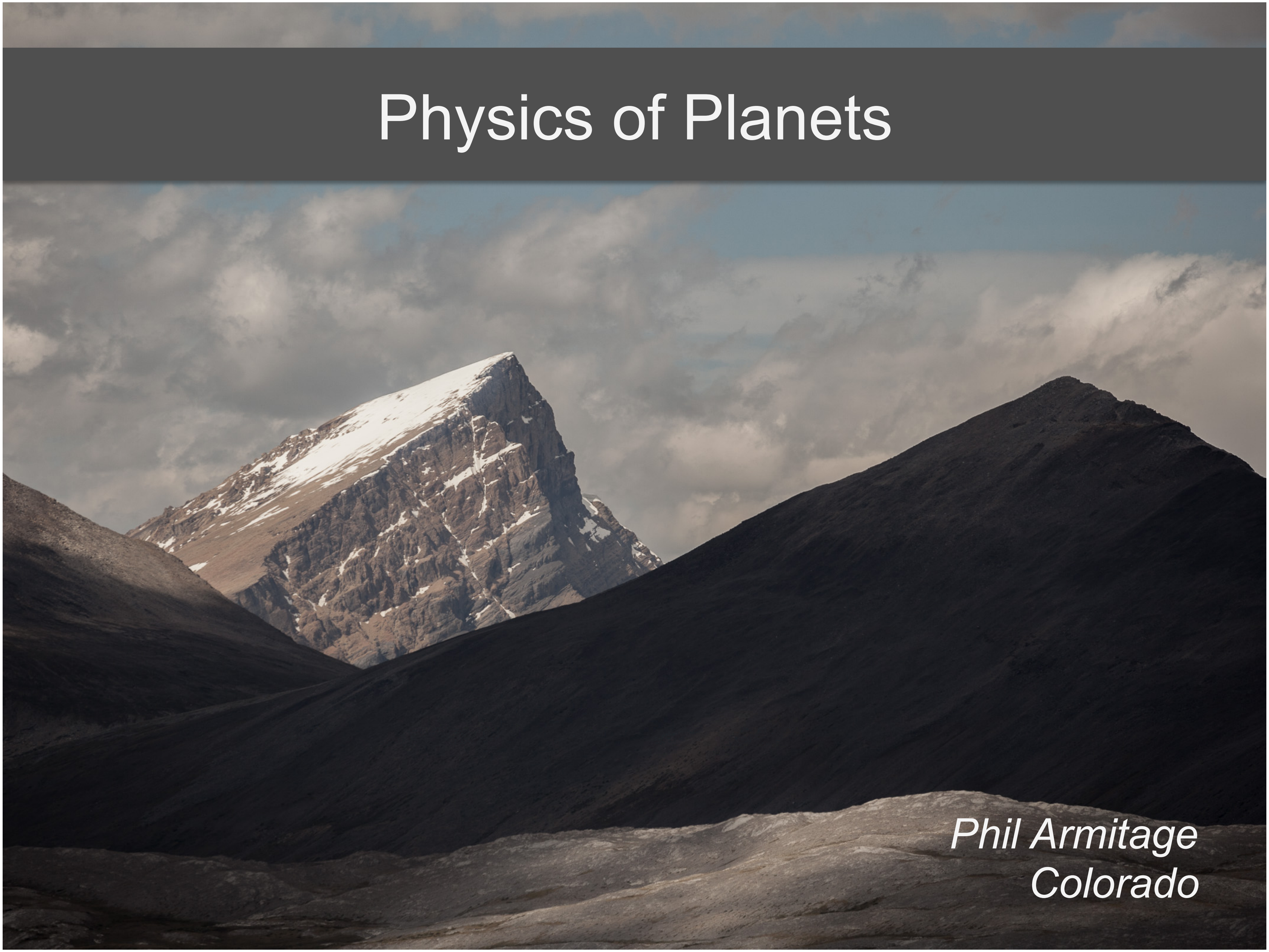
Physics of Planets



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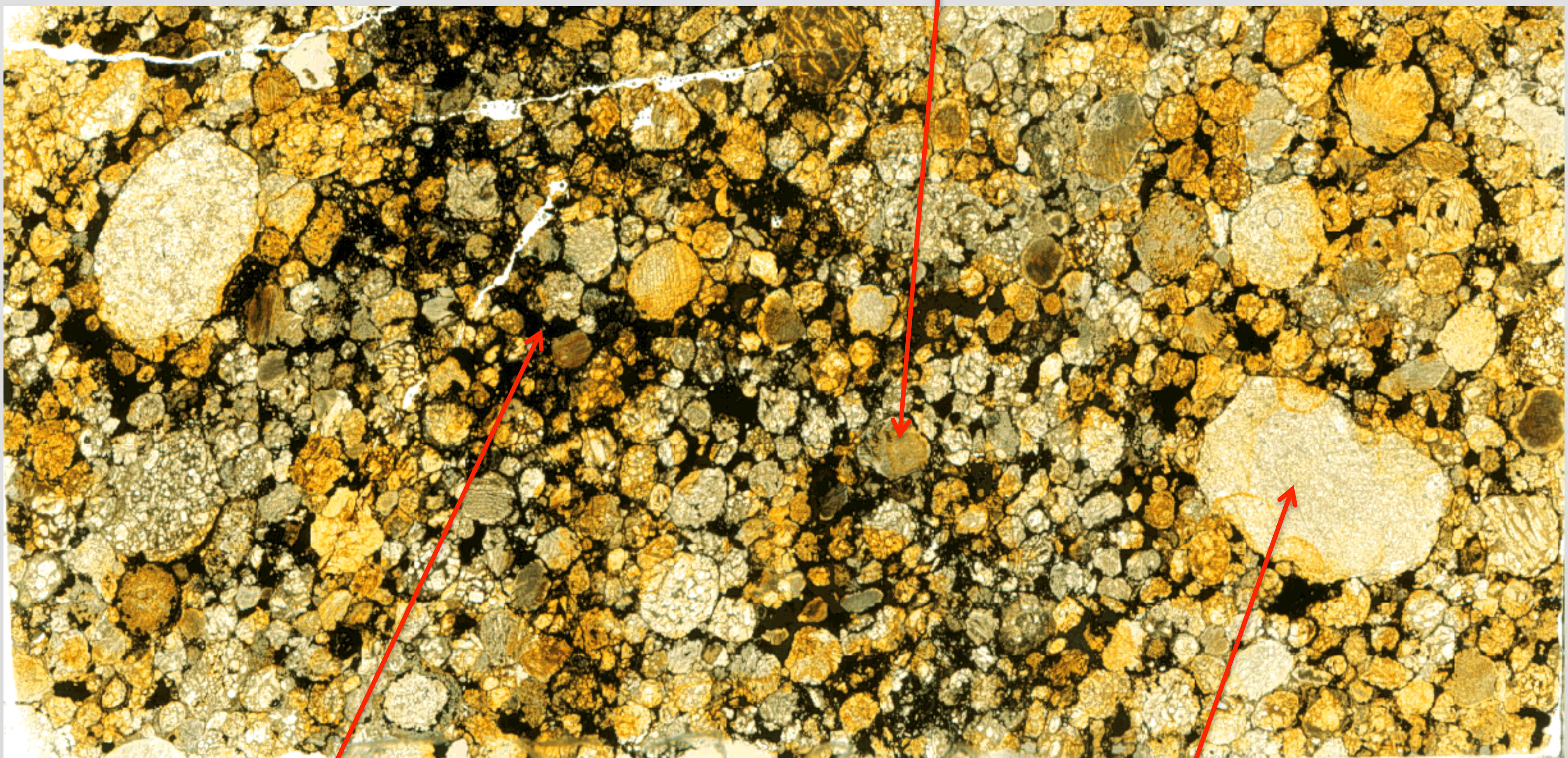
What can we learn from meteorites, specifically from **chondrules**?

