Disk Dispersal by Star-driven Photoevaporation
Progress and Perspective

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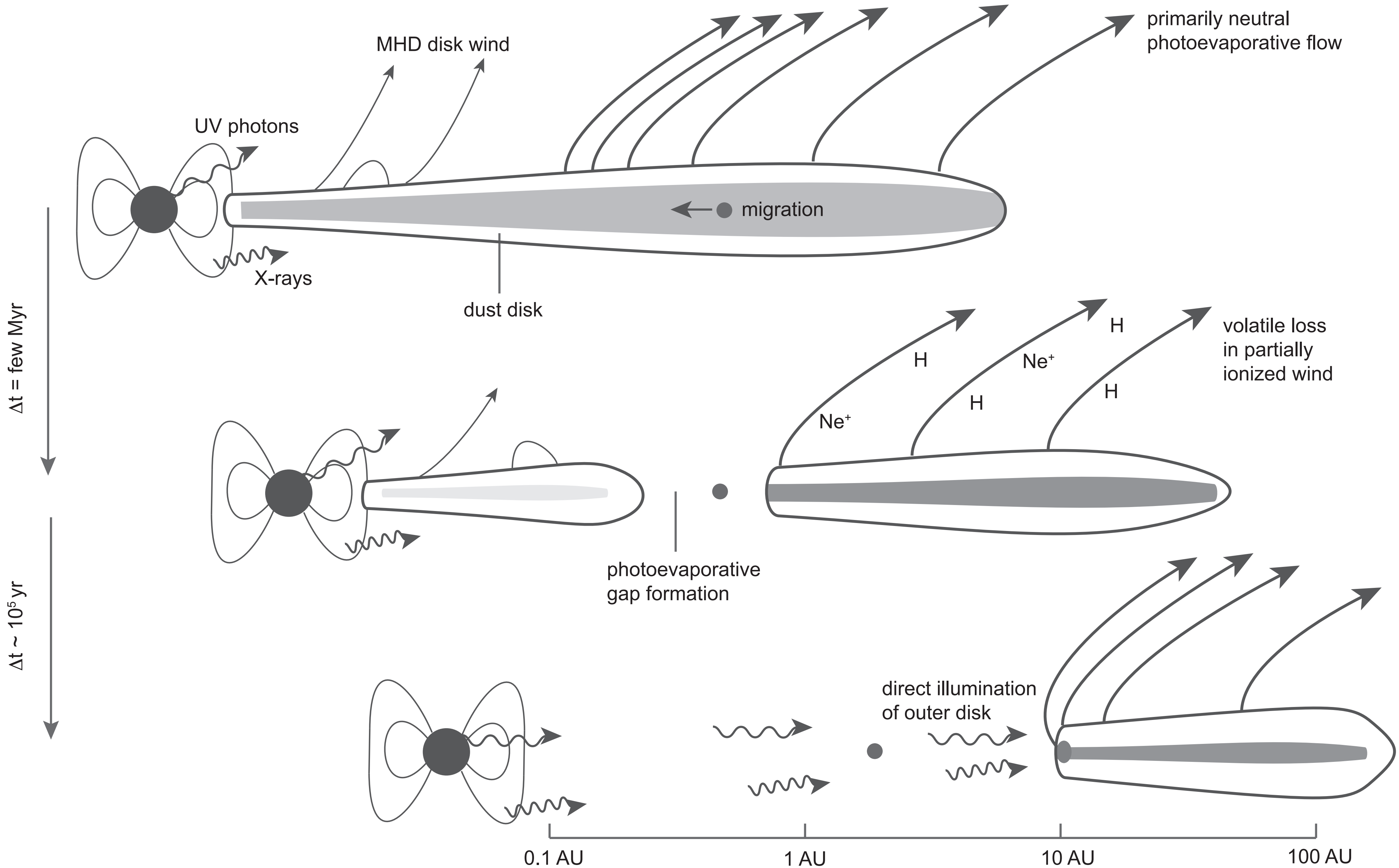
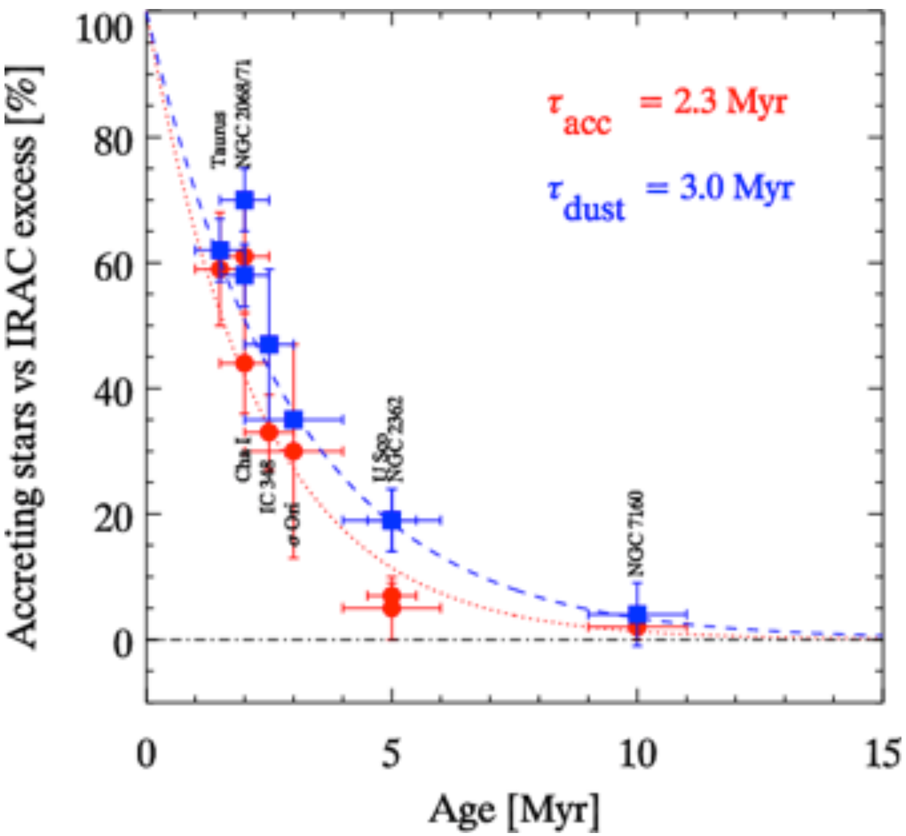
Schematic picture of disk evolution



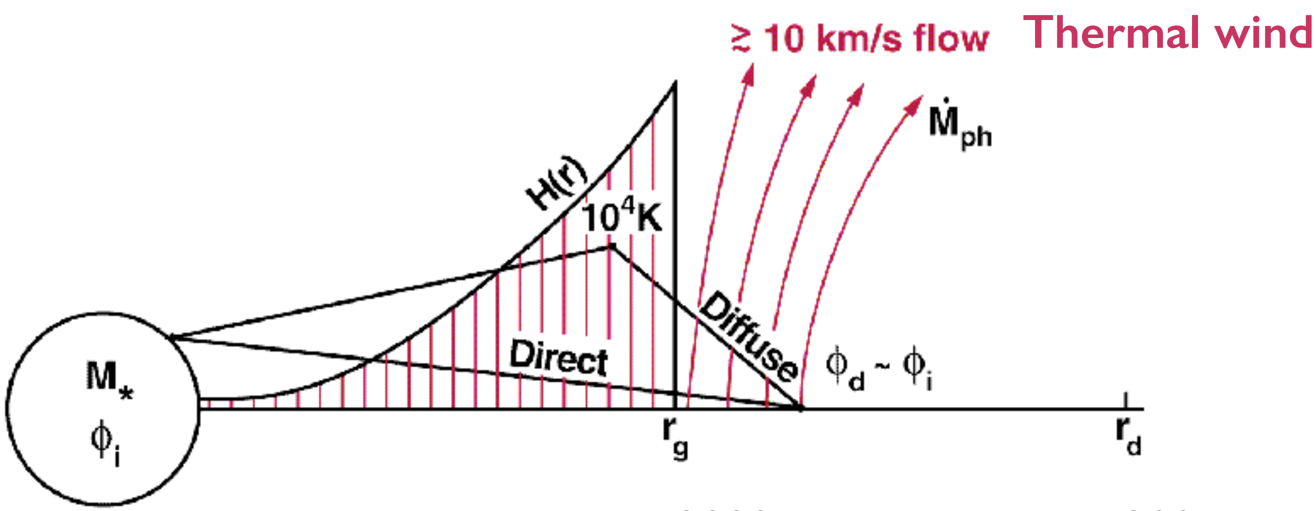
from Alexander, Pascucci, Andrews, Armitage, Cieza 2014 (PPVI, review chapter)

