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

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arXiv: 1706.05020 (SH), 1707.02997 (HS)

+ Eric Moseley & Stefania Moroianu (in prep)

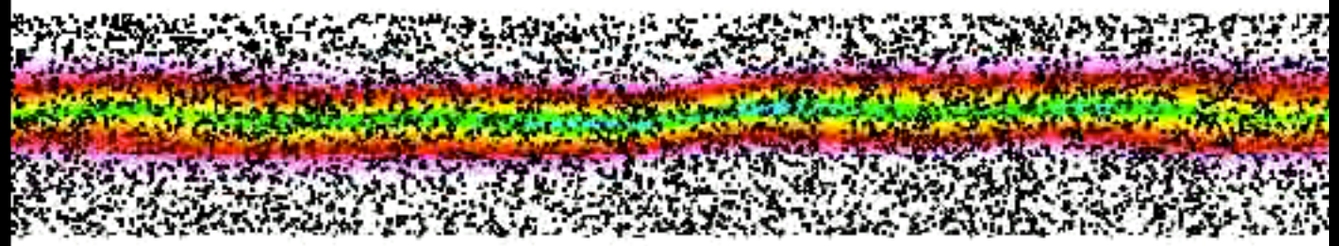
Why Worry About Dust?

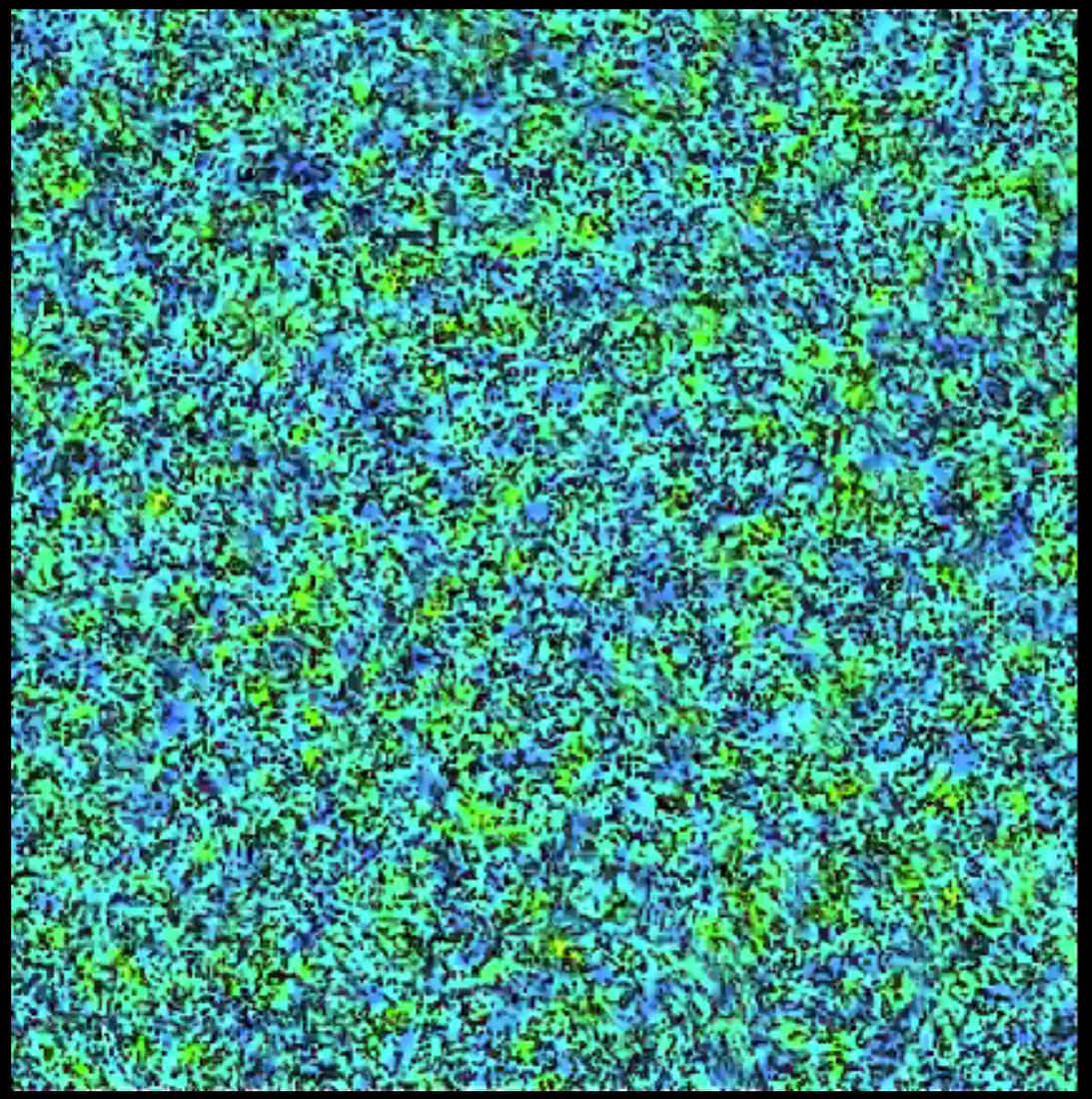
- Dust:
  - Critical for: cooling, planet formation, starburst/AGN/cool star winds, extinction/reddening, polarization (BICEP)
  - Not enough metals (Draine+; Jenkins+; worse today!)
  - Too many big grains (Ulysses,Cassini, Helios, Arecibo; Kruger ’06, Draine ’09, Poppe ’10)
  - Forms too early (Perley ’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)

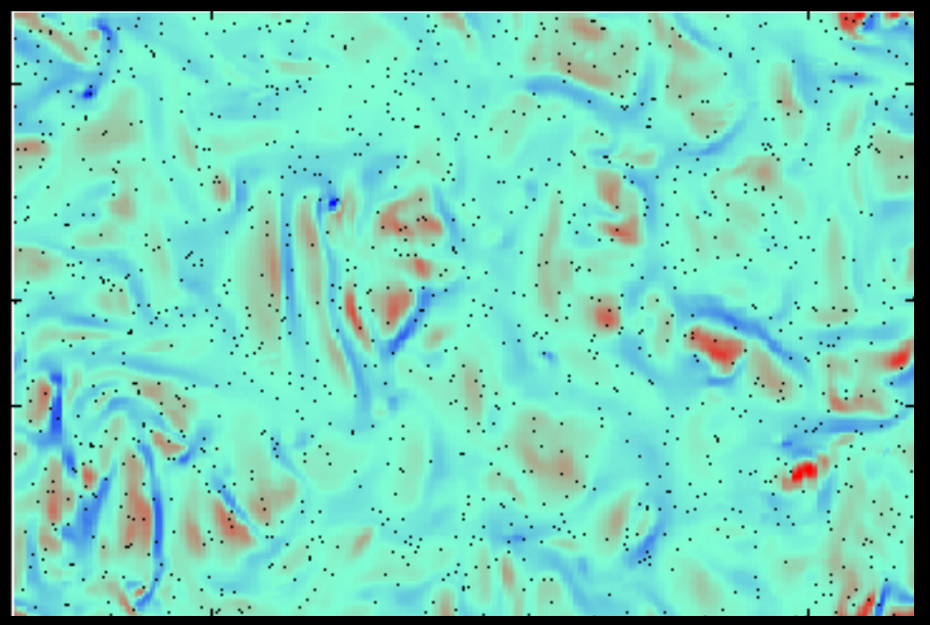
Dust Is Not Gas

EXPERIMENT & EVERYDAY EXPERIENCE

Dust in turbulence







e.g. Squires & Eaton 1991

The Setup:

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

Gas equations = (anything that supports a linear mode)

Dust equations = continuity + momentum:

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

Arbitrary operator

e.g.

