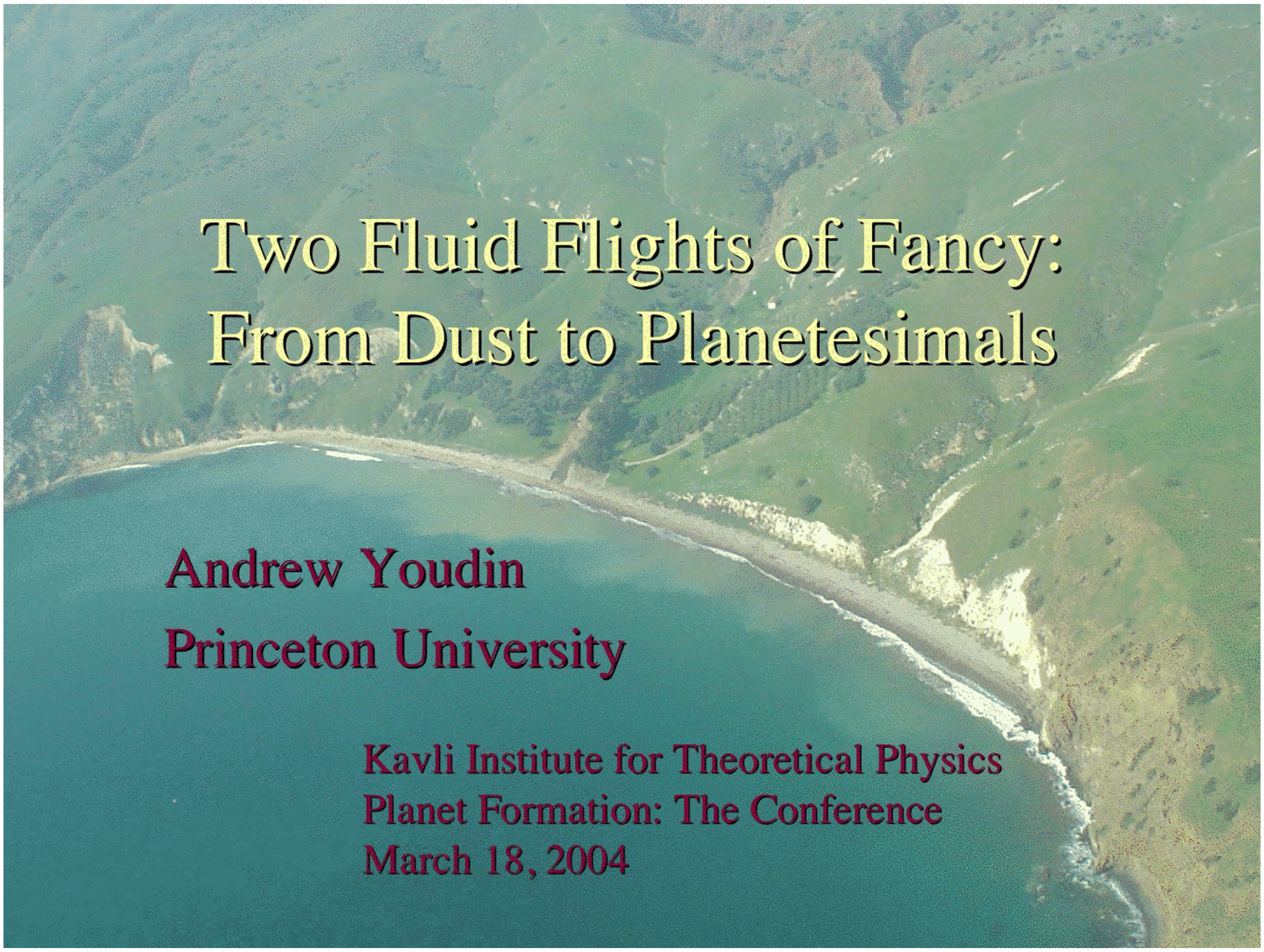

Two Fluid Flights of Fancy: From Dust to Planetesimals

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Princeton University

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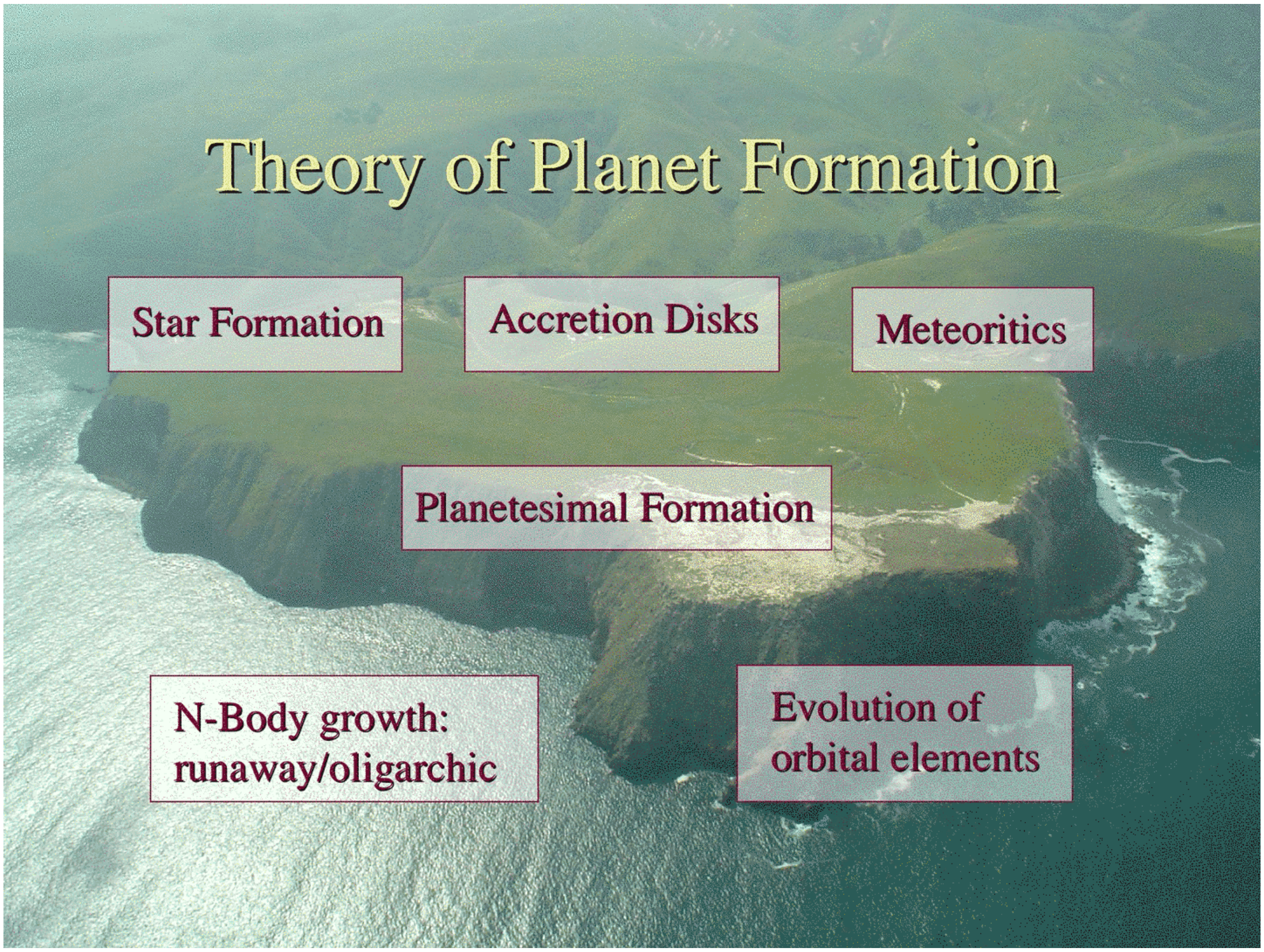
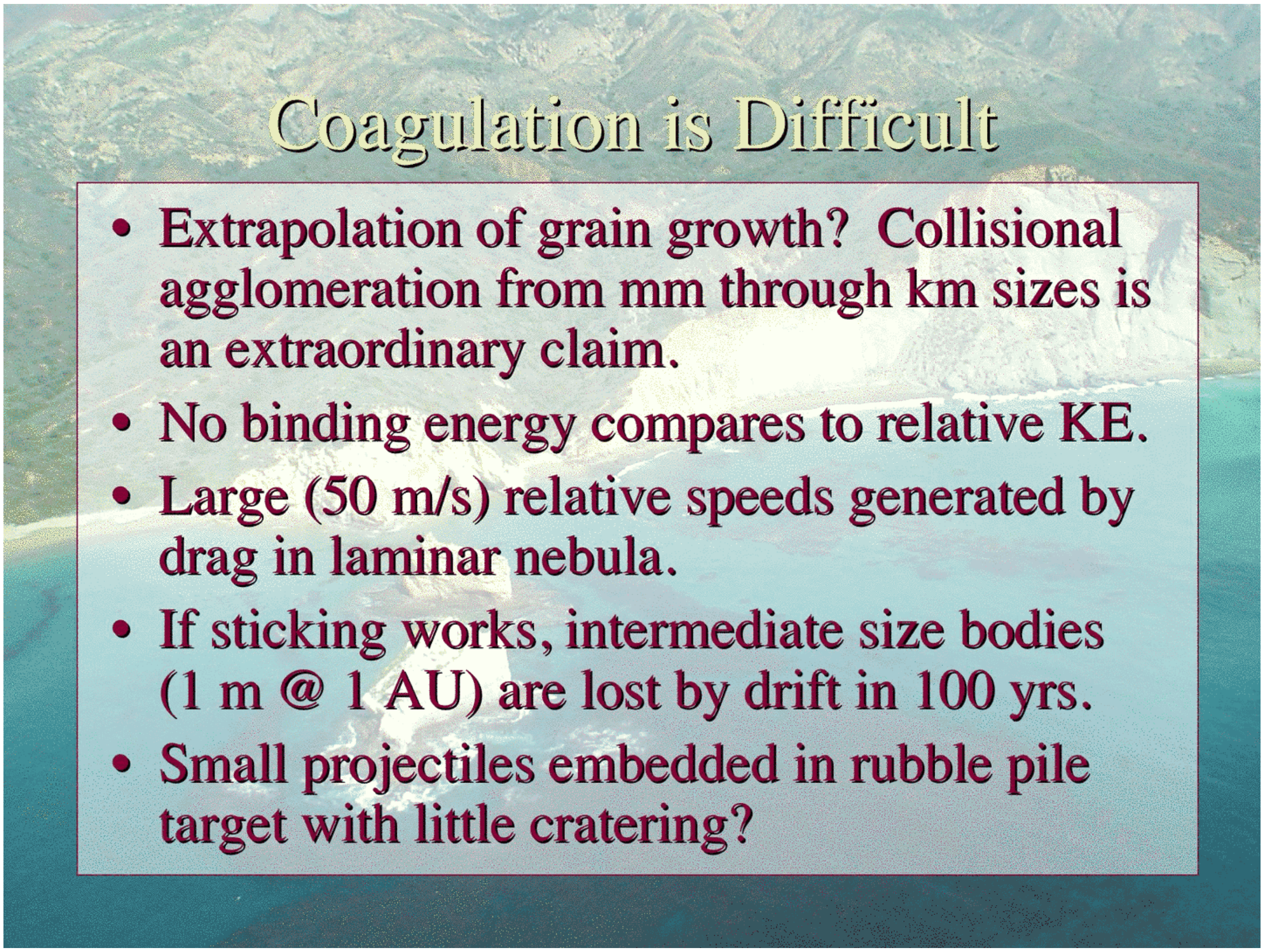
Planet Formation: The Conference
March 18, 2004



