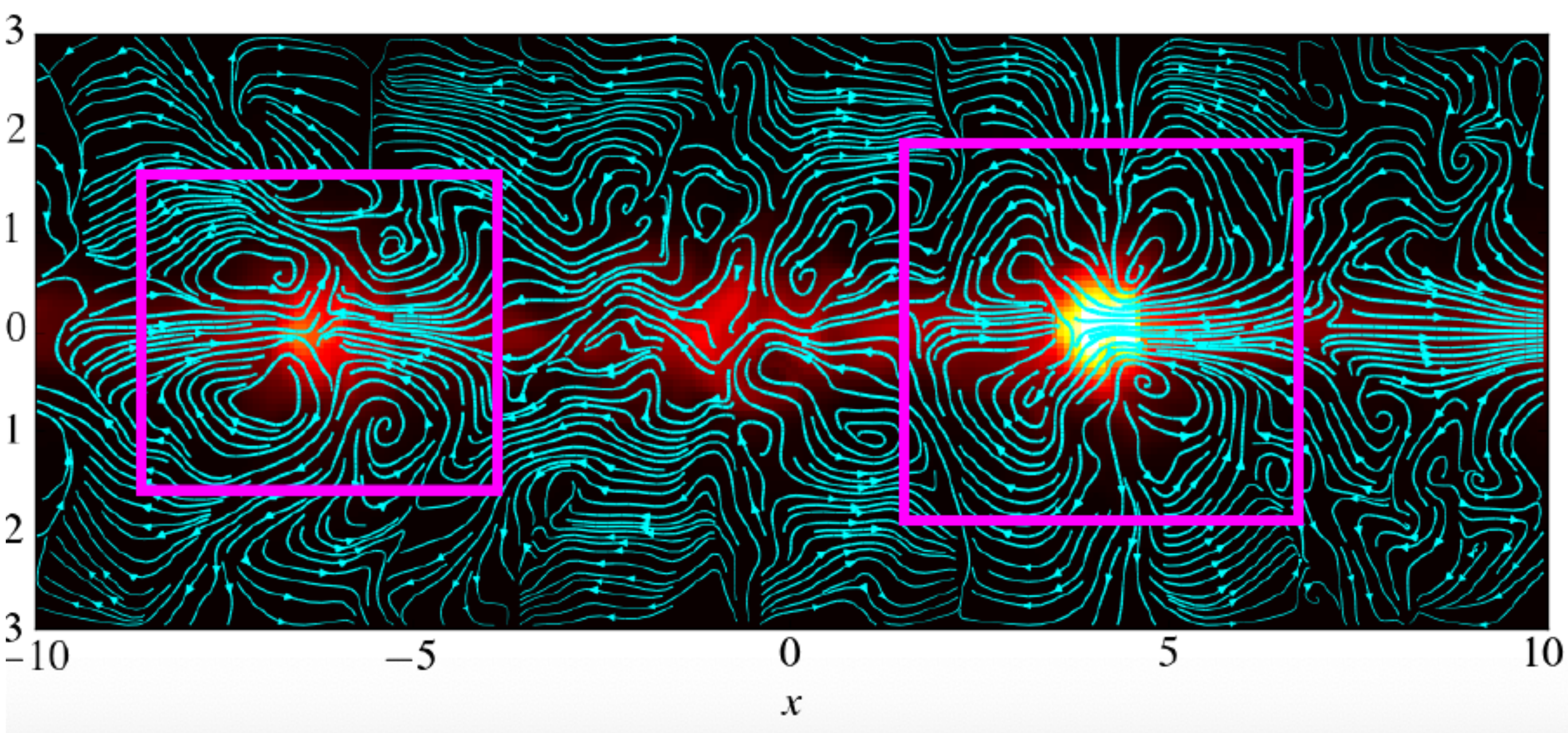
Dynamo generated by vertical circulation around spiral density wave intensity maxima

