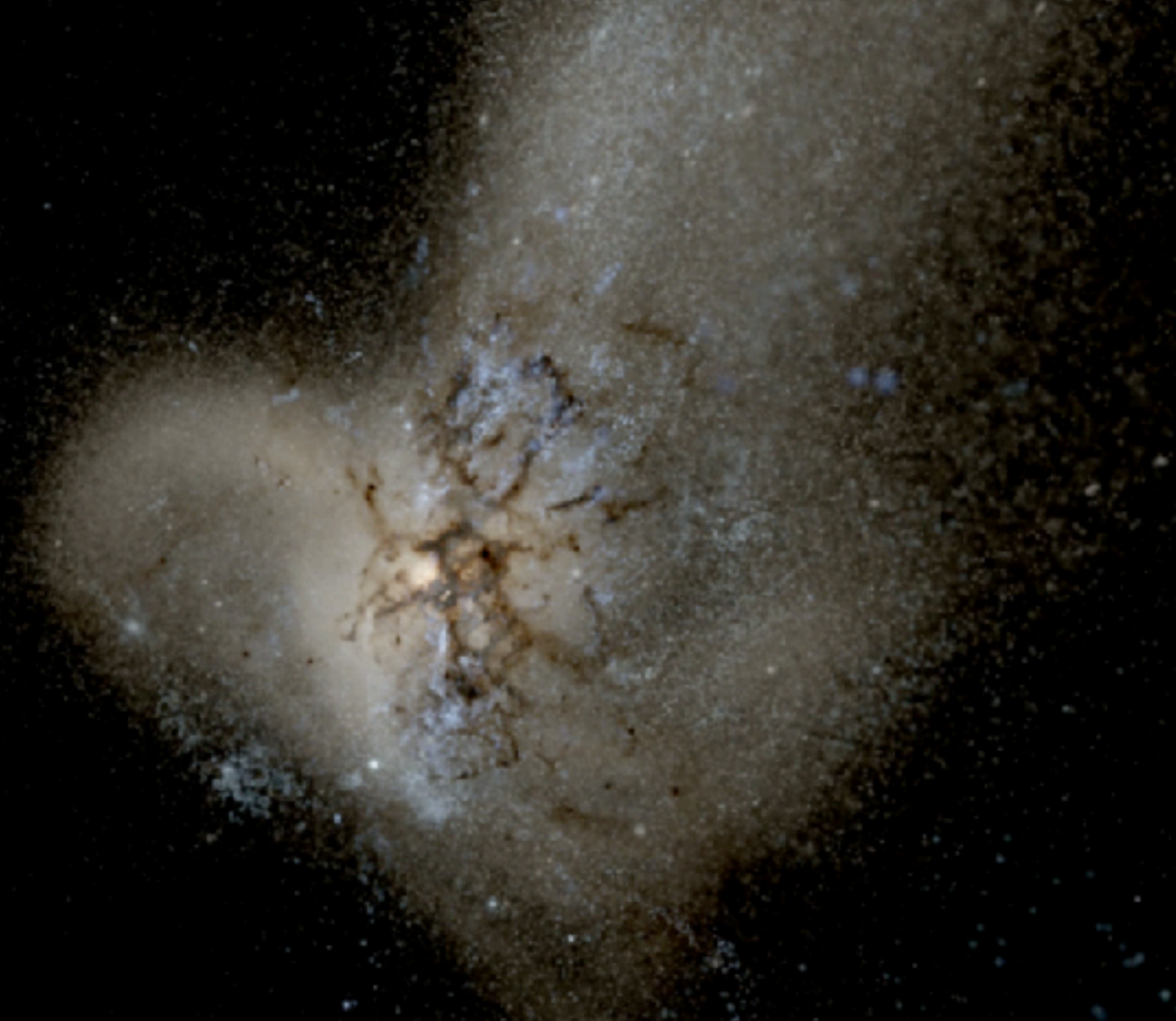


The Resonant Drag Instability (RDI): A New Class of Instabilities in Dusty Gas



Philip F. Hopkins & Jonathan (Jono) Squire (Caltech)

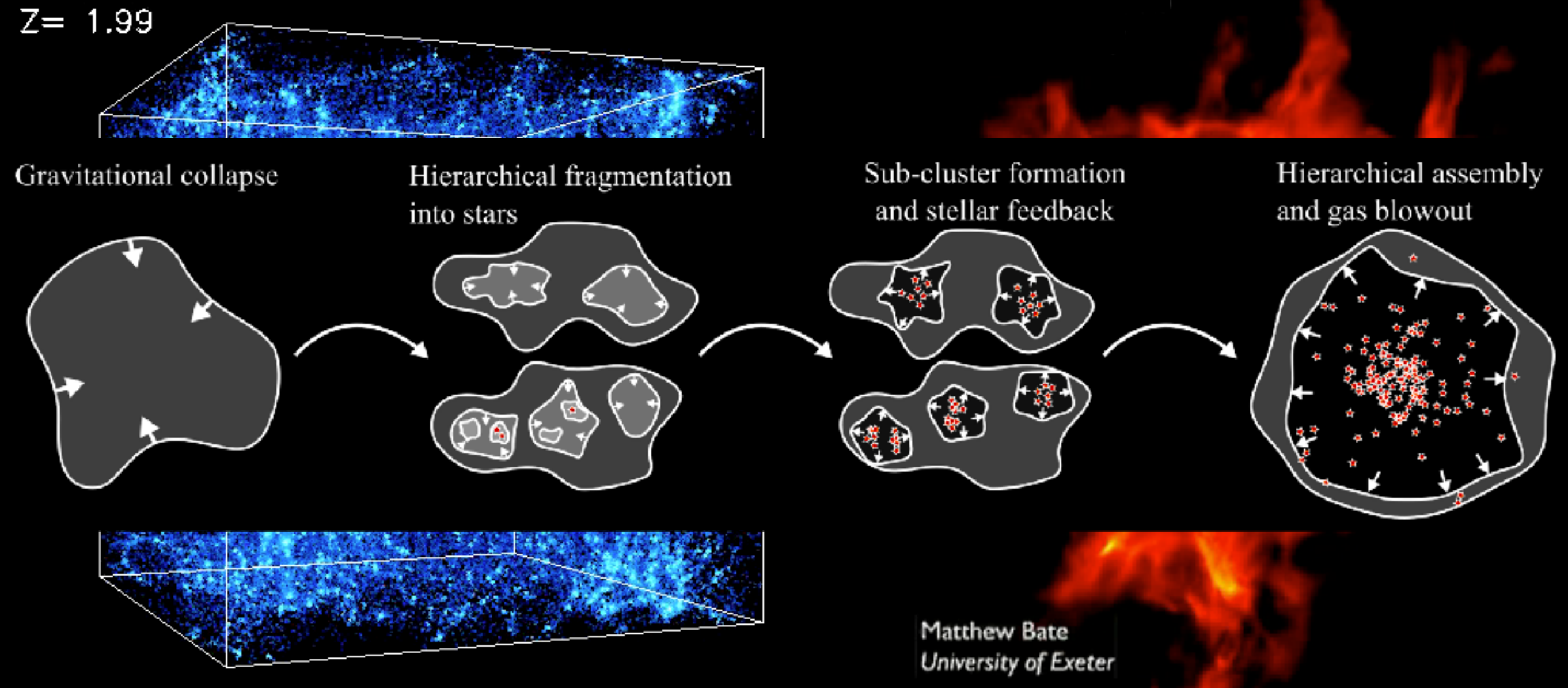
arXiv: 1706.05020 (SH), 1707.02997 (HS)



(Not Talking About:) Turbulent Fragmentation on All Scales

STRUCTURE FORMATION

STAR FORMATION



Guszejnov 15,16, 17a, 17b (arXiv later this week)
PFH 12,13,14
Grudic 16, 17 (prep)

Why Worry About Dust?



- Dust:
 - Critical for: cooling, planet formation, starburst / AGN / cool star winds, extinction / reddening, polarization (BICEP)
 - Not enough metals (Draine+; Jenkins+; worse today!)
 - Too many big grains (Ulysses, Cassini, Helios, Arecibo; Kruger '06, Draine '09, Poppe '10)
 - Forms too early (Perley '12, Zafar '13, Kuo '13, De Cia '13, Sparre '14, Mattsson '15)
 - Wrong polarization / charge (Planck '15, BICEP 2, Lazarian '09)
 - Does *crazy* stuff (see all planet formation literature)

Why Worry About Dust?

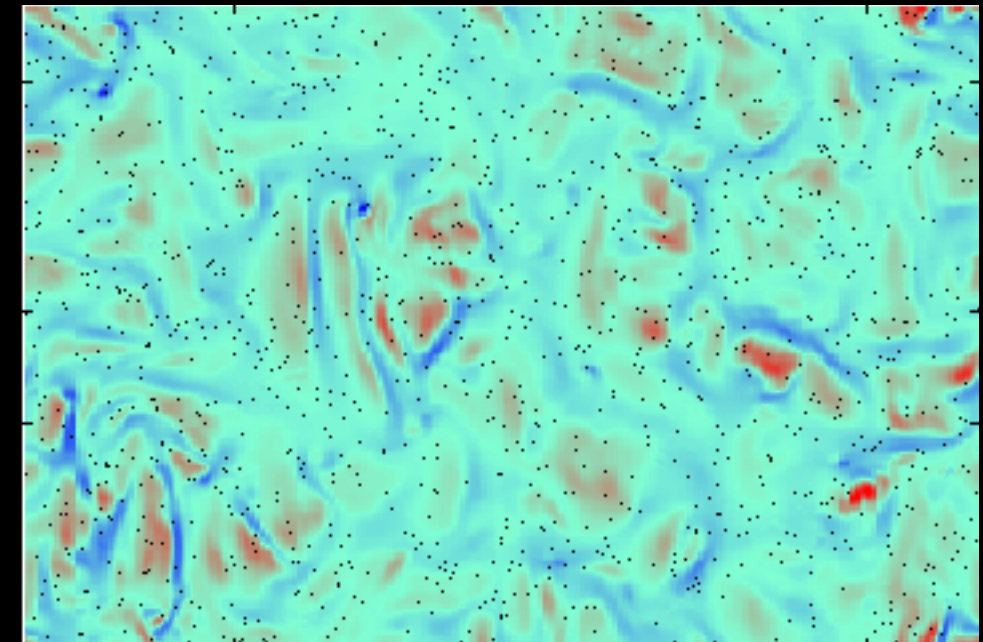
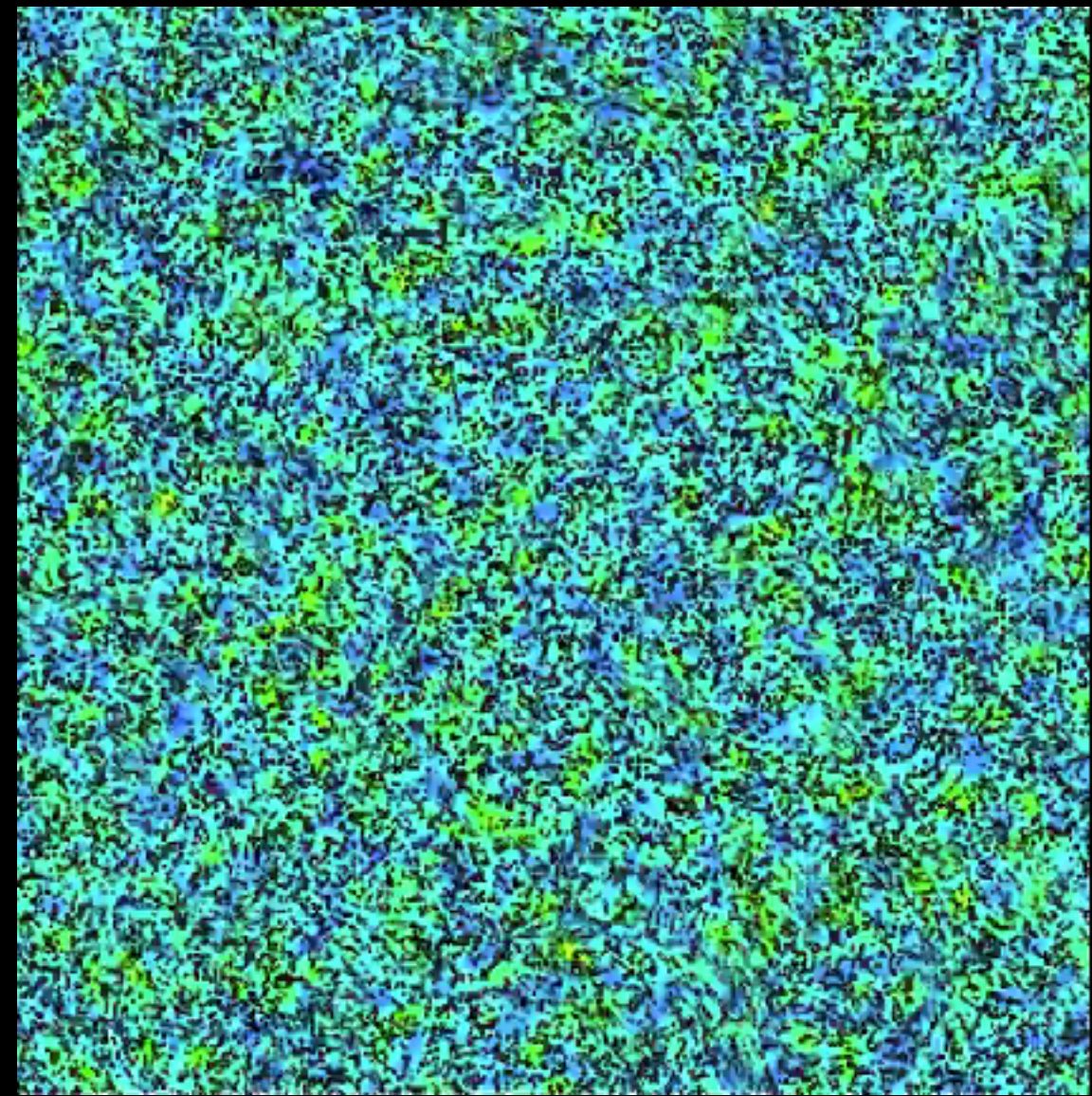
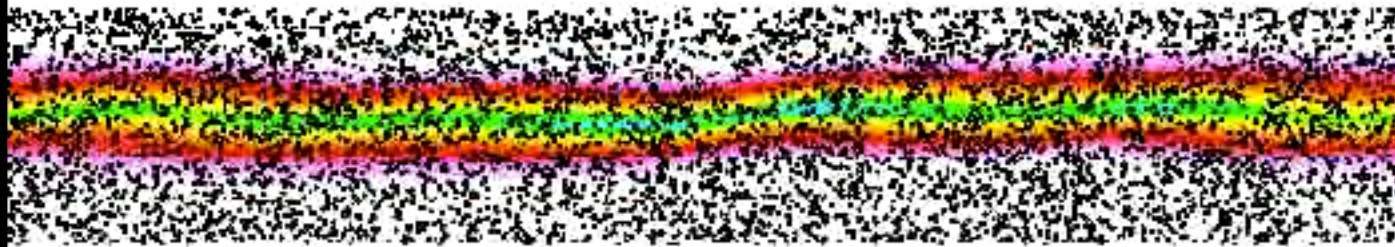


- Dust:
 - Critical for: cooling, planet formation, starburst / AGN / cool star winds, extinction / reddening, polarization (BICEP)
 - Not enough metals (Draine+; Jenkins+; worse today!)
 - Too many big grains (Ulysses, Cassini, Helios, Arecibo; Kruger '06, Draine '09, Poppe '10)
 - Forms too early (Perley '12, Zafar '13, Kuo '13, De Cia '13, Sparre '14, Mattsson '15)
 - Wrong polarization / charge (Planck '15, BICEP 2, Lazarian '09)
 - Does *crazy* stuff (see all planet formation literature)

Dust Is Not Gas

EXPERIMENT & EVERYDAY EXPERIENCE

Dust in turbulence



e.g. Squires & Eaton 1991

Background

The Setup:

SQUIRE & HOPKINS '17 (SH; arXiv:1706.05020)

Gas equations = (anything that supports a linear mode)

Dust equations = continuity + momentum:

$$\frac{d\mathbf{v}_{\text{dust}}}{dt} = -\mathbf{M}_{\text{coupling}} \cdot (\mathbf{v}_{\text{dust}} - \mathbf{v}_{\text{gas}}) + \mathbf{a}_{\text{other}}(\dots)$$

Arbitrary operator

e.g.

$$\frac{d\mathbf{v}_{\text{dust}}}{dt} = -\frac{\mathbf{v}_{\text{dust}} - \mathbf{v}_{\text{gas}}}{t_s(\dots)} + \mathbf{a}_{\text{other}}(\dots)$$

Stopping/drag time



The Setup:

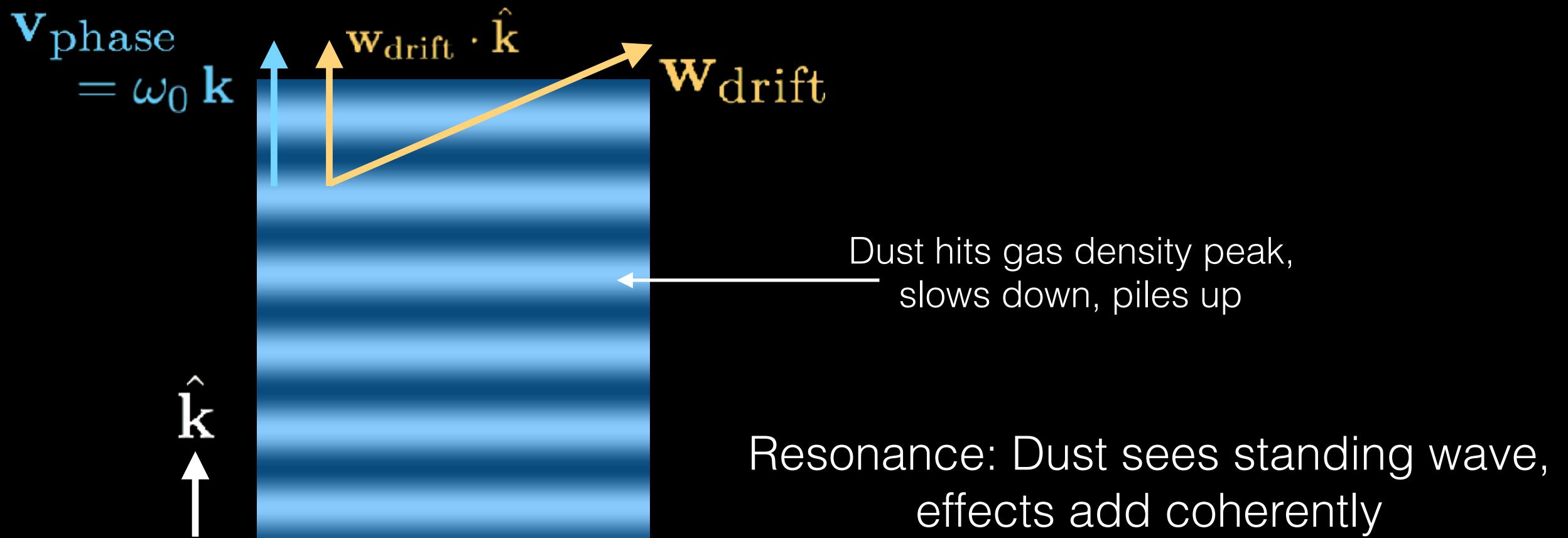
SQUIRE & HOPKINS '17 (SH; arXiv:1706.05020)

Drift: $\mathbf{w}_{\text{drift}} \equiv \langle v_{\text{dust}} - \mathbf{v}_{\text{gas}} \rangle \neq \mathbf{0}$

