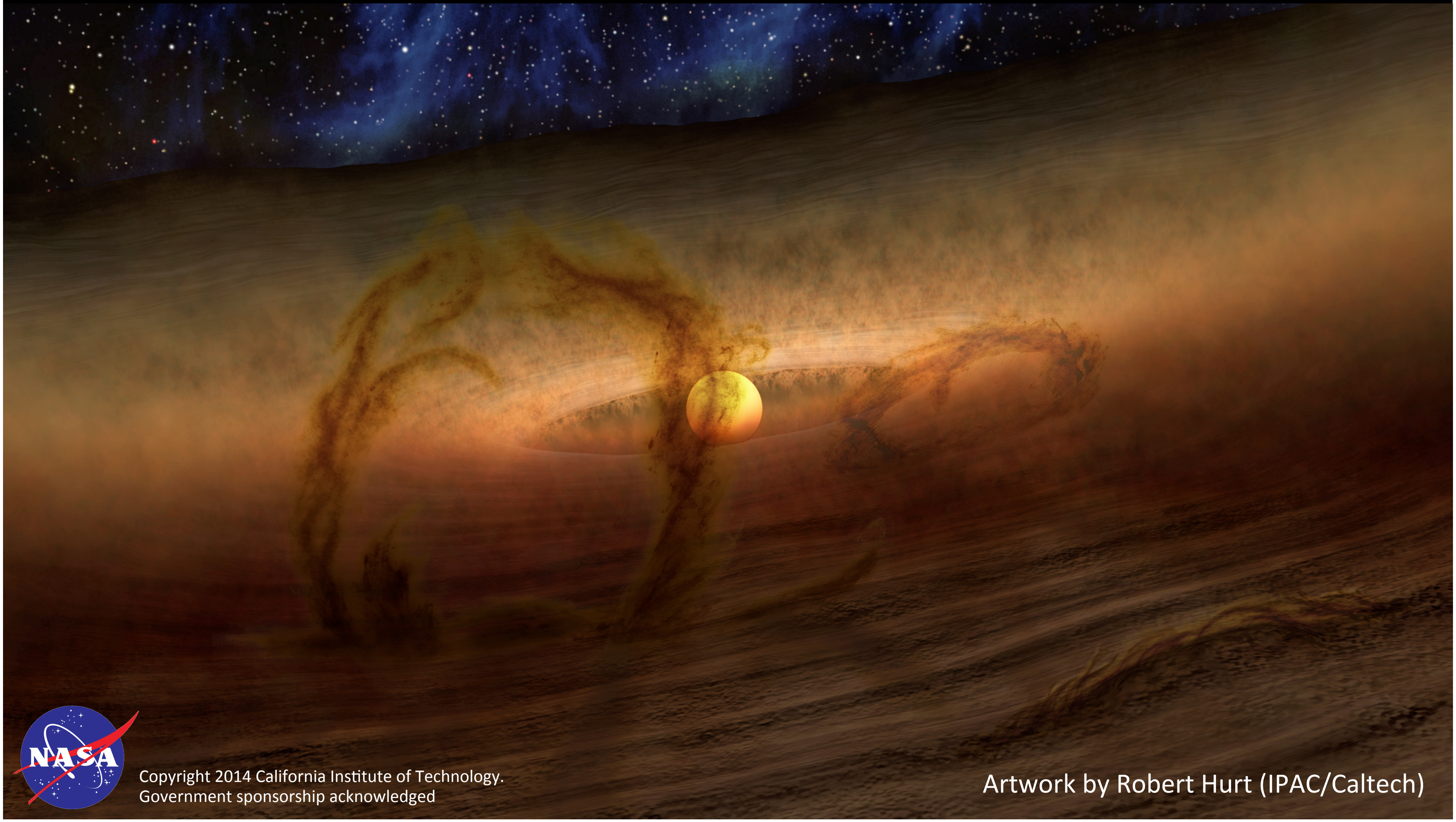
Magnetic Coupling in Protostellar Disks

Neal Turner (JPL/Caltech)



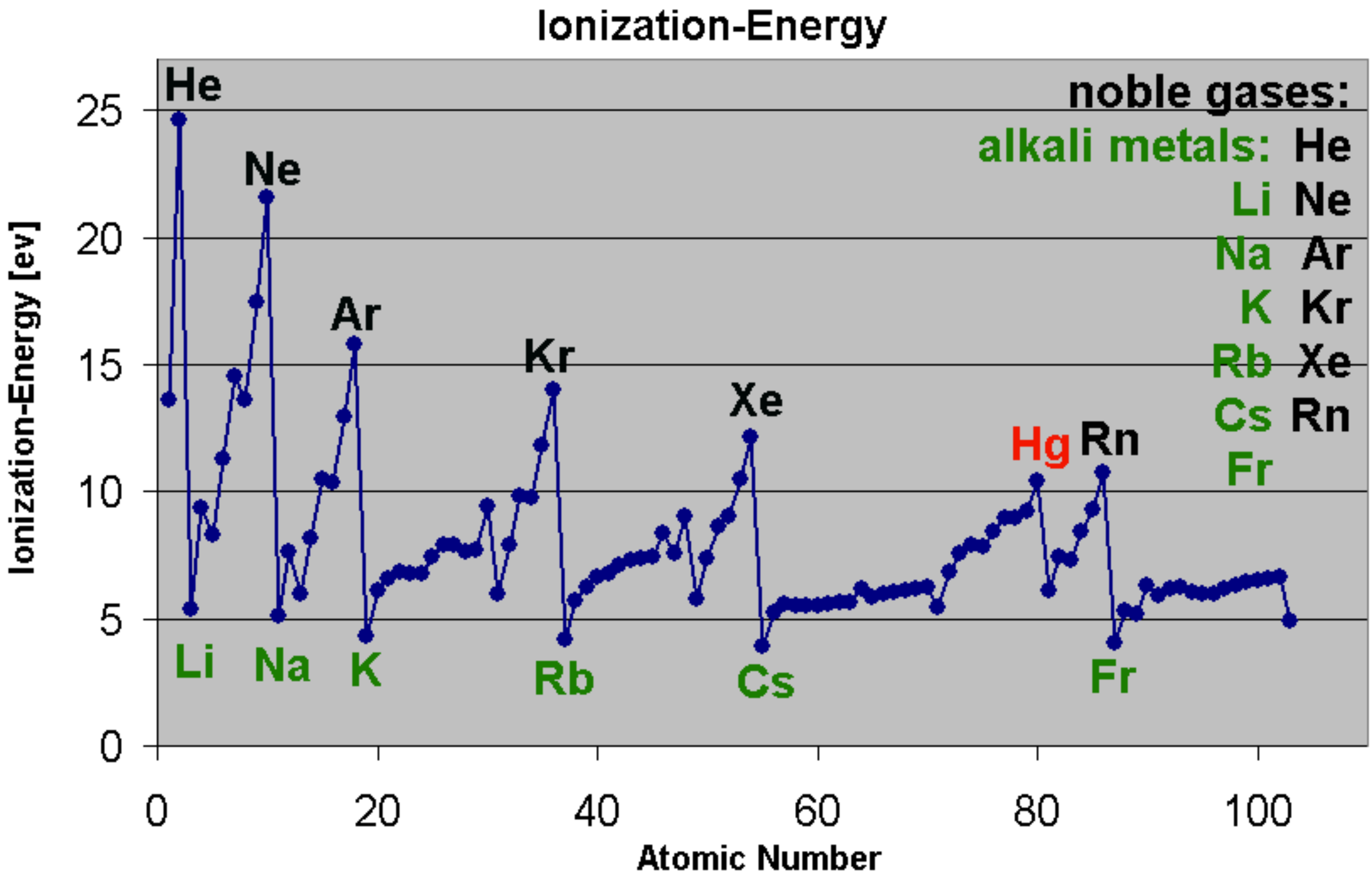
Artwork by Robert Hurt (IPAC/Caltech)

Outline

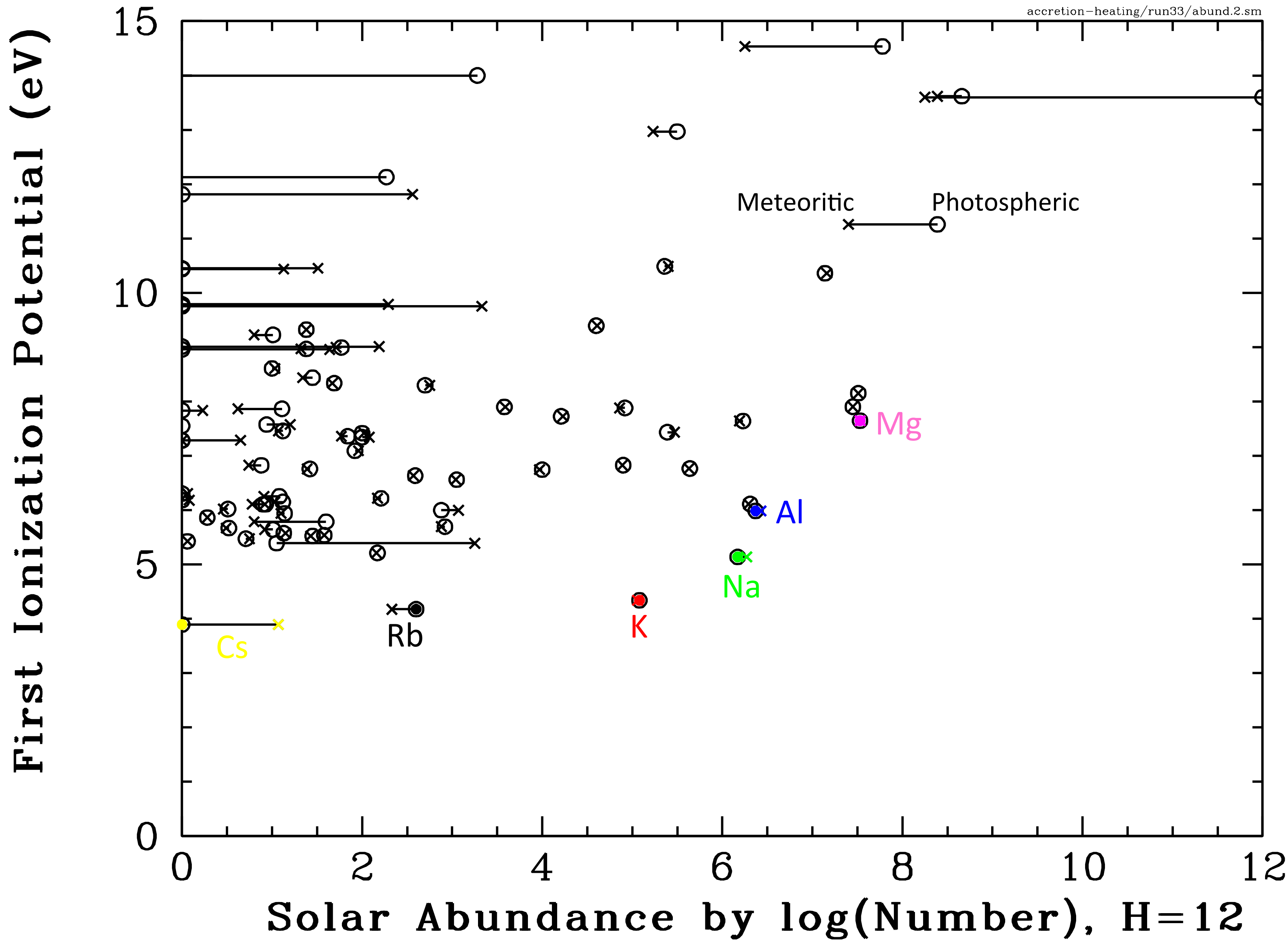
1. **Thermally-ionized zone**
   - *Which elements contribute?*
   - *When are they in the gas phase?*

2. **Zone ionized by energetic radiation**
   - *How much of the radiation enters?*
   - *Where do the Ohmic, Hall and A.D. terms dominate?*

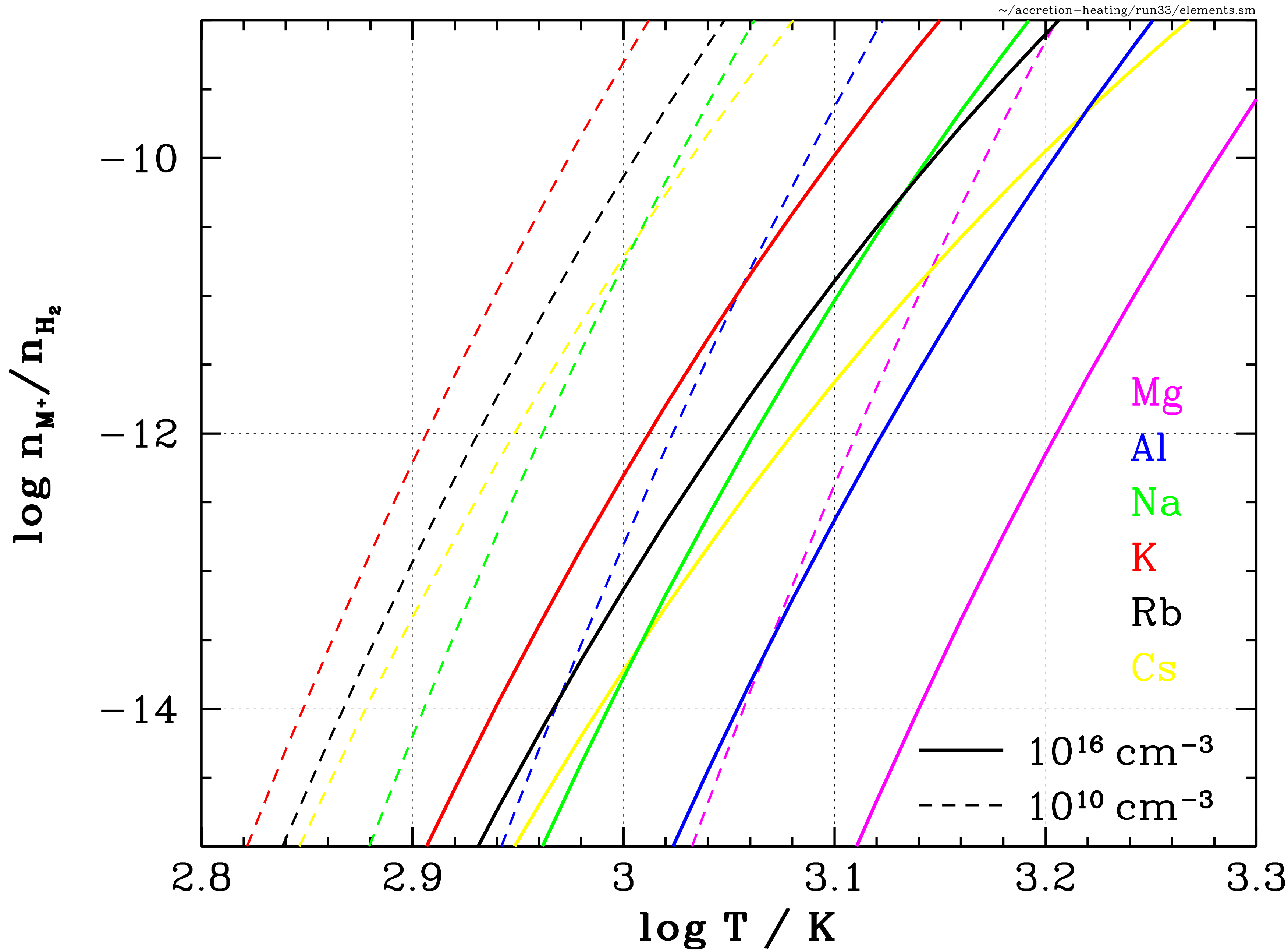
3. **Signs that magnetic activity is taking place**
   - *Herbig disks are too near-IR bright to be hydrostatic*
   - *Brief fadings are common*



