The outbursts of young stars: impact on planet formation

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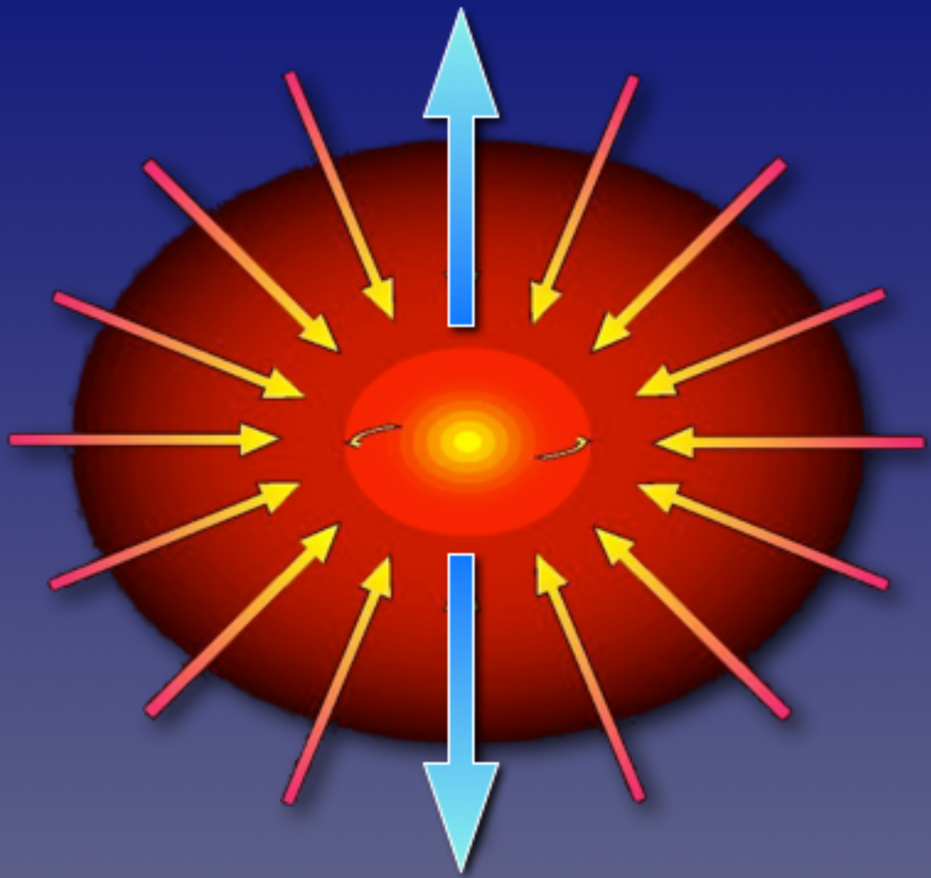
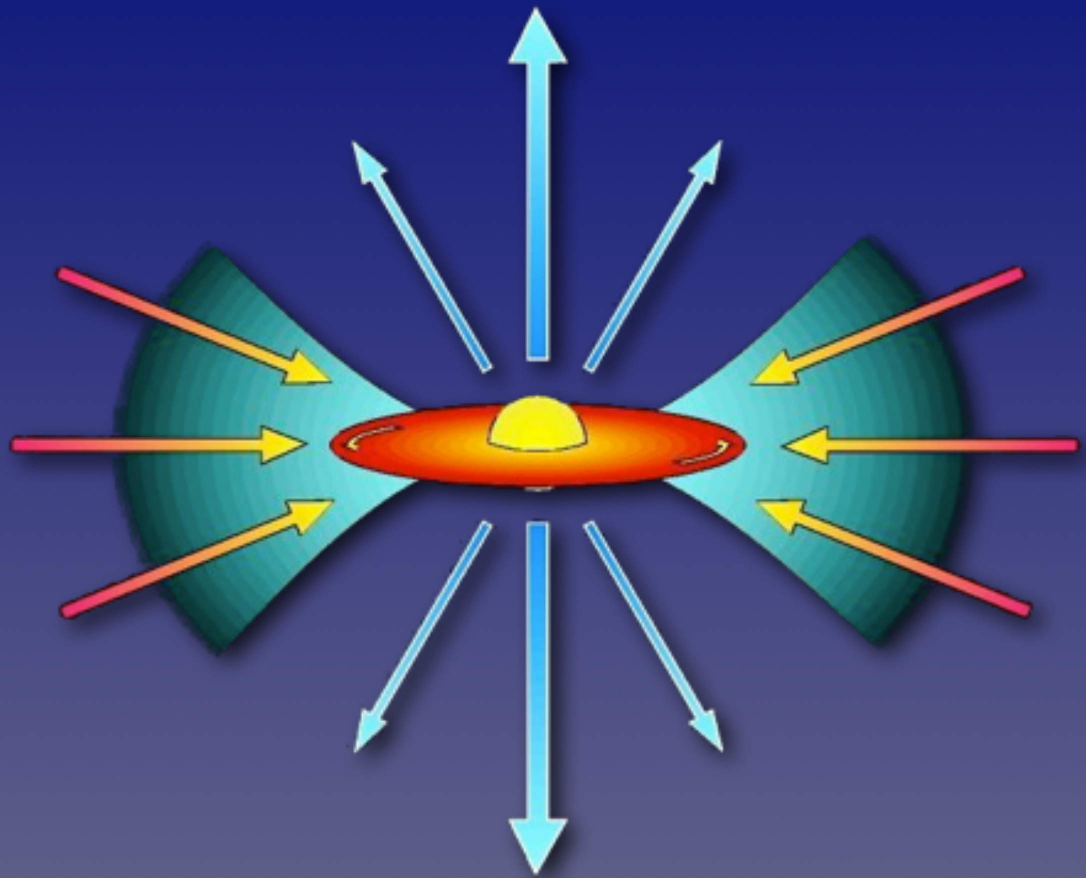
The isolated star formation paradigm



Class 0:
10^4 yrs; 10-10^4 AU; 10-300 K



Class I-II:
$10^{5\text{-}6}$ yrs; 1-1000 AU; 100-3000 K

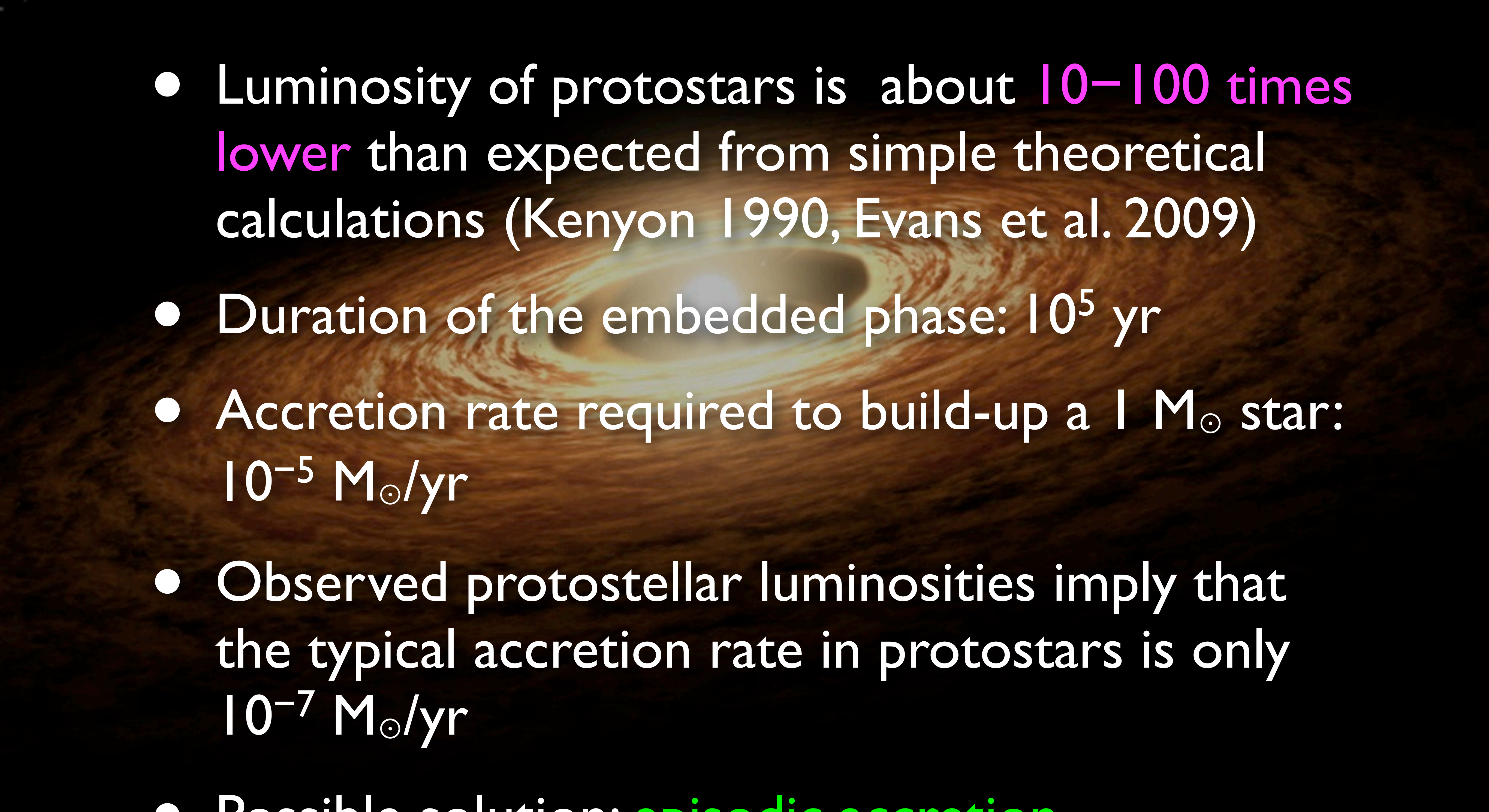
Class II-III:
$10^{6\text{-}7}$ yrs; 1-100 AU; 100-5000 K

