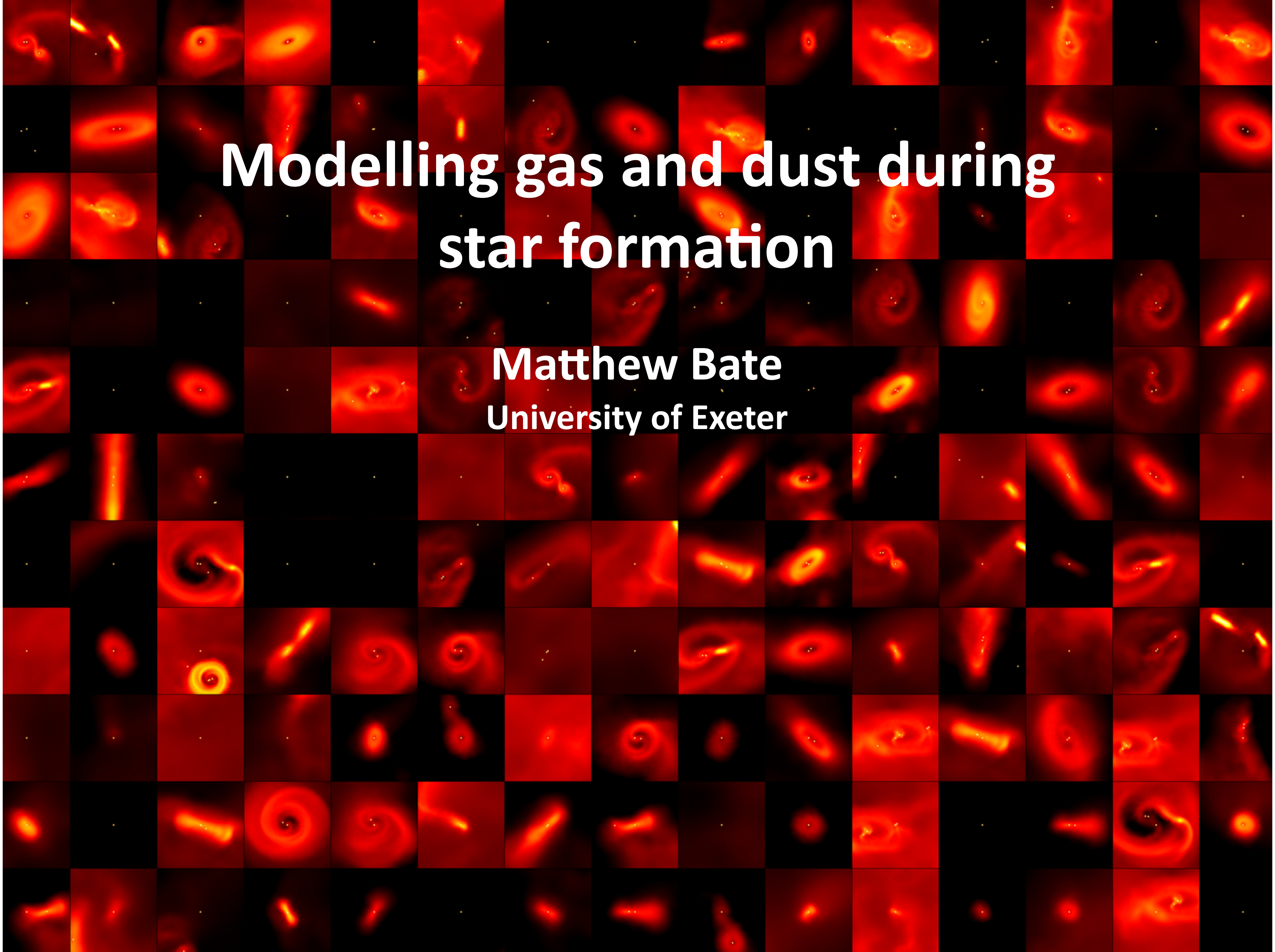