Images and discussion in this lecture substantially based on reviews from Steve Desch, e.g. Desch et al. (2012)

Carbon-rich *carbonaceous* asteroids are the most common type observed in the main asteroid belt

Carbonaceous chondrites are meteorites derived from these asteroids. Other chondritic meteorites (ordinary and enstatite) come primarily from within the snow line

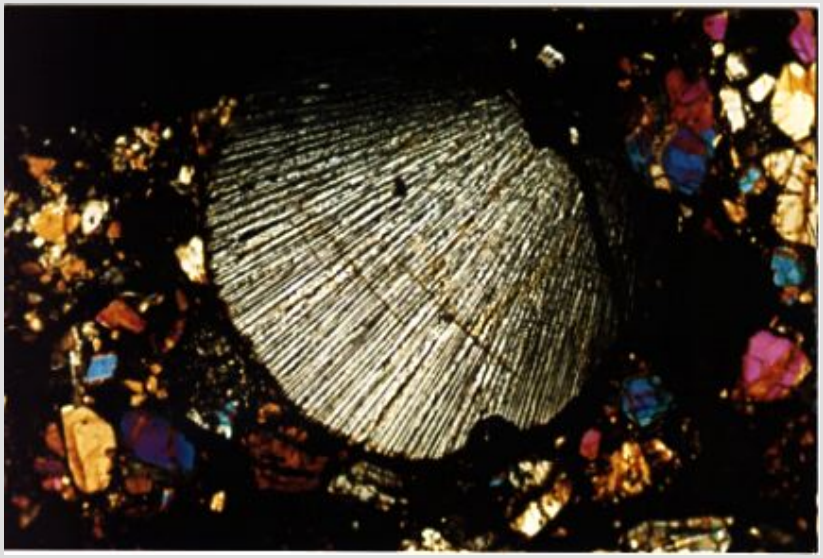
Chondrites



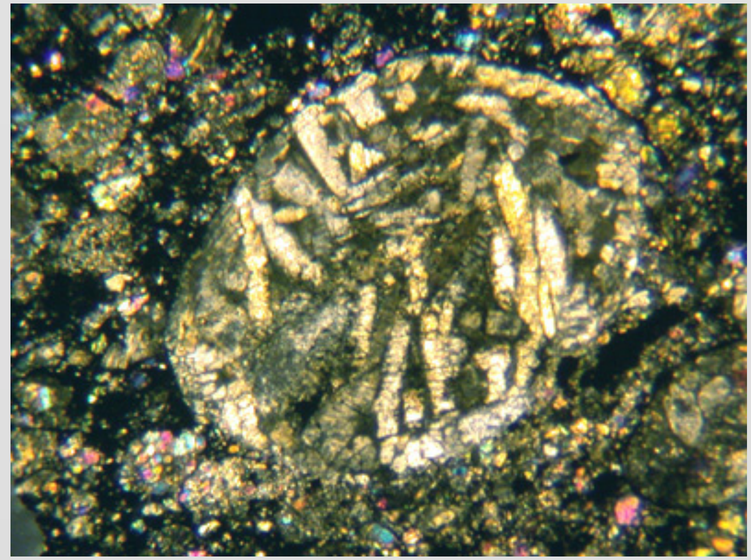
CAIs – small (order mm) rocky inclusions consistent with a high temperature ($T > 1350$ K) origin. These are the oldest materials dated in the Solar System.

Matrix – fine grained μm-sized particle of crystalline minerals and amorphous silicates

Chondrules – 0.1 – 1mm sized spheres of igneous rock, with properties consistent with very fast heating and fast cooling. Up to 80% of the mass of the chondrite.



radial pyroxene texture



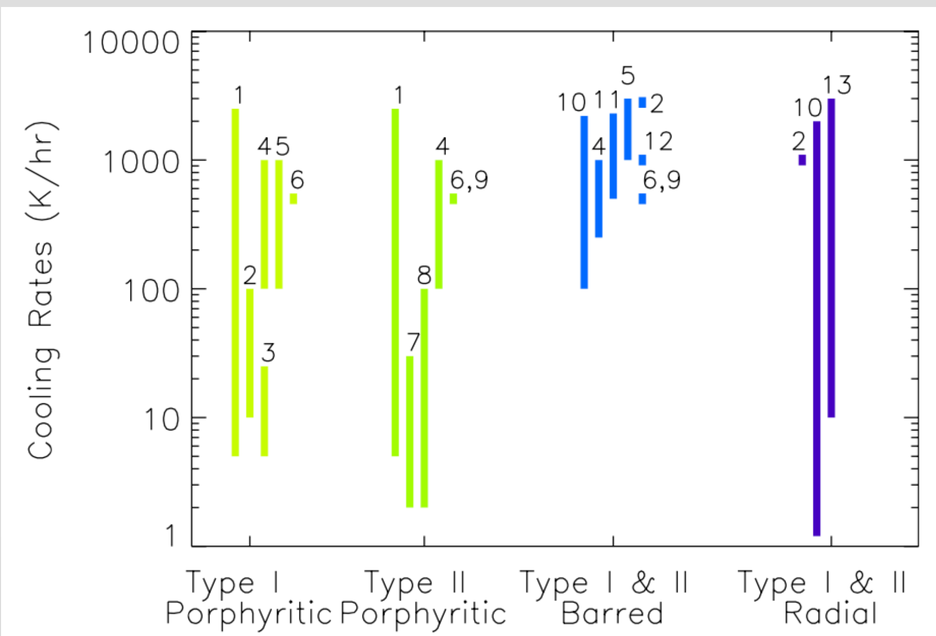
porphyritic texture

Chondrules have a chemical composition and texture that constrain their thermal history:

- texture tells us something about number of nucleation sites, interpreted as constraint on peak temperature and duration of that temperature, generally high and rapid (e.g. T = 1750-2400K, times of minutes)

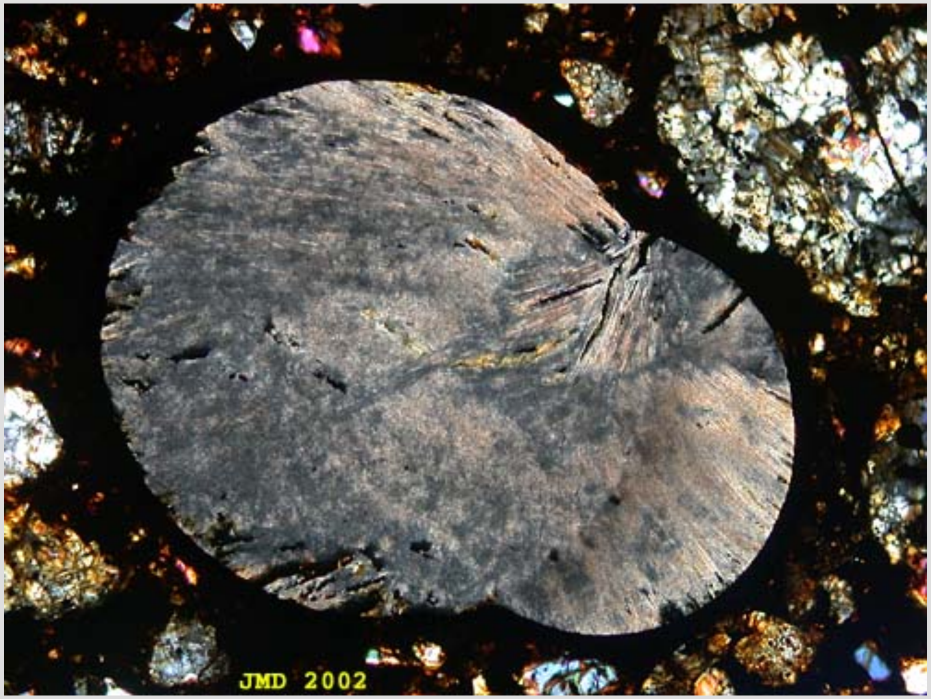
Chondrules have a chemical composition and texture that constrain their thermal history:

- retain volatile elements (Na, S) that would be lost on time scale of minutes while the chondrule was liquid (unless very high partial pressure of these species in the gas phase)



- subsequent cooling was slower, likely on time scale of hours

Desch et al. (2012)



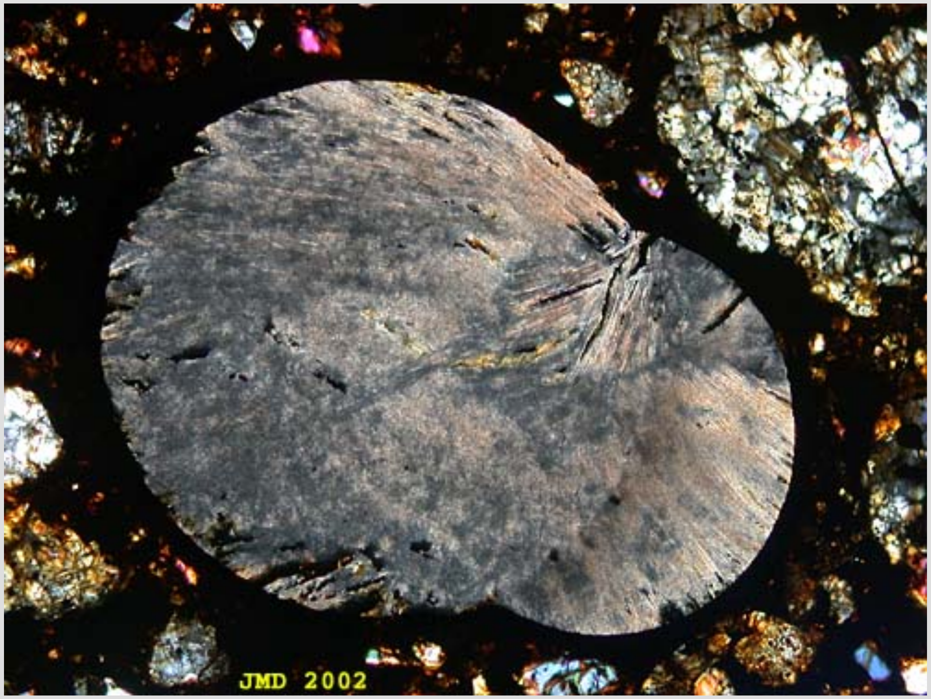
About 4% of chondrules are *compound* – stuck together while molten