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

Stopping/drag time

The Setup:

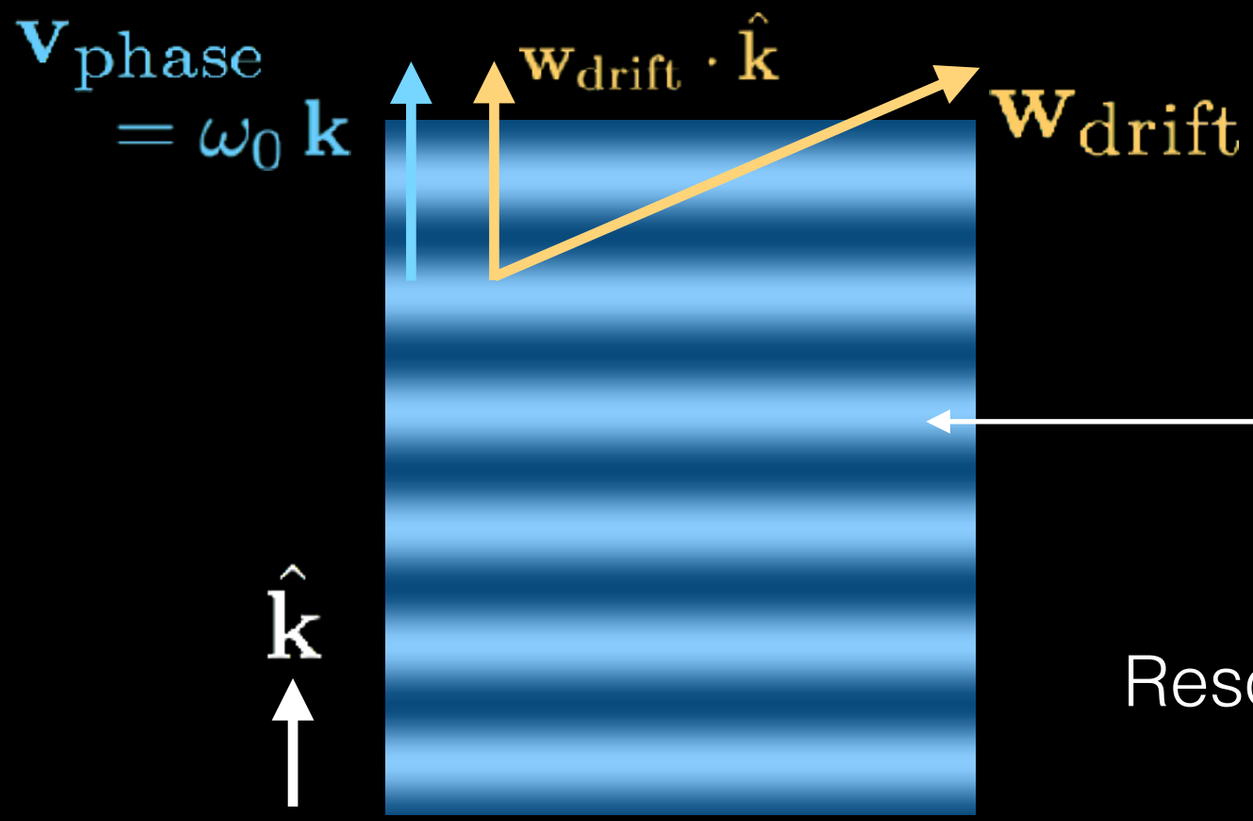
SQUIRE & HOPKINS '17 (SH; arXiv:1706.05020)

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

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

"natural" gas response

wavevector

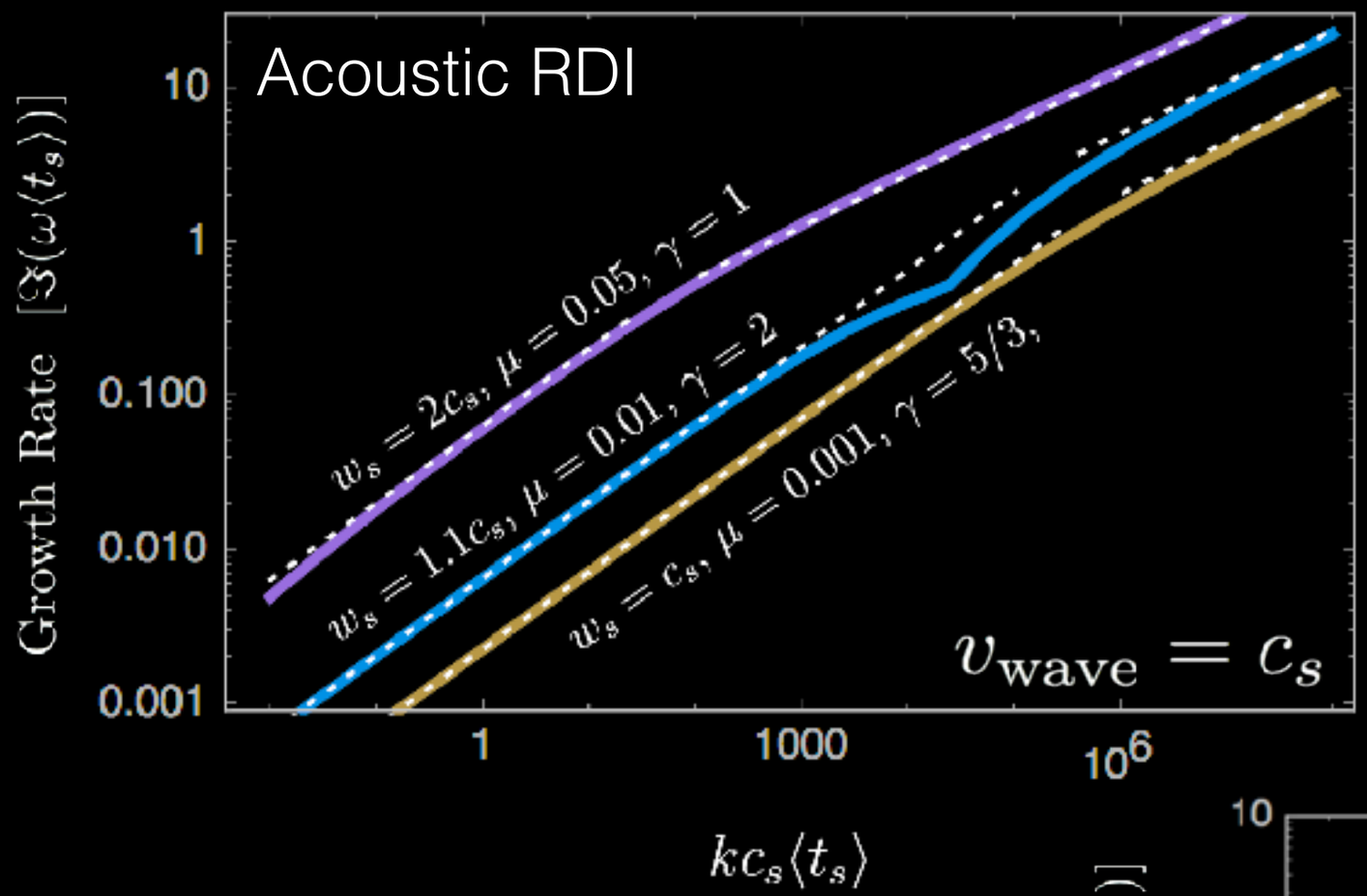


Dust hits gas density peak, slows down, piles up

Resonance: Dust sees standing wave, effects add coherently

Acoustic & Magnetosonic RDI

RESONANCE WITH FIXED PHASE SPEED (SH '17)



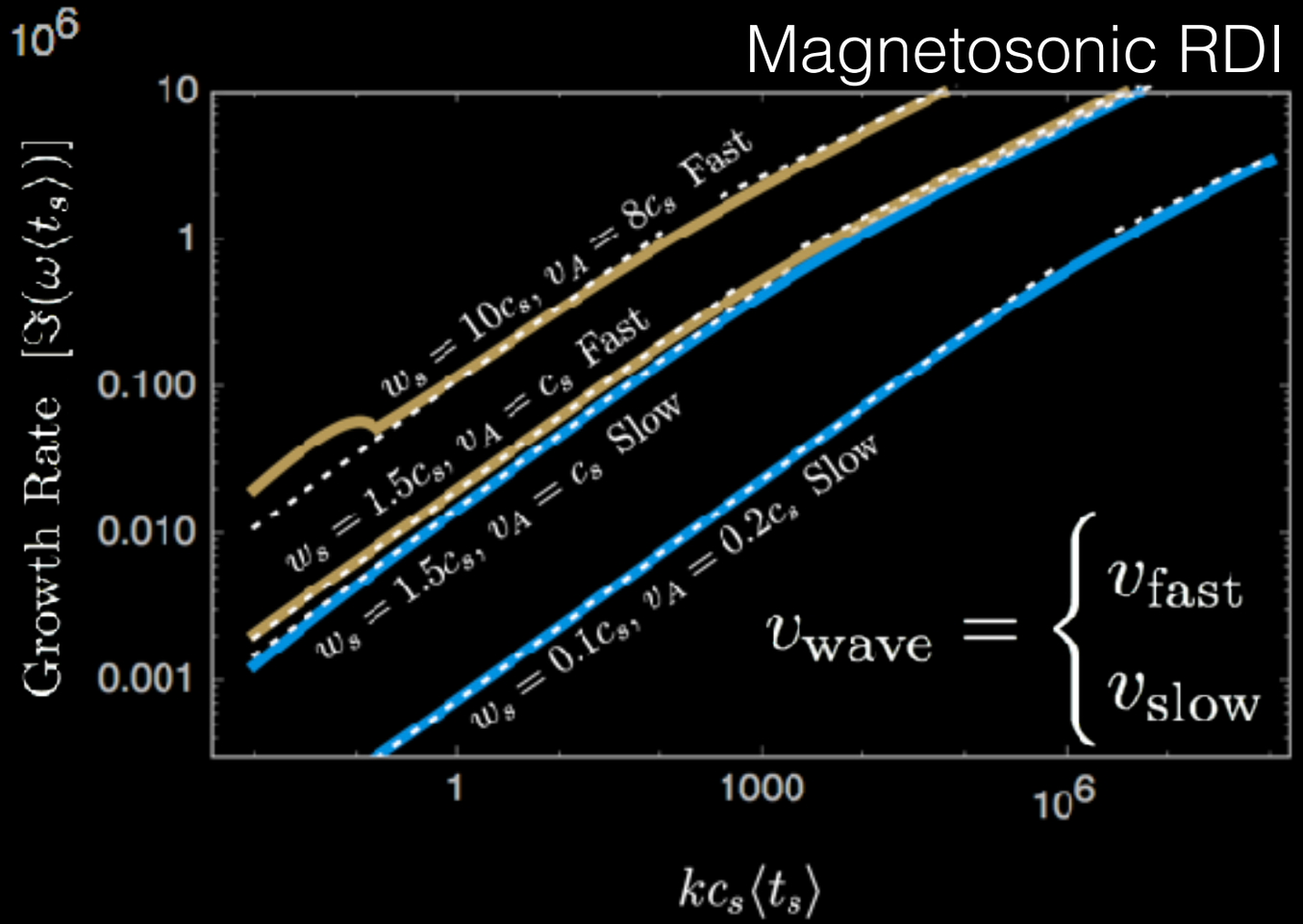
$$\mathbf{w}_{\rm drift} \cdot \mathbf{k} = \omega_0$$

