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

Philip F. Hopkins & Jonathan (Jono) Squire

arXiv: 1706.05020 (SH), 1707.02997 (HS)
1711.03975 (SH), 1801.10166 (HS)

+ Eric Moseley & Stefania Moroianu (in prep)

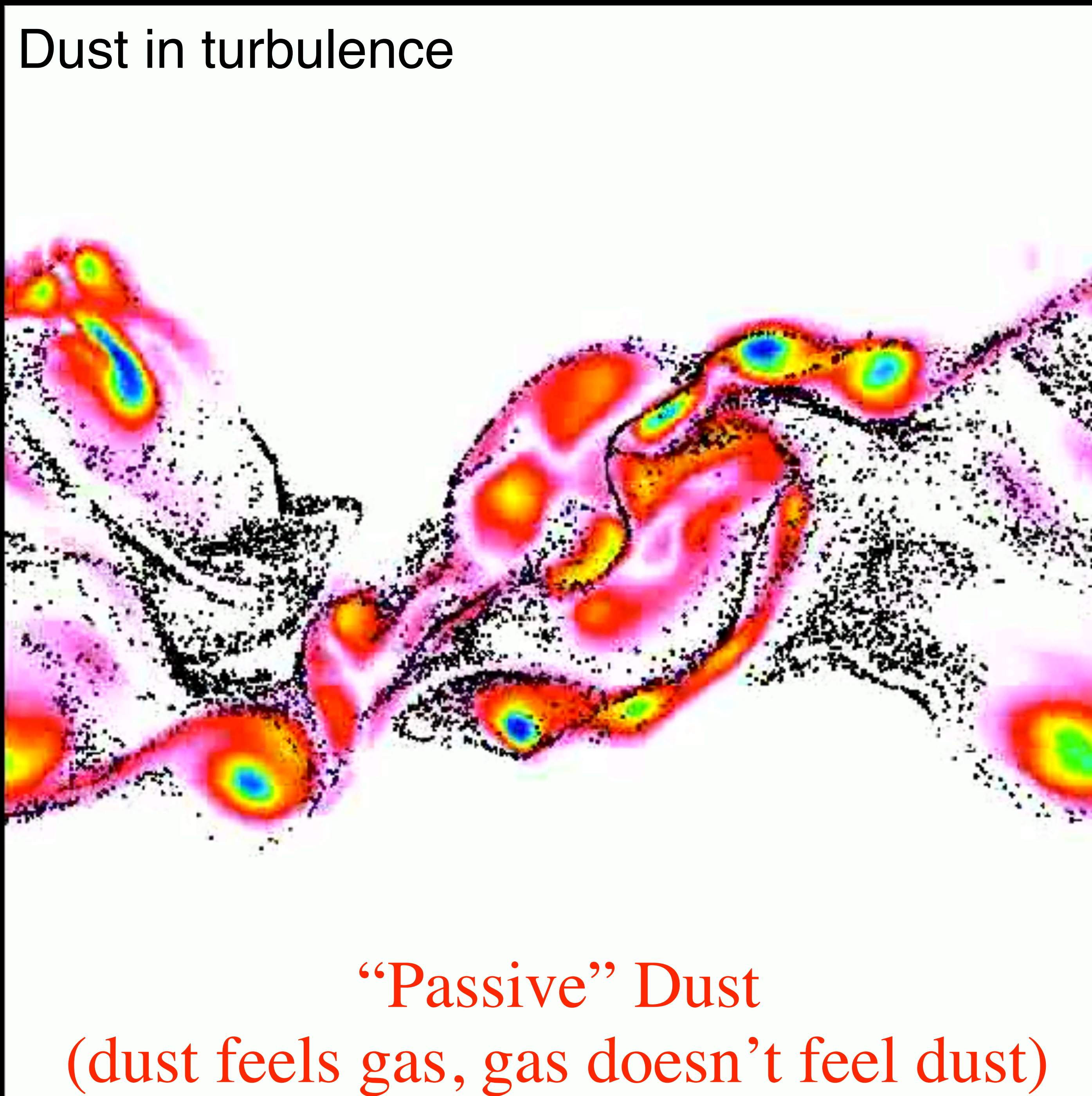
# Background

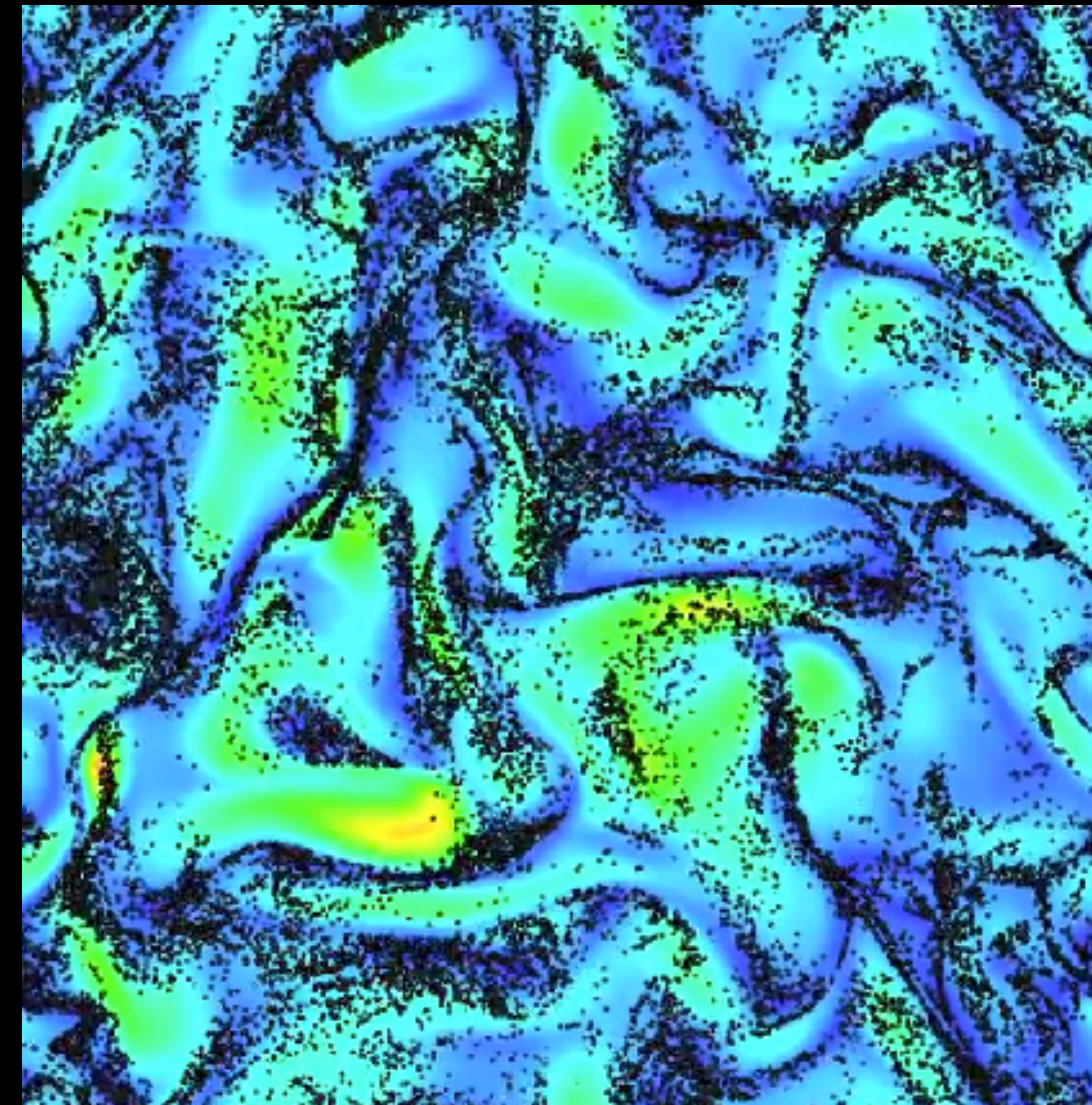
## Why Worry About Dust?

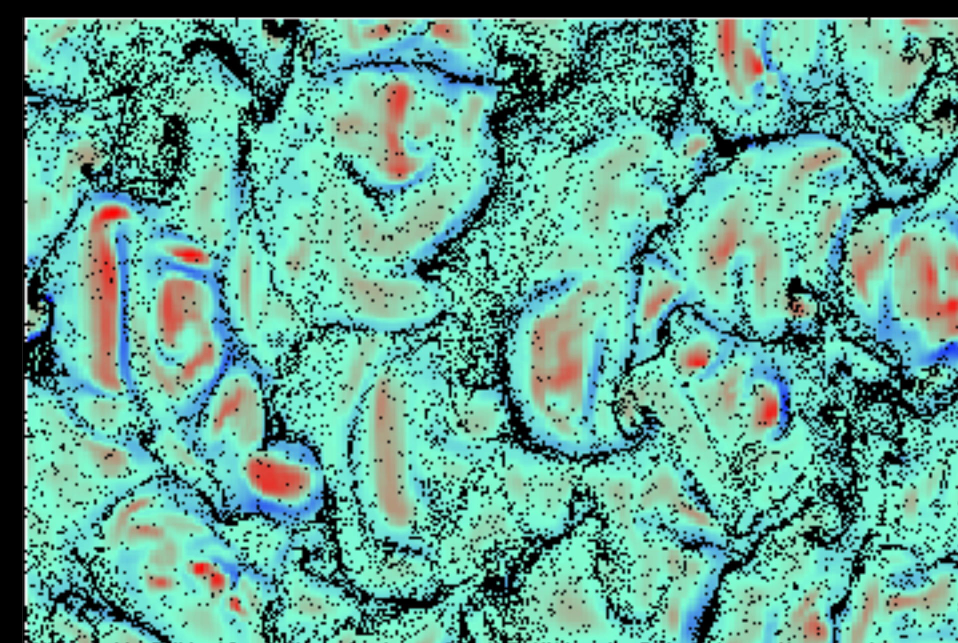
- Dust:
  - Critical for: cooling, planet formation, starburst / AGN / cool star winds, extinction / reddening / polarization
  - Not enough metals (Draine+; Jenkins+)
  - Too many big grains (Ulysses,Cassini, Helios, Arecibo; Kruger '06, Draine '09, Poppe '10)
  - Forms too early (Perley '12, Zafar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

# Dust Is Not Gas

## EXPERIMENT & EVERYDAY EXPERIENCE





e.g. Squires & Eaton 1991

# “Active” Dust

## The Setup:

Squire & PFH: arXiv:1706.05020

Gas equations = (anything that supports a linear mode) + dust

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:

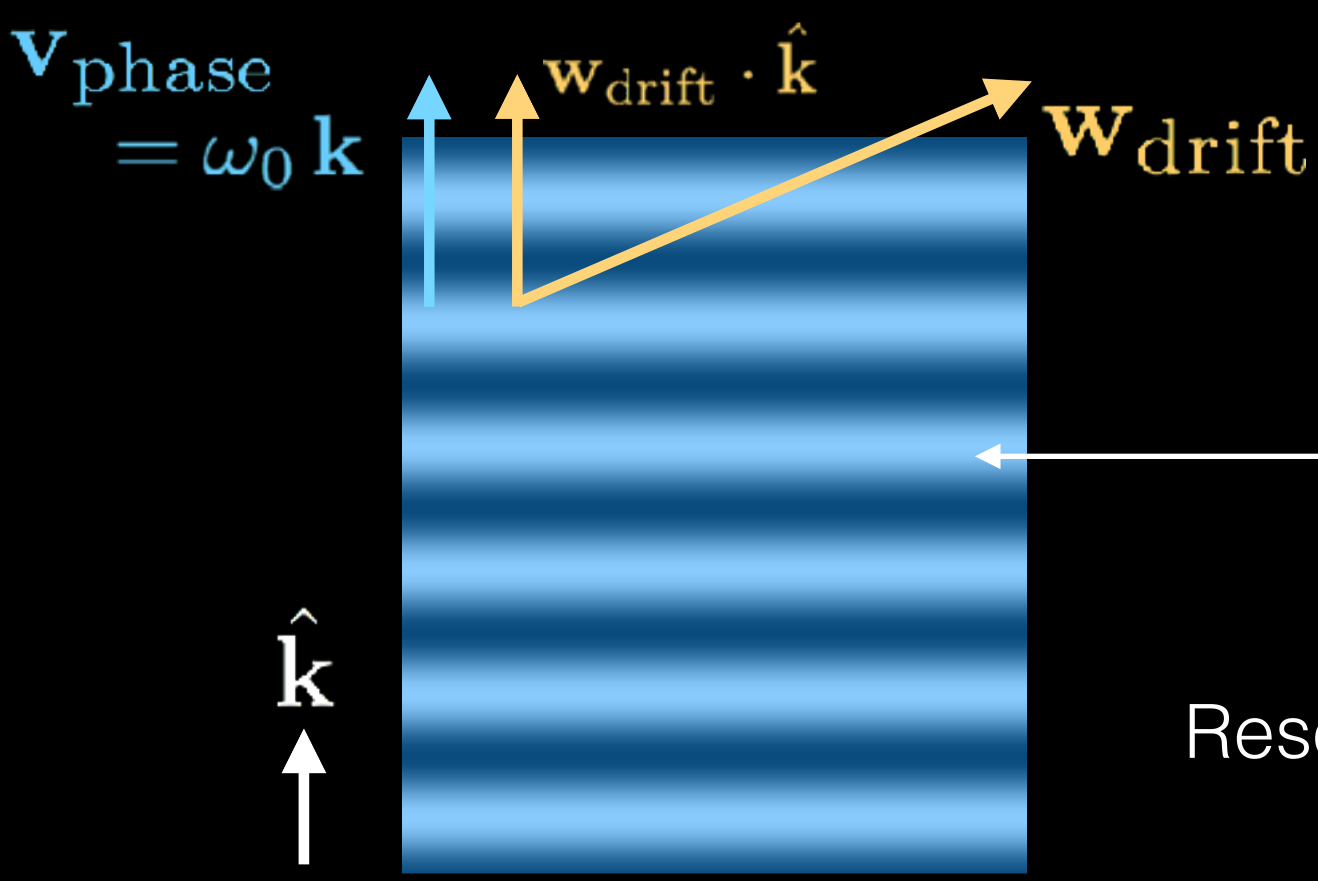
Squire & PFH: arXiv:1706.05020

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

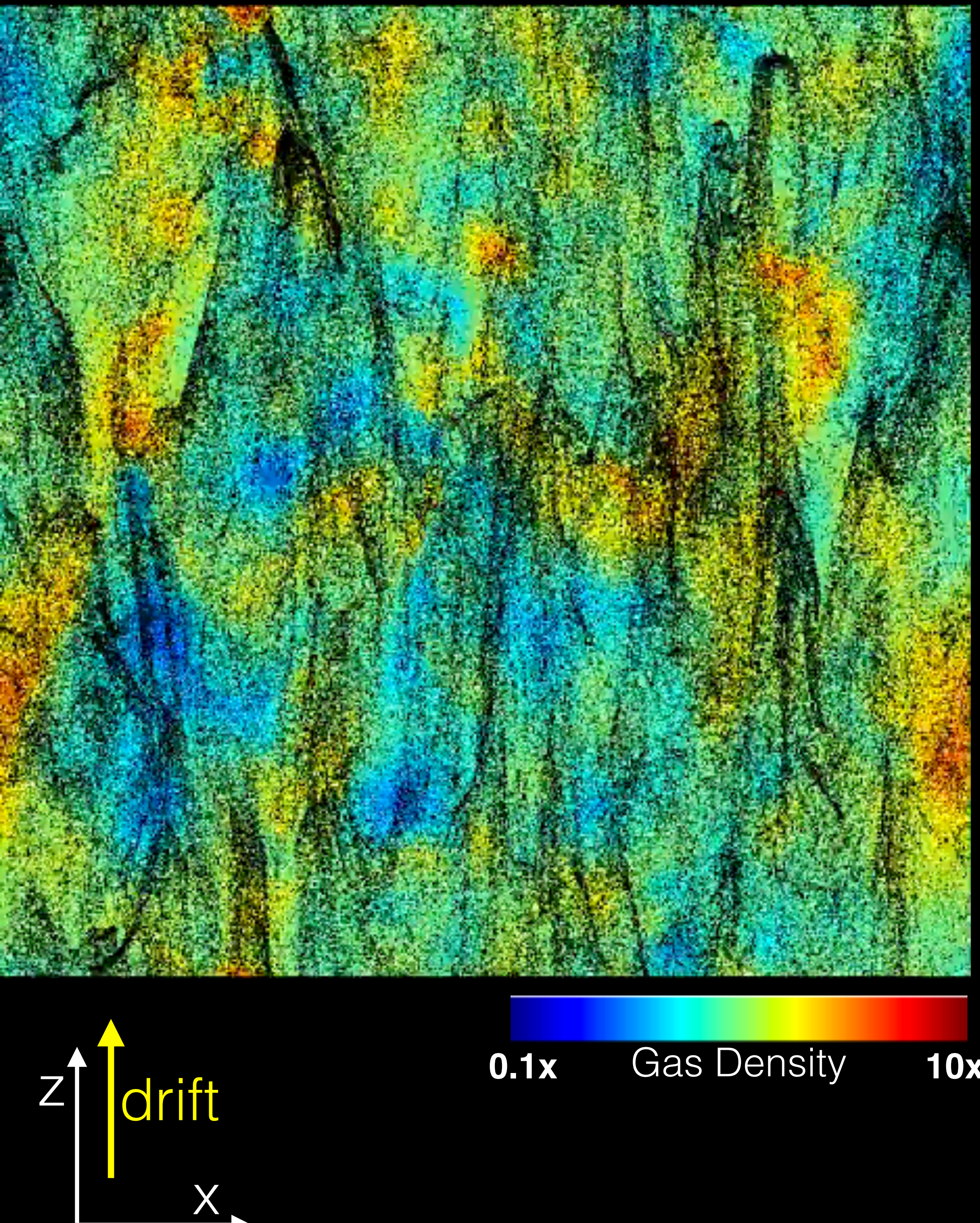


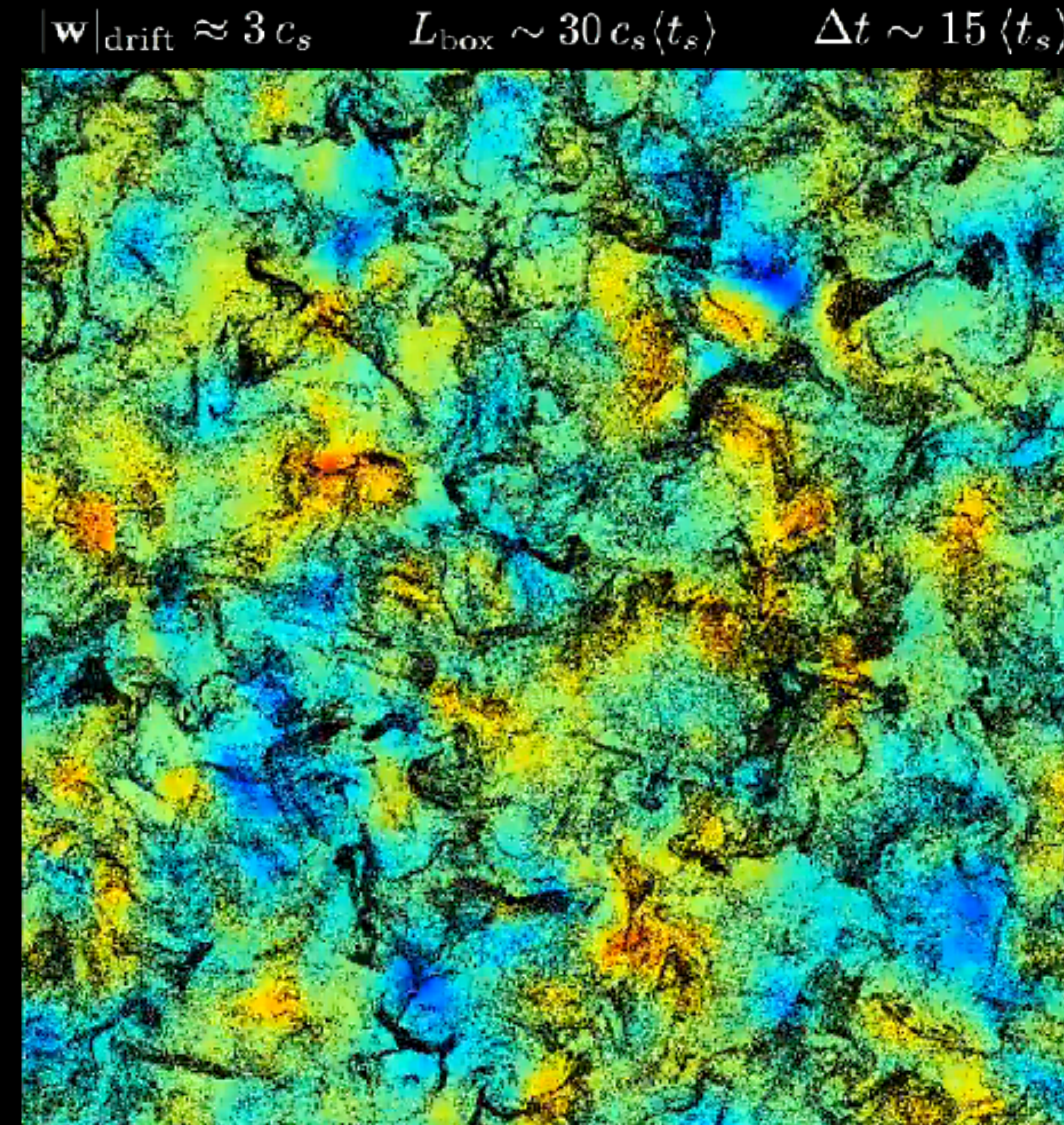

Dust hits gas density peak, slows down, piles up

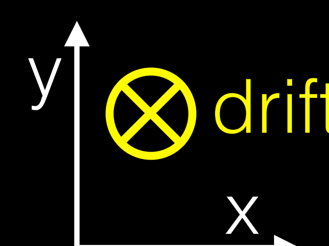
Resonance: Dust sees standing wave, effects add coherently

# What Does This Look Like?
## (DETAILS TO FOLLOW)

Squire & Hopkins
(1706.05020, 1707.02997,
1711.03975, 1801.10166)




Some examples:
Brunt-Vaisala RDI
Settling RDI, Epicyclic/Streaming RDI
Acoustic RDI, Fast/Slow Magnetosonic RDI
Alfven RDI, Gyro RDIs, CR-Type (Bell) RDIs