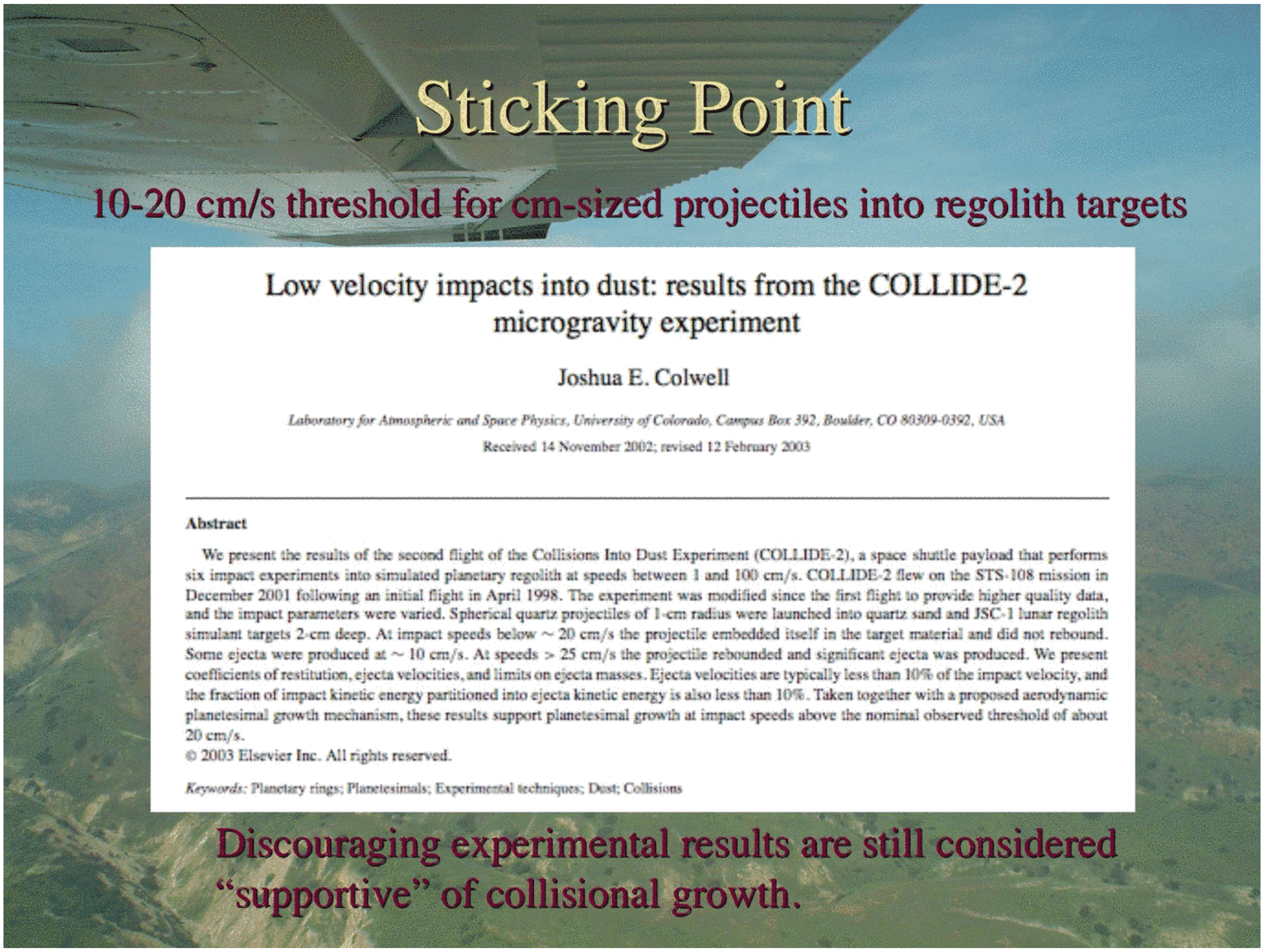
Theory of Planet Formation

- Star Formation
- Accretion Disks
- Meteoritics
- Planetesimal Formation
- N-Body growth: runaway/oligarchic
- Evolution of orbital elements



Coagulation is Difficult

- Extrapolation of grain growth? Collisional agglomeration from mm through km sizes is an extraordinary claim.
- No binding energy compares to relative KE.
- Large (50 m/s) relative speeds generated by drag in laminar nebula.
- If sticking works, intermediate size bodies (1 m @ 1 AU) are lost by drift in 100 yrs.
- Small projectiles embedded in rubble pile target with little cratering?



Sticking Point

10-20 cm/s threshold for cm-sized projectiles into regolith targets

Low velocity impacts into dust: results from the COLLIDE-2 microgravity experiment

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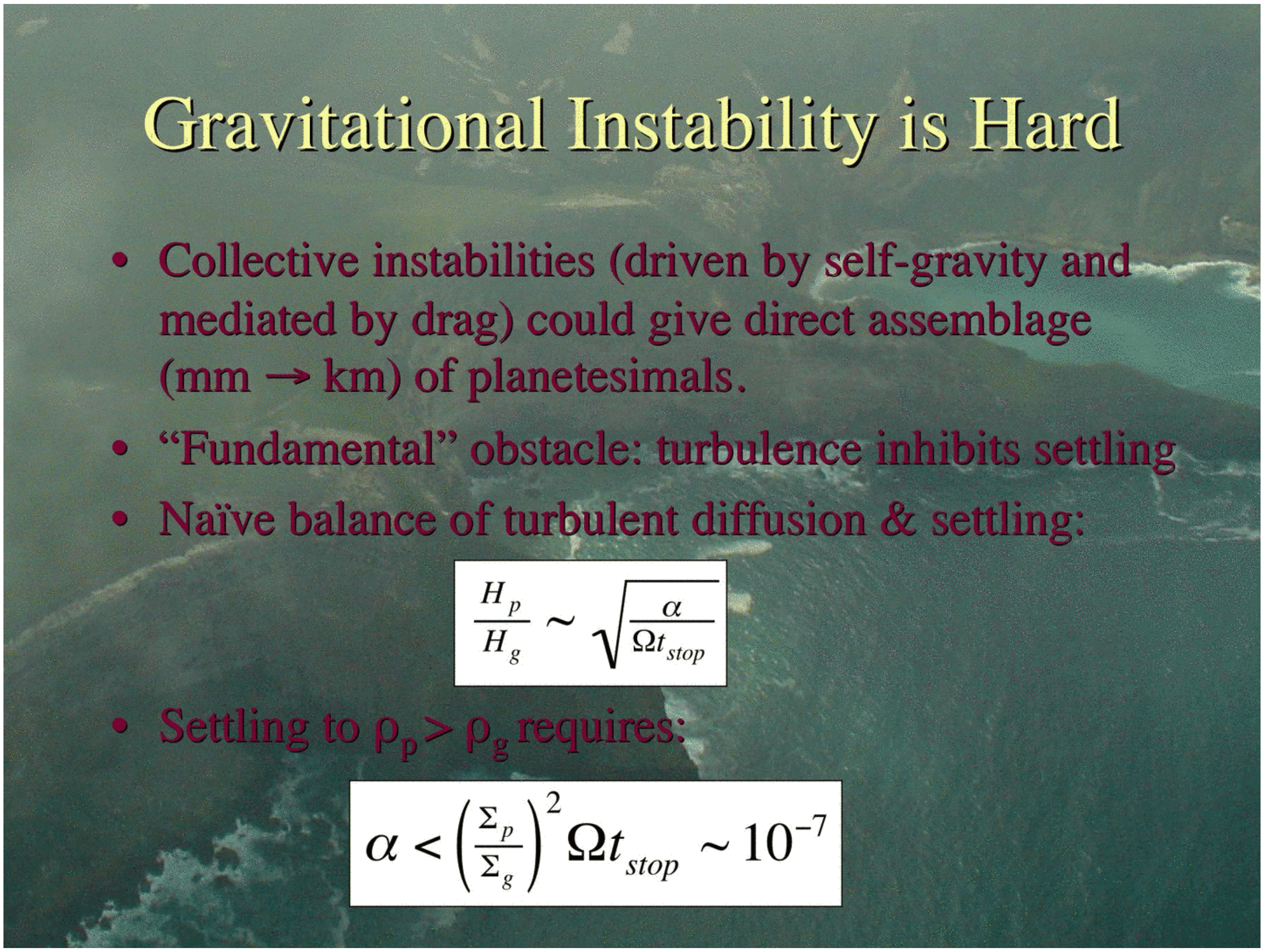
Abstract

We present the results of the second flight of the Collisions Into Dust Experiment (COLLIDE-2), a space shuttle payload that performs six impact experiments into simulated planetary regolith at speeds between 1 and 100 cm/s. COLLIDE-2 flew on the STS-108 mission in December 2001 following an initial flight in April 1998. The experiment was modified since the first flight to provide higher quality data, and the impact parameters were varied. Spherical quartz projectiles of 1-cm radius were launched into quartz sand and JSC-1 lunar regolith simulant targets 2-cm deep. At impact speeds below ~ 20 cm/s the projectile embedded itself in the target material and did not rebound. Some ejecta were produced at ~ 10 cm/s. At speeds > 25 cm/s the projectile rebounded and significant ejecta was produced. We present coefficients of restitution, ejecta velocities, and limits on ejecta masses. Ejecta velocities are typically less than 10% of the impact velocity, and the fraction of impact kinetic energy partitioned into ejecta kinetic energy is also less than 10%. Taken together with a proposed aerodynamic planetesimal growth mechanism, these results support planetesimal growth at impact speeds above the nominal observed threshold of about 20 cm/s.

Keywords: Planetary rings; Planetesimals; Experimental techniques; Dust; Collisions

Discouraging experimental results are still considered "supportive" of collisional growth.



