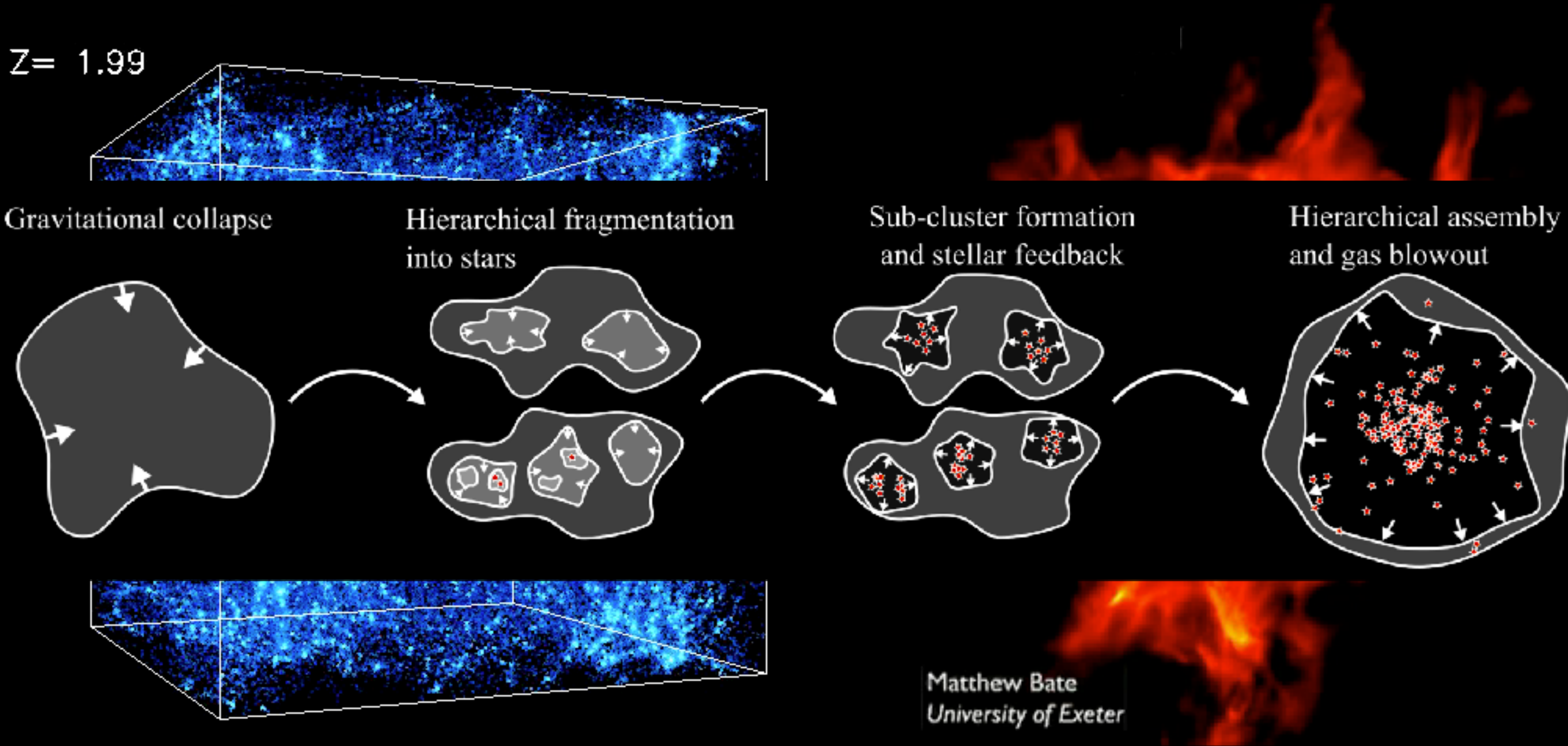
The Resonant Drag Instability (RDI): A New Class of Instabilities in Dusty Gas

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)

Background

The Setup:
SQUIRE & HOPKINS ’17 (SH; arXiv:1706.05020)

Gas equations = (anything that supports a linear mode)

Dust equations = continuity + momentum:

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

Arbitrary operator

e.g.

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

Stopping/drag time

The Setup:

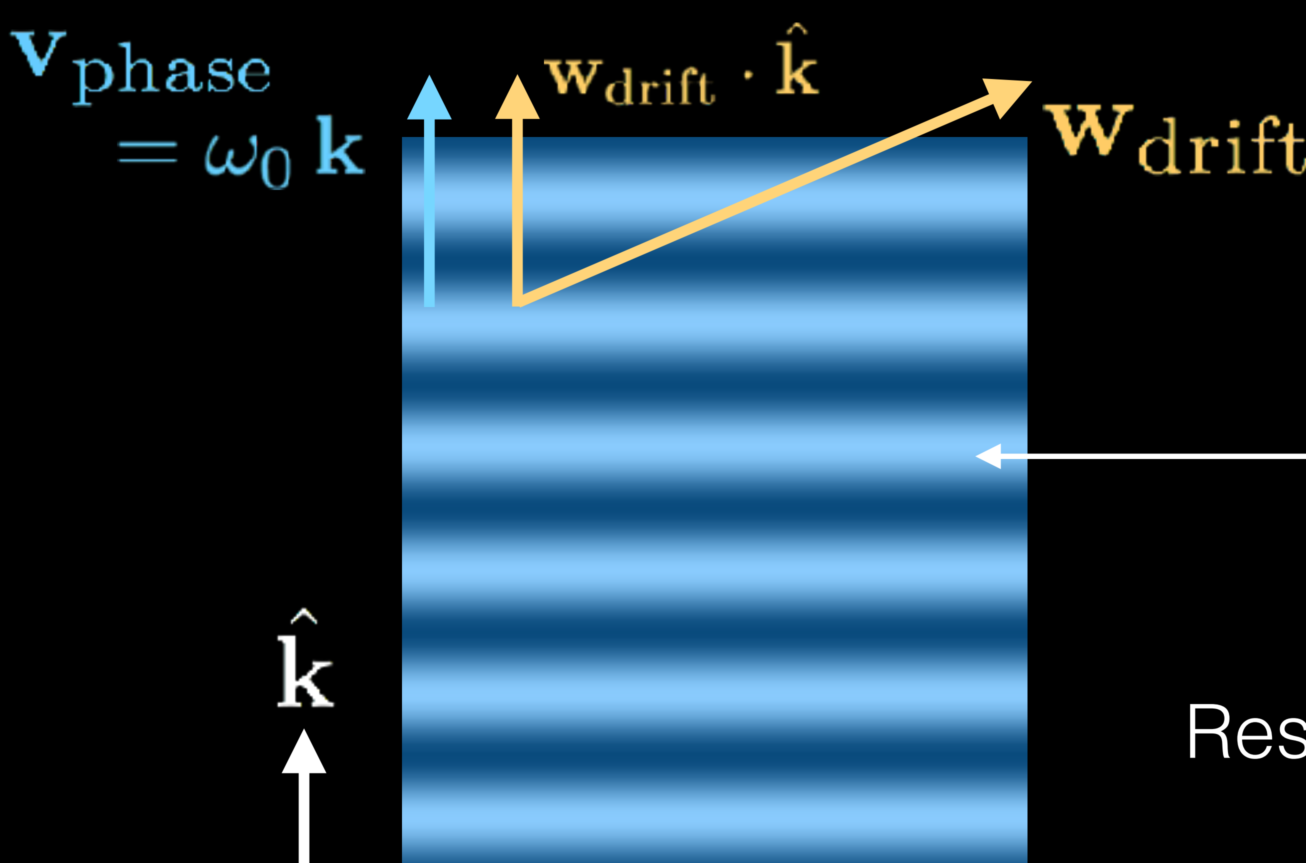
SQUIRE & HOPKINS '17 (SH; arXiv:1706.05020)

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

"natural" gas response

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

wavevector



Dust hits gas density peak, slows down, piles up

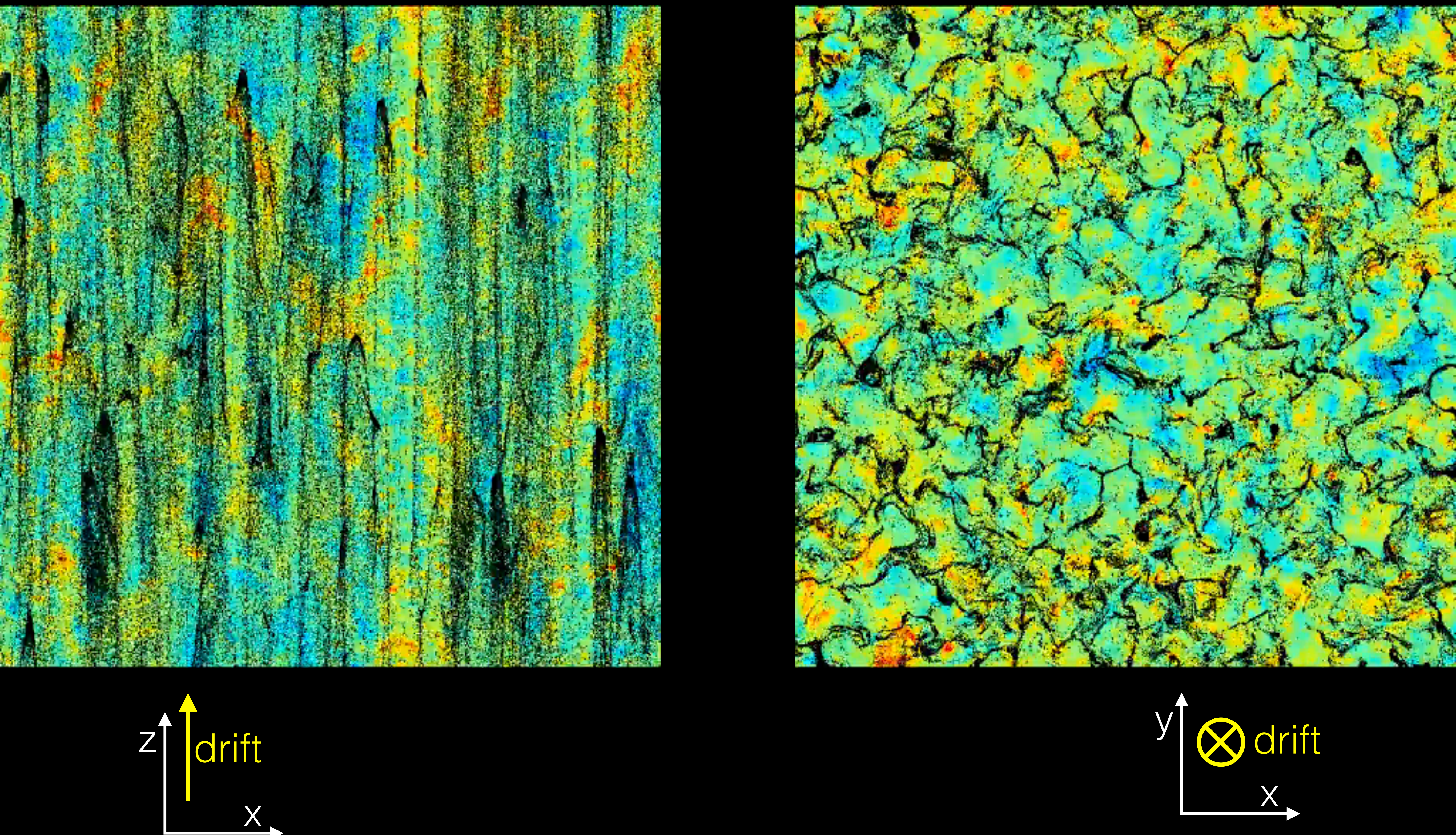
Resonance: Dust sees standing wave, effects add coherently

Example in Simulations: Acoustic RDI

(RESONANCE WITH SOUND WAVE)

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

$L_{\rm box} \sim 100\, c_s \langle t_s \rangle$ $\Delta t \sim 80\, \langle t_s \rangle$



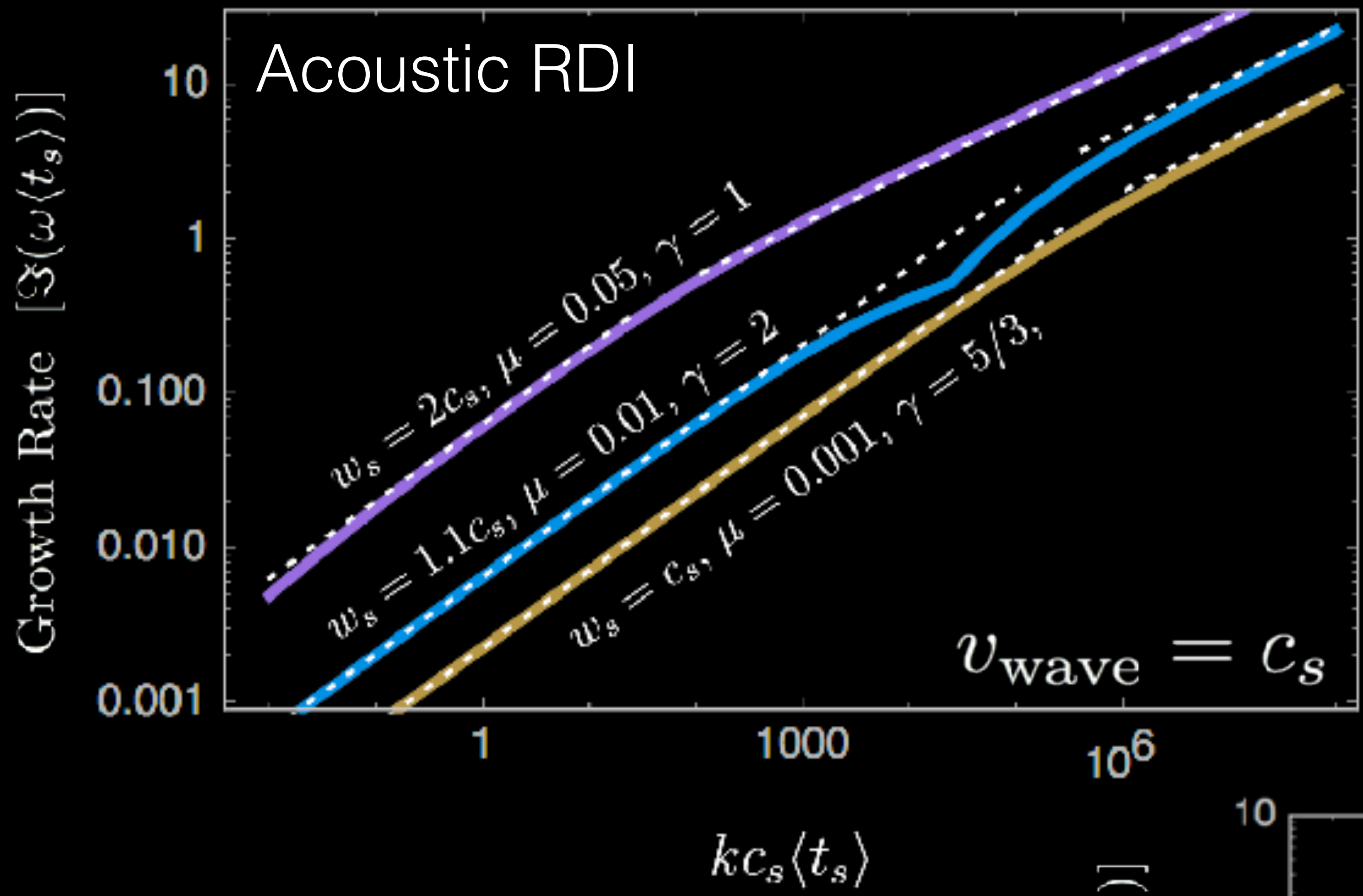
Examples of the RDI

Acoustic & Magnetosonic RDI

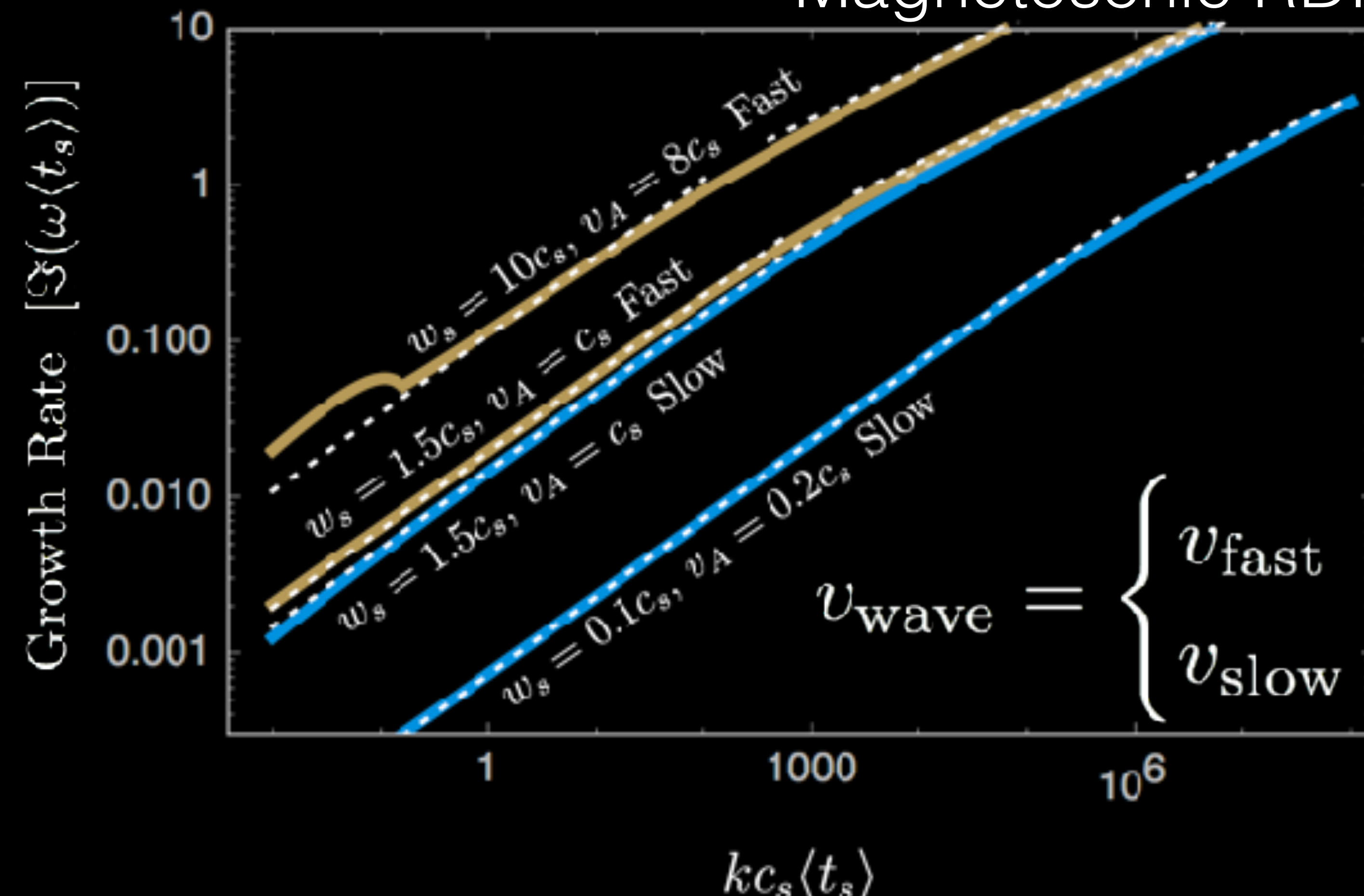
RESONANCE WITH FIXED PHASE SPEED (SH '17)