Ionization-Energy
Ionization-Energy [ev]
Atomic Number
0
5
10
15
20
25
0
20
40
60
80
100
He
Ne
Ar
Kr
Xe
Hg
Rn
Li
Na
K
Rb
Cs
Fr
noble gases:
alkali metals: He
Li Ne
Na Ar
K Kr
Rb Xe
Cs Rn
Fr

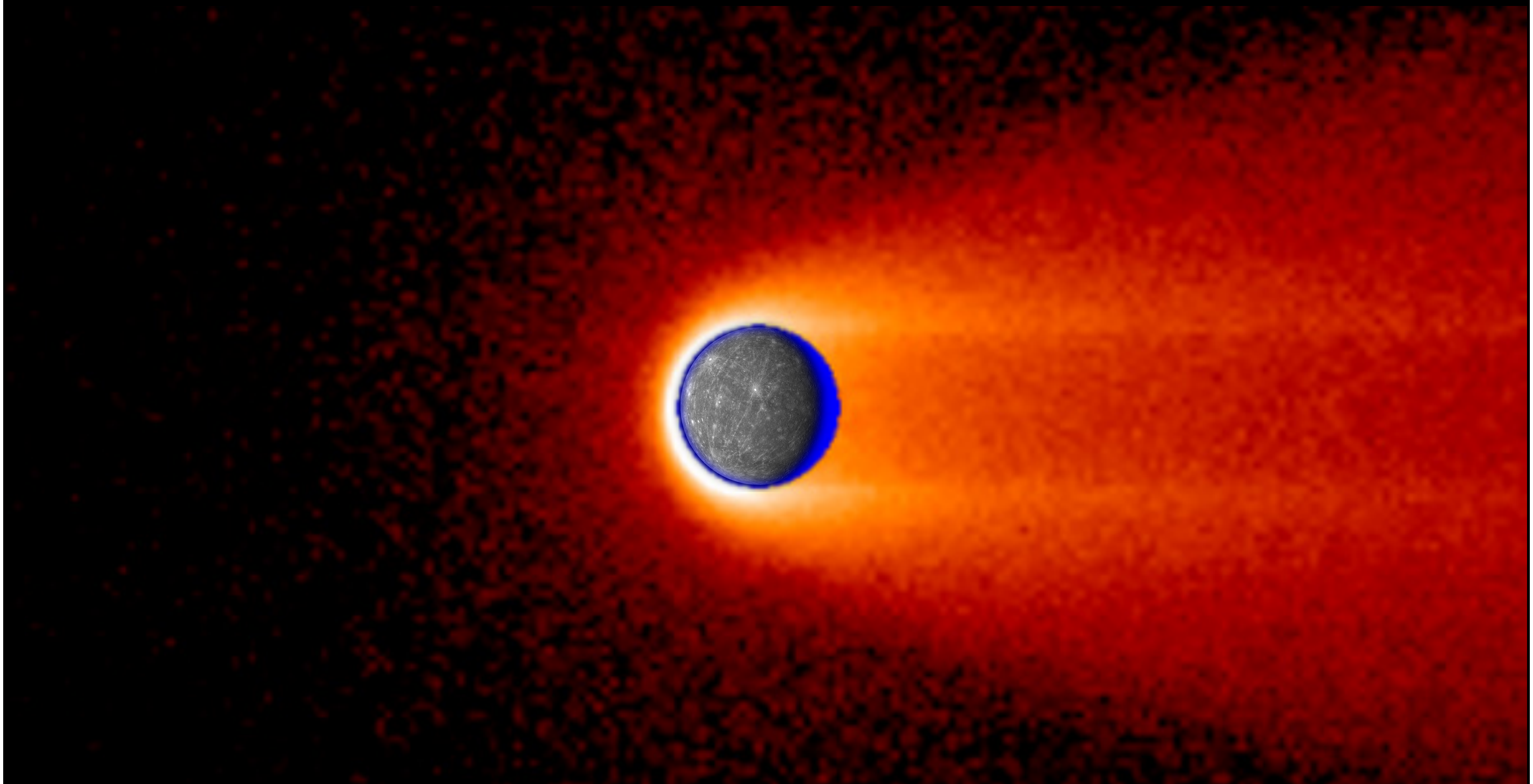


accretion−heating/run33/abund.2.sm
First Ionization Potential (eV)
Solar Abundance by log(Number), H=12
Meteoritic
Photospheric
Mg
Al
Na
K
Rb
Cs
0
5
10
15
0
2
4
6
8
10
12

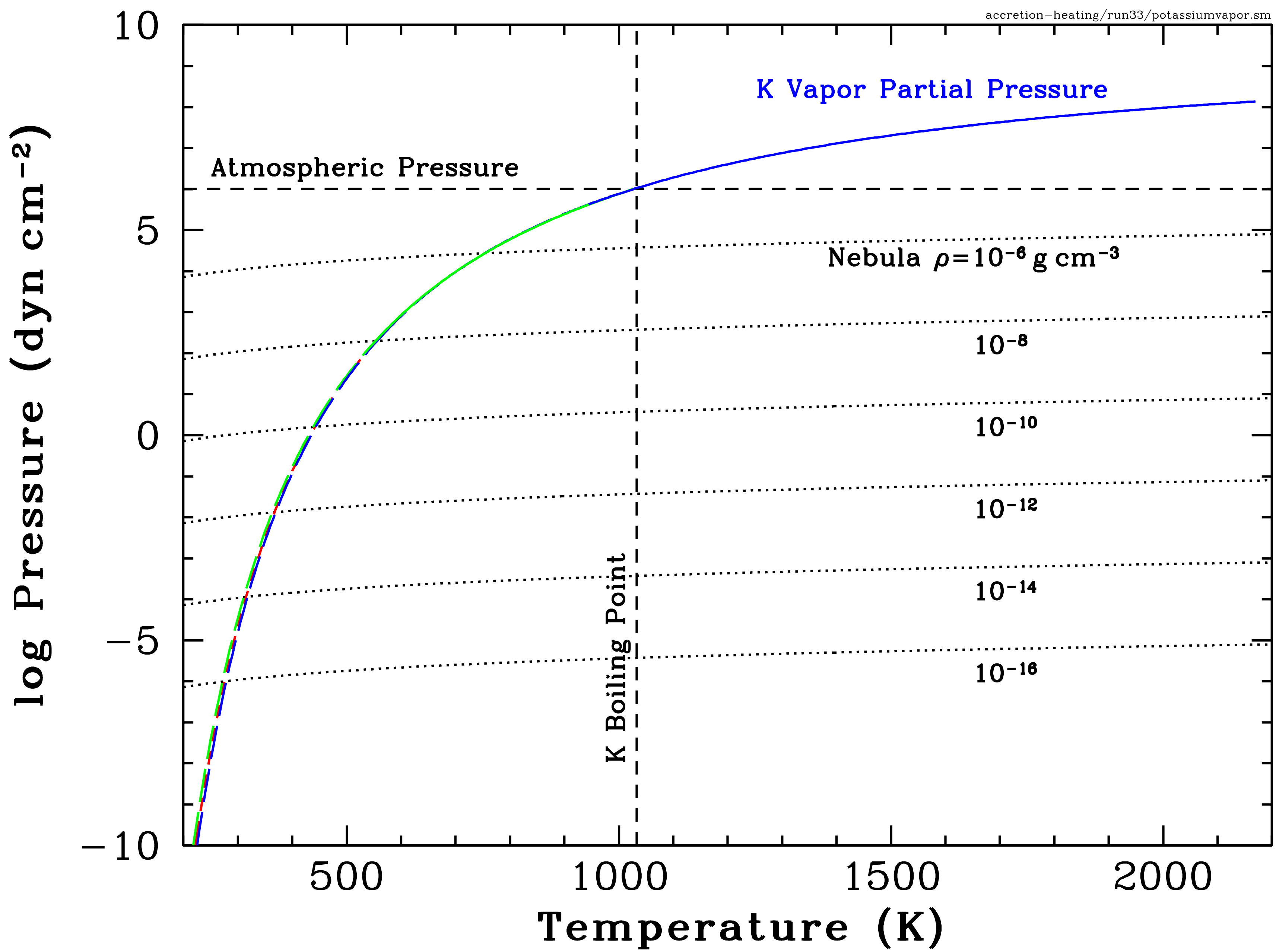


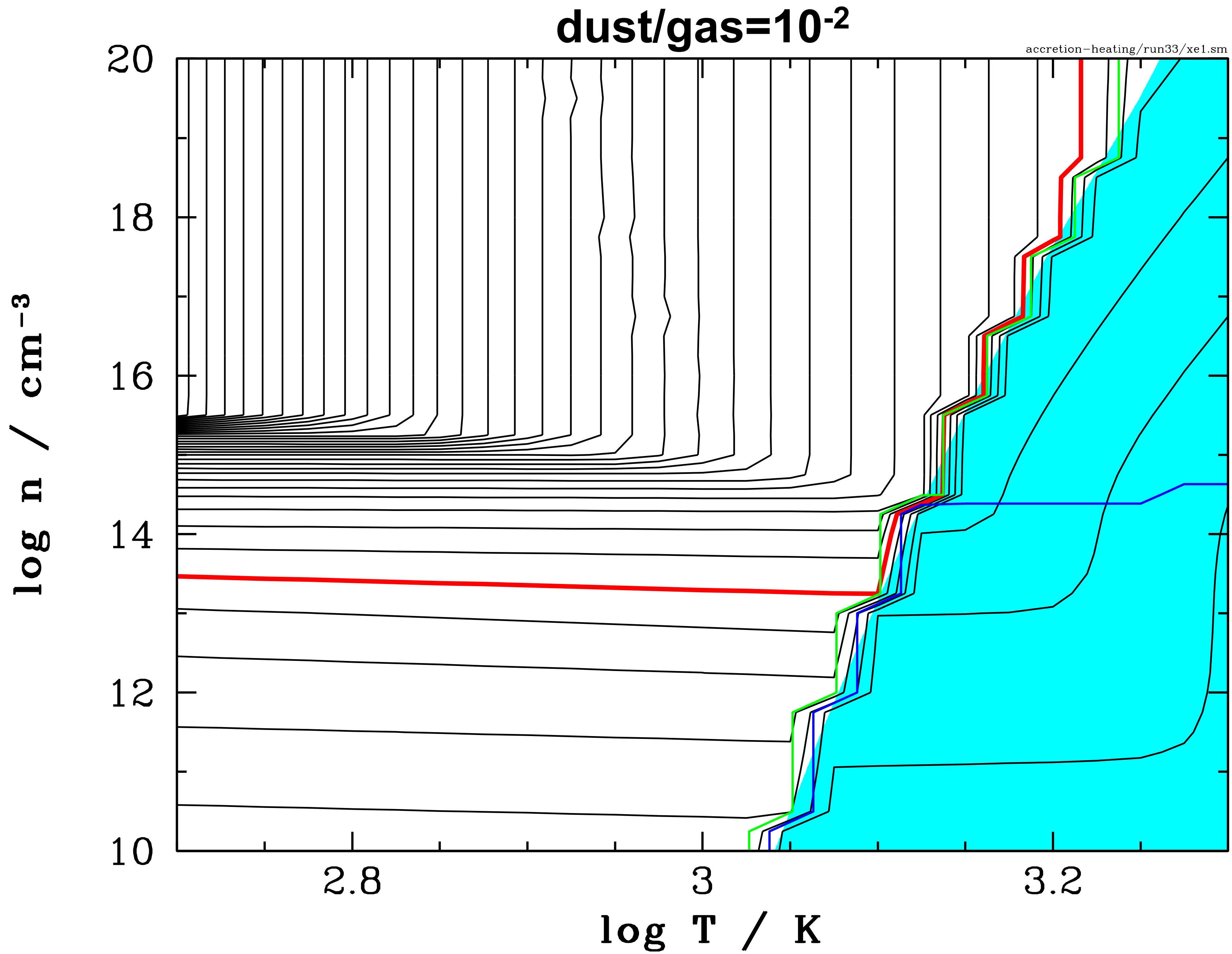
~/accretion-heating/run33/elements.sm
log n_{M^+}/n_{H_2}
log T / K
−10
−12
−14
2.8
2.9
3
3.1
3.2
3.3
Mg
Al
Na
K
Rb
Cs
10^{16} cm^{-3}
10^{10} cm^{-3}