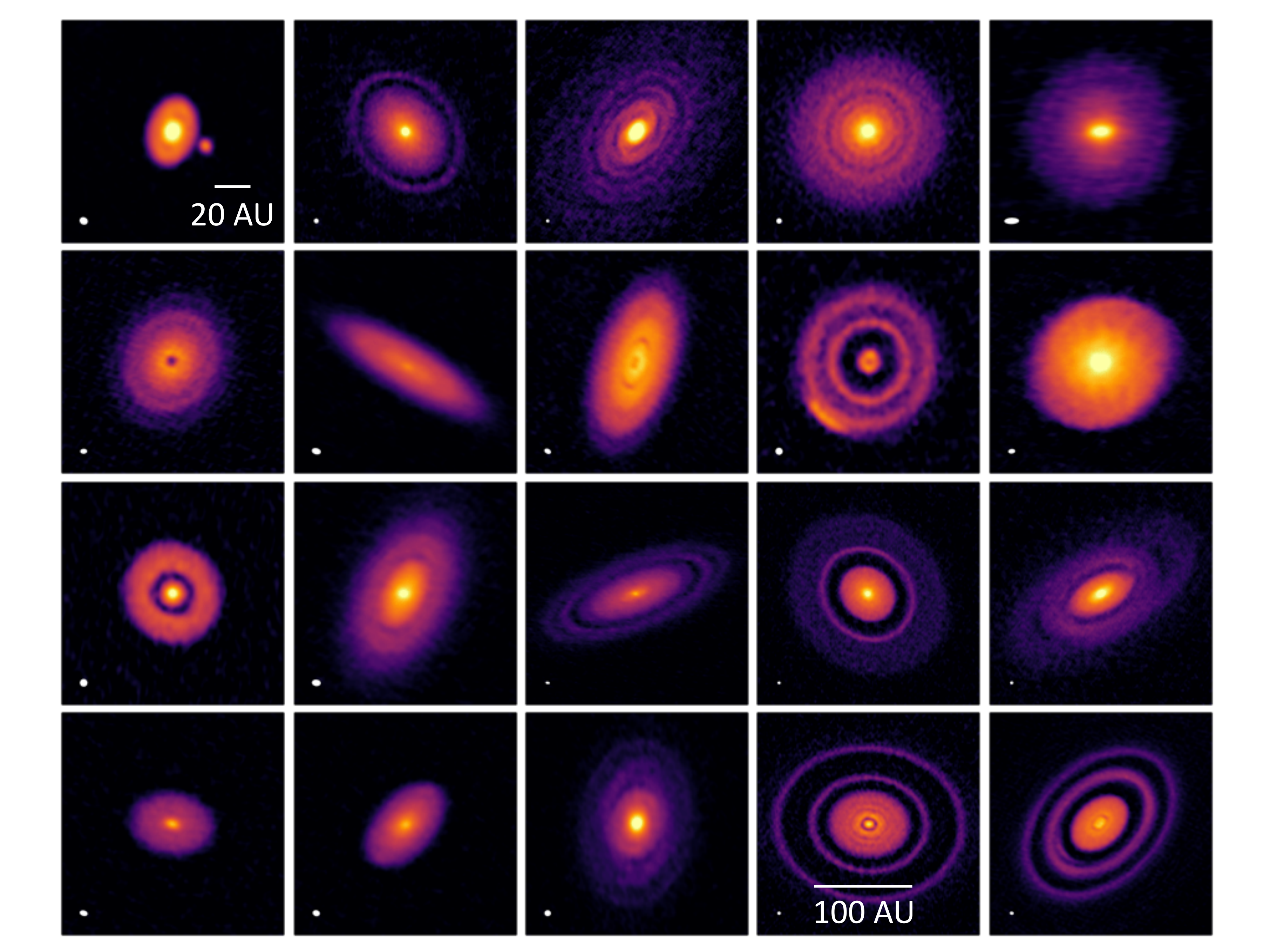