- implies very high densities

$$f = n\sigma v t_{\mathrm{sticky}}$$

$\sigma \sim 5 \times 10^{-3}$ cm^2, v = 10^2 cm s^{-1}, $t_{sticky} = 10^4$ s

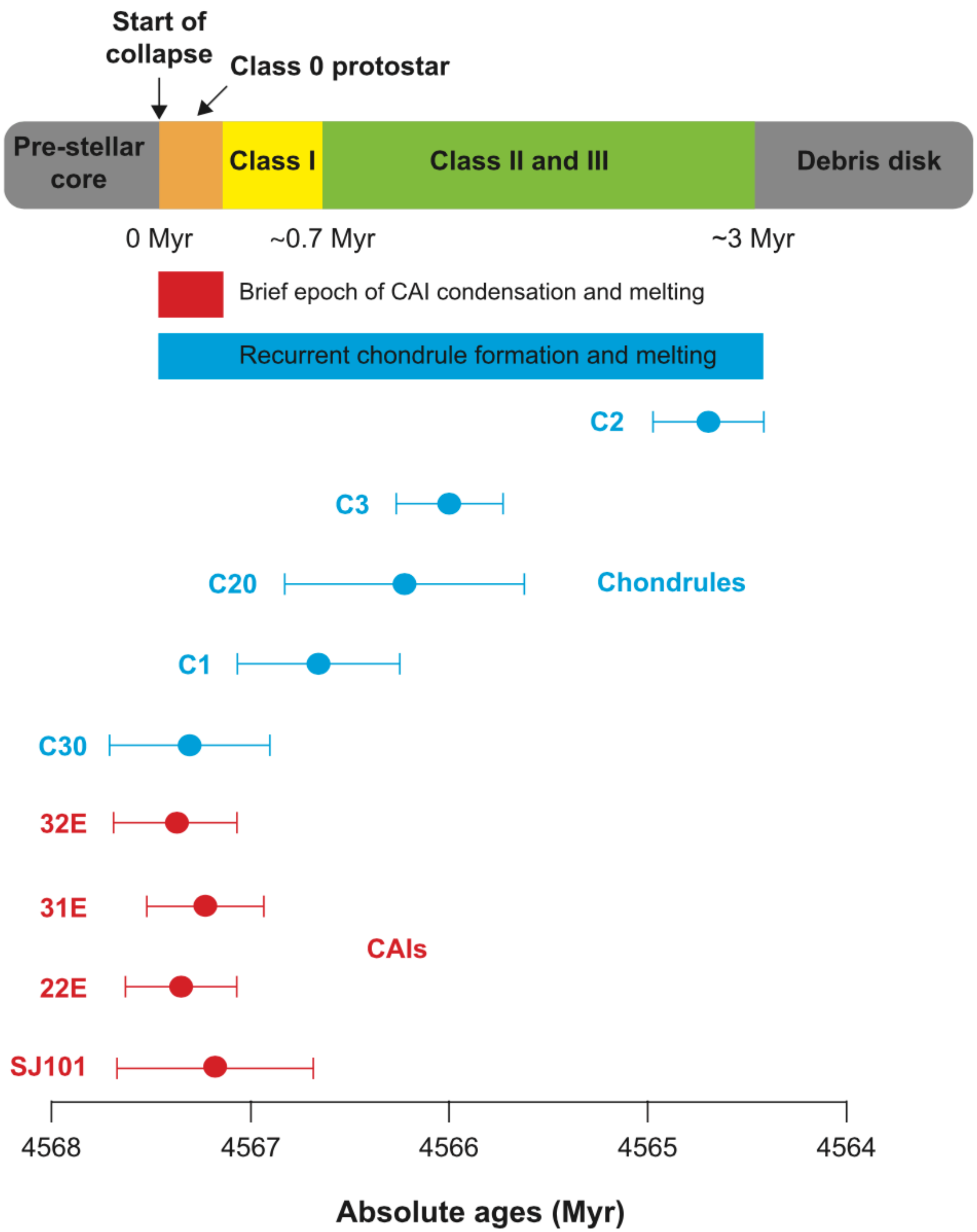
$\Rightarrow$ $\boxed{n \sim 8 \times 10^{-6}\ \mathrm{cm}^{-3}}$



Some elements have been lost via evaporation (e.g. K, Fe, Si), but no measured isotope fractionation

Constraint on **size** of chondrule formation region: likely to be large (> 10^3 km) so that the vapor did not have time to diffuse away significantly

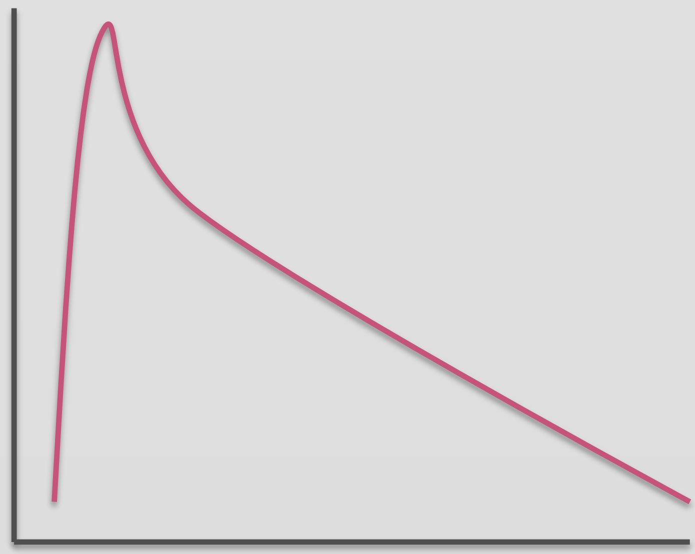
Similar constraint from mean-free path for collisions



Absolute age dating, *Connelly et al. (2012)*

At least 3 Myr dispersion in chondrule ages, no measureable dispersion in CAI ages

Summary



- fast heating to ~2000K
- initially very fast cooling
- slower cooling for hours
- very high density
- surrounding gas
- large-ish volume

How much mass is involved? At a minimum, reasonable fraction of current mass of asteroid belt (~10^{24} g), possibly reasonable fraction of mass in terrestrial planet region (~10^{27} g)