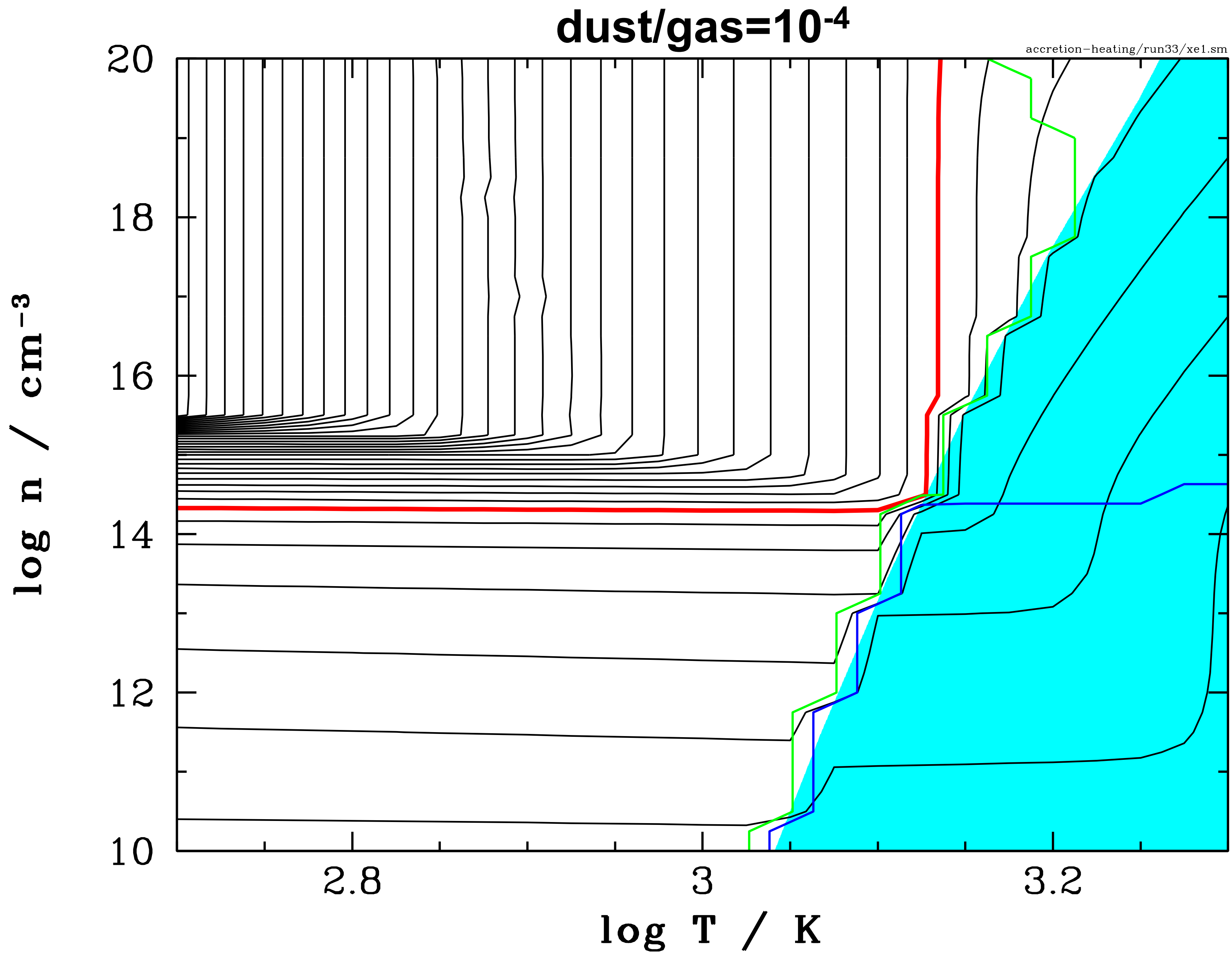
Mercury's Exosphere



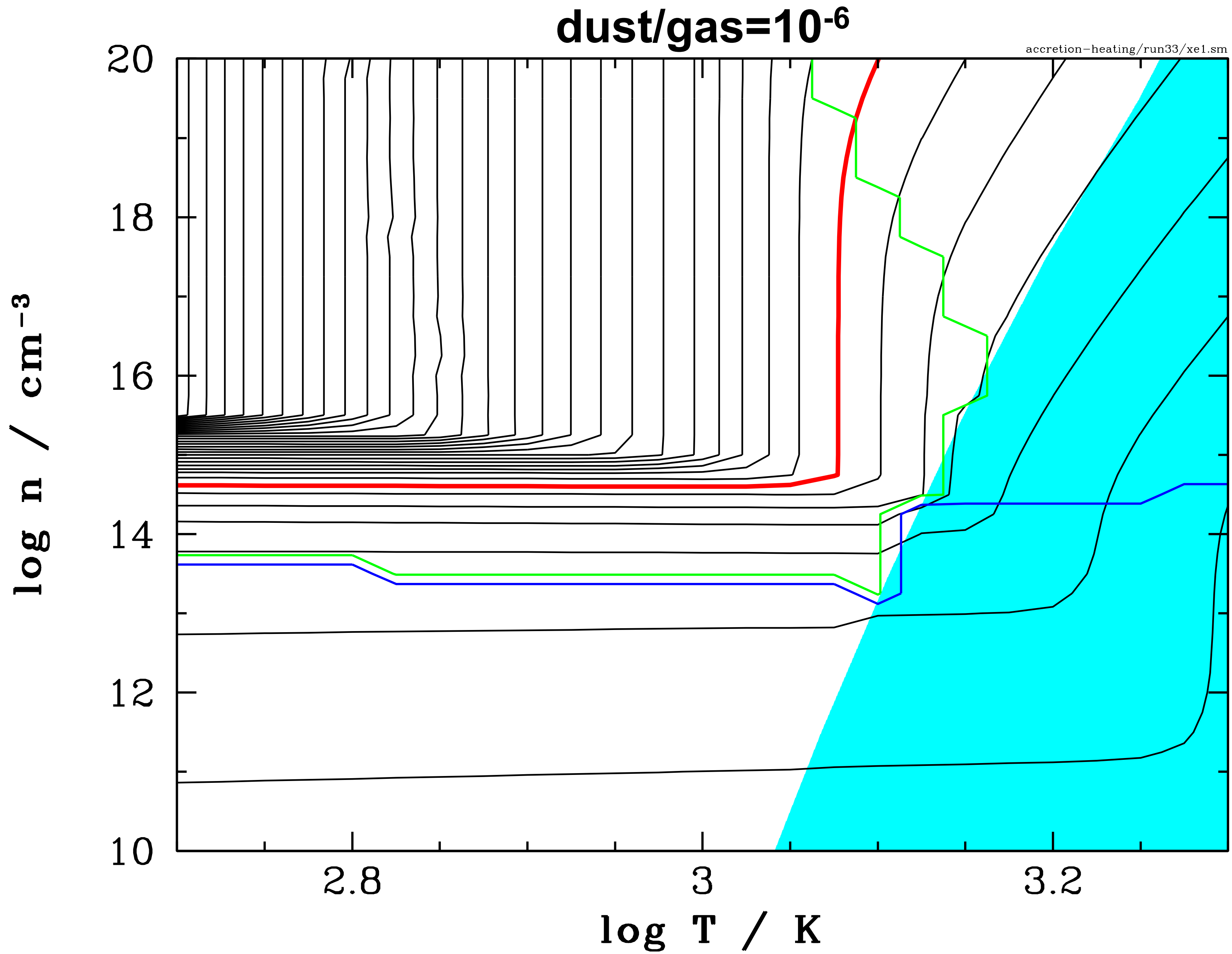
M. Burger, NASA-GSFC


accretion−heating/run33/potassiumvapor.sm
K Vapor Partial Pressure
Atmospheric Pressure
Nebula ρ=10⁻⁶ g cm⁻³
10⁻⁸
10⁻¹⁰
10⁻¹²
10⁻¹⁴
10⁻¹⁶
K Boiling Point
log Pressure (dyn cm⁻²)
Temperature (K)
10
5
0
−5
−10
500
1000
1500
2000


dust/gas=10^{-2}
accretion−heating/run33/xe1.sm
log n / cm^{-3}
20
18
16
14
12
10
2.8
3
3.2
log T / K



dust/gas=10^{-4}
accretion−heating/run33/xe1.sm
20
18
16
14
12
10
log n / cm^{-3}
2.8
3
3.2
log T / K

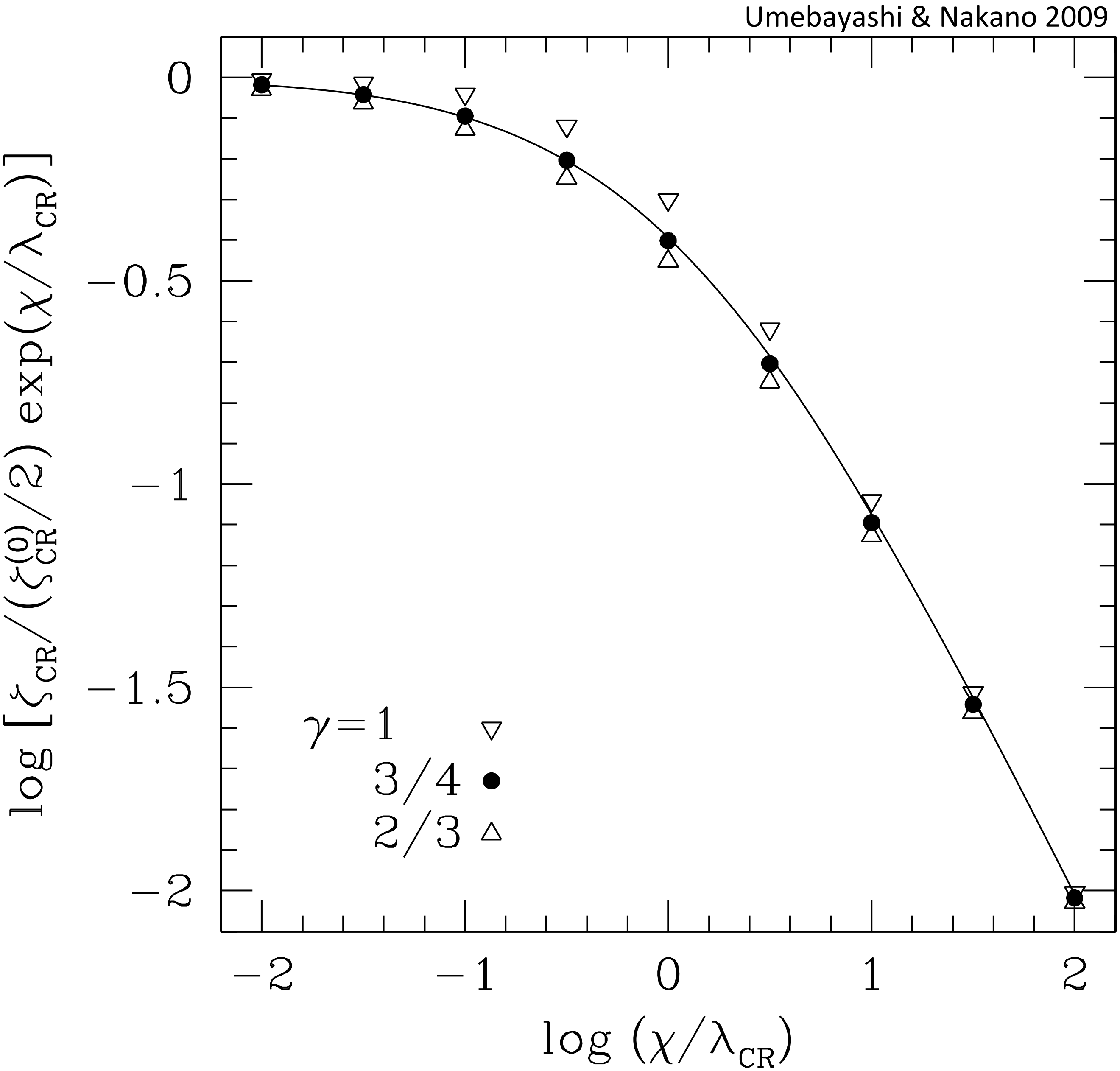


dust/gas=10^-6
accretion−heating/run33/xe1.sm
20
18
16
14
12
10
log n / cm^-3
2.8
3
3.2
log T / K

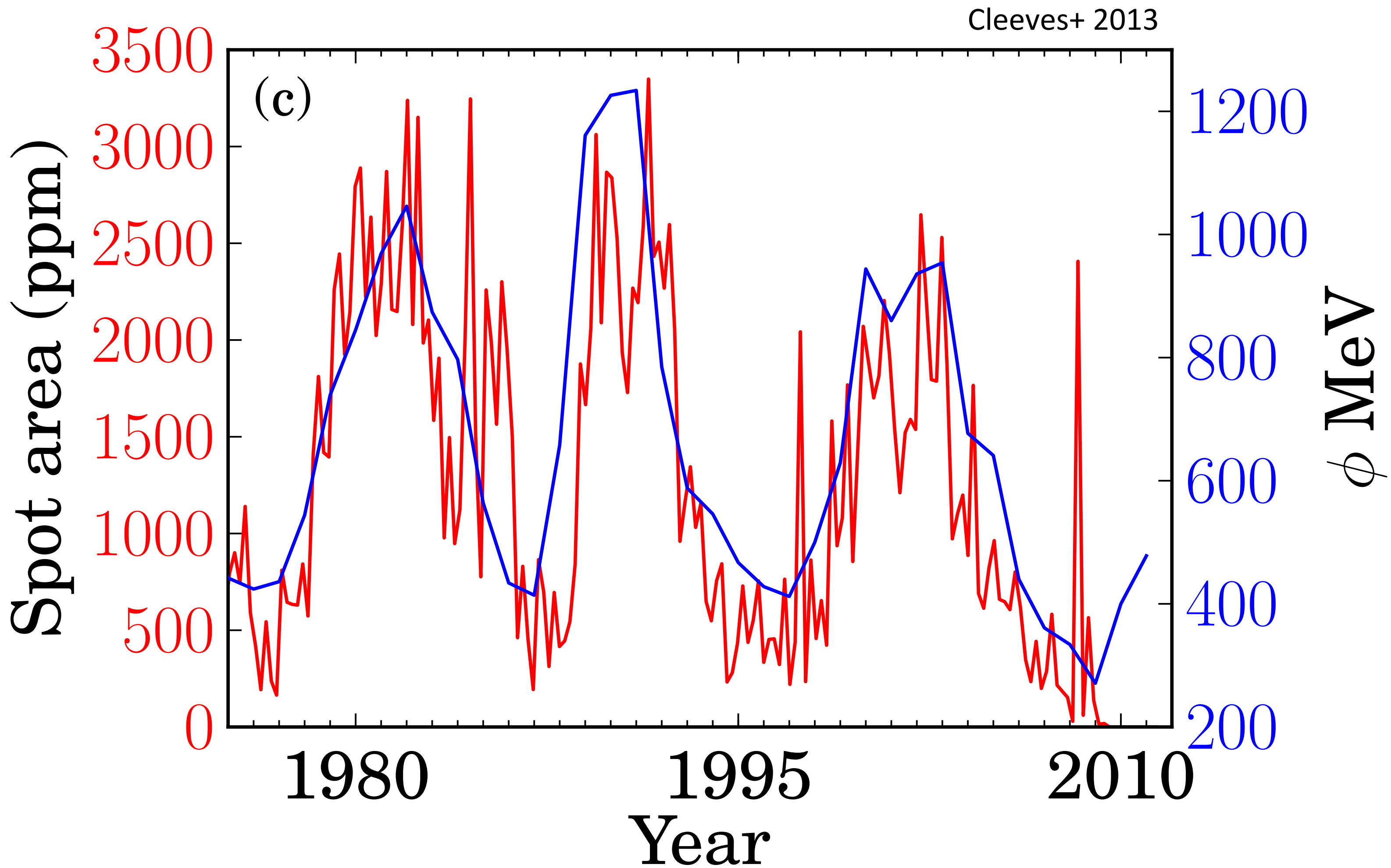
Outline

1. **Thermally-ionized zone**
   - *Which elements contribute?*
   - *When are they in the gas phase?*
2. **Zone ionized by energetic radiation**
   - *How much of the radiation enters?*
   - *Where do the Ohmic, Hall and A.D. terms dominate?*
3. **Signs that magnetic activity is taking place**
   - *Herbig disks are too near-IR bright to be hydrostatic*
   - *Brief fadings are common*

