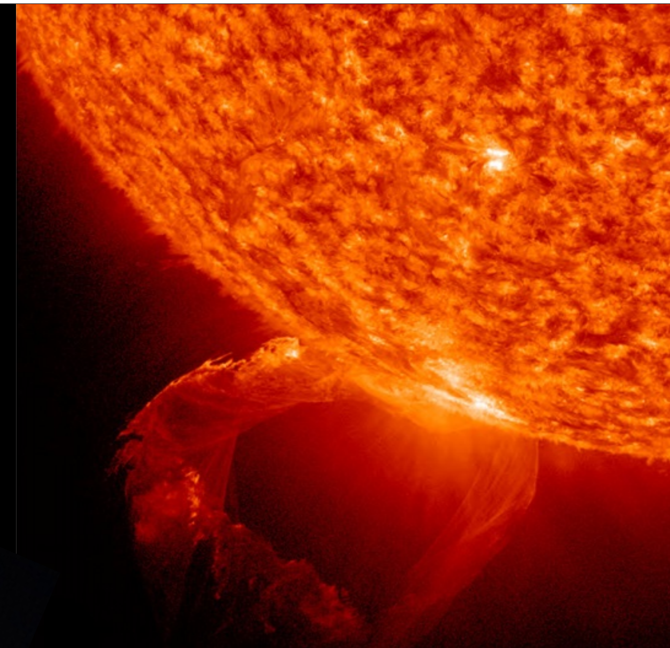
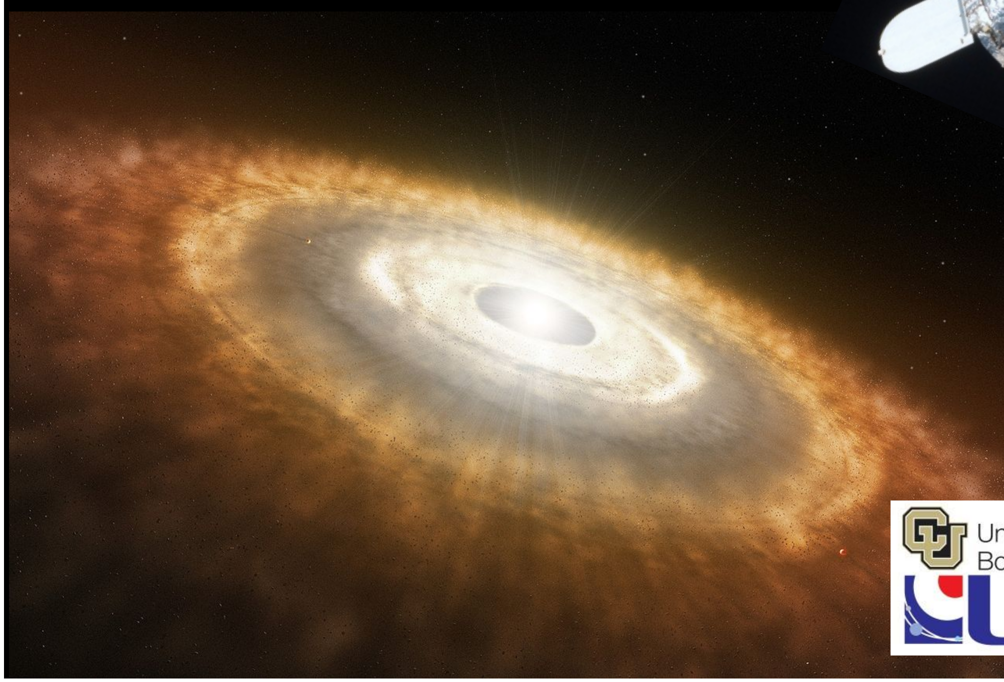
The Ultraviolet View of Protoplanetary Disks: from Hubble To LUVOIR



Kevin France

University of Colorado

LUVOIR Web Seminar – August 10th 2016



University of Colorado Boulder

LASP

Outline

1. Circumstellar gas and dust are the building blocks of planetary systems. New molecular disk diagnostics probed using HST-COS

2. Structure, evolution, and composition of molecular gas at planet-forming radii (r < 10 AU) in protoplanetary environments

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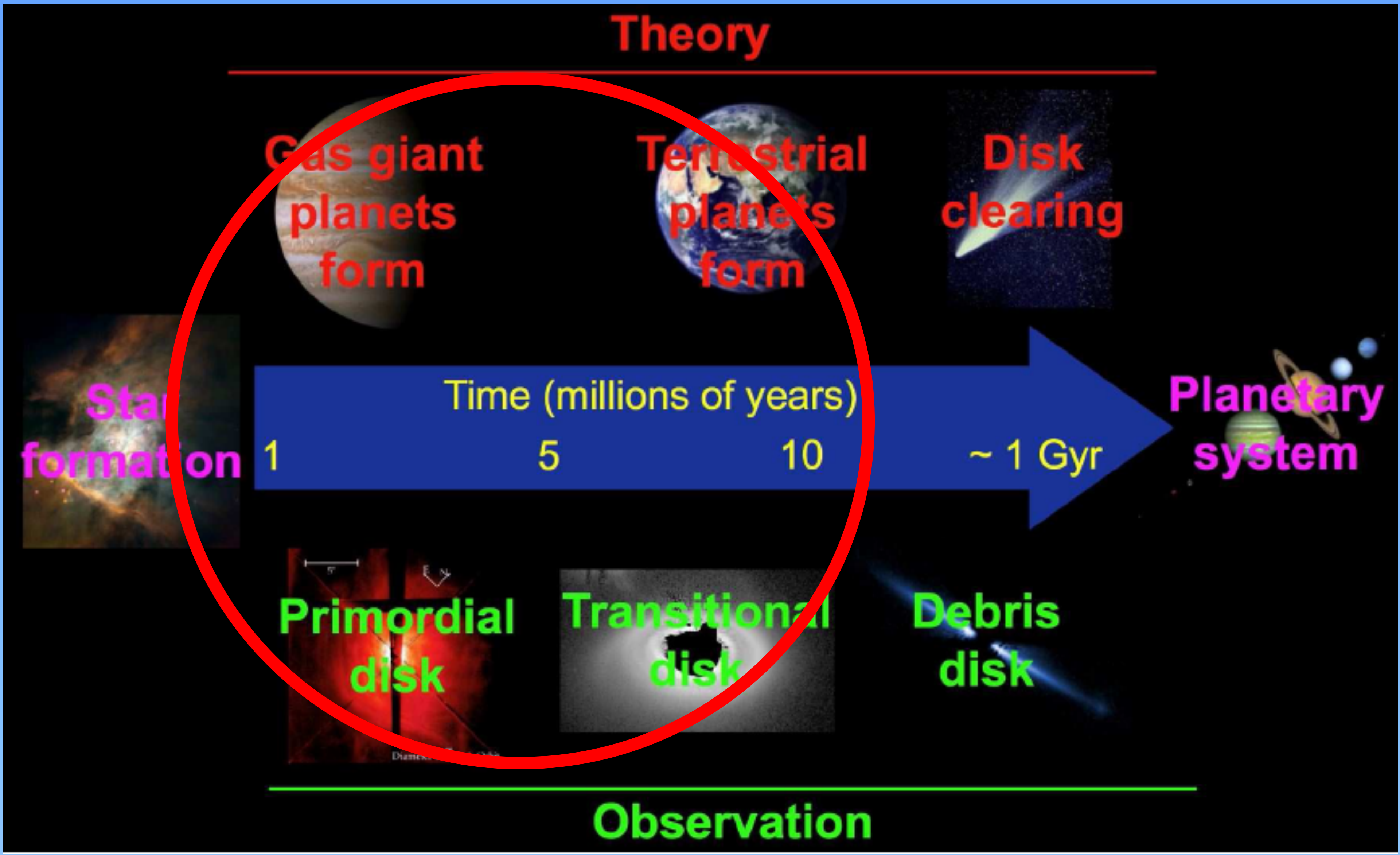
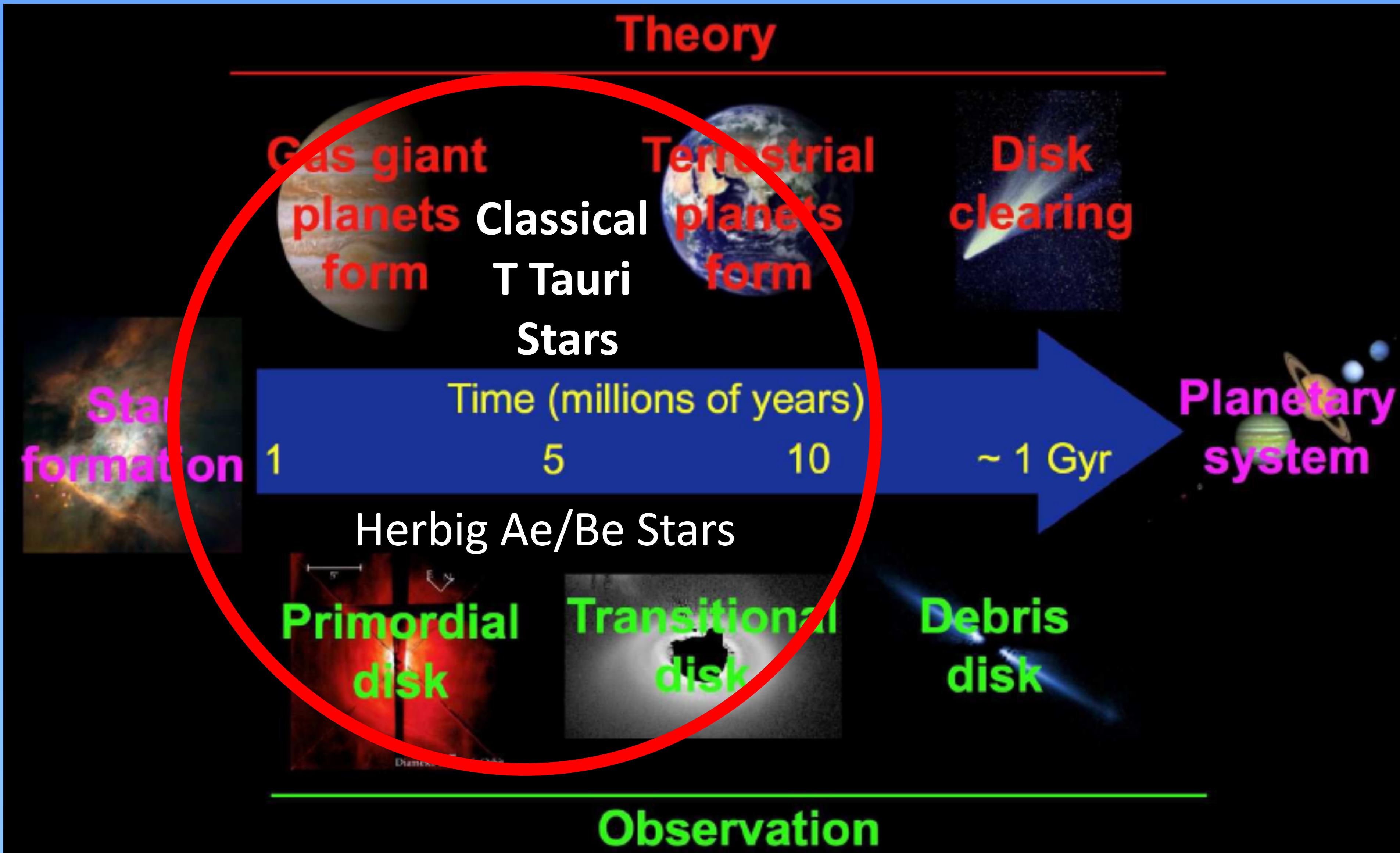
3. The future: Statistical surveys, absorption line spectroscopy towards nearly edge-on disks. Need more effective area, more field-of-view, more spectral resolution…

4. The CHISL spectrograph concept: high-resolution and multi-object FUV spectroscopy with LUVOIR

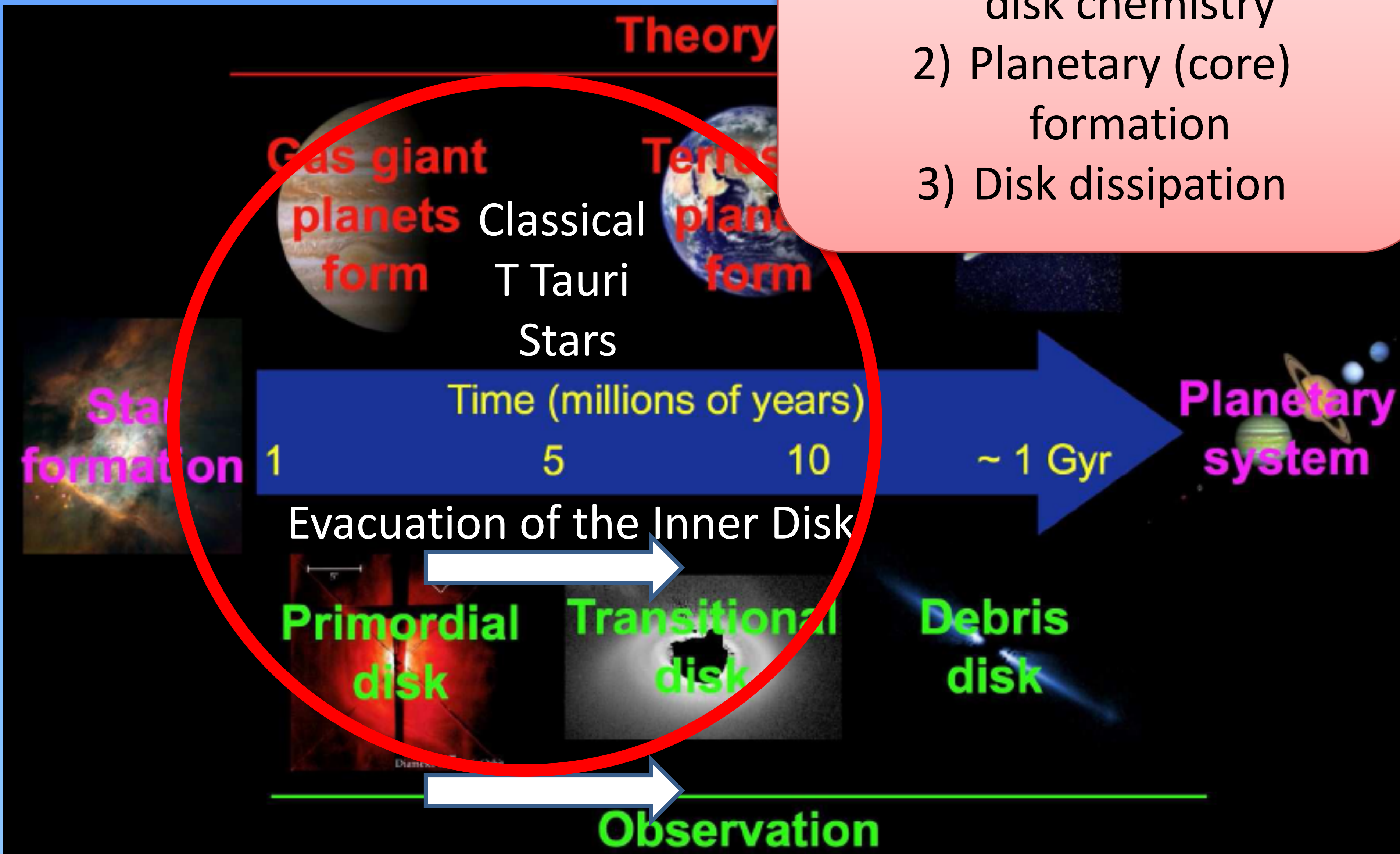


A. Roberge et al. 2009 – Astro2010 White Paper



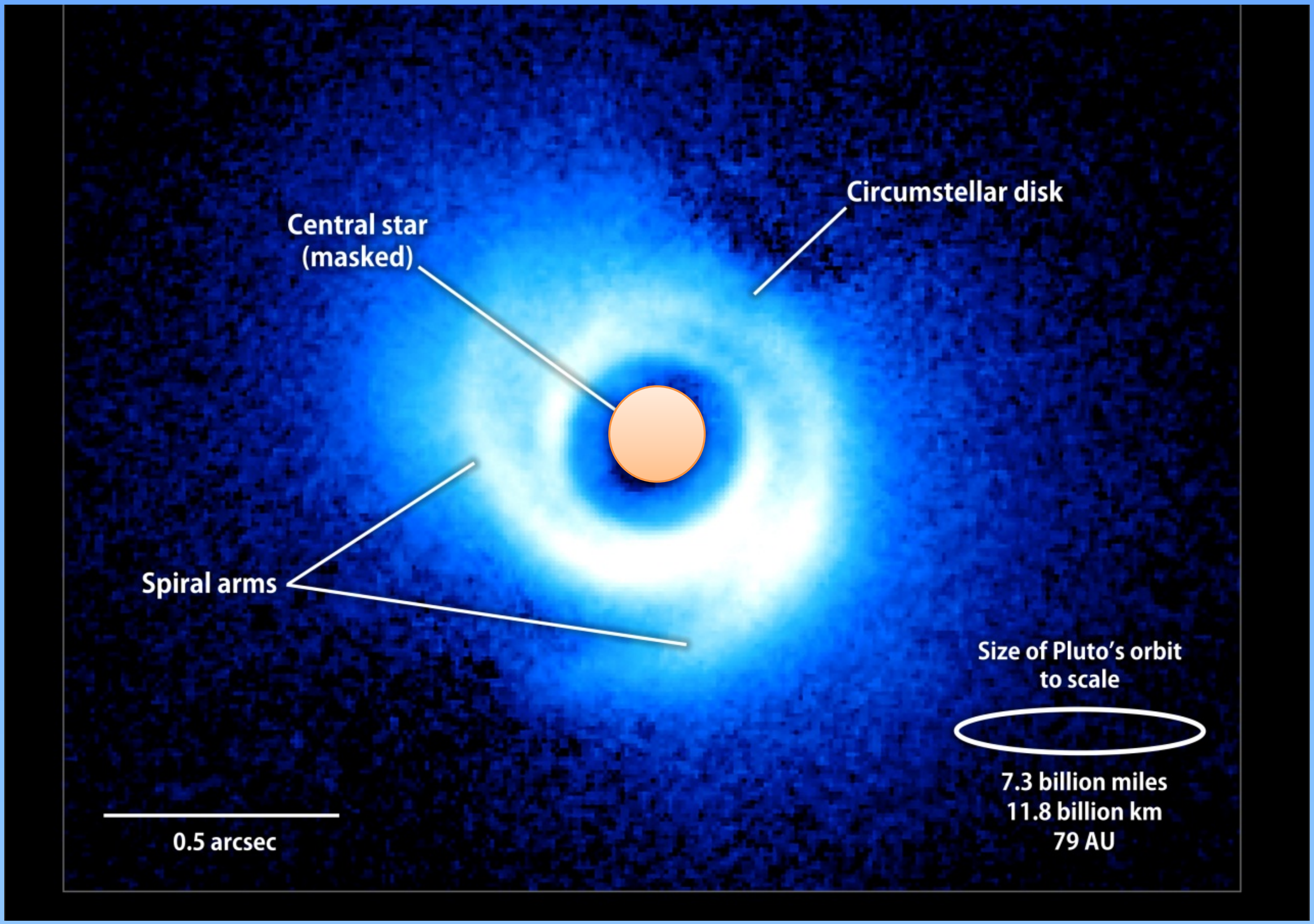
A. Roberge et al. 2009 – Astro2010 White Paper

1) Dark cloud chemistry to disk chemistry
2) Planetary (core) formation
3) Disk dissipation



A. Roberge et al. 2009 – Astro2010

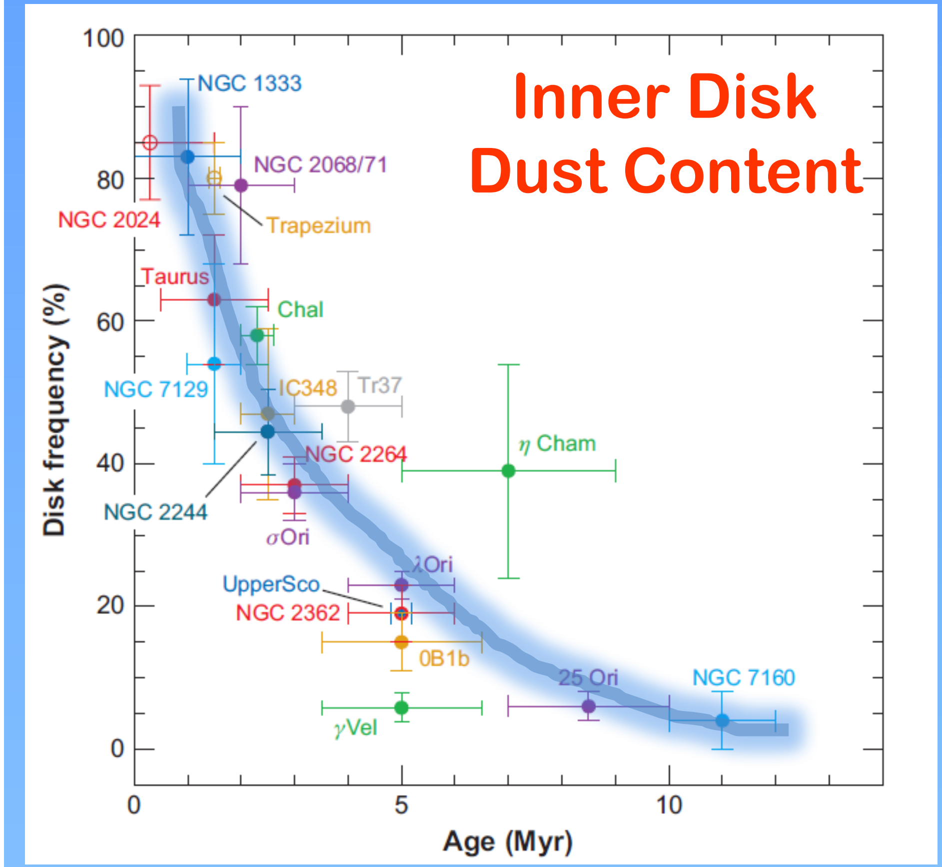
Gas & Dust Disk Structure and Evolution



Muto et al. 2012, Subaru/HiCIAO

Garufi et al. 2013 VLT/NACO

Dust at r < 10 AU

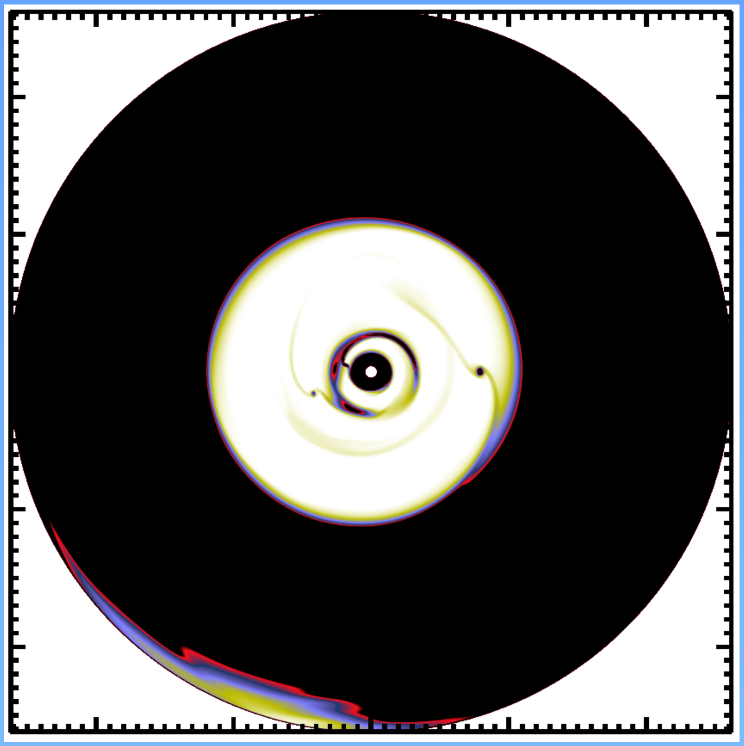


Hernandez+ 2007
Wyatt, ARAA, 2008

Dust disks are observed to clear between ~ 1 – 10 Myr

"Primordial" $\rightarrow$ "Debris"

Dust and Gas at *r* < 10 AU



13 μm optical depth
(Dodson-Robinson & Salyk 2011)

Dust disks clear between
~ 1 – 10 Myr

"Primordial" → "Transitional"?
→ "Debris"

- (multi-)Planetary systems
  (w/Magnetorotational instability?)

Dong & Dawson 2016
Dodson-Robinson & Salyk 2011
Chiang & Murray-Clay 2007

- UV + X-ray photoevaporation

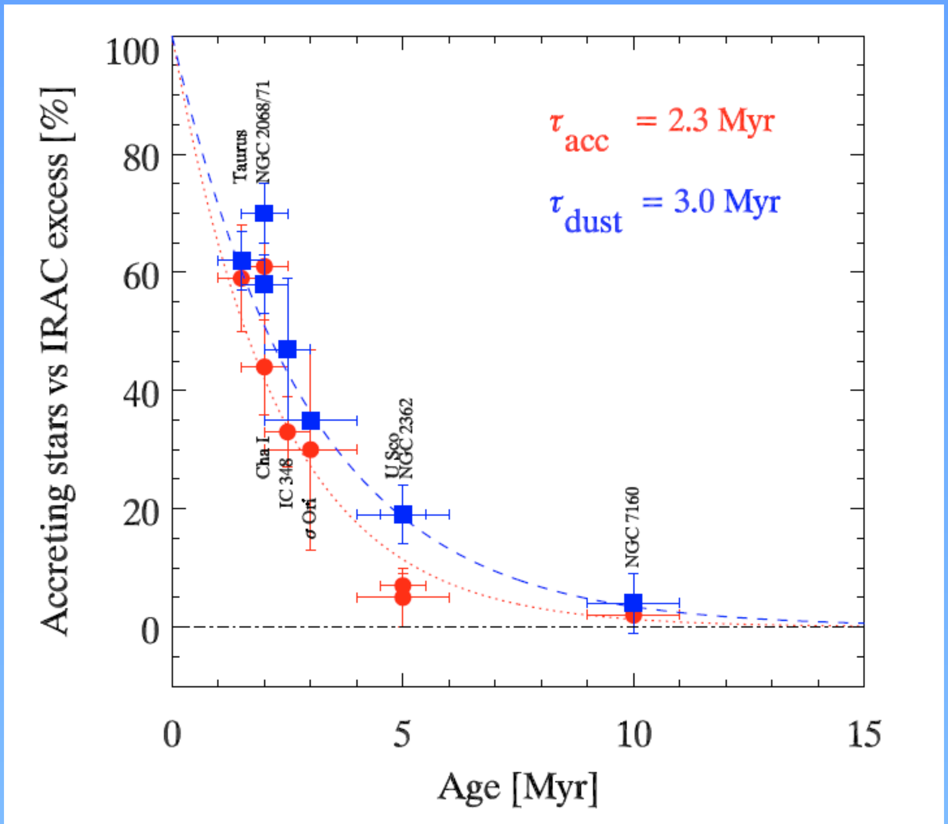
Alexander et al. 2006
Alexander & Armitage 2007
Gorti & Hollenbach 2009
Alexander et al. PPVI 2014

Gas at r < 10 AU

Our definition of inner disk evolution is *mostly* driven by dust characteristics

Does dust content = gas content?

