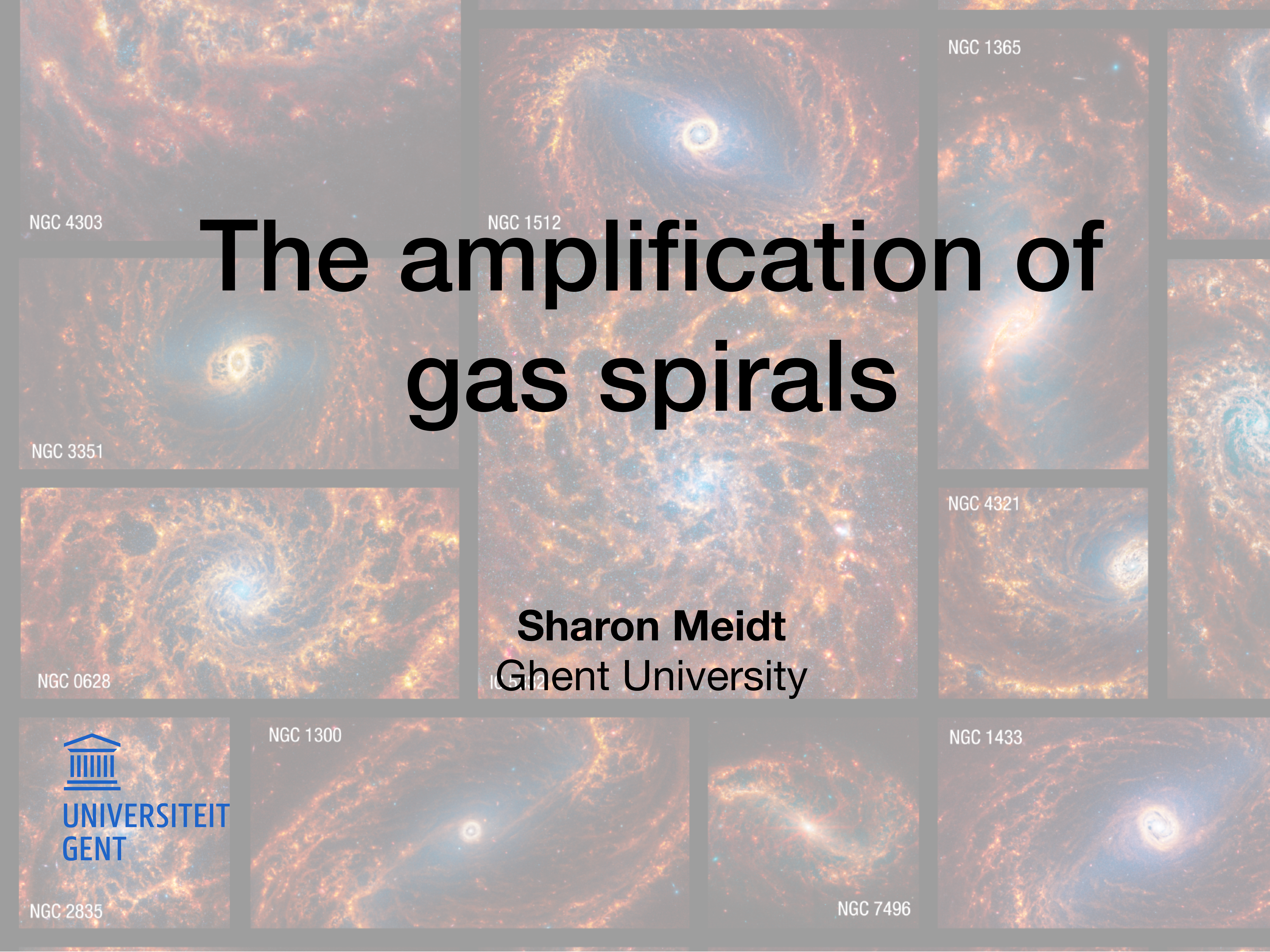
The amplification of gas spirals

Sharon Meidt
Ghent University



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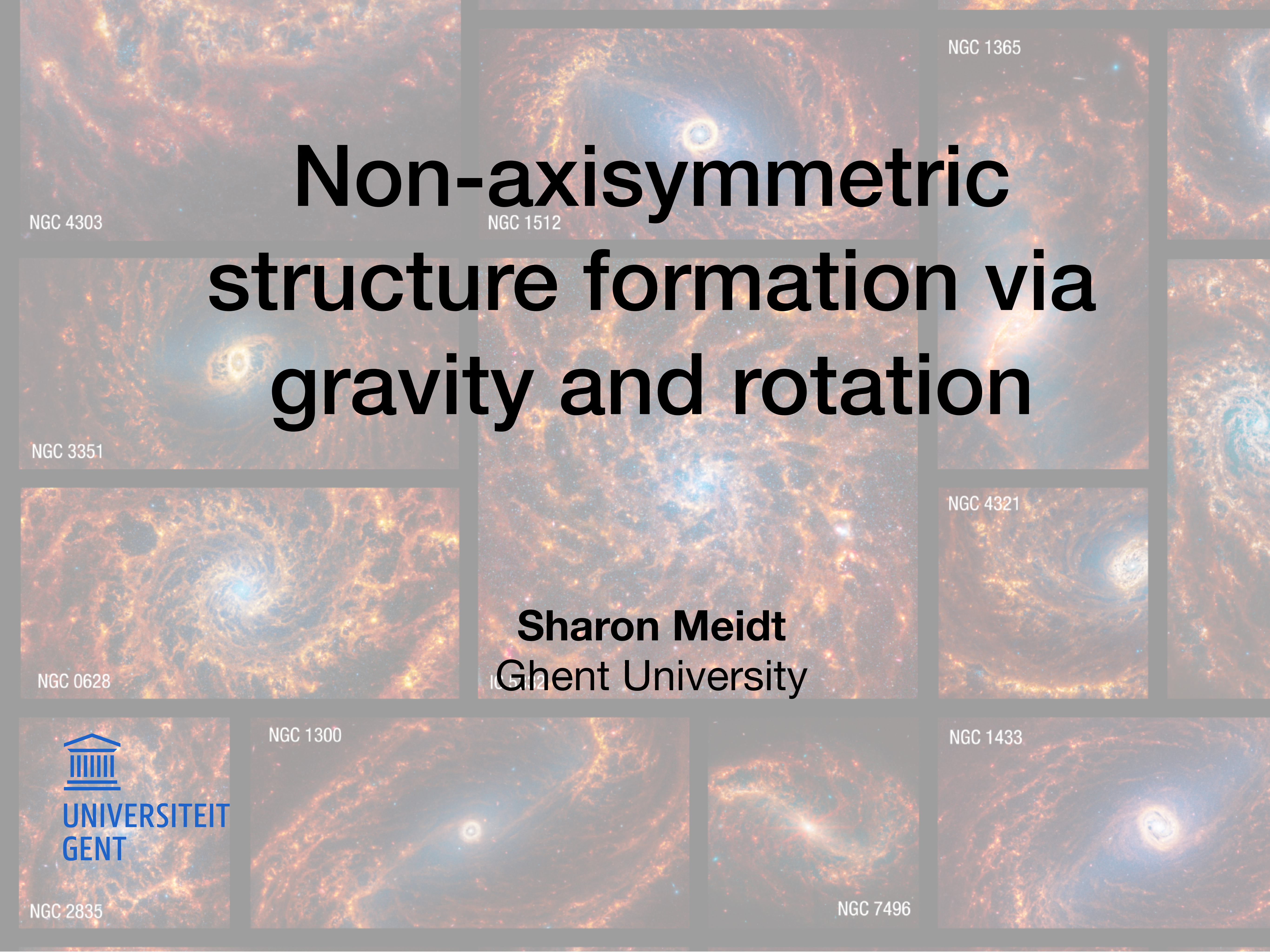
Non-axisymmetric structure formation via gravity and rotation



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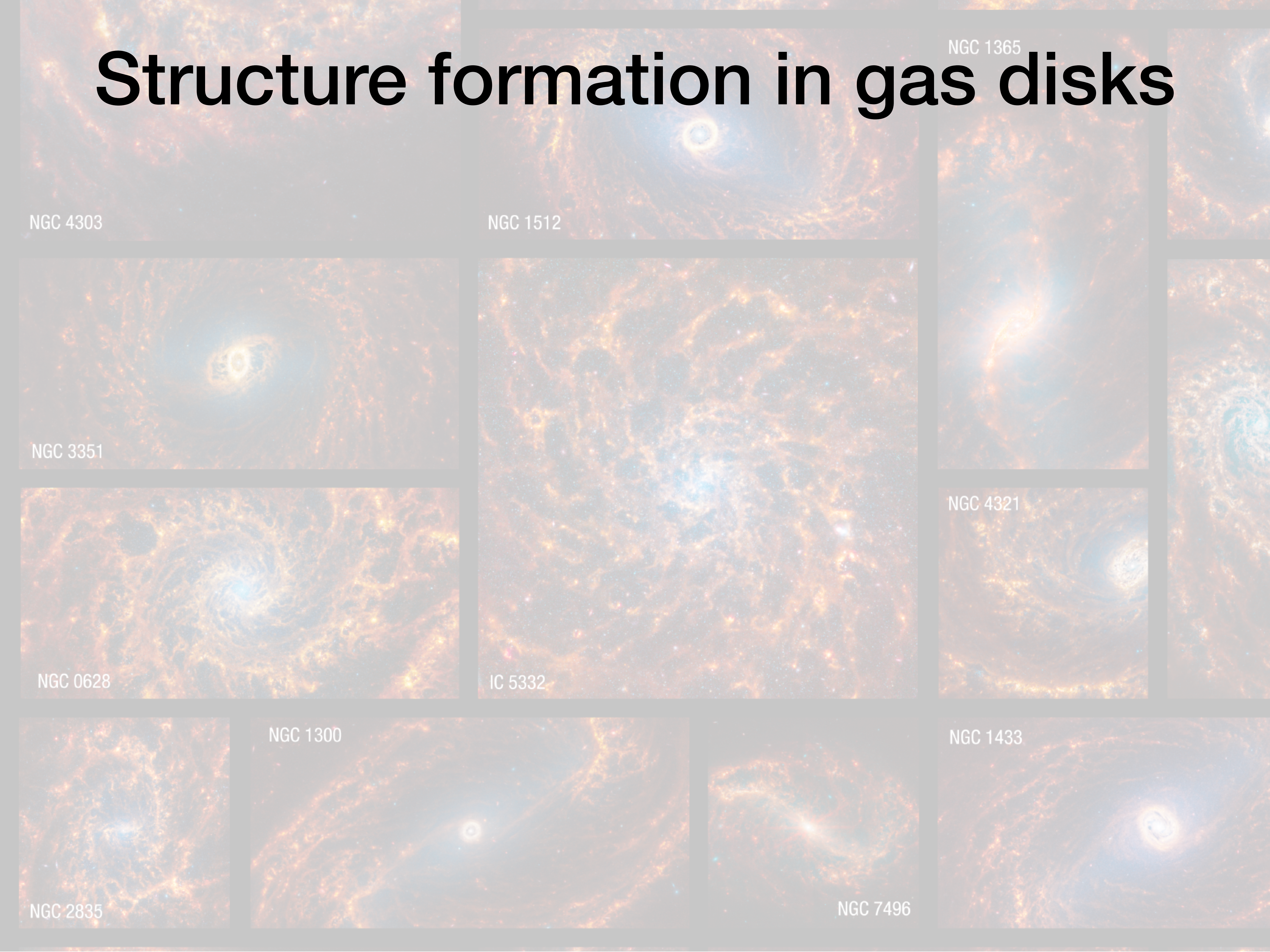
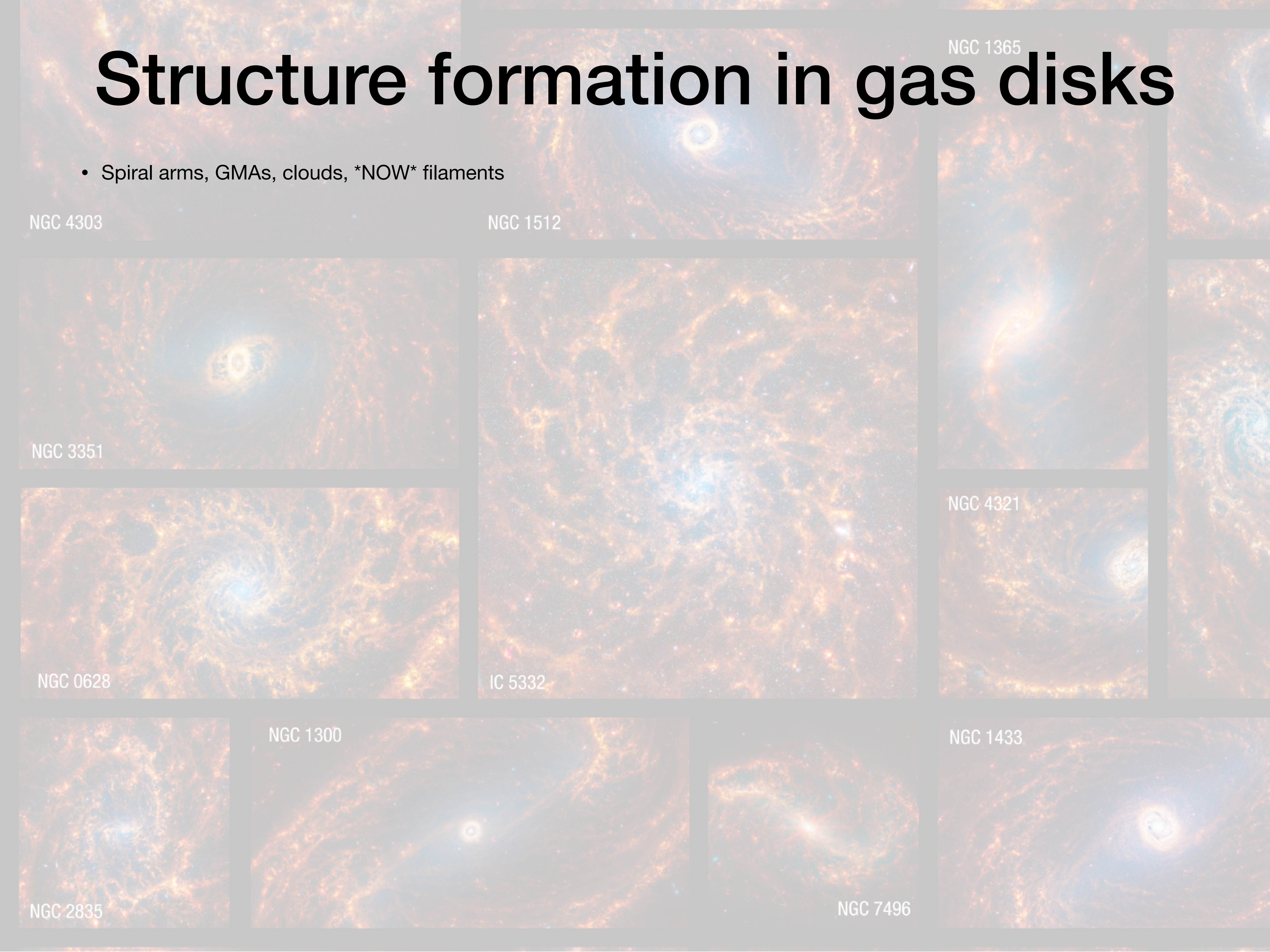
Structure formation in gas disks



Structure formation in gas disks

- Spiral arms, GMAs, clouds, *NOW* filaments



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    - Q>1?
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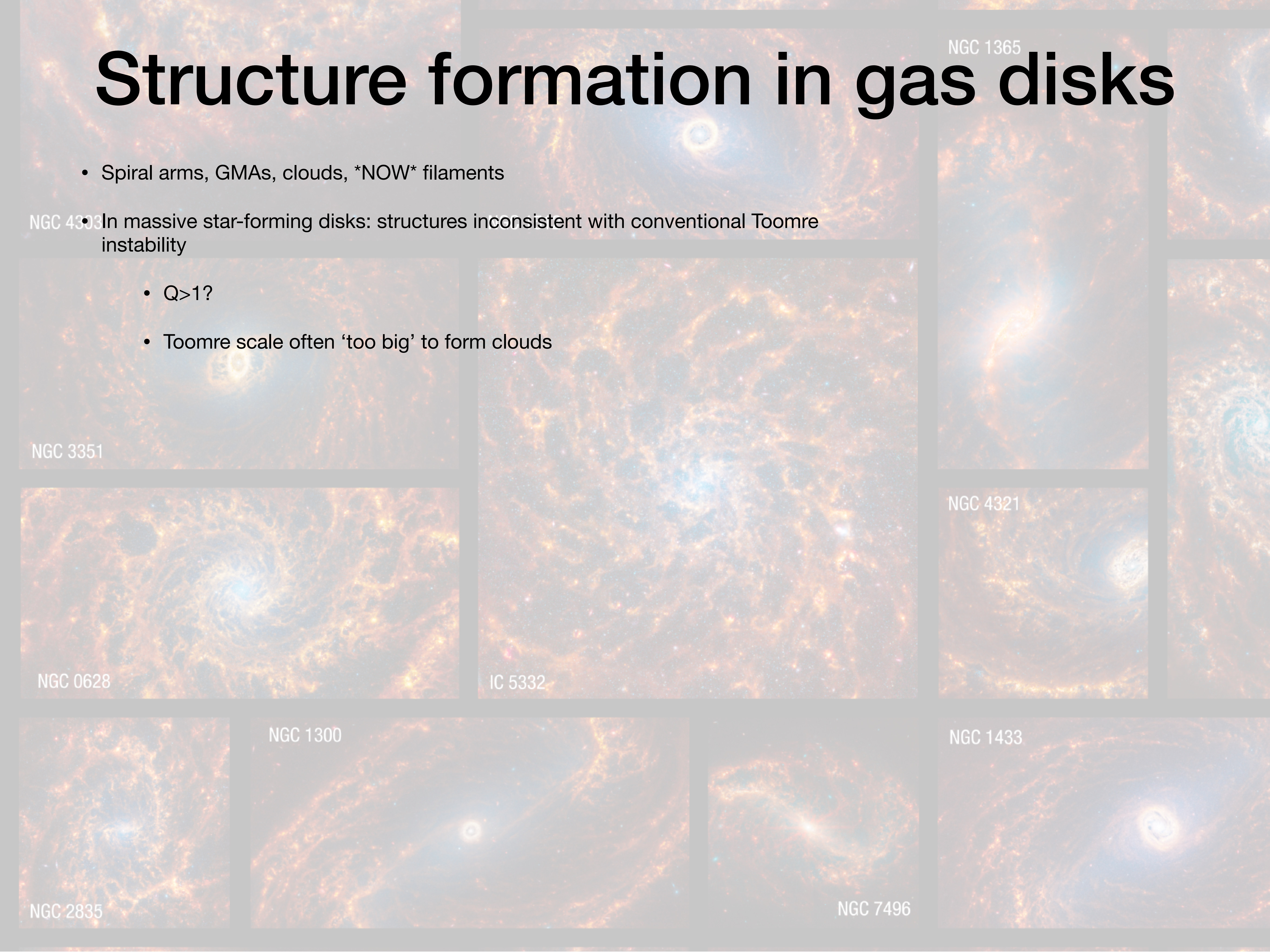

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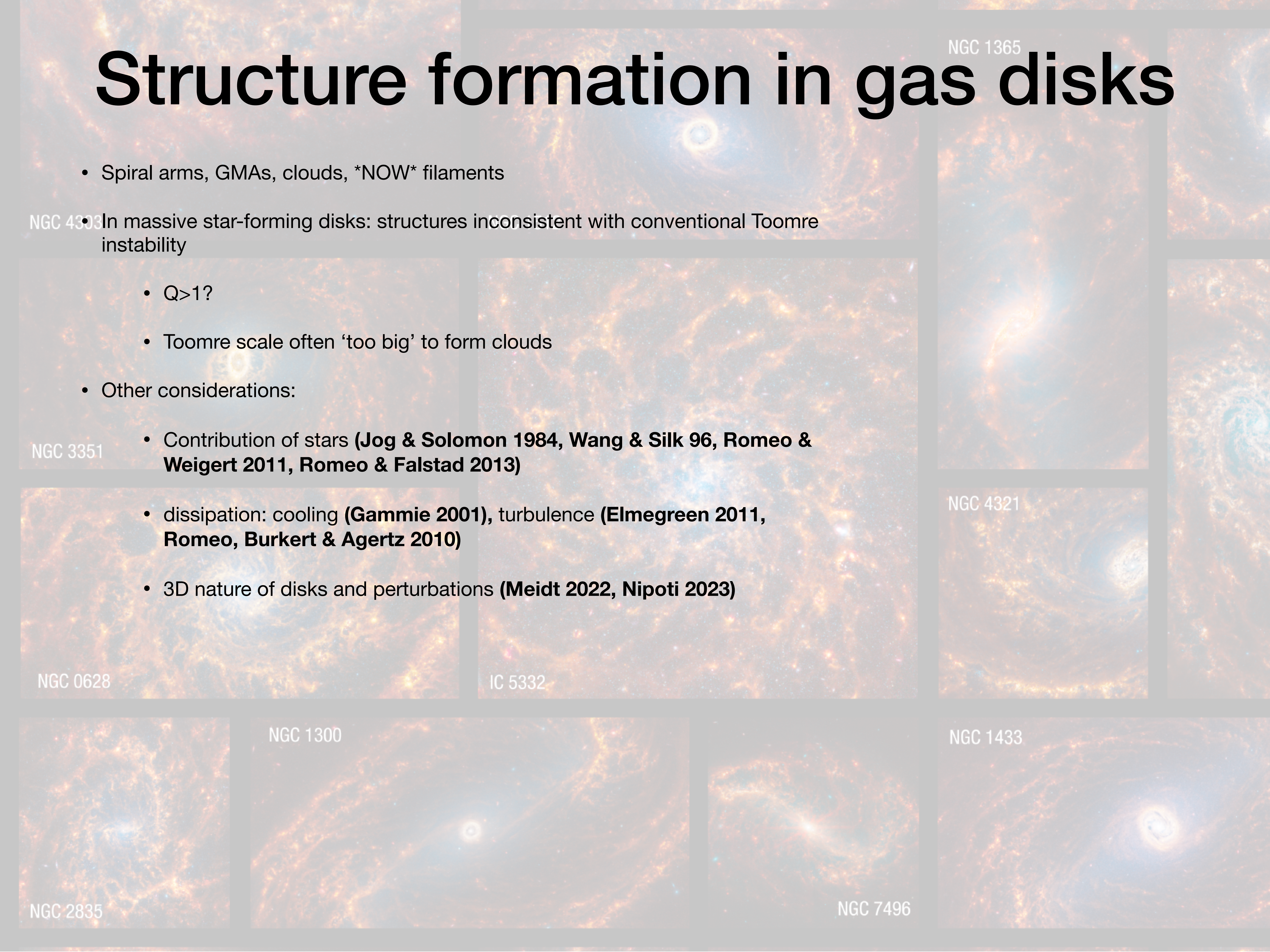
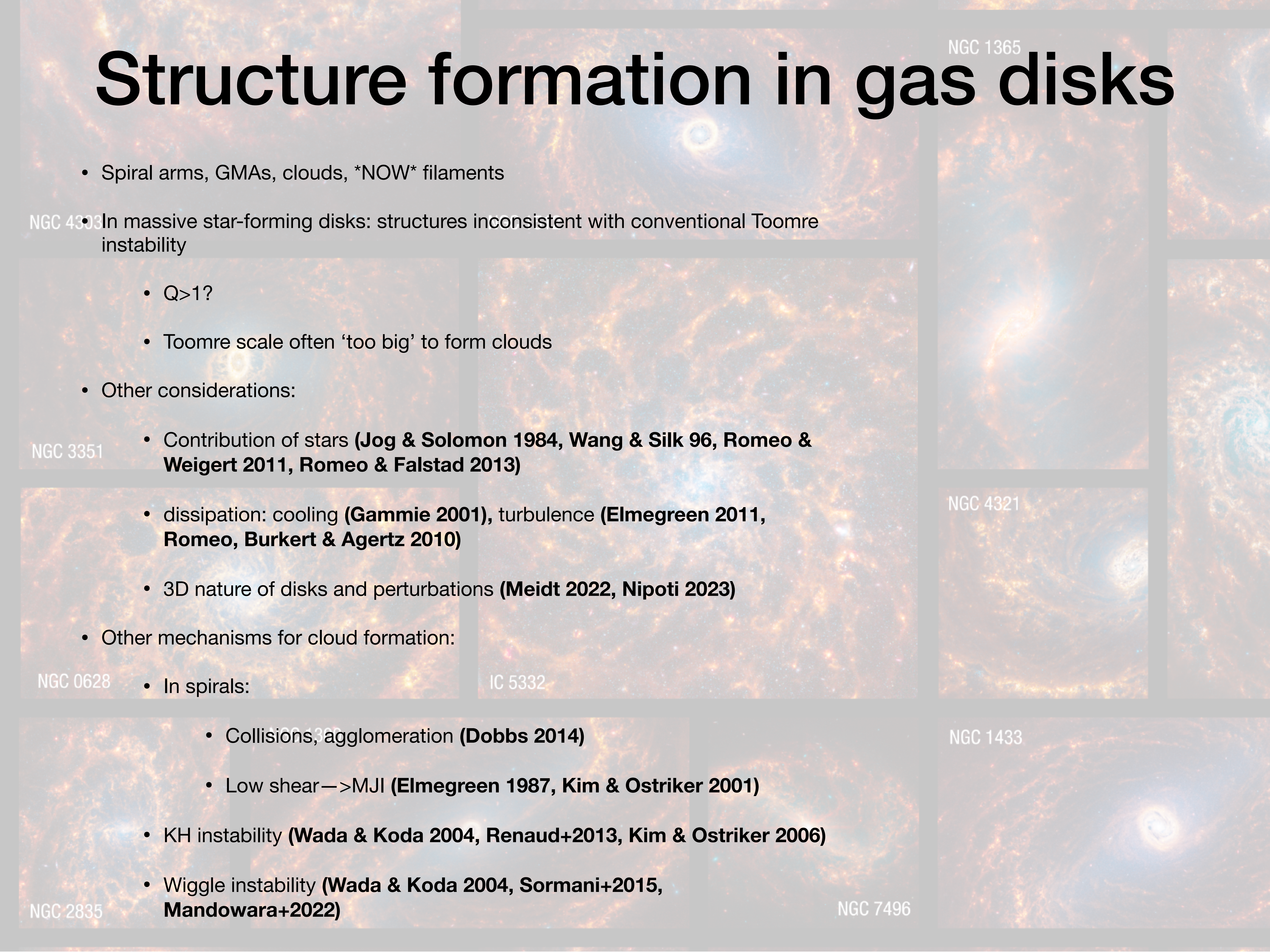
- Other considerations:
  - Contribution of stars **(Jog & Solomon 1984, Wang & Silk 96, Romeo & Weigert 2011, Romeo & Falstad 2013)**
  - dissipation: cooling **(Gammie 2001),** turbulence **(Elmegreen 2011, Romeo, Burkert & Agertz 2010)**
  - 3D nature of disks and perturbations **(Meidt 2022, Nipoti 2023)**





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    - 3D nature of disks and perturbations **(Meidt 2022, Nipoti 2023)**
- Other mechanisms for cloud formation:
    - In spirals:
        - Collisions, agglomeration **(Dobbs 2014)**
        - Low shear—>MJI **(Elmegreen 1987, Kim & Ostriker 2001)**
    - KH instability **(Wada & Koda 2004, Renaud+2013, Kim & Ostriker 2006)**
    - Wiggle instability **(Wada & Koda 2004, Sormani+2015, Mandowara+2022)**

Structure formation in gas disks

- Interarm (filaments and/or) clouds?
    - Long-lived? **(Scoville & Wilson 2004, Koda+15,21,25)**
    - roughly virialized? **(Larson 1981, Solomon+1987, Bolatto+2008)**
- Today: need to grapple with
    - Rapid destruction via: feedback **(Chevance+20, Kim+22…)**, shear **(Meidt+2015)**
    - Departures from virialization **(PHANGS: Meidt+2013,Sun+18, 20, Meidt+18)**

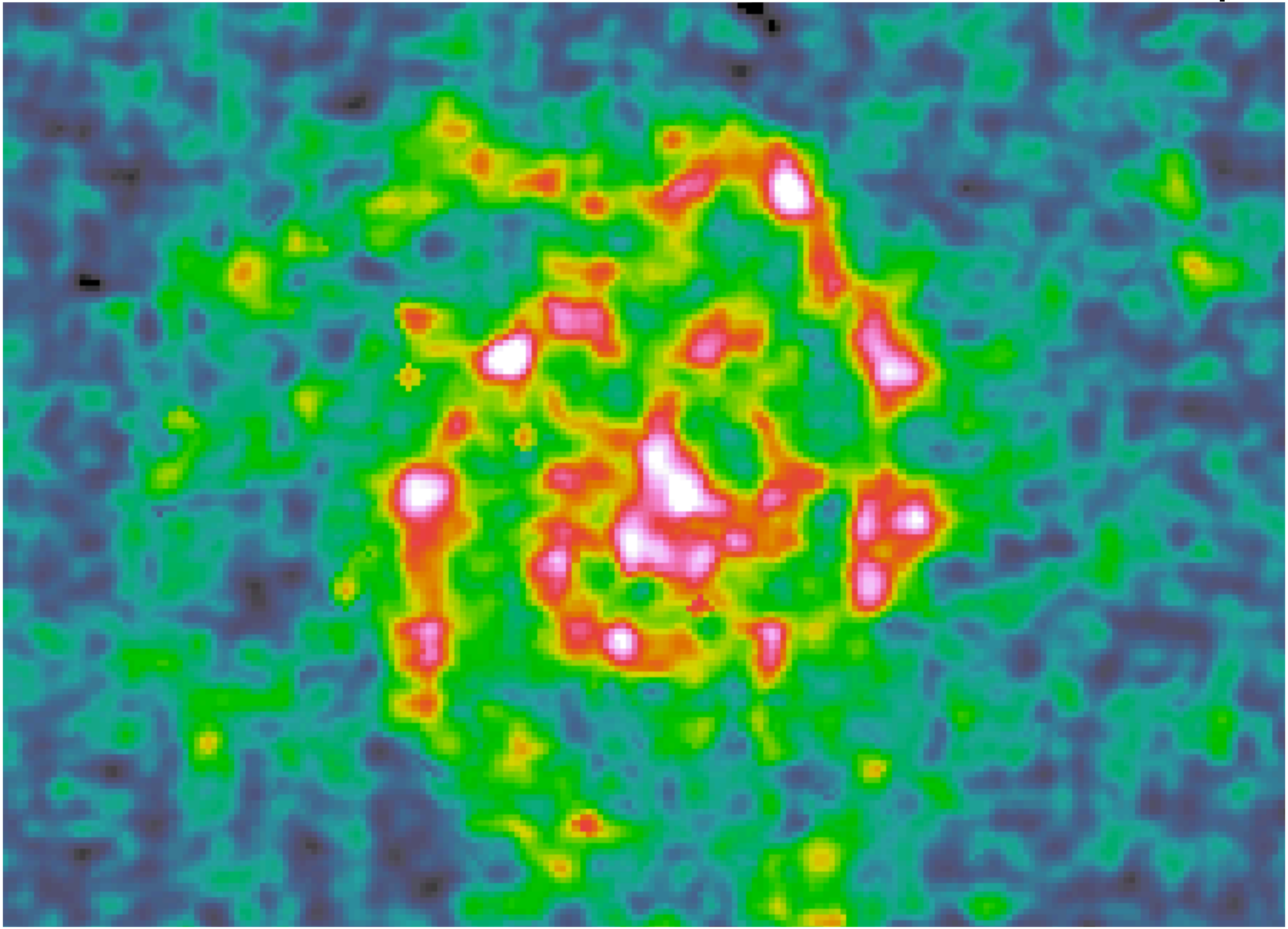
PHANGS-ALMA (Leroy+2021a,b): Structure of molecular gas in nearby ‘main sequence’ galaxies

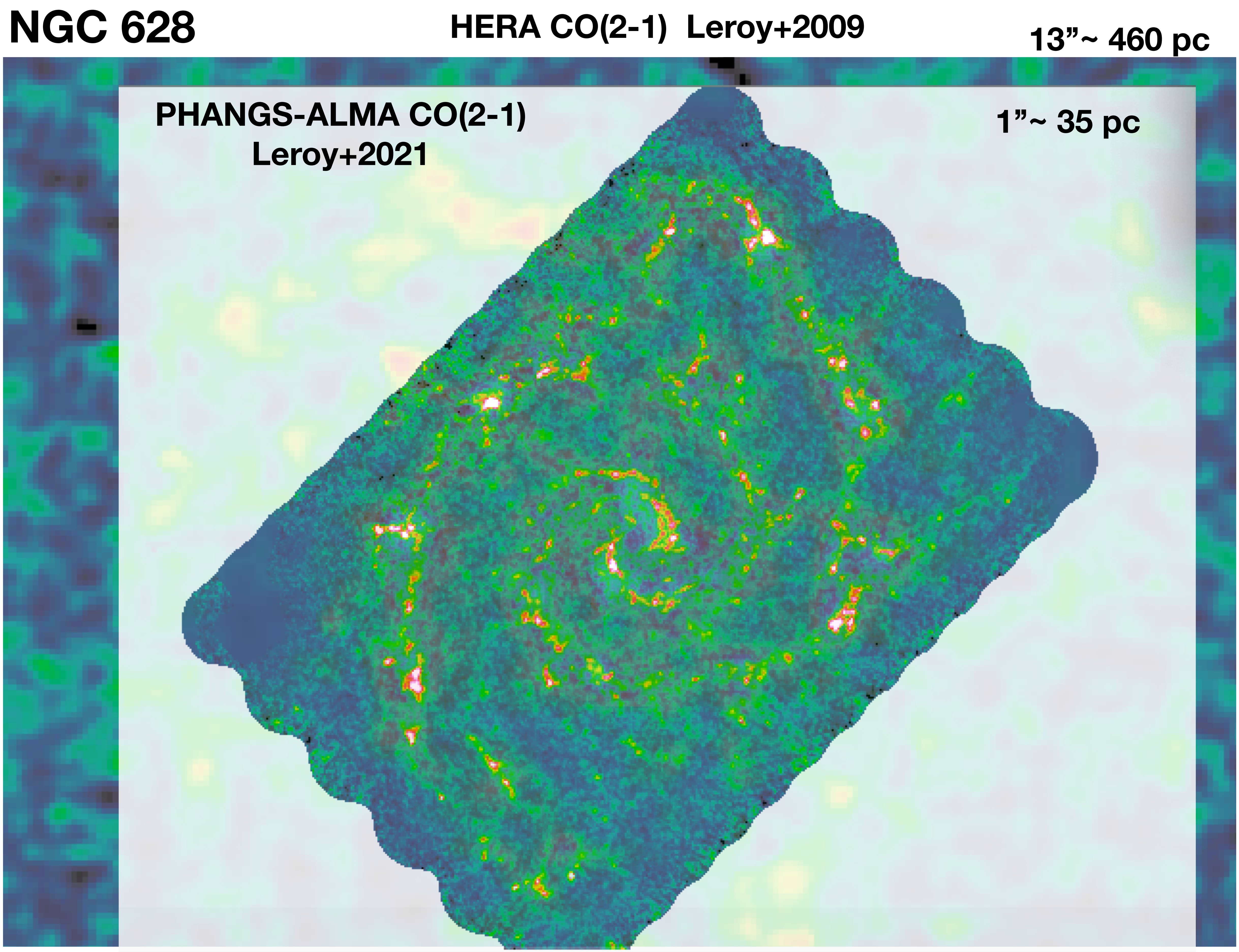
(at high spatial resolution)

NGC 628

HERA CO(2-1) Leroy+2009

13"~ 460 pc

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PHANGS-ALMA CO(2-1)
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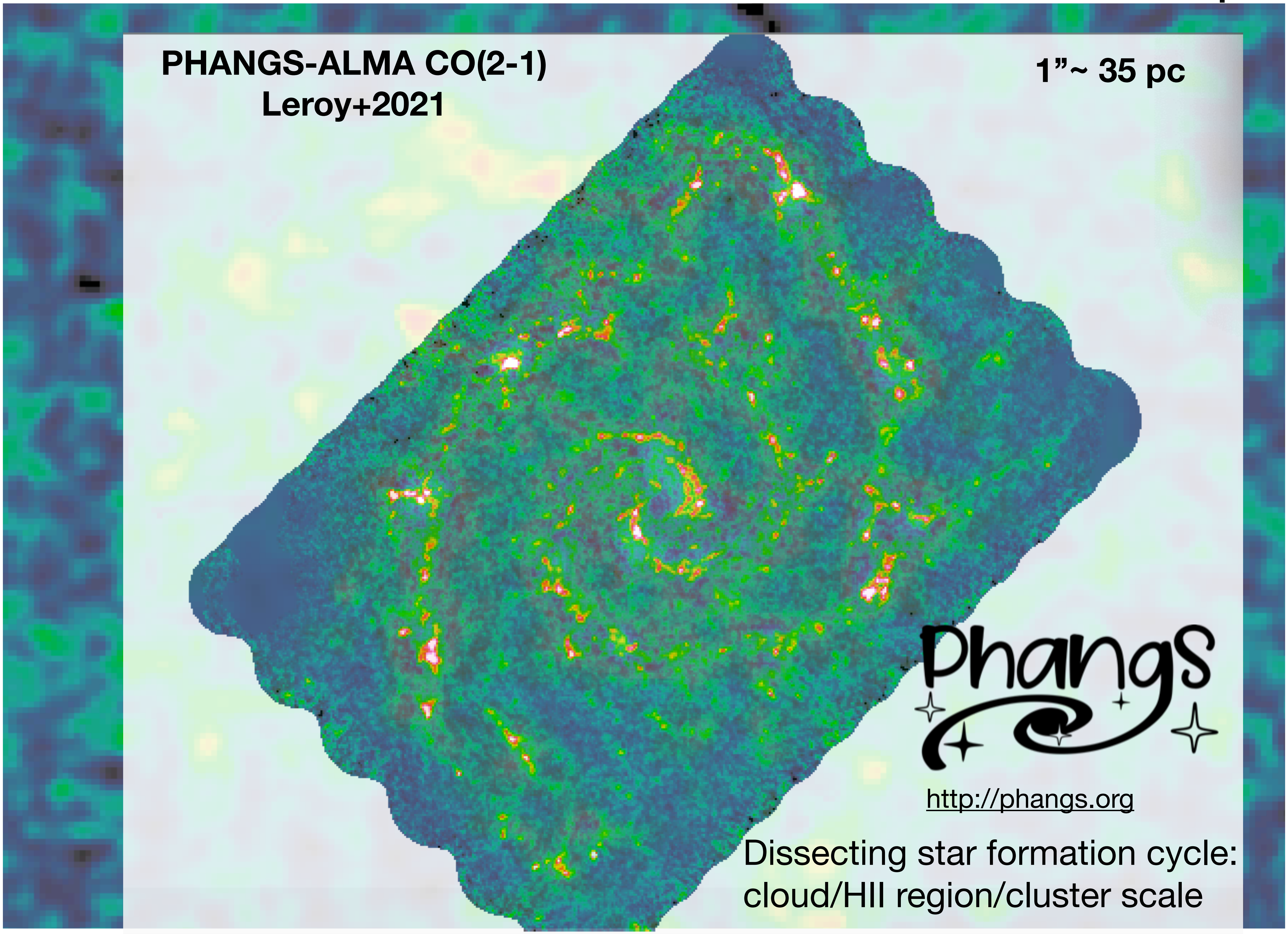
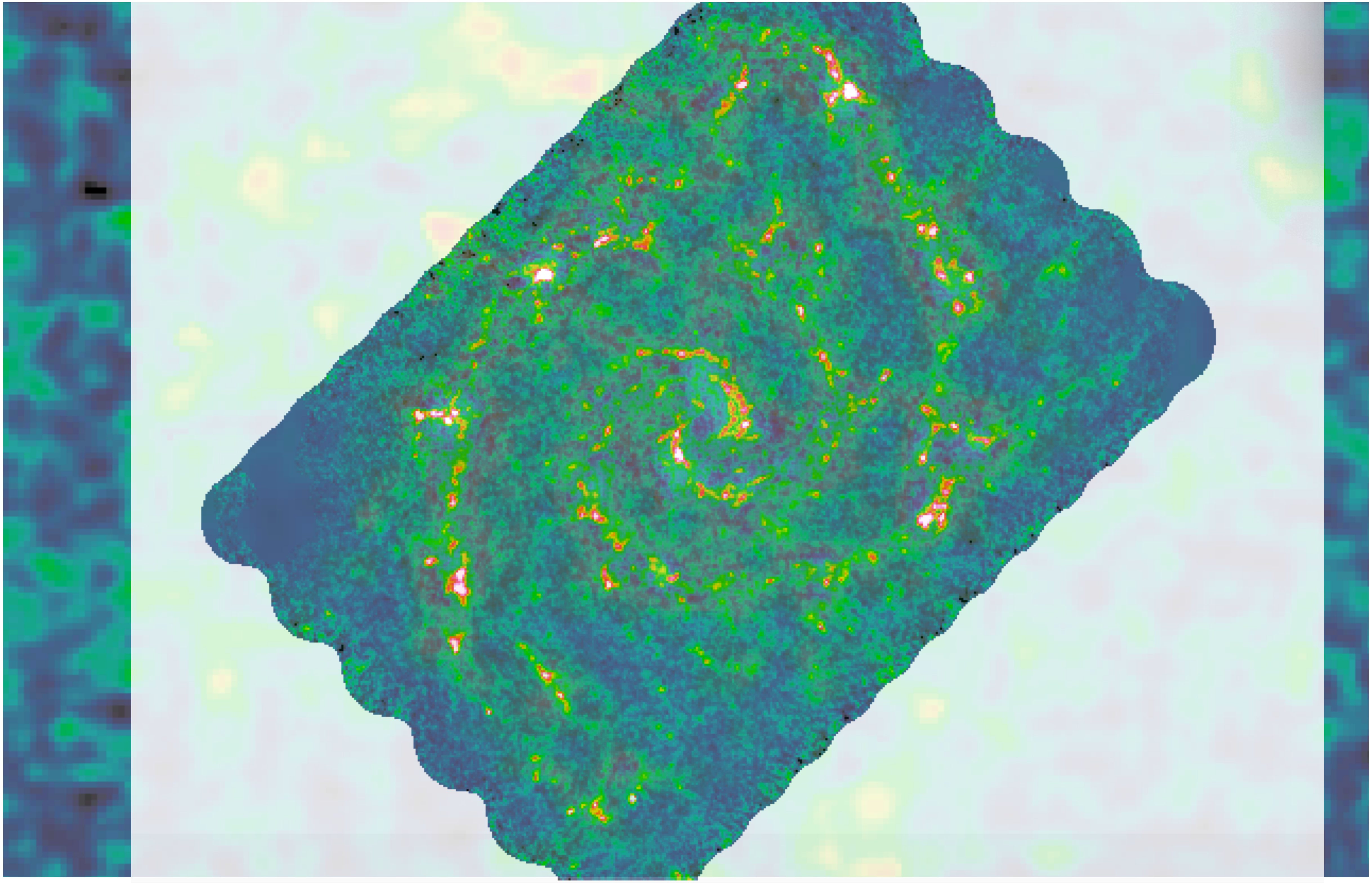


