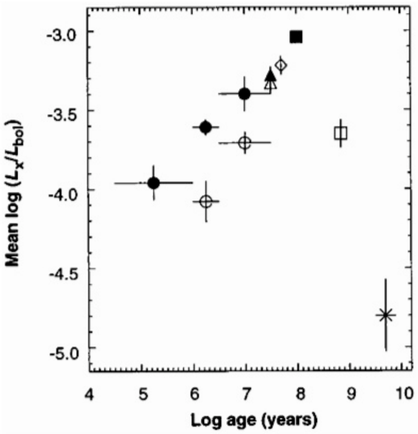

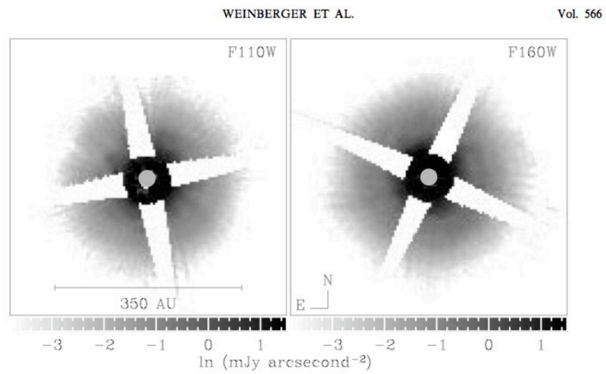

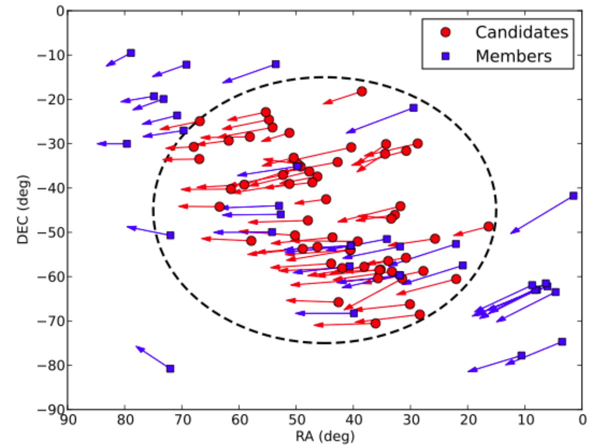

Nearby Young Moving Groups*
and Their (Rare!) Protoplanetary Disks**

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and
School of Physics & Astronomy
Director, Laboratory for Multiwavelength Astrophysics

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** Adapted from invited mini-talk at ``Beta Pic: Thirty Years of Debris Disk Studies'' (Paris, Sept. 2014)…also see reviews by, e.g., de la Reza et al. (2001, in "Young Stars Near Earth" proceedings), Zuckerman & Song (2004, Ann. Rev. A&A), Torres et al. (2008, in "Handbook of Star Forming Regions")*
*** Adapted from contributed talks at "15 Years of Chandra" (Cambridge MA, Nov. 2014) and Jan. 2015 AAS meeting*

The story of young stars near Earth begins with *TW Hya:*

classical T Tauri star without a birthplace

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TW Hya: a T Tauri star far from any dark cloud*

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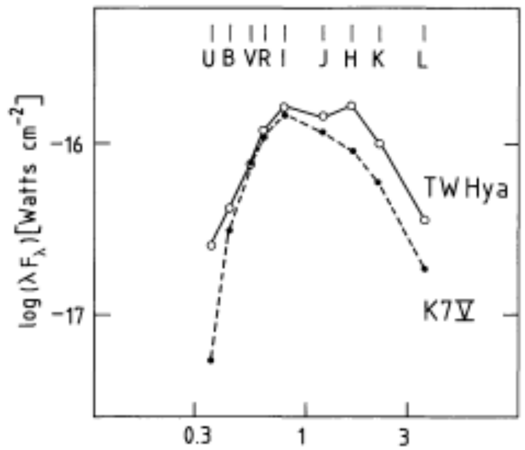
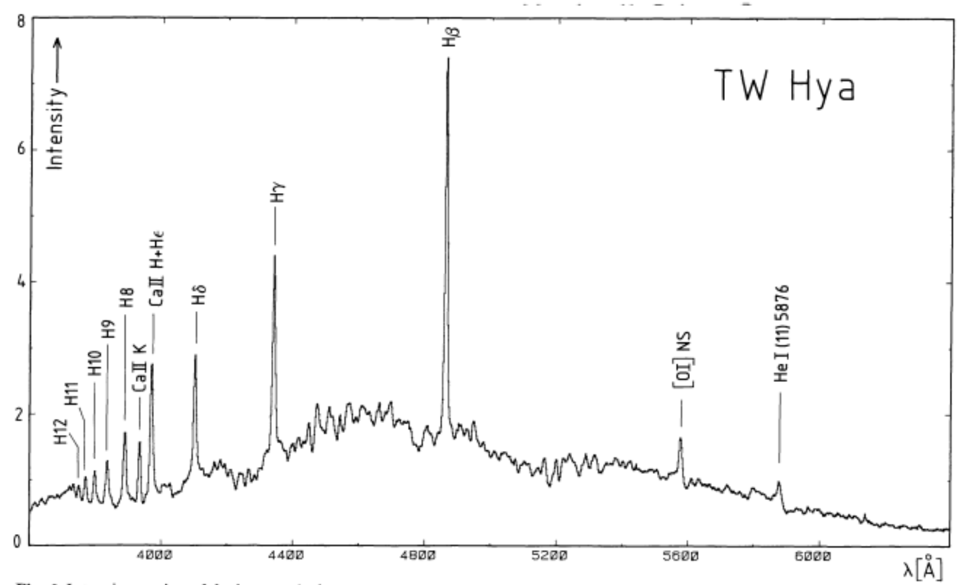
Received October 22, accepted December 14, 1982



Henize (1976), Herbig (1978), and Rucinski & Krautter (1983) share credit for putting this seminal nearby, young star/ disk system "on the map"

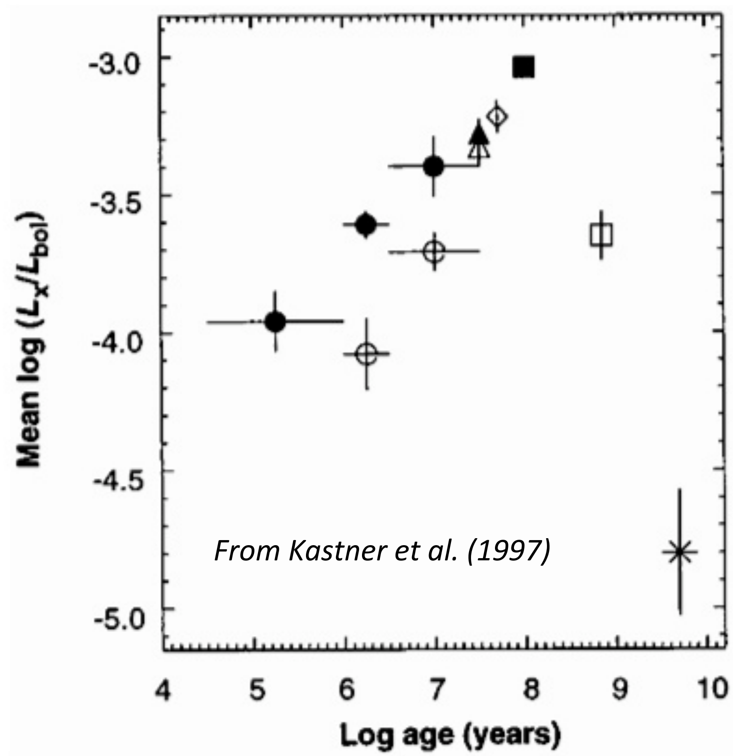


"Isolated T Tauri stars"

- de la Reza et al. (1989, ApJL) and Gregorio-Hetem et al. (1992 AJ), combining IRAS excesses w/ Li measurements, identify a handful of young stars in the general vicinity of TW Hya
  - Are these 5 stars runaways from some cloud, or were they formed in situ from a low-mass cloud?
  - How old are they?
  - Are they nearby, as suggested by their high galactic latitudes?

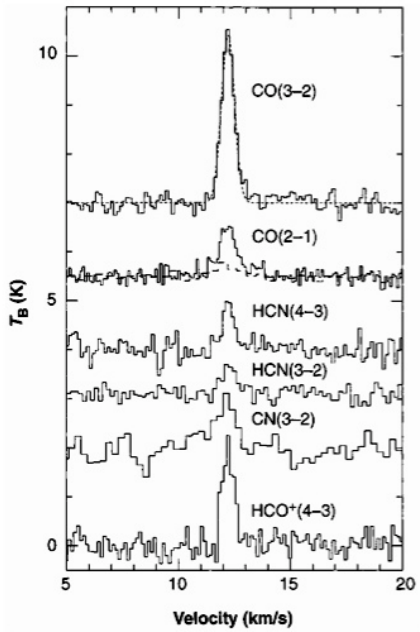
The identification of the TW Hya Association:
The "nearest [known] region of recent star formation"

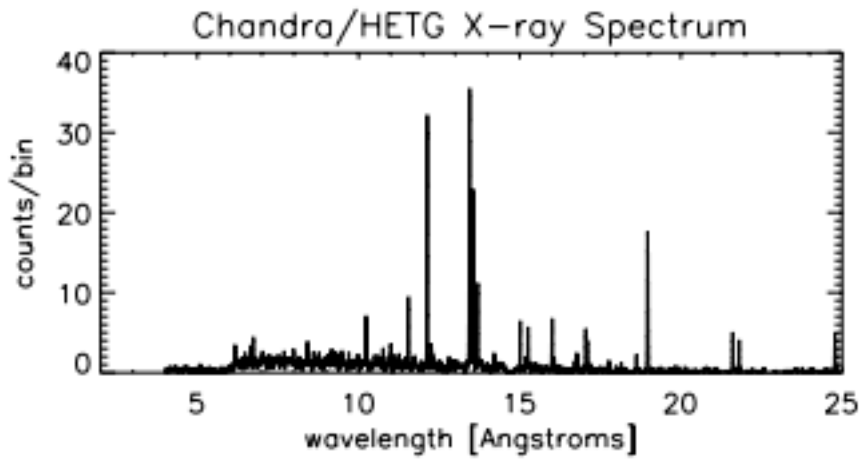
- RASS X-ray data demonstrates these 5 stars are indeed young & nearby (Kastner et al. 1997, Science)
  - Evidence that all 5 are near peak L_X/L_{bol} for K&M stars
    - => not as young as cloud-embedded TTS
    - yet have strong Li
  - => age constrained at ~10-20 Myr
- D estimates then follow
  - all 5 are all ~50 pc distant
  - Hipparcos confirms D's of ~50 pc to TW Hya & HD 98800
- Over the next 10+ years, the candidate membership of the TWA would increase to >30 stars, and age estimates would converge on ~8 Myr…



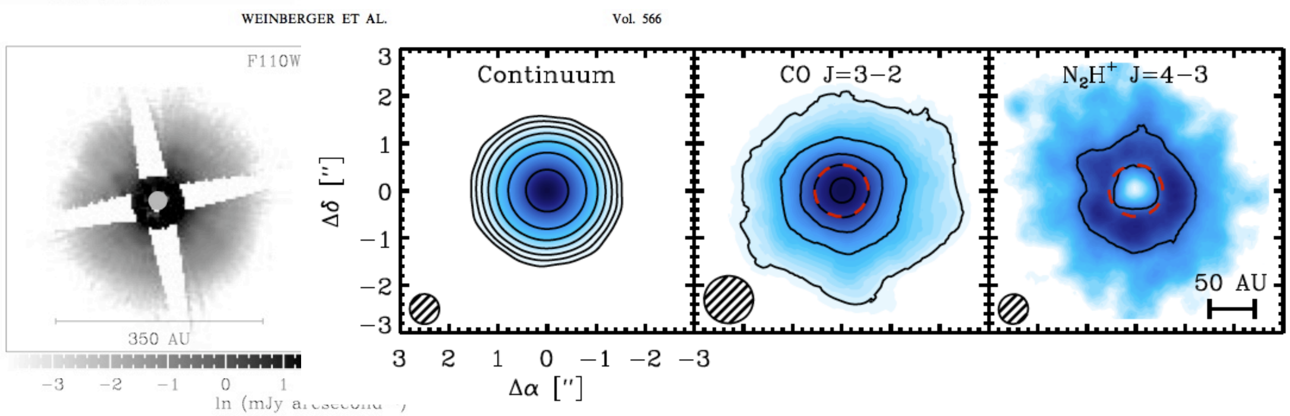
…while TW Hya has become the "Crab Nebula"* of late-stage pre-MS accretion and protoplanetary disk evolution studies