Indirect Gas Observations at r < 10 AU

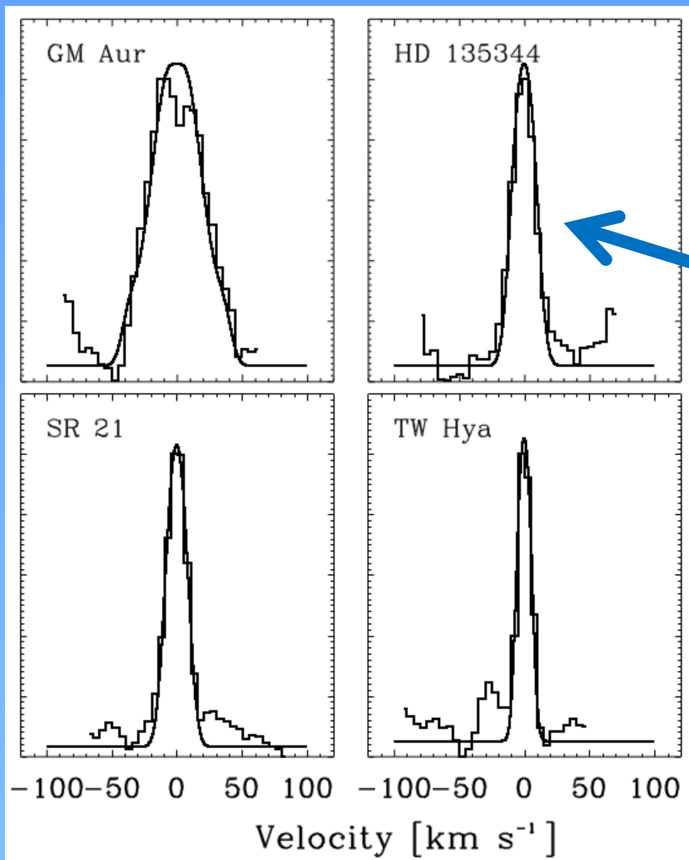


Fedele+, 2010

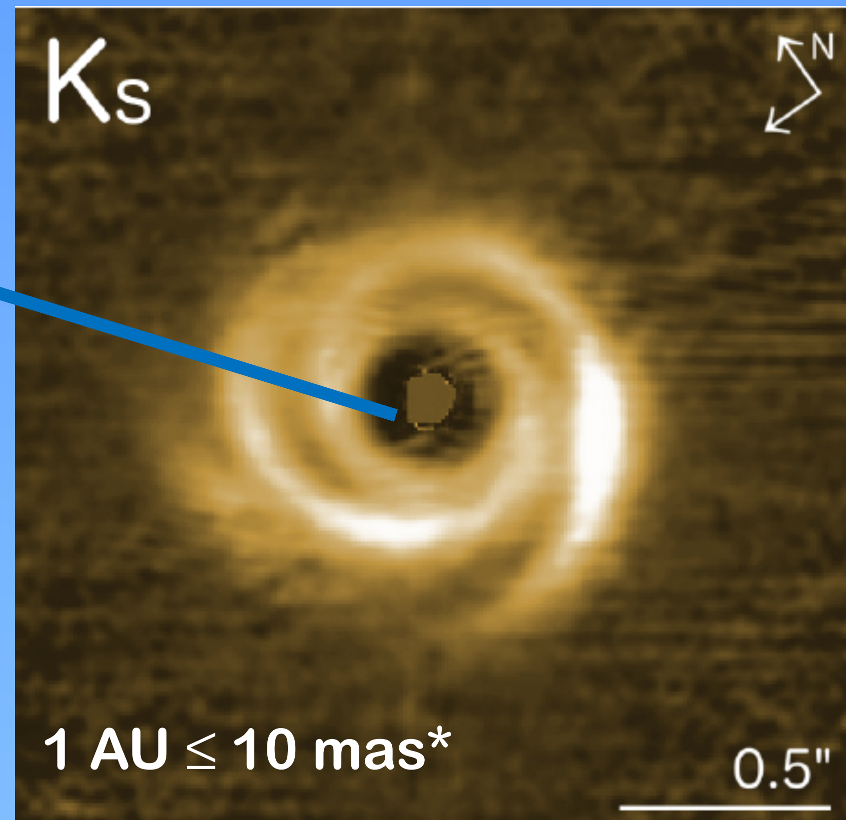
Accretion indicates that gas depletes on comparable time-scales: ~ 2.5 Myr*

*τ_{dust} ~ 4 – 6 Myr @ 24 μm ; Ribas et al. (2014)

Molecules at r < 10 AU



Salyk et al. 2009, Brown et al. 2013,
Banzatti & Pontoppidan 2015



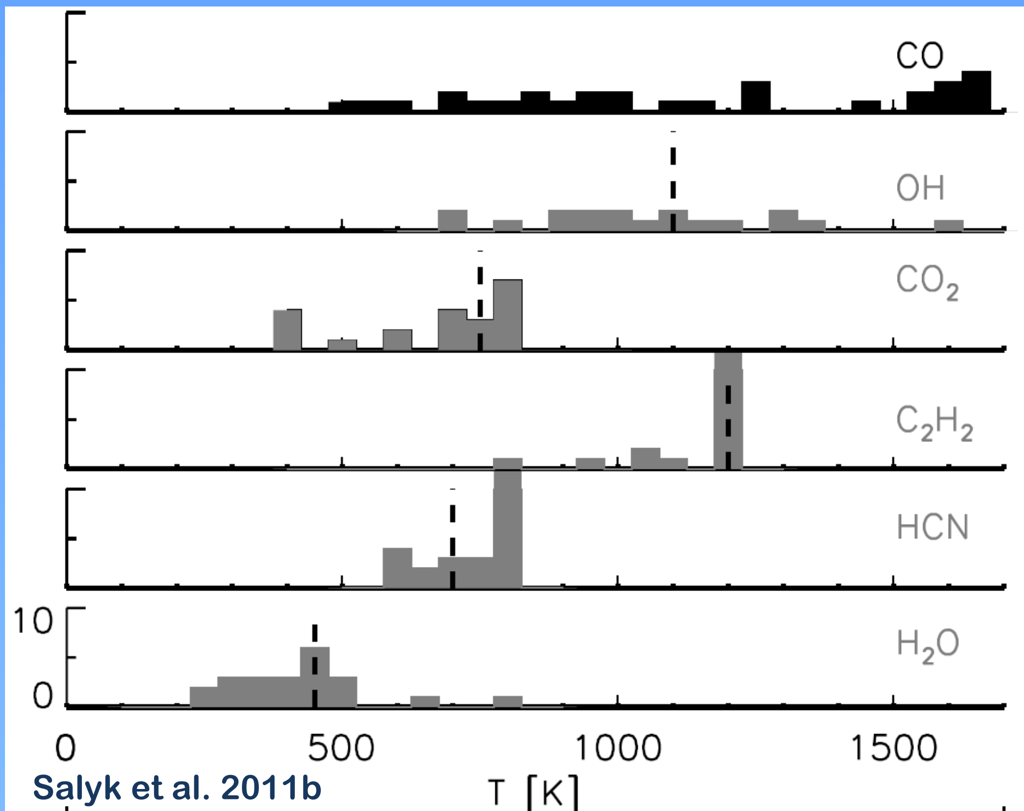
Muto et al. 2012,
Subaru/HiCIAO

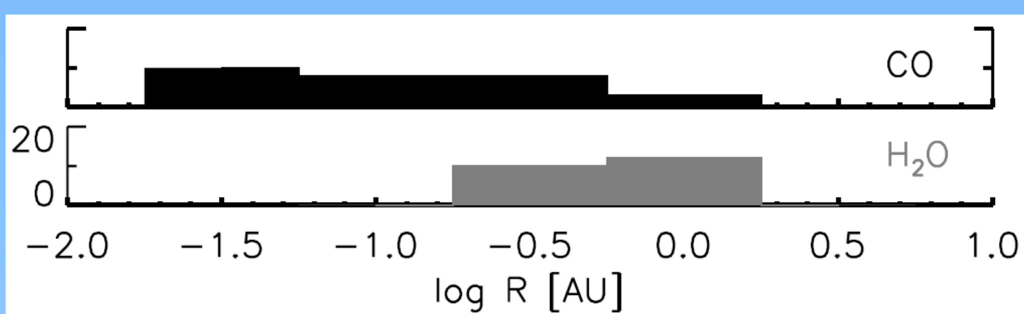
Garufi et al. 2013
VLT/NACO

Collisionally and photo-excited CO disks remain at $r \leq 1$ AU* in systems older than 5 Myr with evolved inner dust disks

*Spectral Line Widths
*Rotational Line Distribution -> T_{exc}

CO, H_2O & organics



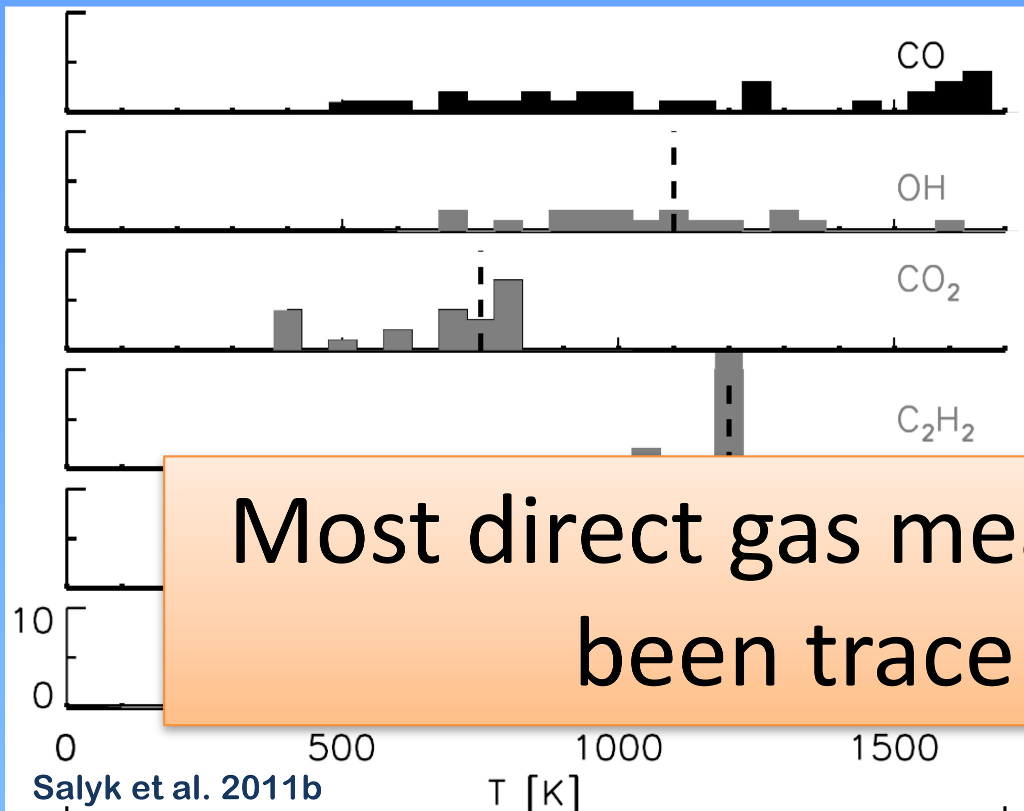


Warm, Inner disk origin:

- R_{mol} < 3 AU
- $T_{mol} \approx 300 - 1200$ K

also Pontoppidan et al. 2011
Mandell et al. 2012

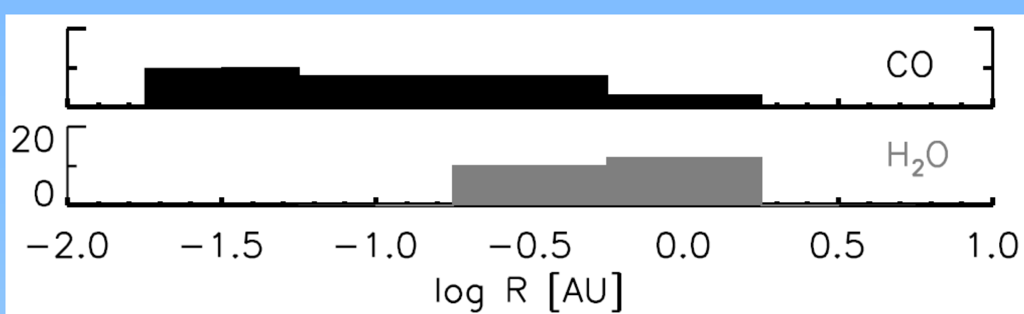
CO, H_2O & organics



Warm, Inner disk origin:

- $R_{mol} < 3$ AU
- $T_{mol} \approx 300 - 1200$ K

Most direct gas measurement have been trace species



also Pontoppidan et al. 2011
Mandell et al. 2012

Molecules at r < 10 AU

- **H_2** makes up > 99% of the molecular gas mass in protoplanetary disks
- Very hard from the ground [may be done with JWST(**?**)]

Molecules at *r* < 10 AU

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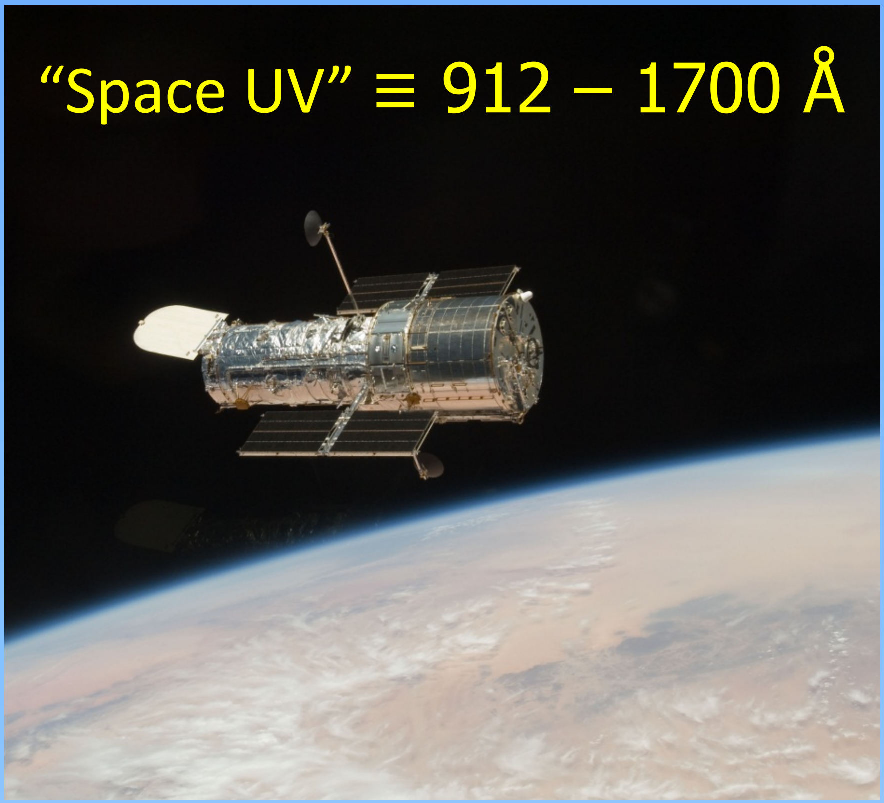


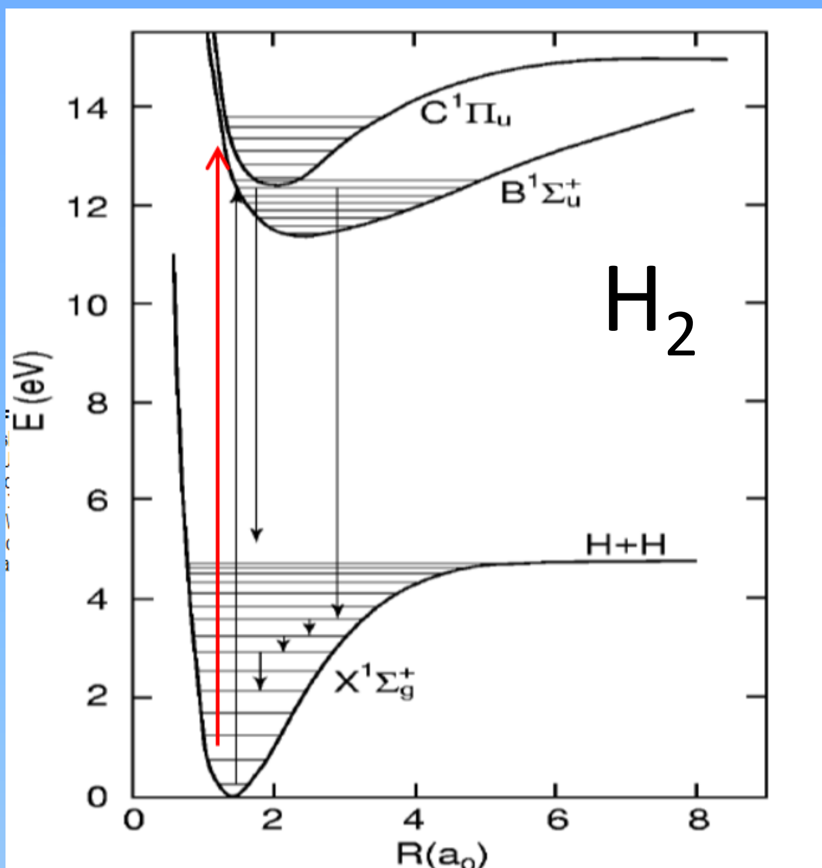
- **H_2** emission lines from warm molecular disk surface

- Molecular absorption lines from deeper in the disk on sightlines to accreting protostar

UV-H_2 and UV-CO

photoexcited H_2 & CO

The electronic band systems of H_2 have transition probabilities ~ 10^{15-18} times greater than near- and mid-IR rovibrational transitions



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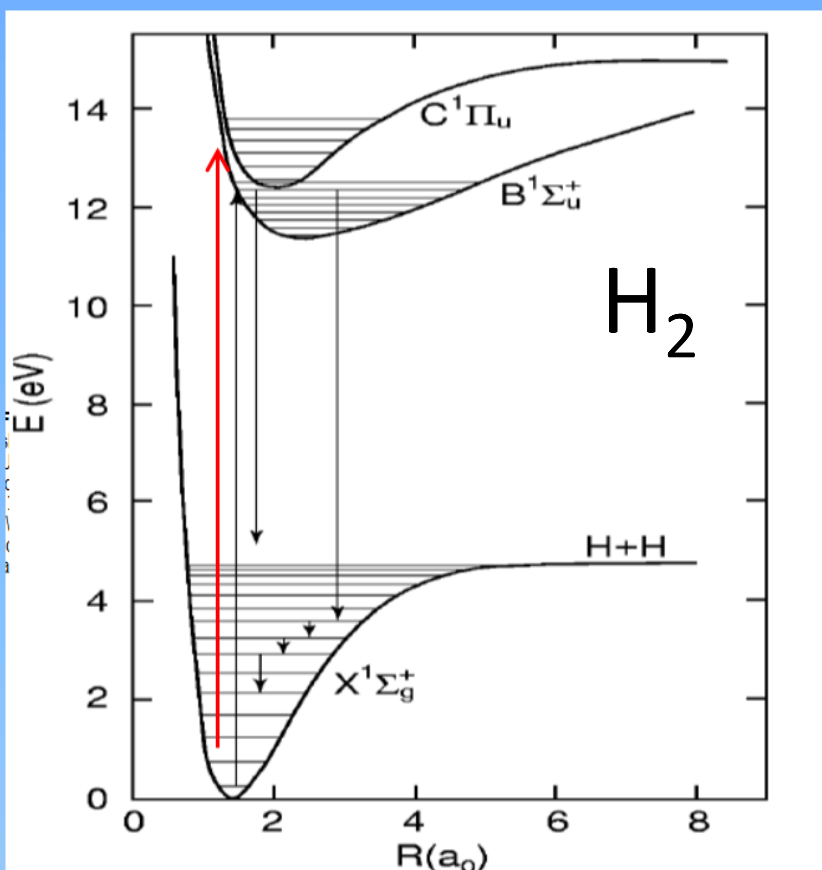
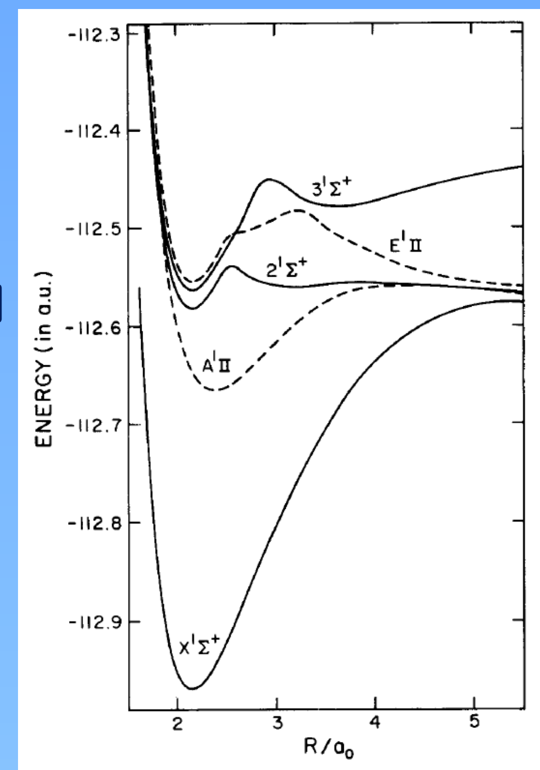


The CO *A-X* Band system in the HST far-UV bandpass



Kirby & Cooper (1989)

HST-Cosmic Origins Spectrograph Protoplanetary Disk Program

- Greg Herczeg – KIAA/Peking
- Eric Schindhelm* – now SwRI
- Matthew McJunkin* - CU
- Keri Hoadley* - CU

Also starring:

Herve Abgrall,	Richard Alexander
David Ardila,	Alex Brown
Joanna Brown,	Ted Bergin
Tom Bethell,	Nuria Calvet
Eric Burgh,	Suzan Edwards
Jim Green,	Scott Gregory
Graham Harper,	Lynne Hillenbrand
Laura Ingleby*,	Chris Johns-Krull
Jeff Linsky,	Christian Schneider
Evelyne Roueff,	Jeff Valenti
Fred Walter,	Hao Yang

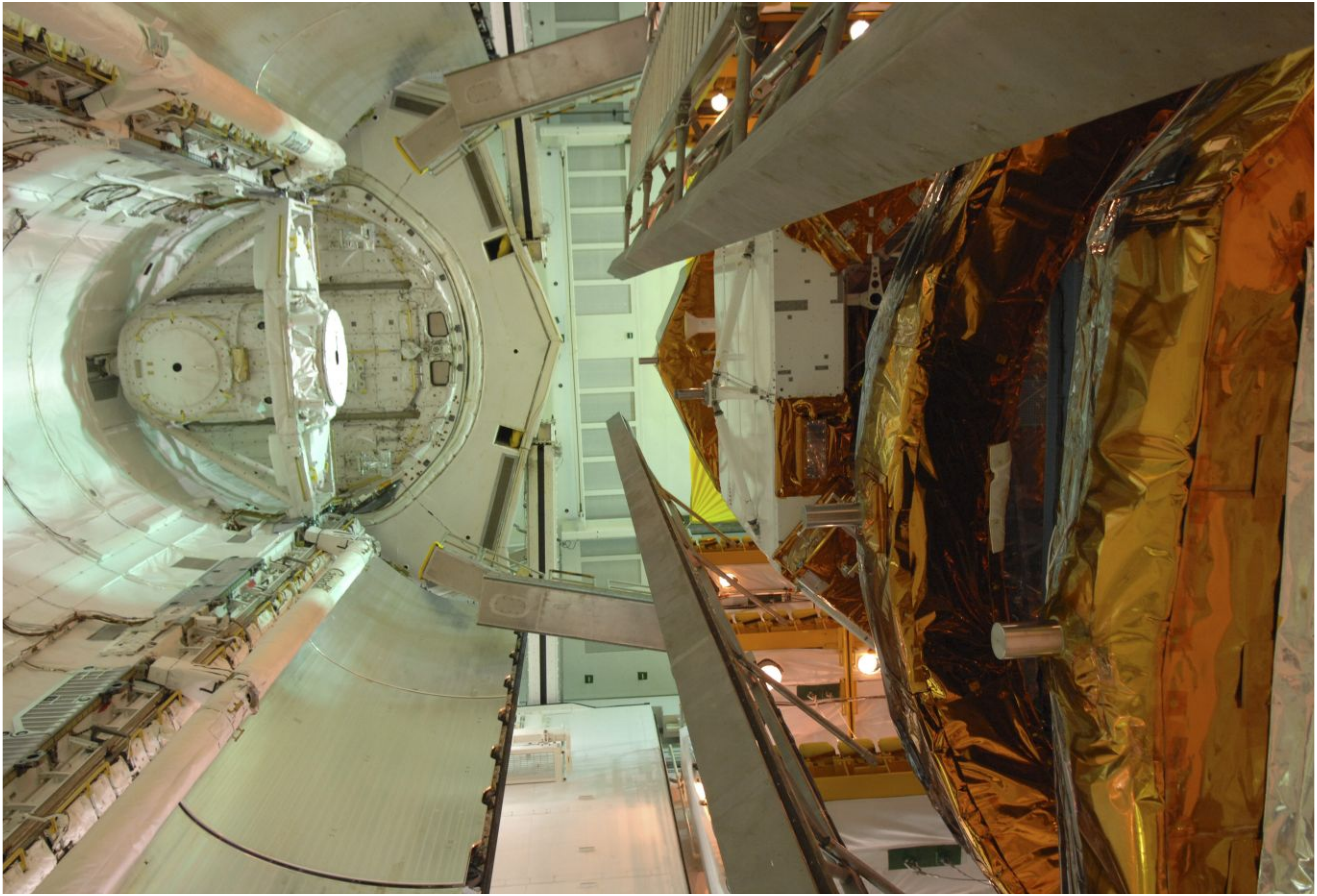
- **Sample of ~50 young stars (Class II and III protostars)**
  - **~80% with active accretion (CTTS)**
  - **~20% w/o accretion (WTTS)**

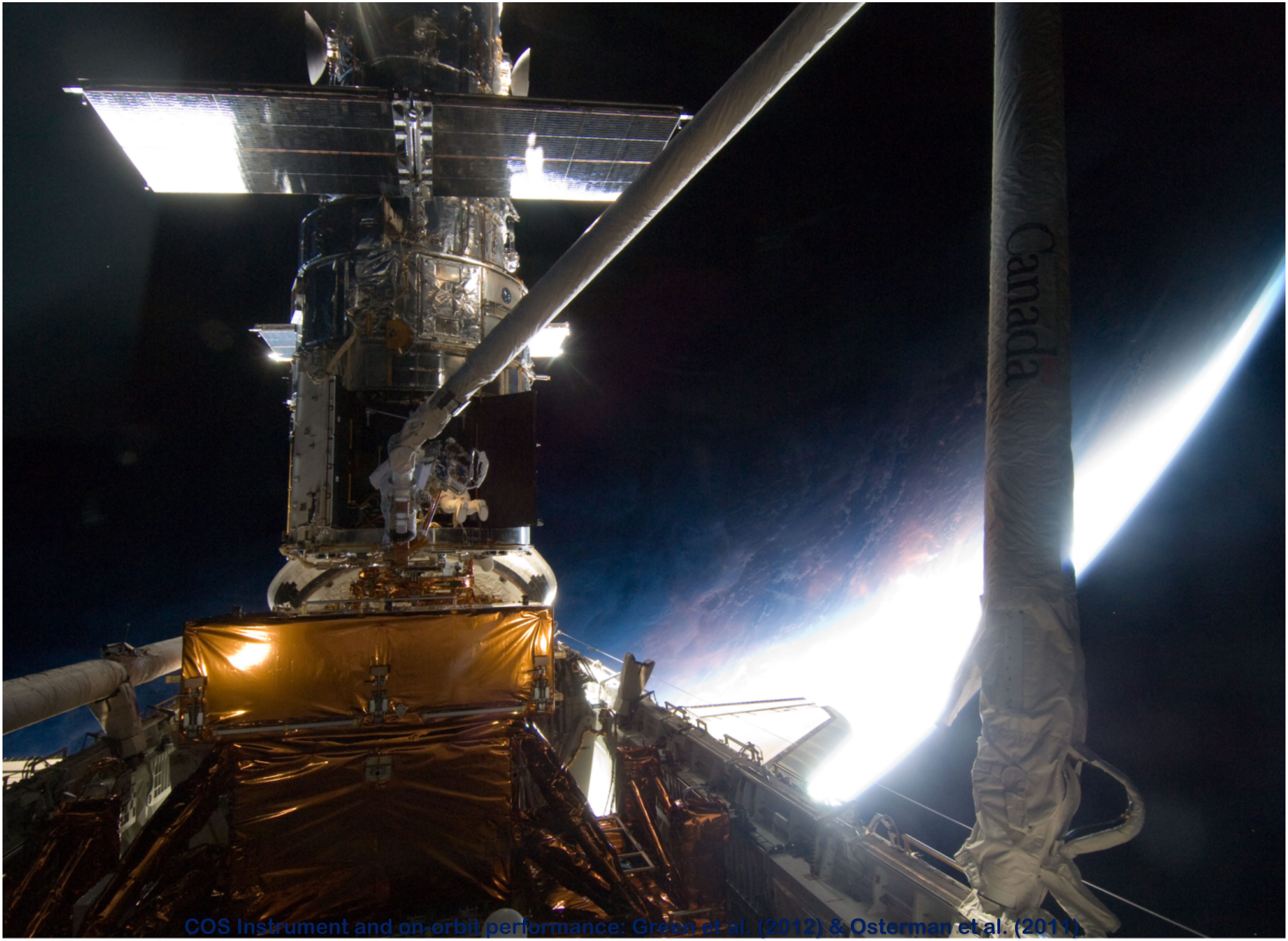
(Ardila et al. 2013; France et al. 2012b)

Cosmic Origins Spectrograph:

10 – 50 times sensitivity increase for medium-res ($R \approx$ 20,000) spectroscopy

COS Instrument and on-orbit performance: Green et al. (2012) & Osterman et al. (2011)

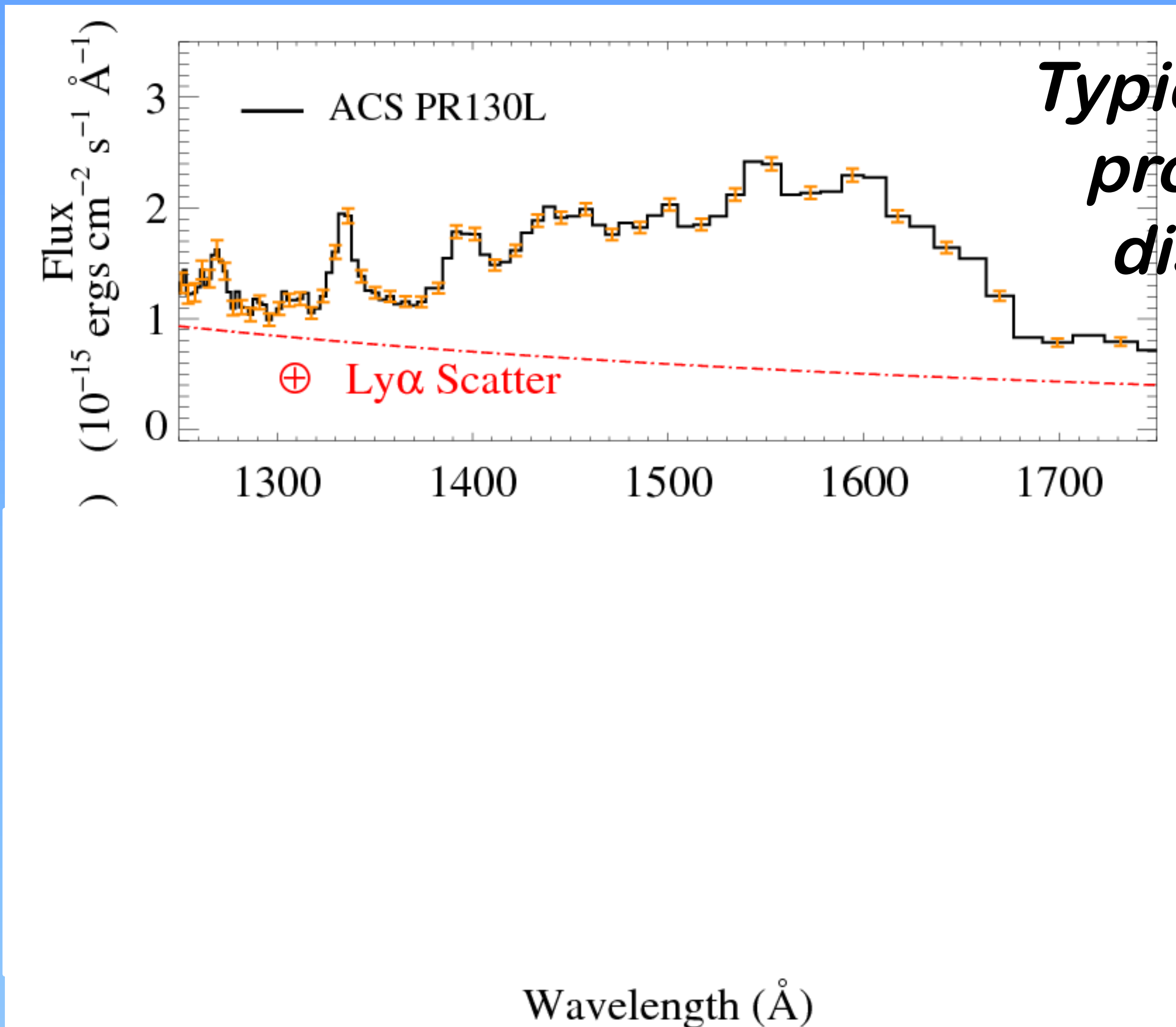




COS Instrument and on-orbit performance: Green et al. (2012) & Osterman et al. (2011)