Clouds as gas filaments: the view with JWST



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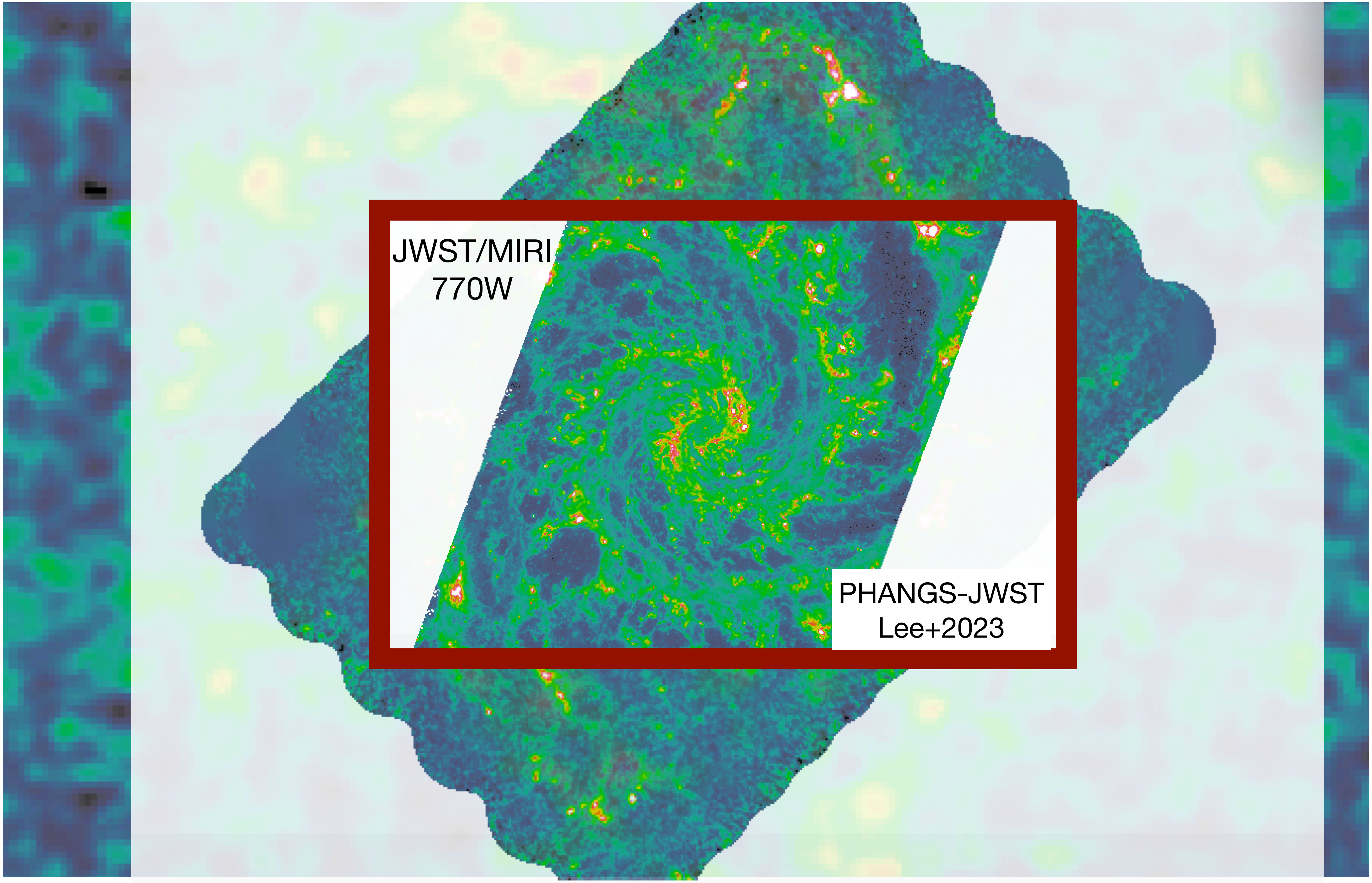
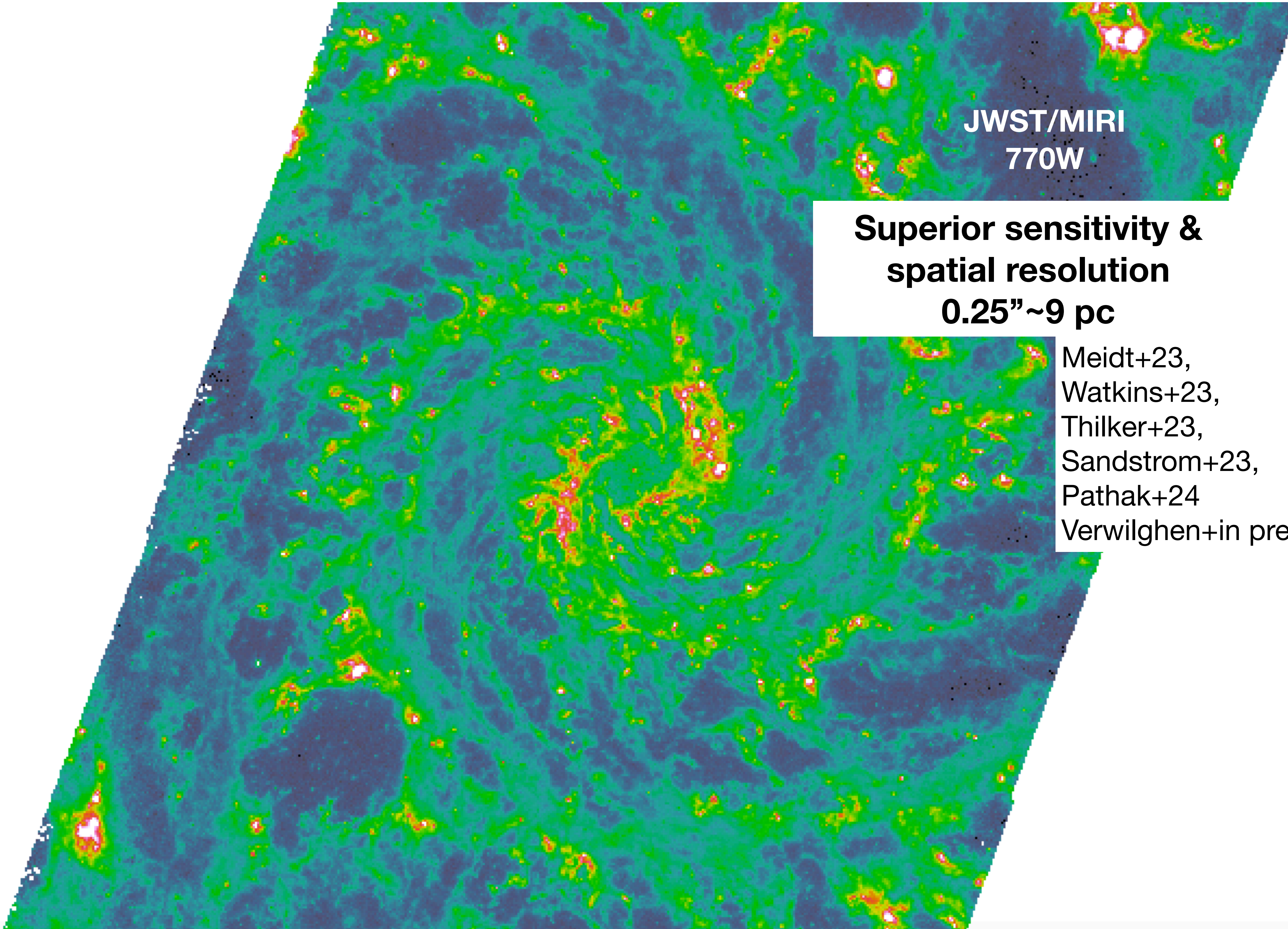


PHANGS-JWST

Lee+2023, Sandstrom+2023, Leroy+2023



Superior sensitivity & spatial resolution 0.25”~9 pc

Meidt+23,
Watkins+23,
Thilker+23,
Sandstrom+23,
Pathak+24
Verwilghen+in prep

PHANGS-JWST

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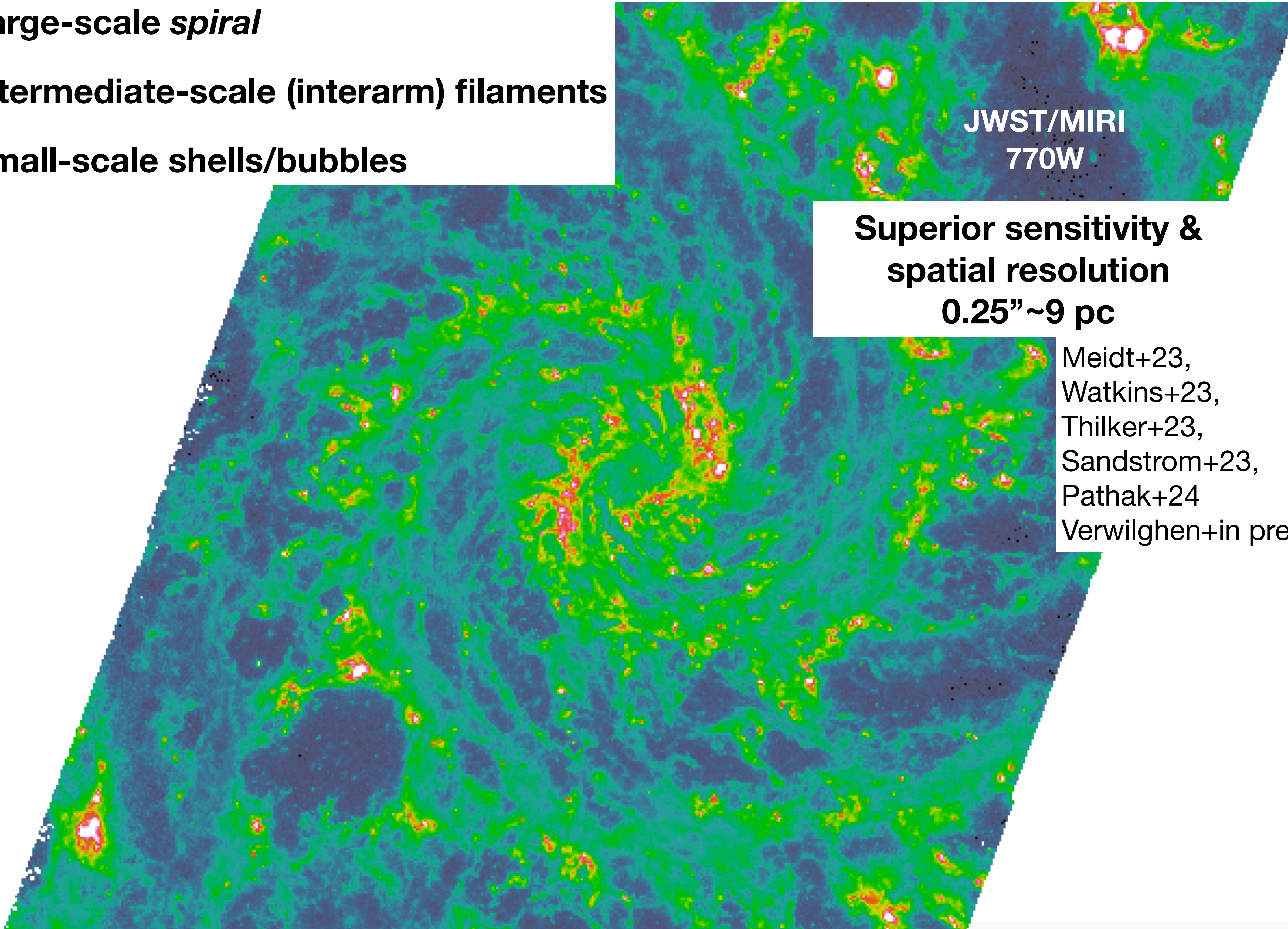
1. Large-scale *spiral*
2. Intermediate-scale (interarm) filaments
3. Small-scale shells/bubbles



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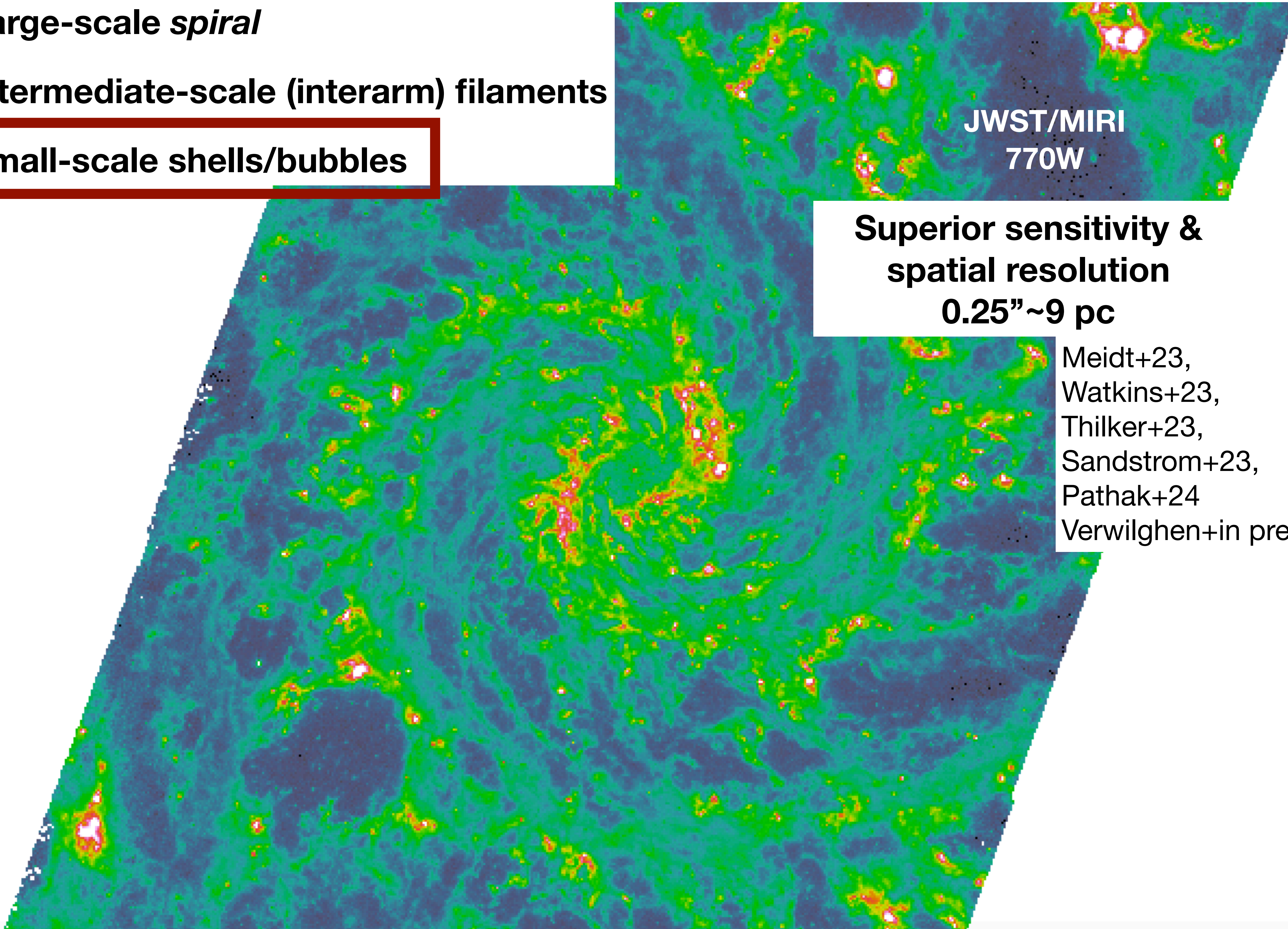

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Structure in PHANGS-JWST MIRI images

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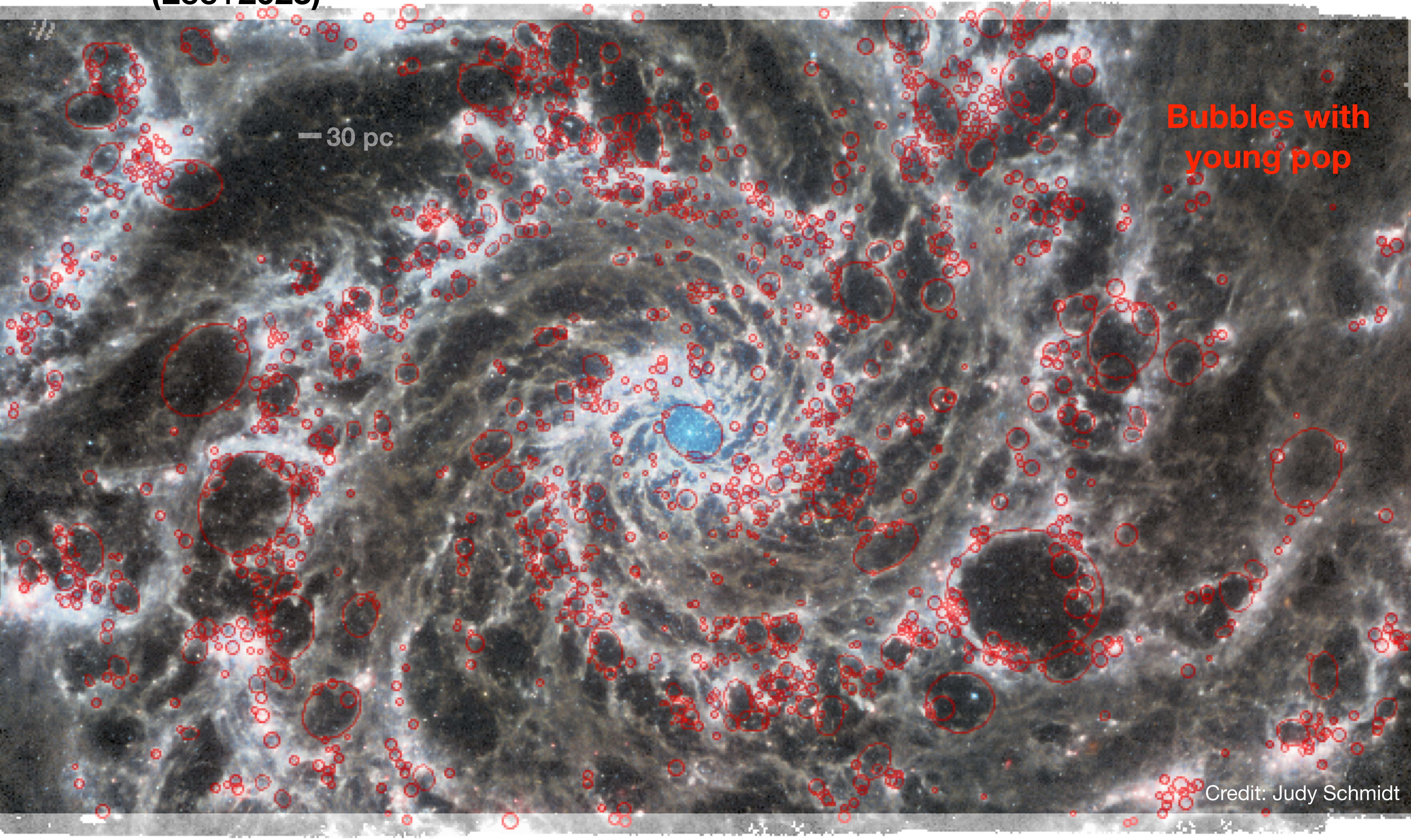

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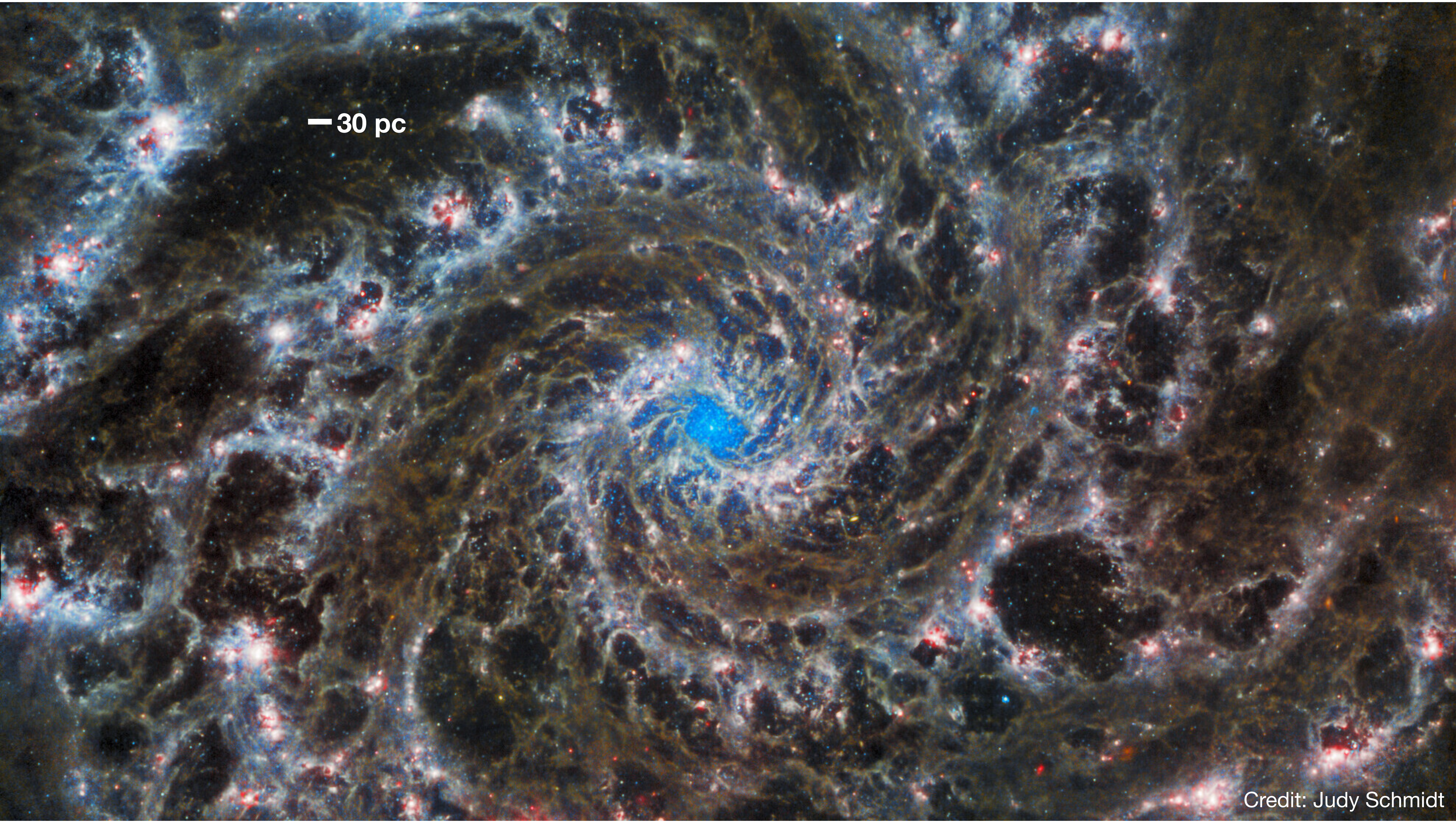

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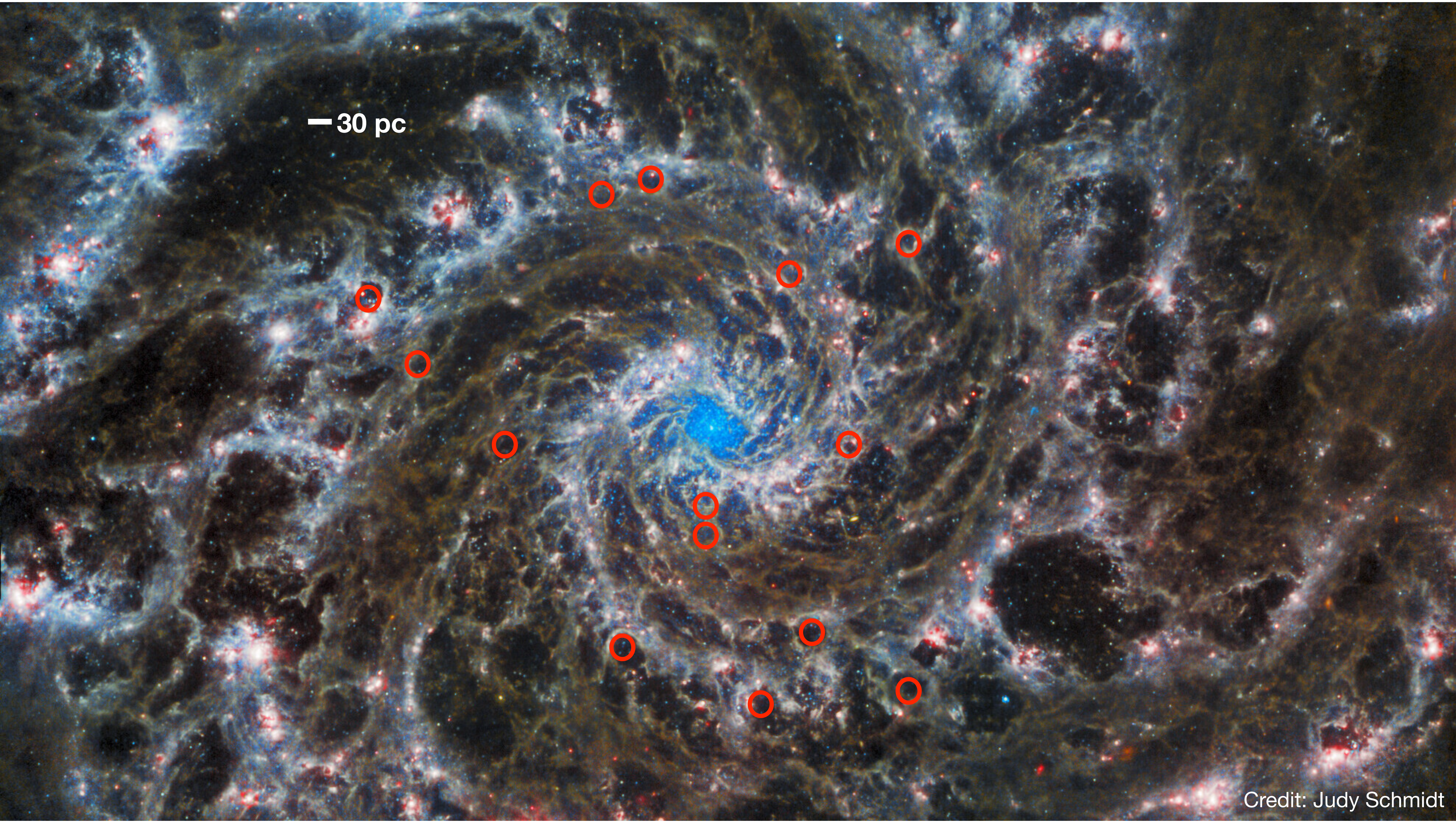

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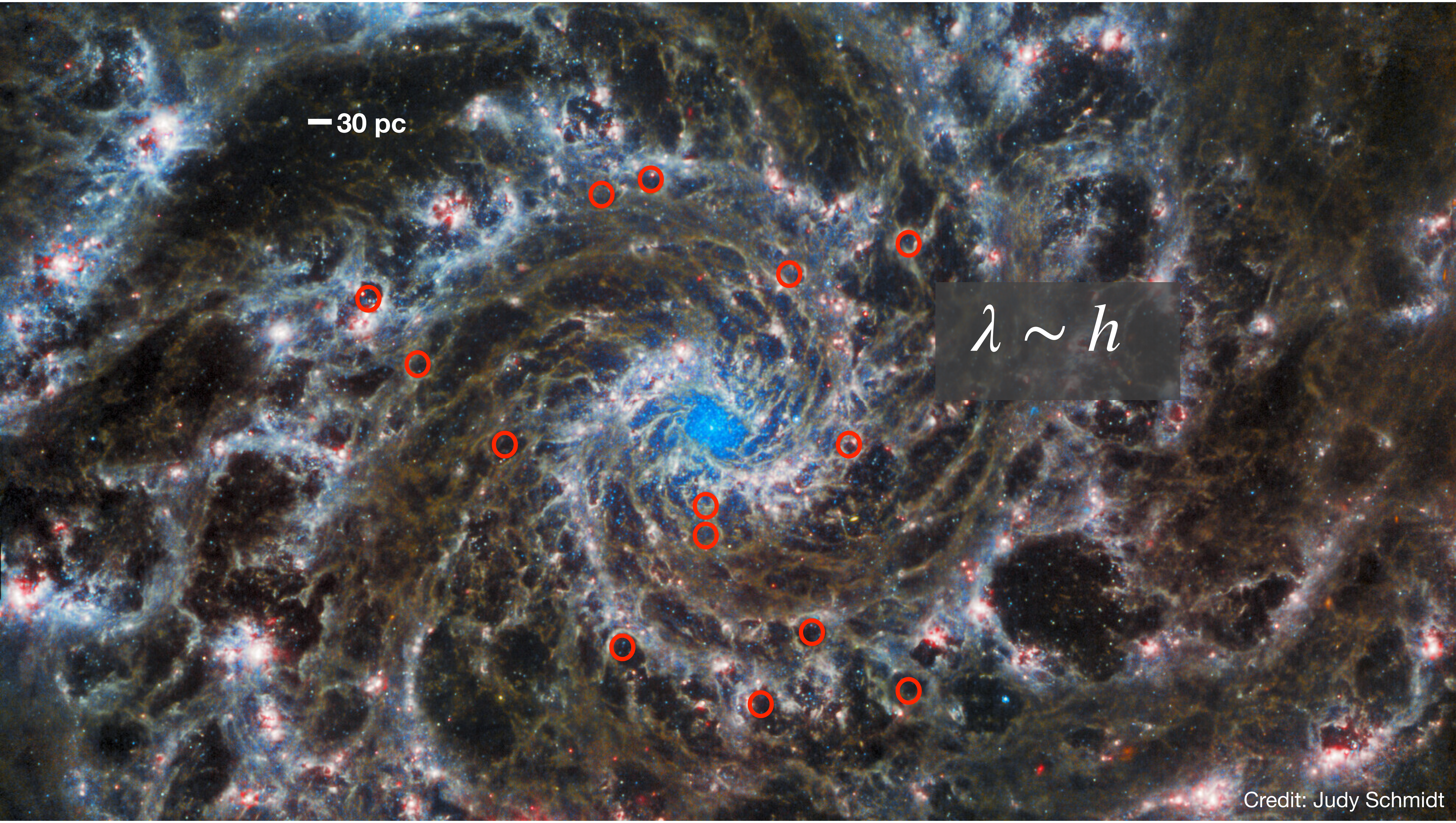

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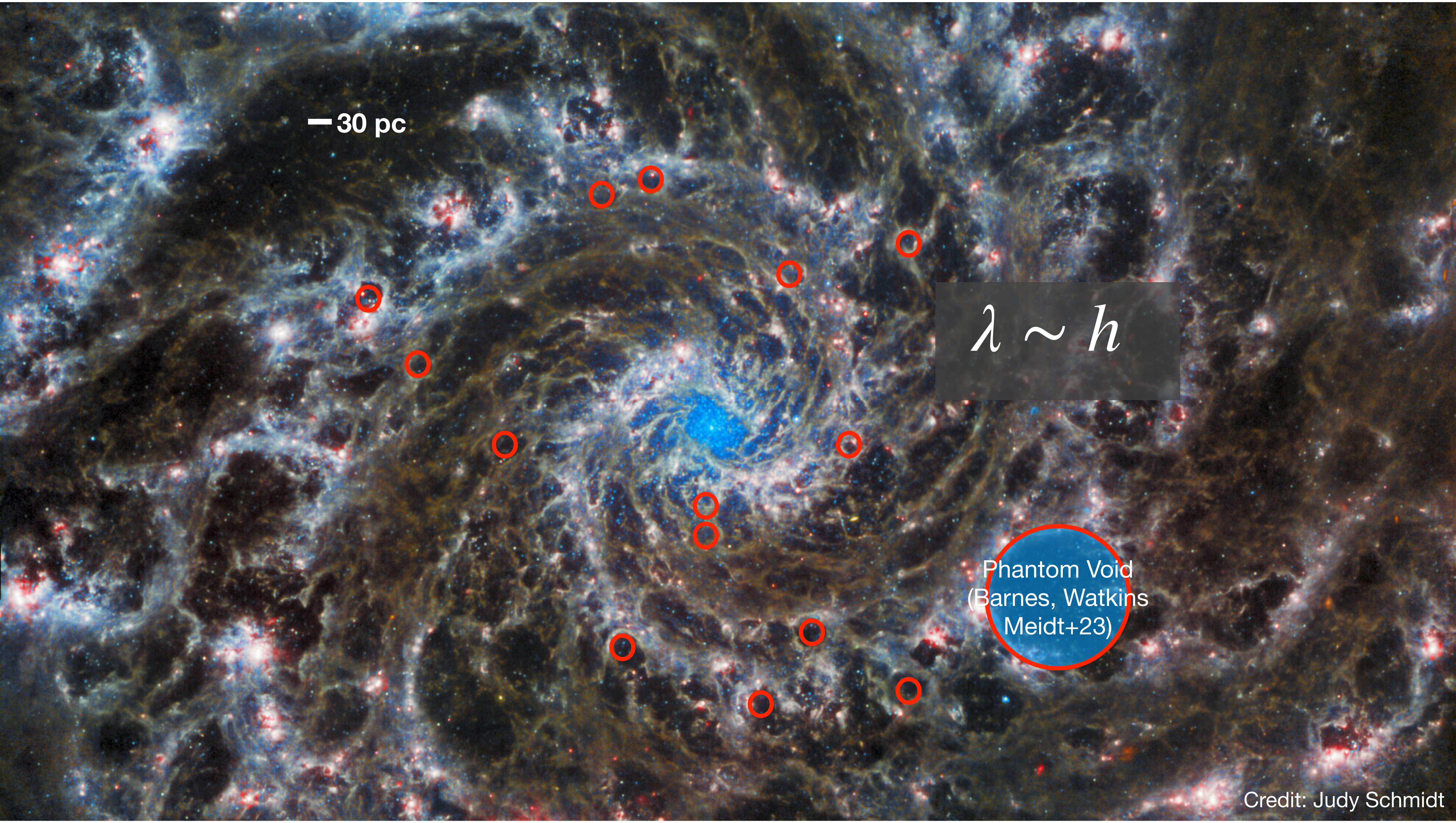

Qualities of Feedback-driven bubbles

- Simulations: expanding bubbles expand in the plane until vertical breakout or stall below *h* (**Fielding+2018, Orr+22**)

- Some ultra-clustered SNe events going off at low density (e.g. Phantom Void; **Barnes+23)**

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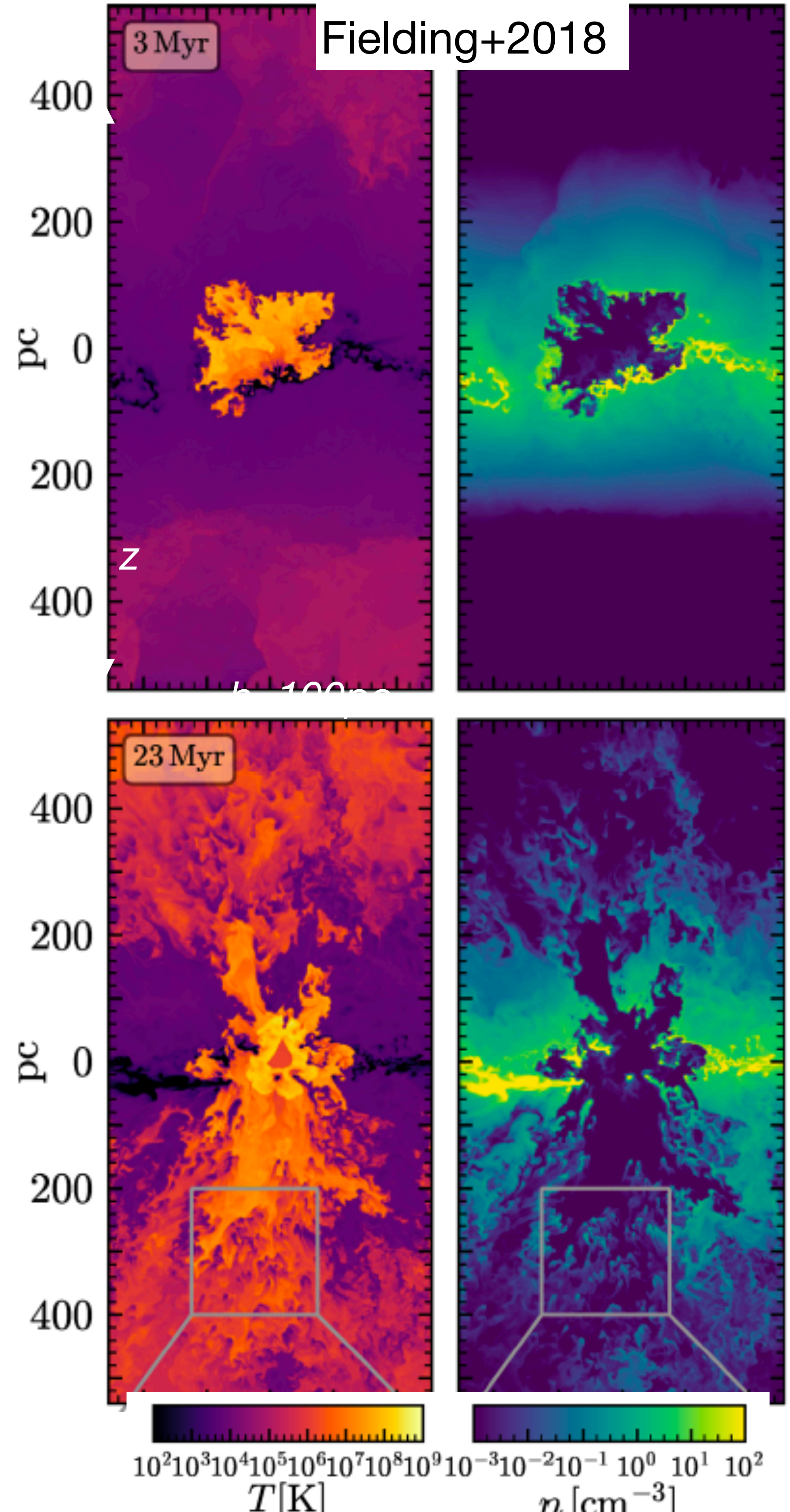

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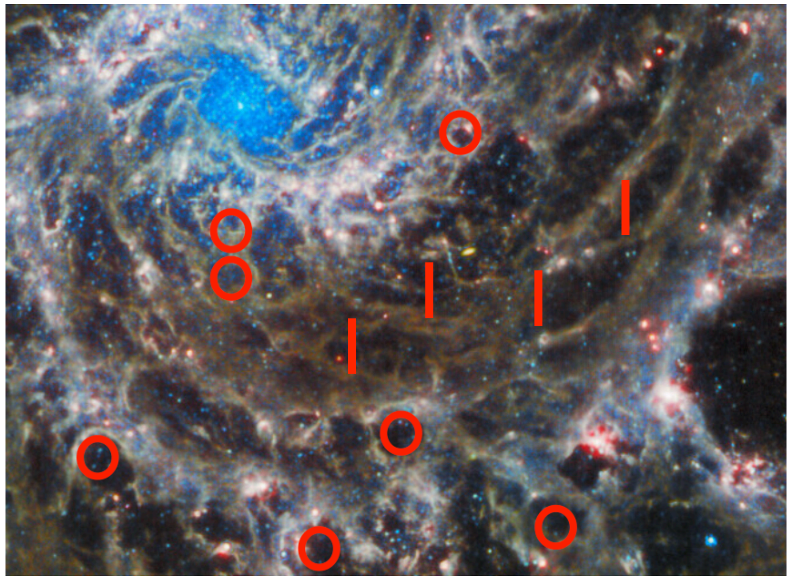
    - observed shear rate and sizes: extremely slow expansion required to explain structures with elongated/elliptical shapes



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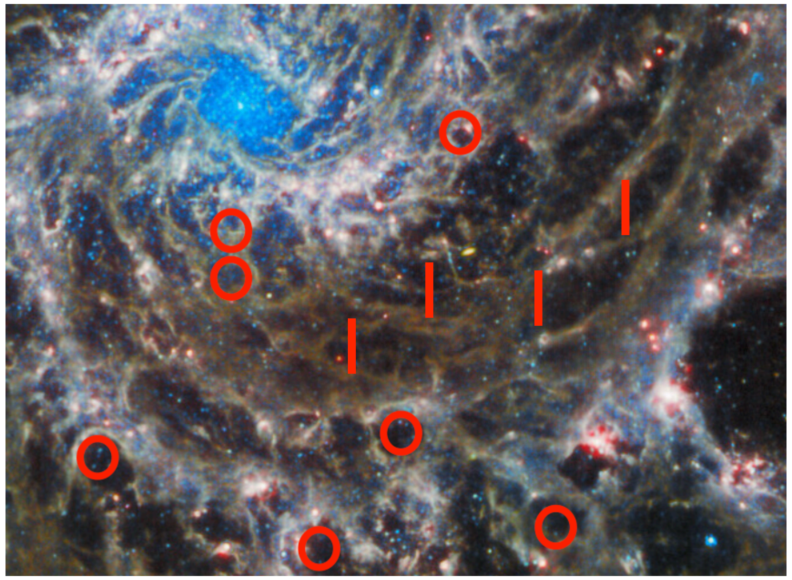
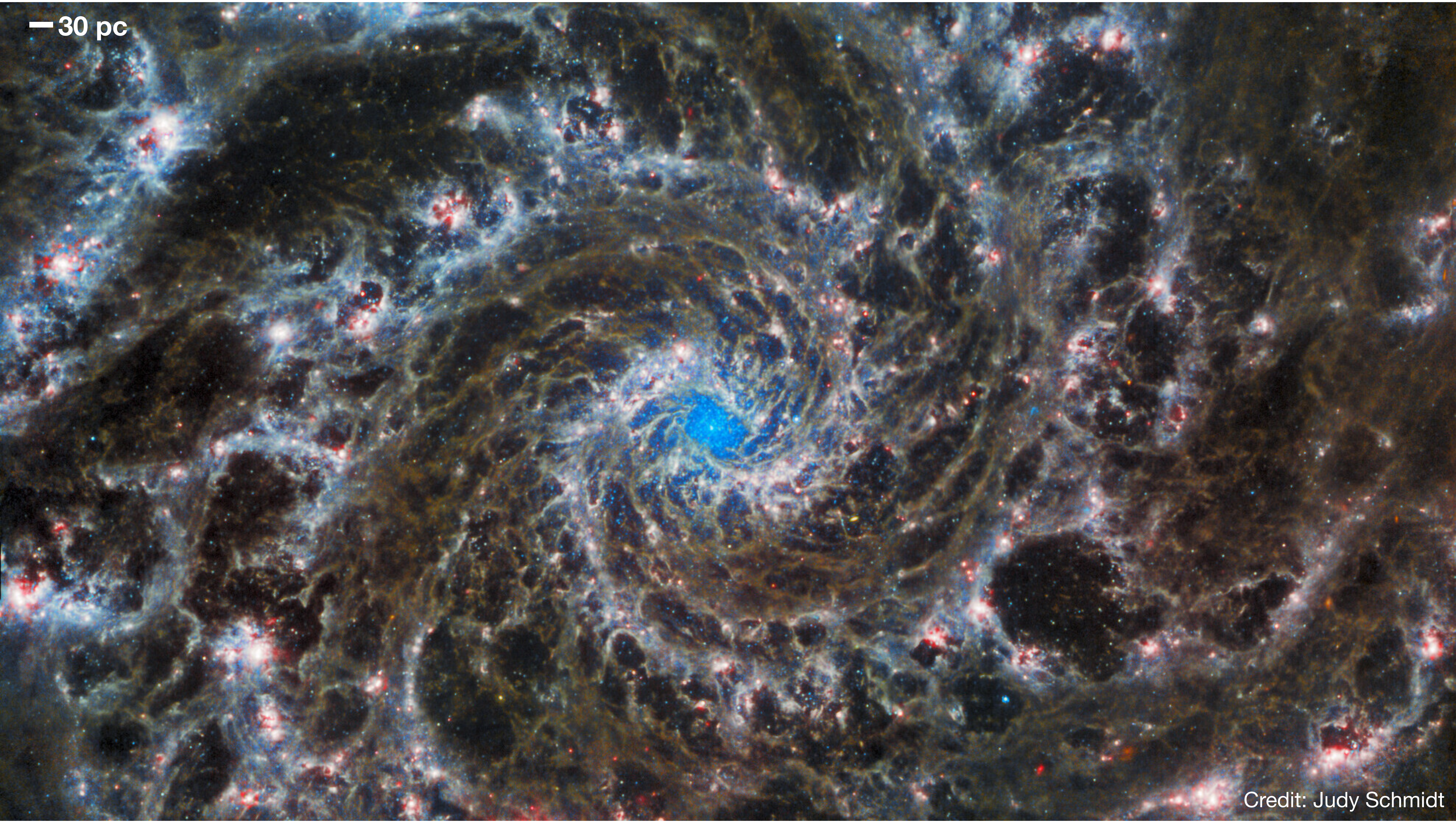


How does structure on intermediate and large scales originate??