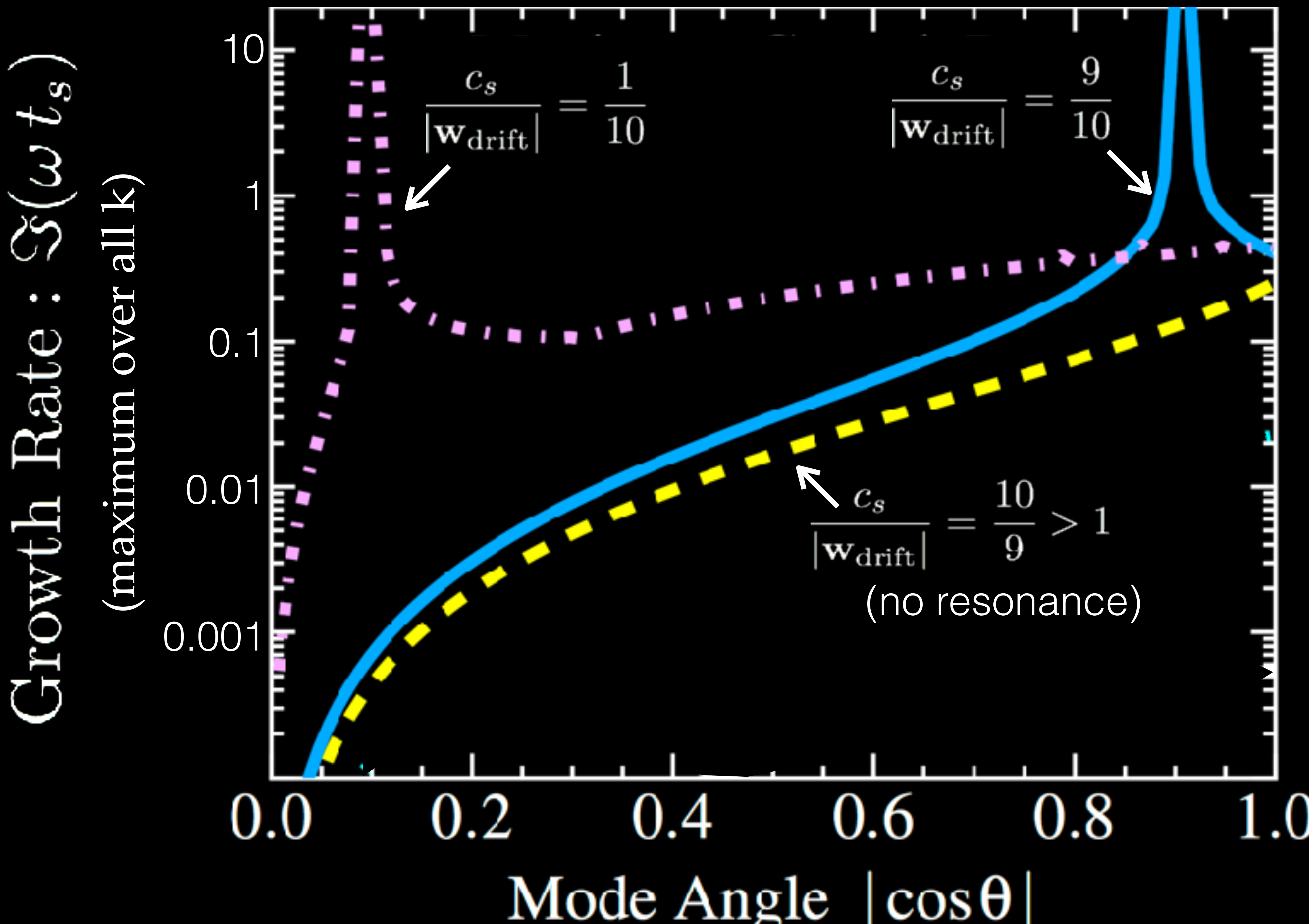
# Example: Simplest (“Acoustic”) Case

PFH & Squire arXiv:1707.02997

# Acoustic: Simplest "Resonance"

PFH & Squire arXiv:1707.02997

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

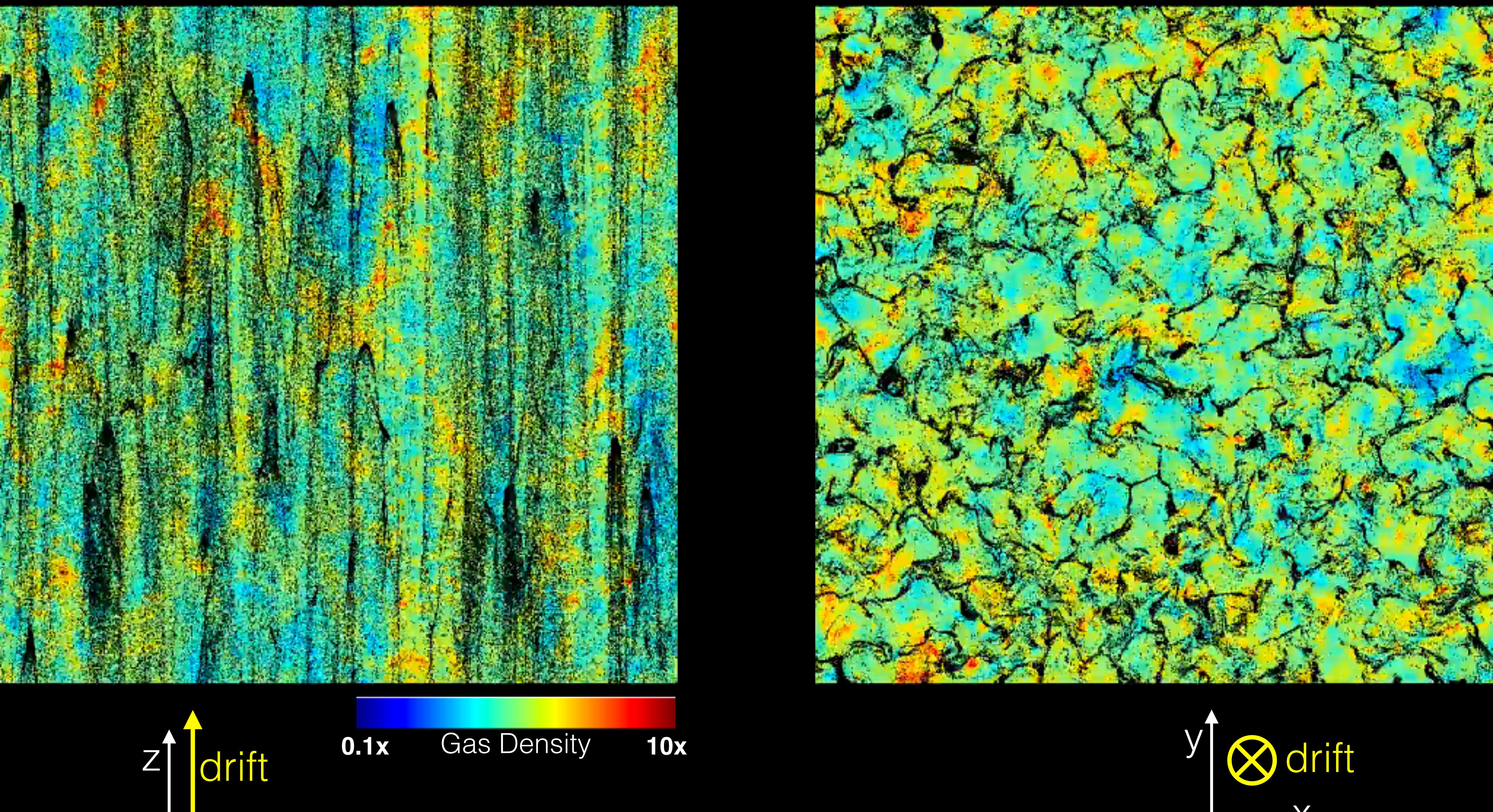


# Acoustic RDI: Non-Linear Behavior

EARLY DEVELOPMENT (Moseley+ in prep.)

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

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




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

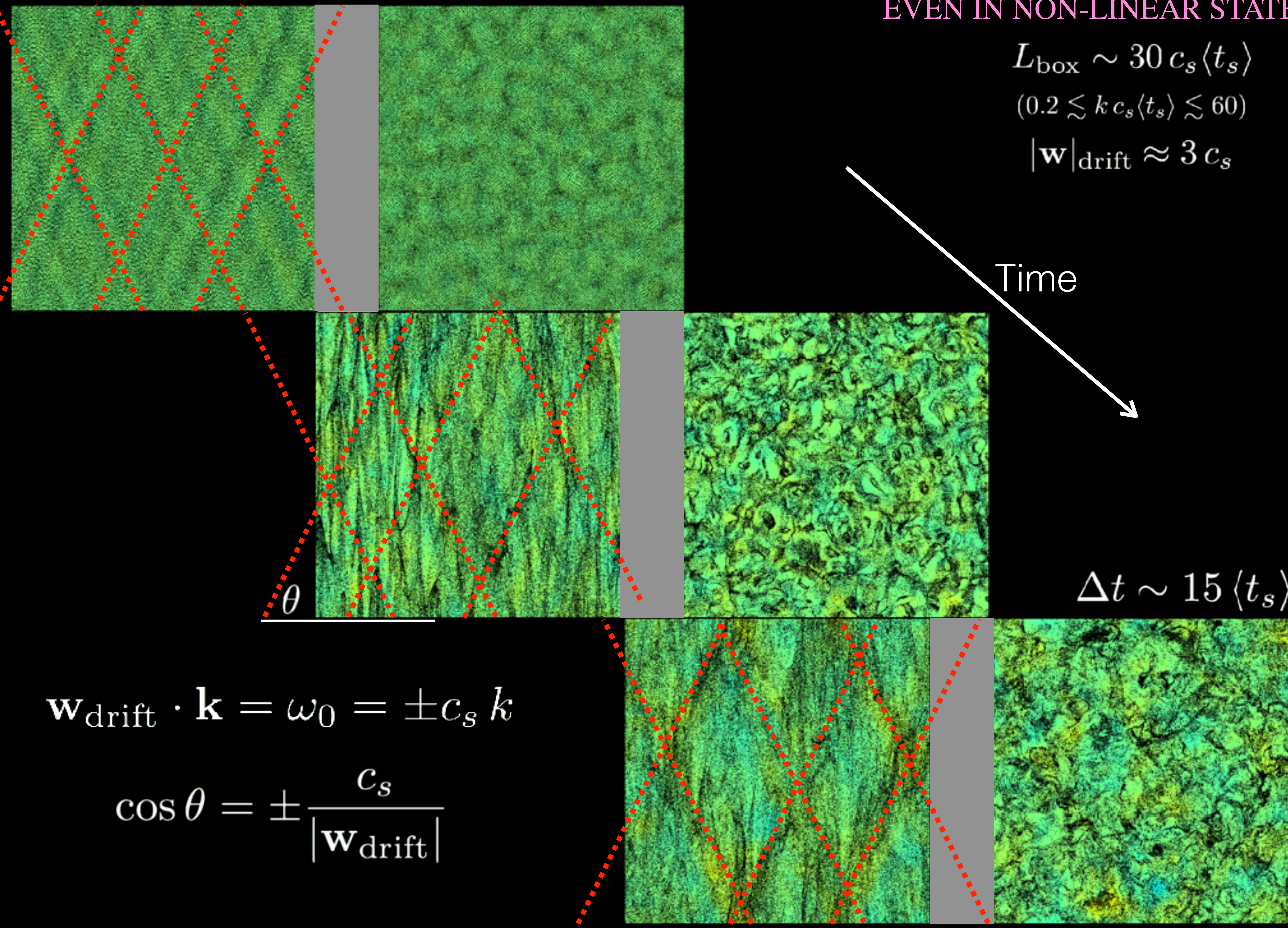
# Resonant Mode Dominates

## EVEN IN NON-LINEAR STATE

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

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

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

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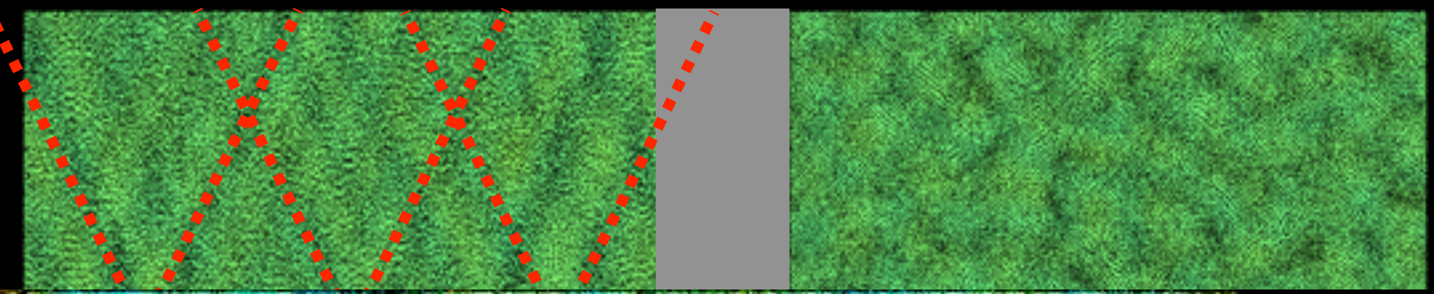
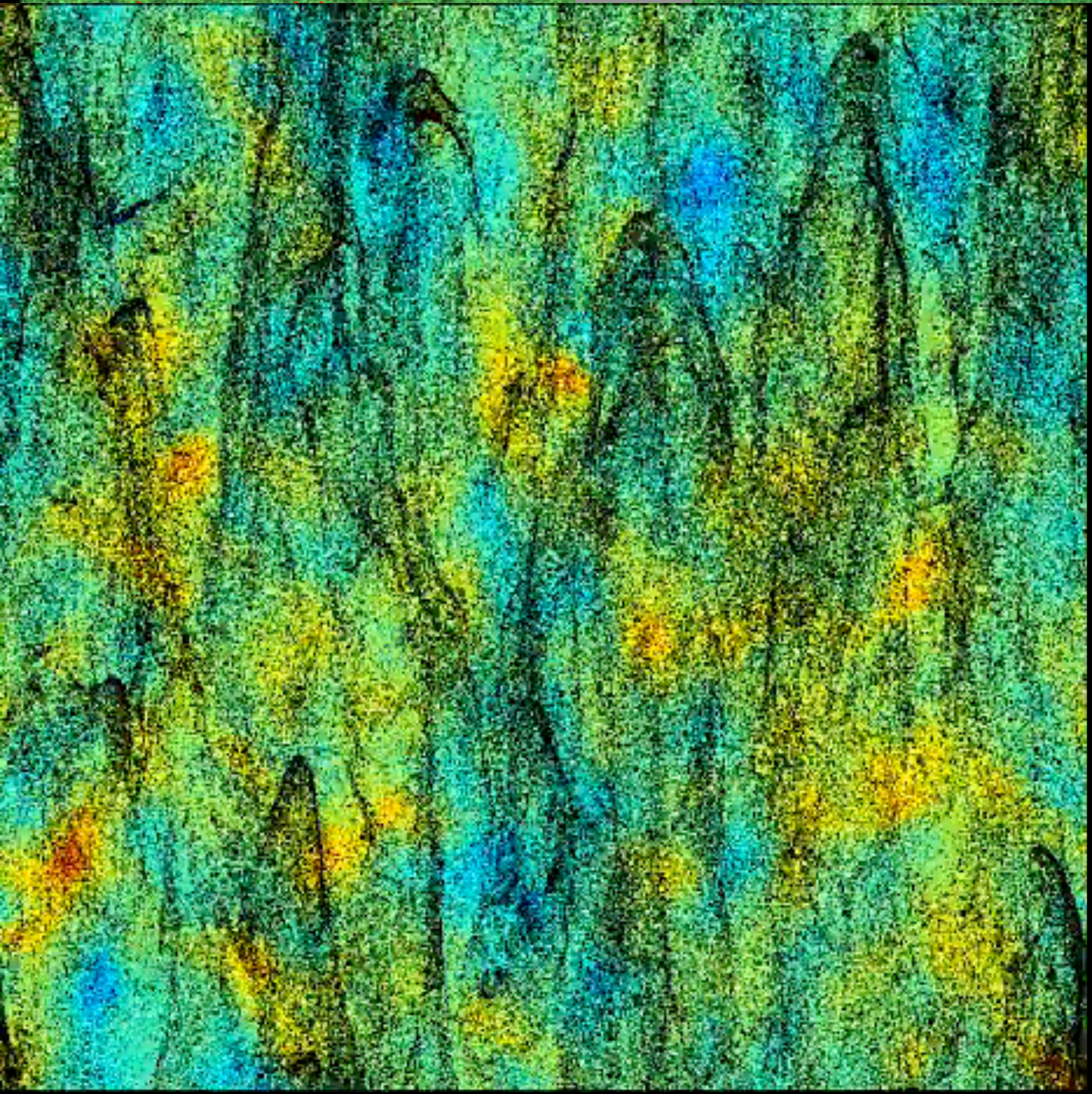
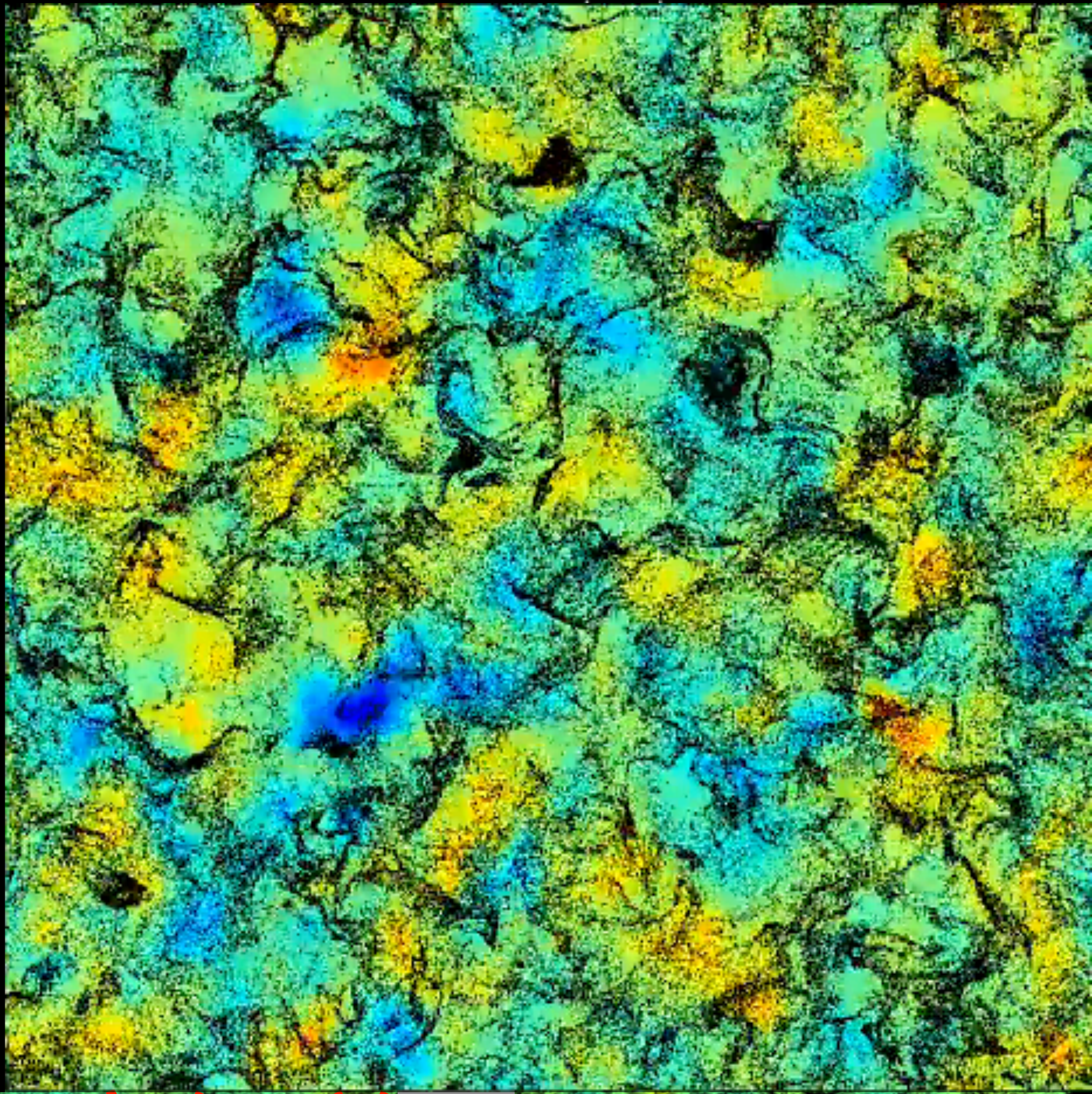
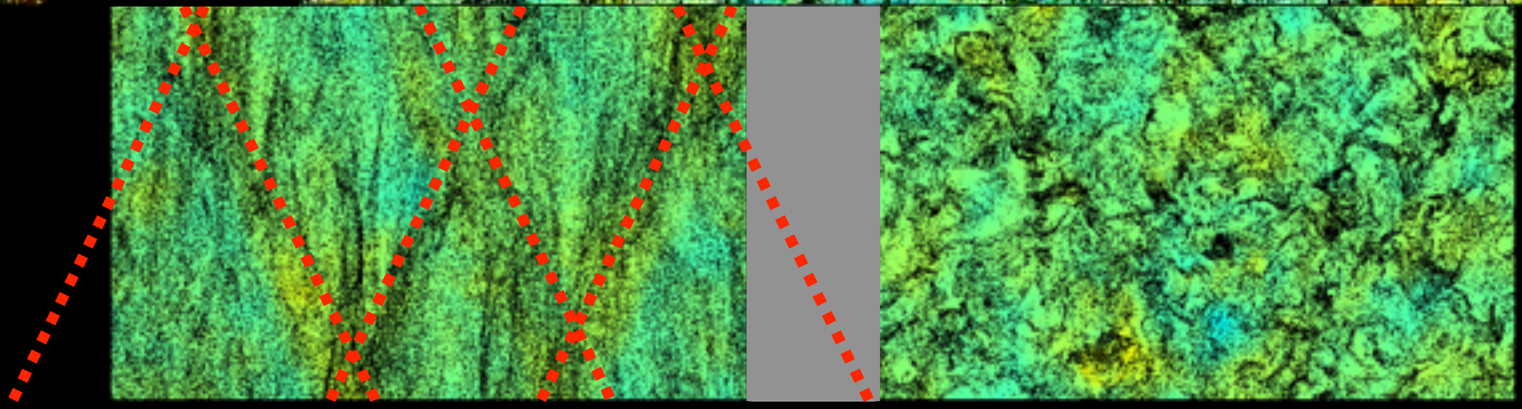








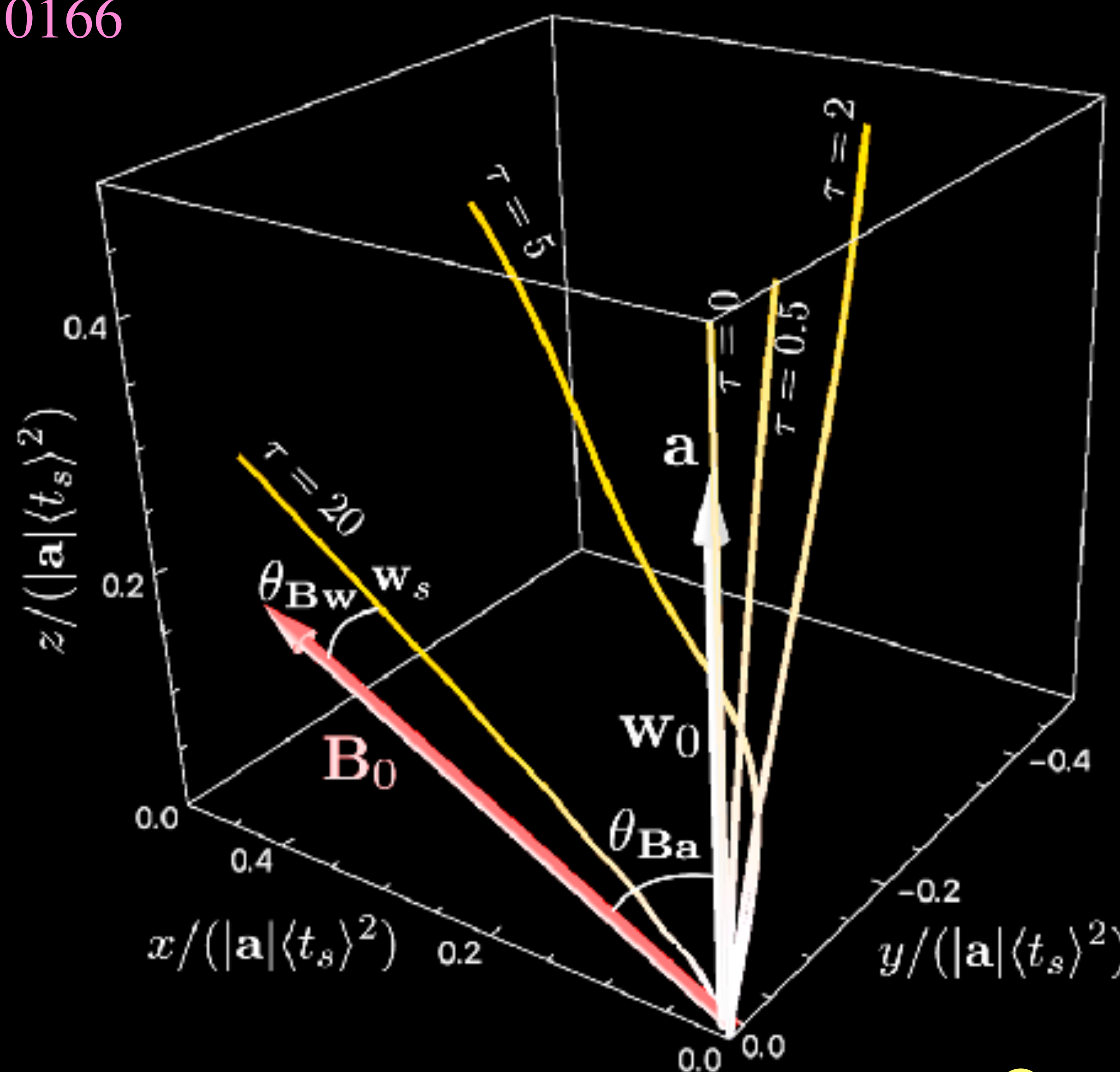
$$\cos\theta = \pm \frac{c_s}{|\mathbf{w}_{\rm drift}|}$$