S125E009194

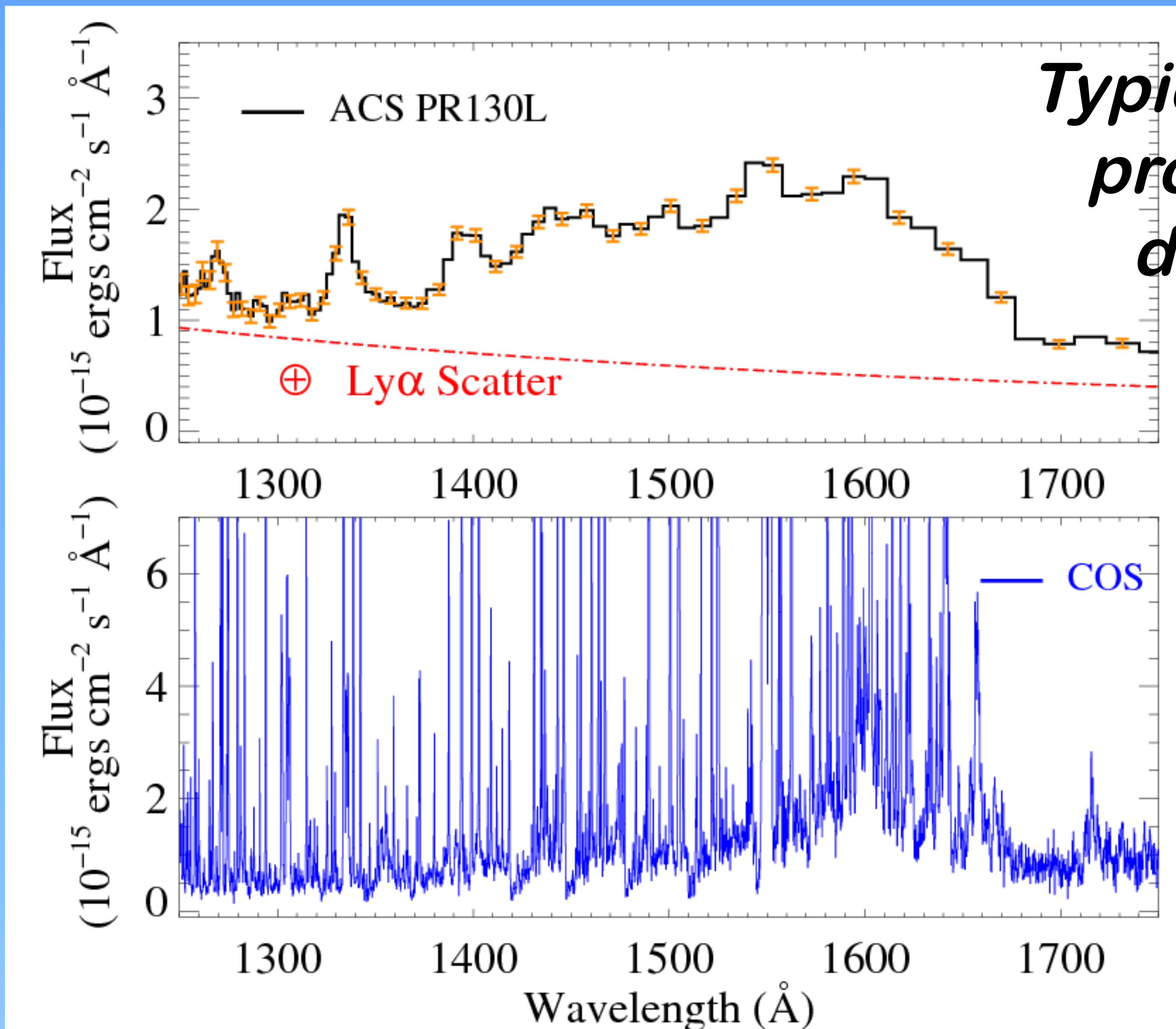
COS Disk Program



Typical (t < 10 Myr) protoplanetary disk, pre-COS

(France et al. 2012a; Green et al. 2012)

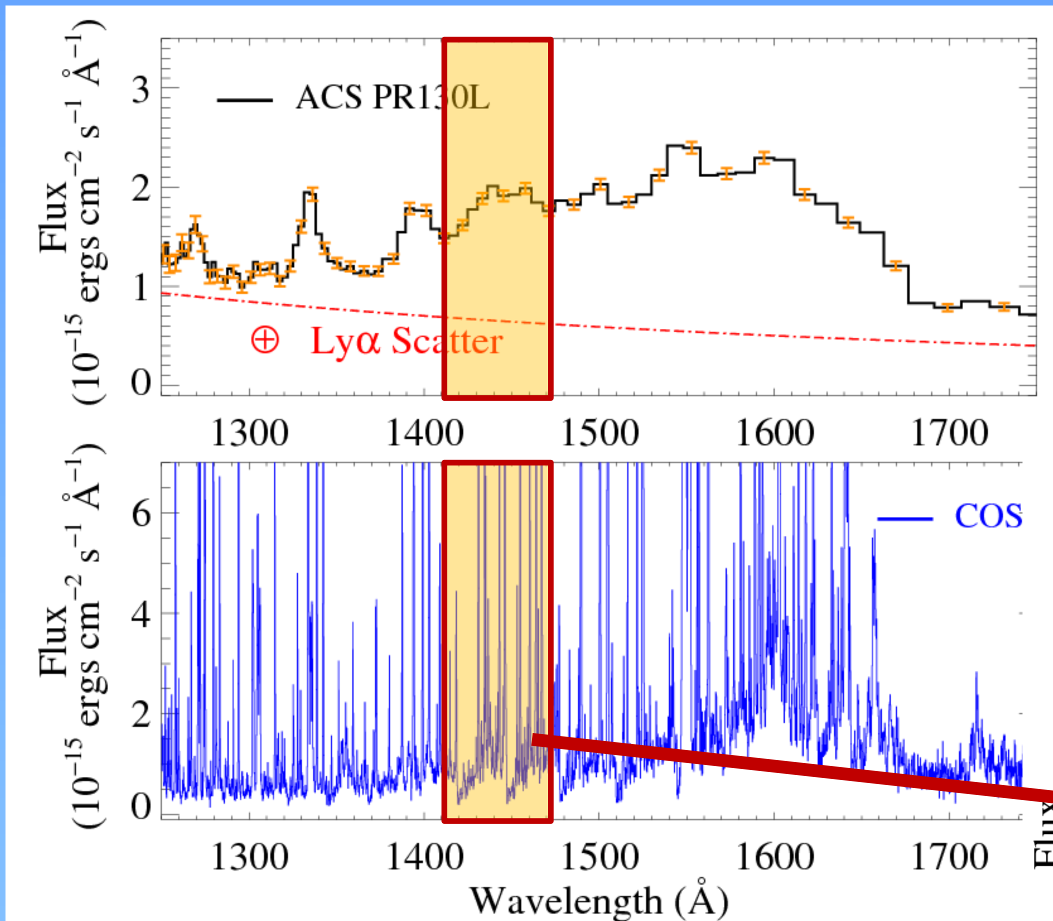
COS Disk Program



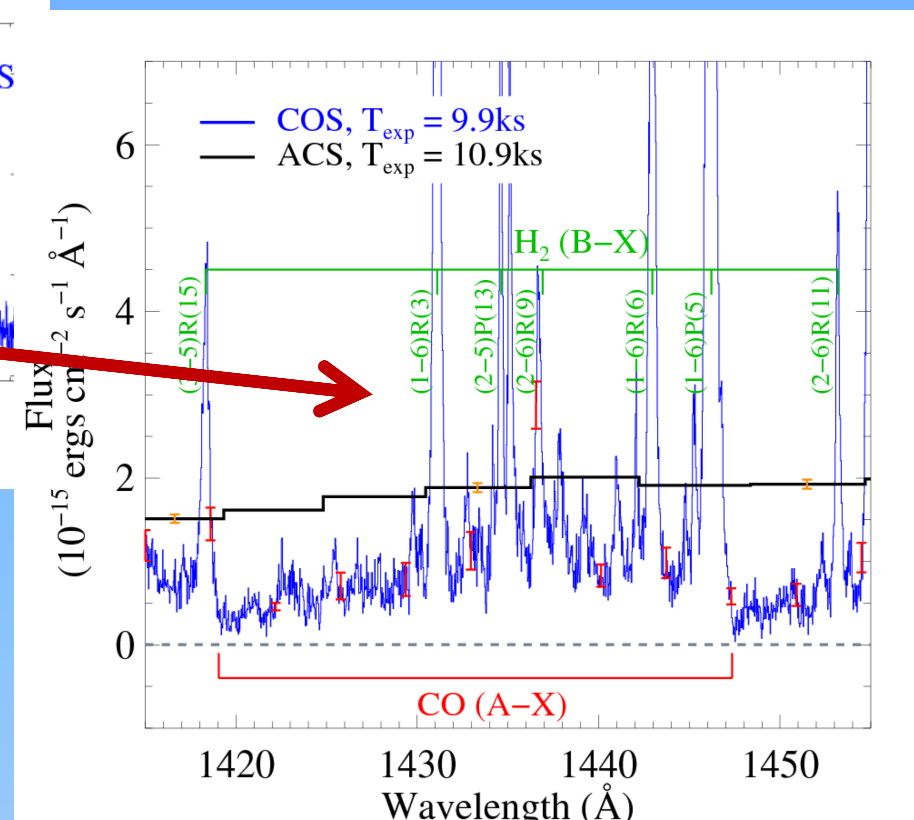
Typical (t < 10 Myr) protoplanetary disk, w/ COS

(France et al. 2012a; Green et al. 2012)

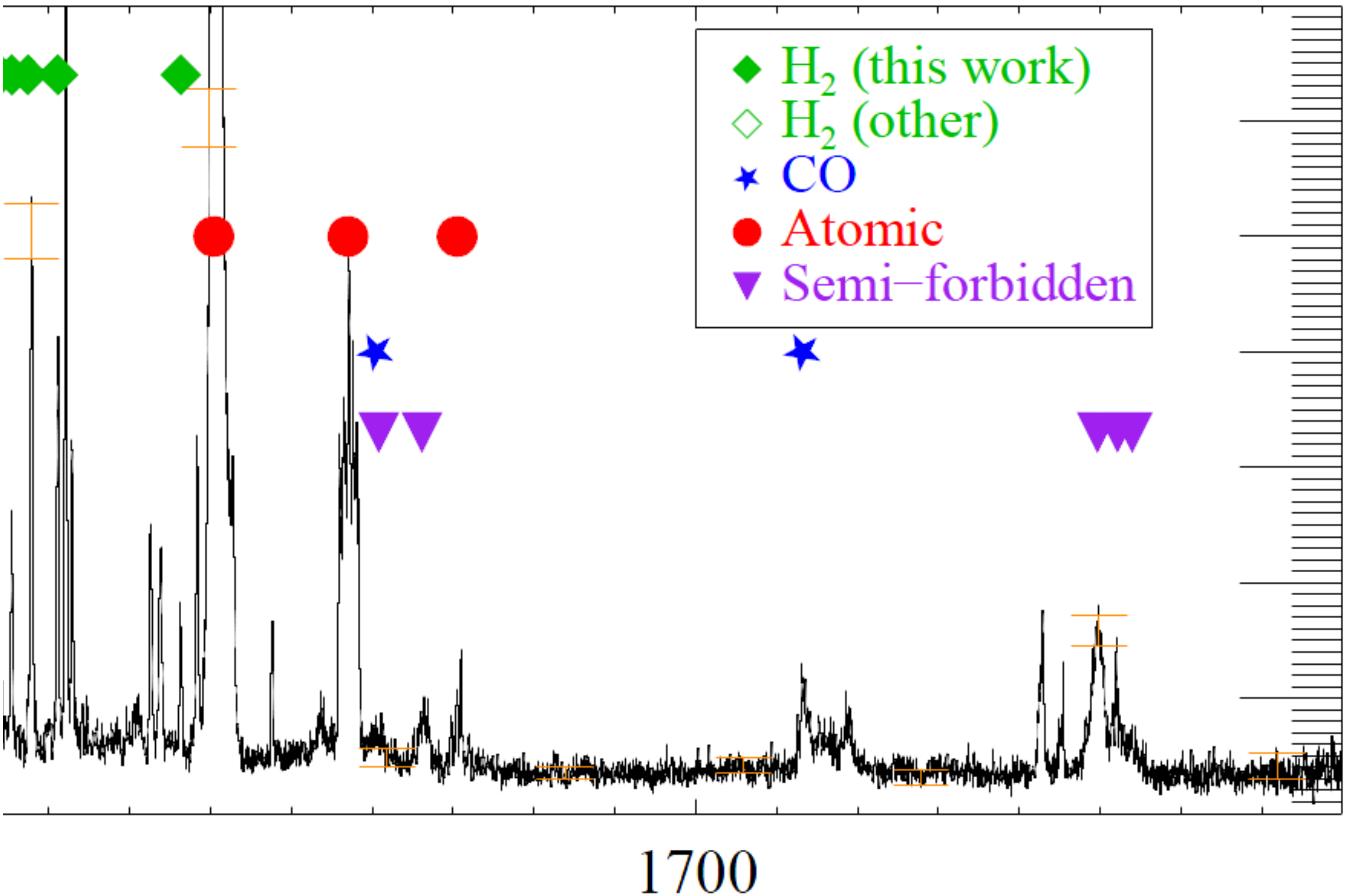
Molecules in Protoplanetary Disks: Ultraviolet Emission from the Inner Disk



Typical (t < 10 Myr) protoplanetary disk, w/ COS



Resolved H_2 and CO emission and absorption features from the disk

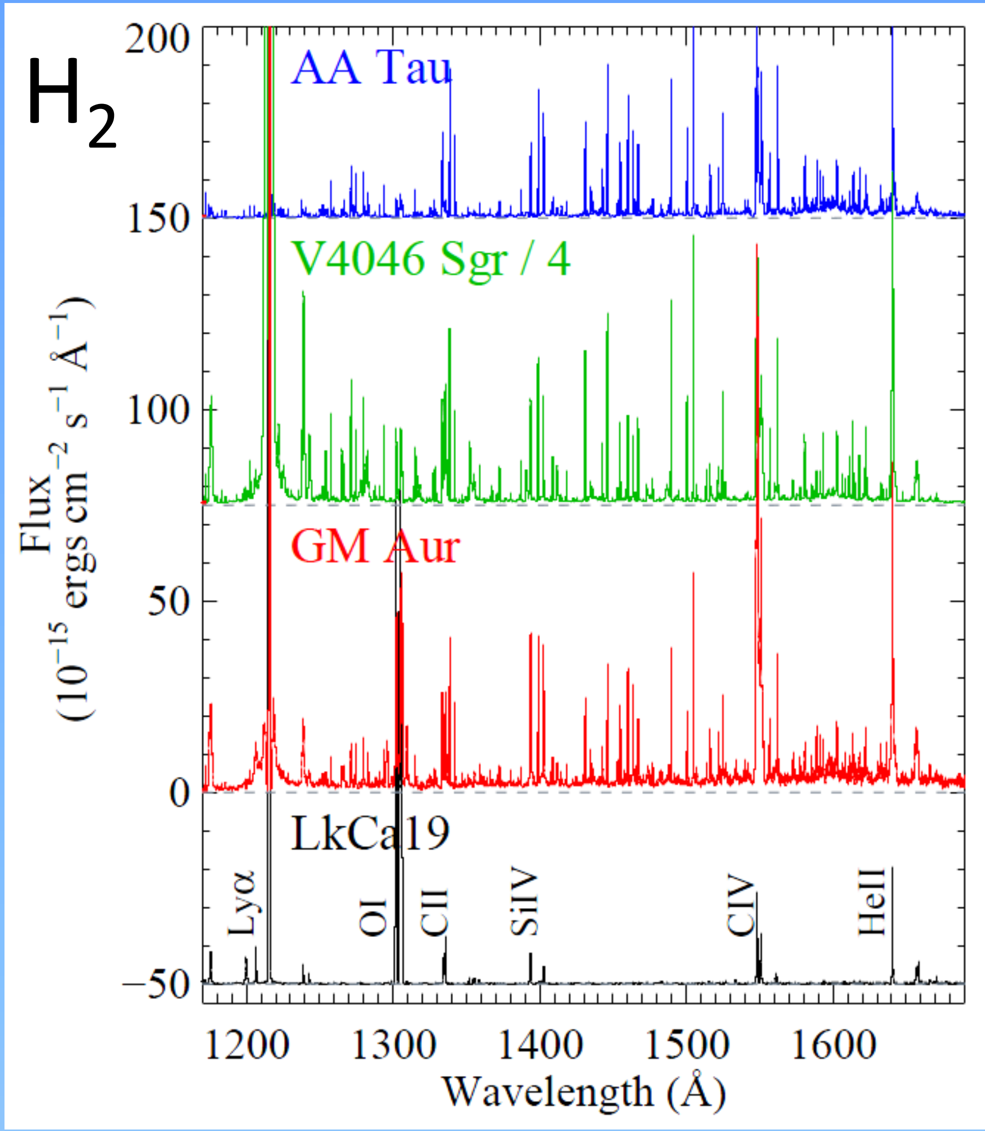

H2 (this work)
H2 (other)
CO
Atomic
Semi−forbidden
1700

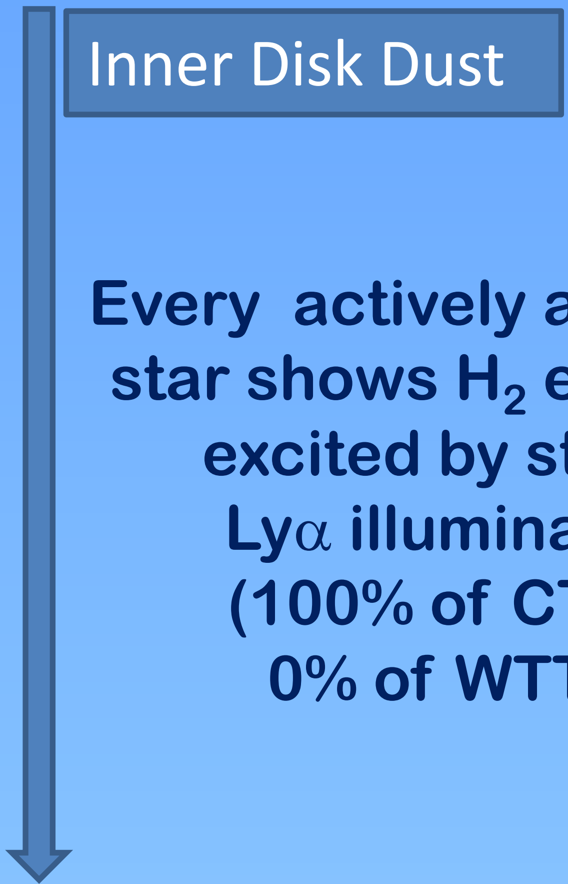
H_2 & CO

EMISSION SPECTRA
LYα - PUMPED FLUORESCENCE

France et al. (2012b)

Molecules in Protoplanetary Disks: Ultraviolet Emission from the Inner Disk

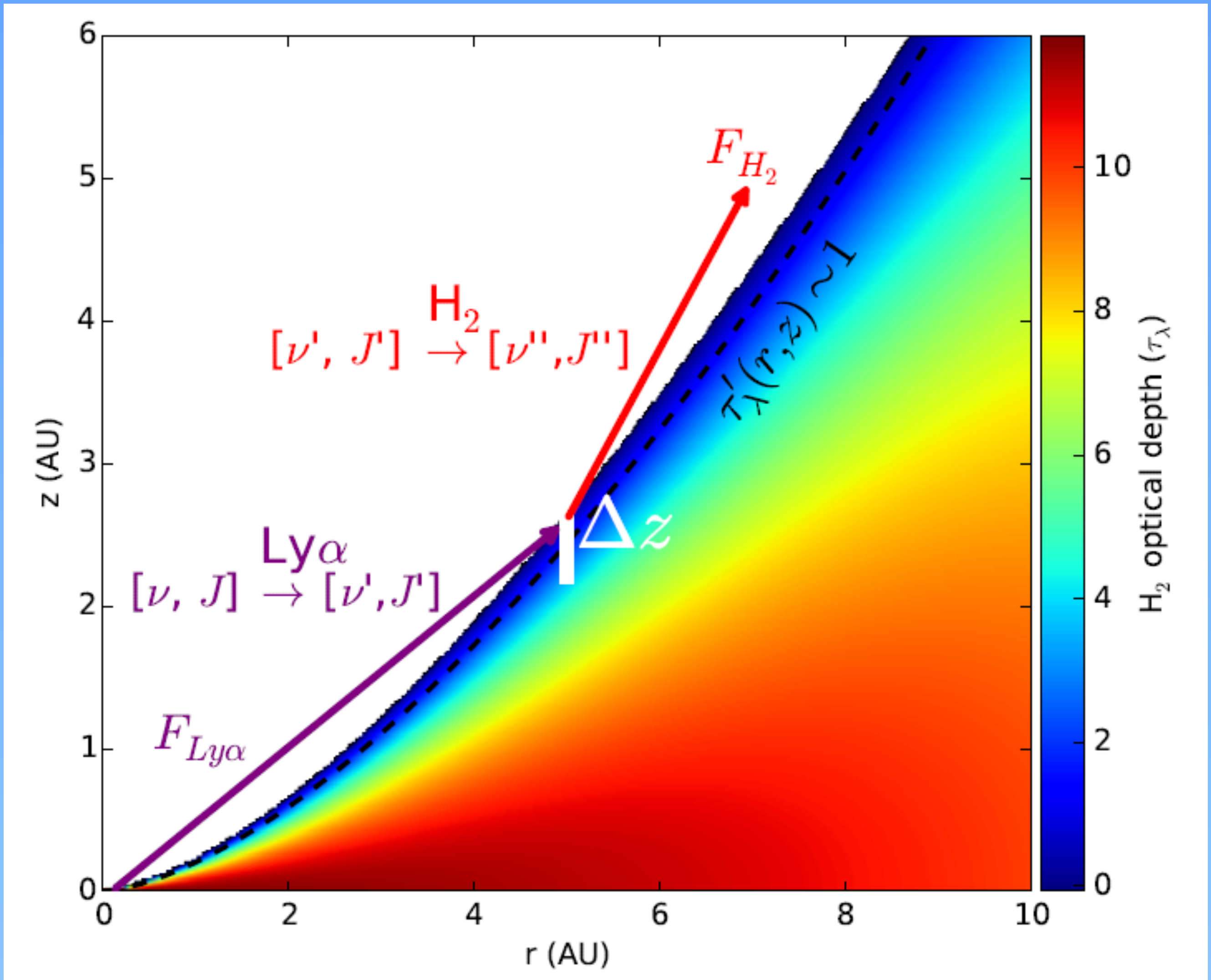




Every actively accreting star shows H_2 emission excited by strong Lyα illumination (100% of CTTS, 0% of WTTS)

France et al. (2012b); also Ingleby et al. (2011a)

Molecular Structure in Protoplanetary Disks: Ultraviolet Emission from the Inner Disk

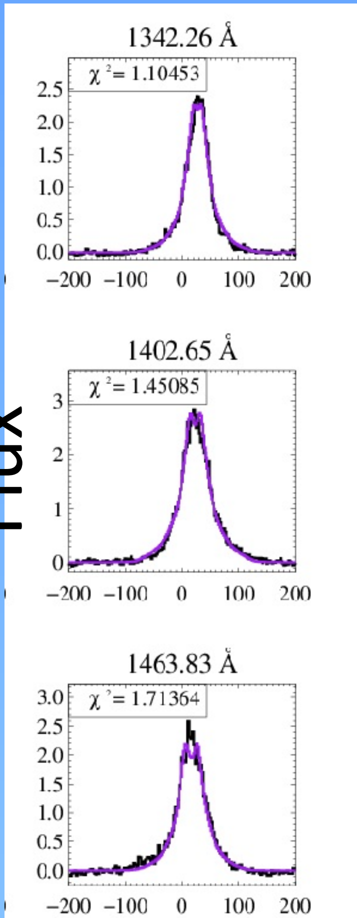


Photoexcitation and Radiative Transfer Modeling of Lyα Fluorescence

Hoadley, France et al. (2015)

Molecular Structure in Protoplanetary Disks: Ultraviolet Emission from the Inner Disk

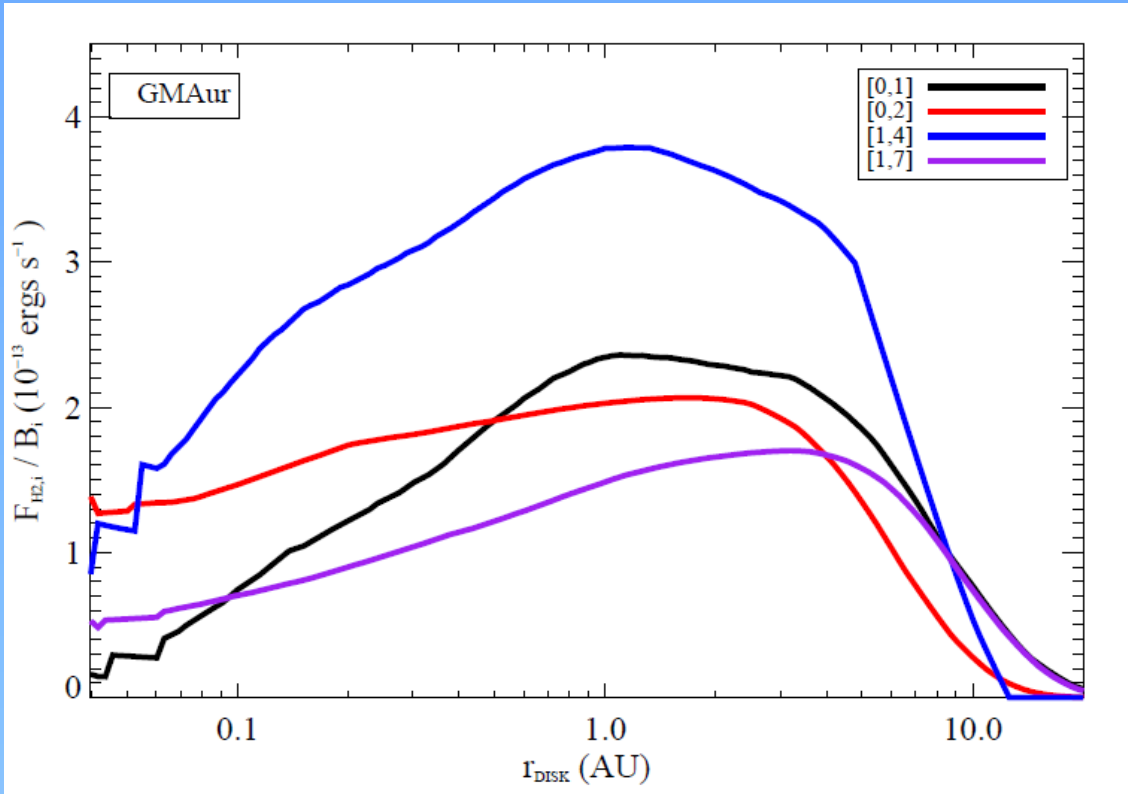
H_2



Flux

Velocity (km/s)

Simultaneously fit emission line flux and profiles from 12 H_2 lines

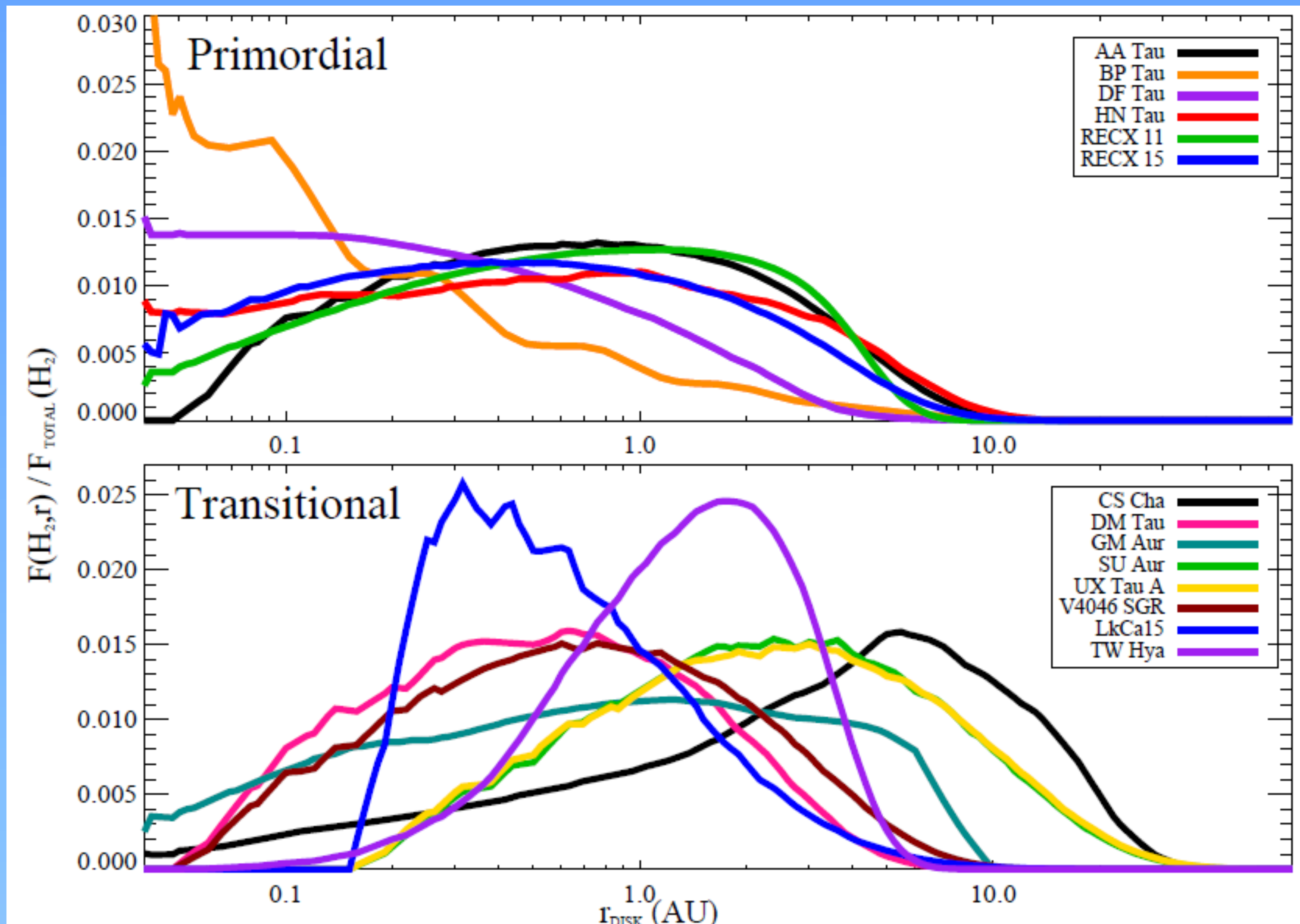


Flux

Radius (AU)

Hoadley, France et al. (2015)

Molecular Structure in Protoplanetary Disks: Ultraviolet Emission from the Inner Disk



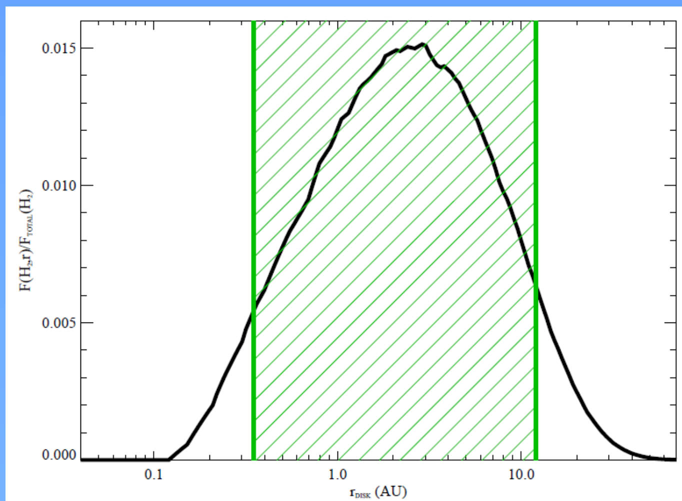
Flux

Radius (AU)

Hoadley, France et al. (2015)