Structure in PHANGS-JWST MIRI images

PHANGS-JWST
(Lee+2023)

(Meidt+23)

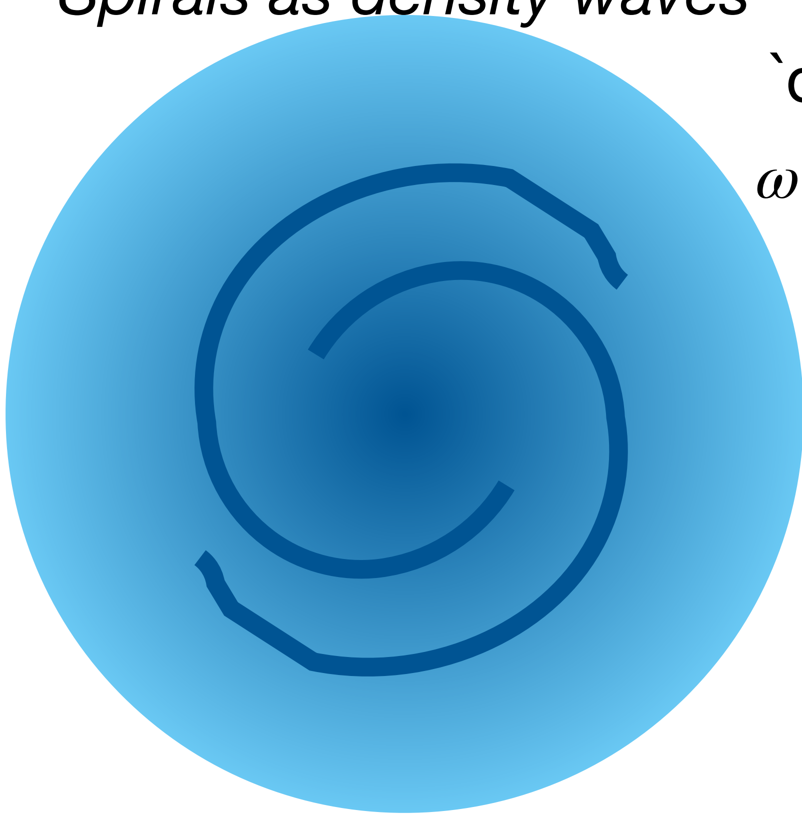


Back to: Spiral formation/disk fragmentation

- Toomre instability
- Lin-Shu spiral waves

Lin-Shu

Spirals as density waves



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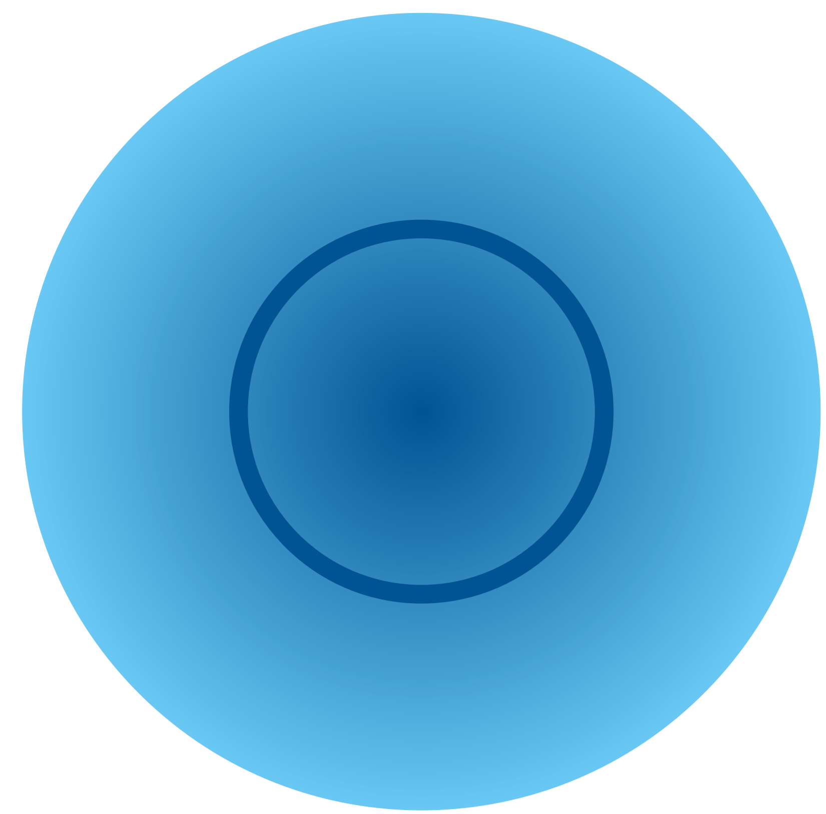
solutions IFF tight-winding modes

Toomre Q

Toomre

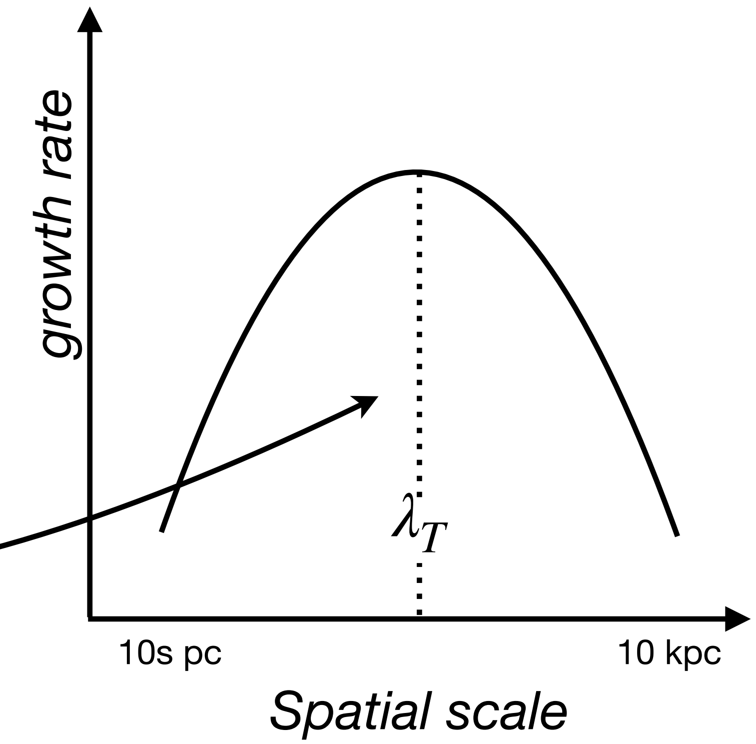
Axisymmetric (ring) instability



Toomre instability in gas & stellar disks

Balance of **pressure** and **rotation** against self-gravity

***Instability on* Toomre length** $\lambda_T = \frac{\kappa^2}{G\Sigma} \sim \boxed{\textbf{few kpcs}}$



dispersion

Rotation

As long as $Q = \frac{\sigma\kappa}{\pi G\Sigma} \leq 1$

Surface density

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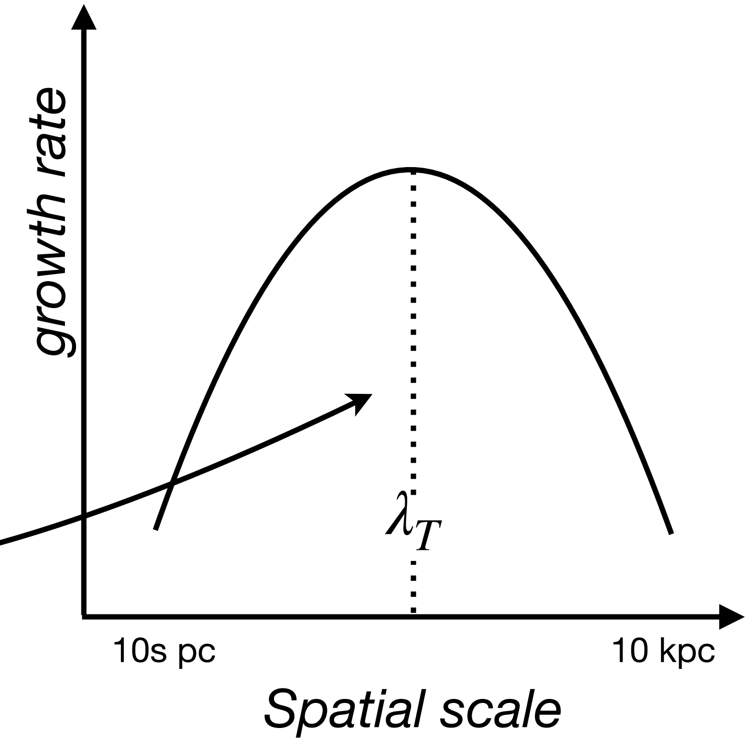

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$Q_{gas} \gtrsim 2$ e.g. Leroy+2008, Williams+in prep., Bacchini+24

$Q_{stars} \sim 1.5 - 2$ e.g. Westfall+2009

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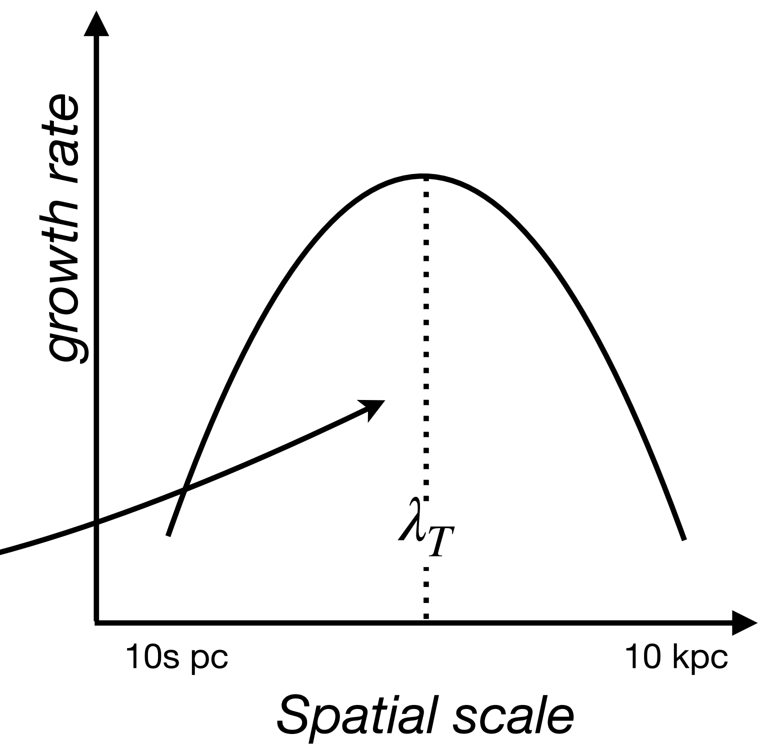

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(Lin & Shu 1966, Jog & Solomon 1984, Wang & Silk 1994, Elmegreen 1995, Rafikov 2001, Romeo & Wiegert 2011, +)

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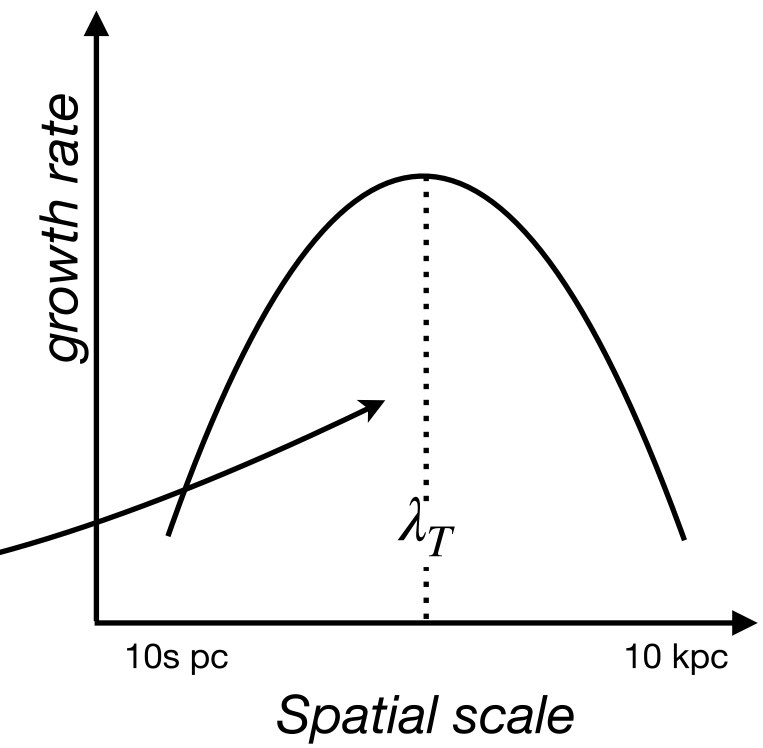

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$$Q_{comb} \gtrsim 1$$

Toomre instability can <u>sometimes</u> be responsible for structures on kpc scales

Some issues with conventional Toomre instability in massive, star-forming spiral galaxies

- ***Spatial scale***

- Even when Q~1, spiral ***pitch angles*** outside tight-winding limit

- Plenty of (intermediate scale) **‘purely-gas’ structures** — no ‘combined disk’ instability

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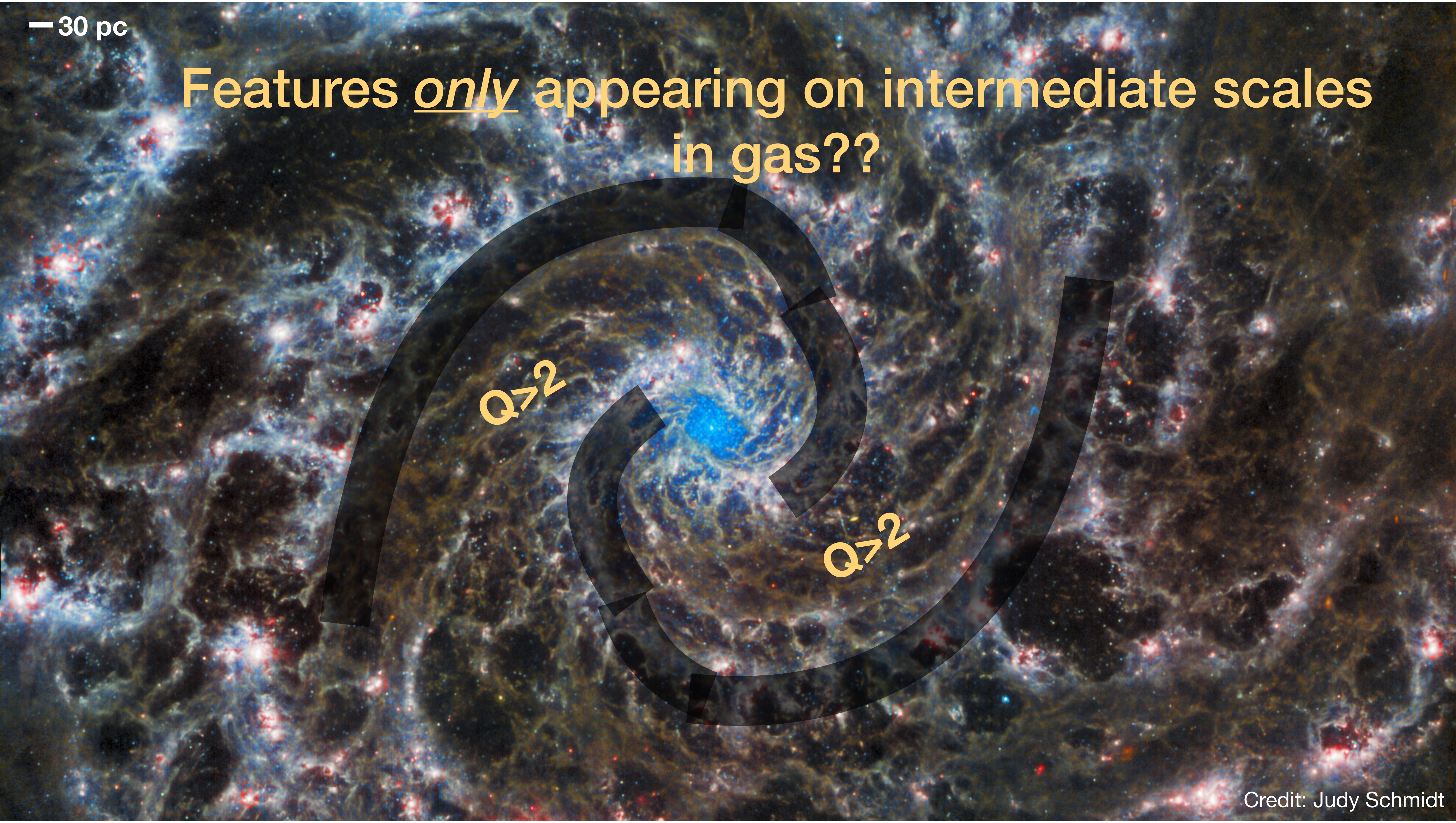
- Structures highly regular

Structure in PHANGS-JWST MIRI images

(Meidt+23)

PHANGS-JWST
(Lee+2023)



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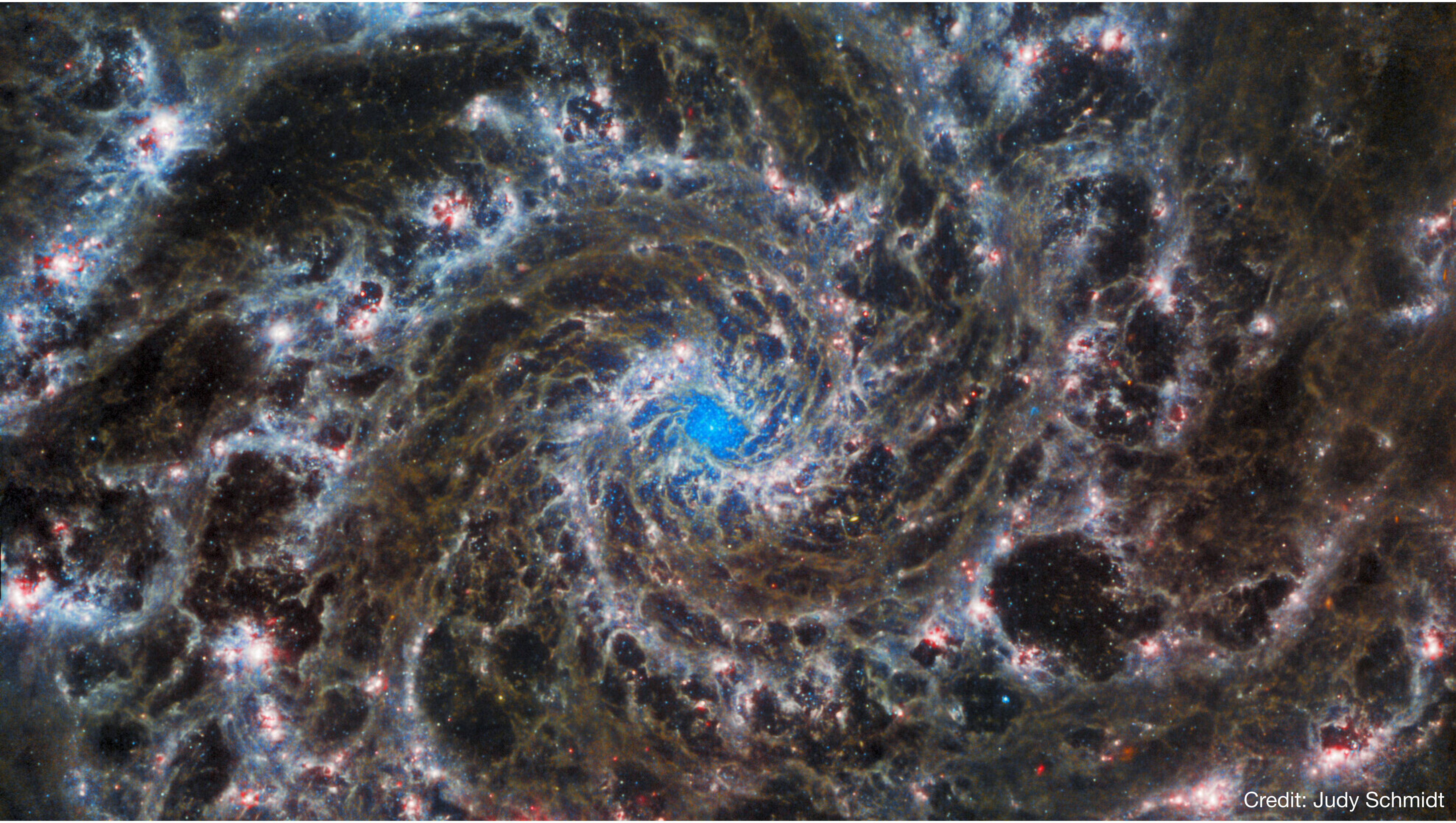

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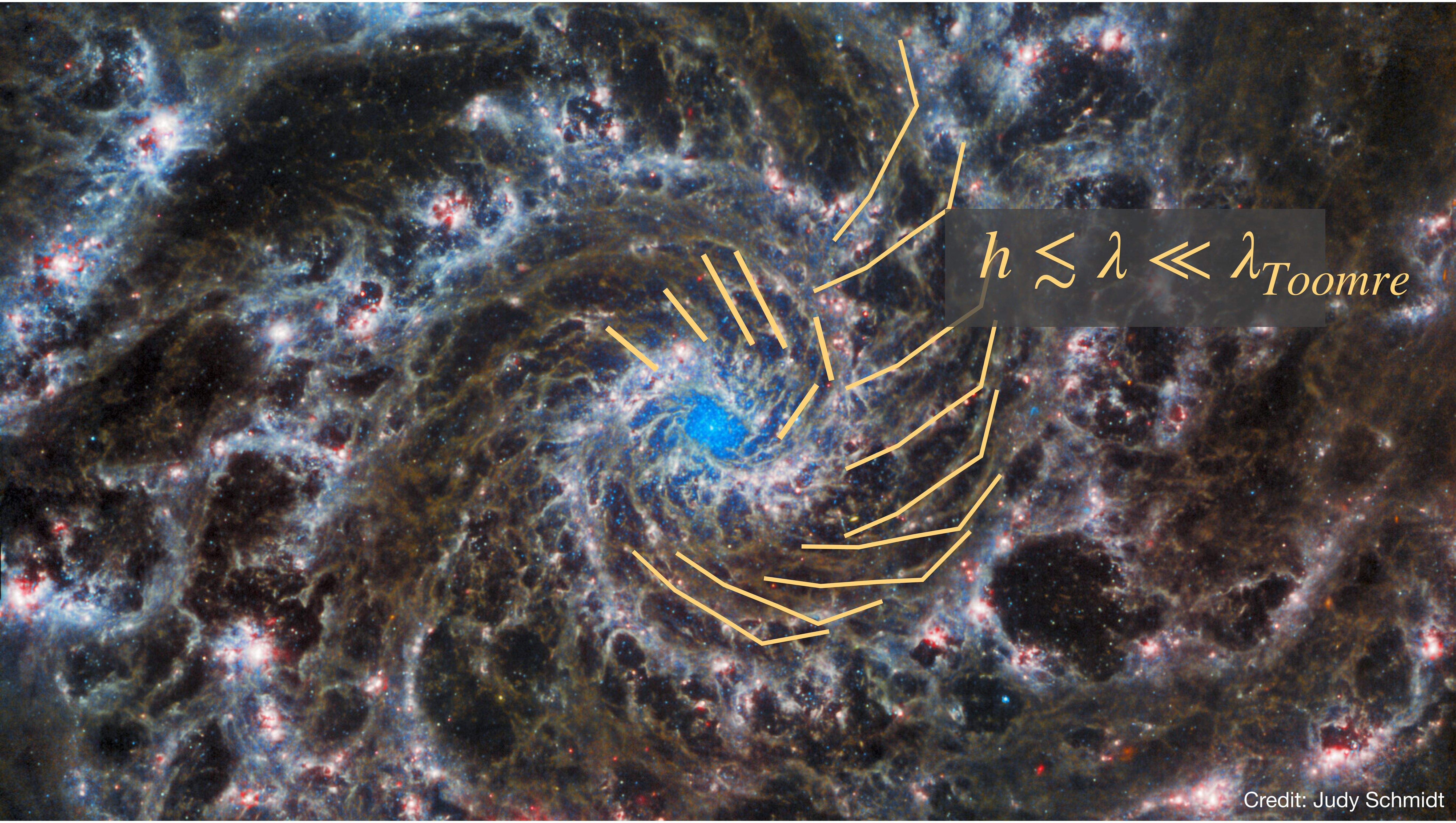

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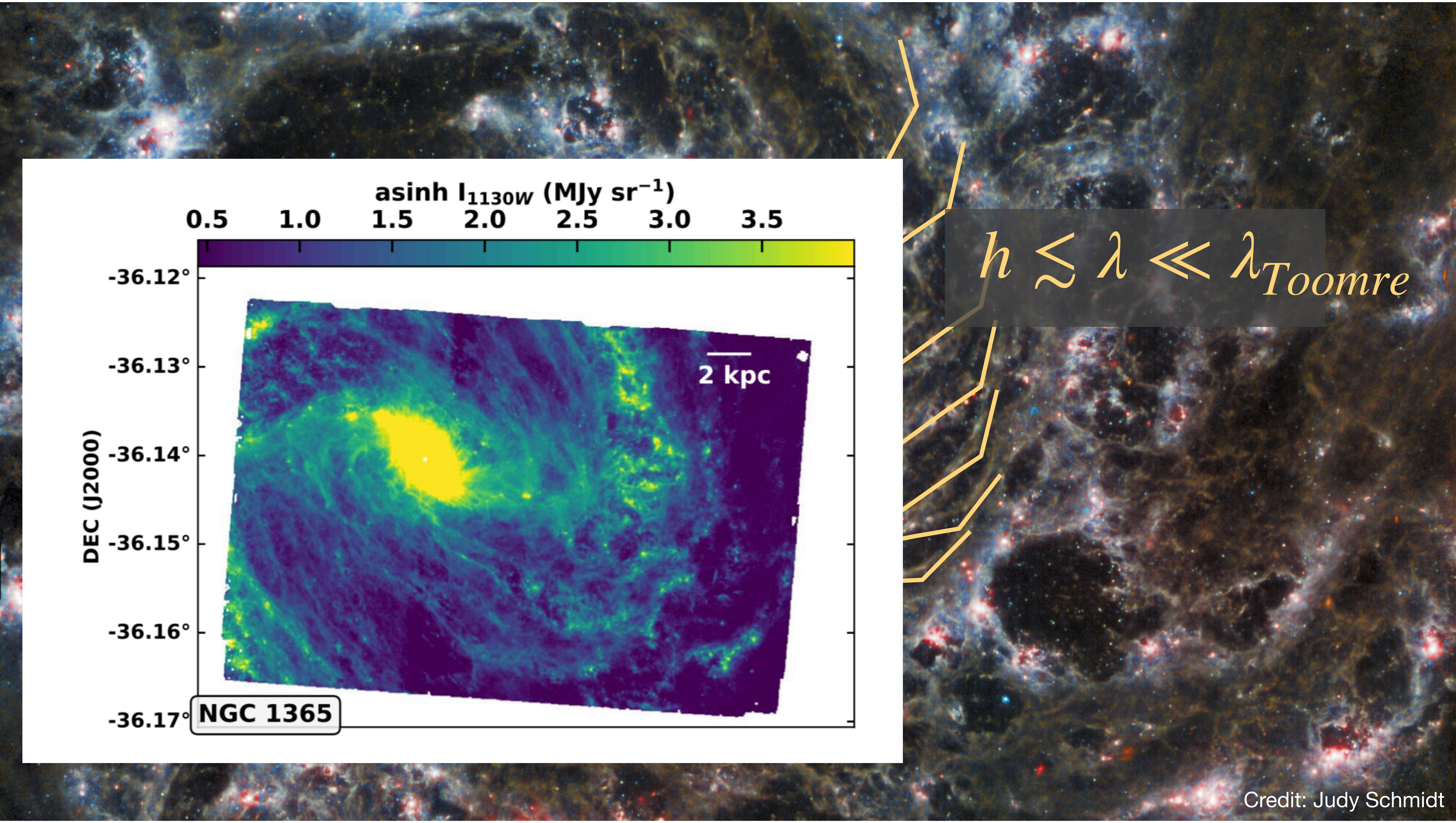

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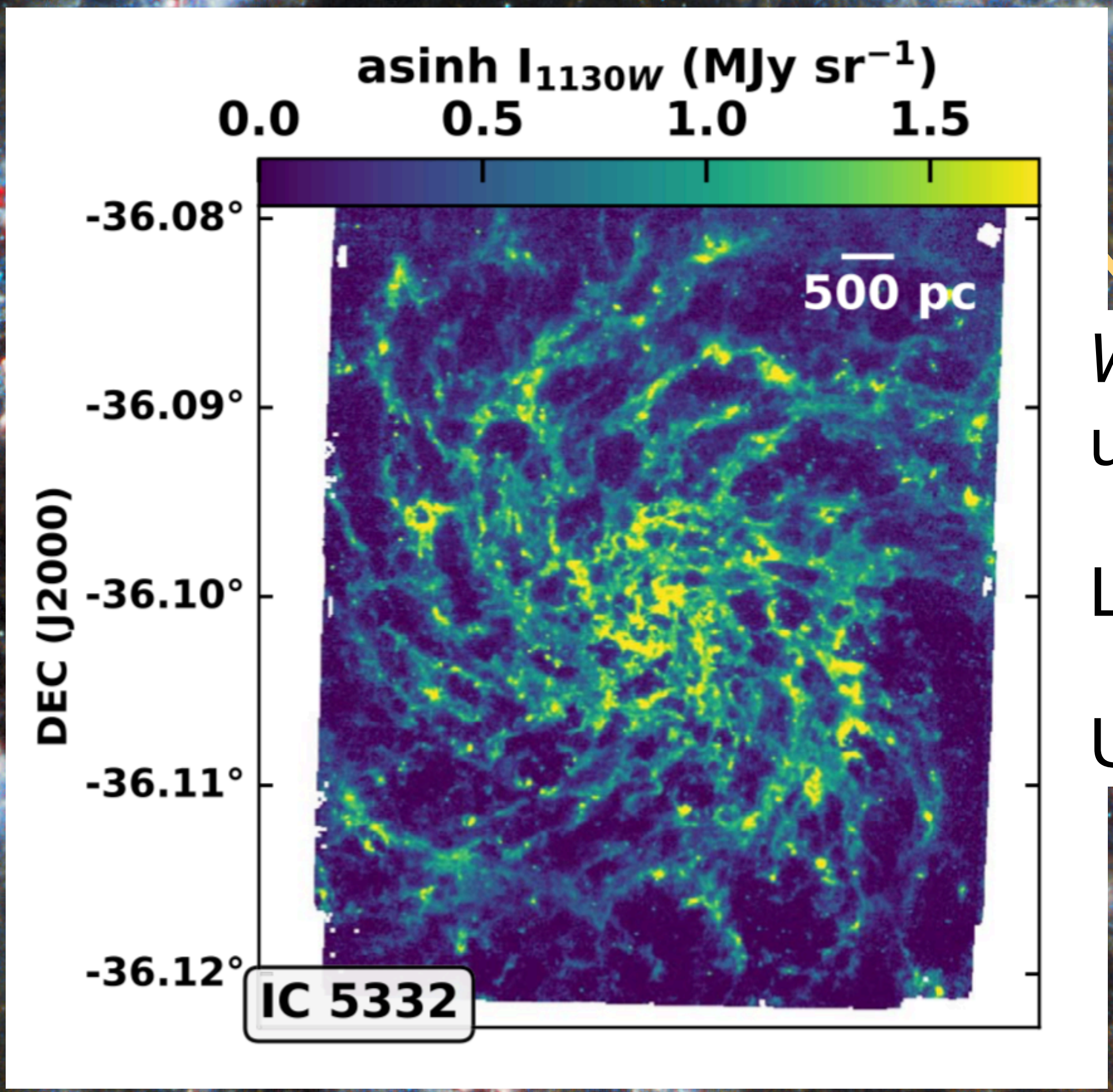


$$h \lesssim \lambda \ll \lambda_{Toomre}$$

Weak global underlying spiral!

Low SFR

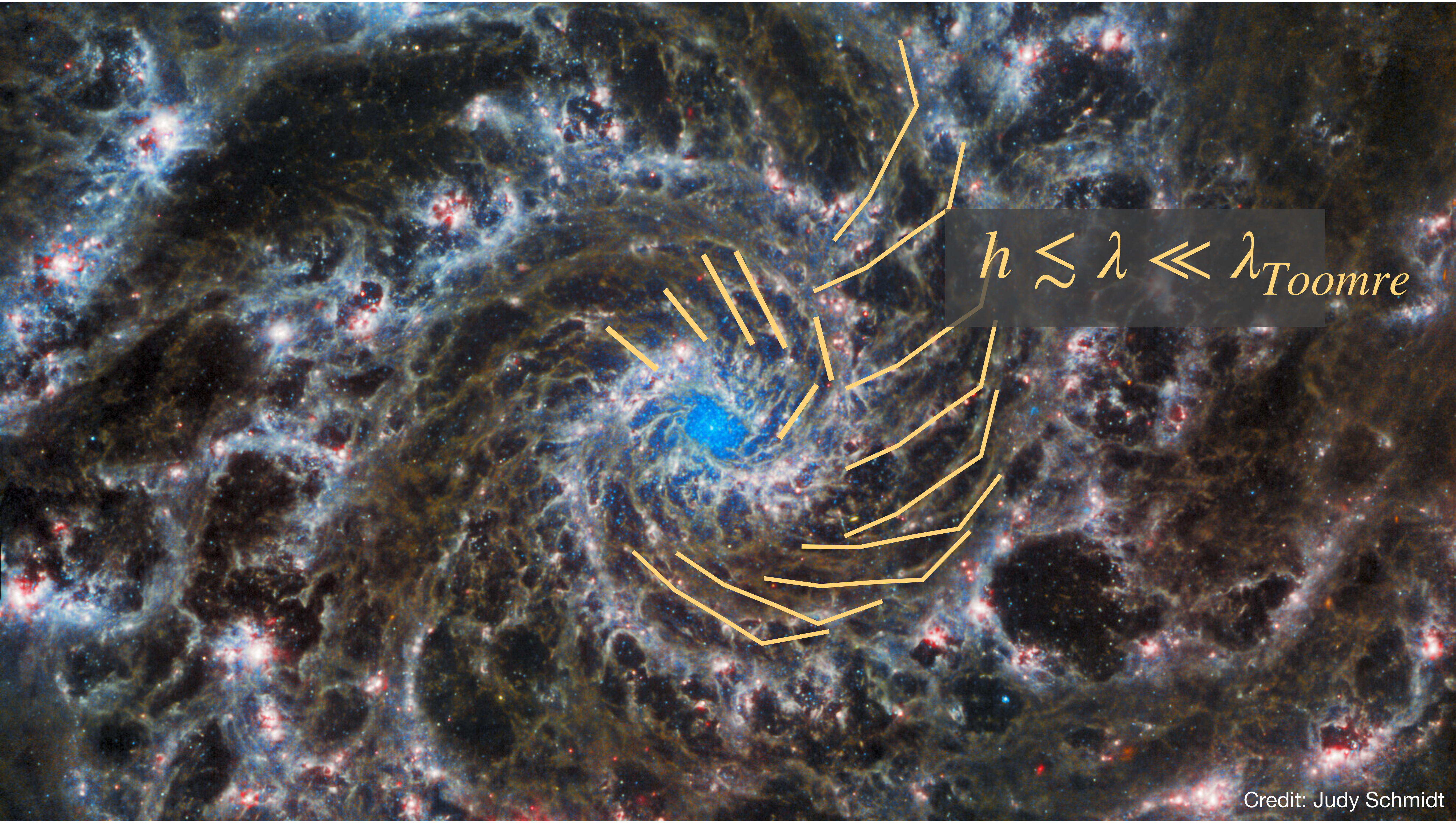
Undetected in CO

Credit: Judy Schmidt

Structure in PHANGS-JWST MIRI images

(Meidt+23)

PHANGS-JWST
(Lee+2023)

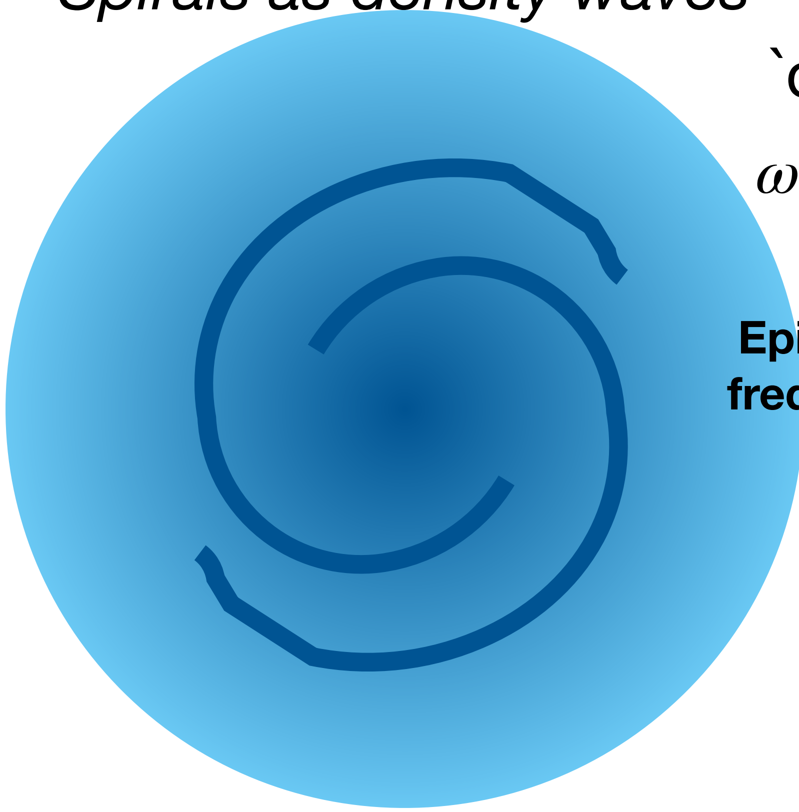


A New look at Disk instability

Meidt & van der Wel (2024)

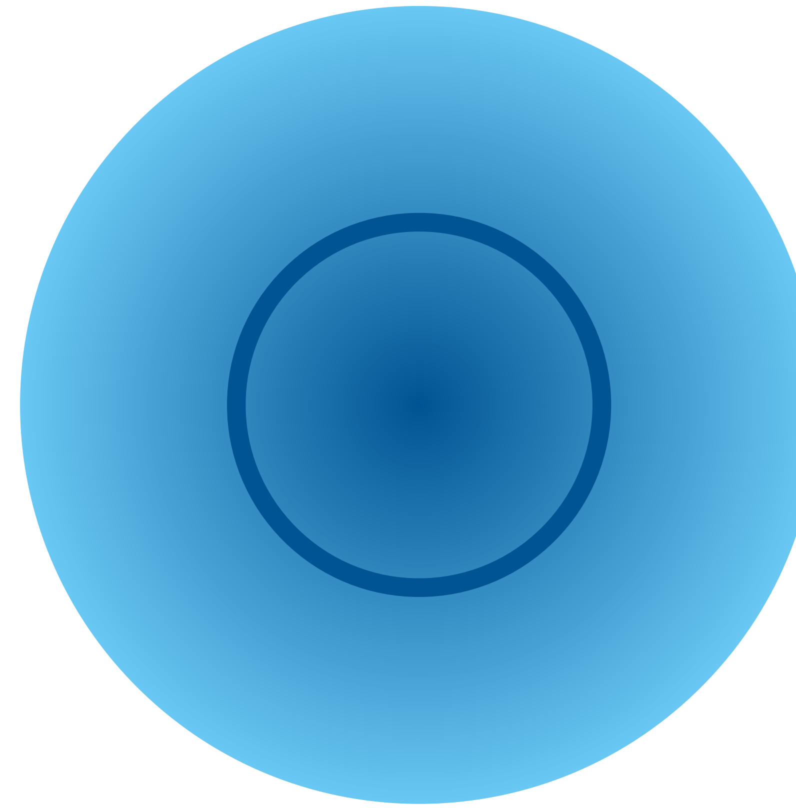
Lin-Shu

Spirals as density waves



Toomre

Axisymmetric (ring) instability



`dispersion relation’