Resonance whenever: $\mathbf{w}_{\text{drift}} \cdot \mathbf{k} = \omega_0$

“natural”
gas response

wavevector



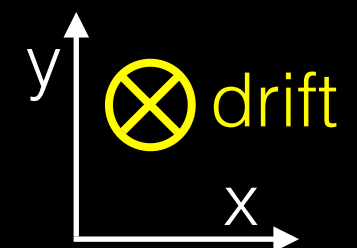
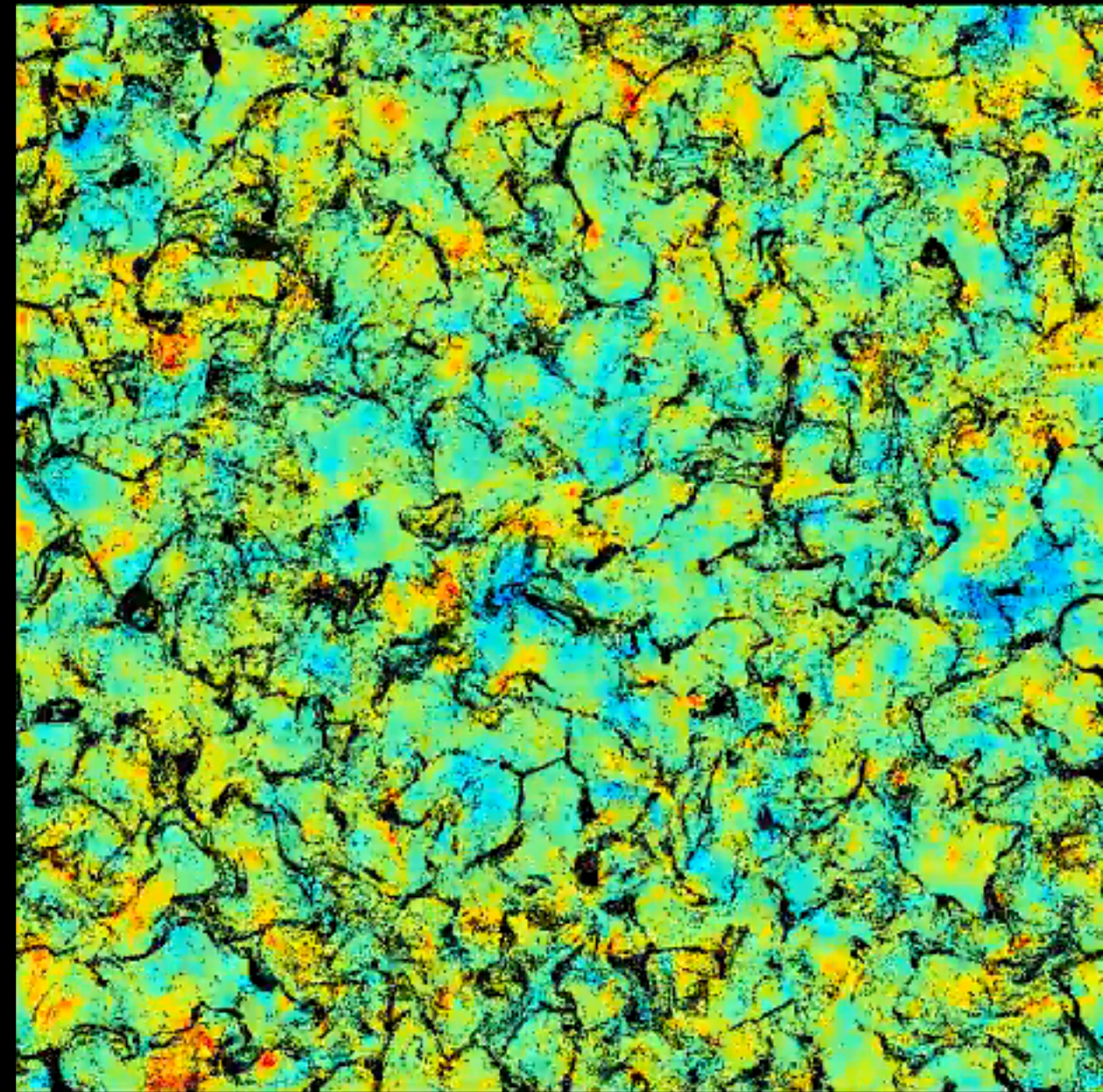
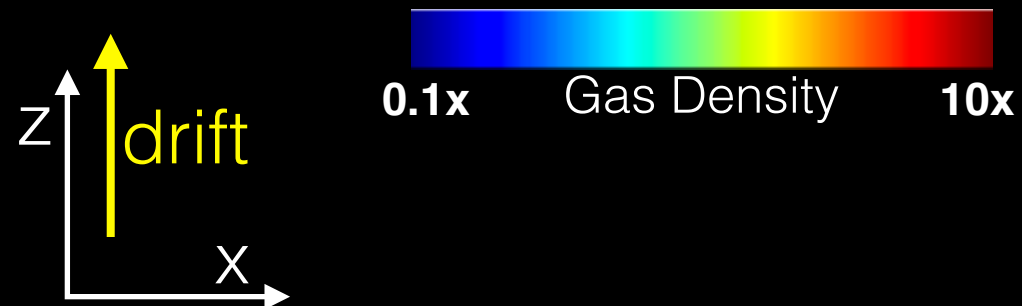
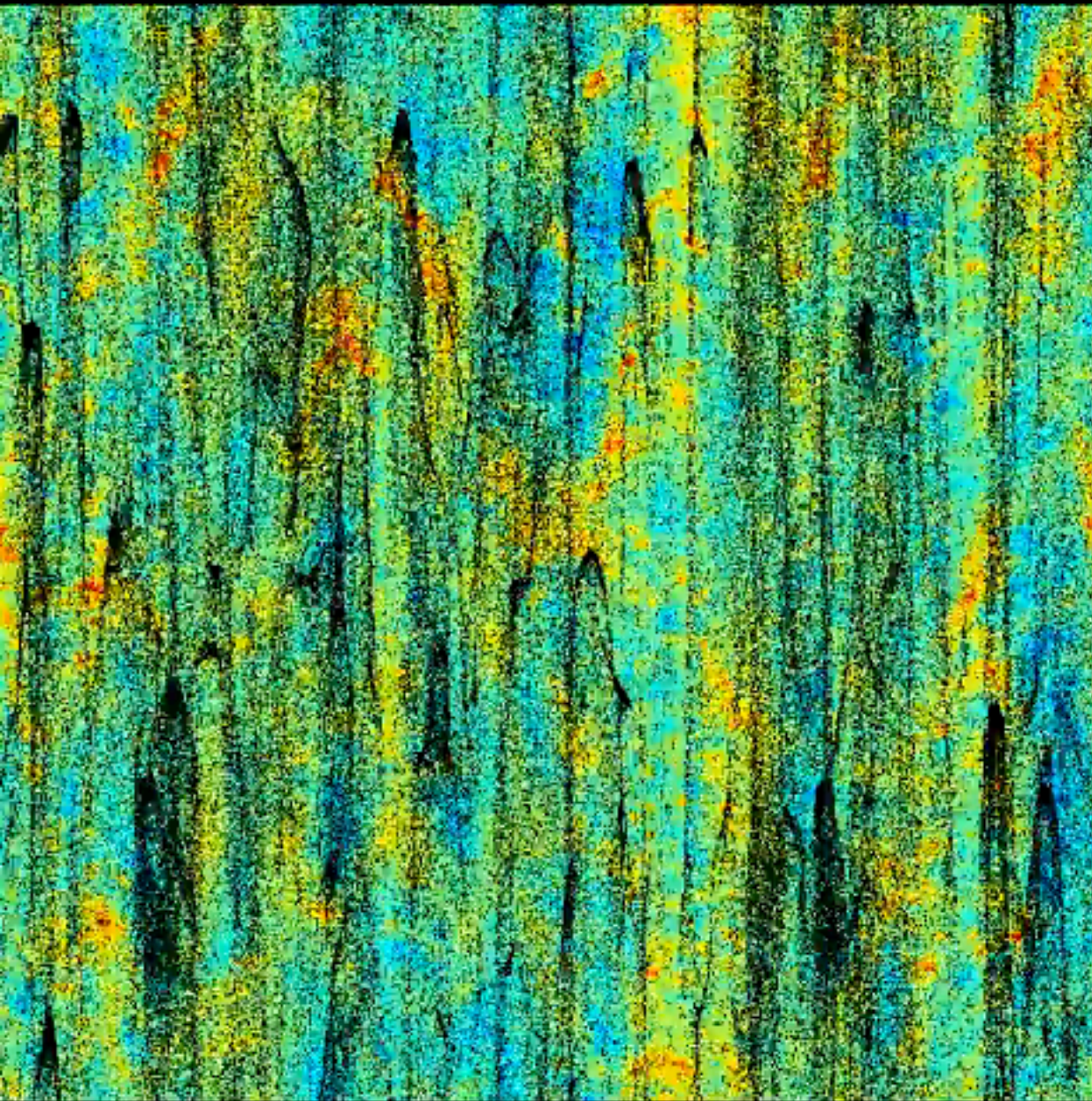
What Does This Look Like?

(WE'LL TALK ABOUT NUMBERS LATER)

$$|\mathbf{w}|_{\text{drift}} \approx 10 c_s$$

$$L_{\text{box}} \sim 100 c_s \langle t_s \rangle$$

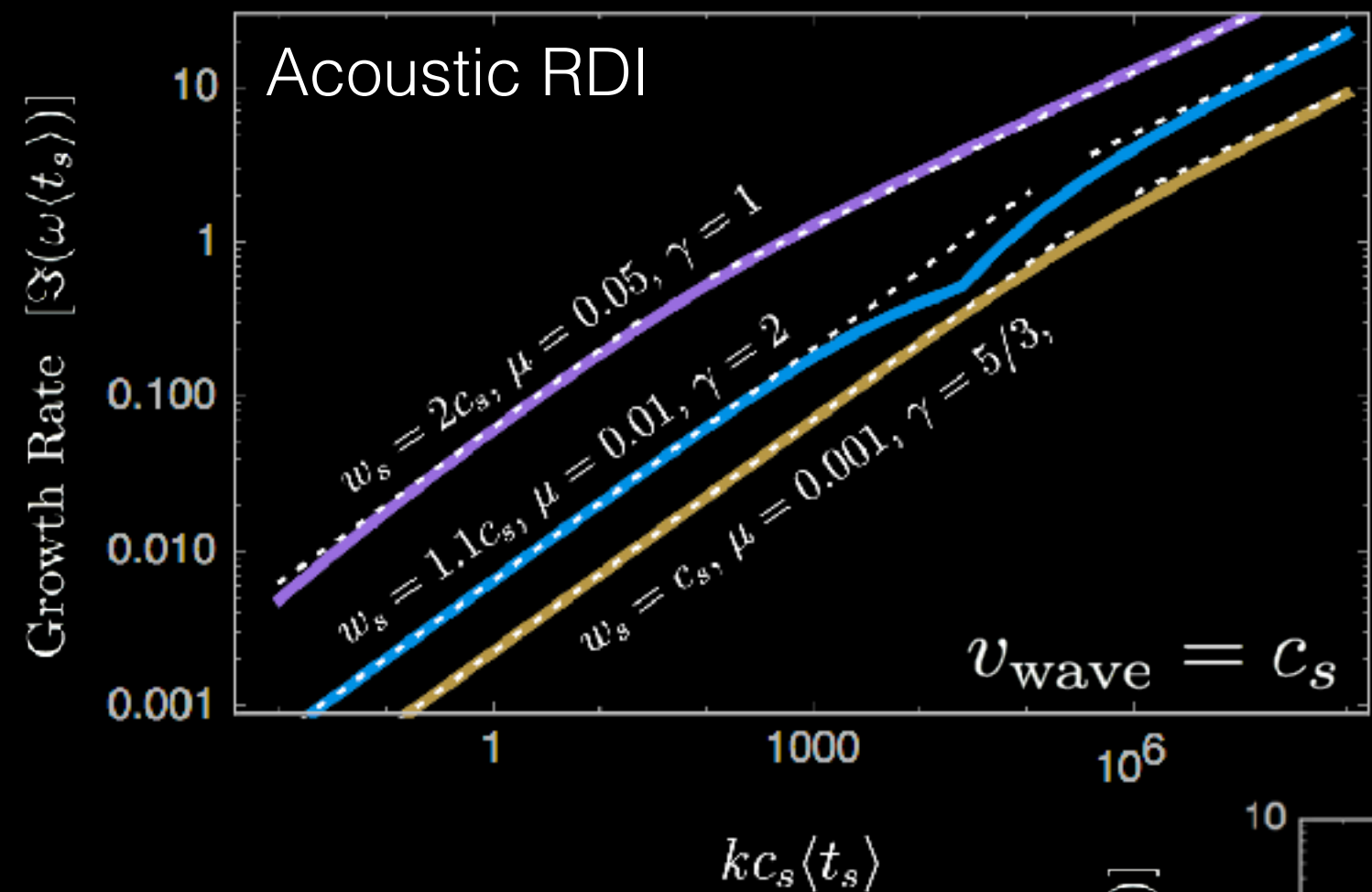
$$\Delta t \sim 80 \langle t_s \rangle$$



Examples of the RDI

Acoustic & Magnetosonic RDI

RESONANCE WITH FIXED PHASE SPEED (SH '17)



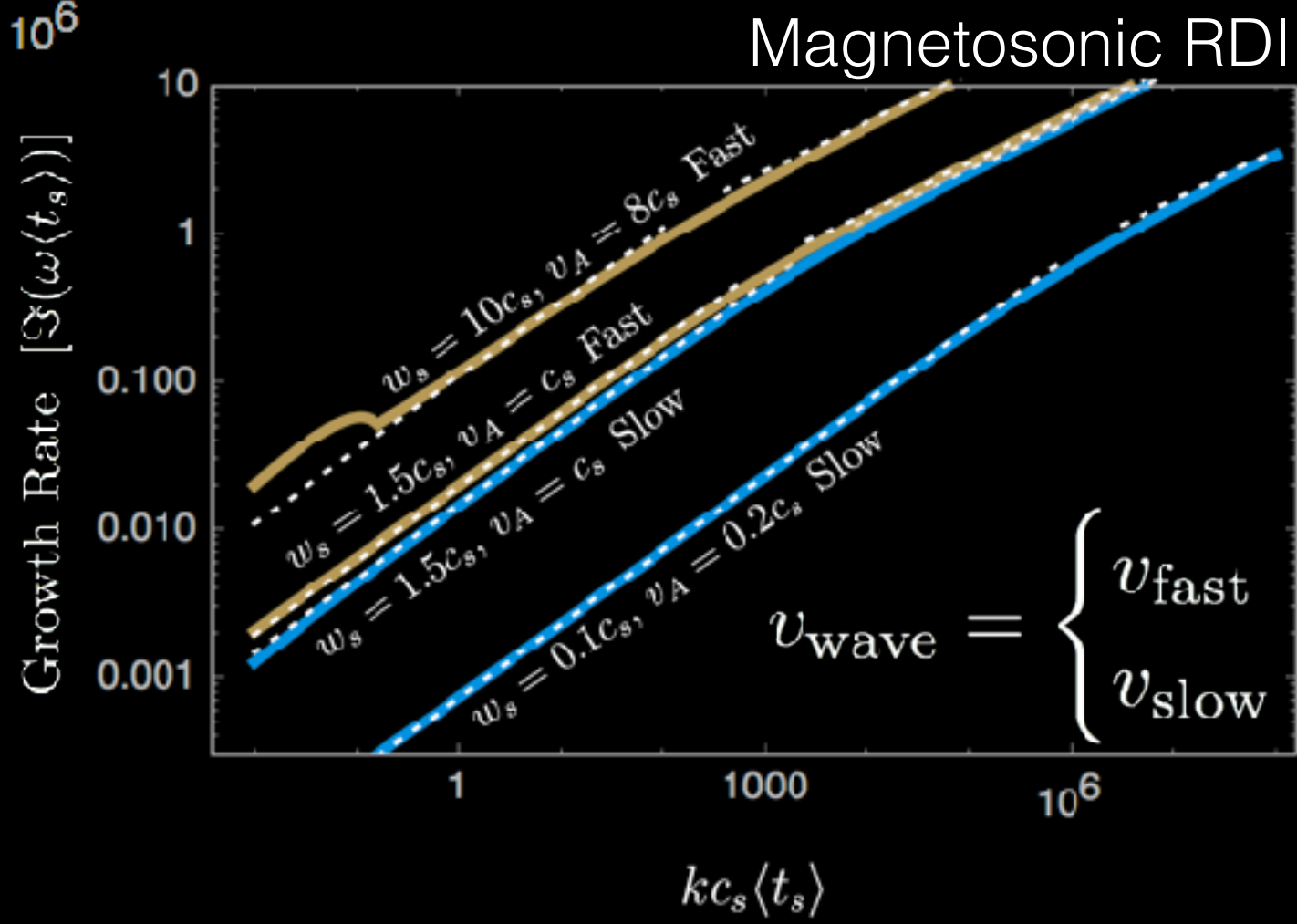
$$\mathbf{w}_{\text{drift}} \cdot \mathbf{k} = \omega_0$$