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

$$\omega_0 = v_{\rm wave}\, k$$



Magnetosonic RDI



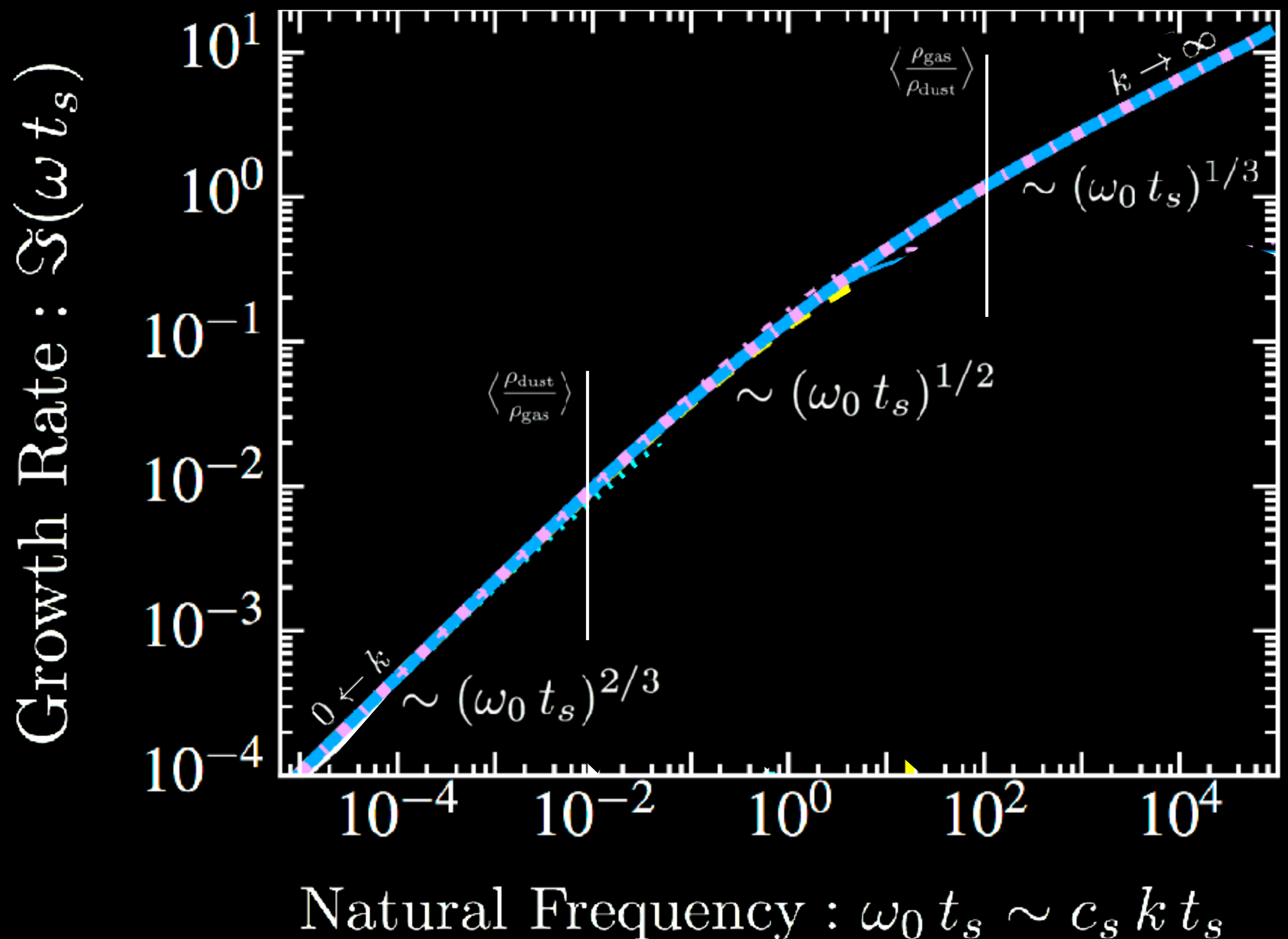
$$v_{\rm slow} \rightarrow 0$$

Resonance ***always*** exists

$$\left(|\mathbf{w}|_{\rm drift} \ll c_s,\, v_A\right)$$

Acoustic & Magnetosonic RDI

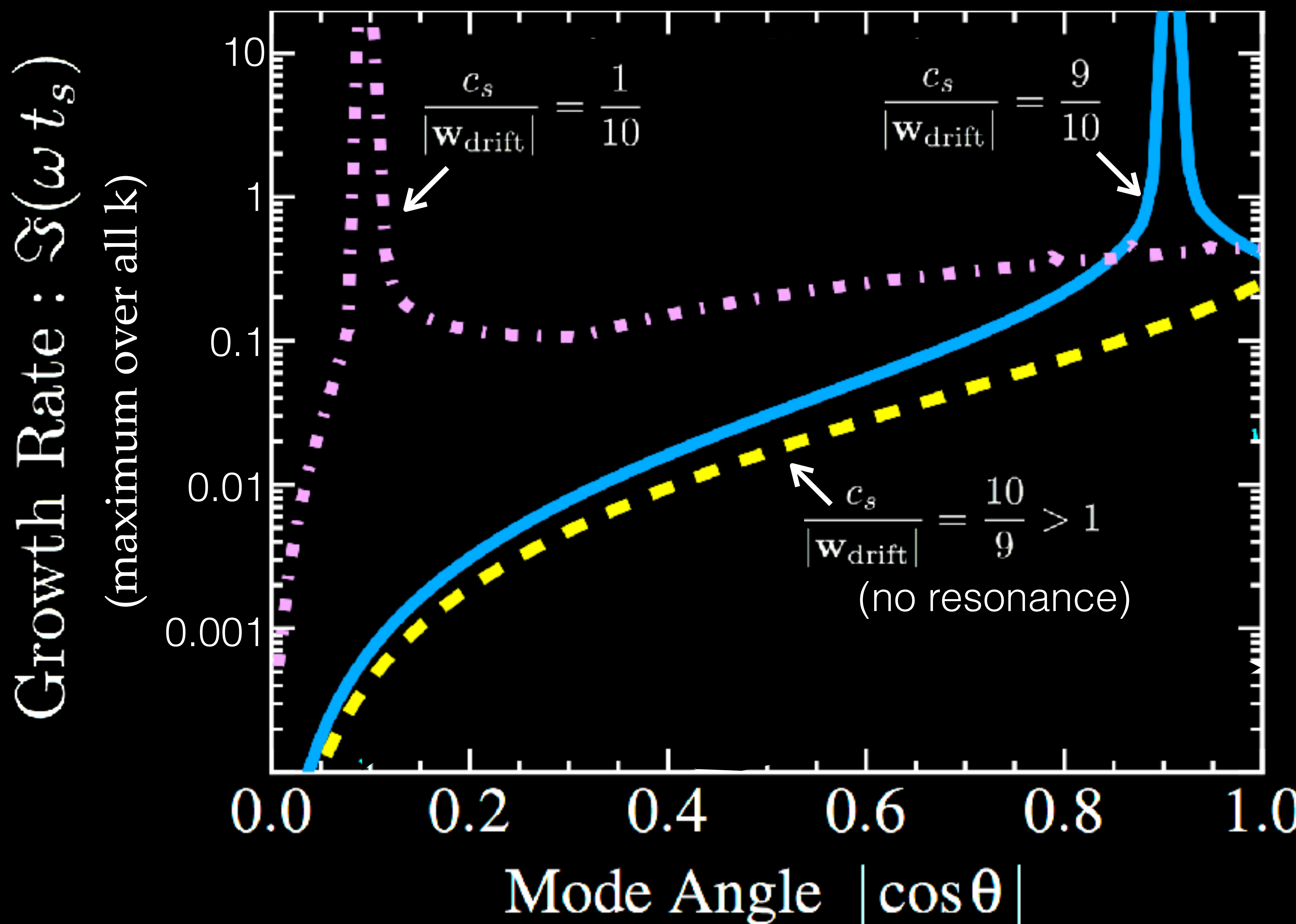
SCALING OF "RESONANT" GROWTH RATES



Acoustic & Magnetosonic RDI

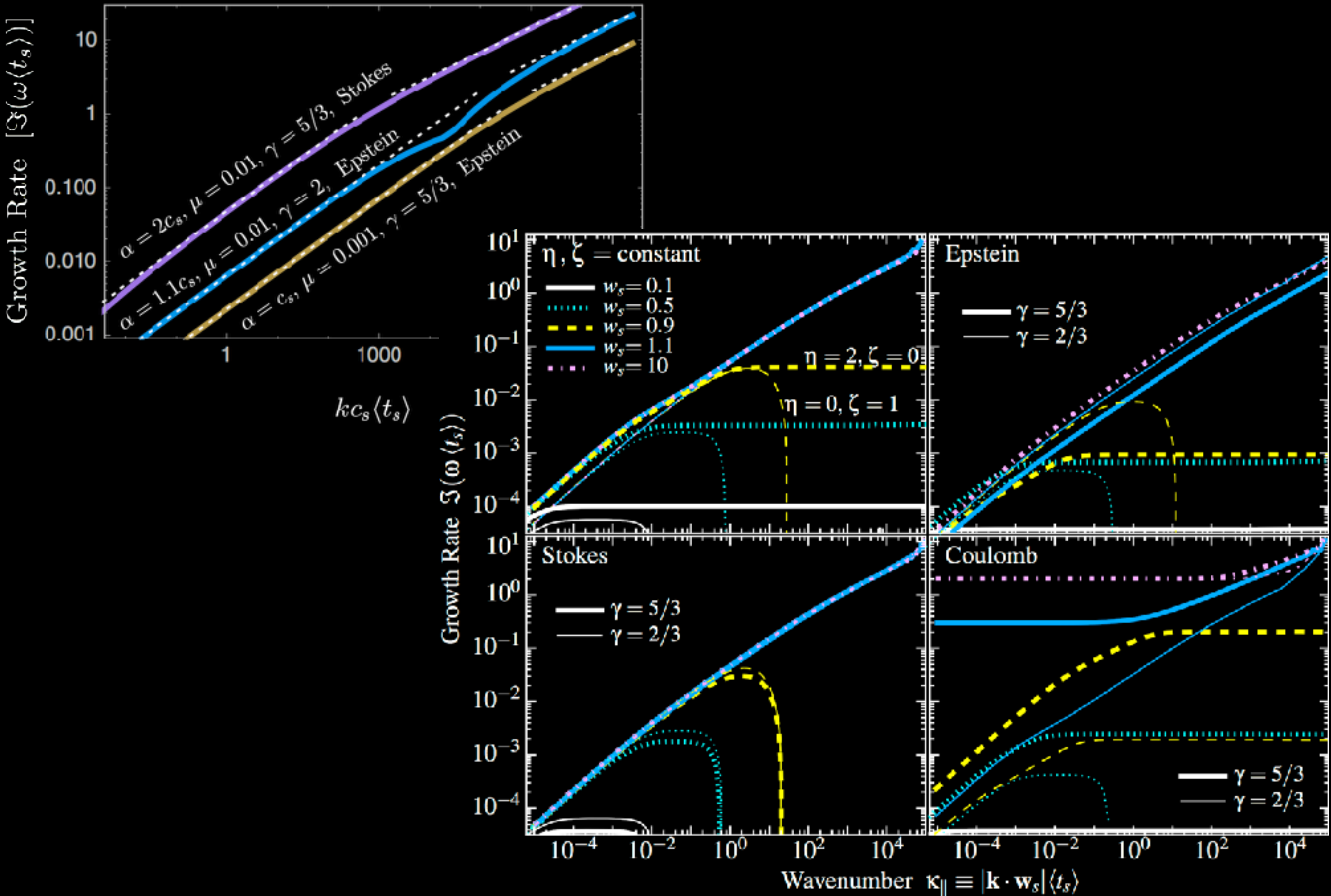
“RESONANT” ANGLES

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



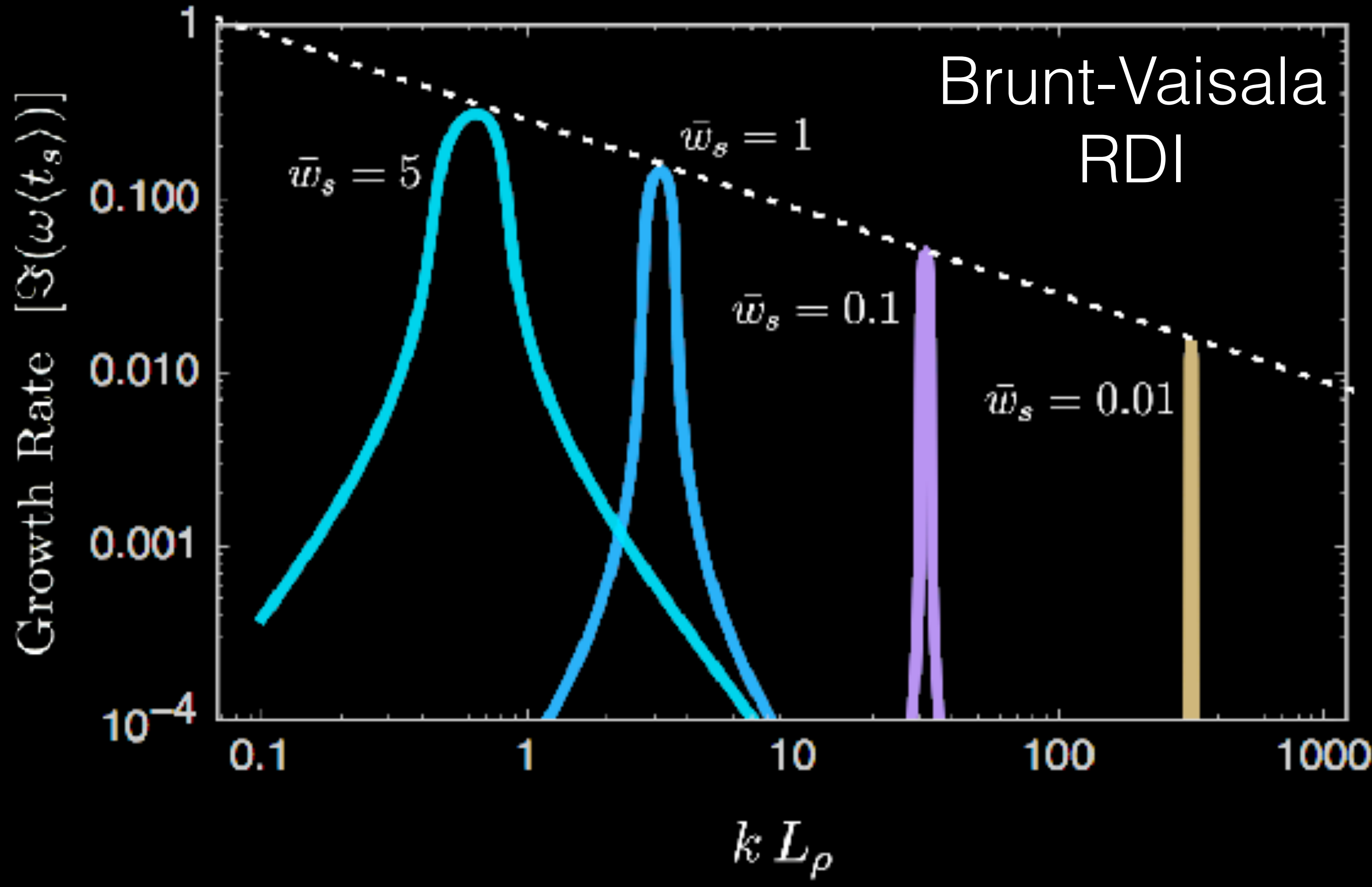
Weak Dependence on Drag Law, Equation-of-State, Dust-to-Gas Ratio

DON'T CHANGE DYNAMICS (HS '17)