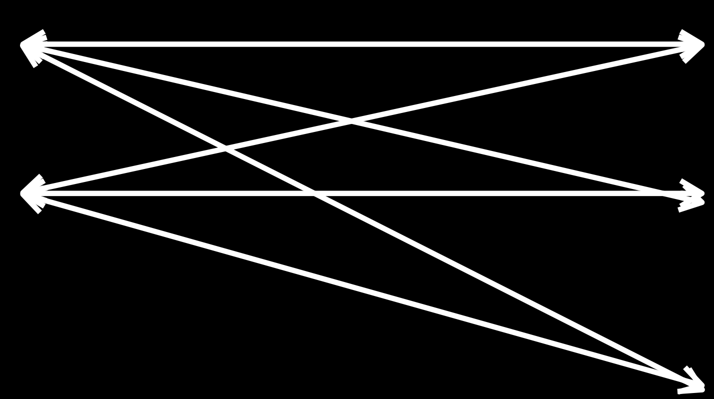
# + Magnetic Fields & Grain Charge

PFH & Squire arXiv:1801.10166

# MHD Adds New Instabilities

PFH & Squire arXiv:1801.10166



**Dust Modes**

- **Drift ($\omega_0 = \mathbf{w}_{\rm drift} \cdot \mathbf{k}$)**
- **Gyro**

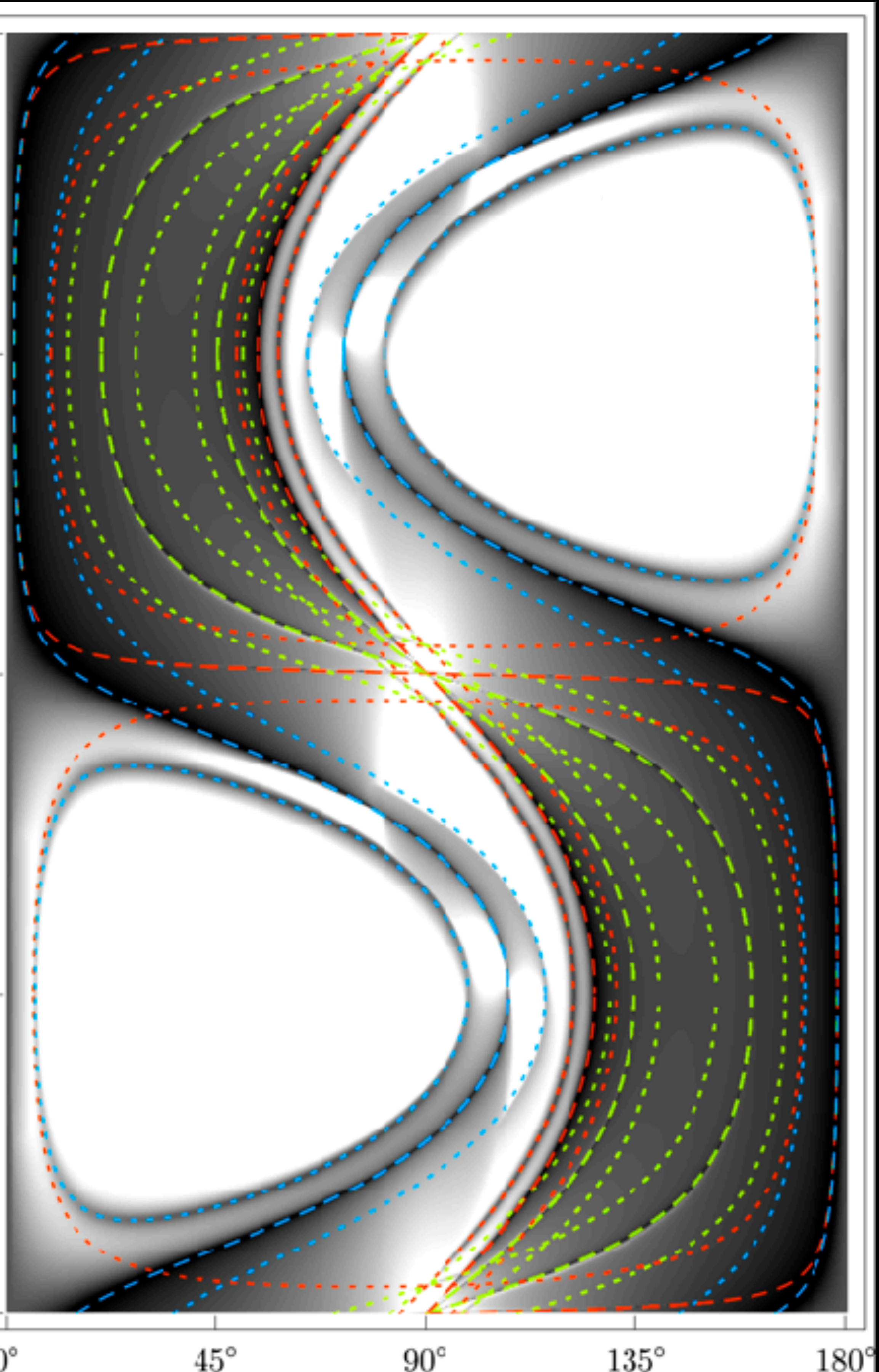
+ other ("non-resonant") modes

**Gas Modes**

- **Fast magnetosonic**
- **Slow magnetosonic**
- **Alfven**

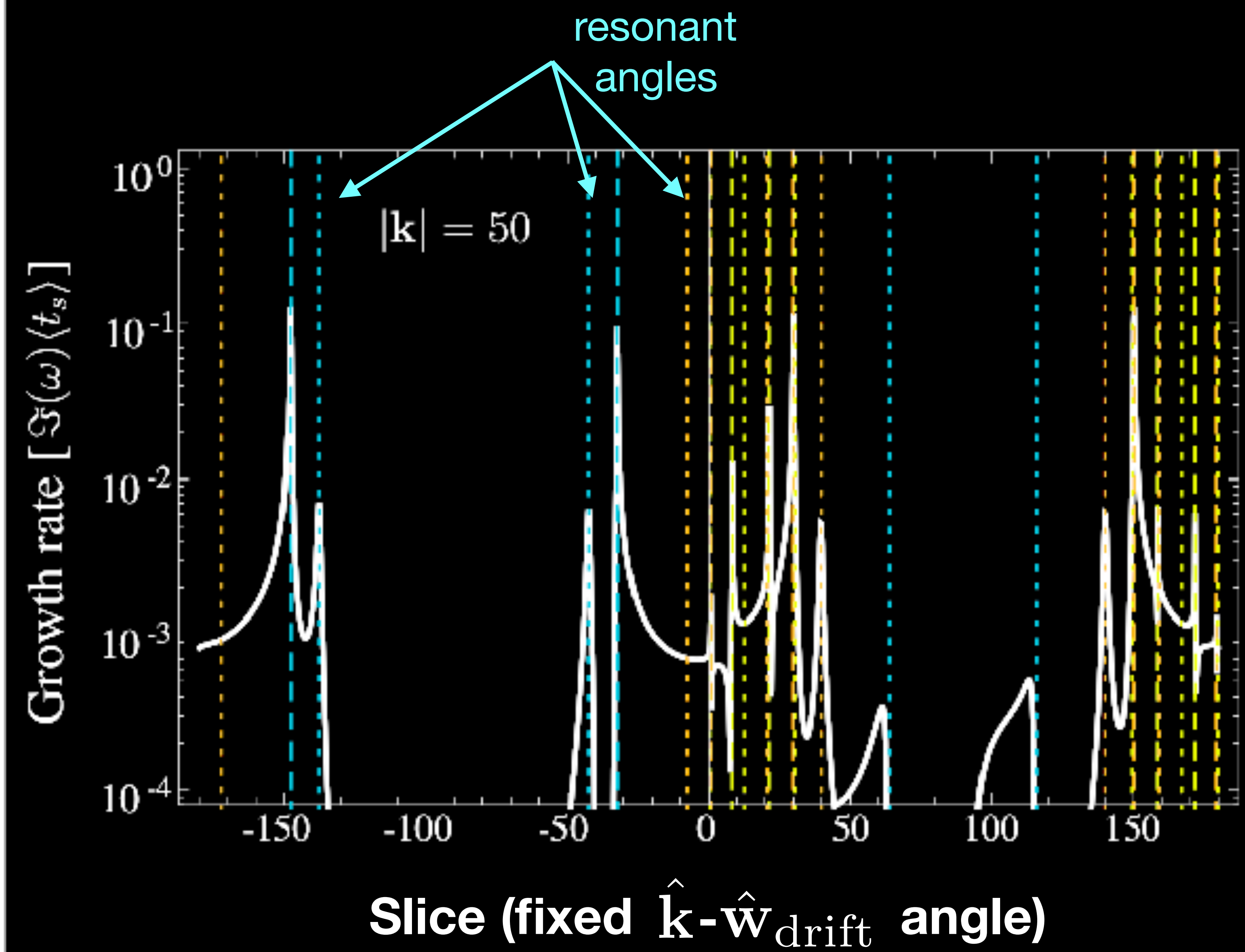
# MHD Adds New Instabilities

PFH & Squire arXiv:1801.10166




**Growth rate vs. angles**

$\hat{\mathbf{k}}$-$\hat{\mathbf{B}}$ & $\hat{\mathbf{k}}$-$\hat{\mathbf{w}}_{\rm drift}$

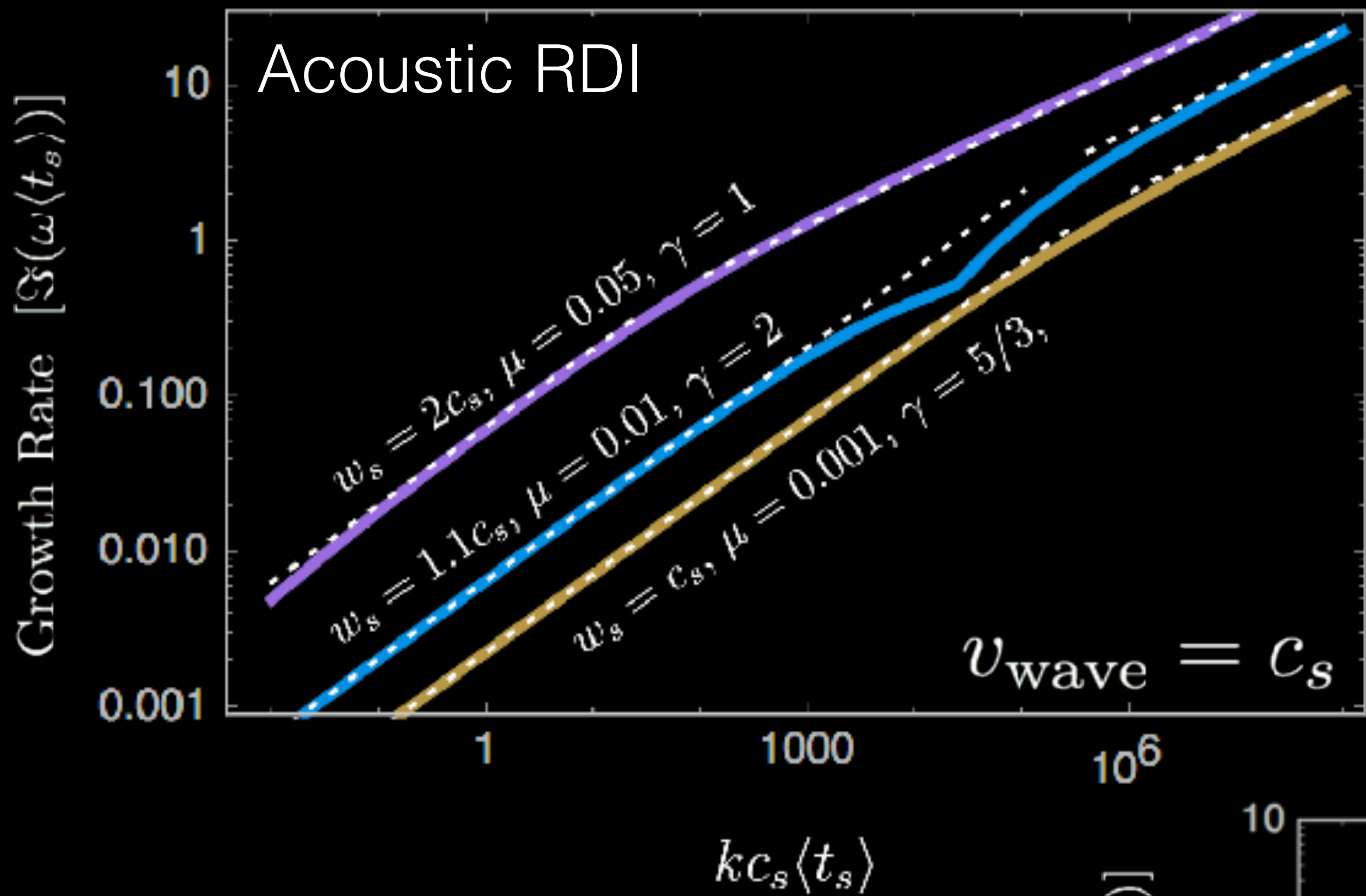


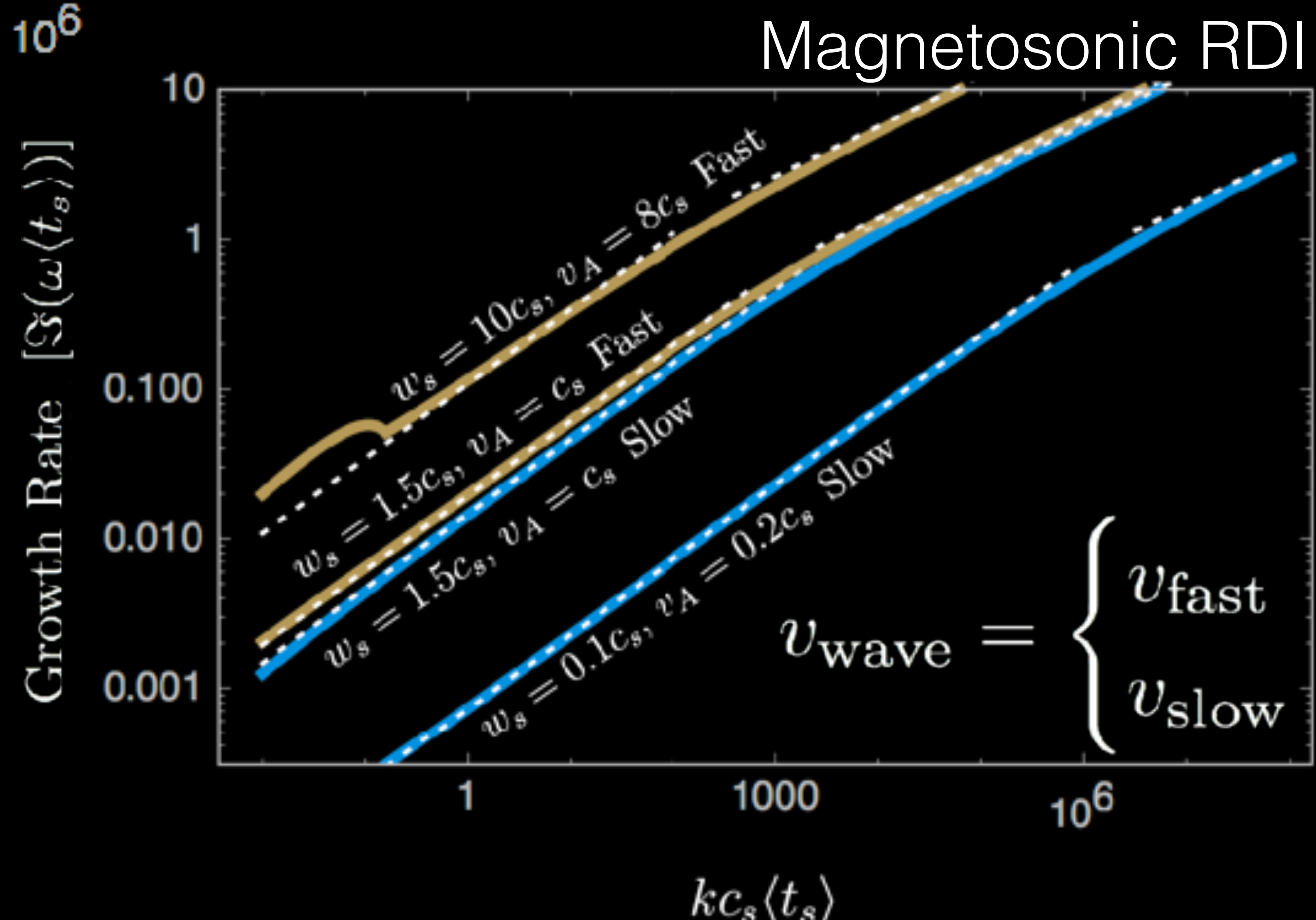
# Magnetosonic-Advection Mode

PFH & Squire arXiv:1801.10166

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

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




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

Resonance ***always*** exists

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

# Alfvén & Gyro RDIs

PFH & Squire arXiv:1801.10166

Alfvén:

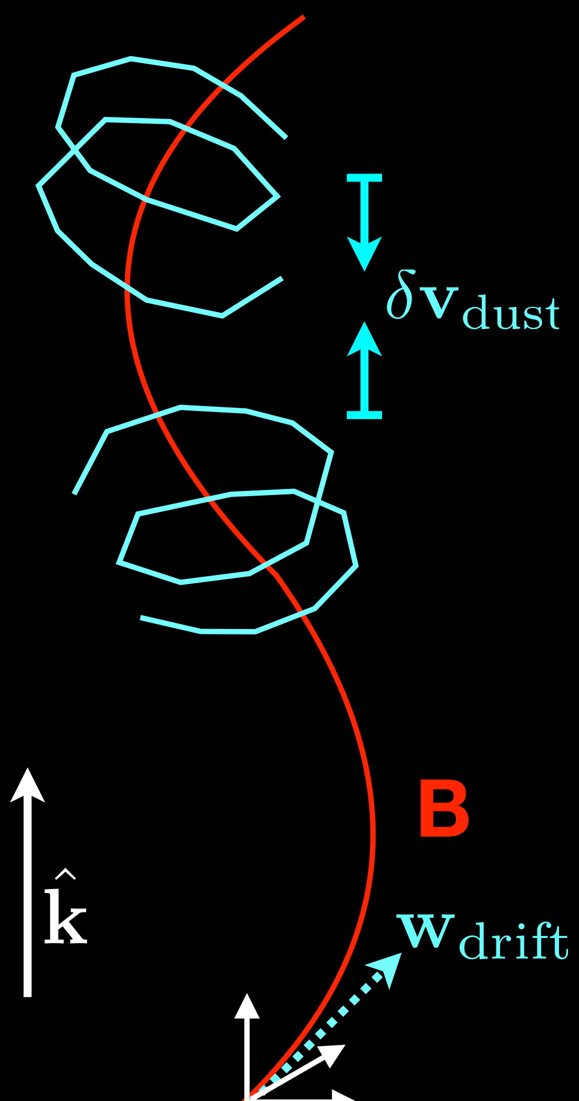
$$\mathbf{w}_{\rm drift} \cdot \mathbf{k} = \pm v_A \, \mathbf{k} \cdot \hat{\mathbf{B}}$$

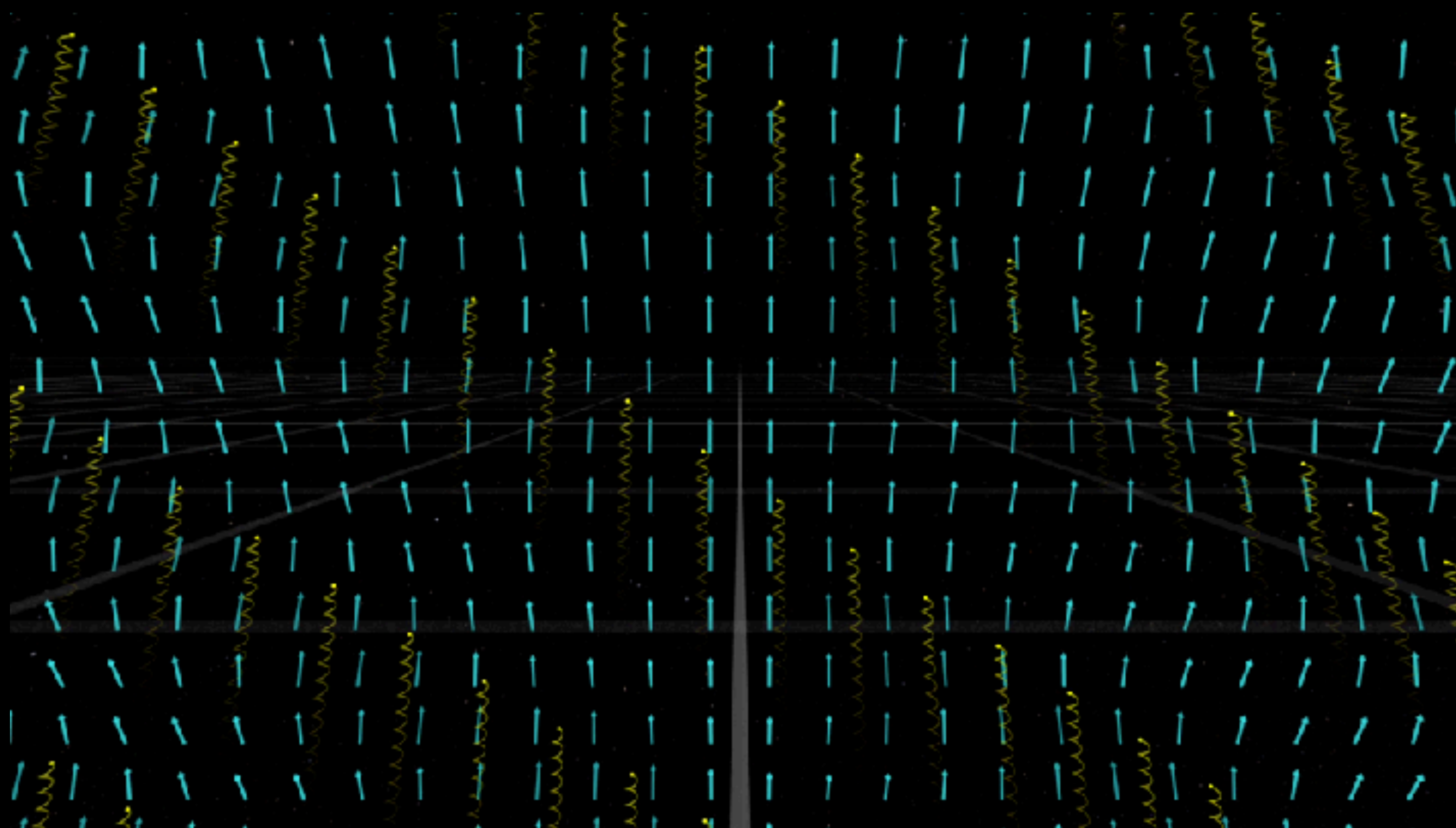
- Resonance always exists
- Not damped by viscosity/conductivity
- Strongly compressible in dust

Gyro:

$$\mathbf{w}_{\rm drift} \cdot \mathbf{k} = \pm v_{\rm wave} \, k \pm \omega_{\rm gyro}$$

- Resonances "peaked" around $k_{\rm crit}$
- Unstable to/below gyro radius
- Weakly compressible in dust