$$\omega_0 = v_{\text{wave}} k$$

$v_{\text{slow}} \rightarrow 0$

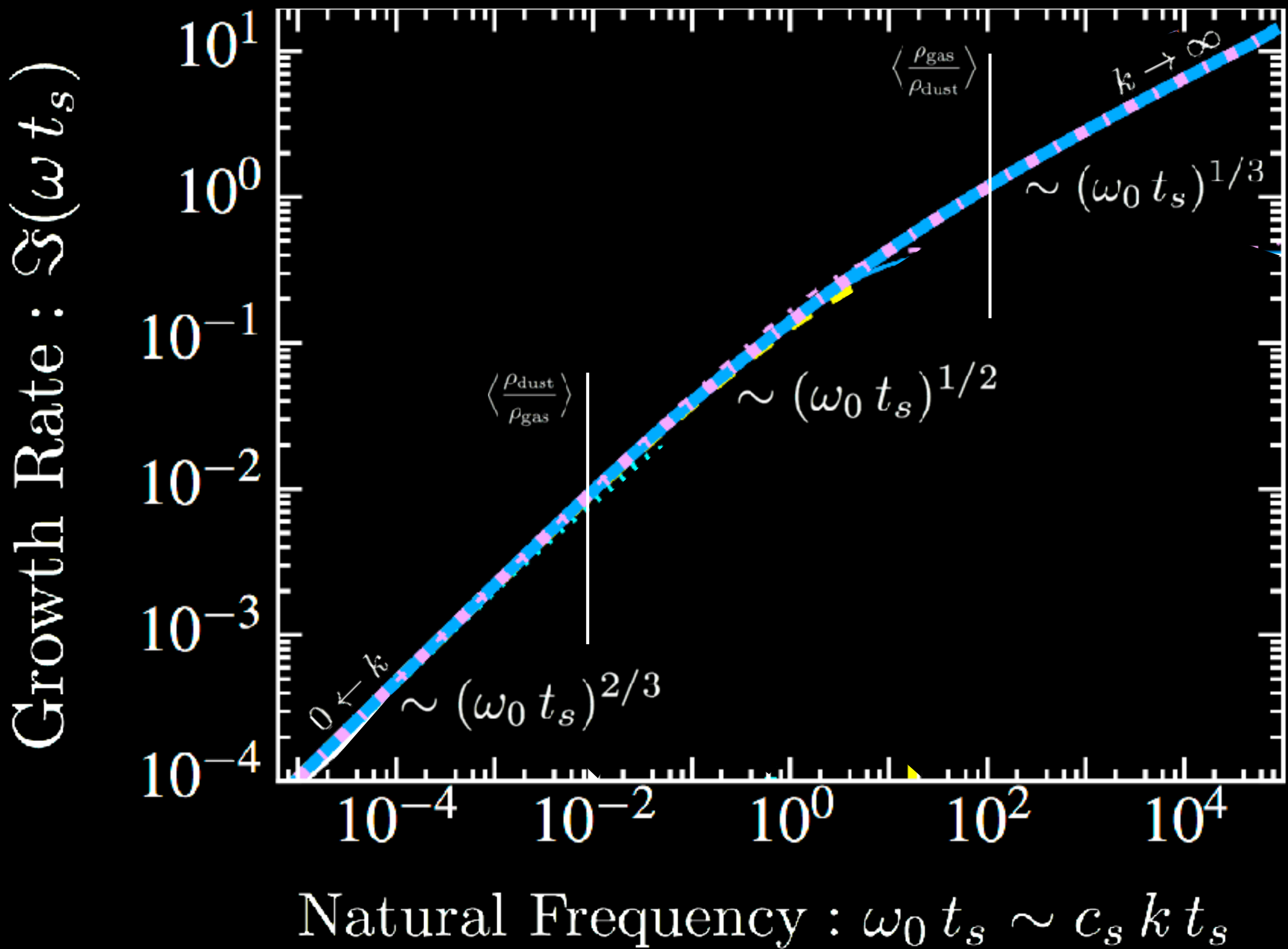
Resonance ***always*** exists

$(|\mathbf{w}|_{\text{drift}} \ll c_s, v_A)$



Acoustic & Magnetosonic RDI

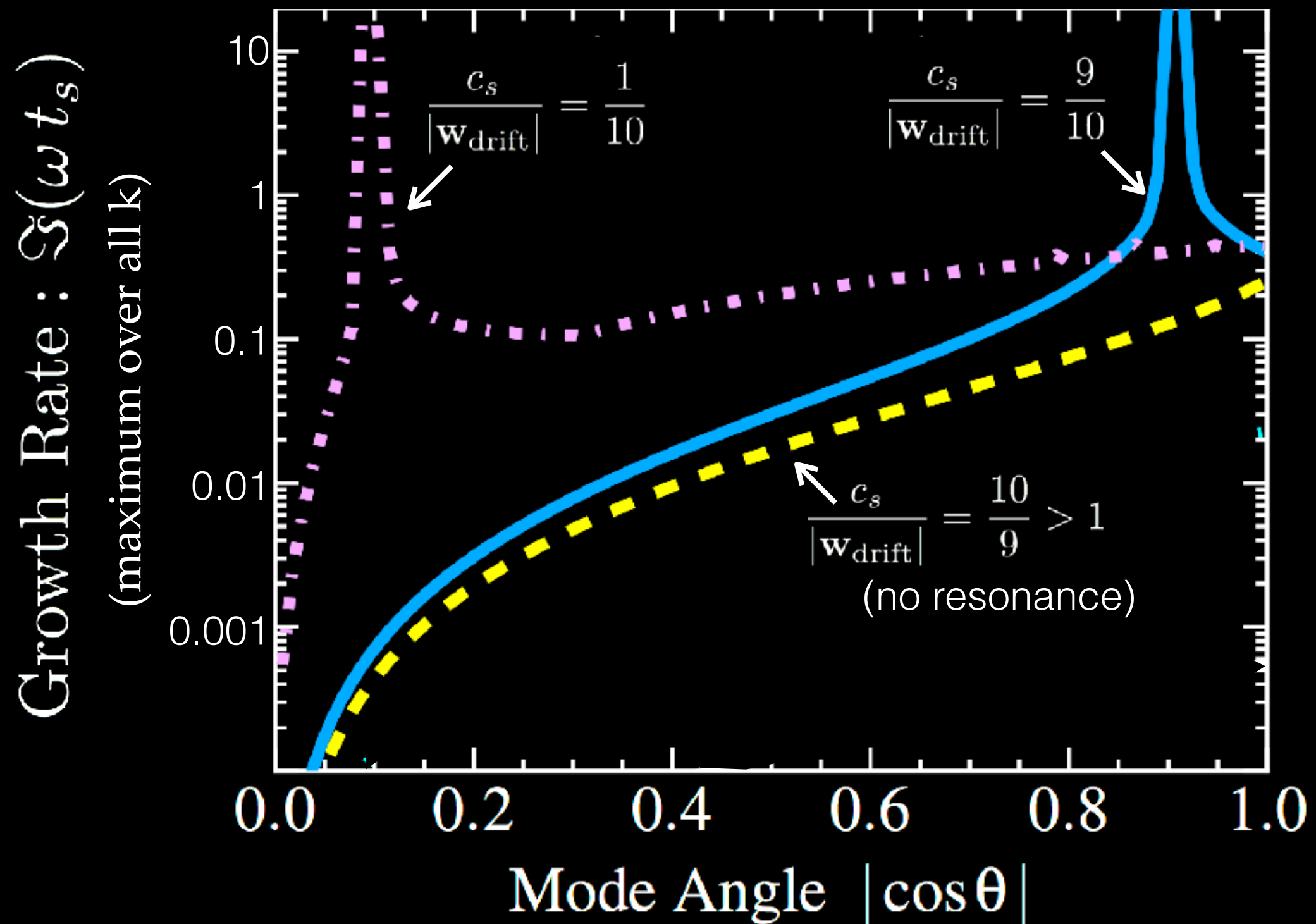
SCALING OF “RESONANT” GROWTH RATES



Acoustic & Magnetosonic RDI

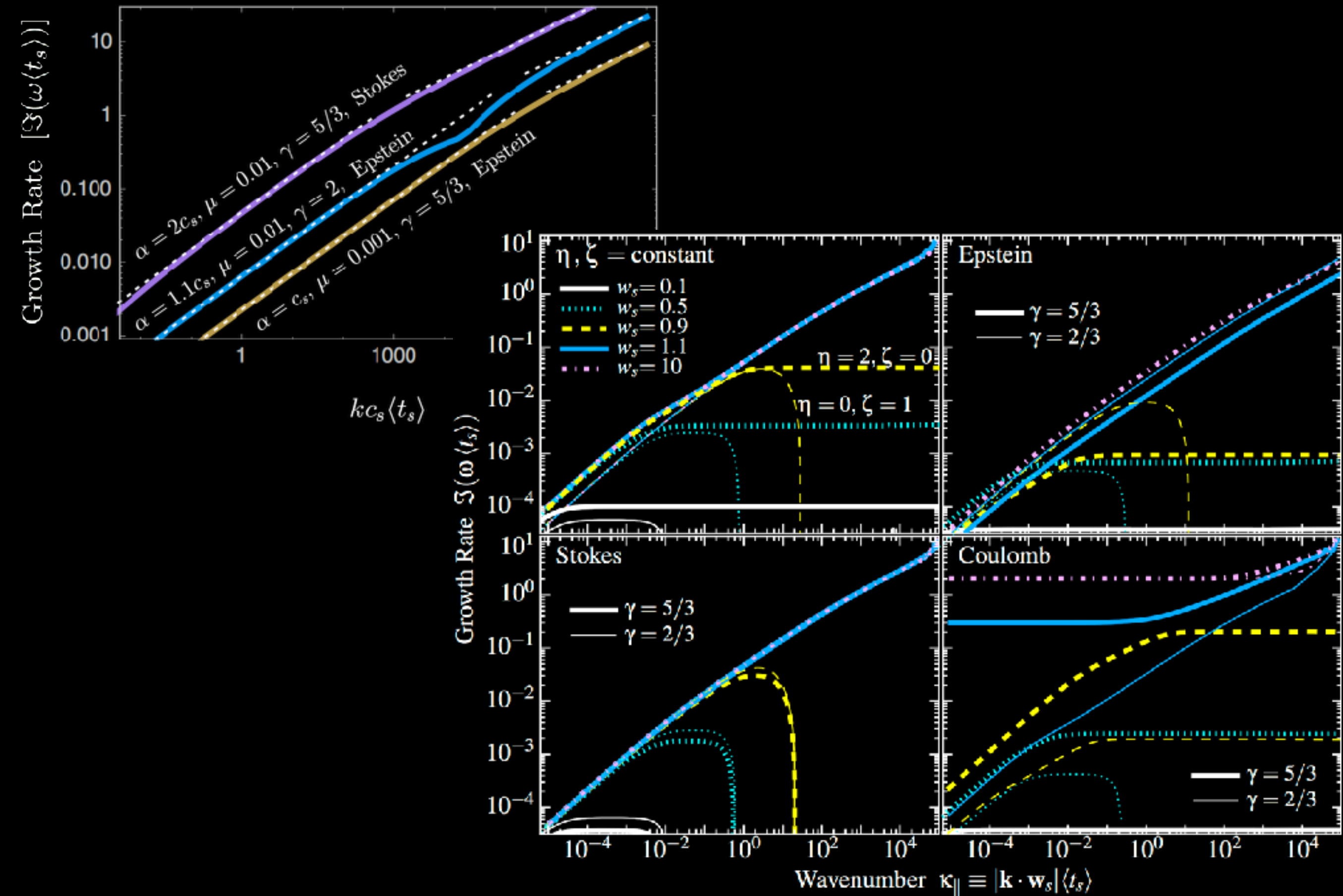
“RESONANT” ANGLES

$$\mathbf{w}_{\text{drift}} \cdot \mathbf{k} = \omega_0 = \pm c_s k \quad \longrightarrow \quad \cos \theta = \pm \frac{c_s}{|\mathbf{w}_{\text{drift}}|}$$



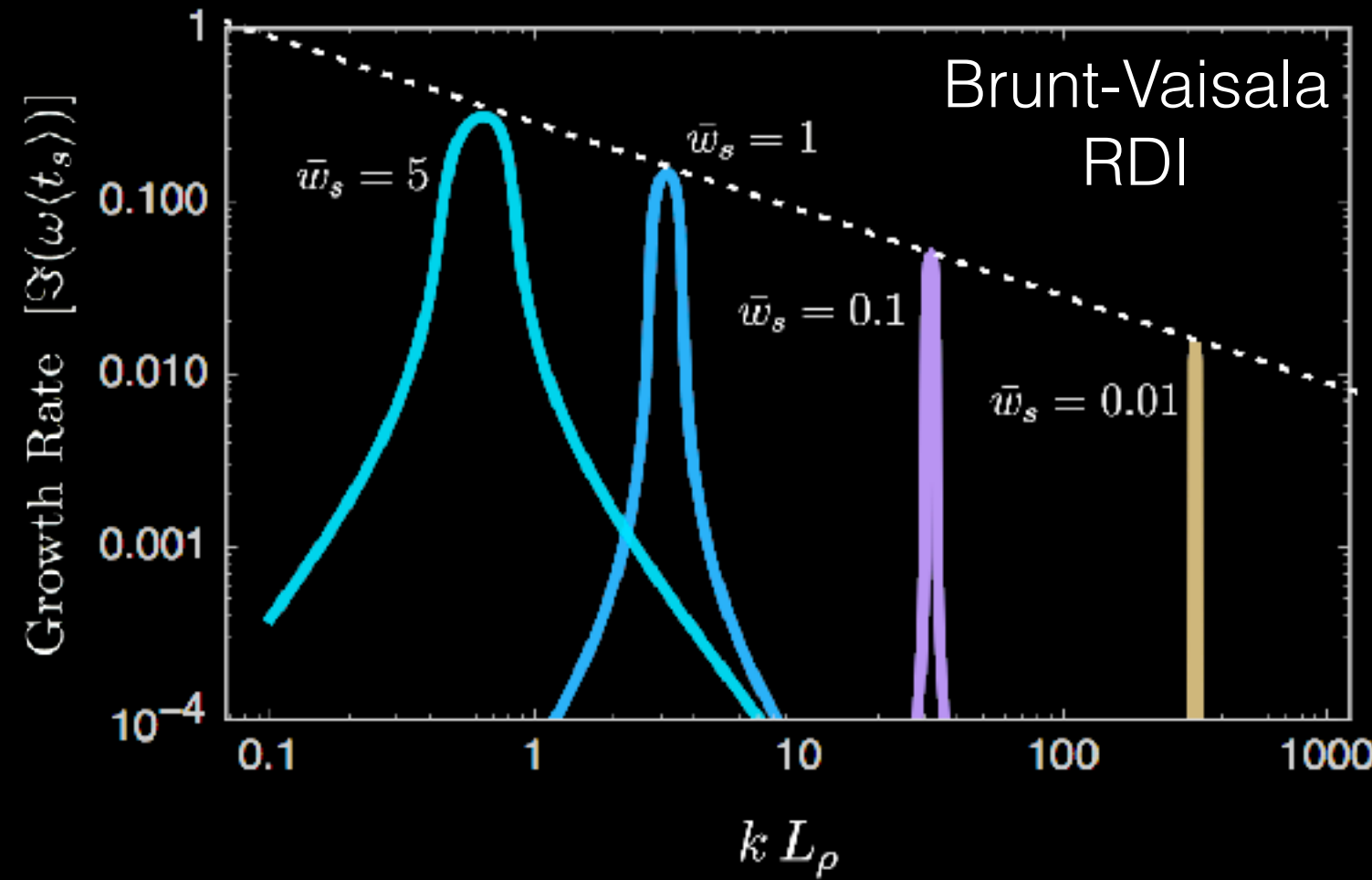
Weak Dependence on Drag Law, Equation-of-State, Dust-to-Gas Ratio

DON'T CHANGE DYNAMICS (HS '17)



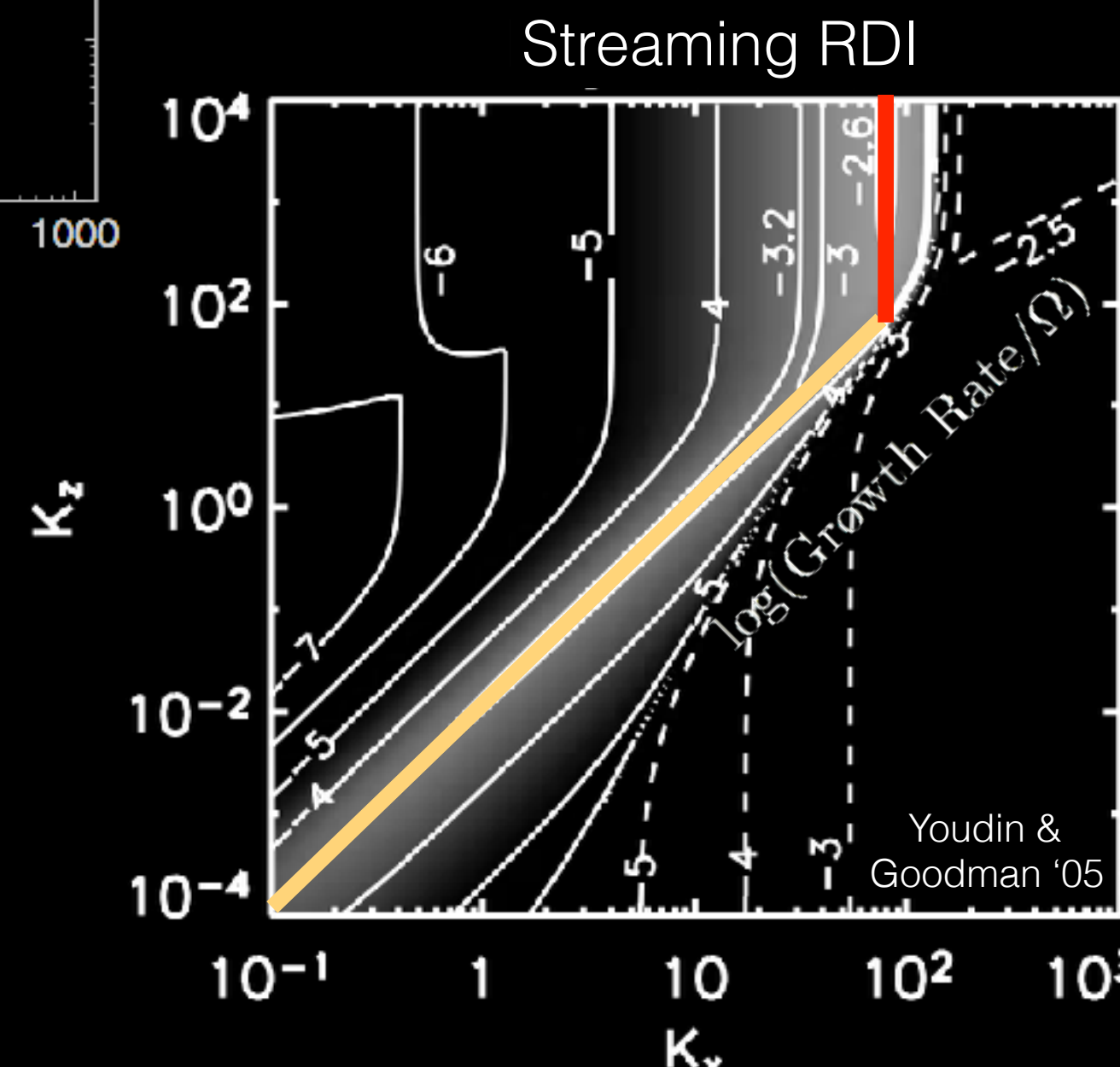
Brunt-Vaisala & Streaming RDI

RESONANCE WITH FIXED-FREQUENCY (SH '17)



$$\omega_0 \sim \begin{cases} N_{BV} = \sqrt{-g \nabla \ln \rho} \\ \kappa_{\text{epicyclic}} \approx \Omega \end{cases}$$

$$k_{\text{drift}} \sim \frac{\omega_0}{|\mathbf{w}|_{\text{drift}}}$$



Simulations: Non-linear Behavior

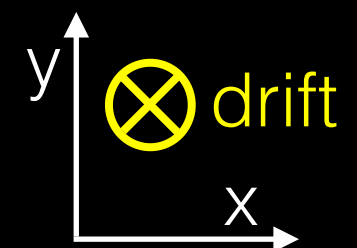
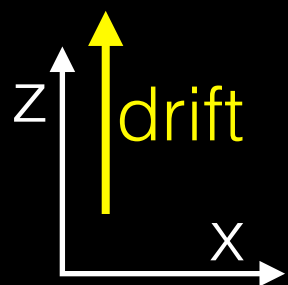
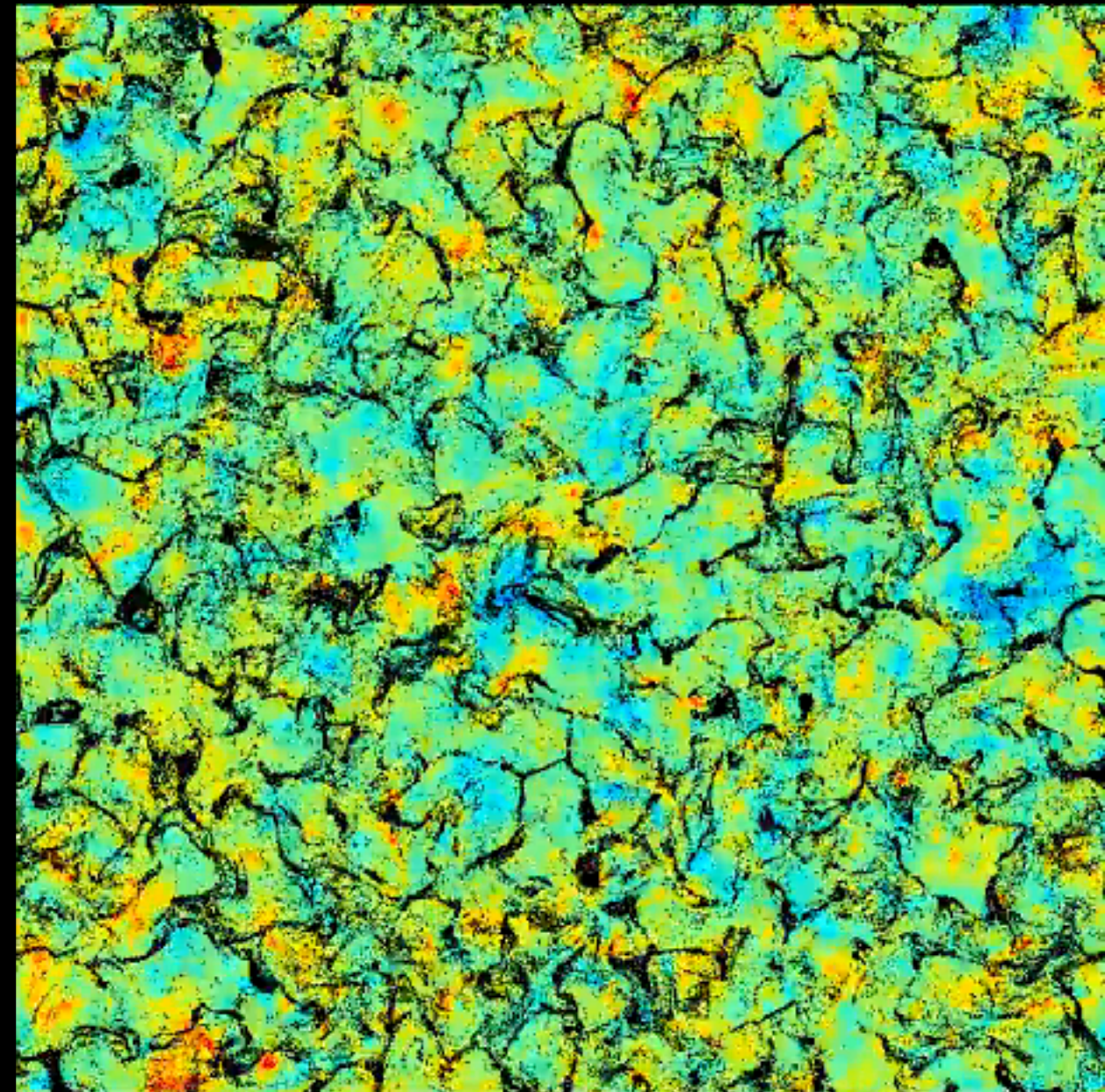
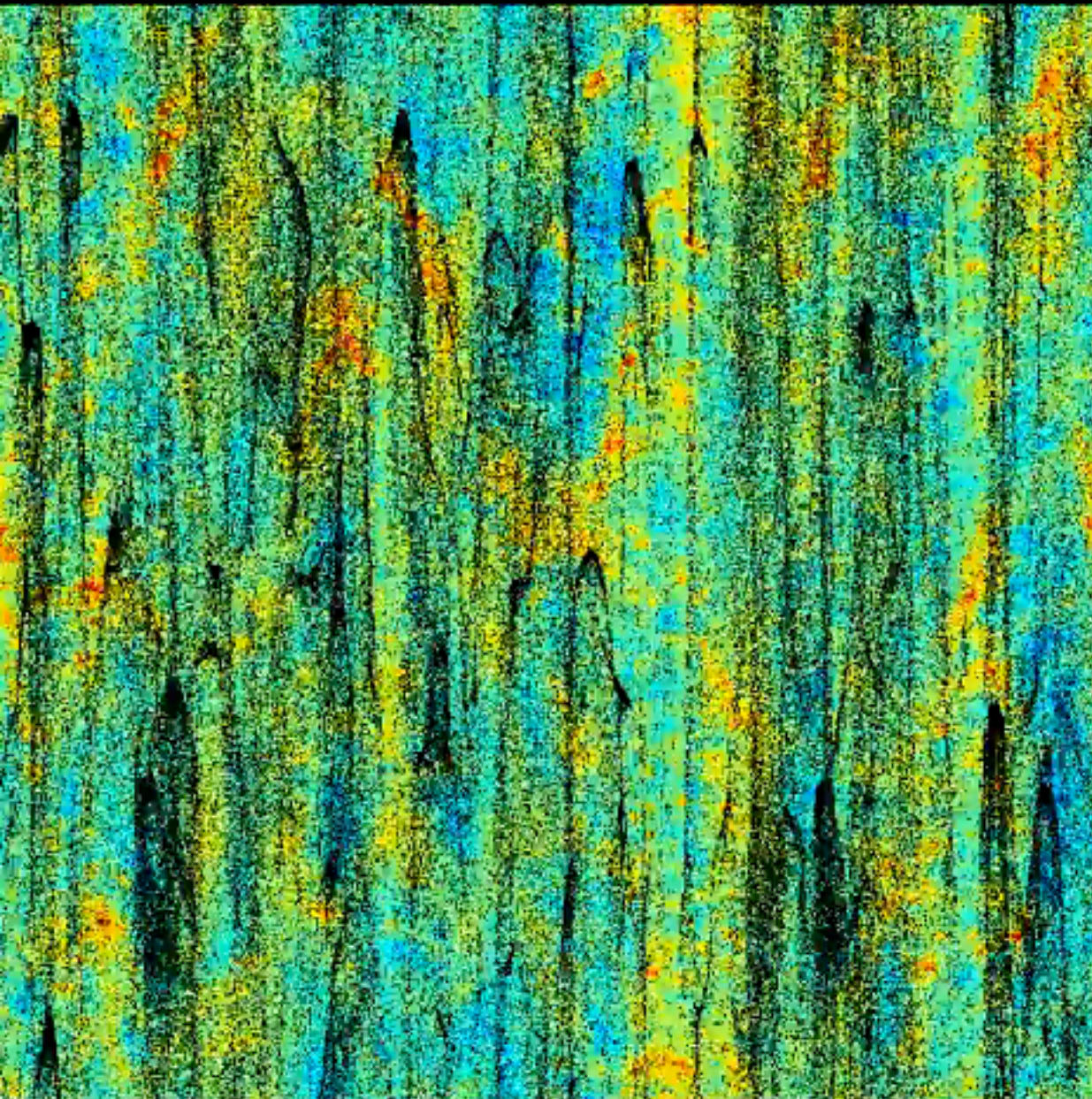
Acoustic RDI: Non-Linear Behavior

