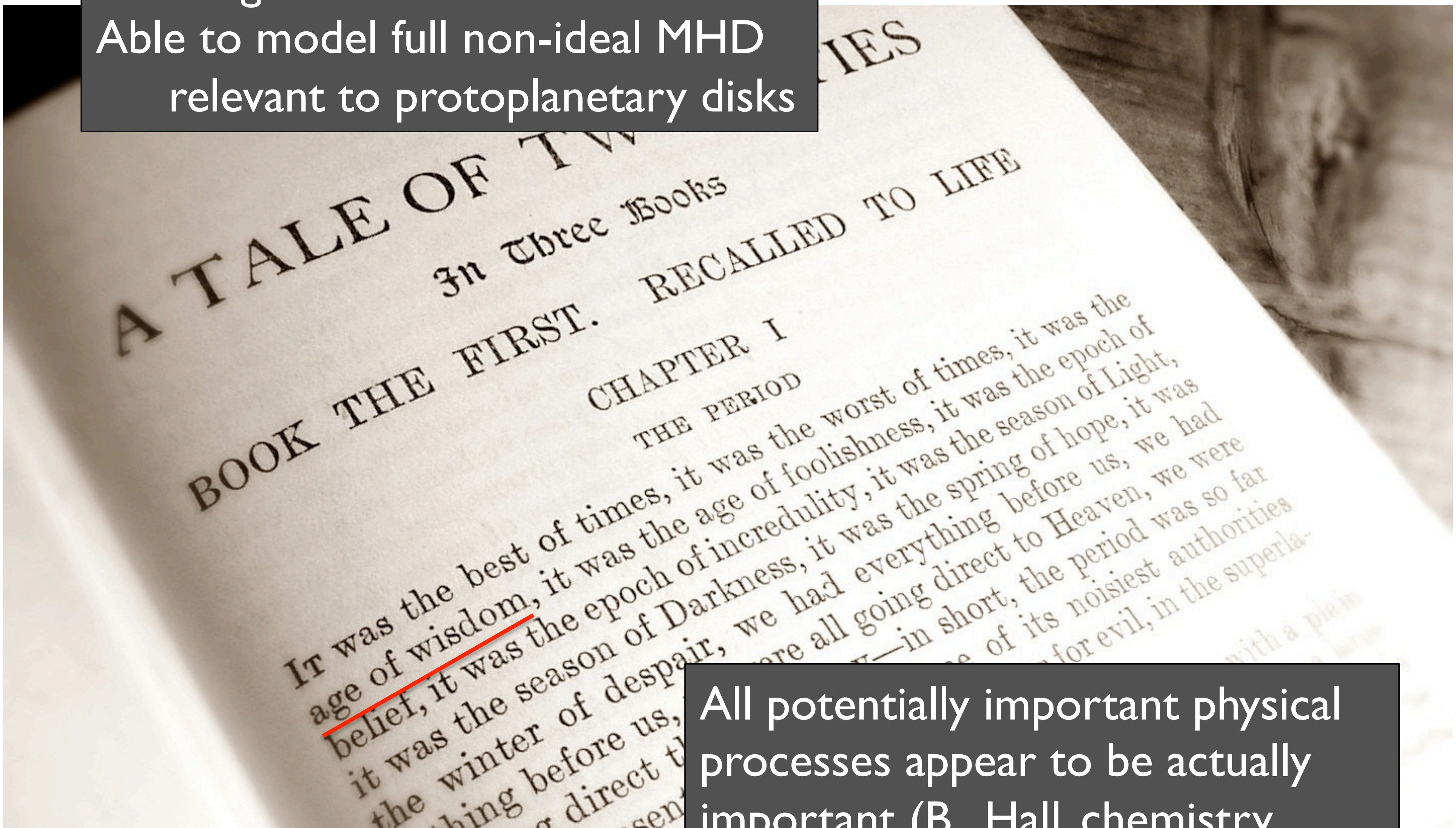
summary and outlook

Phil Armitage, Colorado

Amazing number of new results
Able to model full non-ideal MHD
relevant to protoplanetary disks



All potentially important physical processes appear to be actually important (B_z, Hall, chemistry, star formation initial conditions…)

transport processes in disks

- first local simulations incorporating all non-ideal terms at physical strength *(Matt Kunz, Geoffroy Lesur, Xuening Bai)*
  - *appearance of strong laminar stresses from Hall*

The Balbus–Hawley instability in weakly ionized discs

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ABSTRACT
MHD in protostellar discs is modified by the Hall current when the ambipolar diffusion approximation breaks down. Here I examine the Balbus–Hawley (magnetorotational) instability of a weak, vertical magnetic field within a weakly ionized disc. Vertical stratification is neglected, and a linear analysis is undertaken for the case in which the wavevector of the perturbation is parallel to the magnetic field.