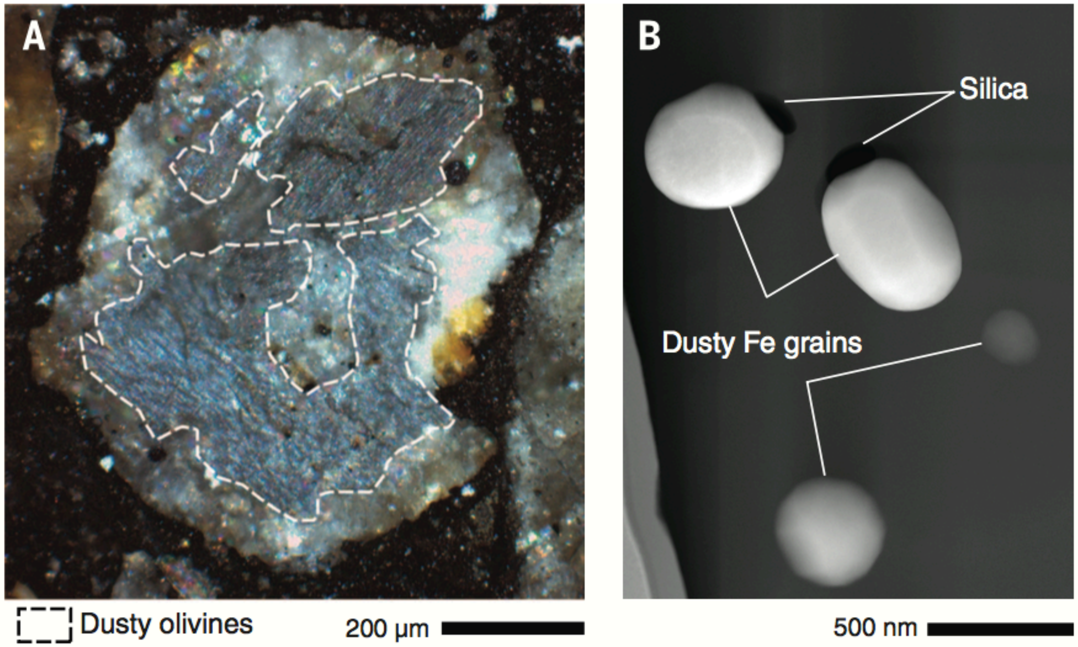


Fig. 1. Dusty olivine-bearing chondrules from the Semarkona meteorite. (**A**) Optical photomicrograph of chondrule DOC4 showing the location of dusty olivine grains. Image taken in reflected light with crossed polarizers. (**B**) Annular dark-field scanning transmission electron microscope (STEM) image of four dusty olivine Fe grains from chondrule DOC5. Brightness in image reflects column-averaged atomic number; darker grains are smaller in size, implying a higher relative abundance of olivine at their location and hence a lower mean atomic number. The euhedral morphology and chemical homogeneity of the Fe grains is apparent, which indicate the lack of secondary recrystallization and alteration. Such Fe grains are the primary carriers of preaccretional magnetization in Semarkona chondrules.

Fu, Weiss et al. (2014)

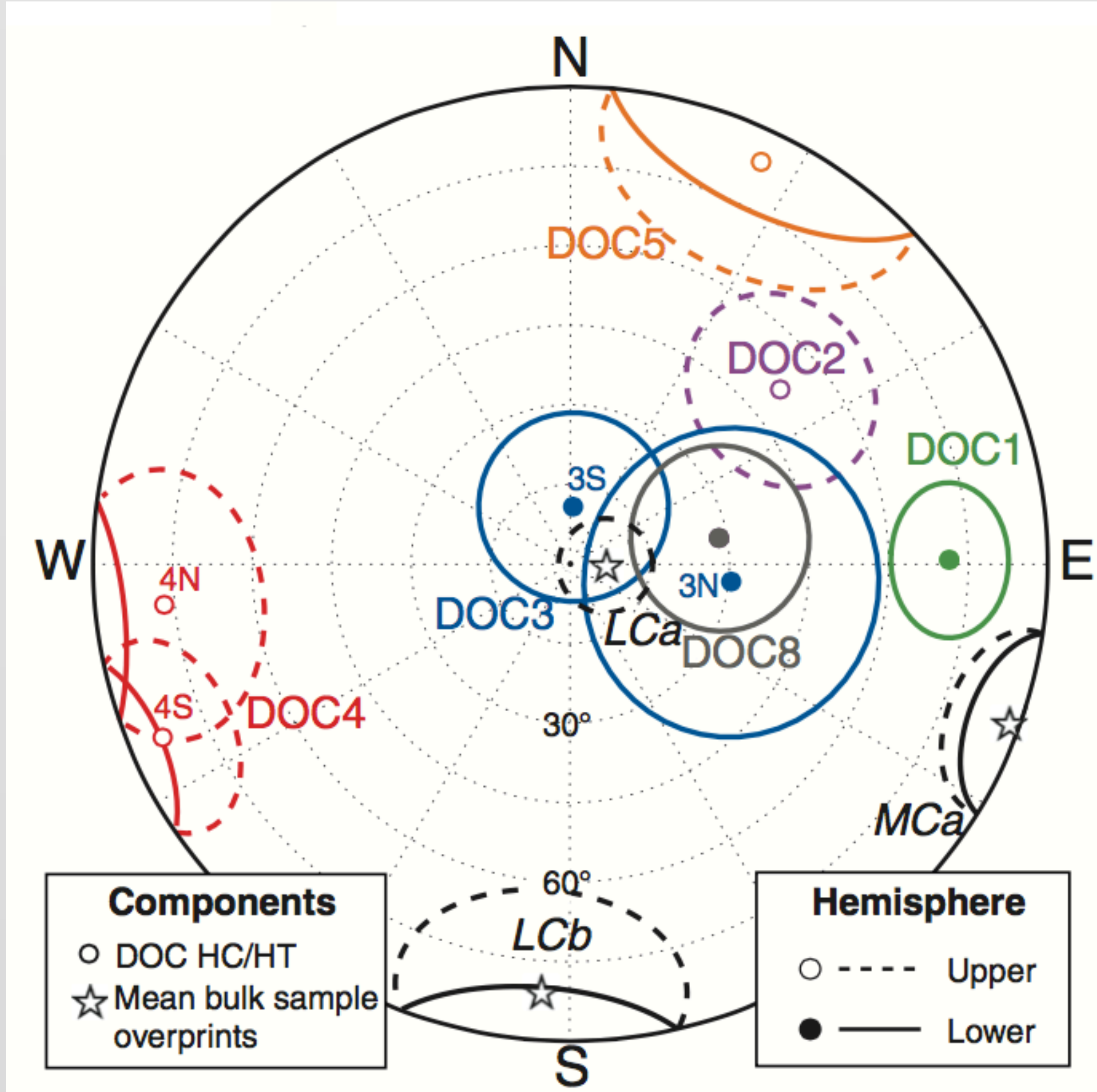
Some chondrules contain Fe grains that preserve magnetization

Fu, Weiss et al. (2014)

Magnetization could have various origins:

- from Nebula
- from asteroid
- from Earth

Random directions of magnetization for different chondrules in same rock suggests primordial