EARLY DEVELOPMENT (Squire, Moseley+ in prep.)

$$|\mathbf{w}|_{\text{drift}} \approx 10 c_s$$

$$L_{\text{box}} \sim 100 c_s \langle t_s \rangle$$

$$\Delta t \sim 80 \langle t_s \rangle$$



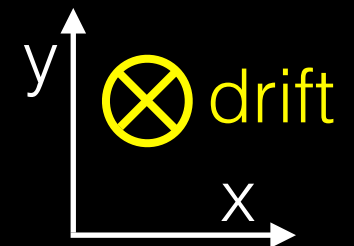
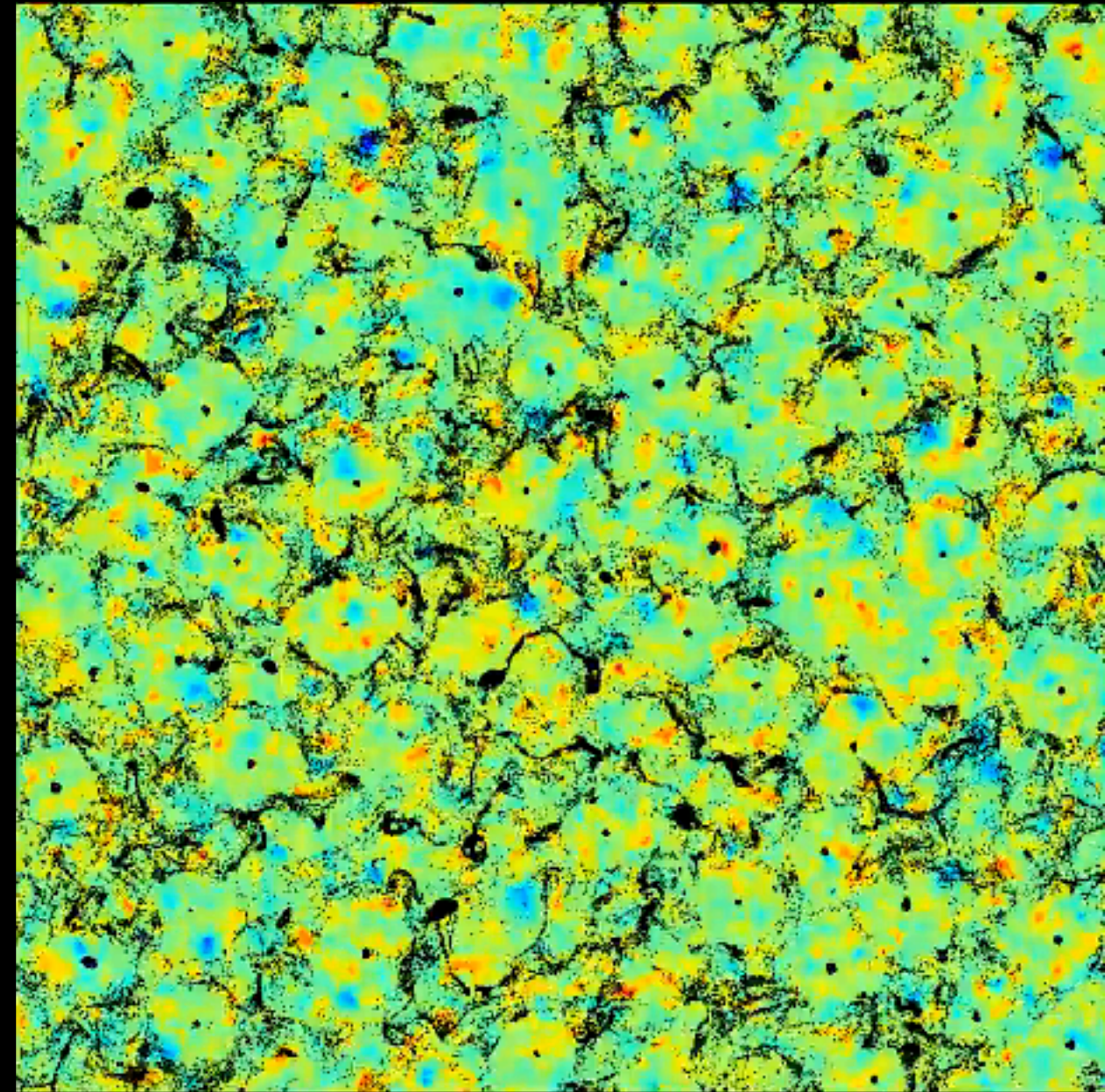
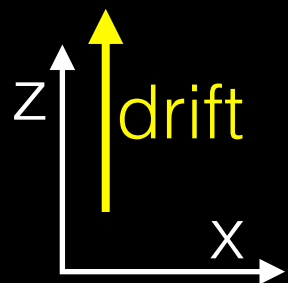
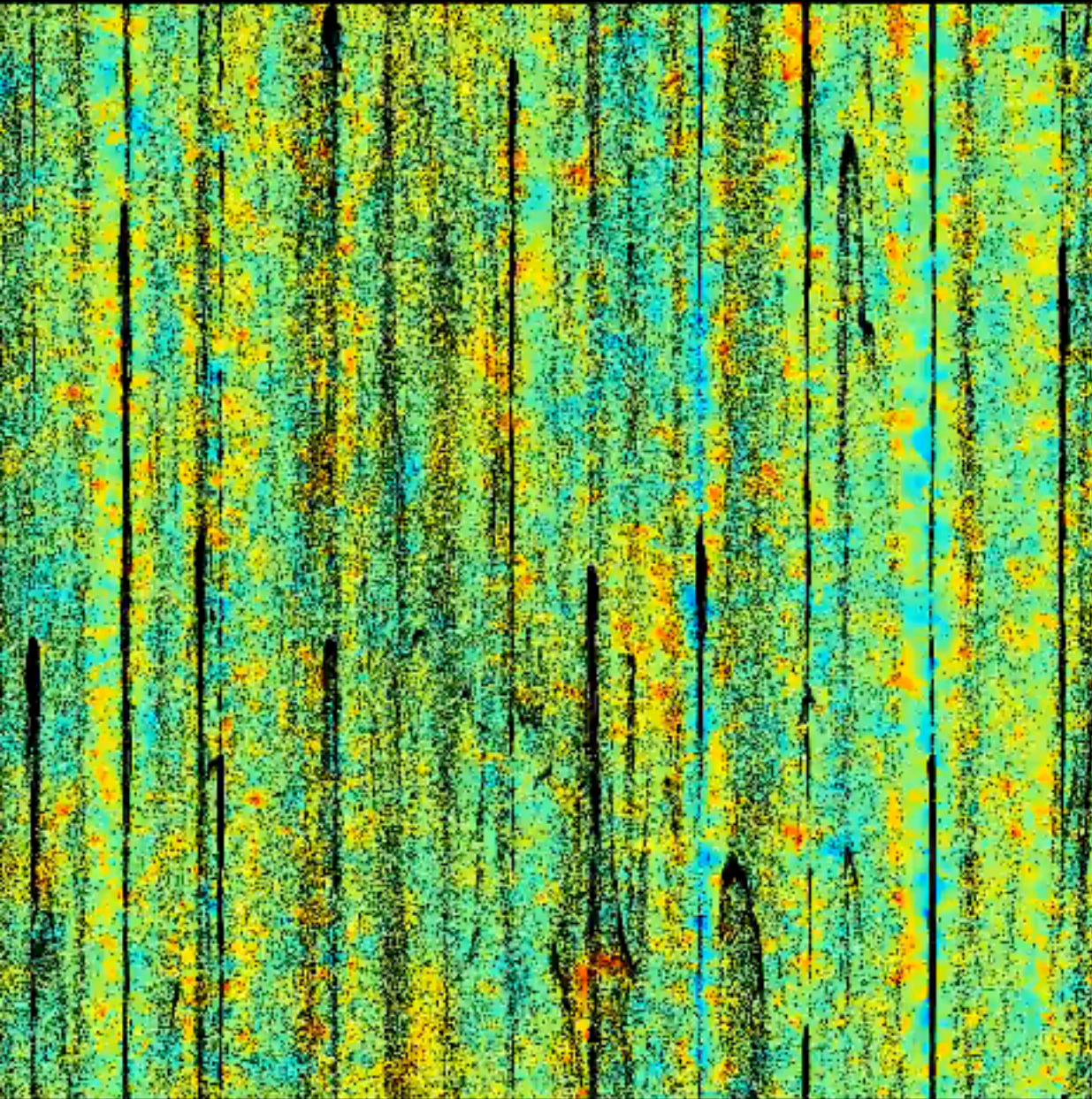
$$0.06 \lesssim k c_s \langle t_s \rangle \lesssim 10$$

Acoustic RDI: Non-Linear Behavior

LATE DEVELOPMENT (Squire, Moseley+ in prep.)

$$L_{\text{box}} \sim 100 c_s \langle t_s \rangle$$

$$\Delta t \sim 500 \langle t_s \rangle$$



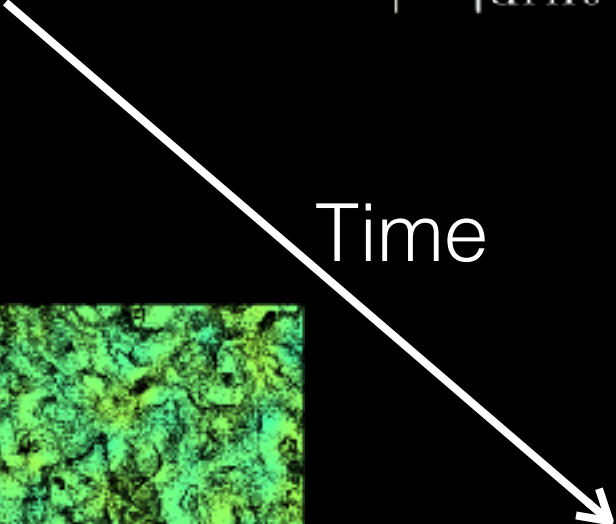
Resonant Mode Dominates EVEN IN NON-LINEAR STATE

$$L_{\text{box}} \sim 30 c_s \langle t_s \rangle$$

$$(0.2 \lesssim k c_s \langle t_s \rangle \lesssim 60)$$

$$|\mathbf{w}|_{\text{drift}} \approx 3 c_s$$

Time

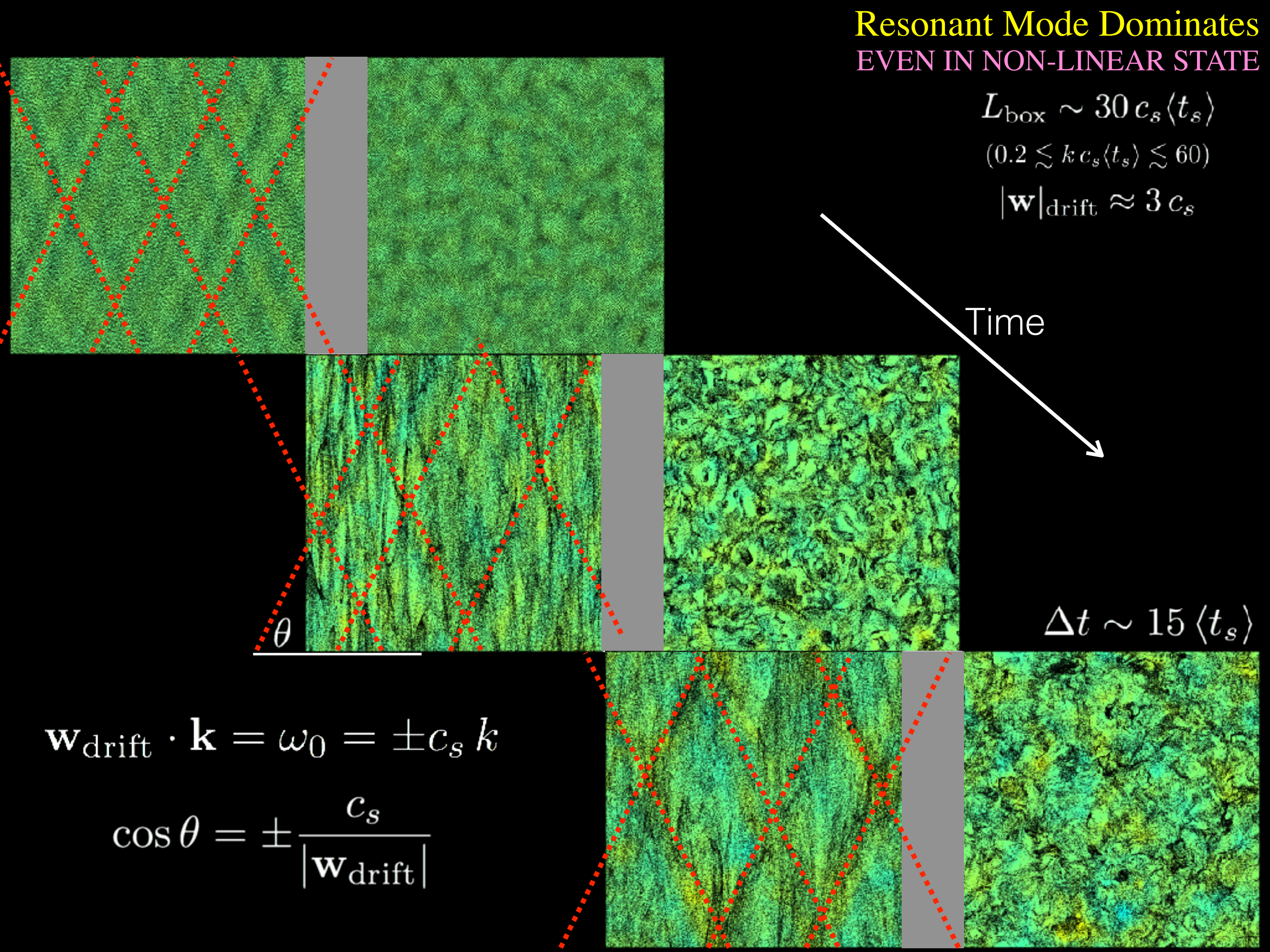


$$\Delta t \sim 15 \langle t_s \rangle$$

$$\mathbf{w}_{\text{drift}} \cdot \mathbf{k} = \omega_0 = \pm c_s k$$

$$\cos \theta = \pm \frac{c_s}{|\mathbf{w}_{\text{drift}}|}$$

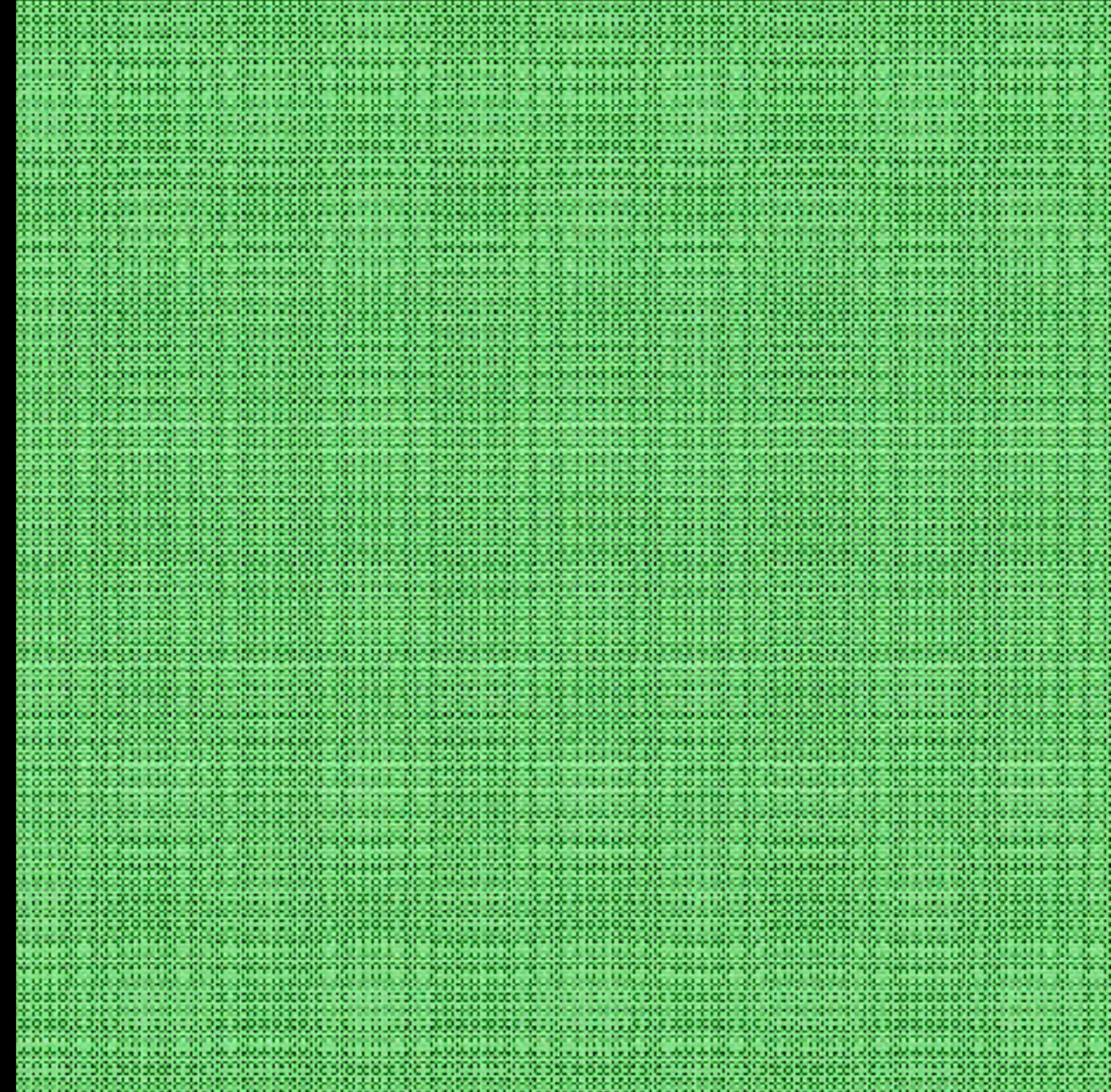
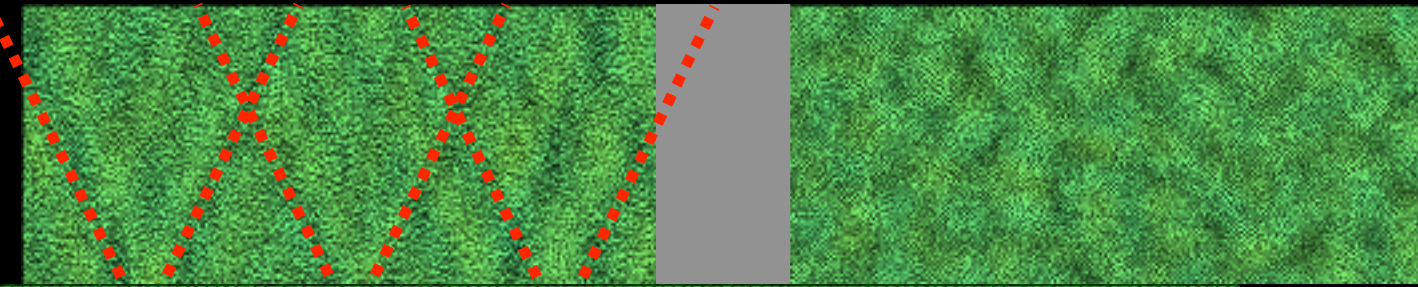
θ