** w/ apologies/thanks to David Wilner*





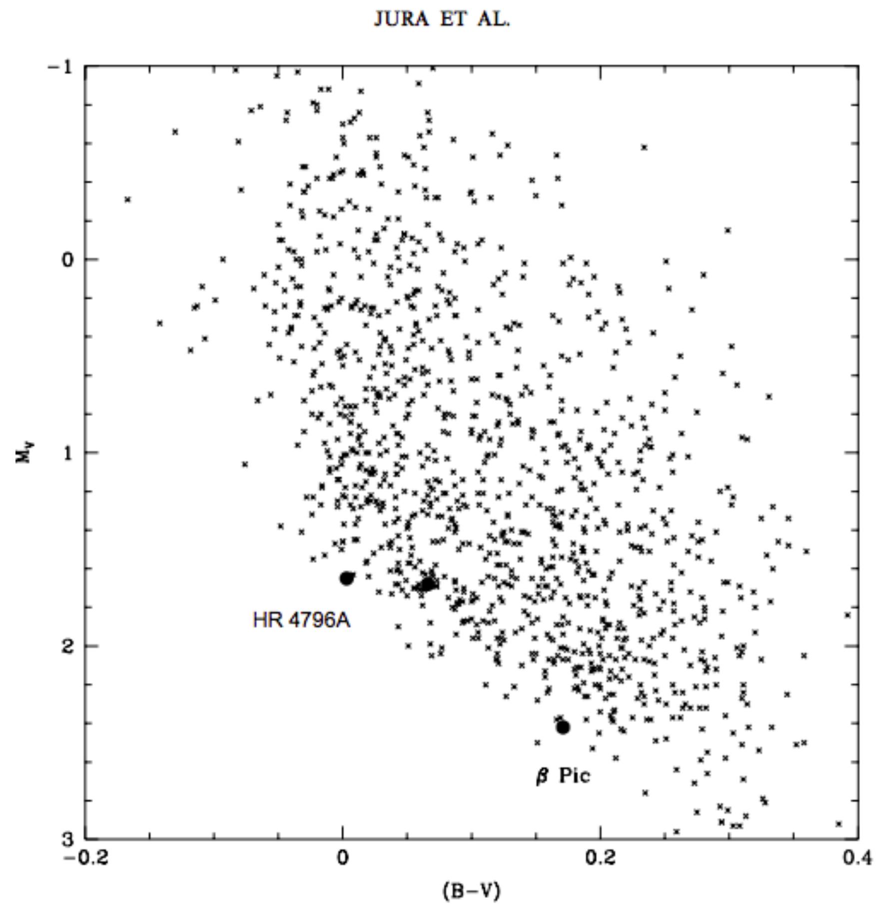
Left: molecular line spectrum of TW Hya, from Kastner et al. (1997)
Above: Chandra X-ray spectrum, from Kastner et al. (2002)



Left panel: HST imaging of TW Hya disk in scattered light (Weinberger et al. 2001); remaining 3 panels: ALMA & SMA mm-wave imaging (Qi et al. 2013)

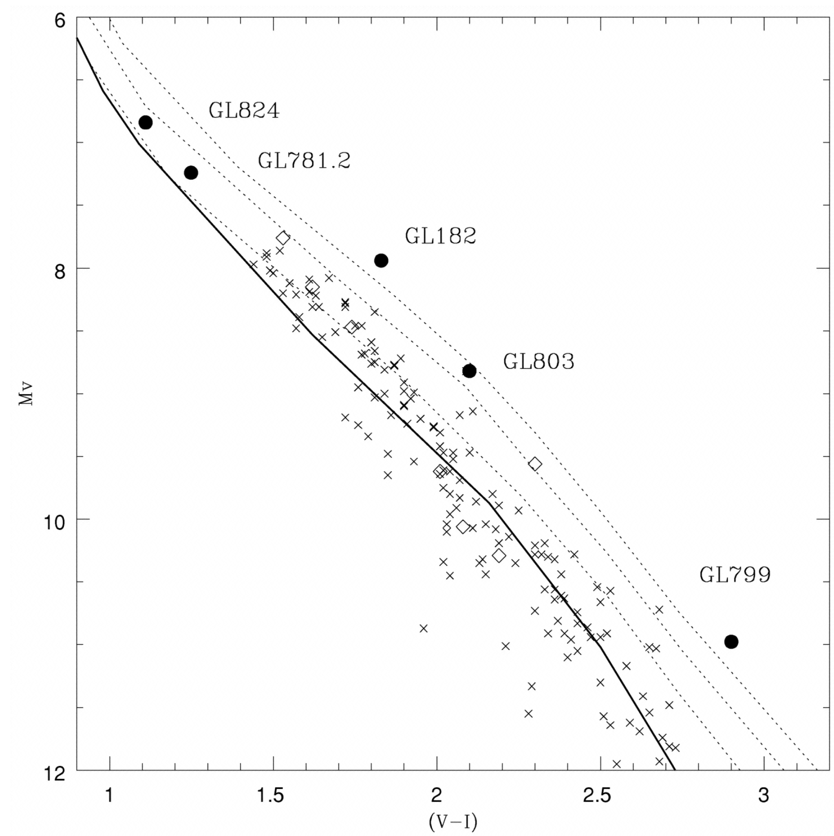
The "young association" link between HR 4796A and β Pic

- Jura et al. (1998 ApJ): large IR-excess A stars HR 4796A, β Pic, and 49 Cet are all underluminous for their colors (T_{eff}'s)
  - Stauffer et al (1995) had previously determined an age of 8 +/- 2 Myr for HR 4796A from isochronal age of its M-type comoving companion
  - Jura et al.: HR 4796AB might be part of the TWA
    - later confirmed by Webb et al. (1999)
- Implies that β Pic & 49 Cet are also `young' (Jura et al. 1998)…do they also have comoving, low-mass "friends"?



The ID of the β Pic Moving Group

- Barrado y Navascues et al. (1999, ApJ, 520, L123): 3 M stars comoving with beta Pic
  - Labeled the "βPMG" even though only 4 stars survive after ByN et al's scutiny of space motions & age diagnostics
  - Isochronal age: 20 +/- 10 Myr
- Wider availability and application of space velocities leads to ID of 17 more βPMG members (Zuckerman et al 2001)
  - "comoving, youthful group [that is] closest to Earth"
- These early βPMG studies engendered much larger efforts to ID nearby young MGs and their members



From Barrado y Navascues et al. (1999)

The Astrophysical Journal, 732:61 (19pp), 2011 May 10

Table 1
Papers Proposing Memberships in the Nearest Known Young Stellar Associations

Paper	Tuc/Hor	AB Dor	TW Hya	β Pic
Kastner et al. (1997)			X	
Webb et al. (1999)			X	
Zuckerman & Webb (2000)	X			
Torres et al. (2000)	X			
Zuckerman et al. (2001a)				X
Zuckerman et al. (2001b)	X			
Zuckerman et al. (2001c)			X	
Gizis (2002)			X	
Song et al. (2003)	X		X	X
Zuckerman et al. (2004)		X		
Zuckerman & Song (2004)	X	X	X	X
Scholz et al. (2005)			X	
Mamajek (2005)			X	
Torres et al. (2006)				X
Lopez-Santiago et al. (2006)		X		
Looper et al. (2007)			X	
Torres et al. (2008)	X	X	X	X
Fernandez et al. (2008)	X	X	X	X
da Silva et al. (2009)	X	X	X	X
Schlieder et al. (2010)		X		X
Looper et al. (2010a, 2010b)			X	
Rodriguez et al. (2011)			X	
Kiss et al. (2011)	X			X
Shkolnik et al. (2011)			X	
This paper	X	X		

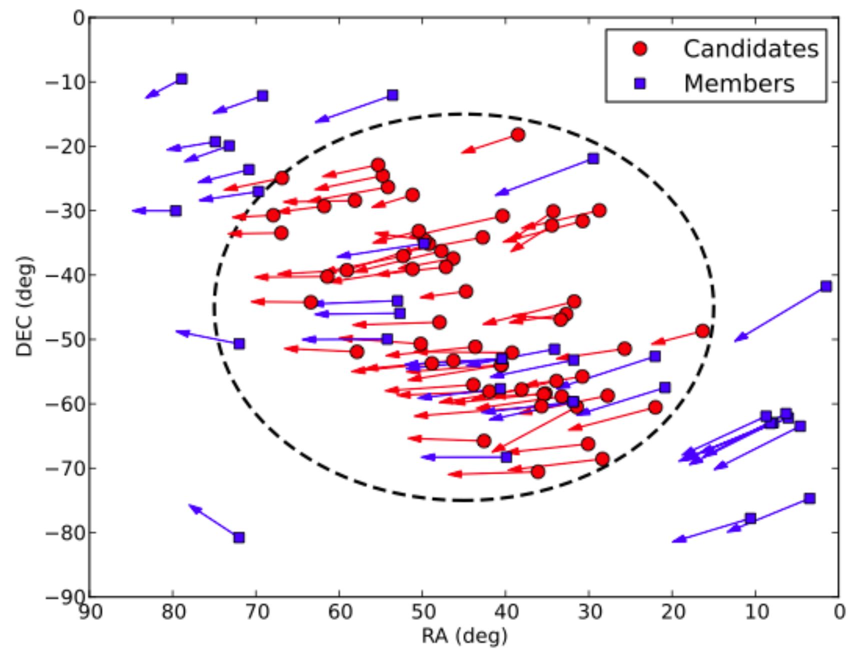
Notes. In addition to the above major young stellar associations nearest to Earth, Zuckerman et al. (2006) proposed the somewhat older and sparser, but comparably nearby, "Carina-Near" moving group. The Carina Association proposed by Torres et al. (2008) has essentially nothing in common with the Carina-Near group; the latter is much nearer to Earth and much older than the former and has a much more negative U component of space motion. While the Carina, Columba, and Argus Associations possess some members close to Earth (see, e.g., Tables 3 and 4), as defined by Torres et al. (2008), stars in these three associations are, on average, substantially more distant from Earth than are stars in the four Table 1 Associations (see Table 2 in Torres et al.).

The steadily growing census of NYMGs and their members

Left: Table 1 from Zuckerman et al. (2011)

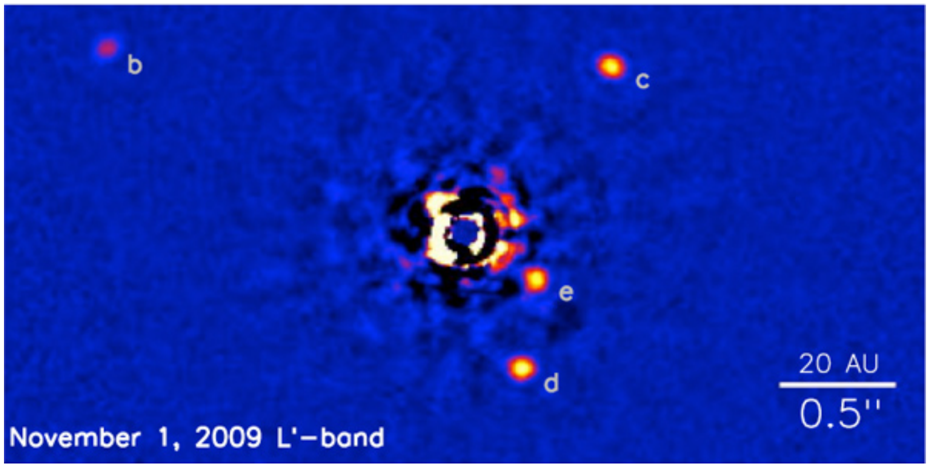
Identifying members of nearby young moving groups: the present State of the Art

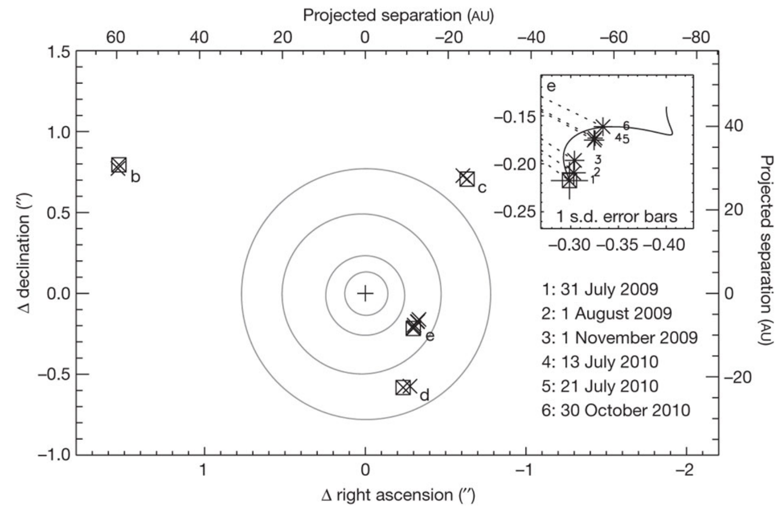
- Galactic kinematics techniques (space velocity analyses) have become increasingly sophisticated
  - Song et al. (2002 & numerous other papers)
  - Torres et al. (2006, 2008)
    - Search for Associations Containing Young Stars (SACY)
  - Malo et al. (2013, 2014a,b)
    - Bayesian Analysis for Nearby Young AssociationNs (BANYAN)
- Coronal X-rays (RASS) have been superceded by chromospheric UV (Galex) as a means to isolate large samples of candidate nearby, young & low-mass (hence magnetically active) stars
  - Rodriguez et al. (2011); Shkolnik et al. (2012)
- Combination of techniques (UV + kinematics) is particularly powerful
  - e.g., Rodriguez et al. (2011, 2013): Galex Near/ Young Star Search ("GALNYSS")



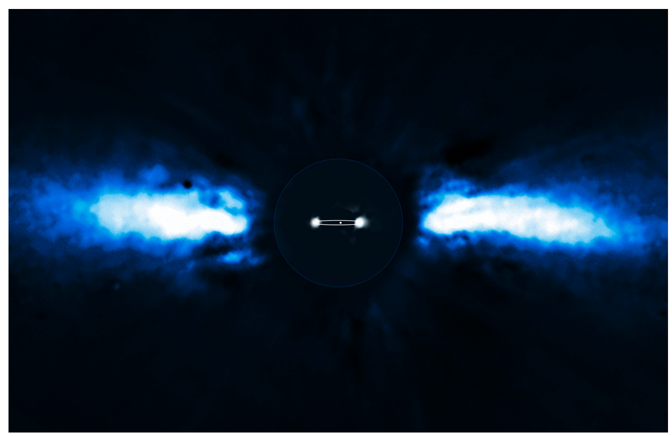
From Rodriguez et al. (2013)

Why focus on Young Stars Near Earth?
Among other things: to *image* young (exo)planets!