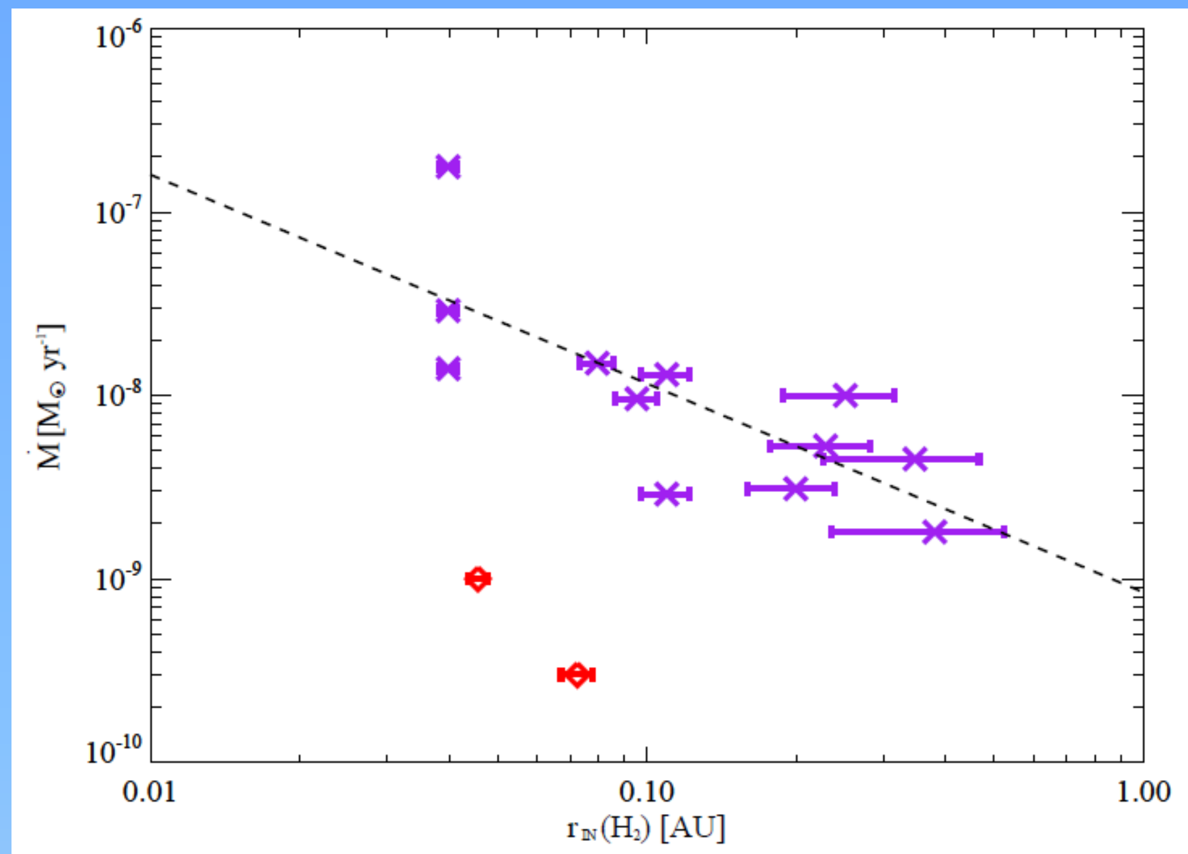
Molecular Structure in Protoplanetary Disks: Ultraviolet Emission from the Inner Disk

Flux



Radius (AU)

M_{acc}

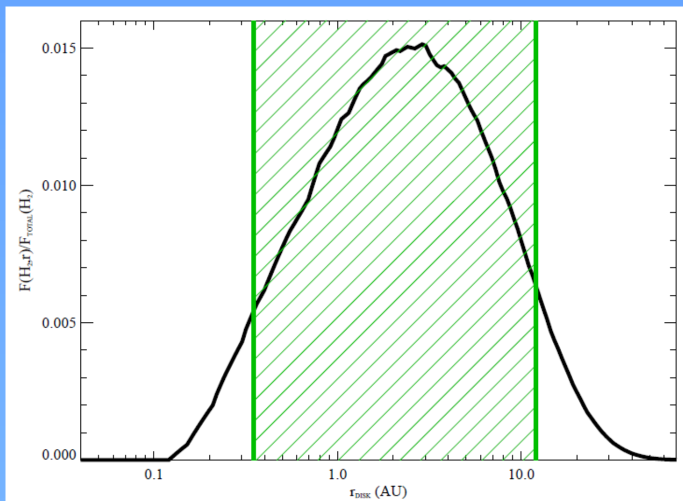


r_{in} (H_2)

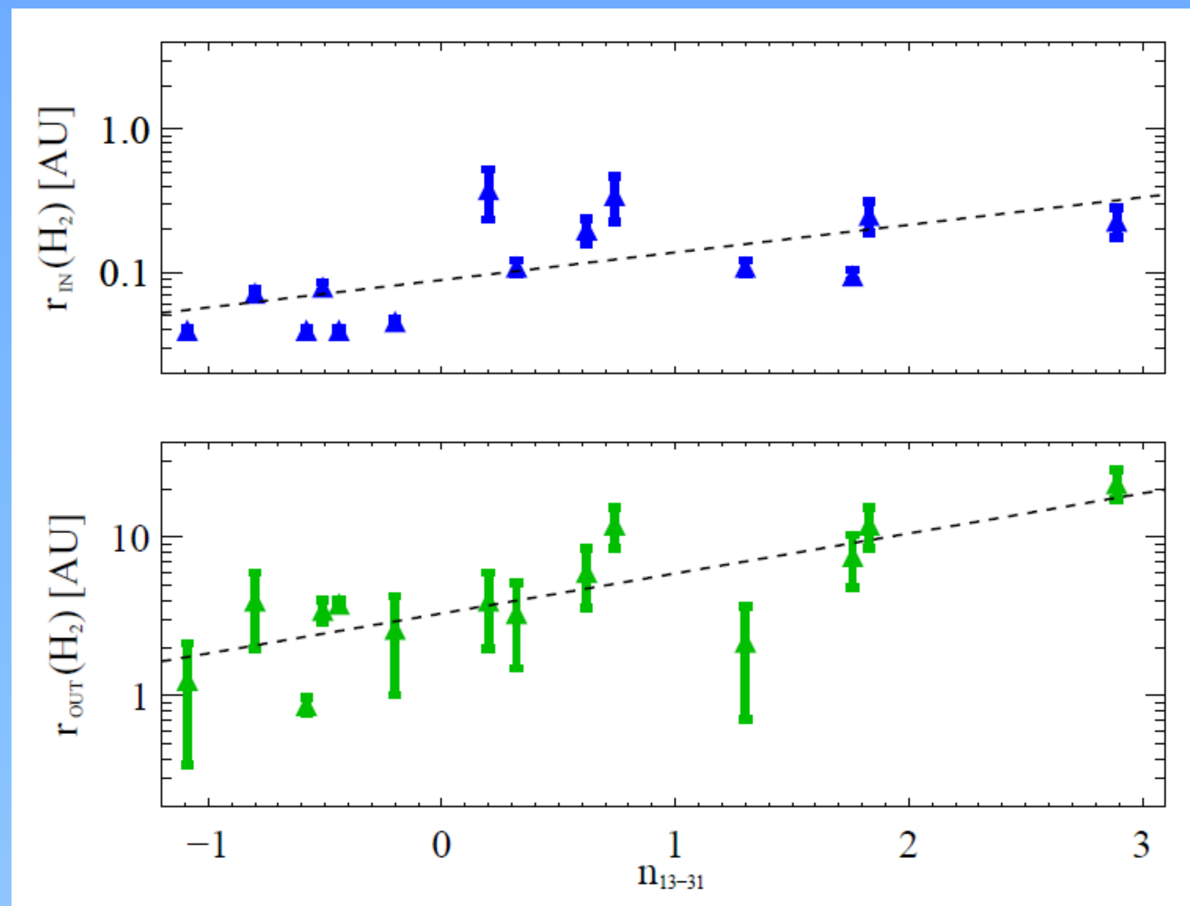
Hoadley, France et al. (2015)

Molecular Structure in Protoplanetary Disks: Ultraviolet Emission from the Inner Disk

Flux



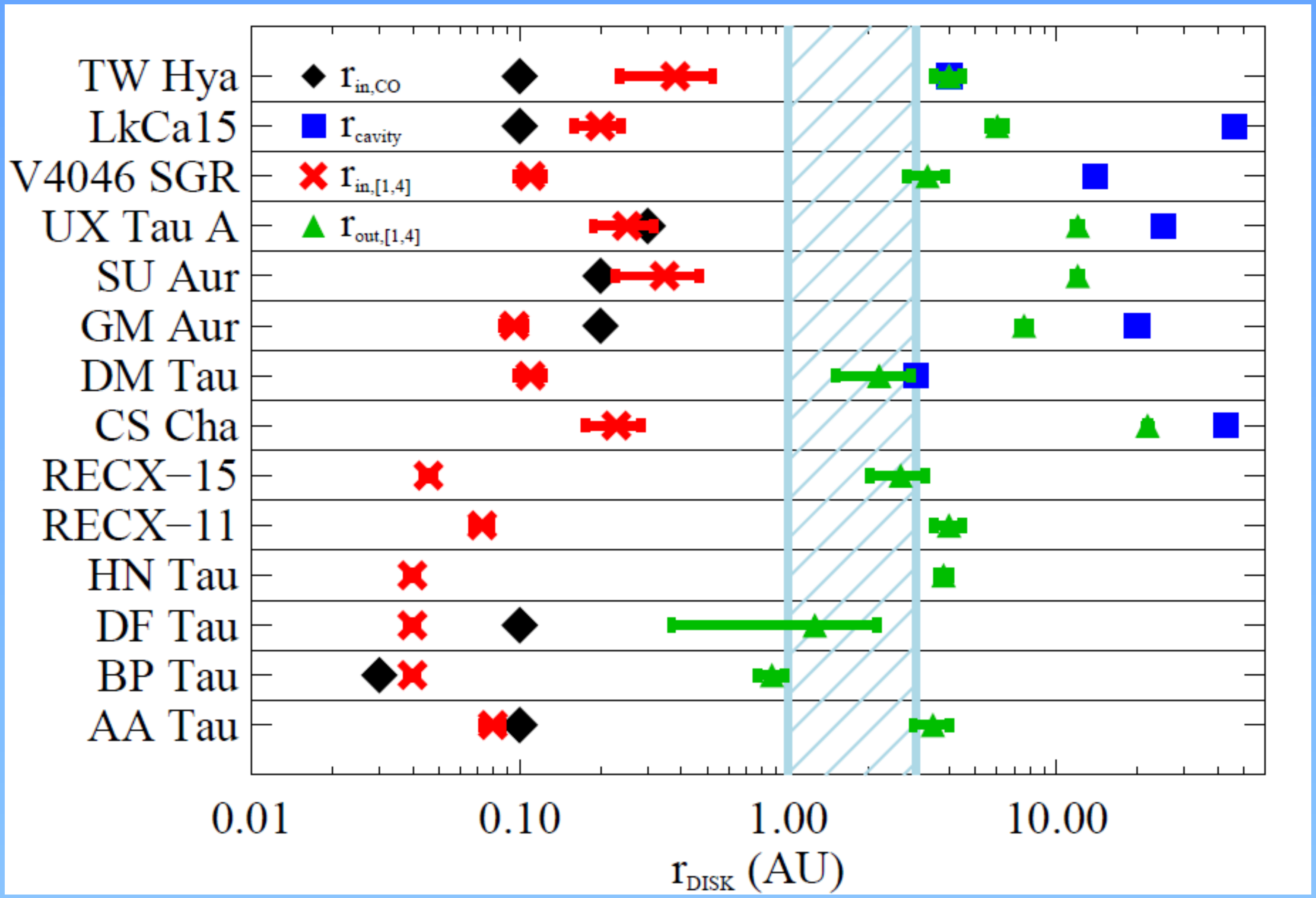
Radius (AU)



$n_{13\text{-}31}$ (dust clearing) →

Hoadley, France et al. (2015)

Molecular Structure in Protoplanetary Disks: Ultraviolet Emission from the Inner Disk



Radius (AU)

Hoadley, France et al. (2015)

Molecular Structure in Protoplanetary Disks: Ultraviolet Emission from the Inner Disk

1) $R_{in}(H_2) \uparrow$ as $M_{acc} \downarrow$
2) $R_{in}(H_2) \uparrow$ as $n_{13\text{-}31} \uparrow$

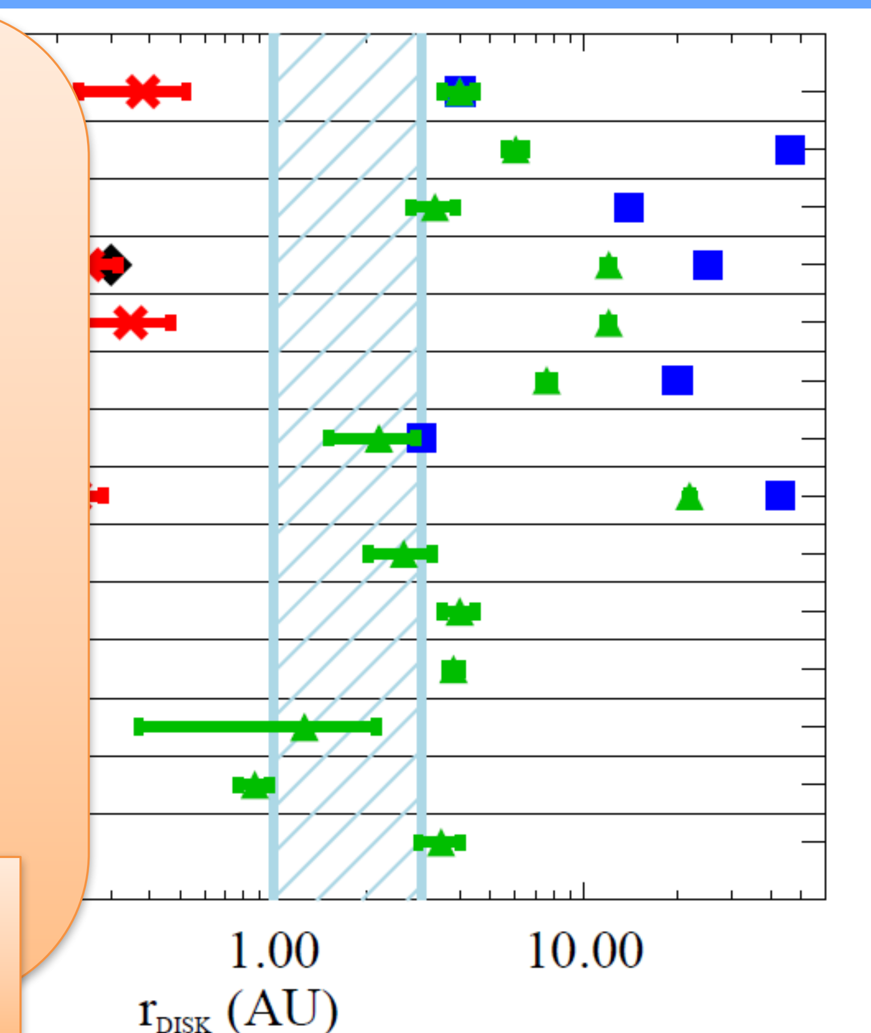
Gas clearing inner disk and/or geometric thinning

3) $R_{out}(H_2) \uparrow$ as $R_{in}(H_2) \uparrow$

Lyα propagating to larger radii

4) $R_{out}(H_2) < R_{cavity}(\text{dust})$

Gas clearing lags dust clearing, possibly cleared by giant planets



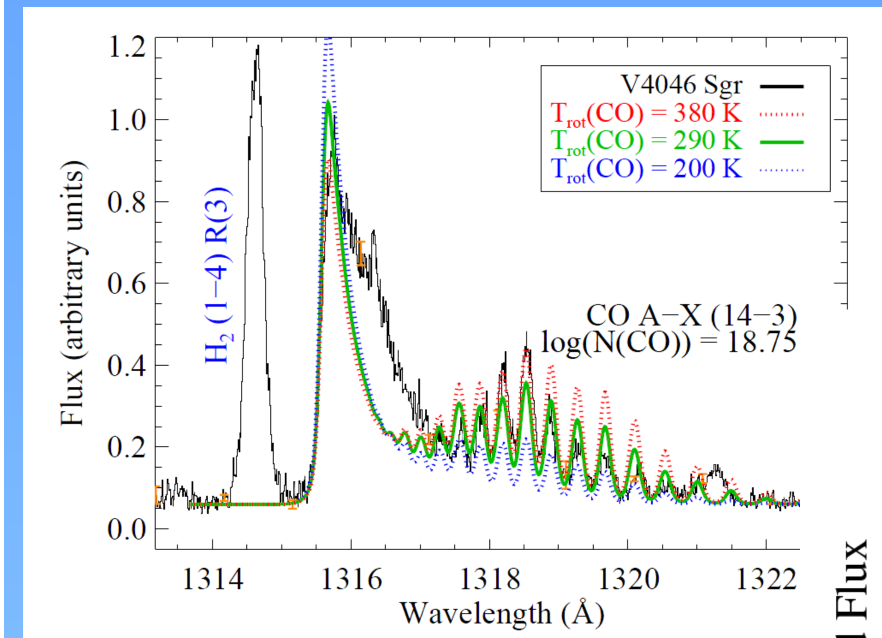
Radius (AU)

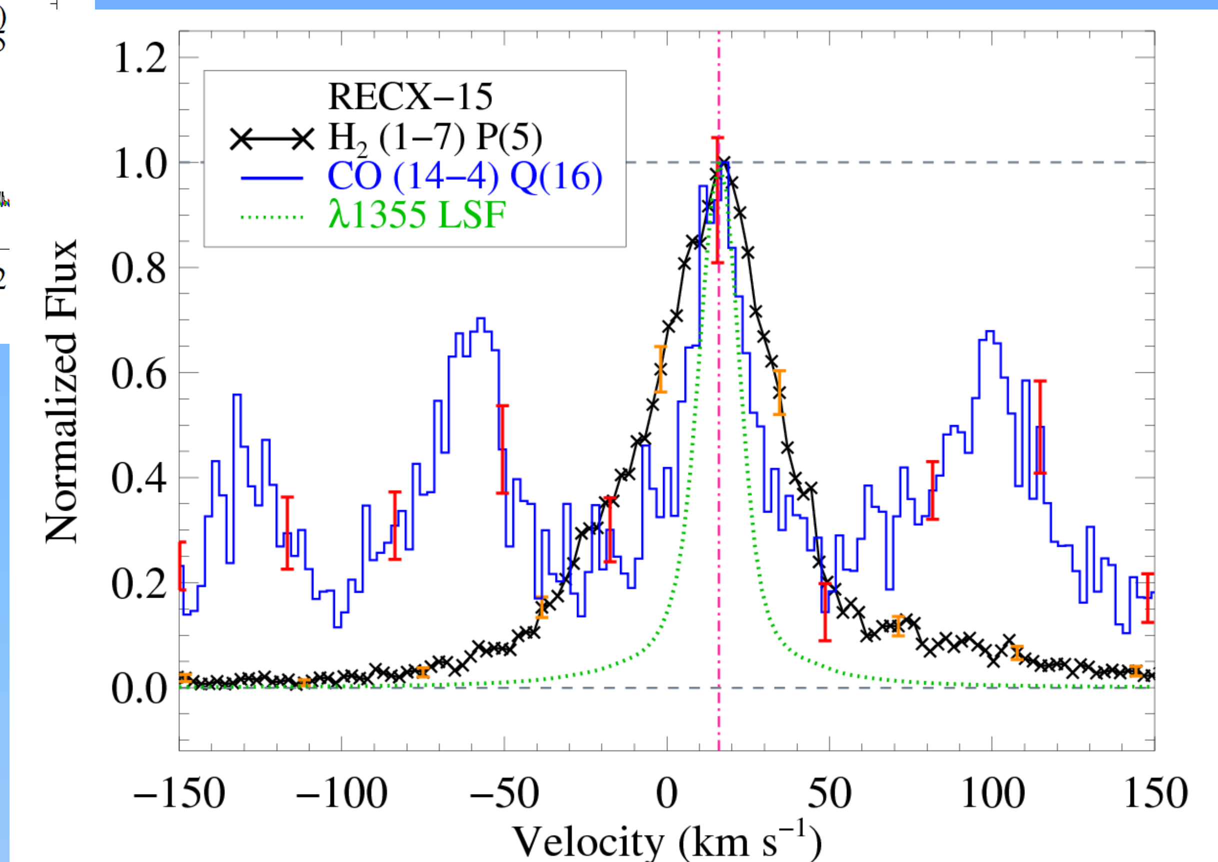
Hoadley, France et al. (2015)

H_2 and CO emission in a single observation

Photoexcited CO observed in UV disk spectra for the first time

Thermal *and* kinematic evidence for separate populations

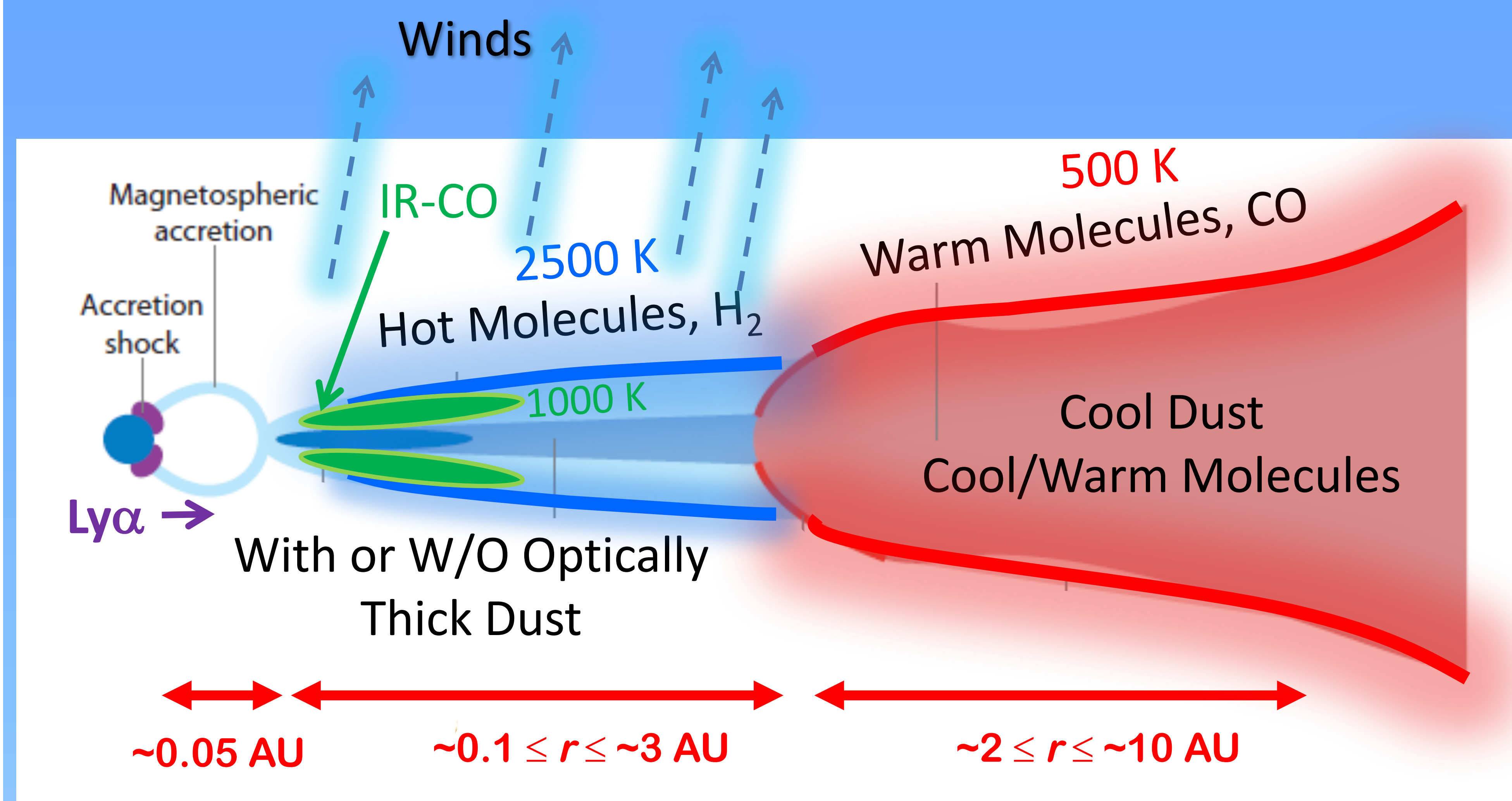




France et al. (2011b)

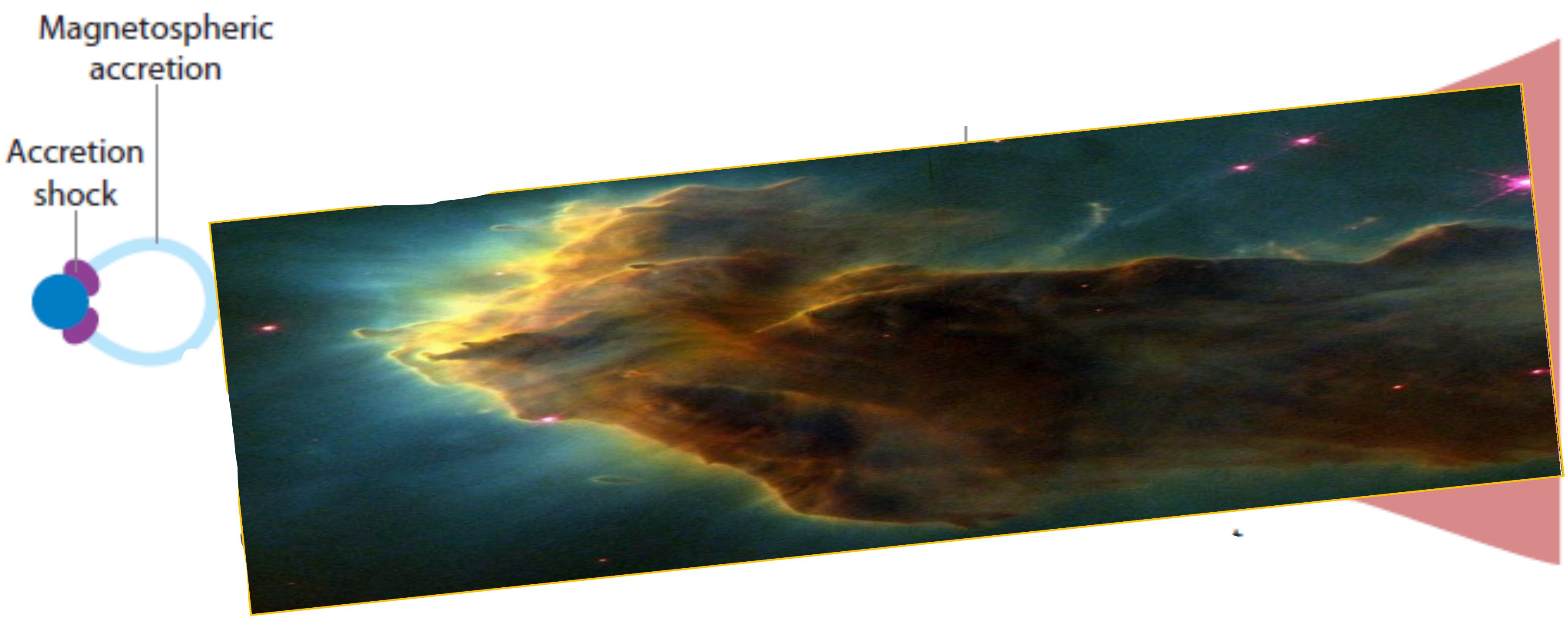
Schindhelm, France et al. (2012a)

Molecular emission from the Inner Disk



Dullemond & Monnier 2010

Molecular emission from the Inner Disk

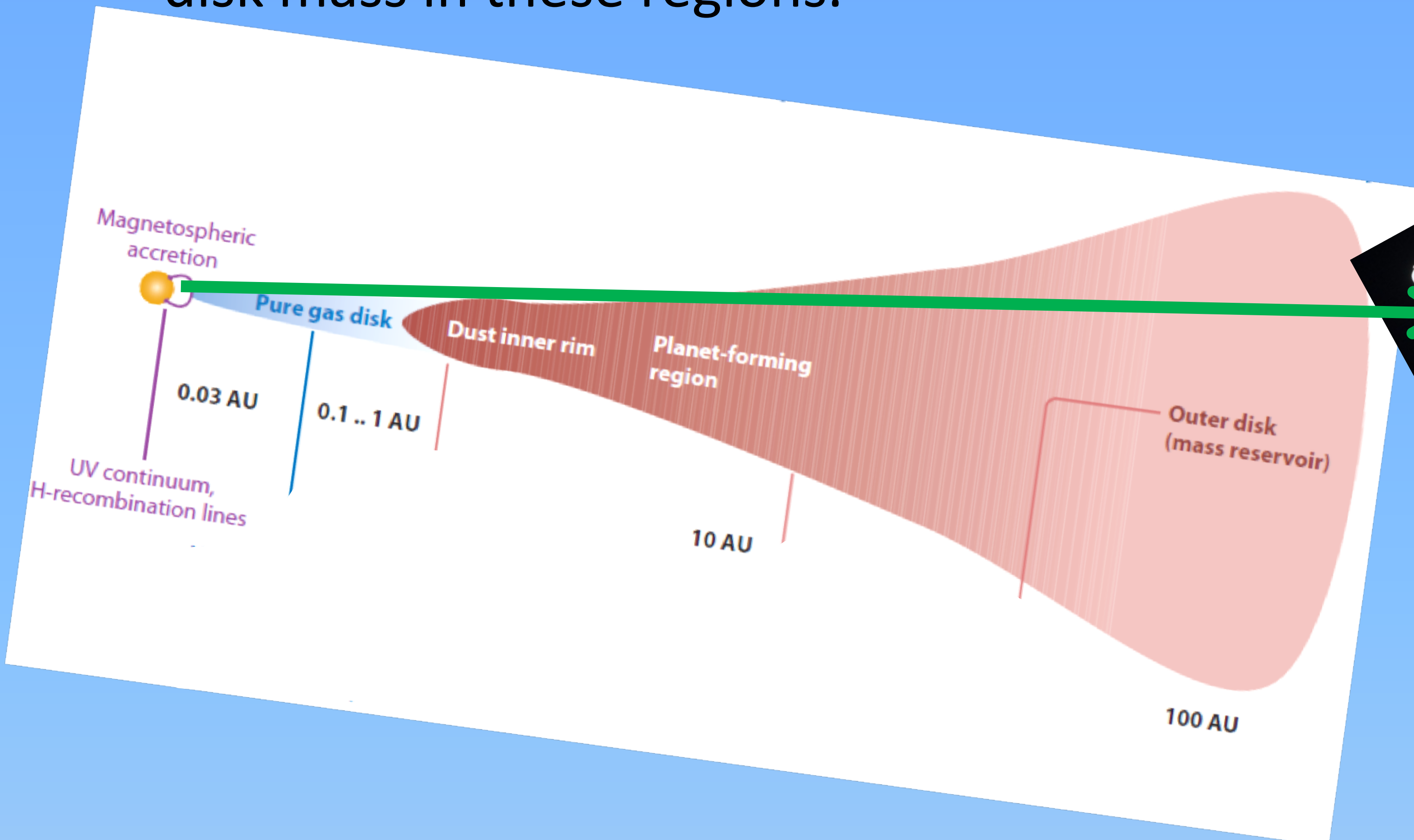


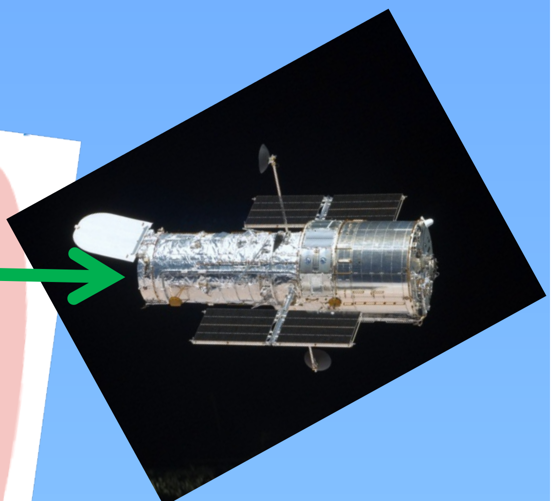
Dullemond & Monnier 2010

(inspirational credit: G. Kriss, STScI)

Composition of Protoplanetary Disks: H_2 and CO Absorption Spectroscopy

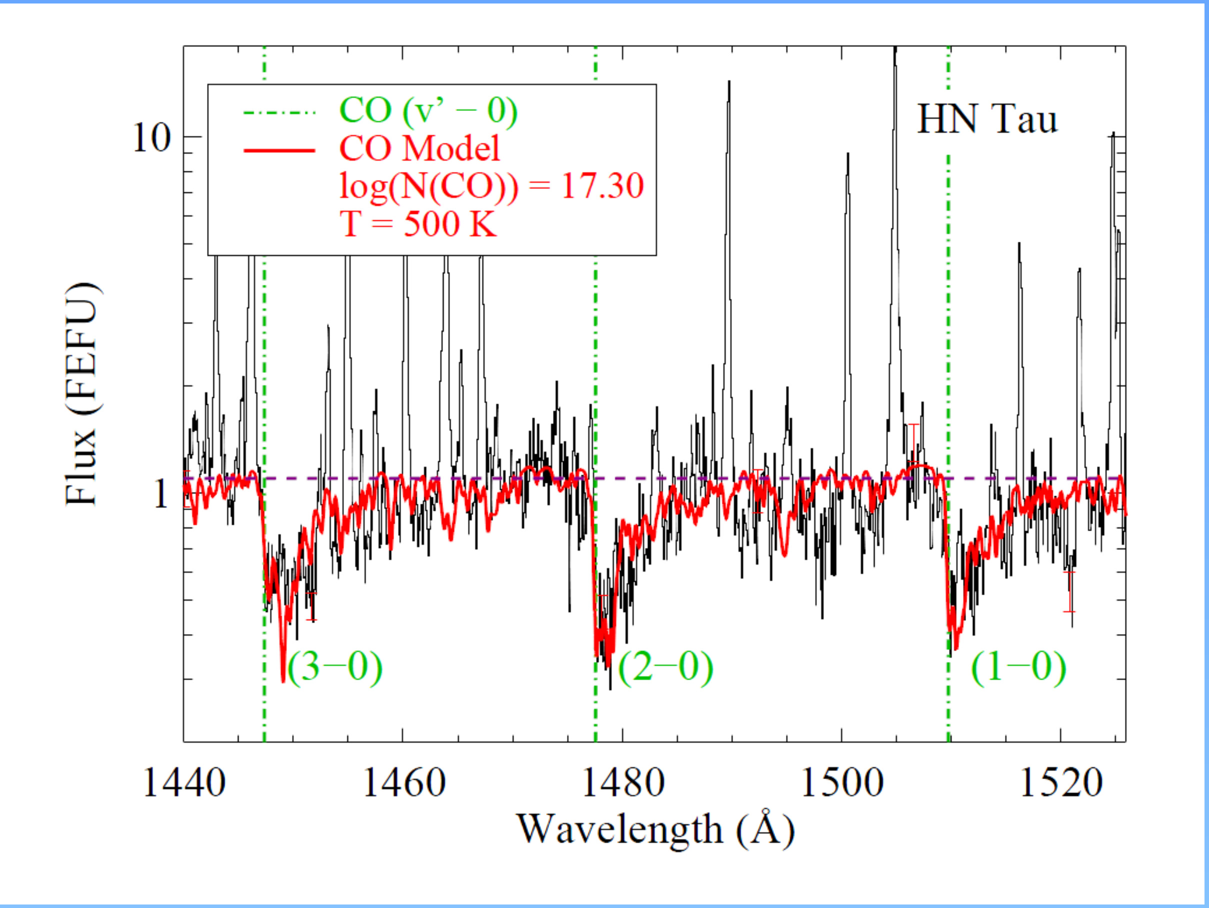
- Direct line-of-sight absorption measurements could allow us to probe H_2 and CO in same, warm (~300 K) parcels of disk gas, set a better basis for molecular abundances and total disk mass in these regions.