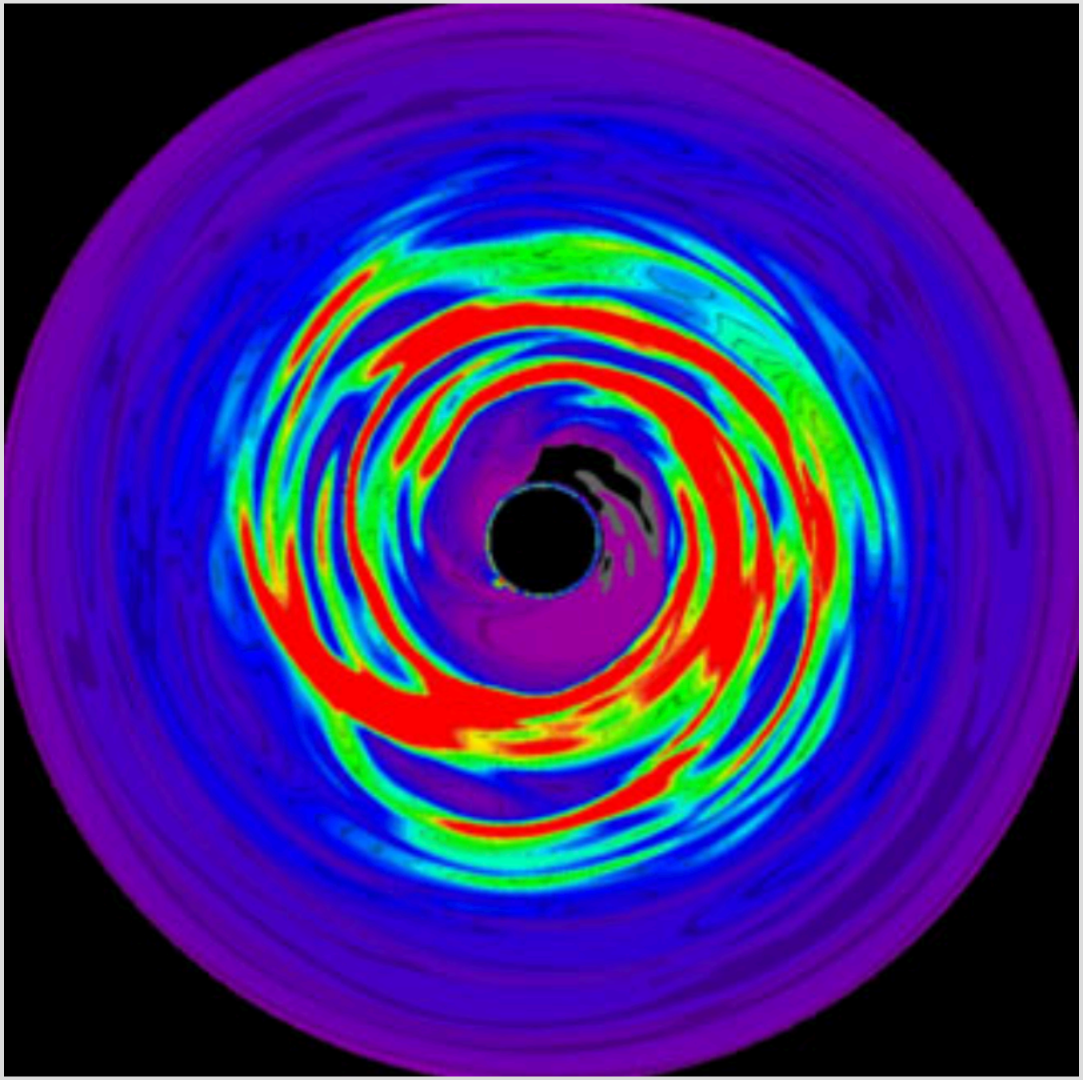


B ~ 0.5 +/- 0.2 G

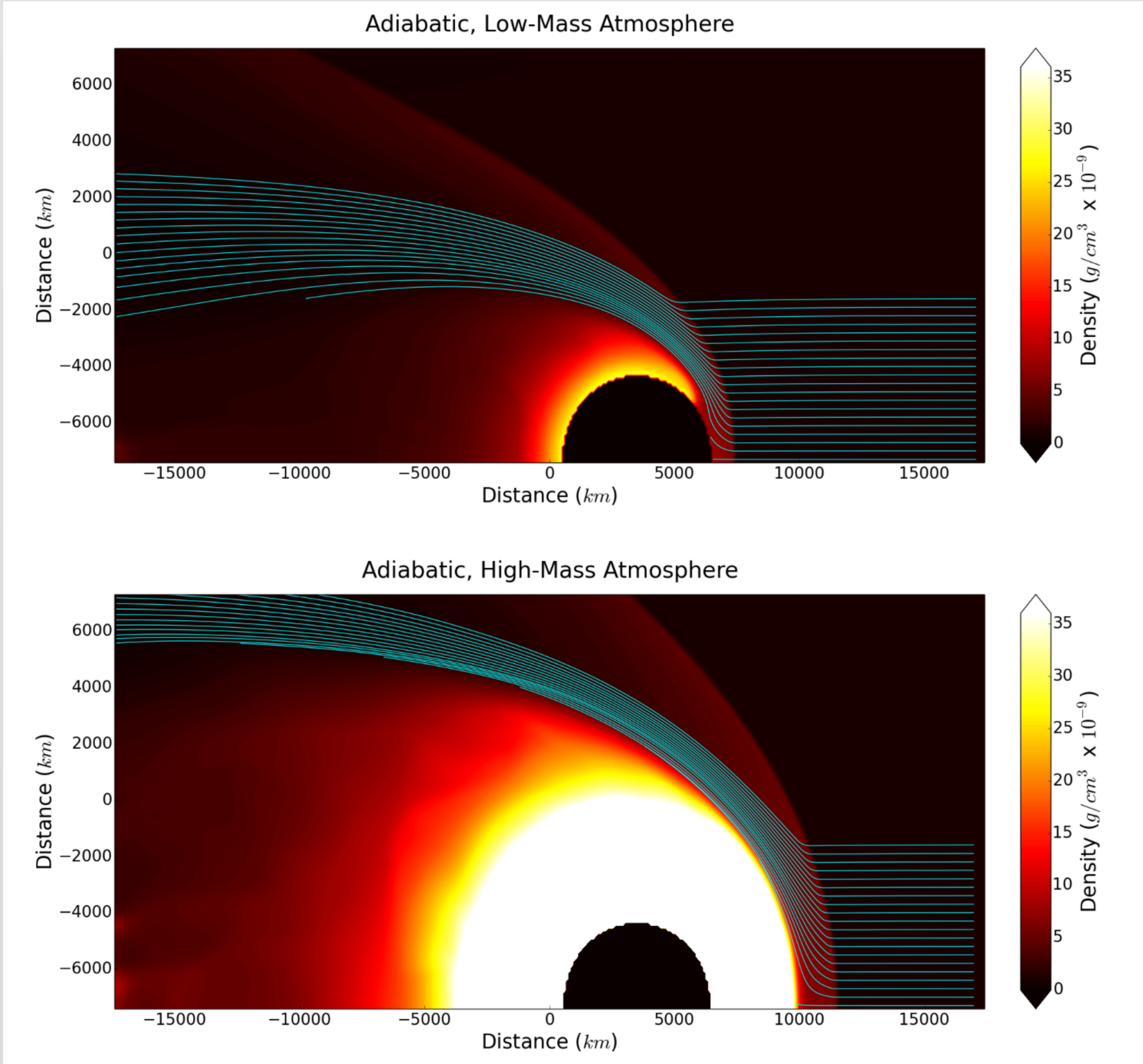
Models

Thermal history is suggestive of passage through a shock

Not clear why the disk would support large scale shocks at radii of r ~ 3 AU



Boss & Durisen (2005), self-gravity



Bow shocks of planetary embryos *(Mann et al. 2016)*, requires that e > (h/r)

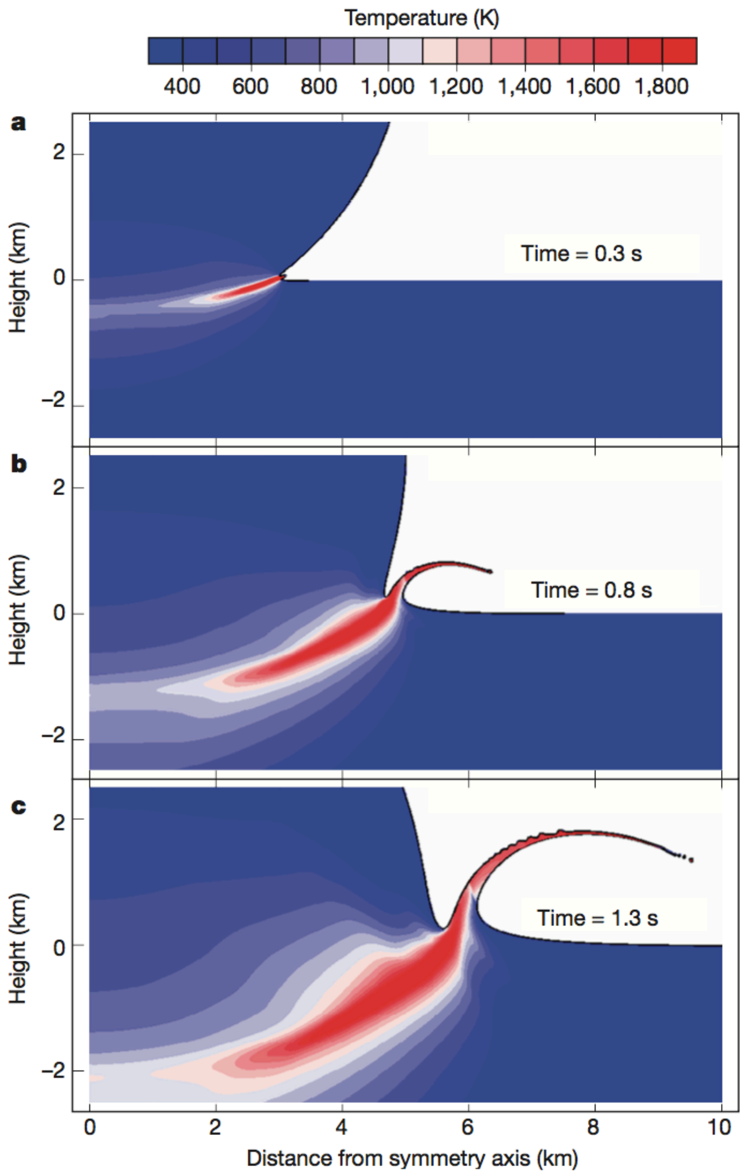


Figure 1 | Jetting of melted material during an accretionary impact. A time series showing a 1% porous projectile 10 km in diameter striking a target at 3 km s^{-1}. Material is coloured according to its temperature at the time shown. The origin is the collision site. In **a** the jet is just beginning to form, 0.3 s into the impact. Panel **b** shows a well-formed hot jet 0.8 s into the impact. Panel **c** roughly shows the end of jetting, when the projectile penetrates halfway into the target. The fastest ejecta have a velocity of about 6 km s^{-1}, or twice the impact velocity. The figure was produced using iSALEPlot.