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

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

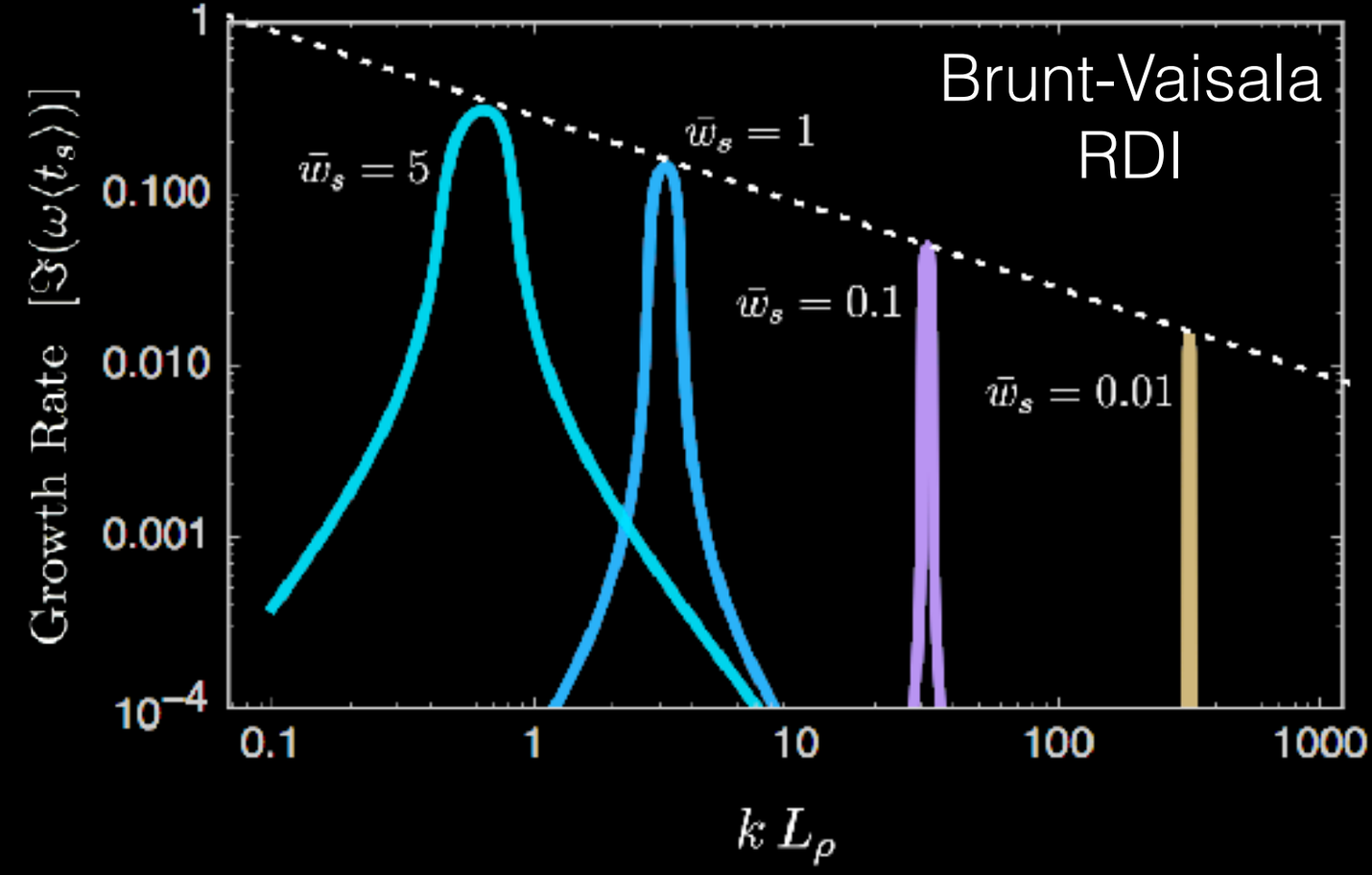
Resonance ***always*** exists

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



Brunt-Vaisala & Streaming RDI

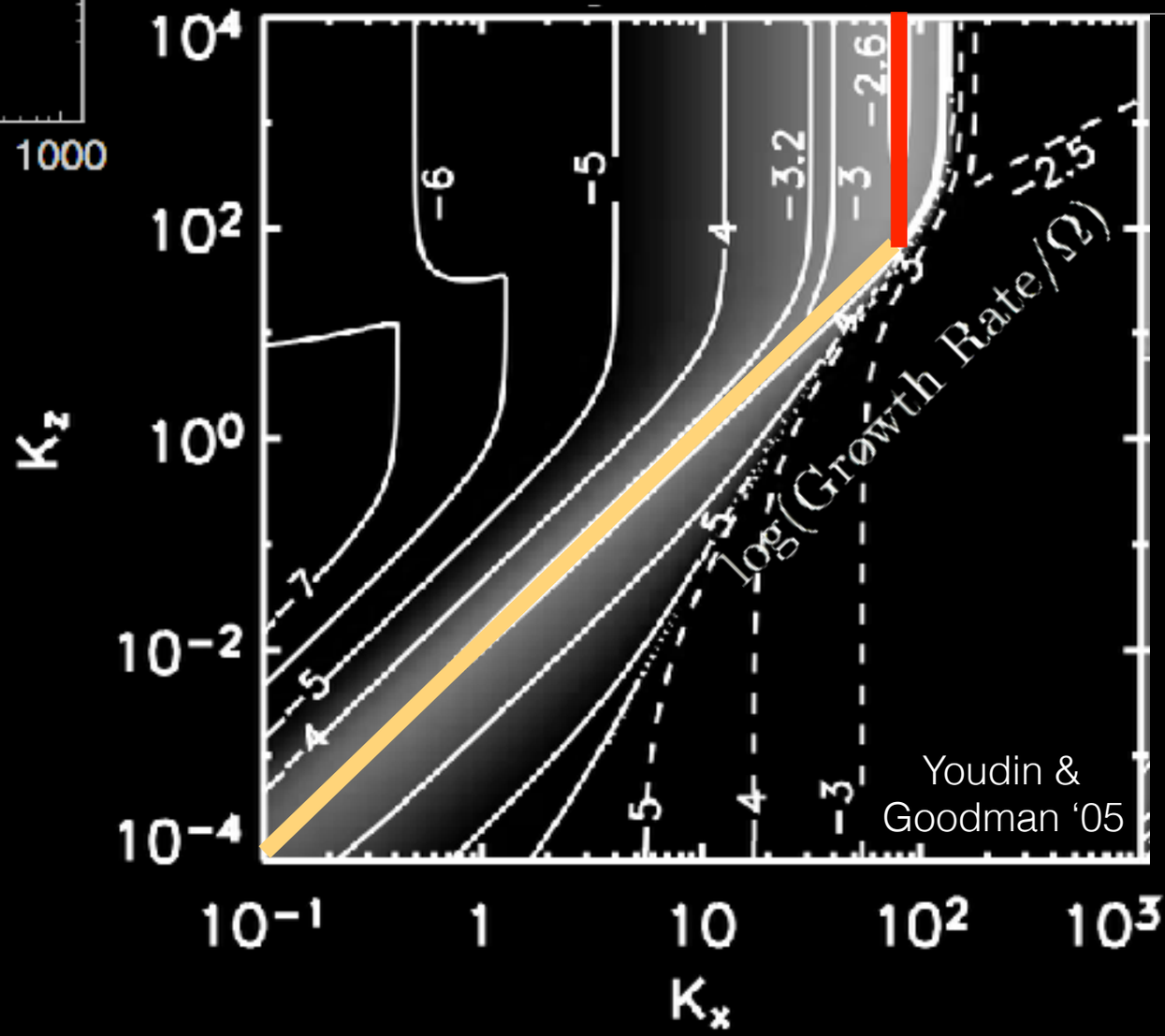
RESONANCE WITH FIXED-FREQUENCY (SH '17)