***Upper left**: The first and (to date) **only** directly-imaged multiple planet system: four super-Jovian planets orbiting HR 8799 – a member of the 30 Myr-old Columba Association (Zuckerman et al. 2011)?*
***Upper right**: Schematic view of the HR 8799 exoplanet system, w/ comparison to the orbits of the outer solar system (Jovian) planets (from Marois et al. 2010)*



***Lower panel**: Composite image of the disk and Jovian(?) planet orbiting the 12-Myr-old star beta Pic (see Lagrange et al. 2010)*

Identifying and age-dating nearby young moving groups and their members: the βPMG as "litmus test"

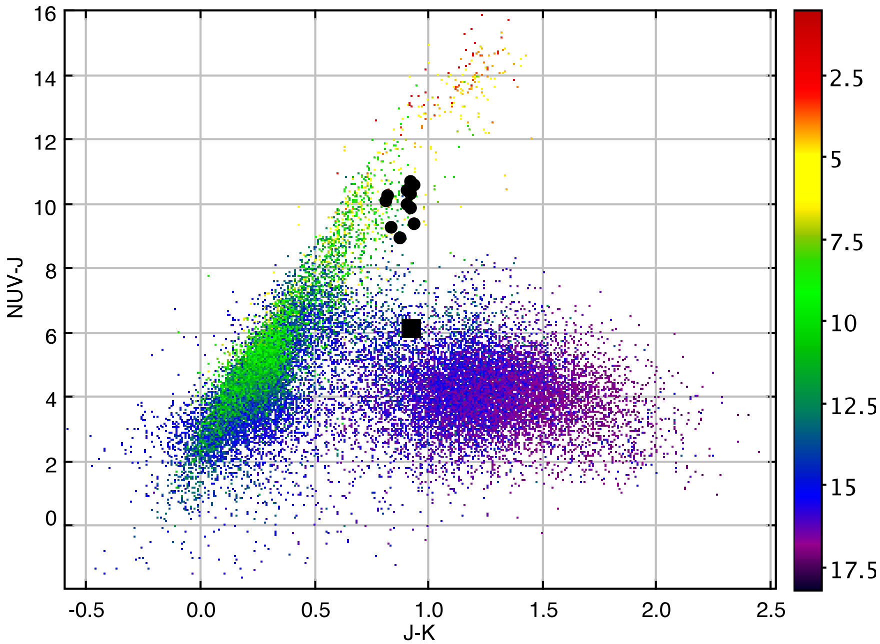
2 *Mamajek & Bell*

Table 1. Literature age estimates for the BPMG. We adopt the terms "traceback age" and "expansion age" generically for any age estimate trying to infer when an unbound group of stars was at its minimum size in the past.

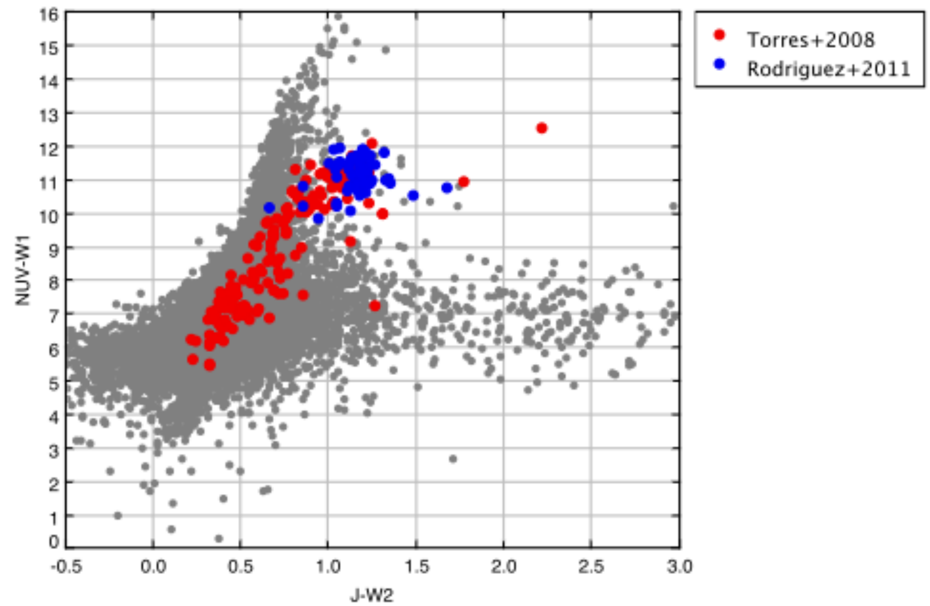
Reference ...	Age (Myr)	Method ...
Barrado y Navascués et al. (1999)	20 ± 10 Myr	CMD isochronal age (KM stars)
Zuckerman et al. (2001)	12^{+8}_{-4} Myr	H-R diagram isochronal age (GKM stars) + Li depletion
Ortega et al. (2002)	11.5 Myr	Traceback age
Song et al. (2003)	12 Myr	Traceback age
Ortega et al. (2004)	10.8 ± 0.3 Myr	Traceback age
Torres et al. (2006)	~ 18 Myr	Linear expansion age
Makarov (2007)	22 ± 12 Myr	Traceback age
Mentuch et al. (2008)	21 ± 9 Myr	Li depletion
Macdonald & Mullan (2010)	~ 40 Myr	Li depletion (magneto-convection models)
Binks & Jeffries (2014)	21 ± 4 Myr	Li depletion boundary
Malo et al. (2014)	26 ± 3 Myr	Li depletion boundary
Malo et al. (2014)	21.5 ± 6.5 Myr ($15 - 28$ Myr)	H-R diagram isochronal age (KM stars)
This work	22 ± 3 Myr	CMD isochronal age (FG stars)
Final	**23 ± 3 Myr (1σ)** **[± 2 Myr (stat.), ± 2 Myr (sys.)]**	Li depletion bounday & CMD isochronal age (FGKM stars)

From Mamajek & Bell (2014)

Young, low-mass stars near Earth: conspicuous in the UV & IR (hence likely to have been detected by Galex and WISE)!



Left: *near-UV vs. near-infrared colors of objects in* Galex *fields, color-coded according to 1.25 micron (J) magnitude; black symbols show known member stars of the TW Hya Association (all have J < 10); TW Hya itself is the square near center of diagram*
(From Rodriguez, Zuckerman, Bessell & Kastner 2011)

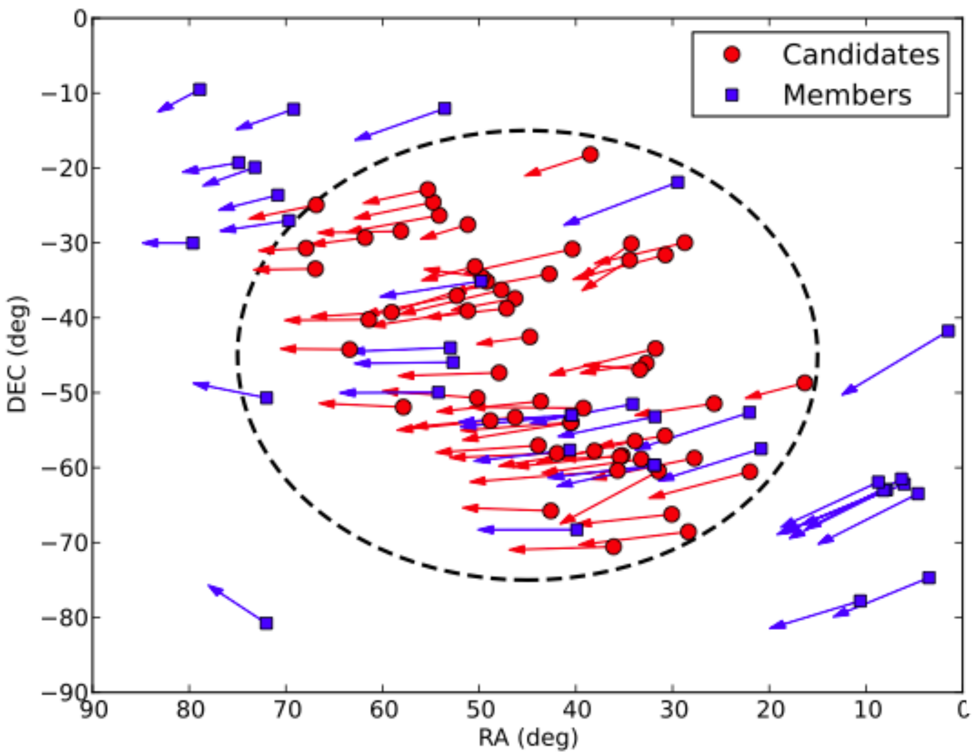


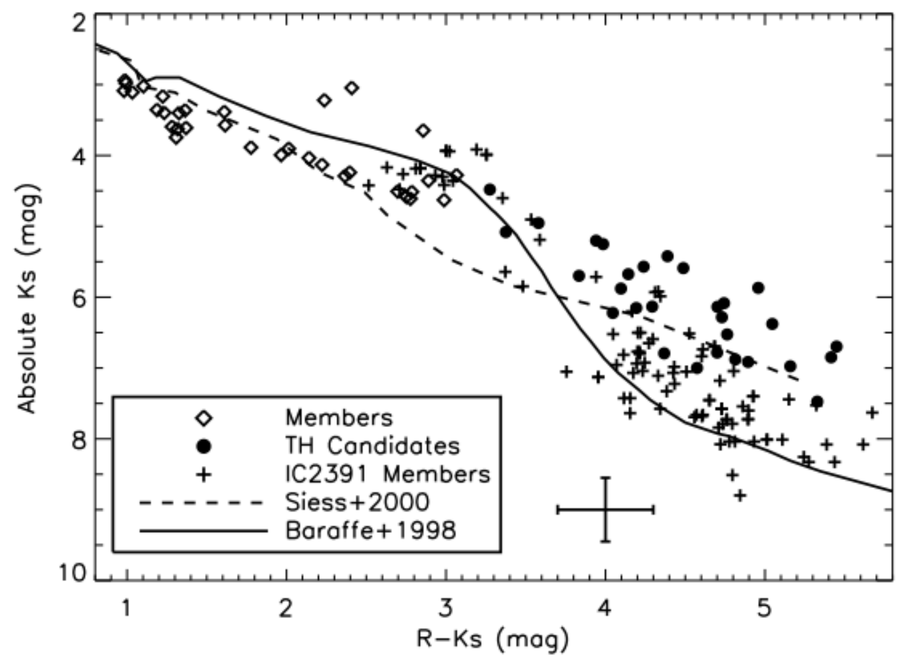
Left: *near-UV vs. WISE/2MASS infrared colors of objects in* Galex *fields; red dots indicate known members of nearby young stellar groups, and blue dots indicate newly discovered nearby young stars*
(From Rodriguez, Zuckerman, Kastner et al. 2013, submitted)

Galex & WISE help reveal the lowest-mass members of the nearby young star population

New M-type members of the Tuc-Hor Association (age ~30 Myr)

…some very promising targets for near-future direct imaging of massive exoplanets!