Jets from high velocity ($v > 2.5$ km s^{-1}) impacts

- generate unbound, molten material on impact
- jet breaks up into mm-sized spheres which cool very rapidly

Johnson et al. (2015)

Wakita et al. (2016)

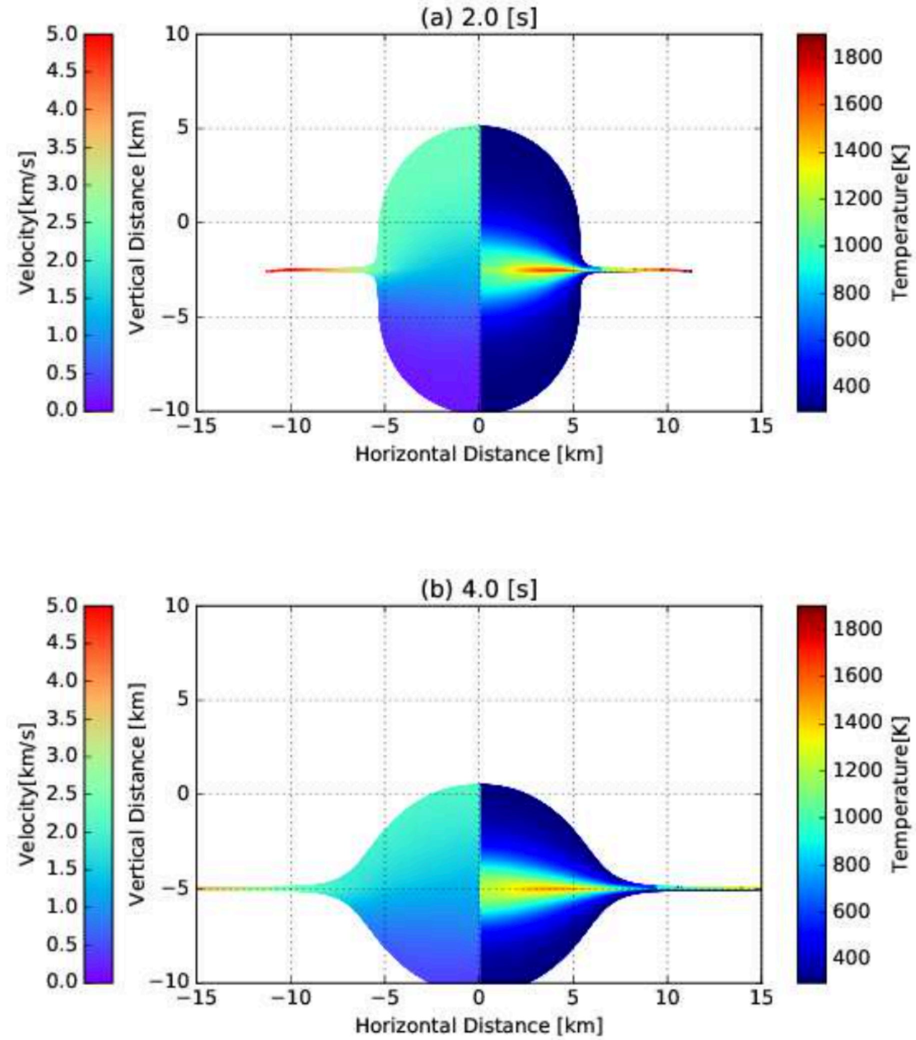
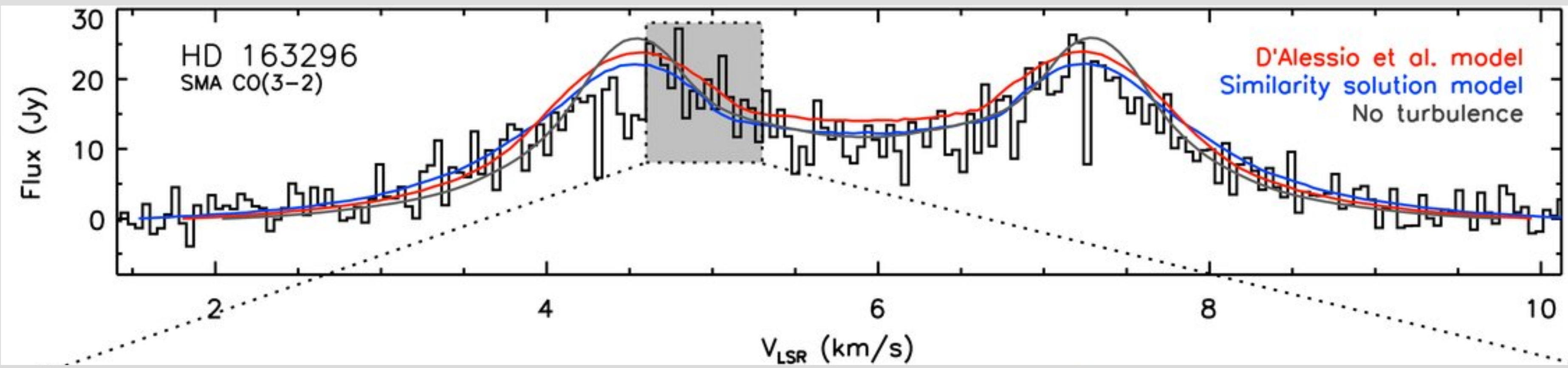


Figure 1. Snapshots of a collision between 10 km sized planetesimals with $v_{imp} = 2.5$ km s^{-1} at 2.0 s (top) and 4.0 s (bottom) after an impact. Velocities and temperatures of materials at each position are shown on the left and right sides with the corresponding color bar, respectively.

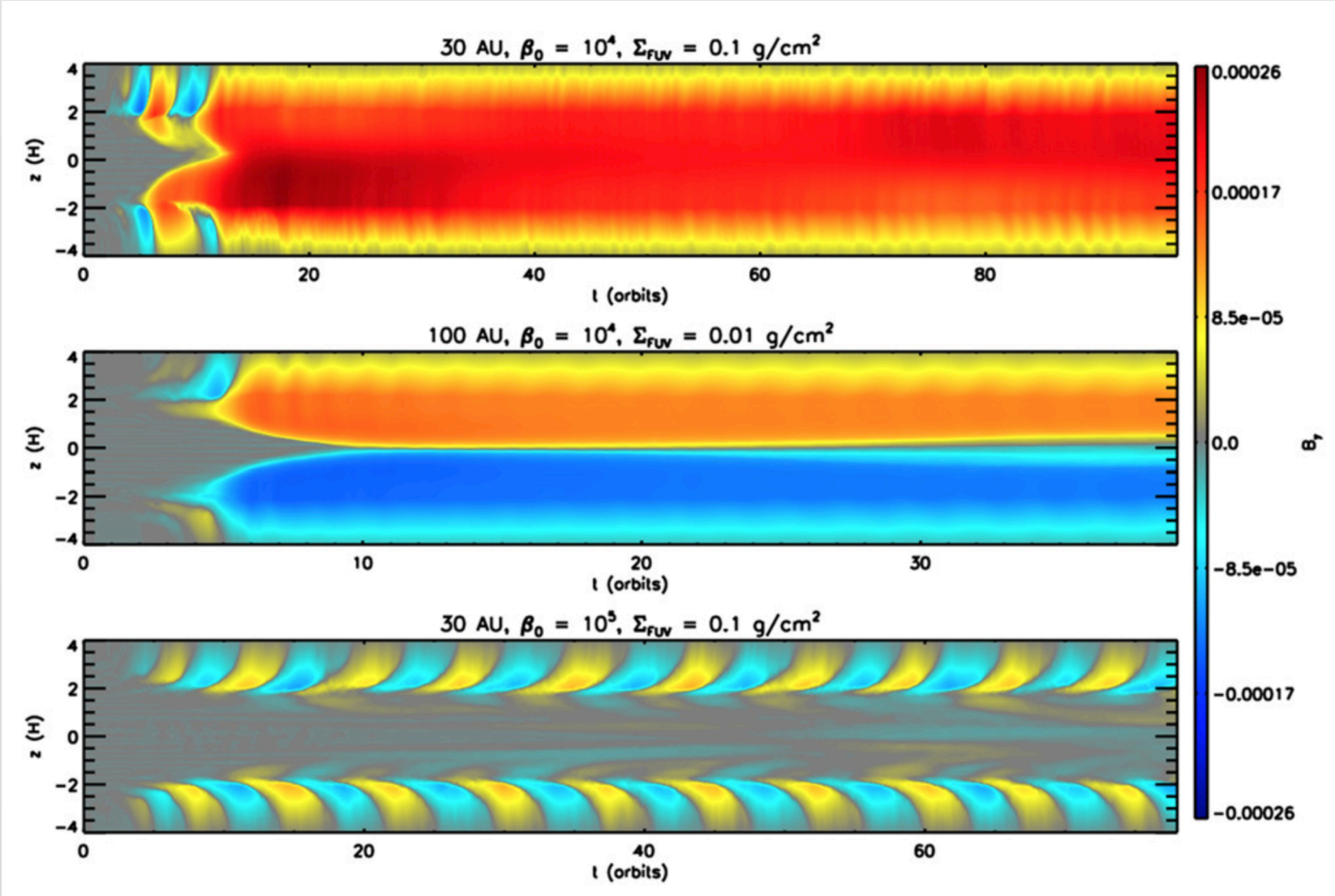
Turbulent line broadening

Potential to measure turbulence from broadening of molecular lines in protoplanetary disks (IR, unresolved, *Carr et al. '04*; sub-mm, resolved, *Hughes et al. '11, Guilloteau et al. 12*)