Photoevaporation ⇔ Two disk timescales

disk lifetime ~3Myr



Fedele et al. (2010)



$$R_g = \frac{GM_*}{c_s^2} \qquad R_c \sim R_g / 5$$

e.g. Hollenbach et al. 2000, Dullemond et al. 2007

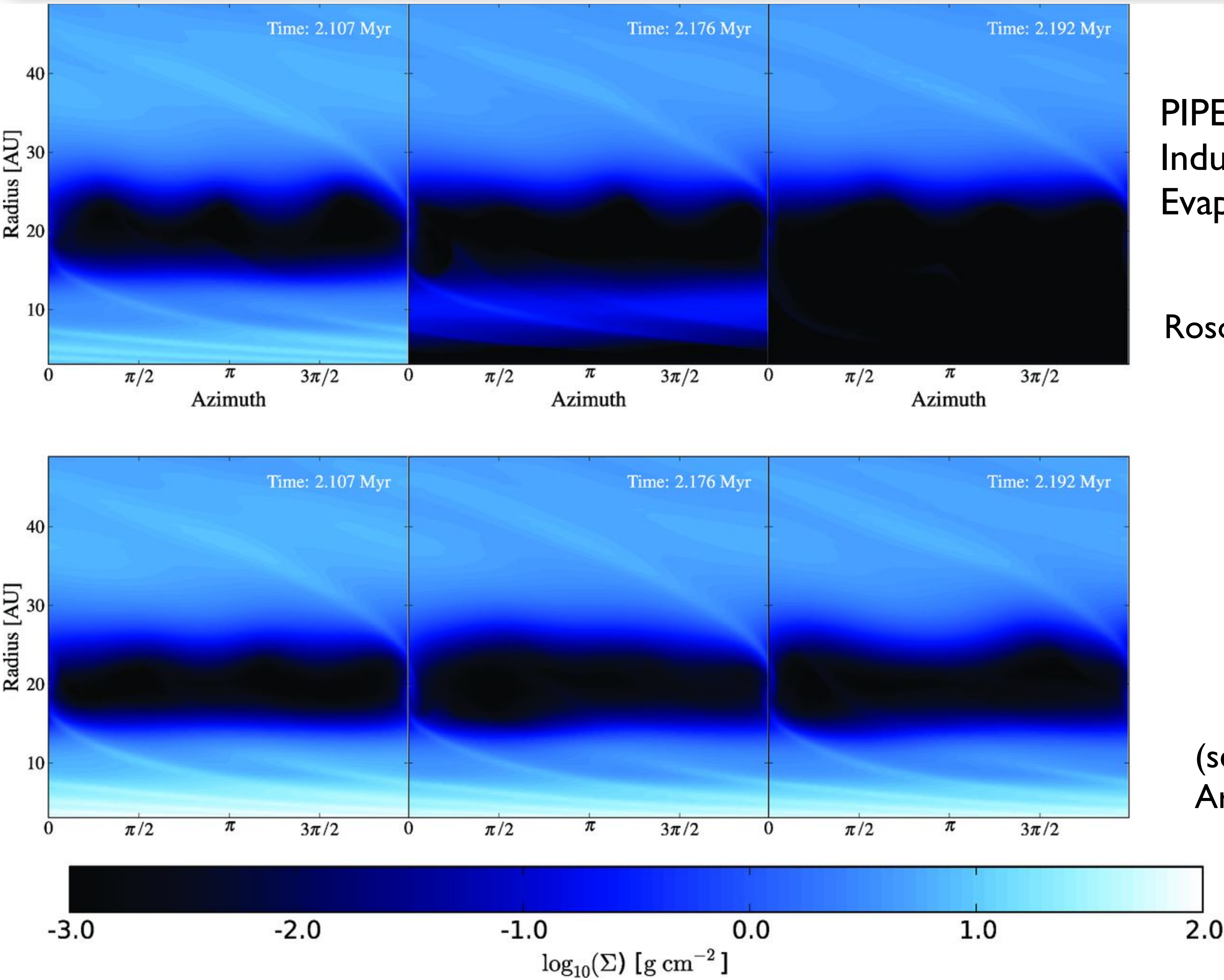
Disk photoevaporation and planets

Photoevaporation increases the dust-to-gas ratio and chemical enrichment of the protoplanetary disk (e.g. Throop & Bally 2005, Guillot & Hueso 2006, Gorti et al. 2015)

Coupling between planet formation and photoevaporation, e.g. transition disks (e.g. Alexander & Armitage 2009, Owen & Clarke 2012, Rosotti et al. 2014)

Deserts and pile-ups of giant planets near the gap opened by photoevaporation (e.g. Alexander & Pascucci 2012, Ercolano & Rosotti 2015)

Coupling between disk dispersal and planet formation



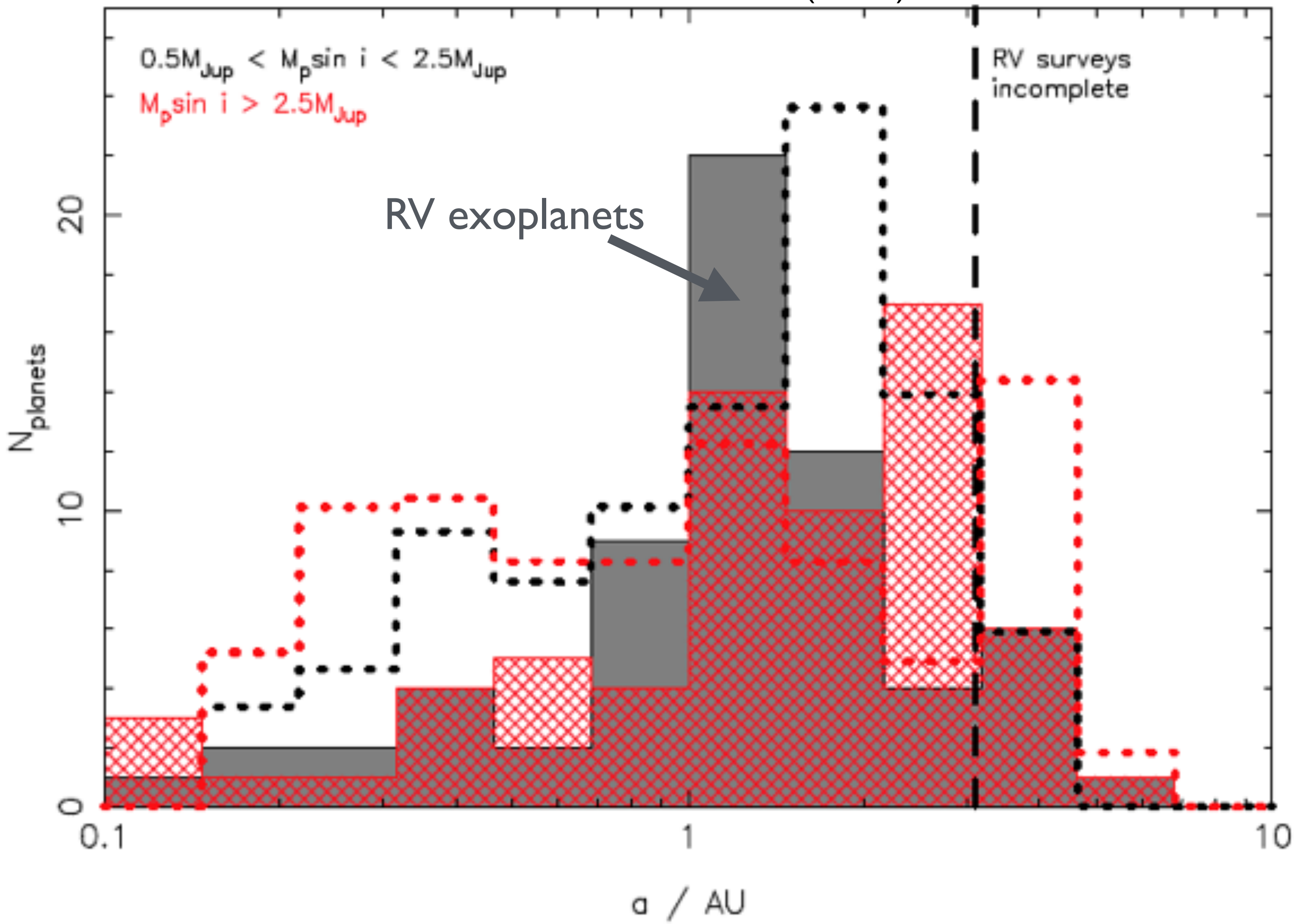
PIPE: Planet formation Induced Photo Evaporation

Rosotti et al. 2013

(see also Alexander & Armitage 2009)