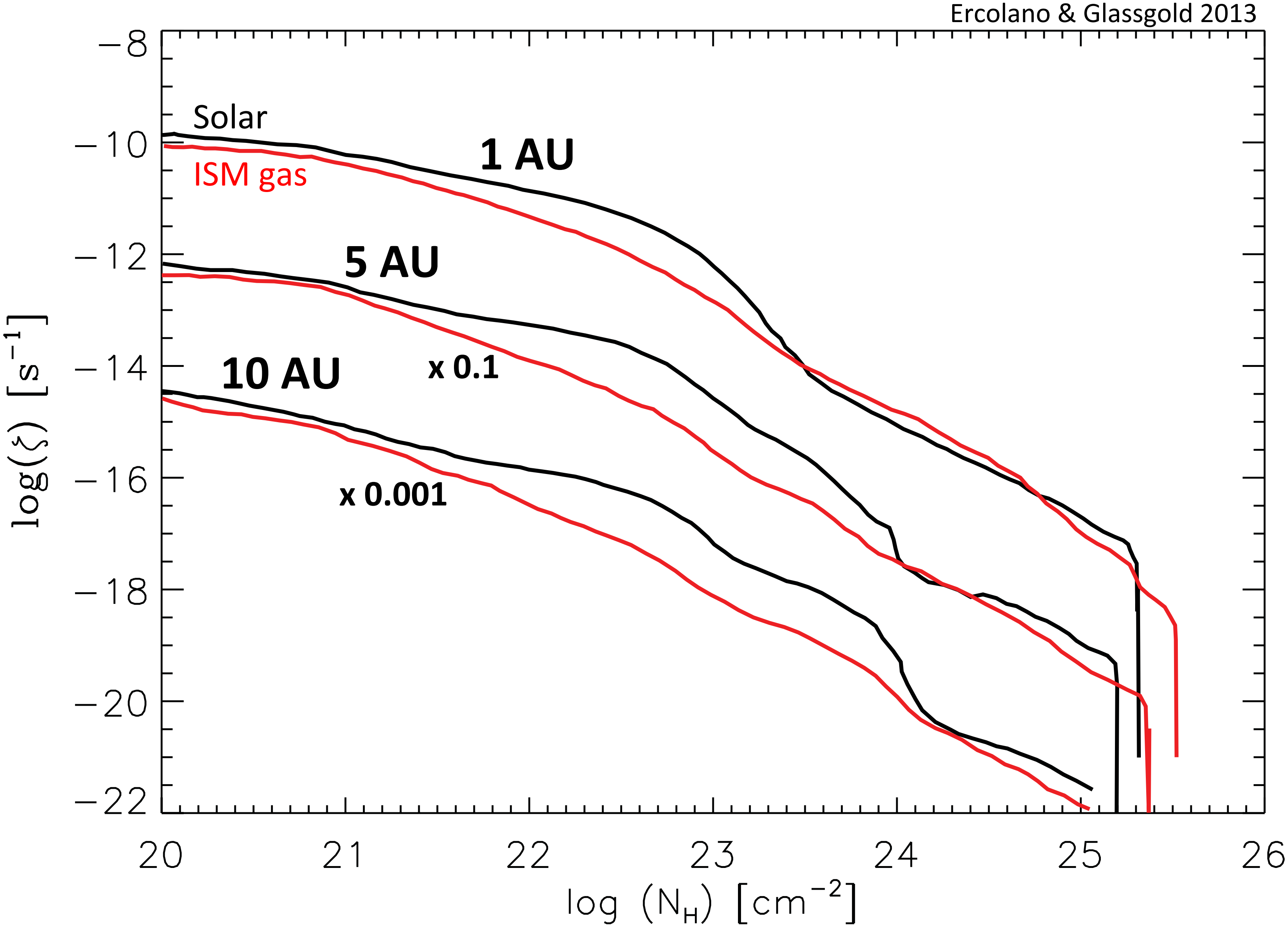
Interstellar Cosmic Rays 1



Interstellar Cosmic Rays 2

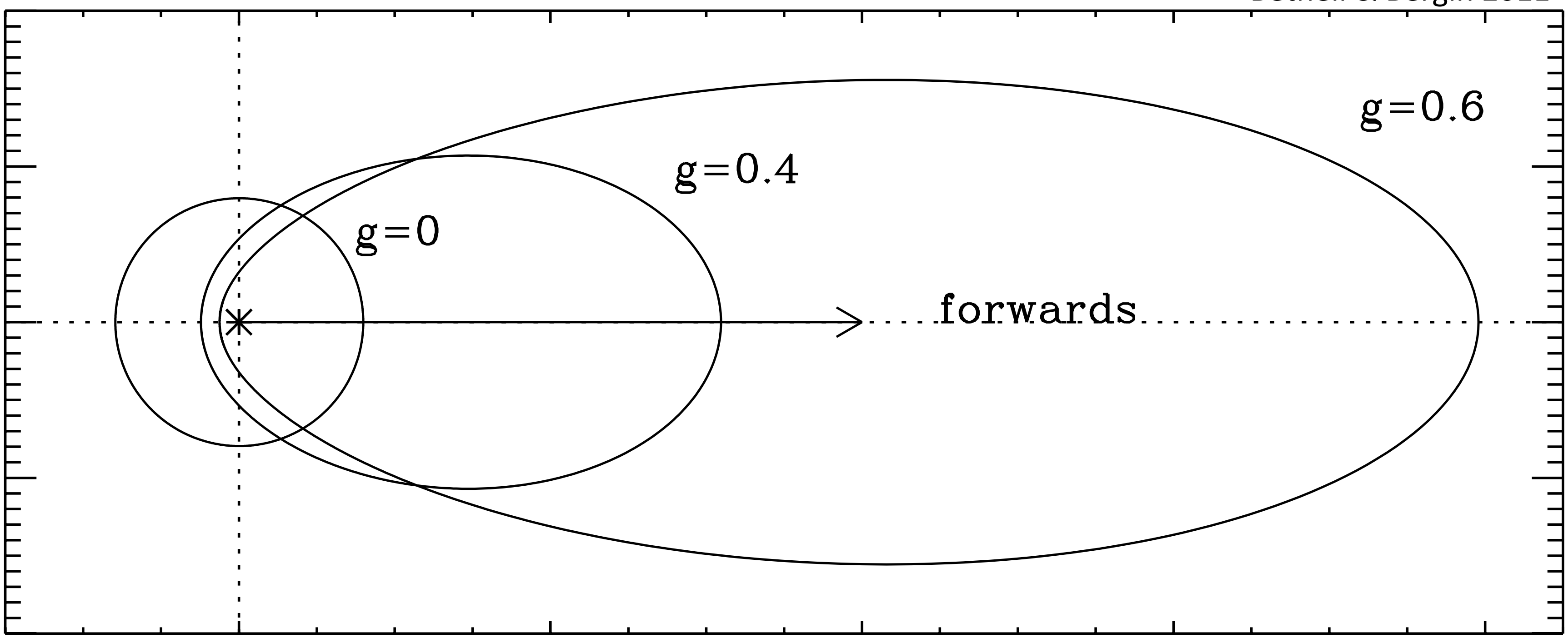


Stellar X-Rays

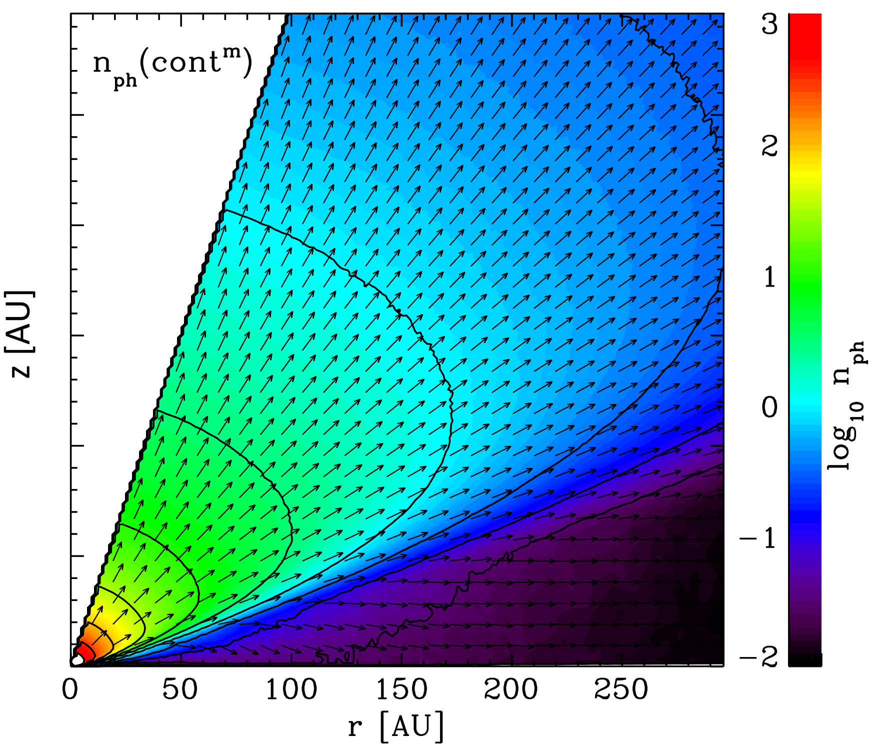


Stellar FUV 1

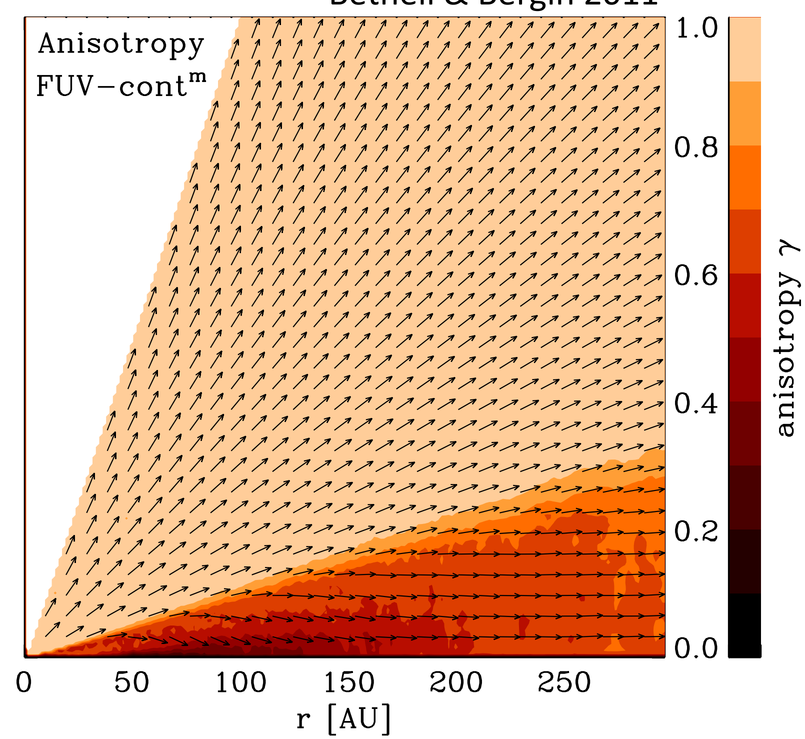
Bethell & Bergin 2011



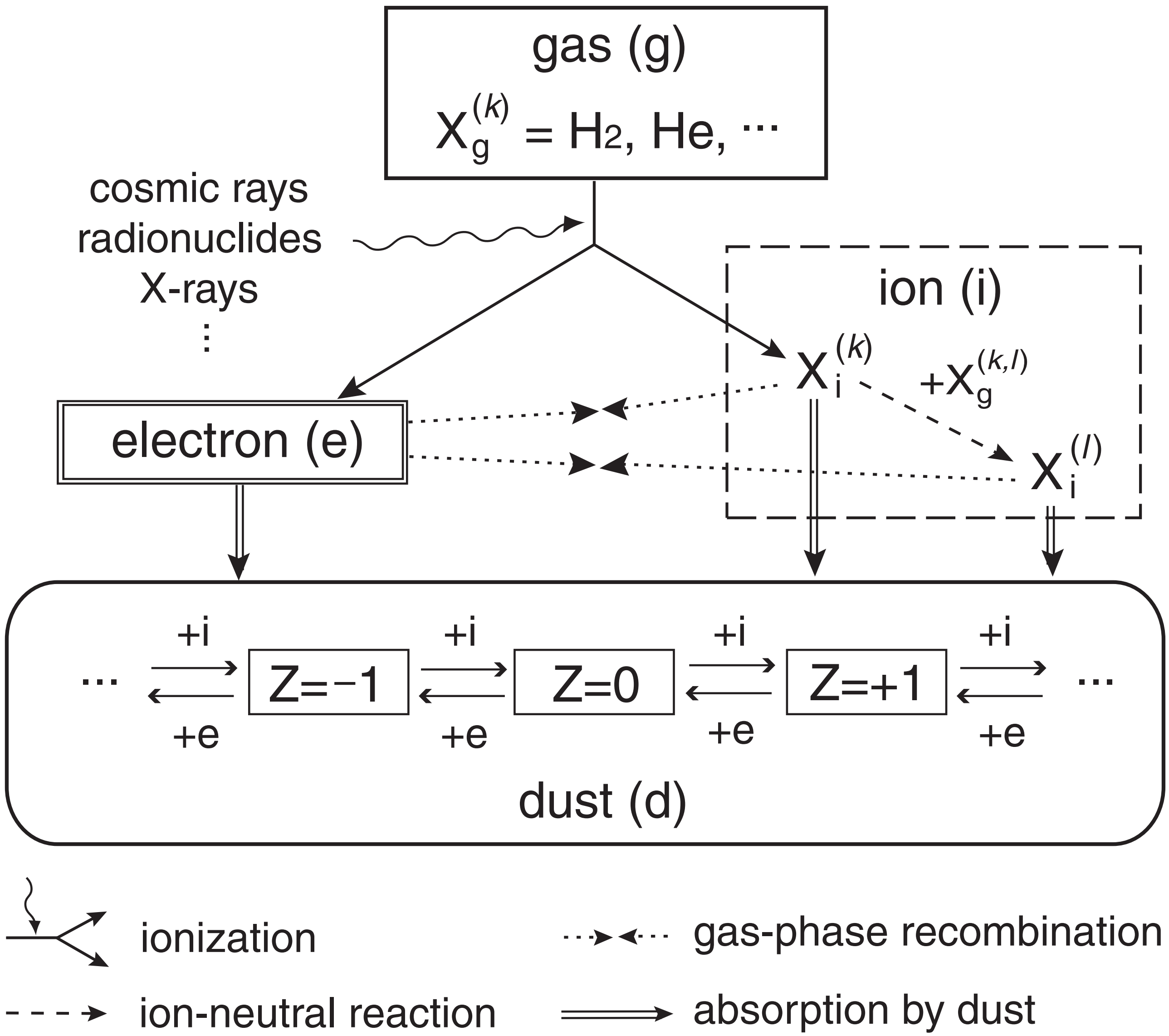
Stellar FUV 2



Bethell & Bergin 2011



Recombination Balancing Ionization



Okuzumi 2009

From Charged Particles to Magnetic Diffusivities

Hall parameter, species j = gyrofrequency x neutral collision time

$$\beta_j = \frac{|Z_j|eB}{m_j c} \frac{1}{\gamma_j \rho}$$