H_2 and CO Absorption Spectroscopy

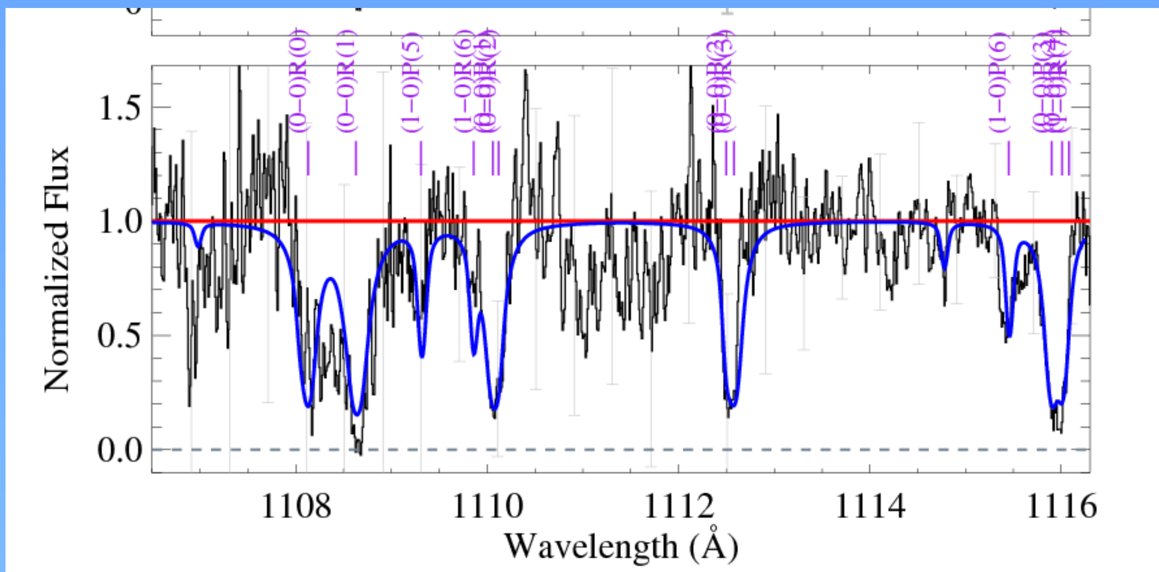
Warm CO, 200 - 500K



France et al. (2011b, 2012a); McJunkin et al. (2013)

Warm CO and H_2 observed in UV spectra of low-mass disk for the first time

H_2 and CO Absorption Spectroscopy



Developed new HST spectroscopic mode for medium-resolution observations at $1070 \le \lambda \le 1130$ Å

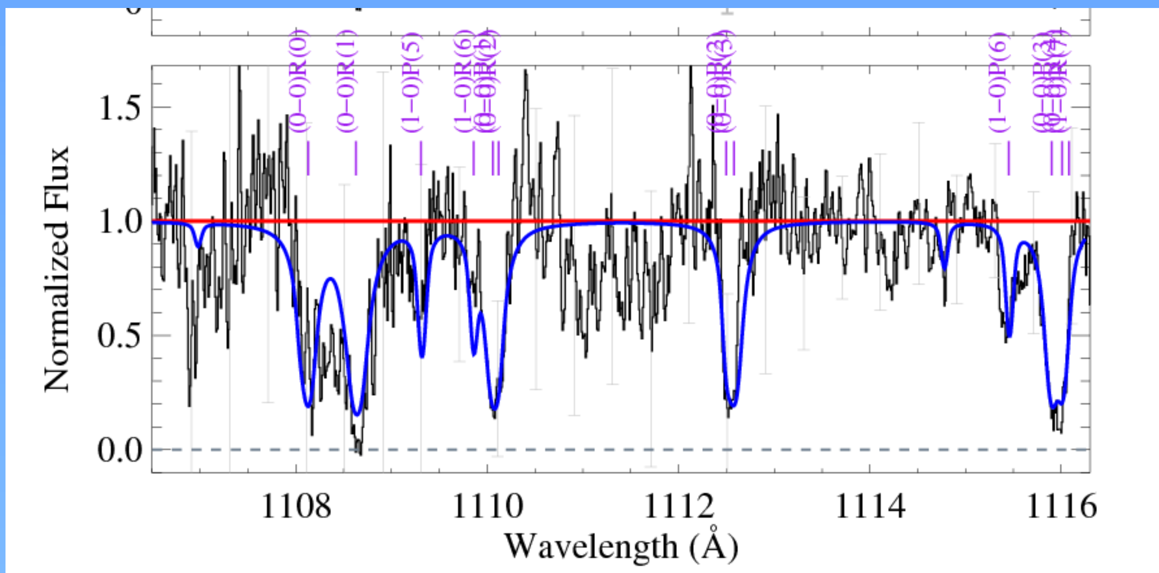
PI – S. Penton (GO 12505)
K. France
S. Osterman

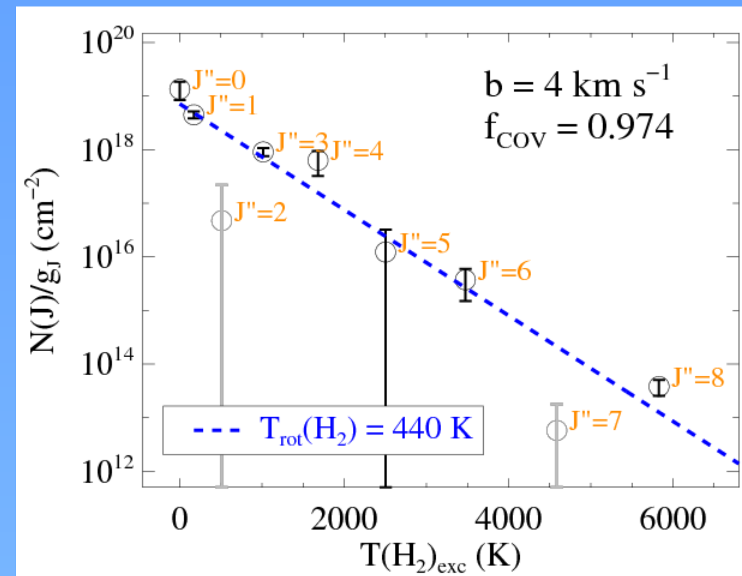
Warm H_2 In Protoplanetary Systems (WH$_2$IPS)

Cycle 20 GO12876, France

France et al. (2014b)

H_2 and CO Absorption Spectroscopy





Warm H_2, 400K observed against FUV continuum in T Tauri Stars for the first time

WH$_2$IPS

(Warm H_2 In Protoplanetary Systems)

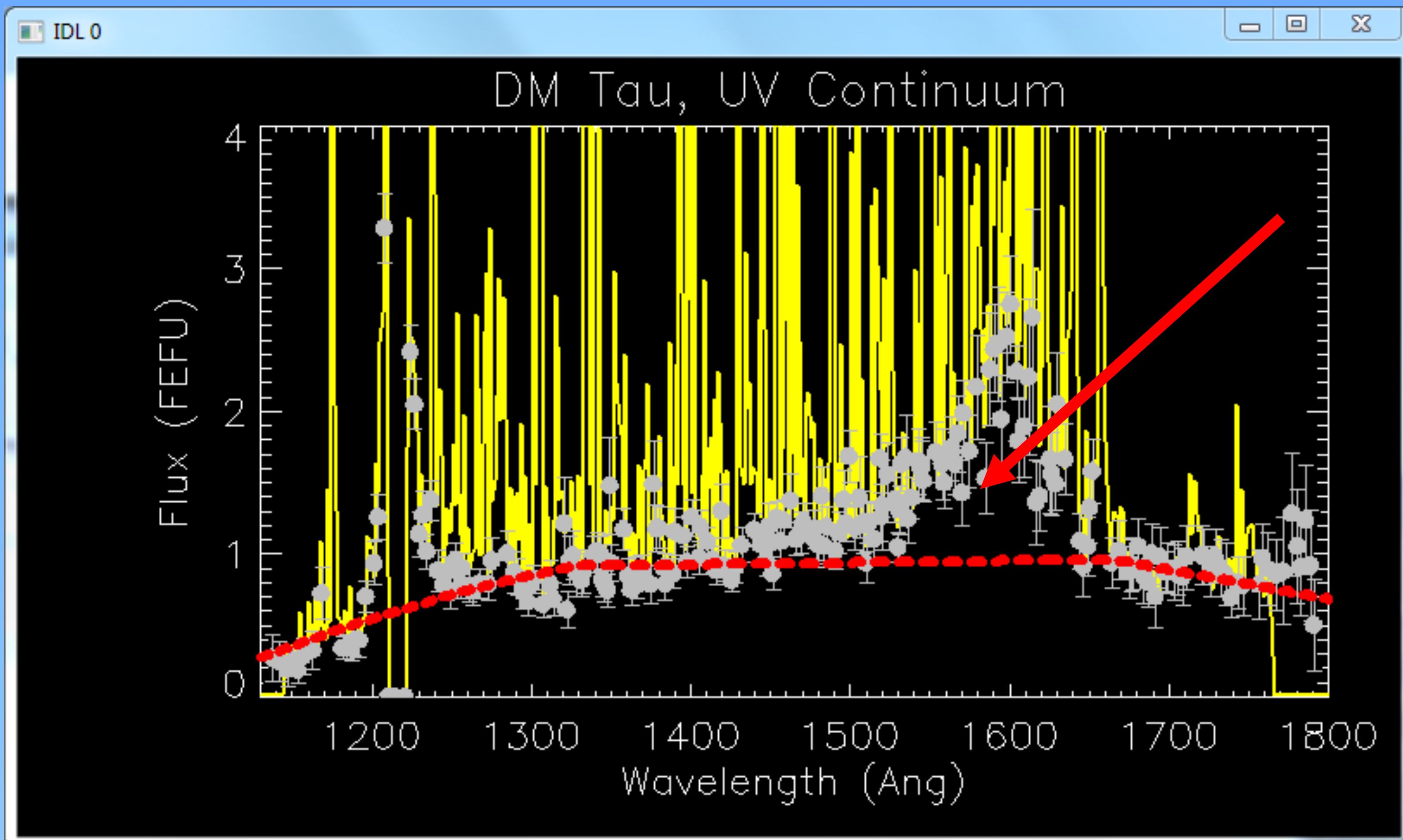
- Direct Abundances

$N(CO)/N(H2) \sim 1.6 \times 10^{-4}$

France et al. (2014b)

Composition of Protoplanetary Disks: Indirect Observations of H_2O at ~1 AU?

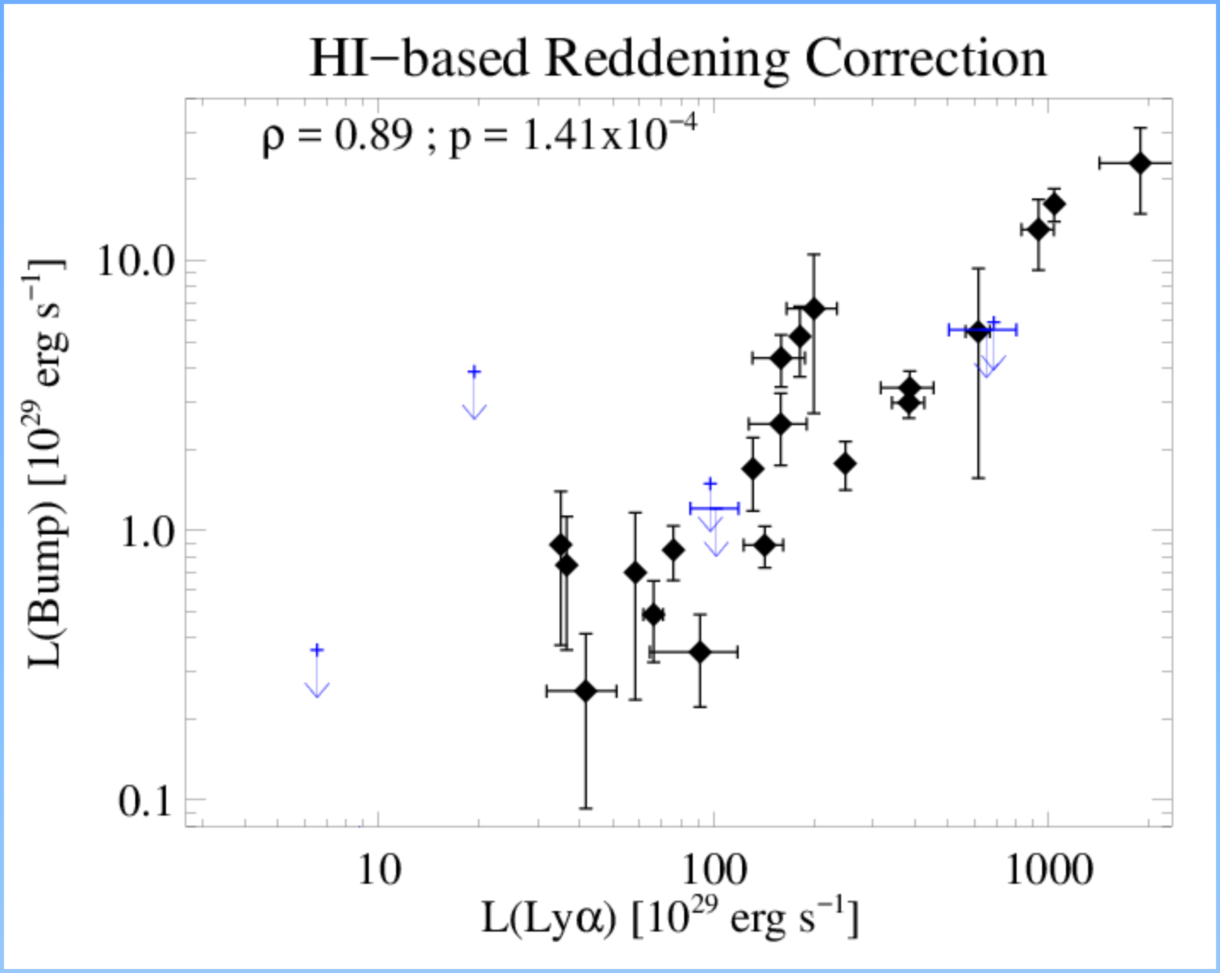
- Additional 'quasi-continuous' emission feature quantified



France et al. (in prep)

Composition of Protoplanetary Disks: Indirect Observations of H_2O at ~1 AU?

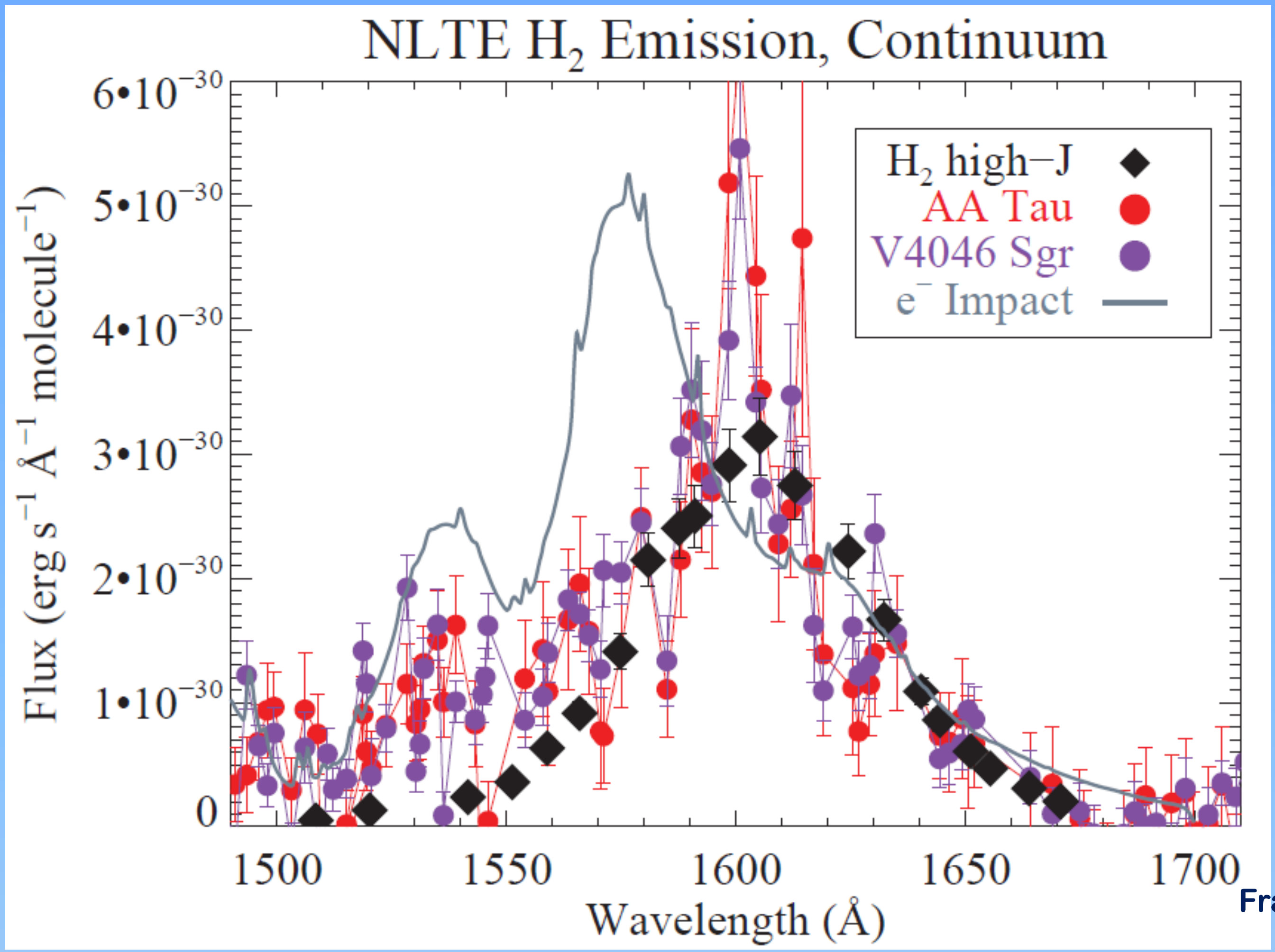
- "1600Å Bump" Measurement and Correlations
- Correlated with Lyα and other accretion tracers



France et al. (in prep)

Composition of Protoplanetary Disks: Indirect Observations of H_2O at ~1 AU?

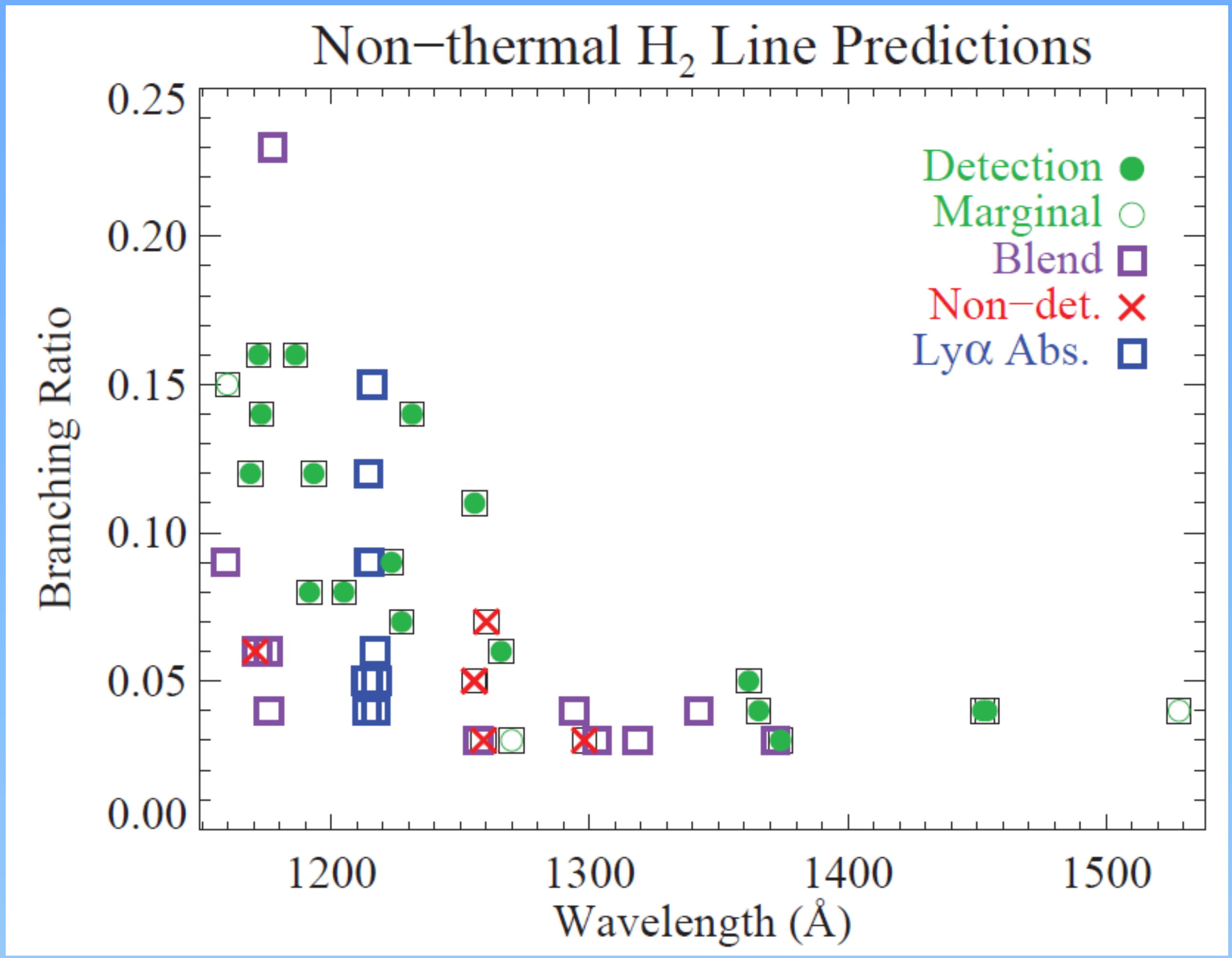
- "1600Å Bump" mechanism: **H_2O + Lyα -> H_2^* + O (with P~10%)**
    - **H_2^* + Lyα -> observed continuum spectra**
- ***Electron-impact does not fit, Lyα-pumped H_2O fragments do***



France et al. (in prep)

Composition of Protoplanetary Disks: Indirect Observations of H_2O at ~1 AU?

- "1600Å Bump" mechanism: **H_2O + Lyα -> H_2^* + O**
  - **H_2^* + Lyα -> observed continuum spectra**
- ***Electron-impact does not fit, Lyα-pumped H_2O fragments do***



Summary: 1978 - 2016

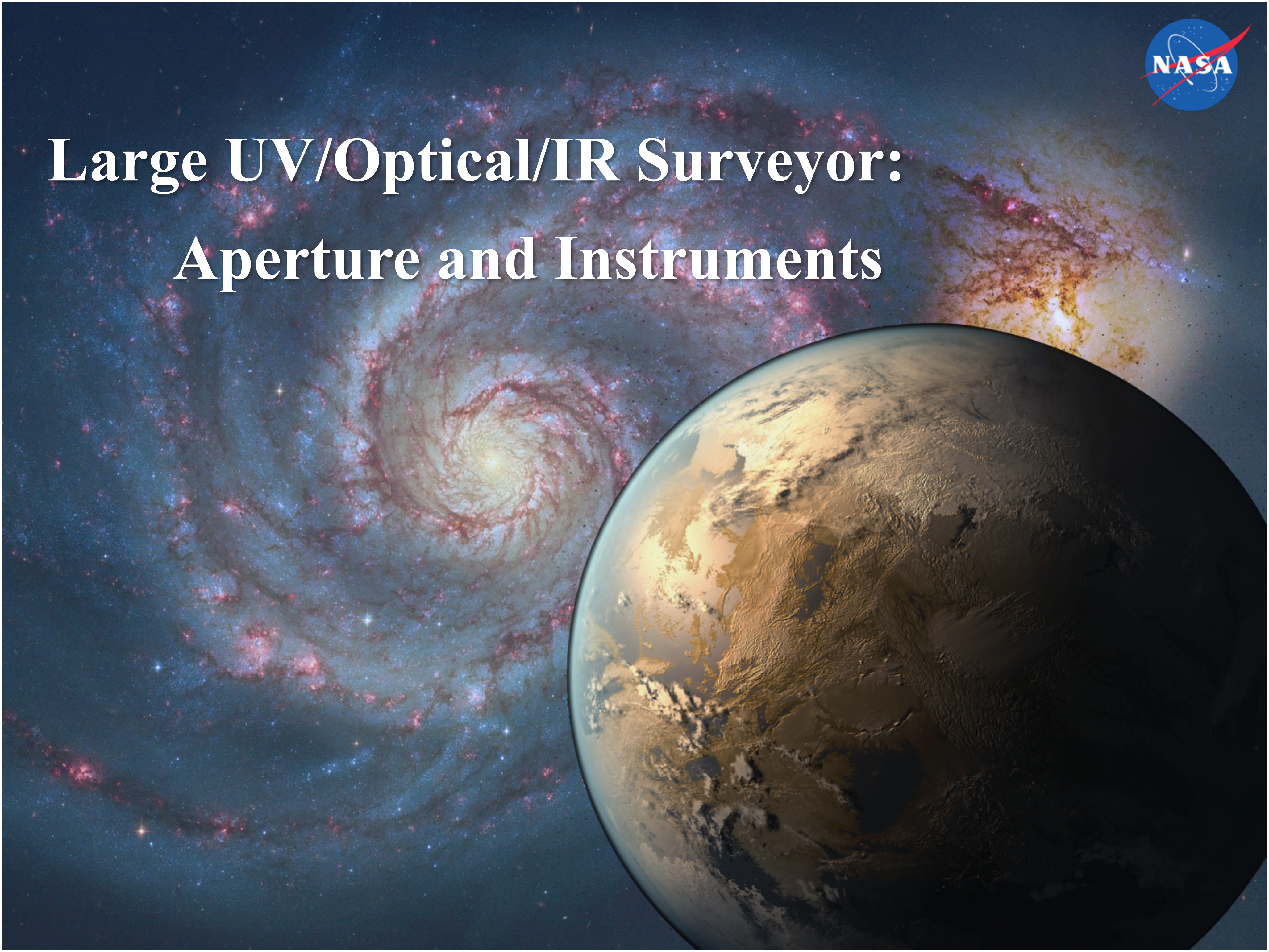
1) HST-COS observations have enabled statistical studies of **both H_2 and CO** in the warm molecular atmospheres of protoplanetary disks for the first time.

2) H_2 fluorescence traces 0.1 – 3 AU (to 10 AU in some transitional disks) while CO fluorescence traces 2 – 10 AU. **H_2 disk inner radii increase with dust dissipation** and **declining mass accretion rate**.

3) CO and H_2 absorption line spectroscopy through inclined disks has revealed **CO/H_2 ratios ~10^{-4}**, suggesting that little CO chemical processing occurs in the first 2 Myr. **H_2O dissociation at ~few AU** is the most likely explanation for the UV molecular continuum in PPD spectra.