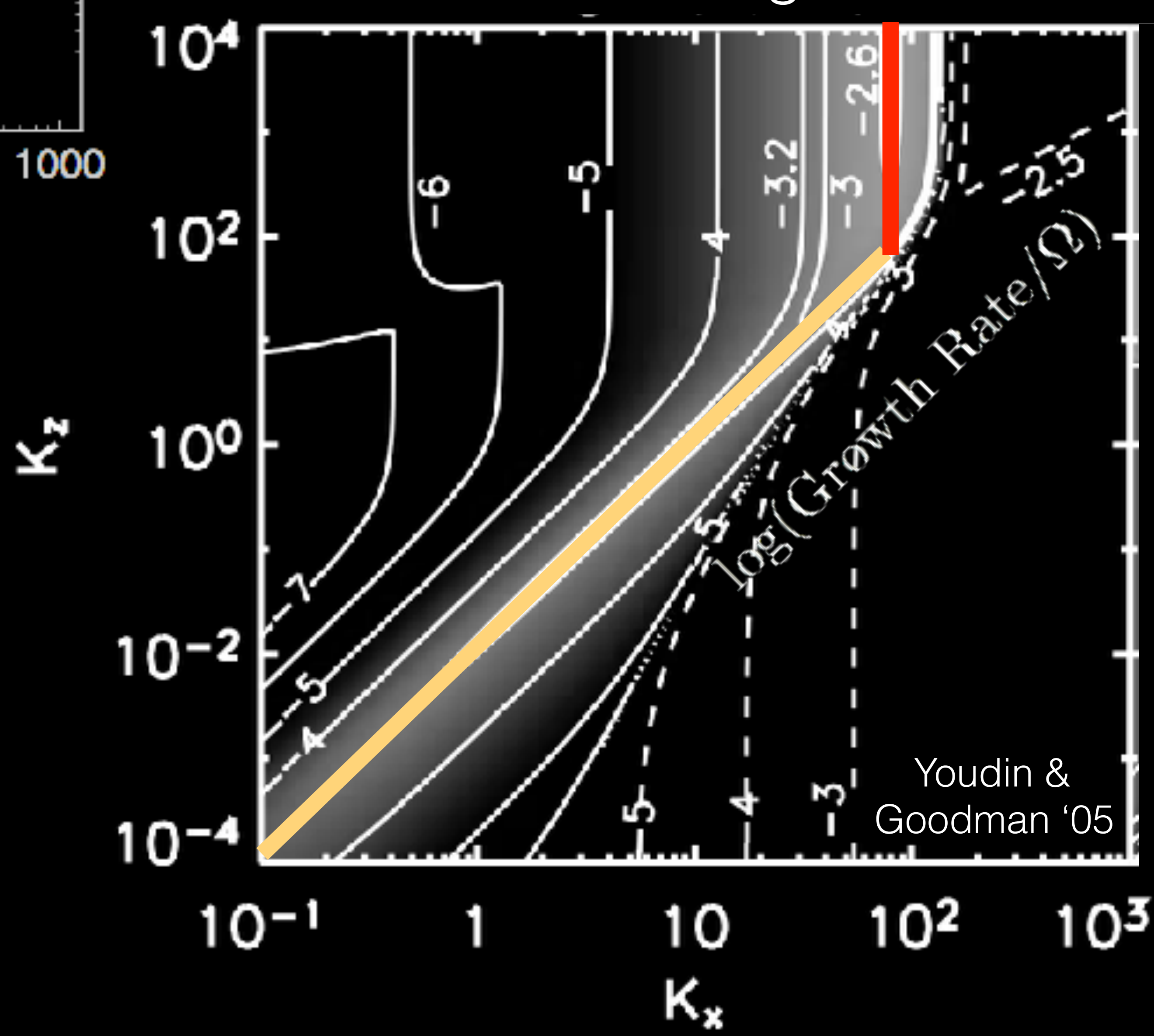
Brunt-Vaisala & Streaming RDI

RESONANCE WITH FIXED-FREQUENCY (SH ’17)



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

Streaming RDI



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

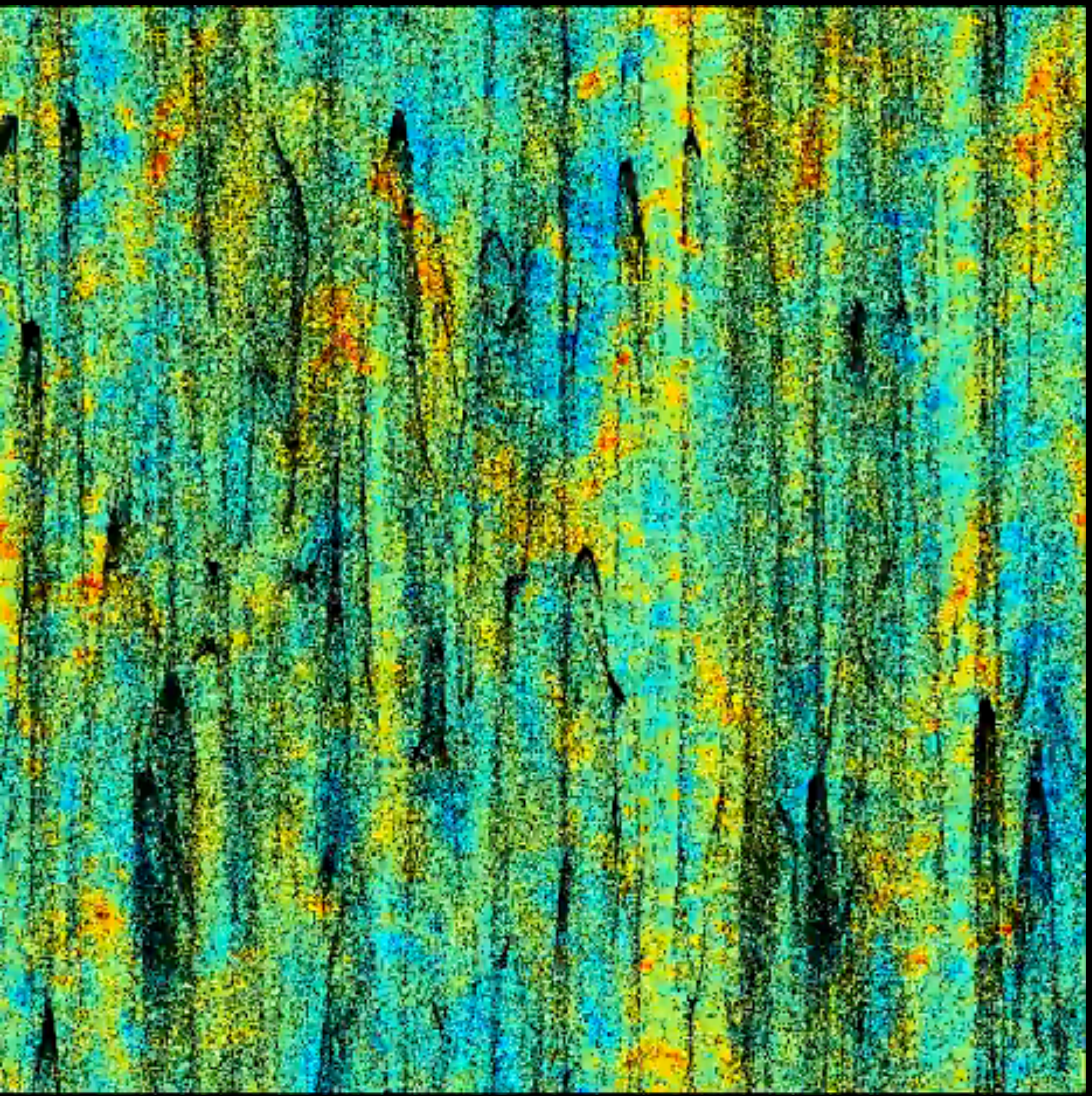
Simulations:
Non-linear Behavior

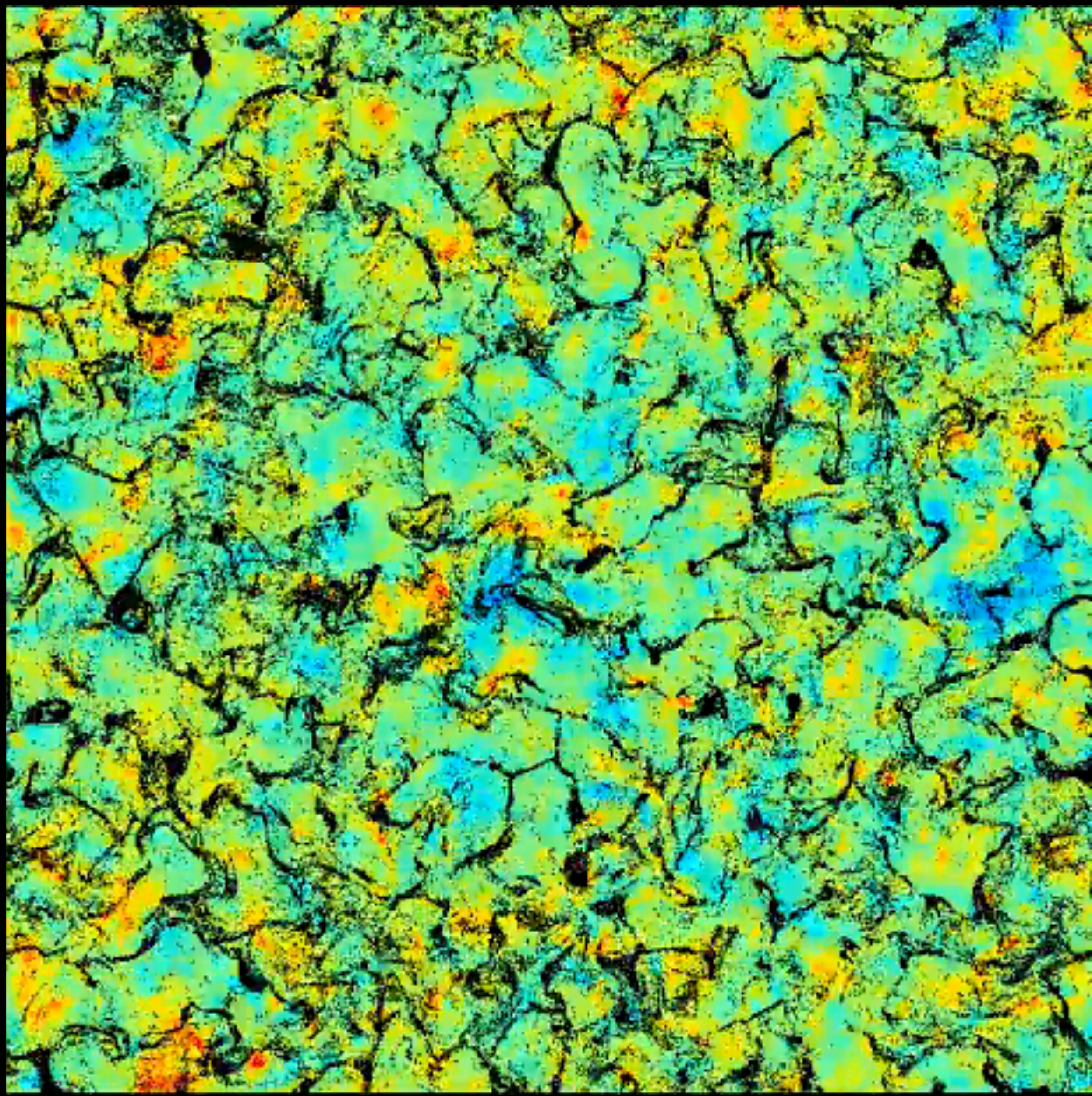
Acoustic RDI: Non-Linear Behavior

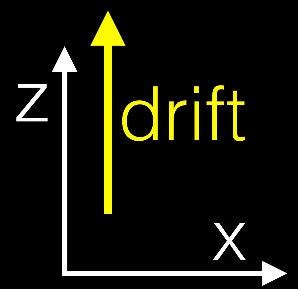
EARLY DEVELOPMENT (Squire, Moseley+ in prep.)

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

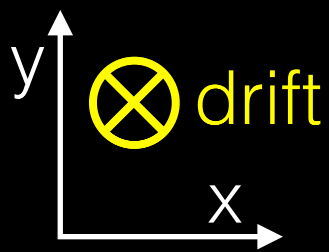
$L_{\rm box} \sim 100\, c_s \langle t_s \rangle$ $\Delta t \sim 80\, \langle t_s \rangle$







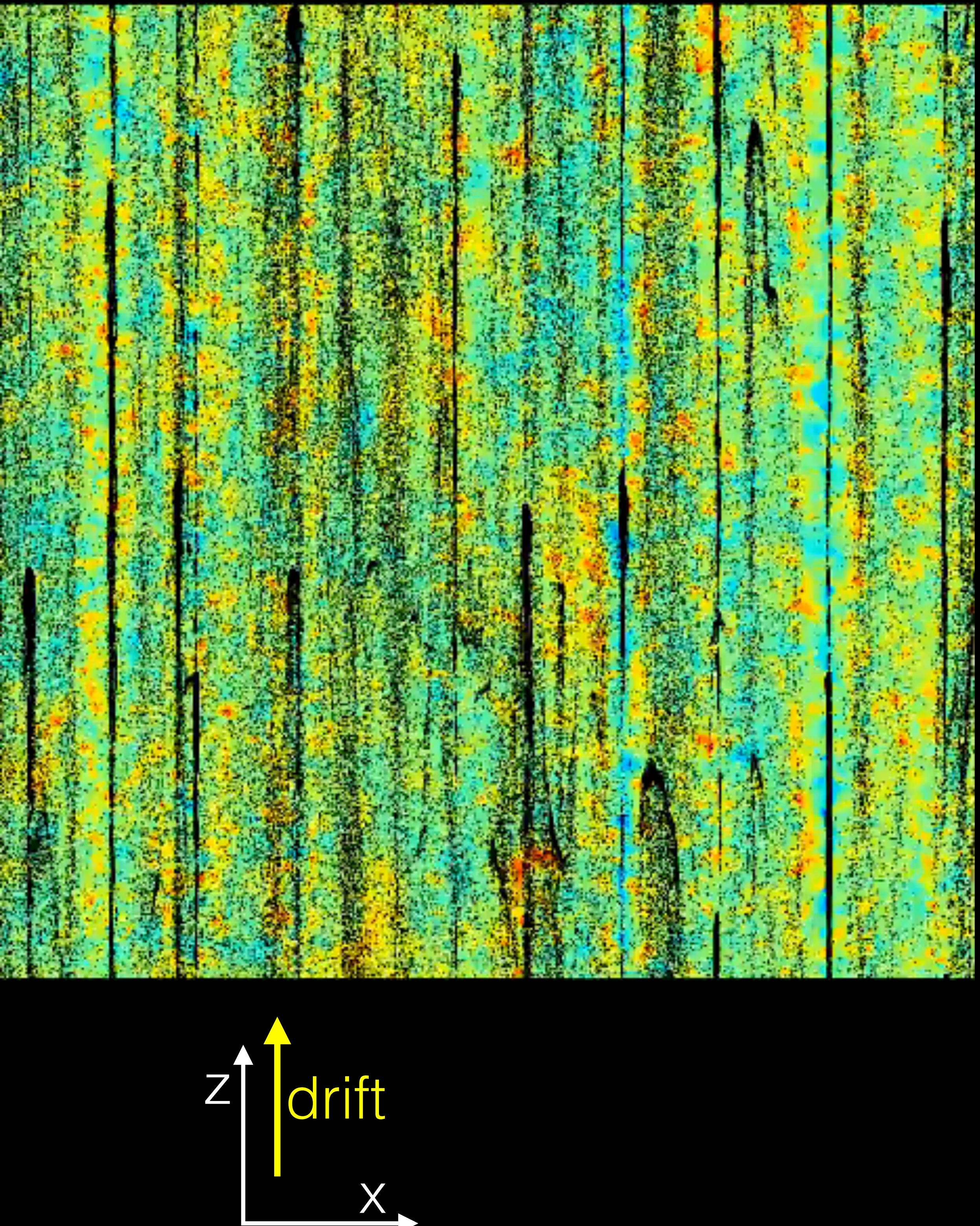
$0.06 \lesssim k\, c_s \langle t_s \rangle \lesssim 10$

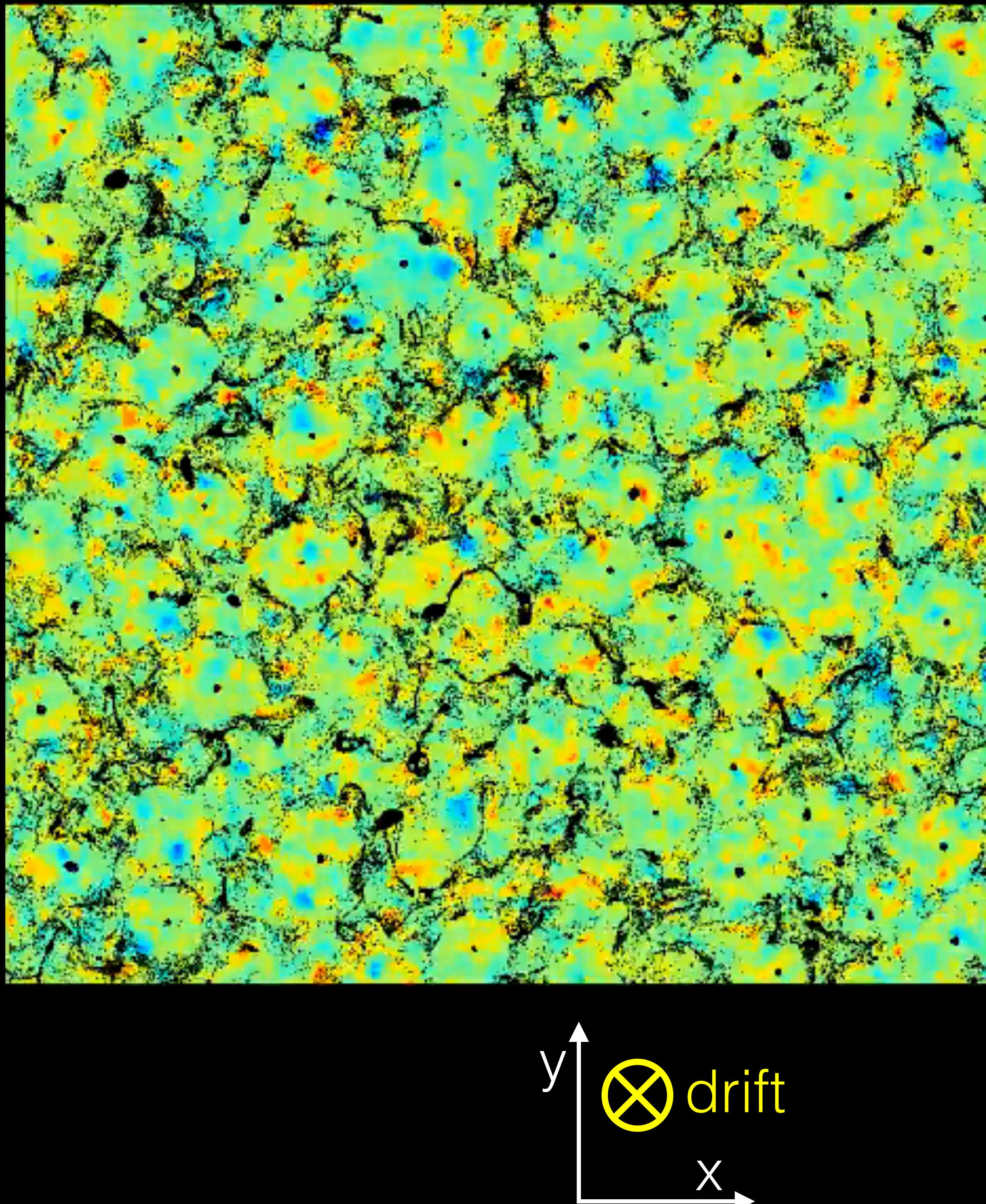


Acoustic RDI: Non-Linear Behavior

LATE DEVELOPMENT (Squire, Moseley+ in prep.)