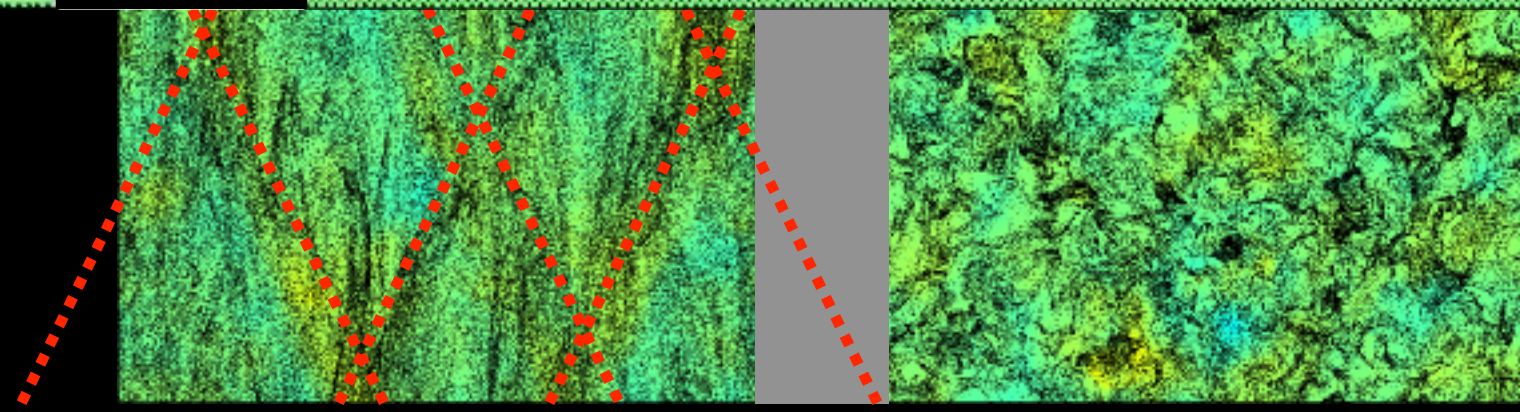
Resonant Mode Dominates EVEN IN NON-LINEAR STATE

$$L_{\text{box}} \sim 30 c_s \langle t_s \rangle$$

$$(0.2 \lesssim k c_s \langle t_s \rangle \lesssim 60)$$



$$\cos \theta = \pm \frac{c_s}{|\mathbf{w}_{\text{drift}}|}$$



Sub-Sonic Drift: Still Unstable

NO RESONANCE: LOW-K, PARALLEL MODES

- Slower than slowest wave-speed: no resonance
- Still unstable! Fastest-growing:

- Parallel:



$\mathbf{k}_{\text{fastest}}$



$\mathbf{w}_{\text{drift}}$

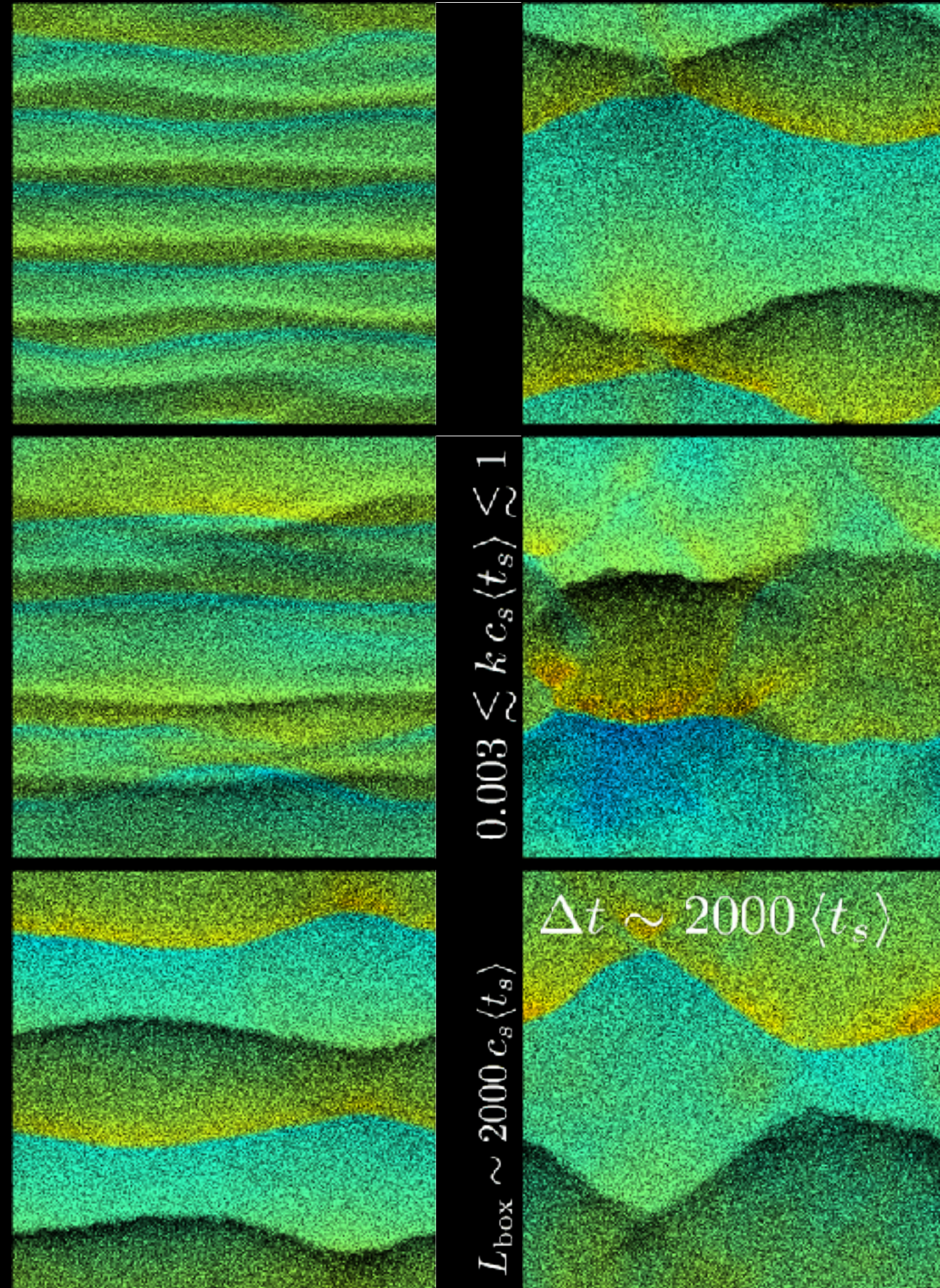
- Long-wavelength:

$$k \lesssim \frac{\langle \rho_{\text{dust}} \rangle}{\langle \rho_{\text{gas}} \rangle} \frac{1}{v_{\text{slowest}} \langle t_s \rangle}$$

- Slow-growing:

$$\text{Growth Rate} \sim \frac{\langle \rho_{\text{dust}} \rangle}{\langle \rho_{\text{gas}} \rangle} \left(\frac{|\mathbf{w}_{\text{drift}}|}{v_{\text{slowest}}} \right)^2$$

$$|\mathbf{w}|_{\text{drift}} \approx 0.5 c_s$$



Consequences



The RDI Persists for:

- *Any* drag coefficient / stopping time / dust size
- *Any* dust-to-gas ratio
- *Any* drag law
 - arbitrary dependence on gas / dust density, sound speed, temperature, dust / gas velocity, charge; e.g. Epstein, Stokes, Coulomb drag
- *Any* gas equation-of-state
- *Any* dust / gas acceleration / “super-luminal” drift velocity
- *Any* large-scale pressure / density profile of the gas

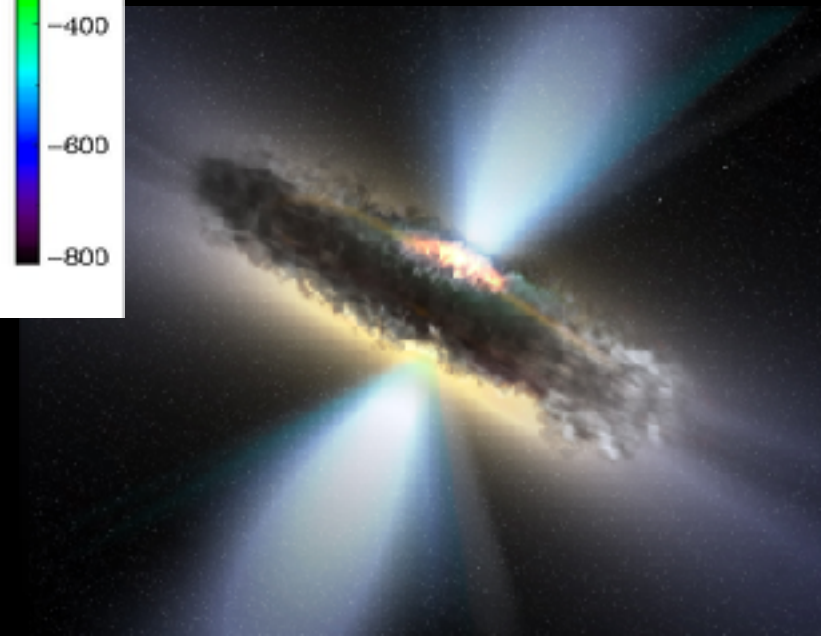
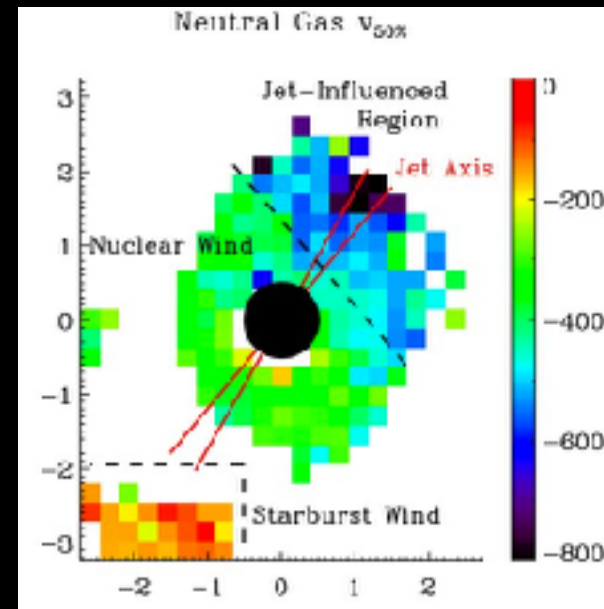
Consequences

THIS IS EVERYWHERE

- AGN torii, outflows, NLR

$$|\mathbf{w}|_{\text{drift}} \gtrsim 100 c_s$$

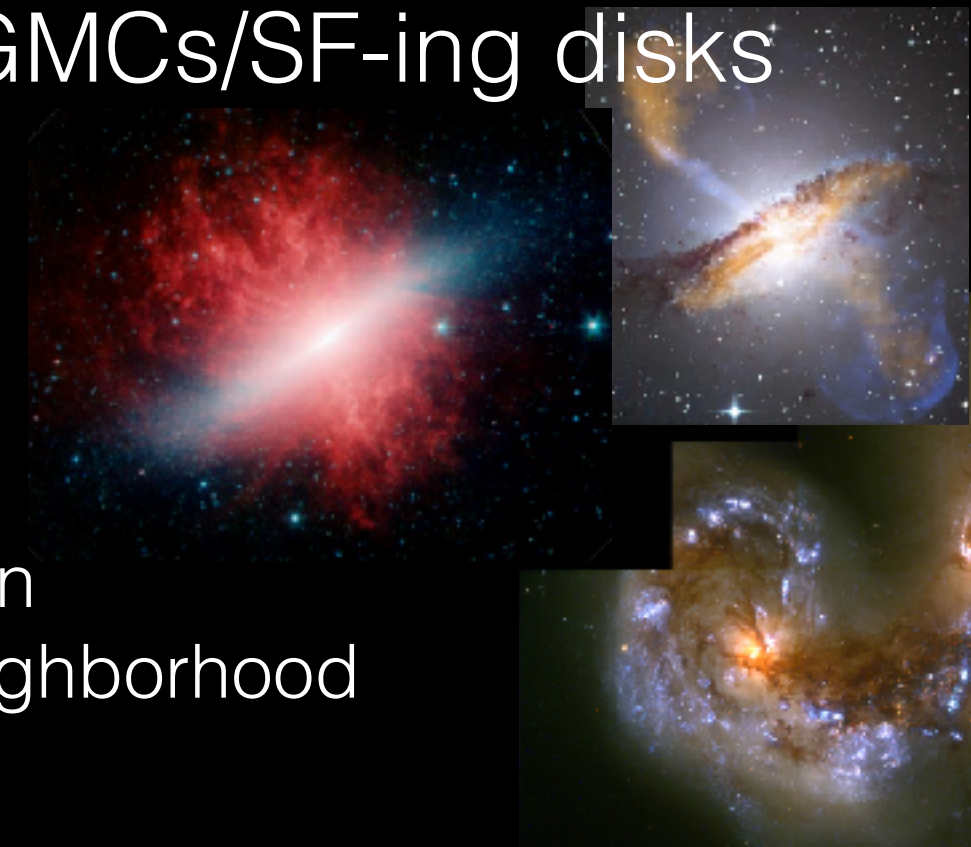
- clumpy obscuration
- time-dependent dust
- wind-launching
- dust formation



- Circum-nuclear disks, starbursts, GMCs/SF-ing disks

$$|\mathbf{w}|_{\text{drift}} \gtrsim 10 c_s$$

- dusty/radiatively-driven winds
- abundance variations in stars
- dust formation/growth & obscuration
- anomalous large grains in solar neighborhood



Consequences

THIS IS EVERYWHERE

- Cool-star/AGB winds, SNe ejecta

$$|\mathbf{w}|_{\text{drift}} \gtrsim c_s$$

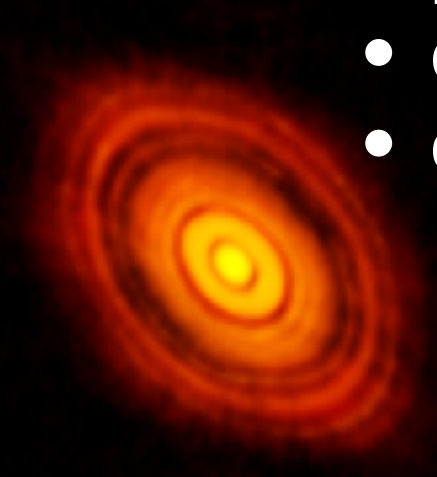
- dust shells/arcs/streamers (e.g. Deguchi '97)
- clumpiness in outflow
- wind-launching, outflow rates
- large grains in SNe ejecta (e.g. 1987a, 2010jl)



- Proto-planetary disks

$$|\mathbf{w}|_{\text{drift}} \ll c_s \quad \text{but} \quad |\mathbf{w}|_{\text{drift}} \gg \begin{cases} v_{\text{slow}}, v_{\text{whistler}} \\ \Omega k^{-1} \\ N_{BV} k^{-1} \end{cases}$$

- planetesimals (overdensity->GI)
- dust traps/asymmetries
- dust growth/sticking (small-k, MHD modes)

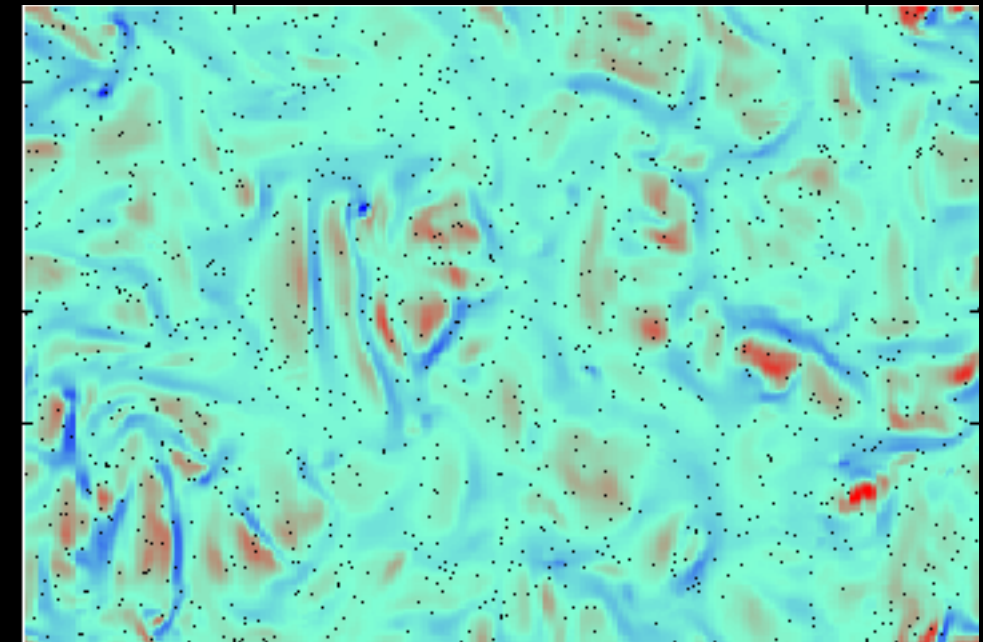
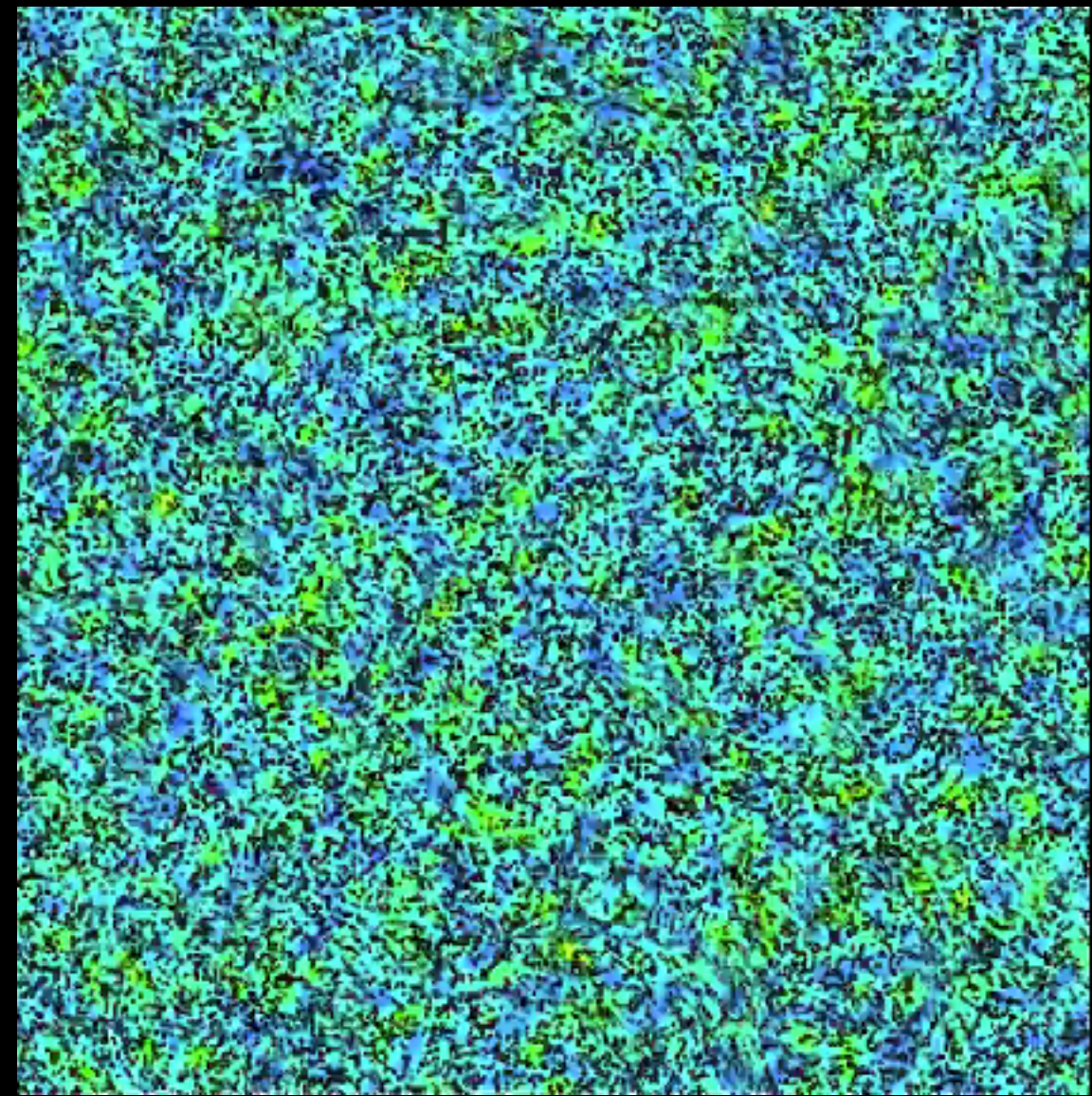
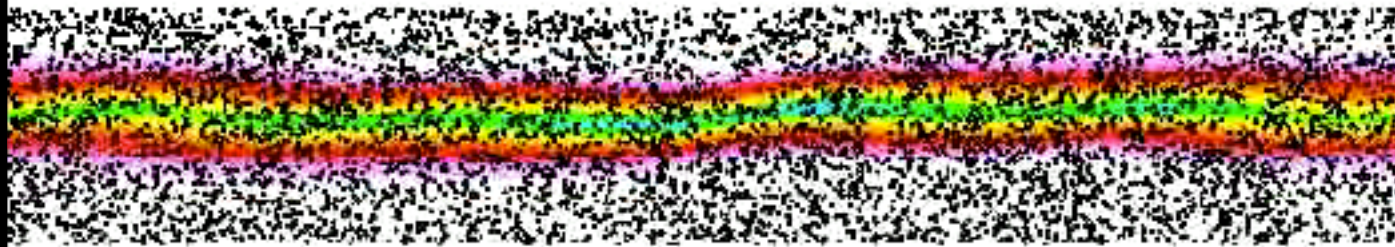