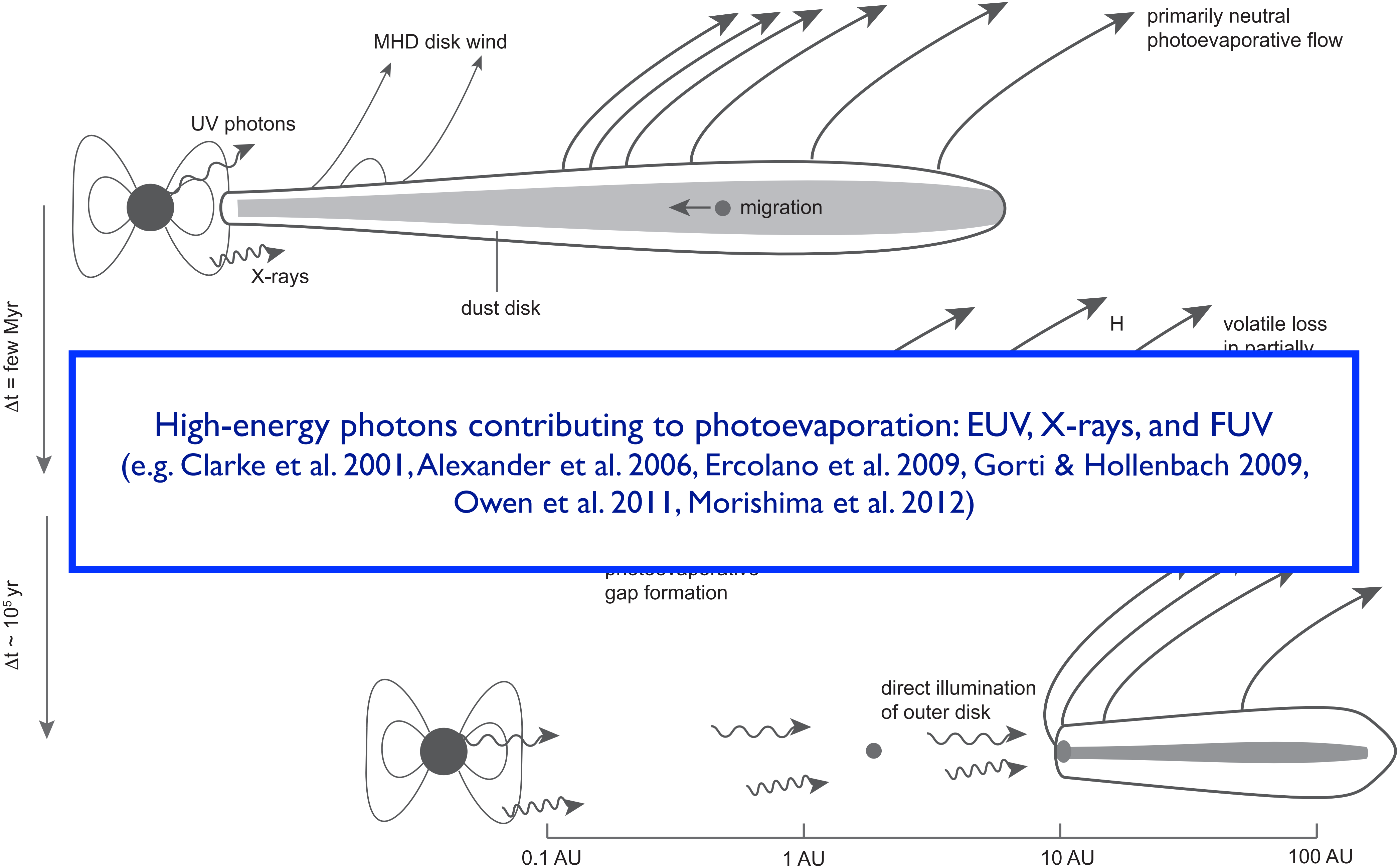
Deserts and pile-ups of giant planets

Alexander & Pascucci (2012)



See also Matsuyama et al. (2003), Hasegawa & Pudritz (2012), Moeckel & Armitage (2012), Ercolano & Rosotti (2015)

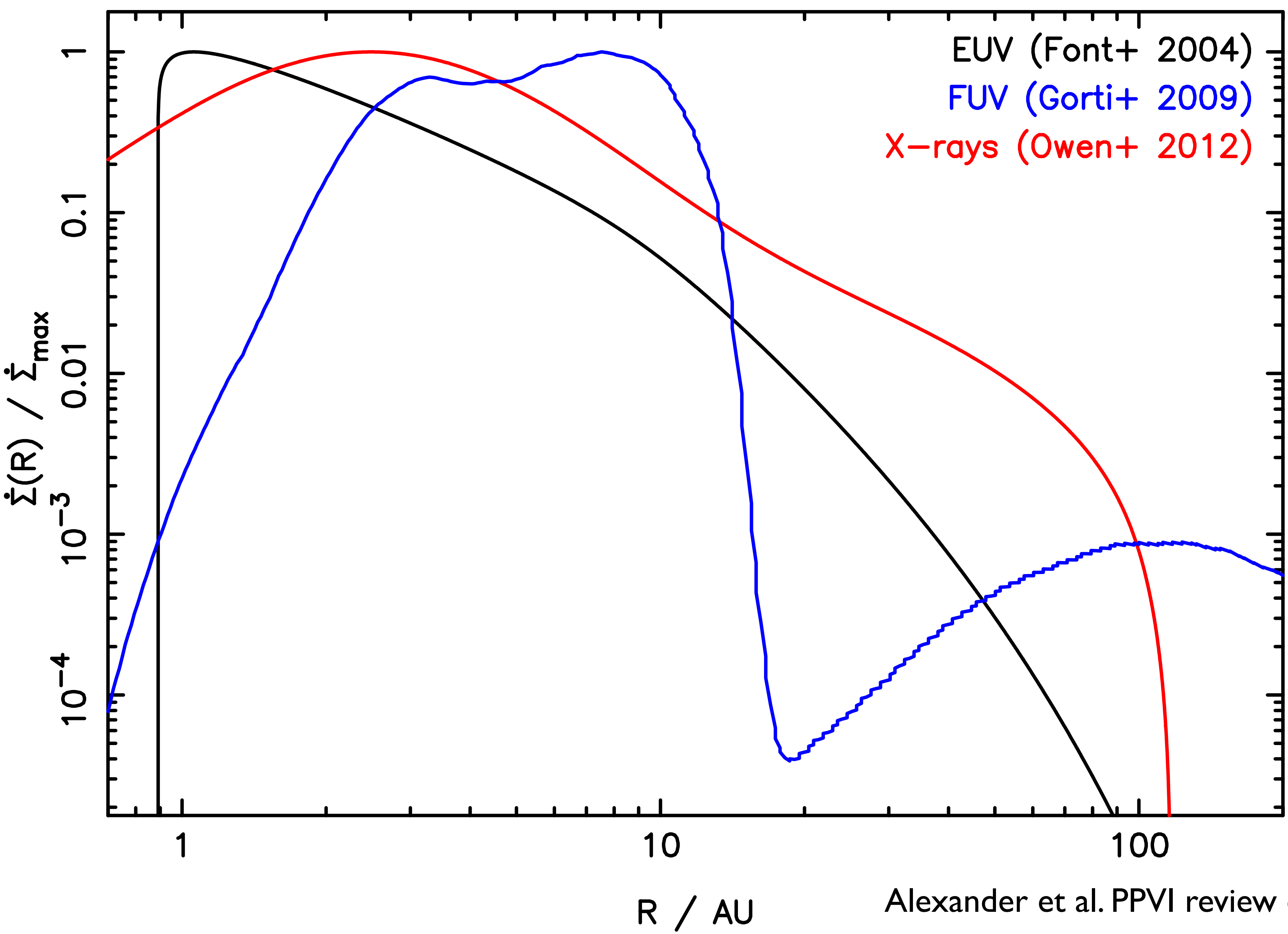
Schematic picture of disk evolution



High-energy photons contributing to photoevaporation: EUV, X-rays, and FUV
(e.g. Clarke et al. 2001, Alexander et al. 2006, Ercolano et al. 2009, Gorti & Hollenbach 2009, Owen et al. 2011, Morishima et al. 2012)