$L_{\mathrm{box}} \sim 100\, c_s \langle t_s \rangle \qquad \Delta t \sim 500\, \langle t_s \rangle$





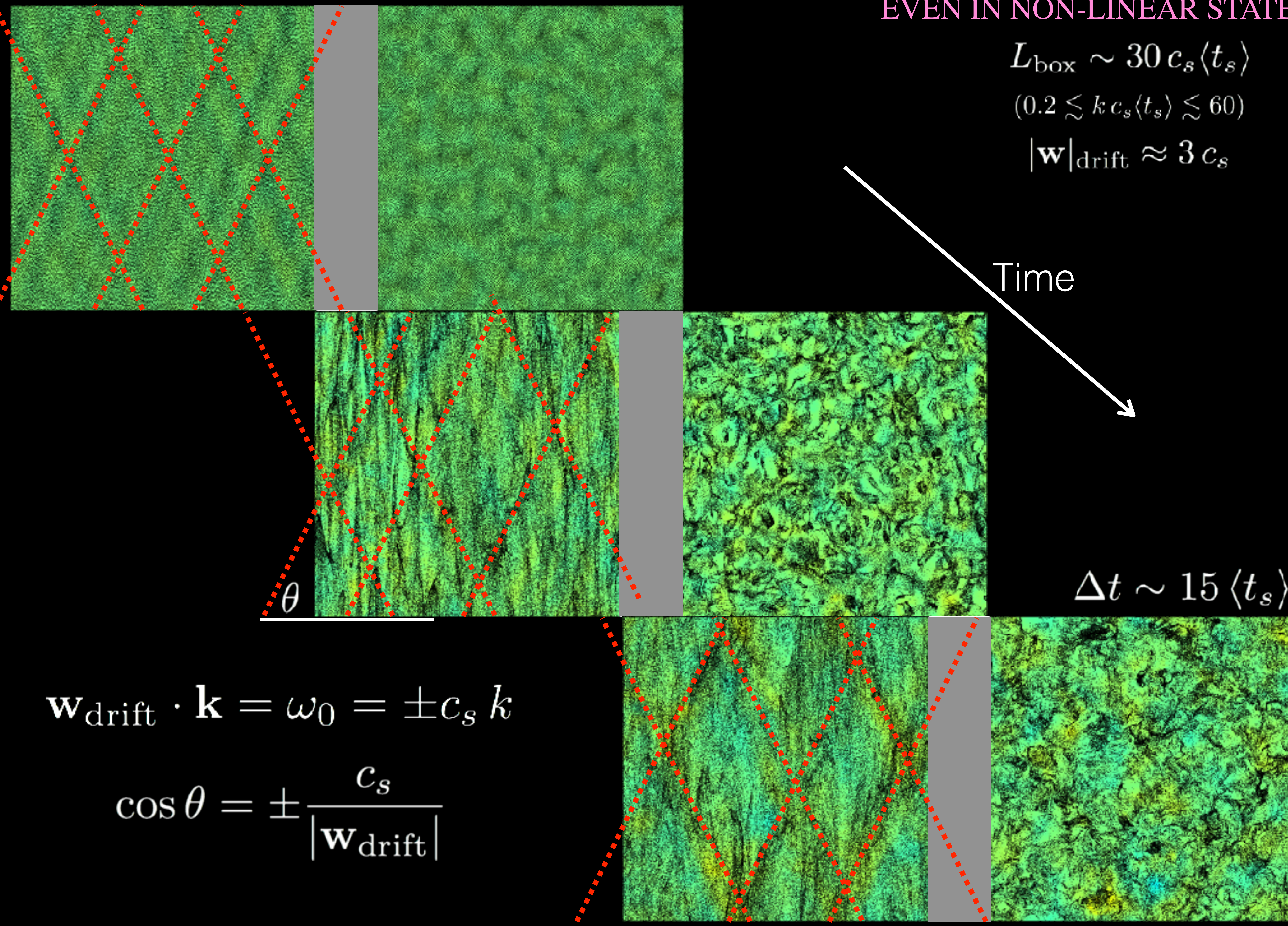
Resonant Mode Dominates

EVEN IN NON-LINEAR STATE

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

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

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



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

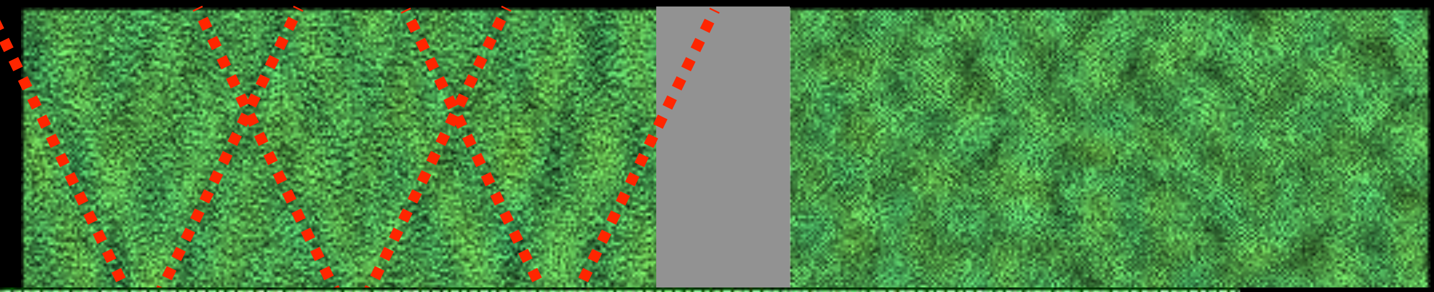
$$\cos\theta = \pm \frac{c_s}{|\mathbf{w}_{\rm drift}|}$$

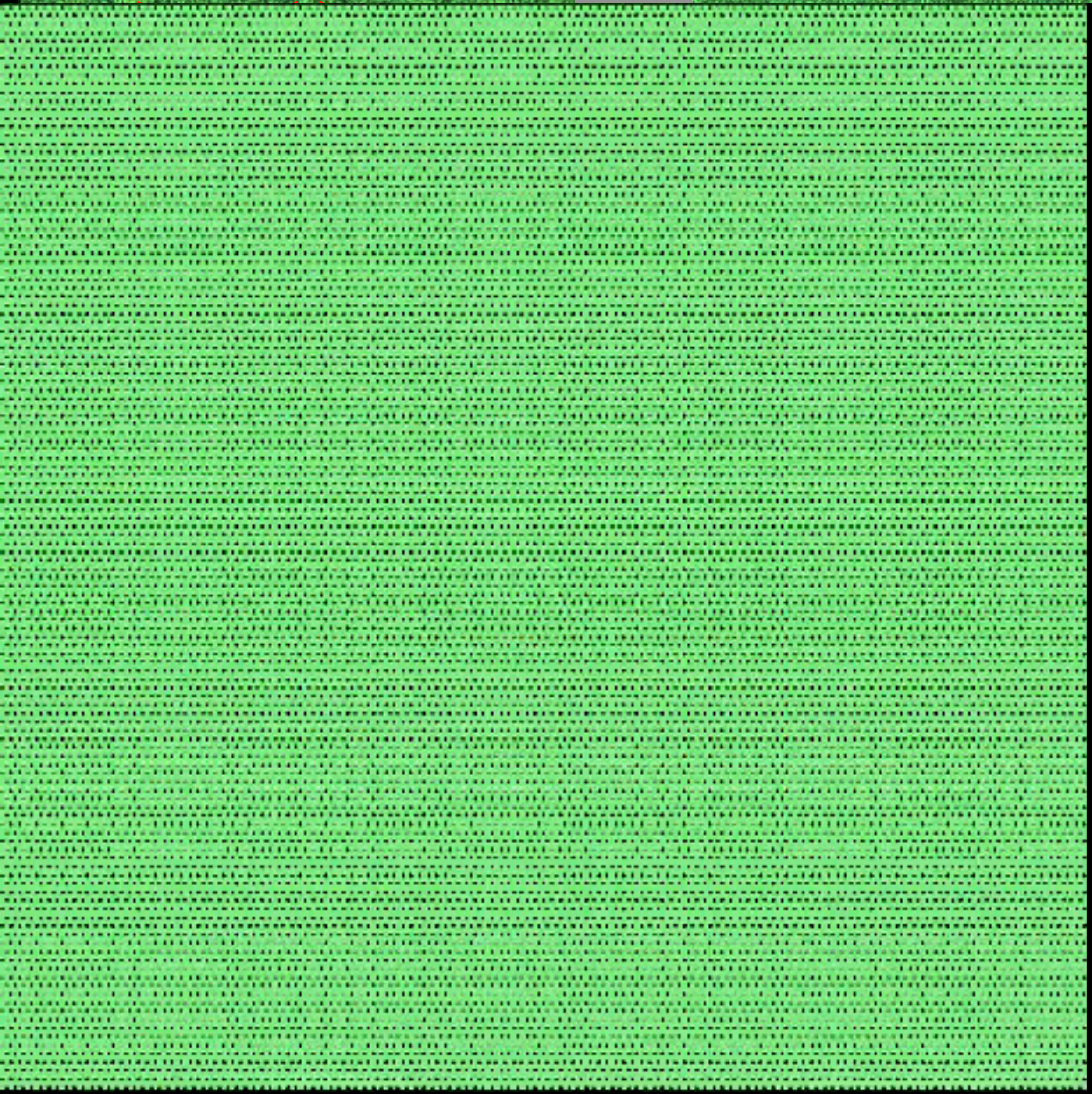
Resonant Mode Dominates

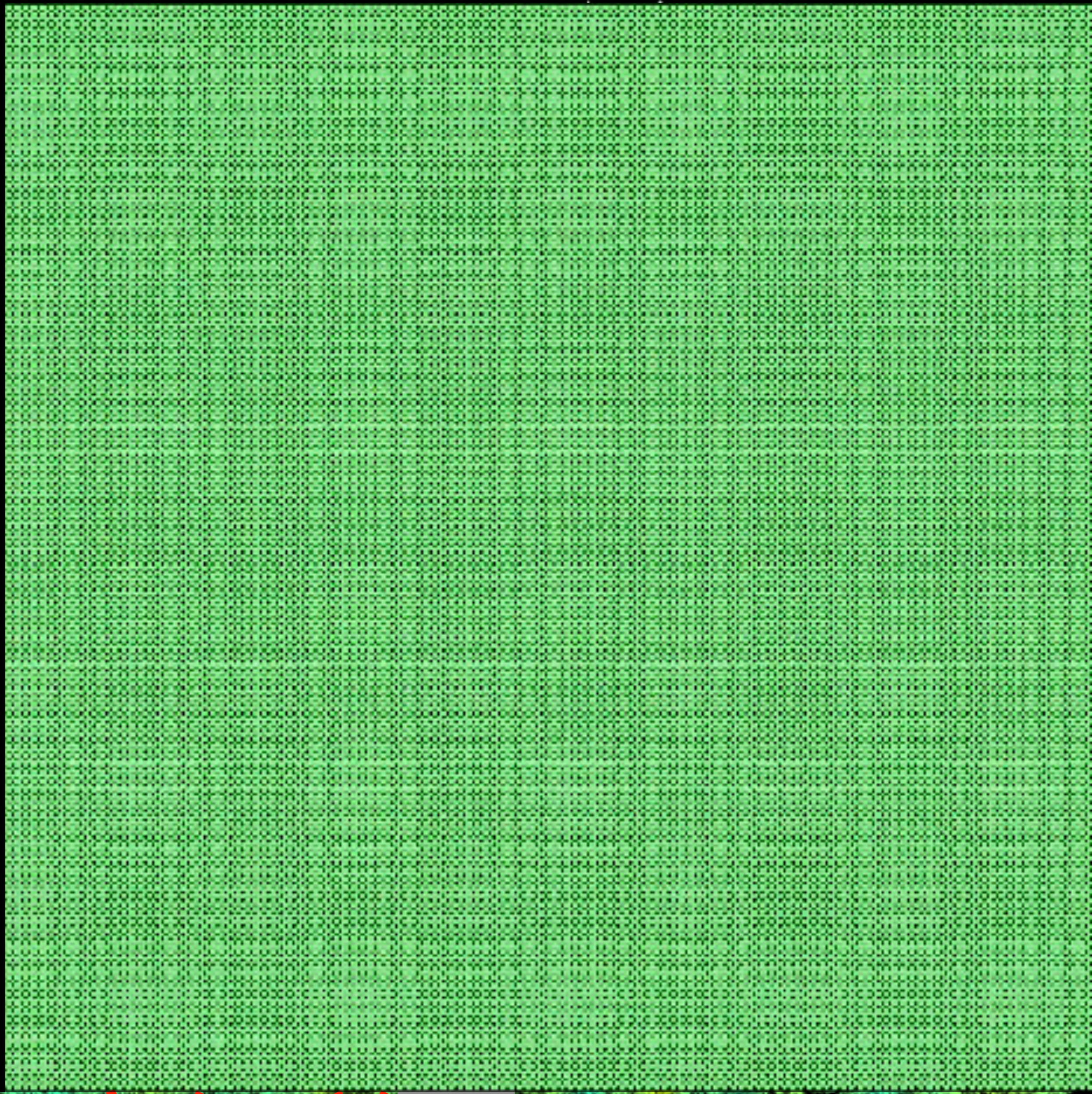
EVEN IN NON-LINEAR STATE

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

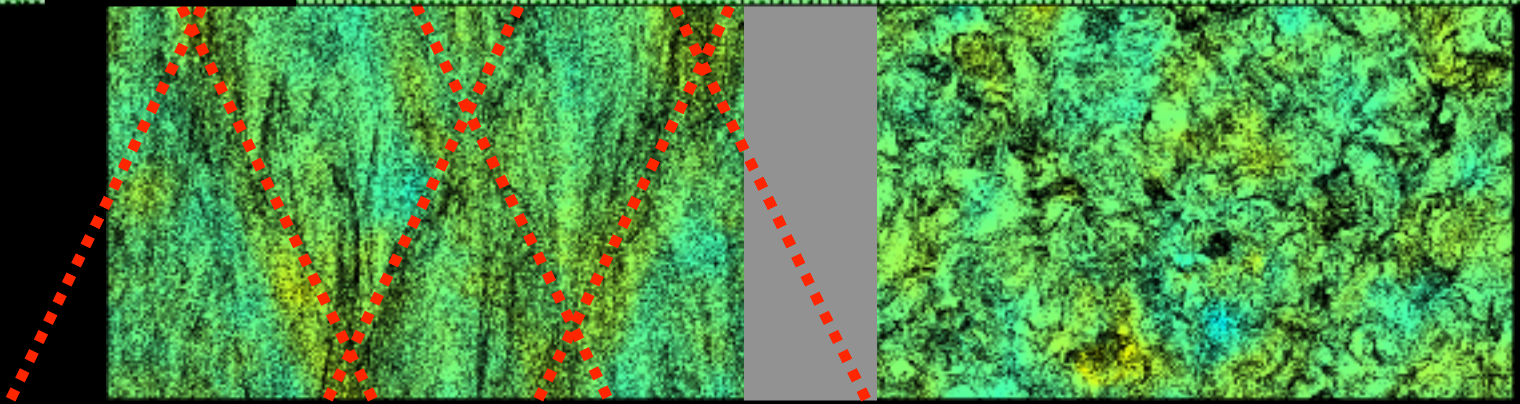
$$(0.2 \lesssim k\, c_s \langle t_s \rangle \lesssim 60)$$







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



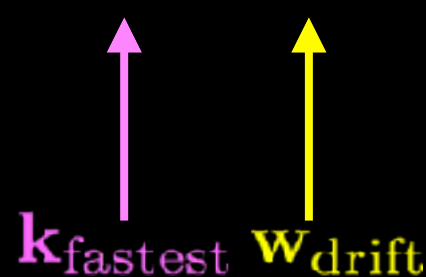
Sub-Sonic Drift: Still Unstable

NO RESONANCE: LOW-K, PARALLEL MODES

- Slower than slowest wave-speed: no resonance

- Still unstable! Fastest-growing:

  - Parallel:

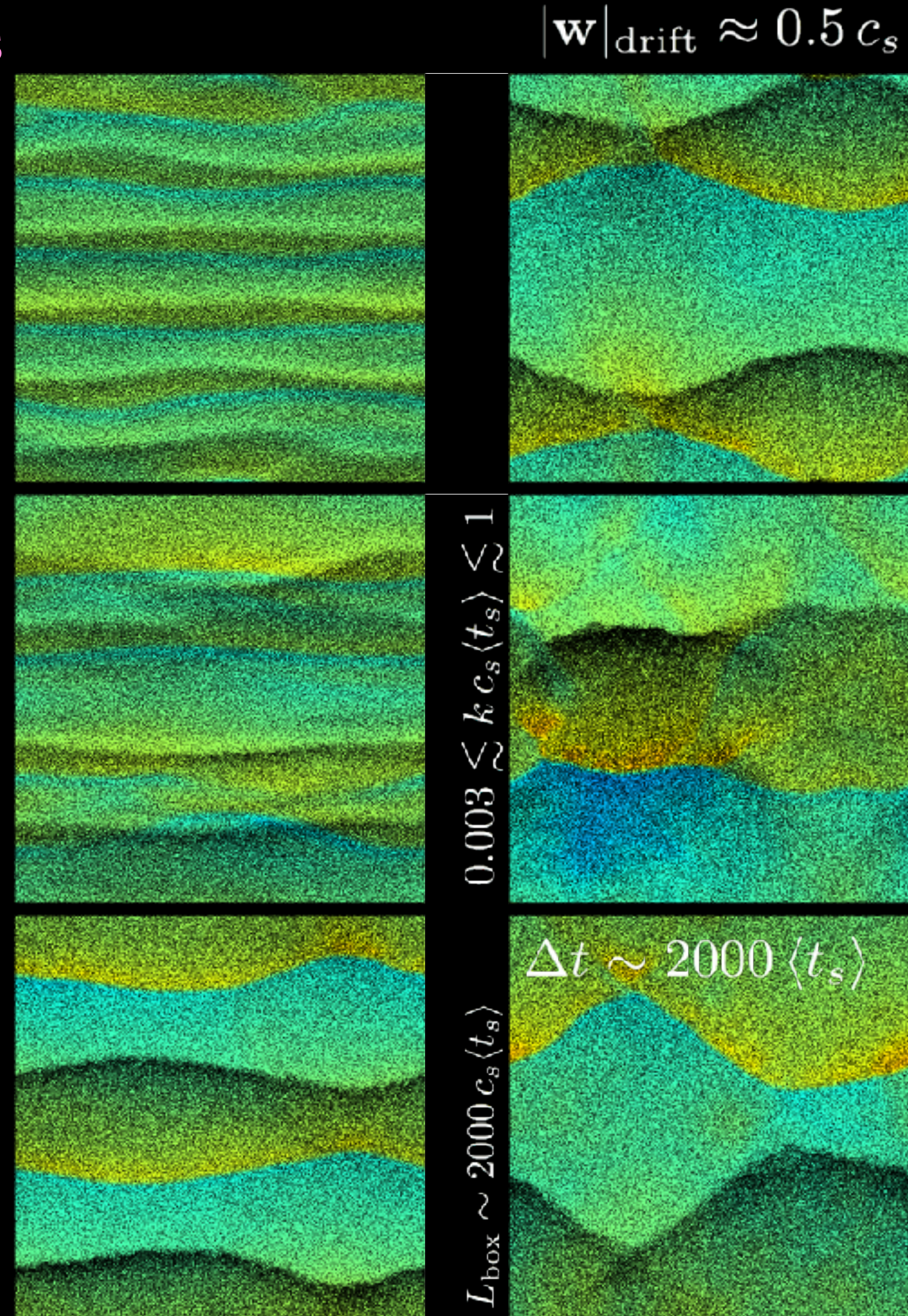


  - Long-wavelength:

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

  - Slow-growing:

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



Consequences

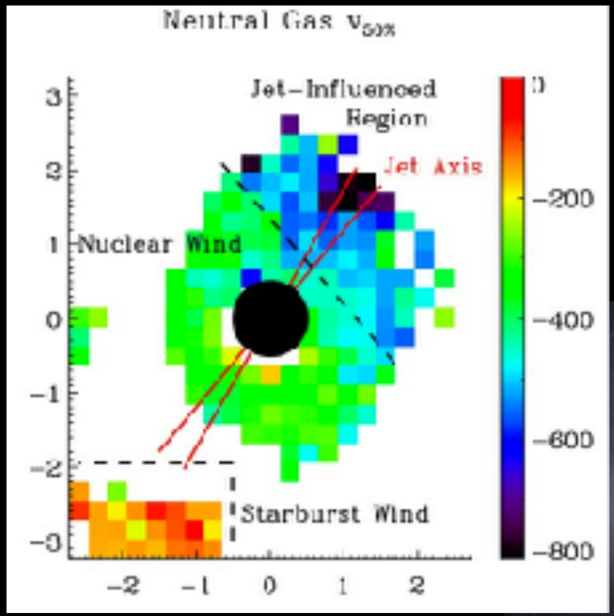
Squire & Hopkins
(arXiv:1706.05020)
Hopkins & Squire
(arXiv:1707.02997)

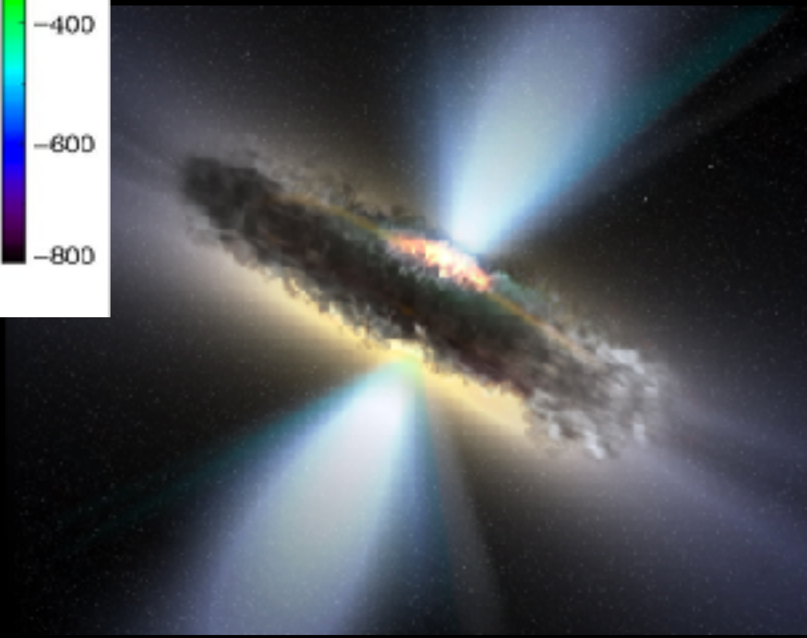
The RDI Persists for:

- *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

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

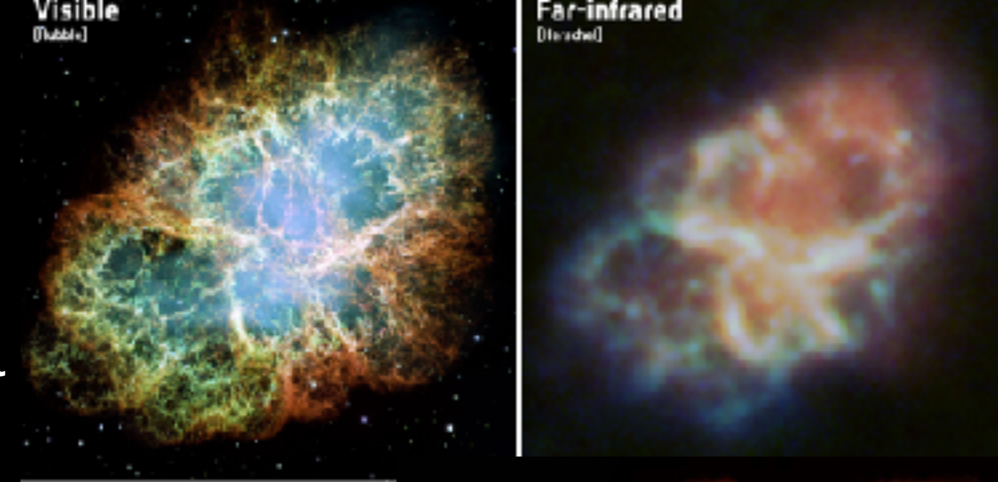
  - clumpy obscuration
  - time-dependent dust
  - wind-launching
  - dust formation

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

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

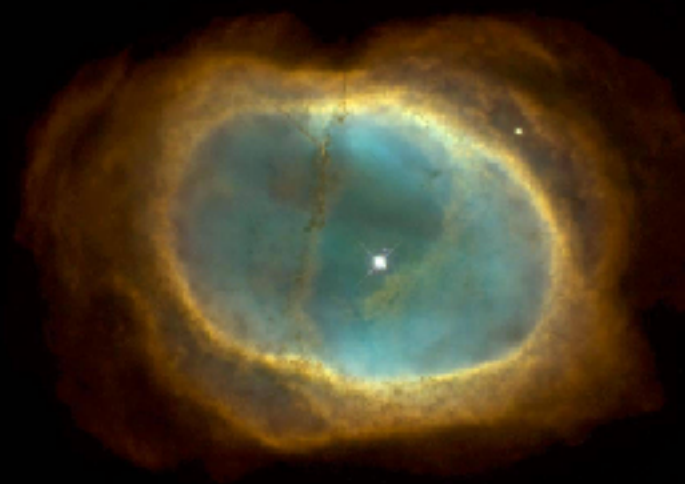
  - dusty/radiatively-driven winds
  - abundance variations in stars
  - dust formation/growth & obscuration
  - anomalous large grains in solar neighborhood

Consequences
THIS IS EVERYWHERE



- Cool-star/AGB winds, SNe ejecta

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

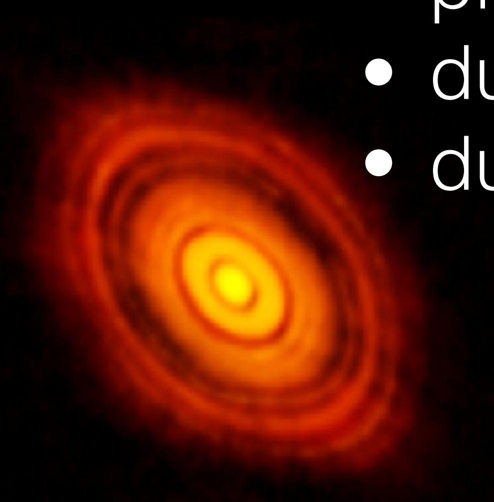


  - dust shells/arcs/streamers (e.g. Deguchi '97)
  - clumpiness in outflow
  - wind-launching, outflow rates
  - large grains in SNe ejecta (e.g. 1987a, 2010jl)

- Proto-planetary disks

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

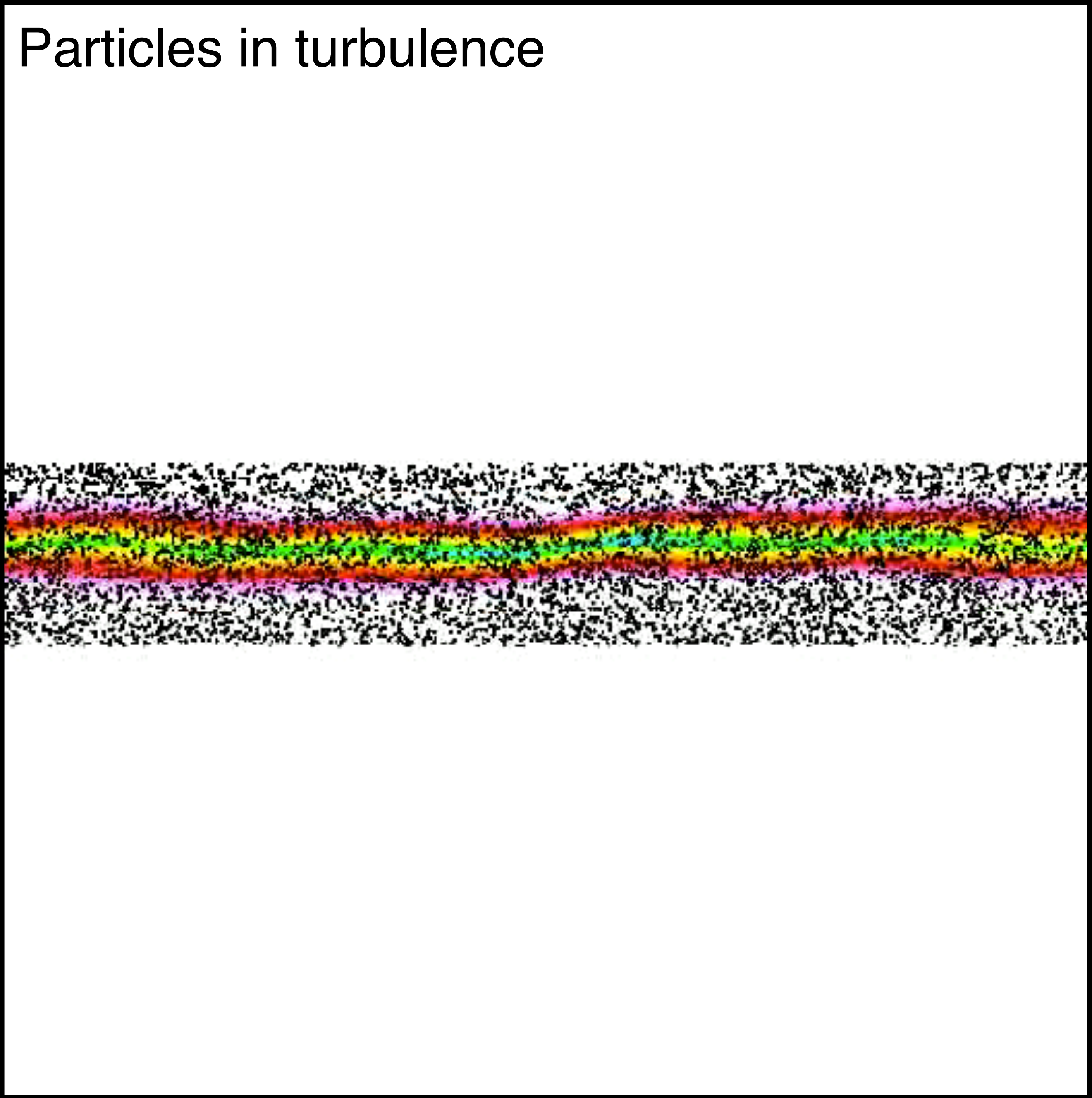
  - planetesimals (overdensity->GI)
  - dust traps/asymmetries
  - dust growth/sticking (small-k, MHD modes)

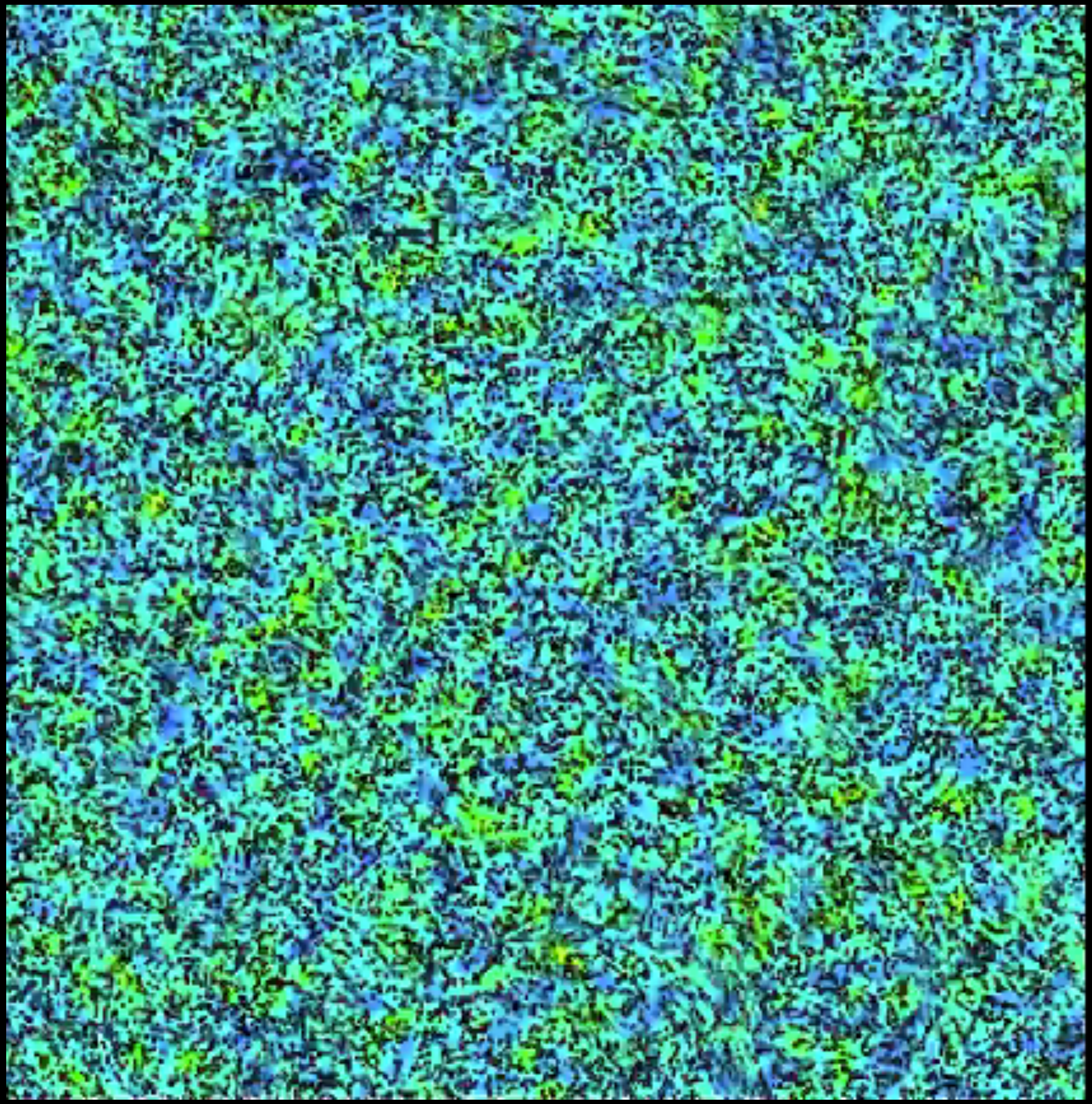


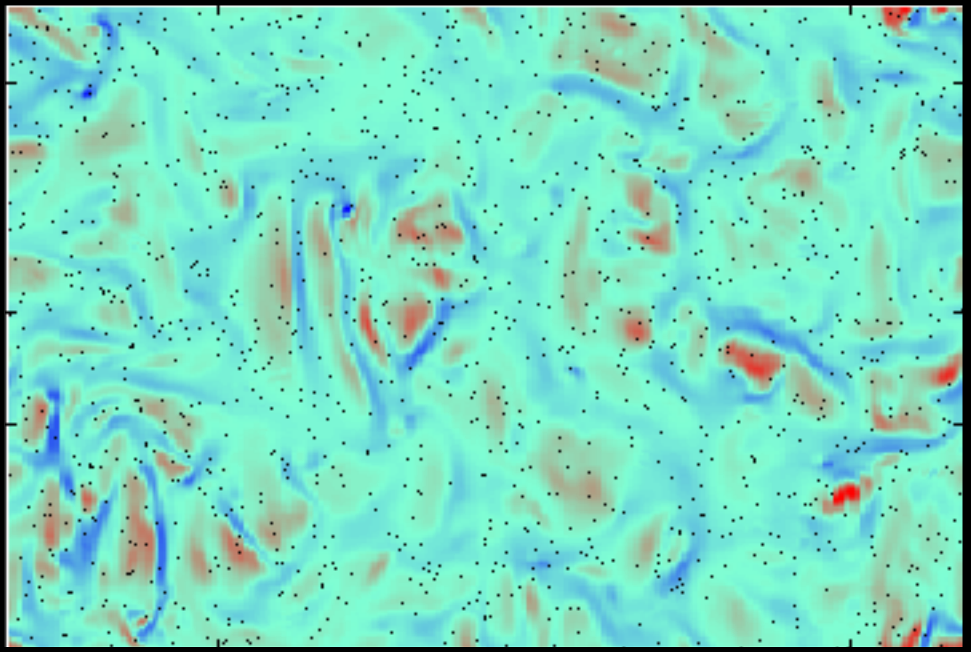
Example: Effects in GMCs/Starburst Disks