Conductivities

$$\sigma_O = \frac{ec}{B} \sum_j n_j |Z_j| \beta_j,$$

$$\sigma_H = -\frac{ec}{B} \sum_j \frac{n_j Z_j \beta_j^2}{1 + \beta_j^2}$$

and

$$\sigma_P = \frac{ec}{B} \sum_j \frac{n_j |Z_j| \beta_j}{1 + \beta_j^2}$$

Diffusivities

$$\eta_O = \frac{c^2}{4\pi \sigma_O},$$

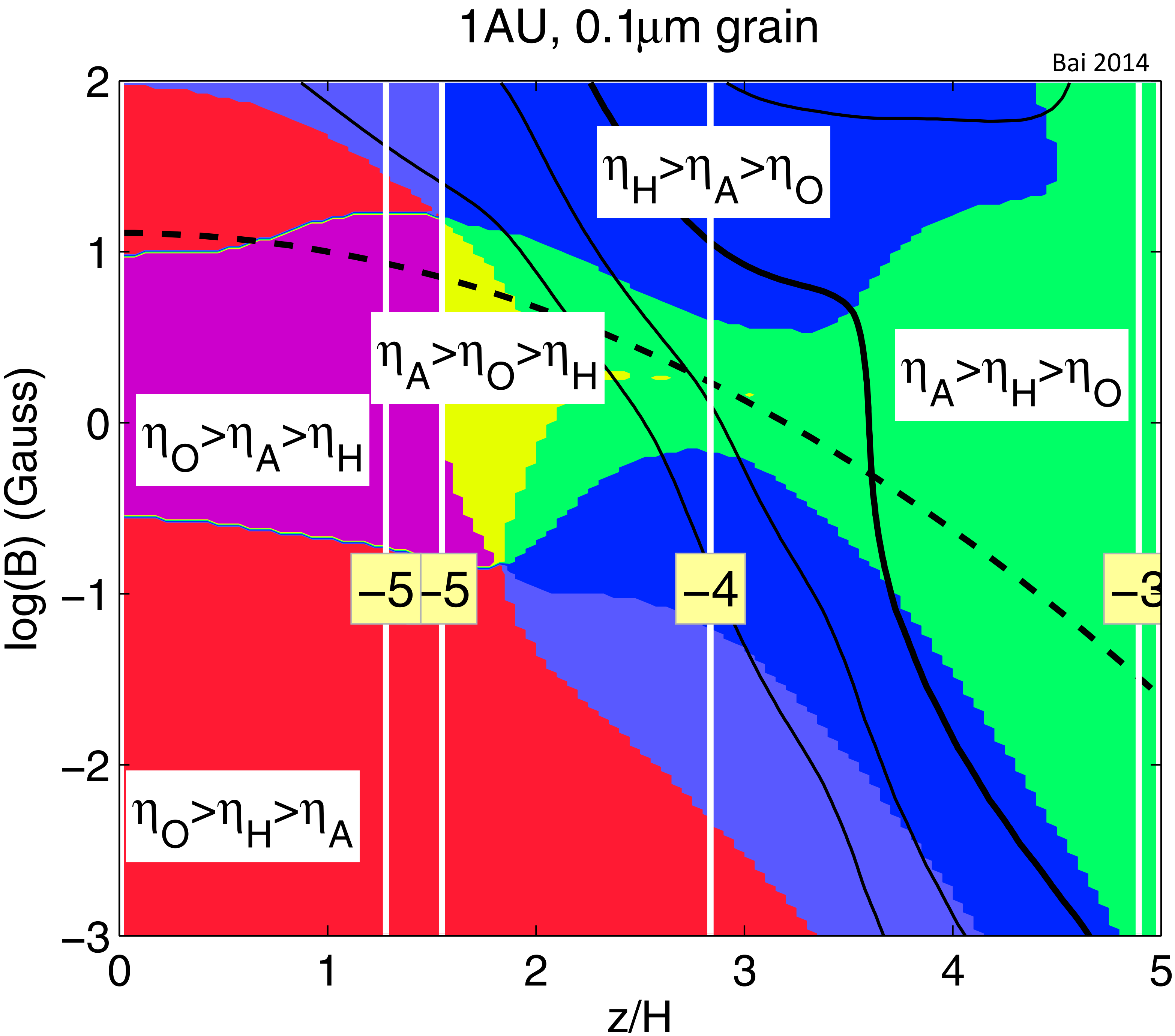
$$\eta_H = \frac{c^2}{4\pi \sigma_\perp} \frac{\sigma_H}{\sigma_\perp},$$

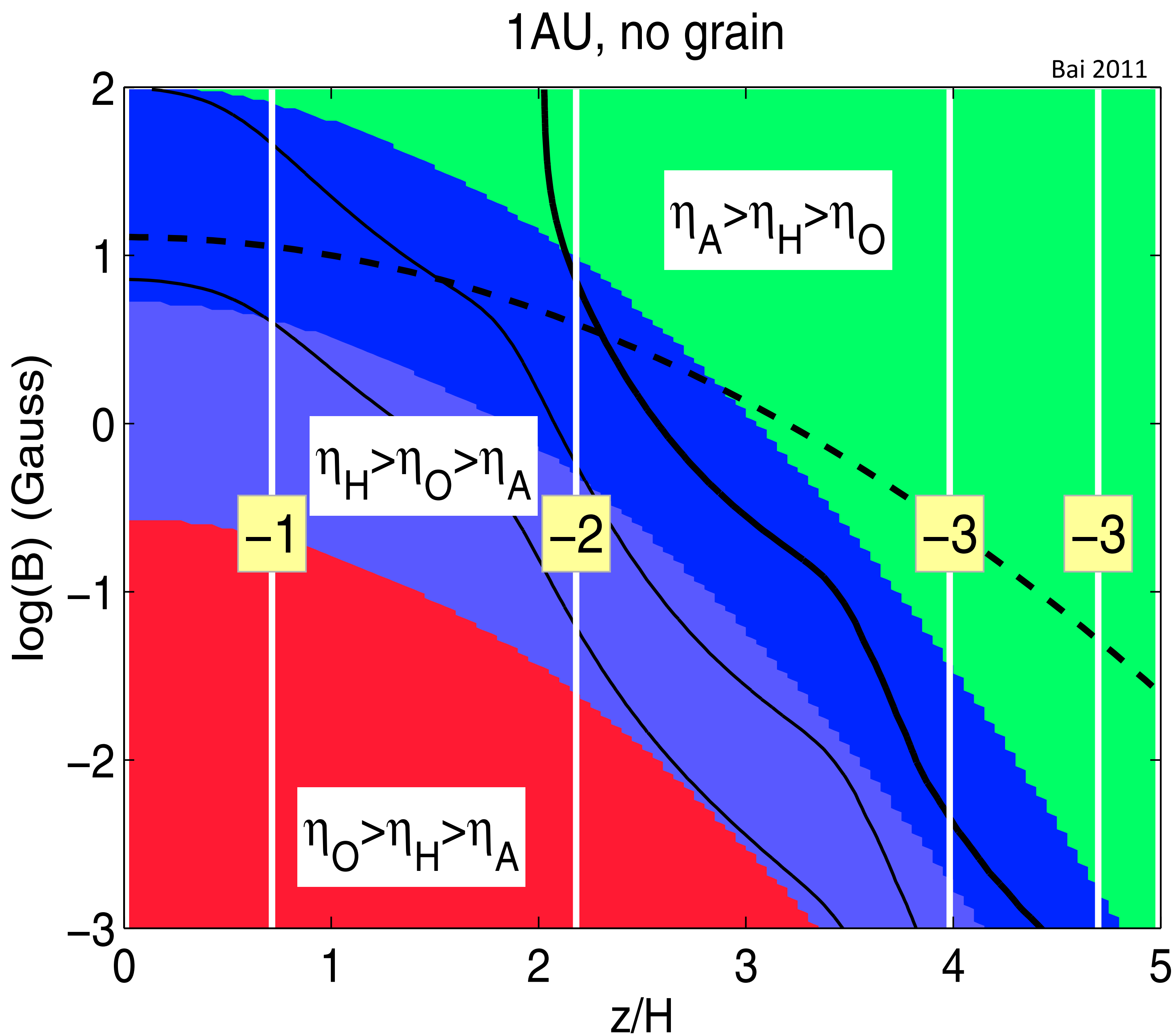
and

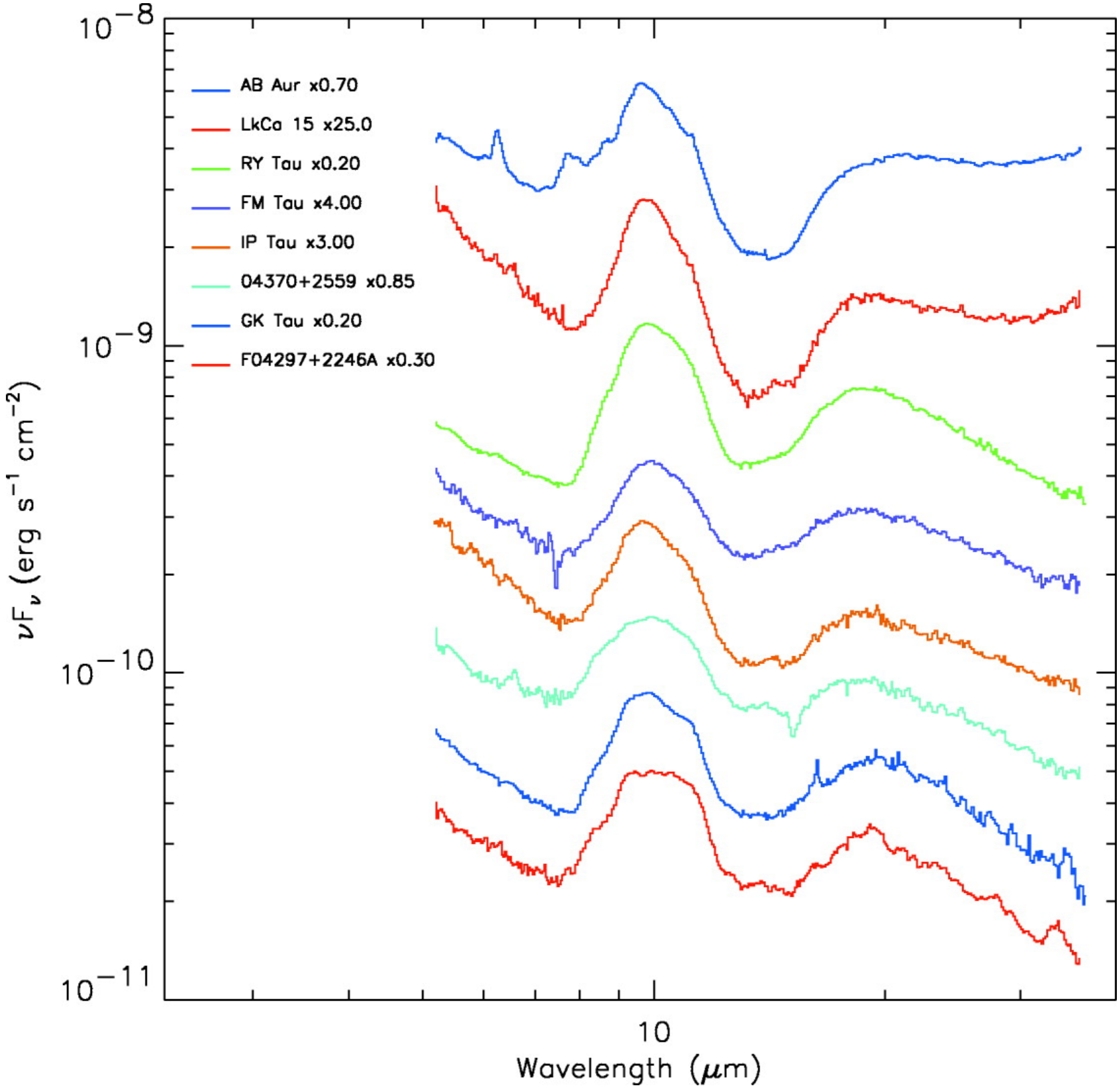
$$\eta_A = \frac{c^2}{4\pi \sigma_\perp} \frac{\sigma_P}{\sigma_\perp} - \eta_O$$