  - *distinct physics from usual MRI*
  - *first attempts at global simulations (Donna Rodgers Lee)*

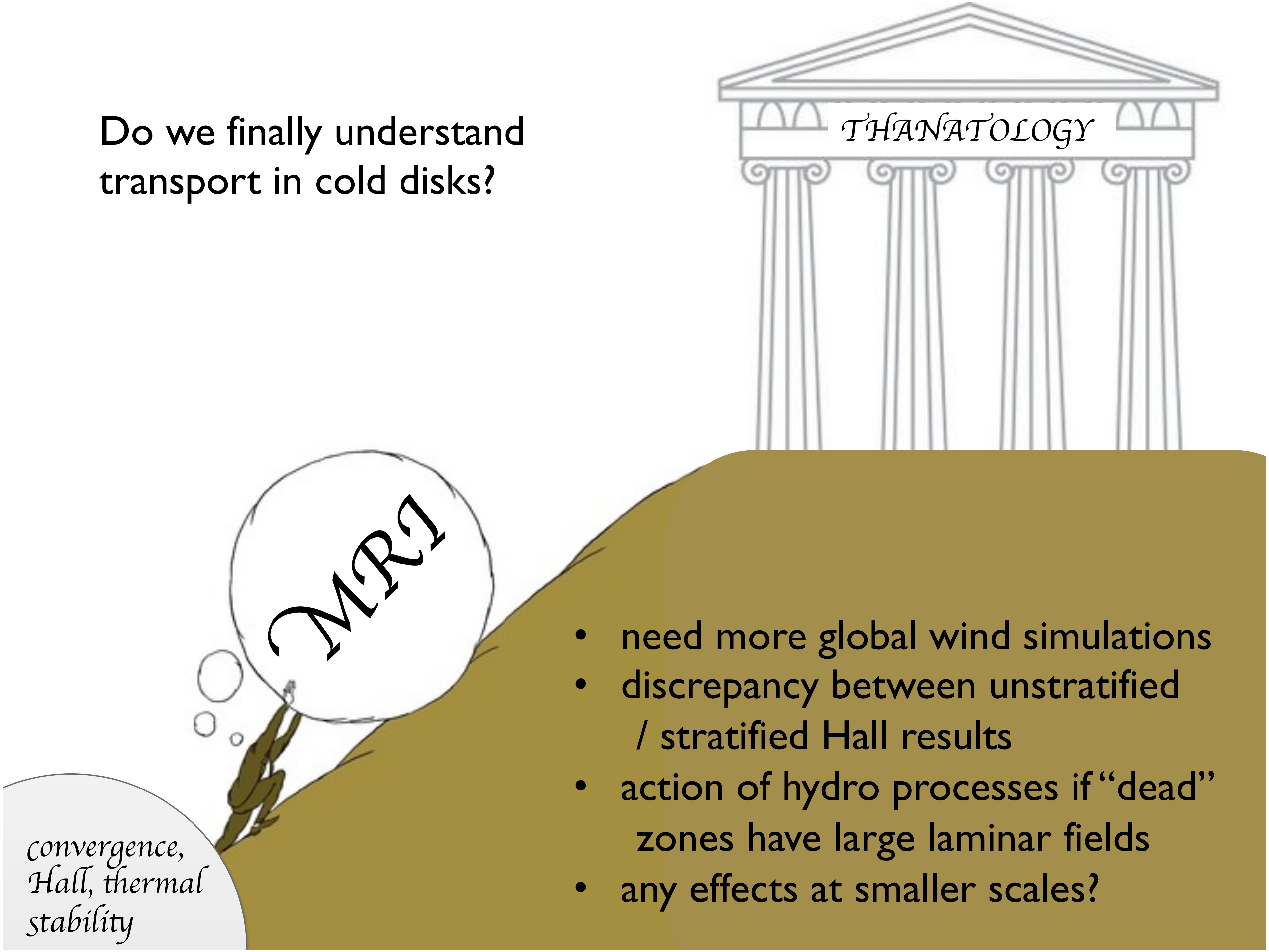
transport processes in disks

- numerical evidence that winds arise whenever disks are threaded by a vertical field *(Takeru Suzuki, Oliver Gressel…)*