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

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

Streaming RDI



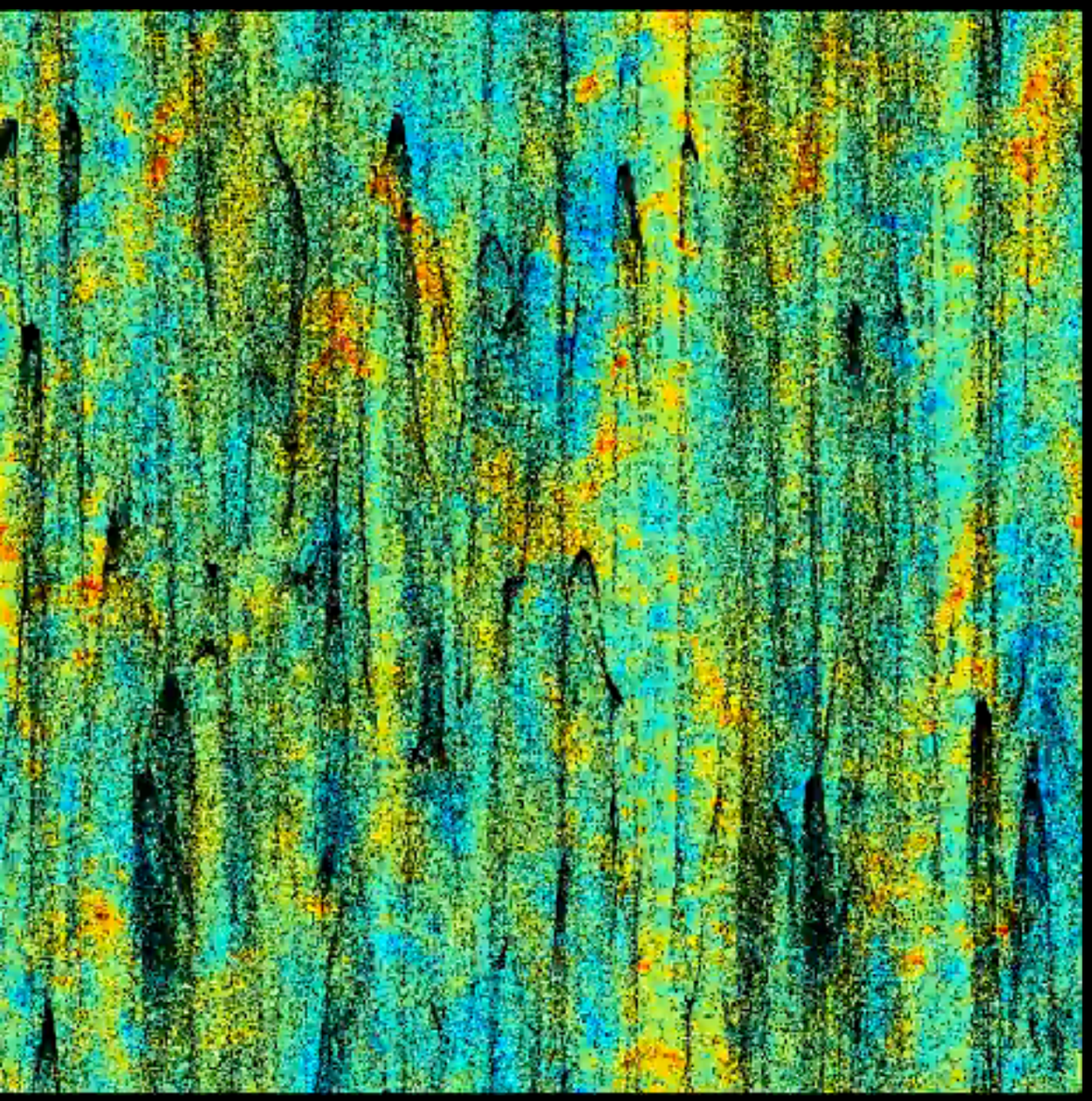
Simulations:
Non-linear Behavior

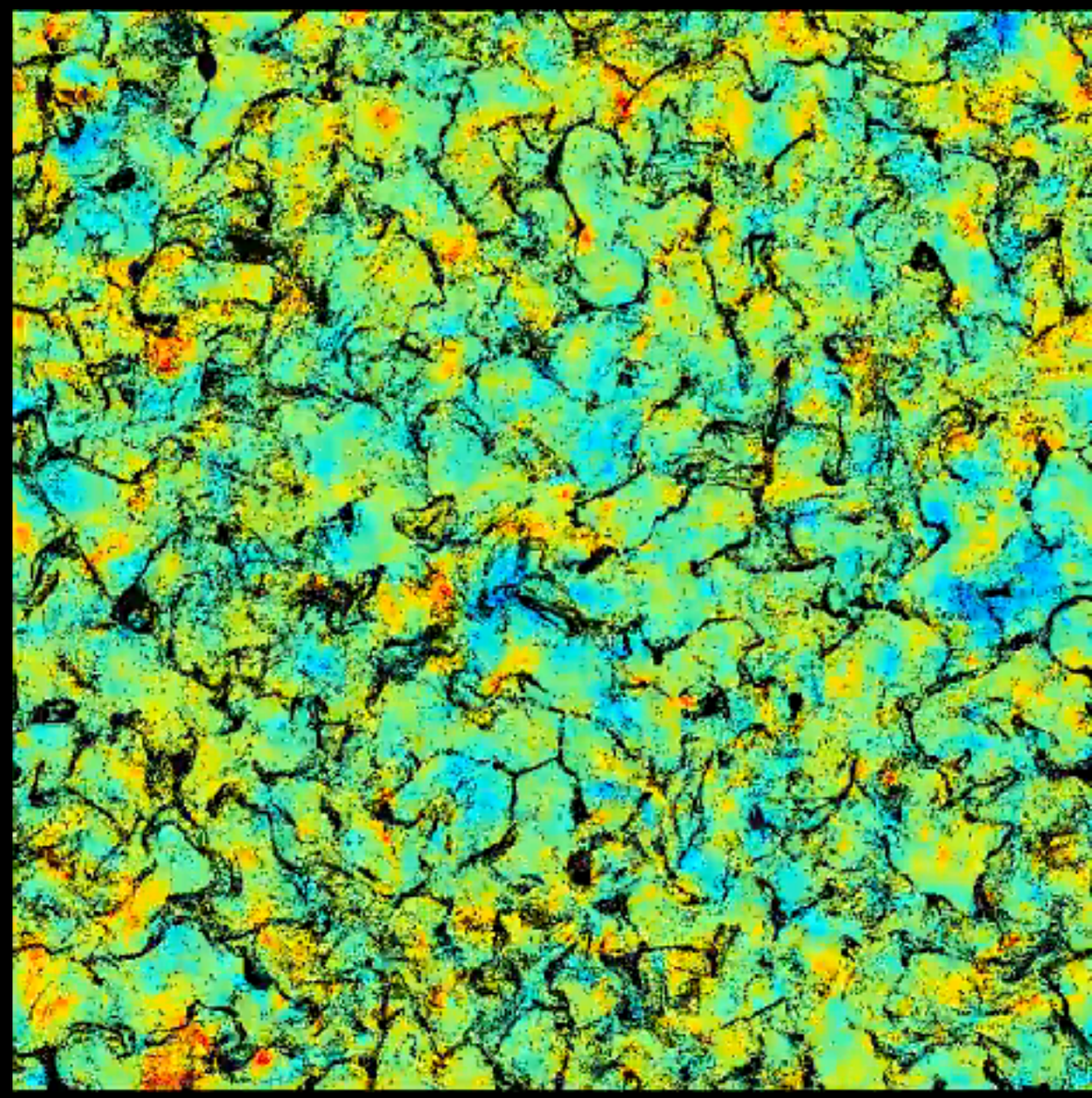
Acoustic RDI: Non-Linear Behavior

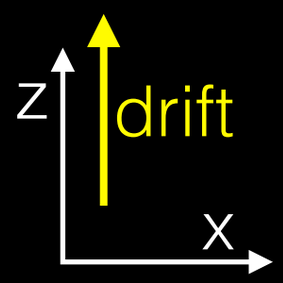
EARLY DEVELOPMENT (Squire, Moseley+ in prep.)