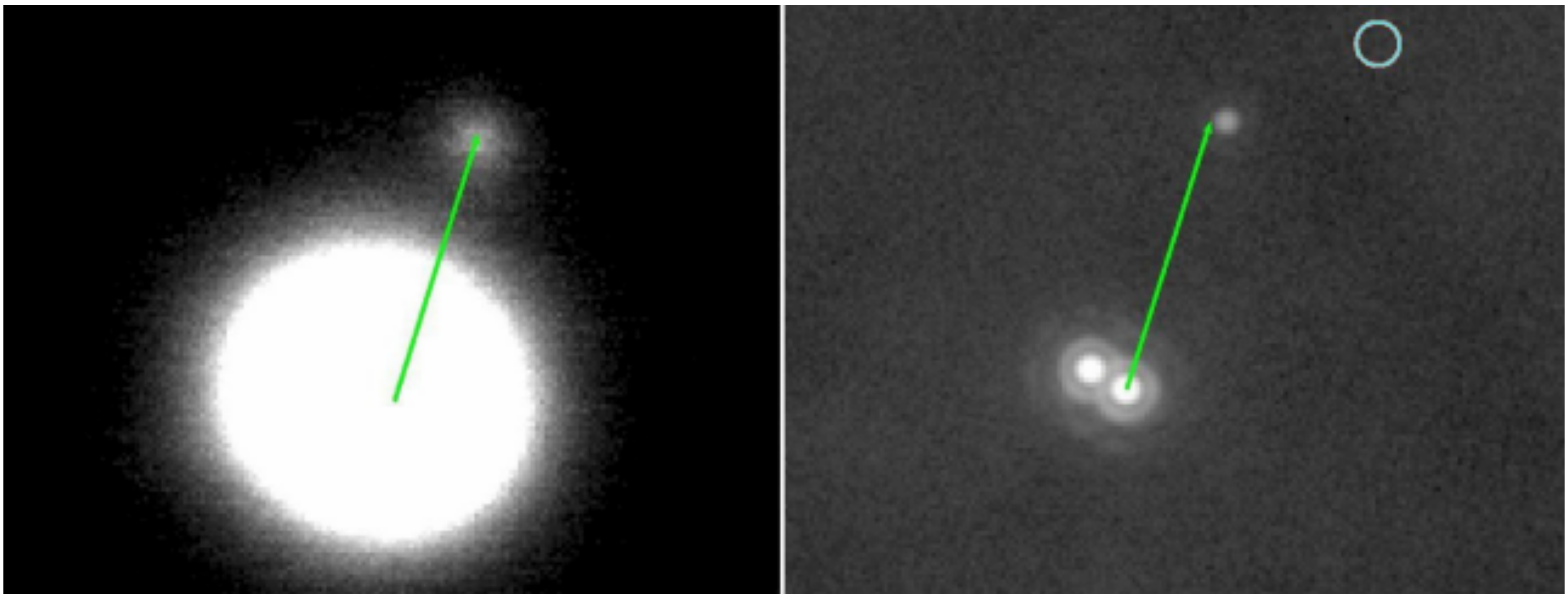




Rodriguez et al. (2013)

First direct image of a *circumbinary* planet?

A massive planet or, perhaps, brown dwarf orbiting a **young binary system in the Tuc-Hor Association**



2002 2012

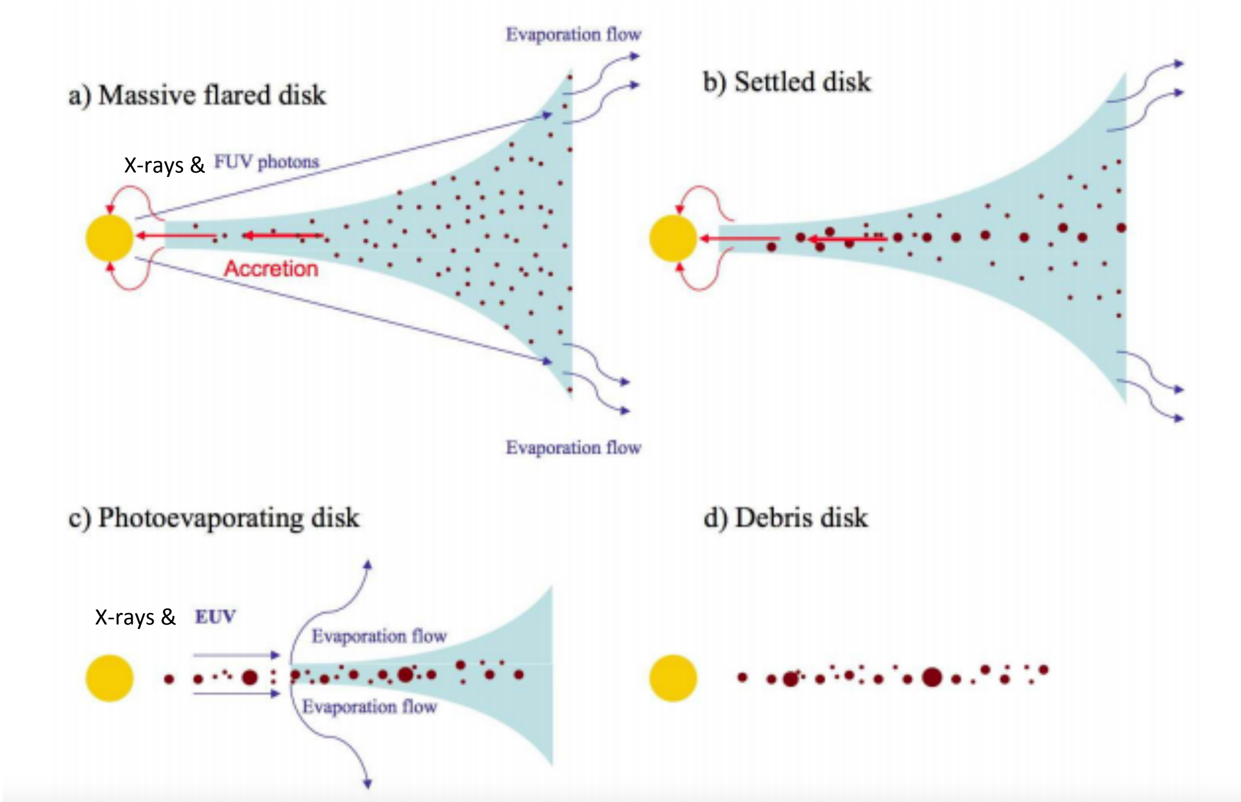
Evidence for common proper motion and orbital motion in two Very Large (8 meter) Telescope near-IR images taken 10 years apart
(Delorme et al. 2013)

Where do these young planets come from?

"Quick" answer:

from a planet-forming disk orbiting the young star

Looks like we know how the story goes…BUT…many open questions, such as:



Theoretical (schematic) view of stages of evolution of a planet-forming disk (from Williams & Cieza 2011, Ann. Rev. Astron. Astrophys.)

- What are the chemical constituents of planet-forming disks?
- How do disks lose their gas and dust?
- How much disk material eventually makes it into rocky (Earth-like) vs. "gassy" (Jupiter-like) vs. icy (Neptune-like) giant planets?
- How long does it take these various types of planets to form around a young star?

The late stages of protoplanetary disk evolution as revealed by the rare examples of *actively accreting* young stars within ~100 pc of Earth

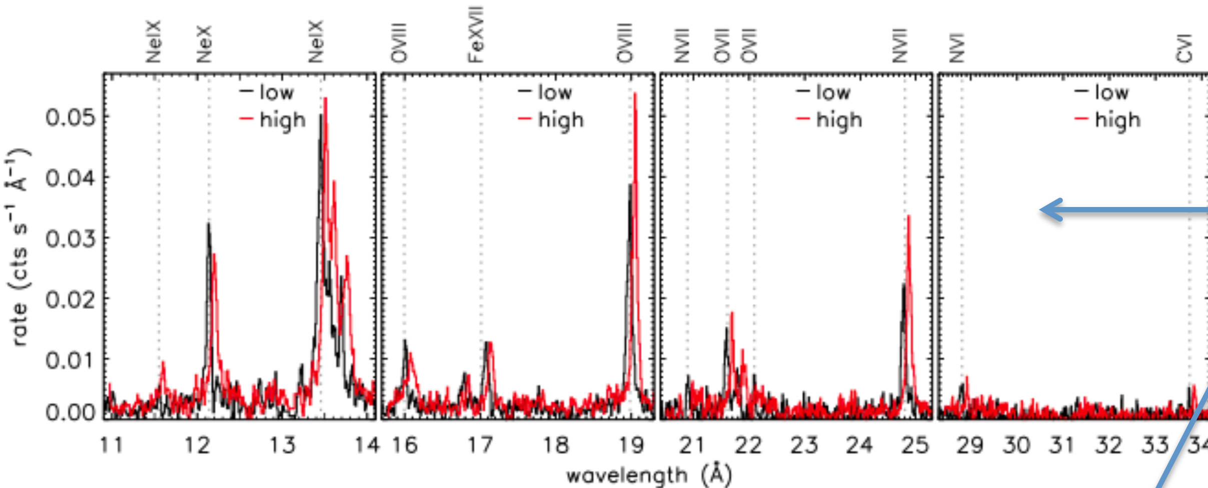
Actively Accreting T Tauri Star Systems* within ~100 pc

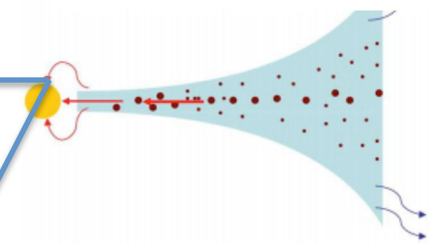
system	spectral type	Assoc.	D (pc)	age (Myr)	$M_\star$ ($M_\odot$)	Disk M_{CO} (M_{Earth})	Disk incl. (°)
T Cha A	K0	ϵ Cha	110	6	1.5	0.08	60
MP Mus	K1	ϵ Cha	103	6	1.2	0.06	30
V4046 Sgr AB	K5+K7	β Pic	73	23	0.90+0.85	0.1	35
TW Hya	K7	TWA	54	8	0.7	0.02	7
Hen 3–600 AB	M3+M3.5	TWA	45	8	0.2+0.2	...	< 45
TWA 30 AB	M4+M5	TWA	42	8	0.1+0.1	...	>60
LDS 5605 AB	M5+M5	β Pic	65	23	0.1+0.1	...	< 45

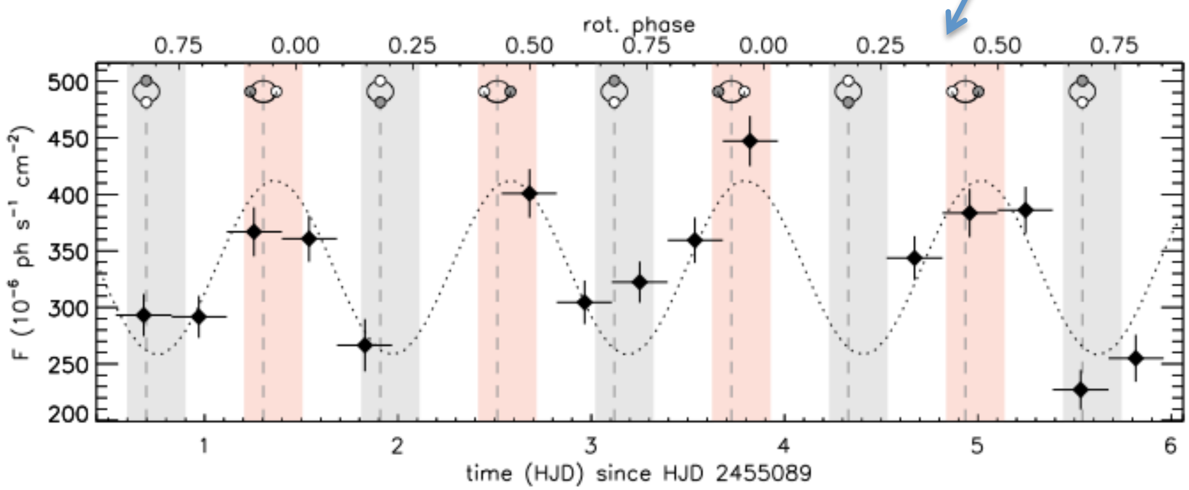
* *Compiled from Sacco et al. (2014), Huenemoerder et al. (2007), Looper et al. (2010), Zuckerman et al. (2014), and refs. therein*

X-rays and pre-MS accretion disks: XMM time-resolved X-ray gratings spectroscopy of V4046 Sgr