Subtle effect: $\delta v \sim \alpha^{1/2}\,(h/r)\,v_K \sim 0.01\,v_K$

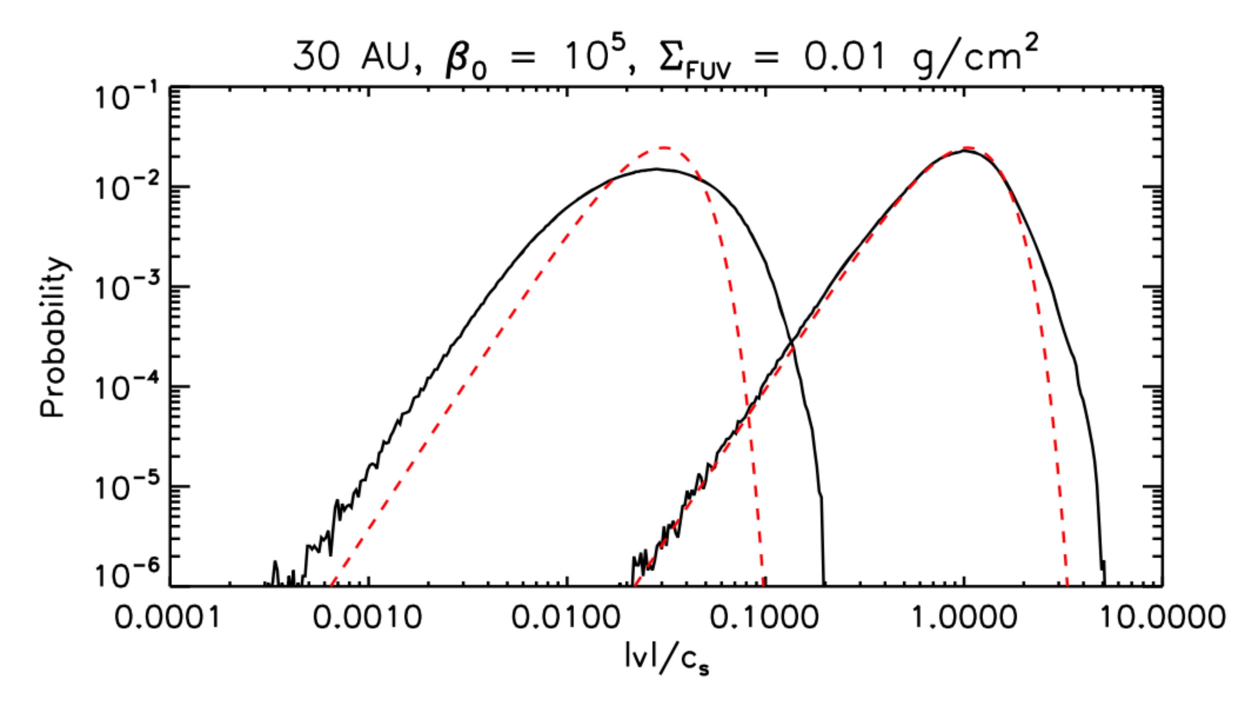
Need to understand predictions of different turbulence models (MRI, self-gravity, vortices…) for observables



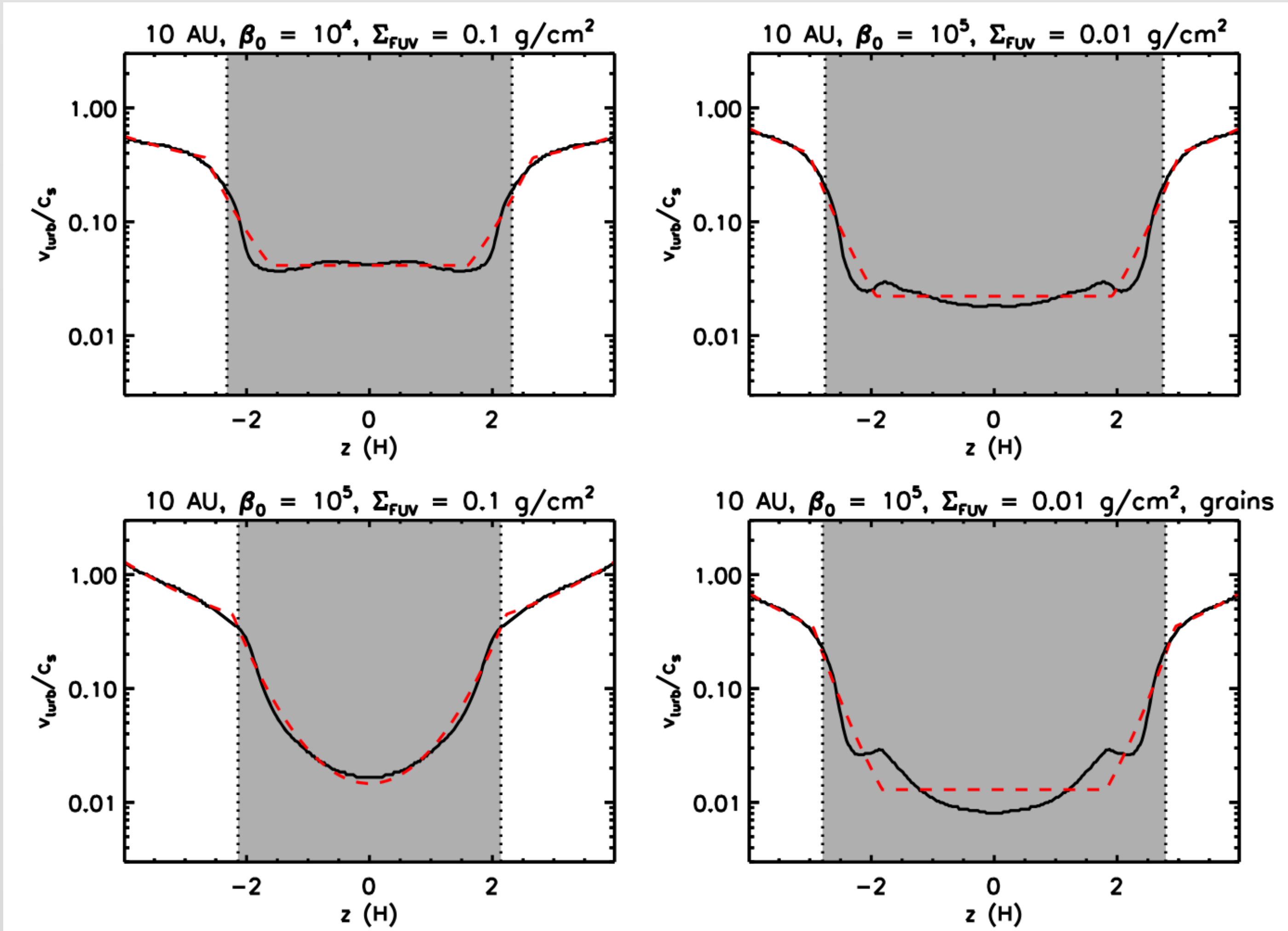
Simulations 10-100 AU (extrapolate to larger r), Ohmic + ambipolar diffusion only – solutions a mix of "dynamo" and non-dynamo

Results

Velocity field can have large scale structure, but small-scale δv can be represented as micro-turbulence