Dust In Turbulence: Even Without RDI

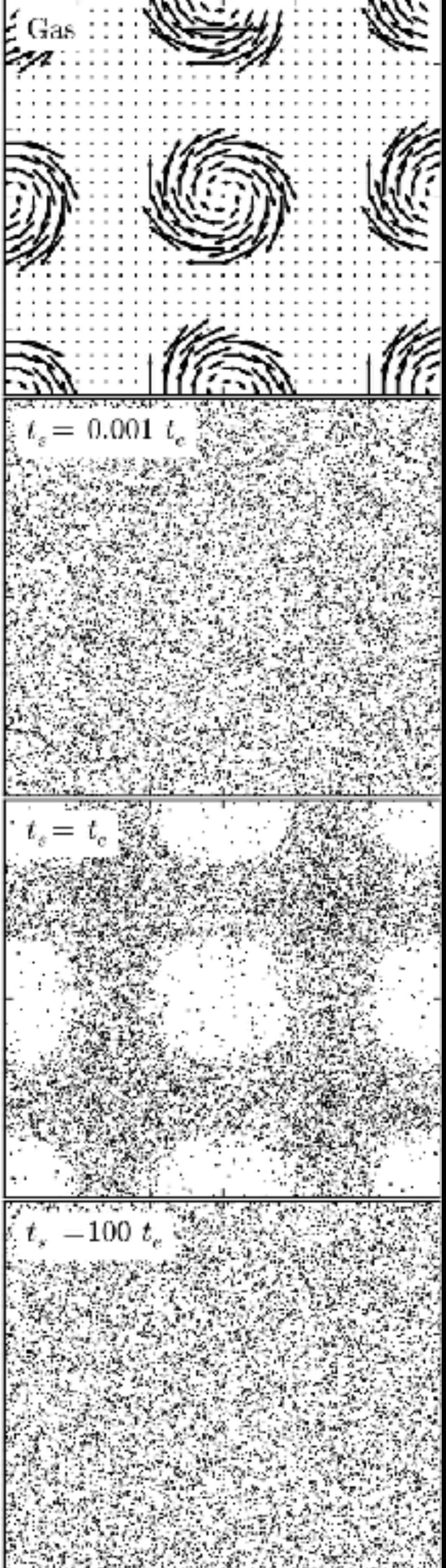
EXPERIMENT & SIMULATION







e.g. Squires & Eaton 1991



The Physics:

PFH, arXiv:1307.7147

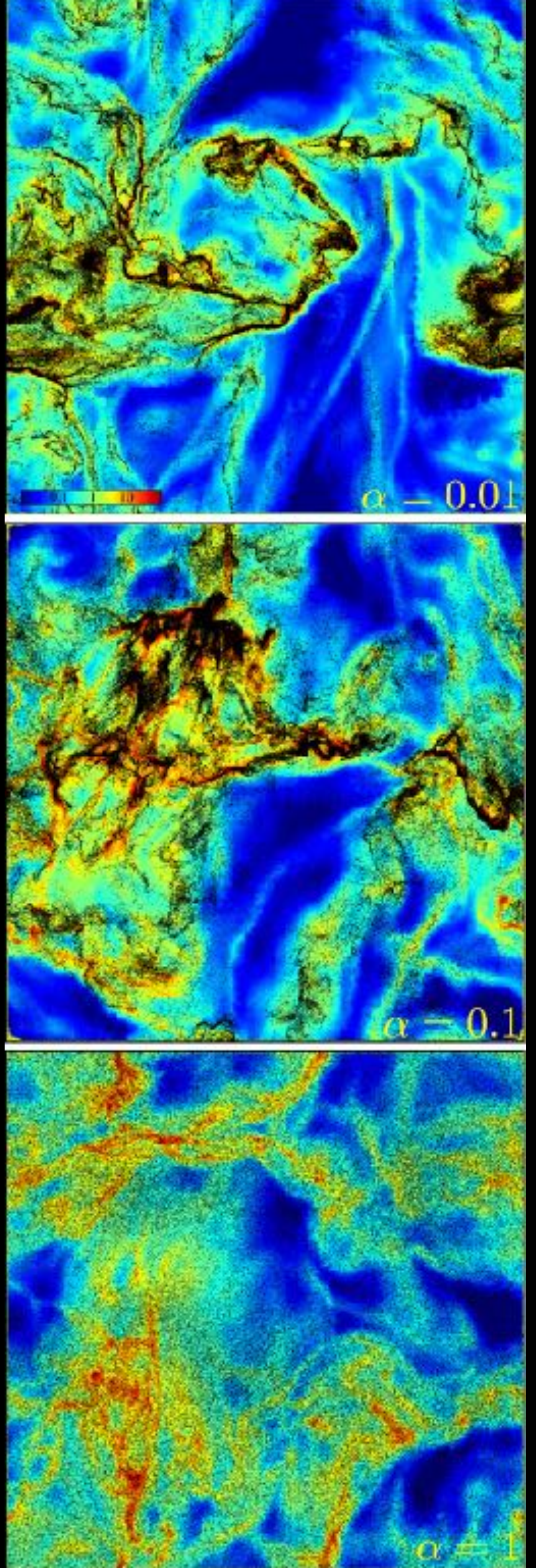
$$\frac{d\mathbf{v}_{\rm grain}}{dt} = -\frac{(\mathbf{v}_{\rm grain} - \mathbf{v}_{\rm gas})}{t_{\rm stop}}$$

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

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

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

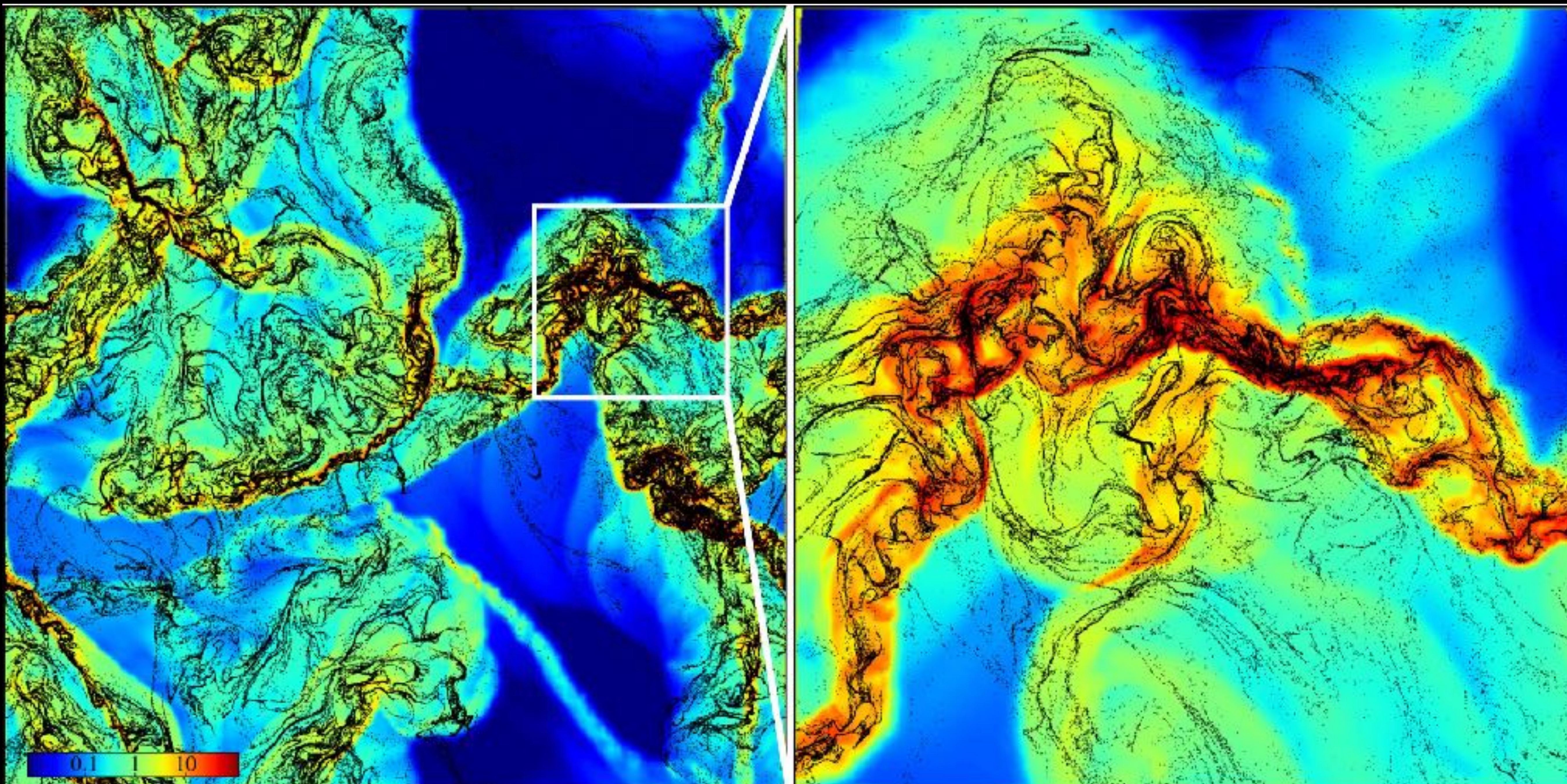
(see Barge & Sommeria '95, Bracco '99, Cuzzi '01, Johansen & Youdin '07, Carballido '08, Lyra '08, Bai & Stone '10, Pan '11, Zhu '14 and others)



Dust In GMCs & Star-forming Disks:

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

Hyunseok Lee
& Jono Squire

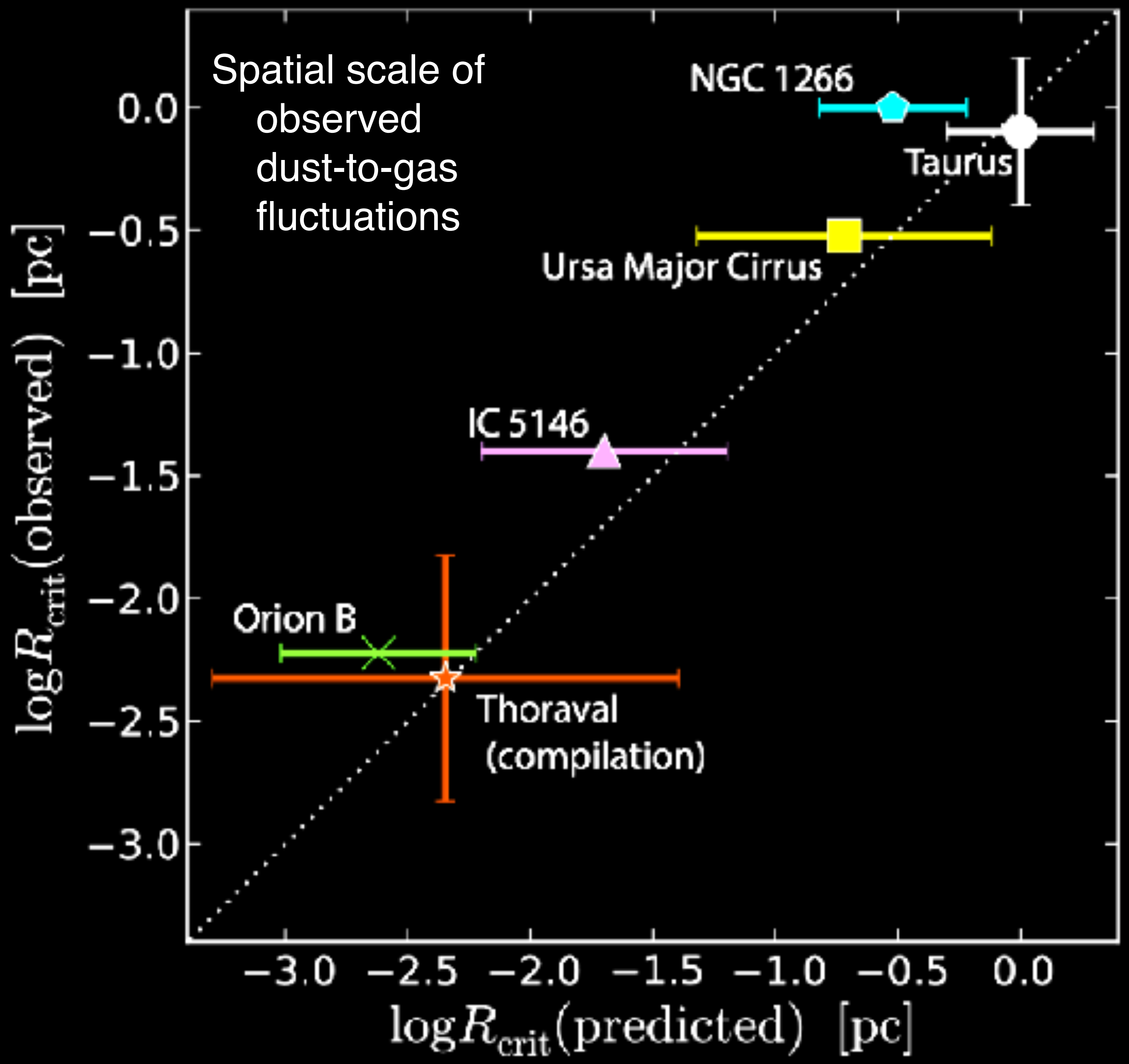


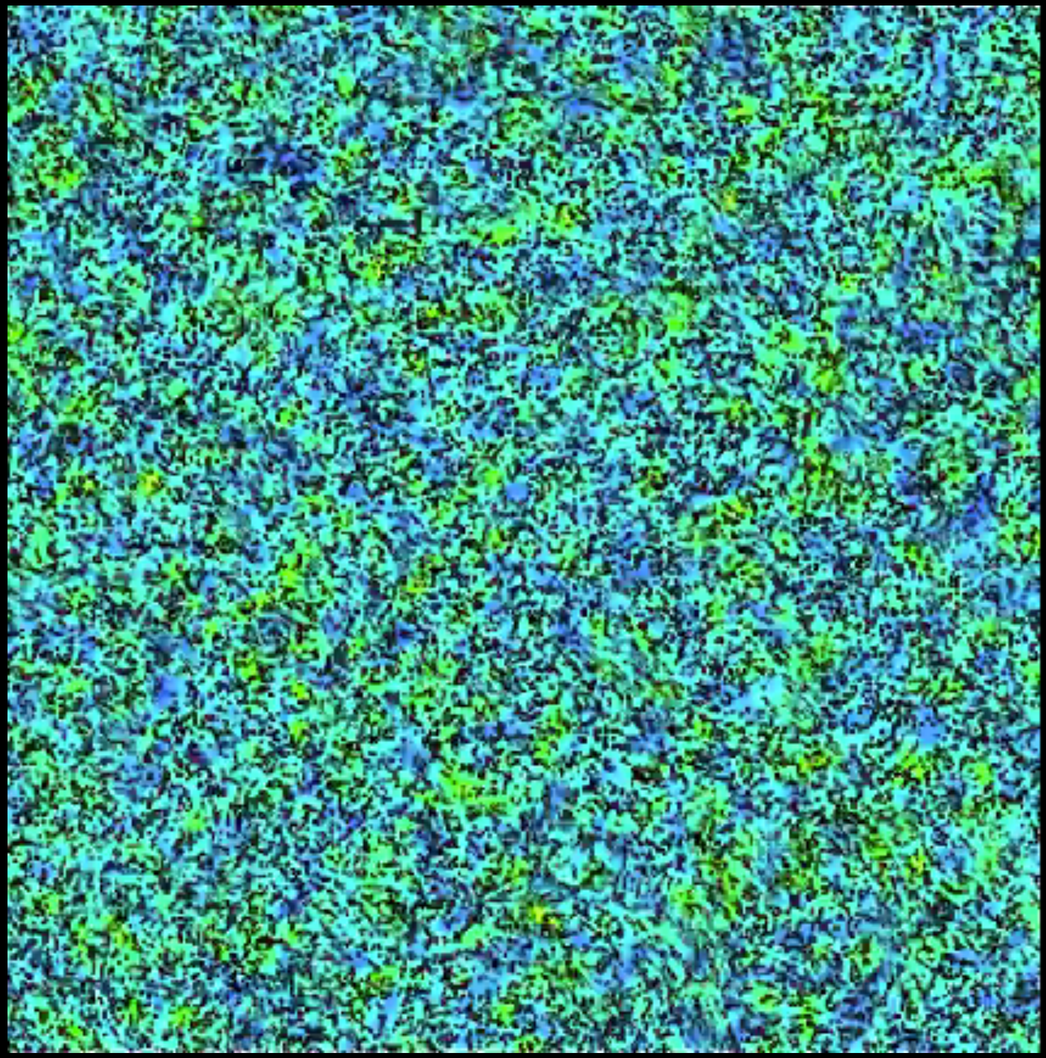
Put dust in a GMC & stir:

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

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)