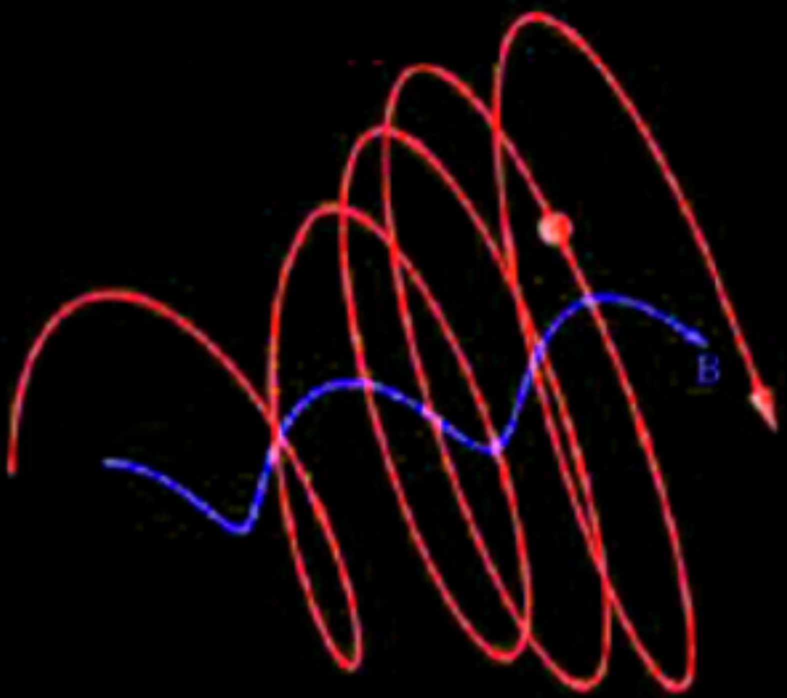



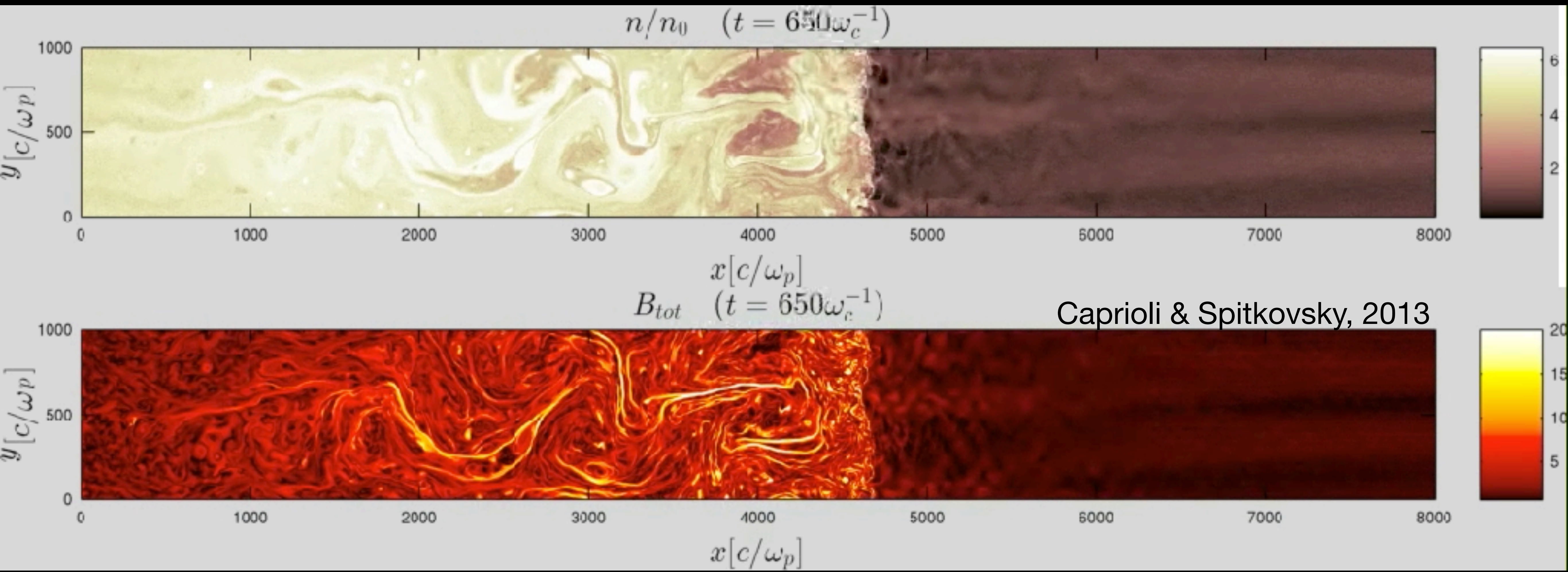
# Cosmic Ray-like Instabilities

PFH & Squire arXiv:1801.10166

Super-Alfvenic drift ⟶

- Non-resonant (Bell)
- Resonant (Kulsrud & Pearce)



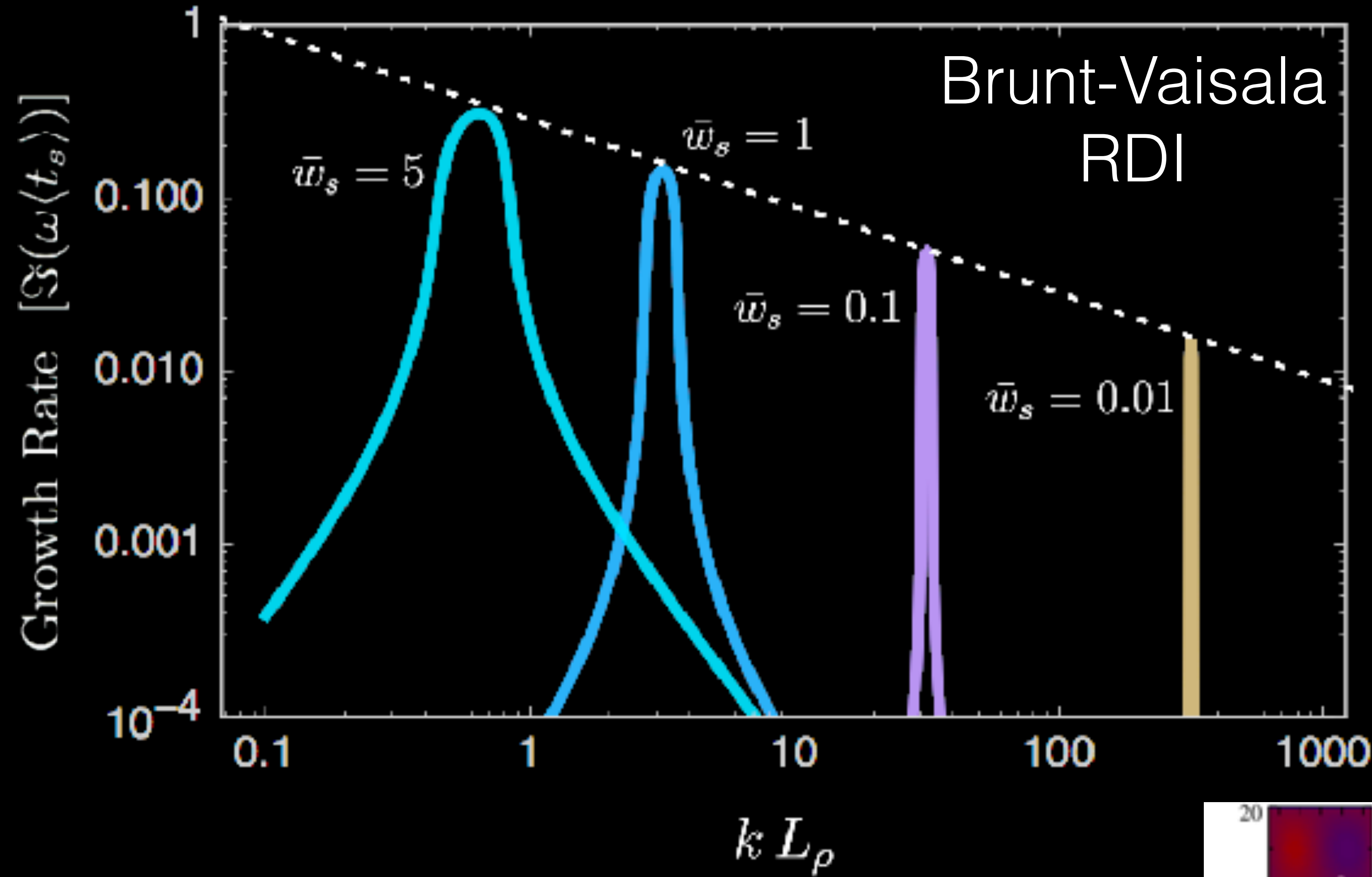

Caprioli & Spitkovsky, 2013

# + Stratification & Bouyancy

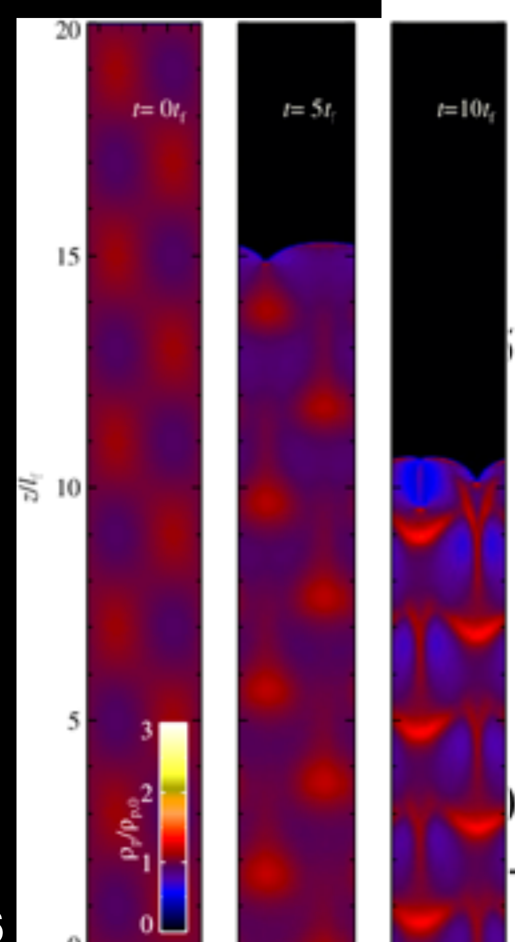
Squire & PFH, arXiv:1711.03975

# Brunt-Vaisala / Bouancy Modes

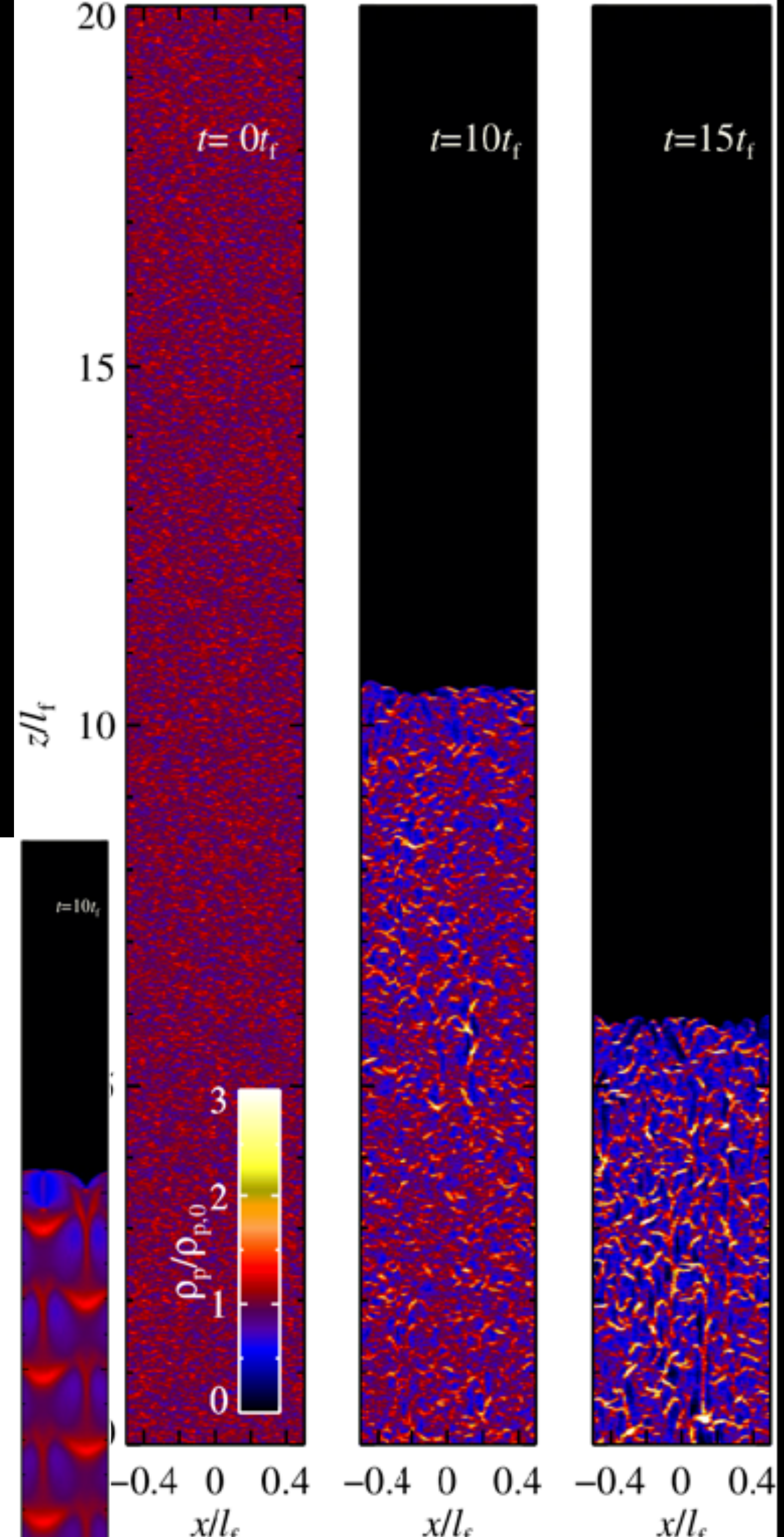
Squire & PFH, arXiv:1711.03975




$$k_{\rm drift} \sim \frac{\sqrt{|g\nabla \ln \rho|}}{|\mathbf{w}|_{\rm drift}}$$




Lambrechts+ 16



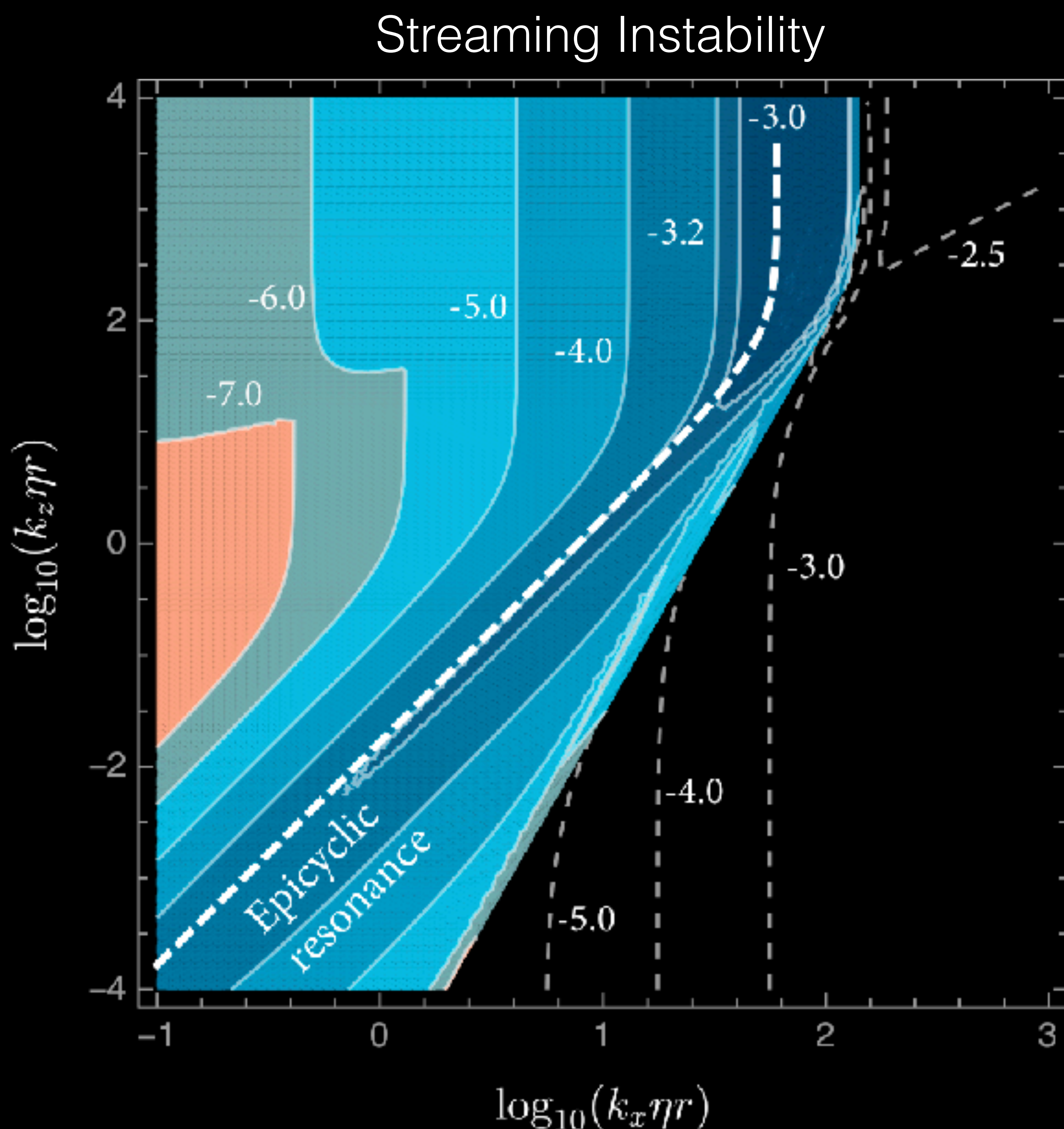
# + Rotation
# (Centrifugal & Coriolis forces)

Squire & PFH, arXiv:1711.03975

The "Epicyclic Resonance" is…
the Youdin & Goodman 2005 "Streaming" Instability!

Squire & PFH, arXiv:1711.03975

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

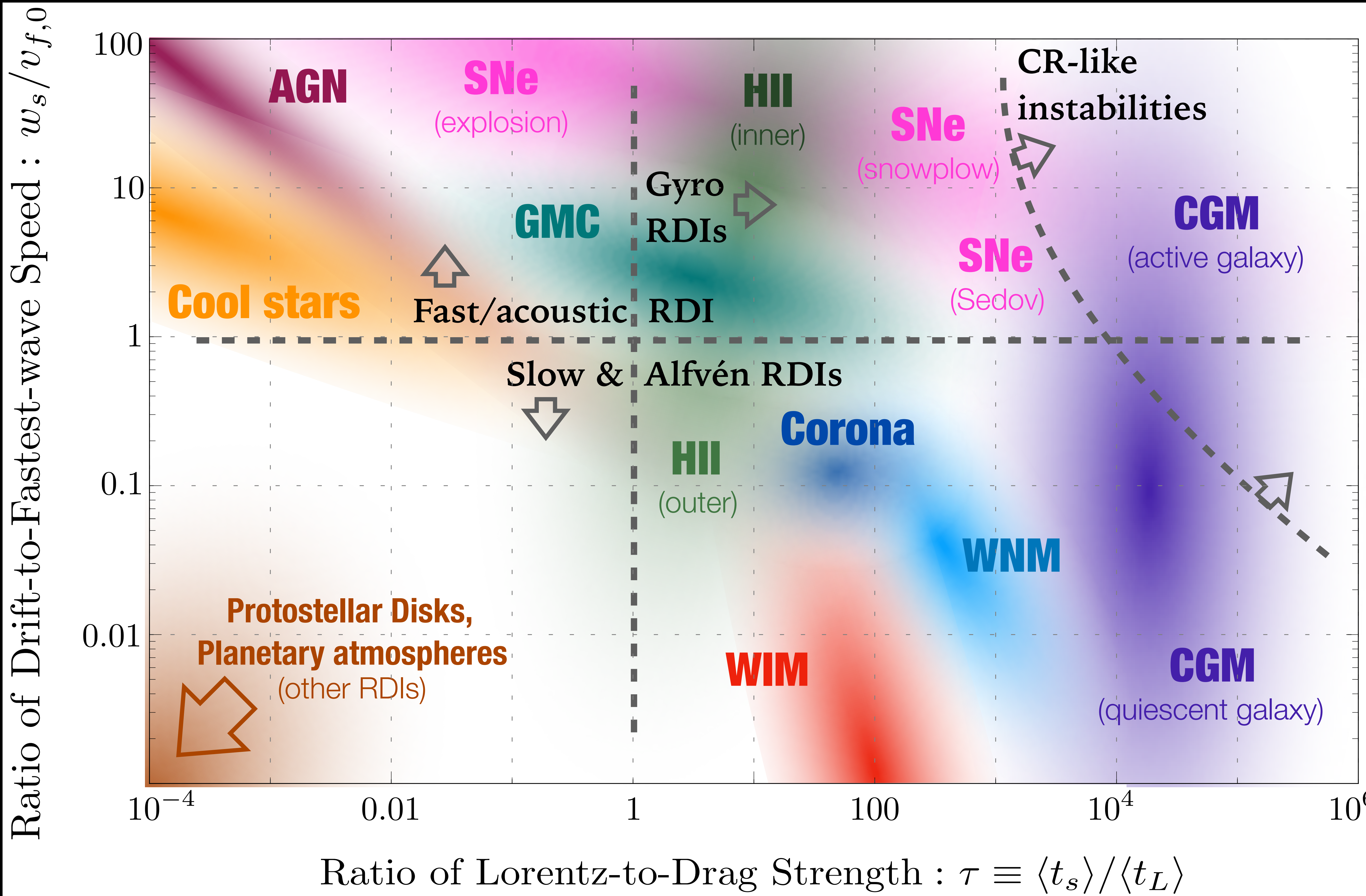


# Astrophysical Consequences

# Astrophysical Systems

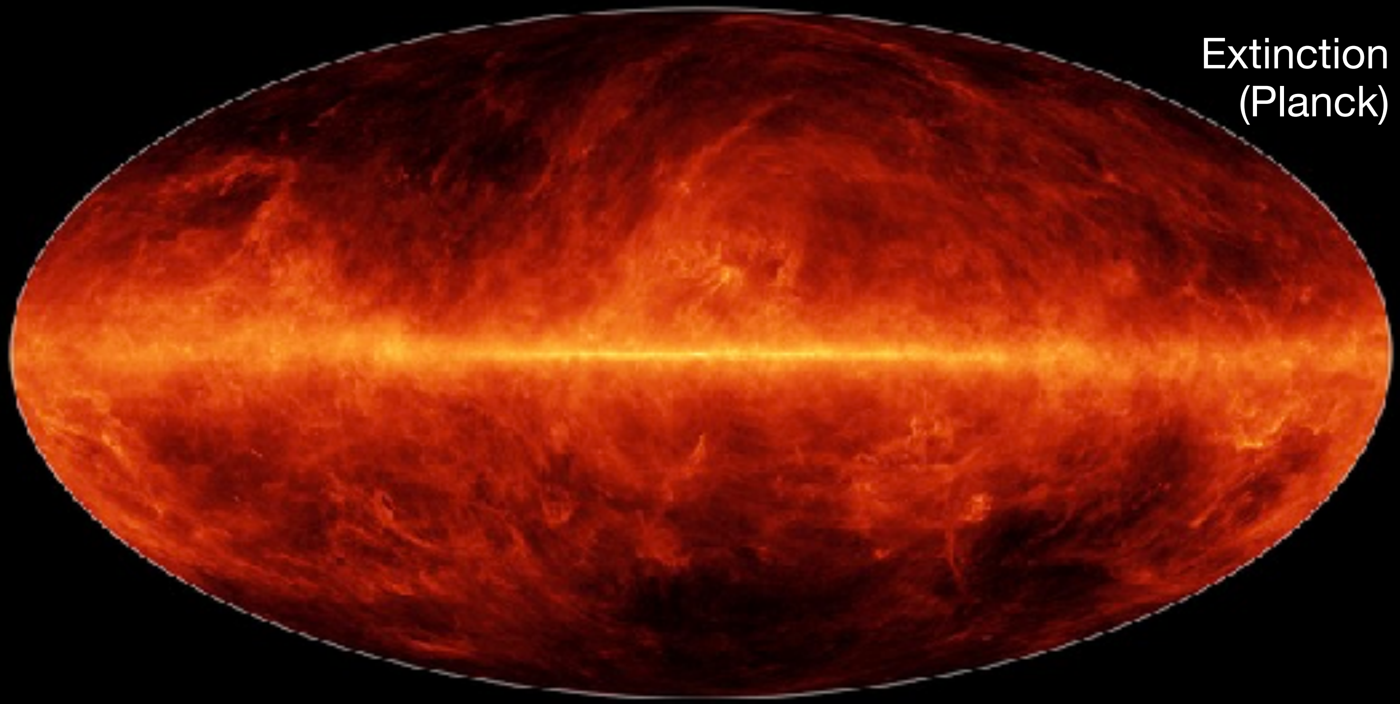
## IT'S ALWAYS THERE: WHAT DOES IT DO?