Example: Effects in GMCs/Starburst Disks

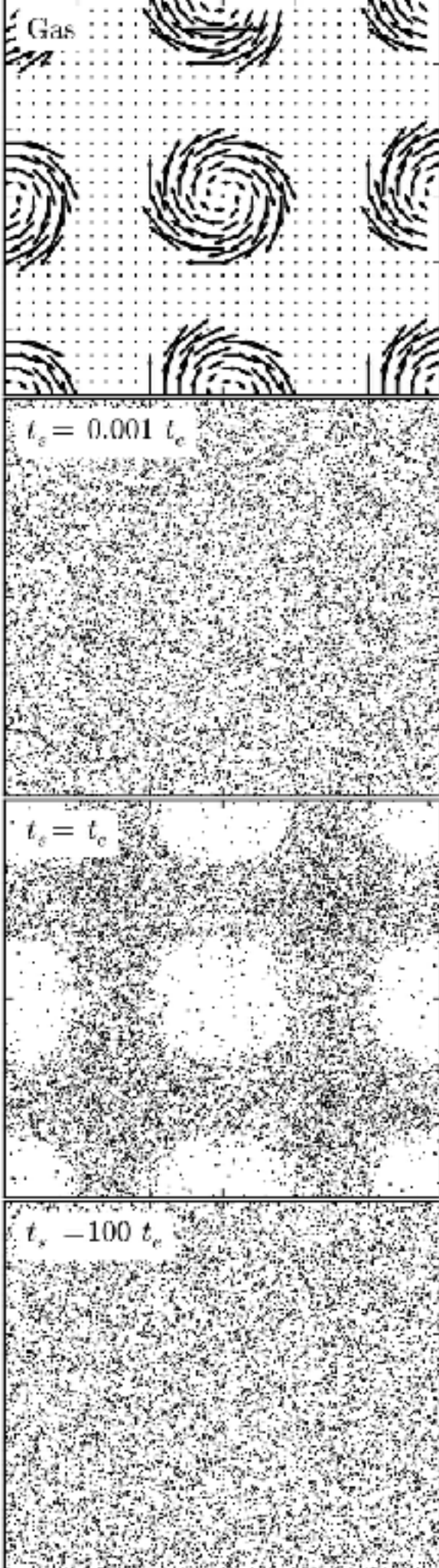
Dust In Turbulence: Even Without RDI

EXPERIMENT & SIMULATION

Particles in turbulence



e.g. Squires & Eaton 1991



The Physics:

PFH, arXiv:1307.7147

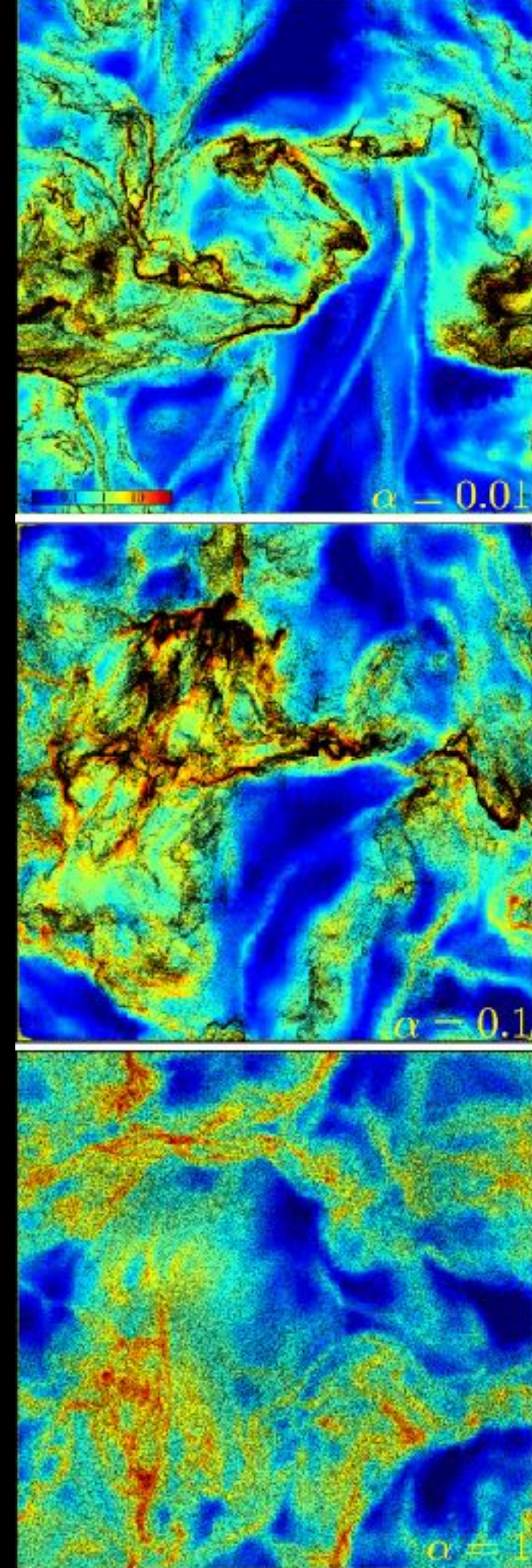
$$\frac{d\mathbf{v}_{\text{grain}}}{dt} = - \frac{(\mathbf{v}_{\text{grain}} - \mathbf{v}_{\text{gas}})}{t_{\text{stop}}}$$

$$t_{\text{stop}} \sim \frac{\bar{\rho}_{\text{solid}} a_{\text{grain}}}{\rho_{\text{gas}} \delta v_{\text{gas-dust}}}$$

$$L_{\text{stream}} \sim 2 \text{ pc} \left(\frac{a_{\text{grain}}}{\mu\text{m}} \right) \left(\frac{10 \text{ cm}^{-3}}{n_{\text{gas}}} \right)$$

- e.g. vortex traps, preferential concentration, zonal flows/pressure traps

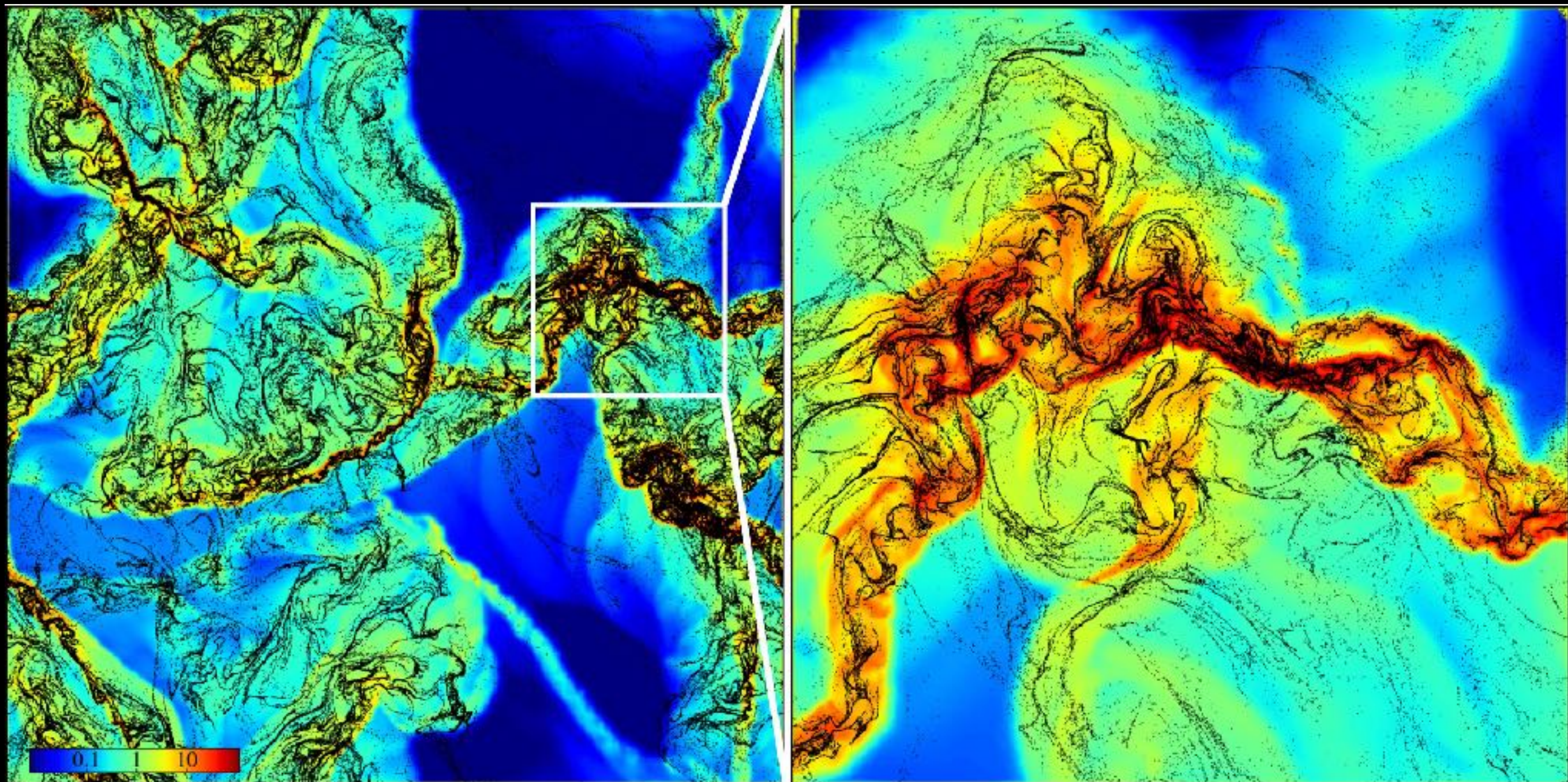
(see Barge & Sommeria '95, Bracco '99, Cuzzi '01, Johansen & Youdin '07, Carballido '08, Lyra '08, Bai & Stone '10, Pan '11, Zhu '14 and others)



Dust In GMCs & Star-forming Disks:

PFH & Lee '16 (arXiv:1510.02477); Lee, Squire & PFH '17 (1612.05264)

Hyunseok Lee
& Jono Squire



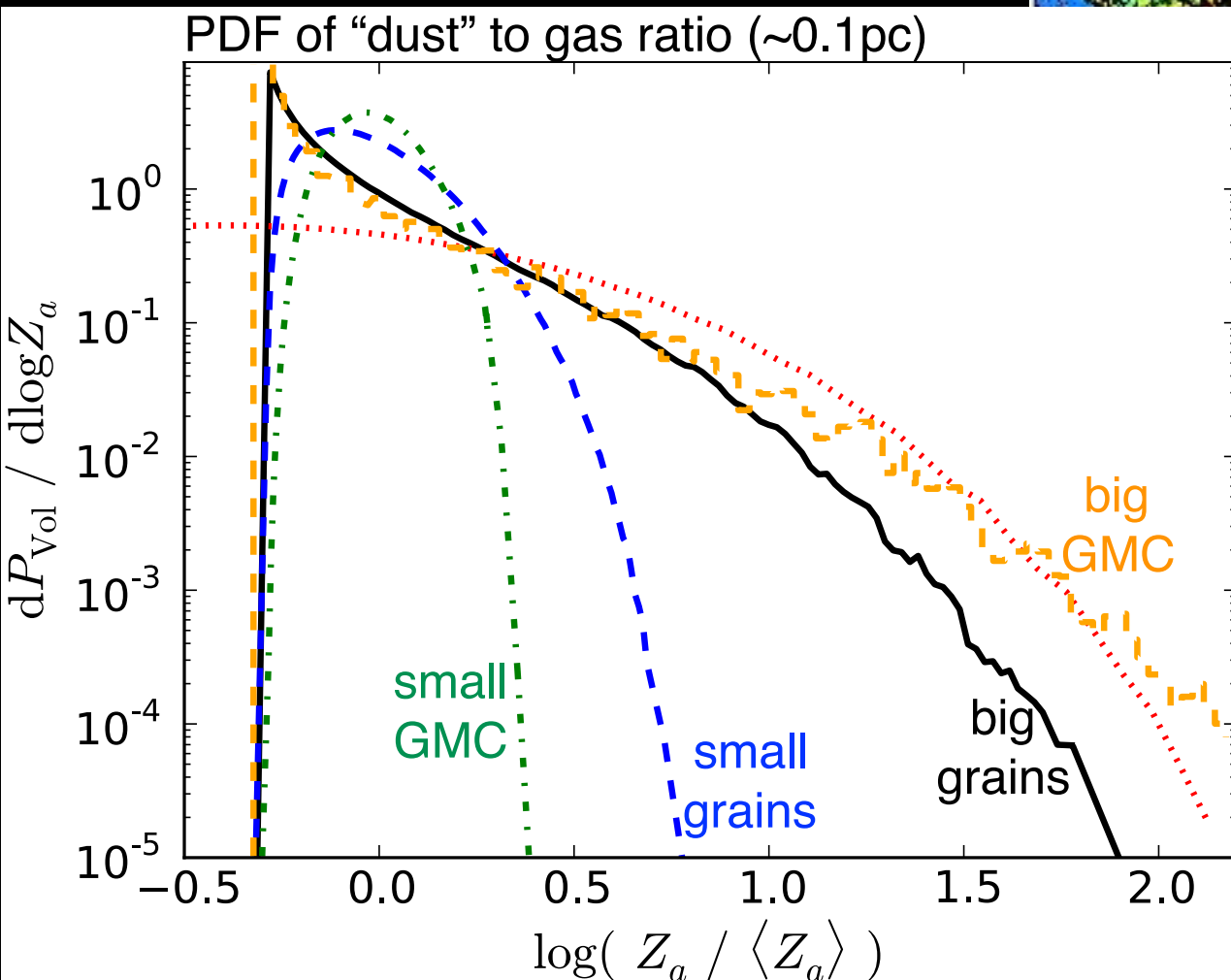
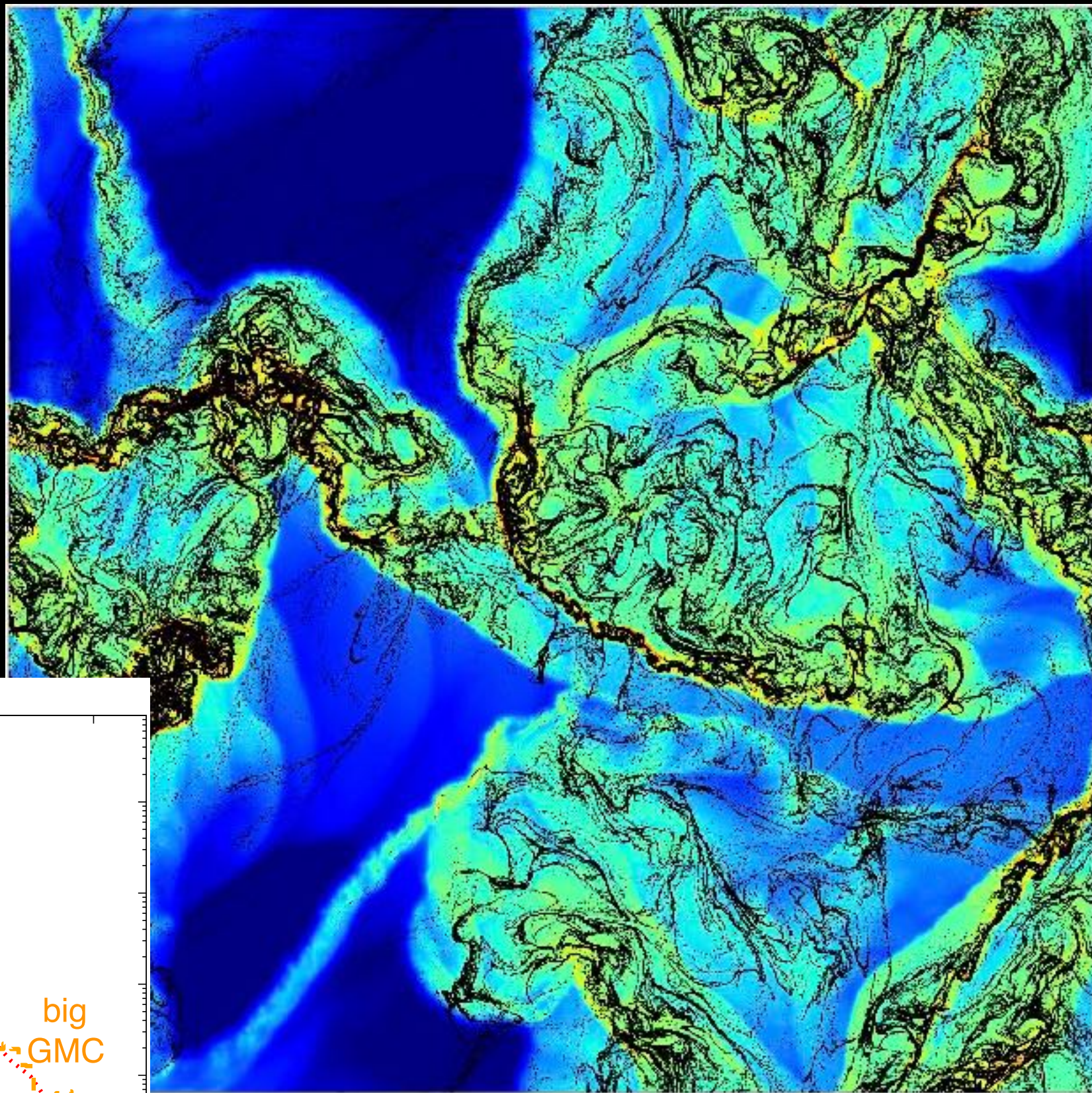
Put dust in a GMC & stir:

(dust+super-sonic MHD turbulence, gravity, disk rotation, Lorentz forces)