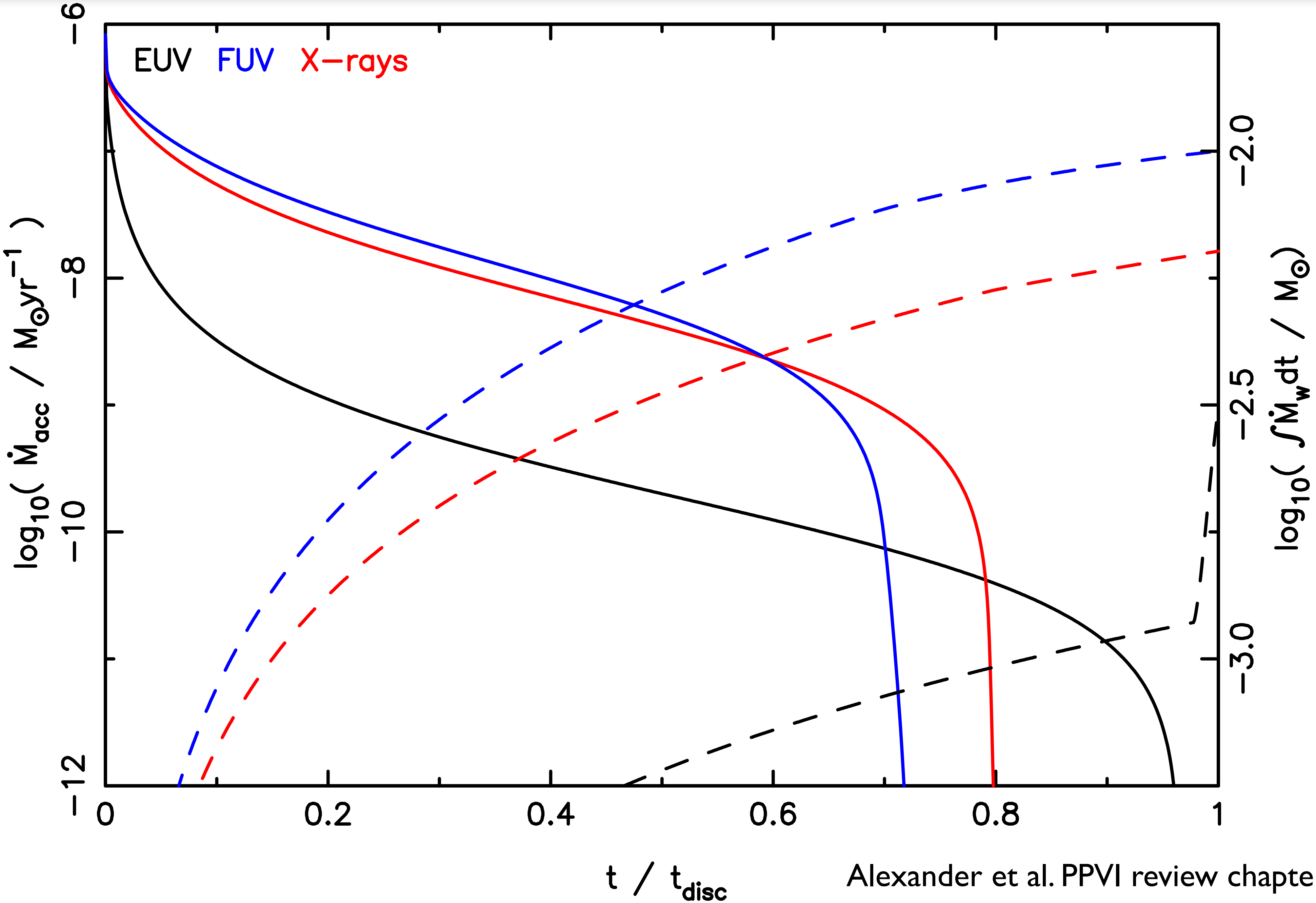
from Alexander, Pascucci, Andrews, Armitage, Cieza 2014 (PPVI, review chapter)

Normalized mass loss profiles



Alexander et al. PPVI review chapter

Stellar accretion rates and total mass lost



Alexander et al. PPVI review chapter

Main uncertainties in theoretical models

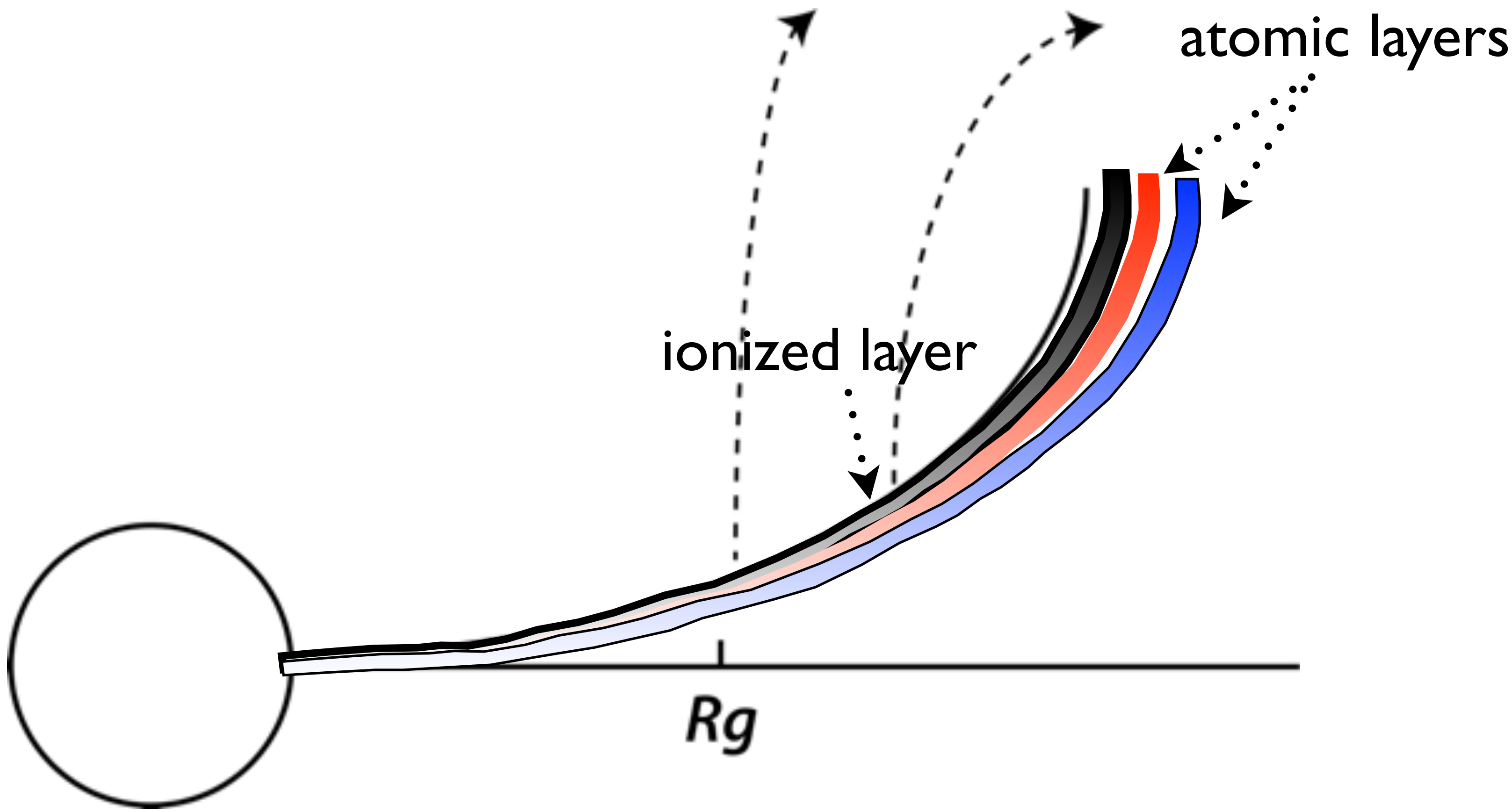
EUV: what is the stellar EUV flux impinging on the disk?

X-rays: amount and evolution of the soft X-ray component reaching the disk + sensitivity to disk chemistry and dust properties (e.g. settling)

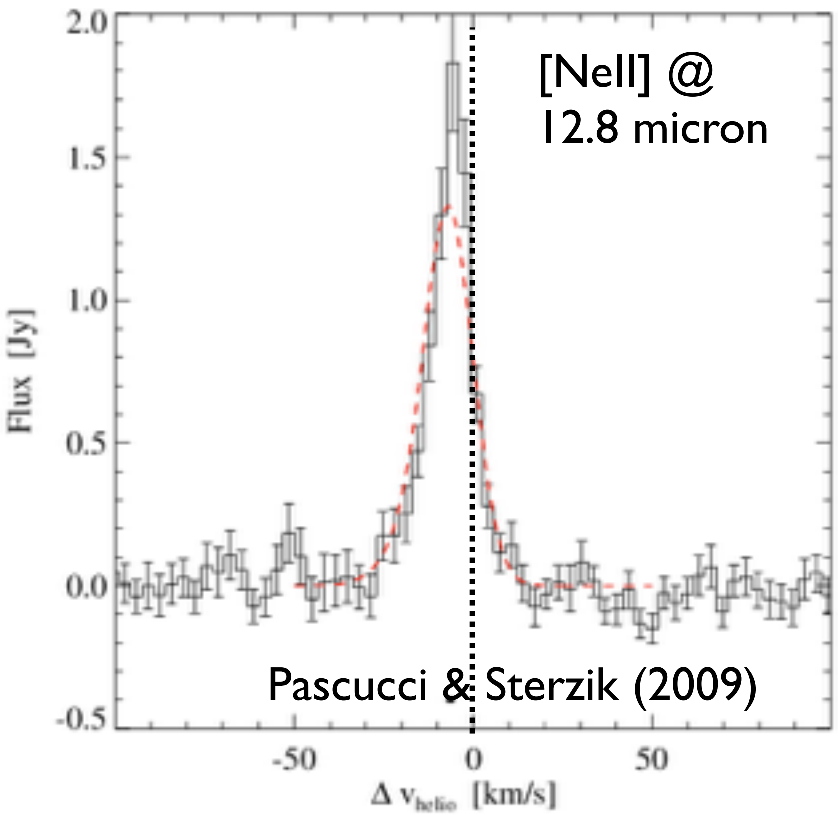
FUV: uncertainties in the FUV flux + sensitivity to dust properties (e.g. PAHs) + lack of hydrodynamics