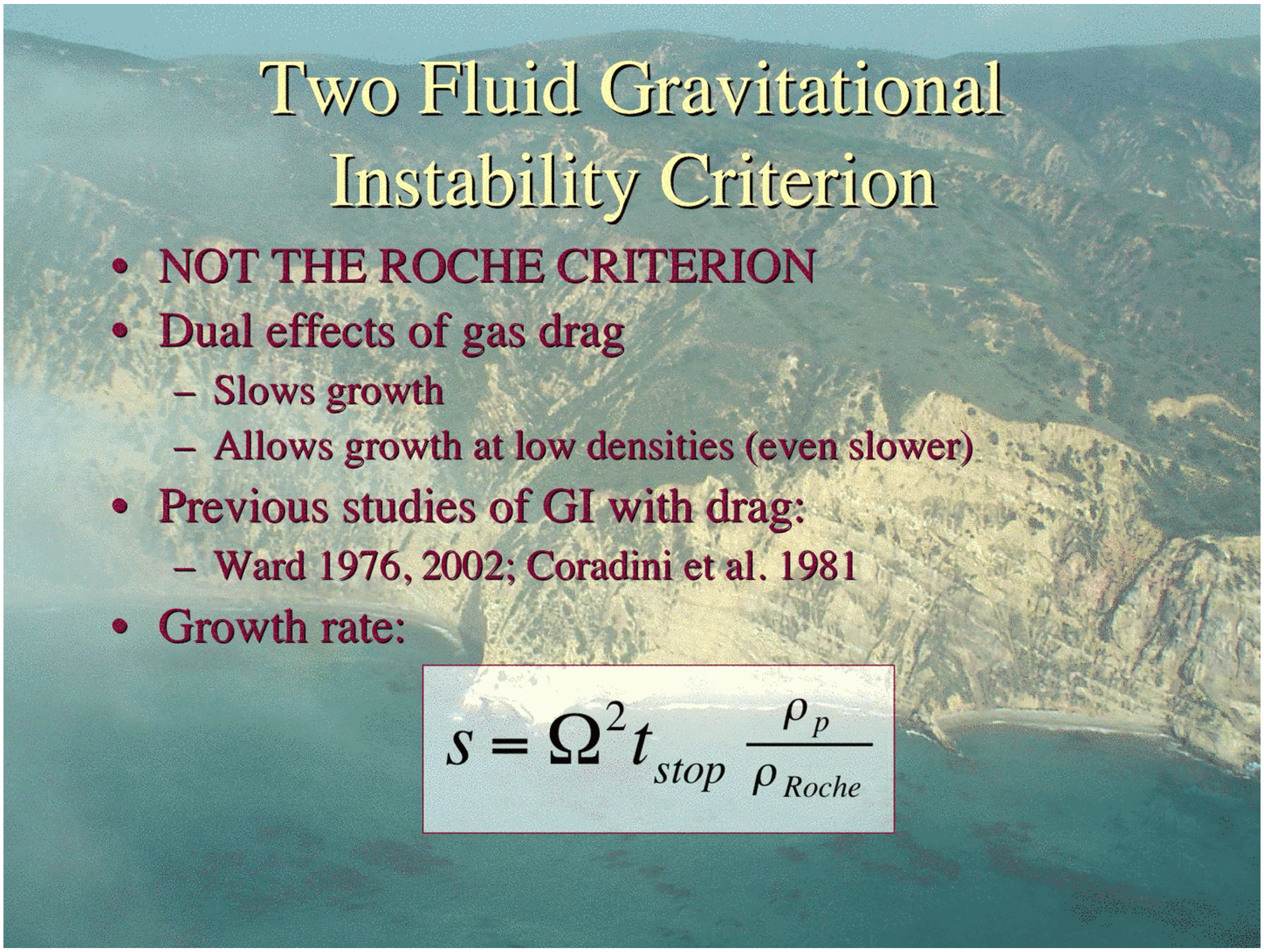
Gravitational Instability is Hard

- Collective instabilities (driven by self-gravity and mediated by drag) could give direct assemblage (mm → km) of planetesimals.
- "Fundamental" obstacle: turbulence inhibits settling
- Naïve balance of turbulent diffusion & settling:

$$\frac{H_p}{H_g} \sim \sqrt{\frac{\alpha}{\Omega t_{stop}}}$$

- Settling to $\rho_p > \rho_g$ requires:

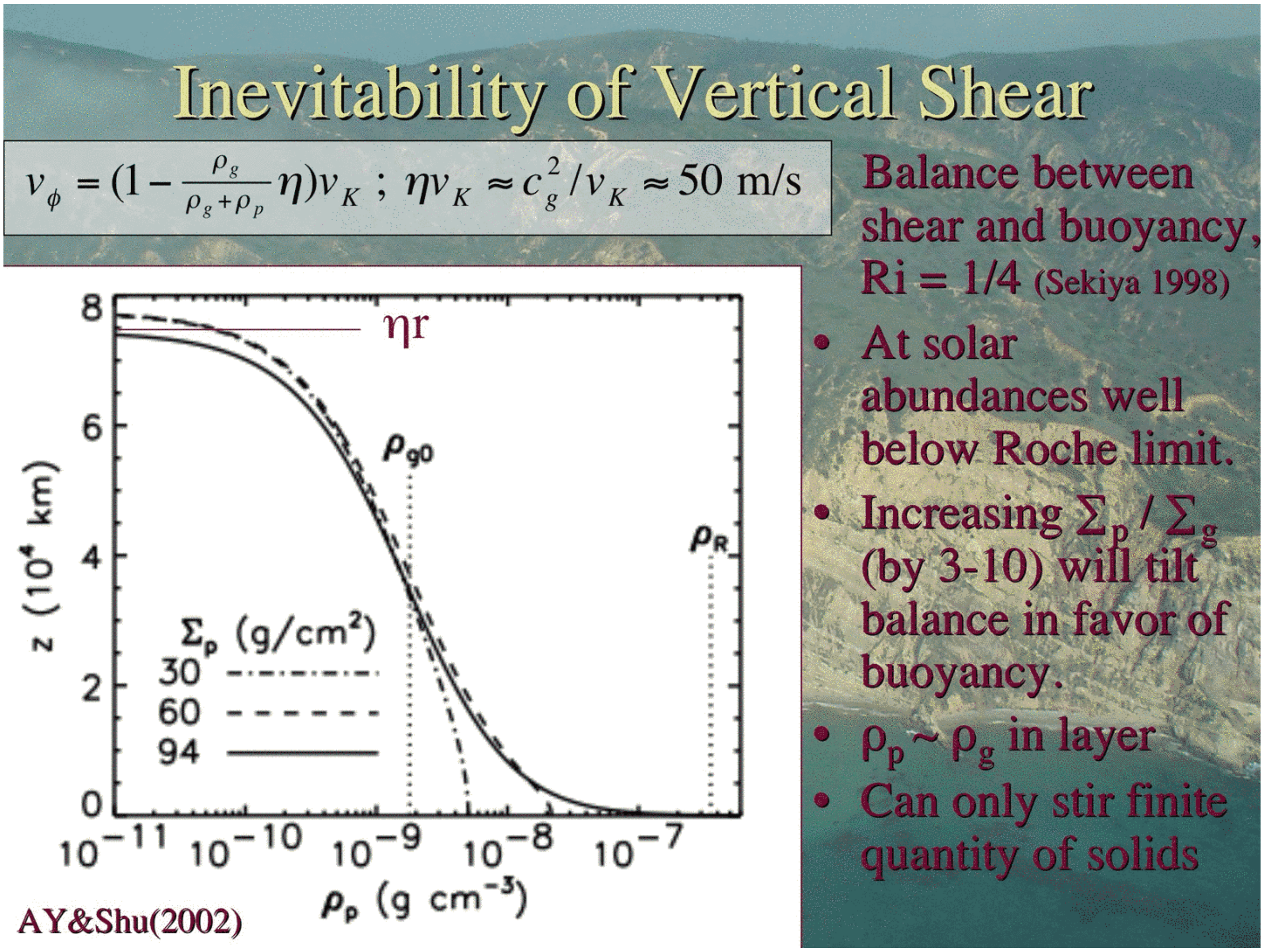
$$\alpha < \left(\frac{\Sigma_p}{\Sigma_g}\right)^2 \Omega t_{stop} \sim 10^{-7}$$



Two Fluid Gravitational Instability Criterion

- NOT THE ROCHE CRITERION
- Dual effects of gas drag
  - Slows growth
  - Allows growth at low densities (even slower)
- Previous studies of GI with drag:
  - Ward 1976, 2002; Coradini et al. 1981
- Growth rate:

$$s = \Omega^2 t_{stop} \frac{\rho_p}{\rho_{Roche}}$$



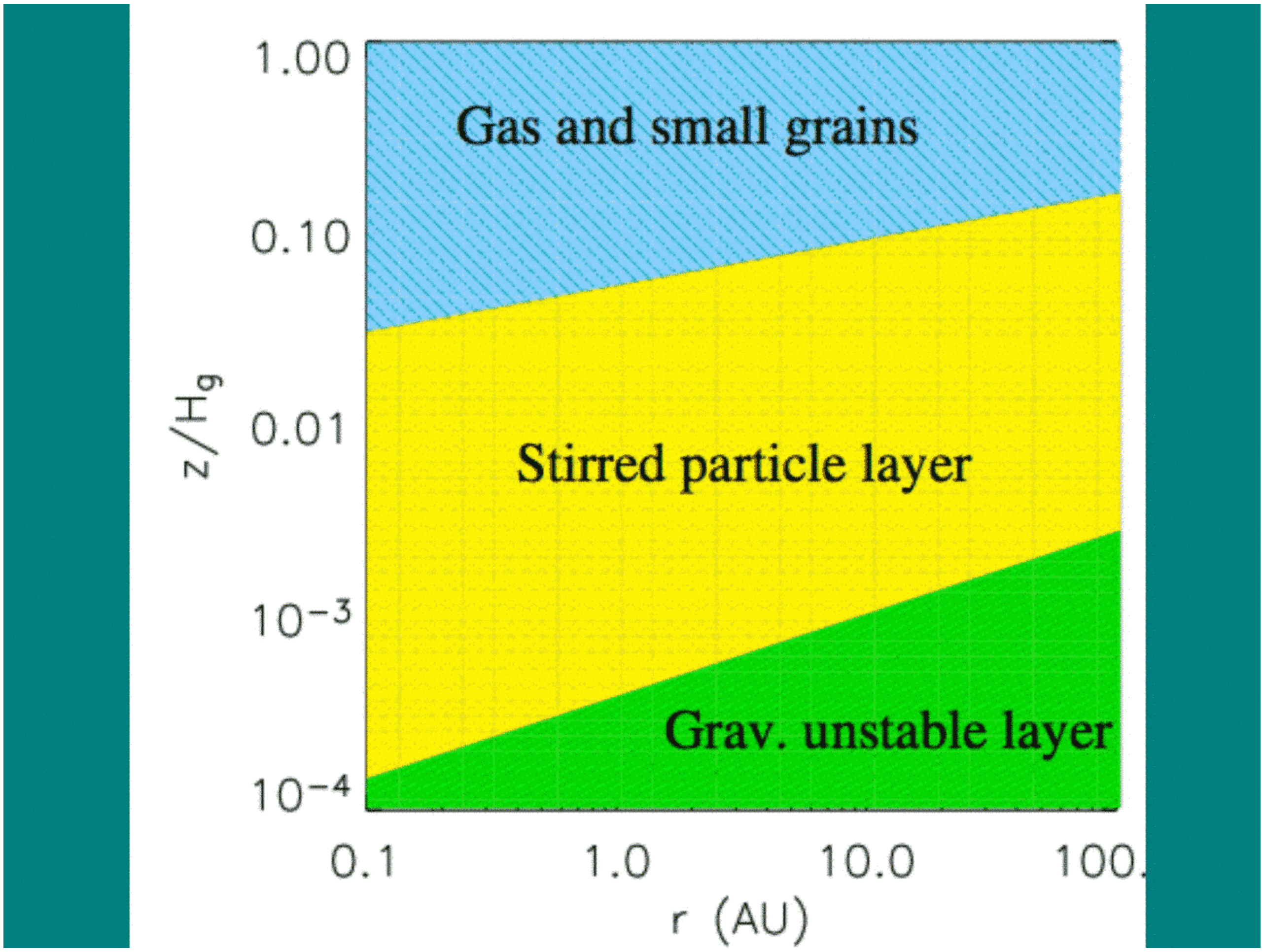
Inevitability of Vertical Shear

$$v_\phi = (1 - \frac{\rho_g}{\rho_g + \rho_p}\eta) v_K \; ; \; \eta v_K \approx c_g^2 / v_K \approx 50 \text{ m/s}$$