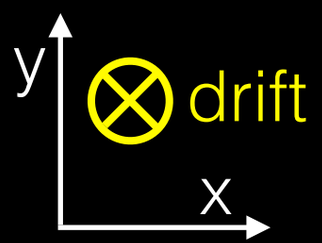
$|\mathbf{w}|_{\rm drift} \approx 10\, c_s$

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







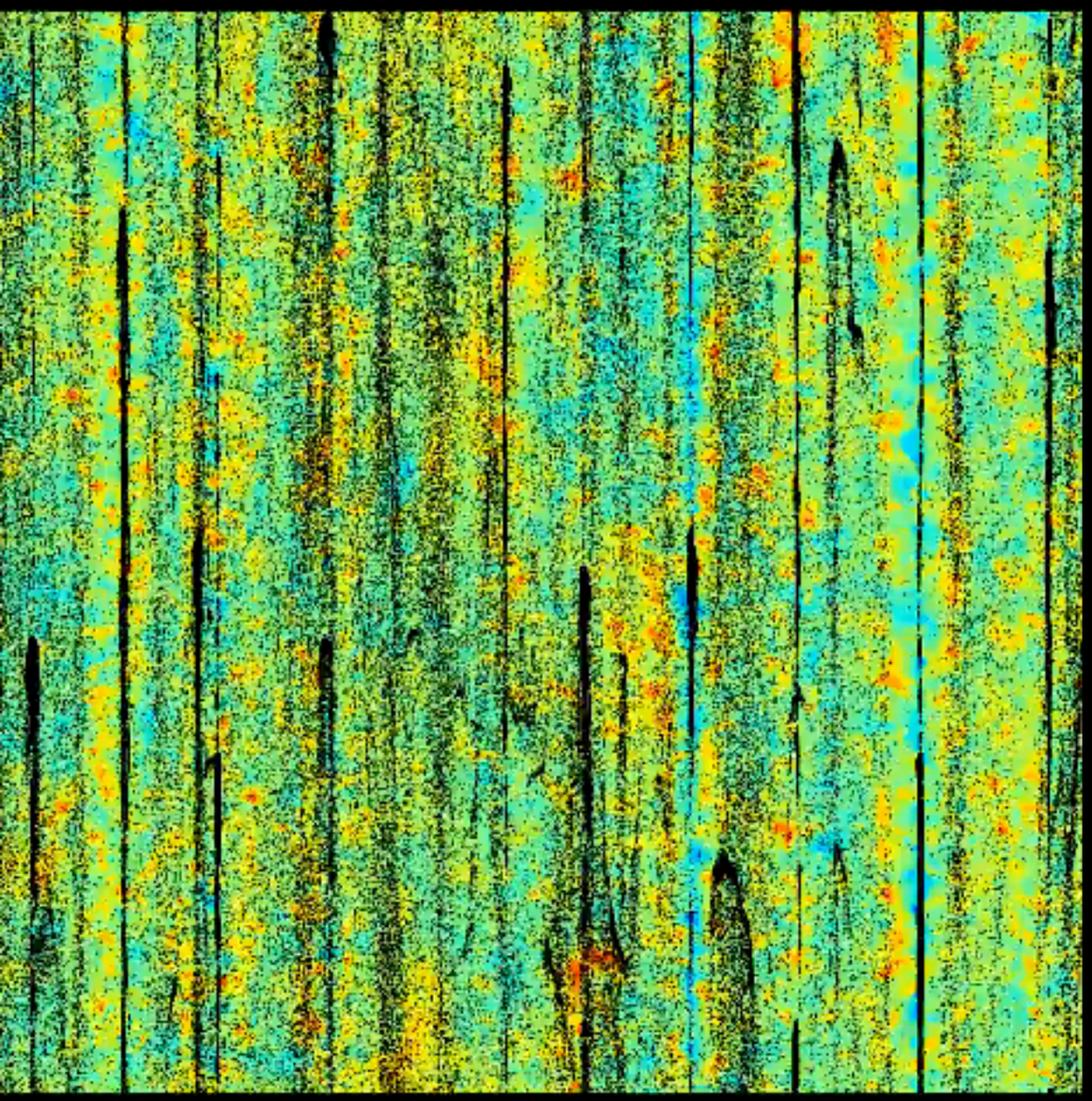


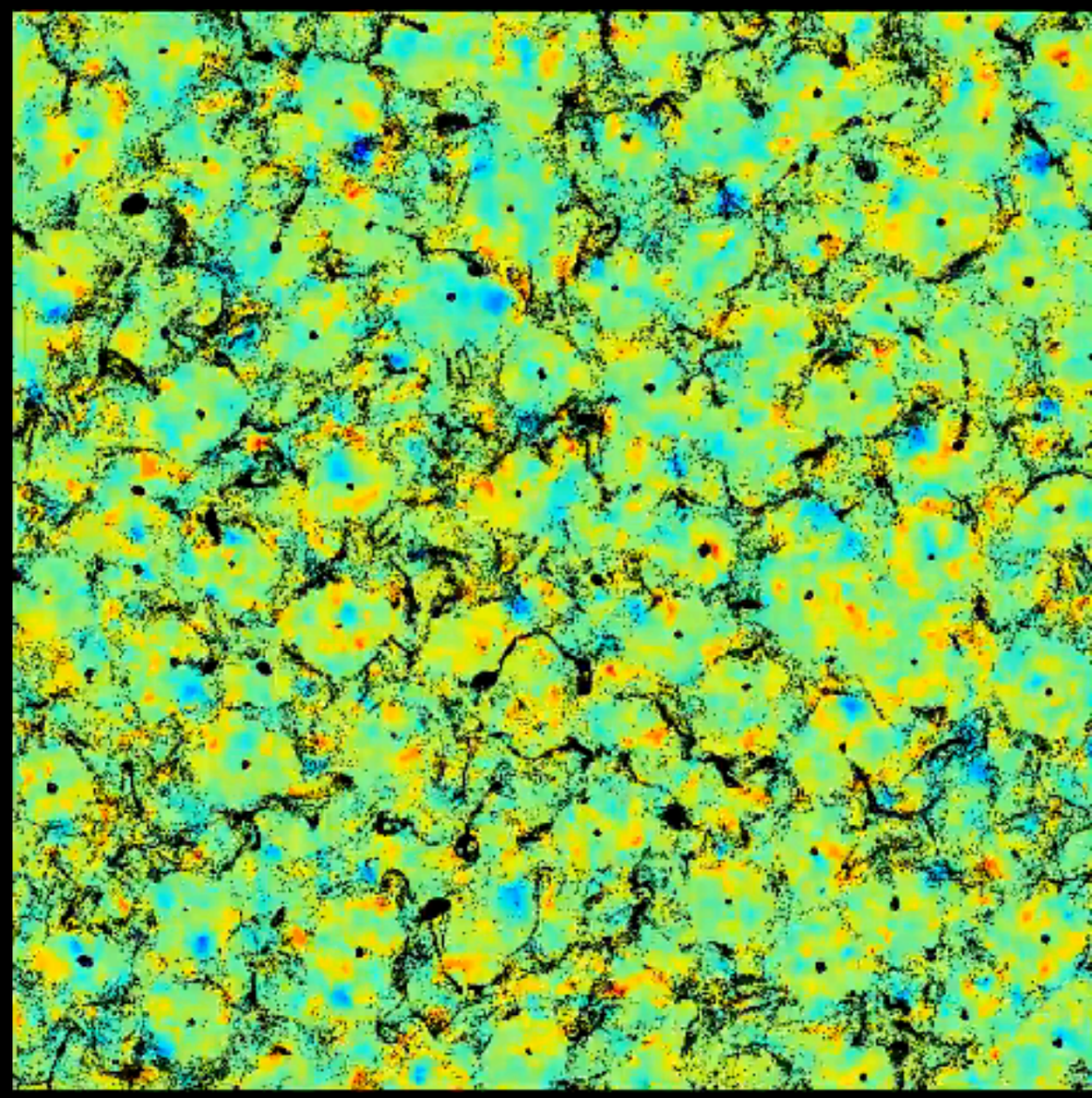
$0.06 \lesssim k\, c_s \langle t_s \rangle \lesssim 10$

Acoustic RDI: Non-Linear Behavior

LATE DEVELOPMENT (Squire, Moseley+ in prep.)