PFH & Squire
arXiv:1801.10166

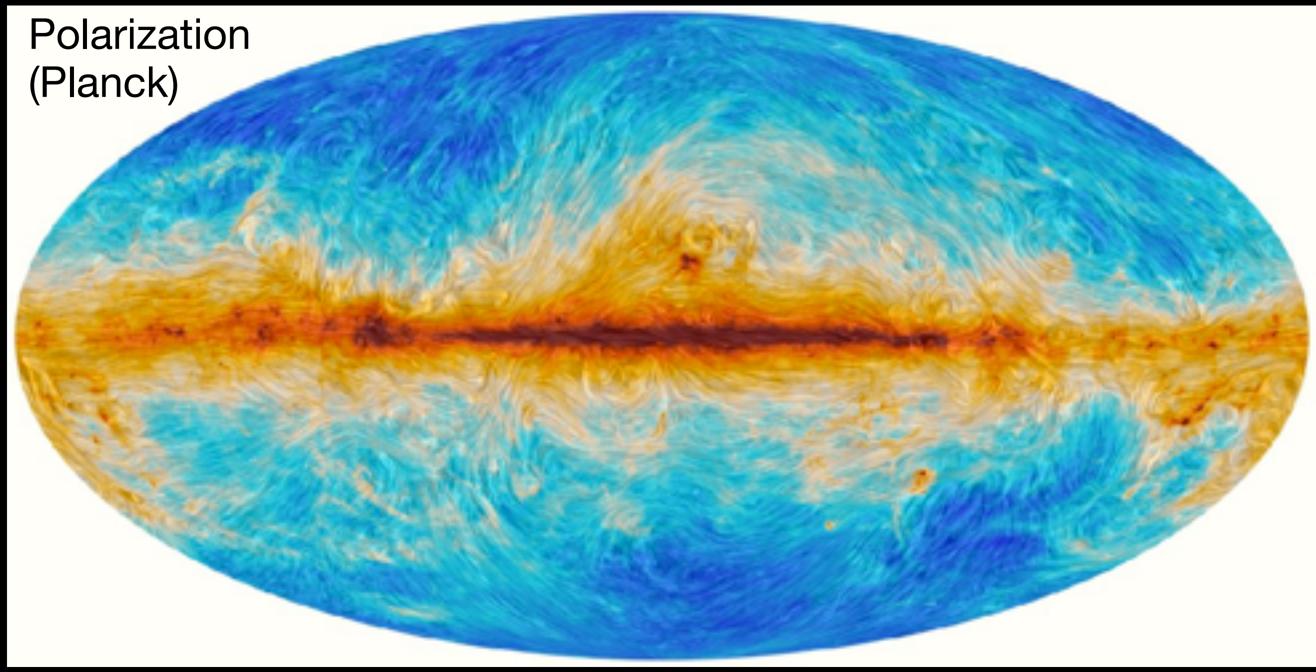


# Diffuse ISM (WIM, WNM, CNM)

$T_{grow}$ ~ 10 yr [1e10 cm] - 70 Myr [100 pc]

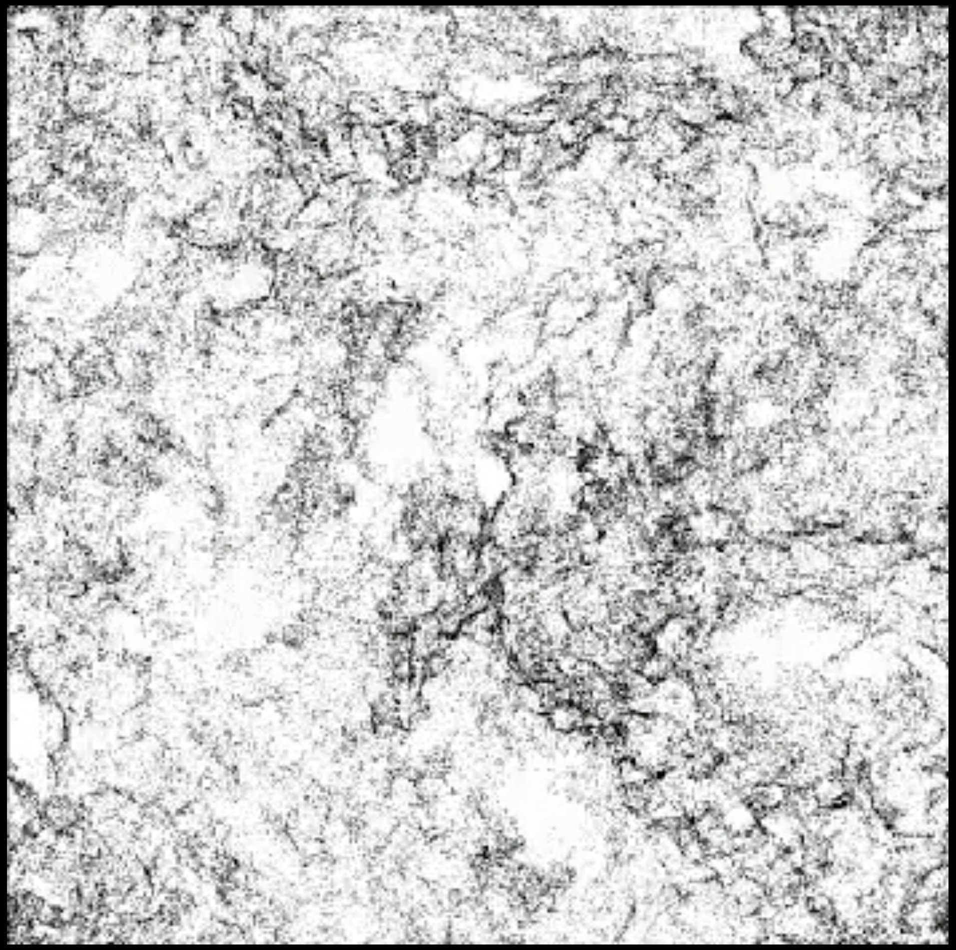


Extinction (Planck)



Polarization (Planck)

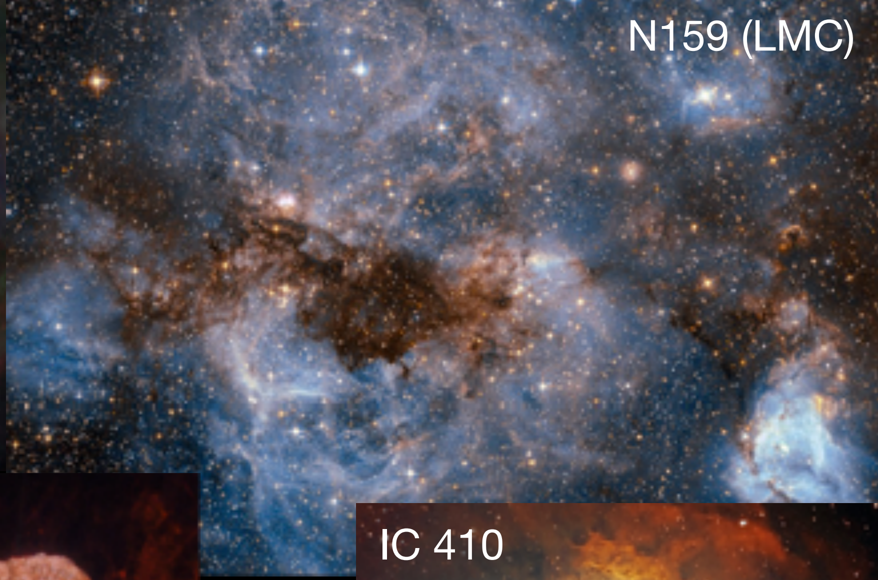
- ISM dust growth (enhanced + modified)
  - "Similar" grains cluster together
- Extinction curve variations (e.g. Schlafly+ 16)
- Influence scintillation "cascade"?
- Large grain excess in solar neighborhood? (e.g. Kruger+ 15, Alexashov+ 16)
- Grain alignment/polarization (E/B mode ratio; e.g. Caldwell+ 17)



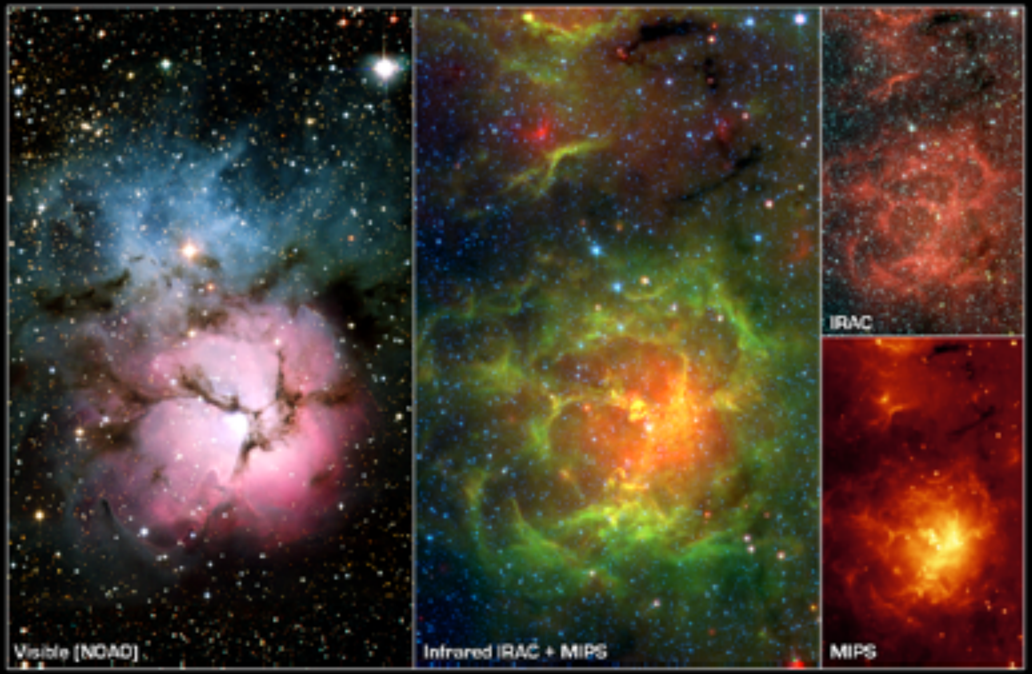
# HII Regions

$T_{grow}$ ~ hours [km] - 0.1 Myr [pc]

- Cooling & chemistry (Kennicutt 95)
- Expansion rates & density structure (Akimkin 17)
- Ionizing photon escape rate (Anderson+ 10)
- Arcs / rings / streamers / whiskers (O'Dell+ 02, Apai+ 05, Topchieva+ 17)
- Apparent grain-size variations (Relano+ 16, Hankins+ 17)

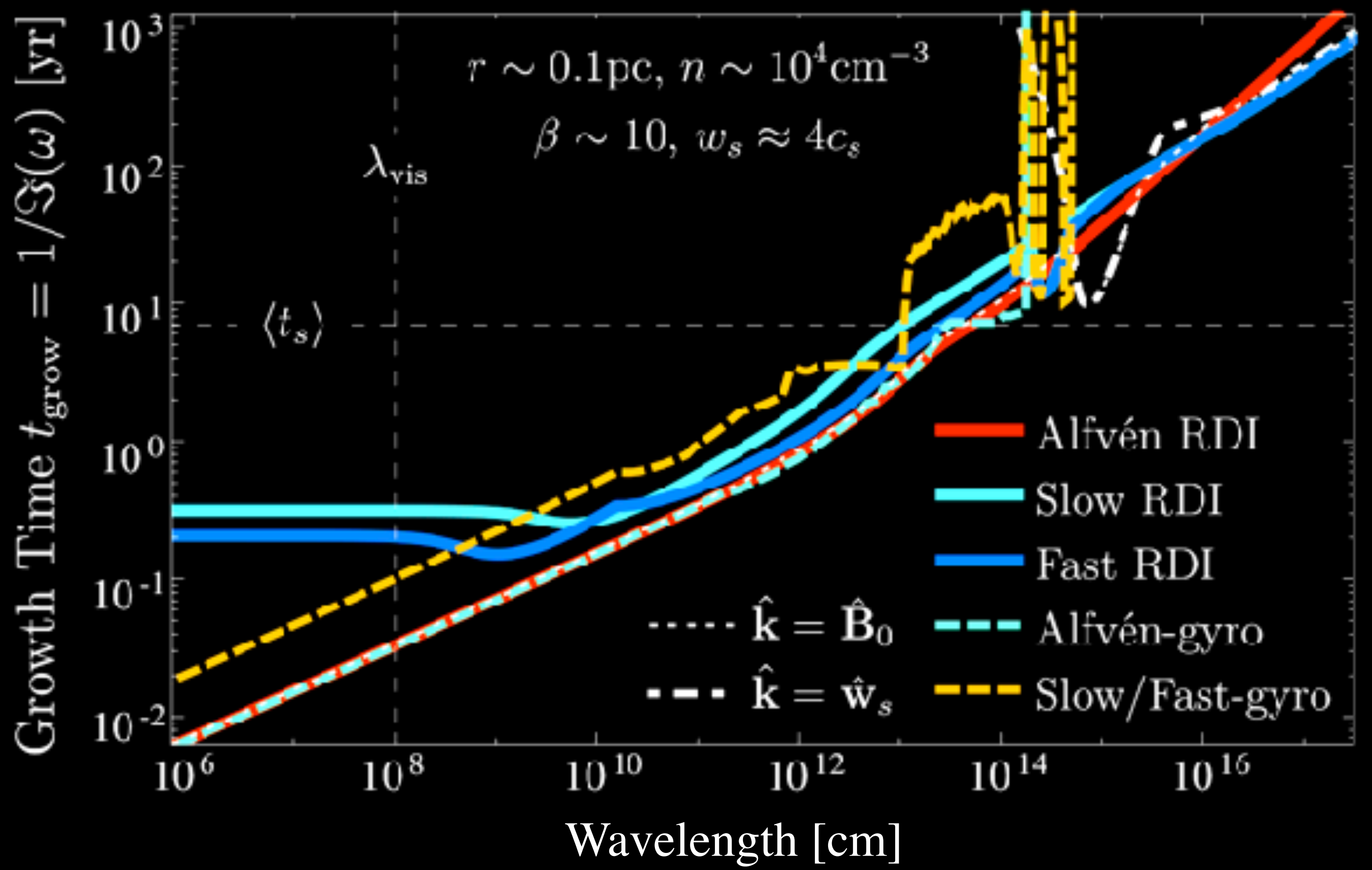





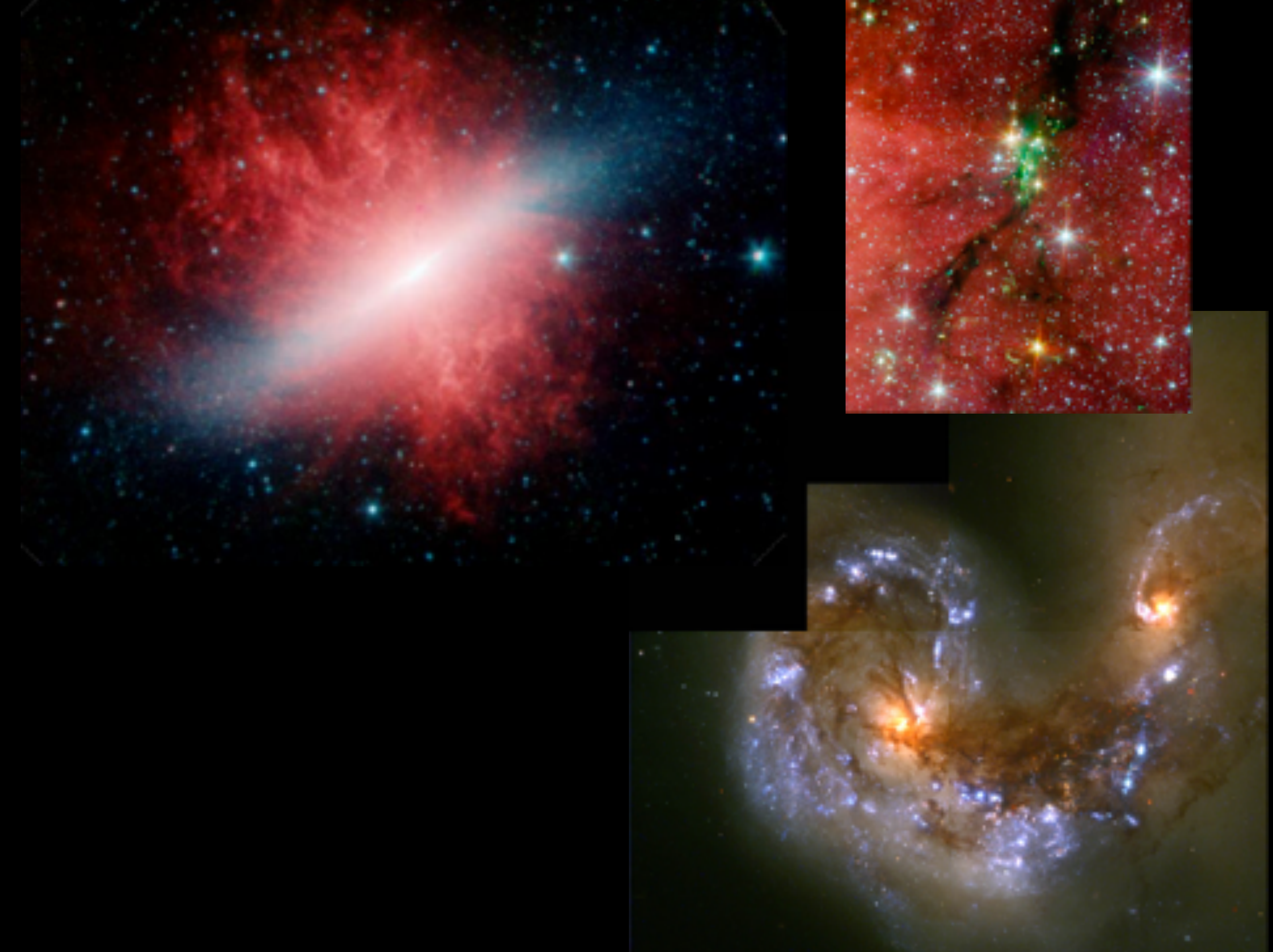

Trifid Nebula/Messier 20 Spitzer Space Telescope • IRAC + MIPS

NASA / JPL-Caltech / J. Rho (SSC/Caltech) ssc2005-02a

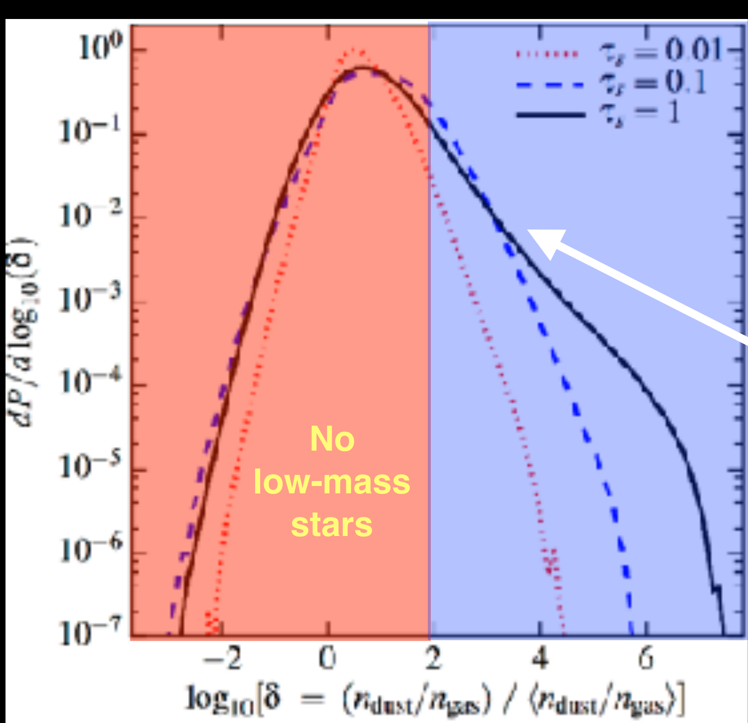


# Starbursts, GMCs, Circum-Nuclear Disks

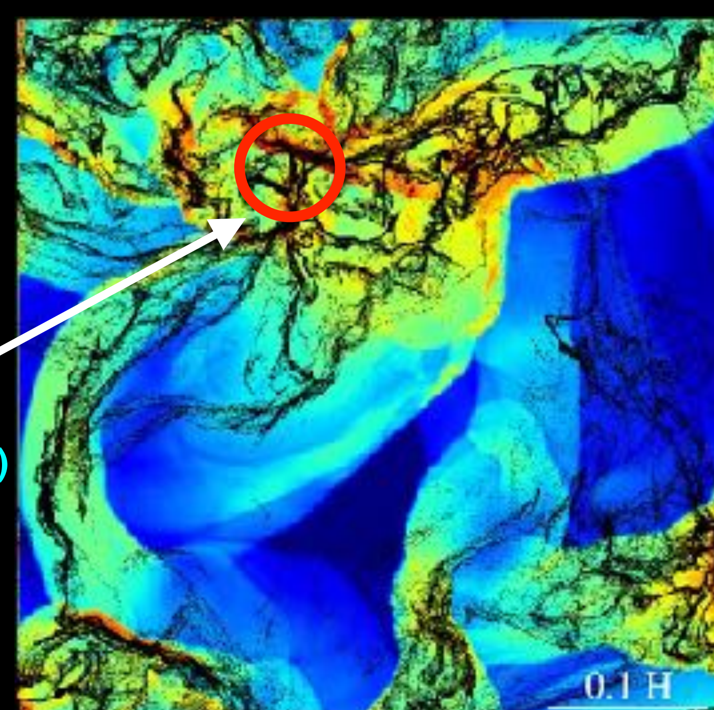
$T_{grow} \sim 0.3\ \mathrm{Myr}\ [L_{0.1pc} / n_{100}]^{1/2}$

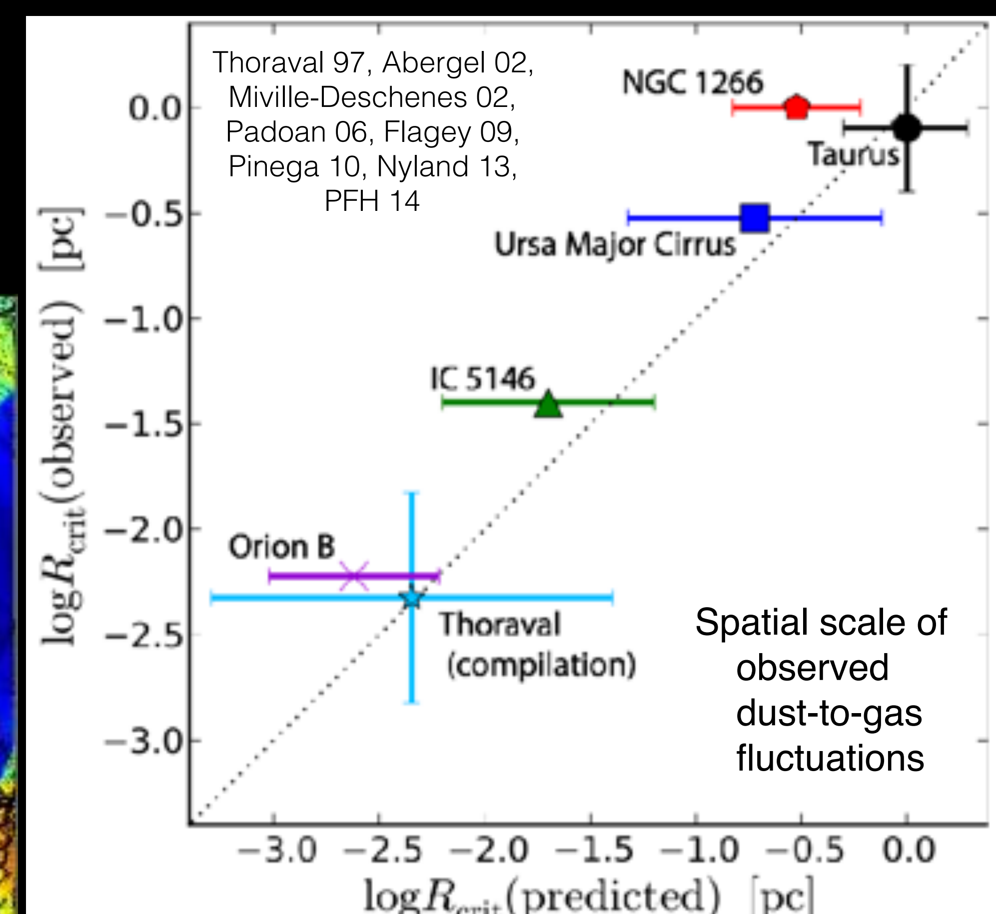


- Radiation-pressure driven winds?
  (can they form? does dust just blow out?)
- ISM dust growth (enhanced+modified)
- Extinction curve variation/dust-to-gas fluctuations
- Chemistry on grains
- 1st low-mass star formation (PFH+Conroy '16)