Class IV:
$10^{7\text{-}9}$ yrs; 1-100 AU; 100-5000 K

After Shu, Adams, & Lada

Figure courtesy of Mark McCaughrean

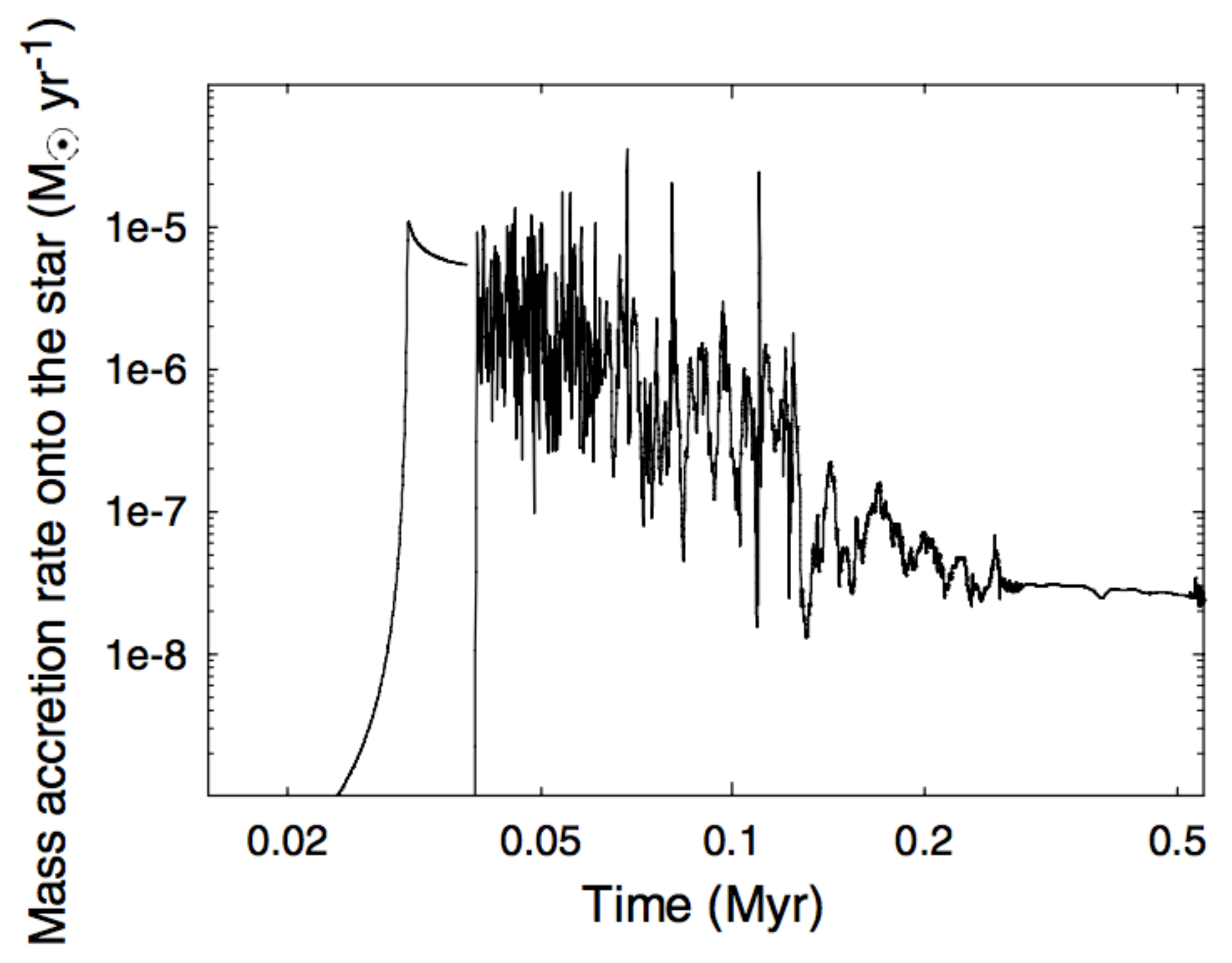
Luminosity problem



- Luminosity of protostars is about 10−100 times lower than expected from simple theoretical calculations (Kenyon 1990, Evans et al. 2009)
- Duration of the embedded phase: 10^{5} yr
- Accretion rate required to build-up a 1 $M_\odot$ star: 10^{-5} $M_\odot$/yr
- Observed protostellar luminosities imply that the typical accretion rate in protostars is only 10^{-7} $M_\odot$/yr
- Possible solution: episodic accretion

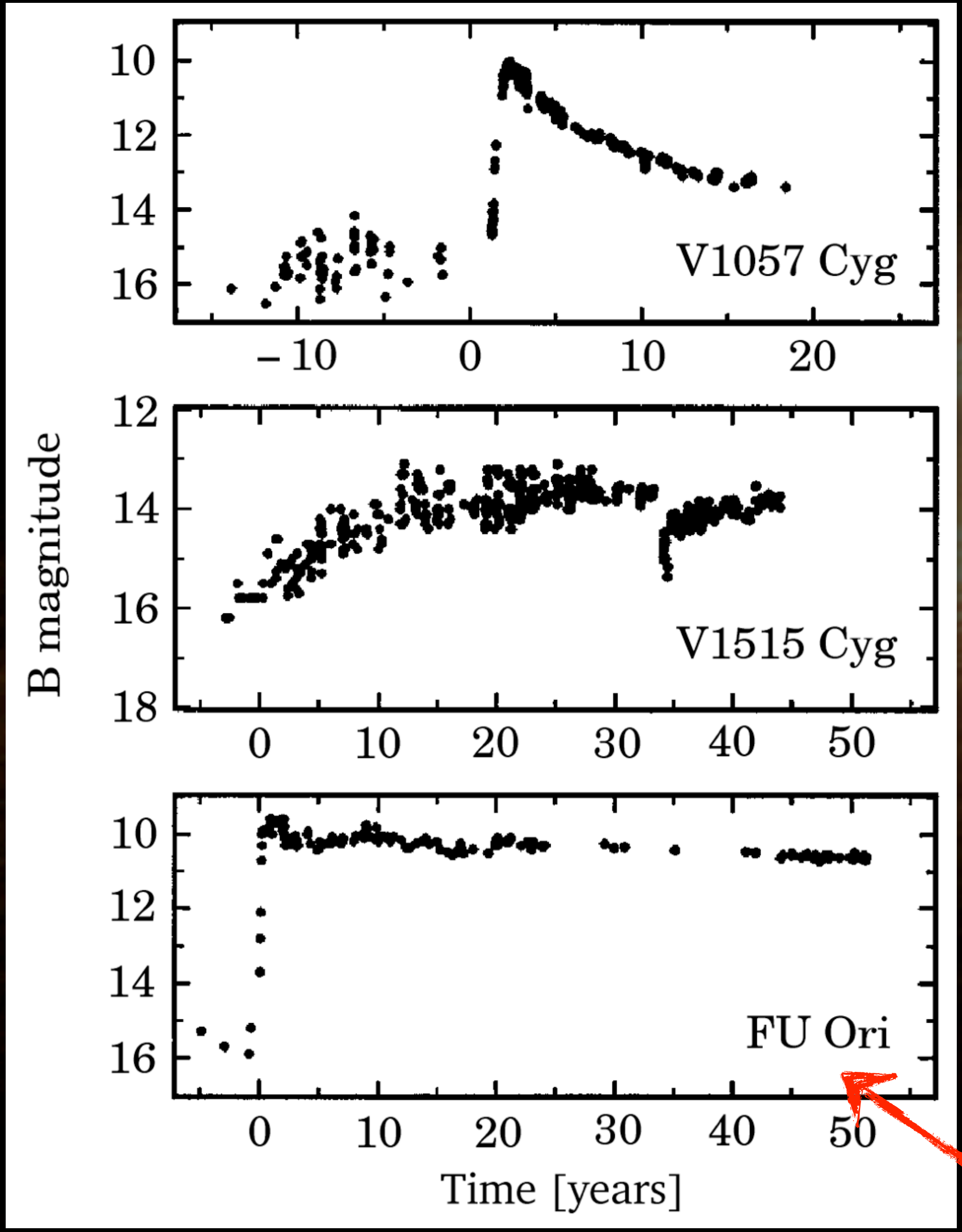
Episodic accretion: theory

- Numerical hydrodynamic simulations of the gravitational collapse of a rotating cloud core
- Model the early embedded phase of disk formation and evolution
- Result: disk is susceptible to fragmentation
- Fragments tend to be driven into the inner disk, from where they eventually fall onto the star, causing accretion bursts