X-rays from stellar accretion and coronal activity



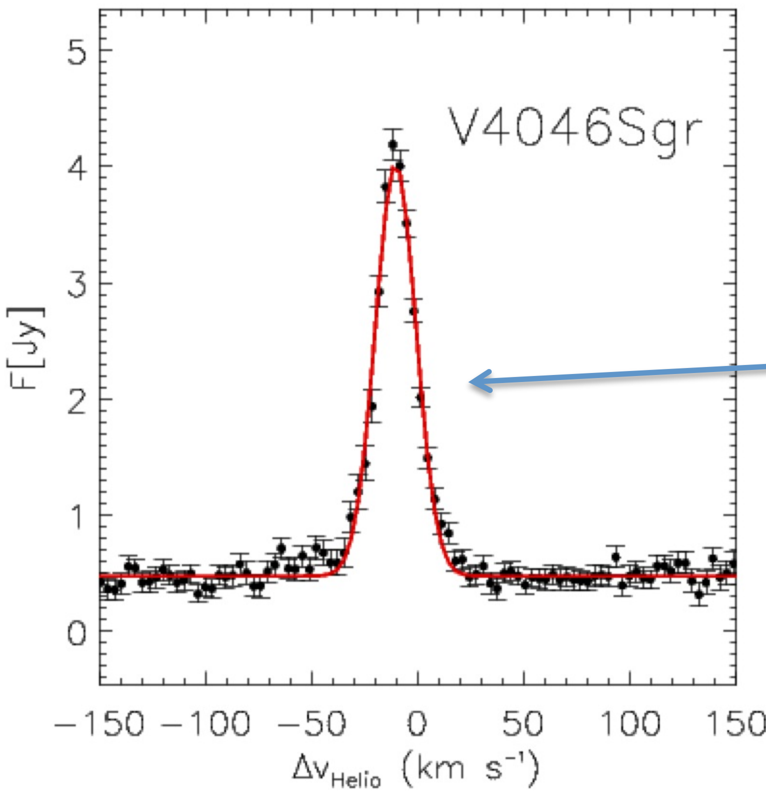




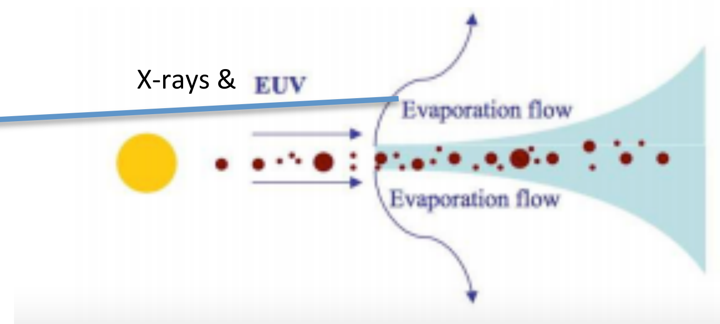
***Top**: XMM/RGS spectra extracted during low (black) and high (red) states; spectra shifted in wavelength, for clarity*

***Bottom**: apparent rotational modulation of low-T lines attributable to accretion shocks (Argiroffi et al., 2012, ApJ)*

VLT/VISIR spectroscopy of mid-IR [Ne II] emission from V4046 Sgr: evidence for *X-ray-induced disk photoevaporation*



Mid-IR line emission from photoevaporative disk wind



VLT/VISIR spectroscopy of 12.8 micron [Ne II] emission from V4046 Sgr; high ionization potential of Ne I requires high-E photon irradiation… …narrow linewidths and small line blueshifts are indicative of photoevaporative flows (Sacco et al. 2012, ApJ)

X-rays from actively accreting young stars near Earth
Probing irradiation of gaseous protoplanetary disks

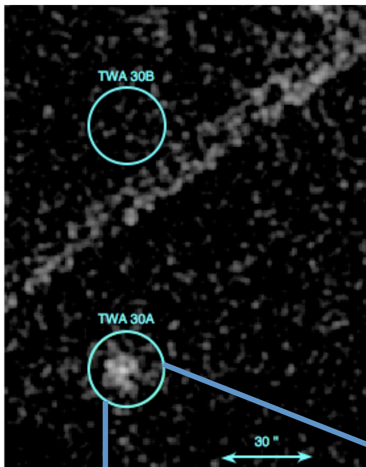
Actively Accreting T Tauri Star Systems* within ~100 pc

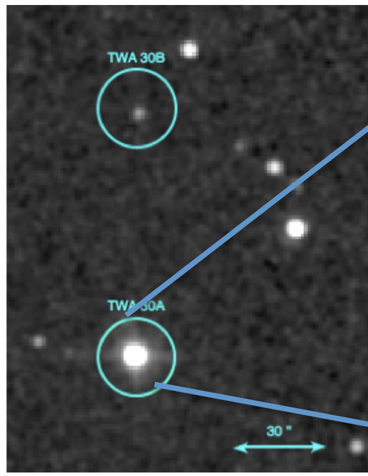
system	spectral type	Assoc.	D (pc)	age (Myr)	$M_\star$ ($M_\odot$)	Disk M_{CO} (M_{Earth})	Disk incl. (°)
T Cha A	K0	ϵ Cha	110	6	1.5	0.08	60
MP Mus	K1	ϵ Cha	103	6	1.2	0.06	30
V4046 Sgr AB	K5+K7	β Pic	73	23	0.90+0.85	0.1	35
TW Hya	K7	TWA	54	8	0.7	0.02	7
Hen 3–600 AB	M3+M3.5	TWA	45	8	0.2+0.2	...	< 45
TWA 30 AB	M4+M5	TWA	42	8	0.1+0.1	...	>60
LDS 5605 AB	M5+M5	β Pic	65	23	0.1+0.1	...	< 45

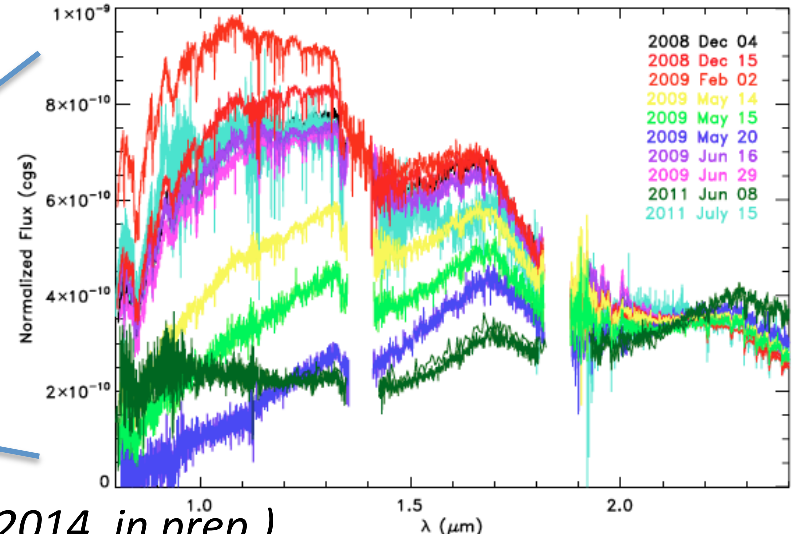
* *Compiled from Sacco et al. (2014), Huenemoerder et al. (2007), Looper et al. (2010), Zuckerman et al. (2014), and refs. therein*

Simultaneous X-ray & near-IR spectroscopy of the nearly edge-on, 8 Myr-old star/disk system TWA 30A

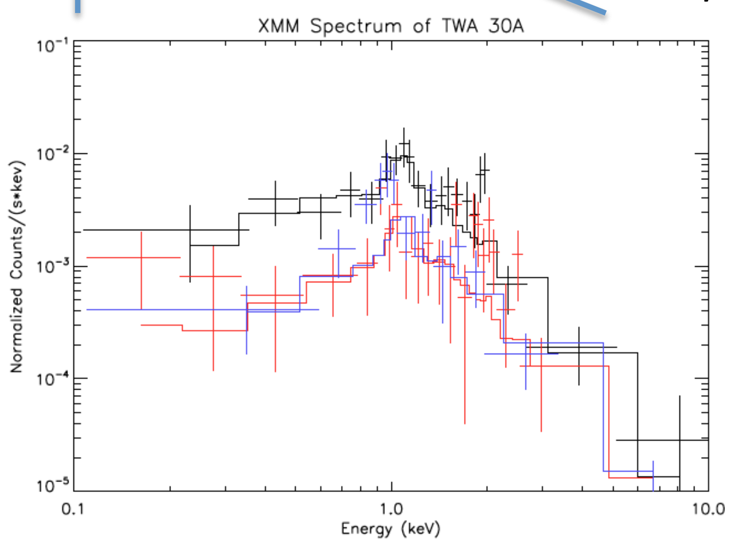
Monitoring the X-irradiation of the protoplanetary disk orbiting ***a young mid-M star***

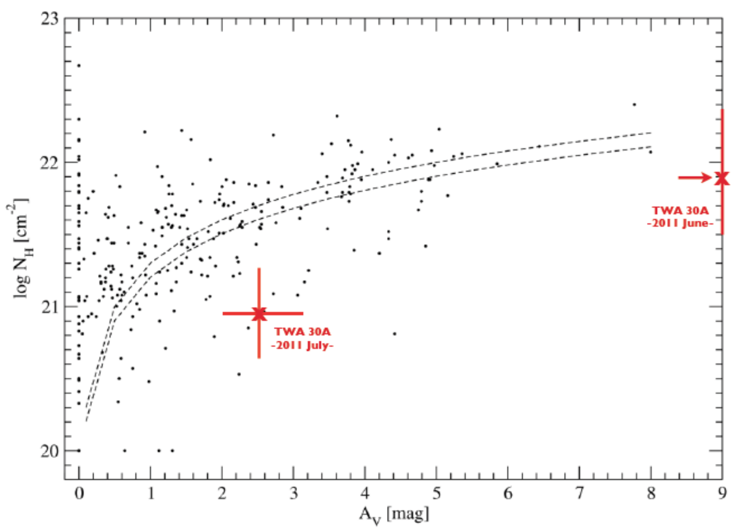






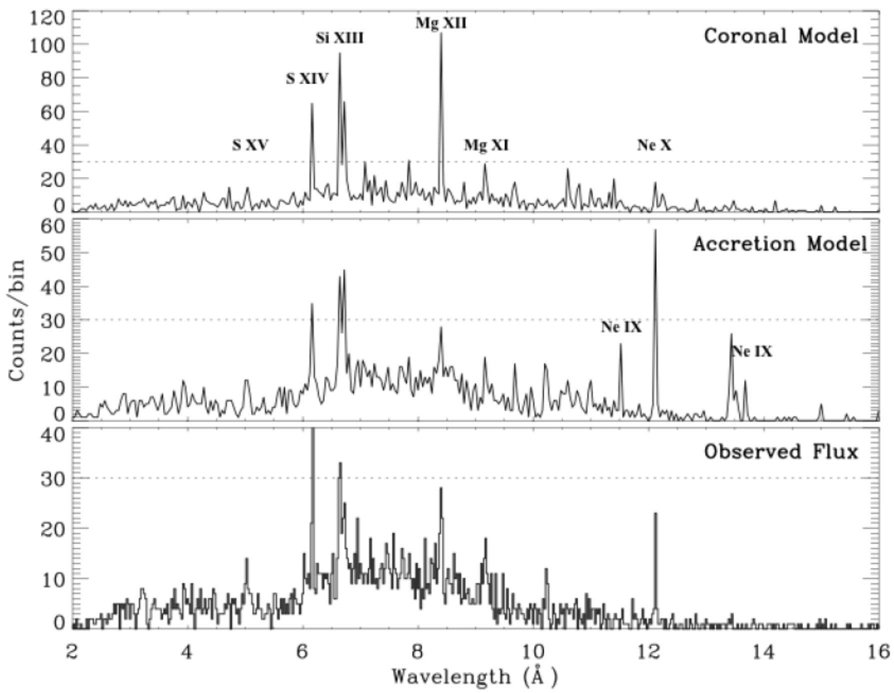
Principe et al. (2014, in prep.)