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

Epicyclic frequency

gravity

Pressure

solutions IFF tight-winding modes

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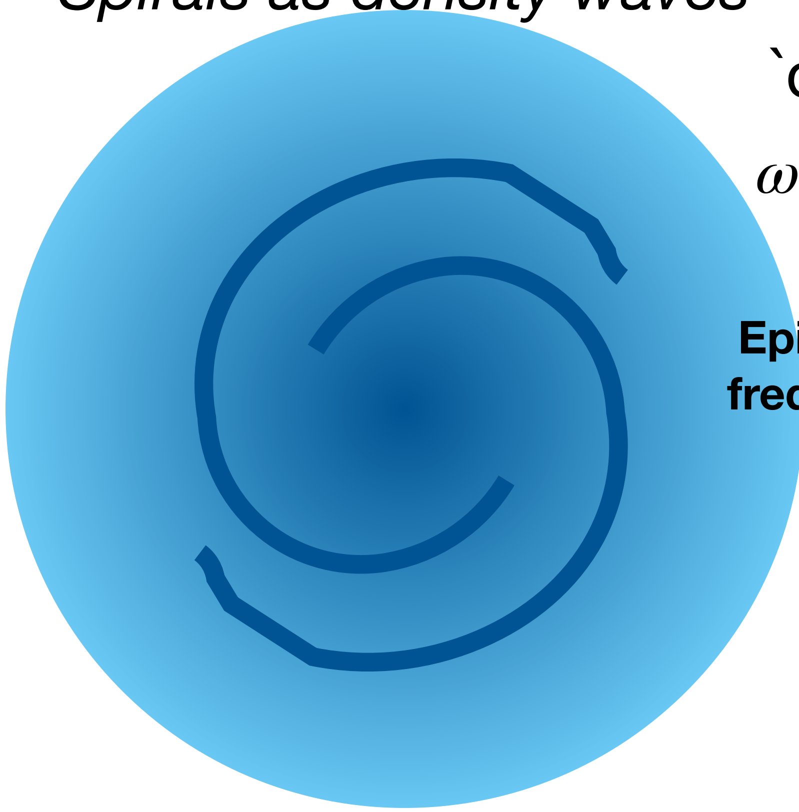

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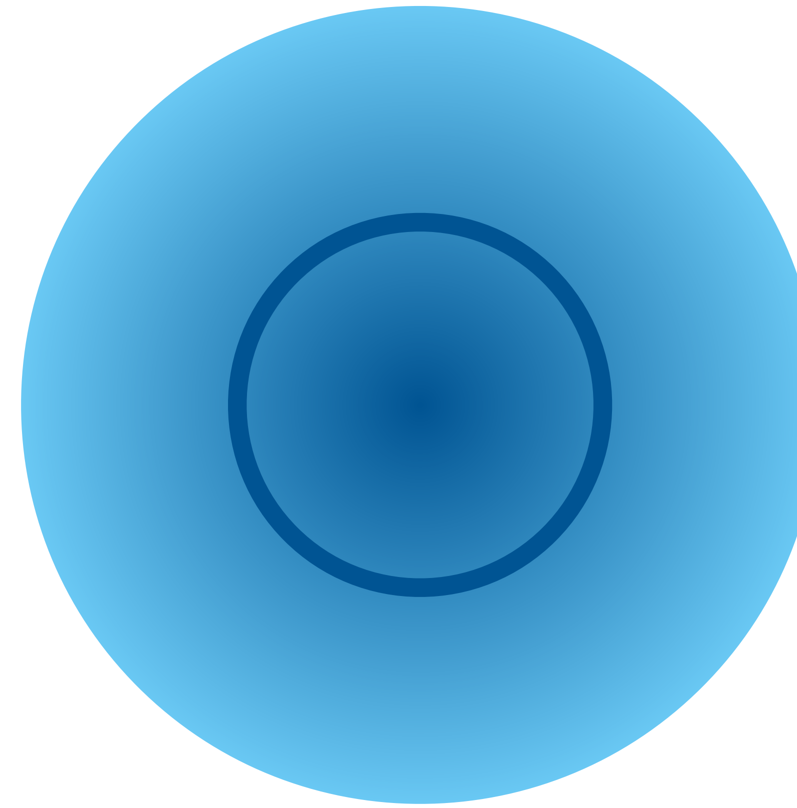

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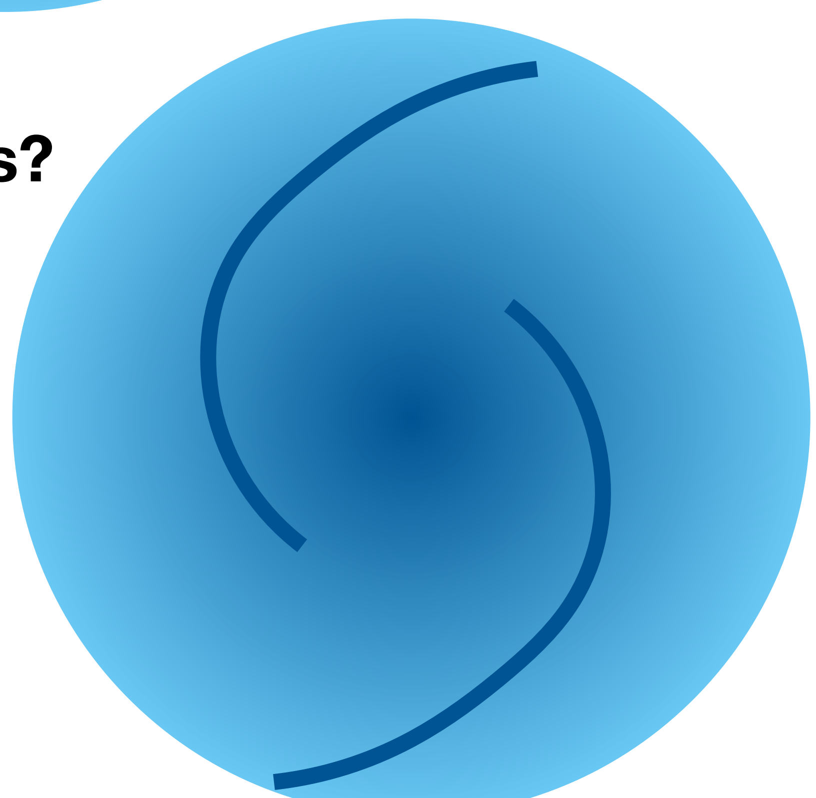
Toomre Q

Open spirals?



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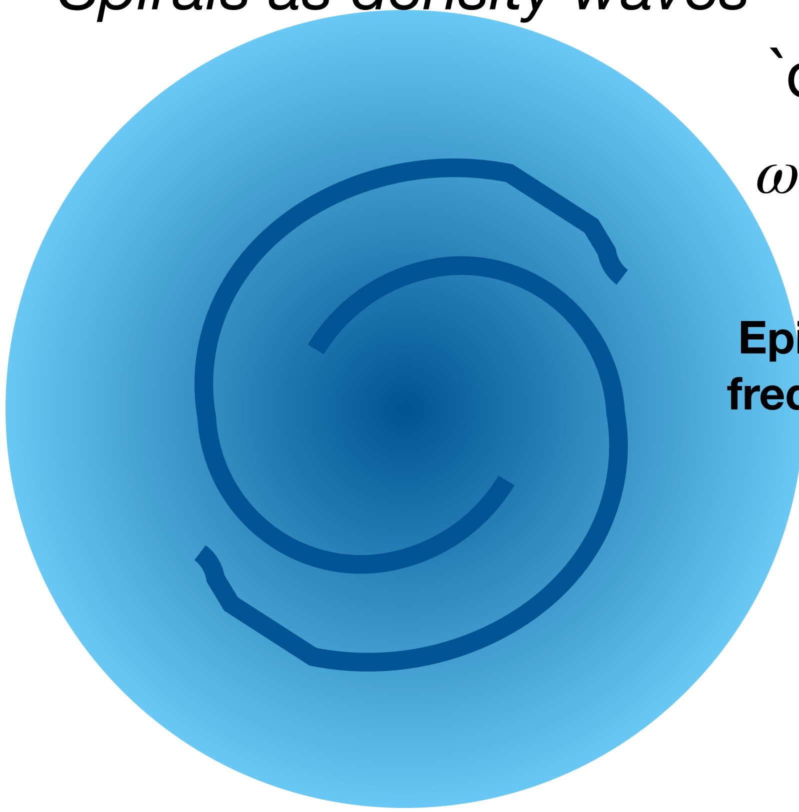

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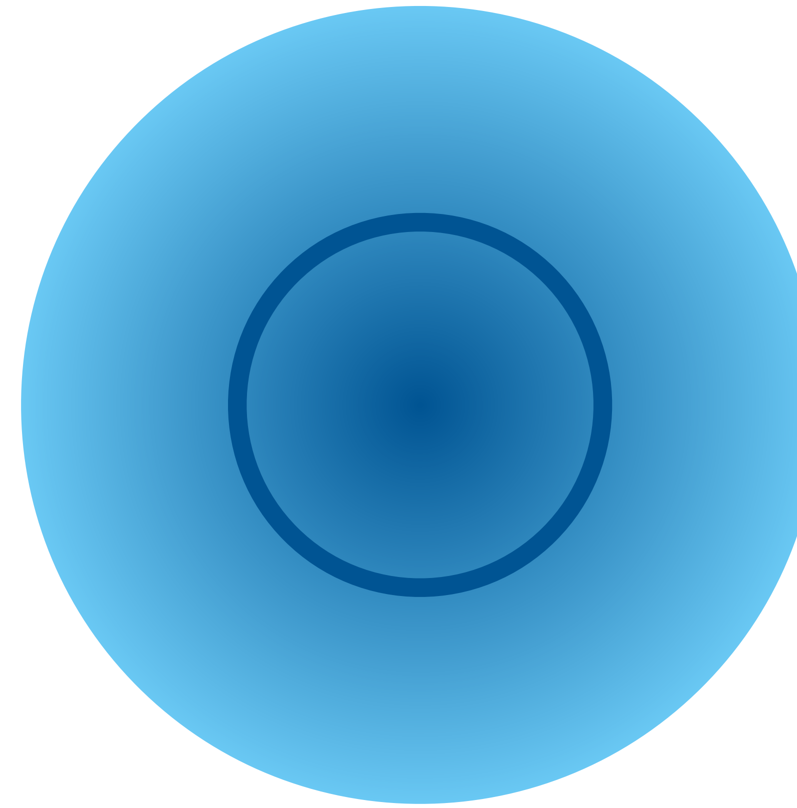
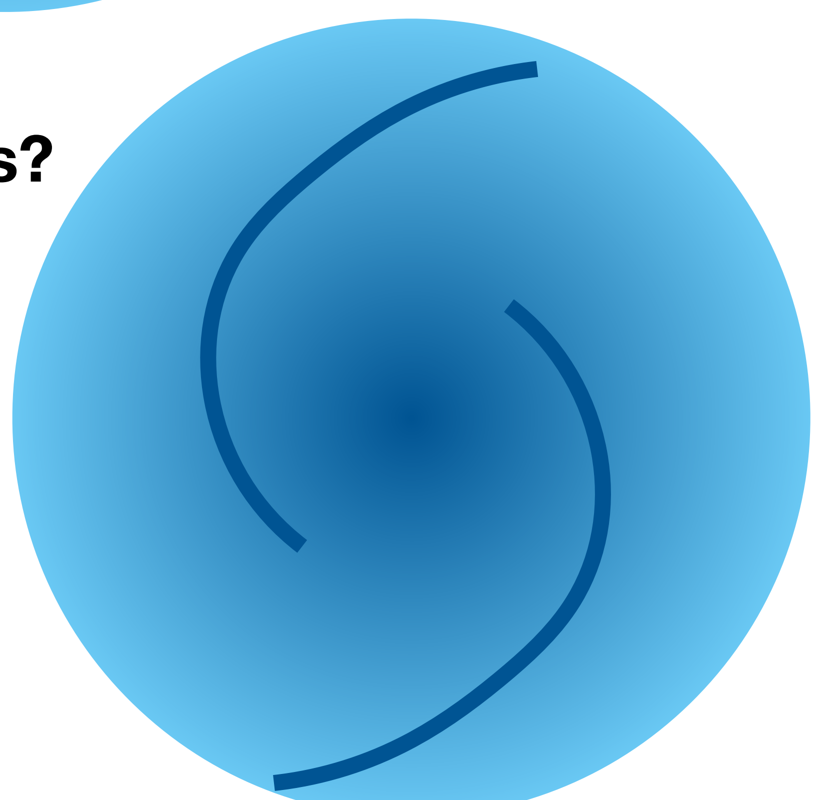


No solutions to Lin-Shu dispersion relation

Open spirals?



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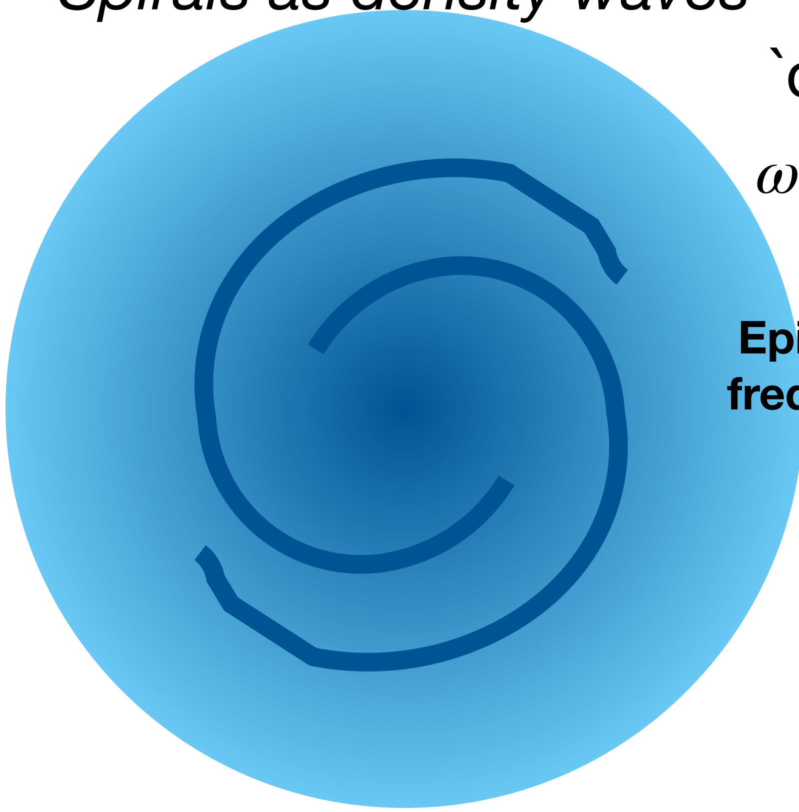


`dispersion relation'

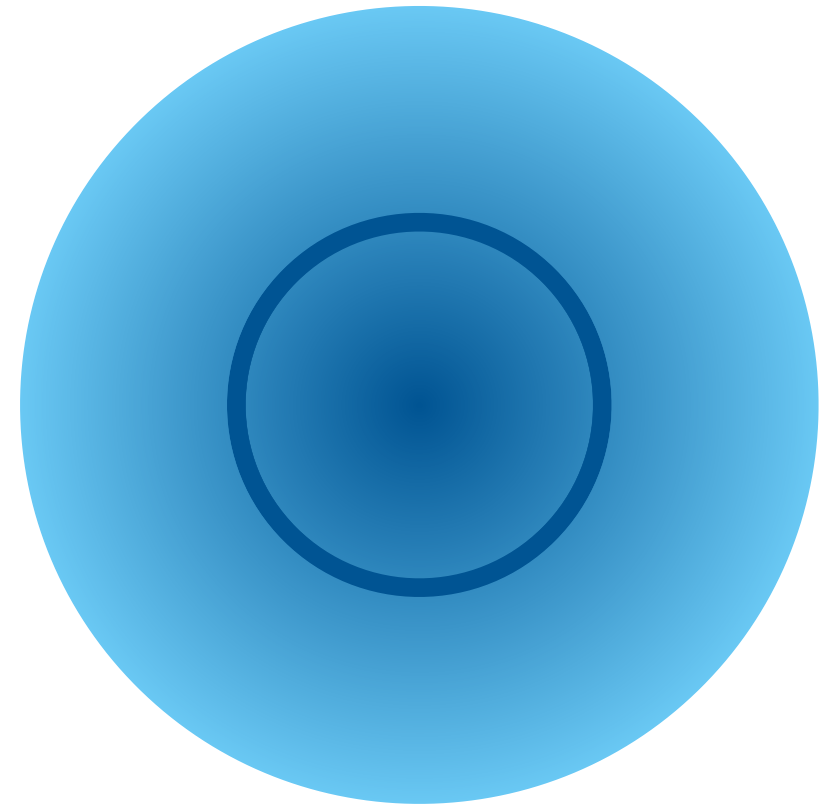
$$\omega^2 = \kappa^2 - 2\pi G\Sigma_0 k + \sigma^2 k^2$$

Epicyclic frequency **gravity** **Pressure**

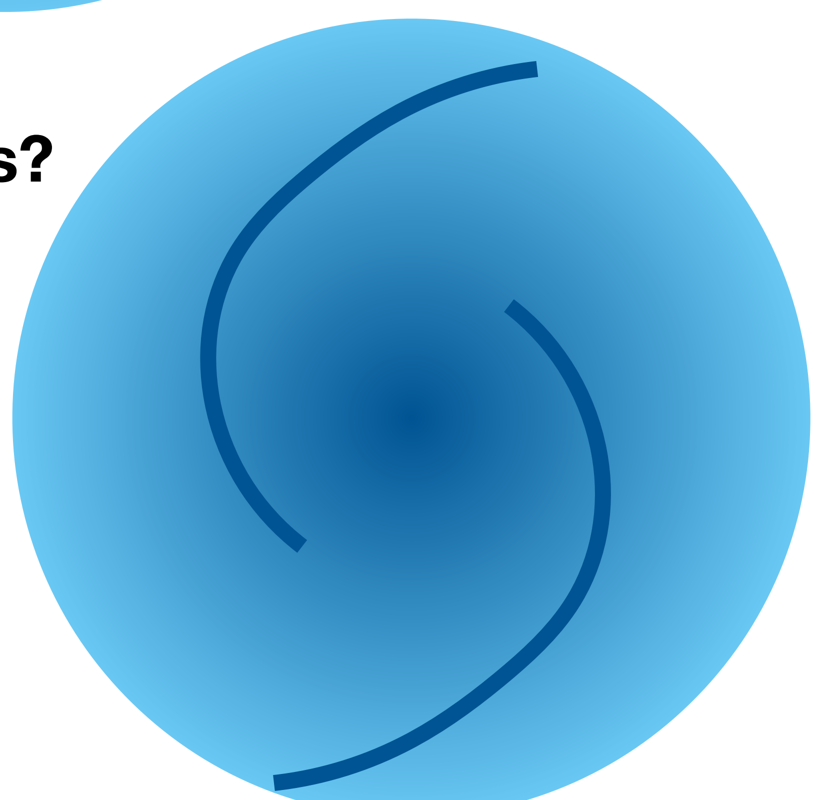
solutions IFF tight-winding modes

Toomre Q

Toomre
Axisymmetric (ring) instability



Open spirals?



No solutions to Lin-Shu dispersion relation

NEW: Extended `open-spiral' 3D dispersion relation

Meidt & van der Wel (2024)

A New look at Disk instability

Meidt & van der Wel (2024)

Lin-Shu

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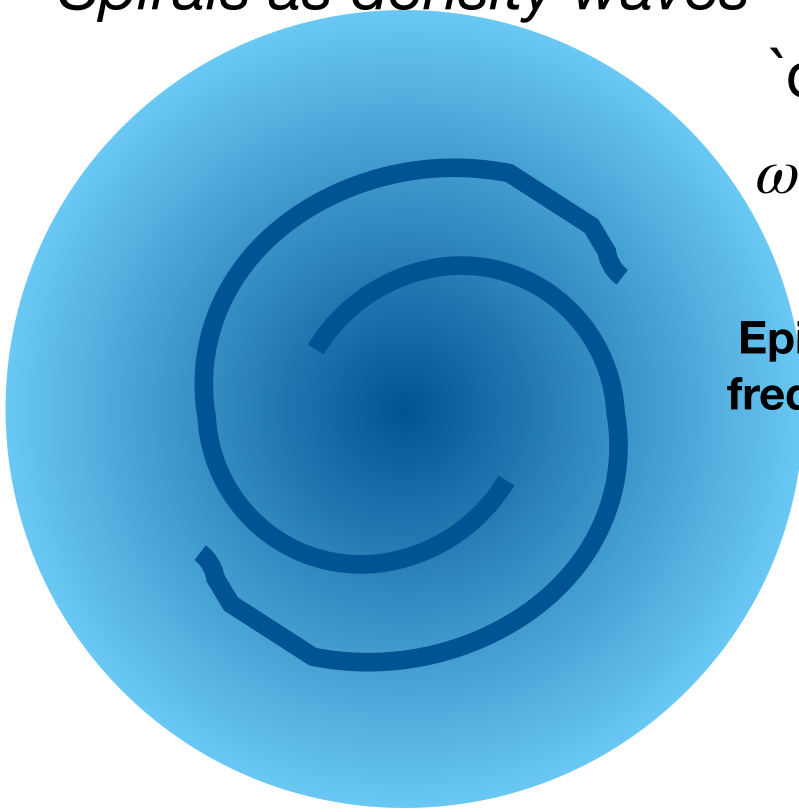

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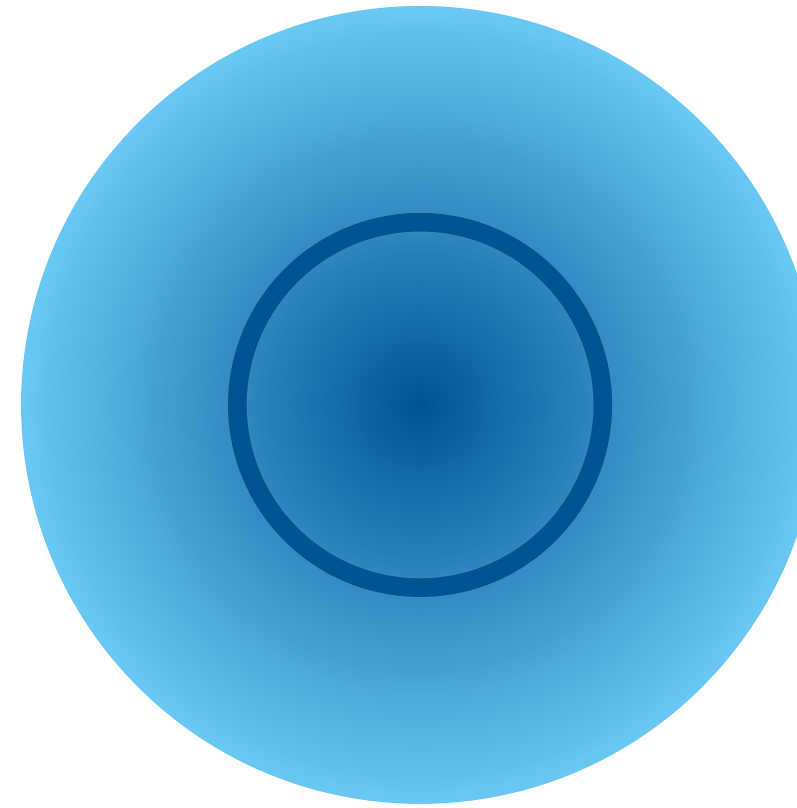

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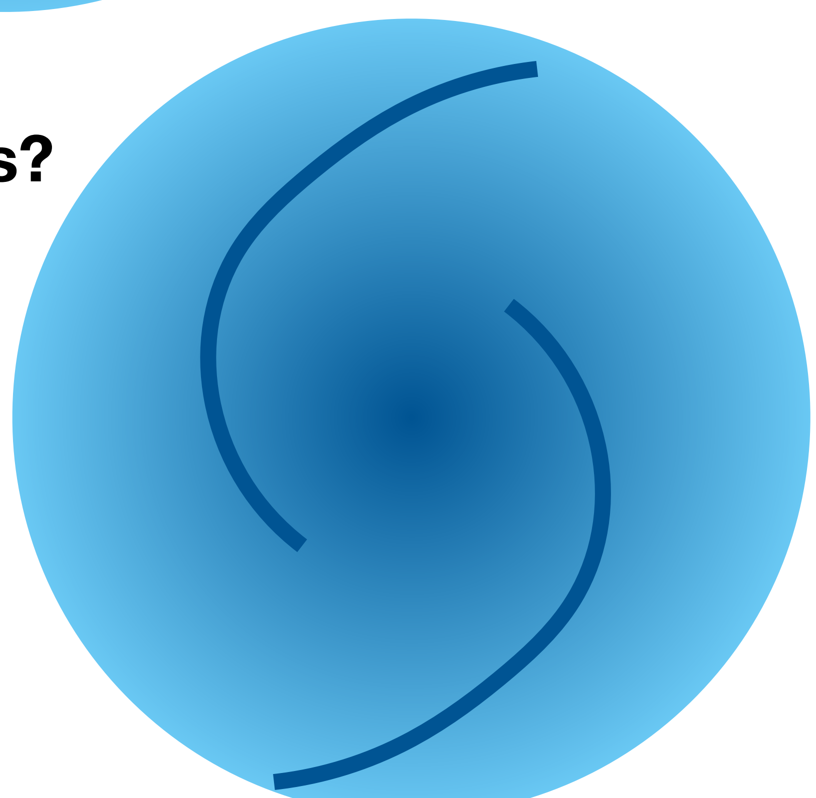

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Meidt & van der Wel (2024)

Solutions IFF spirals + disks <u>shearing</u>

Overview of a new approach for describing spirals in disks *Meidt & van der Wel (2024)*

1. Disks as constantly subject to

Abundant perturbations

e.g. Embedded corotating objects
(clusters, DM substructure)

& for gas disks: underlying stellar bars/spirals,
star formation feedback

Radial wavenumber $k = 2\pi/\lambda_R$

$$\rho_1 = \rho_a e^{i(kr+m\phi-\int\omega(R)dt)} \quad m=1\ldots\mathrm{N}$$

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Question becomes: Which grow to prominence?

(rather than how any one originates)

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2. Fluid equations

$$\frac{\partial \rho}{\partial t} = \vec{\nabla} \cdot (\rho \vec{v}) = 0$$

$$\frac{\partial \vec{v}}{\partial t} + (\vec{v} \cdot \vec{\nabla})\vec{v} = -\frac{1}{\rho}\vec{\nabla} p - \vec{\nabla}\Phi\,.$$

In cylindrical coords.

Easy to insert perturbations

Straightforward to obtain analytical dispersion relation

Useful approx. for stars esp. for $k<k_J$

isothermal, No B fields, feedback…

Lin & Shu
Lau & Bertin
Goldreich & Tremaine
Goldreich & Lynden-Bell *Shearing coords*

Overview of the approach

Meidt & van der Wel (2024)

3. Broader set of perturbations of interest:

- Modes or Material (**radially varying** $\omega = m\Omega_p$)
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3D disks (vertically extended but flattened parallel to rotation axis; Meidt 2022)

→instability at mid-plane (Meidt 2022, Nipoti 2023)

The 3D characteristic relation in the open short-wave limit

$kR \sim m$
$kR \gg 1$

$$(\omega_e - m\Omega)^3 = (\omega_e - m\Omega)\left[\kappa^2 + \left(k_e^2 + \frac{m^2}{R^2}\right)s_0^2\right]$$
$$+ i\left(\frac{2Ak_e m}{R}\right)s_0^2$$

Cubic relation.

NOTE: Constant term changes in long-wave limit $k \to 0$
(Meidt & van der Wel in prep.)

$$\omega_e = \omega - \dot{k}R$$

$$k_e = k - \int \frac{\partial \omega}{\partial R} dt$$

External perturbation

$\mathcal{F}_e / \mathcal{F} \ll 1$

$$s_0^2 = \frac{-4\pi G\rho_0}{k_e^2 + \frac{m^2}{R^2}}\left(1 + \frac{\mathcal{F}_e}{\mathcal{F}}\right) + \sigma^2$$

$$\Phi_1 \approx \frac{-4\pi G\rho_1}{k^2 + \frac{m^2}{R^2}}$$

At mid-plane, for `short' waves

Poisson's eqn.

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Dominates solutions for $Q \gtrsim 1$

Ready amplification of non-axisymmetric structures **(Goldreich & Lynden-Bell 1965, Julian & Toomre 1966)**

‘Swing amplification’

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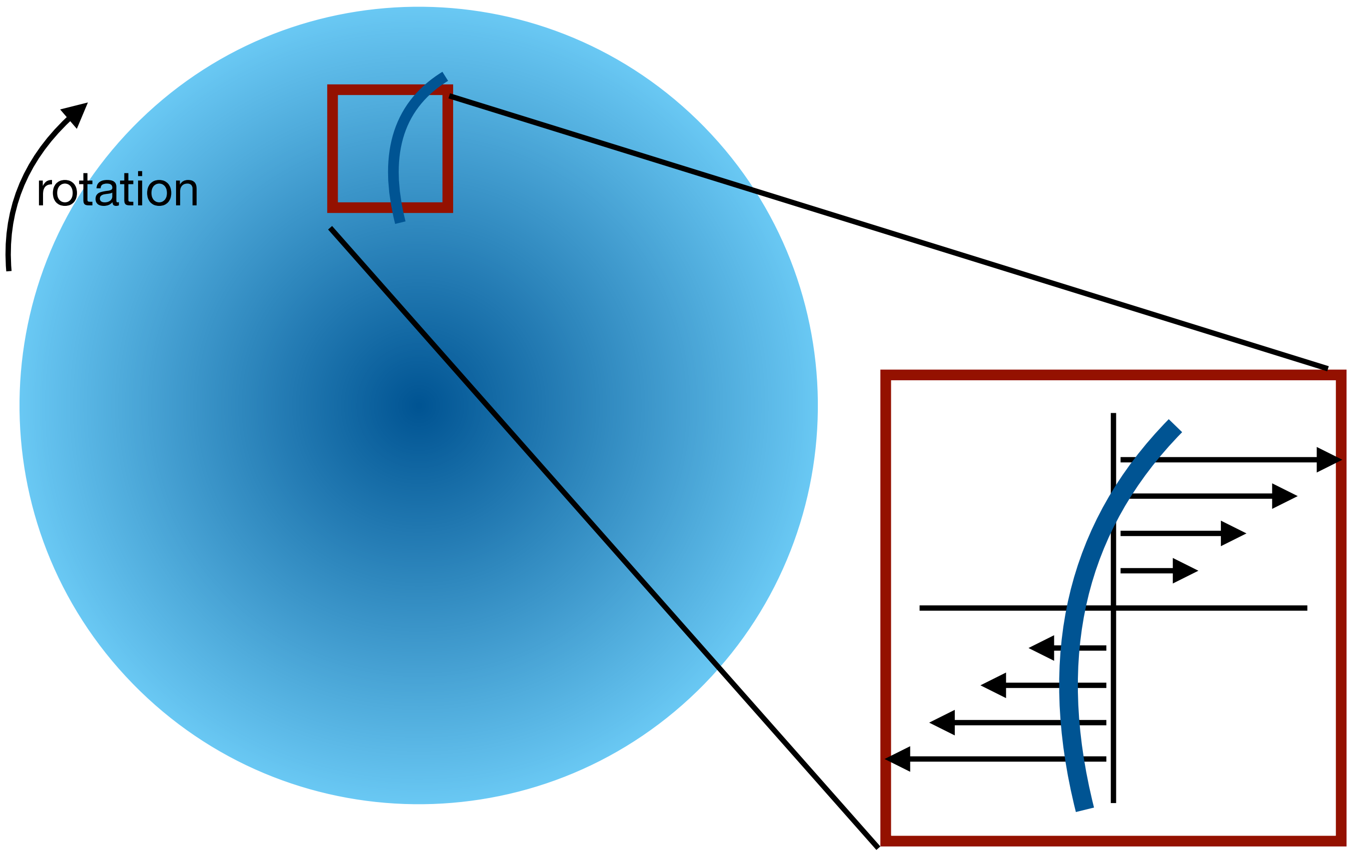
'Swing amplification'

Past treatments:

Shearing coordinates centered on a shearing patch of a galaxy

(Goldreich & Lynden-Bell 1965, Julian & Toomre 1974)



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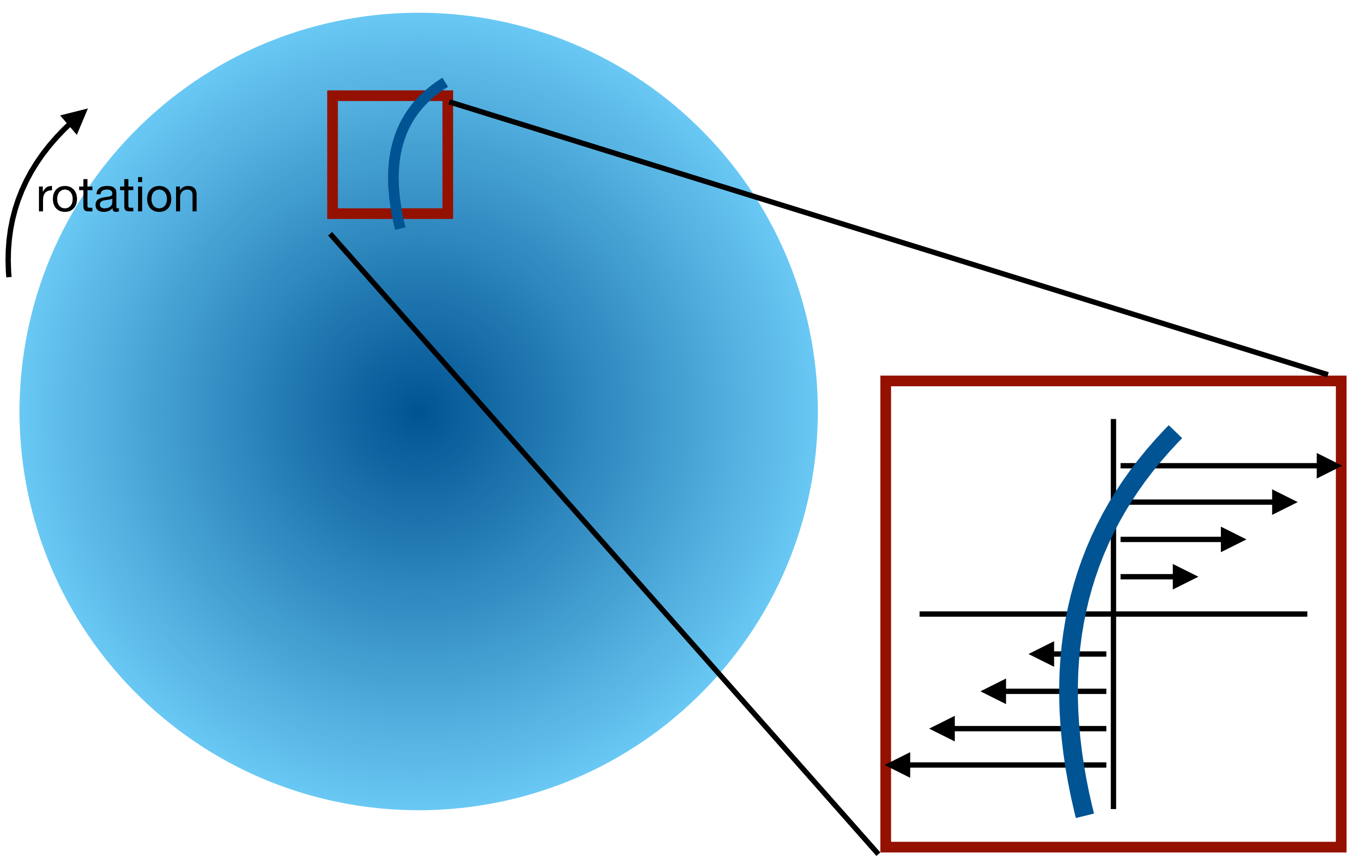

Wakelets in response to orbiting bodies

New treatment:

for global structure formation

(Meidt & van der Wel subm.)