where $\sigma_\perp = \sqrt{\sigma_H^2 + \sigma_P^2}$

Wardle 2007

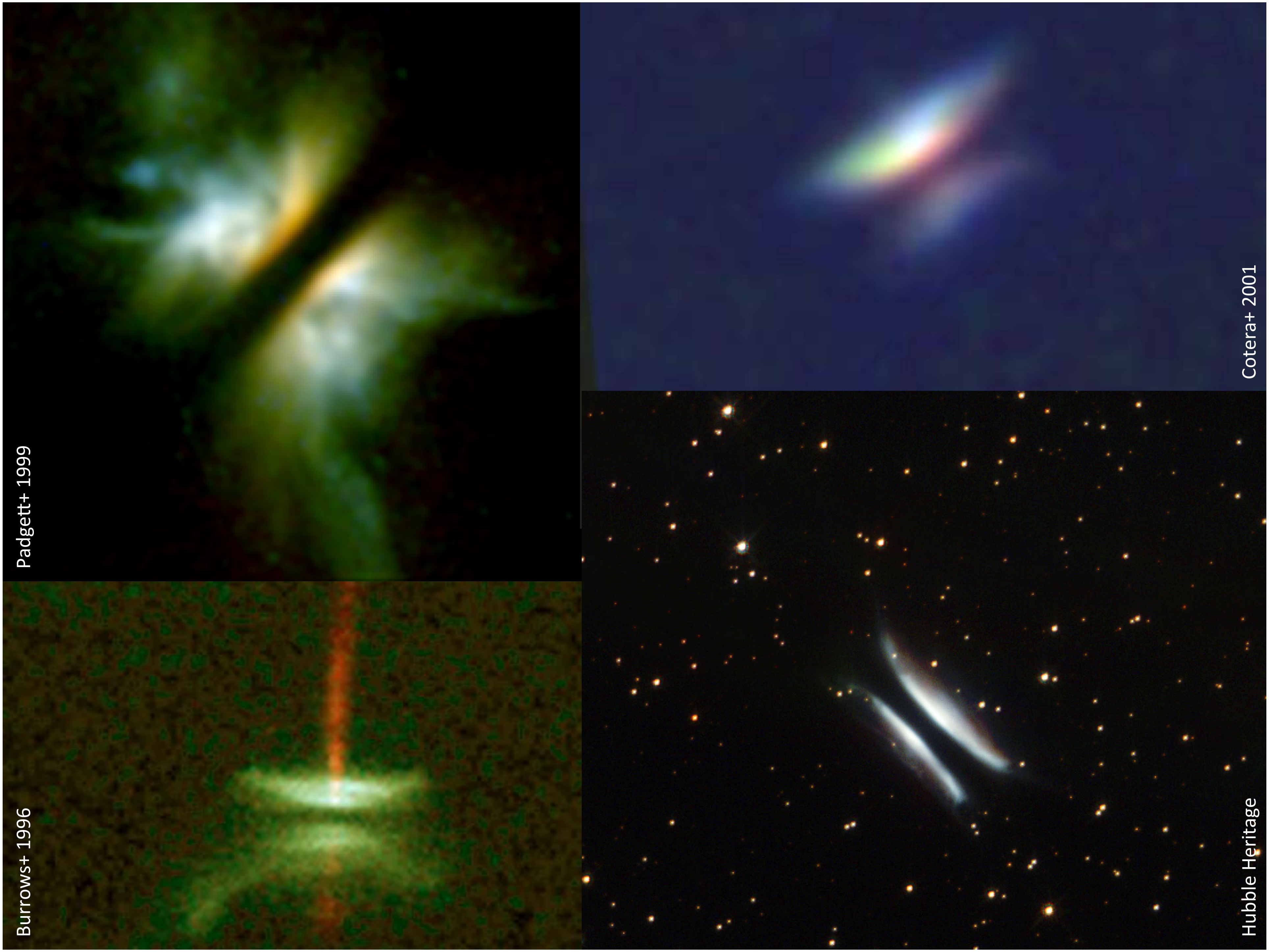

1AU, 0.1μm grain
Bai 2014
$\eta_H>\eta_A>\eta_O$
$\eta_A>\eta_O>\eta_H$
$\eta_A>\eta_H>\eta_O$
$\eta_O>\eta_A>\eta_H$
$\eta_O>\eta_H>\eta_A$
−5
-5
−4
−3
log(B) (Gauss)
z/H
2
1
0
−1
−2
−3
0
1
2
3
4
5

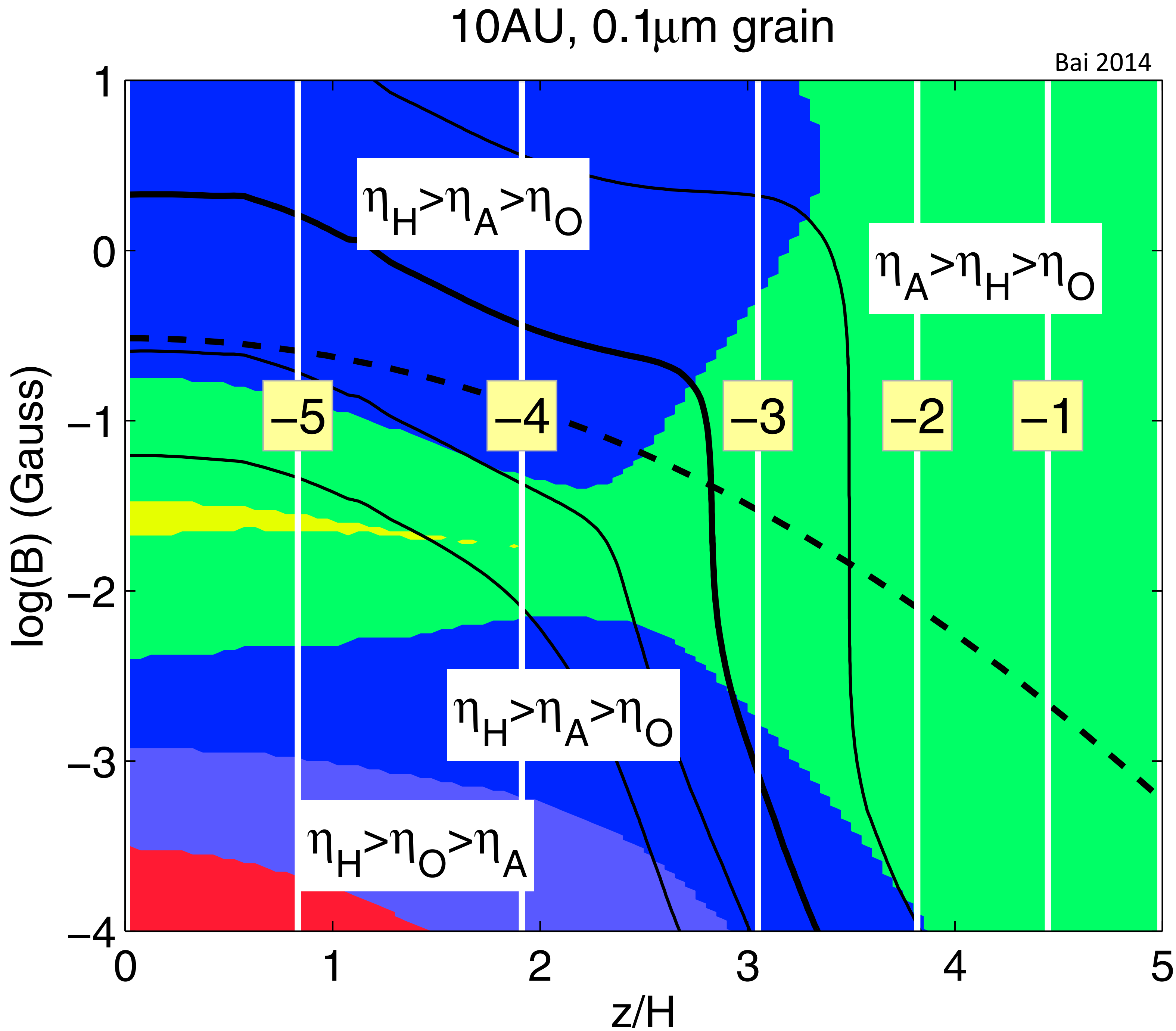

1AU, no grain
Bai 2011
$\eta_A > \eta_H > \eta_O$
$\eta_H > \eta_O > \eta_A$
$\eta_O > \eta_H > \eta_A$
−1
−2
−3
−3
log(B) (Gauss)
z/H
2
1
0
−1
−2
−3
0
1
2
3
4
5



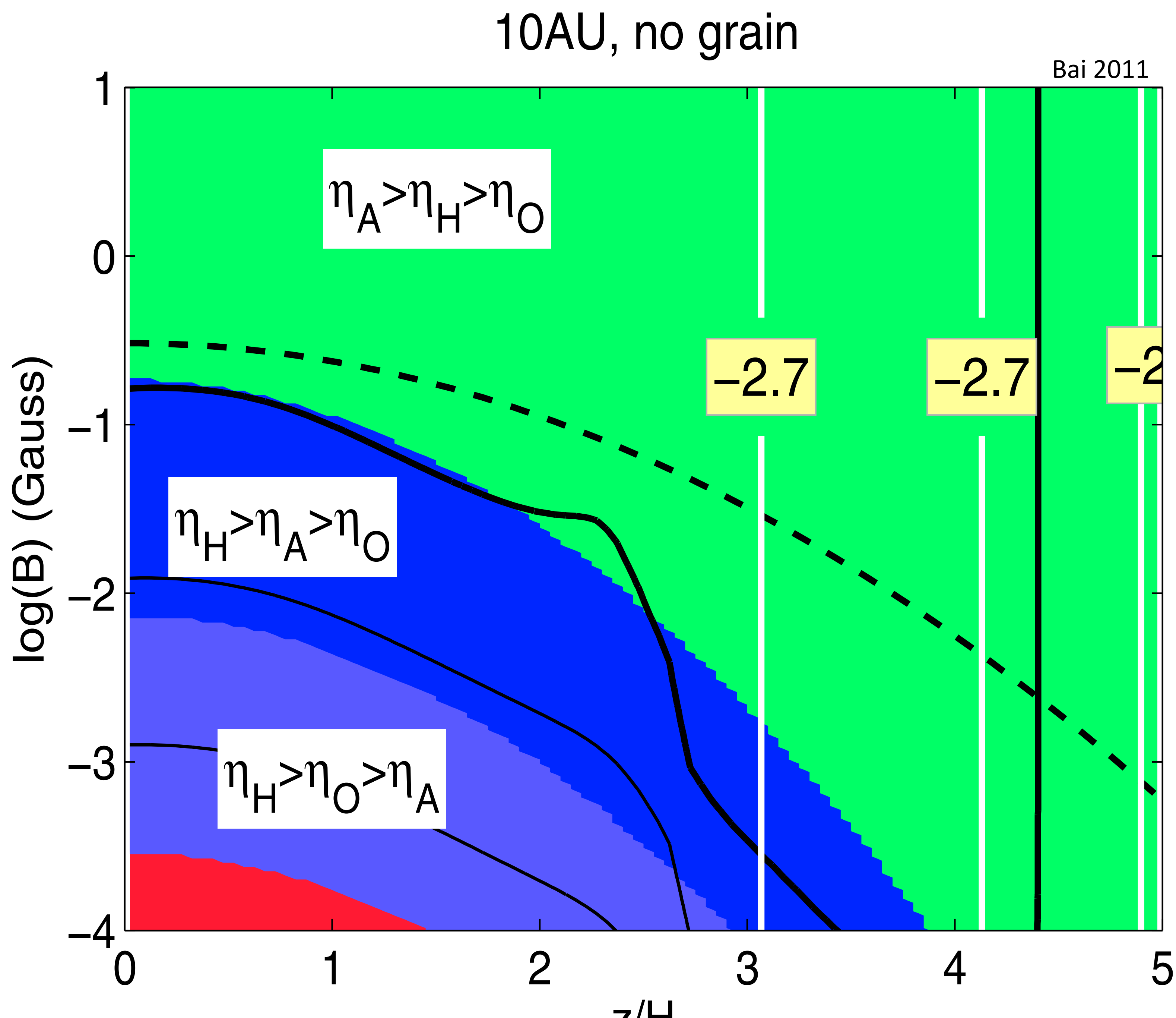
AB Aur x0.70
LkCa 15 x25.0
RY Tau x0.20
FM Tau x4.00
IP Tau x3.00
04370+2559 x0.85
GK Tau x0.20
F04297+2246A x0.30
10^{-8}
10^{-9}
10^{-10}
10^{-11}
νF_ν (erg s^{-1} cm^{-2})
10
Wavelength (μm)

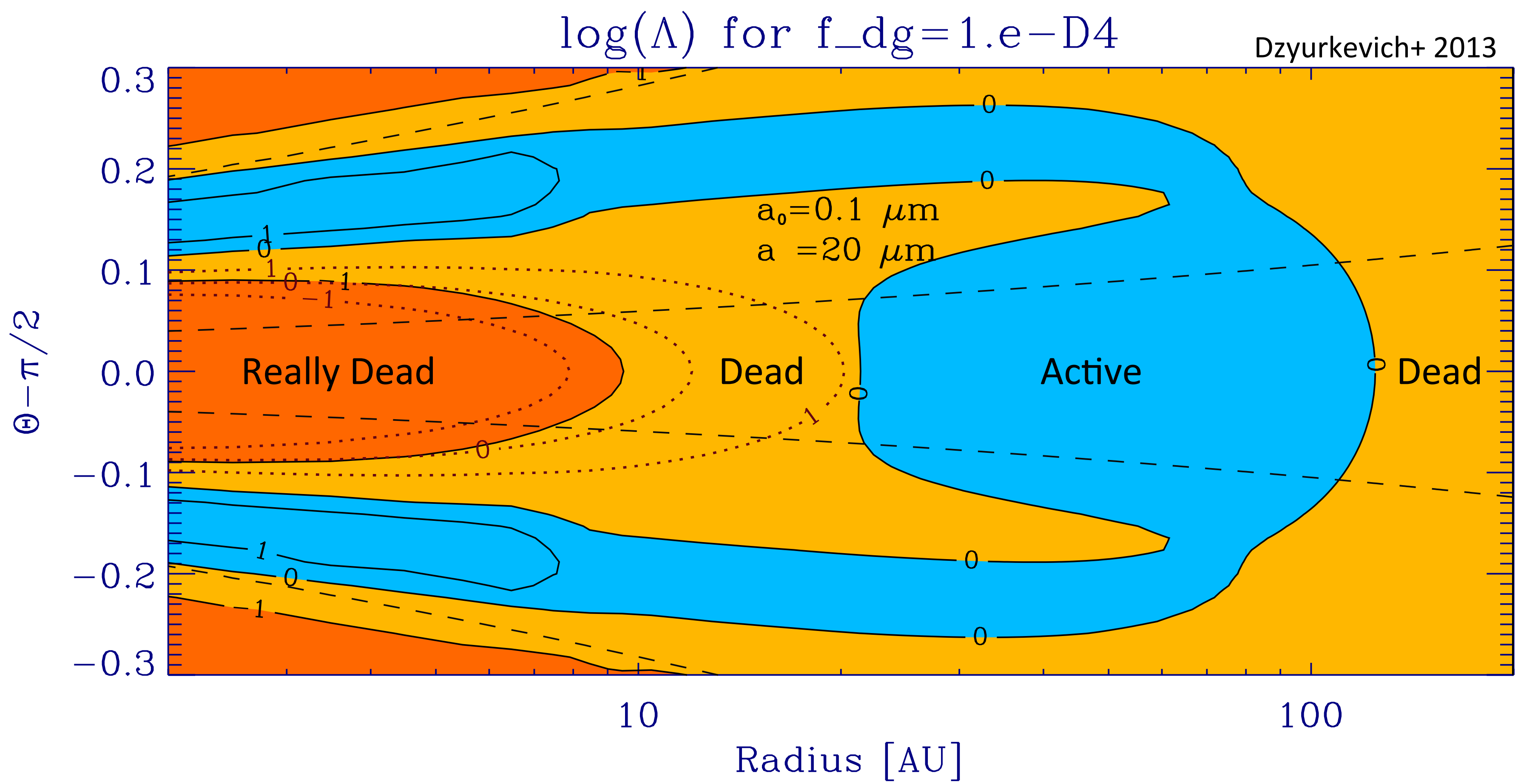
Furlan+ 2006


Padgett+ 1999
Cotera+ 2001
Burrows+ 1996
Hubble Heritage



10AU, 0.1μm grain
Bai 2014
ηH>ηA>ηO
ηA>ηH>ηO
ηH>ηA>ηO
ηH>ηO>ηA
−5
−4
−3
−2
−1
log(B) (Gauss)
z/H
1
0
−1
−2
−3
−4
0
1
2
3
4
5