  - ***two*** *new ways to drive transport in weakly ionized disks, laminar stresses / winds…*
  - *not clear how numerical results related to analytic disk wind theory (Raquel Salmeron)*
  - *turbulence "vs" winds is not right way to frame problem*

- robust evidence for hydrodynamic transport given appropriate thermal structure *(Richard Nelson, Hubert Klahr)*

Do we finally understand transport in cold disks?



- need more global wind simulations
- discrepancy between unstratified / stratified Hall results
- action of hydro processes if "dead" zones have large laminar fields
- any effects at smaller scales?

issues raised

- success to **form** disks that are "weakly" magnetized ($\beta_z \sim$ 10-100) *(Shu-ichiro Inutsuka, Troels Haugbolle)*

- much weaker fields seem to imply fast evolution via disk winds ($\beta_z \sim 10^3$-10^4)

  - *local simulations are horribly wrong*
  - *winds and fast evolution persist throughout disk lifetime (Ake Nordlund)*
  - *flux is further reduced early on (self-gravitating phase?)… but if so, why not to ~zero?*

…and then there was chemistry

issues raised

- at what point will our understanding become limited by chemical rather than dynamical uncertainties?
- what differences are there between "reasonable" chemical models for ionization, depth of FUV layers… *(Neal Turner, Jeremy Goodman, Jon Ramsey)*

Useful to compare different models, develop / use open and possibly simplified models

neglected microphysics?

Are other processes important at leading order?

- almost all simulations are isothermal
  - *role of dT / T in solid processsing (Colin McNally)*
  - *effect on outflows?*
  - *need radiation physics for photoevaporation (Jon Ramsey), need it otherwise? Migration? (Jim Stone)*
- reconnection and heating in almost neutral plasmas *(Satoshi Okuzumi)… 3% of the accretion energy would sustain ionization (Shu-ichiro Inutsuka)*

global vs local

- is the shearing box useful? *(Alex Hubbard)*
- can the shearing box be improved? *(Martin Pessah)*
- are protoplanetary disks "sufficiently isolated" for even a **global** treatment to be adequate? *(Troels Haugbolle, Ake Nordlund)*