Direct observations of photoevaporative winds

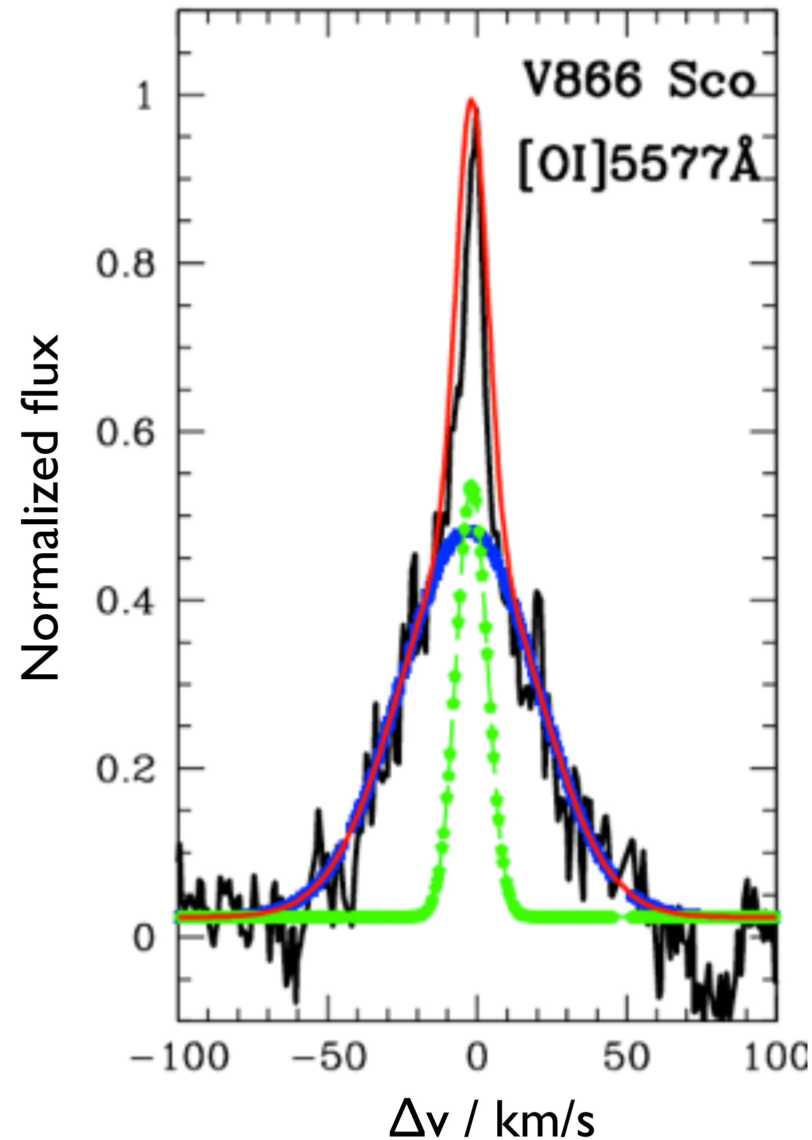
Direct evidence = flowing gas from the ionized and atomic layers

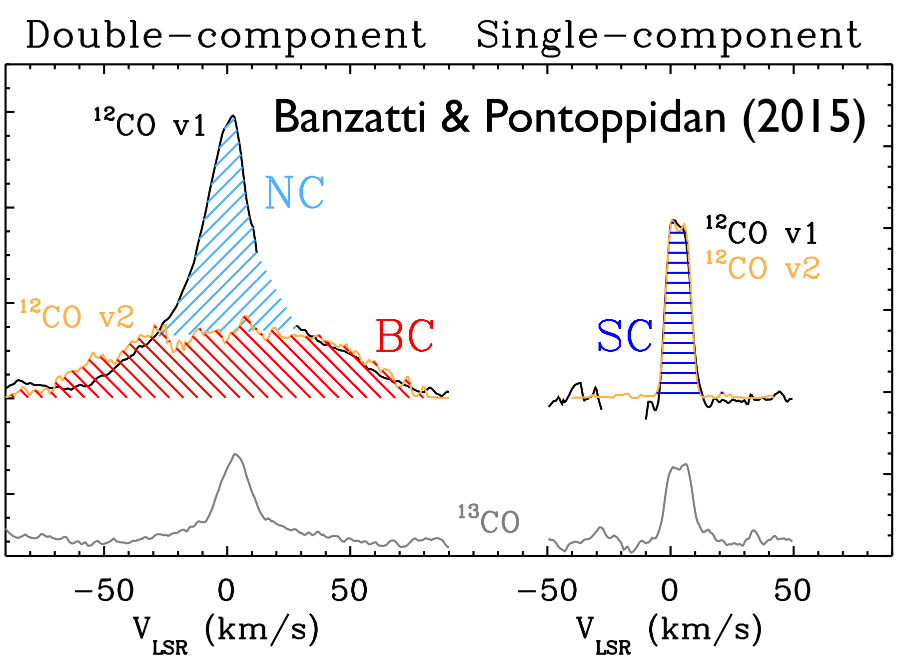


diagnostics predicted by: Font et al. 2004, ApJ, 607, 890; Alexander 2008, MNRAS, 391, L64; Hollenbach & Gorti 2009, ApJ, 703, 1203; Ercolano & Owen 2010, MNRAS 406, 1553



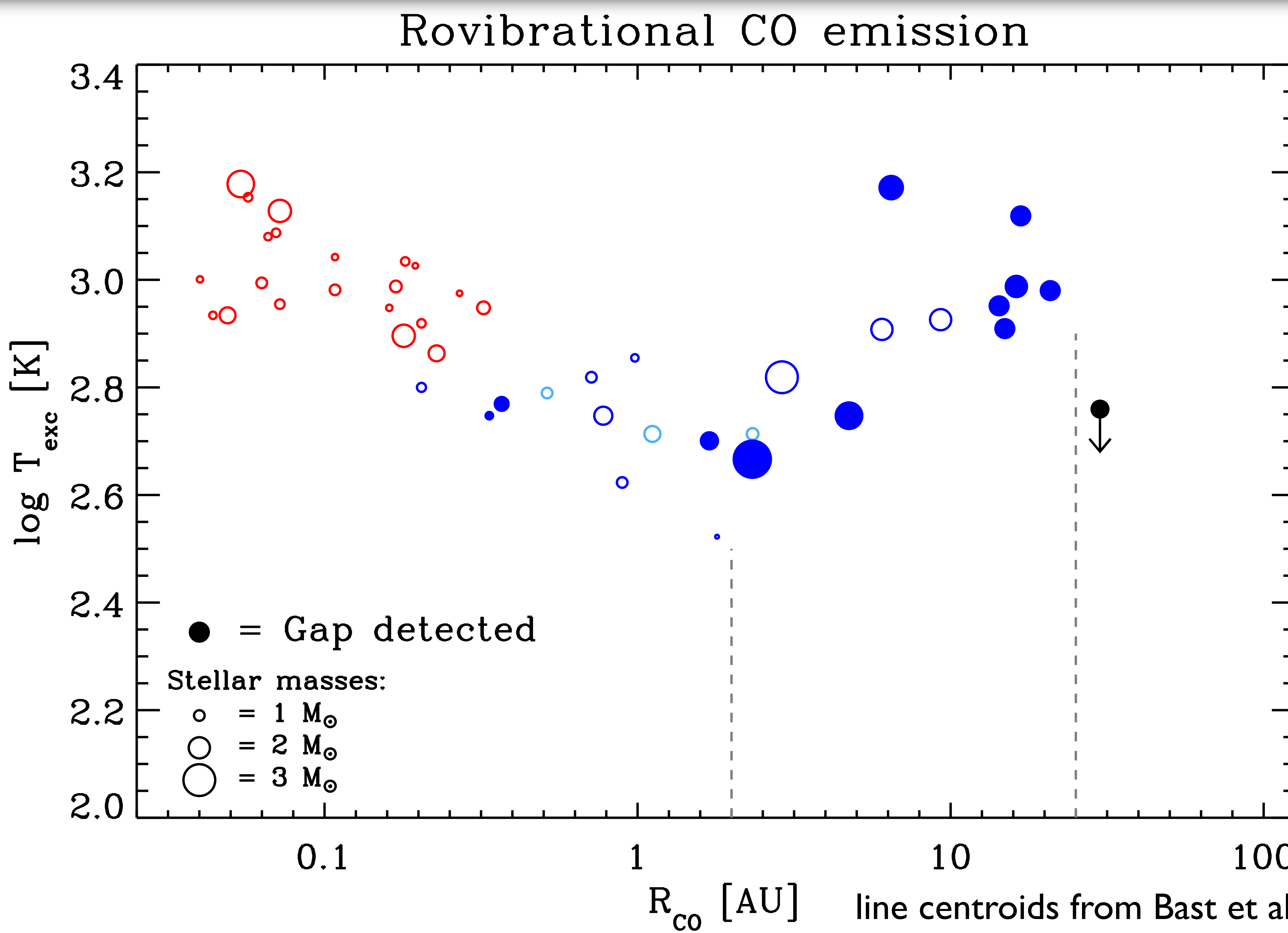
Rigliaco et al. (2013)