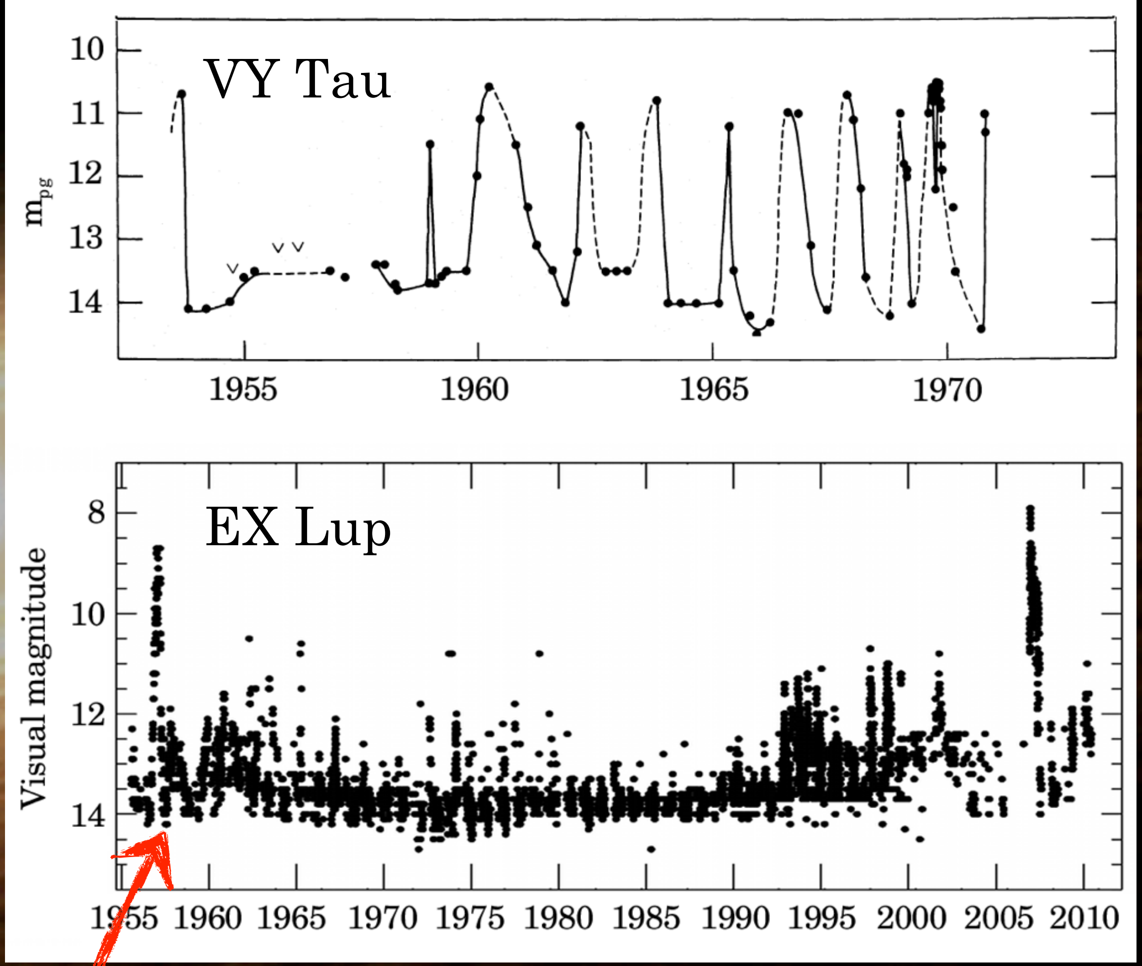


Vorobyov & Basu (2010)

Episodic accretion: observations



Hartmann & Kenyon (1996)



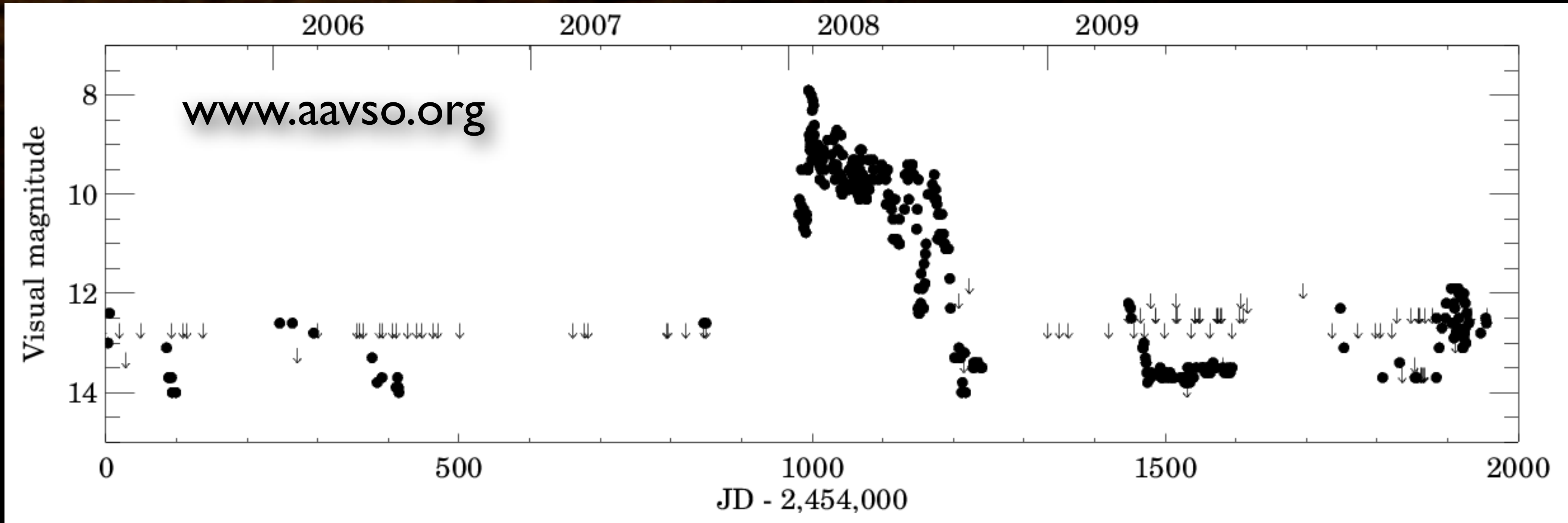
Herbig (1977), AAVSO

Accretion rate: up to 10^{-6} $M_{\odot}$/yr

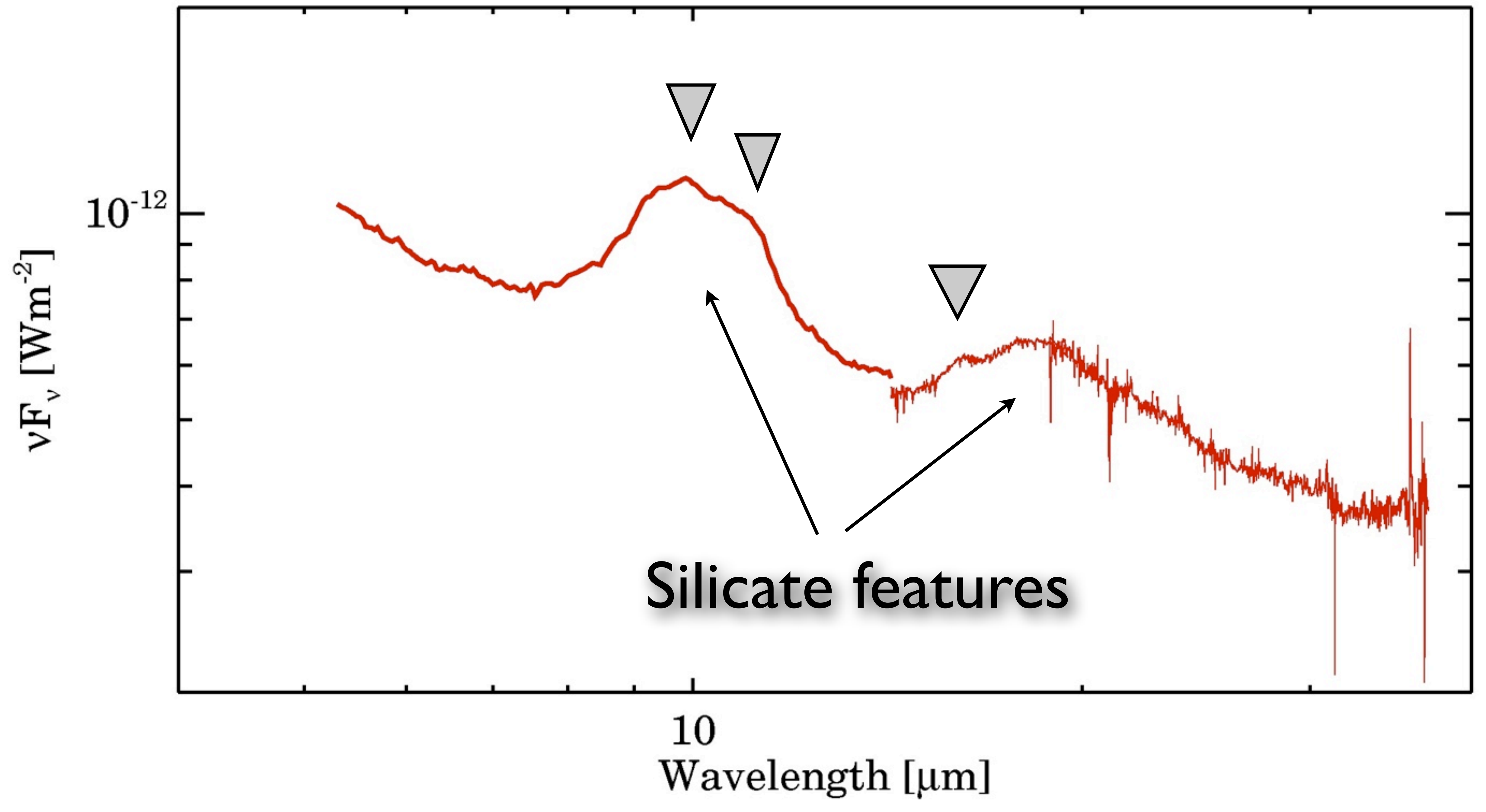
Accretion rate: up to 10^{-4} $M_{\odot}$/yr