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



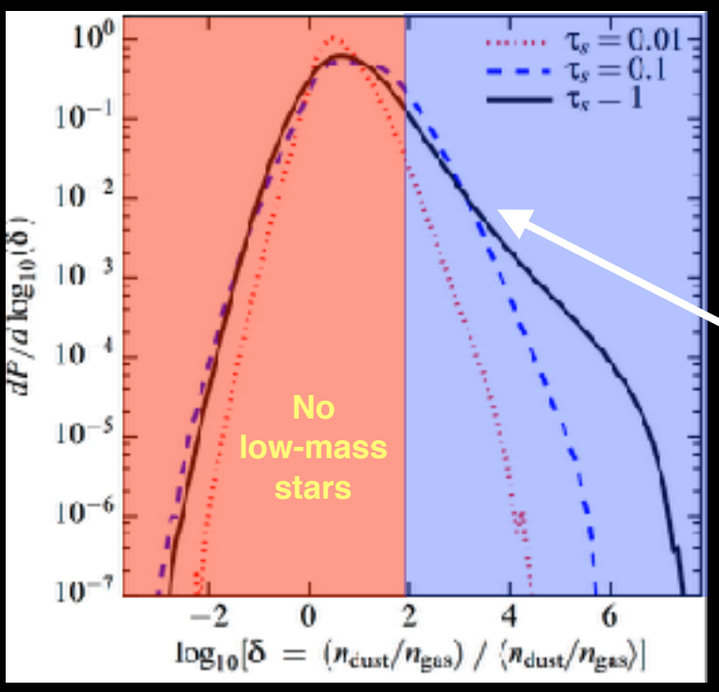


Circum-nuclear disks, Starbursts, GMCs

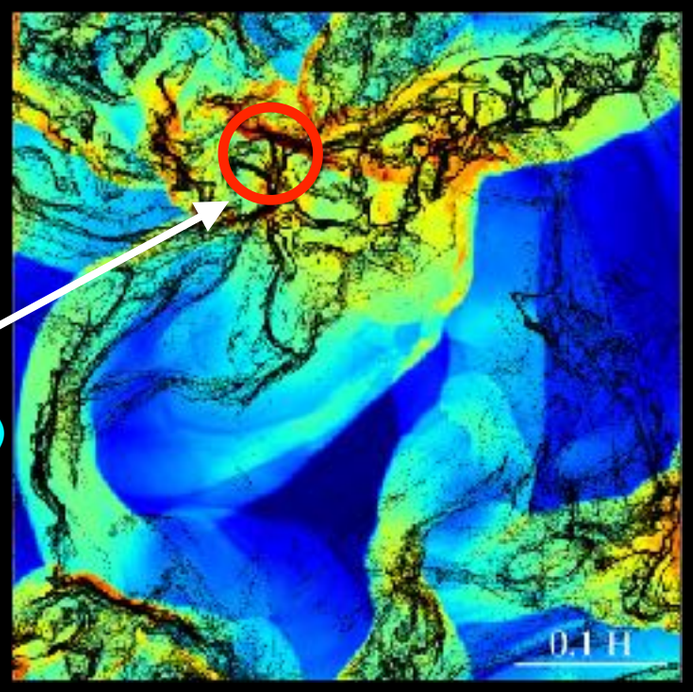
$|\mathbf{w}|_{\rm drift} \gtrsim 10\, c_s$

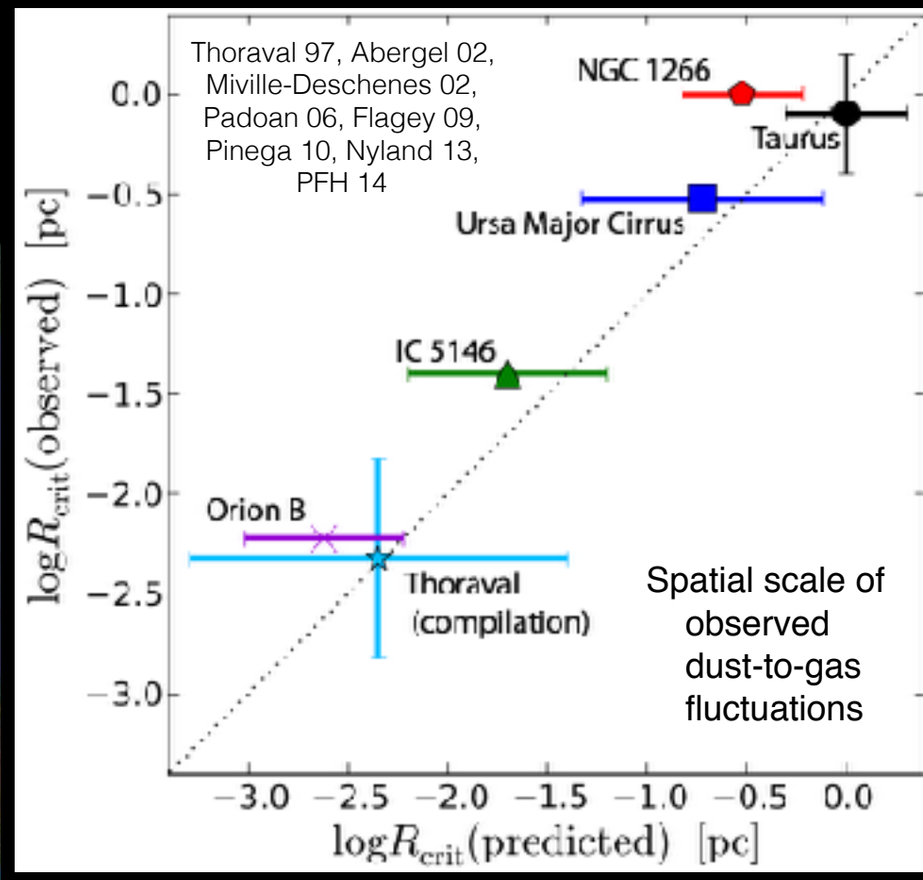
- Radiation-pressure driven winds?
  (can they form? does dust just blow out?)
- ISM dust growth (enhanced)
- Extinction curve variation/dust-to-gas fluctuations

- 1st low-mass star formation (PFH+Conroy)



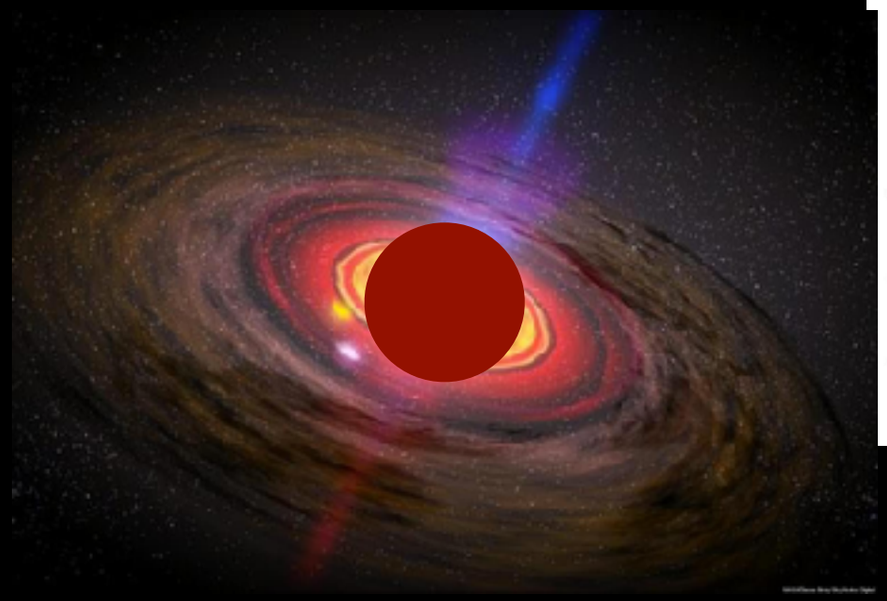
low-mass stars ([Z/H] > critical)