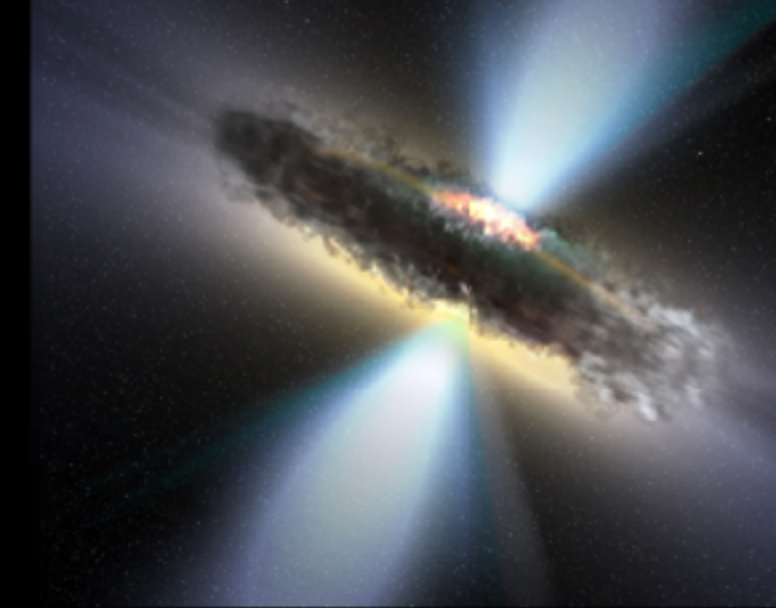

low-mass stars ([Z/H] > critical)

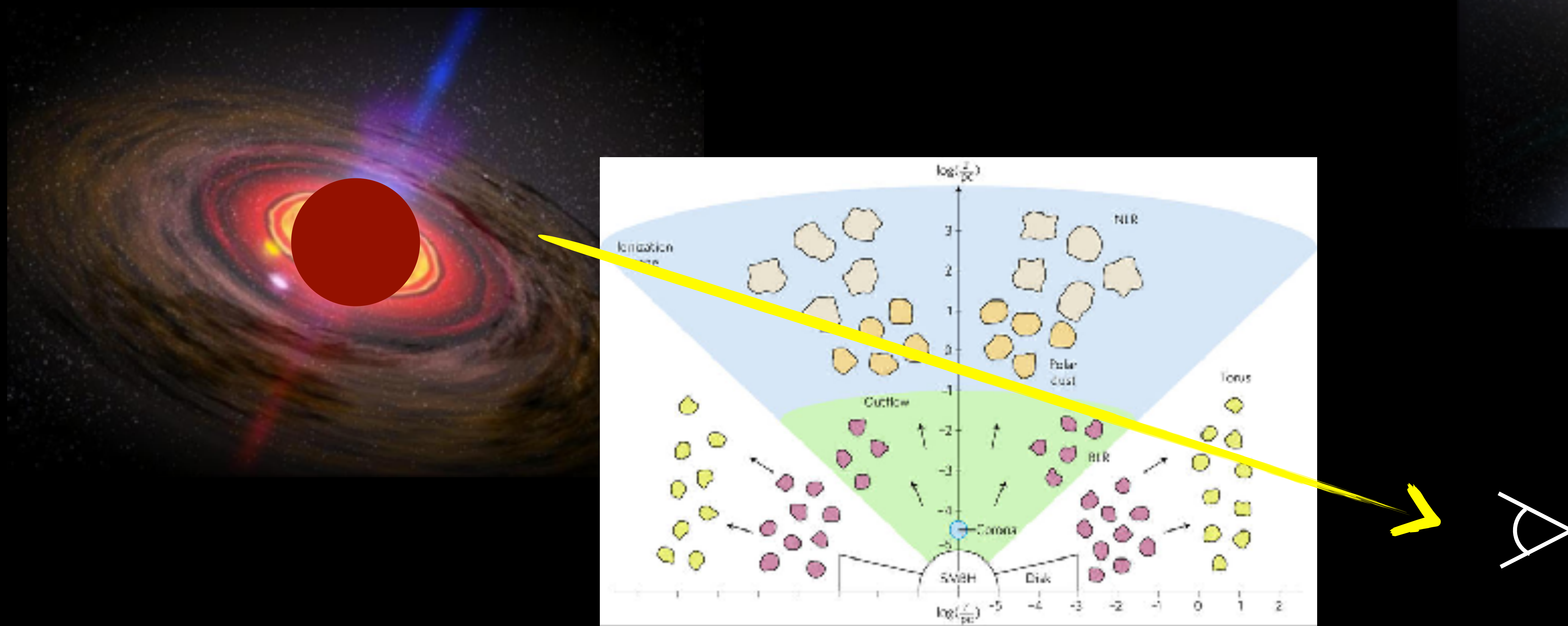


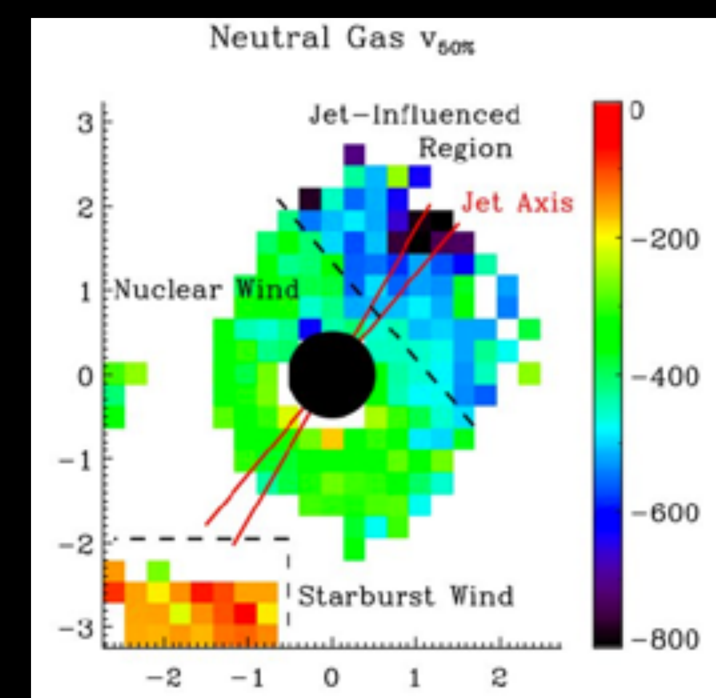



# AGN & Quasars

$T_{grow} \sim$ 10 hr [viscous scale ~ au] - 10 yr $(L/0.1pc)^{2/3}$





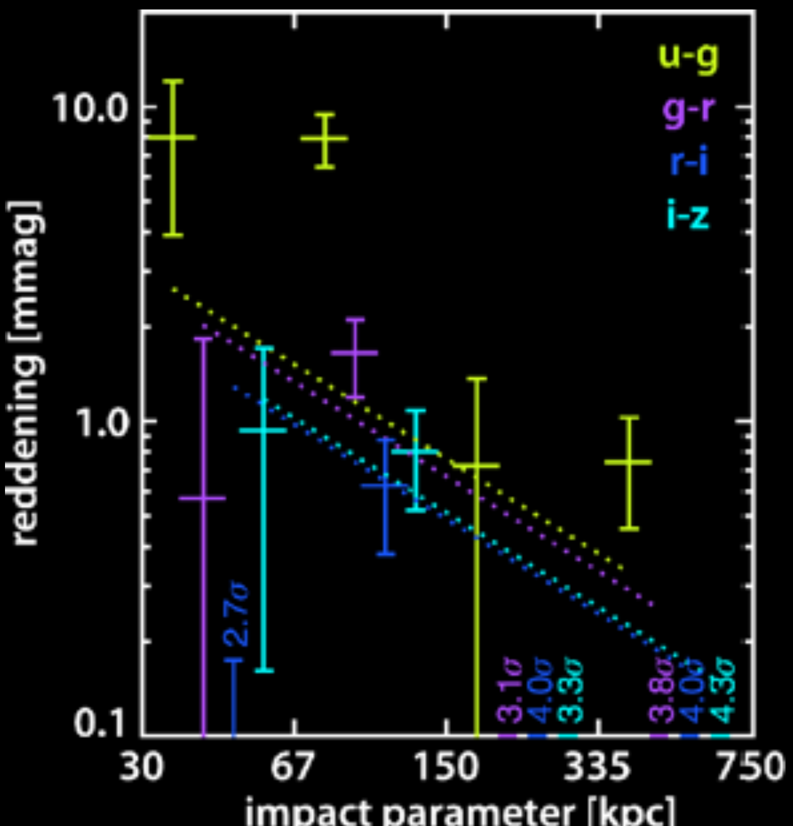

Mrk 231 (Veilleux)

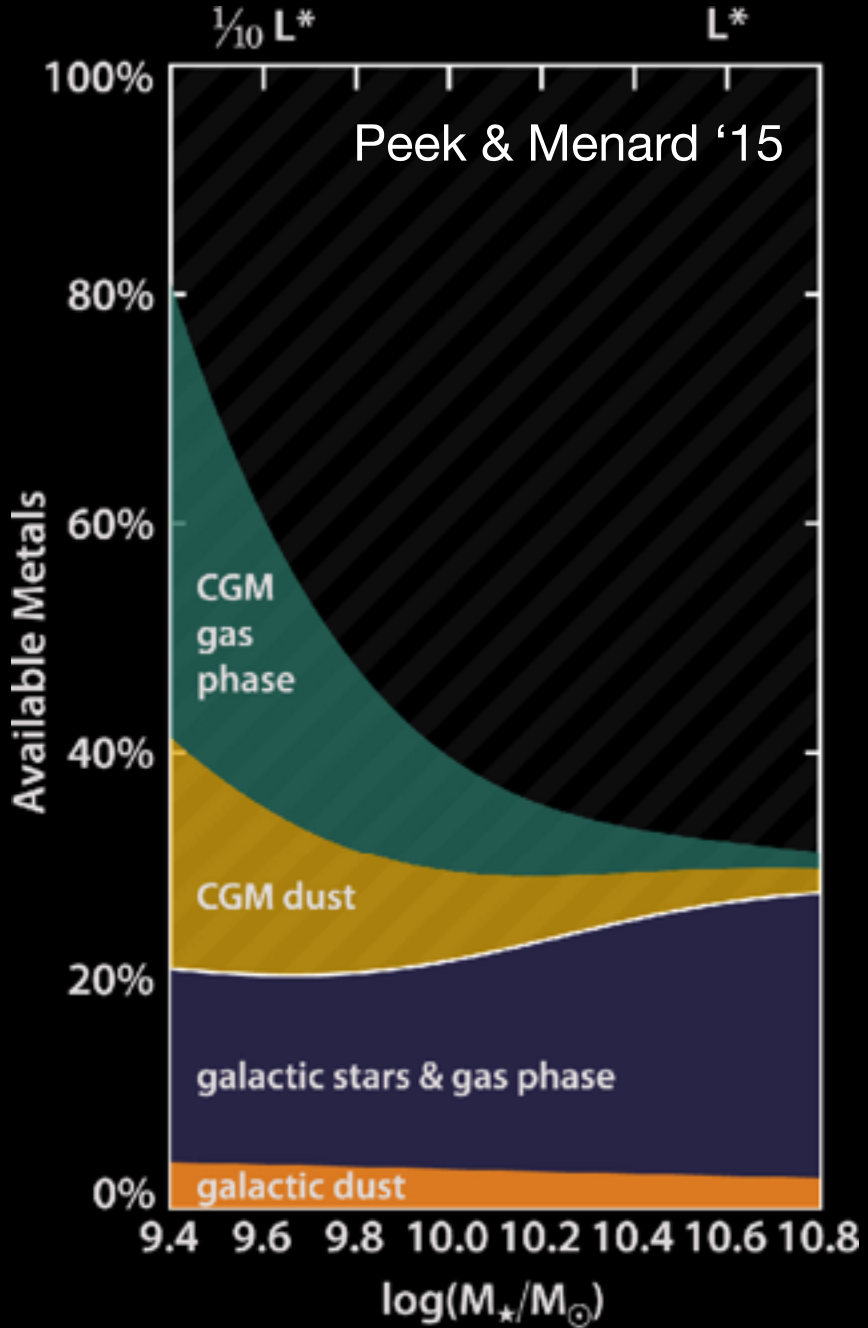
- "Changing Look" AGN: timescales ~months - years (at >pc)
- Wind-launching (BLR, NLR, Torus; Murray+05, Elitzur+ 06, etc)
- "Clumpy Torus" (observed obscuration; Honig+Kishimoto review)
- Optical-X-ray obscuration discrepancies (Hickox, Silverman, Maiolino+ 06)

# CGM & IGM

$T_{grow}$ ~ 1000 yr [pc] - Myr [kpc] (~100 kpc from QSO),
or > Gyr (around 'quiescent' galaxy)

- "Ejection" of dust grains to CGM (e.g. Ishibashi+Fabian 16) & survival vs. sputtering (retention; Menard+ 10)
- Cooling & molecule formation in galactic outflows (depends on dust survival+clumping; Richings+Faucher-Giguere+ 18)
- Scattering (reflection nebulae/light echos)
- Cosmic ray-like instabilities:
  - thermalize radiative power
  - re-align B-fields?



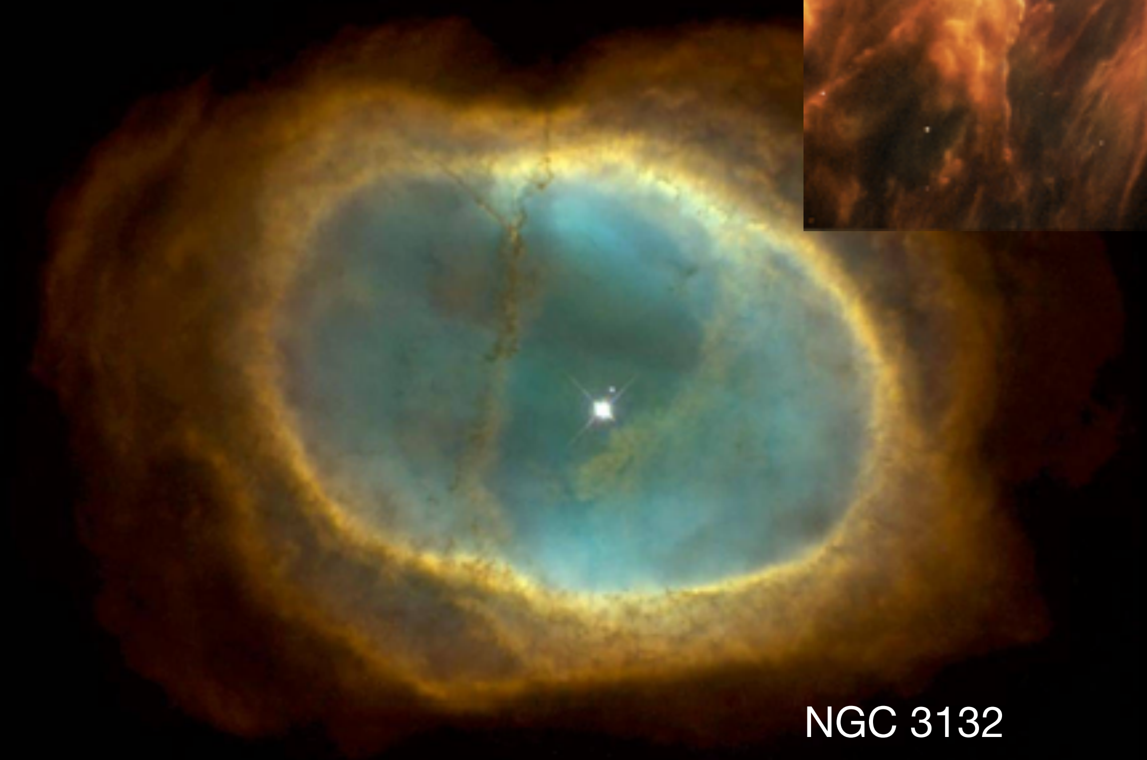



# Cool-star/AGB Winds

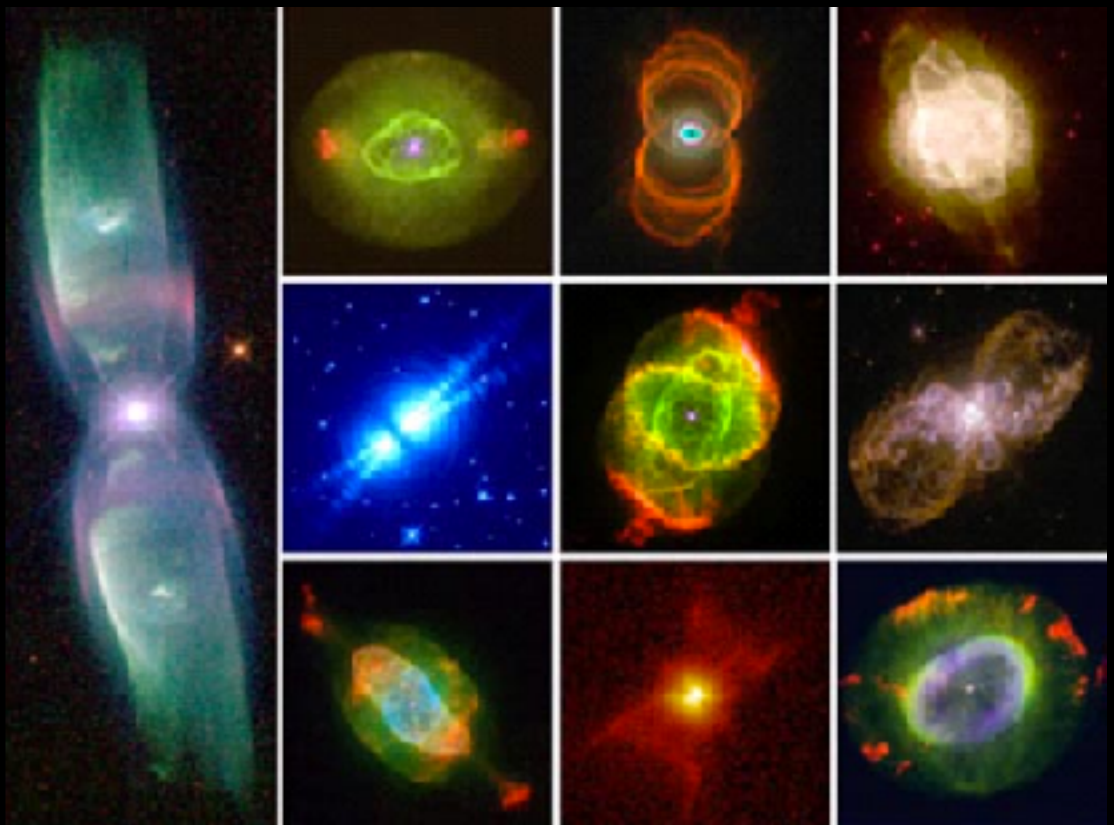
$T_{grow}$ ~ 0.1 sec [~10cm viscous] - days [~100 $R_{sun}$] - years [>> au]

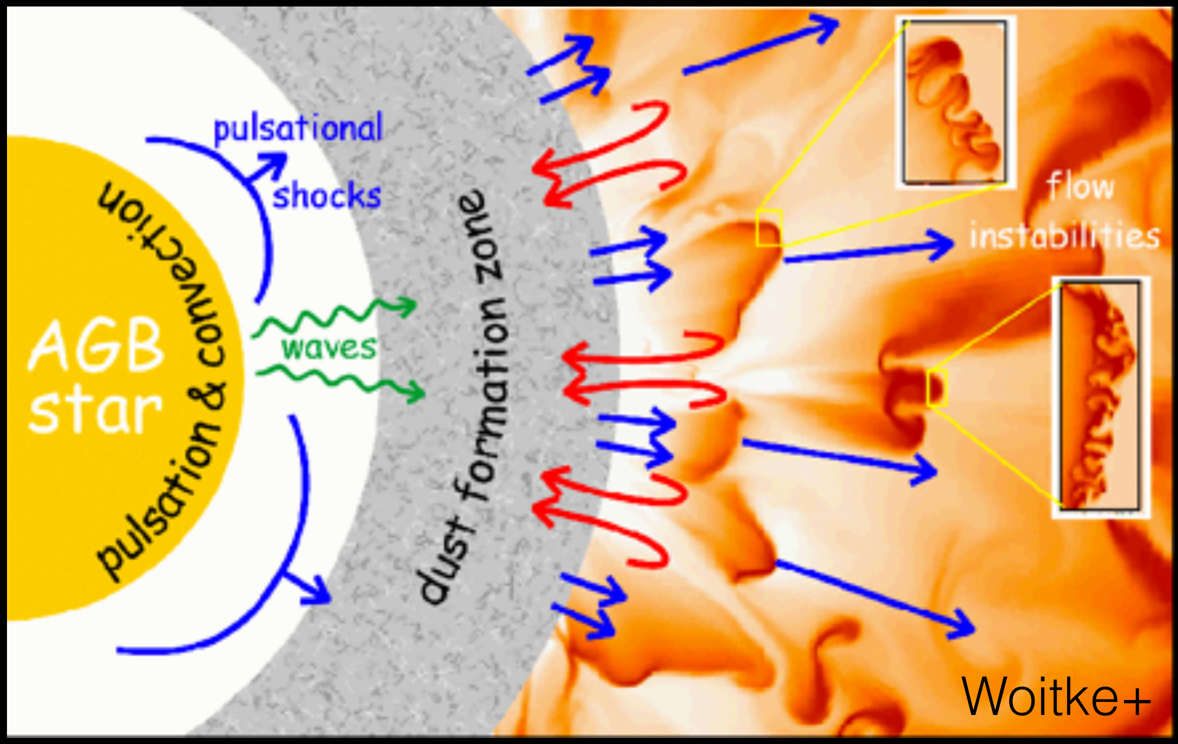
Bug

- Dust shells/arcs/streamers
  (e.g. Deguchi '97, Matsuura+ 09)
- Clumpiness & time-variability
  in outflow (e.g. Cox+ 12)
- Wind-launching (does it work?)