10AU, no grain
Bai 2011
ηA>ηH>ηO
ηH>ηA>ηO
ηH>ηO>ηA
−2.7
−2.7
−2
log(B) (Gauss)
z/H
1
0
−1
−2
−3
−4
0
1
2
3
4
5


log(Λ) for f_dg=1.e−D4
Dzyurkevich+ 2013
a₀=0.1 μm
a =20 μm
Really Dead
Dead
Active
Dead
Θ−π/2
Radius [AU]
0.3
0.2
0.1
0.0
−0.1
−0.2
−0.3
10
100

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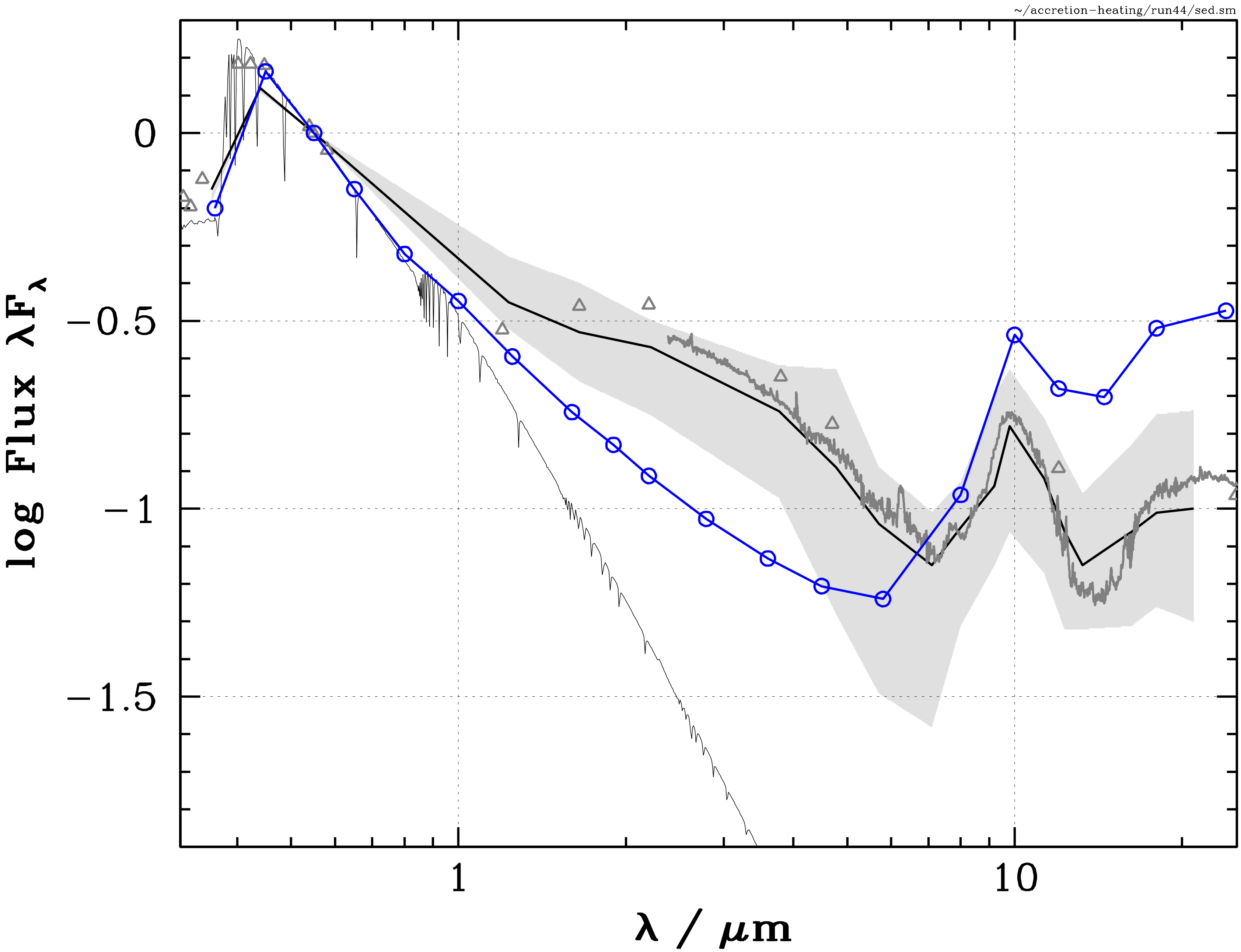
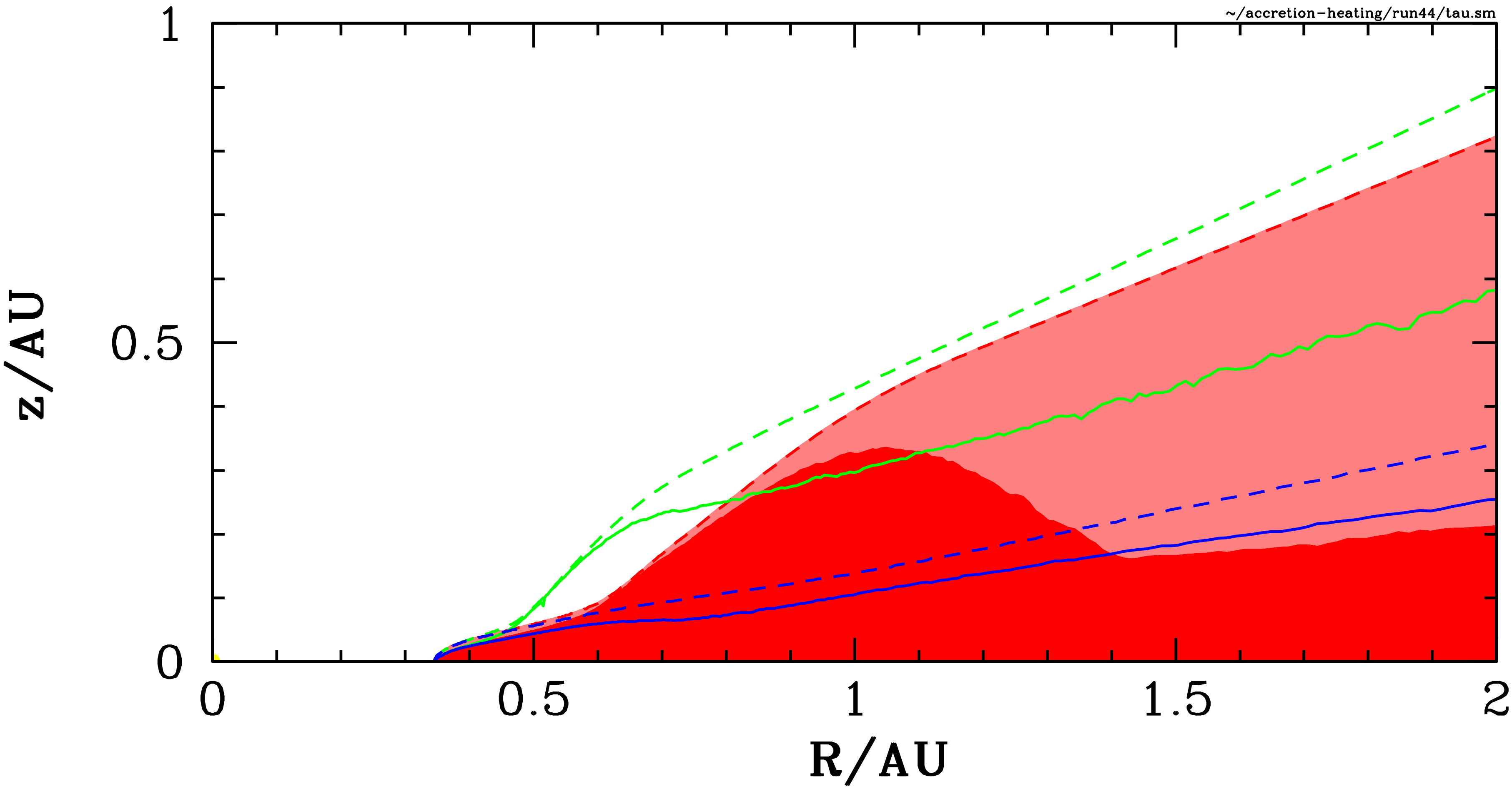
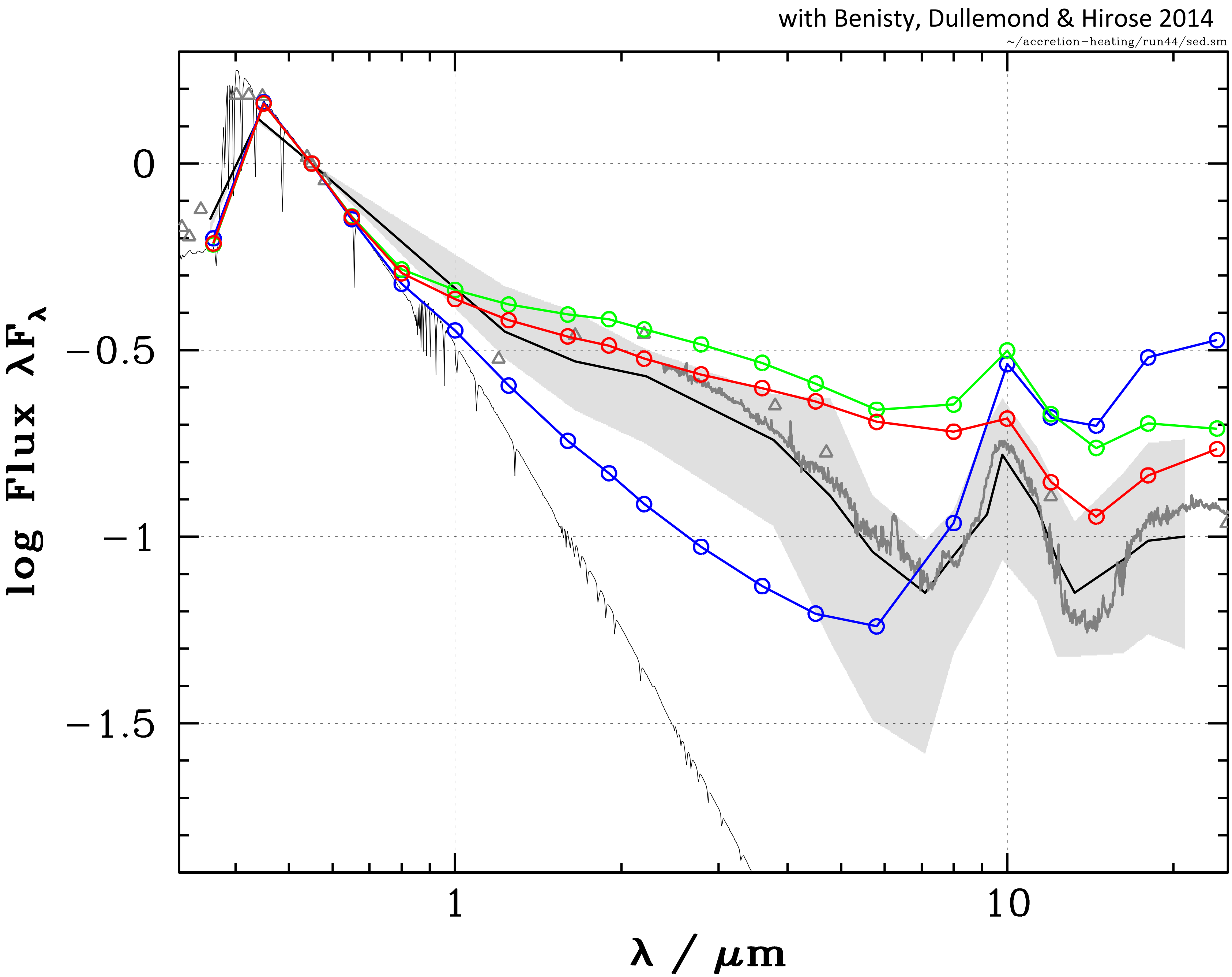
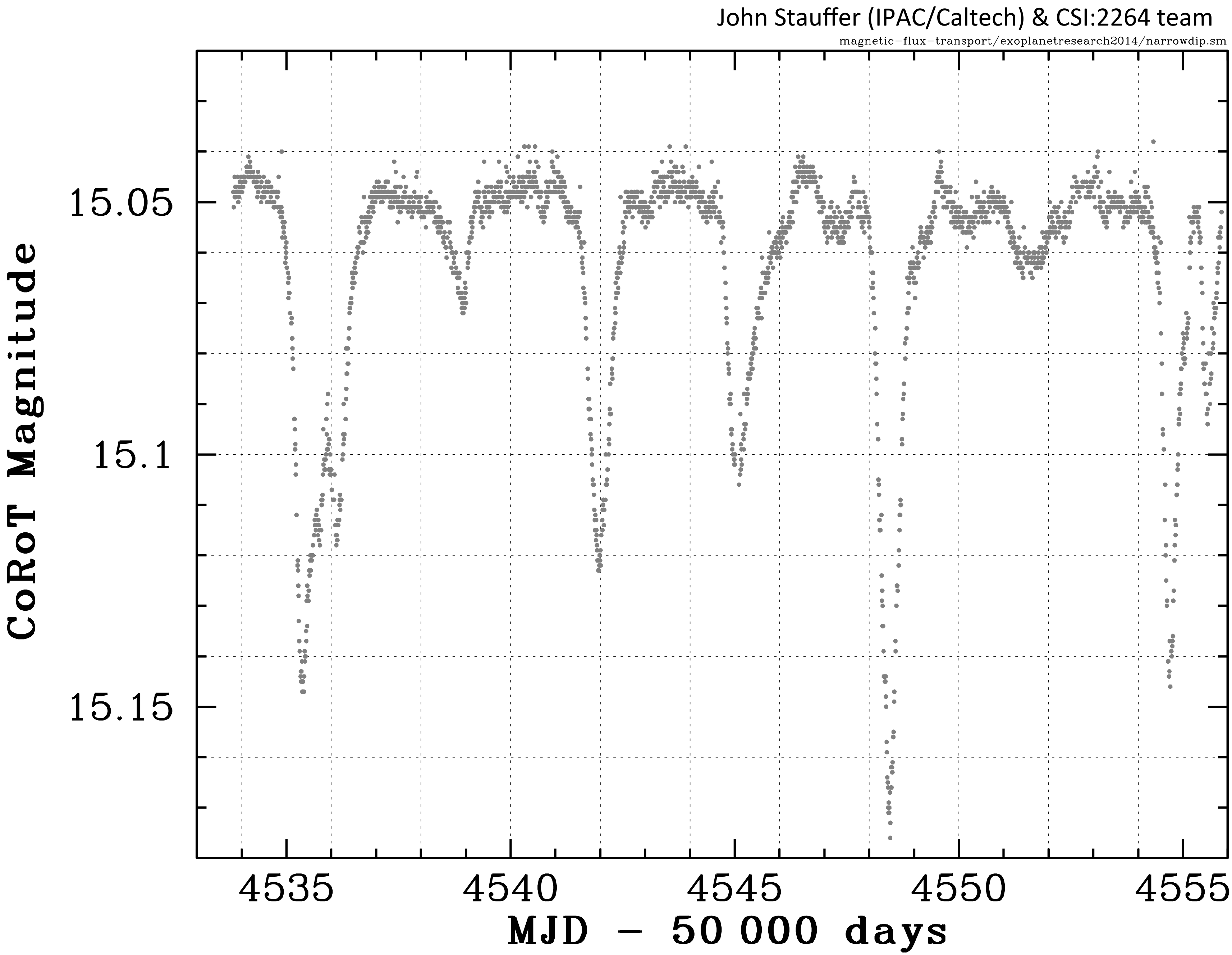
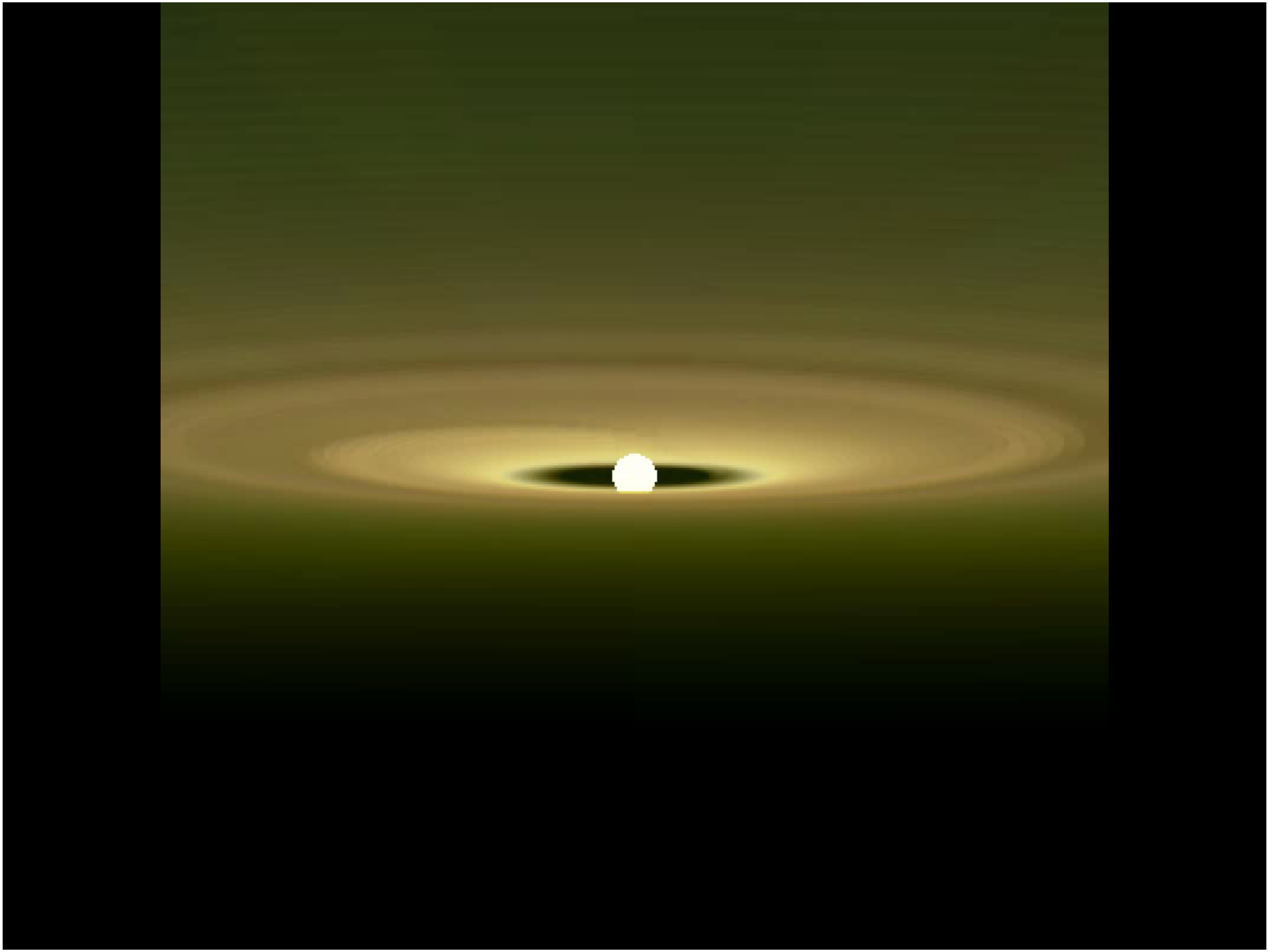
with Benisty, Dullemond & Hirose 2014