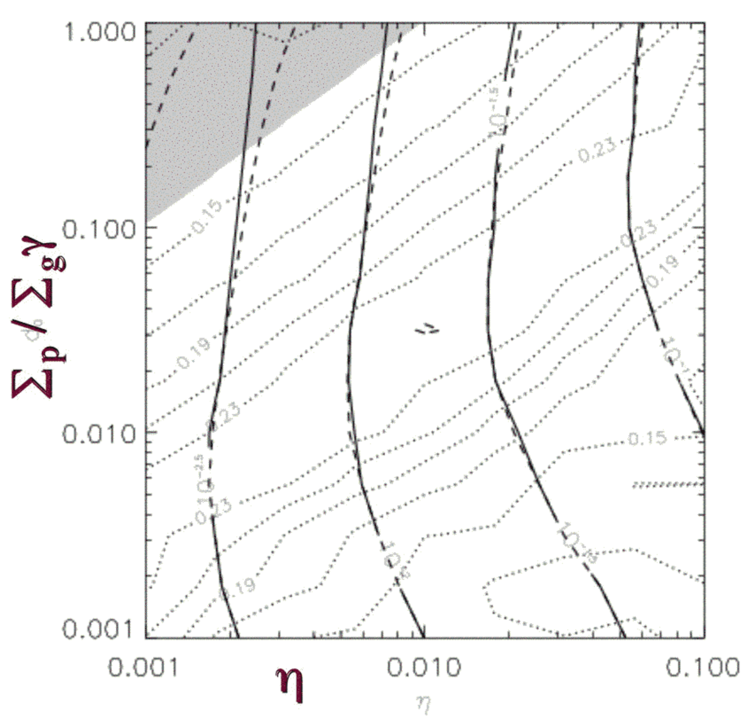
AY&Shu(2002)

Balance between shear and buoyancy, Ri = 1/4 (Sekiya 1998)

- At solar abundances well below Roche limit.
- Increasing Σ_p / Σ_g (by 3-10) will tilt balance in favor of buoyancy.
- $\rho_p \sim \rho_g$ in layer
- Can only stir finite quantity of solids



Garaud & Lin (2004)



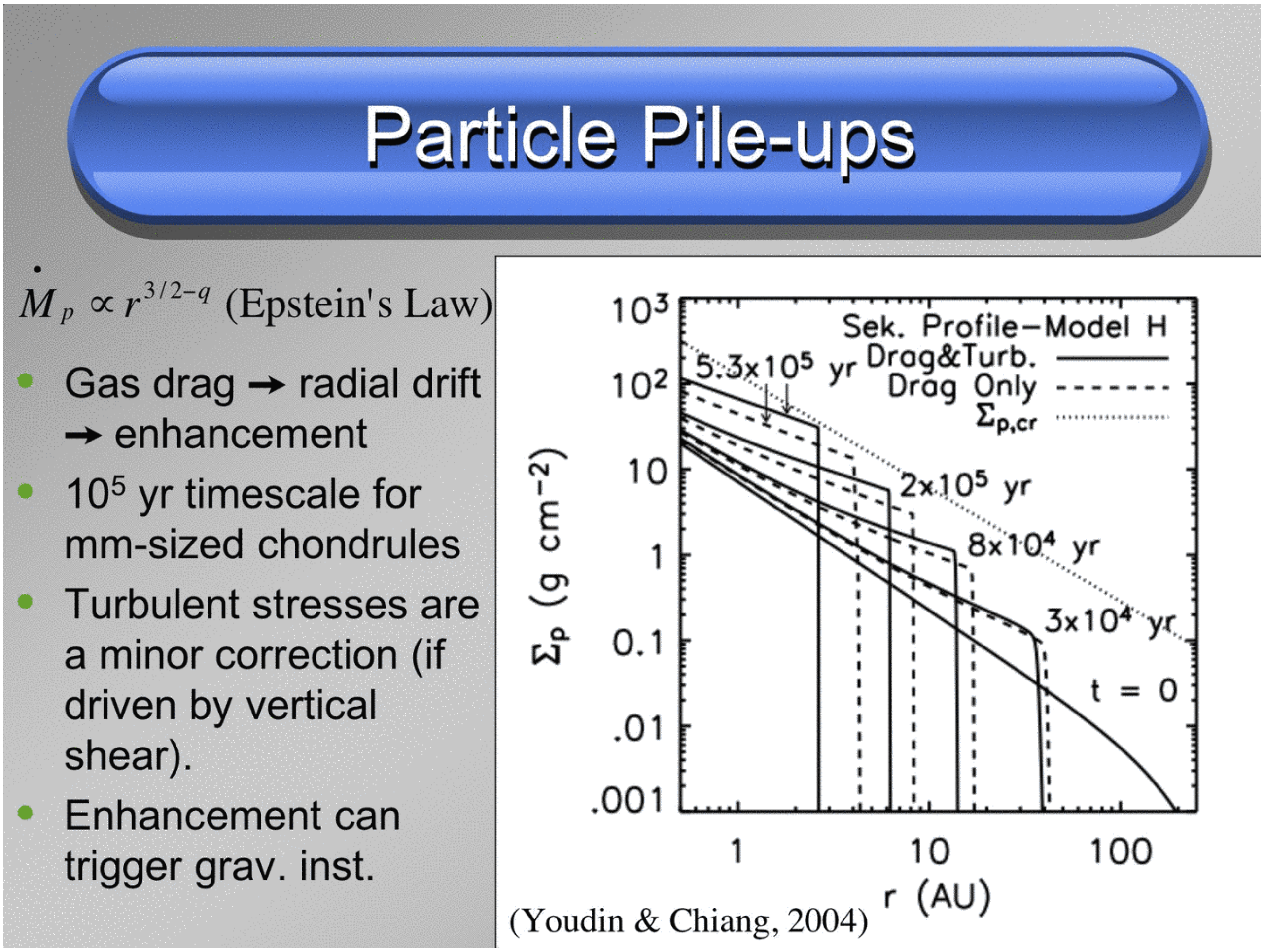
- Verify that vertical shear instability is described by Richardson crit.
- Two fluid, 2D (z,ϕ), linear perts. in strong coupling limit
- Background state settles until instability triggered:
  $0.15 < Ri < 0.25$
- At high Σ_p / Σ_g, GI occurs before KHI.

2 Fluid Normal Mode Analysis

$$\frac{D\vec{U}}{Dt} = -\frac{\vec{U}-\vec{U}_g}{t_{stop}} - \frac{GM_*}{r^3}\vec{r}$$

$$\frac{D\vec{U}_g}{Dt} = -\frac{\rho_p}{\rho_g}\frac{\vec{U}_g-\vec{U}}{t_{stop}} - \frac{GM_*}{r^3}\vec{r} - \frac{\nabla P}{\rho_g}$$

- Simple model: no vertical structure or self-gravity, inviscid, uniform size
- Basic state: relative drift of gas and solids
- Perturbations: particle concentration and 3D velocities in axisymmetric shearing sheet (k_x, k_z) incompressible gas.

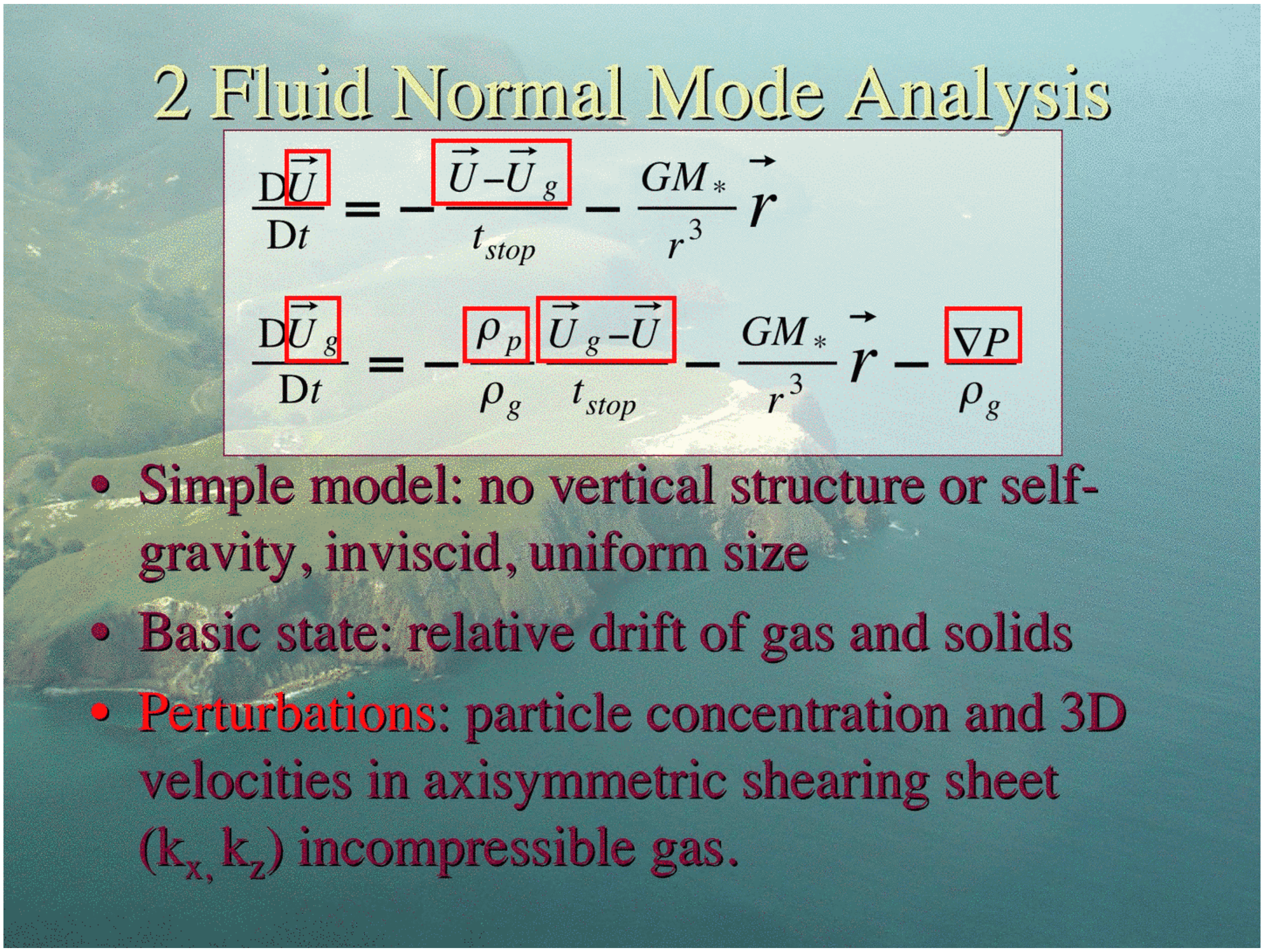


Particle Pile-ups

$\dot{M}_p \propto r^{3/2-q}$ (Epstein's Law)

- Gas drag → radial drift → enhancement
- 10^5 yr timescale for mm-sized chondrules
- Turbulent stresses are a minor correction (if driven by vertical shear).
- Enhancement can trigger grav. inst.