Modelling gas and dust during star formation

Matthew Bate

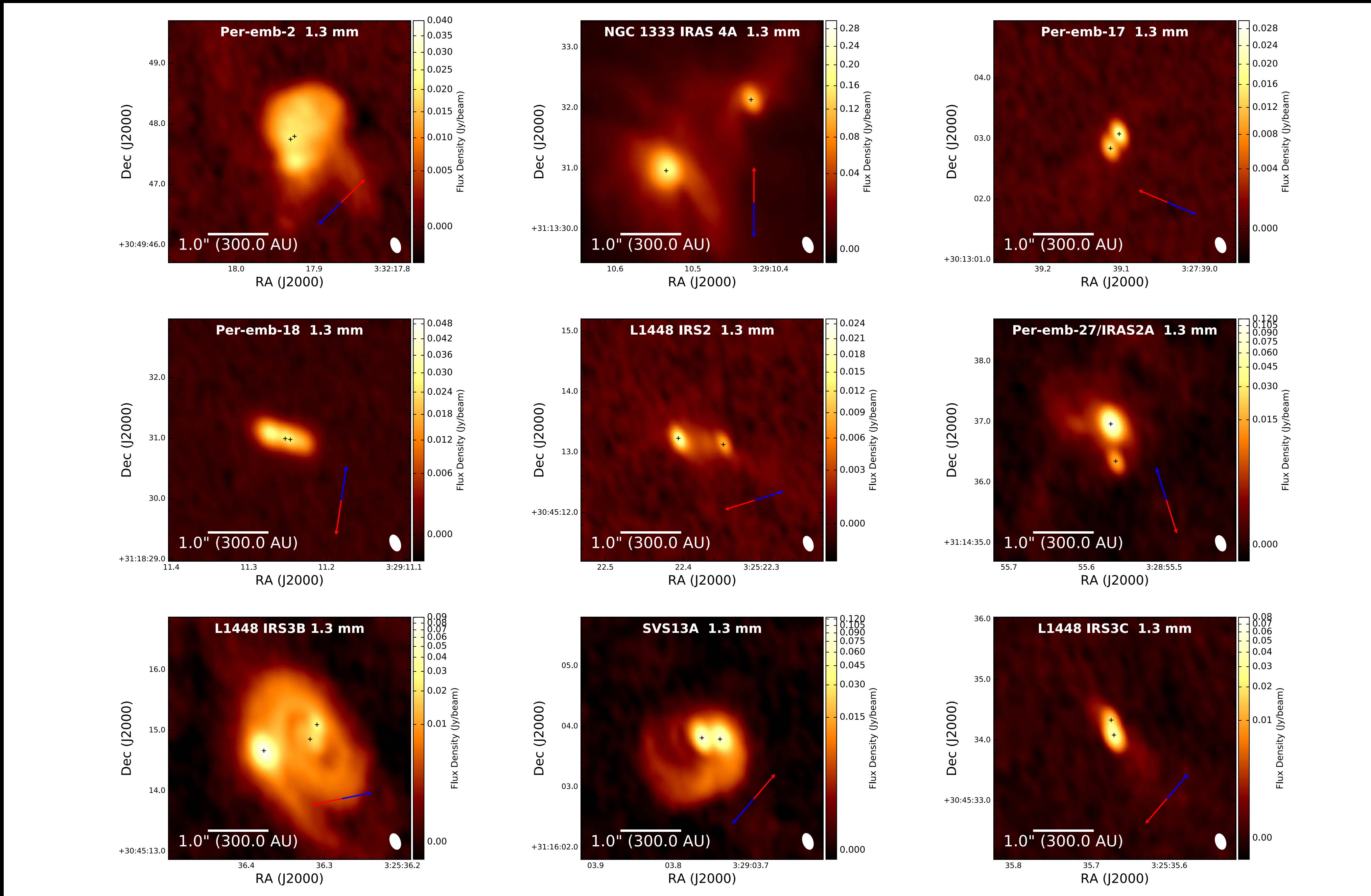
University of Exeter

ALMA images of discs in nearby star forming regions



DSHARP ALMA Large Program; Andrews et al. 2018

ALMA images of Class 0 multiple systems



VANDAM Survey; Tobin et al. 2018

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Dust dynamics during star formation

- Two methods for modelling drag force between gas and dust with SPH:
  - Two-fluid method (Laibe & Price 2012; Ayliffe et al. 2012; Loren-Aguilar & Bate 2014)
  - One-fluid method (Laibe & Price 2014a,b; Price & Laibe 2015)
- One-fluid method cannot handle large grains
- Two-fluid prone to artificial clumping and resolution-dependent over-dissipation