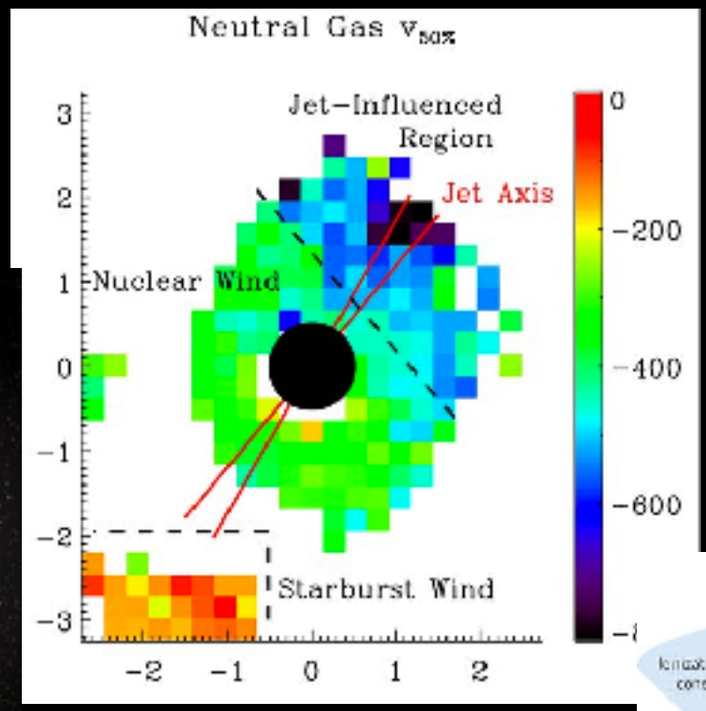


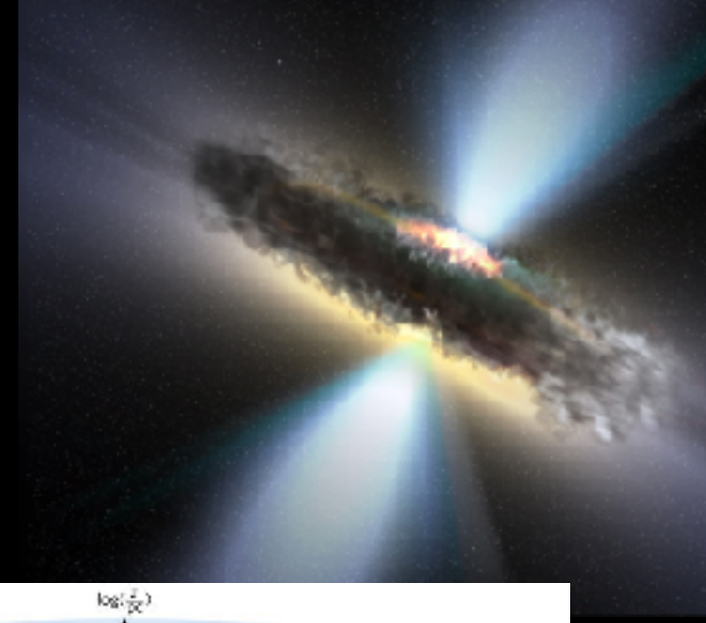


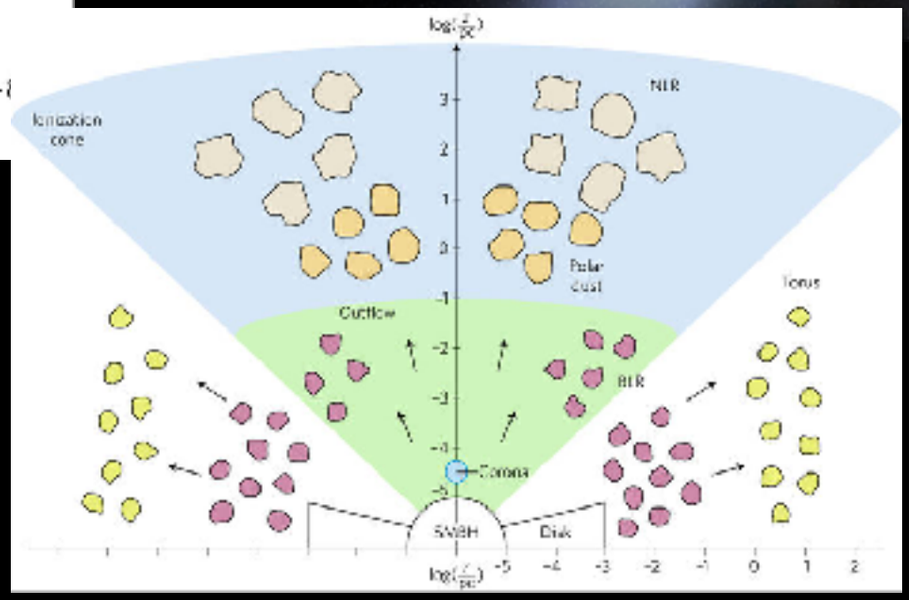
AGN & Quasars

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





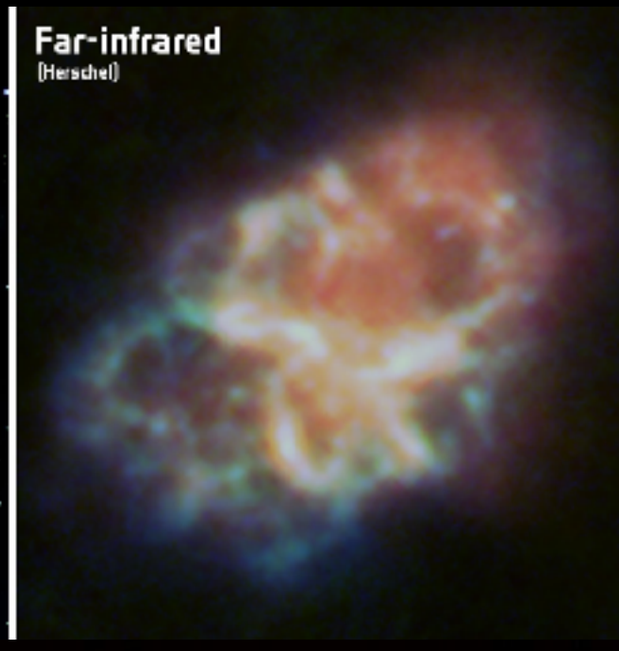




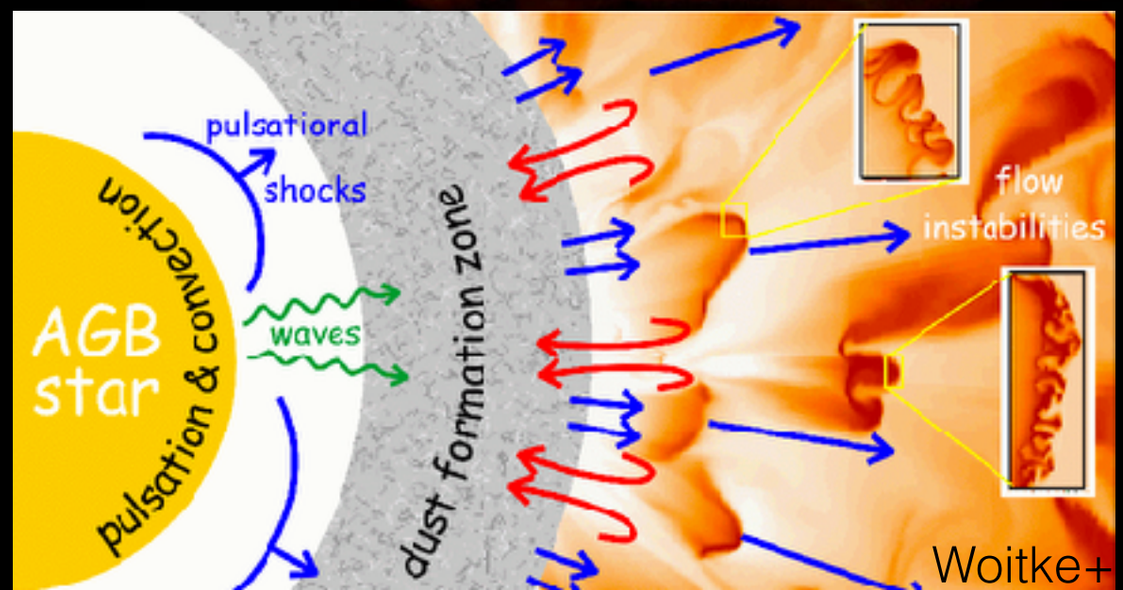
- “Changing Look” AGN: timescales ~months - years (at >pc)
- Wind-launching (BLR & NLR)
- “Clumpy Torus” (observed obscuration)
- Optical-X-ray obscuration discrepancies

Cool-star/AGB Winds, SNe Ejecta

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



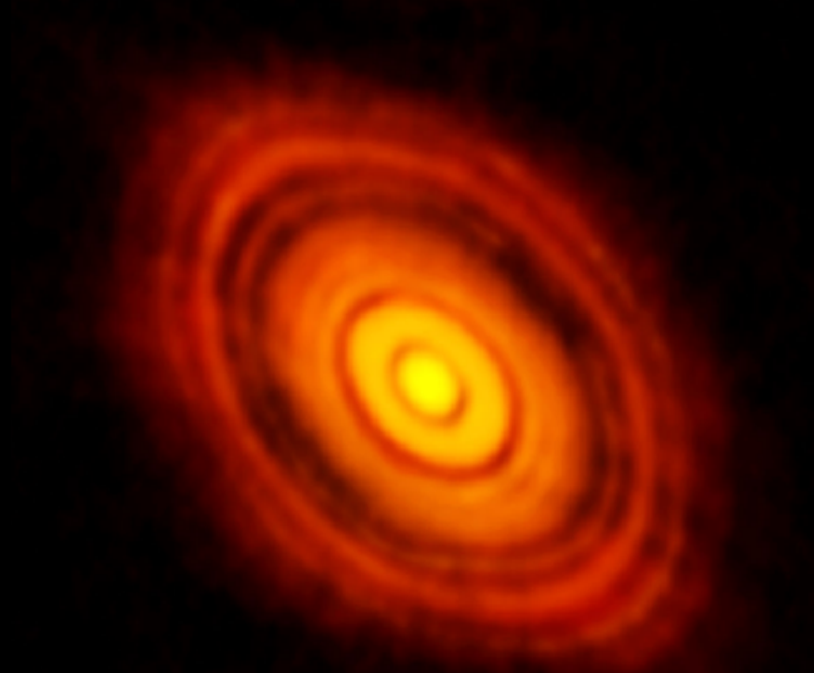
- Dust shells/arcs/streamers (e.g. Deguchi ’97)
- Clumpiness in outflow (guaranteed)
- Wind-launching (does it work?)
- Large grains in SNe ejecta (e.g. 1987a, 2010jl)