WHERE DO WE GO FROM HERE?

Large UV/Optical/IR Surveyor: Aperture and Instruments



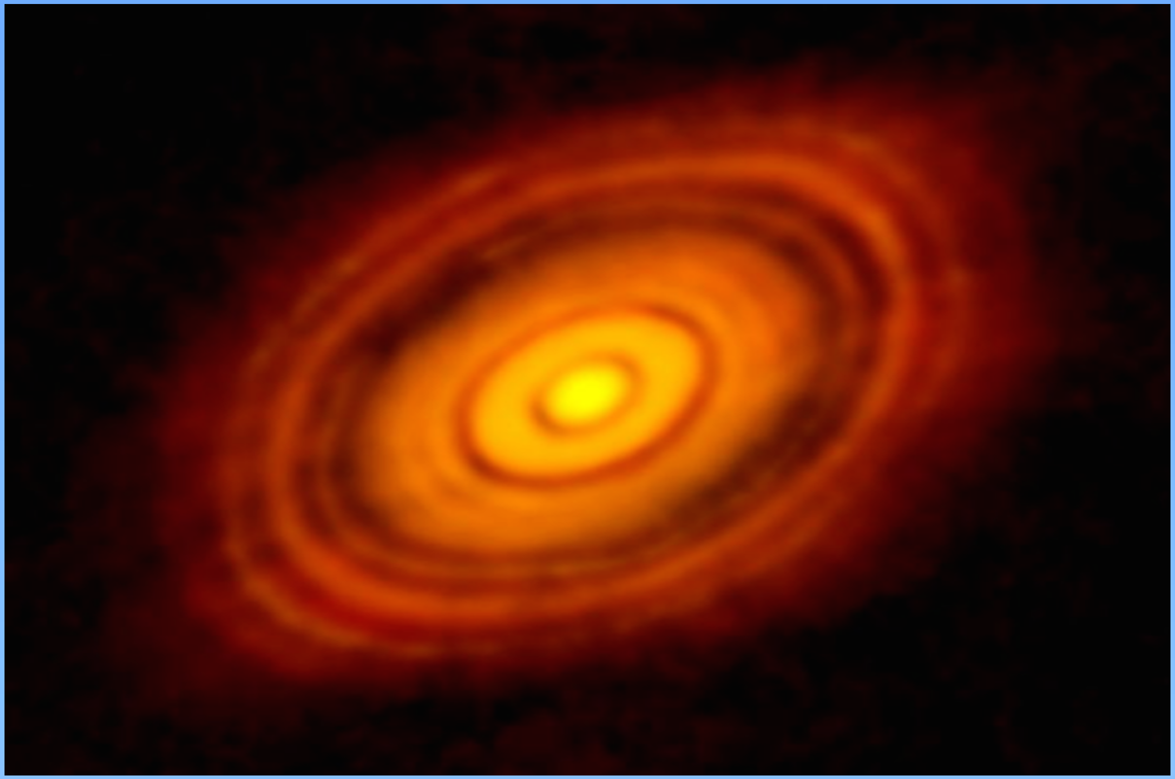
To take the next step towards using UV spectroscopy to characterize the structure and composition of planet-forming disks at $r < 10$ AU, we need **higher sensitivities** combined with **multi-plexed spectroscopy** (e.g., a UV multi-object spectrograph or IFU).

A notional two channel instrument would Combine High-resolution and Imaging Spectroscopy:

1) High-resolution (echelle) point source spectrograph

2) Multi-object imaging spectrograph, medium- and low-resolution spectral modes.

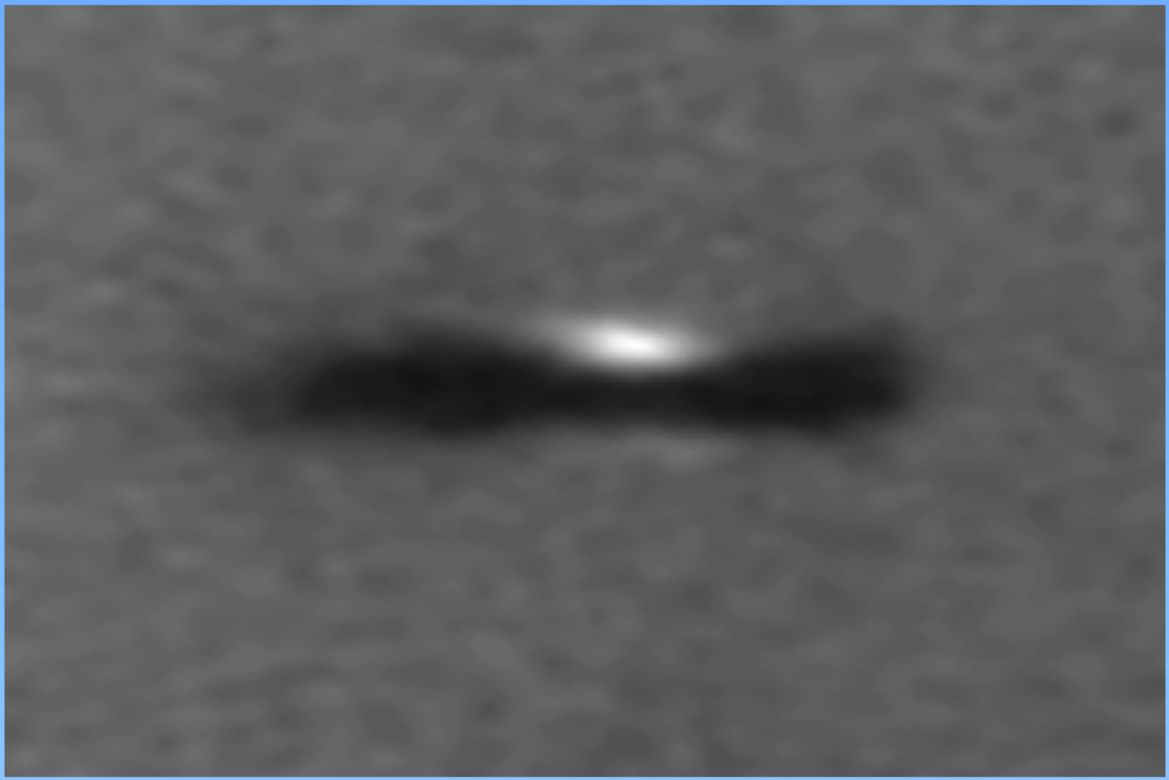
Combined ***High-resolution*** and Imaging Spectrograph for LUVOIR



LUVOIR: Characterizing the Exoplanet "Circle of Life"

Composition of planet forming region, connection to eventual bulk composition of exoplanets and their atmospheres.

Combined ***High-resolution*** and Imaging Spectrograph for LUVOIR

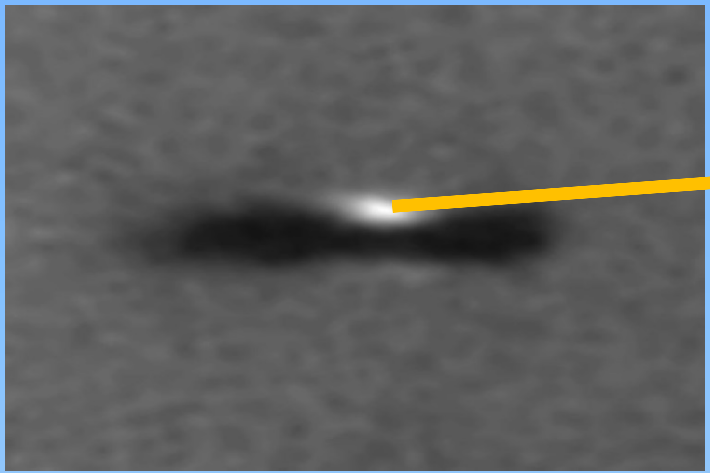


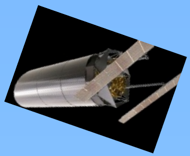
LUVOIR: Characterizing the Exoplanet “Circle of Life”

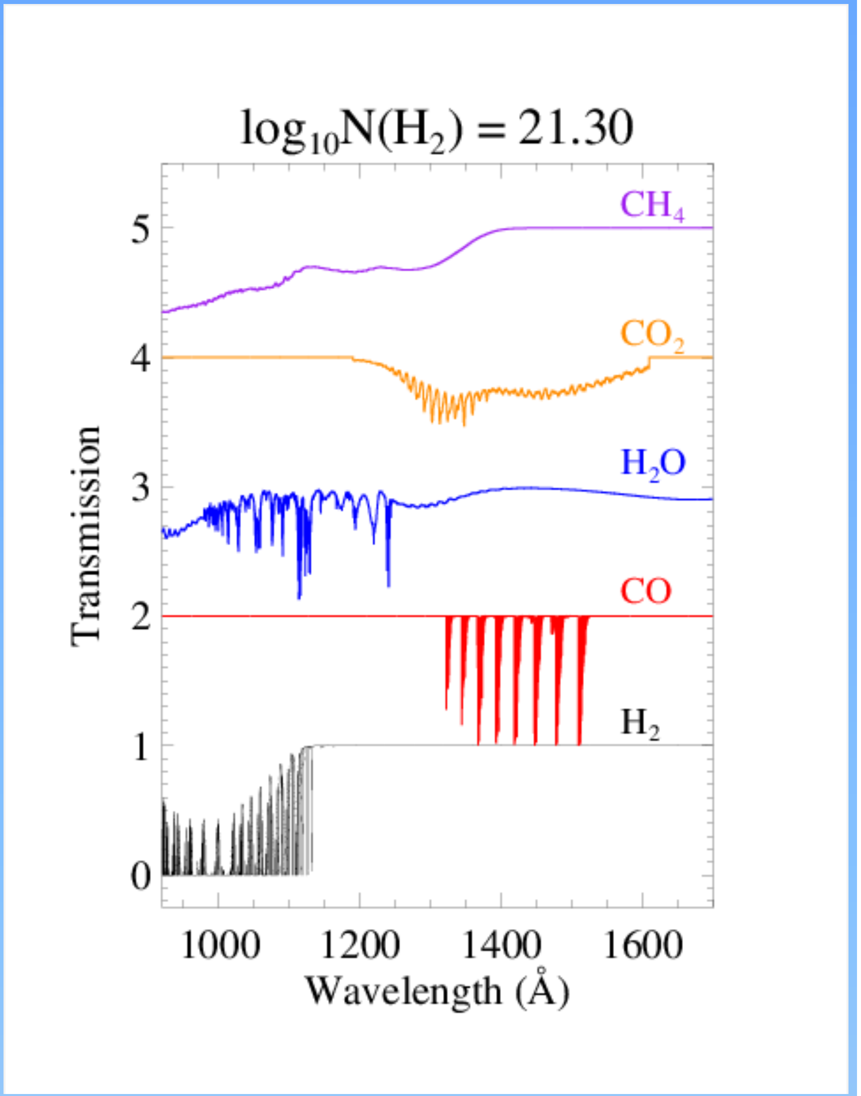
Composition of planet forming region, connection to eventual bulk composition of exoplanets and their atmospheres.

Combined ***High-resolution*** and Imaging Spectrograph for LUVOIR

- High sensitivity + high-resolution far-UV **absorption line spectroscopy** of CO, H_2, and H_2O enable quantitative compositional analysis of planet-forming disks

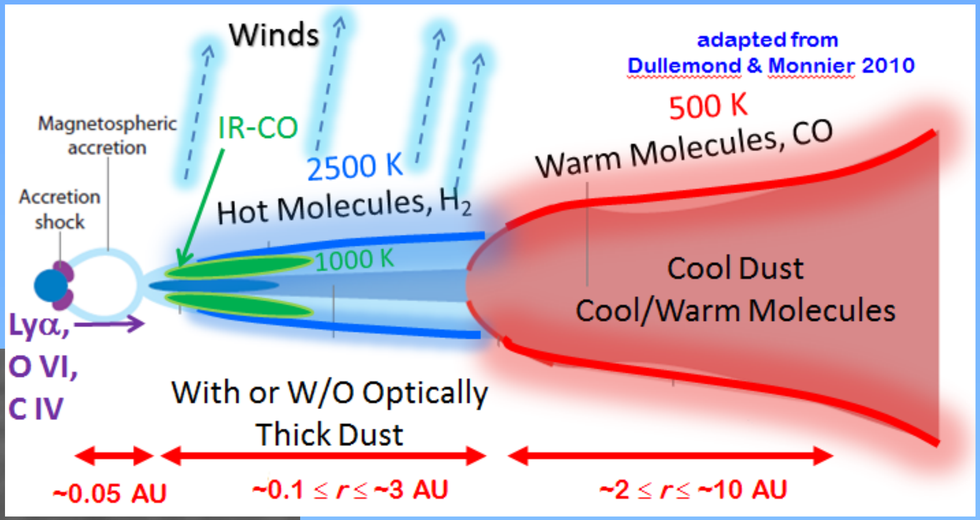


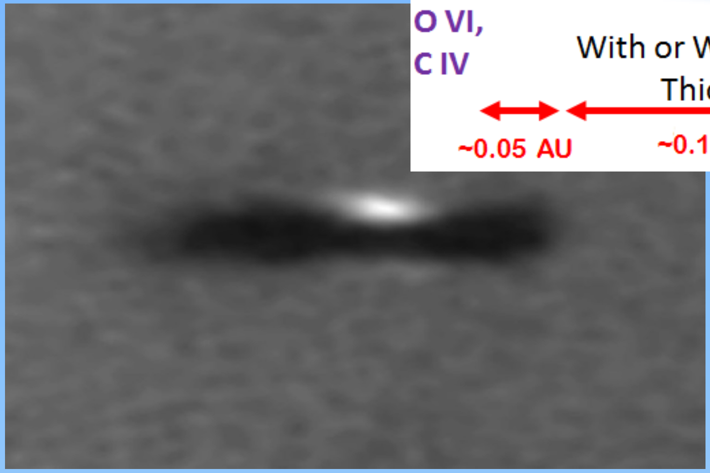




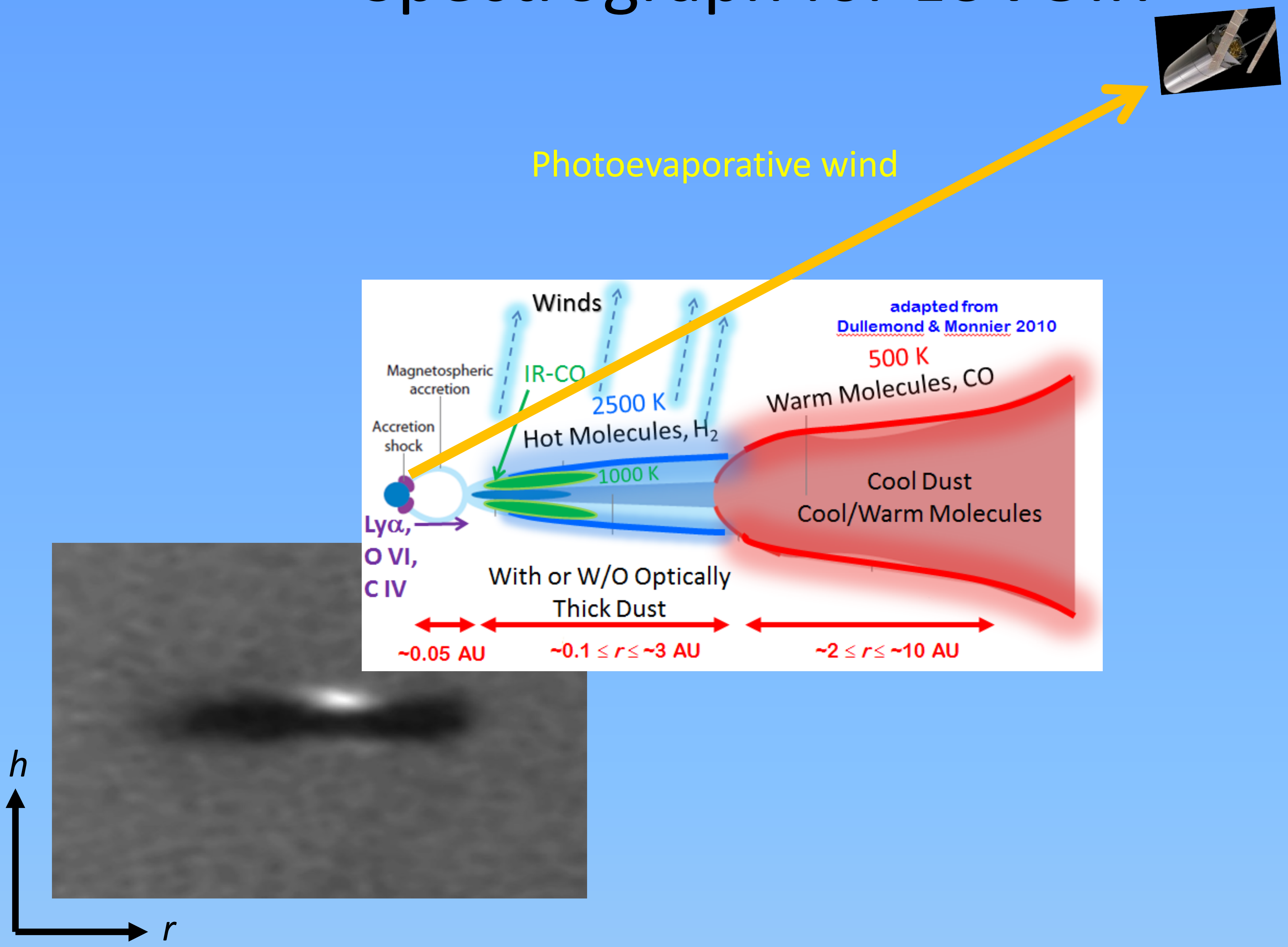
Combined ***High-resolution*** and Imaging Spectrograph for LUVOIR

- **Multi-object + high-sensitivity** enables statistical surveys of inclination angle and ages

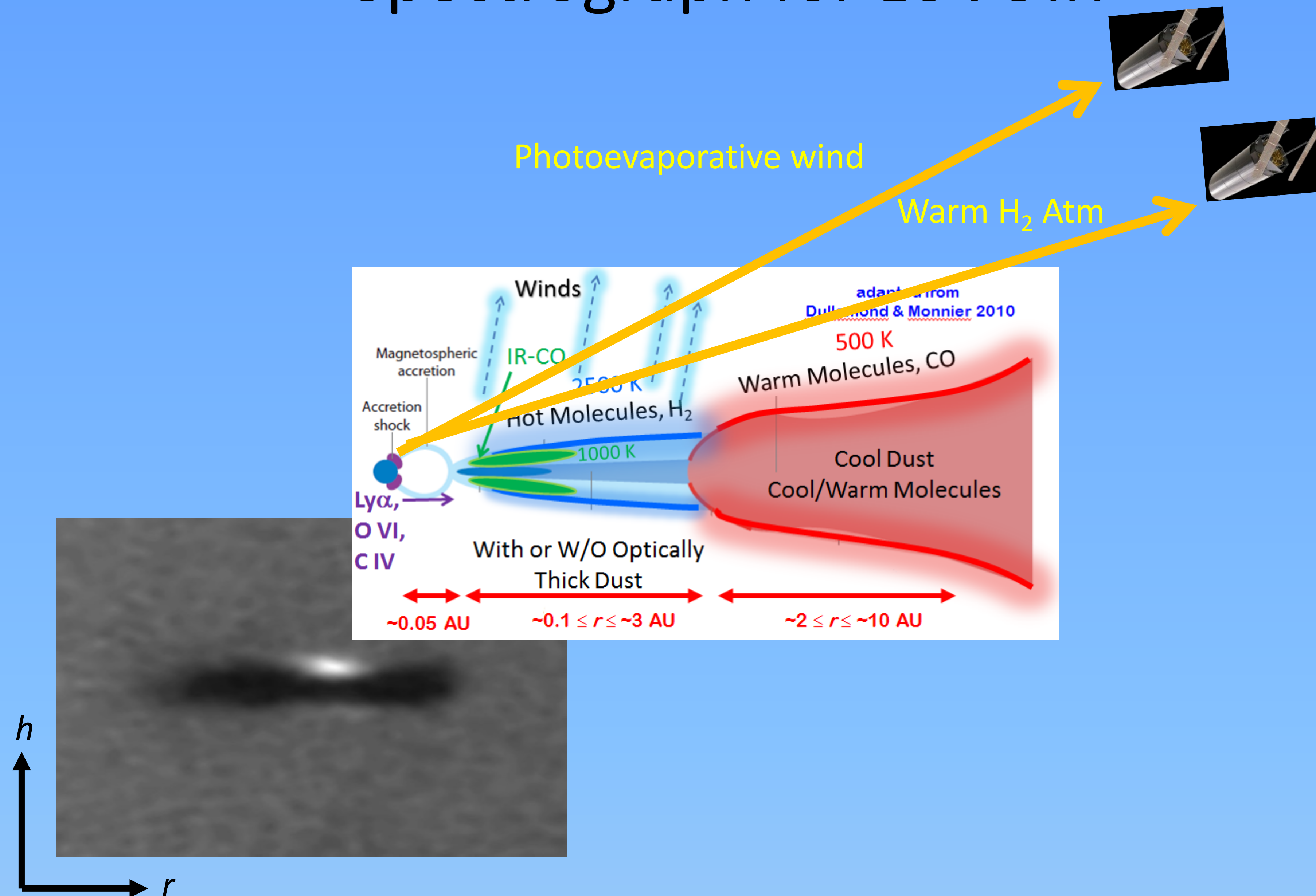




Combined ***High-resolution*** and Imaging Spectrograph for LUVOIR



Combined ***High-resolution*** and Imaging Spectrograph for LUVOIR



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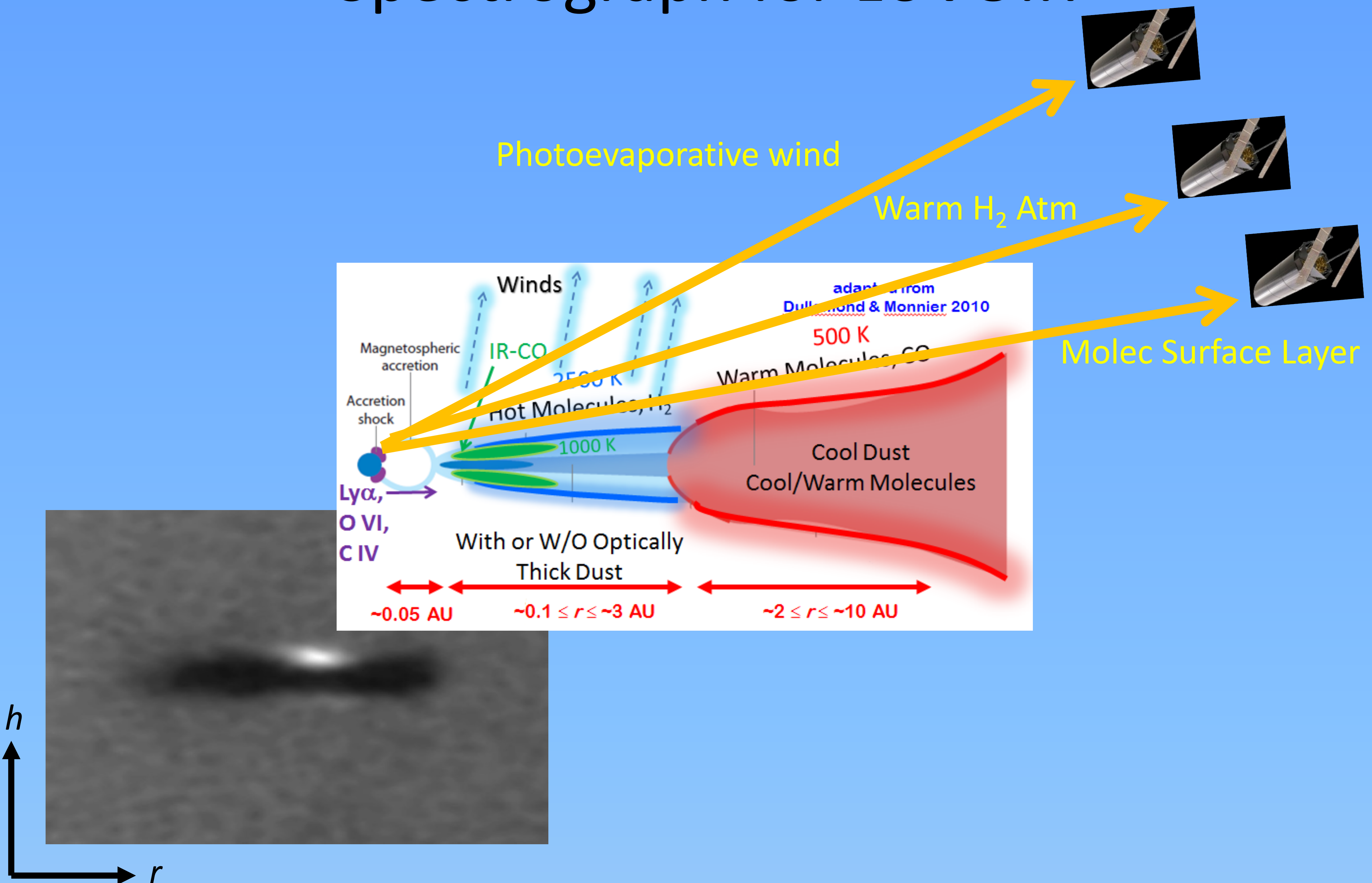
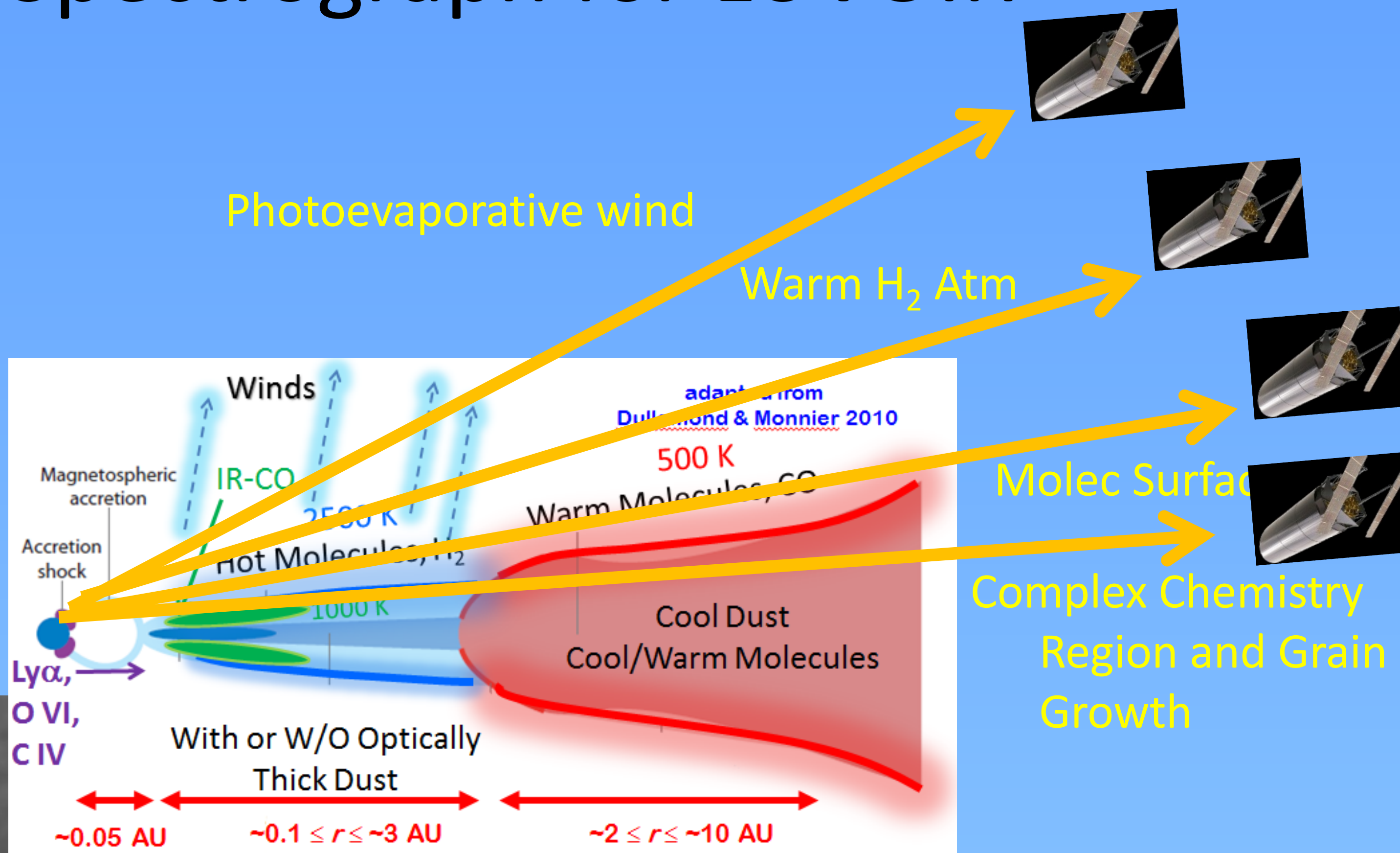
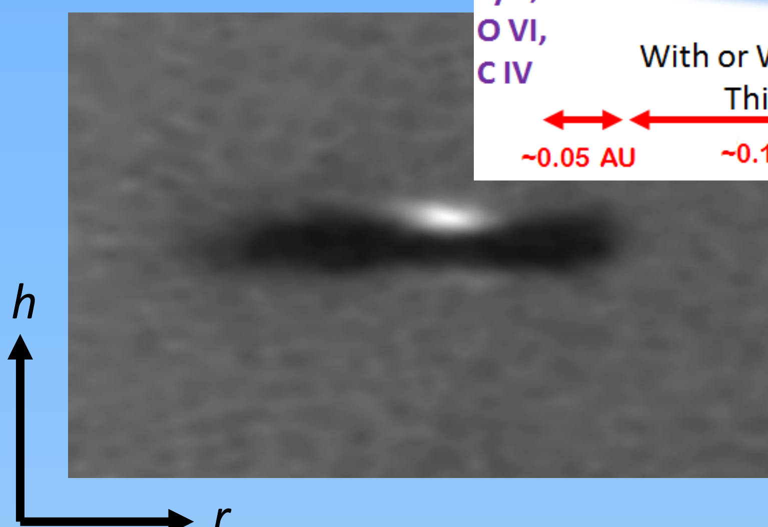


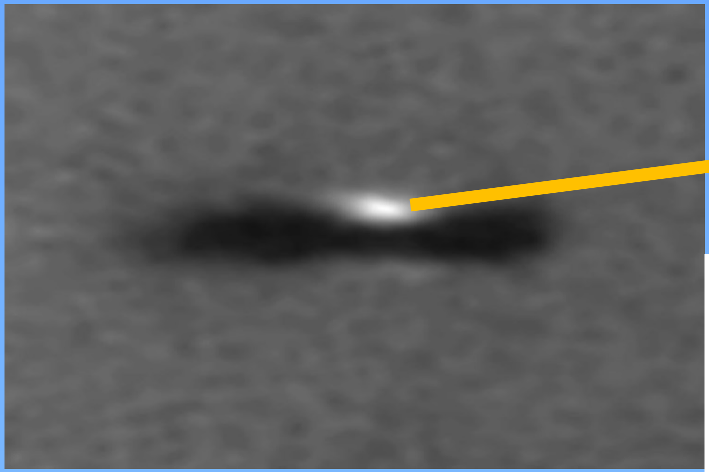
Combined ***High-resolution*** and Imaging Spectrograph for LUVOIR