Two-fluid equations

$$\frac{\partial \hat{\rho}_{\mathrm{g}}}{\partial t} + \nabla . \left(\hat{\rho}_{\mathrm{g}} \boldsymbol{v}_{\mathrm{g}}\right) = 0,$$

$$\frac{\partial \hat{\rho}_{\mathrm{d}}}{\partial t} + \nabla . (\hat{\rho}_{\mathrm{d}} \boldsymbol{v}_{\mathrm{d}}) = 0,$$

$$\hat{\rho}_{\mathrm{g}} \left(\frac{\partial \boldsymbol{v}_{\mathrm{g}}}{\partial t} + \boldsymbol{v}_{\mathrm{g}} . \nabla \boldsymbol{v}_{\mathrm{g}} \right) = -\theta \, \nabla P_{\mathrm{g}} + \hat{\rho}_{\mathrm{g}} \boldsymbol{f} - \boldsymbol{F}^{\mathrm{V}}_{\mathrm{drag}},$$

$$\hat{\rho}_{\mathrm{d}} \left(\frac{\partial \boldsymbol{v}_{\mathrm{d}}}{\partial t} + \boldsymbol{v}_{\mathrm{d}} . \nabla \boldsymbol{v}_{\mathrm{d}} \right) = -\nabla P_{\mathrm{d}} - (1-\theta) \, \nabla P_{\mathrm{g}} + \hat{\rho}_{\mathrm{d}} \boldsymbol{f} + \boldsymbol{F}^{\mathrm{V}}_{\mathrm{drag}},$$

$$\boldsymbol{F}^{\mathrm{V}}_{\mathrm{drag}} = K(\boldsymbol{v}_{\mathrm{g}} - \boldsymbol{v}_{\mathrm{d}}).$$

One-fluid equations

$$\frac{\mathrm{d}\rho}{\mathrm{d}t} = -\rho(\nabla \cdot \boldsymbol{v}),$$

$$\frac{\mathrm{d}\boldsymbol{v}}{\mathrm{d}t} = -\frac{\nabla P_{\mathrm{g}}}{\rho}, \qquad \boldsymbol{v} = \frac{\rho_{\mathrm{g}} \boldsymbol{v}_{\mathrm{g}} + \rho_{\mathrm{d}} \boldsymbol{v}_{\mathrm{d}}}{\rho_{\mathrm{g}} + \rho_{\mathrm{d}}}.$$

$$\frac{\mathrm{d}\epsilon}{\mathrm{d}t} = -\frac{1}{\rho} \nabla \cdot (\epsilon t_{\mathrm{s}} \nabla P_{\mathrm{g}}),$$

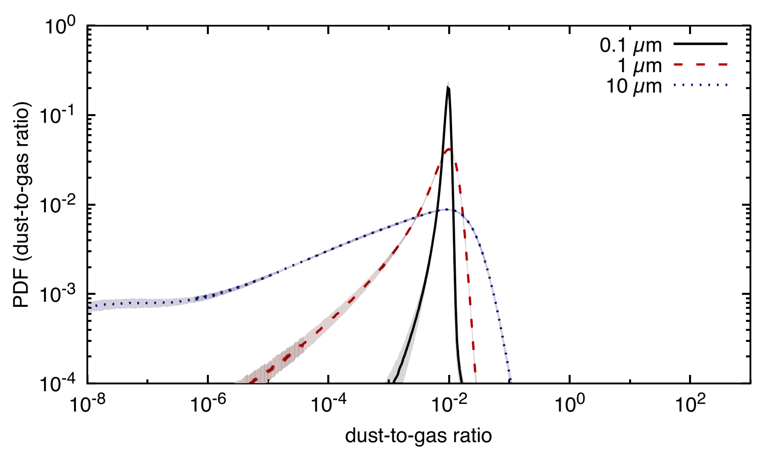
$$P = c_{\mathrm{s}}^2 \rho_{\mathrm{g}} = c_{\mathrm{s}}^2 (1-\epsilon)\rho,$$