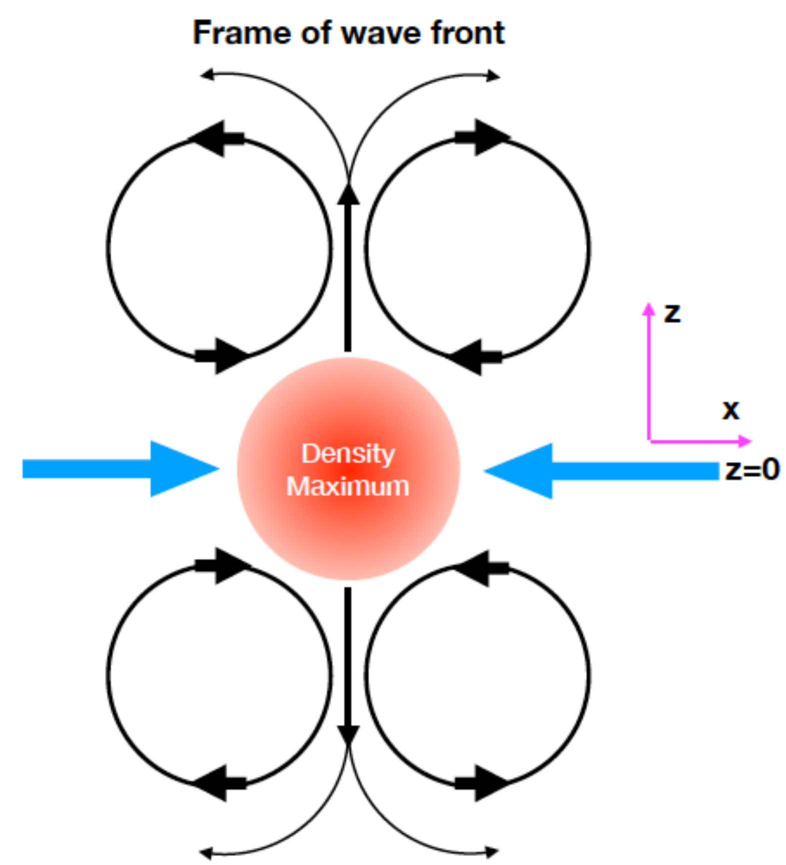


Magnetic energy grows >~10 times larger than in identical. non-self gravitating disk with MRI (plasma β ~ 7-10 rather than β >~ 100)

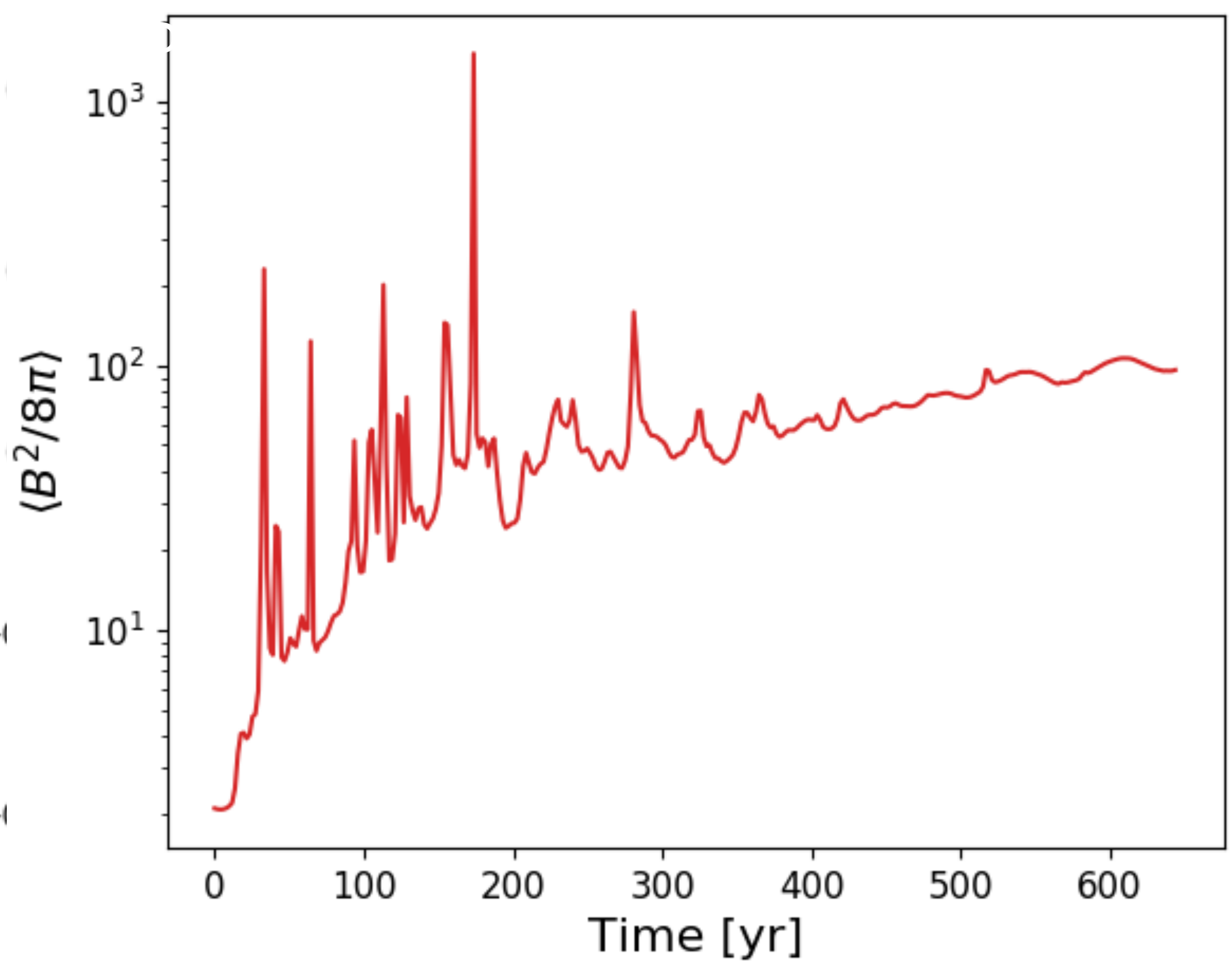
First local shearing box simulations by Riols and Latter 2017;2018) with PLUTO code uncovered gravitational instability (GI) driven spiral dynamo loop:

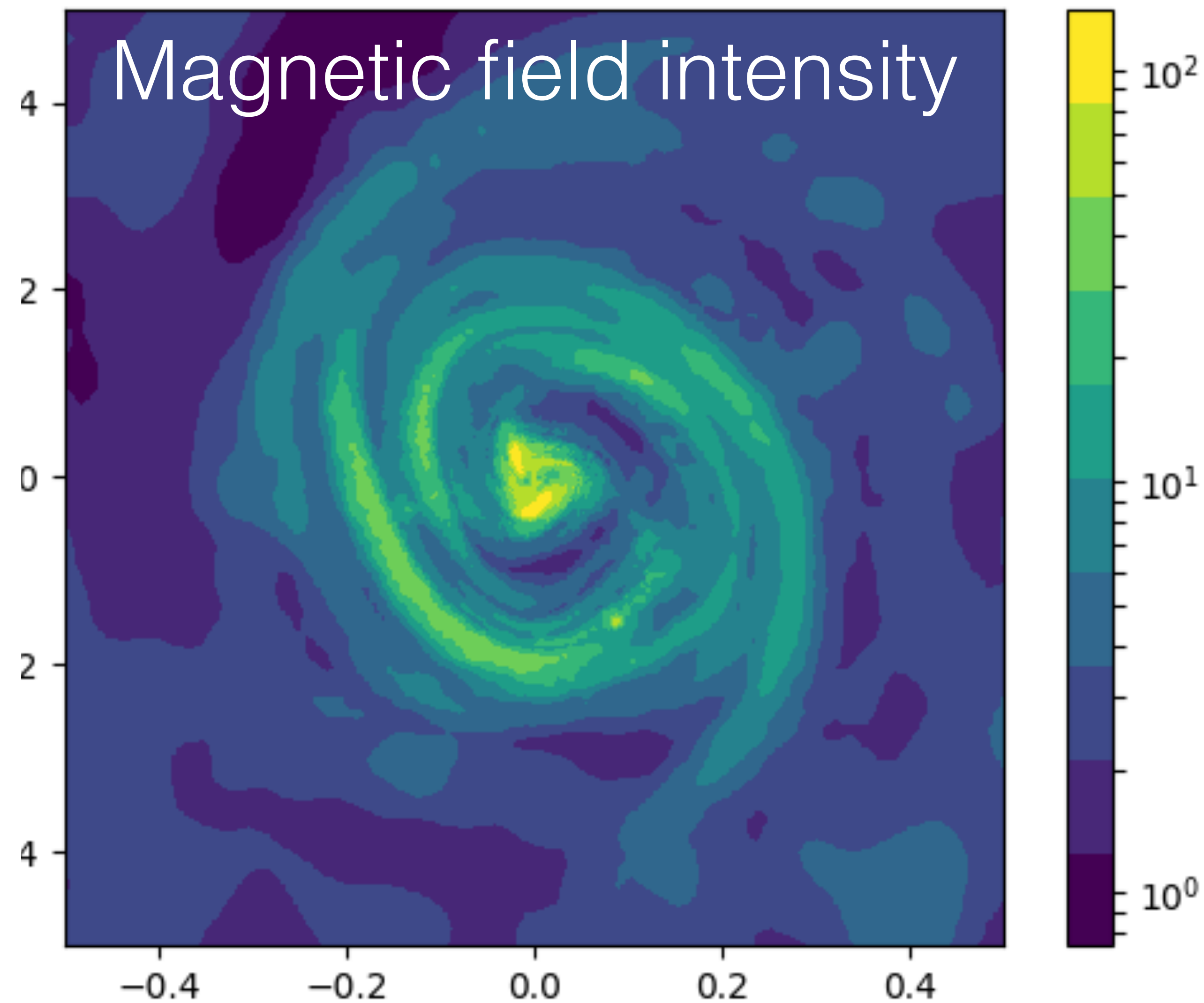
(I) radial compression of B field by spiral density waves + **(II)** lifting and folding of B field by vertical rolls generates new radial field + **(III)** shearing of new radial field back into toroidal by differential rotation *(toroidal —> poloidal —> toroidal loop with net mean field growth)*





Preliminary results: field amplification in self-gravitating nuclear disk in high-z merger remnant in Mayer et al. (2015)





()Caution: current simulation *adiabatic* without cooling gravitational instability weakens over time —-> weaker dynamo trigger

() Will need to add cooling to assess increased stability against fragmentation