Cylindrical coordinates centered on galaxy center

Swing amplification in context of **Lin-Shu framework**

Revisioned in terms of spiral forcing (rather than only shear)

Concrete predictions for orientations/ pitch angles

‘open growth term’

Meidt & van der Wel (2024)

(The swing-amplifier term)

Q>1 Cubic solutions:

Straightforward growth for $(\omega - m\Omega) = 0$ $\left\{ \begin{array}{l} \textbf{i/ Material patterns} \\ \textbf{ii/ Modes at corotation} \end{array} \right.$

$$\longrightarrow \quad \omega_i^3 = \left(\frac{2Ak_e m}{R}\right) 4\pi G\rho_0 \left(\frac{1}{k_e^2 + \frac{m^2}{R^2}} - \frac{1}{k_J^2}\right)$$

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For stars: good to 2nd order in $\frac{\sigma^2 k_T^2}{\kappa^2}$ in Kalnajs reduction factor

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Non-zero m: introduces `donkey’ behaviour See Lynden-Bell & Kalnajs (1972)

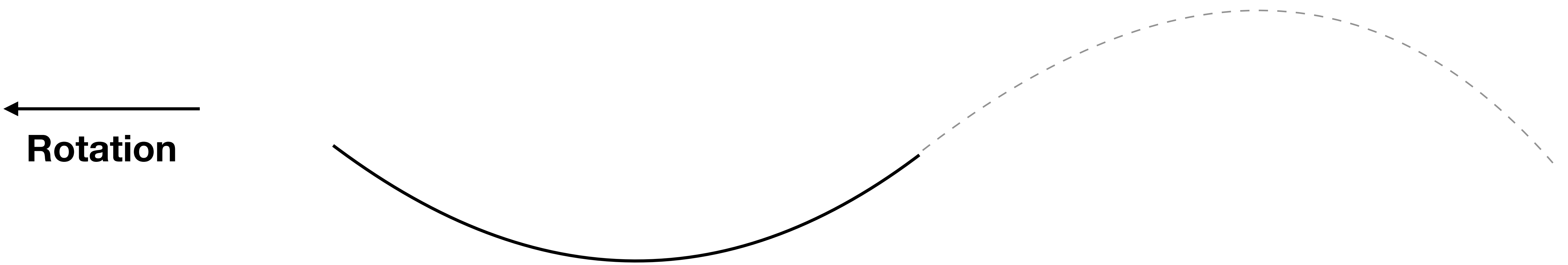
Needs to be trailing given typical rotation in gal. disks

Spiral arm frame

Meidt & van der Wel (2024)

With azimuthal forcing:

1. **Reduction in epicyclic frequency**
2. **Donkey behaviour**



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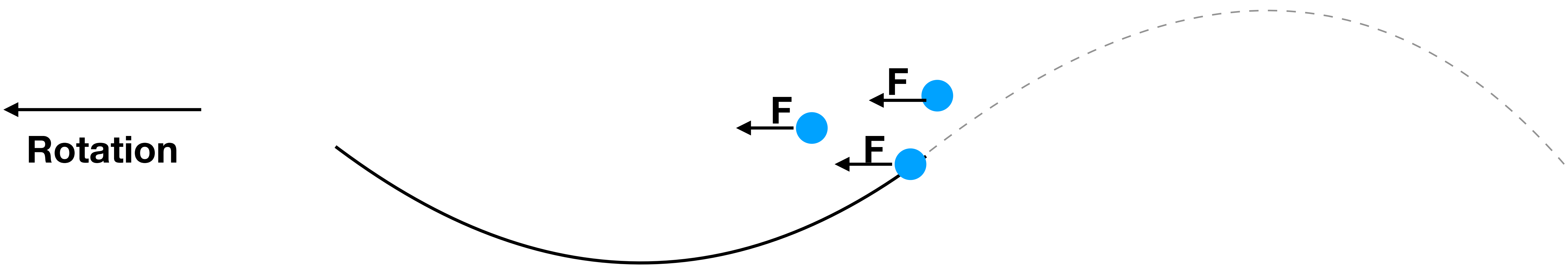

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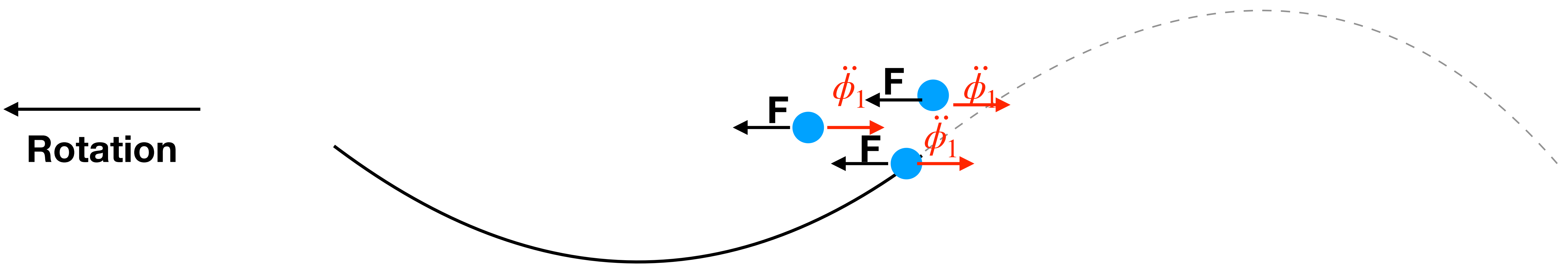

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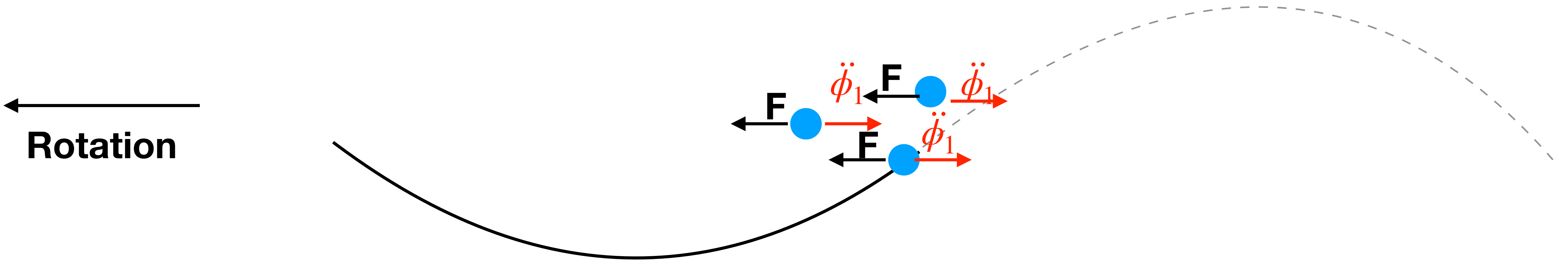

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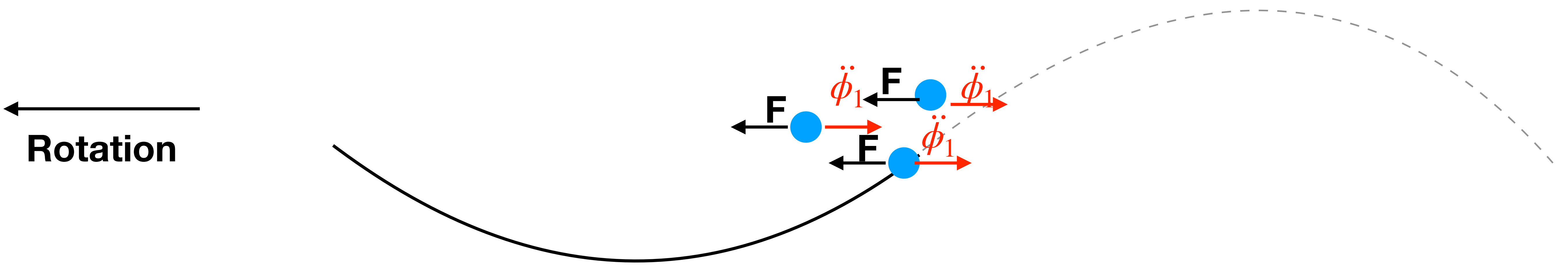

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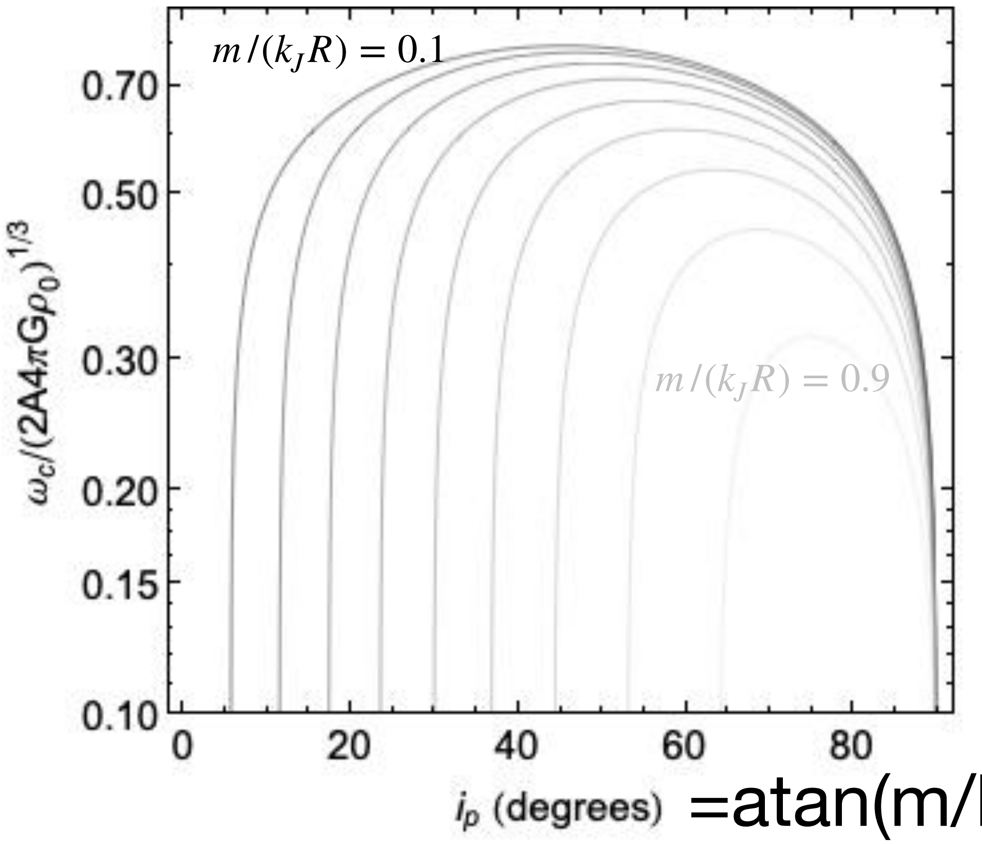
Result: departure from minimum & libration in inter-arm
(Small-angle limit of horseshoe orbits)

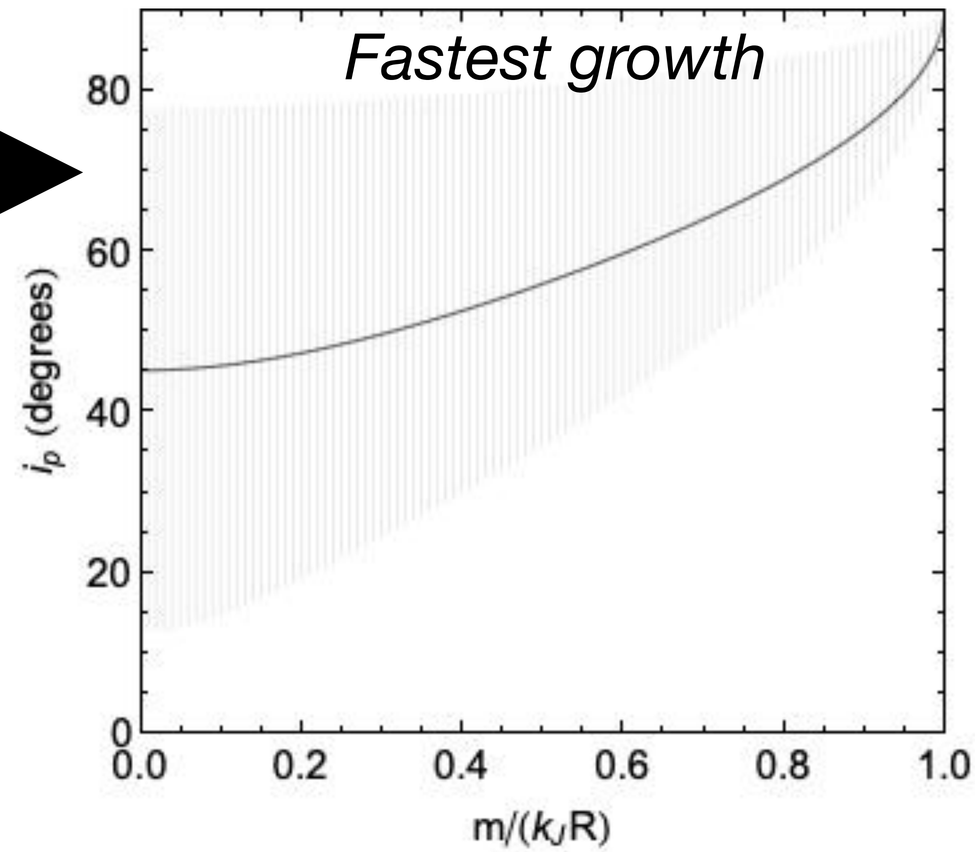
stars/particles take energy/angular momentum from wave→ amplification

The critical pitch angle

Meidt & van der Wel (2024)



=atan(m/kR)



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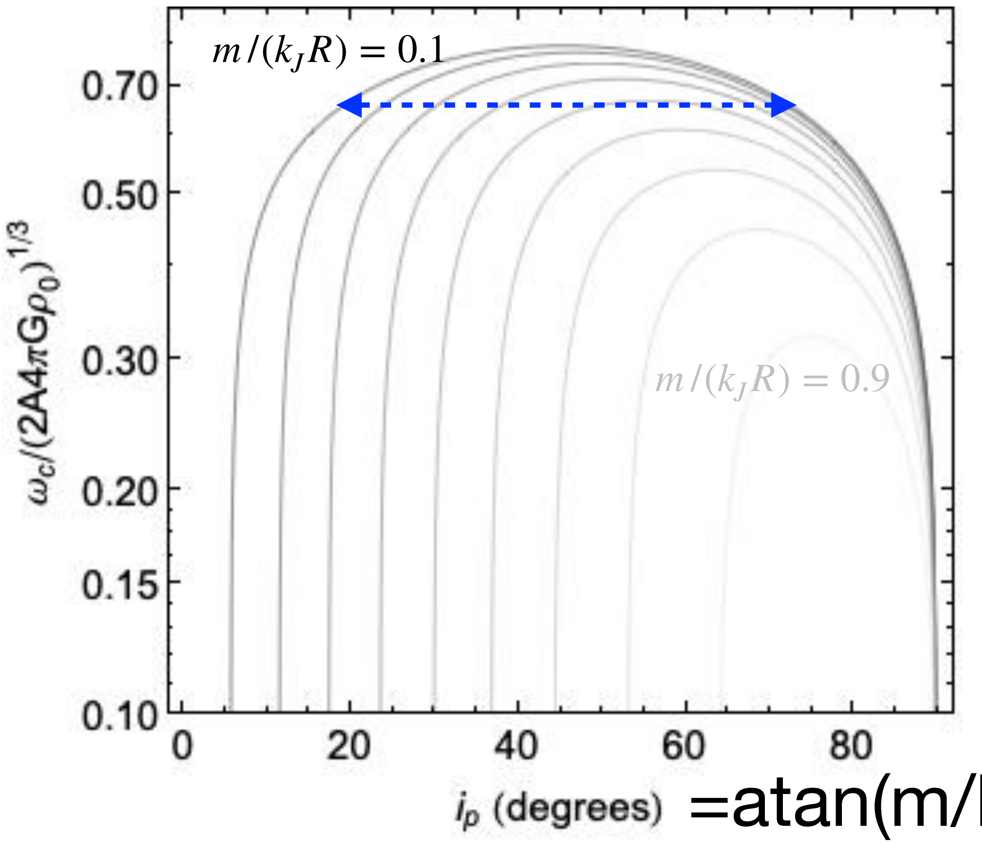

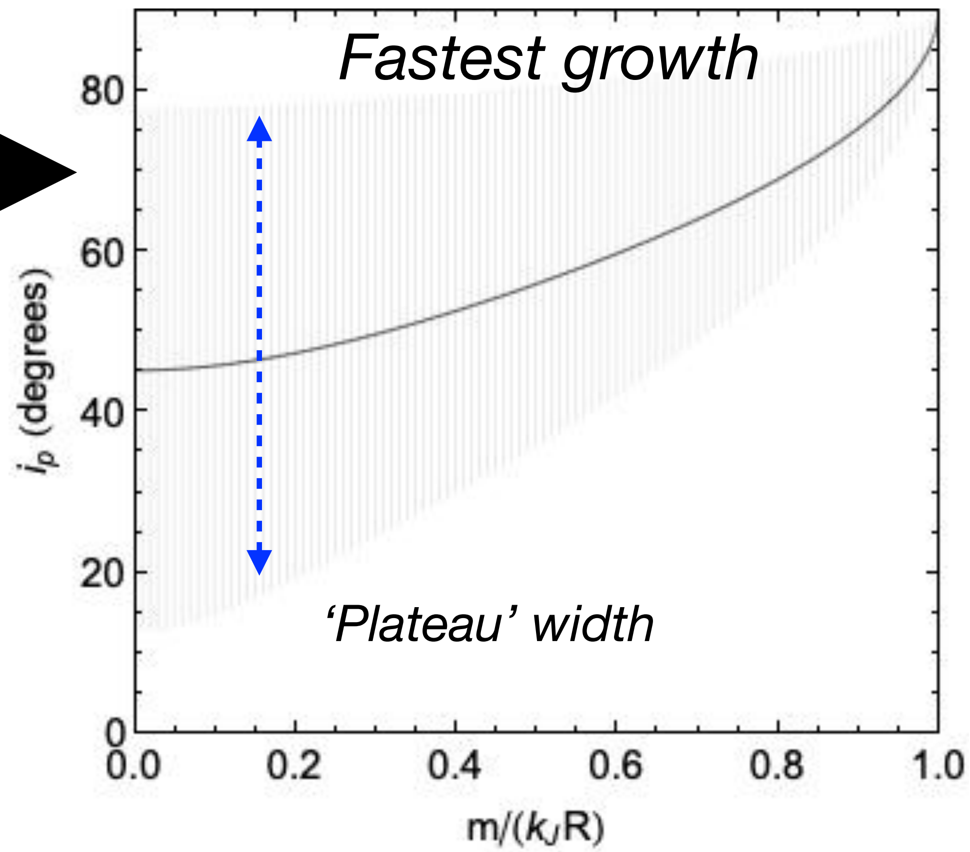

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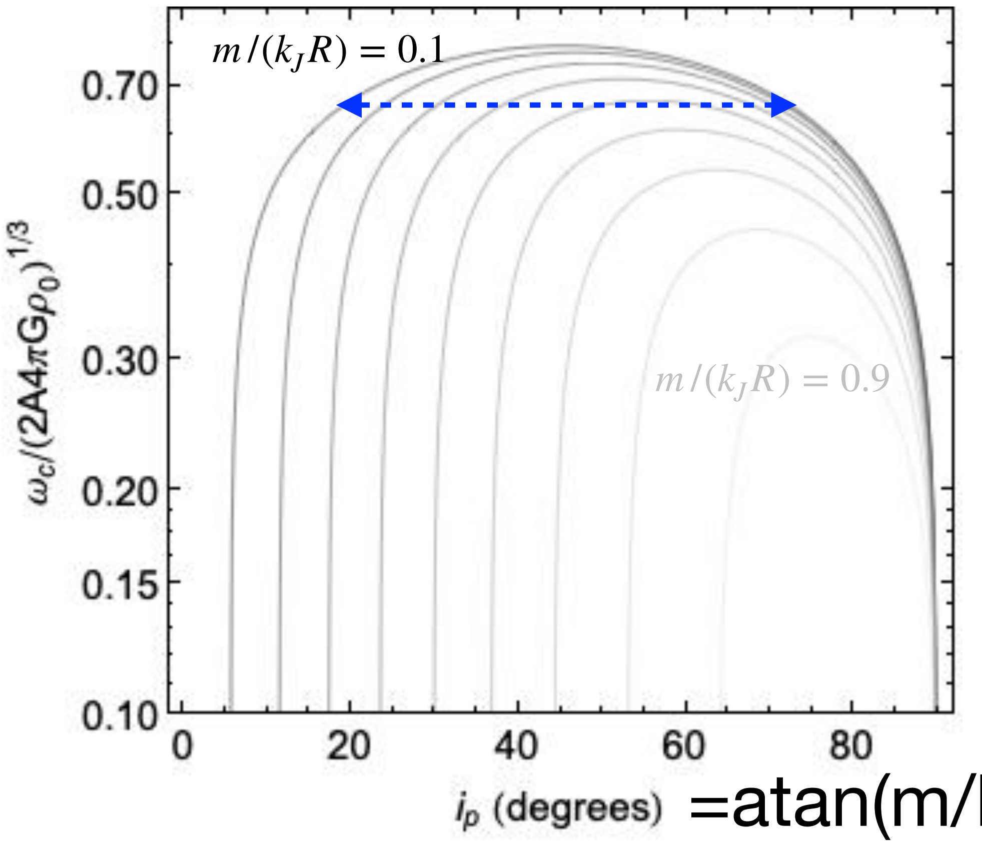

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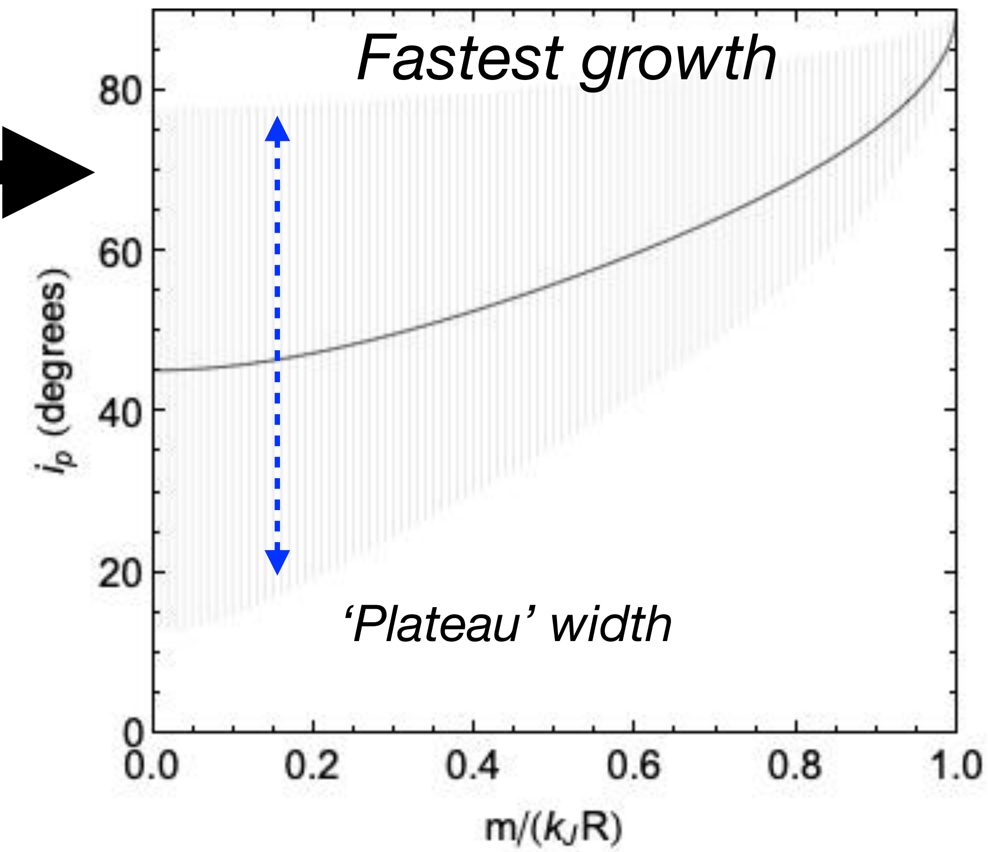
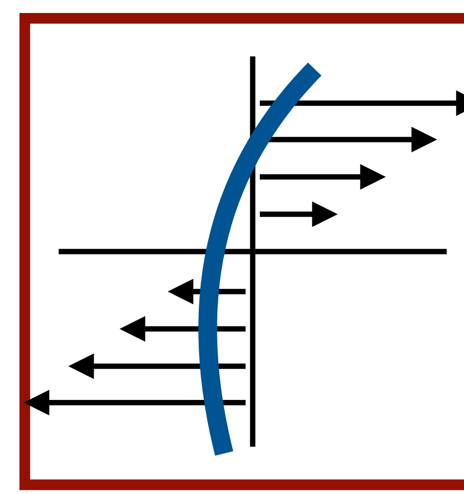


<u>Material patterns</u>:

K swings, evolve through critical pitch angle.

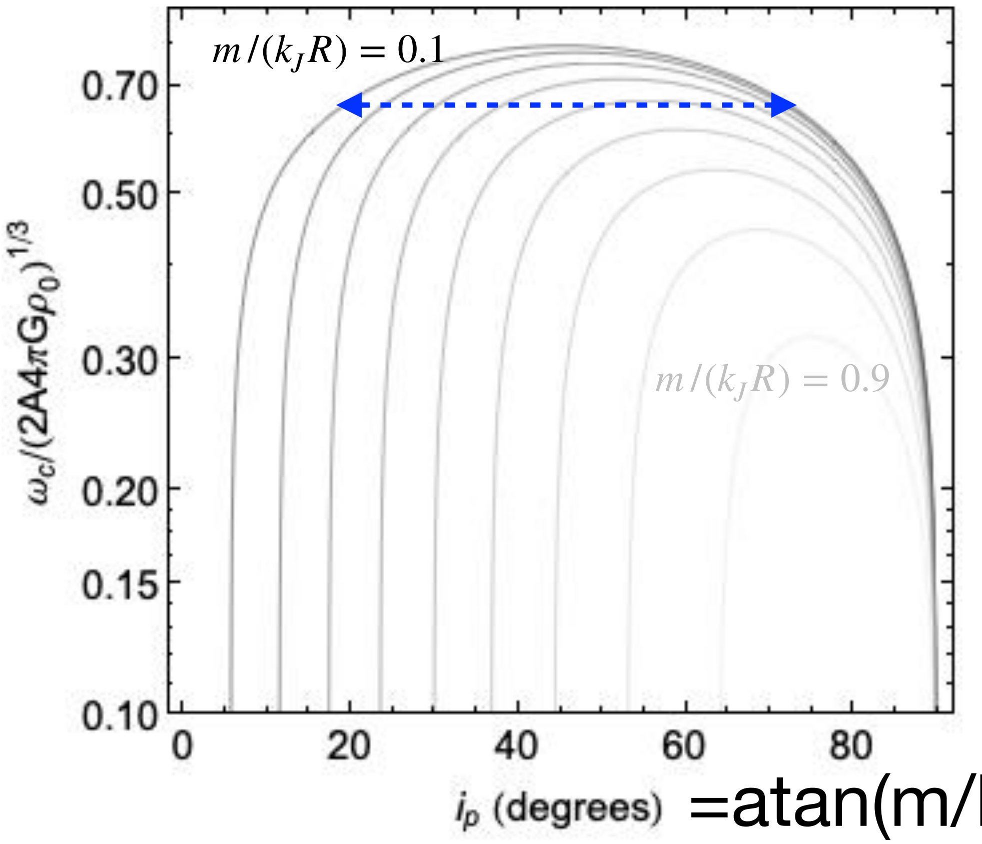
Where forcing supports max donkey behavior



Donkey behavior stops being effective past critical angle

The critical pitch angle

Meidt & van der Wel (2024)



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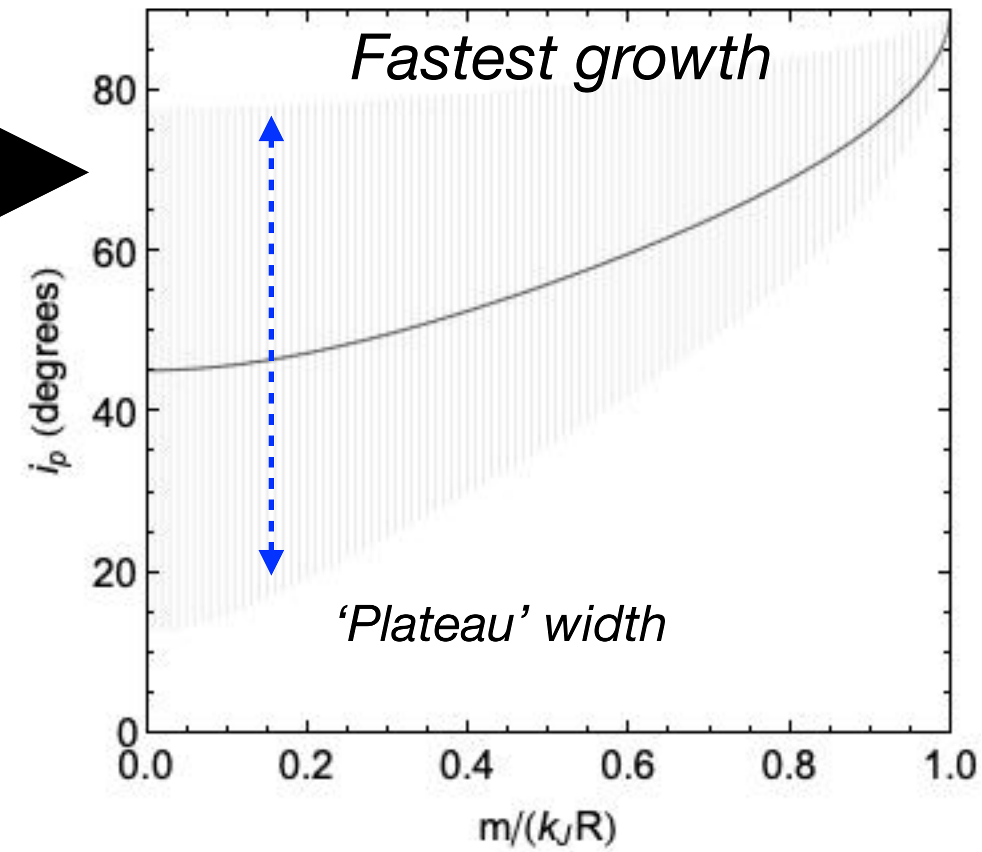

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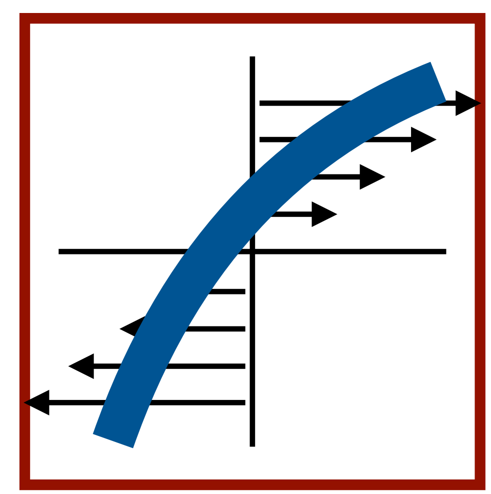

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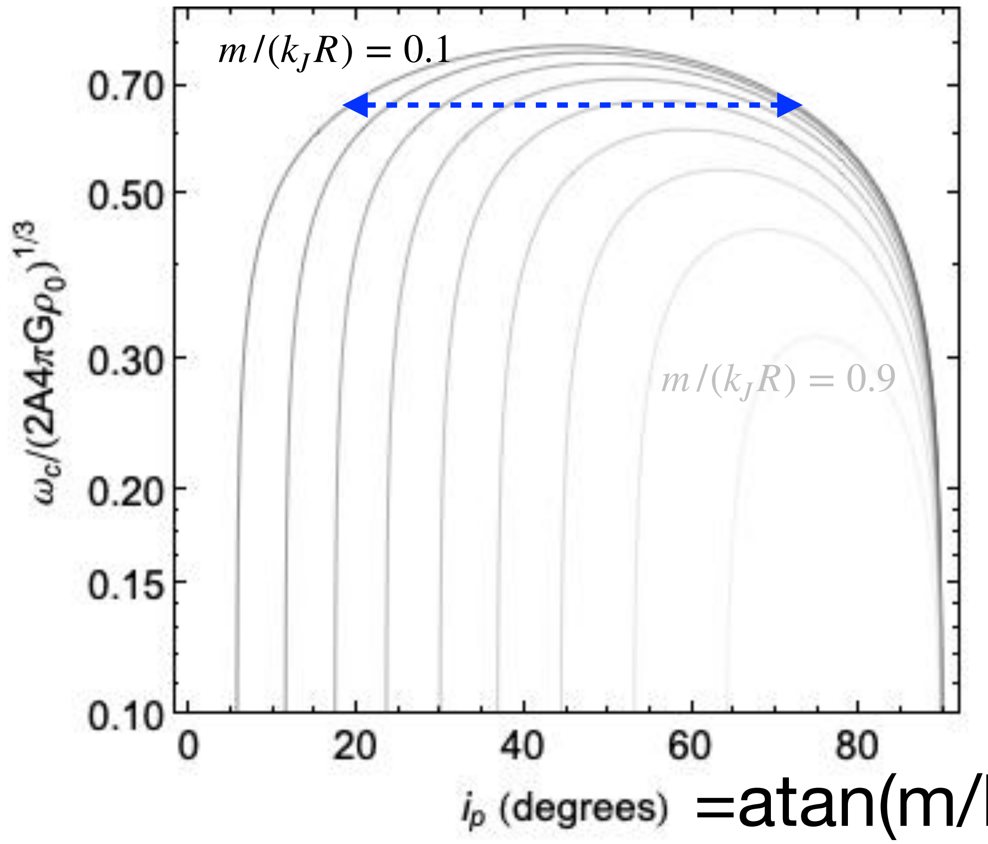

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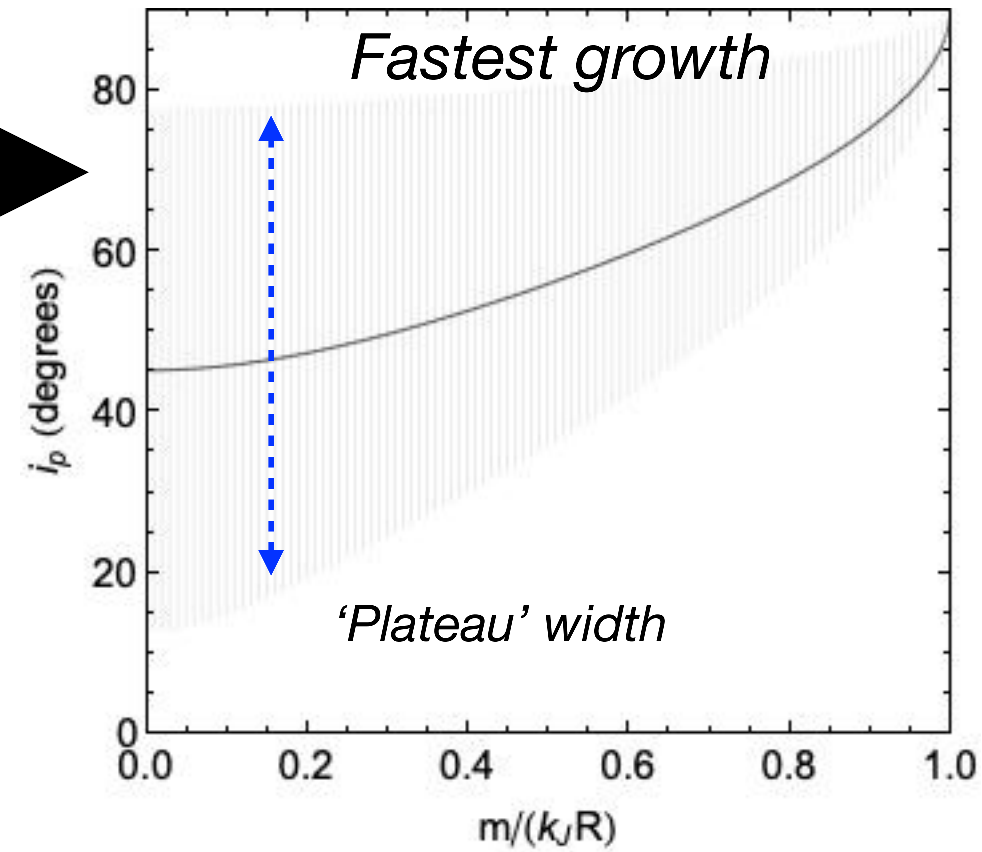

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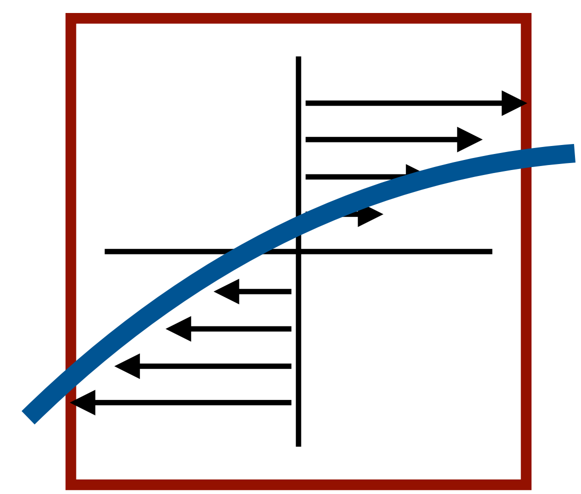

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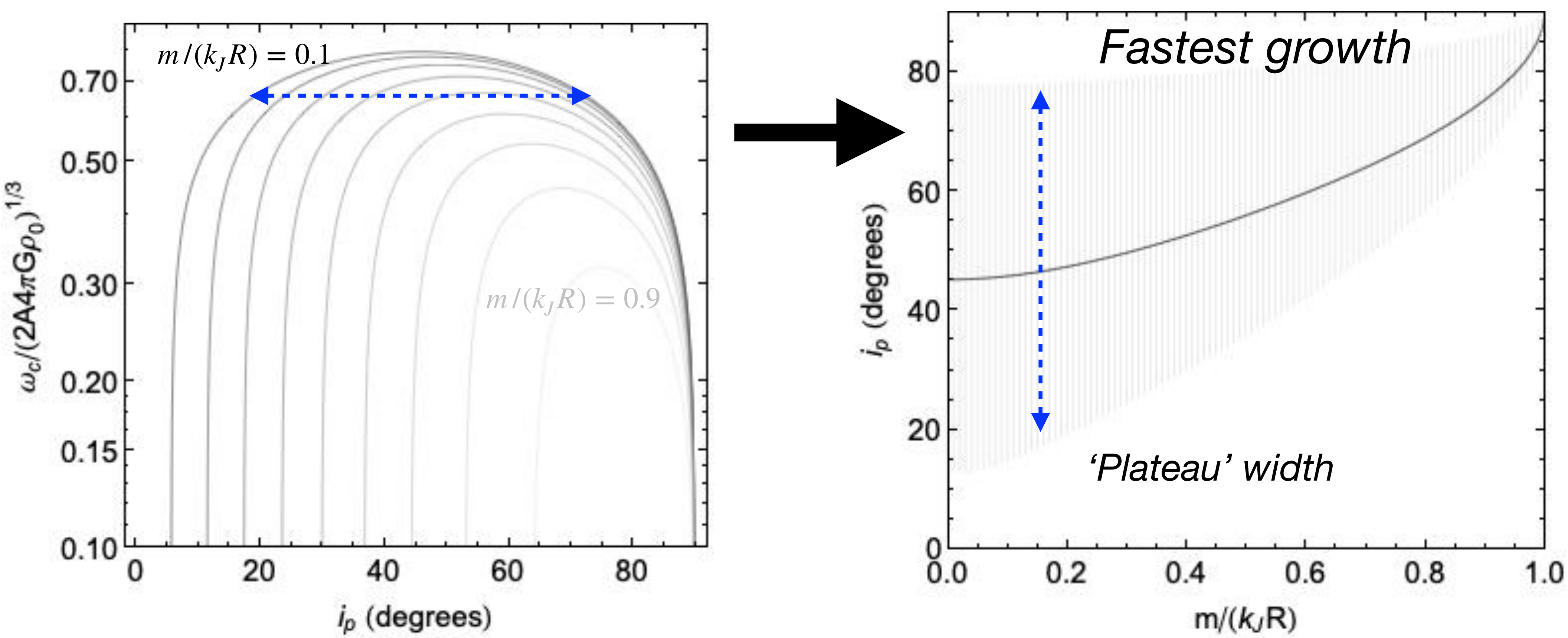
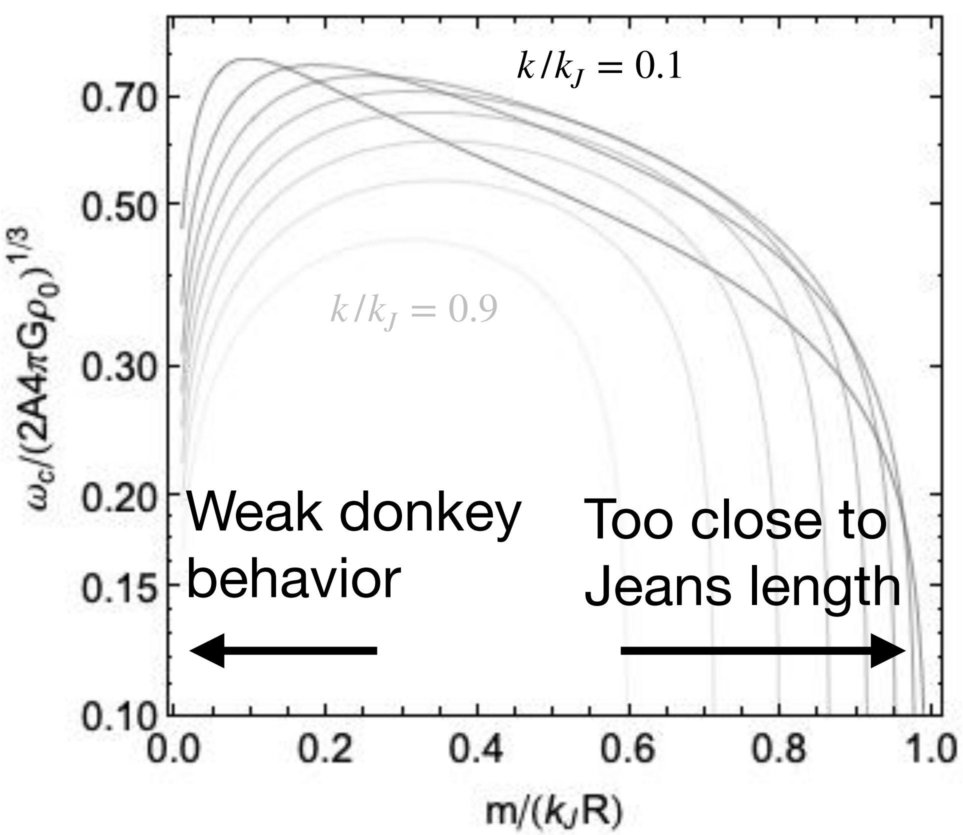


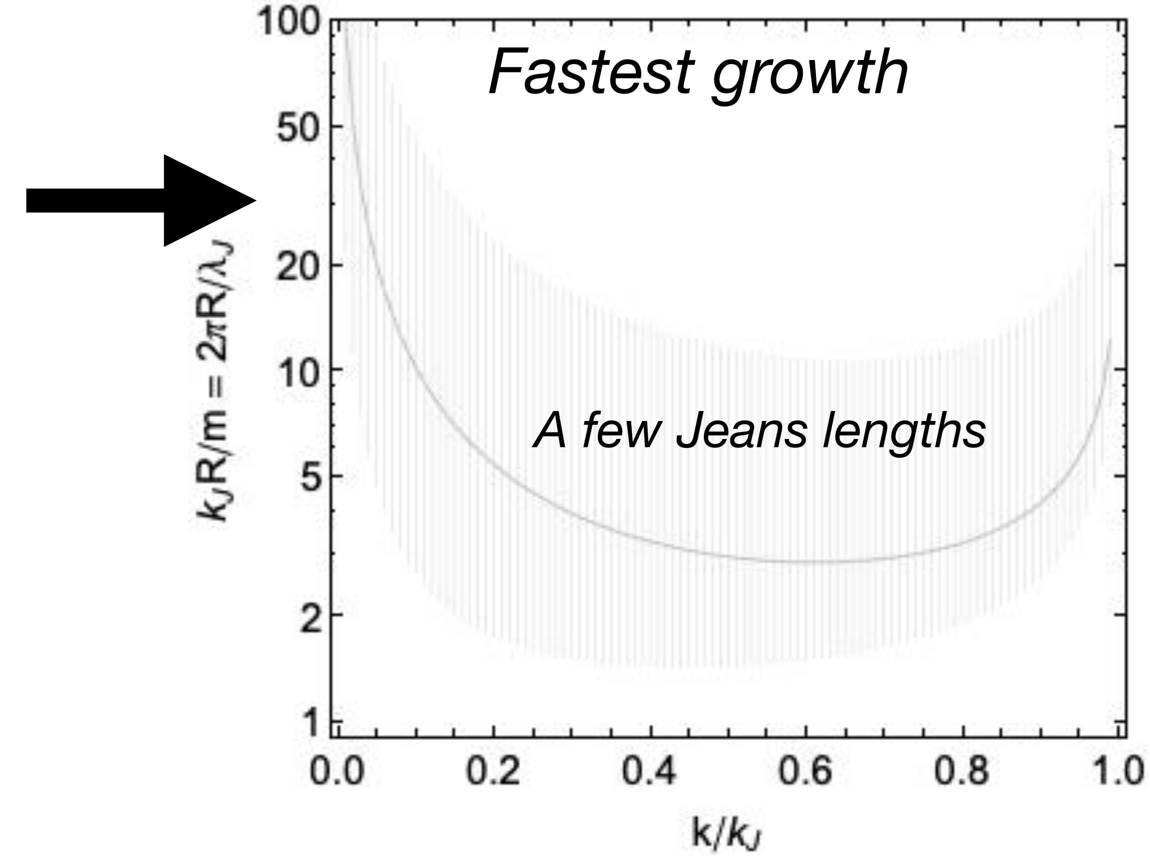
<u>Rigid Modes</u>:

Fastest growth limited to critical orientation.

The critical pitch angle

Meidt & van der Wel (2024)





Modes at corotation

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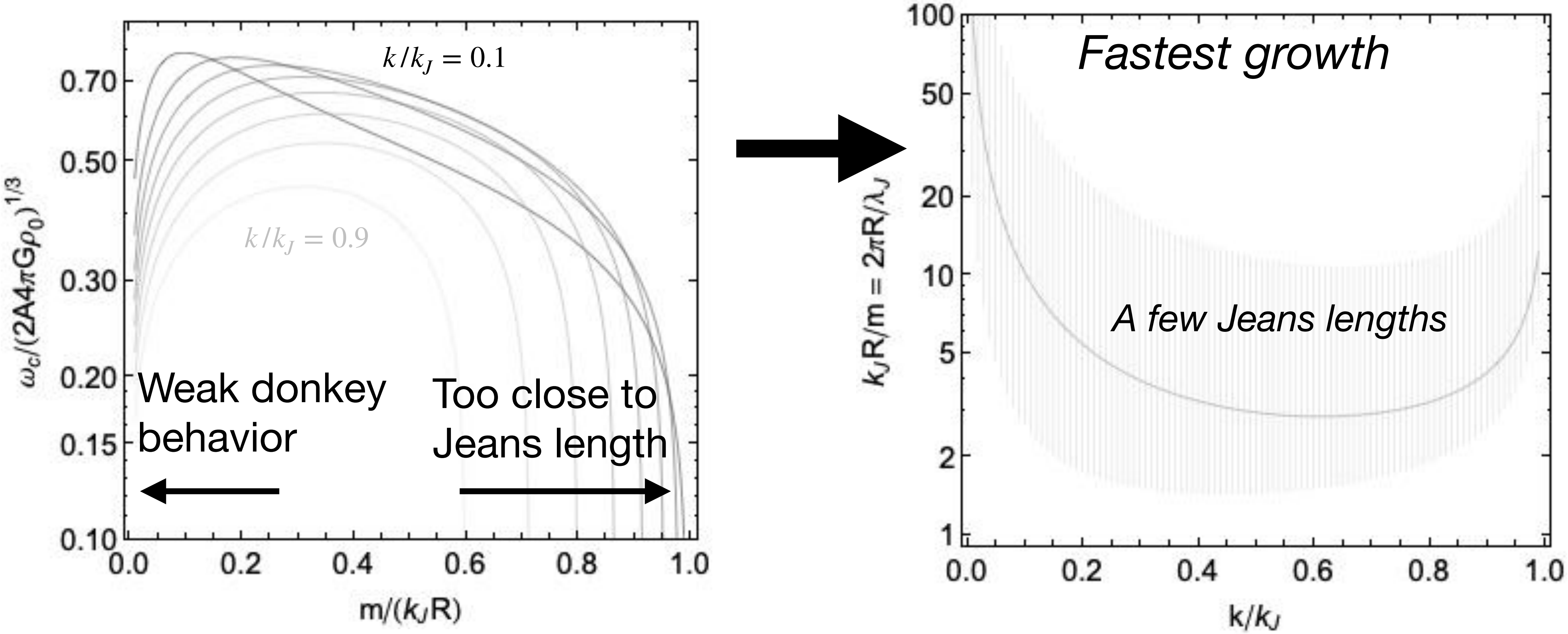

Modes at corotation

<u>Rigid Modes</u>:

Fastest growth limited to critical orientation.