Simon, Hughes et al. '15

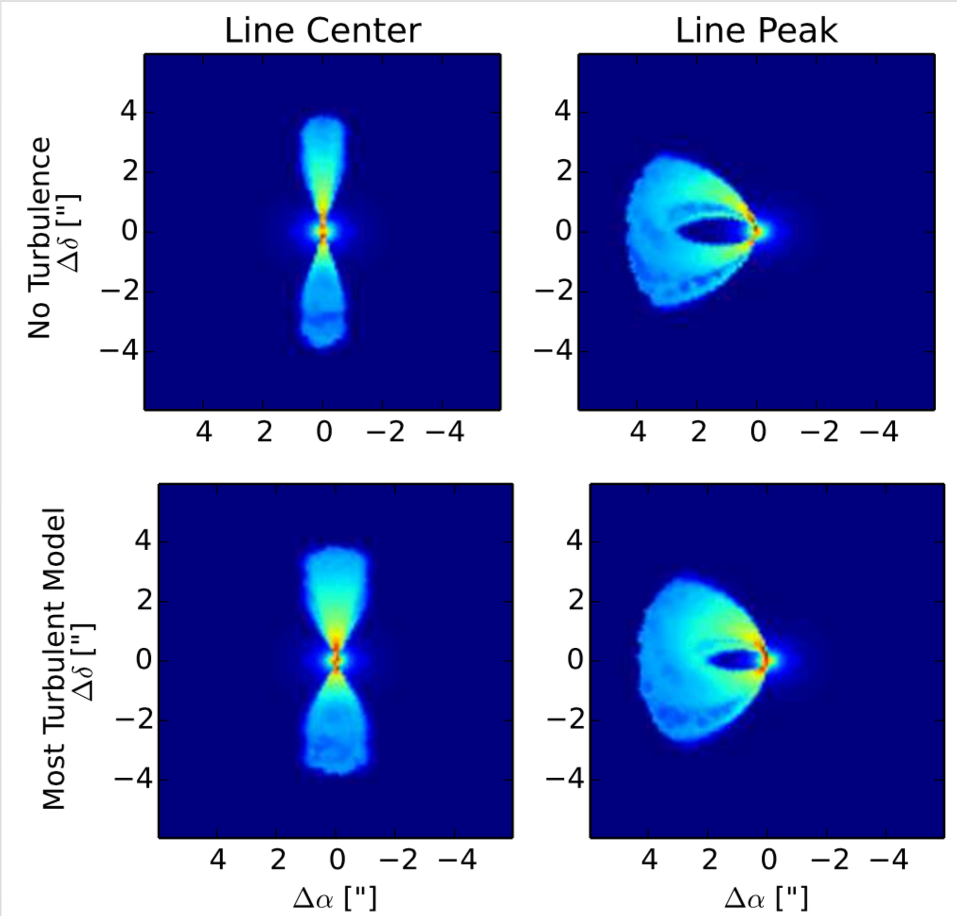


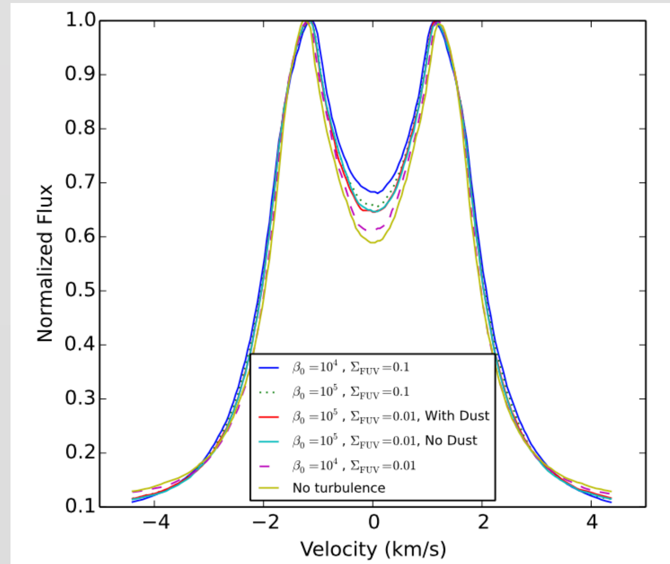
Generally damping near the mid-plane (ambipolar diffusion), near-sonic velocities near disk surface

Optically thick lines expected to show more broadening

Simon, Hughes et al. '15

Results





Line radiative transfer (LIME) for CO 3-2

- turbulence vs. no-turbulence ~15% variation in peak-to-trough ratio (with free flux normalization)
- measuring the “MRI-signature” of $\delta v(z)$ with different lines may be attainable…

Observational results

Only an upper limit on δv

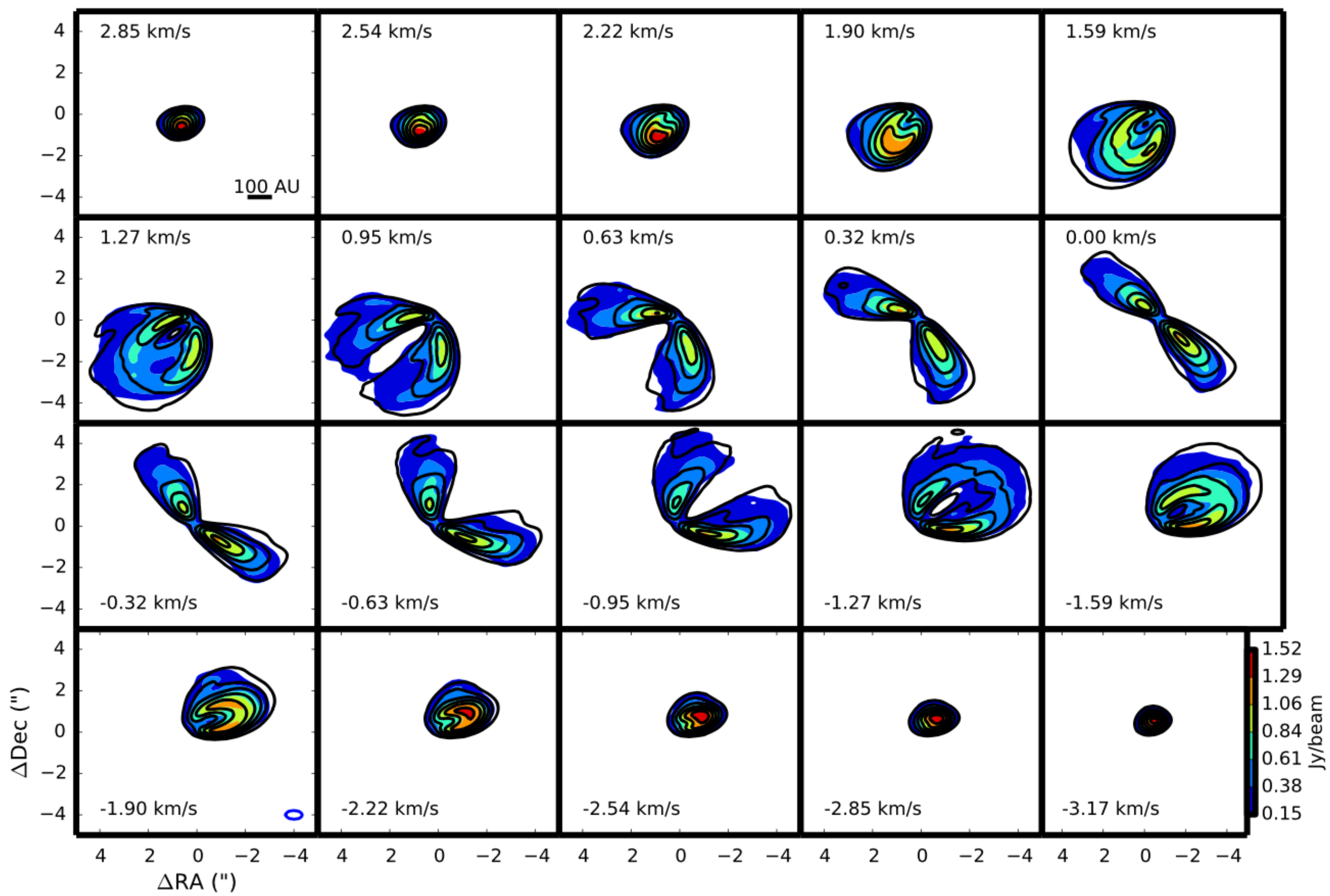


Figure 1. Images of select channels from the high-resolution CO(3-2) data (colored filled contours) along with the best fit model (black contours). Contour levels are set at 10%, 25%, 40%, … of the peak flux, where 10% peak flux = 0.15 Jy/beam ∼ 18σ, as marked on the scale. Overall the model successfully reproduces much of the emission.

Flaherty et al. (2015): CO(3-2)

Observational results

- rich molecular diagnostics of different disk layers
- analysis is not consistent with MRI expectations if the outer disk is accreting
- powerful constraint on models
- *Teague et al. (2016),* using a different approach, find evidence for non-zero turbulence in TW Hya
- stay tuned…