(Youdin & Chiang, 2004)



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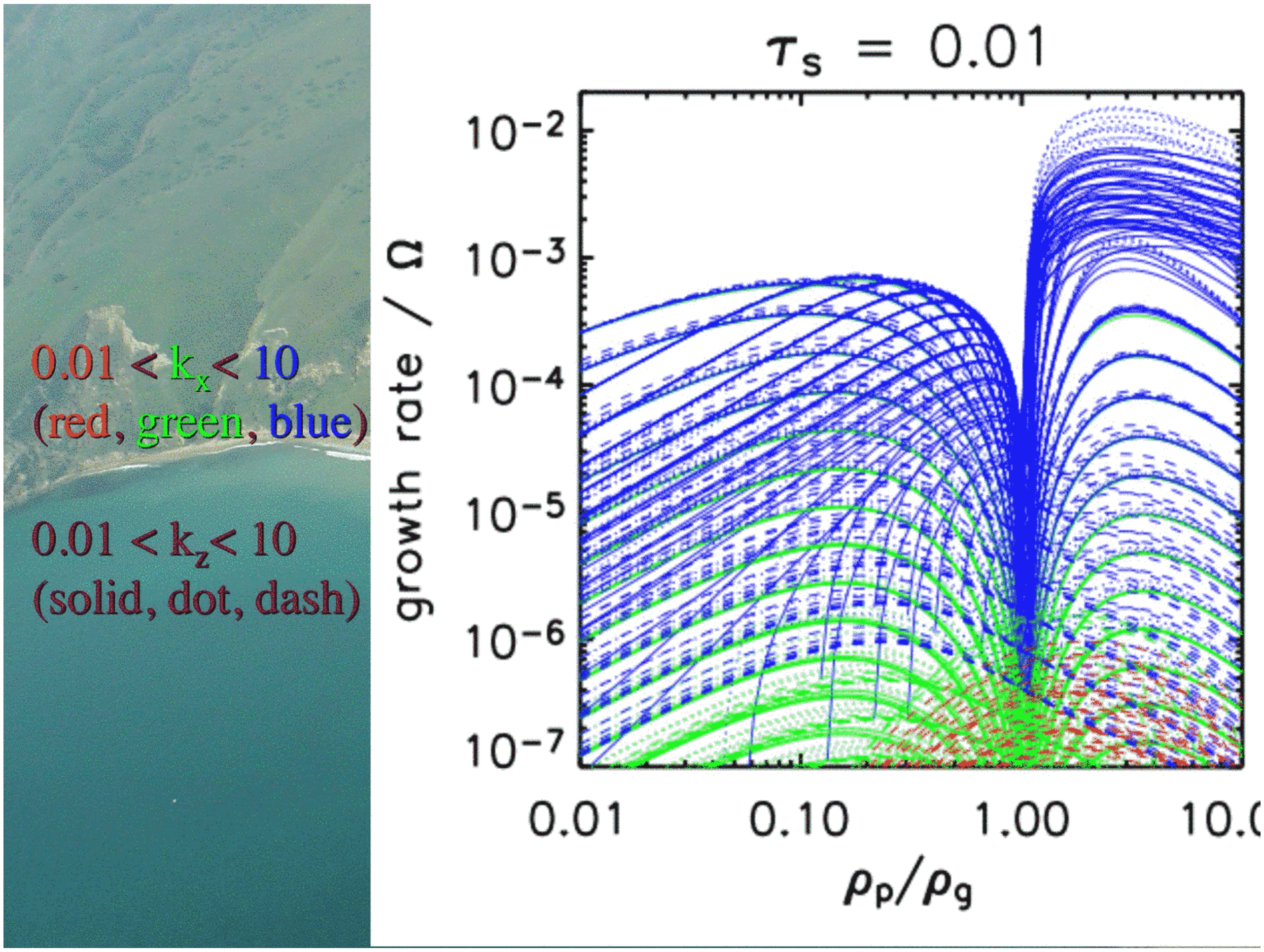
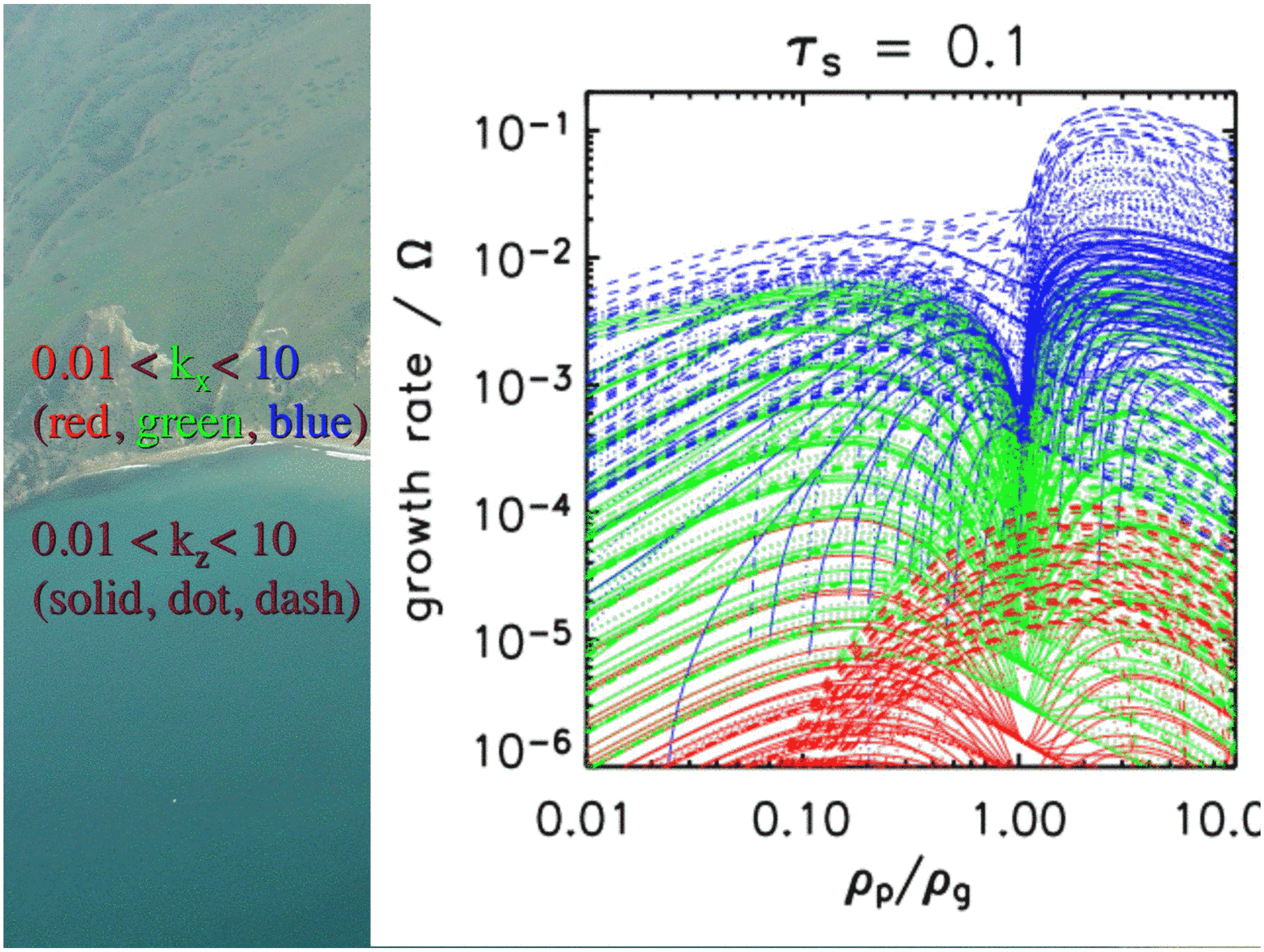
Solution Space

- Normal modes $\exp[(s + i\omega)t + i(k_x x + k_z z)]$
- 6 complex eigenvalues: growth rate & frequency $(s + i\omega)$.
  - – 3 strongly damped
  - – 2 epicycles (growing for large k_z/k_x)
  - – Growing secular mode
- 4 dimensionless #s:
  - – $\tau_s \equiv \Omega t_{stop} << 1$
  - – $\mu \equiv \rho_p/\rho_g$
  - – 2 wavenumbers: $k_x\eta r$, $k_z\eta r$ $(\eta \approx c_s^2/v_K^2)$



$0.01 < k_x < 10$
(red, green, blue)

$0.01 < k_z < 10$
(solid, dot, dash)