Young eruptive stars: key objects

- Enhanced accretion → build-up of the final stellar mass
- Eruption affects the inner disk
  - density, temperature, chemical structure
  - conditions for rocky planet formation
- “Accretion laboratories”
- EX Lup: extreme outburst in 2008

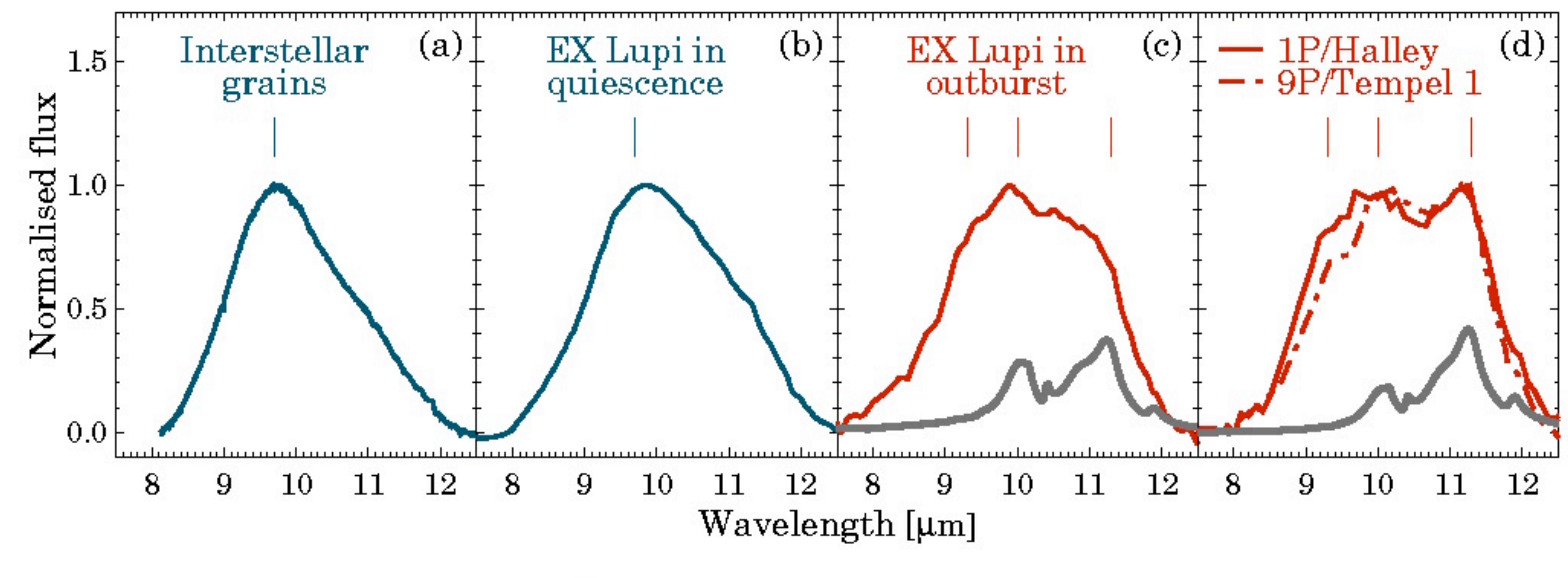

www.aavso.org

Silicate dust in EX Lup's disk

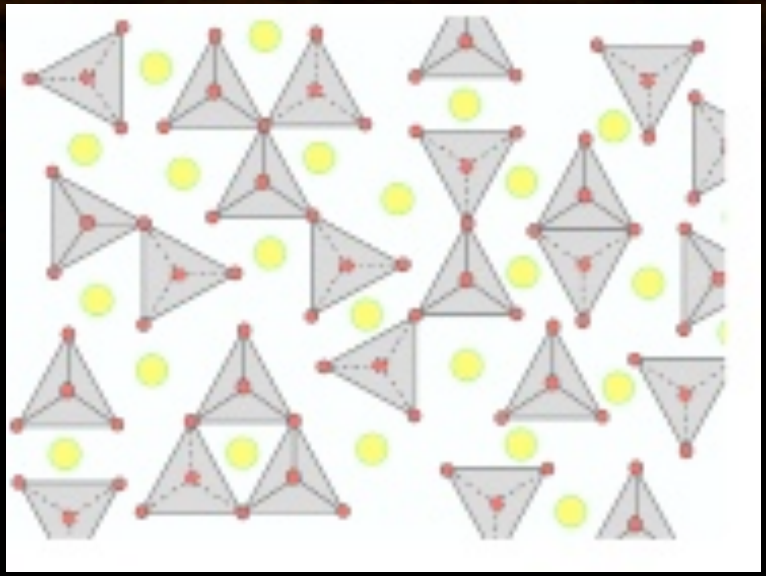


Silicate features

Episodic crystallization

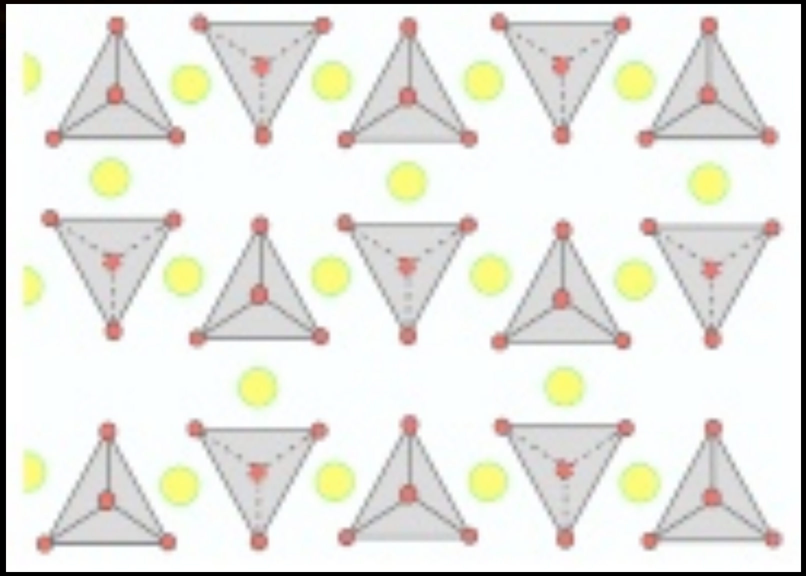


Ábrahám, Juhász, Dullemond, Kóspál, et al. (Nature, 2009)