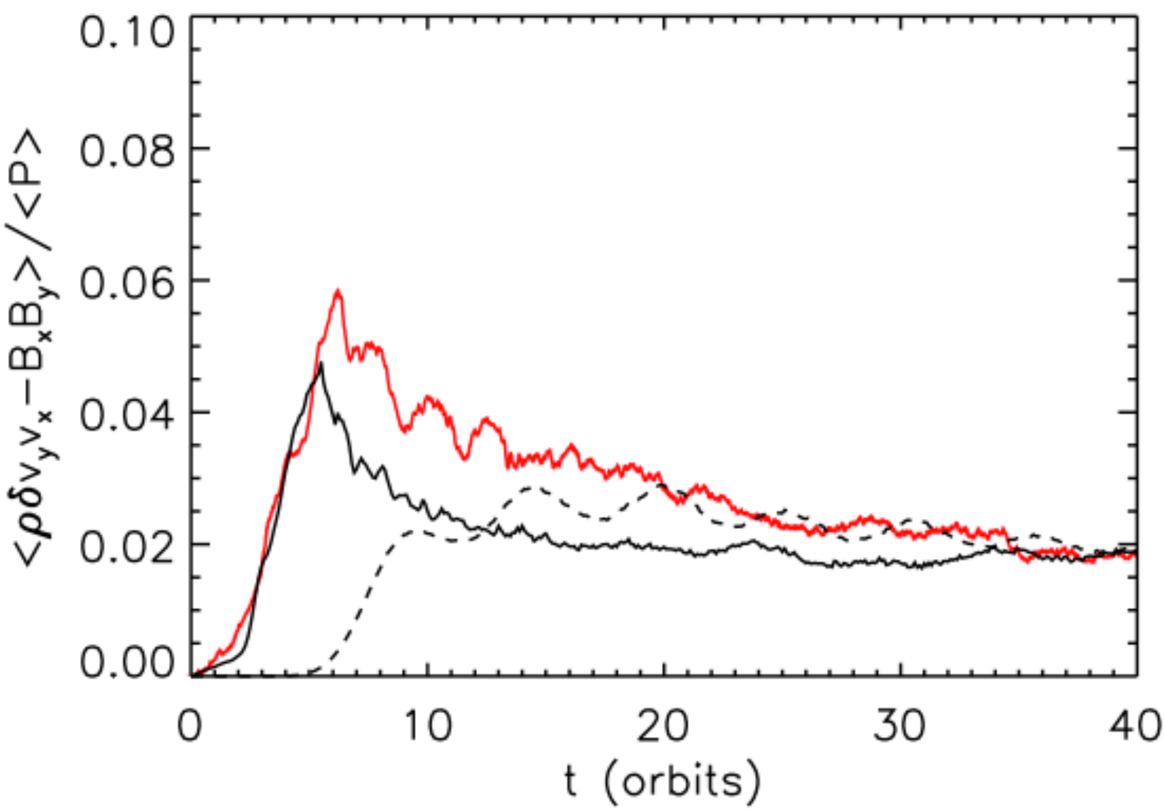
global is better, local is cheaper…

- “box-filling” laminar stresses seen in Hall runs are new
- winds cannot be represented locally
- old questions in viscous disk theory can be revisited

  “what is the propagation speed of radial fluxes?”
- early accretion phase necessarily messy

  - how long does “initial” turbulence take to decay?

Precise comparisons between local and global simulations are not so easy…



Beckwith et al. '11
see Sorathia et al. '12

New experiments designed to test "locality" would be very useful

saturation

to a strong interchange instability. The resulting radial motions produce field geometries that are conducive to reconnection, suggesting a possible mechanism for mode saturation. Even for very weak fields, whose most

Hawley & Balbus '92

the latter group suggest that they may promote rapid reconnection of the MRI field. Thus, parasitic modes *may* stop MRI growth at subequipartition amplitudes if it develops from a sufficiently weak initial field.

Goodman & Xu '94

- weakly non-linear calculation for Taylor-Couette geometry *(Susan Clark)… saturation via shear modification*
- numerical study of parasitic modes *(Gareth Murphy)… evidence for role via stress tensor analysis*

10. SUMMARY

The major uncertainties in accretion disc theory are the dissipation process (viscosity) and the emission process. Disc modeling is in some sense more of an art than a science, and since a steady disc can be constructed for almost any combination of viscosity and radiation process the possibilities for extending one's list of publications are almost endless. Conversely we are likely to learn more about the properties of accretion discs in astrophysics by observation and subsequent modeling than by pure theorizing. Thus, although accretion discs may play a major role in

Pringle (1981)

Dwarf novae *still* give the most interesting constraints on transport!

observations

Existing observations

Solar System

- *measured B fields from meteorites (Steve Desch) seem OK*
- *inferred extent of transport, survival time (Martin Bizzarro) in some tension with simplest models*

Astronomical

- *SED fitting consistent with magnetic support (Neal Turner)*
- *first principles simulations of thermal instability (Shingenobu Hirose)… very encouraging for dwarf novae*
- *should we be most interested in outburst states?*

observations

Prospective observations

- *inner disk CO lines as probe of accretion energy (Jeremy Goodman)… data exists*
- *turbulent broadening of spatially resolved molecular lines as MRI signature (Jake Simon)… data coming*
- *vortex-like structures forming from global zonal flows (Mario Flock)*
- *planet-induced vortices as upper limit on stress (Zhaohuan Zhu)*

Cautions

- *nearest / oldest / best-studied disks may not be typical (more isolated than average, much lower external FUV flux) (Jon Ramsey, Steve Desch)*