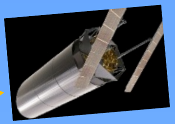


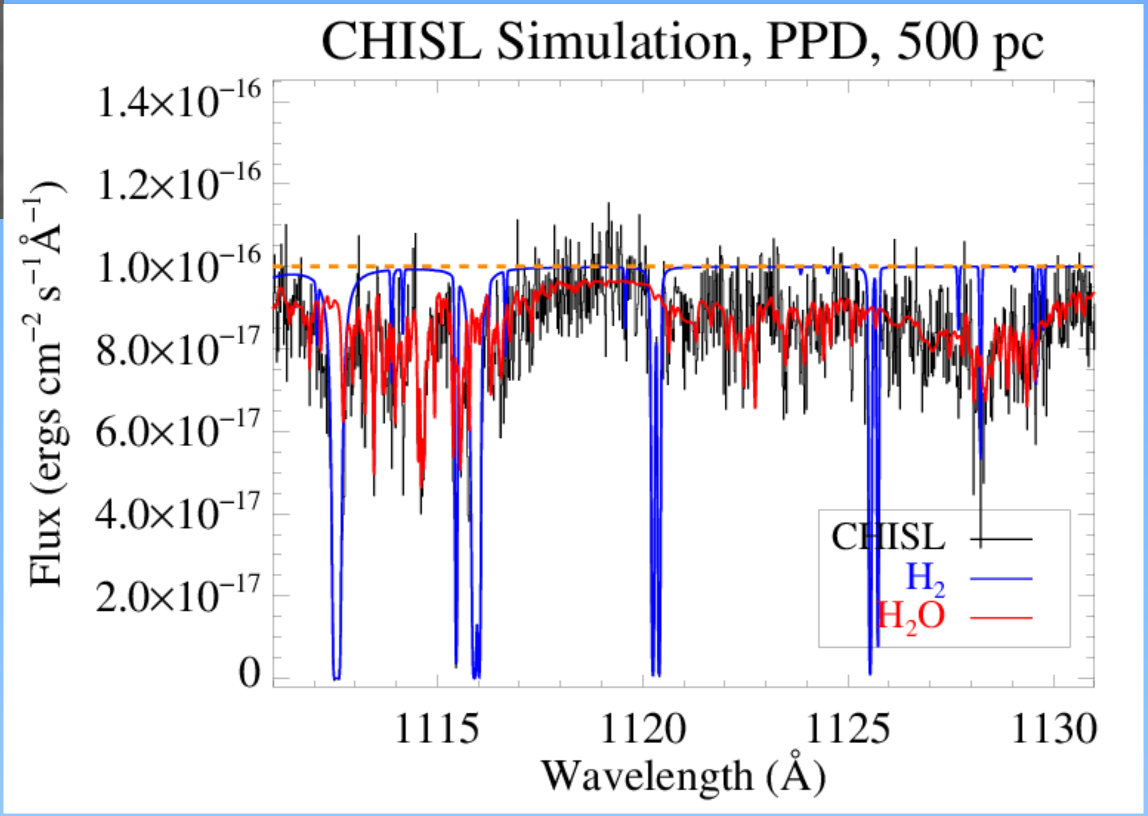


- ***Distribution of inclination angle and ages allows 4-D mapping of disks [r,h,t,λ]***

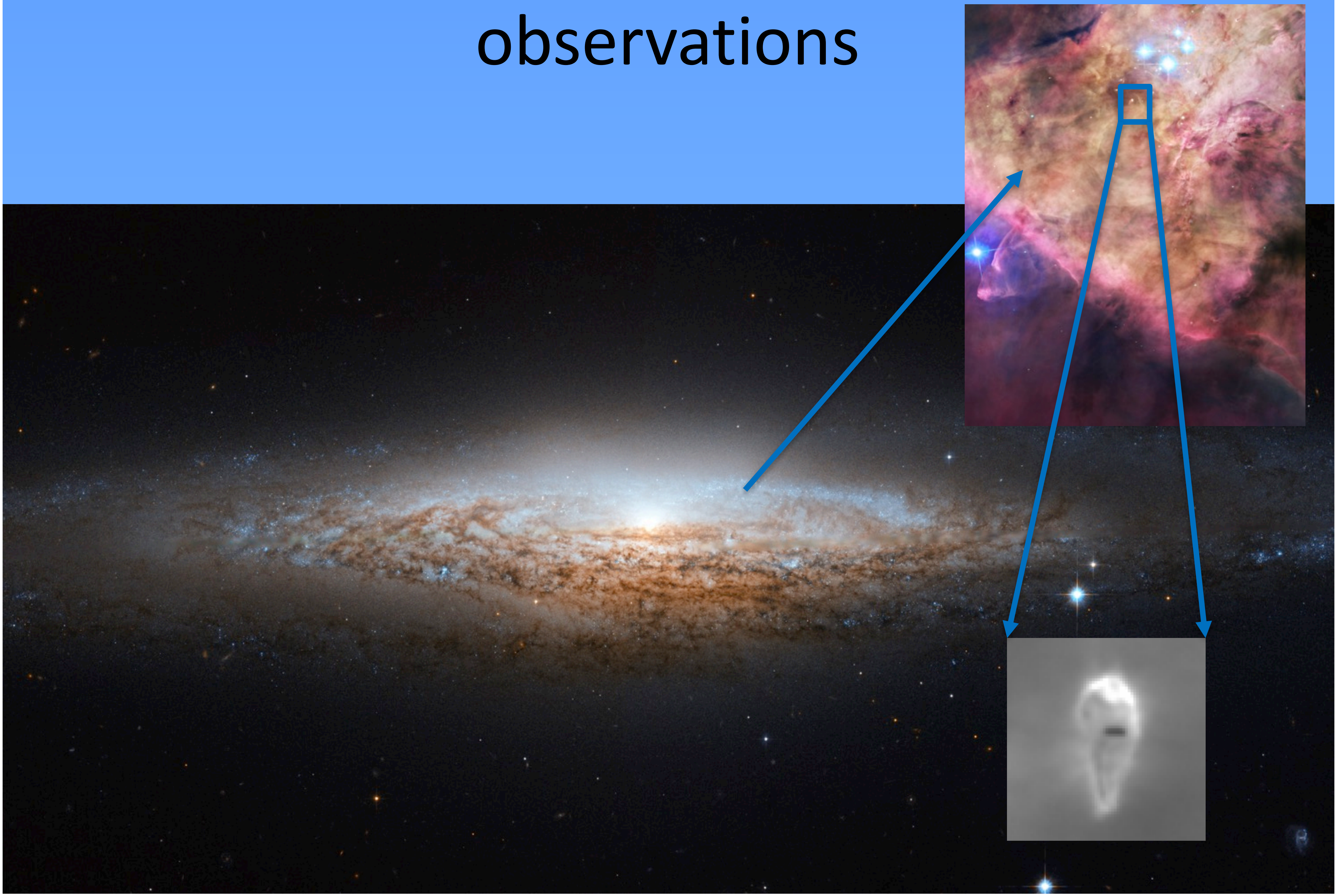
Combined ***High-resolution*** and Imaging Spectrograph for LUVOIR

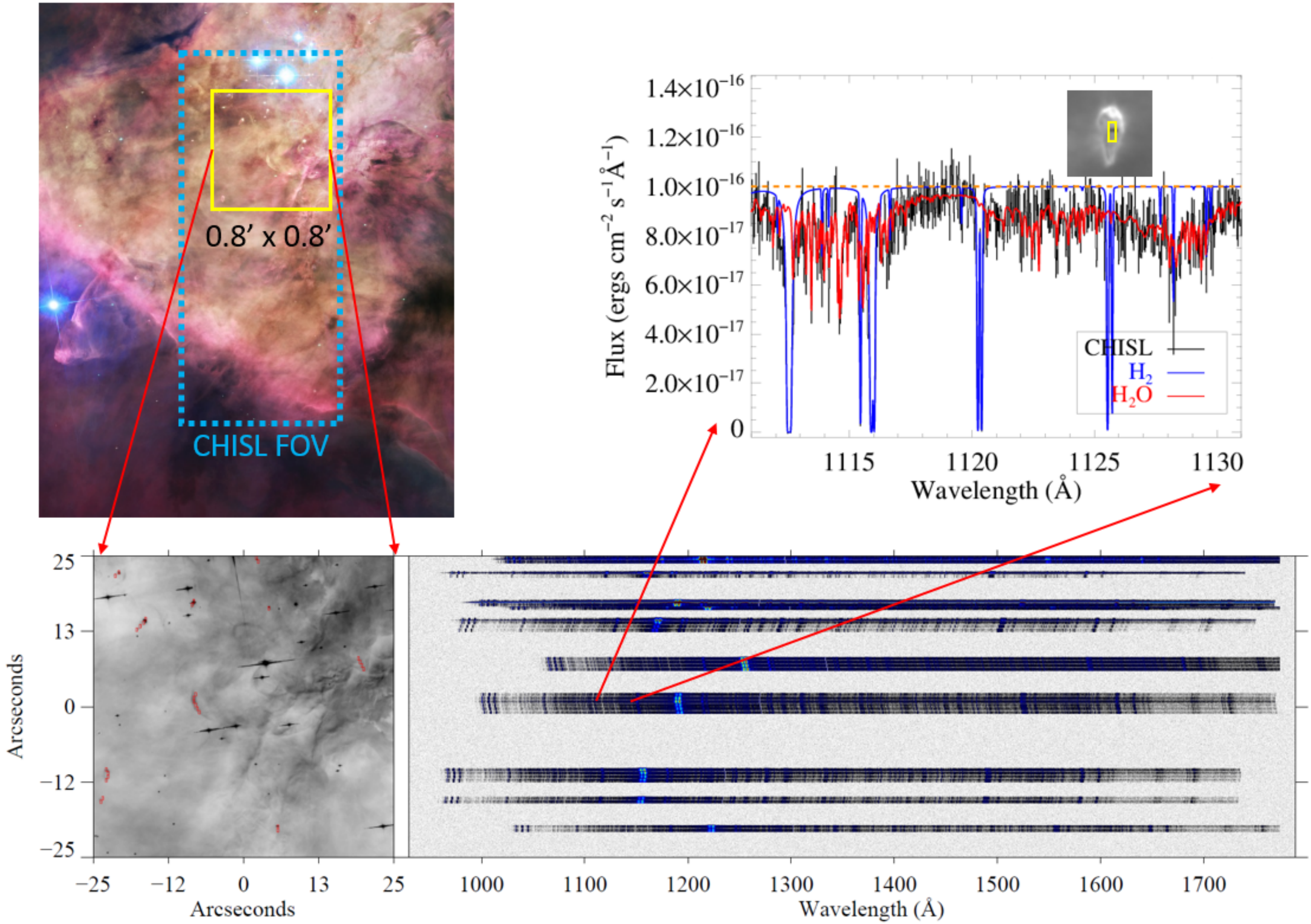






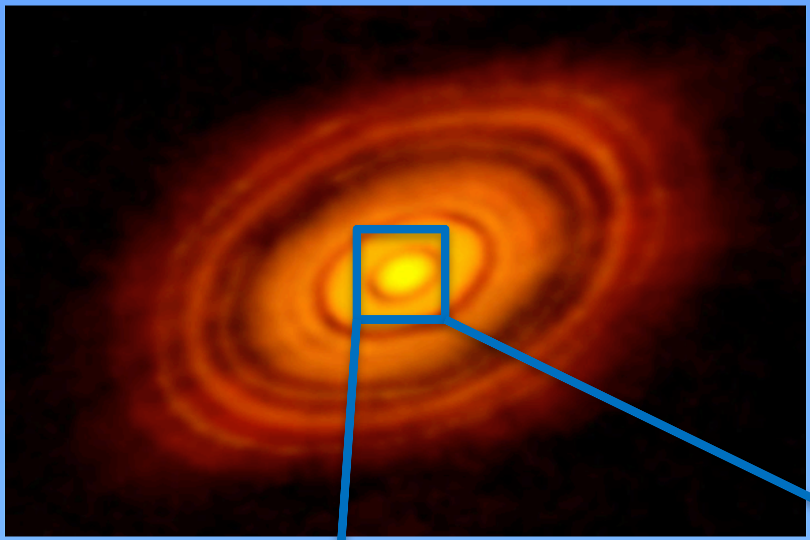
Multi-object observations



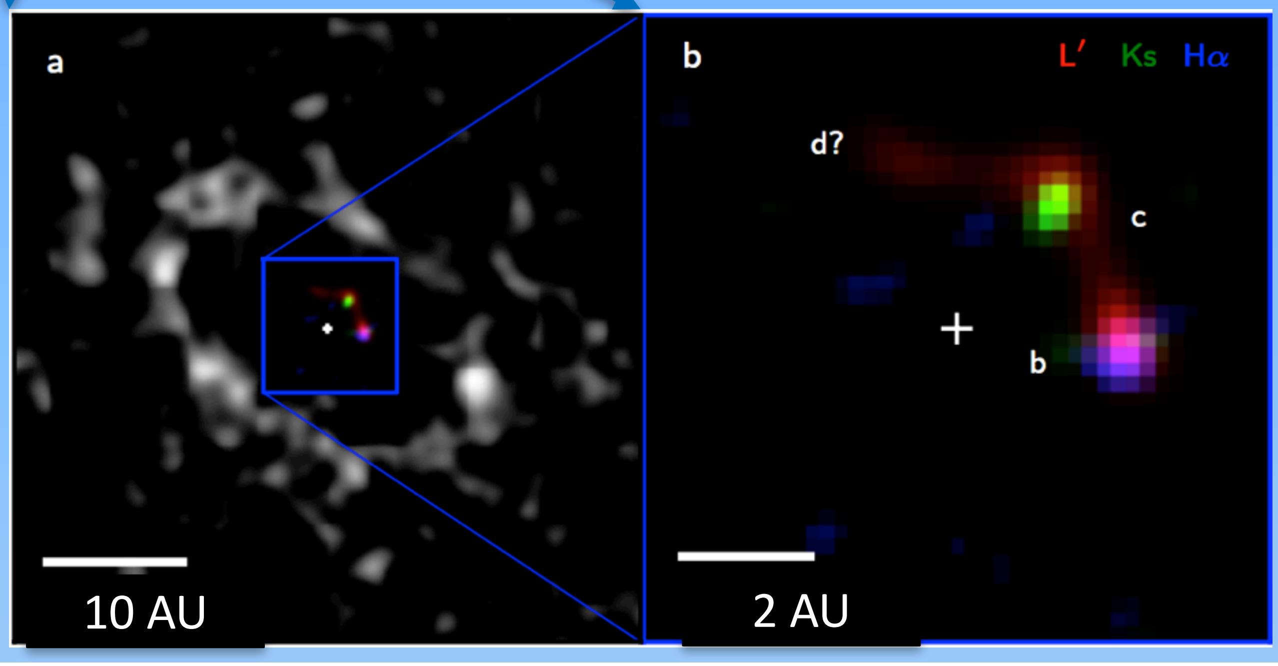


0.8′ x 0.8′
CHISL FOV
Flux (ergs cm^{-2} s^{-1} Å^{-1})
1.4×10^{-16}
1.2×10^{-16}
1.0×10^{-16}
8.0×10^{-17}
6.0×10^{-17}
4.0×10^{-17}
2.0×10^{-17}
0
1115
1120
1125
1130
Wavelength (Å)
CHISL
H_2
H_2O
Arcseconds
25
13
0
−12
−25
−25
−12
0
13
25
Arcseconds
1000
1100
1200
1300
1400
1500
1600
1700
Wavelength (Å)

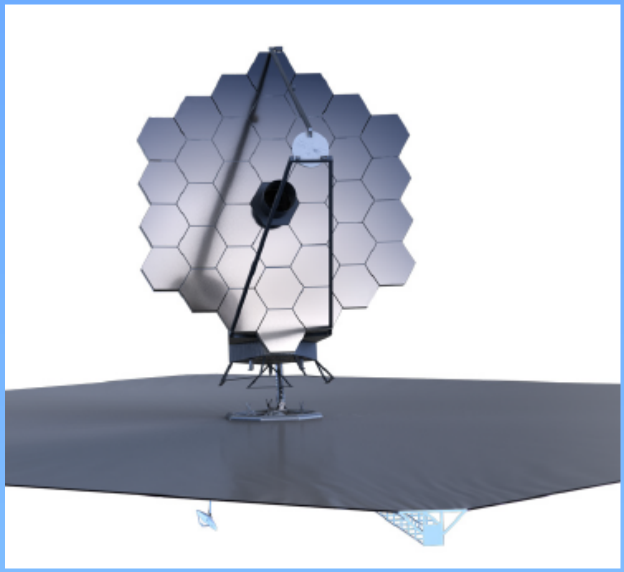
Complementarity with other science instruments for disk and protoplanet science

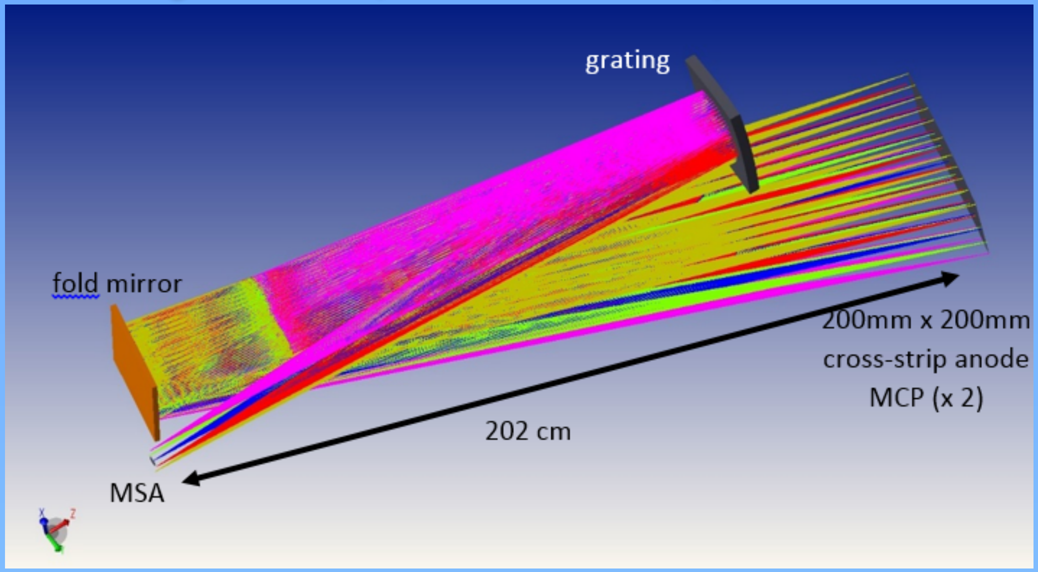


Composition of planet forming region, connection to bulk composition of protoplanets, exoplanets, and their atmospheres.



The Combined High-resolution and Imaging Spectrograph for the LUVOIR Surveyor (CHISL)





(with Brian Fleming, Keri Hoadley)

NOTIONAL LUVOIR INSTRUMENT SUITE

First Generation Science Instruments (*to be defined by STDTs, strictly my own interpretation):

1) Coronagraph to detect and characterize (potentially inhabited) exoplanets (10^{-10} contrast ratio – *discovery*, feeding an $R > 70$ Vis/NIR spectrometer - *characterization*)

2) “Wide field” imager (6’ x 6’; $V = 32$ in 1 hr)

3) UV spectrograph (multi-object over > 1’ x 1’ FOV at medium res [$R > 25{,}000$]; high-res capability [$R \geq 10^5$])

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The Combined High-resolution and Imaging Spectrograph for the LUVOIR surveyor (CHISL)

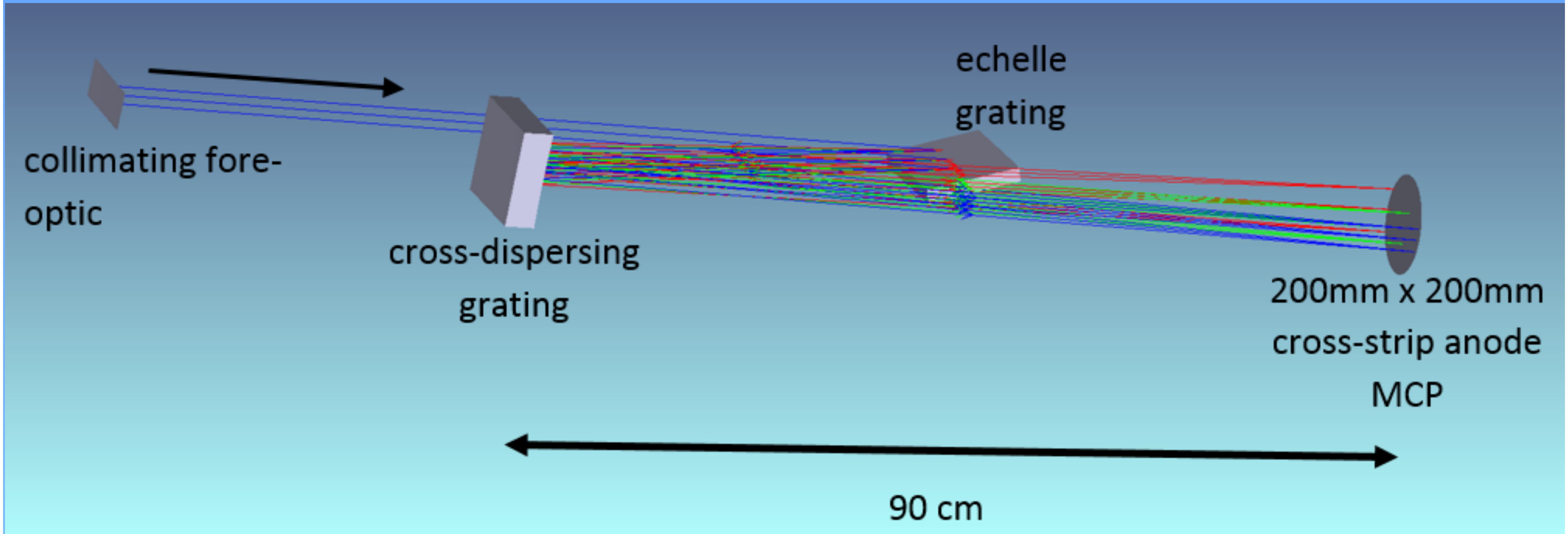
Combined ***High-resolution*** and Imaging Spectrograph for LUVOIR

A two channel instrument :

1) High-resolution (echelle) point source spectrograph

2) Multi-object imaging spectrograph, medium- and low-resolution spectral modes.

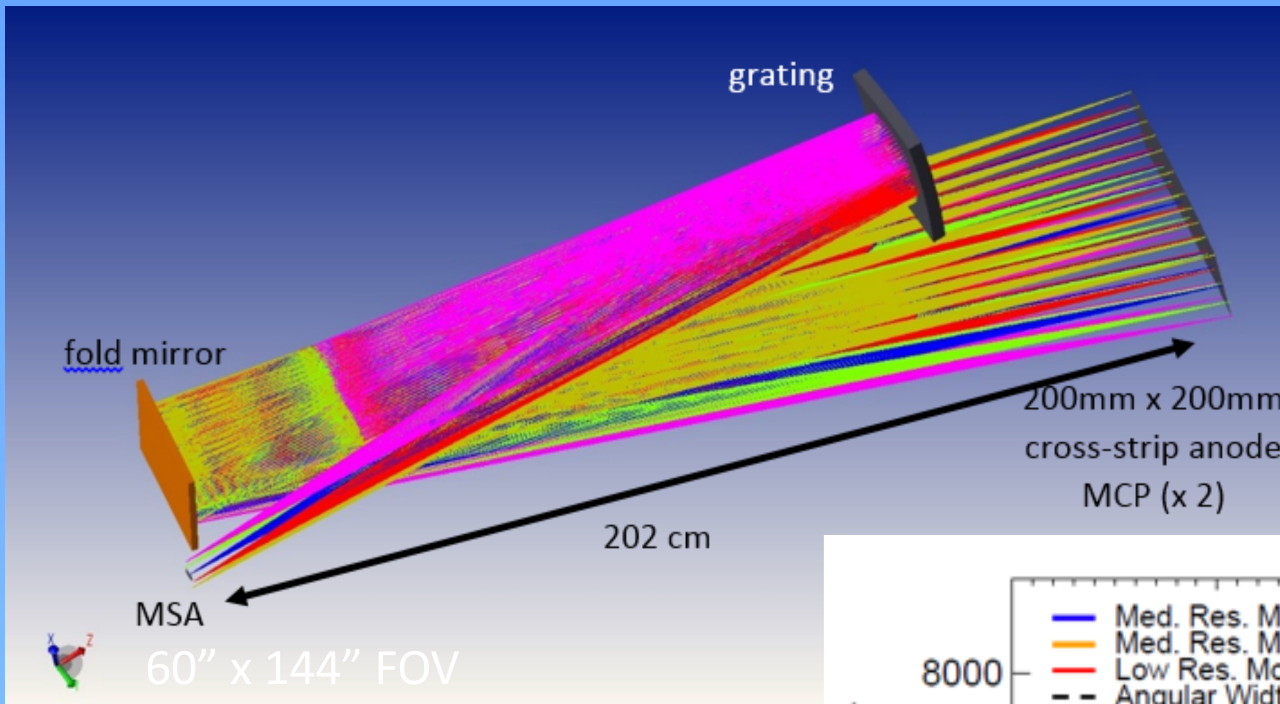
Combined ***High-resolution*** and Imaging Spectrograph for LUVOIR



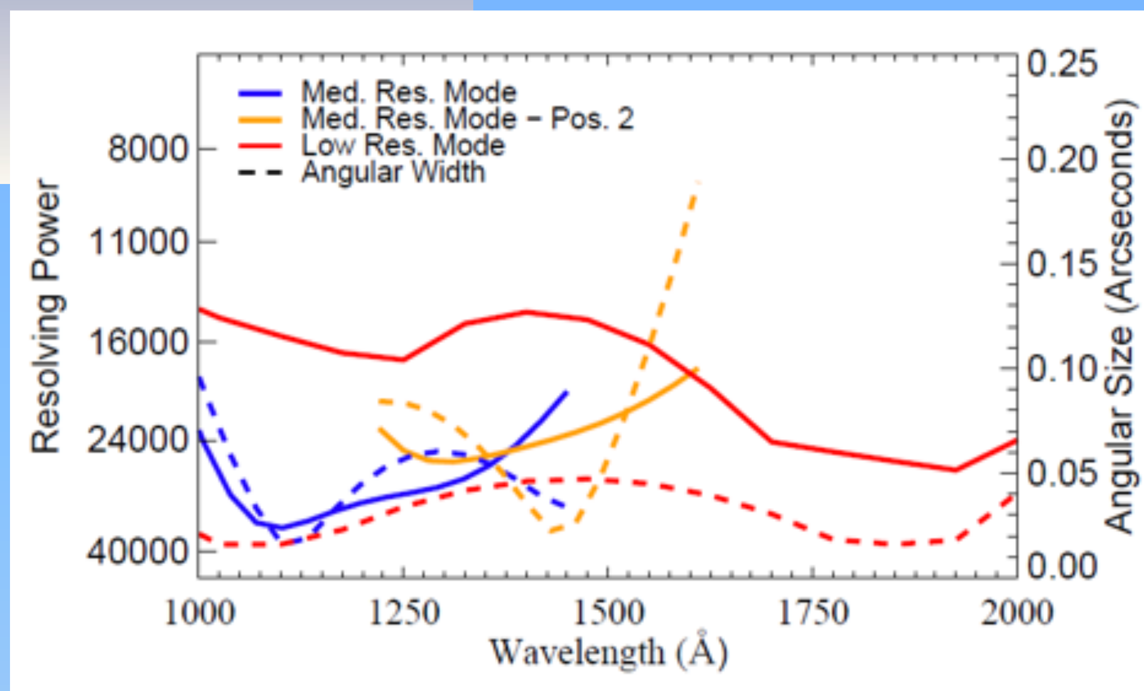
- Optical Telescope Assembly → collimator
- TBD -- echelle grating*
- Holographically ruled cross-dispersing/focusing grating

NEED: stable advanced coatings (reflectivity ≥ 85% at λ > 1000 Å, large-format detector array (~200mm x 200mm)

Combined High-resolution and ***Imaging Spectrograph*** for LUVOIR

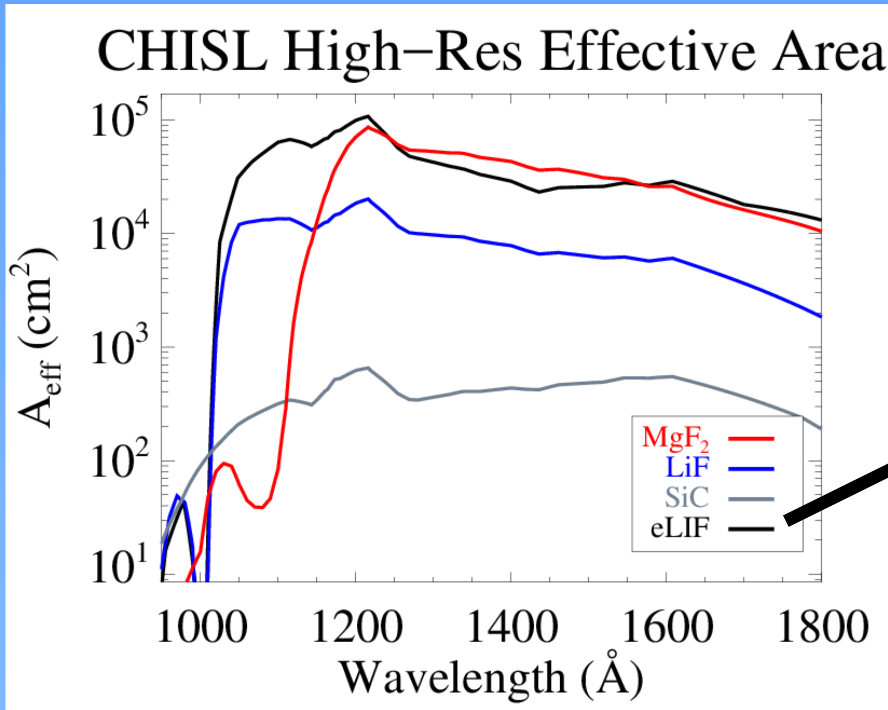


- JWST-like microshutter array (1’ x 2.4’)
- Holographic grating
- Fold mirror

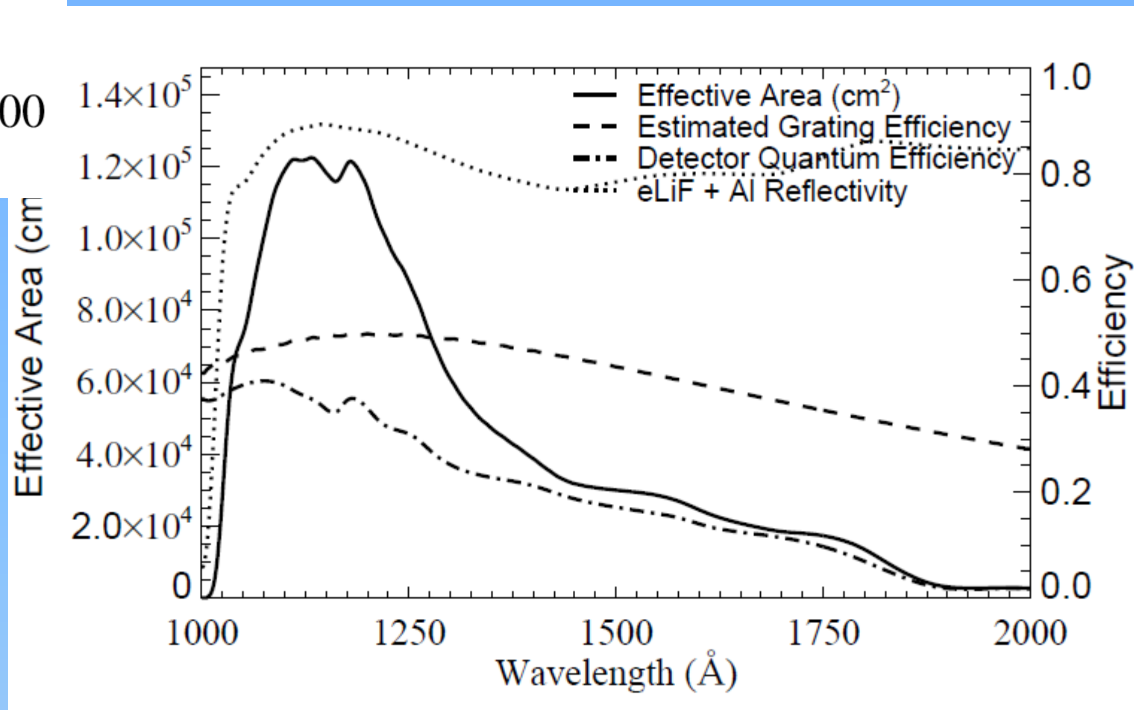


<u>NEED</u>: stable advanced coatings, large-format detector arrays (~200mm x 200mm x 2), UV MSAs