Forsterite

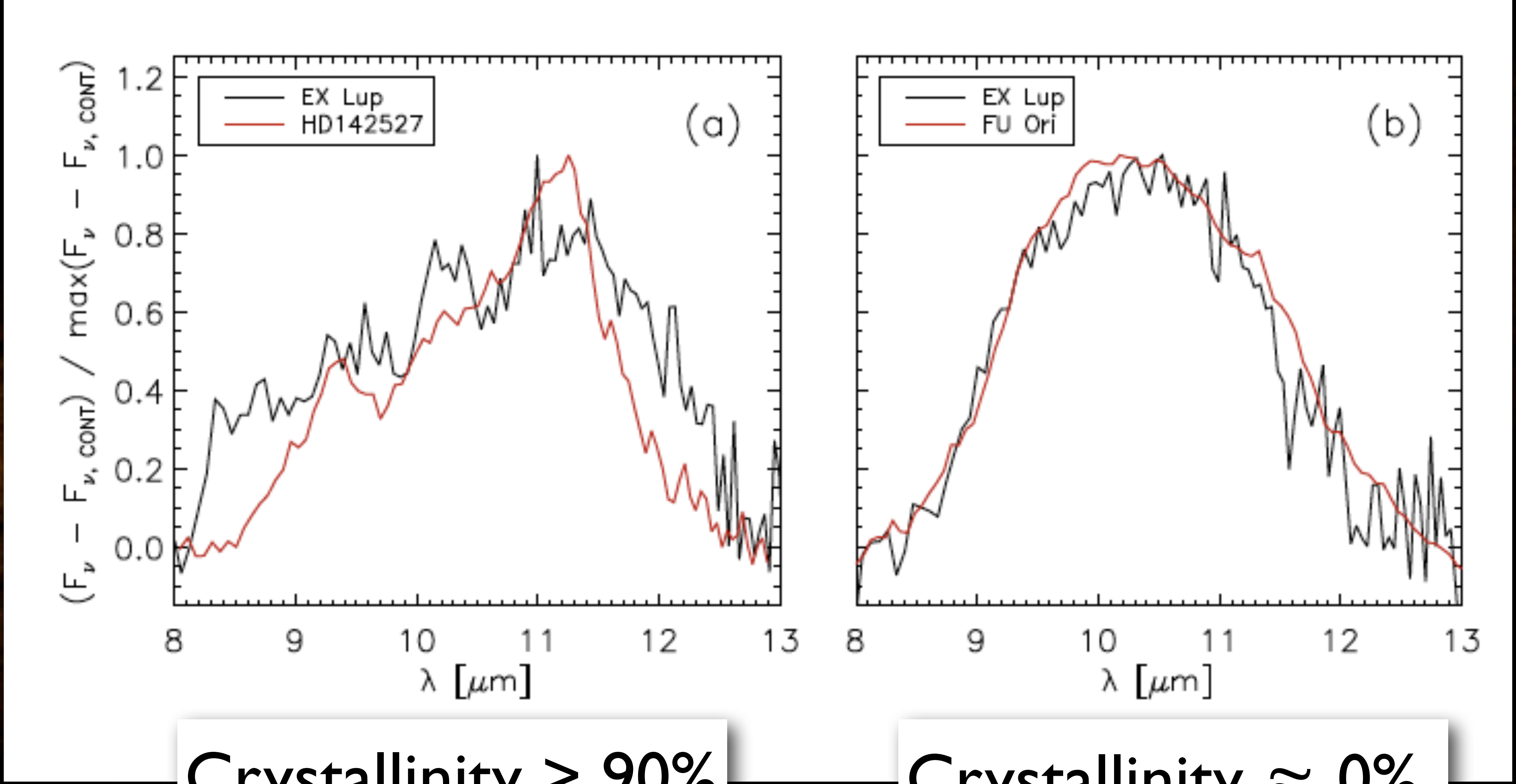
Mg_2SiO_4



Location of the crystals

Inner disk

Outer disk



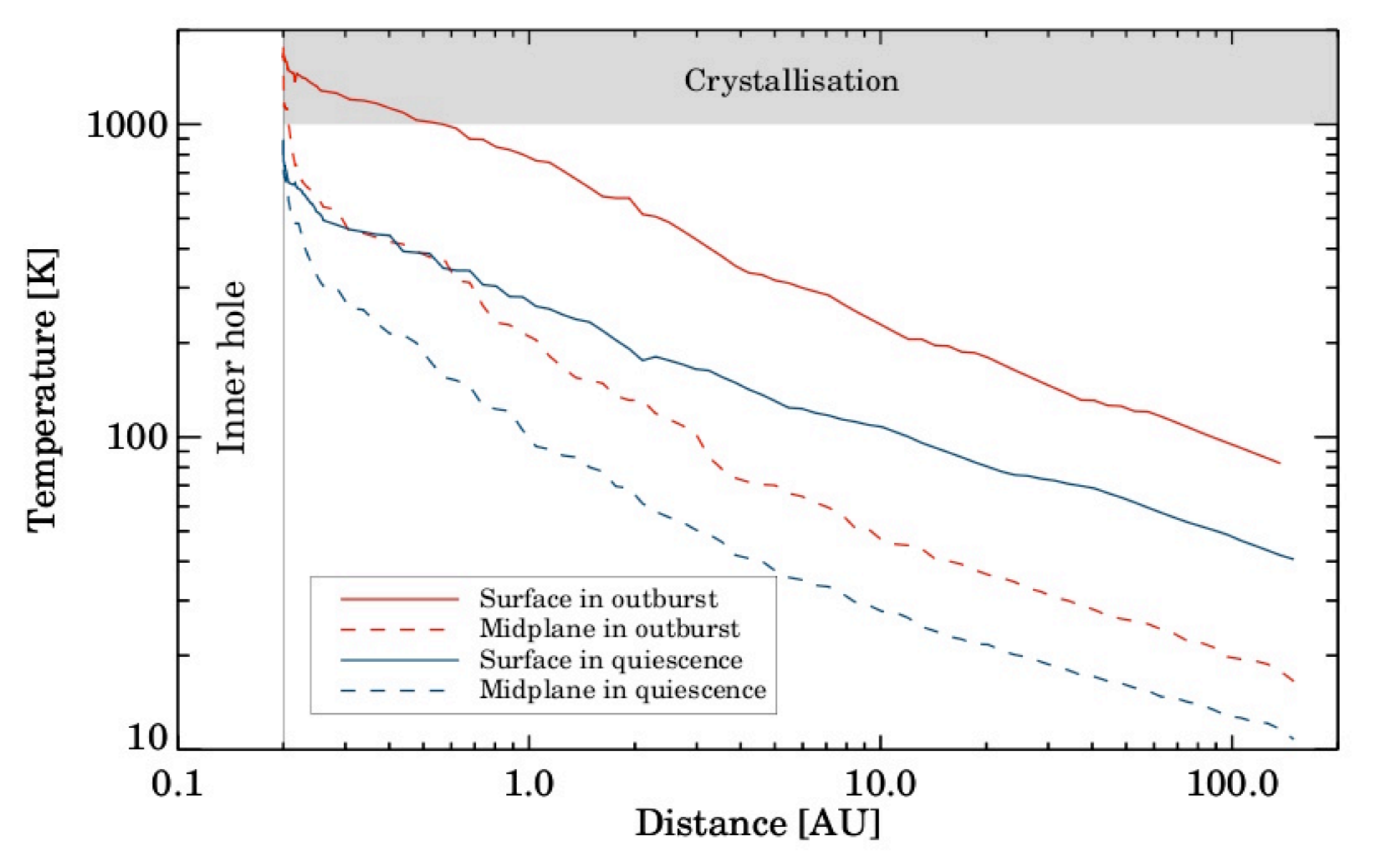
Crystallinity > 90%

Crystallinity ≈ 0%

Juhász et al. (2012)