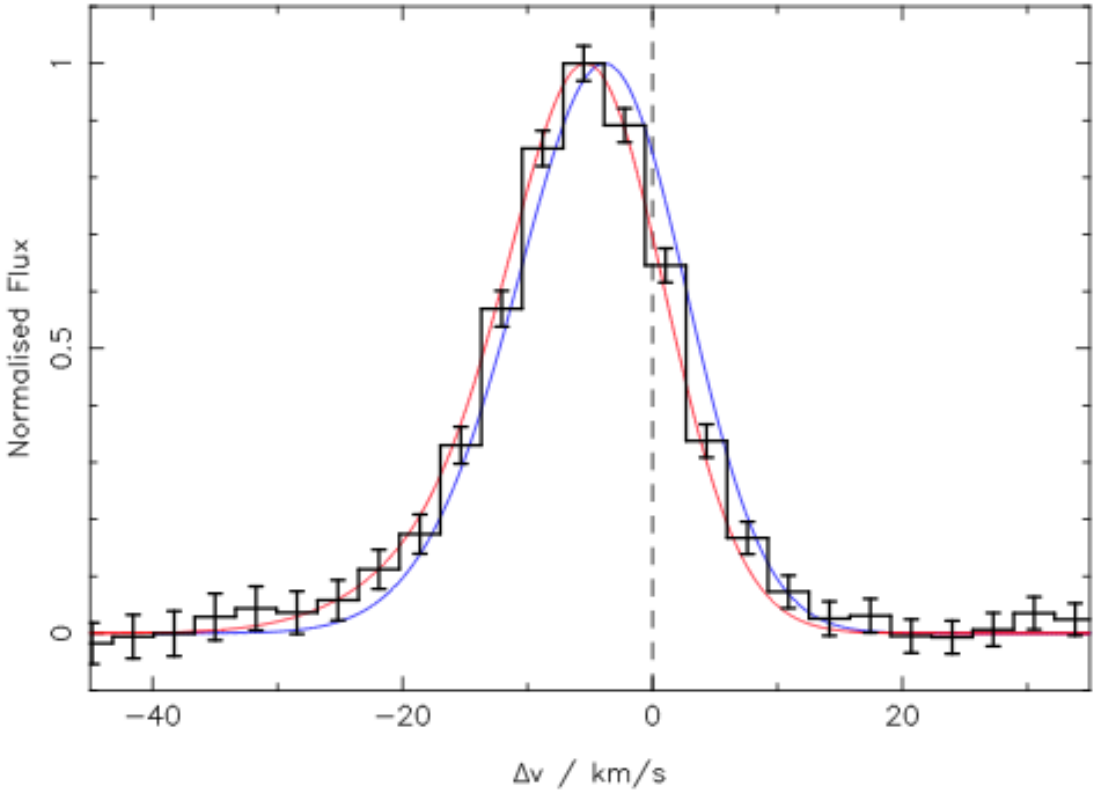


Fig. 5.— [Ne II] 12.81μm line profile from the near face-on disk around TW Hya. The black line (and error bars) show the observed profile from *Pascucci et al.* (2011), obtained by co-adding the spectra from the different position angles at which they observed. The red curve shows the theoretical prediction for an EUV-driven wind (*Alexander*, 2008b), while the blue curve shows the corresponding prediction for X-ray photoevaporation (*Ercolano and Owen*, 2010); both profiles have been normalised by their peak flux. The observed blue-shift of 5.4 ± 0.6km s^{-1} represents an unambiguous detection of a slow, ionized wind, but [Ne II] observations alone do not distinguish between the different models.

Unclear how well these approaches will work

Reasons for optimism:

- *new facilities*
- *relevant data already exists (wind lines, transition disks…)*
- *observers are smart*

planets

Mobility of solids underlies most of our problems

- *dust, mm-sized particles (Zhaohuan Zhu)*
- *planets of all masses (Jim Stone)*

Dust remains much easier to observe than gas – *extra physics to track small particles is well understood*

Turbulence – settling, collision velocities, planetesimal formation *(Chao-Chin Yang, Anders Johansen)*

Aspiration – physically well-motivated model for evolution of disk structure as $f(M_{initi}, J_{init}, B_{init})$

outlook

Many of the results shown here did not seem possible just a few years ago

- *MRI simulations with net fields*
- *Hall effect at physical strength*
- *global planet-disk simulations with non-ideal MHD*
- *simulations with 29 levels of AMR*

What problems seem infeasible now?
Where can we make a connection to observations?

Thanks! to Oliver, Colin, Gareth & Martin…