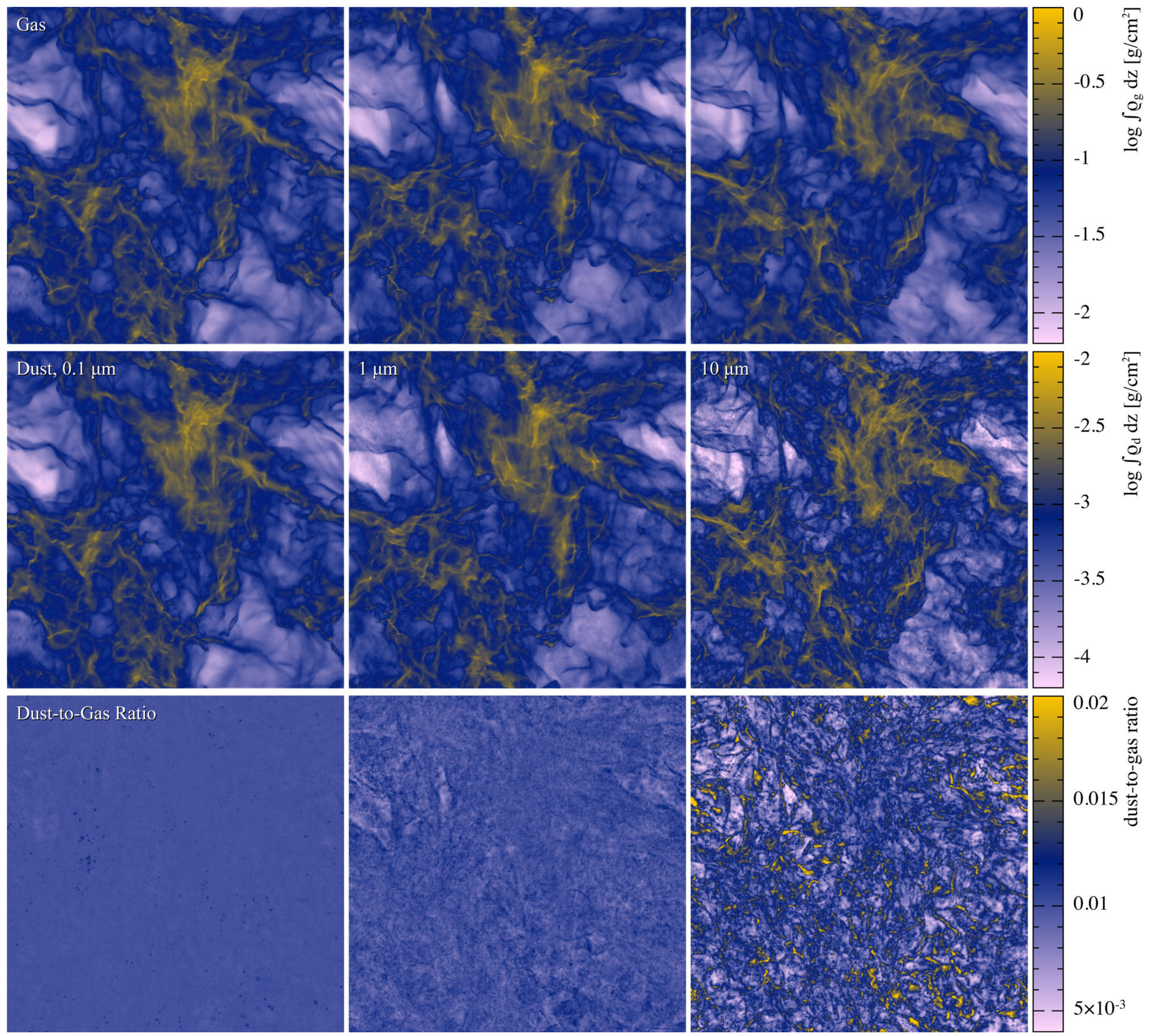
Dust dynamics in molecular clouds

- Small dust particles (~0.1µm) are collisionally coupled to gas
  - Usually assume that dust and gas are well mixed in molecular clouds
  - Gas to dust ratio ~100
- But large dust particles may be poorly coupled
- May be a population of large grains (>1µm) in molecular clouds
  - Cloud-shine observations (e.g. Foster & Goodman 2006; Steinacker et al. 2014, 2015)
  - Mid-IR extinction (e.g. Wang, Li & Jiang 2015a,b) and sub-mm emissivity (e.g. Miettinen et al. 2012; Schnee et al. 2014)

Dust dynamics in molecular clouds

- Dust dynamics depend on grain size
  - Small grains (~0.1 micron) are well-coupled to the gas
  - Dust-to-gas ratio of larger grains can vary
  - Leads to size-sorting in molecular clouds