The silicate crystals are located within the inner few AUs

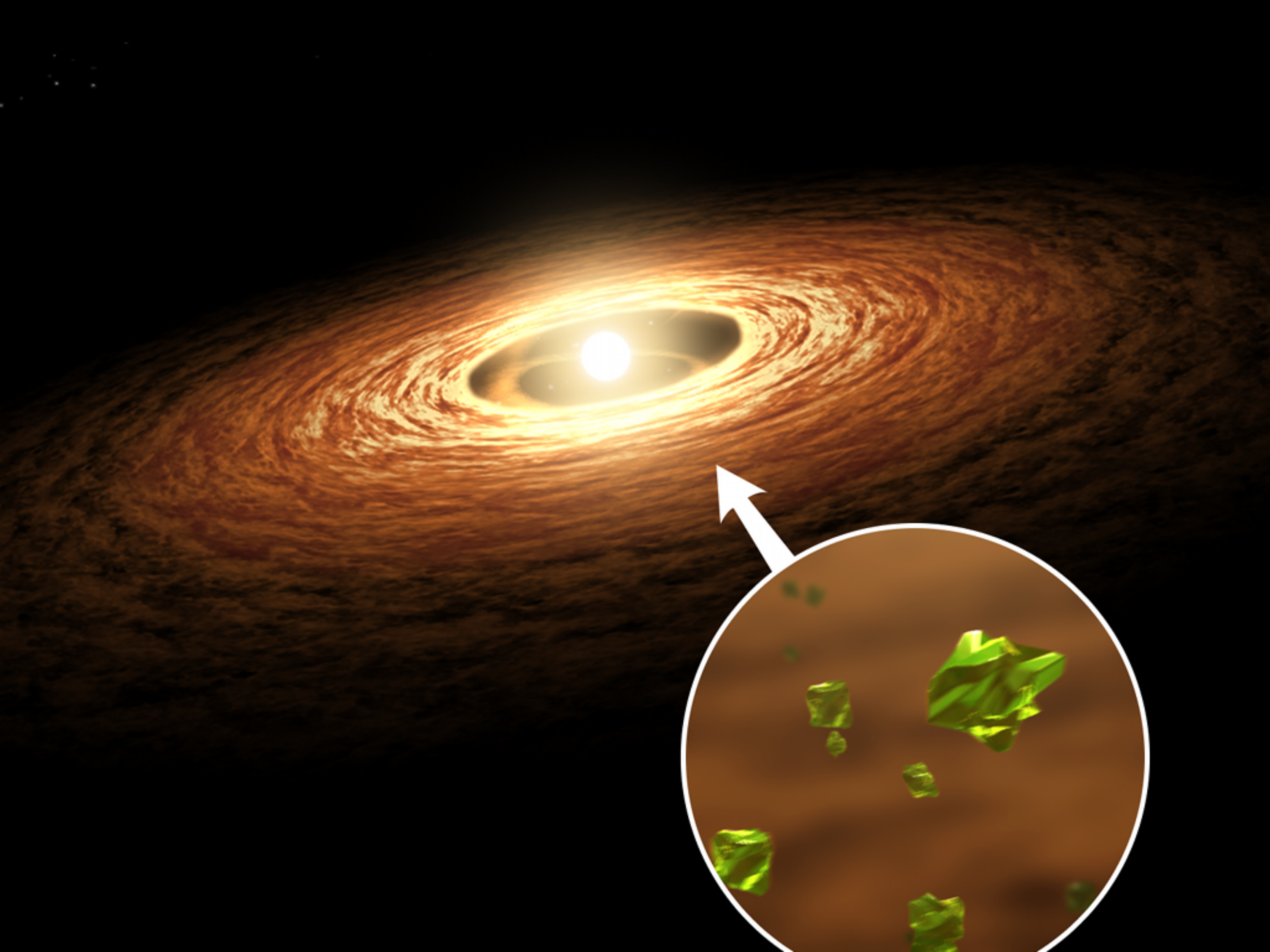
Origin of silicate crystals



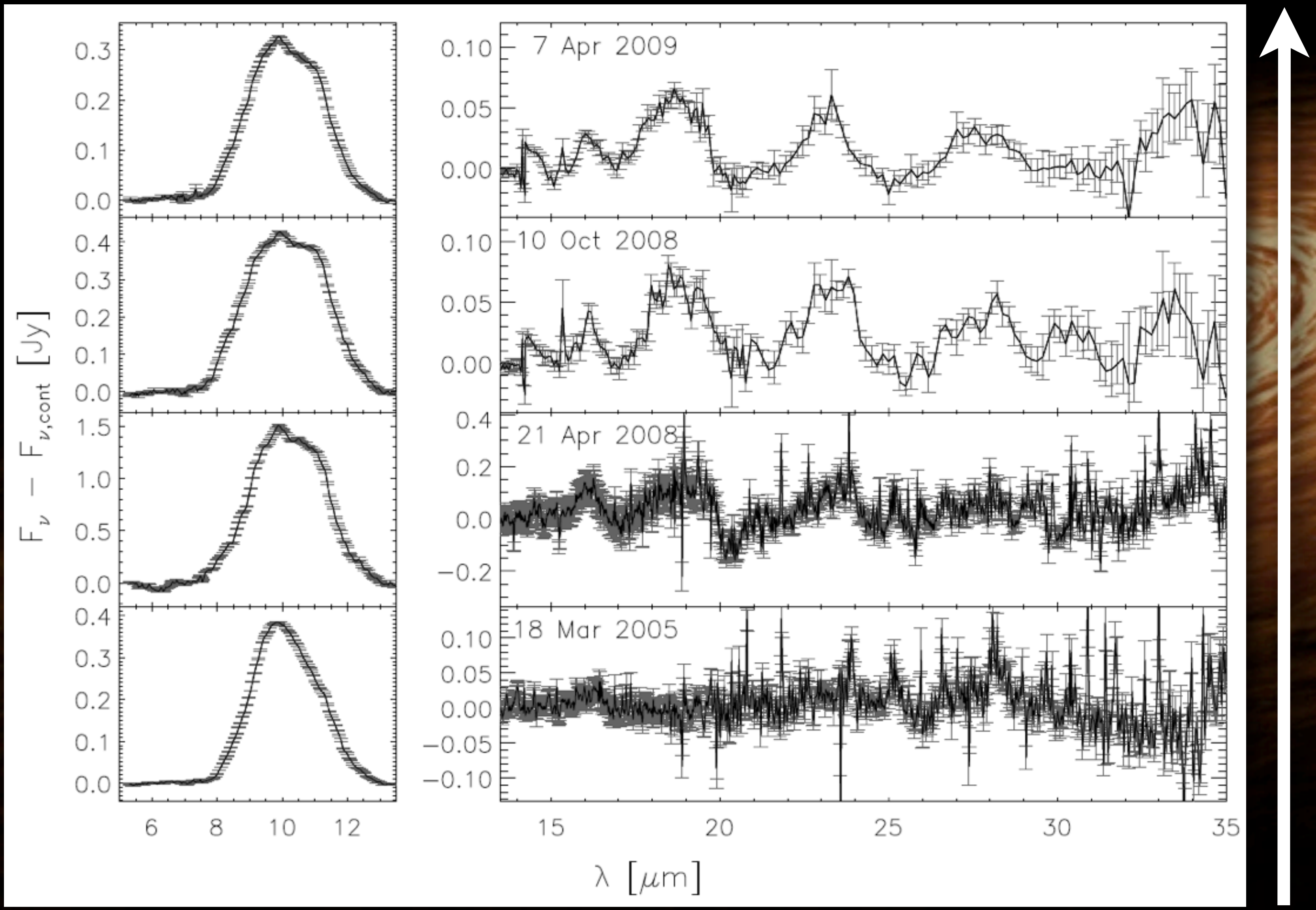
Ábrahám et al. (2009)

- Above 1000 K: thermal annealing
- Above 1500 K: evaporation

- Annealing in the inner 0.4 AU led to crystallization on the surface of the disk



Silicate crystals in motion



Juhász et al. (2012)

- Forsterite bands at longer wavelengths were also detected

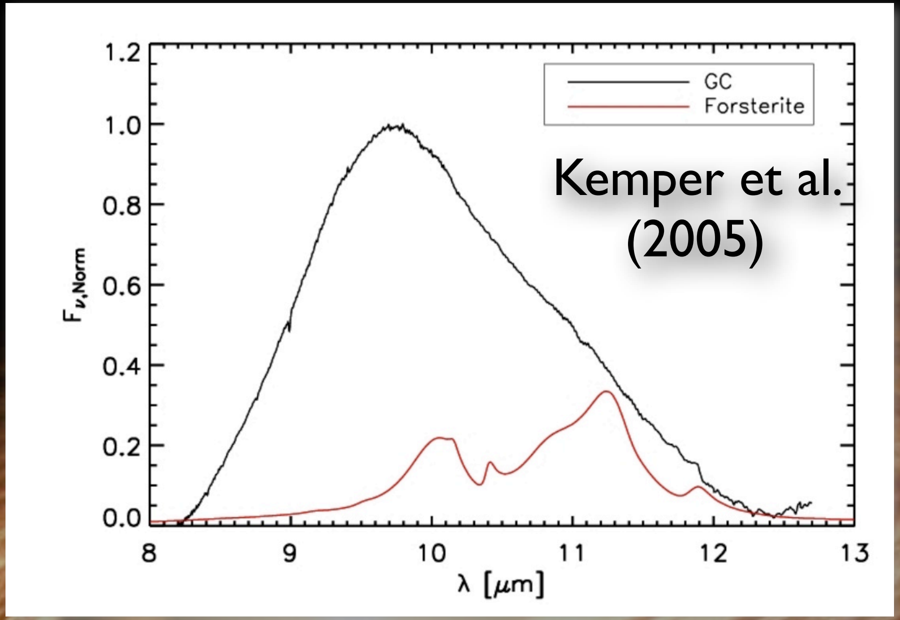
- The variation of the far-infrared features indicates radial transportation of crystals into outer disk regions

Dust evolution

SGR A*

Crystalline fraction: < 3%

Stéphan Guisard

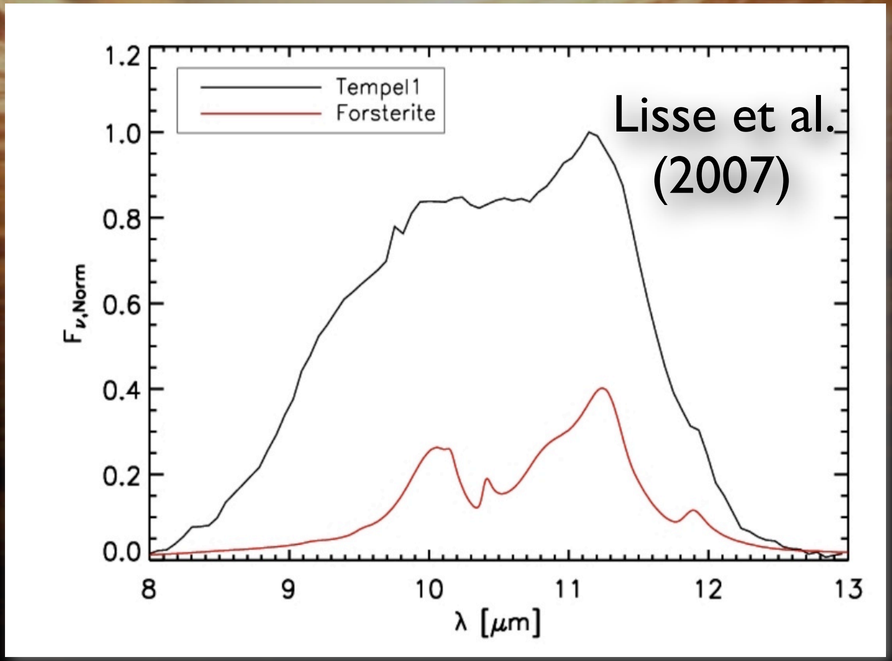


Kemper et al. (2005)