Growth also temporary:

‘Saturation’-like behavior (see also **Hamilton 2022**):

Increase in density changes force, suppresses donkey behavior

‘open growth term’

Meidt & van der Wel (2024)

(The swing-amplifier term)

Only ever temporary

Material spirals shear through pitch angle

Modes: too much amplification and donkey behavior gives out

Individually transient spirals stitch together long-lived spiral morphology

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Predicted features

Only certain patterns amplify, others suppressed/sheared away

$\Longrightarrow$ **set by local conditions**

Arm spacing $2\pi R/m$ **:** minimum **~2x turbulent Jeans λ**

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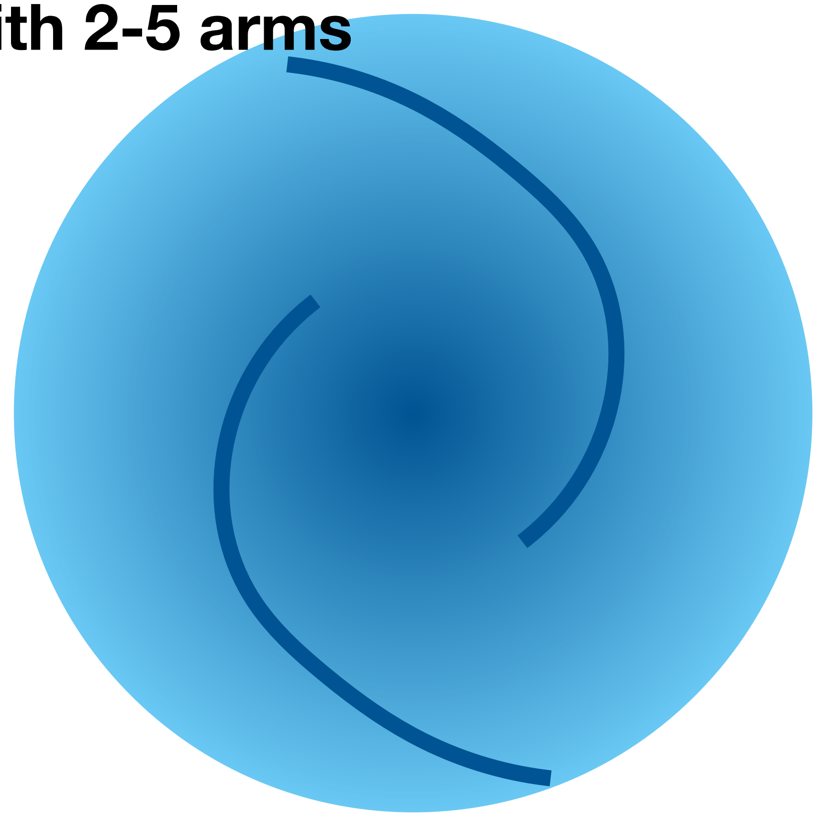
in stellar disks

Spirals with 2-5 arms



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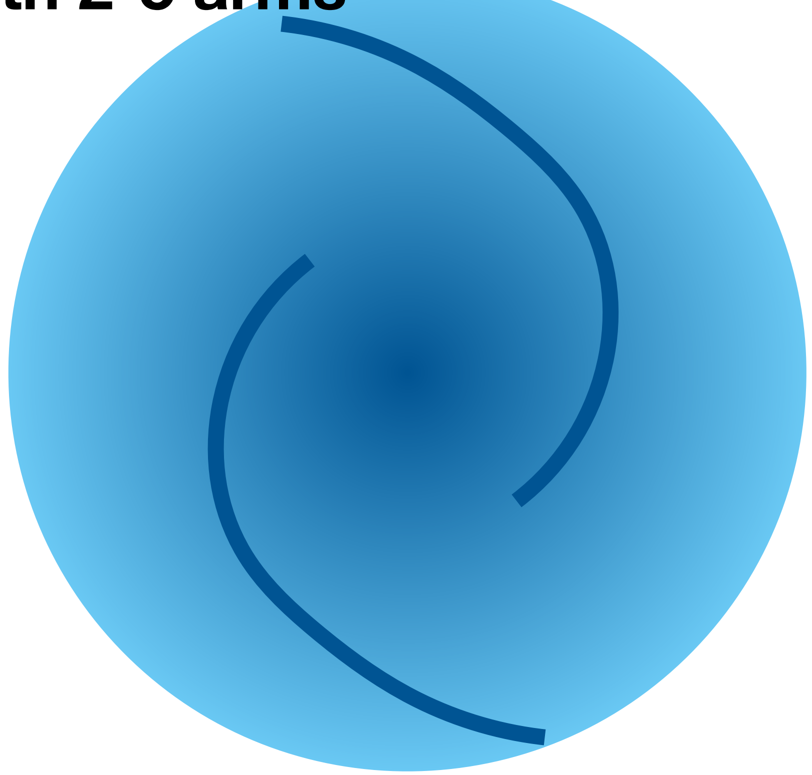
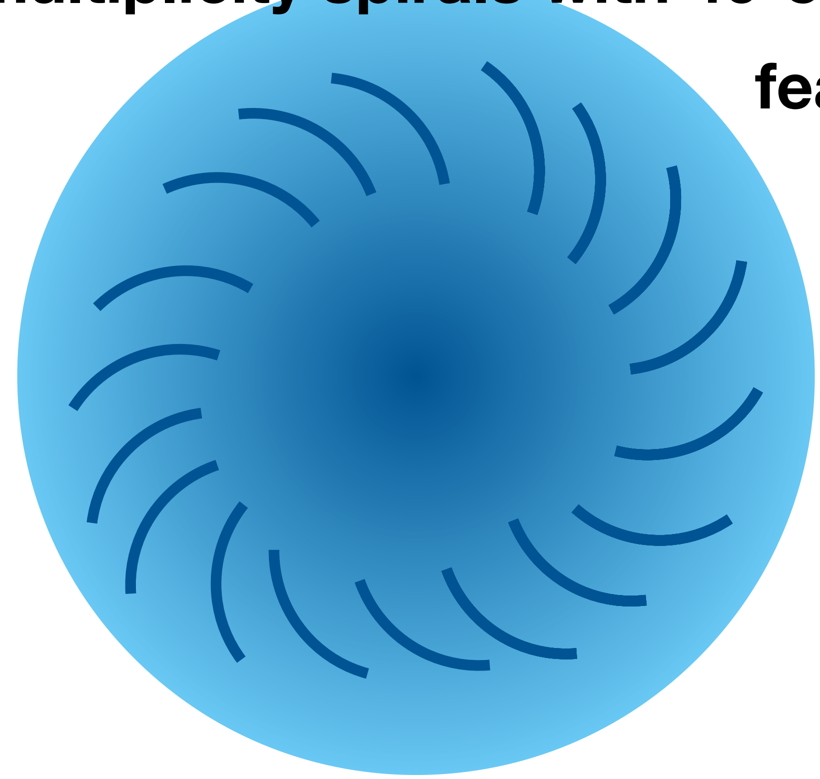


in gas disks

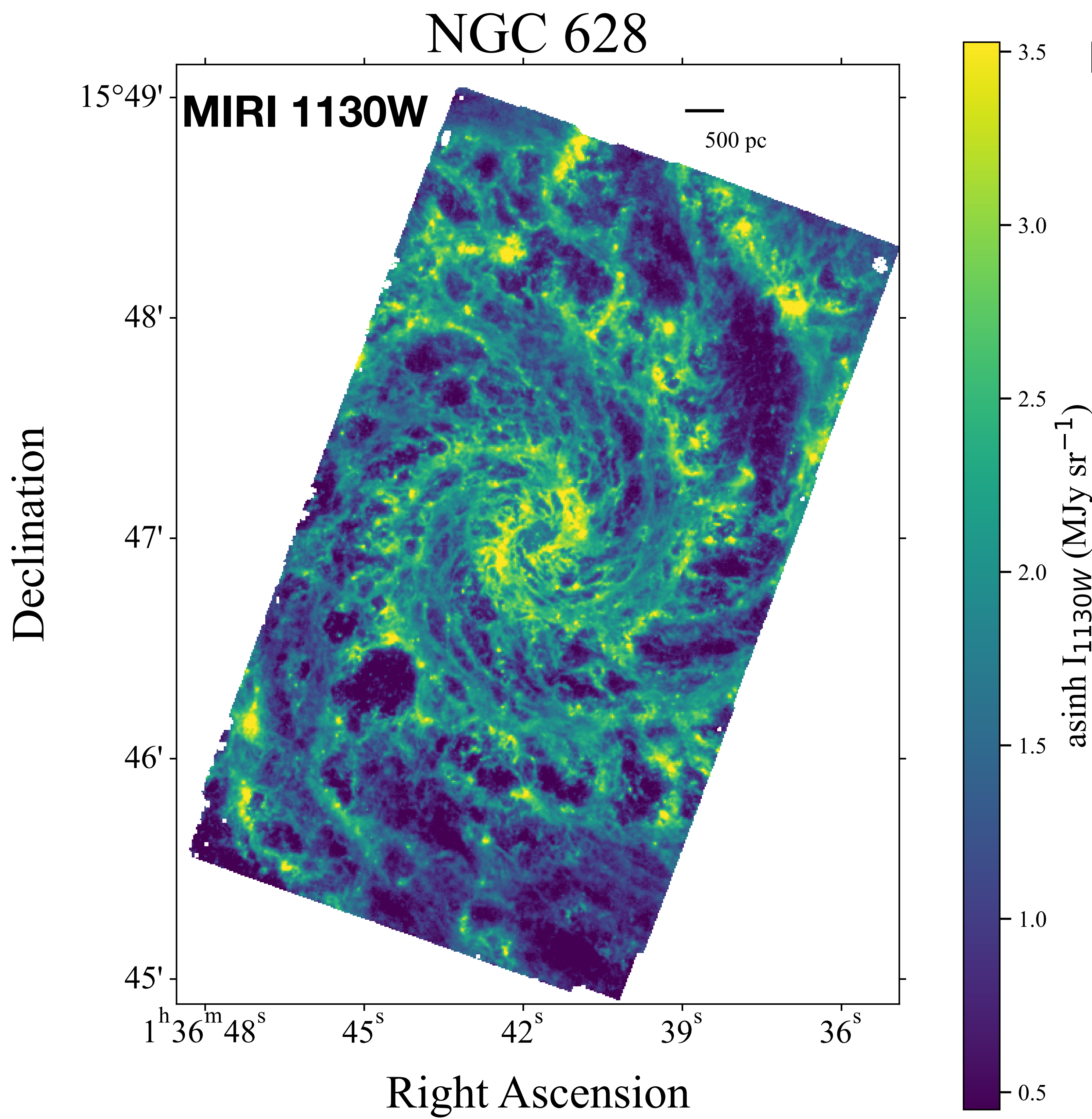
High-multiplicity spirals with 40-50 arms

feathers



Structure in PHANGS-JWST MIRI images

(Meidt+23)



FilFinder *(Koch & Rosolowsky 2015)*

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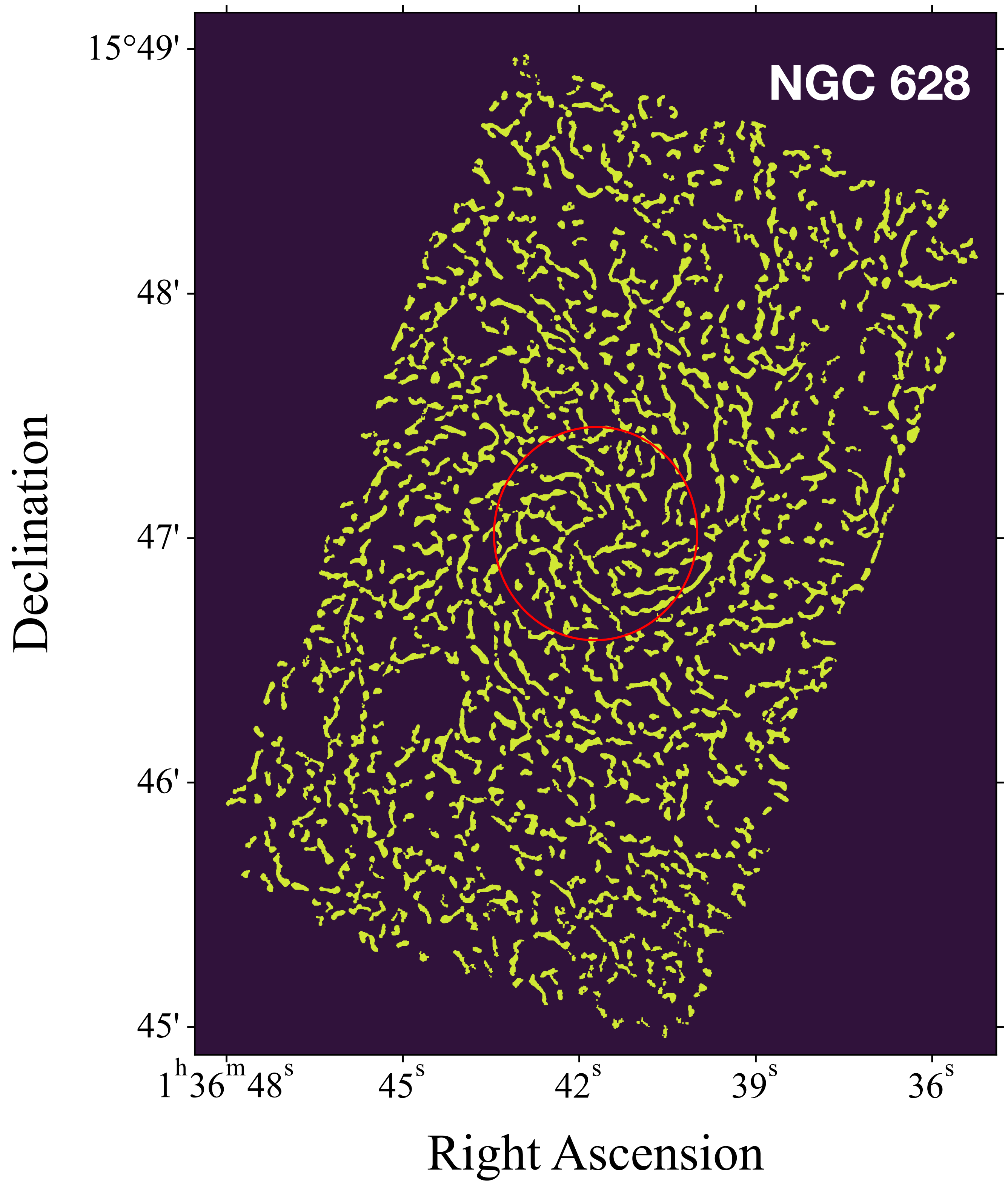

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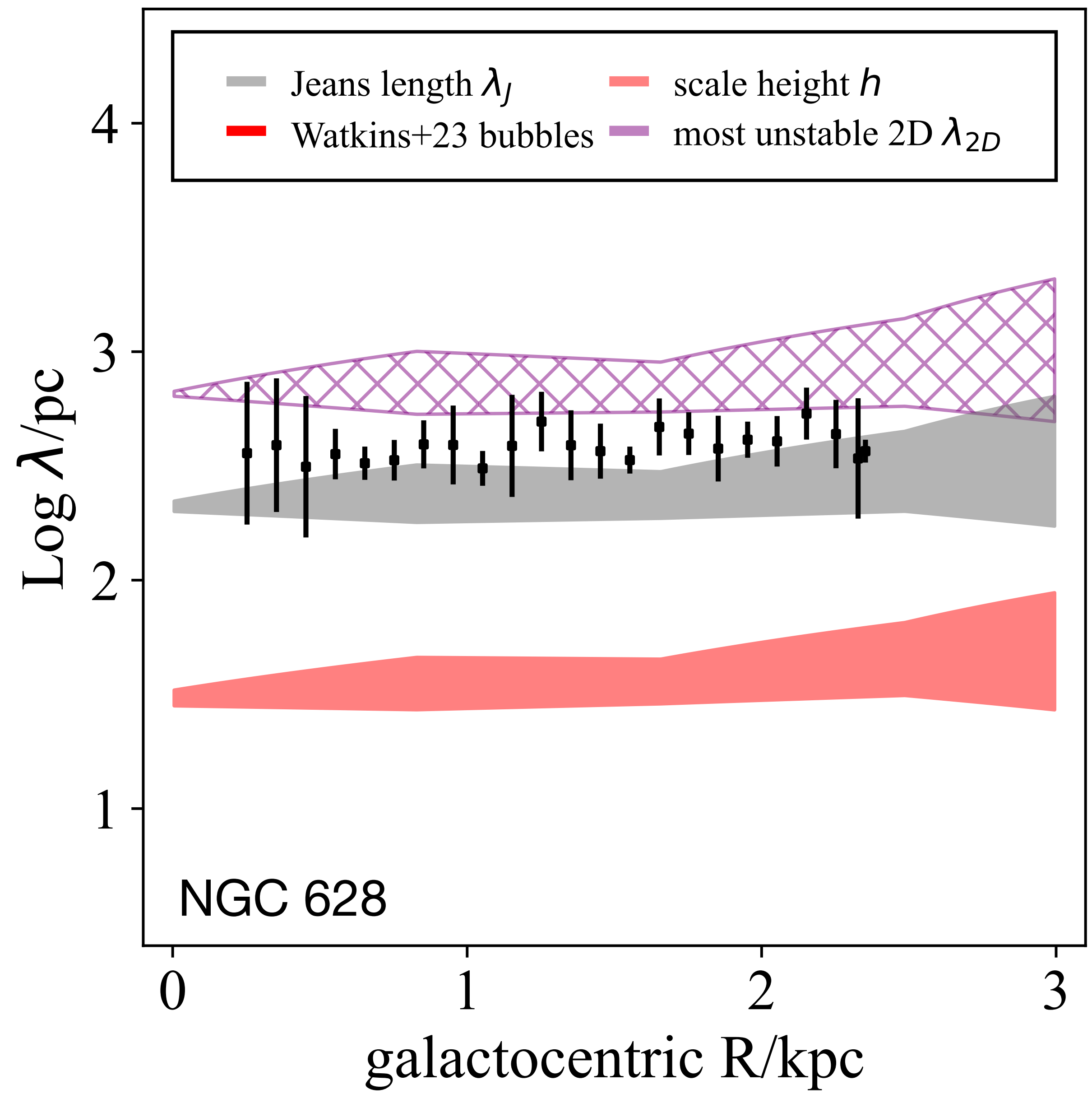
$$\lambda_J = \frac{\sigma \pi^{1/2}}{(G\rho)^{1/2}}$$



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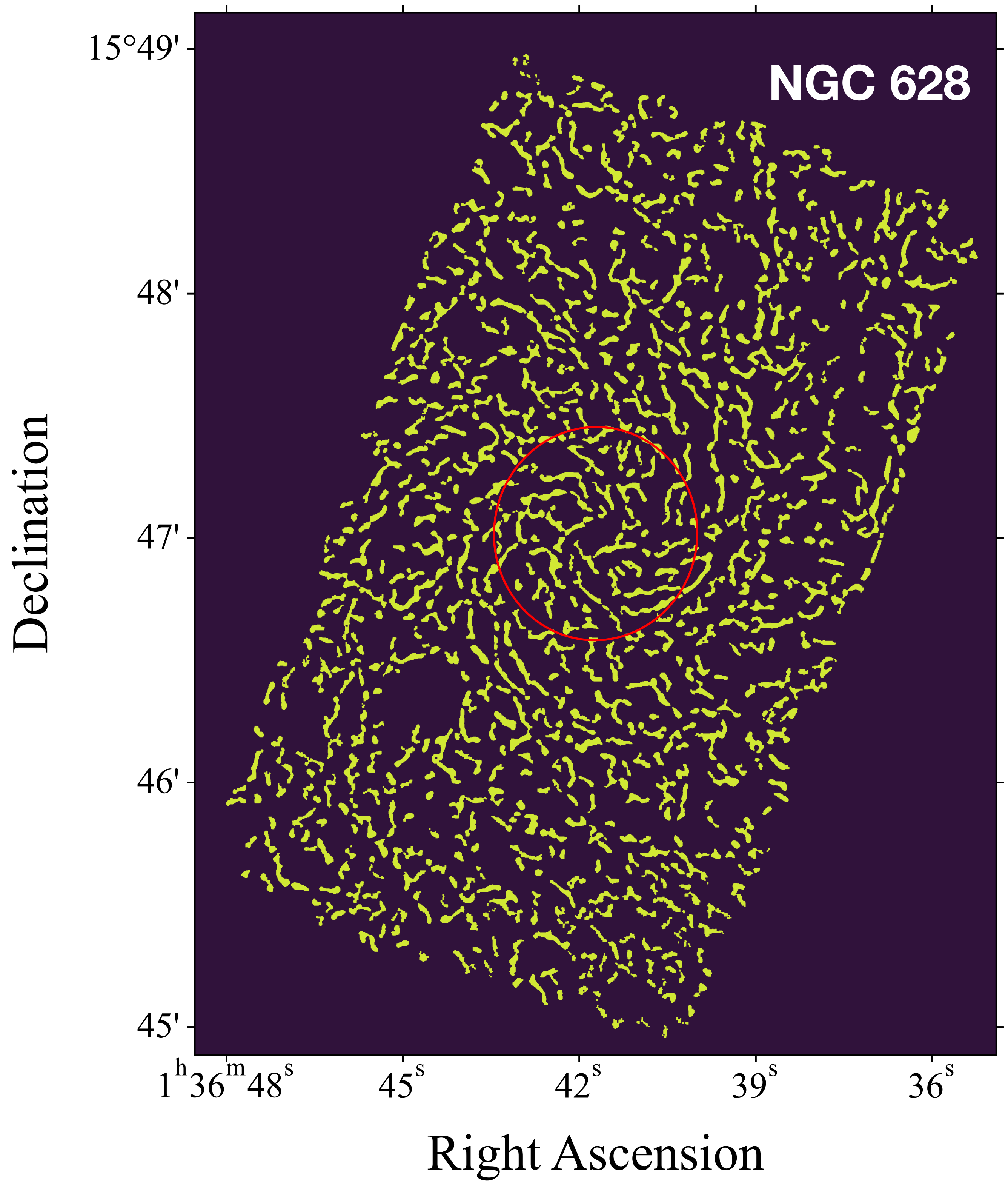

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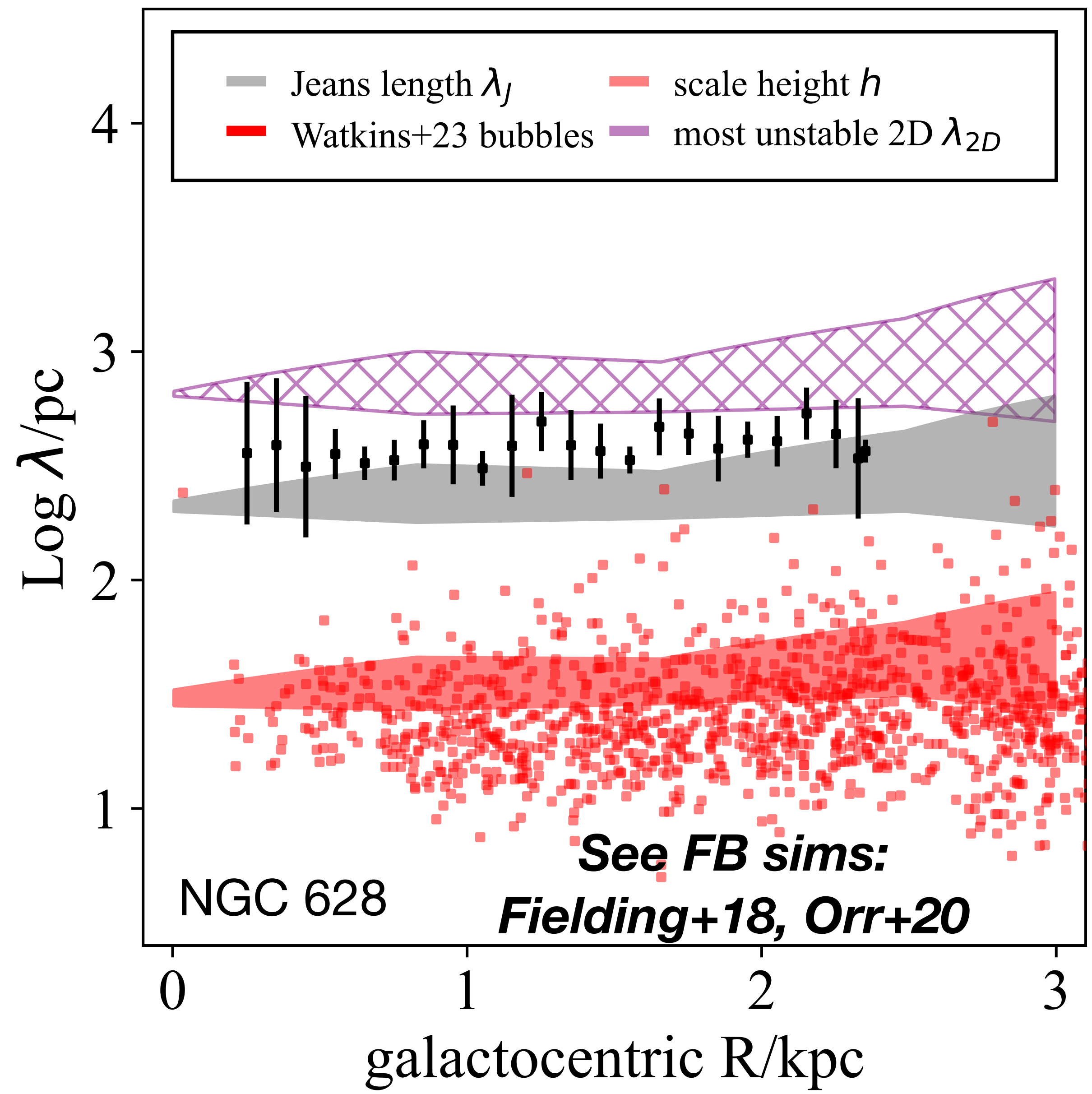

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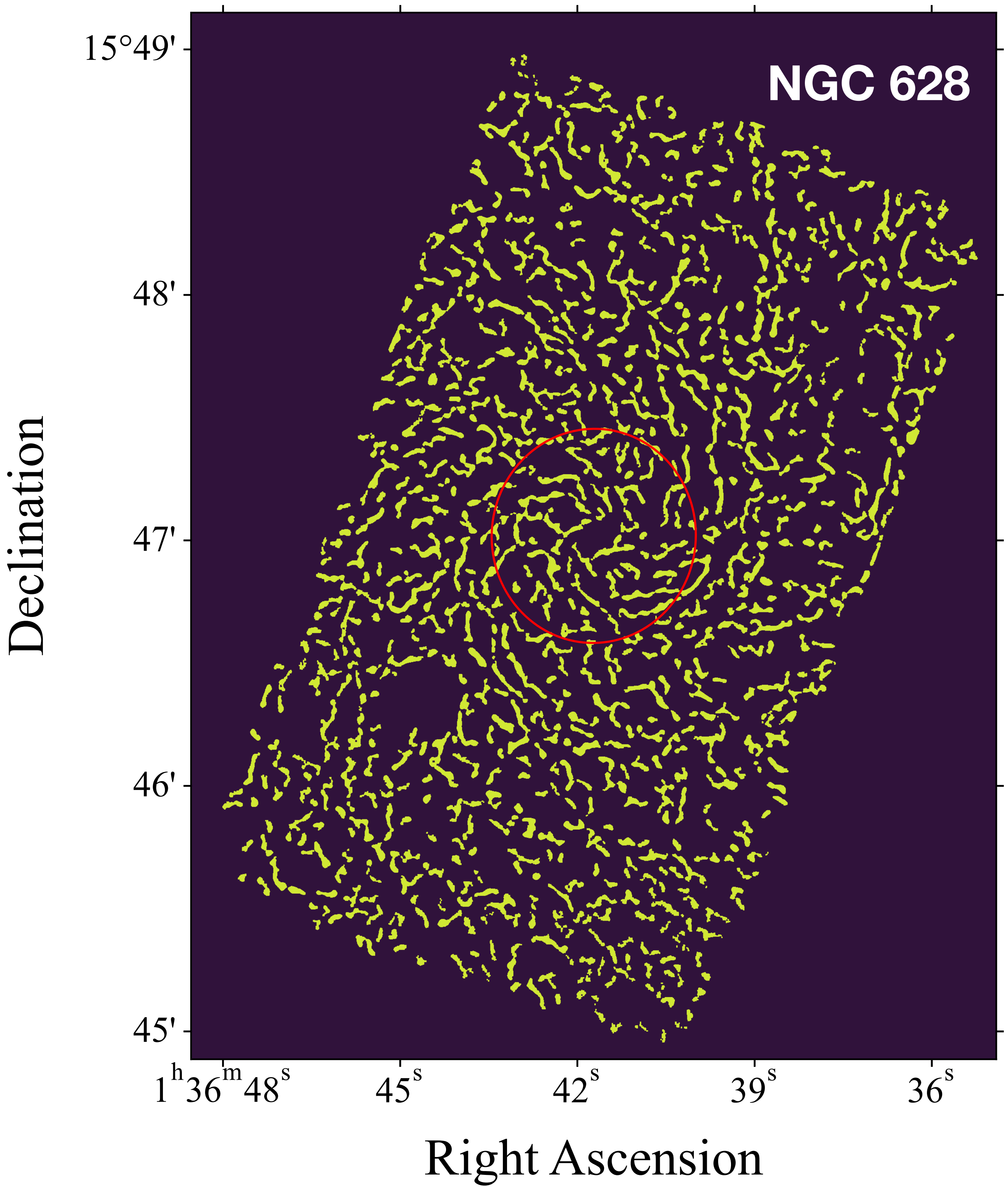

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Burton, Rosolowsky, Meidt et PHANGS (in prep.)

Angular cross-correlations.

Spacings & orientations

Take away

<u>**Pervasive**</u> **(non-axisymmetric) structure formation** *predicted and observed* **in rotating disks even when Q > 1**

Modes and shearing patterns amplify similarly

Individual patterns short lived, but replaced by nearly identical structures

Properties: depend on local conditions

→ **Long-lived spirals**

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See also **Sellwood & Carlberg (2014,19)**

Take away *Gas disks*

Gas responds to global potential perturbations
And its own self-gravity

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And its own self-gravity

Intermediate and small scale structures

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Intermediate and small scale structures

Wealth of regular structures on ~Jeans length

Spirals filaments as molecular clouds

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Rapid replacement of structures destroyed via feedback

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ISM pre-‘pre-processed’ <u>before</u> star formation feedback

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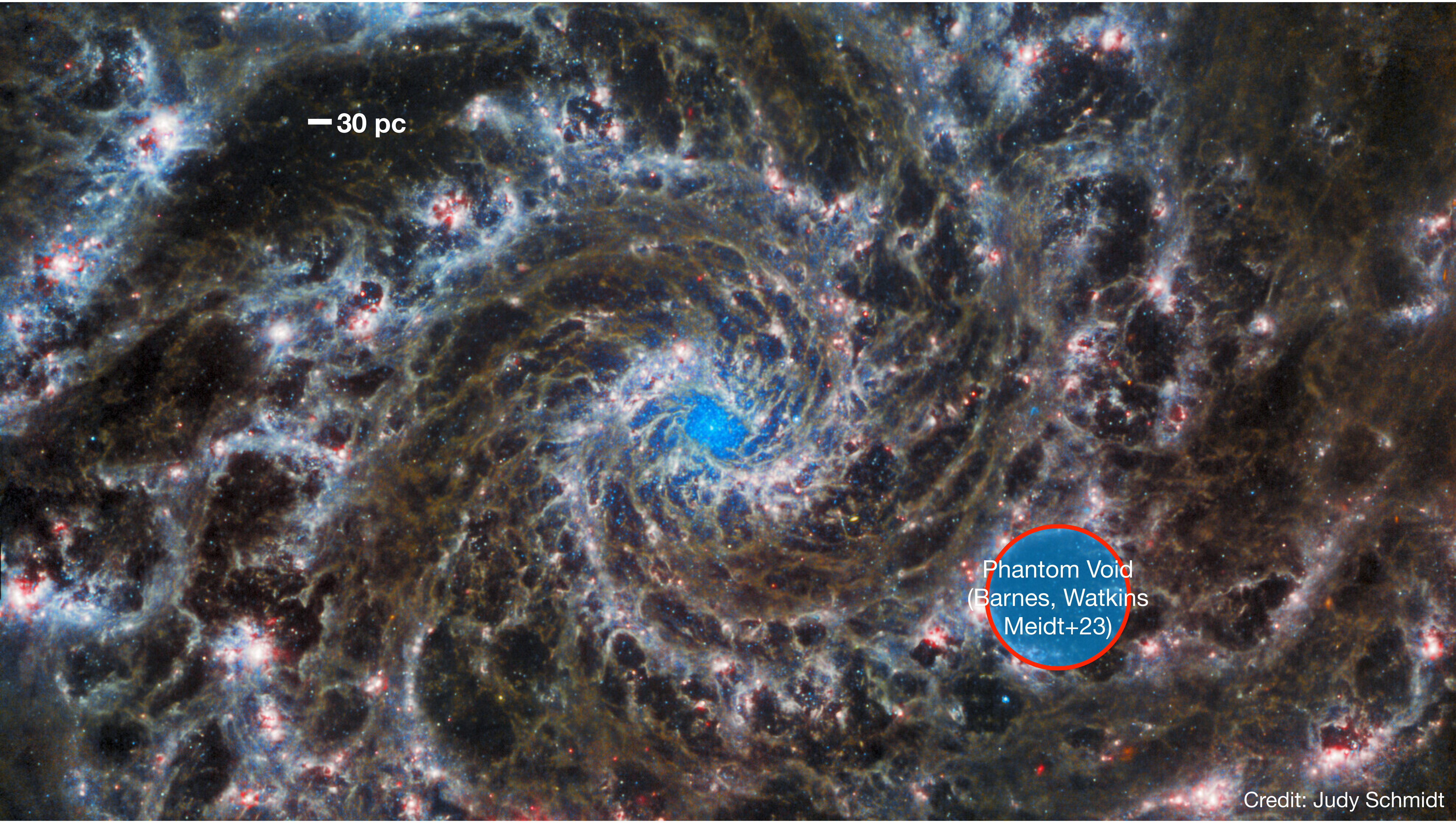
Revisit: dynamical heating of stars and gas, angular momentum changes

Structure in PHANGS-JWST MIRI images

PHANGS-JWST
(Lee+2023)

Watkins+2023



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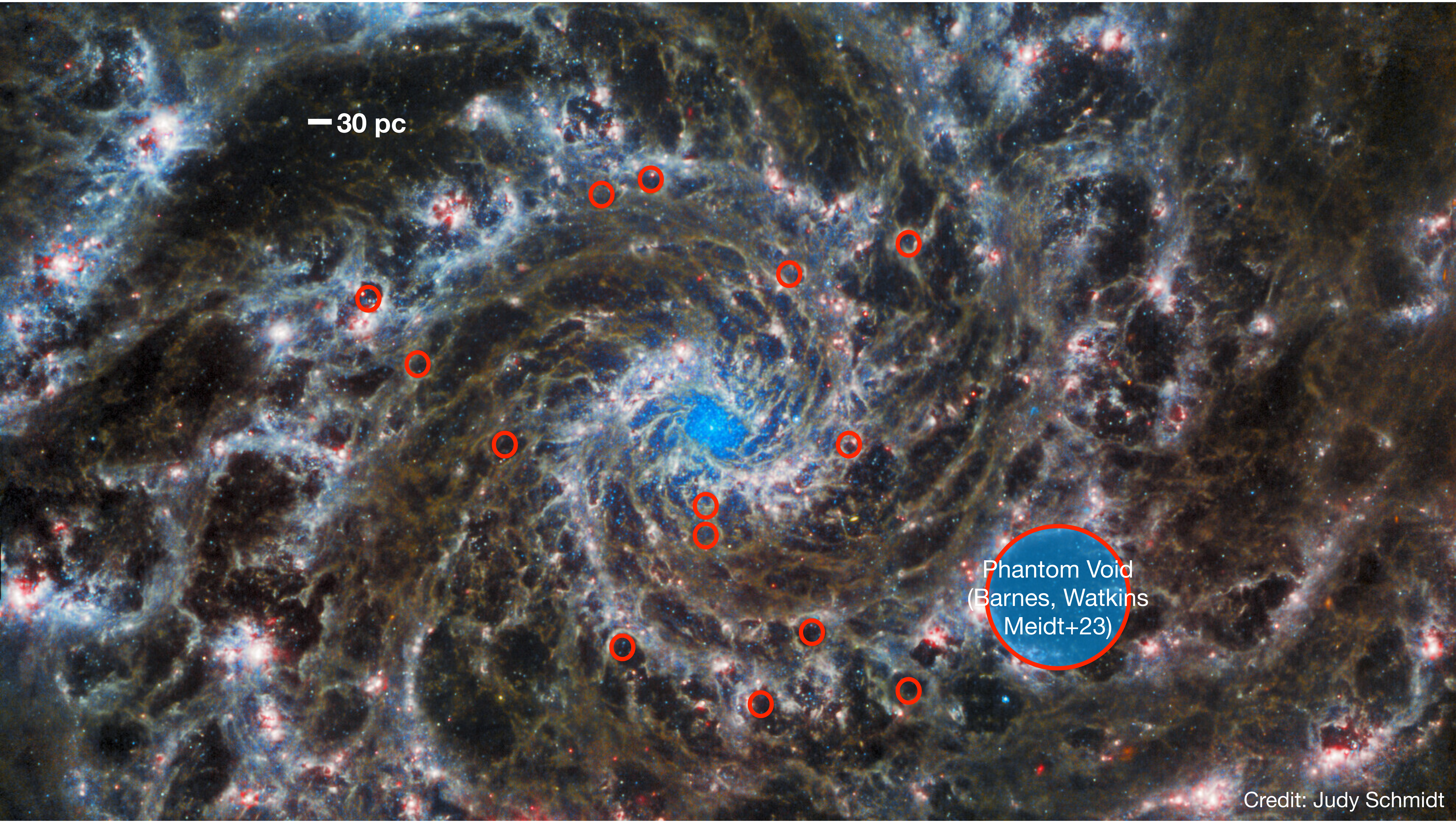