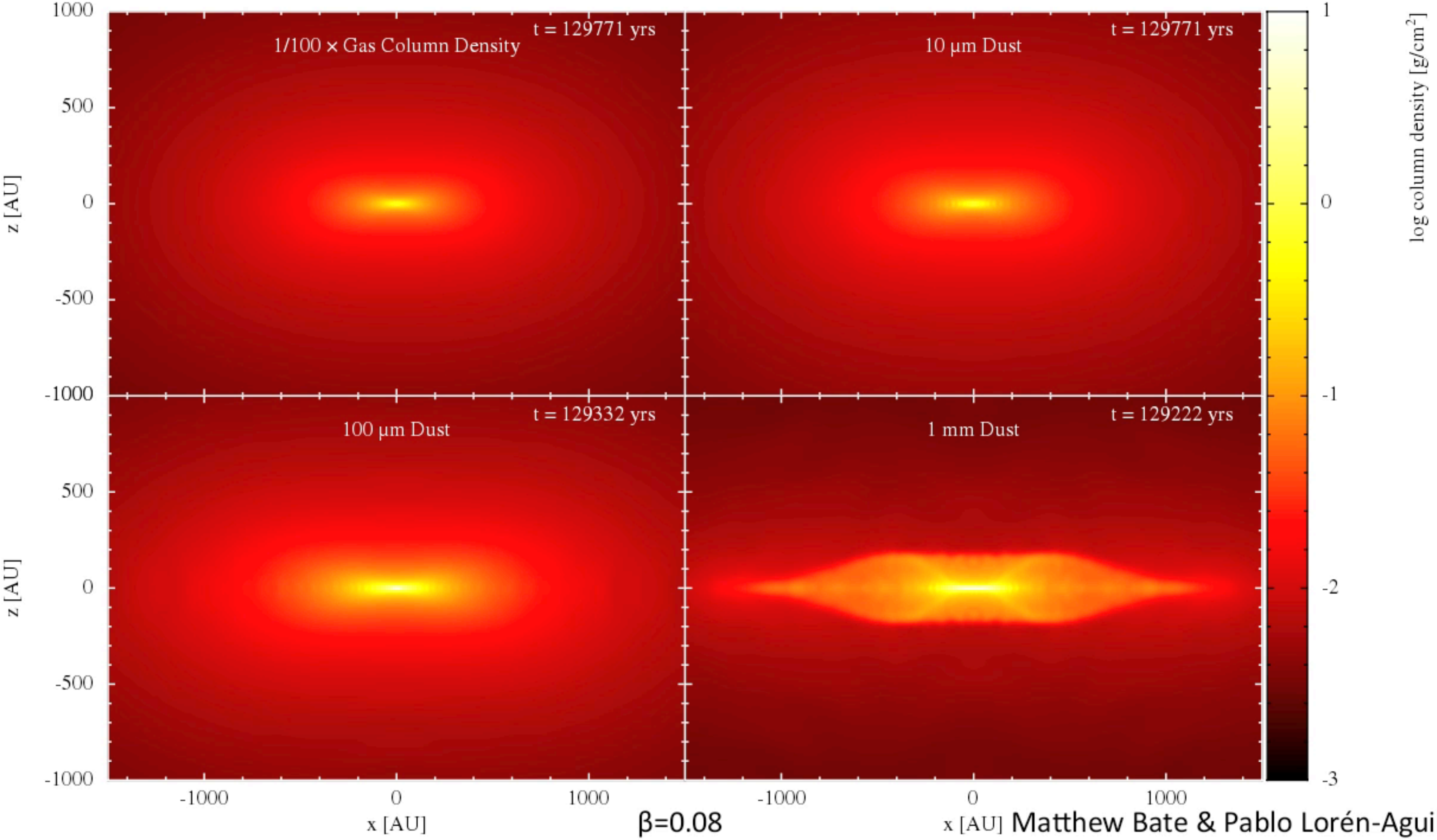


Tricco, Price & Laibe (2017)

Dust dynamics during protostellar collapse

- In Exeter, we've been starting to study smaller scales
- Using two-fluid dust-gas SPH simulations
- Studying dynamics of different grain sizes during protostellar collapse
  - Used two-fluid gas/dust SPH simulations (Bate & Loren-Aguilar 2017)
  - Rotating Bonnor-Ebert spheres, dust initially well-mixed and moving with gas