Proto-Stellar & Proto-Planetary Disks

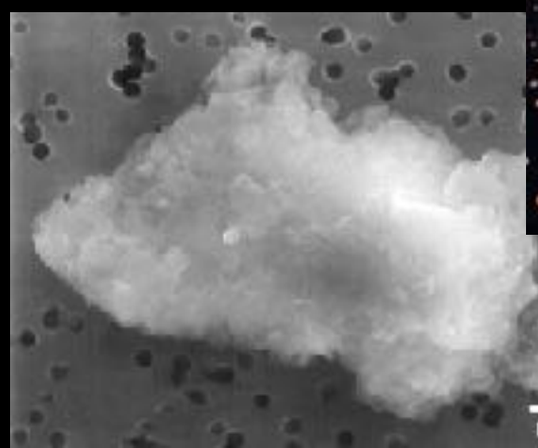
$$|\mathbf{w}|_{\rm drift} \ll c_s$$

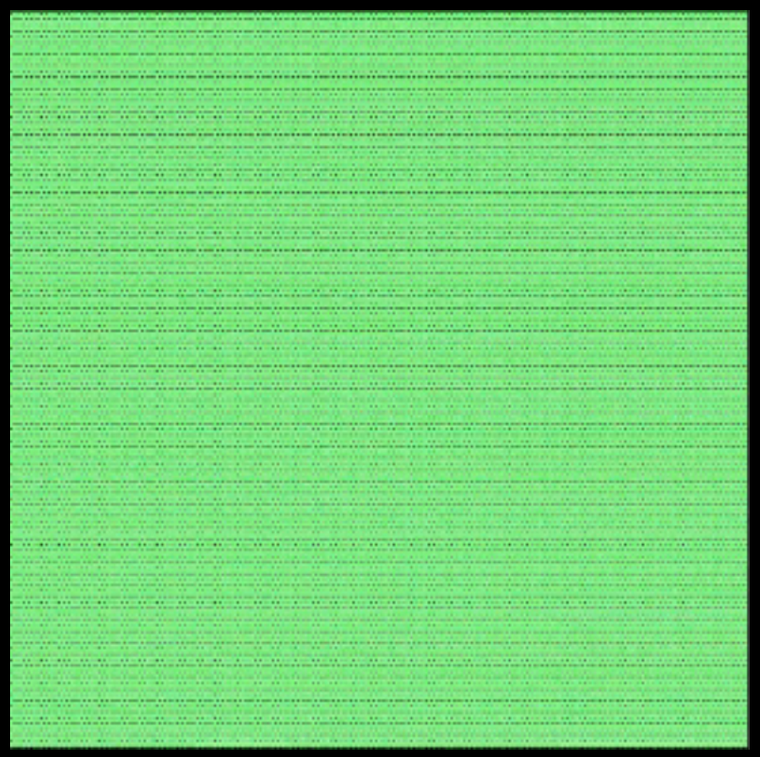
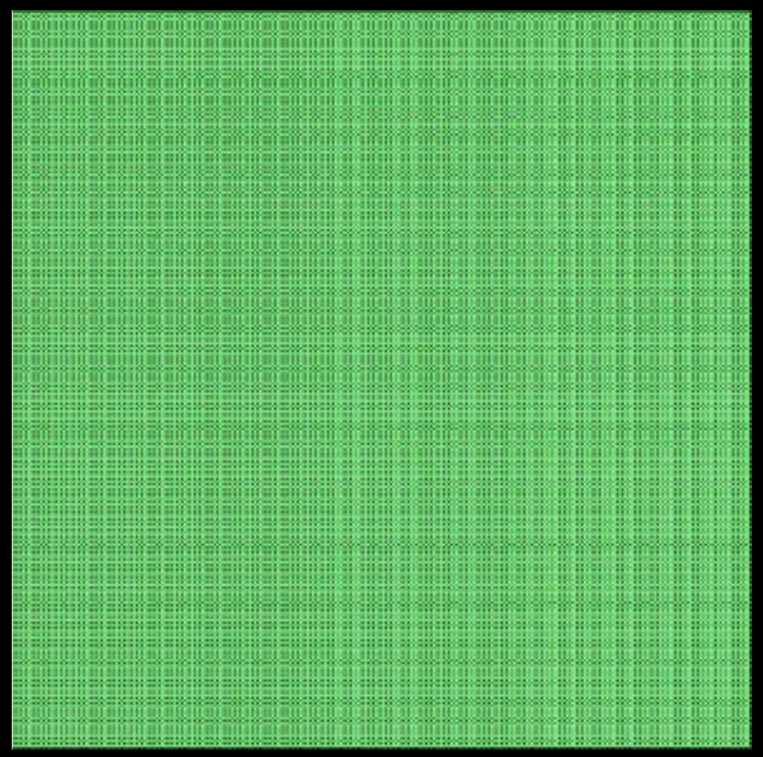
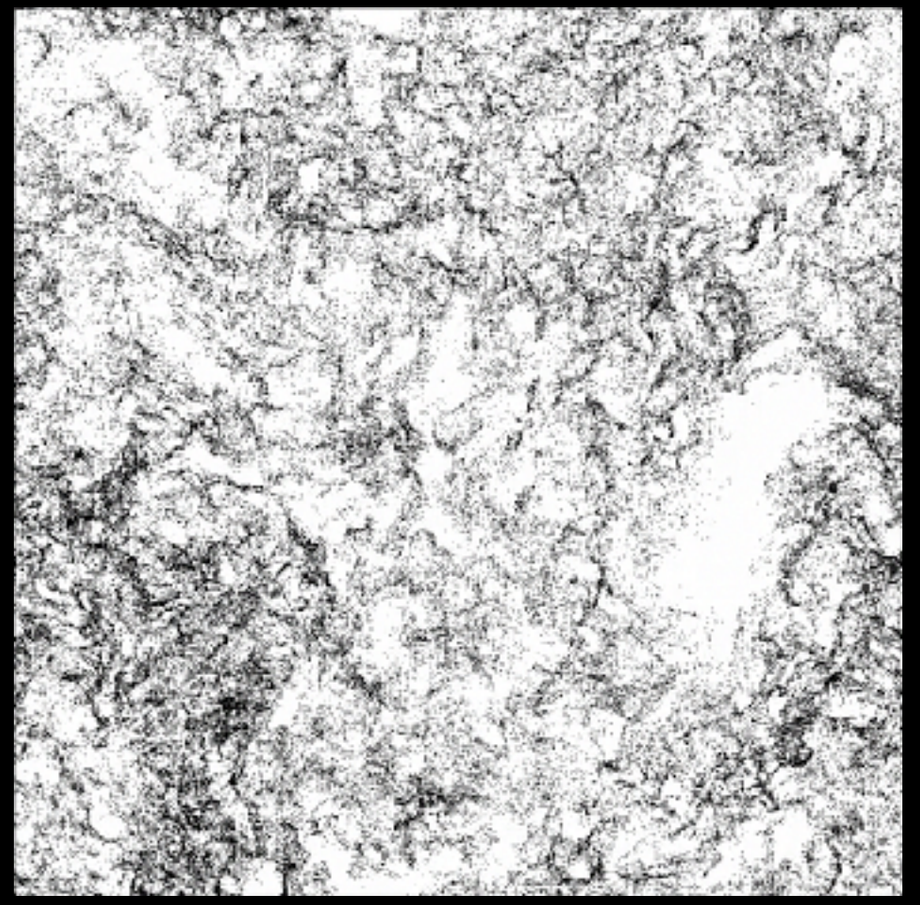
$$\text{BUT} \quad |\mathbf{w}|_{\rm drift} \gg \begin{cases} v_{\rm slow},\, v_{\rm whistler} \\ v_{\rm epicylic} = \Omega/k \\ v_{\rm Brunt\,Vaisala} = N_{\rm BV}/k \end{cases}$$



- New *families* of instabilities: Squire+Hopkins '17 (prep)
  - e.g. vertical "Settling Instability" for mm grains:
    - 5000x faster than streaming instab. at ~100x larger wavelengths

- Dust traps/asymmetries (long-wavelength modes)
- Planetesimals (overdensity->GI)
- Dust growth/coagulation/sticking (high-k modes, low velocity)



Summary

- **Resonant Drag Instability (RDI):** dust-gas mixtures generically unstable
- **Dust growth**/clumping / **Dust-driven winds** radically altered
- Streaming instability: Now ~10+ instabilities! **Dust-assisted GI?**
- High-Redshift: **Dust-enhancement** ***could enable*** **low-mass star formation**:
  - Explains strange **light-element** patterns: [CNO, Mg, Si, Na]?