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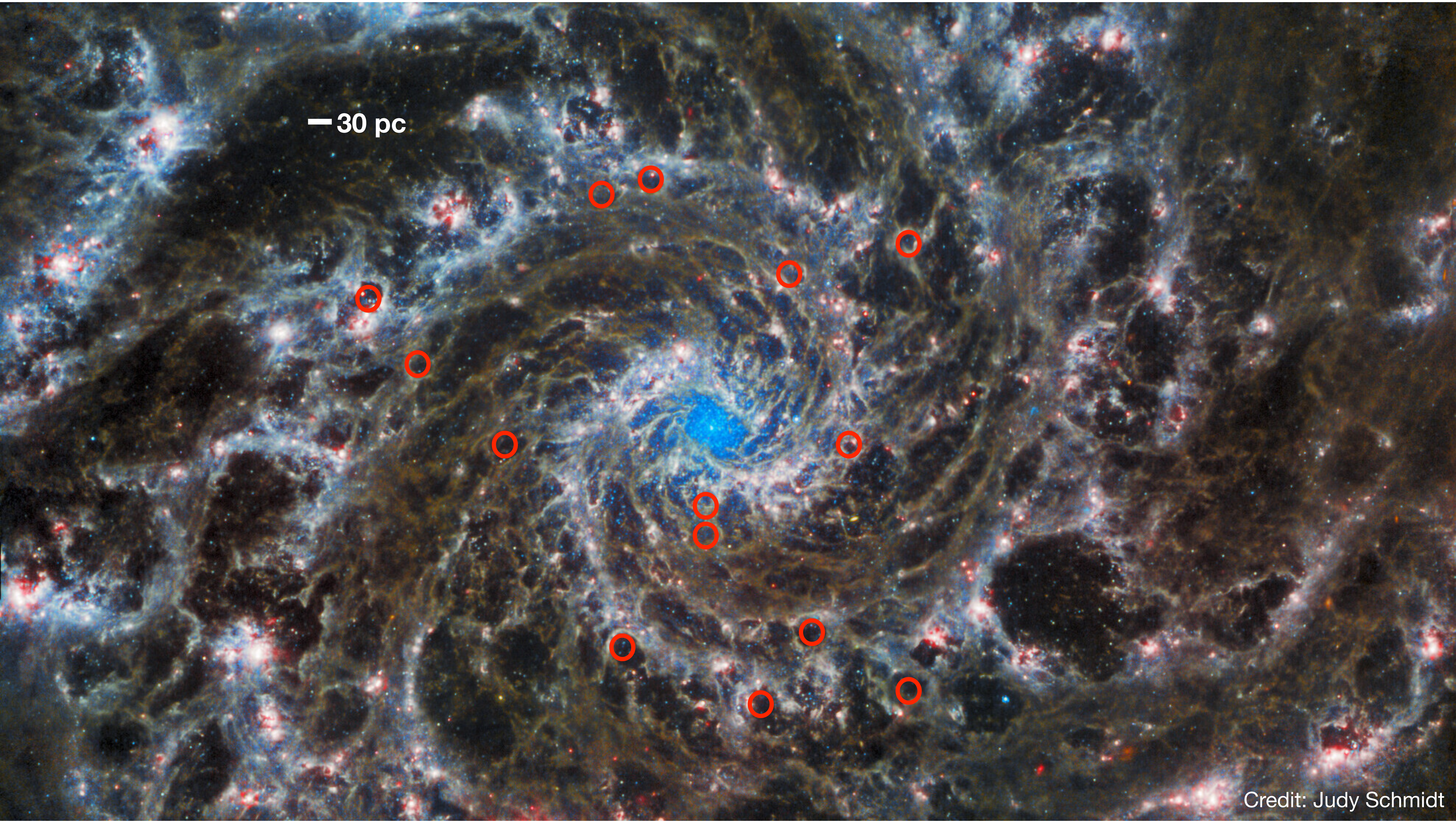
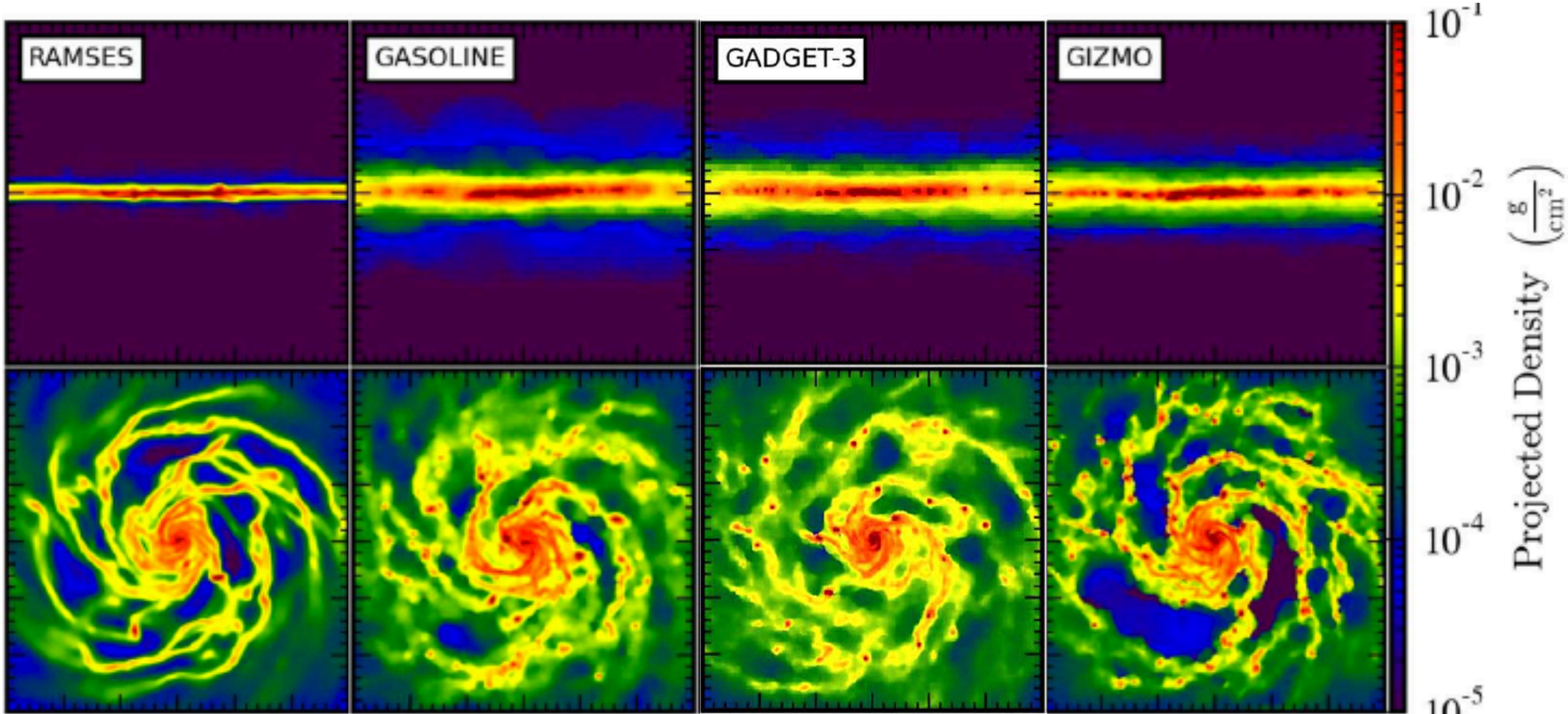


Kim, Agertz, Teyssier+2015, Agora project



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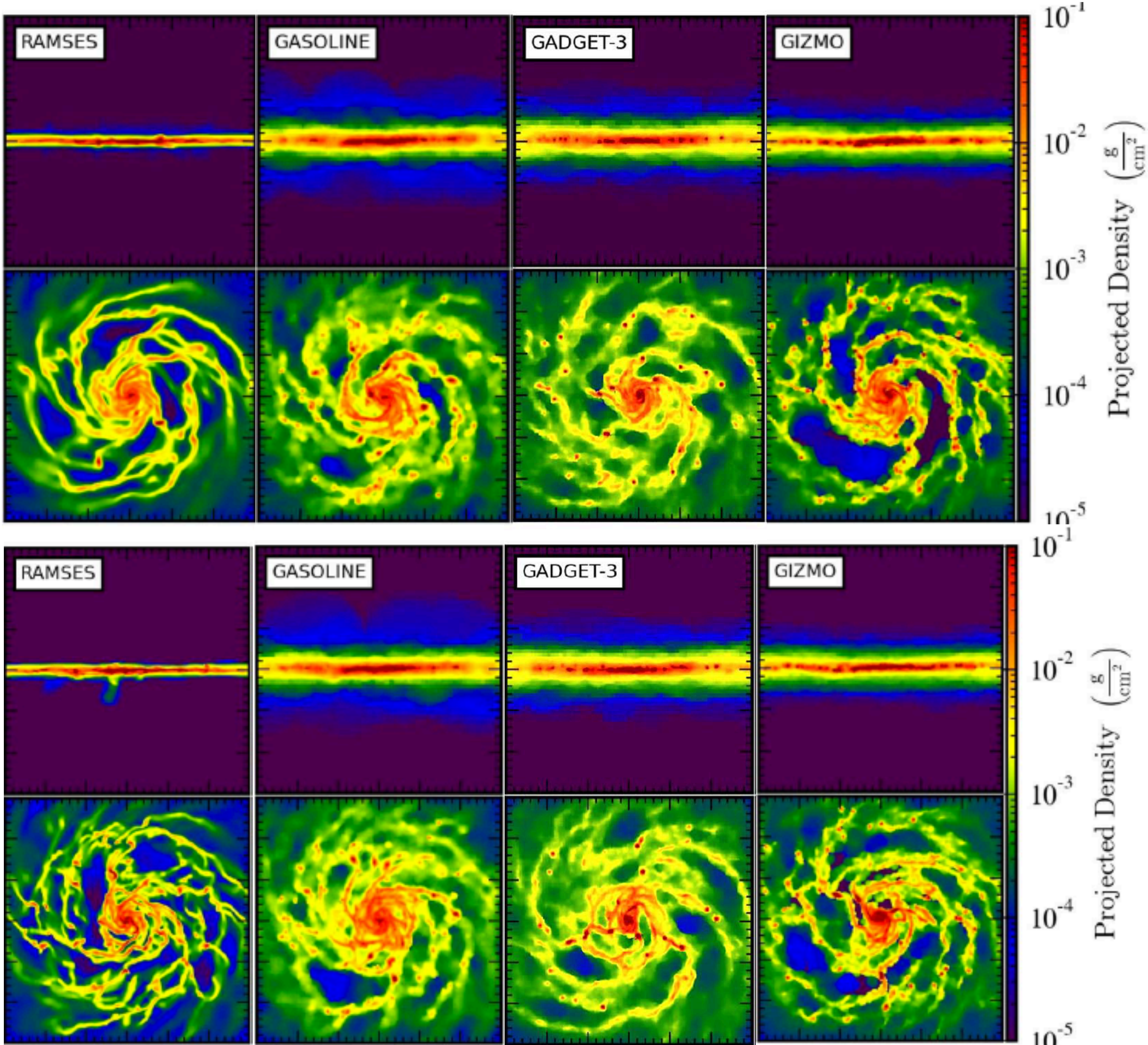
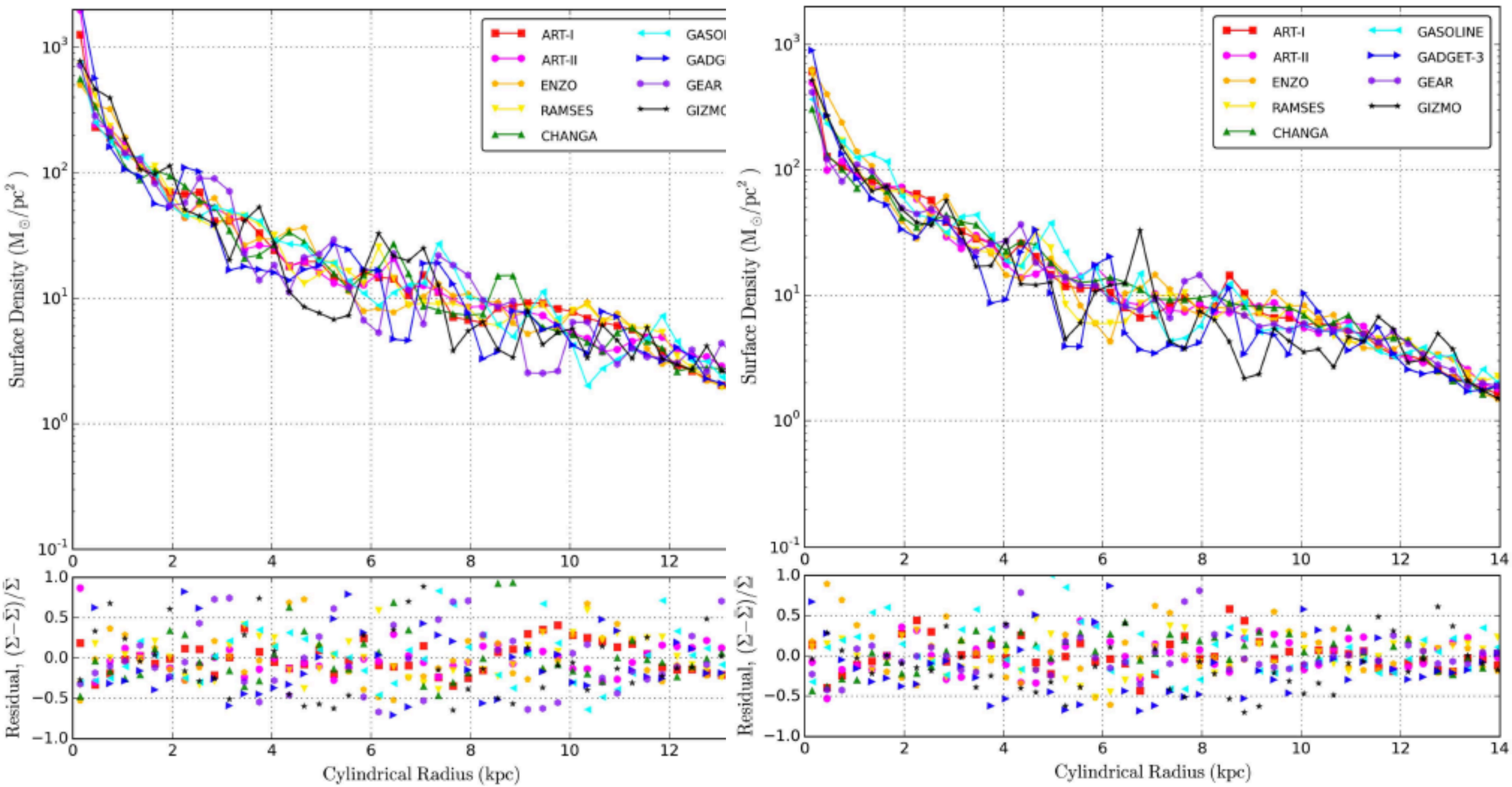


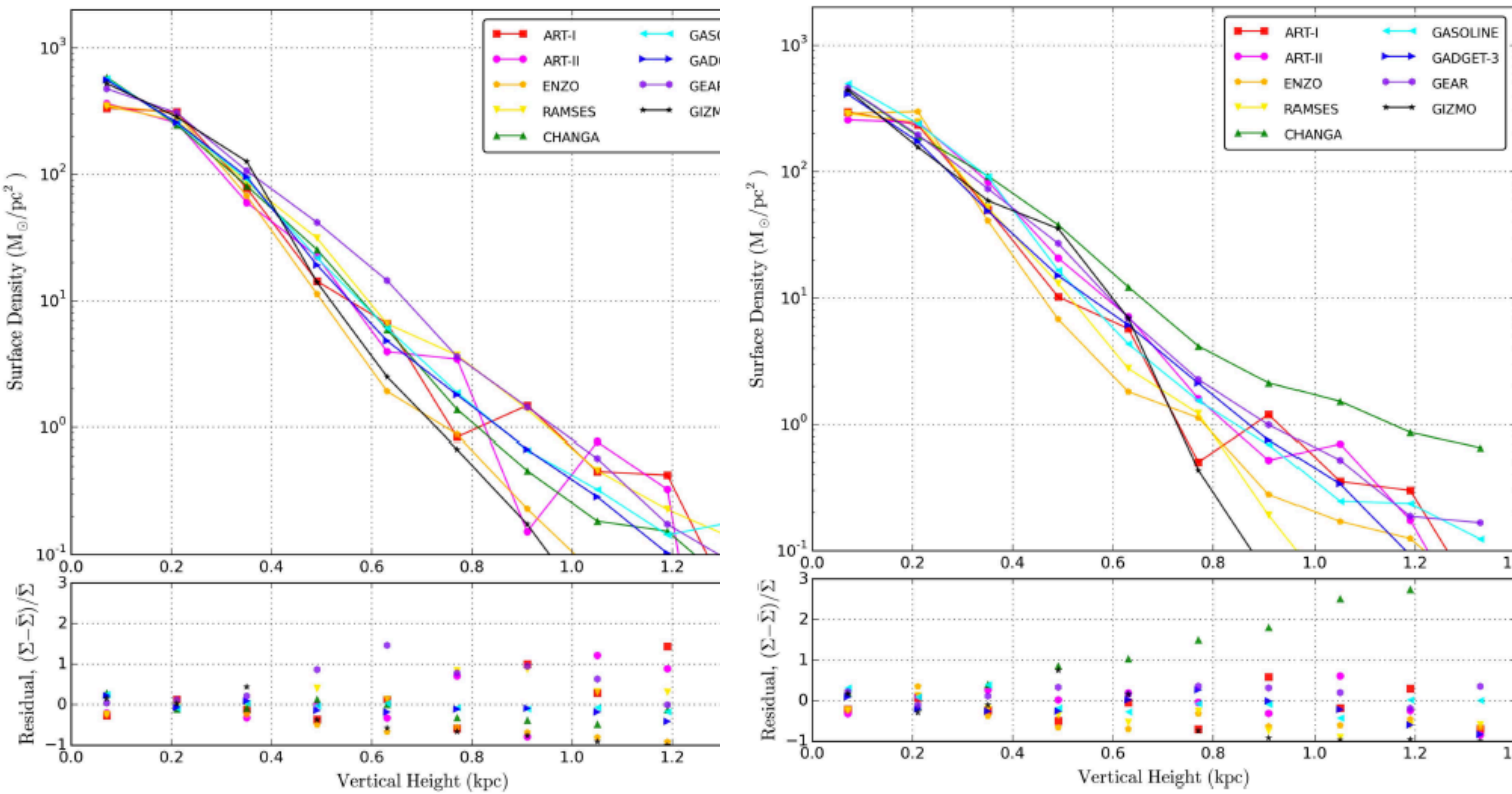
NO SFFb **With SFFb**



Radial gas surface density profile

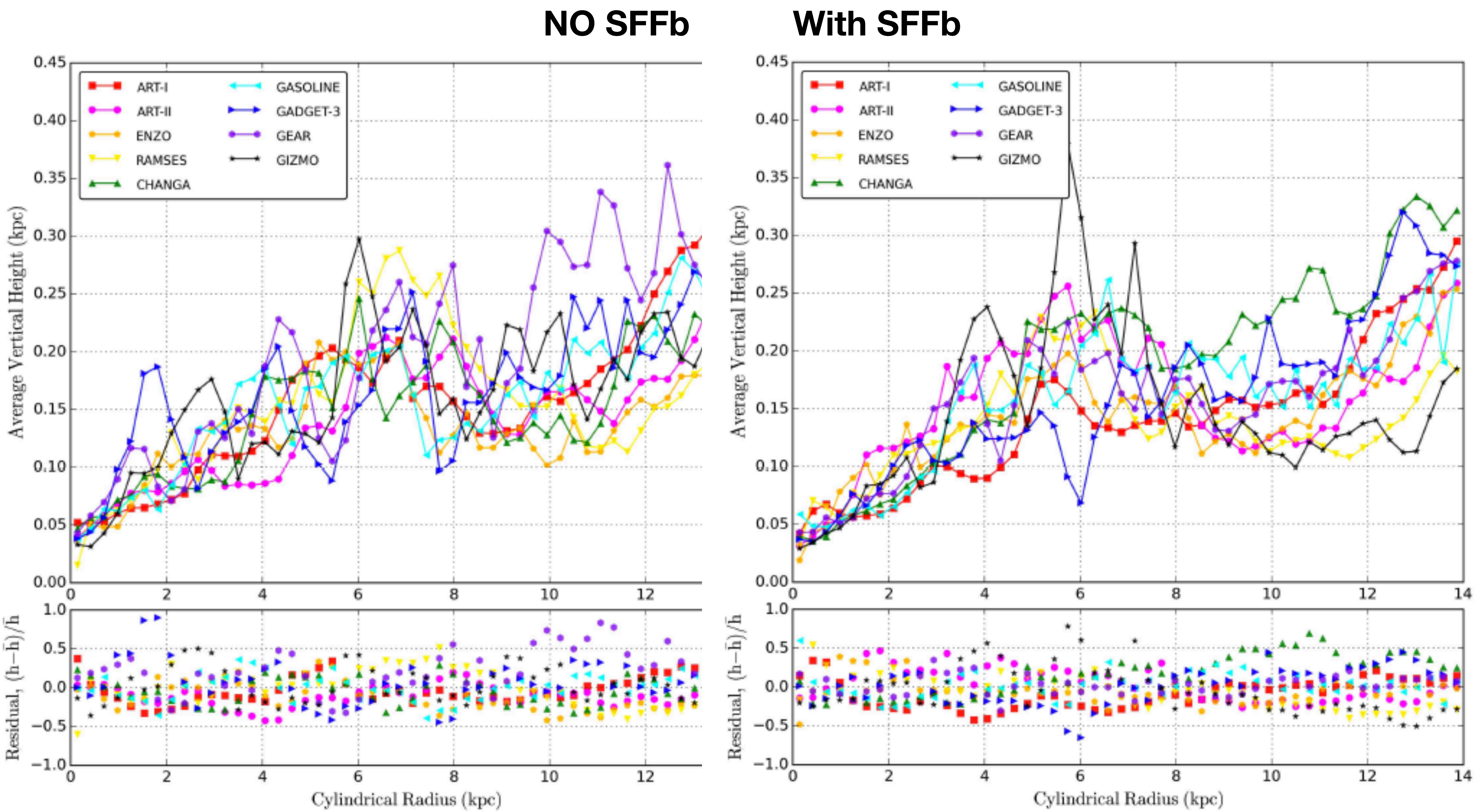
Kim, Agertz, Teyssier+2015, Agora project

NO SFFb With SFFb



Vertical gas surface density profile

Kim, Agertz, Teyssier+2015, Agora project



Gas scale height

Kim, Agertz, Teyssier+2015, Agora project

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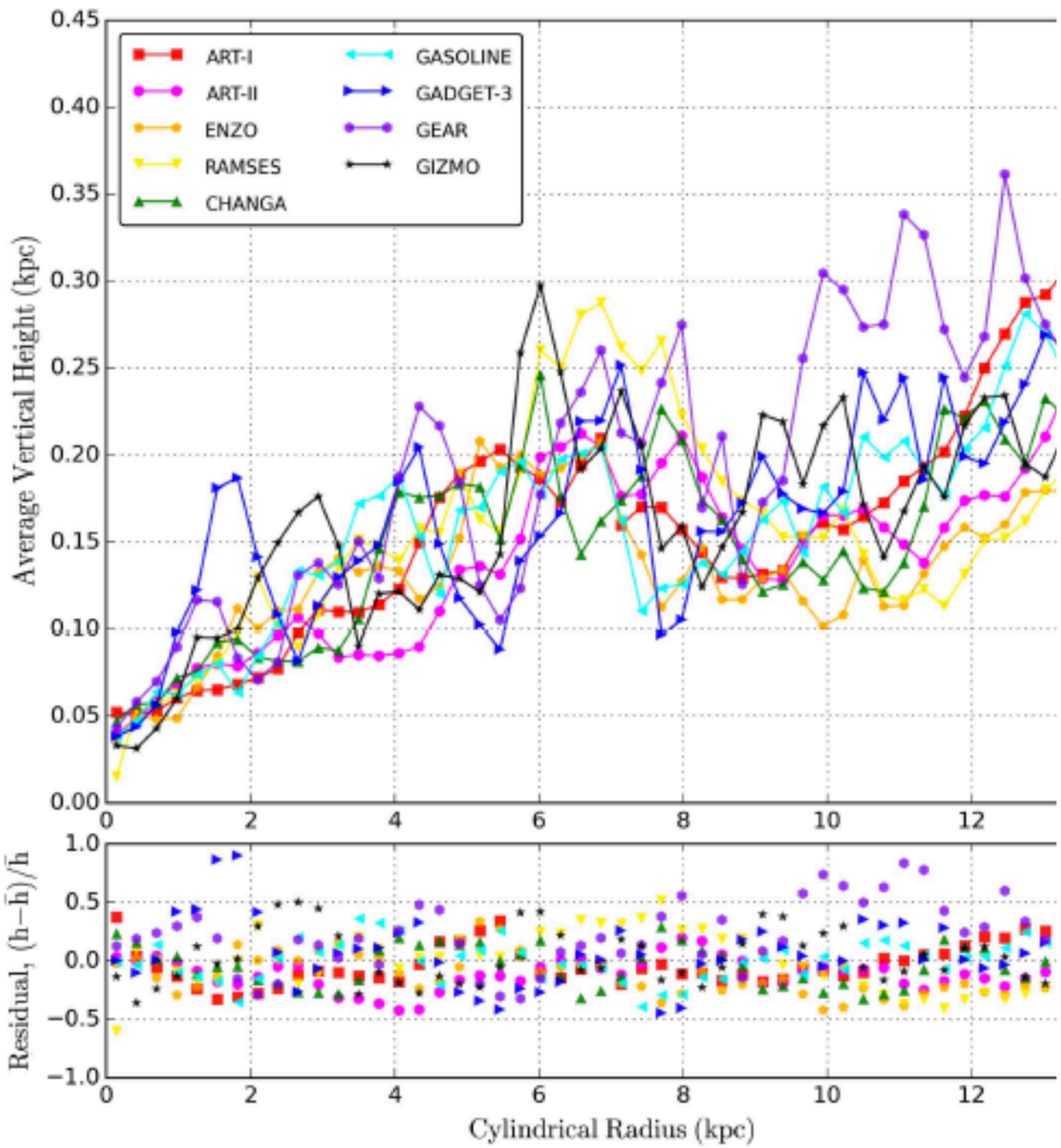

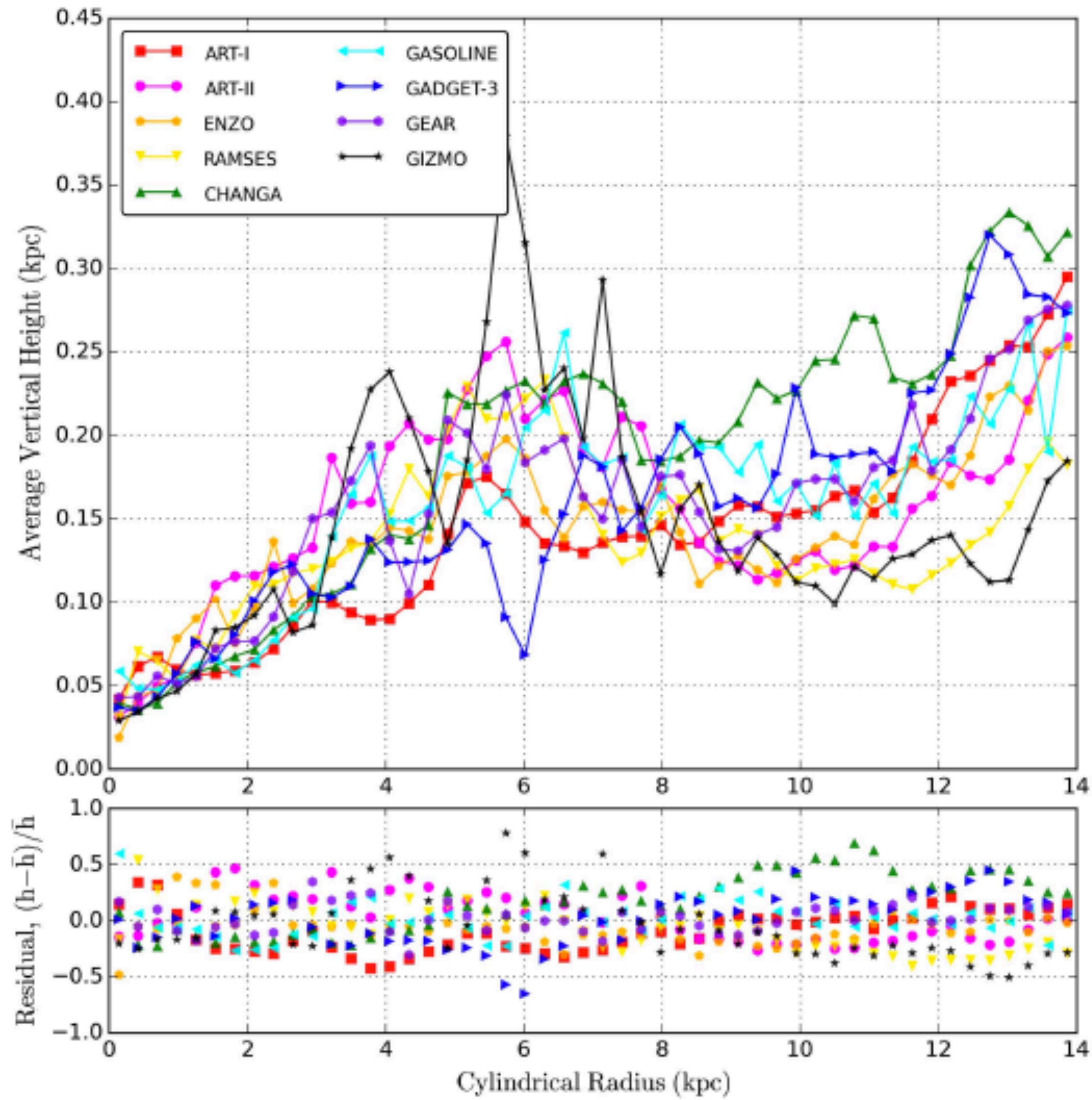

BIG differences: thermal structure (Kim+17 and refs. therein)

Kim, Agertz, Teyssier+2015, Agora project

Part 2: impact of transient spirals —

Dynamical heating: Non-thermal gas motions

Different from Krumholz+ ‘transport’ model:

No restriction to Q=1, from ‘viscous-disk’ approx to `perturbed-disk’

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Dynamical heating: Non-thermal gas motions

- Steady spirals exchange angular momentum at resonances/ heat at ILR **(Lynden-Bell & Kalnajs 1972, Goldreich & Tremaine 1978,79)**
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Stars/material placed on eccentric orbits (blurring)

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Spiral Heating and angular momentum transport

(vdWel & Meidt in prep.)

kR~m

Modes		Material patterns
kR>>1 ‘Short wave’	kR~1 ‘Long wave’	

$$\Delta E = (\Omega_p - \Omega)\Delta L$$

$$\Delta E = (-2A)\Delta L$$

Over lifetime of spiral

→ many spirals, ultimately lots of changes

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(Meidt & vdWel 24)		
Growth @ CR		
Heating @ LRs		

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A model of cloud-scale gas motions

Model galactic potential on `cloud’ (50-100 pc) scales in epicyclic approx **(Meidt+2018,20)**

Epicyclic motions small, but so is gas self-gravity on 10s pc scales

Meidt+ (in prep.)

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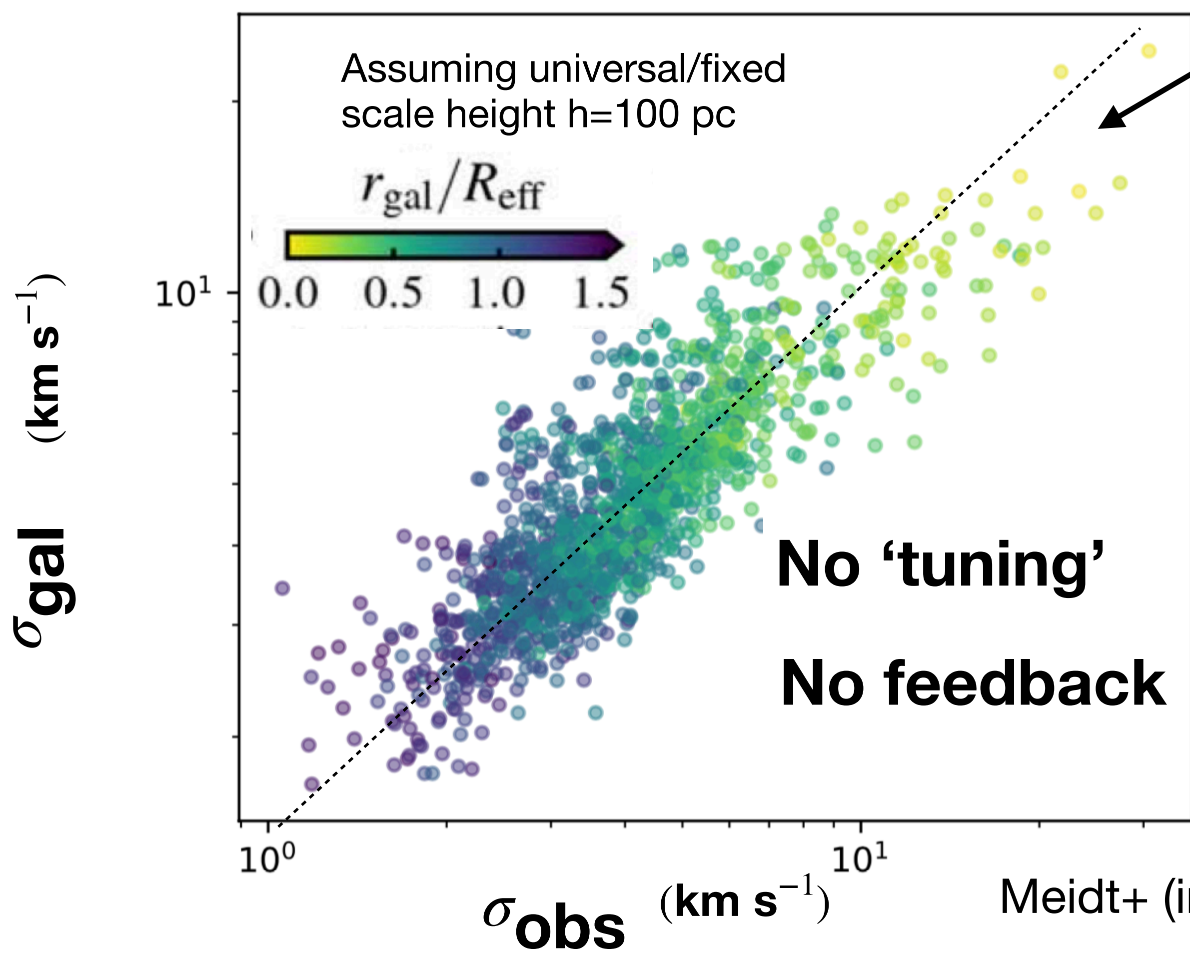


Meidt+ (in prep.)

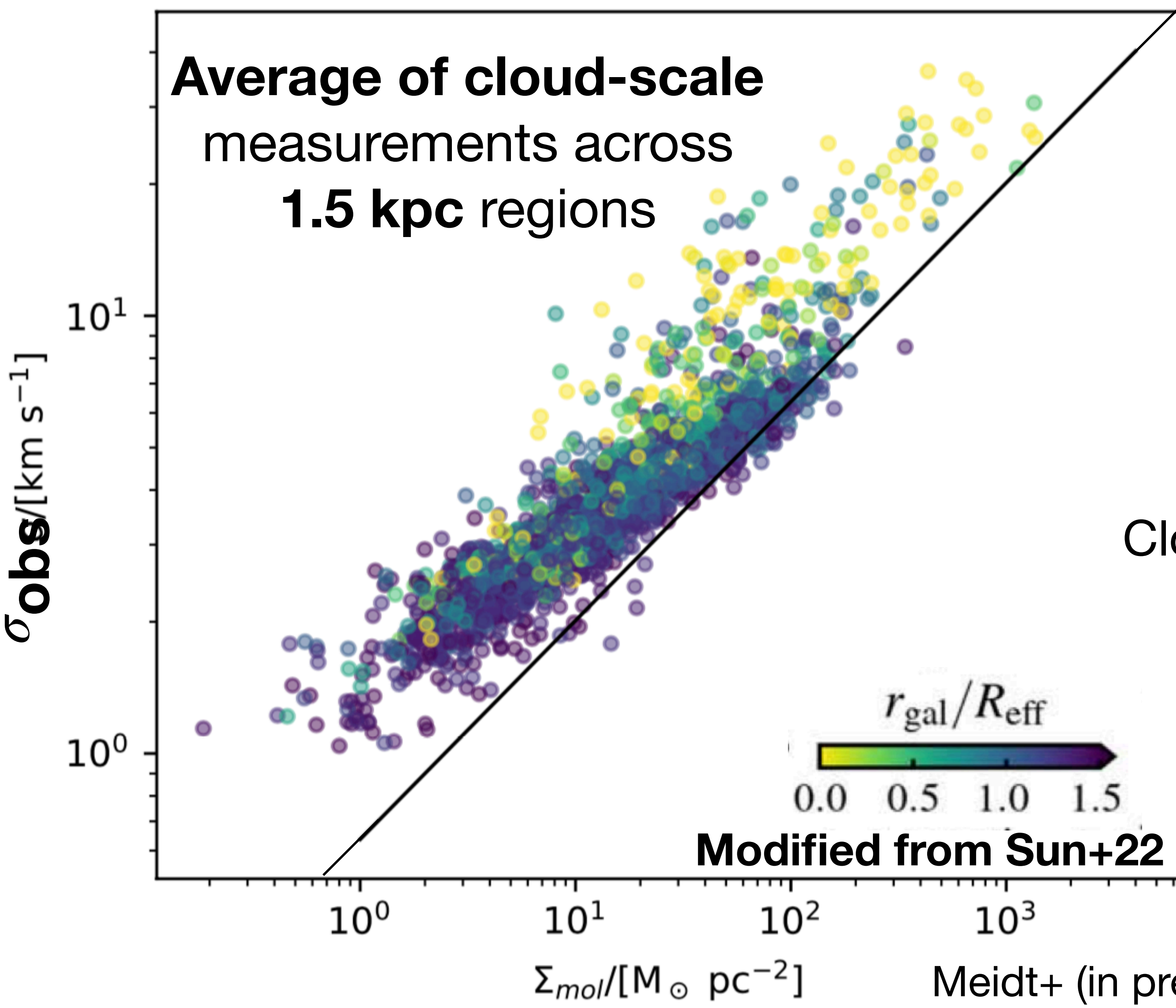
Using characteristic epicyclic frequencies κ, ν in the gravitational potential

Estimated from **PHANGS** potentials == rotation curves *(Lang+20) and mass distributions (Leroy+23, Querejeta+21)*

Cloud-scale values averaged across kpc-regions

Match to observed 'super-virial' motions

PHANGS: Clouds in the context of their host galaxies: systematic variation with galactic environment **(Rosolowsky+21, Sun+20,22)**



Meidt+ (in prep.)

PHANGS-ALMA 150pc -> R~75pc

CO(2-1) *(Leroy+22a,b)*

'elevated' especially in centers: Bars, rotational gradients

Cloud-scale values averaged of kpc-regions

Role of SNe feedback in molecular gas

Star formation feedback-driven turbulence

Dynamical pressure equilibrium

(Kim & Ostriker, Kim+22)

SNe momentum injection

$$\rho\sigma^2 = \left(\frac{1}{4}\right)\left(\frac{p*}{m*}\right)\Sigma_{\mathbf{SFR}}$$

$$\sigma^2_{\mathbf{FB}} = 2h\left(\frac{1}{4}\right)\left(\frac{p*}{m*}\right)\left(\frac{1}{\tau_{dep}}\right)$$

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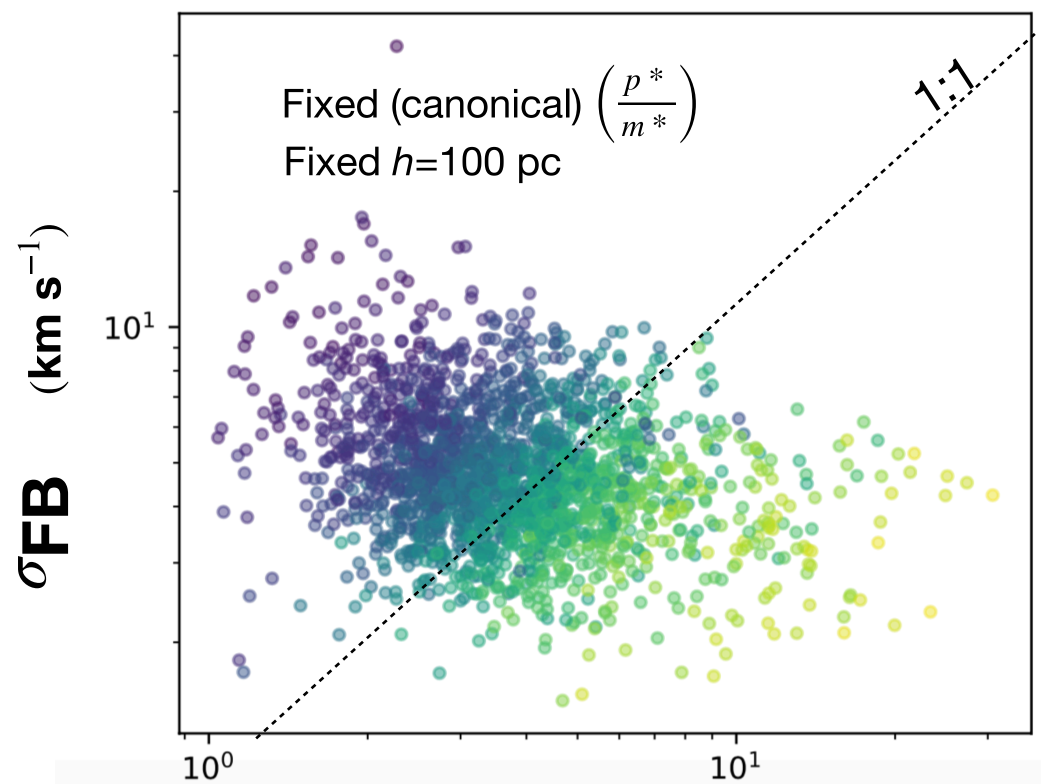

$\sigma_{\mathbf{obs}}$ (**km s**$^{-1}$) Meidt+ (in prep.)

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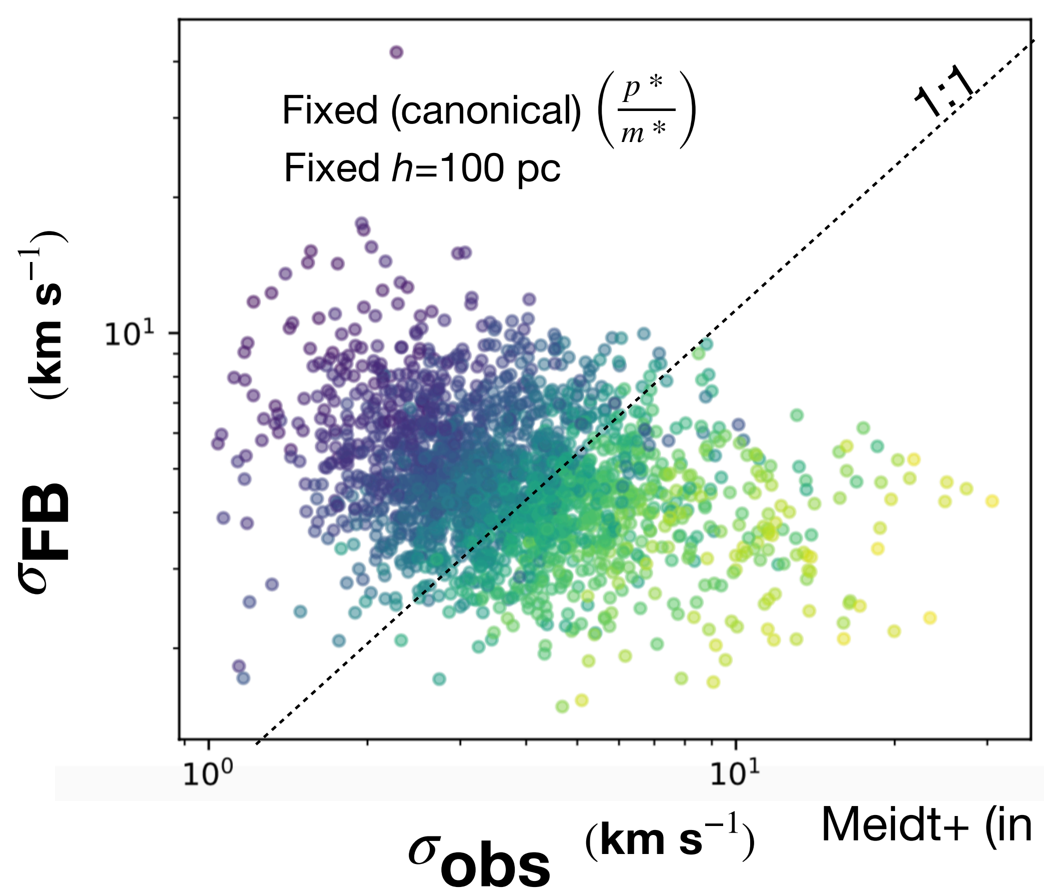

Meidt+ (in prep.)

SNe momentum injection

$$\rho\sigma^2 = \left(\frac{1}{4}\right)\left(\frac{p*}{m*}\right)\Sigma_{\mathbf{SFR}}$$

$$\sigma^2_{\mathbf{FB}} = 2h\left(\frac{1}{4}\right)\left(\frac{p*}{m*}\right)\left(\frac{1}{\tau_{dep}}\right)$$

- Systematic variation in $\left(\frac{p*}{m*}\right)$?