Rapidly-rotating molecular cloud core

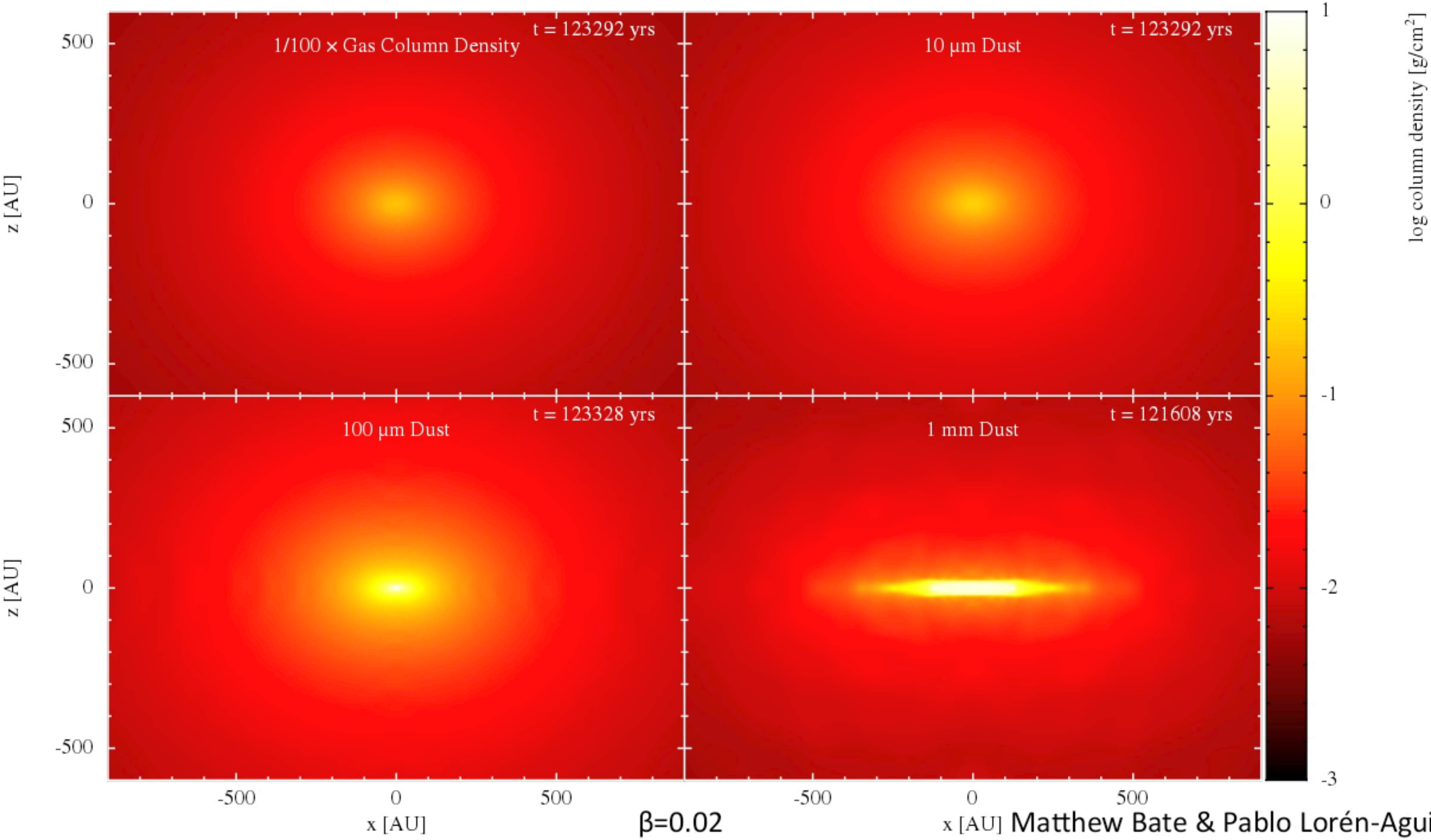


β=0.08

Matthew Bate & Pablo Lorén-Aguilar

Bate & Loren-Aguilar (2017)

Slowly-rotating molecular cloud core



β=0.02

Matthew Bate & Pablo Lorén-Aguilar

Bate & Loren-Aguilar (2017)