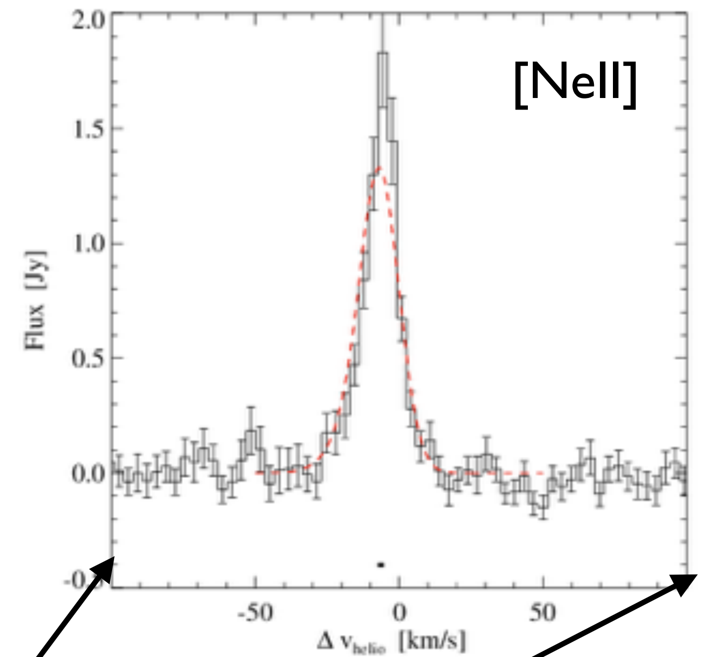
see talks from Rigliaco, Ercolano, and discussion led by Edwards

Tracing gas dispersal with CO (a molecular flow?)

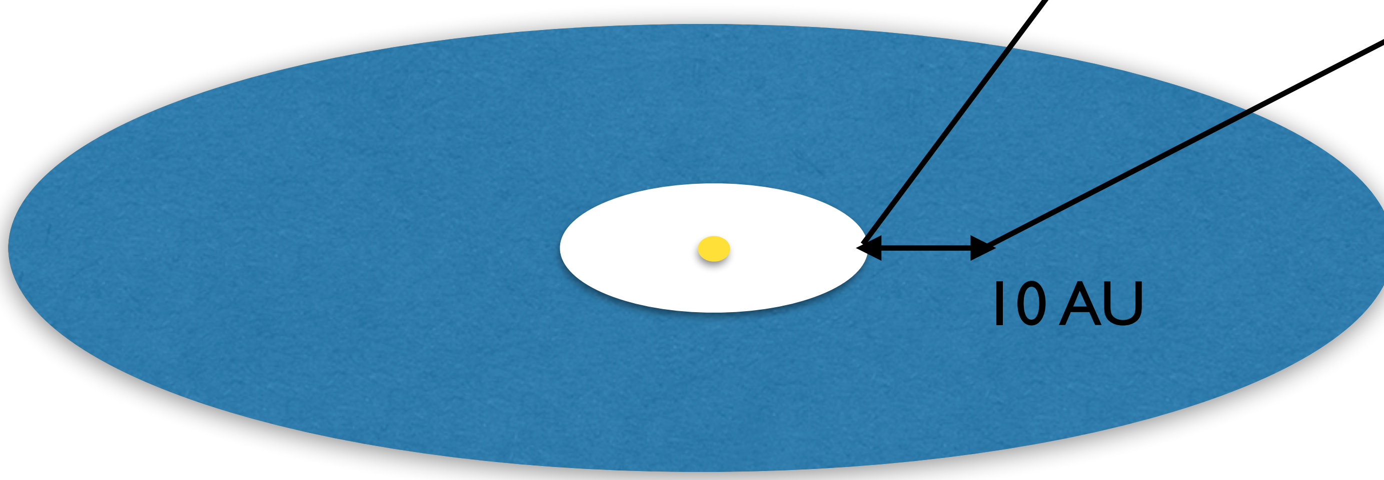


line centroids from Bast et al. (2011)

The location and extension of the wind

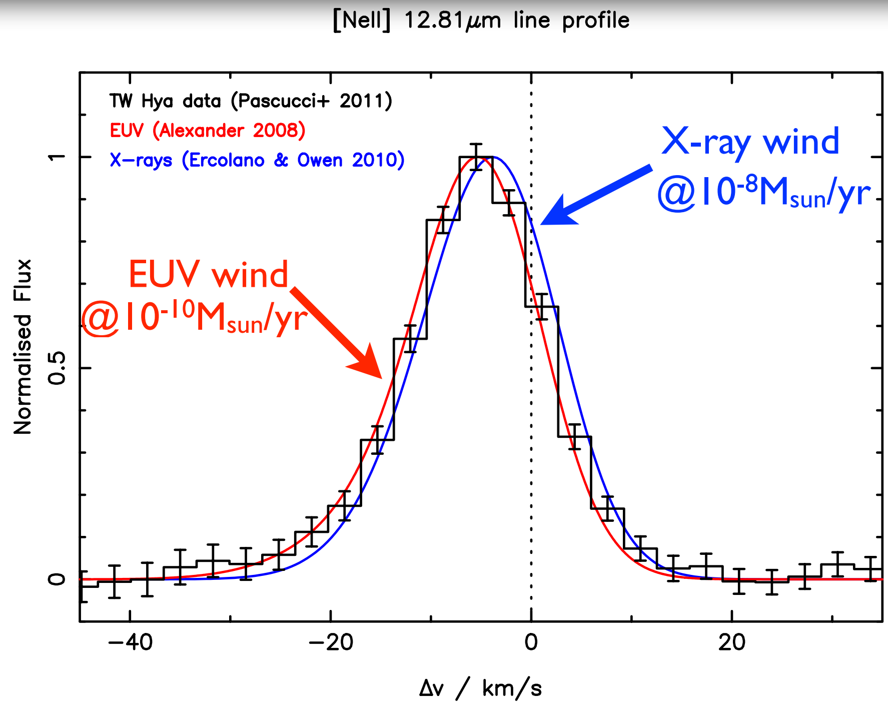


Most of the [NeII] wind emission from TWHya comes from beyond the dust inner cavity and extends out to 10AU in agreement with model predictions (i.e. inside R_g, Pascucci et al. 2011, ApJ, 736,13)



Schematic of the TWHya transition disk

Open questions

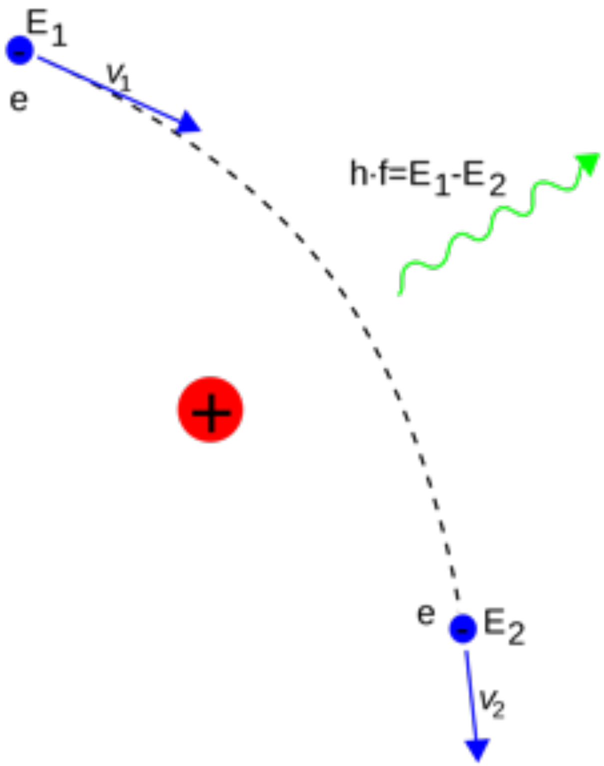


1. What is the mass loss rate?

2. Which stellar high-energy photons drive photoevaporation?

Φ_{EUV} must be larger than ~10^{42}phot/s for EUV alone to clear out protoplanetary material in the observed timescale (e.g. Alexander et al. 2006)