Comet Tempel/1

Crystalline fraction: > 80%

ESA/NASA

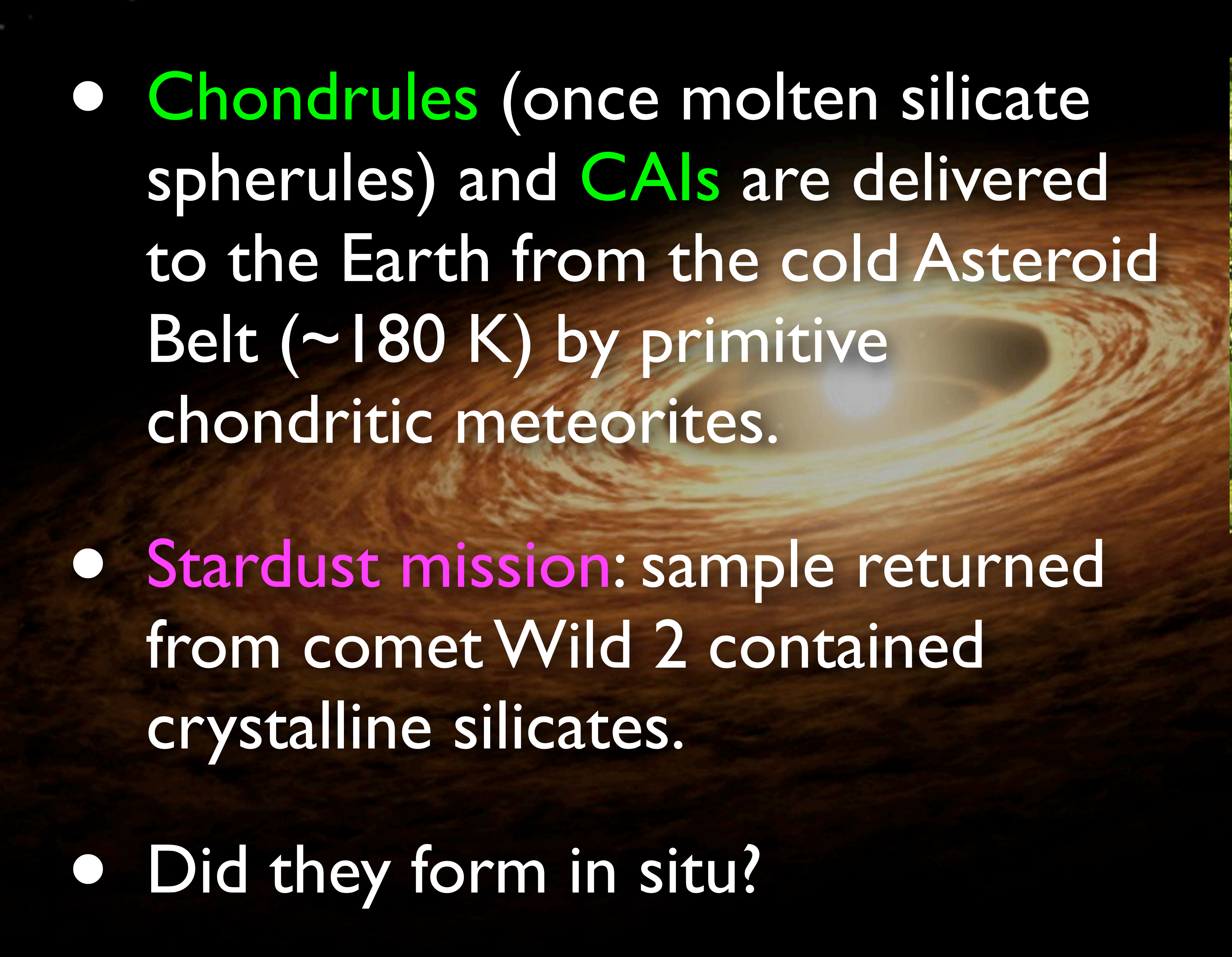


Lisse et al. (2007)

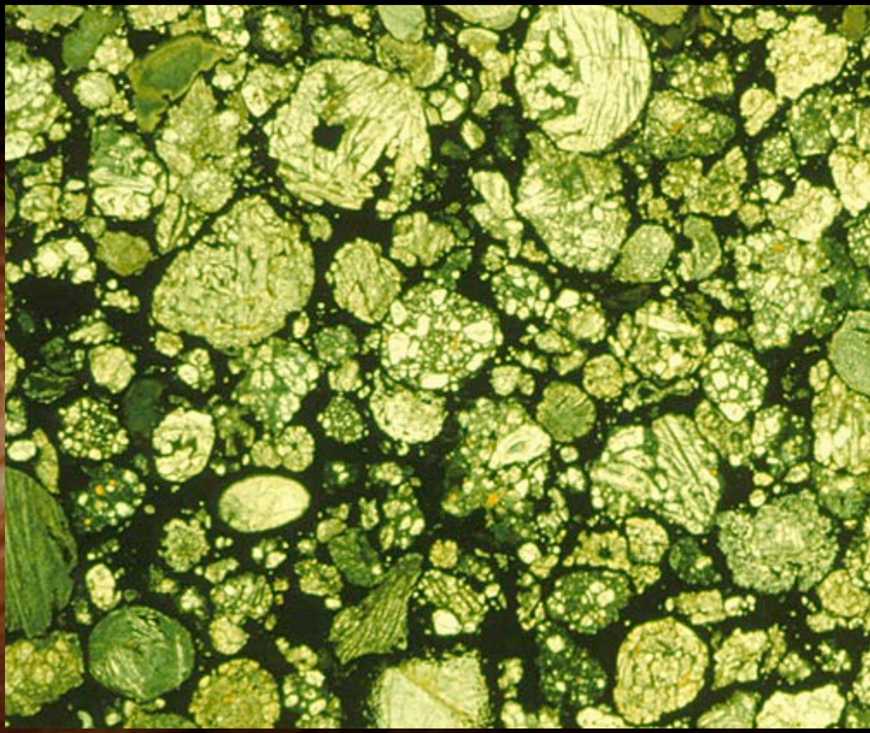
- How does the amorphous silicate turn into crystalline? We do not know.
- Episodic surface crystallization is only one possibility.

- Crystallinity fraction in disks does not correlate with any stellar or disk parameter.

Thermal processing in the Solar System

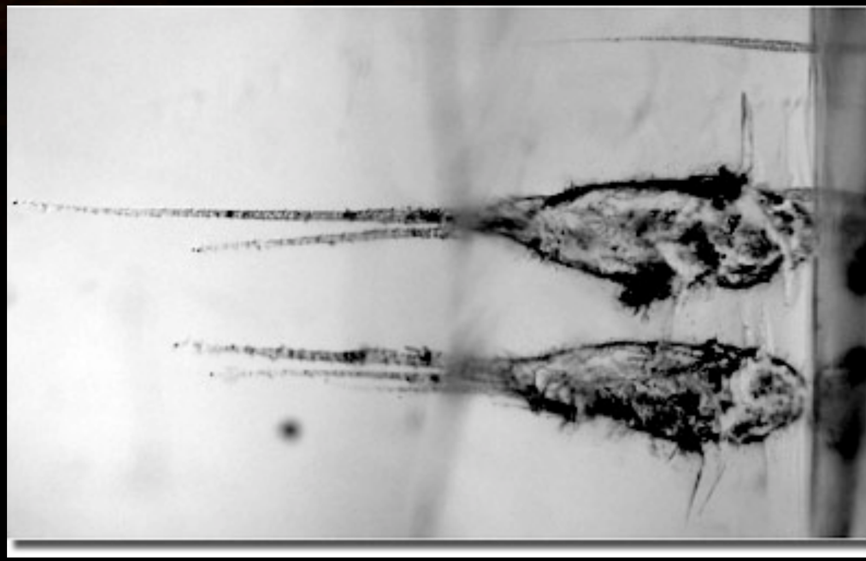


- Chondrules (once molten silicate spherules) and CAIs are delivered to the Earth from the cold Asteroid Belt (~180 K) by primitive chondritic meteorites.



Semarkona meteorite
http://meteorite.unm.edu

- Stardust mission: sample returned from comet Wild 2 contained crystalline silicates.

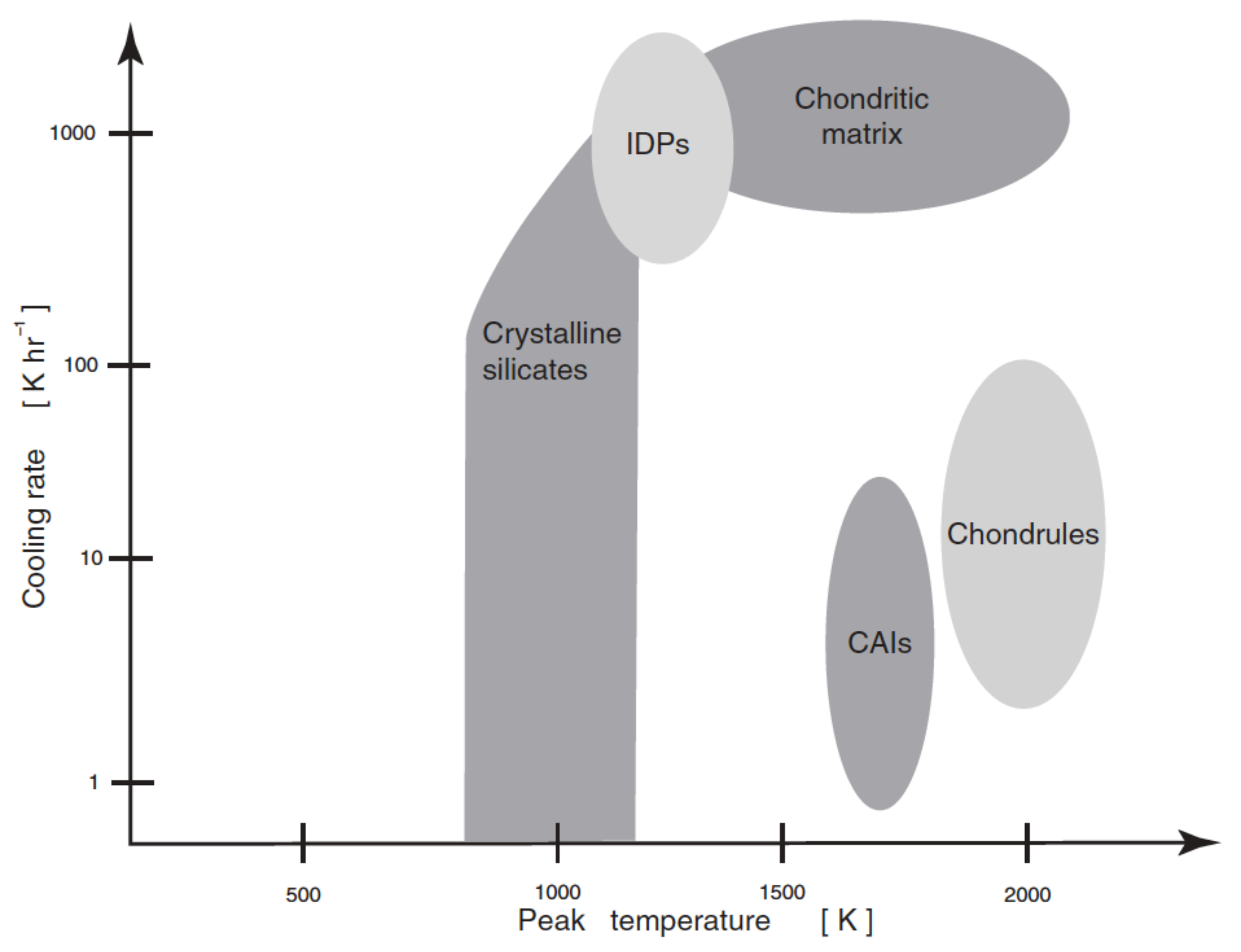


Stardust impact tracks
NASA/JPL

- Did they form in situ?
- Were they mixed outward from the hot inner disk?