Dust dynamics during protostellar collapse

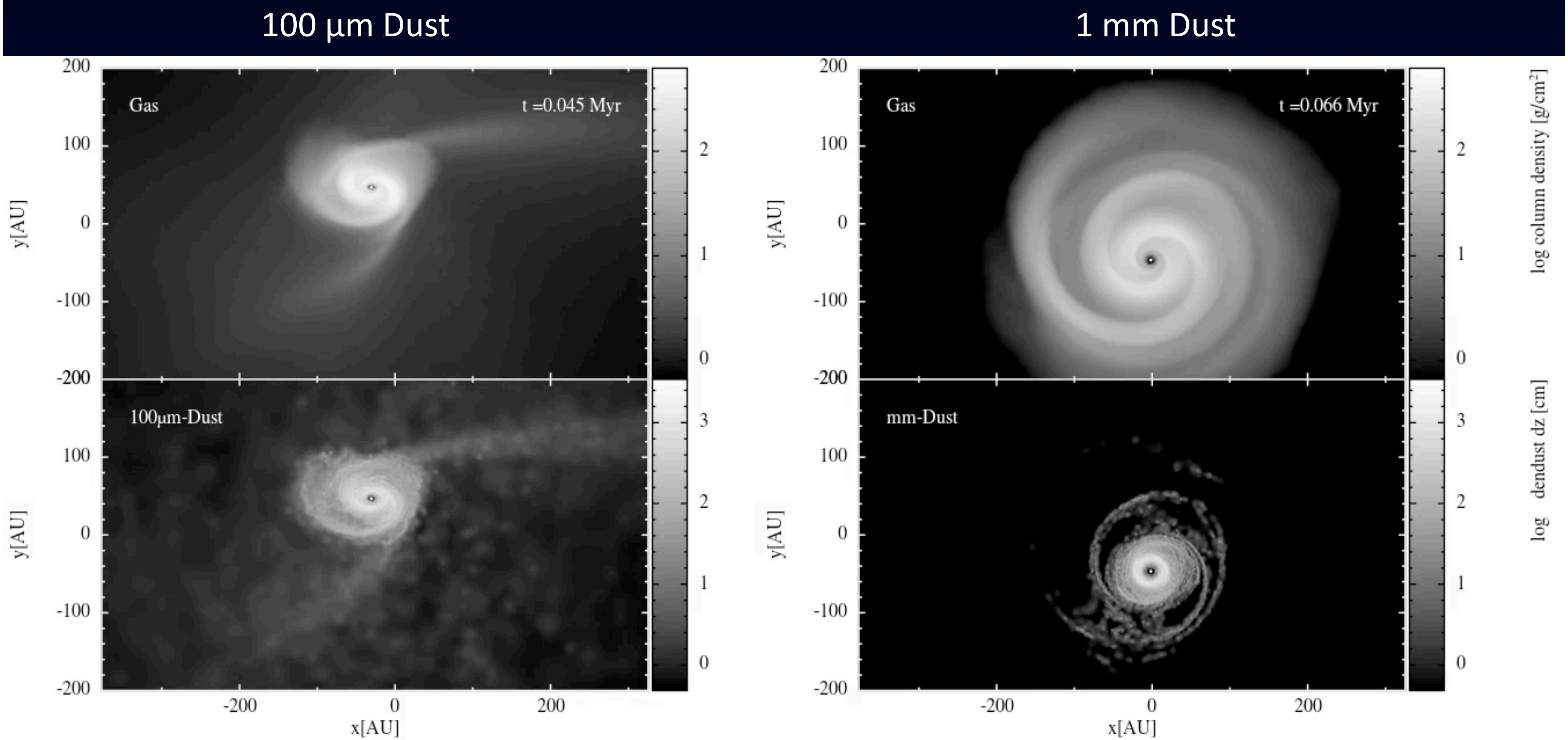
- Large grains (size >10μm) collapse faster than gas
  - Experience gravity, but not gas pressure

- Implications if large grains are present
  - Dust-to-gas ratio (of large grains) may increase in central regions
  - Produces a size-distribution favouring large grains without grain growth (size sorting)
  - Large grains pass through the midplane, oscillate, and settle to disc-like geometry *before* gas has collapsed to form a protostar

Dust dynamics during disc formation

- Potential numerical issues
  - Self-gravity can exacerbate clumping of dust particles
  - Produce local gravitational collapse
- Use sink particles to follow collapse beyond first hydrostatic core phase
- Initial conditions
  - Unstable Bonnor-Ebert sphere
  - Solid body rotation + turbulent velocity field
  - Dust-to-gas ratio initially uniform

Dust in a turbulent, collapsing molecular cloud core



Bate, in preparation

Dust dynamics during disc formation

- Grains with sizes <100μm are well-coupled to the gas

- Larger grains, if present
  - Tend to enhance structures (e.g. spiral arms and filaments)
  - Rapidly undergo radial migration - mm dust disc smaller than gas disc

- Future work
  - Need to begin with small grains and treat dust growth