Free-free emission from an ionized disk surface



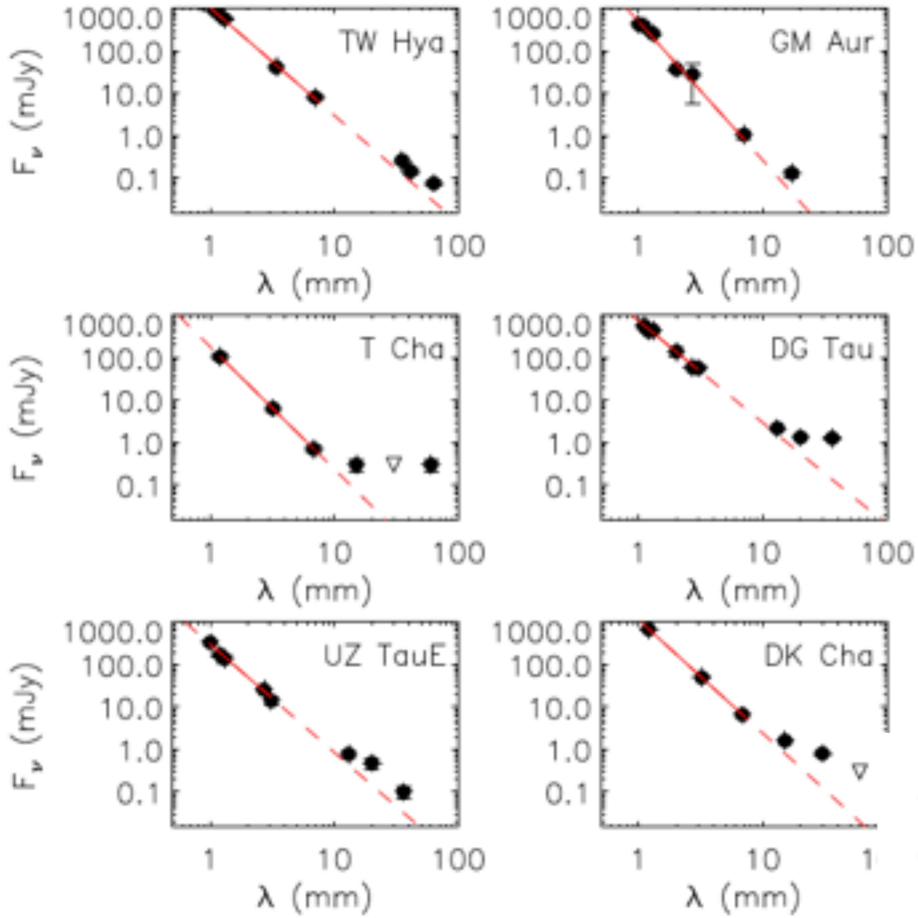
Free-free emission from the disk surface

$$F_{3.5\,\mathrm{cm}} = 2.9 \times 10^{-39} \left(\frac{51}{d}\right)^2 \Phi_{\mathrm{EUV}} \ \ (\mu\mathrm{Jy})$$

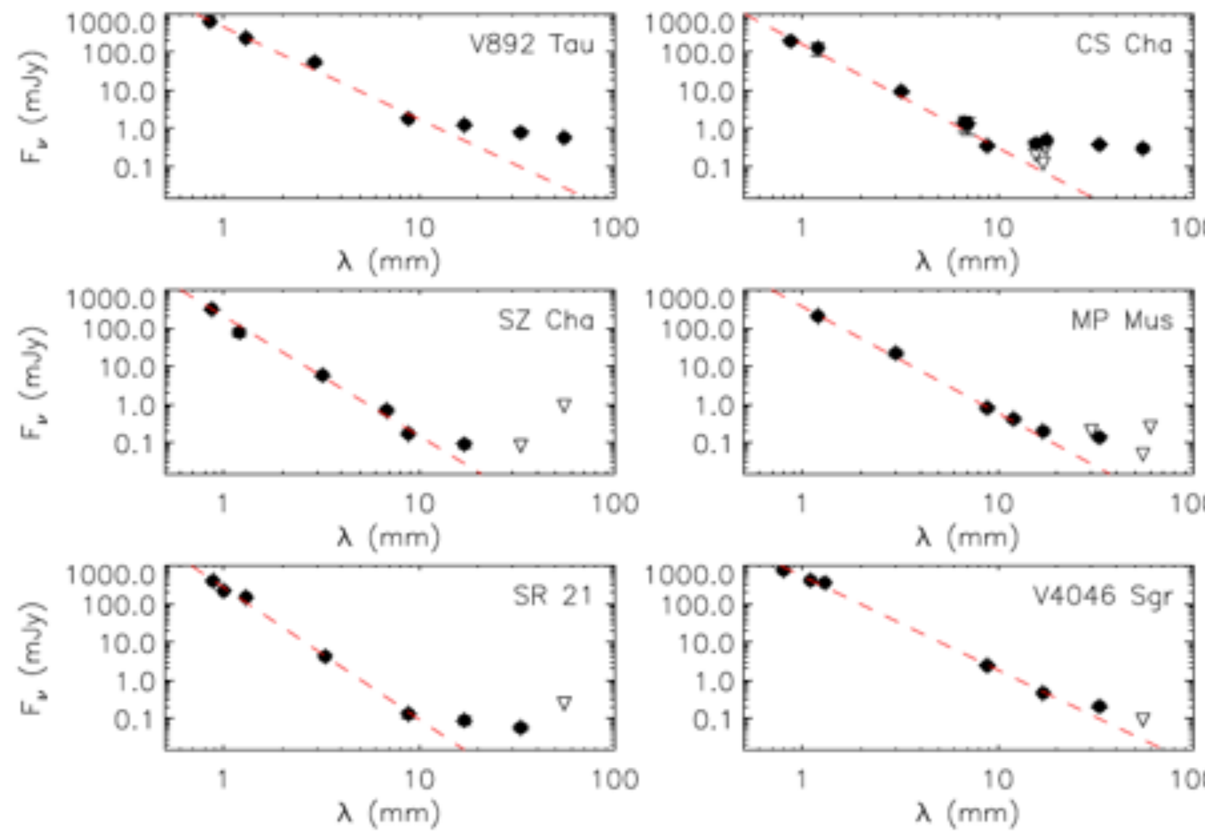
assuming T=10,000K see Pascucci, Gorti & Hollenbach (2012)
[see also Owen et al. 2013]

The free-free disk emission should be detectable with current facilities. It should appear as an excess emission on top of the dust thermal emission

Φ_{EUV} (from the star) = $10^{41} - 10^{44}\ \mathrm{s}^{-1}$ (e.g. Alexander et al. 2005)



new ATCA data



Literature (VLA)

Pascucci et al. (2014)