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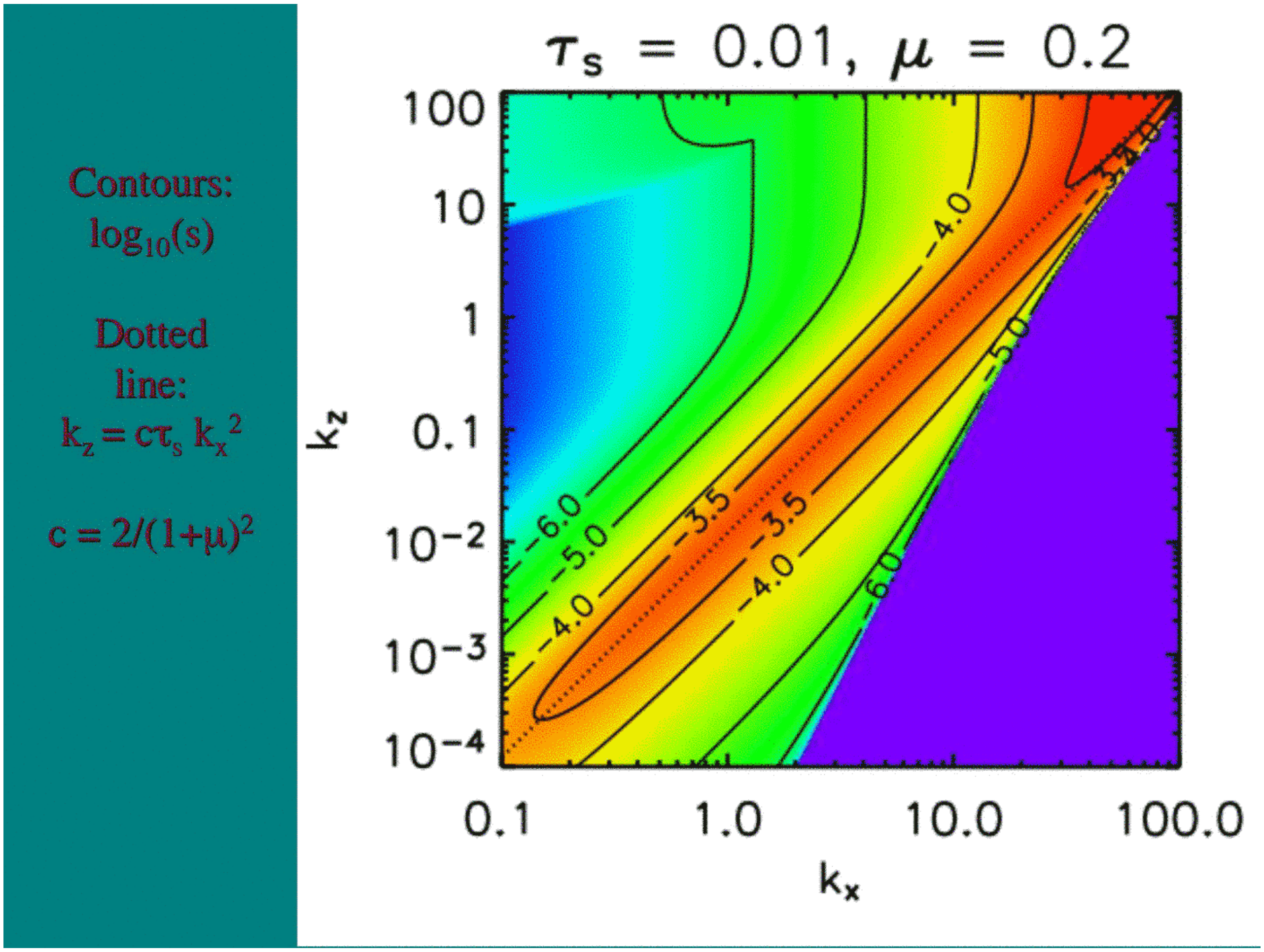

Contours:
$\log_{10}(s)$

Dotted
line:
$k_z = c\tau_s k_x^2$

$c = 2/(1+\mu)^2$

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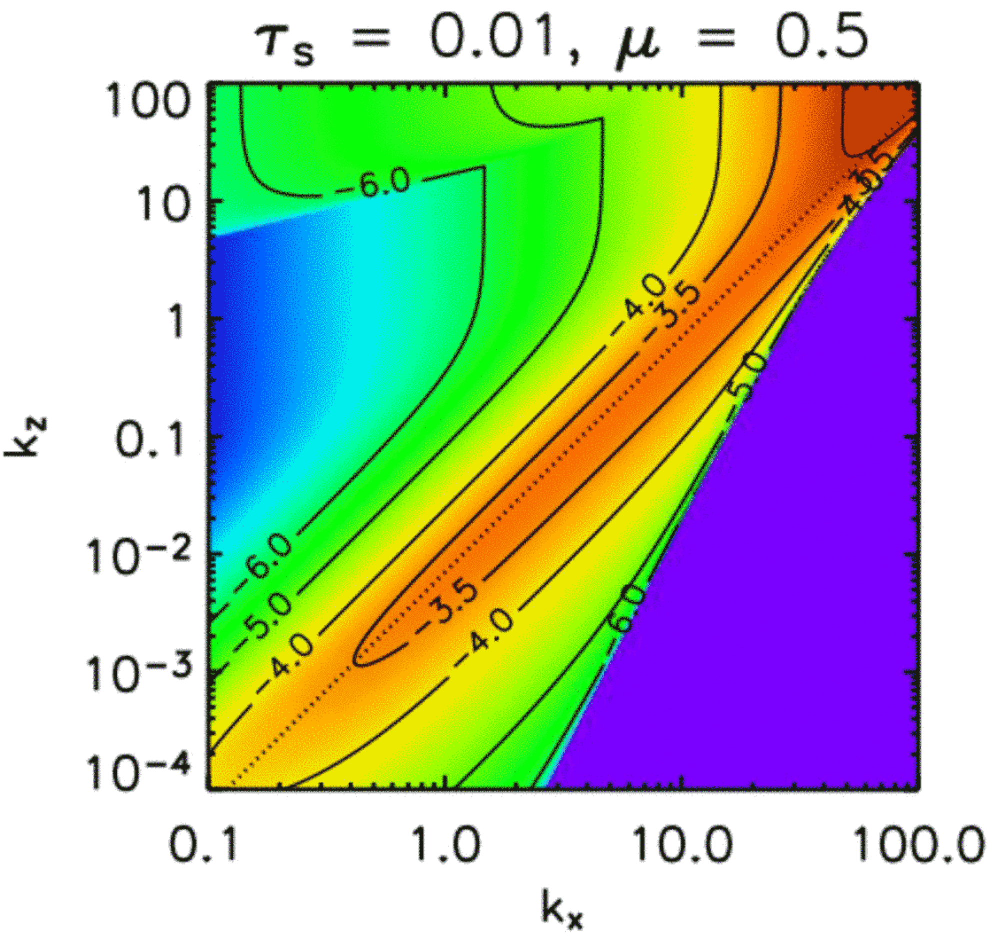

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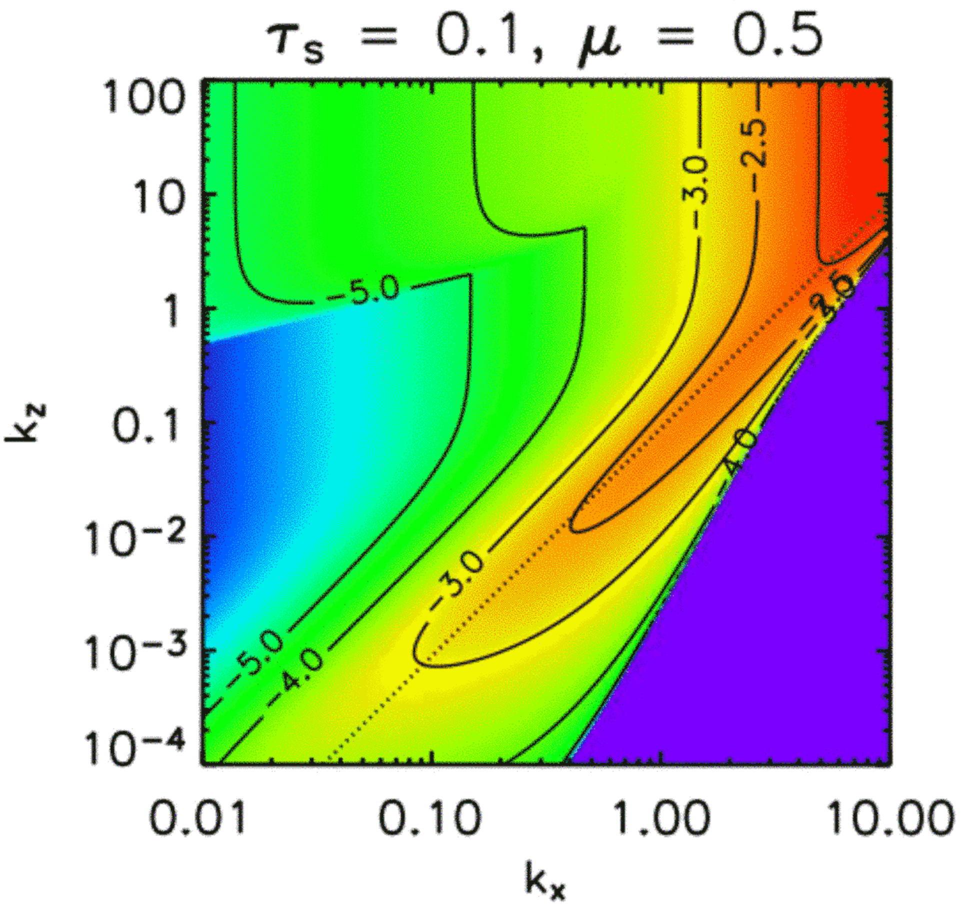

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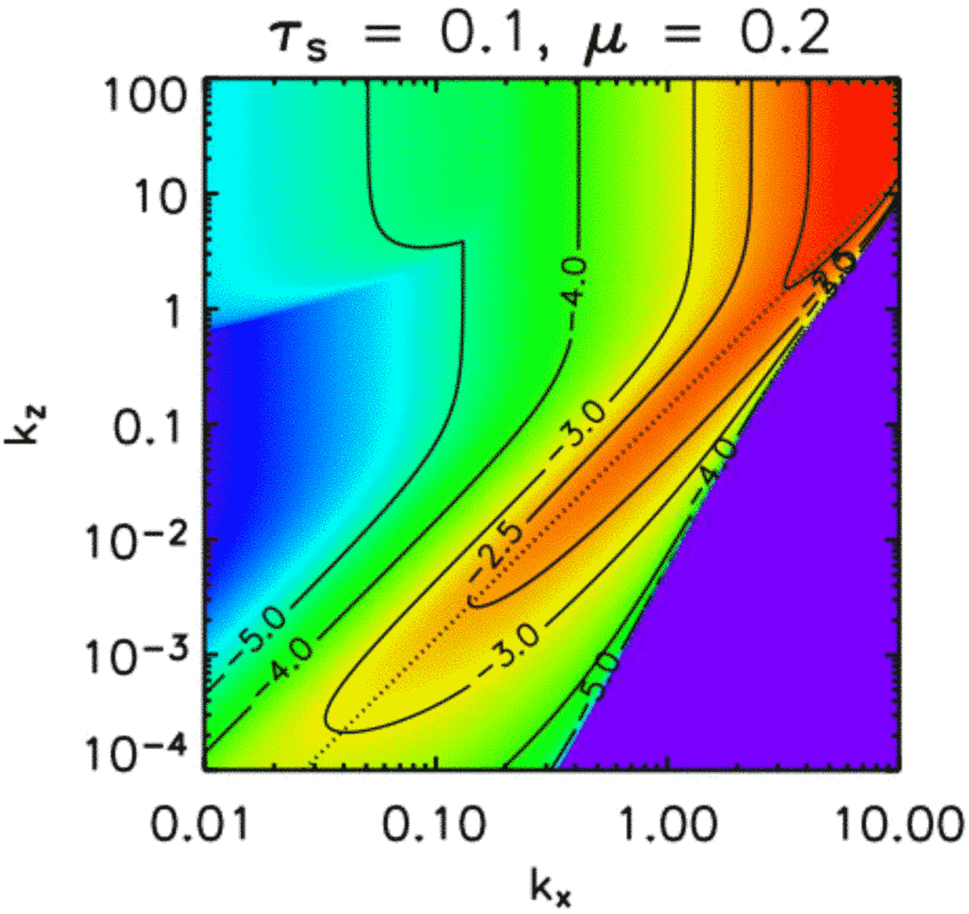