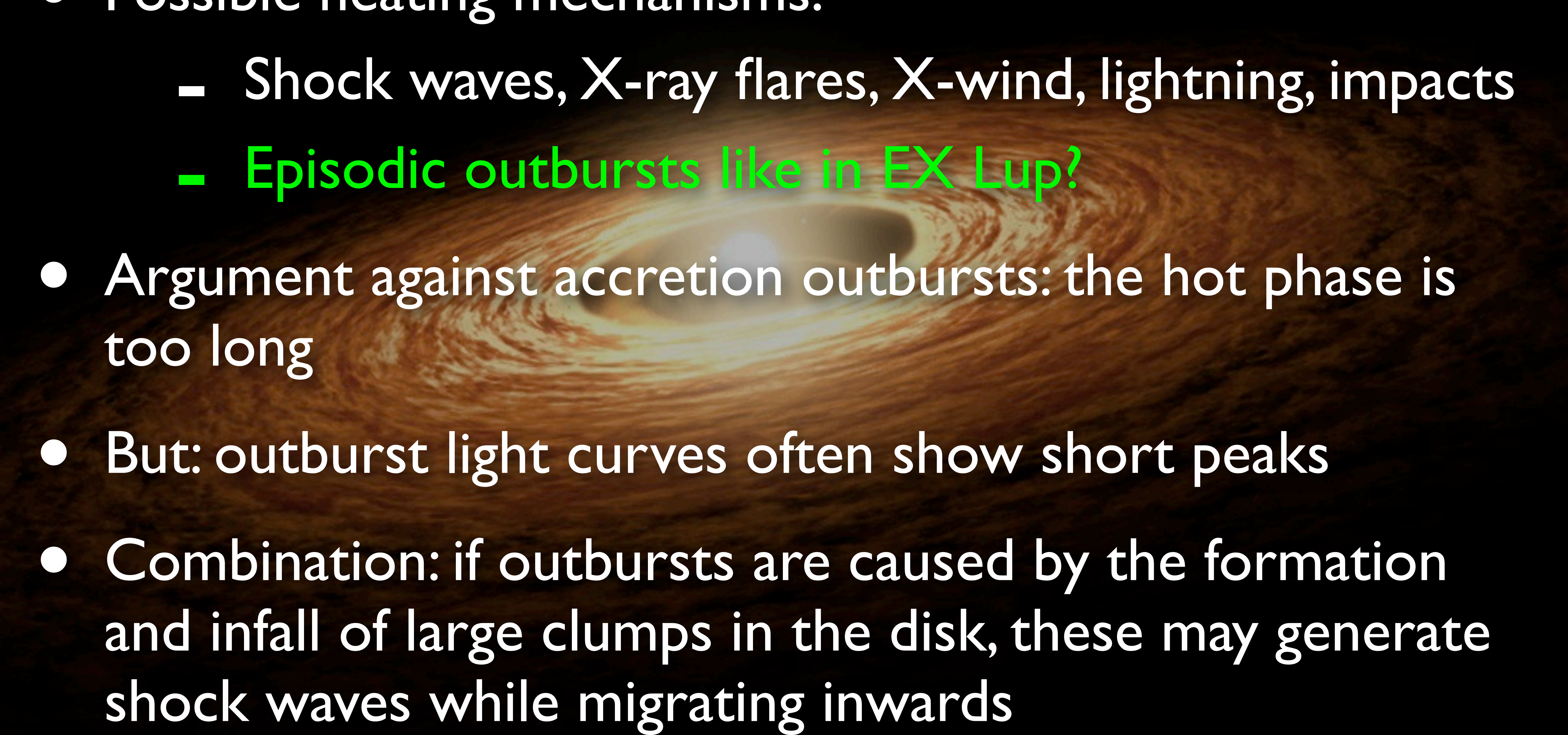
Thermal history of meteorites

- Most of the primitive material in the Solar System (e.g. chondrules and some CAIs) shows evidence for multiple transient heating events.
- They were formed in a transient high-temperature heating event (initial melting needed 2200 K for minutes to seconds)
- Multiple transient heating events afterwards of various intensity (peak temperatures of 1300−1500 K for hours to days)



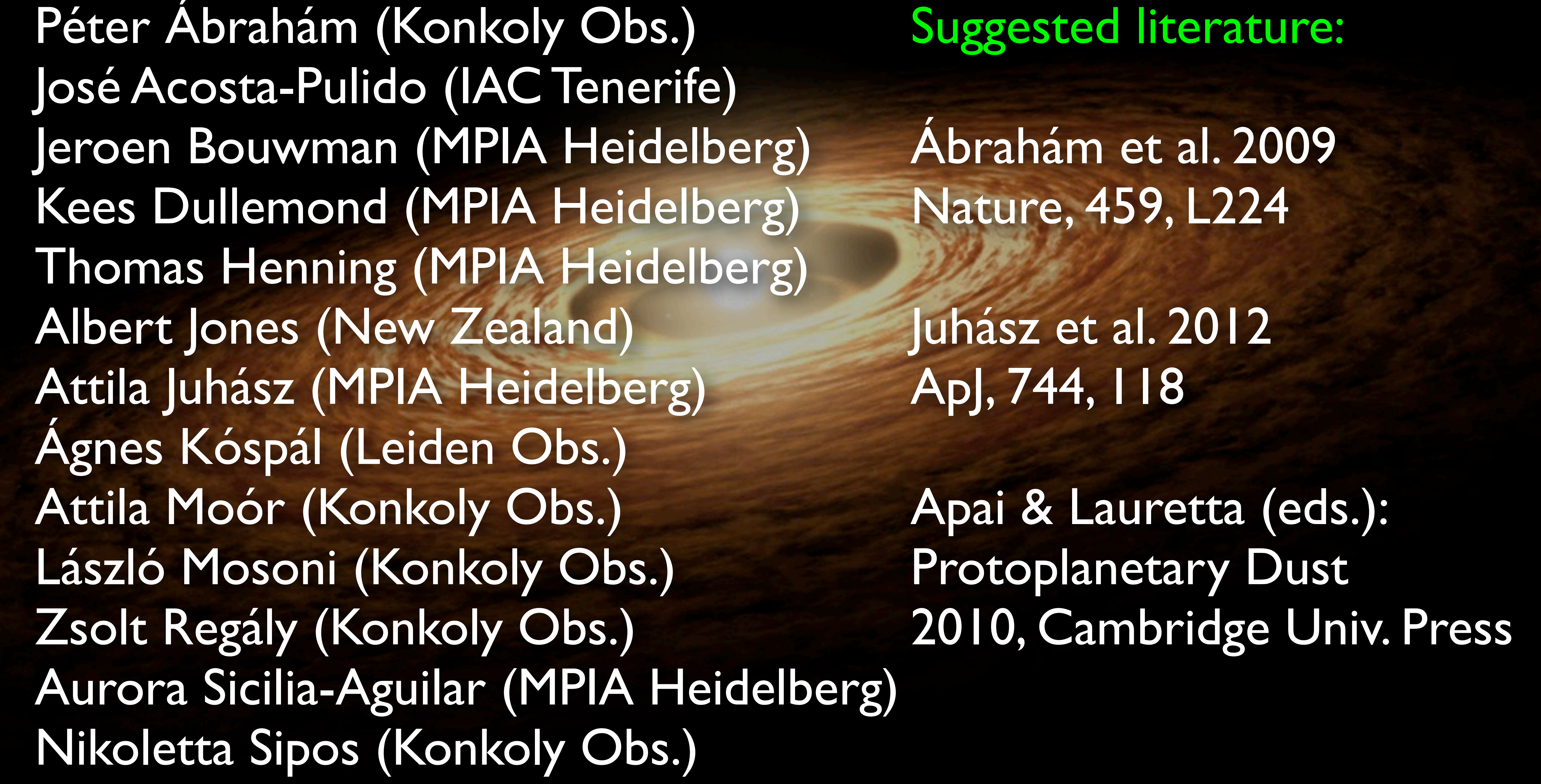
Apai et al. (2010)

Outbursts in the early Solar System?



- Possible heating mechanisms:
  - Shock waves, X-ray flares, X-wind, lightning, impacts
  - Episodic outbursts like in EX Lup?
- Argument against accretion outbursts: the hot phase is too long
- But: outburst light curves often show short peaks
- Combination: if outbursts are caused by the formation and infall of large clumps in the disk, these may generate shock waves while migrating inwards
- We need to study outbursts with better time and spatial resolution

Acknowledgements



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Suggested literature:

Ábrahám et al. 2009
Nature, 459, L224

Juhász et al. 2012
ApJ, 744, 118

Apai & Lauretta (eds.):
Protoplanetary Dust
2010, Cambridge Univ. Press