NGC 3132



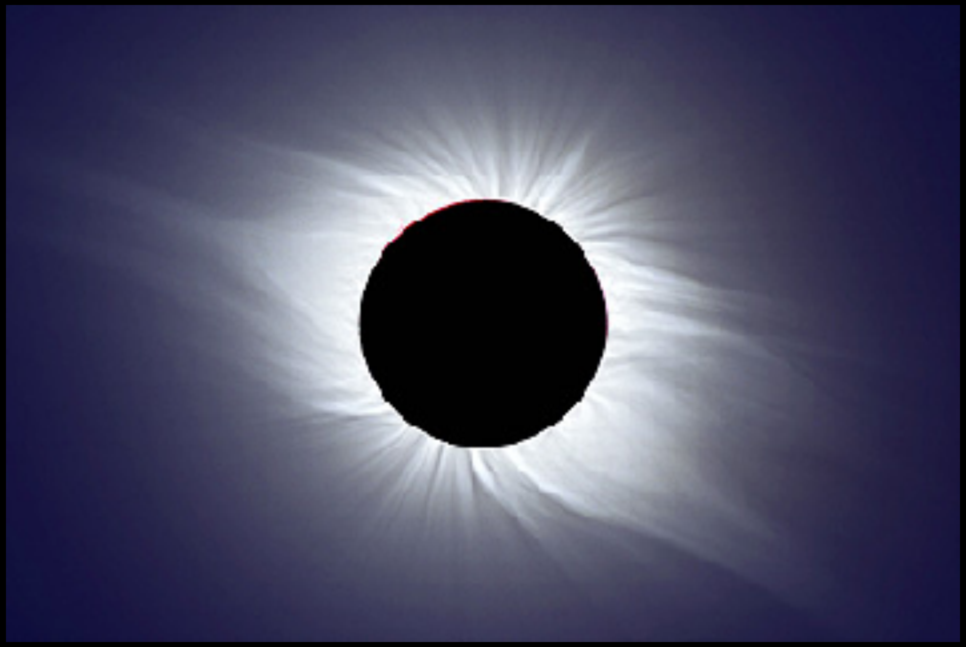


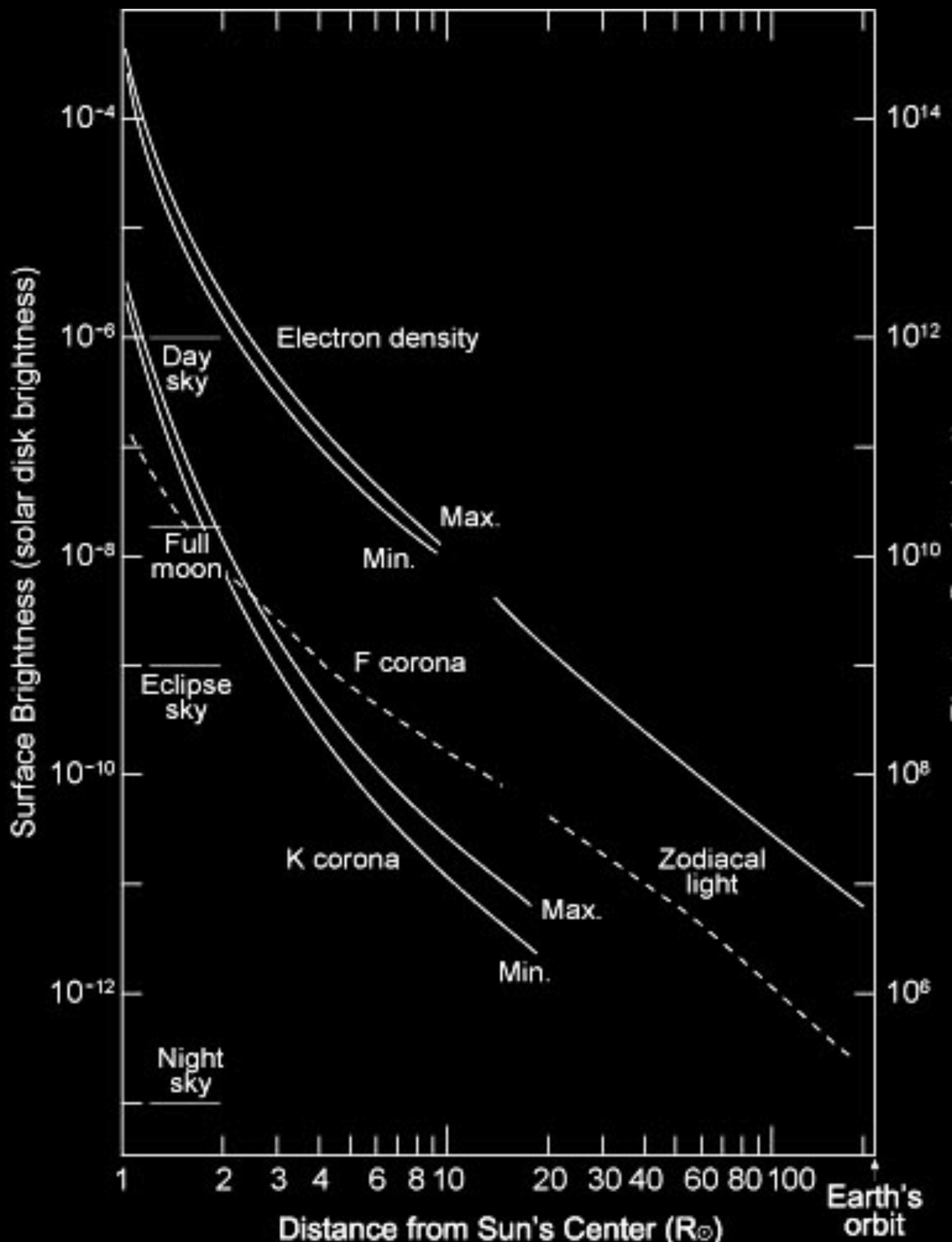

Woitke+

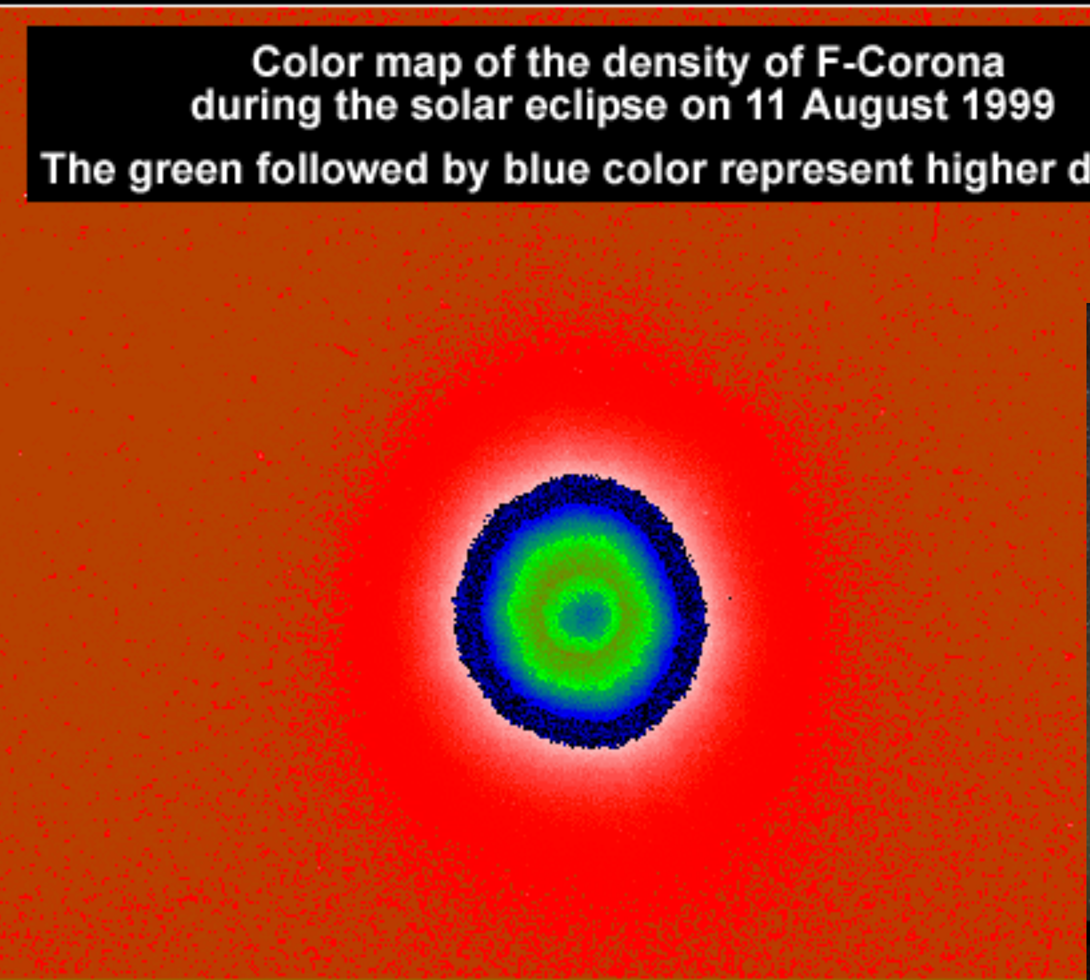
# Coronal Dust

$T_{grow}$ ~ 1 sec [km] - days [Rsun] x $(\rho_{gas}/100\,\rho_{dust})^{1/2}$

- Rings / streamers / time-variability
  (e.g. Mann+ 00, Shopov+ 08, Kobayashi+ 09)
- Dust fluctuations in solar wind
  (e.g. Ragot+Kahler 03, Strub+ 15)

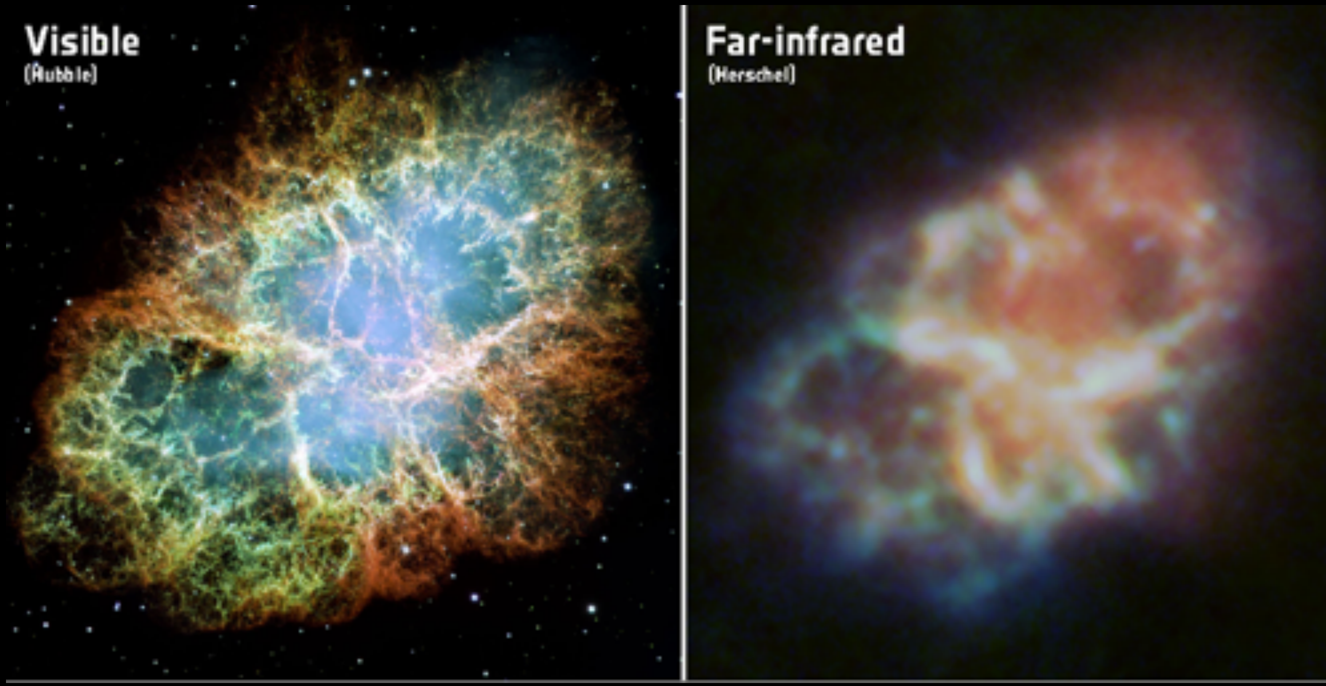




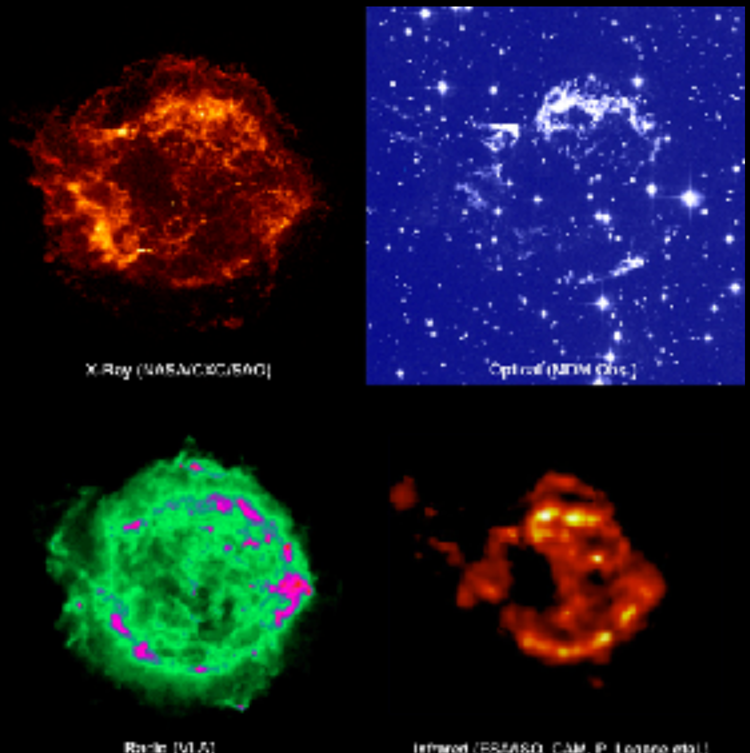



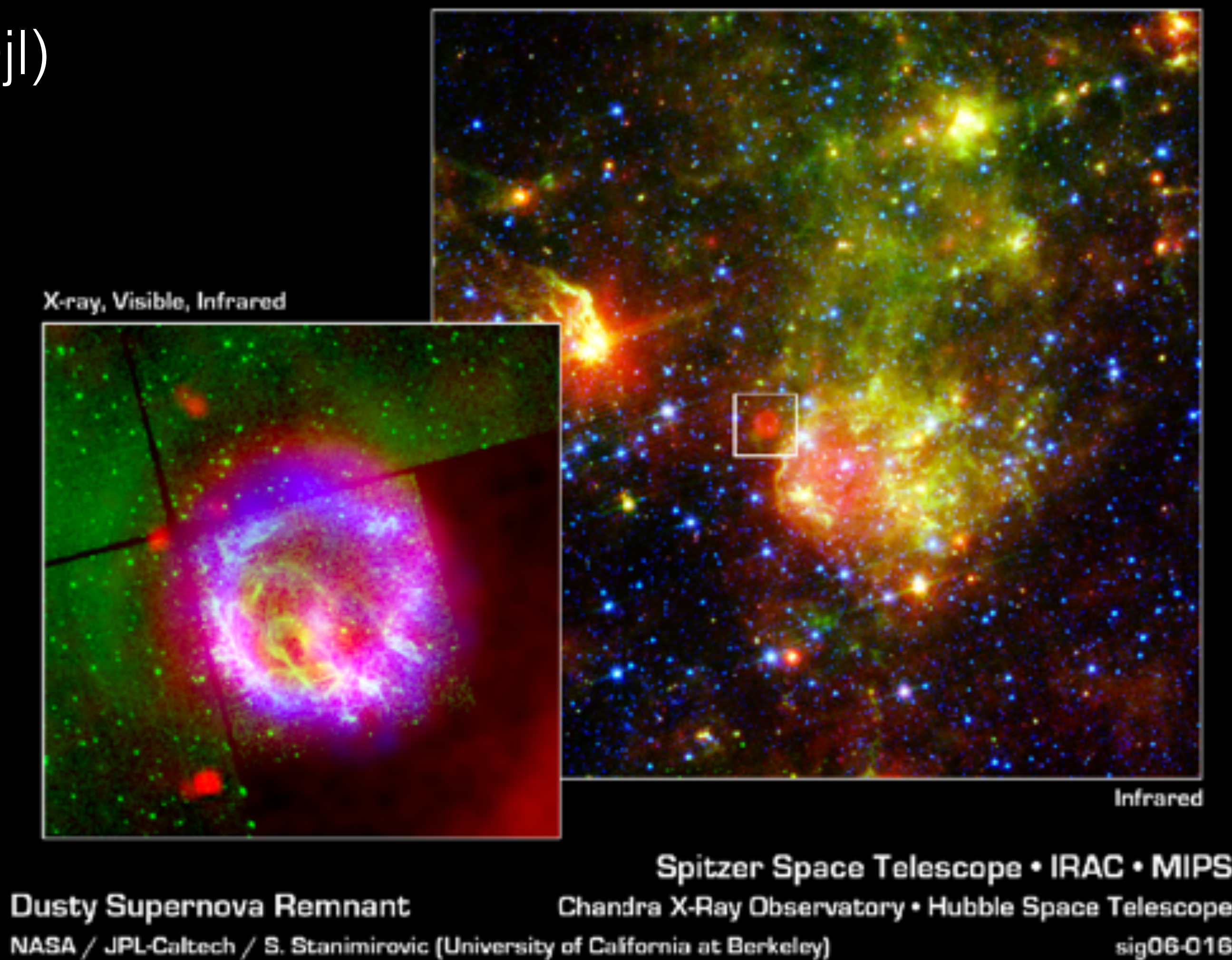

# SNe Ejecta [various stages]

$T_{grow}$ ~ 3 yr [accelerated by SNe radiation]
~ 3-40 yr [free expansion], >Myr [Sedov],
~ 300 yr [gyro - Snowplot], ~$t_{expand}$ [Alfvén]



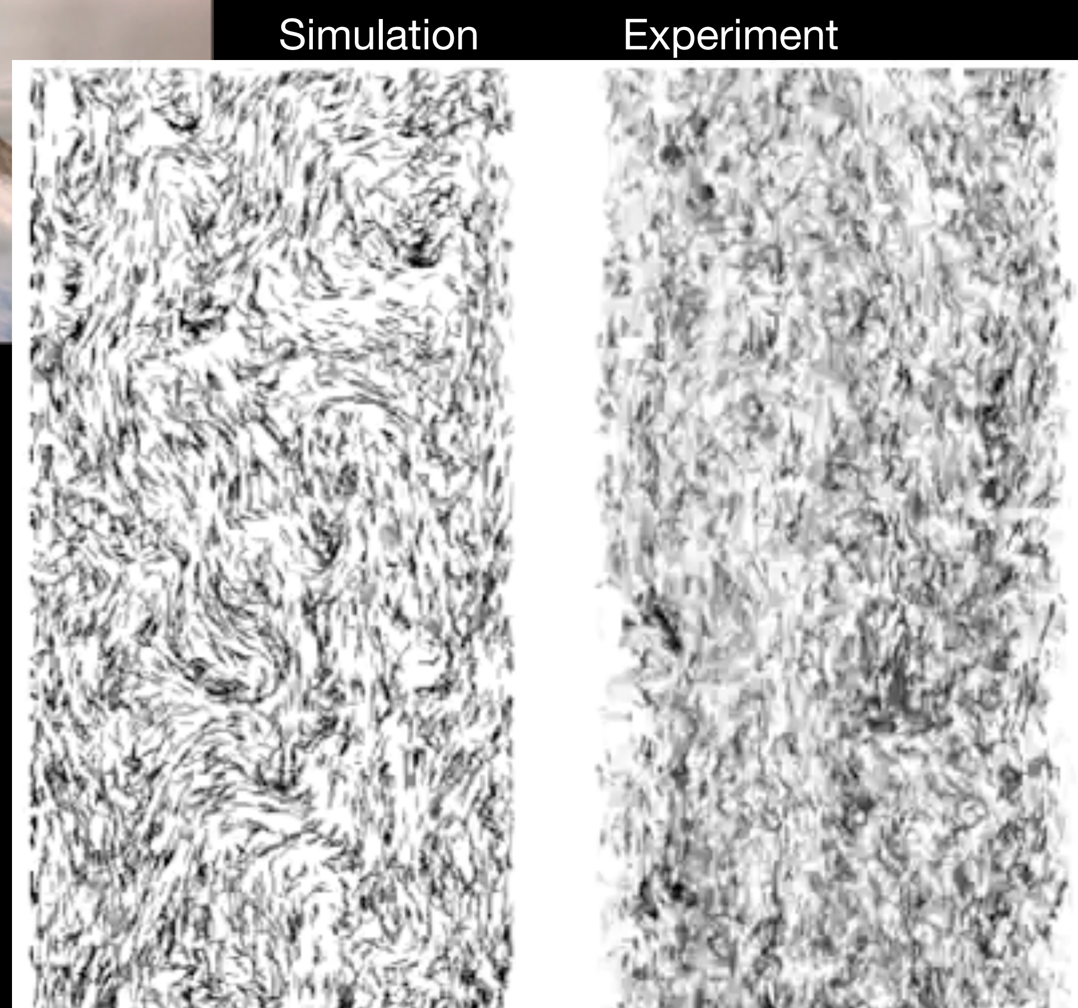

- Dust shells/arcs/streamers (again)
- Grain survival in reverse shock (Bianchi+Schneider 07, Silvia+ 10)
- Large grains in SNe ejecta (e.g. 1987a, 2010jl)

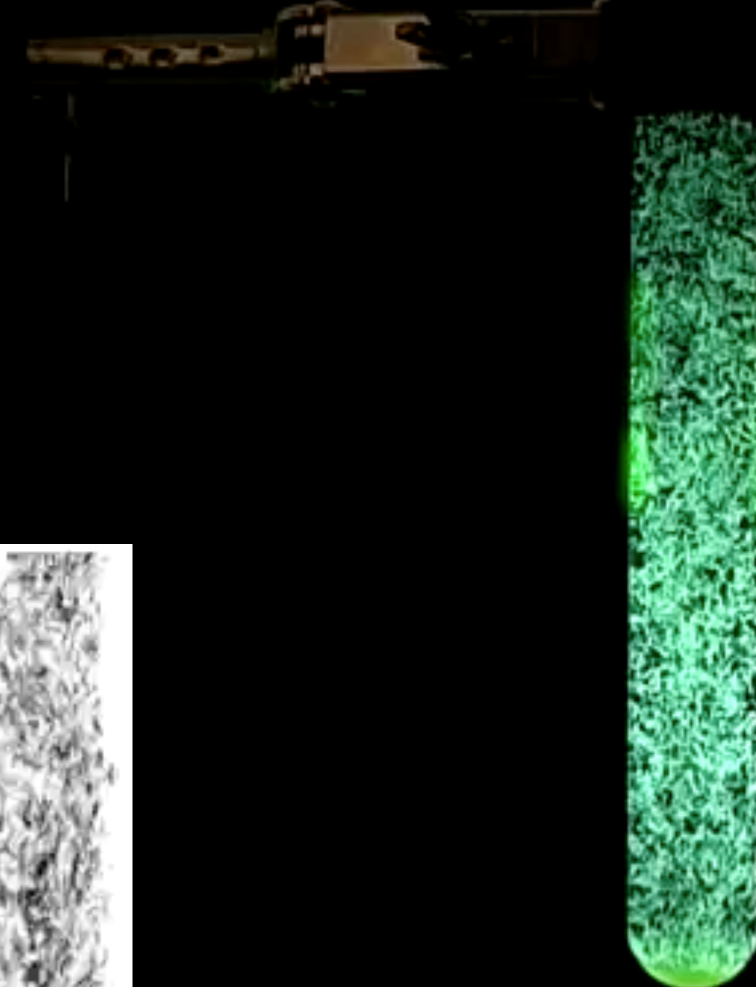




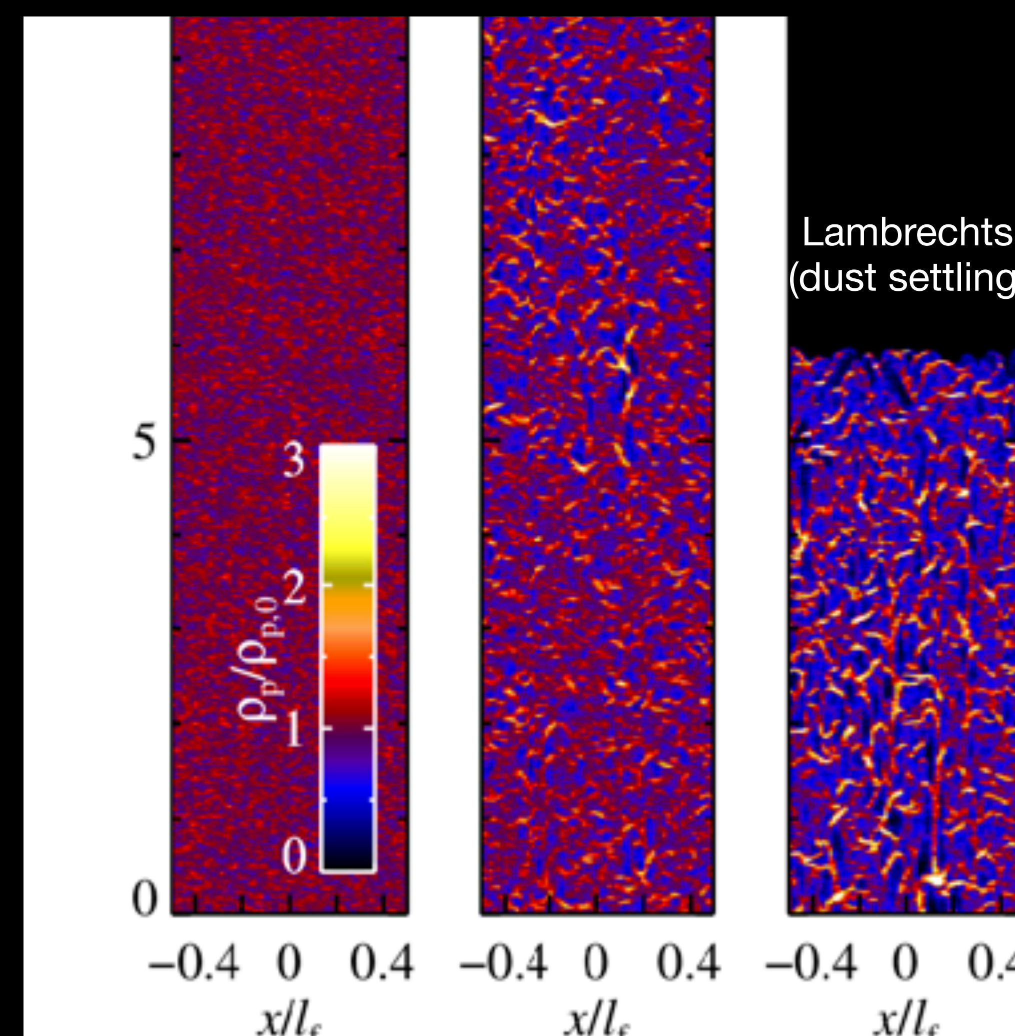
# Atmospheres

$T_{grow} \sim (\rho_{gas}/\rho_{dust})^{1/2} N_{BV}^{-1}$ [few bouyancy times]