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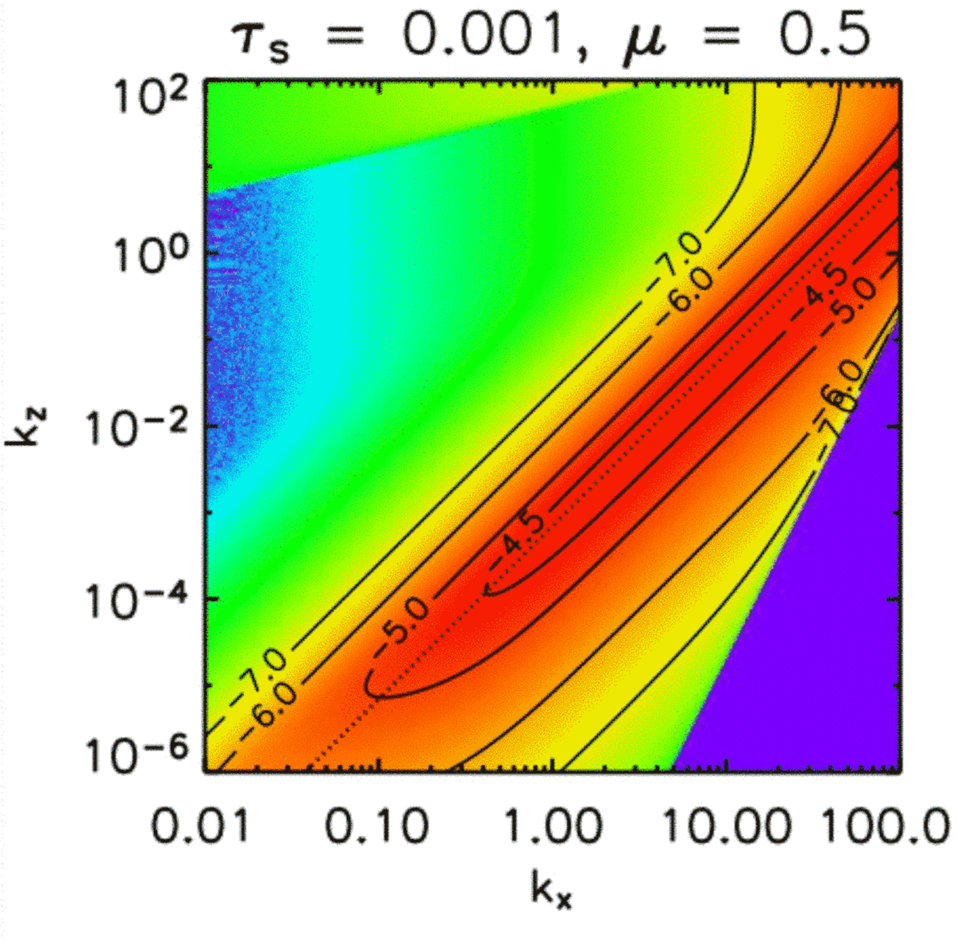
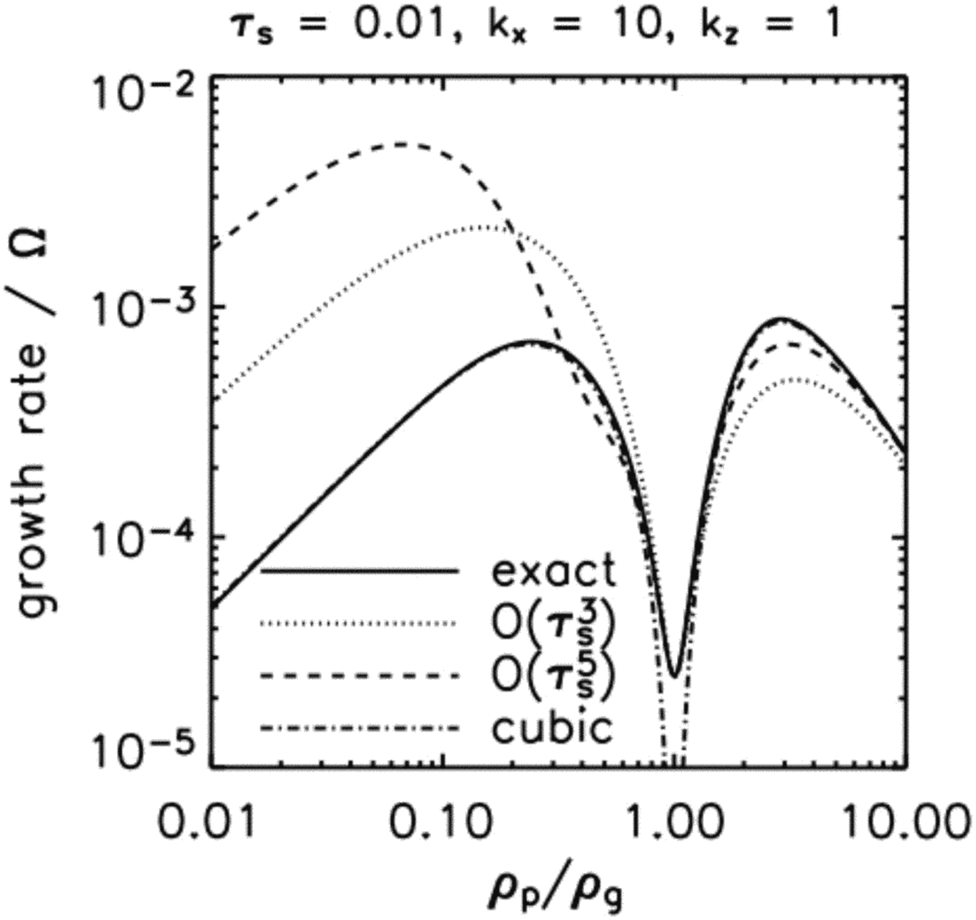
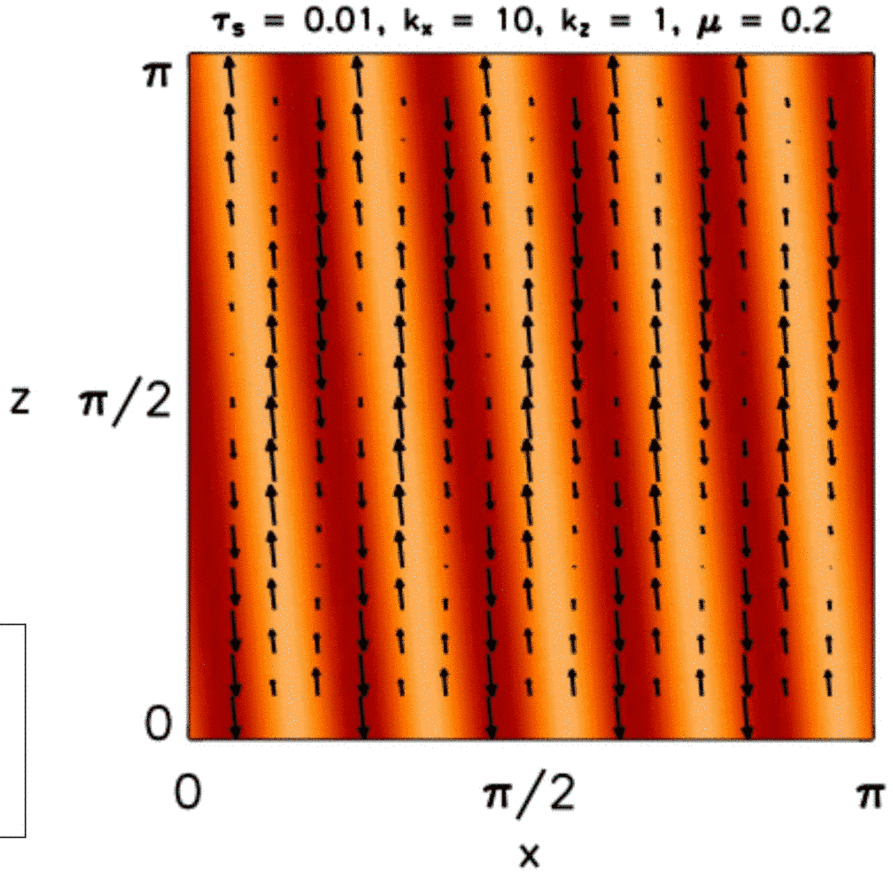