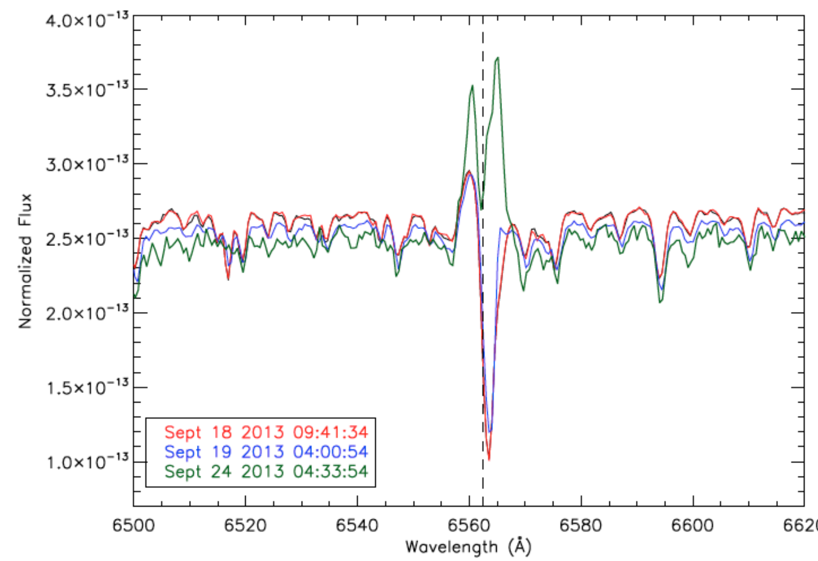


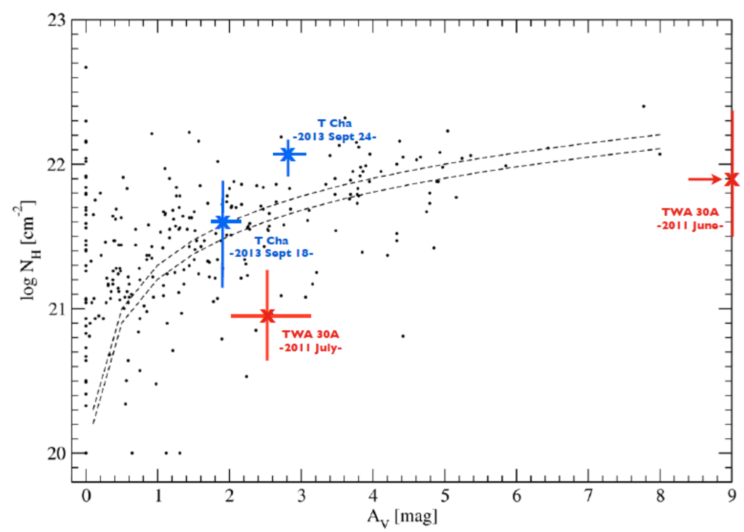


Simultaneous X-ray & optical spectroscopy of the highly inclined, 6 Myr-old star/disk system T Cha

*Monitoring the X-irradiation of the protoplanetary disk orbiting a **young solar analog***



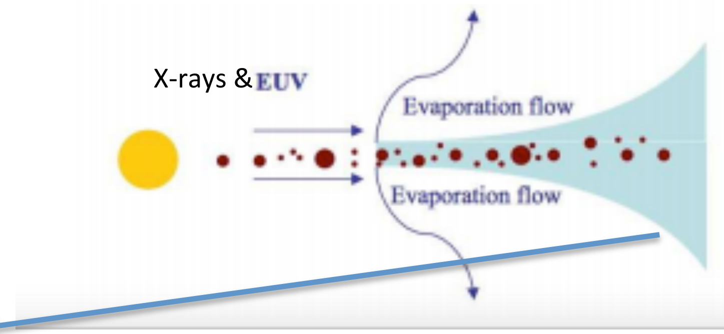




Principe et al. (2014, in prep.)

Molecular spectroscopy with the APEX 12 m: Fingerprint of an *irradiated molecular disk* orbiting V4046 Sgr (& TW Hya)

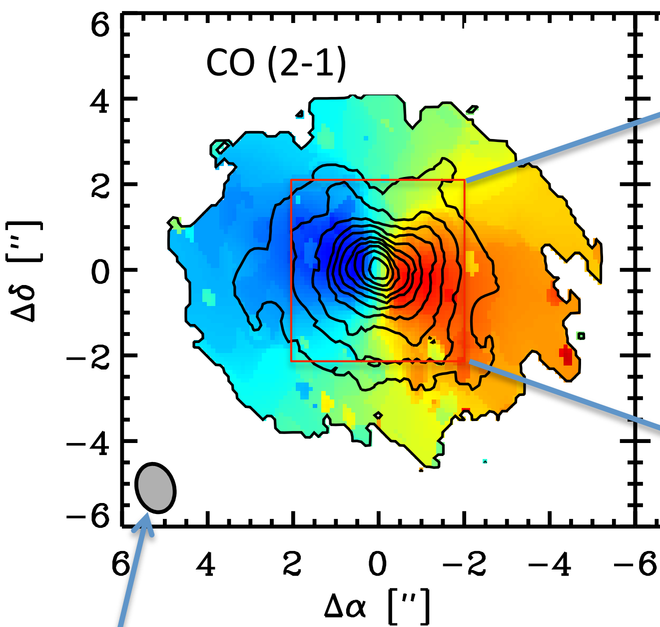
Radio line emission from cold, irradiated gas in the outer disk

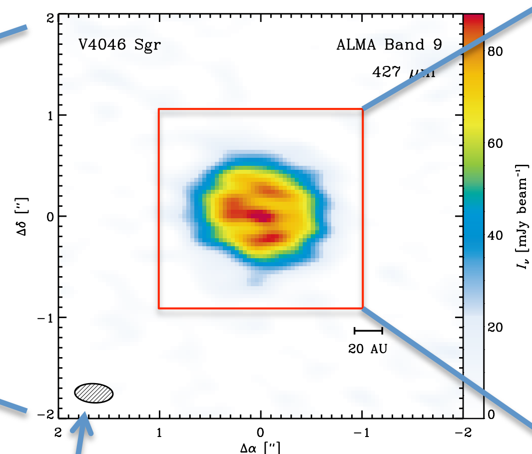


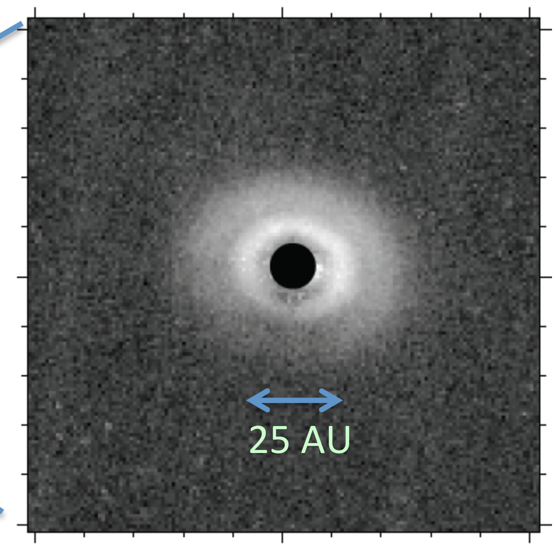
(Kastner et al. 2014, ApJ)

Evidence for *circumbinary* planet formation in the X-irradiated disk orbiting V4046 Sgr

Early Science imaging w/ ALMA and Gemini Planet Imager







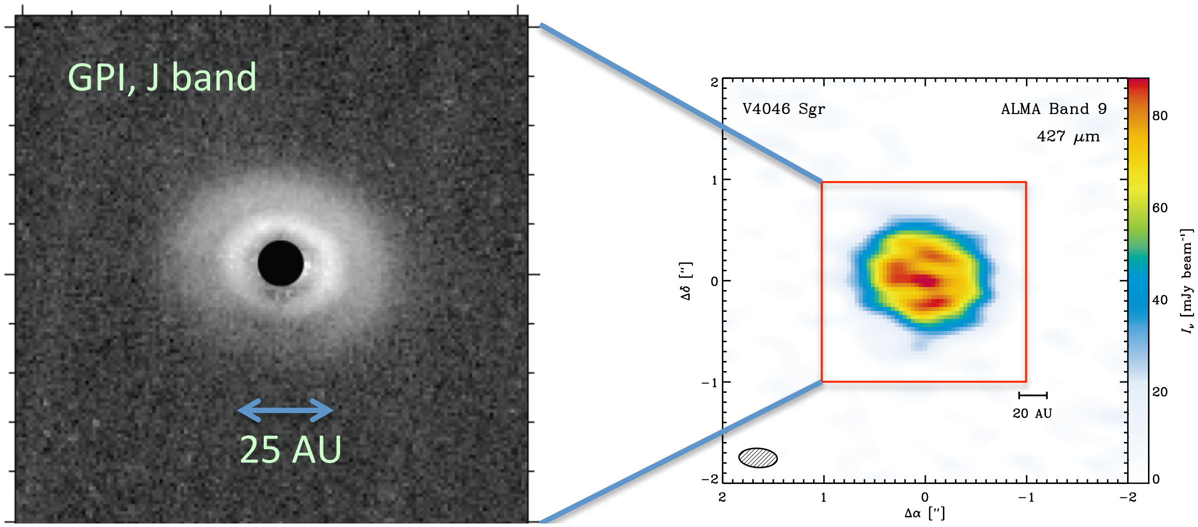
SMA beam: similar to orbit of Neptune, at distance of V4046 Sgr
(Rosenfeld, Andrews, et al. 2013)

*ALMA beam…similar to orbit of **Saturn**…Reveals dust ring w/ radius similar to orbit of Neptune.*

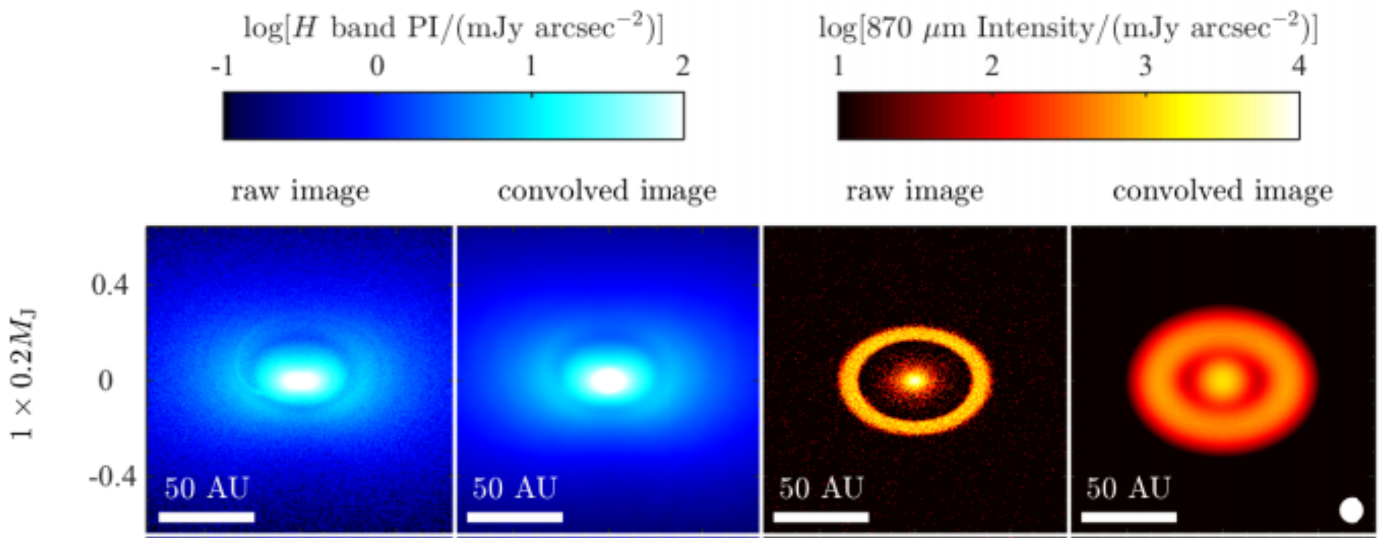
(Andrews, Rosenfeld, Kastner et al. in prep.)

*GPI near-infrared polarimetric imaging… reveals **inner dust ring** with radius similar to the orbit of **Saturn***
(Rapson, Kastner, Andrews, et al., 2015, submitted to ApJ)

The V4046 Sgr dust ring system: evidence for planet formation

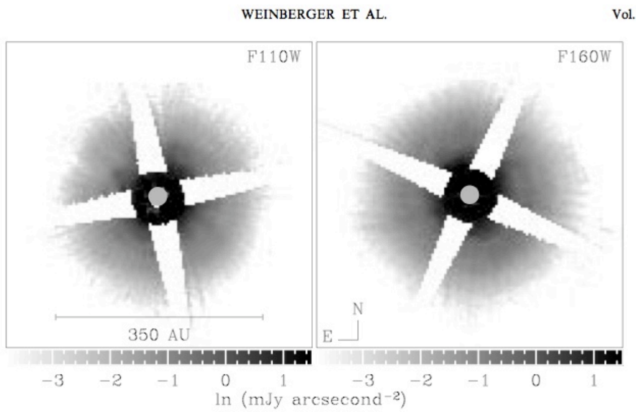


GPI scattered-light (near-IR) & thermal (submm) images from Rapson et al. (2015 ApJ, submitted) and Andrews et al. (2015, in prep.)