Dust In GMCs

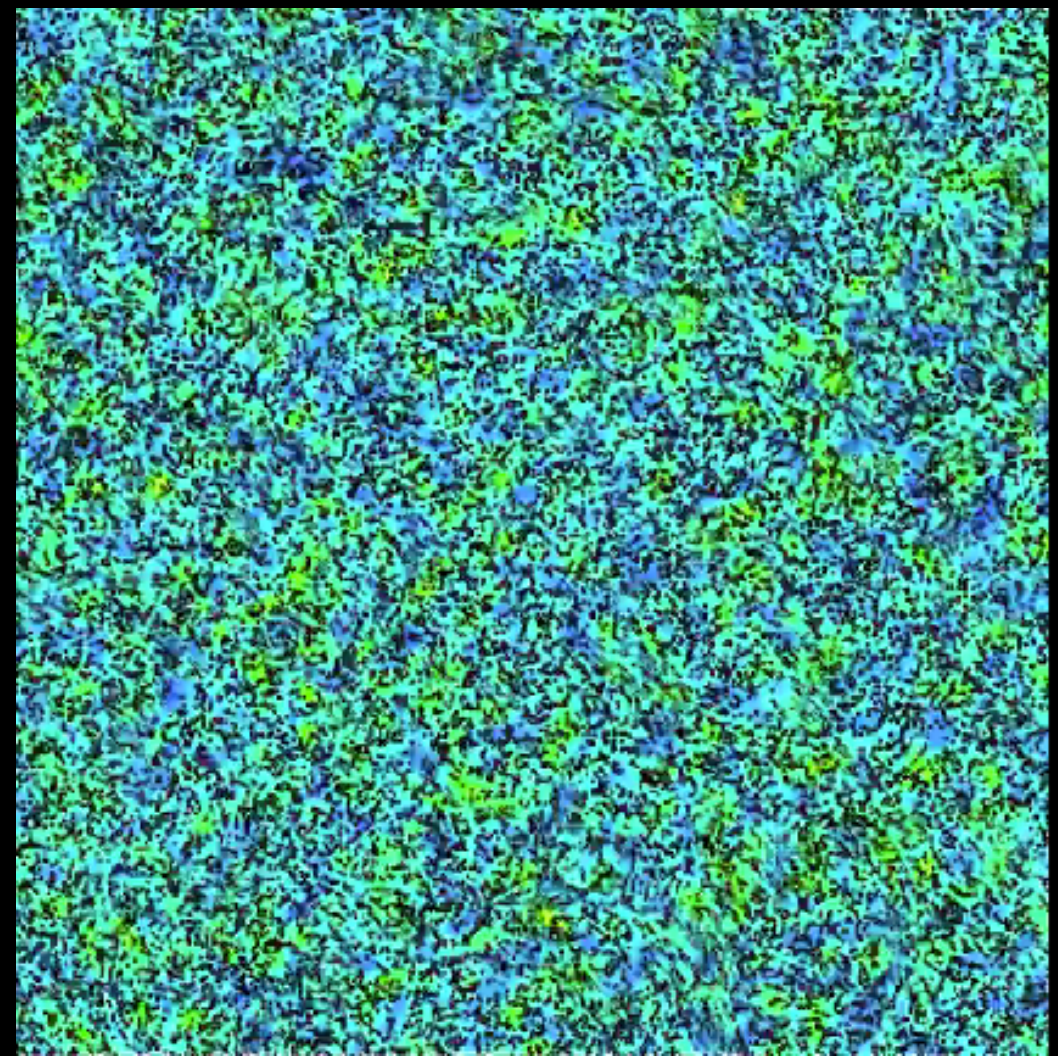
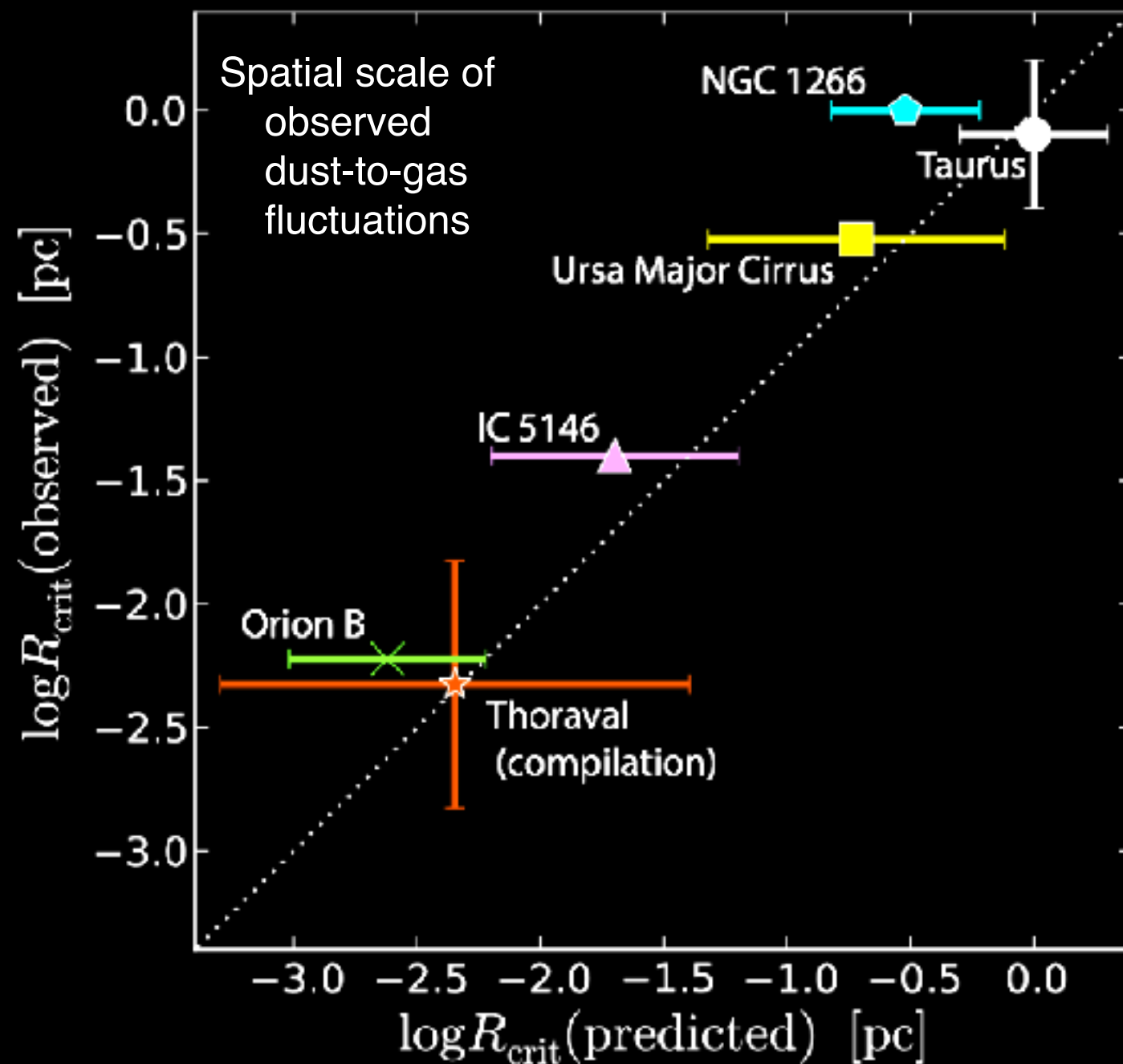
PFH & Lee '16 (arXiv:1510.02477);
Lee, Squire & PFH '17 (1612.05264)

In a
GMC



Is This Happening In Our Backyard?

PFH, arxiv:1406.5509



- Dust-to-gas fluctuations observed: seed abundance fluctuations?

(see Thoraval 97, Abergel 02, Miville-Deschenes 02, Padoan 06, Flagey 09, Pinega 10, Nyland 13, PFH 14)

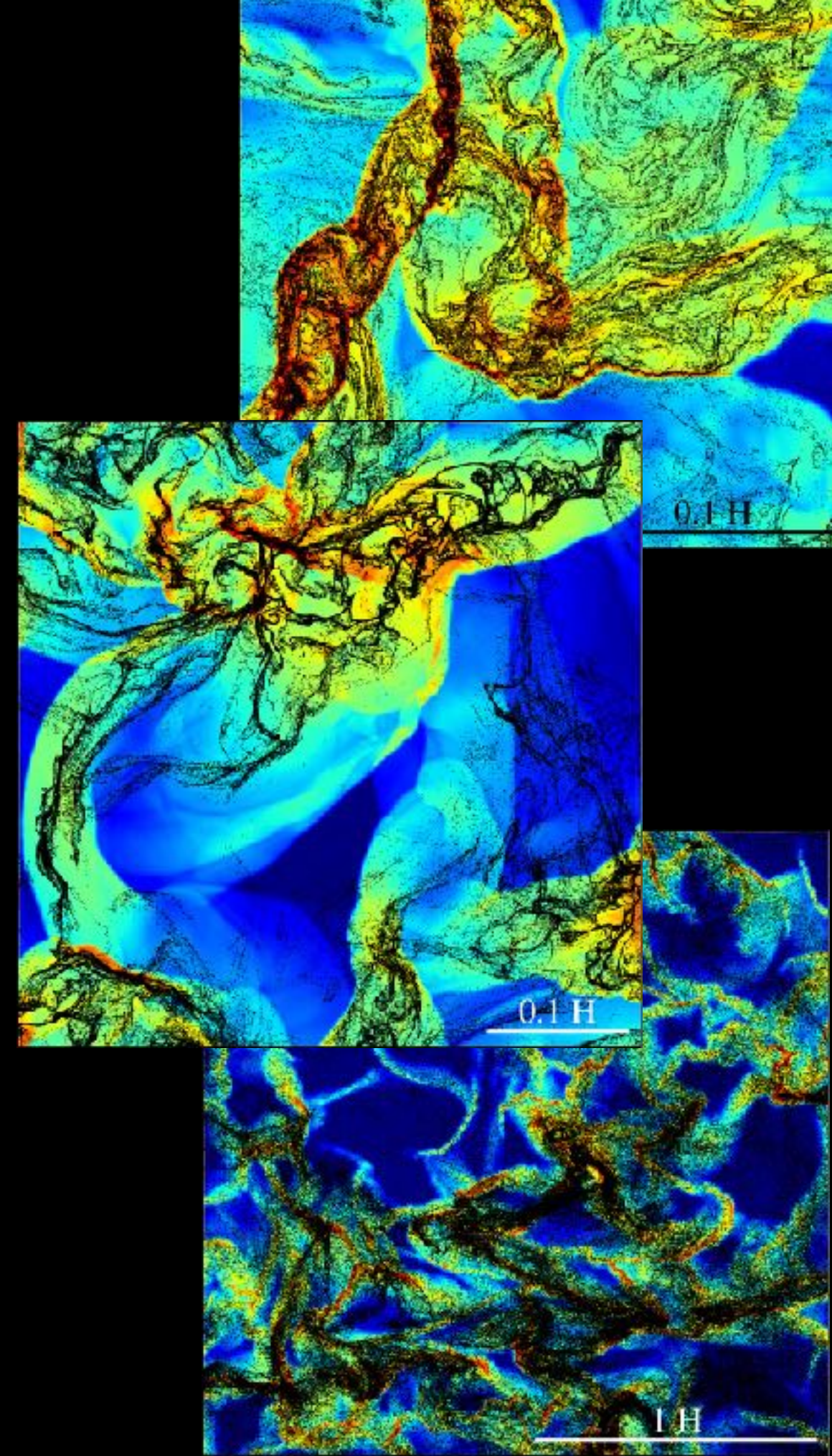
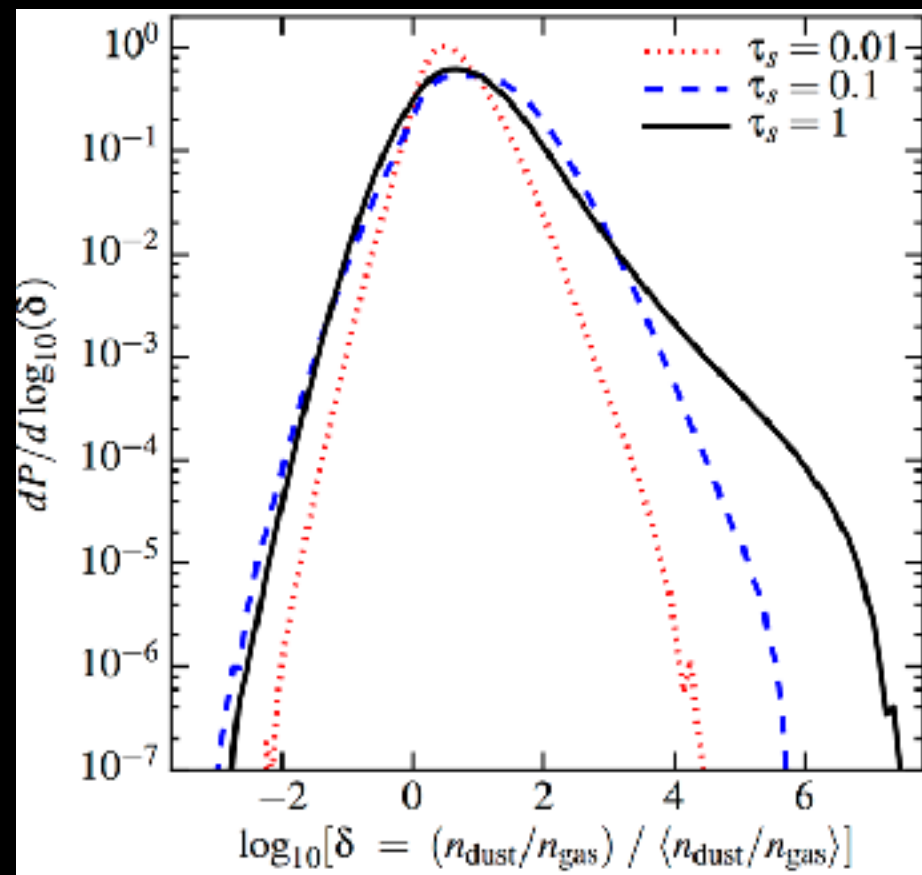
Dust-Assisted Star Formation: One Example

What about High Redshifts?

PFH & Conroy, arXiv:1512.03834

- High-redshift proto-galaxy: neutral disk, modestly turbulent ($\text{Mach} \sim 1$), low-metallicity ($[Z/H] \ll -3$)

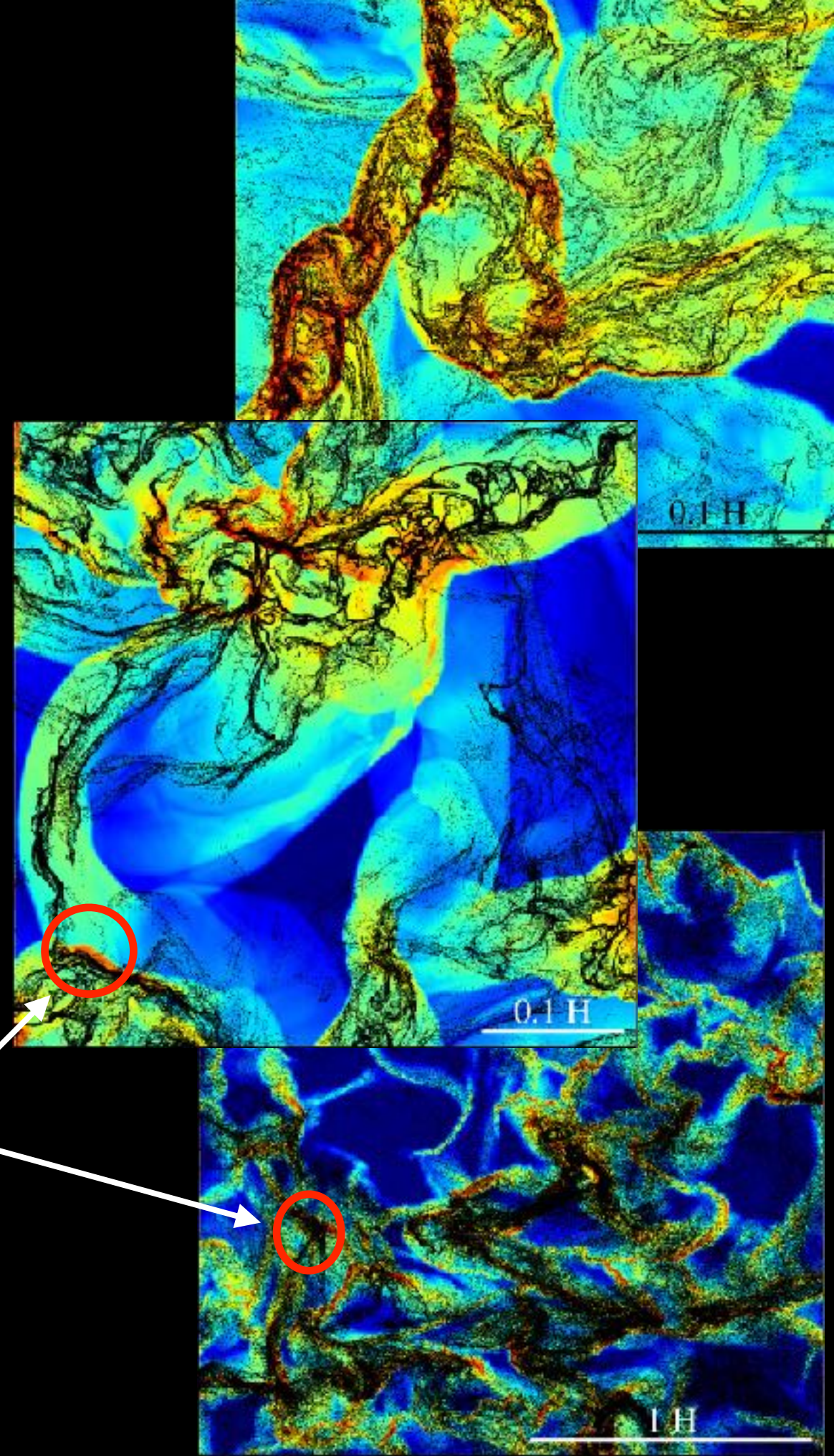
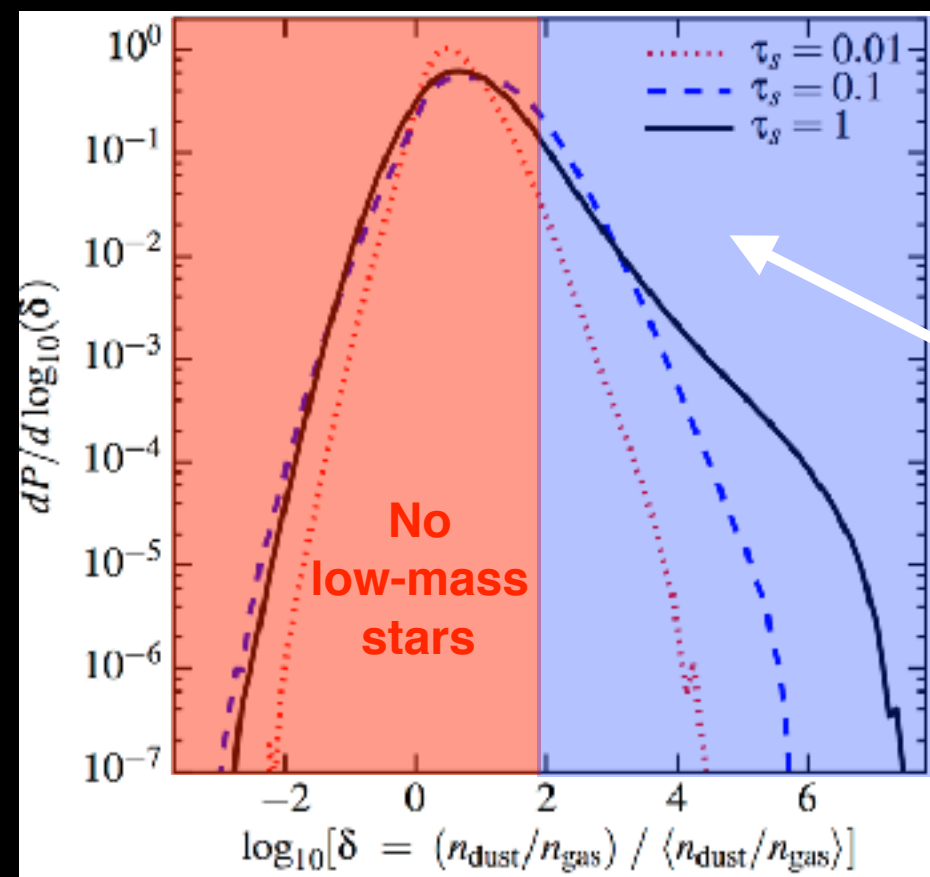
Dust fluctuations enhanced!



What about High Redshifts?