Guazzelli & Hinch (experiment)

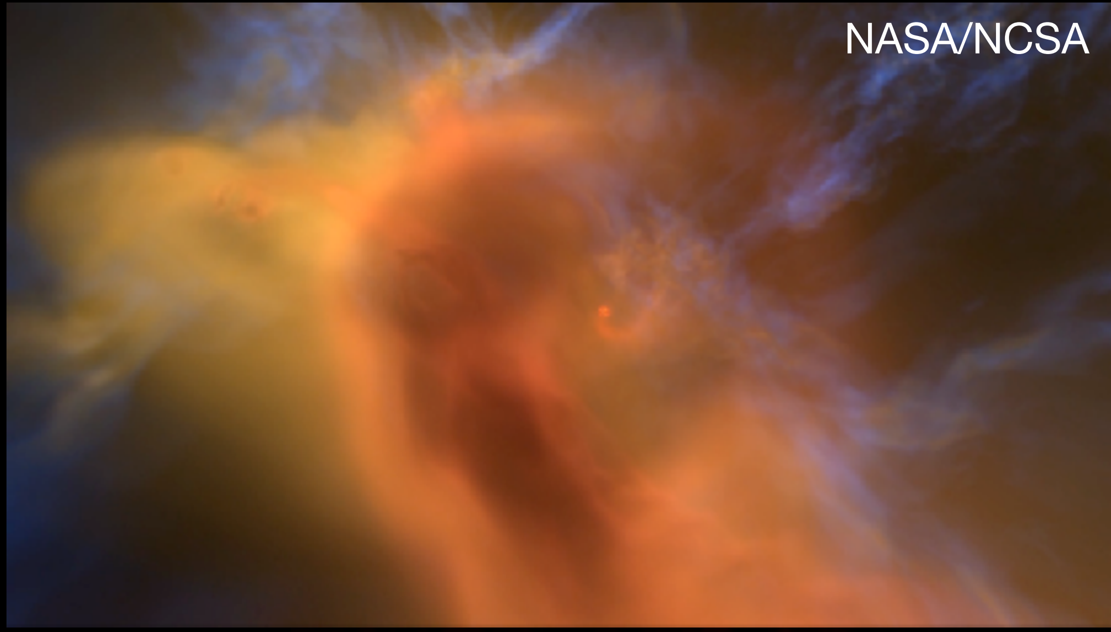



Lambrechts (dust settling)

- “Pebble Accretion” & Planetary atmosphere accretion
- Volcanic ash settling & raindrop seeding
- Colloidal sedimentation (sediment beds in water)

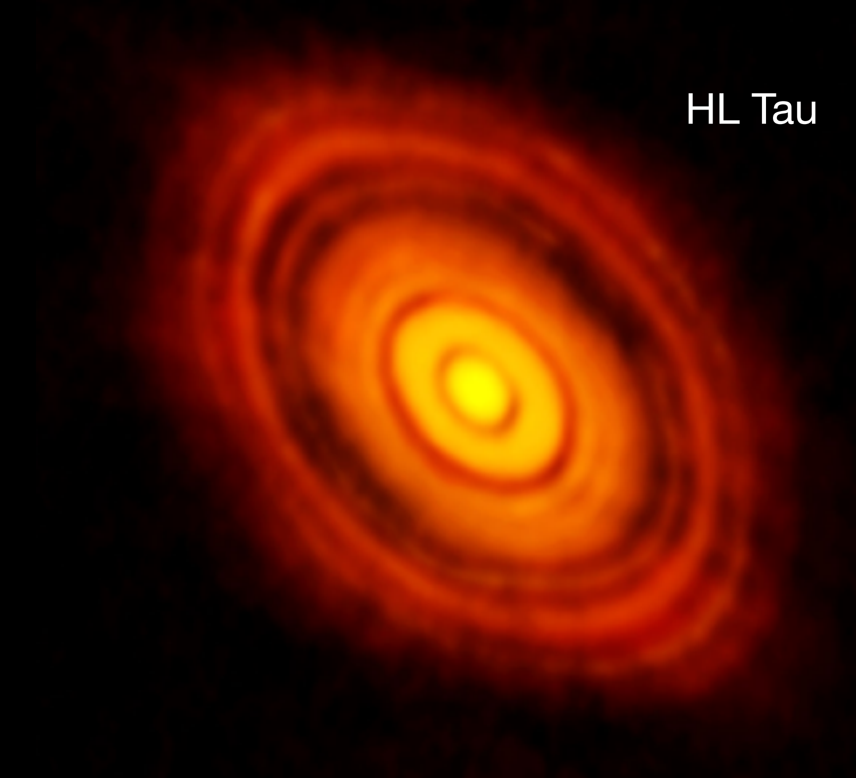
# Proto-Stellar & Proto-Planetary Disks

$T_{grow}$ ~ 1 - 1000s of orbital times [settling or streaming]

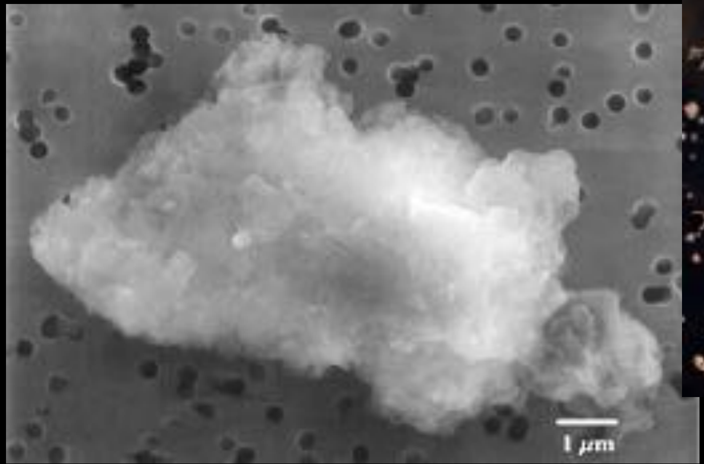



$$|\mathbf{w}|_{\rm drift} \ll c_s$$

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

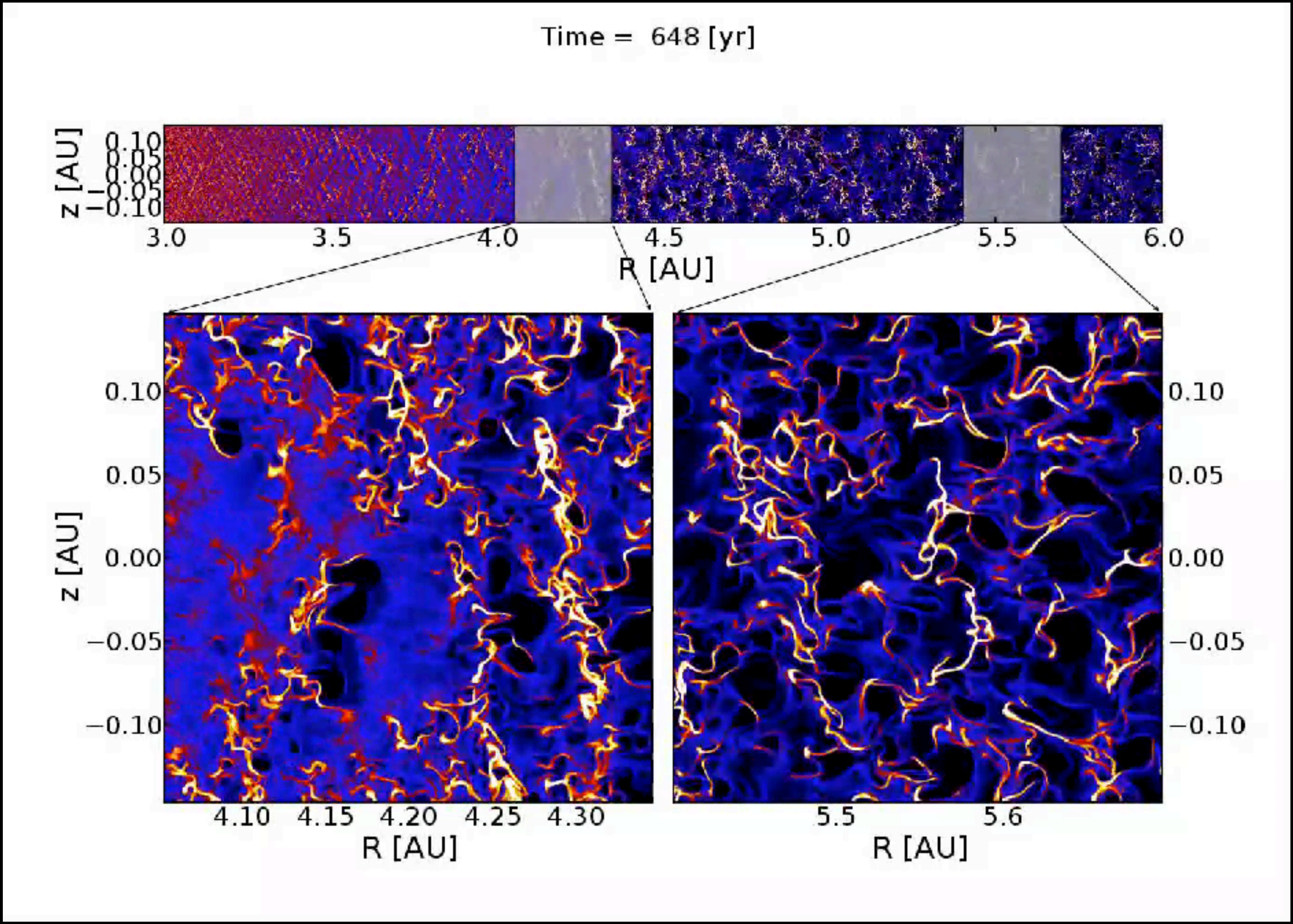



- Coagulation / sticking of grains (pairing, different velocities)
- Dust "traps" / gaps (long-wavelength modes)
- Planetesimal formation
  (GI of "pebble piles"; "pebble accretion")
- "Seeding" midplane structure



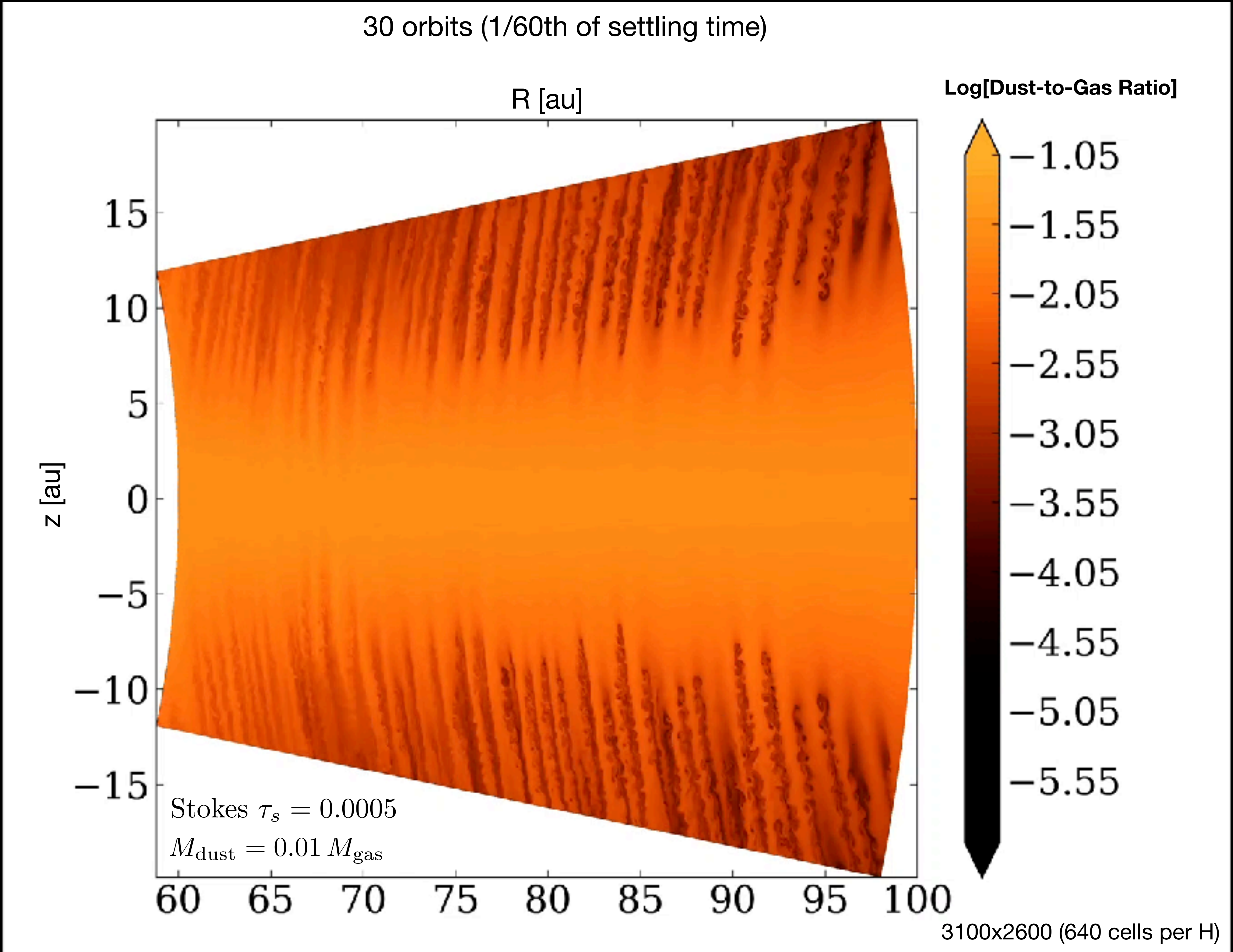

# The “Streaming” Instability: (midplane epicyclic RDI)

Youdin & Goodman 2005; Simulations by Johansen+Youdin ‘07



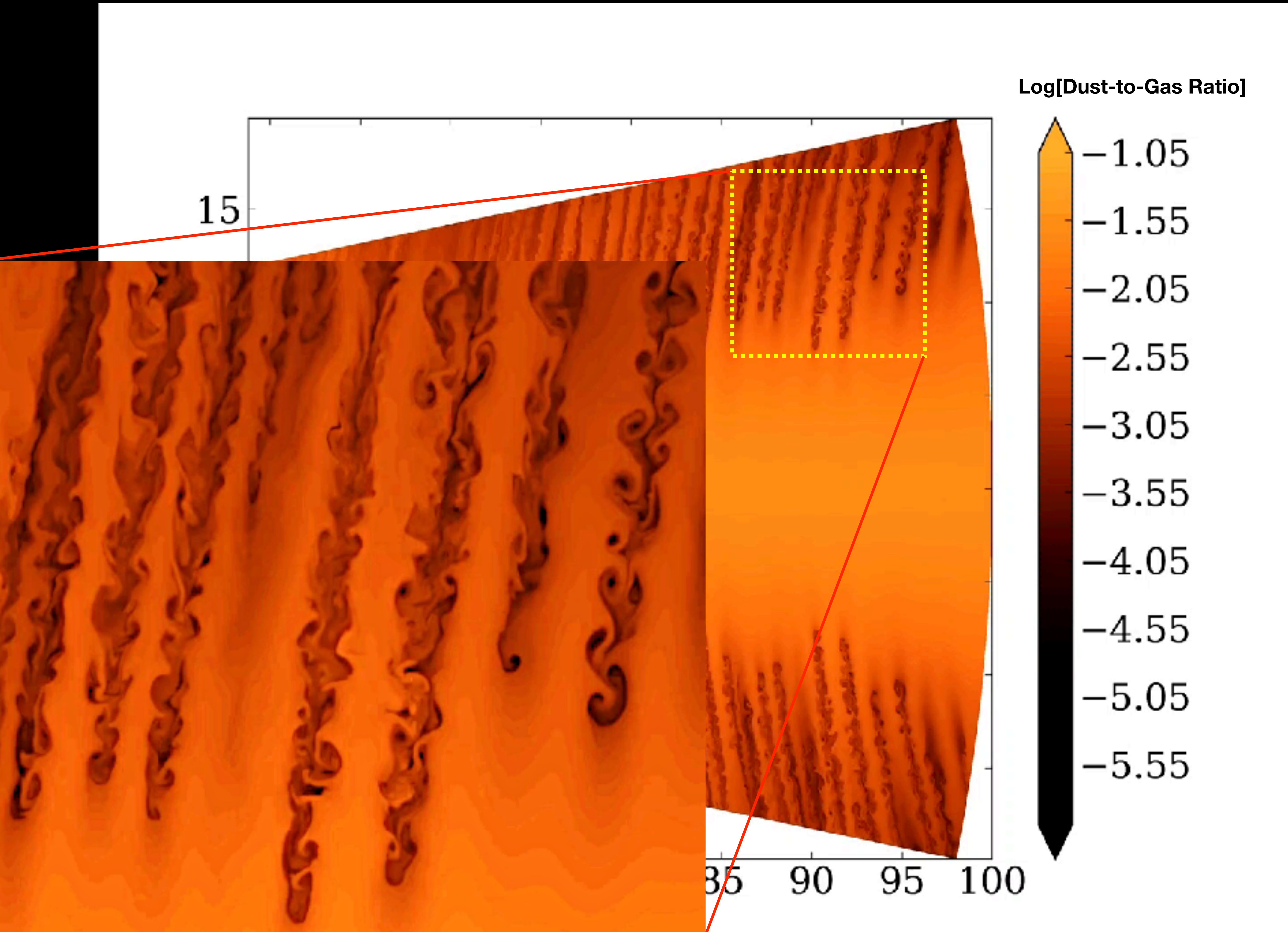
# The “Settling” Instability: Vertical-Epicyclic-Brunt-Vaisala RDI

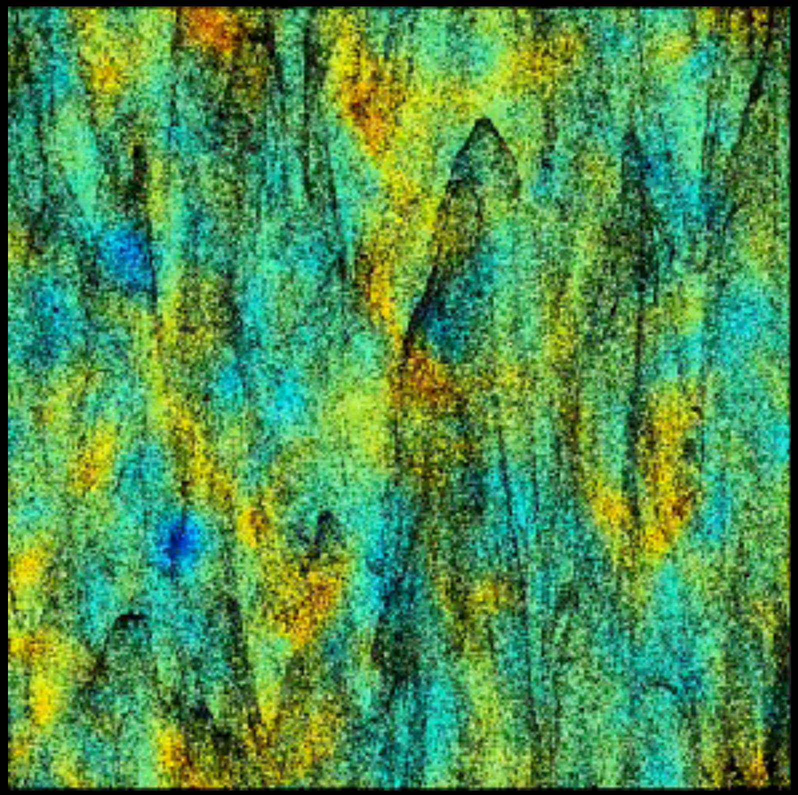
Early Development (Flock, Squire, PFH in prep.)

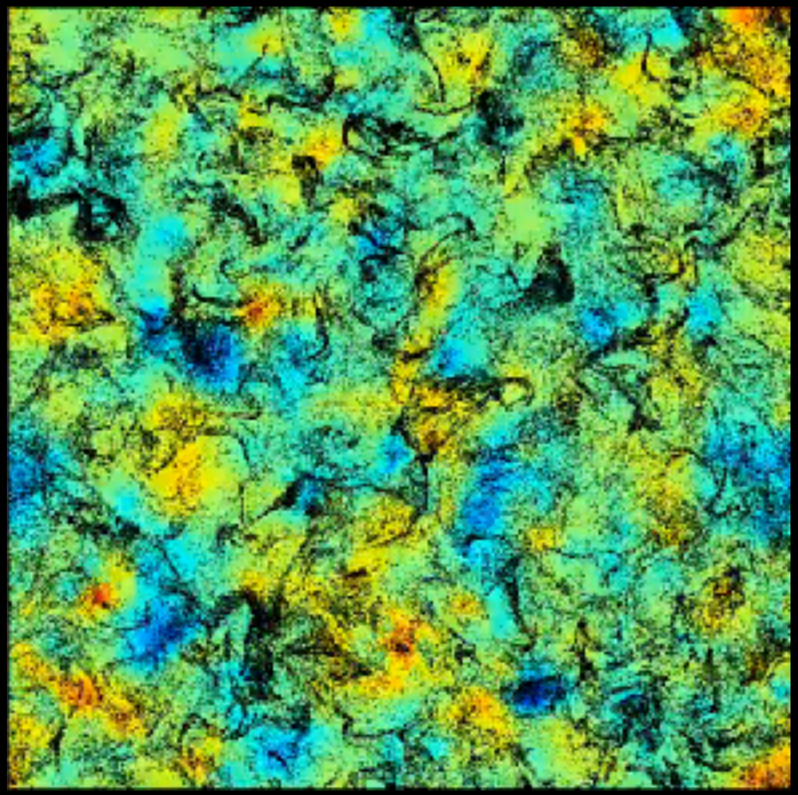


# The "Settling" Instability: Vertical-Epicyclic-Brunt-Vaisala RDI

Early Development (Flock, Squire, PFH in prep.)







Philip F. Hopkins & Jonathan (Jono) Squire

arXiv: 1706.05020 (SH), 1707.02997 (HS)
1711.03975 (SH), 1801.10166 (HS)

(+ Moseley & Moroianu in prep)

- **Resonant Drag Instability (RDI):** dust-gas mixtures generically unstable
- **Dust growth / clumping / dust-driven flows / ISM turbulence** strongly altered
- MHD, Stratification, Rotation, Non-Ideal Effects — all add new instabilities
- Diverse instability-assisted channels for planet formation
- Growth times relevant in huge range of astrophysical systems:
  ISM (CNM, WNM, WIM); GMCs / Starbursts; AGN; CGM / IGM; Coronae; Cool-star winds; Proto-planetary / stellar disks; SNe ejecta; HII regions; Planetary atmospheres