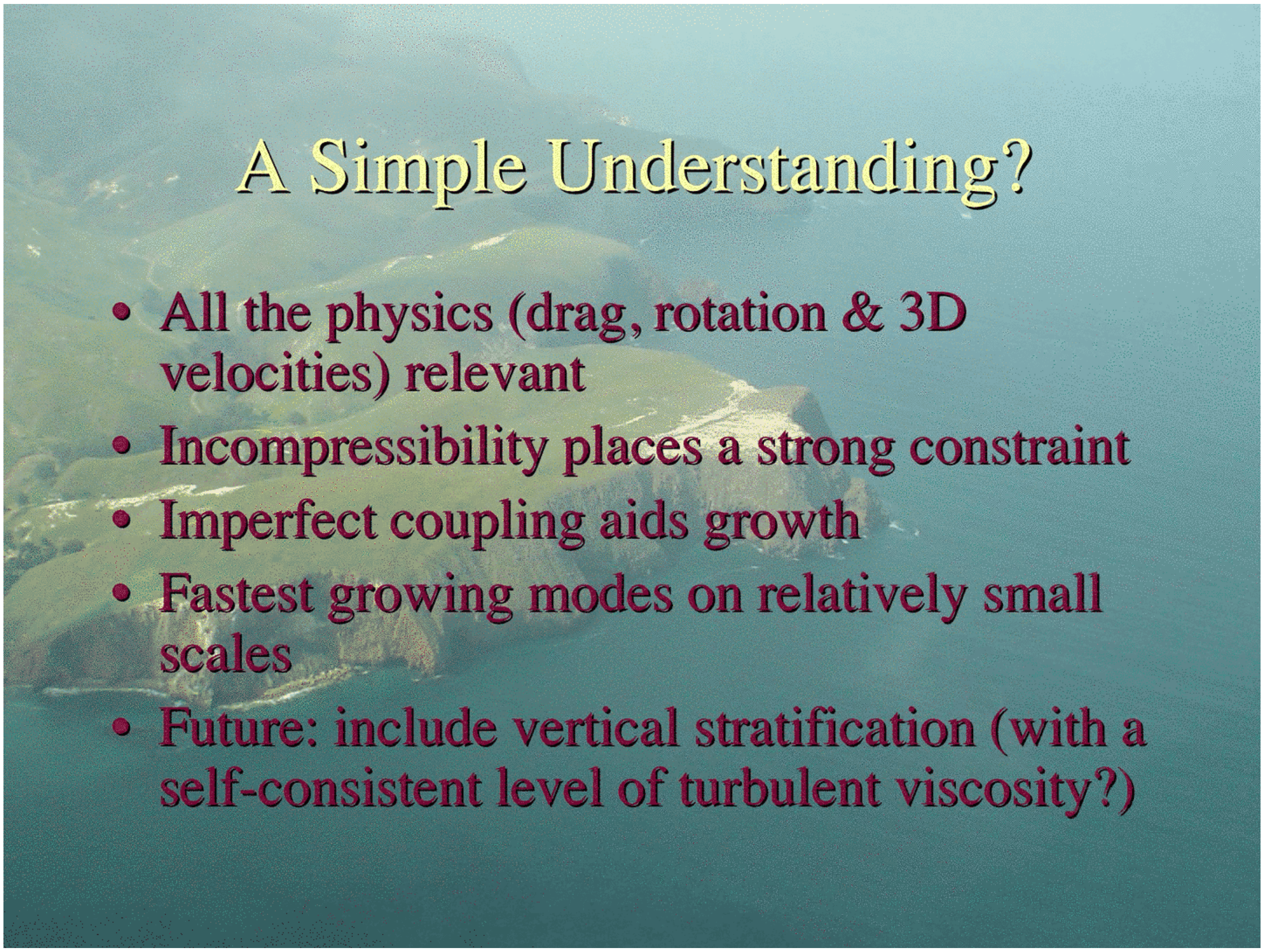


arrows:
velocities

redscale:
density

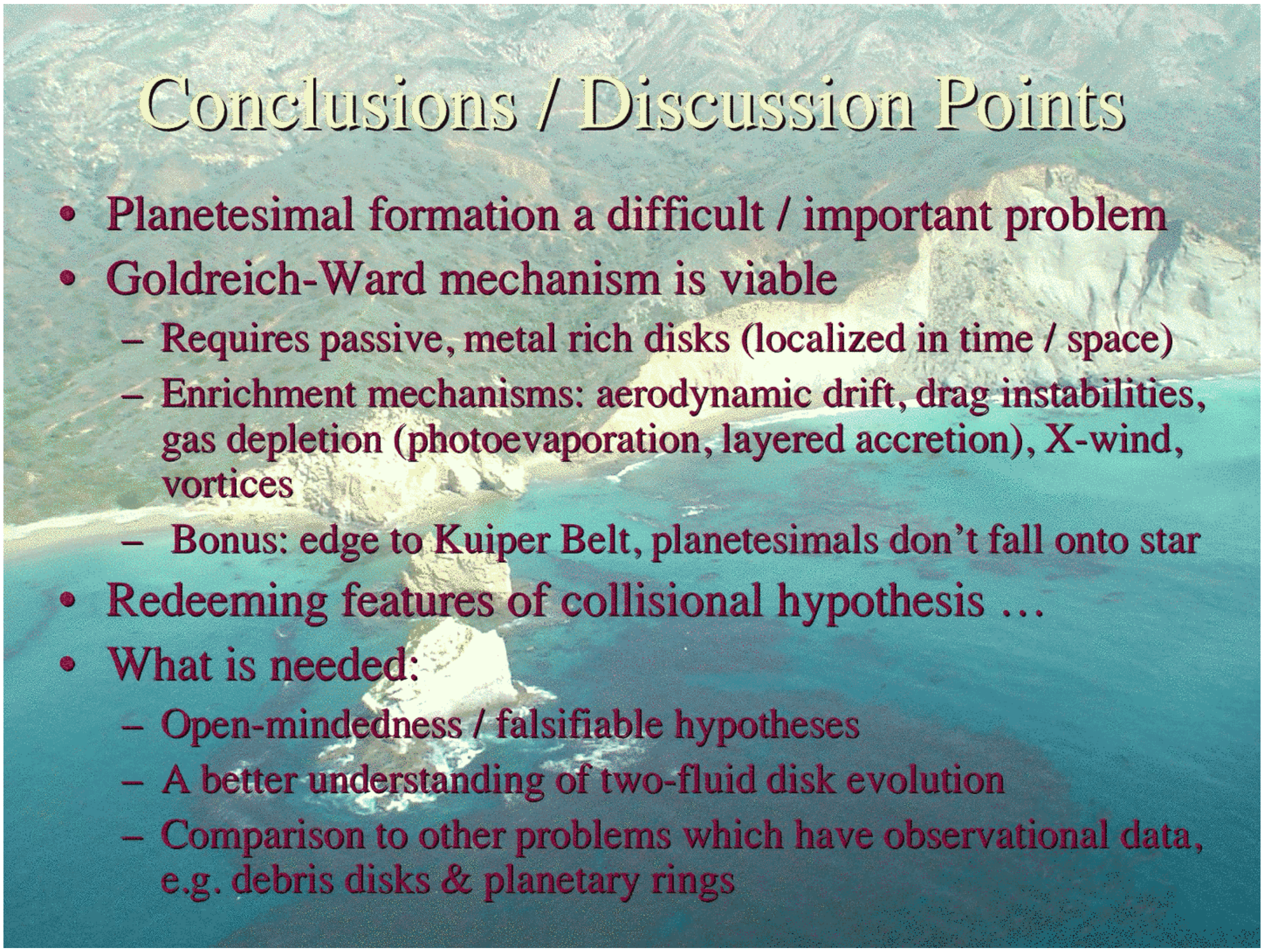


$$\frac{|\delta\rho_p/\rho_p|}{|\vec{v}/\eta v_K|} \cong 1.7$$



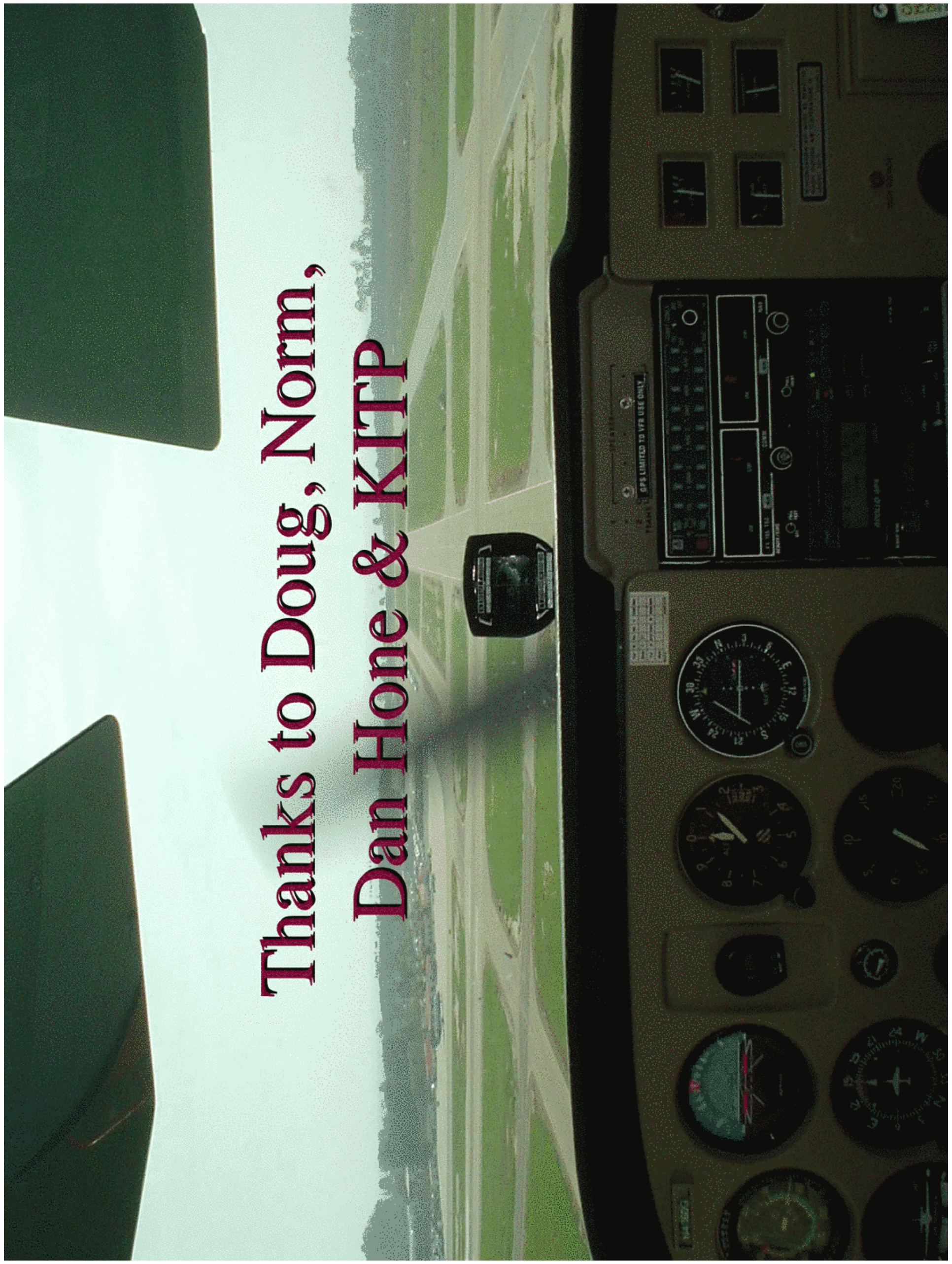
A Simple Understanding?

- All the physics (drag, rotation & 3D velocities) relevant
- Incompressibility places a strong constraint
- Imperfect coupling aids growth
- Fastest growing modes on relatively small scales
- Future: include vertical stratification (with a self-consistent level of turbulent viscosity?)



Conclusions / Discussion Points

- Planetesimal formation a difficult / important problem
- Goldreich-Ward mechanism is viable
  - Requires passive, metal rich disks (localized in time / space)
  - Enrichment mechanisms: aerodynamic drift, drag instabilities, gas depletion (photoevaporation, layered accretion), X-wind, vortices
  - Bonus: edge to Kuiper Belt, planetesimals don’t fall onto star
- Redeeming features of collisional hypothesis …
- What is needed:
  - Open-mindedness / falsifiable hypotheses
  - A better understanding of two-fluid disk evolution
  - Comparison to other problems which have observational data, e.g. debris disks & planetary rings



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