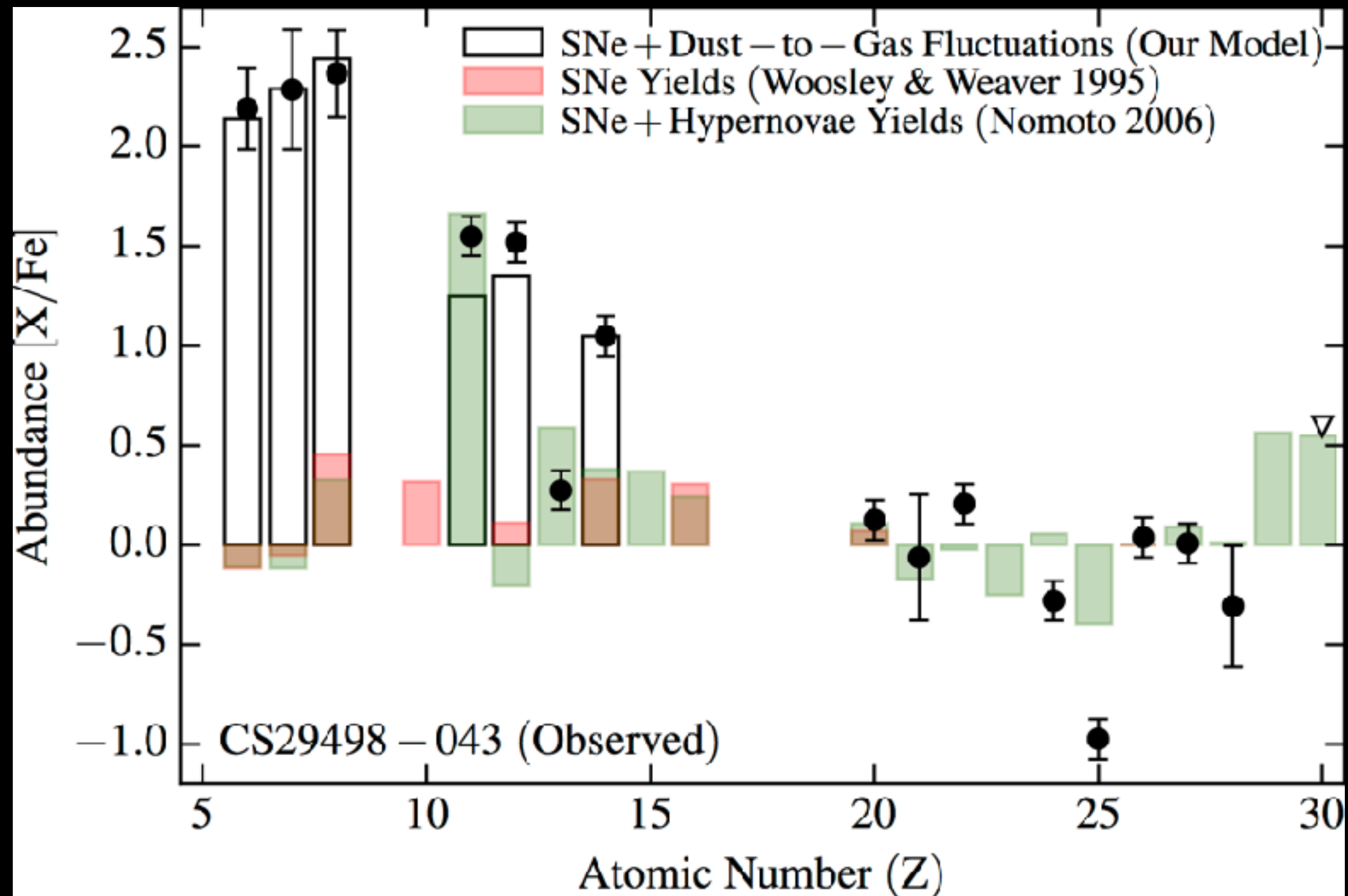
PFH & Conroy, arXiv:1512.03834

- High-redshift proto-galaxy: neutral disk, modestly turbulent ($\text{Mach} \sim 1$), low-metallicity ($[Z/H] \ll -3$)
- Need critical $[Z_{\text{dust}}/H]$ to fragment & form low-mass stars
(Klessen '12, Nozawa '12, Chiaki '14, Ji '14)

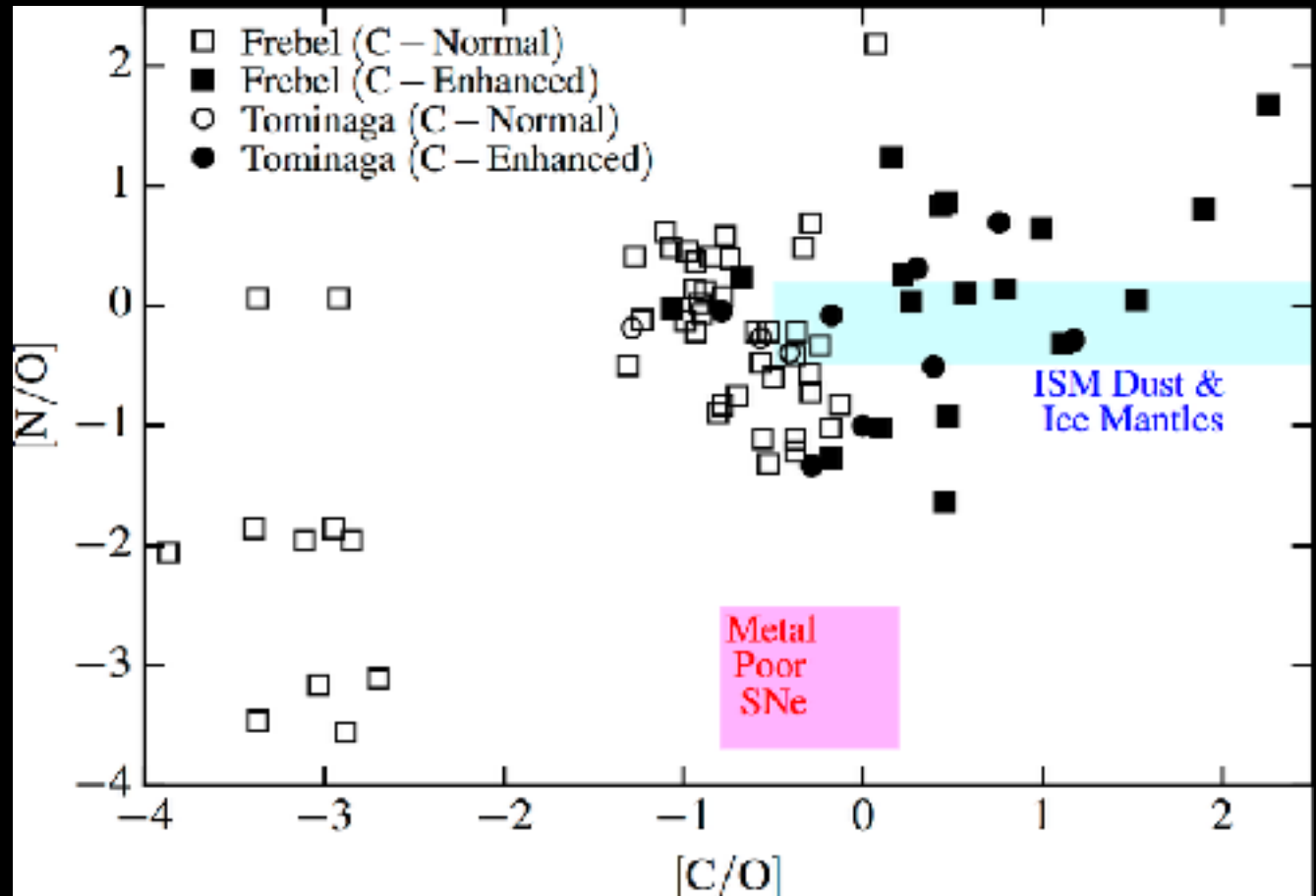


What Would a “Dust Enhanced” Star Look Like?

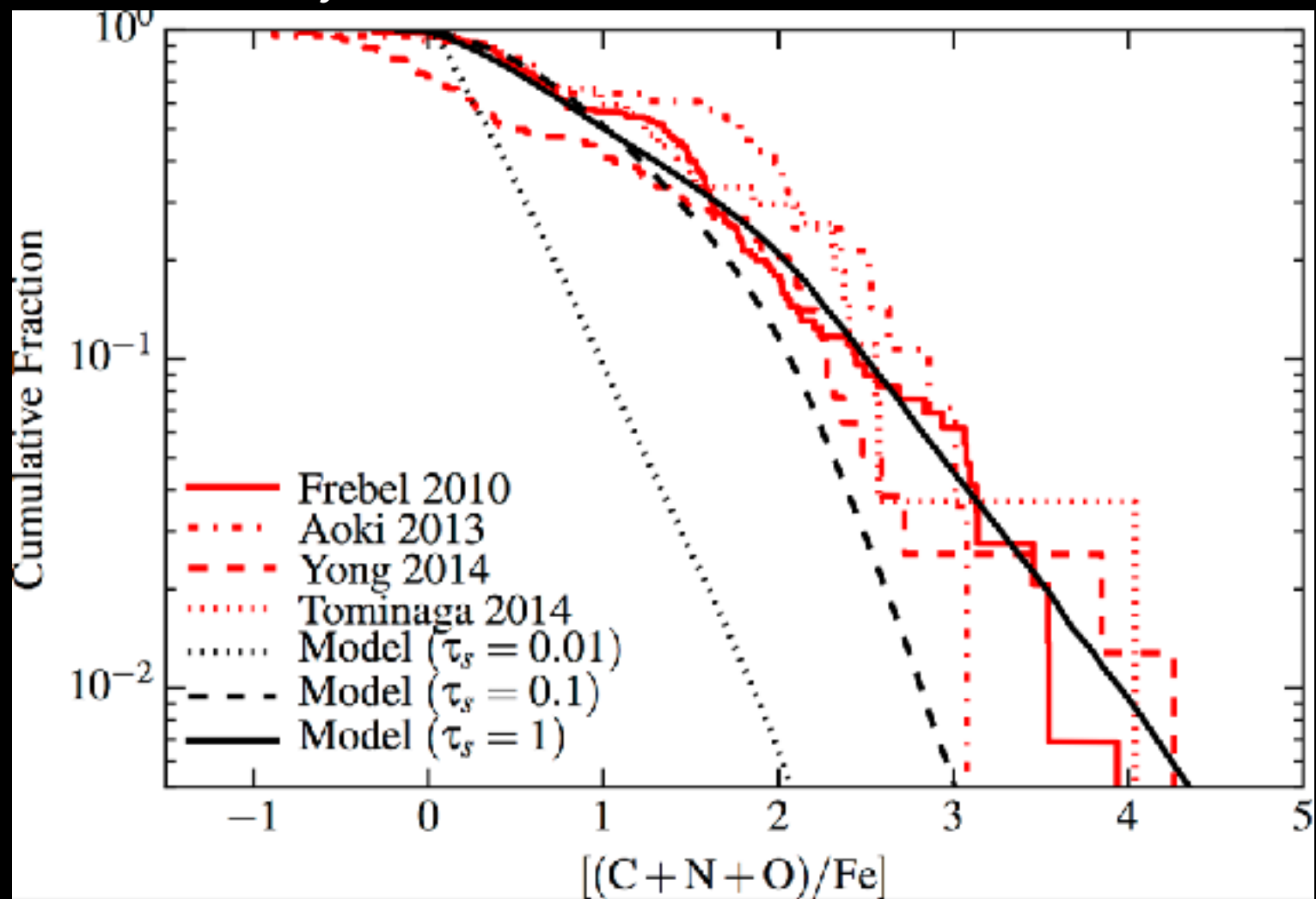
FROM A METAL-POOR PROGENITOR



Can Dust Explain CNO Enhancements? (CEMP-no, [Fe/H]<-3)



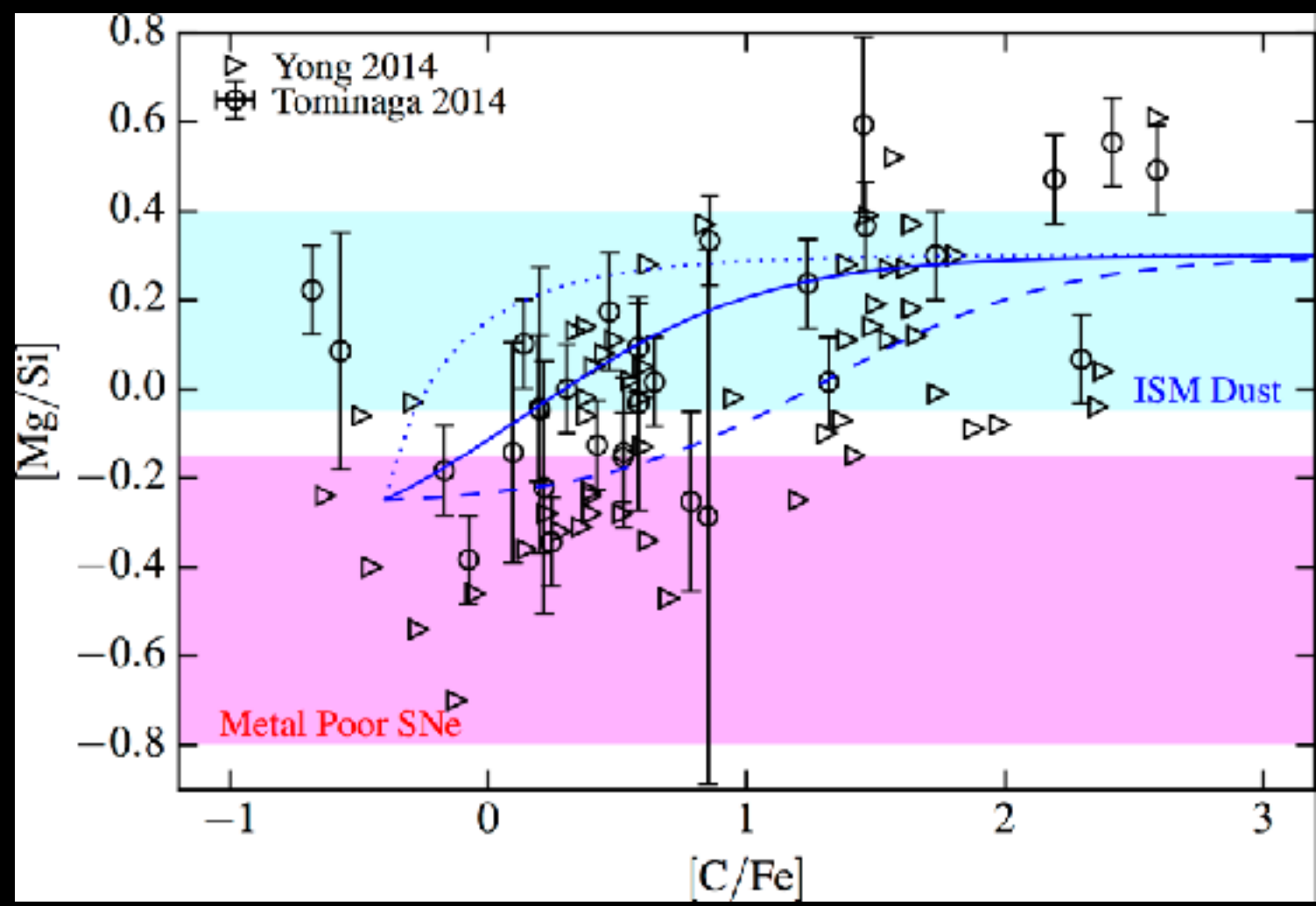
Distribution of C-Enhancement:
Remarkably similar to dust enhancement



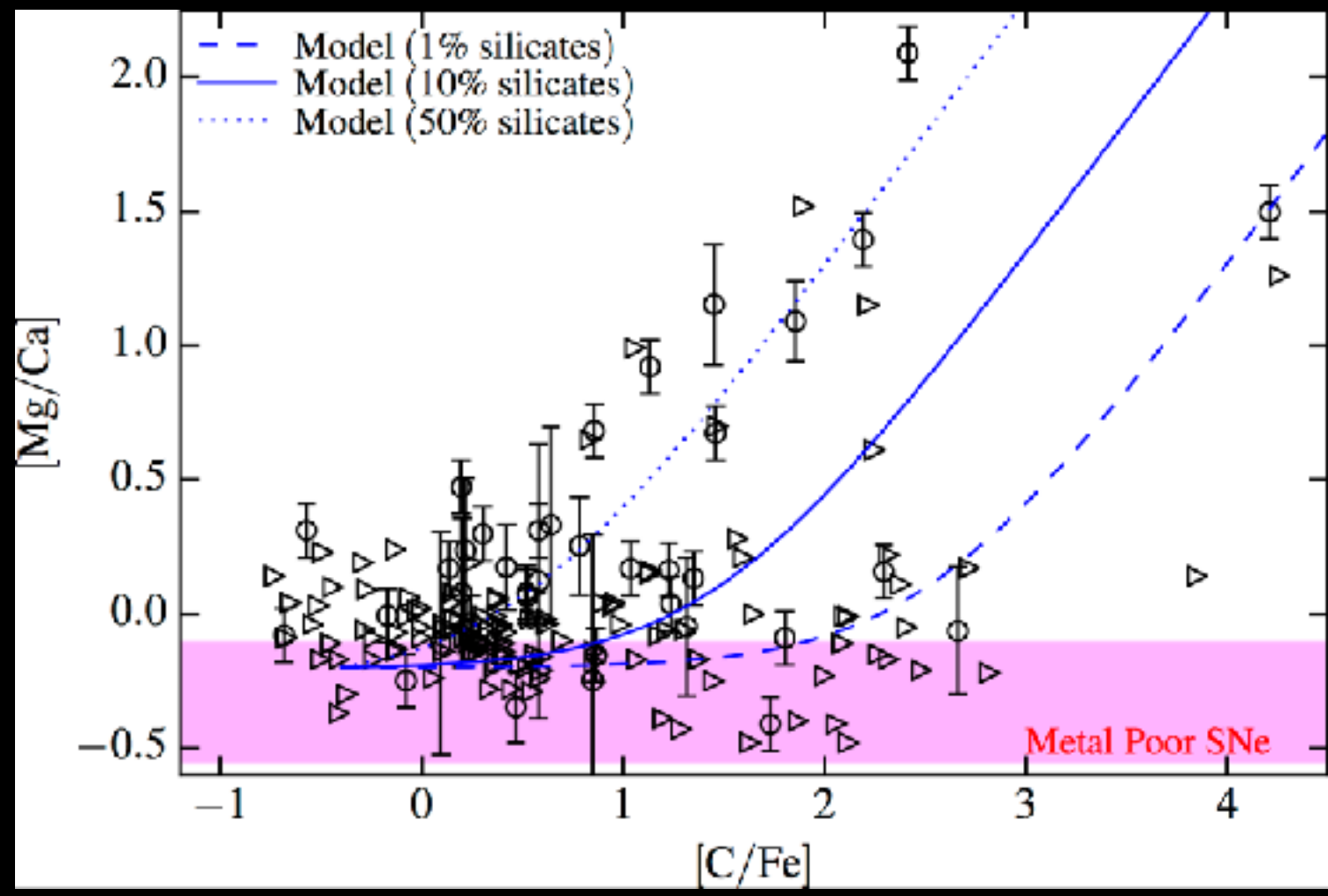
CNO: Ices or SNe yields?
(*caution*: stellar evolution
important here!)

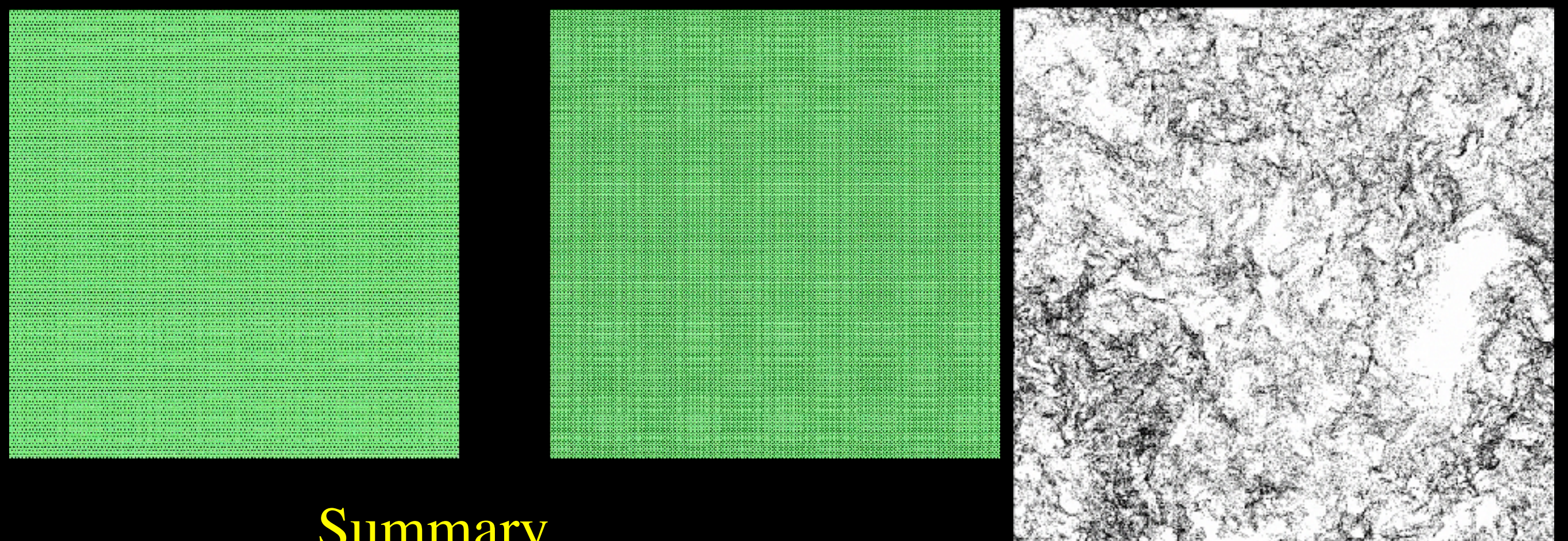
Silicates Fit the Picture
(Unknown Si-to-C Grain Ratio)

[Mg/Si]: From the same grains
Look more like dust as [C/Fe] increases



[Mg/Ca]: Closely-related in burning
But not in dust





Summary

- **Resonant Drag Instability (RDI):** dust-gas mixtures generically unstable
- **Dust growth** / evolution / clumping radically altered
- High-density dust clumps: **dust-assisted GI**
- High-Redshift: **Dust-enhancement *could enable* low-mass star formation:**
 - Explains strange **light-element** patterns: [CNO, Mg, Si, Na]?