(Sun+20; e.g. Fielding+18,Matrizzi+20,Smith+21)

Role of SNe feedback in molecular gas

Star formation feedback-driven turbulence

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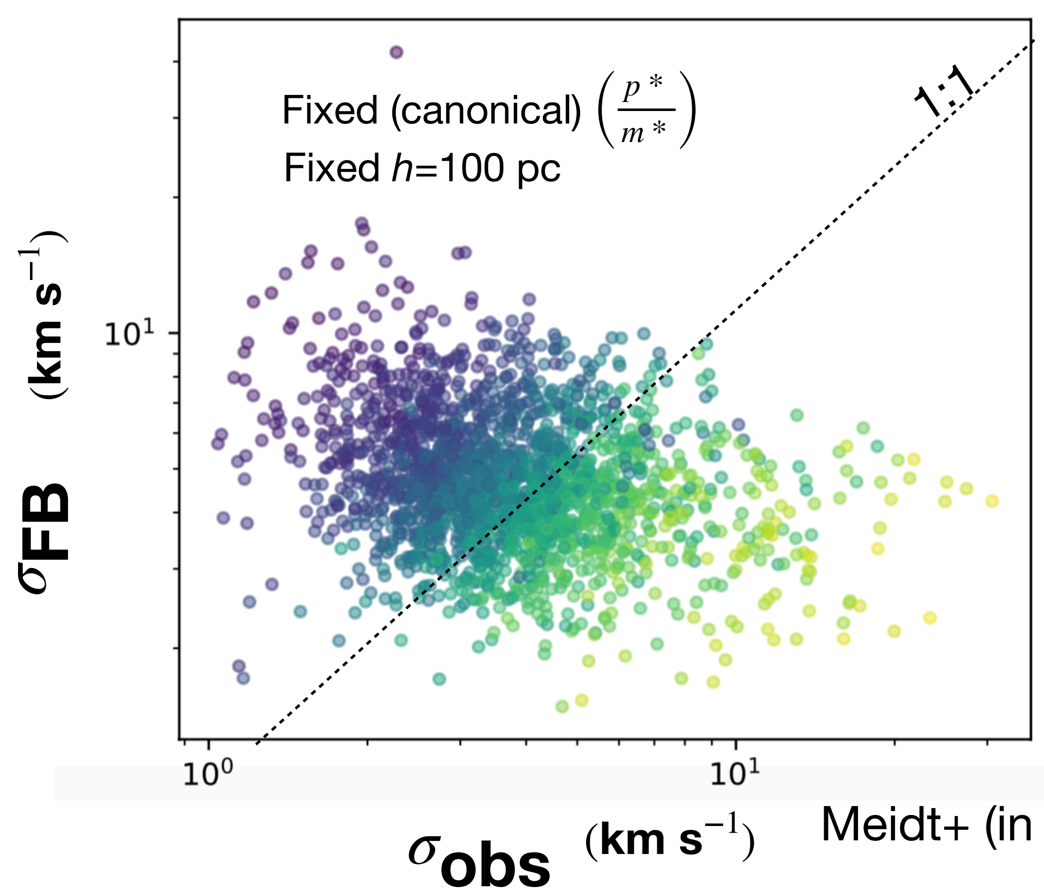

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- **Additional 'large scale' driver (cloud and beyond)**

*(**obs**: e.g. Fisher+20, Elmegreen+22)*
*(**sims**: e.g. Colman+22,Brucy+23,Fensch+23)*

Take away Part 2

The nature of spirals in disks influences observed disk properties

<u>Transient</u> **non-axisymmetric structure dynamically heats gas disks, places material on 'epicycles' (non-circular orbits)**

Motion in galactic potential: source of non-thermal (turbulent) gas motion

Impact on Star formation?

- Material on non-circular orbits —> kinetic energy on cloud scale
  (Meidt+2018)
- Must be ‘overcome’ for gas to collapse and ultimately form stars
  (Meidt+2020)

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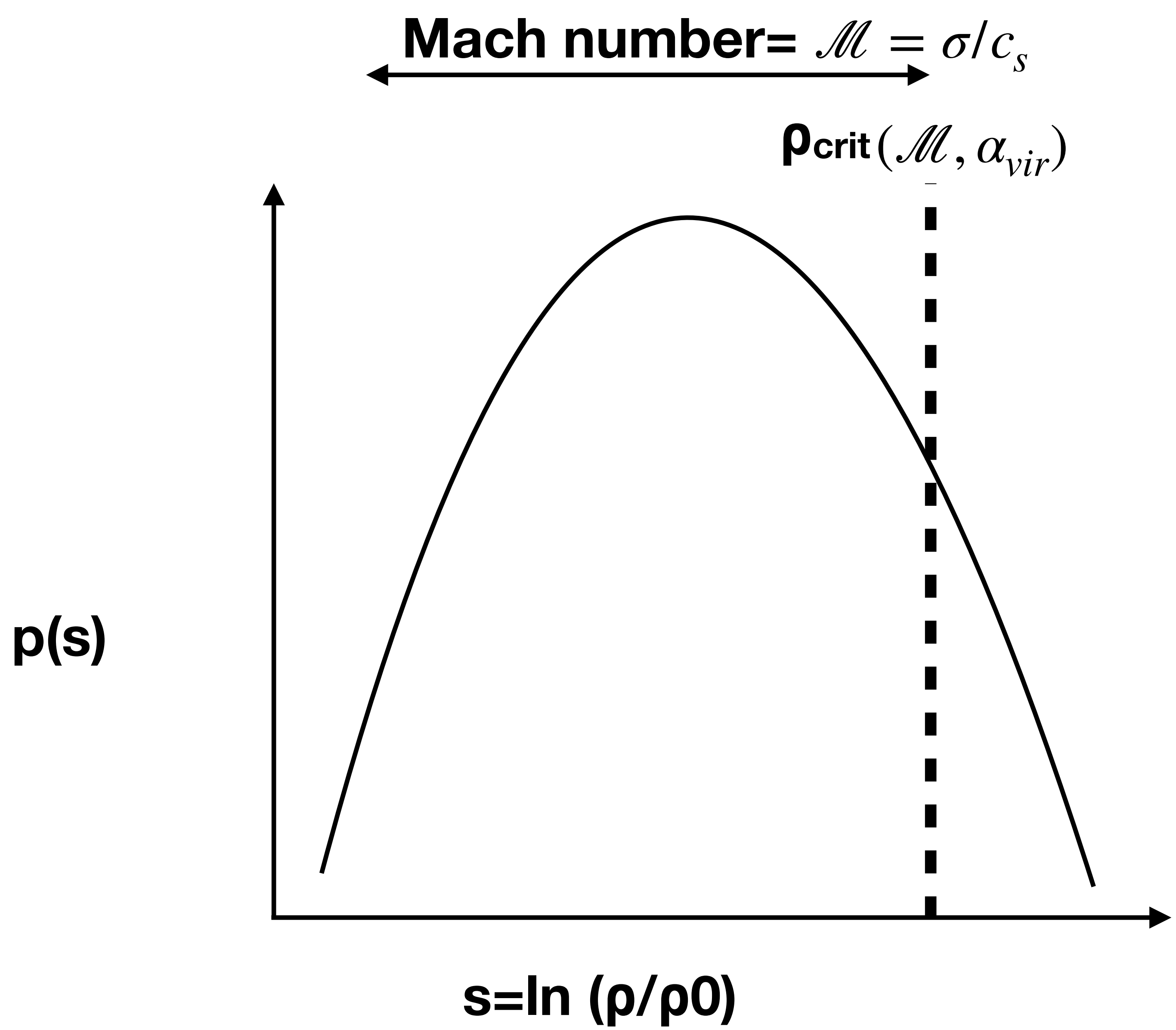
→ wrap around turbulence-regulated star formation. **(Meidt+2025)**

What happens ‘below the beam scale’?

Turbulence-regulated star formation



$$\alpha_{vir} = \frac{5\sigma^2}{\pi G \Sigma R}$$

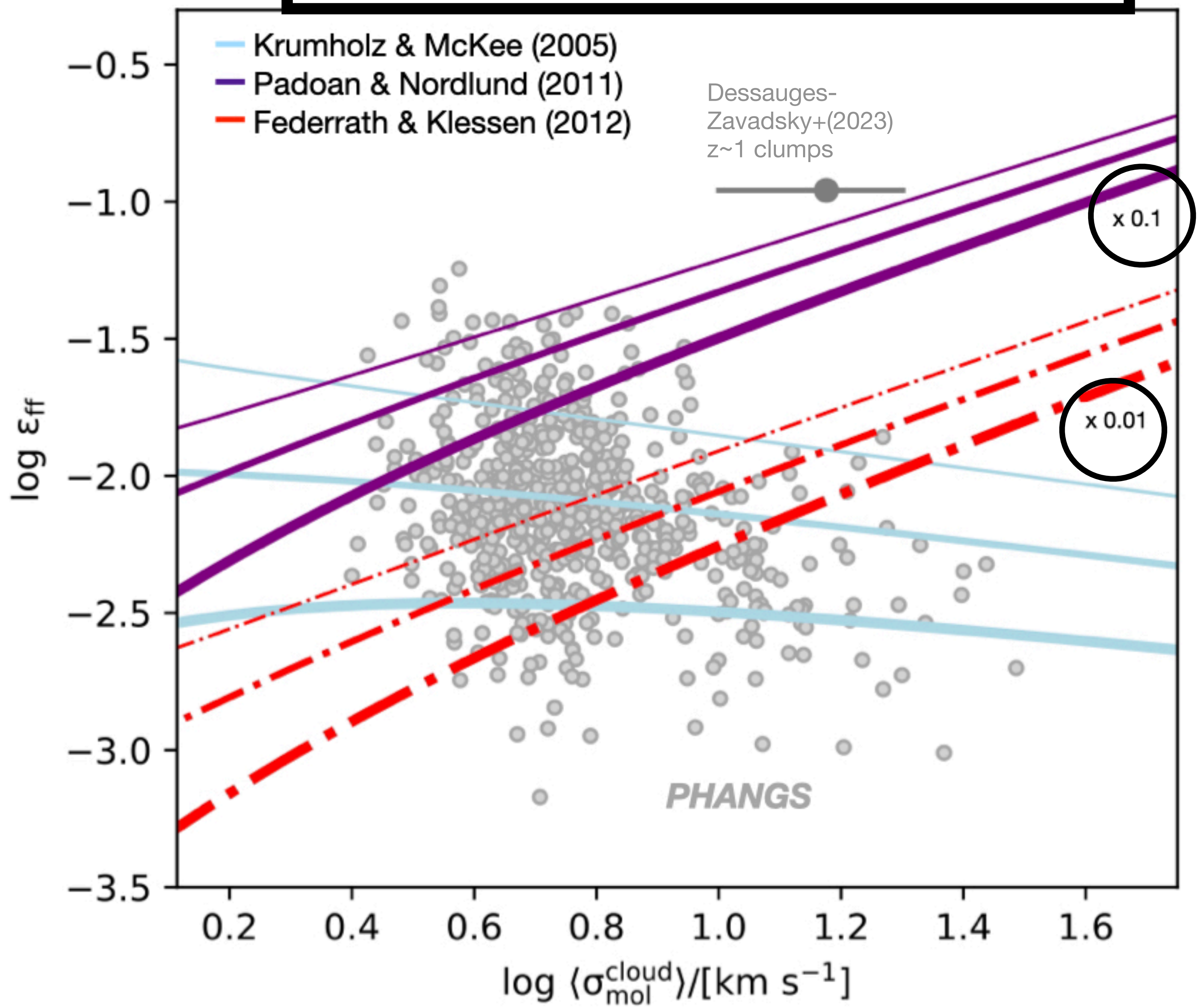
Krumholz & McKee 2005
Padoan & Nordlund 2011
Hennebelle & Chabrier 2011
Federrath & Klessen 2012

Star formation

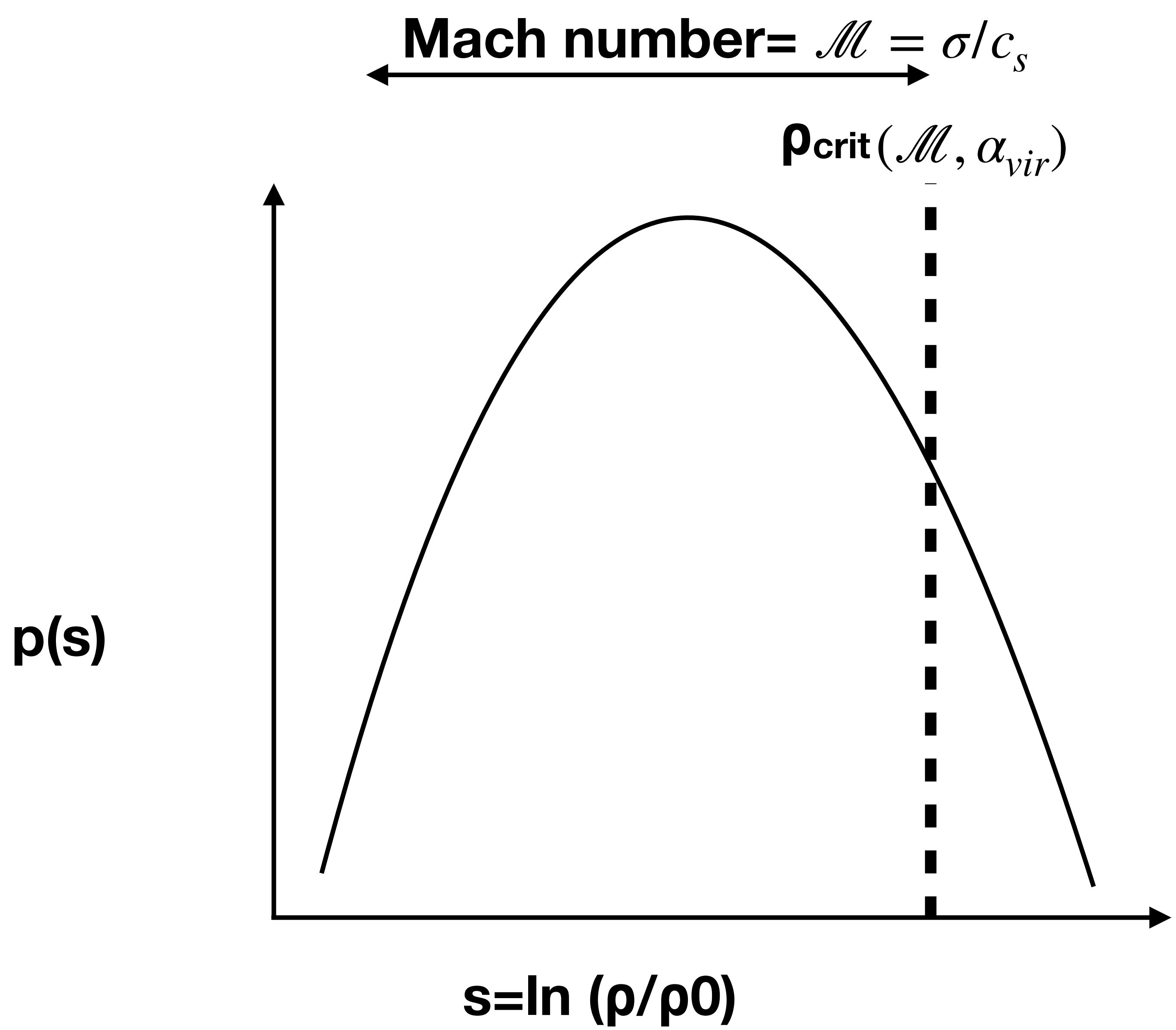
Each data point:

Cloud-population averages of 100-pc scale properties measured in 1 kpc -sized regions **(see Leroy+17,Sun+18,20, Leroy+25)**

Models with lognormal PDFs



Turbulence-regulated star formation



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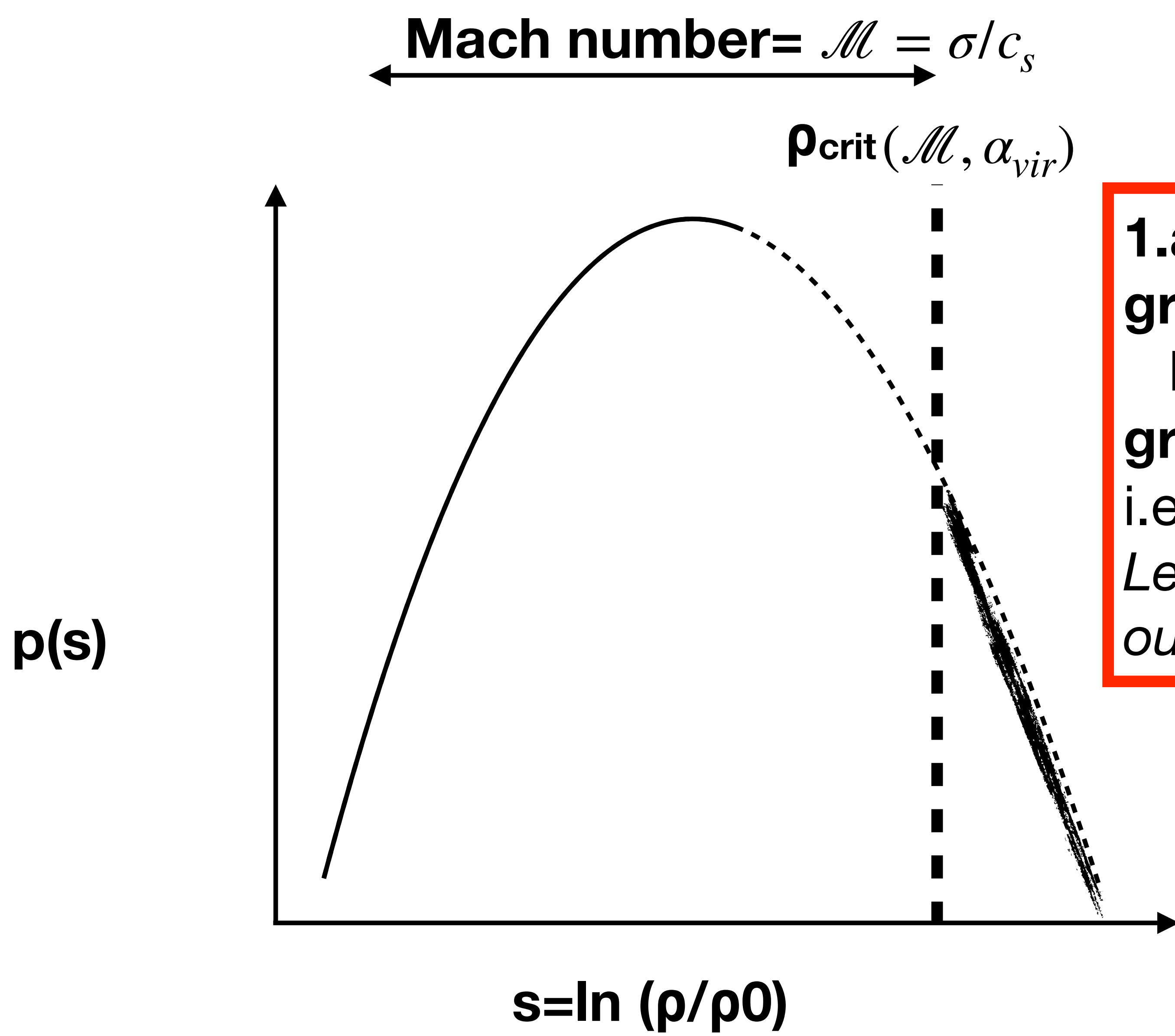
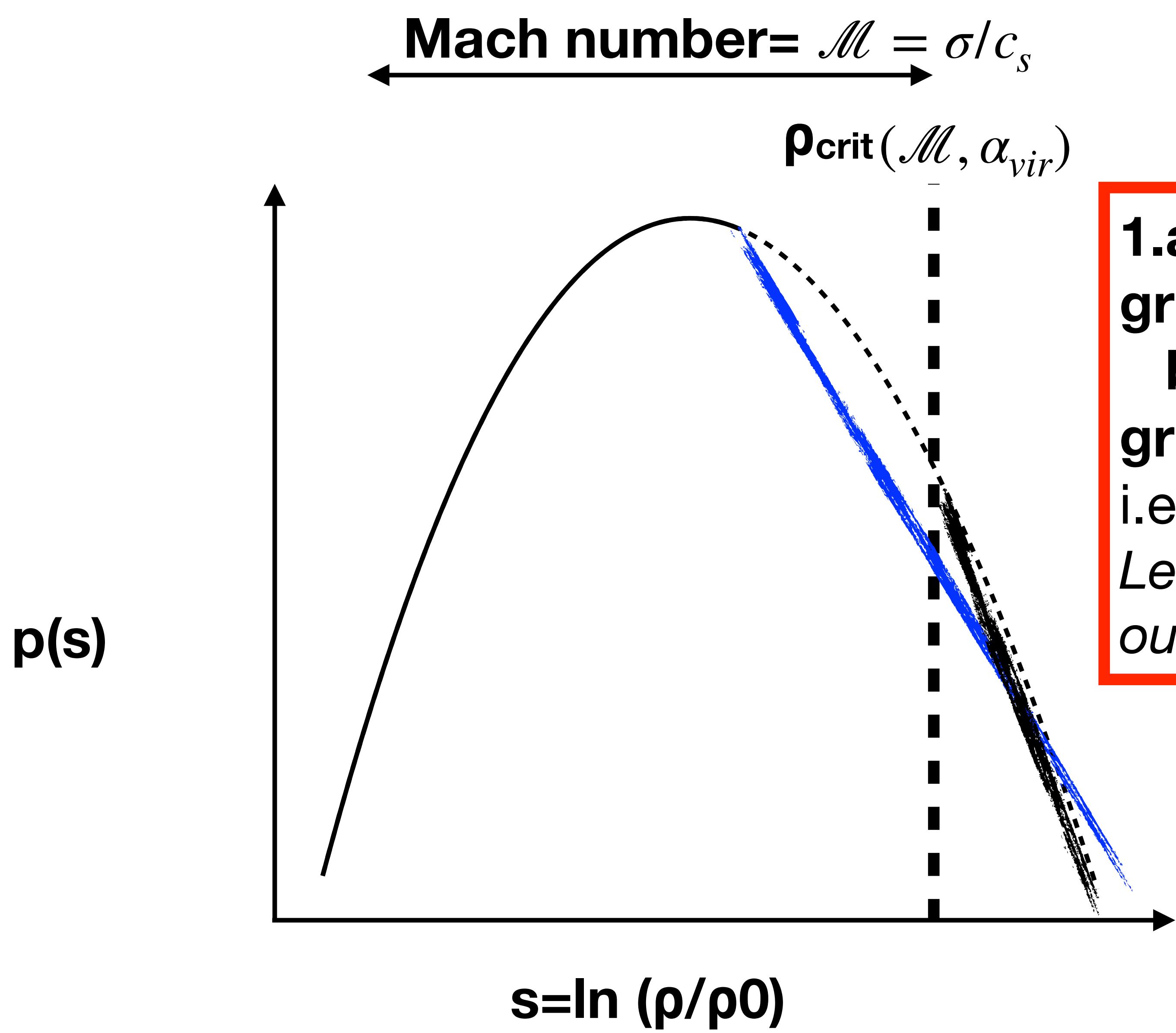


1.a. Include a power-law (gas self-gravity)
b. Lower threshold for self-gravitation (broader PL component, i.e. than Burkhart & Mocz 2018)
Less dense gas->reduced MFF output

Turbulence-regulated star formation



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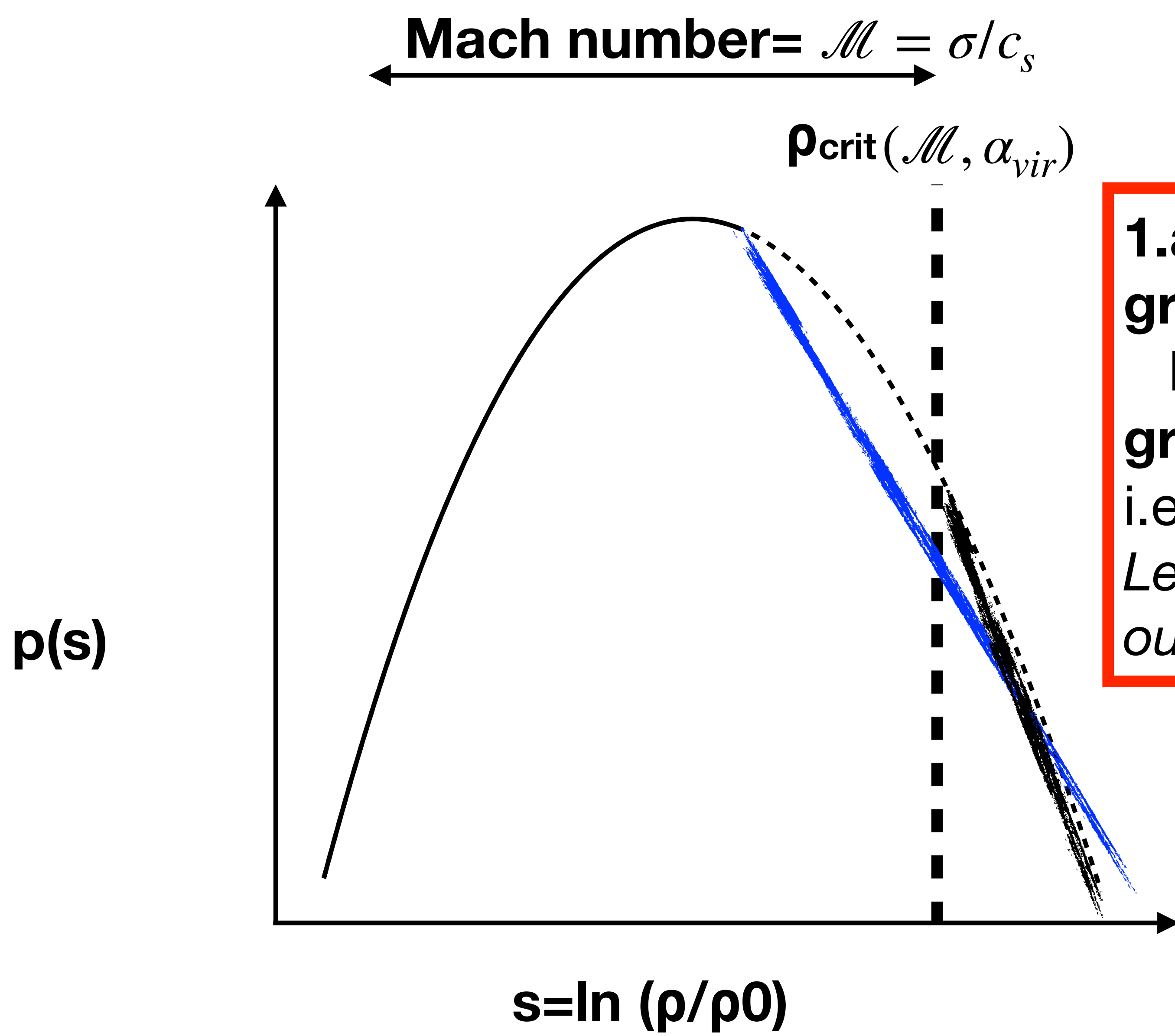

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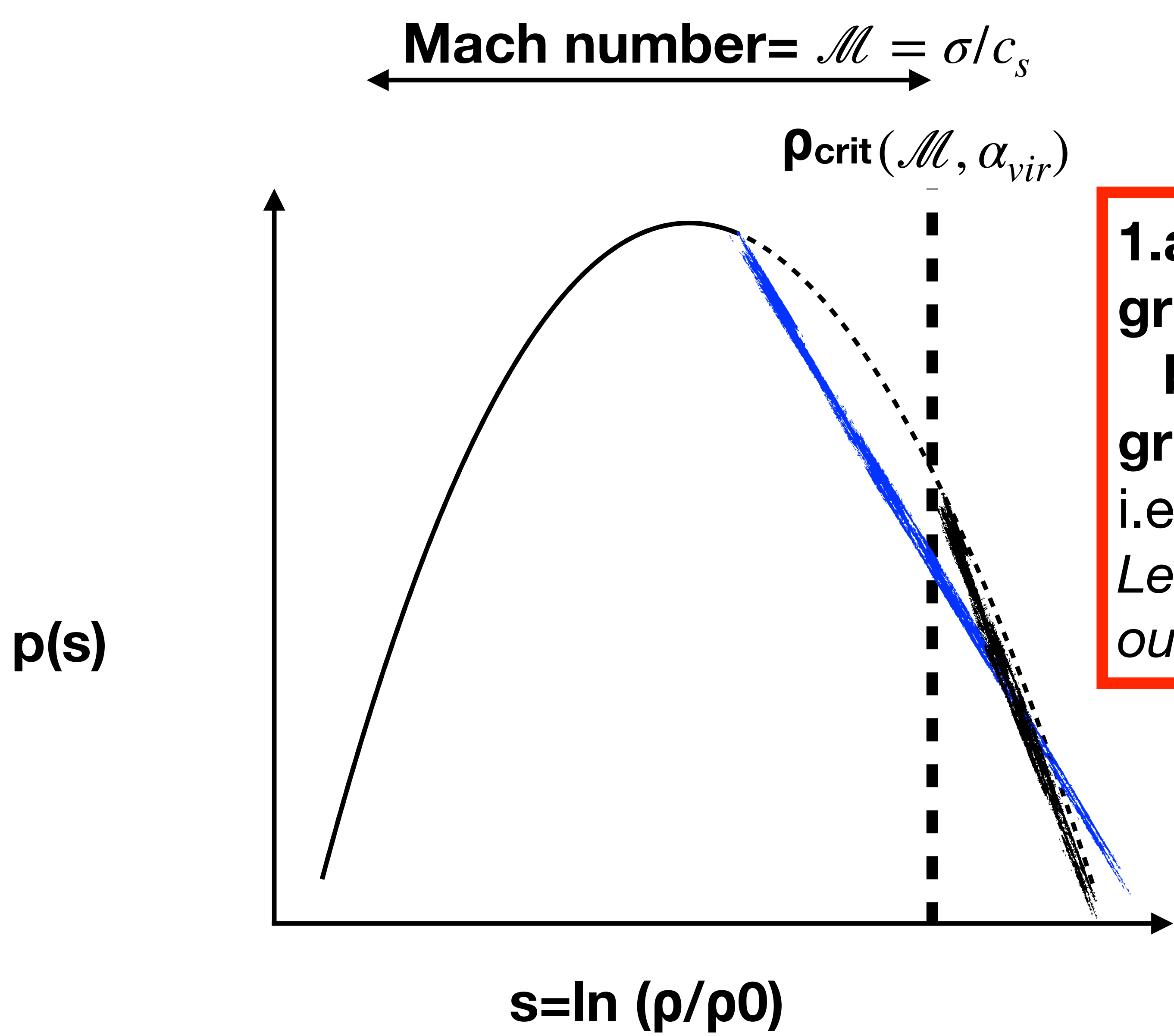
Turbulence-regulated star formation



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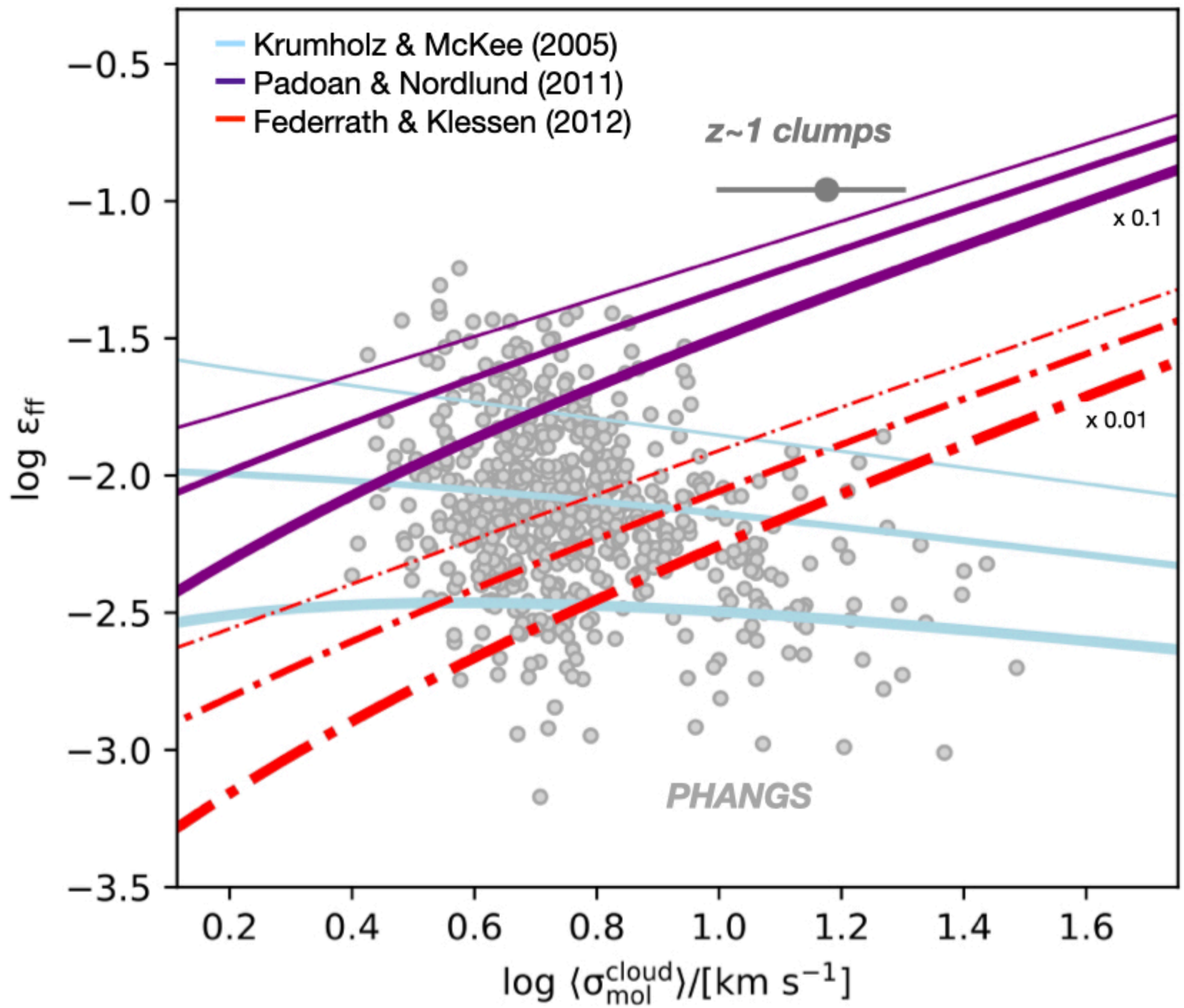
2. **Shorten the duration of turbulence replenishment to t_{ff} @ self-gravitation threshold**

Star formation terminates before one free fall time

Star formation

Result:

- Reduction to multi-free fall star formation efficiencies
    - + Variations strongly tied to variations in PL slope α (cf. **Burkhart 2019**)
- More similar to original ‘single free fall’ virialized cloud predictions (**Krumholz & McKee 2005**)



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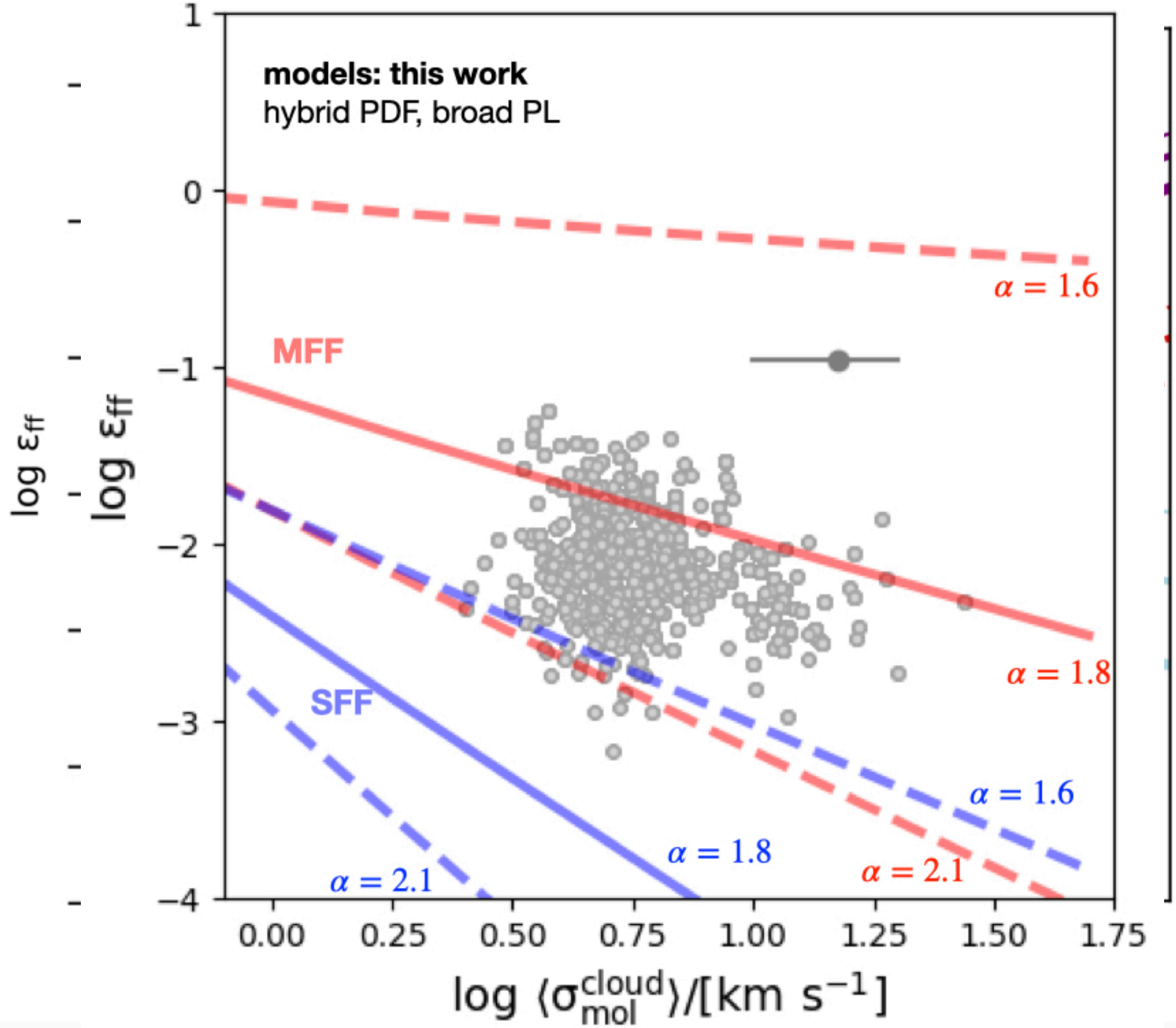

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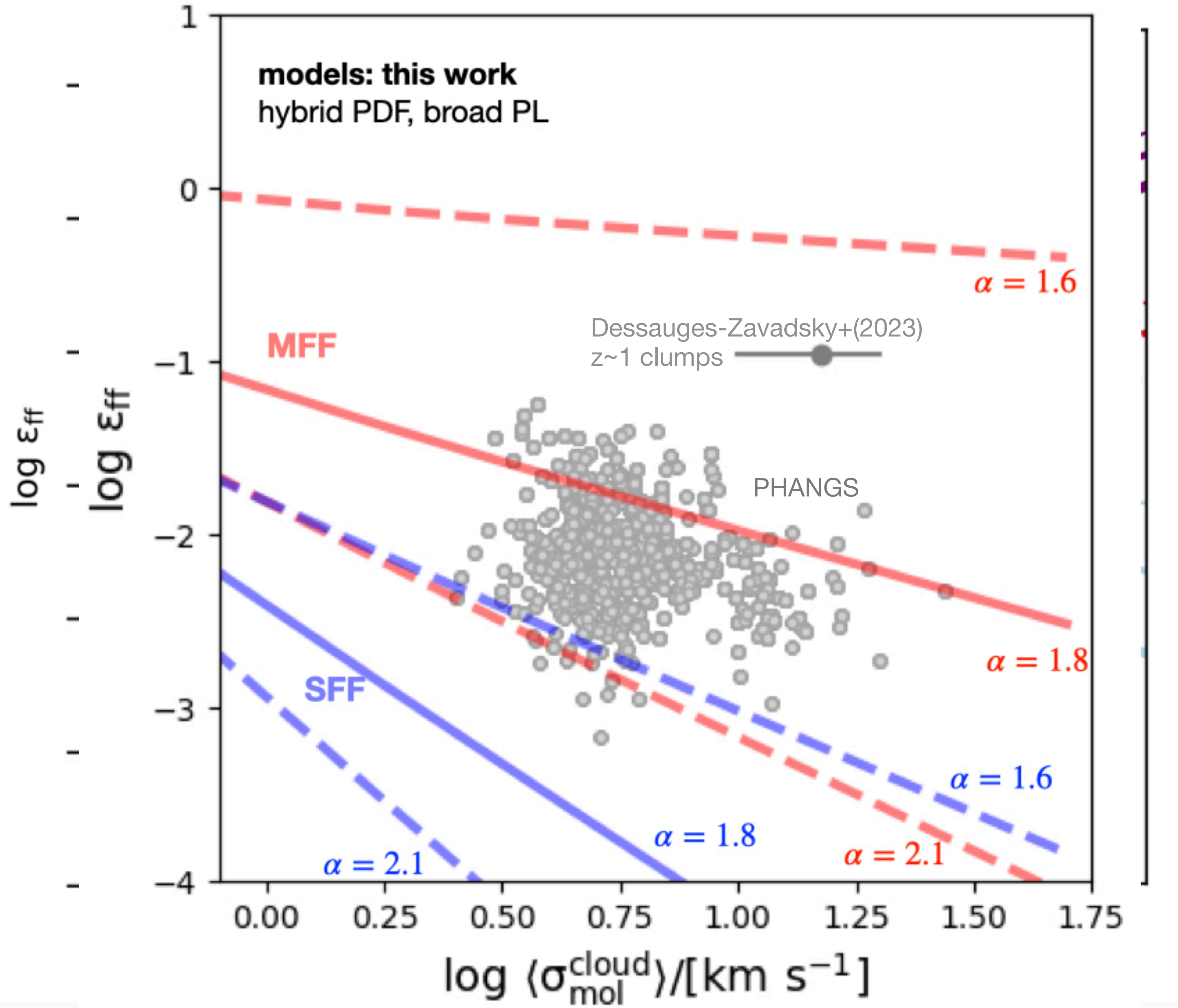

To match PHANGS measurements

Systematic variation in power-law slope α

Lower α (more dense gas) needed to offset where gas becomes less bound (higher virial parameter)

(<u>Conventionally</u>:

Higher virial parameter, higher threshold for star formation. Predicted efficiency lowered.)