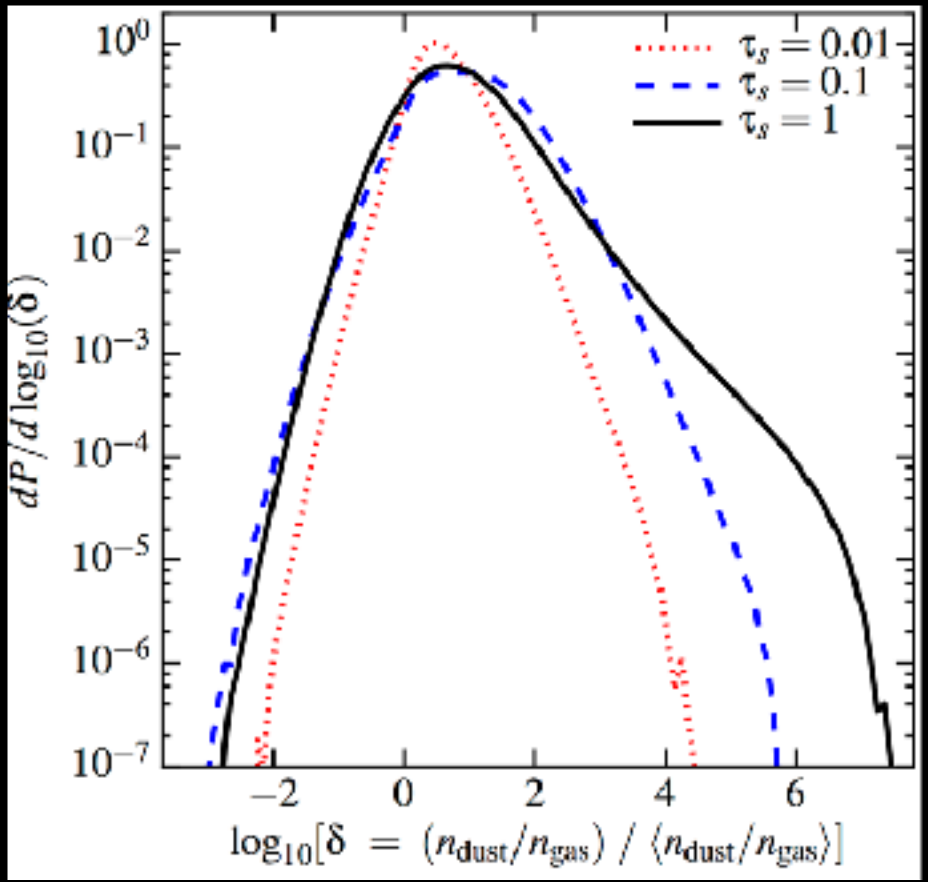
Dust-Assisted GI: One Example

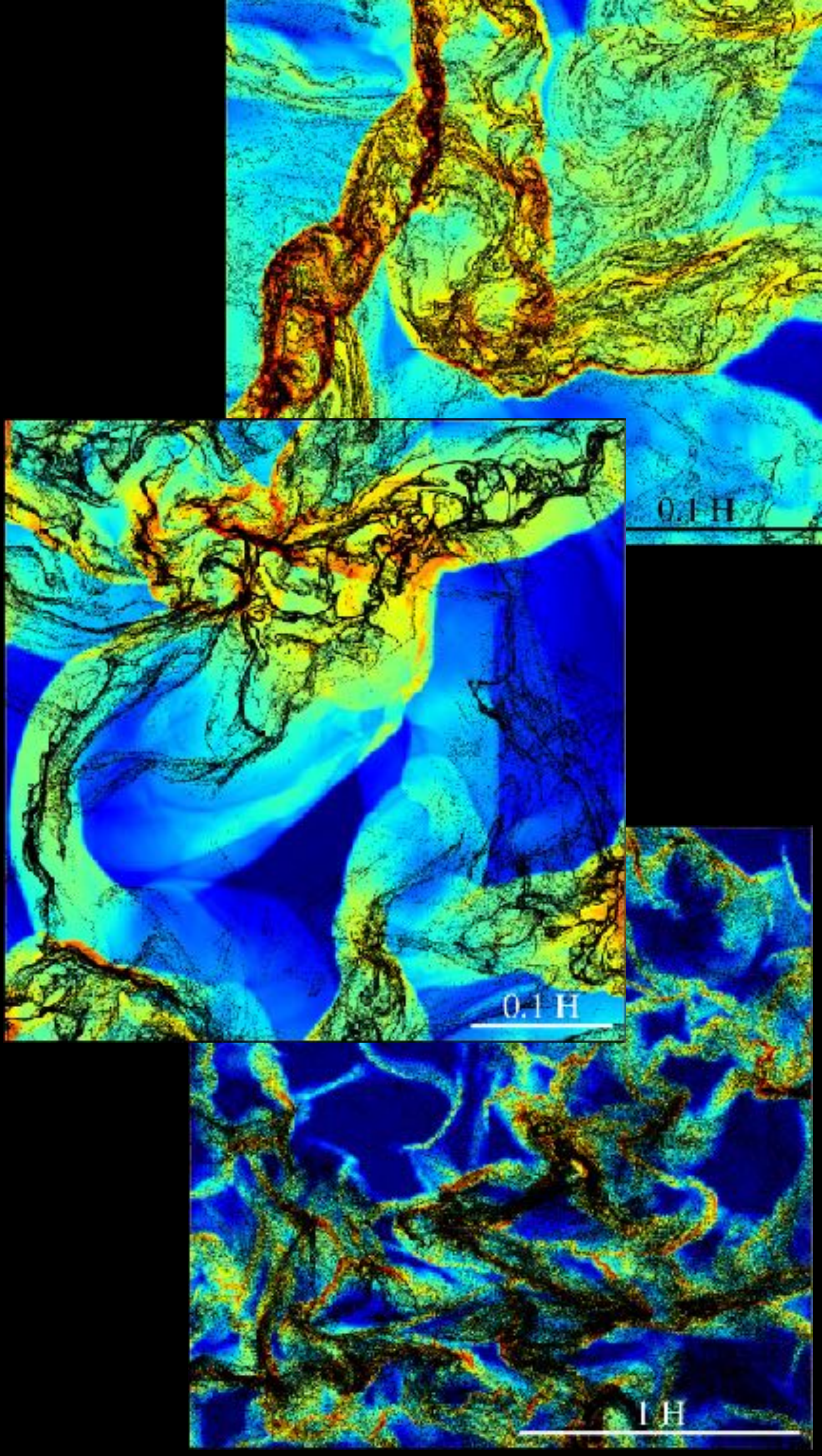
What about High Redshifts?

PFH & Conroy, arXiv:1512.03834

- High-redshift proto-galaxy: neutral disk, modestly turbulent (Mach~1), low-metallicity ([Z/H] << -3)

Dust fluctuations enhanced!



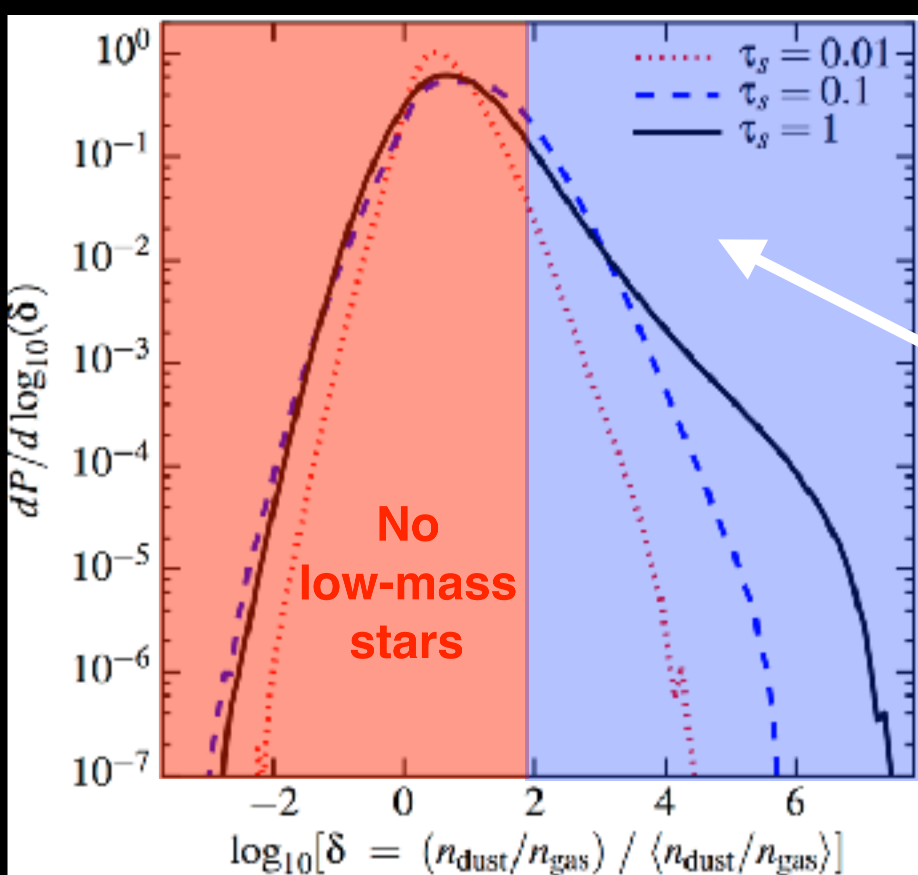


What about High Redshifts?

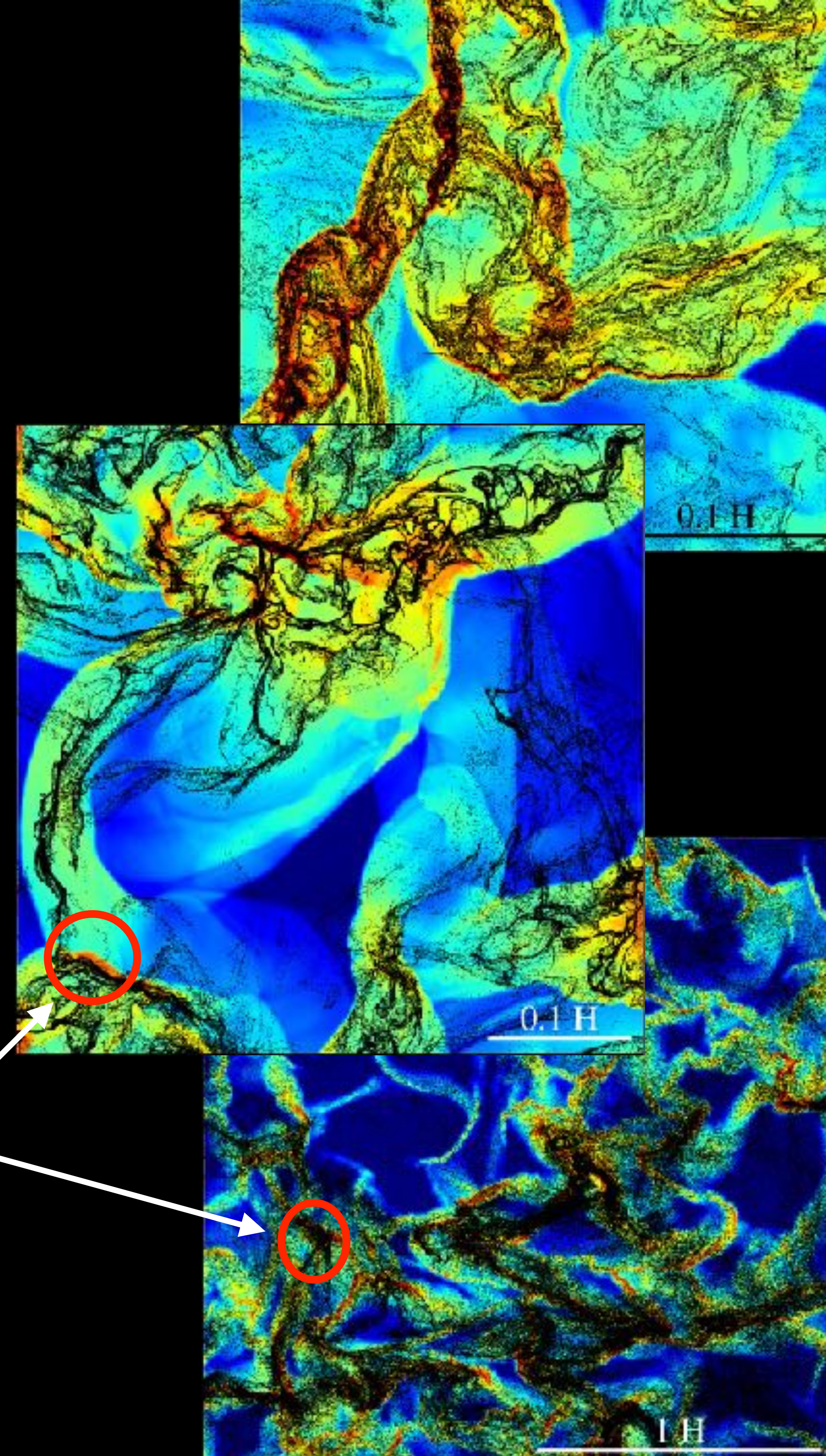
PFH & Conroy, arXiv:1512.03834

- High-redshift proto-galaxy: neutral disk, modestly turbulent (Mach~1), low-metallicity ([Z/H] << -3)

- Need critical [Z_{dust}/ H] to fragment & form low-mass stars
  (Klessen '12, Nozawa '12, Chiaki '14, Ji '14)

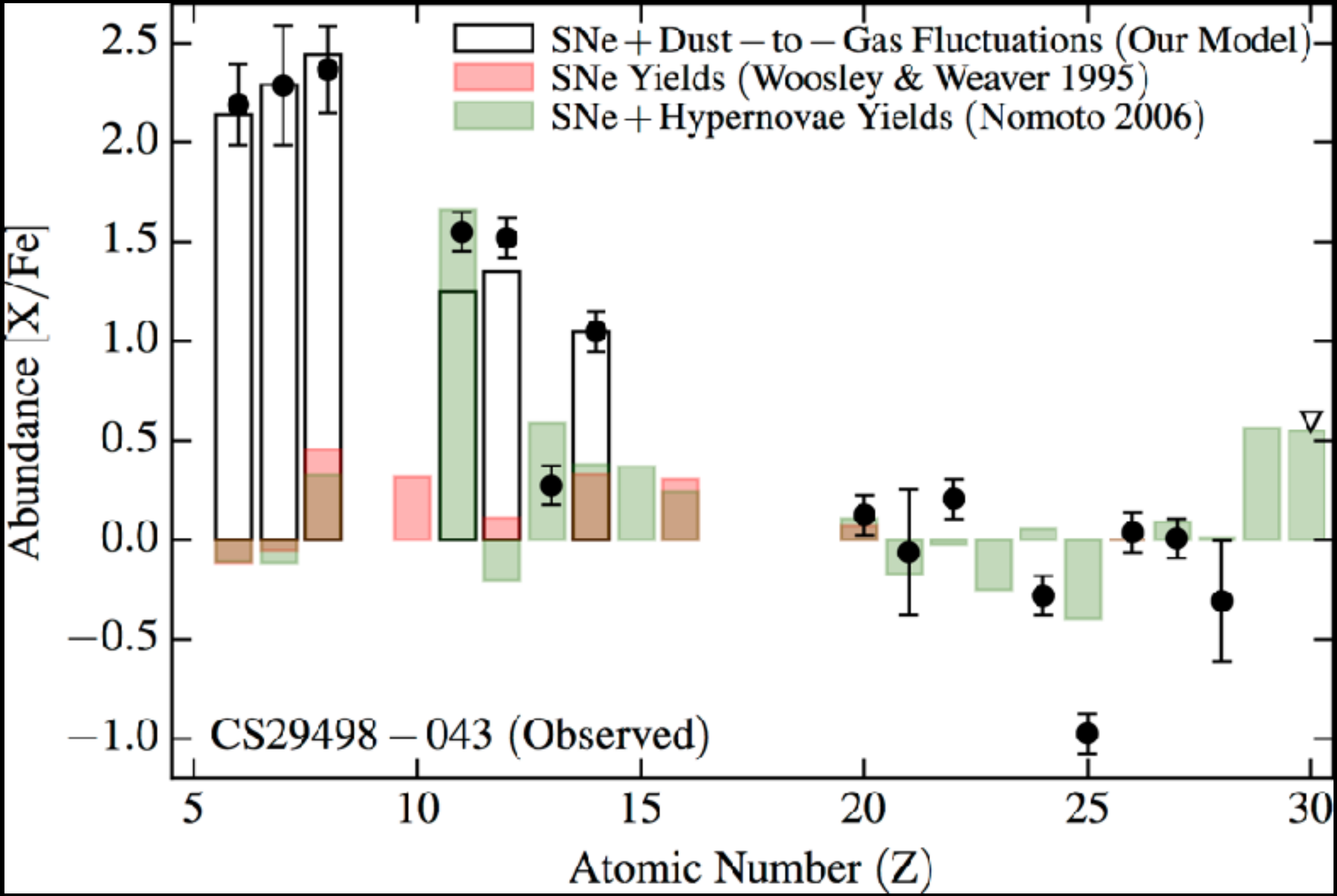


low-mass stars ([Z/H] > critical)



What Would a "Dust Enhanced" Star Look Like?

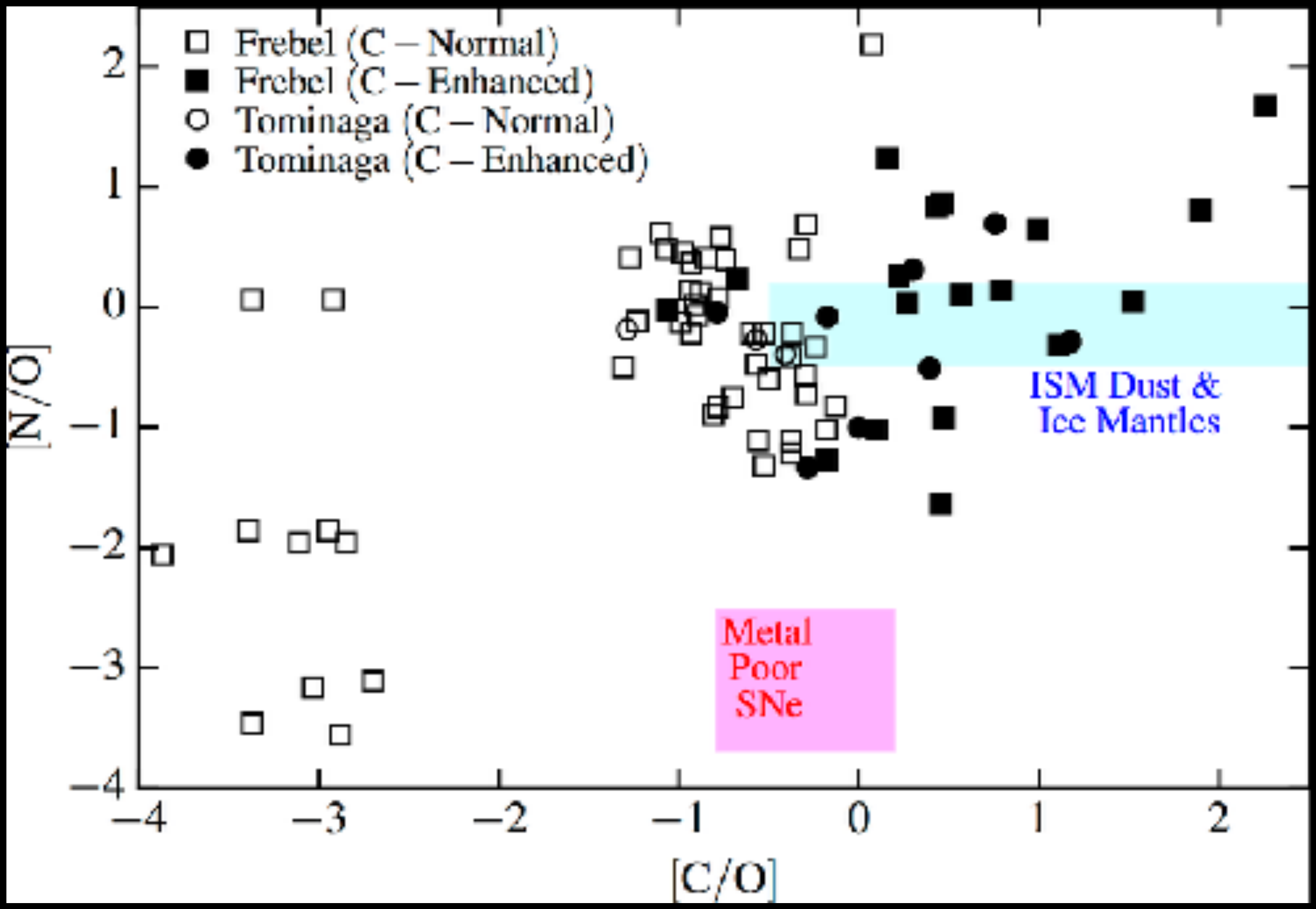
FROM A METAL-POOR PROGENITOR



PFH & Conroy (arXiv:1512.03834)