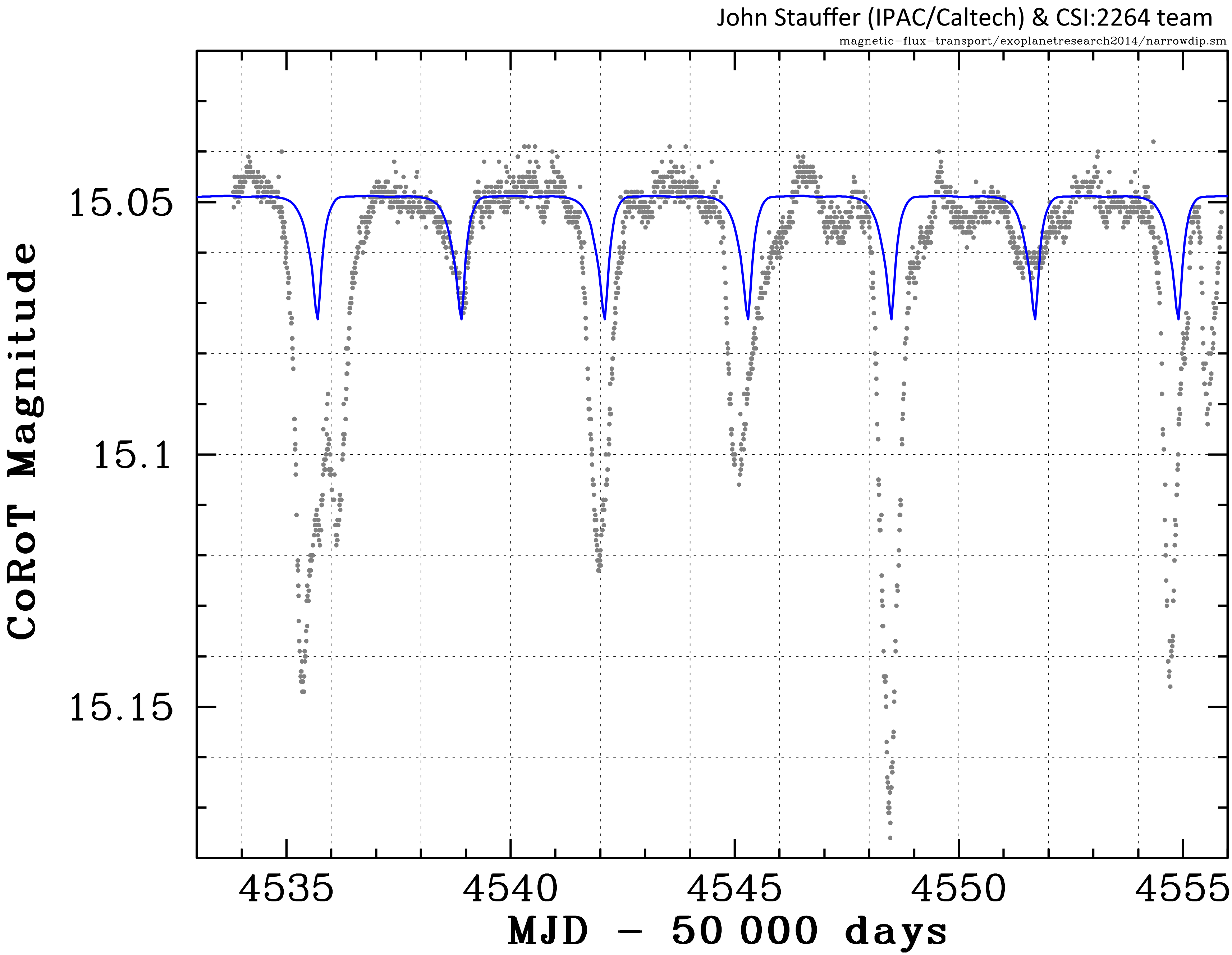


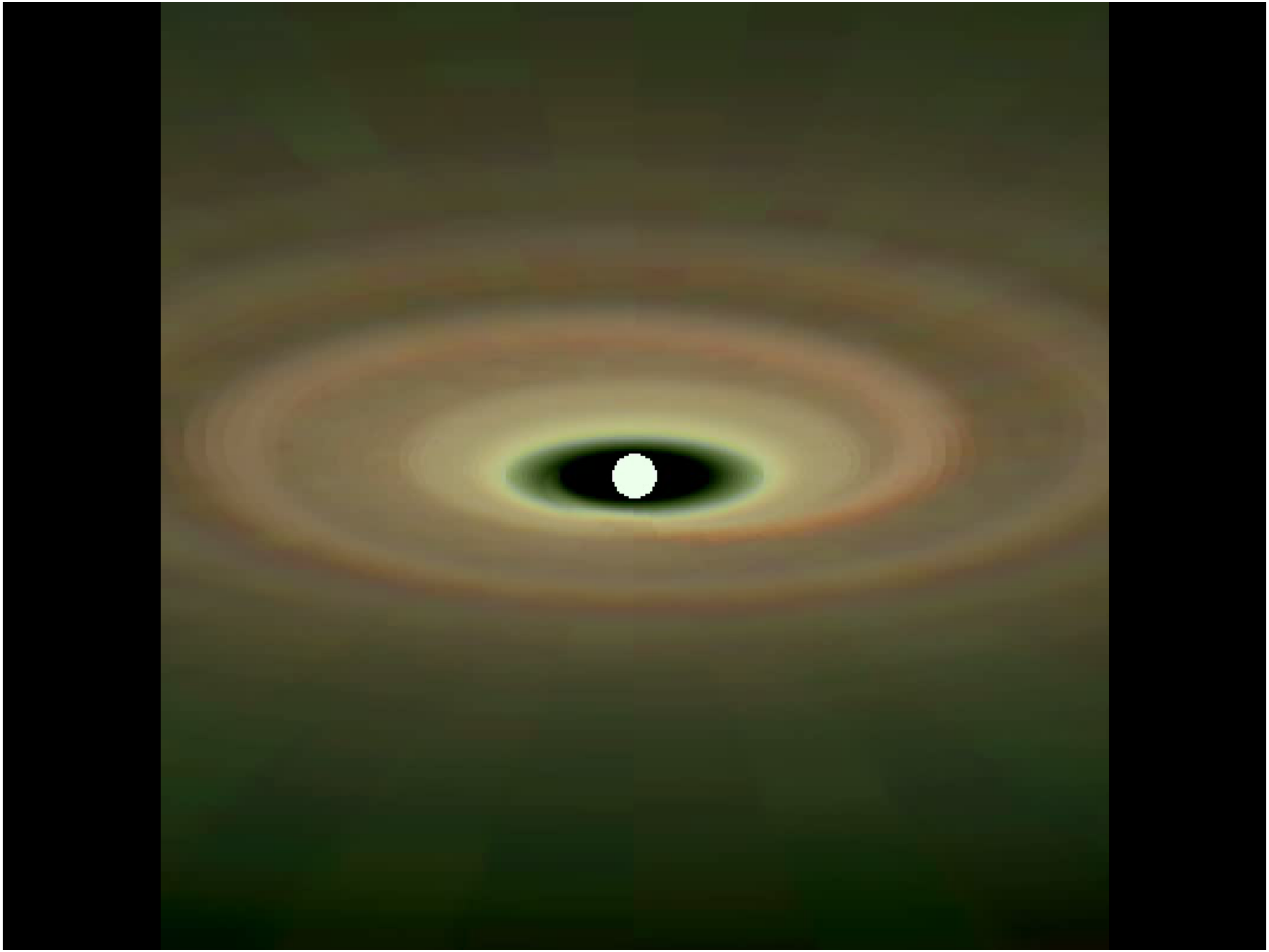

~/accretion-heating/run44/tau.sm
z/AU
R/AU
0
0.5
1
1.5
2
0
0.5
1


with Benisty, Dullemond & Hirose 2014
~/accretion-heating/run44/sed.sm
0
−0.5
−1
−1.5
1
10
log Flux λFλ
λ / μm


John Stauffer (IPAC/Caltech) & CSI:2264 team
magnetic-flux-transport/exoplanetresearch2014/narrowdip.sm
CoRoT Magnitude
15.05
15.1
15.15
4535
4540
4545
4550
4555
MJD − 50 000 days




John Stauffer (IPAC/Caltech) & CSI:2264 team
magnetic-flux-transport/exoplanetresearch2014/narrowdip.sm
CoRoT Magnitude
15.05
15.1
15.15
4535
4540
4545
4550
4555
MJD − 50 000 days



Outlook

1. Dust is suspended in protostellar disk atmospheres. Keeping it there requires stirring.
2. Few observations yet distinguish between stirring mechanisms. However, many disks' central regions appear thicker than hydrostatic support allows.
3. Magnetic forces can provide the extra support and the stirring if the conductivity is high enough.
4. Magnetic coupling is good in the hottest zone near the star, and in photo-ionized surface layers where the Hall and ambipolar terms are important.