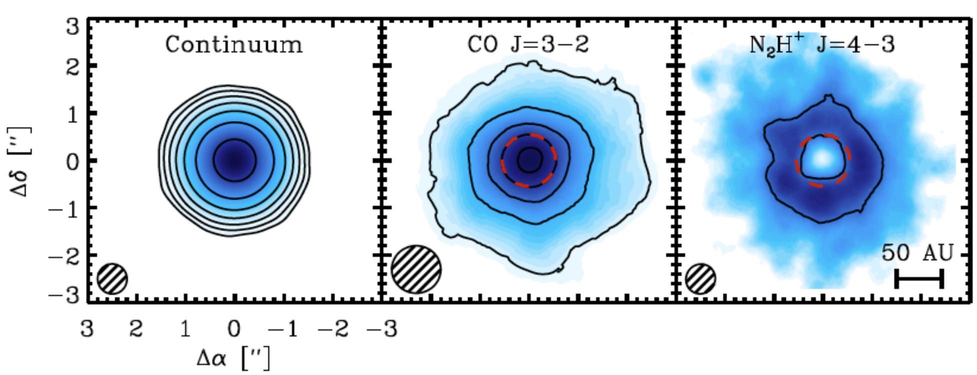


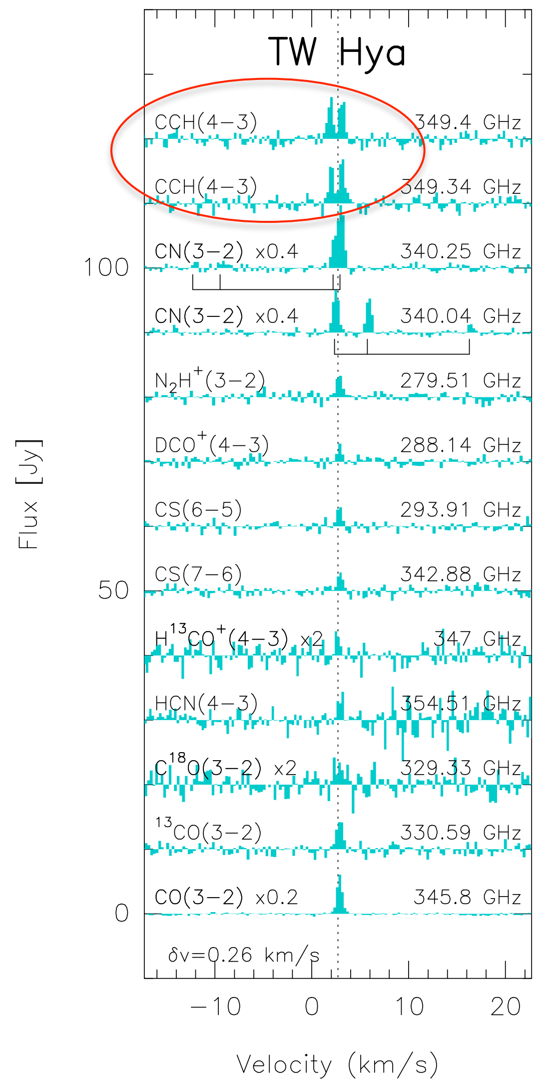
Monte Carlo radiative transfer model scattered-light (near-IR) & thermal (submm) images from Dong et al. (2014, arxiv:1411.6063)

But, back to TW Hya…(what else?)

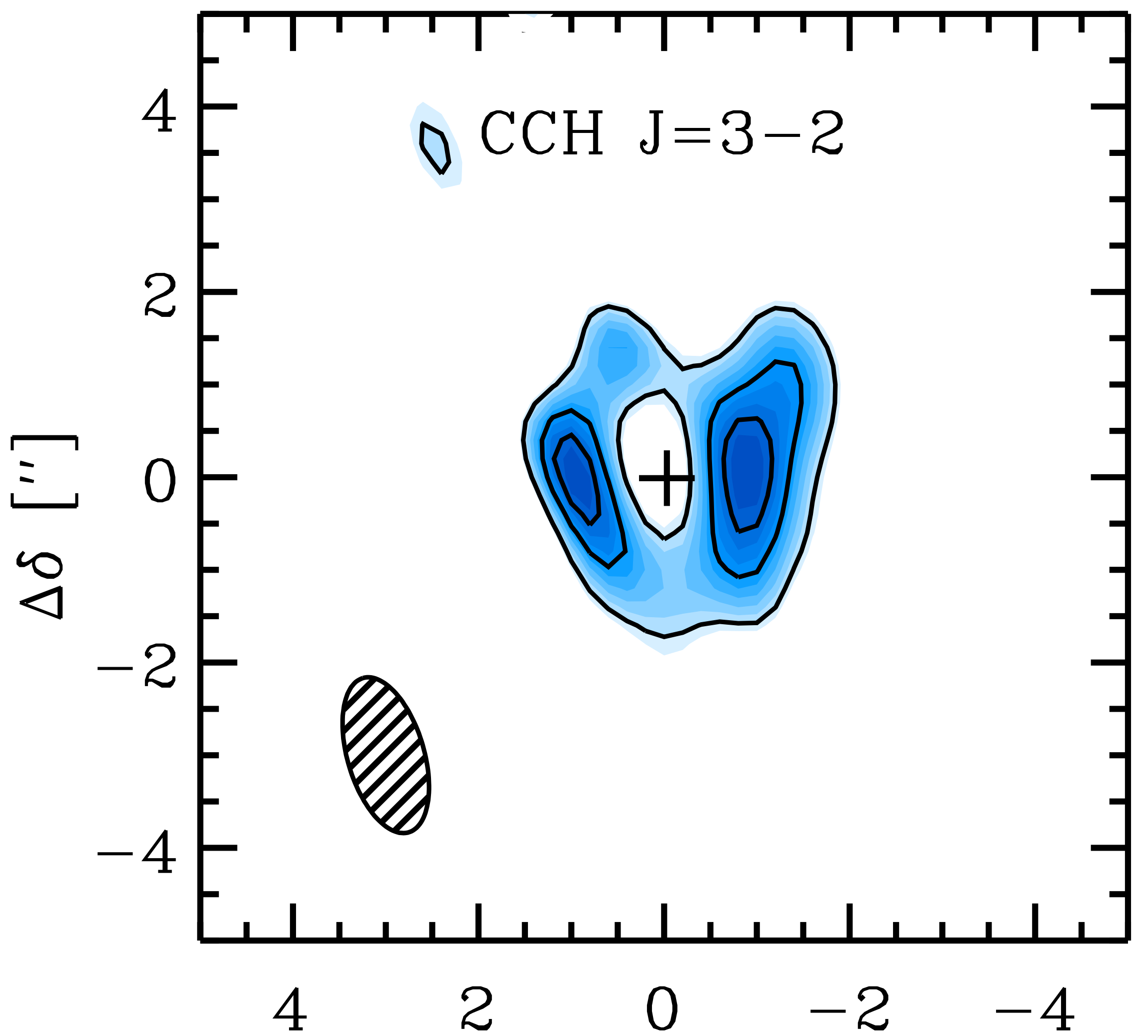


Above: HST imaging of TW Hya disk in scattered light (Weinberger et al. 2001); below: ALMA & SMA mm-wave imaging (Qi et al. 2013); Right: APEX single-dish molecular line survey (Kastner et al. 2014)





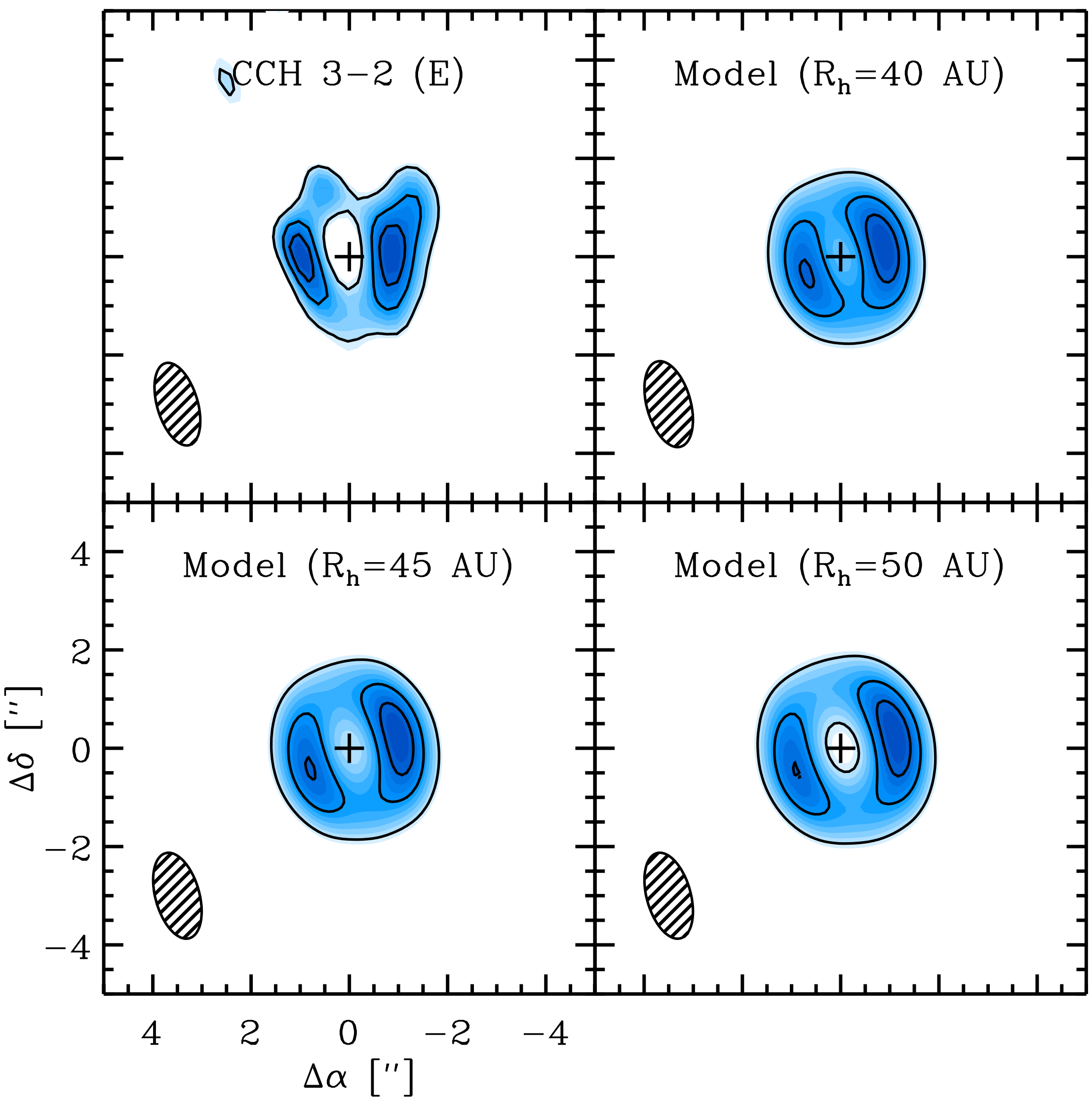
SMA imaging reveals a ring of C_2H in the protoplanetary disk orbiting TW Hya



- Observations of C_2H N = 3 -> 2 (262 GHz)
  - 2013 April and 2014 April
- Compact & extended SMA configurations
  - Image from extended config. data shown at left

(Kastner et al. 2015, submitted to ApJ)

SMA imaging reveals a ring of C_2H in the protoplanetary disk orbiting TW Hya



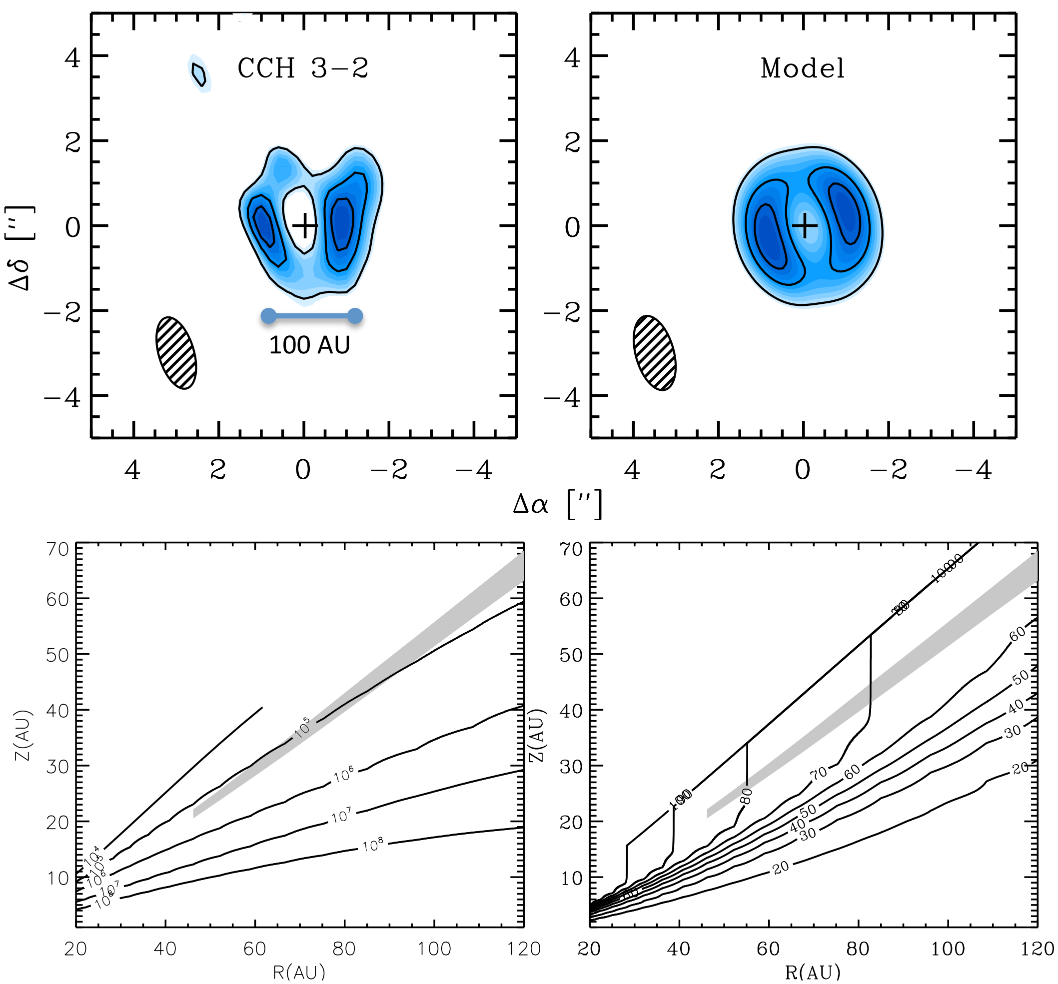
Assumptions:

- Ring-like distribution
- **C_2H confined to disk surface layers**
    - Constraint: 4-3/3-2 line ratio (implies subthermal excitation)

Results:

- **R_{in} = 45 (±10) AU**
- R_{out} ≈ 120 AU
- Radial power-law index: p ≈ −1.8
- **C_2H emitting layer lies at z/R ≈ 0.5**
- Peak C_2H column density ≅8e14 cm^{-2}

Modeling* the ring of C_2H in the protoplanetary disk orbiting TW Hya



Assumptions:

- Ring-like distribution
- **C_2H confined to disk surface layers**
  - Constraint: 4-3/3-2 line ratio (implies subthermal excitation)

Results:

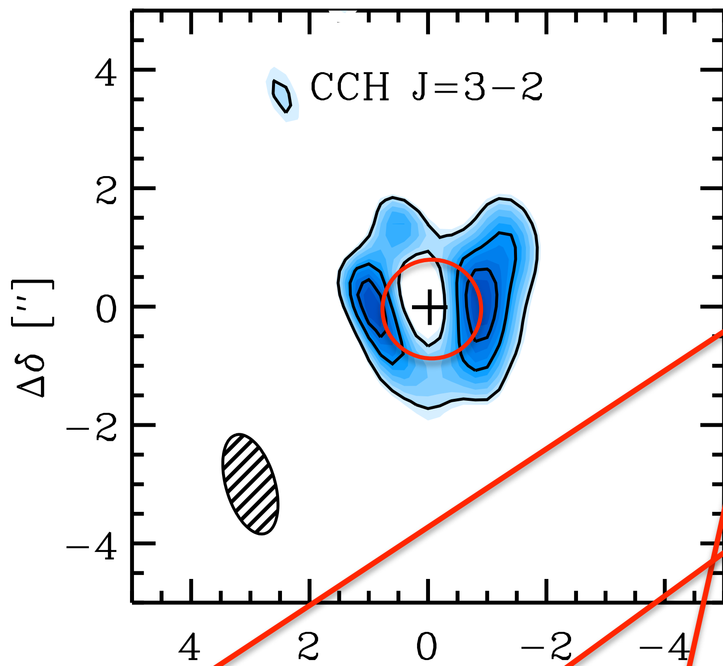
- **R_{in} = 45 (±10) AU**
- $R_{out} \approx 120$ AU
- Radial power-law index: $p \approx -1.8$
- **C_2H emitting layer lies at $z/R \approx 0.5$**
- Peak C_2H column density ≅8e14 cm^{-2}

* *See Qi et al. (2013, Science)*

Comparing C_2H with other tracers of gas & dust in the protoplanetary disk orbiting TW Hya

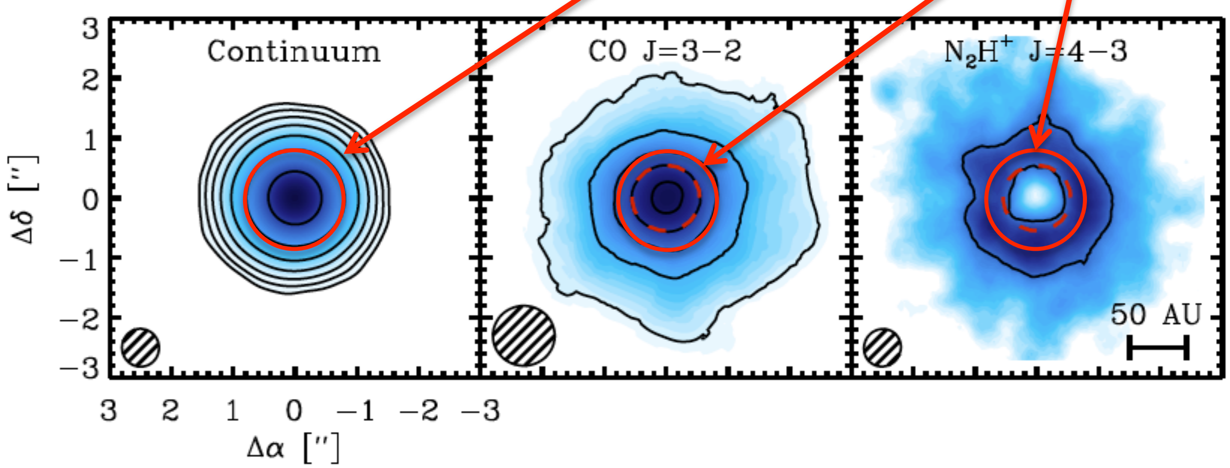
Top panel: SMA image of C2H (Kastner et al. 2015, in prep.)

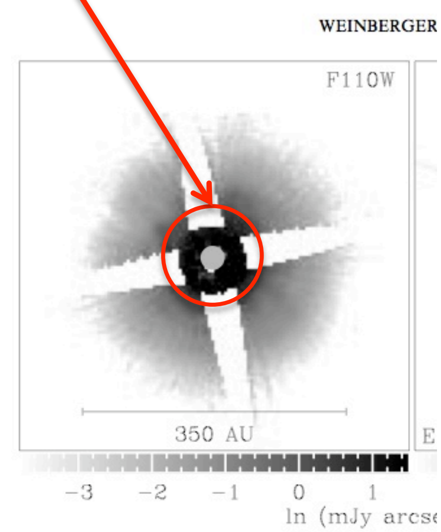
Lower 4 panels: ALMA, SMA, & HST imaging (Qi et al. 2013; Weinberger et al. 2000)



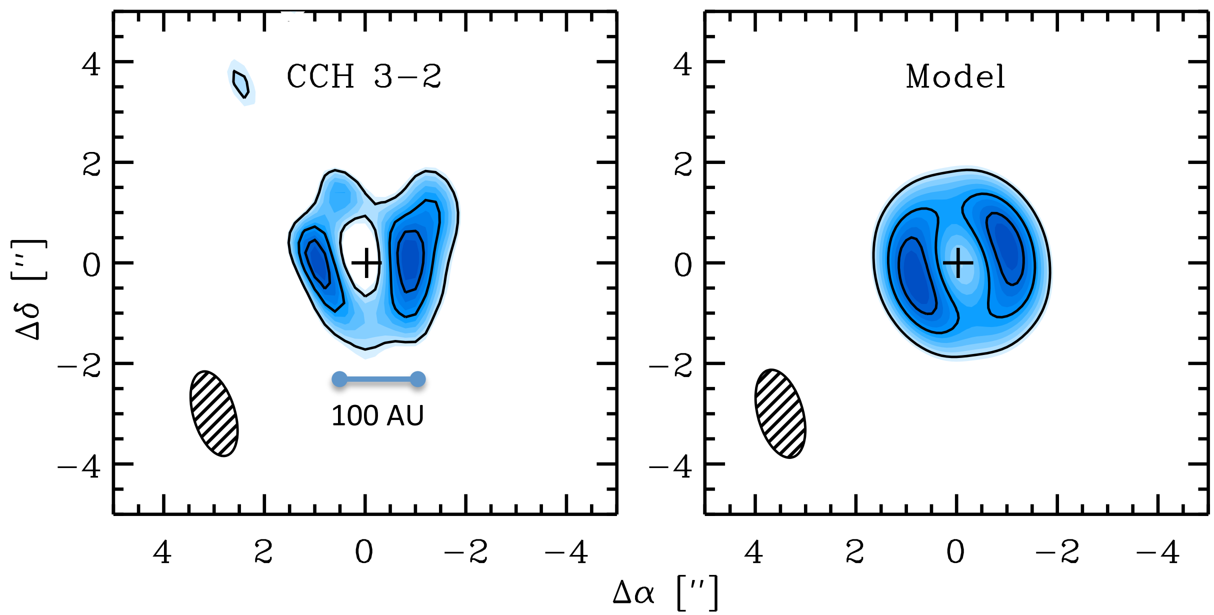
C_2H inner hole radius (~45 AU):

- Larger than CO “snow line” (~30 AU)
- Smaller than outer cutoff of large grain population (~60 AU)
- Much smaller than gas disk and extent of disk’s small grain population (~200 AU)





What has produced this ring of C_2H in the protoplanetary disk orbiting TW Hya?

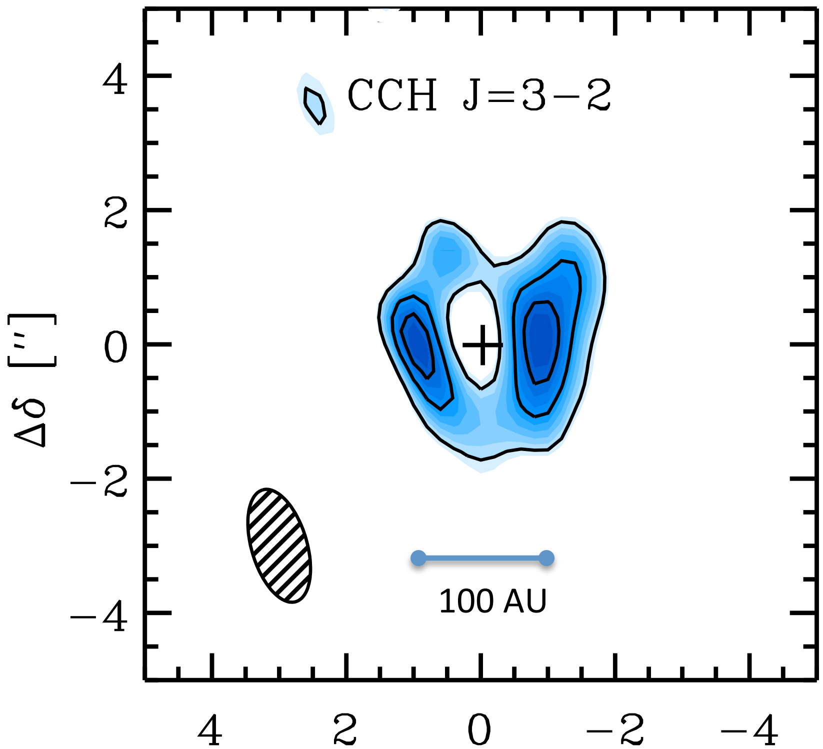


We propose that the C_2H ring most likely traces some combination of:

1. photodestruction of small grains and PAHs by stellar UV & X-rays
   - Motivation: C_2H ring coincides with disk region where small grains begin to dominate dust grain population
2. stellar X-ray photodesorption of grain ice mantles composed of complex organic molecules
   - Motivation: lab astrochemisty experiments (Mendoza et al. 2013)

Shadowing of outer disk (to ~45 AU) by inner disk material (within ~4 AU) may also play a role.

Following up on the ring of C_2H in the protoplanetary disk orbiting TW Hya: *stay tuned!*



- HST/STIS & Gemini Planet Imager optical & near-IR coronagraphic imaging at ≈2 AU resolution
  - Spring 2015; PIs: V. Rapson, J. Debes
    - see Rapson's poster (340.10) on GPI Early Science imaging of V4046 Sgr
  - ***Will starlight scattered off small grains trace similar disk irradiation/ shadowing structure?***
- ALMA imaging of CN and HCN emission at ≈30 AU resolution
  - Cycle 2; PI: P. Hily-Blant
  - ***Will CN trace the same UV- & X-irradiated disk regions and hence also appear as a ring?***
- Further modeling that incorporates stellar UV & X-ray fields irradiating small grains, ices, & hydrocarbons

IAU Symposium 314

Young Stars & Planets Near the Sun

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2. What NYMGs teach us about early stellar evolution
3. Dispersal of protoplanetary disks; nature & origins of debris disks
4. How NYMGs inform us about early evolution of planetary systems
5. Nearby young stars and planets: the lik*ely impacts of new and future facilities*

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