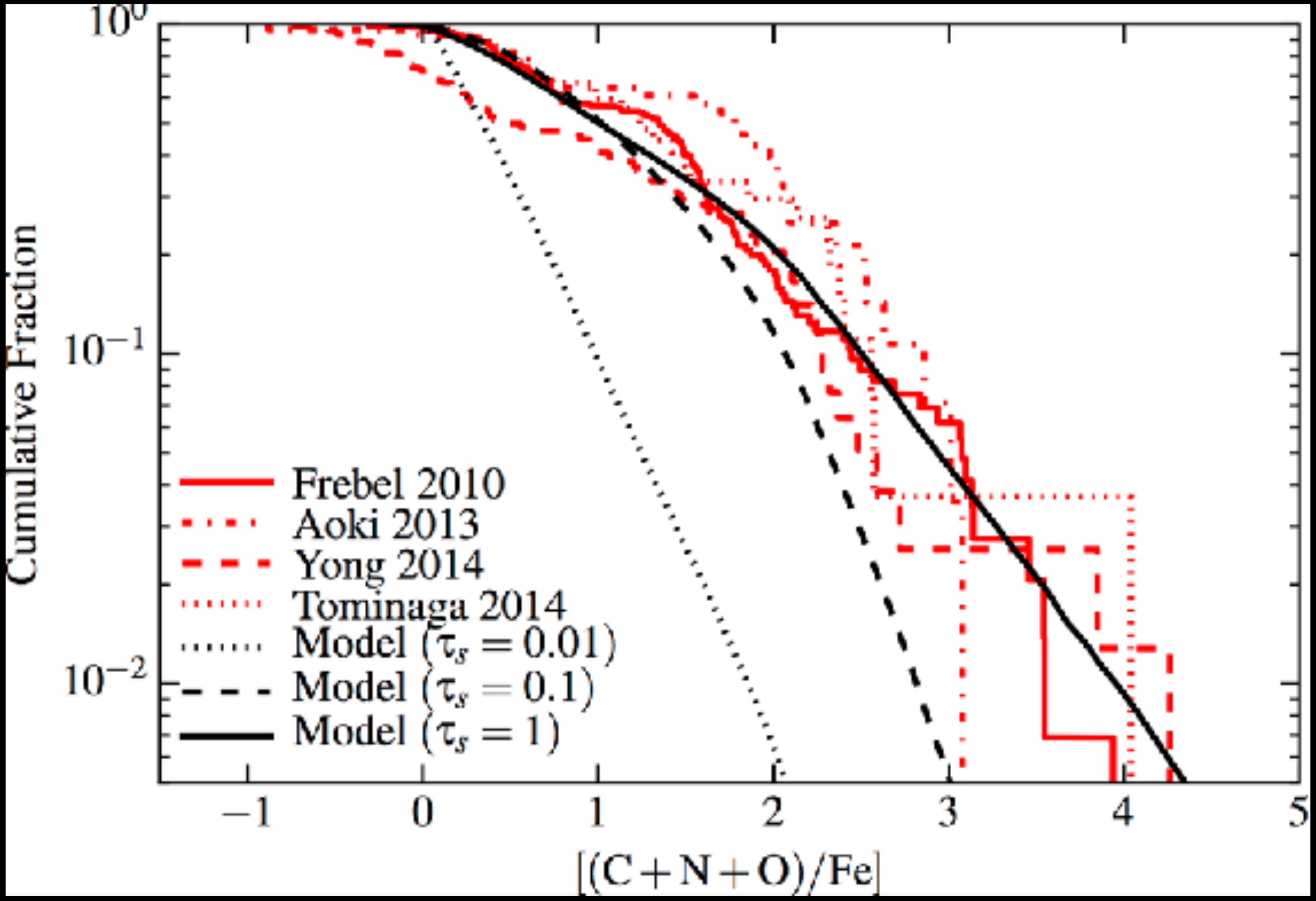
Can Dust Explain CNO Enhancements?

(CEMP-no, [FE/H]<-3)



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

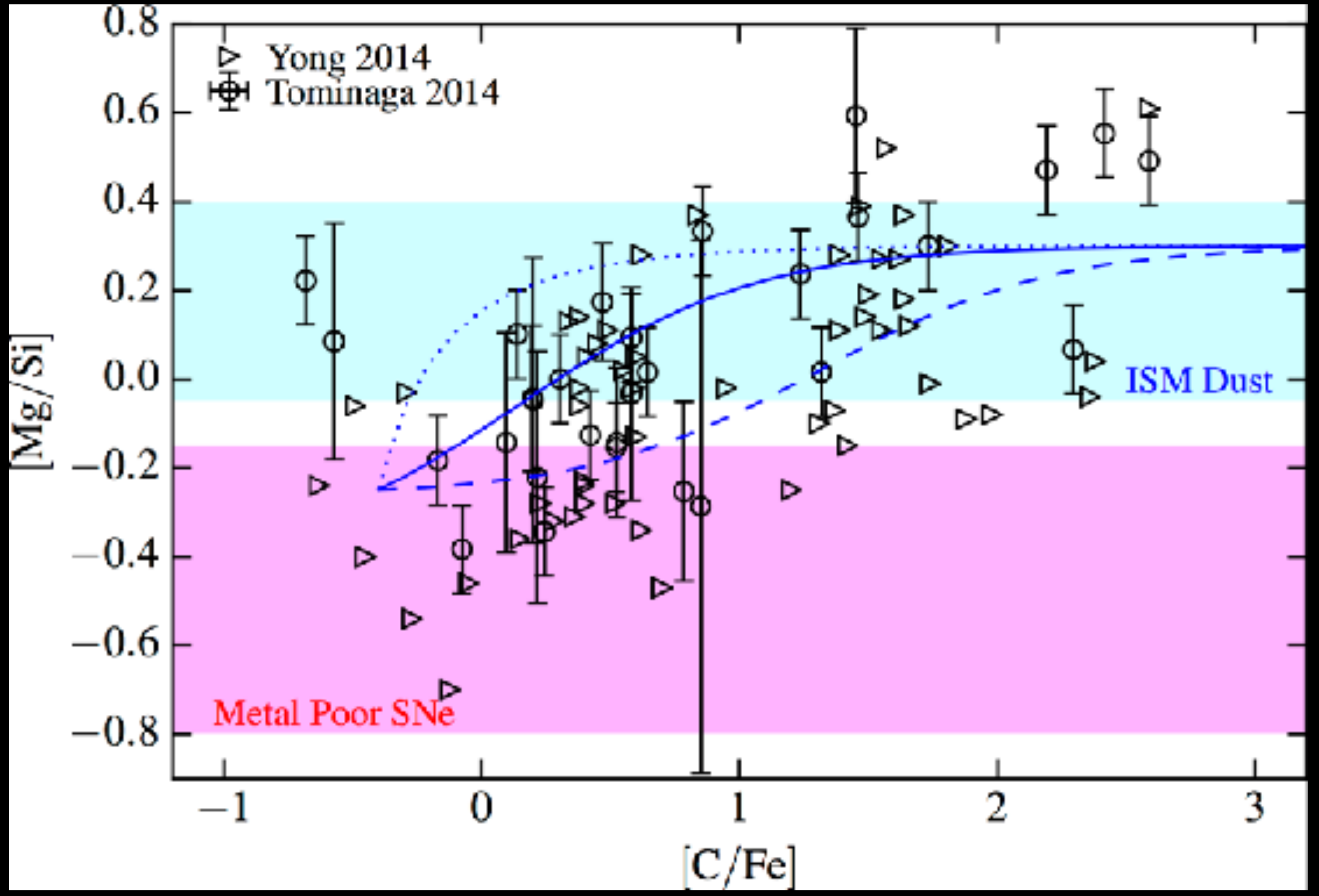
Distribution of C-Enhancement:
Remarkably similar to dust enhancement



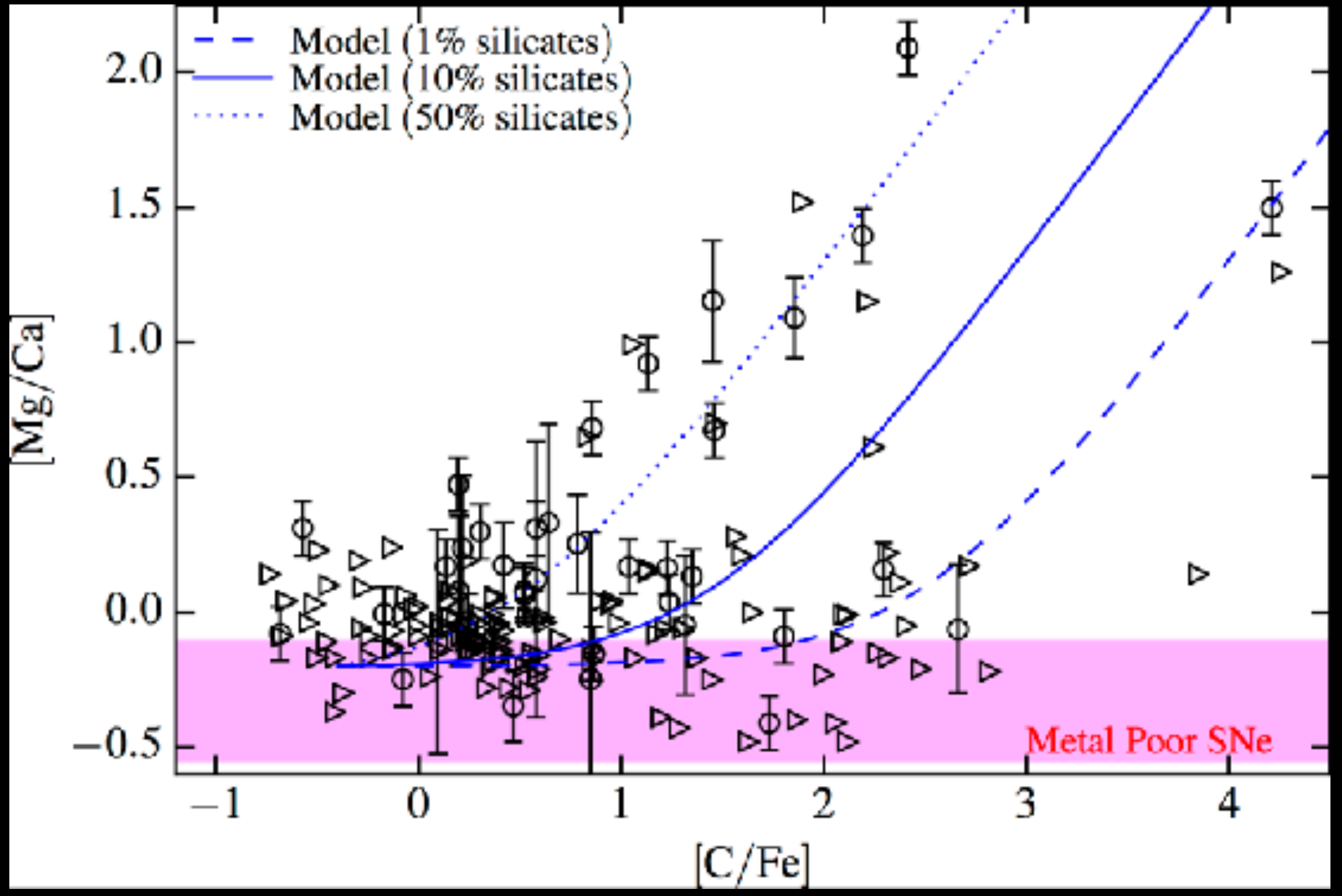
PFH & Conroy (arXiv:1512.03834)

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

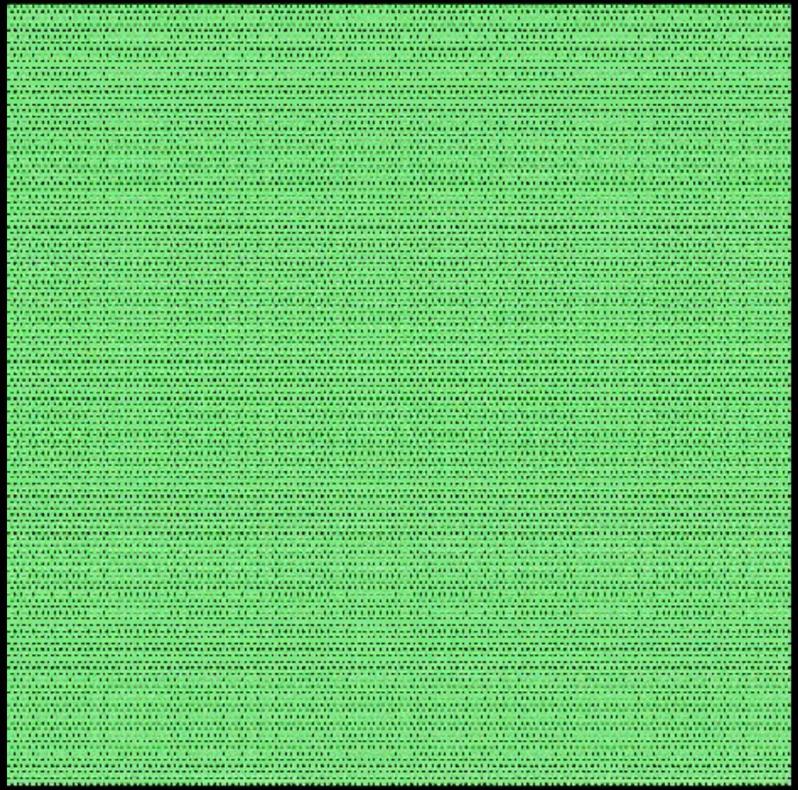
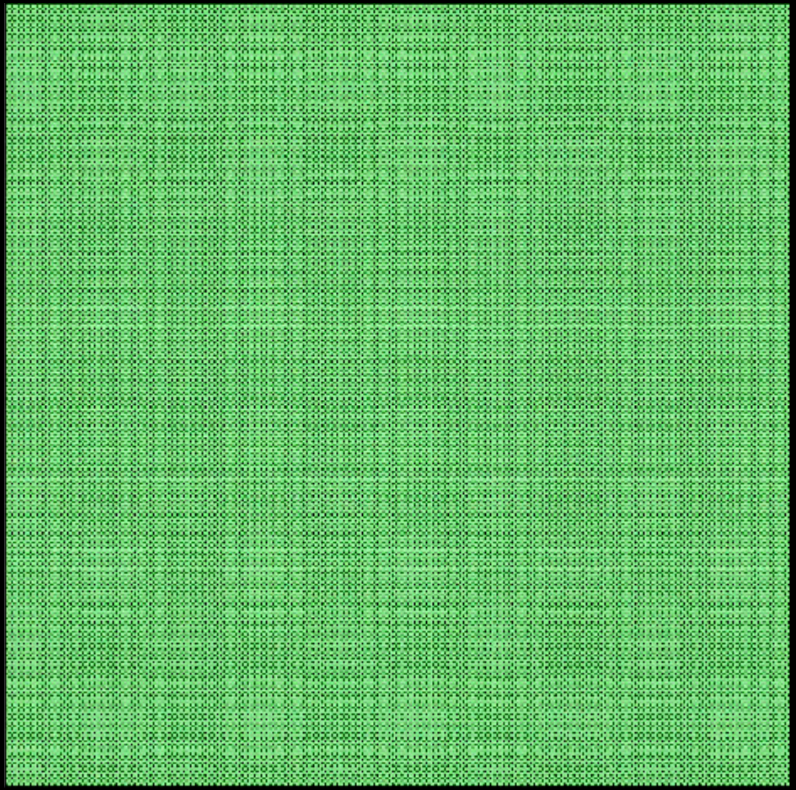
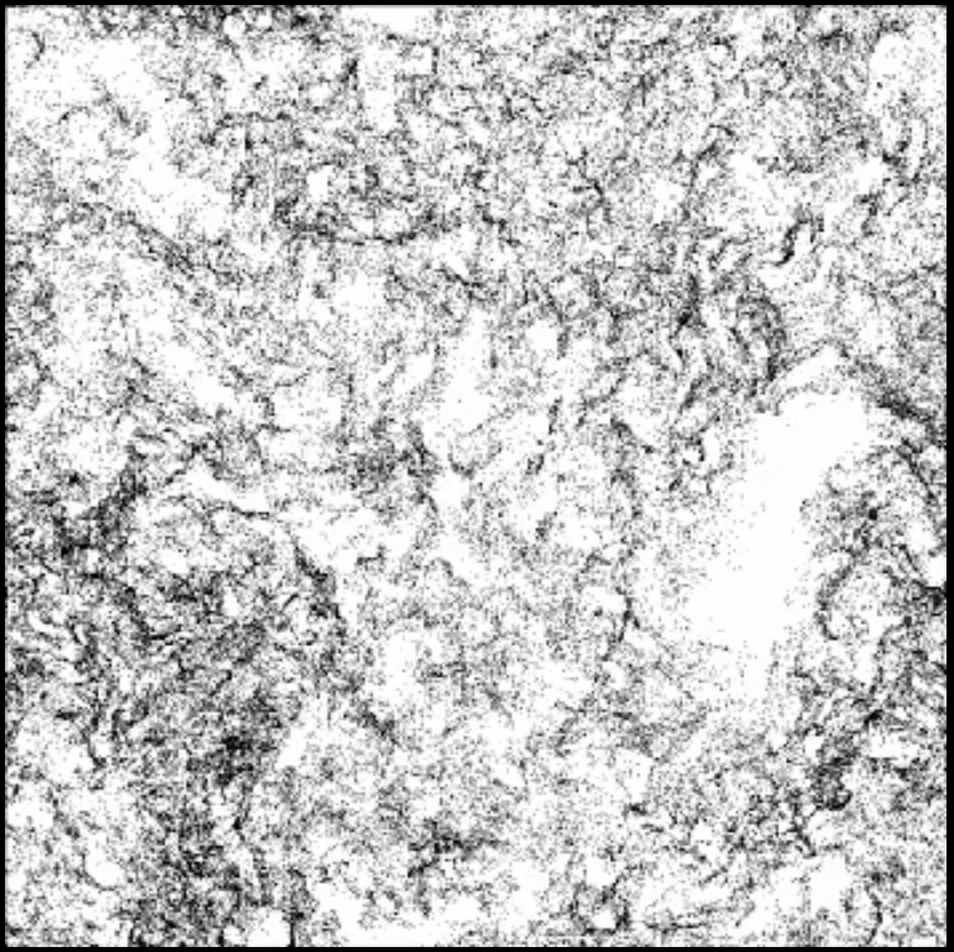
[Mg/Si]: From the same grains
Look more like dust as [C/Fe] increases



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



PFH & Conroy (arXiv:1512.03834)

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]?