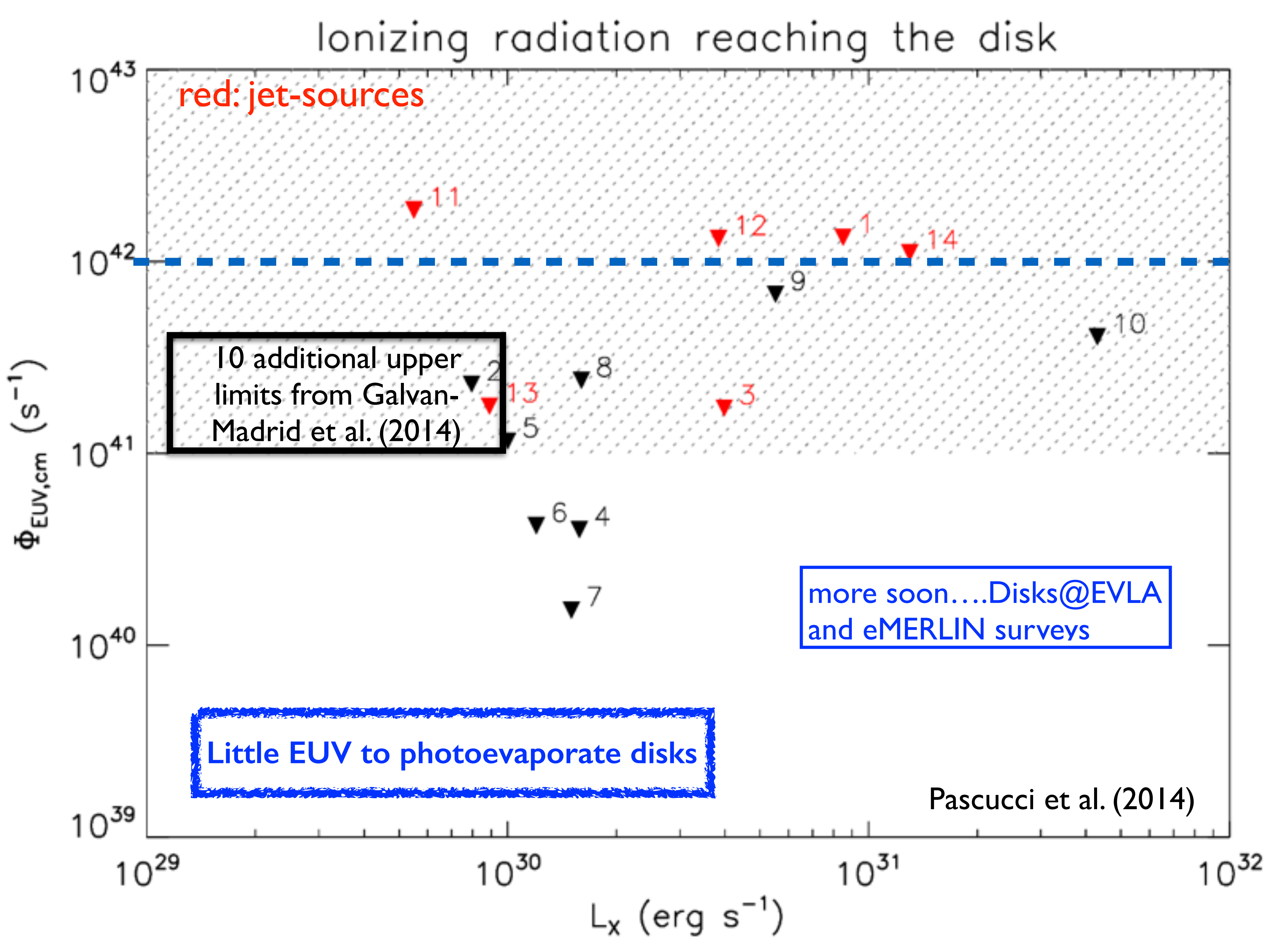
Mechanisms producing cm emission

– Free-free from a fully or partially ionized disk (e.g. Pascucci et al. 2012)

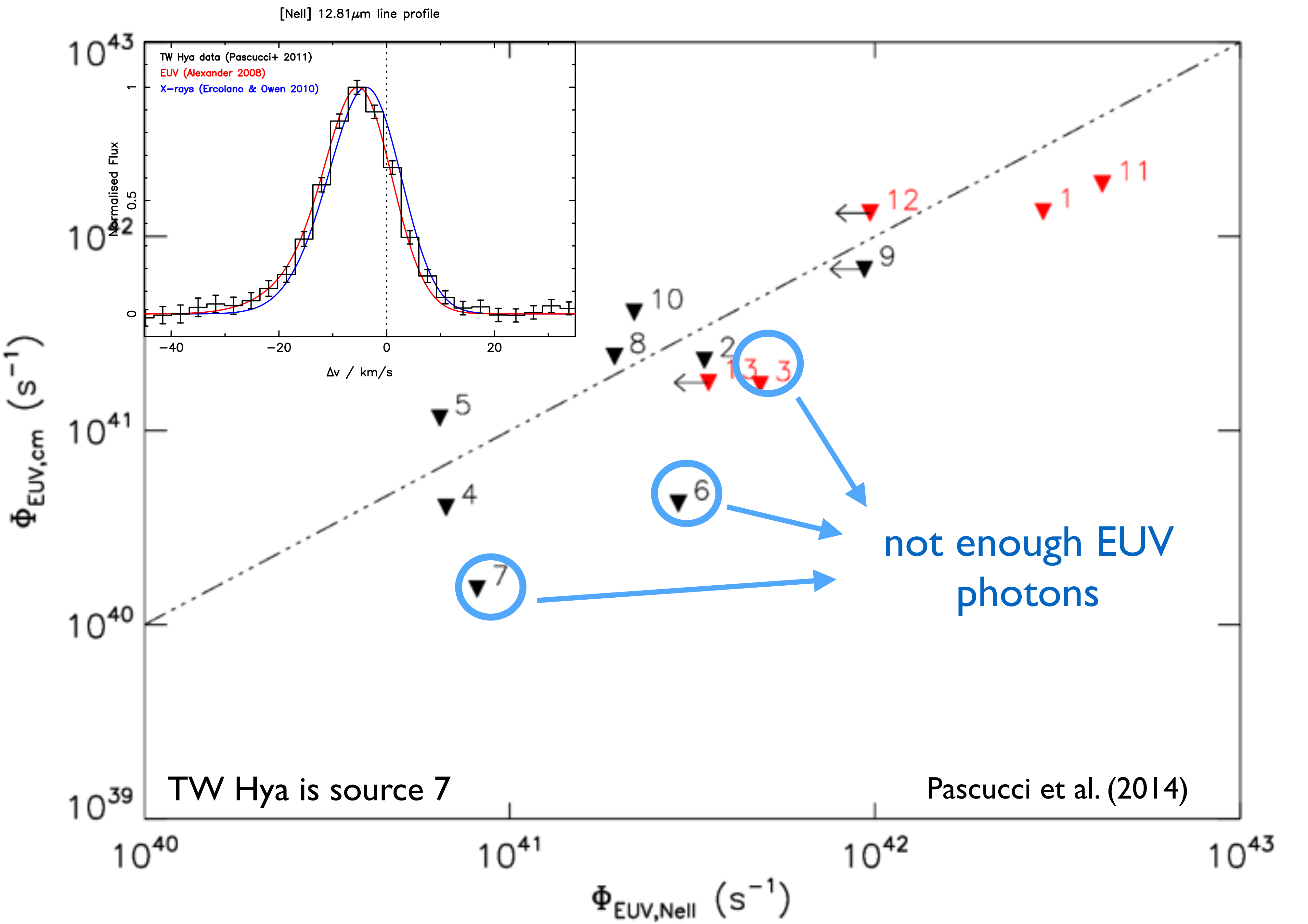
– Free-free from ionized jets (Class I and II, e.g. Anglada et al. 1998)

– (Gyro)-Synchrotron emission (stellar magnetic fields, e.g. Dzib et al. 2013)

– Emission from dust grains (e.g. Wilner et al. 2005, Rafikov et al. 2006)


Ionizing radiation reaching the disk
red: jet-sources
10 additional upper limits from Galvan-Madrid et al. (2014)
more soon….Disks@EVLA and eMERLIN surveys
Little EUV to photoevaporate disks
Pascucci et al. (2014)
$\Phi_{EUV,cm}$ (s^{-1})
L_X (erg s^{-1})
10^{43}
10^{42}
10^{41}
10^{40}
10^{39}
10^{29}
10^{30}
10^{31}
10^{32}
11
12
1
14
9
10
2
13
8
3
5
6
4
7

[NeII] traces the partially ionized disk layer → mass loss rates > $10^{-10} M_{sun}/yr$



Key Points

- Theory predicts that protoplanetary disk evolution on ~Myr timescales is mainly driven by accretion, but photoevaporative winds may drive significant mass loss

- Theory predicts that photoevaporation affects planet formation *and* planetary architectures

- Slow winds consistent with photoevaporative winds are directly detected

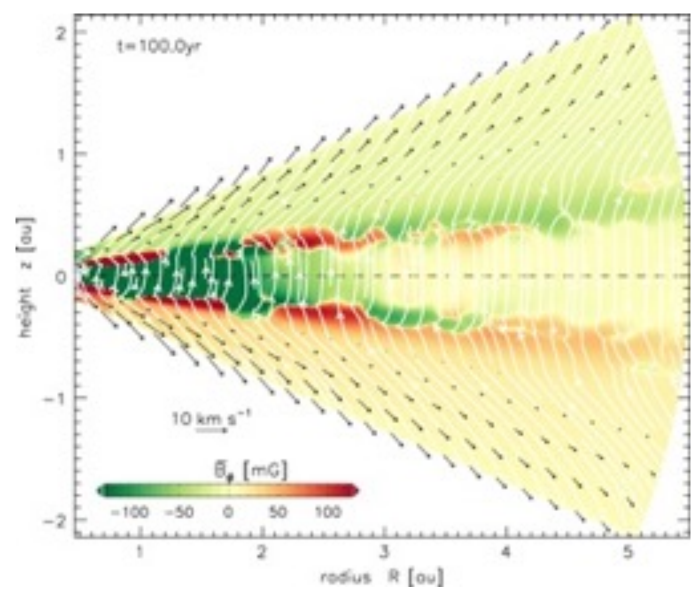
- Stellar high-energy photons (other than EUV) dominate photoevaporation

My wish list

1. Observations: a) Have a statistically significant sample of disks with multiple diagnostics of photoevaporation; b) Image a photoevaporative wind

2. Photoevaporation theory: we need diagnostics to distinguish X-rays vs FUV driven winds

3. MHD theory: we need predictions and diagnostics to clearly distinguish MHD from photoevaporative winds



Gressel et al. (2015)