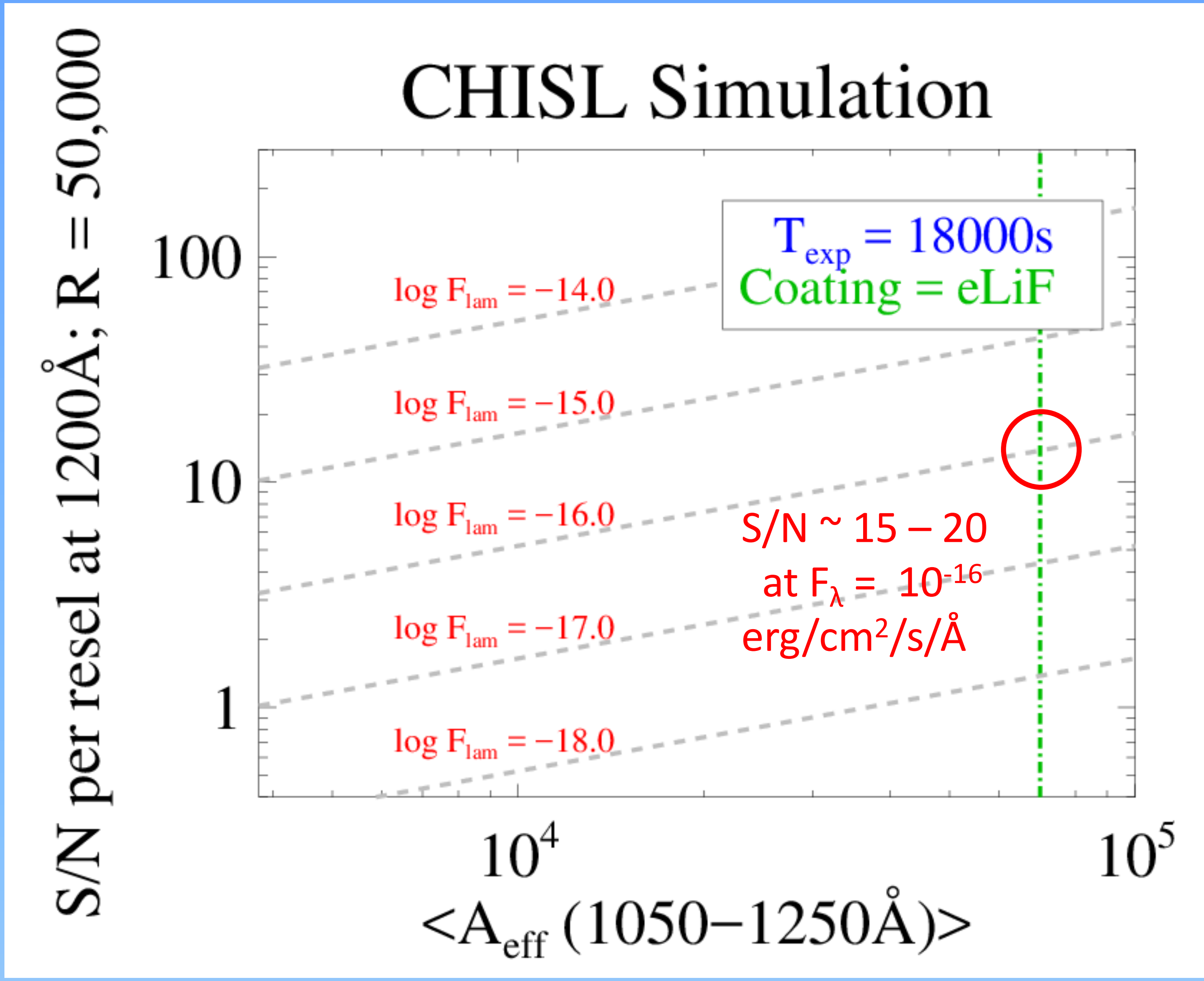
Combined ***High-resolution*** and ***Imaging Spectrograph*** for LUVOIR



-Quijada et al. 2014;
-Fleming et al. 2016;
-Hennessey et al. 2016



3. Combined ***High-resolution*** and Imaging Spectrograph for LUVOIR



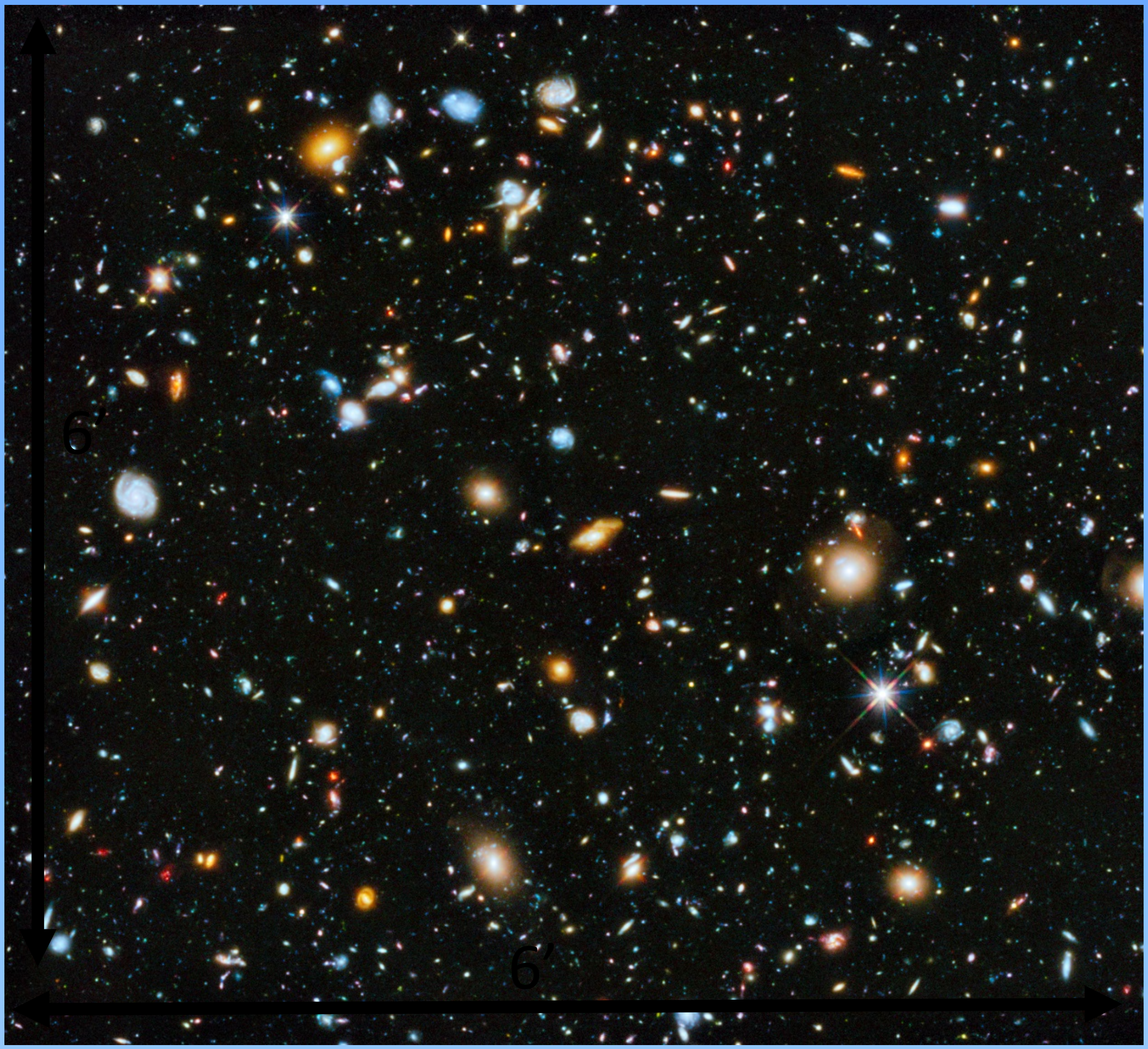
Combined High-resolution and ***Imaging Spectrograph*** for LUVOIR

Comparison with HST-STIS

Instrument Parameter	STIS G140M	CHISL (Imaging Modes)
Spectral Resolving Power	10,000	16,000 – 40,000
Total Spectral Bandpass	1140 – 1740 Å	1000 – 2000 Å
Spectral Bandpass per Exposure	50 Å	450 – 1000 Å
Number of Exposures to Cover Spectral Bandpass	12	1 (Low Res) 3 (Med Res)
Imaging Field-of-View	0.2” x 28’’	60” x 144”
Spectrograph Throughput	1.2%	11.7%

Combined High-resolution and ***Imaging Spectrograph*** for LUVOIR

What can we do with LUVOIR + CHISL?

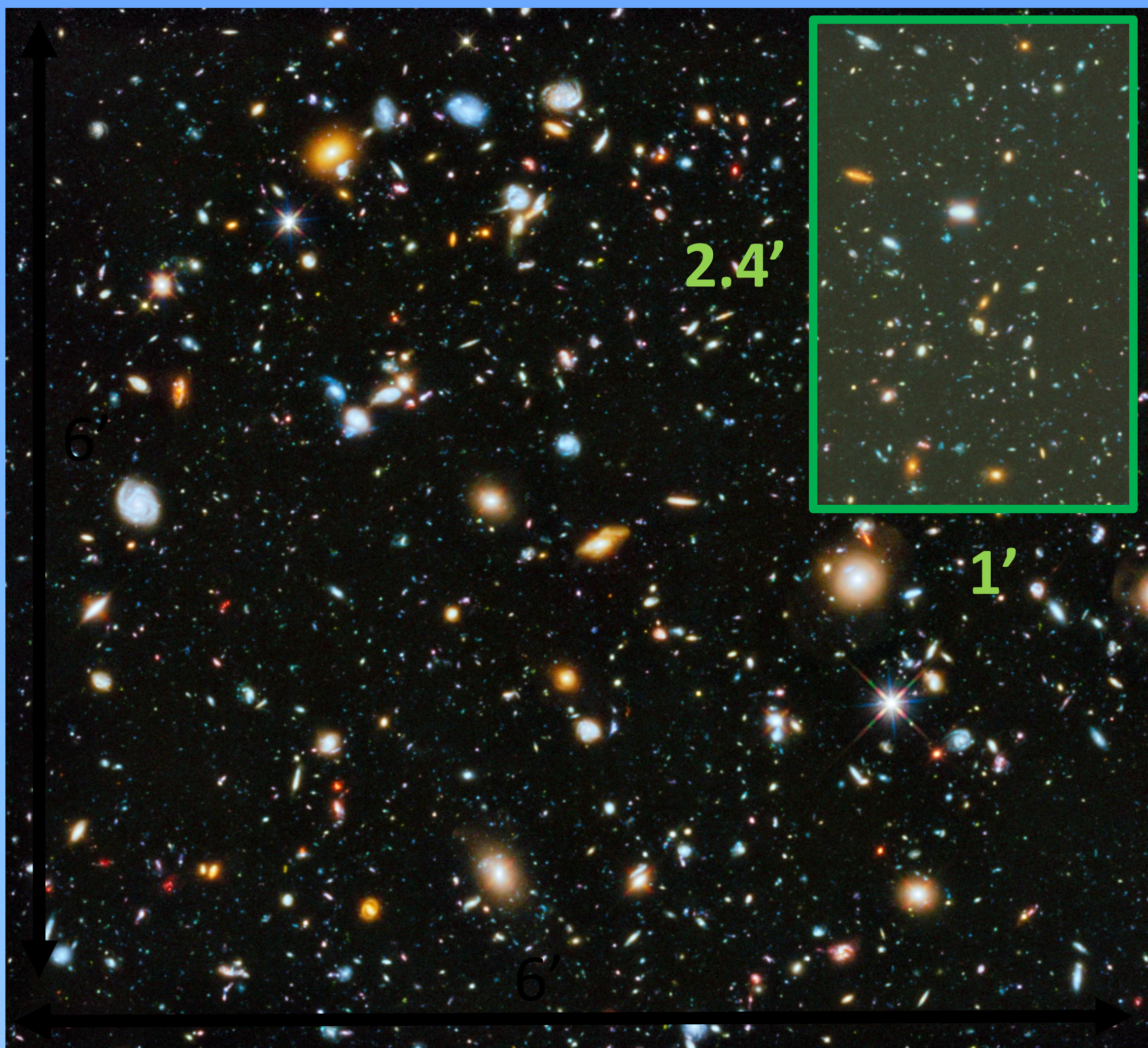


Deep fields will be produced automatic via parallel observations during coronagraphy

Spectroscopic observations of low/intermediate redshift galaxies and CGM/IGM

Combined High-resolution and ***Imaging Spectrograph*** for LUVOIR

What can we do with LUVOIR + CHISL?



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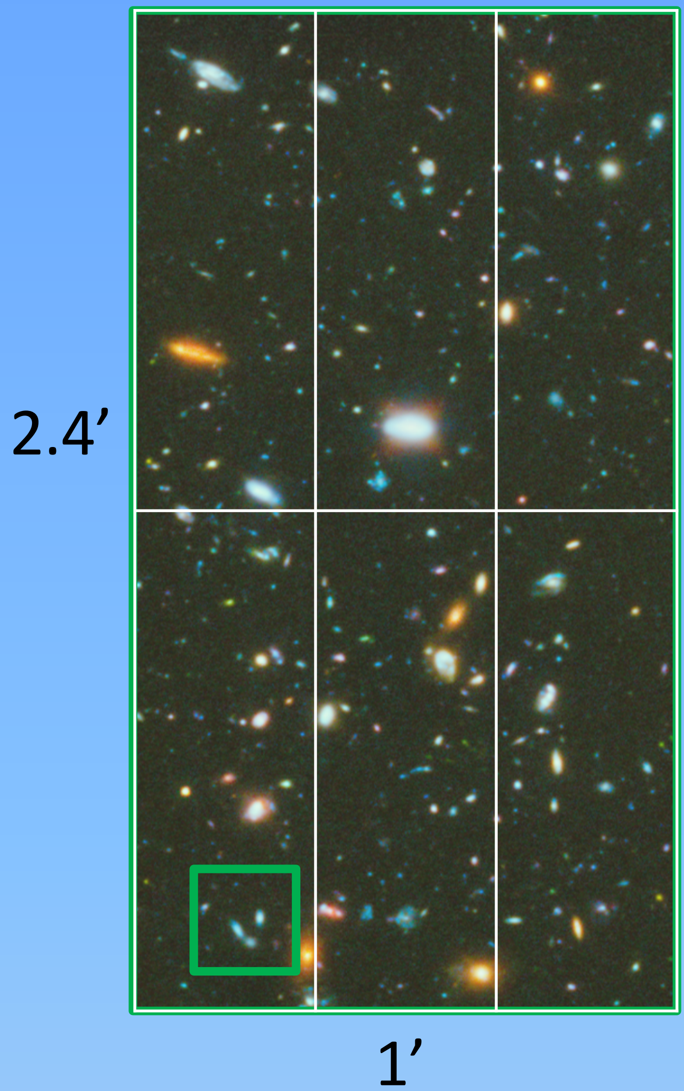
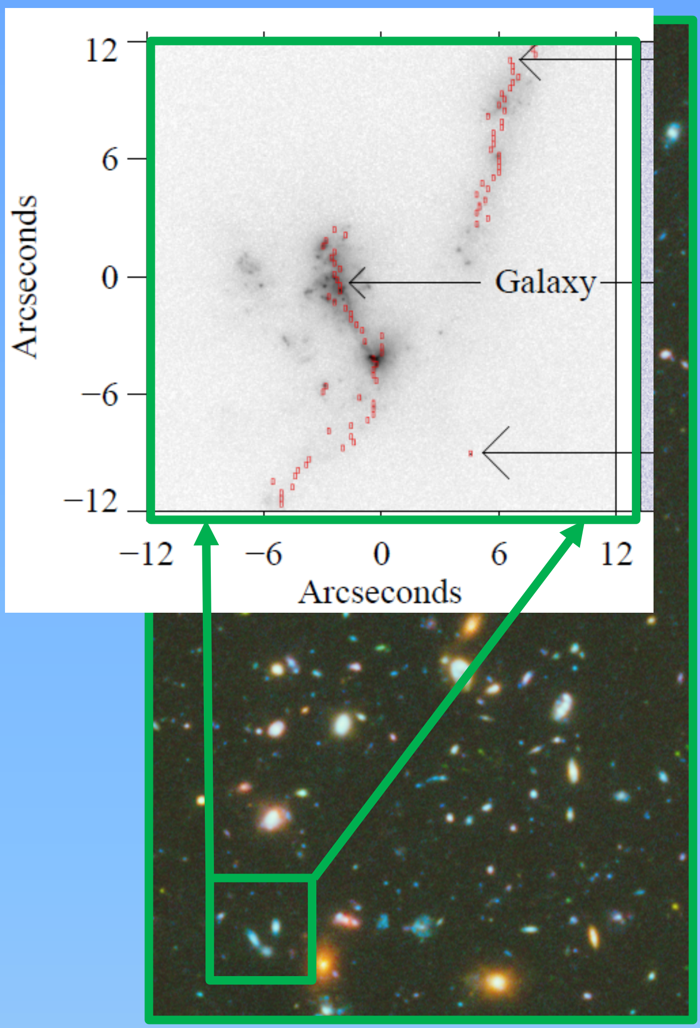


- 3 microshutter arrays, each 20” x 48” FOV
- 100 x 200 micron slits
- < 0.1” spectral imaging across most of FOV
  - (0.03” – 1.0” spectral imaging across full FOV)

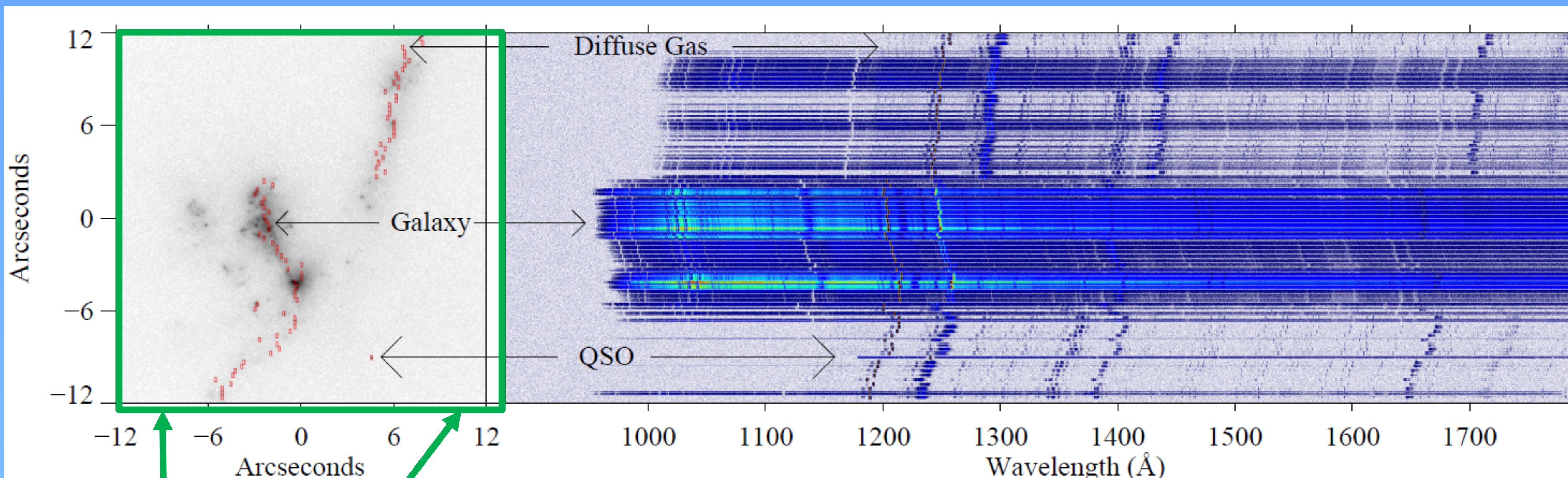
Combined High-resolution and ***Imaging Spectrograph*** for LUVOIR

What can we do with LUVOIR + CHISL?



Combined High-resolution and ***Imaging Spectrograph*** for LUVOIR

What can we do with LUVOIR + CHISL?



R > 15,000 1000 – 2000 Å spectroscopy of hundreds of objects *simultaneously*.

Background quasars, numerous galactic regions, circumgalactic halo

CHISL Technology – Current Laboratory and Flight Testing

NASA CASA LASP
University of Colorado Boulder

CHISL Technology – Current Laboratory and Flight Testing

- Colorado UV Rocket Program

  - High-resolution spectroscopy of the local ISM (**<u>CHESS</u>**); Imaging spectroscopy of nearby galaxies and exoplanet host stars (**<u>SISTINE</u>**); Ionizing radiation from local OB stars (**<u>DEUCE</u>***)

  - **Hardware Development**:
    1. High-efficiency UV/visible optical coatings
    2. Large format, high dynamic range UV detectors
    3. Diffraction grating technology

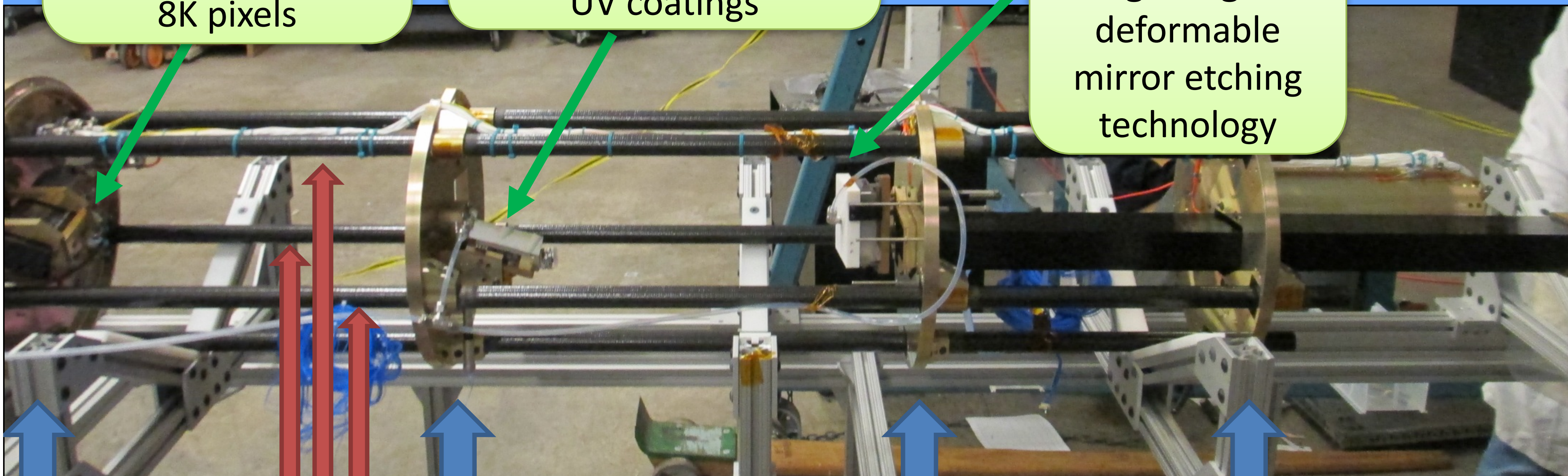
PI – K. France
*PI – J. Green

CHESS Payload

MCP detector
5 MHz global rate, photon counting, 40cm diam, 8K x 8K pixels

Echelle grating: 70% groove efficiency, testing with advanced UV coatings

Cross-disp grating: deformable mirror etching technology



X-strip MCP

Echelle

Cross disperser

Mechanical collimator

Carbon fiber mechanical structure

France et al. 2012
Hoadley et al. 2014
France et al. 2016
Hoadley et al. 2016
Fleming et al. 2015, 2016

Summary: The future

4) High-res FUV spectroscopy: gas phase abundances at rocky planet radii. Multi-object: statistical analysis of 0.1 – 10 AU gas structure and evolution from 0.5 – 20 Myr.

5) CHISL: high-resolution (echelle) point source spectrograph, [$R \geq 10^5$]

6) CHISL: Imaging / multi-object spectrograph, medium- and low-resolution spectral modes. multi-object over 1’ x 2.4’ FOV at medium res [R = 16,000 - 40,000]

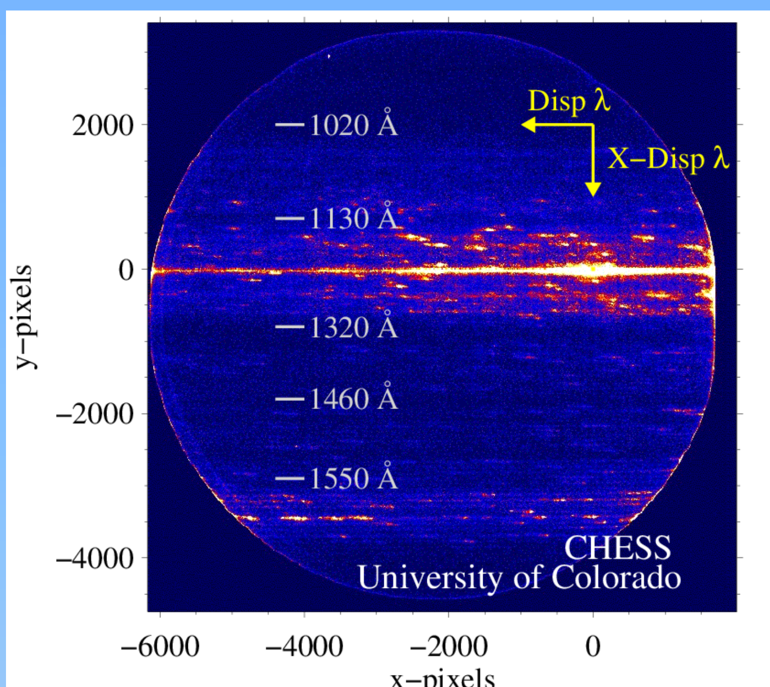

Questions?

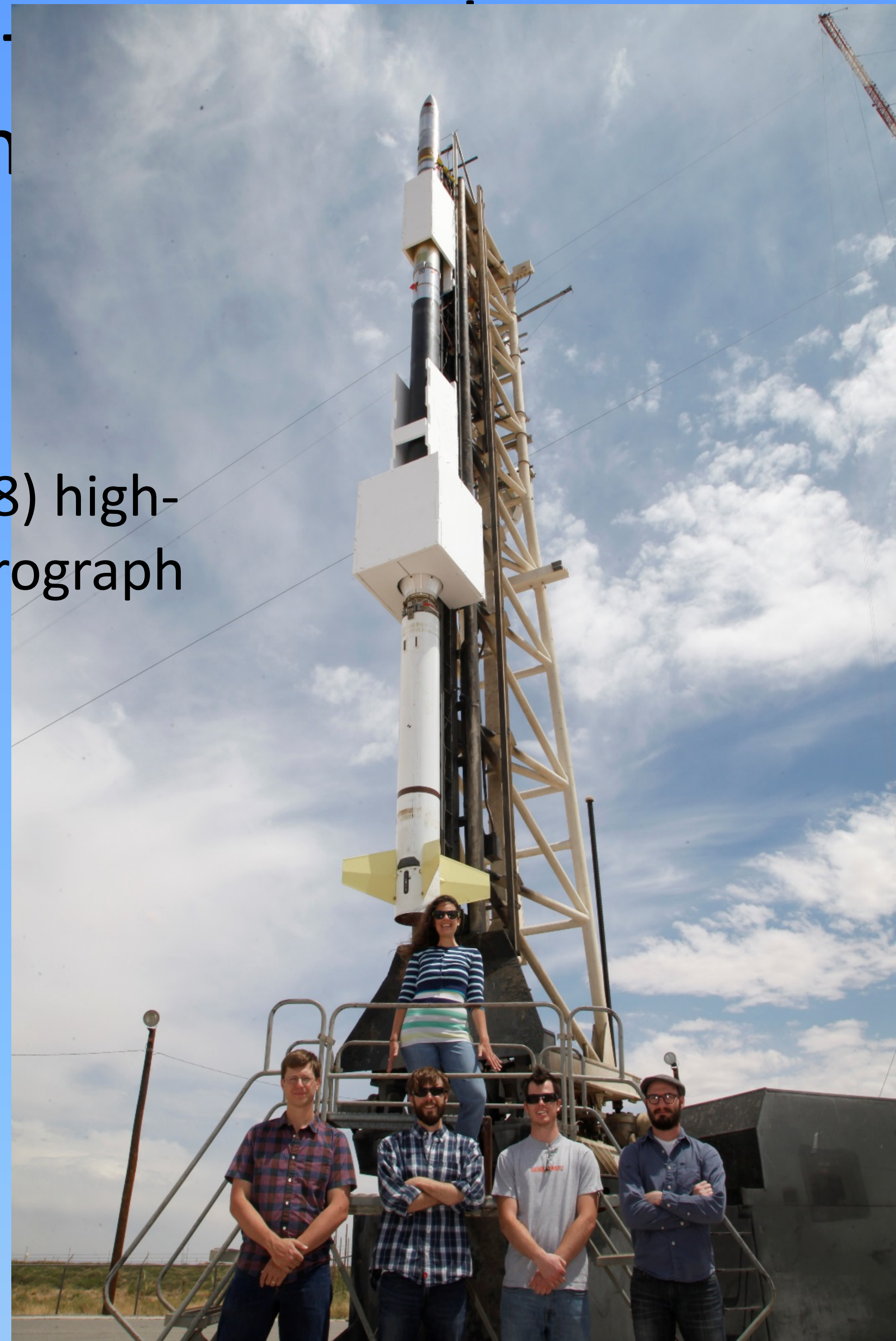
BREAK

4. CHISL Technology – and Fligh

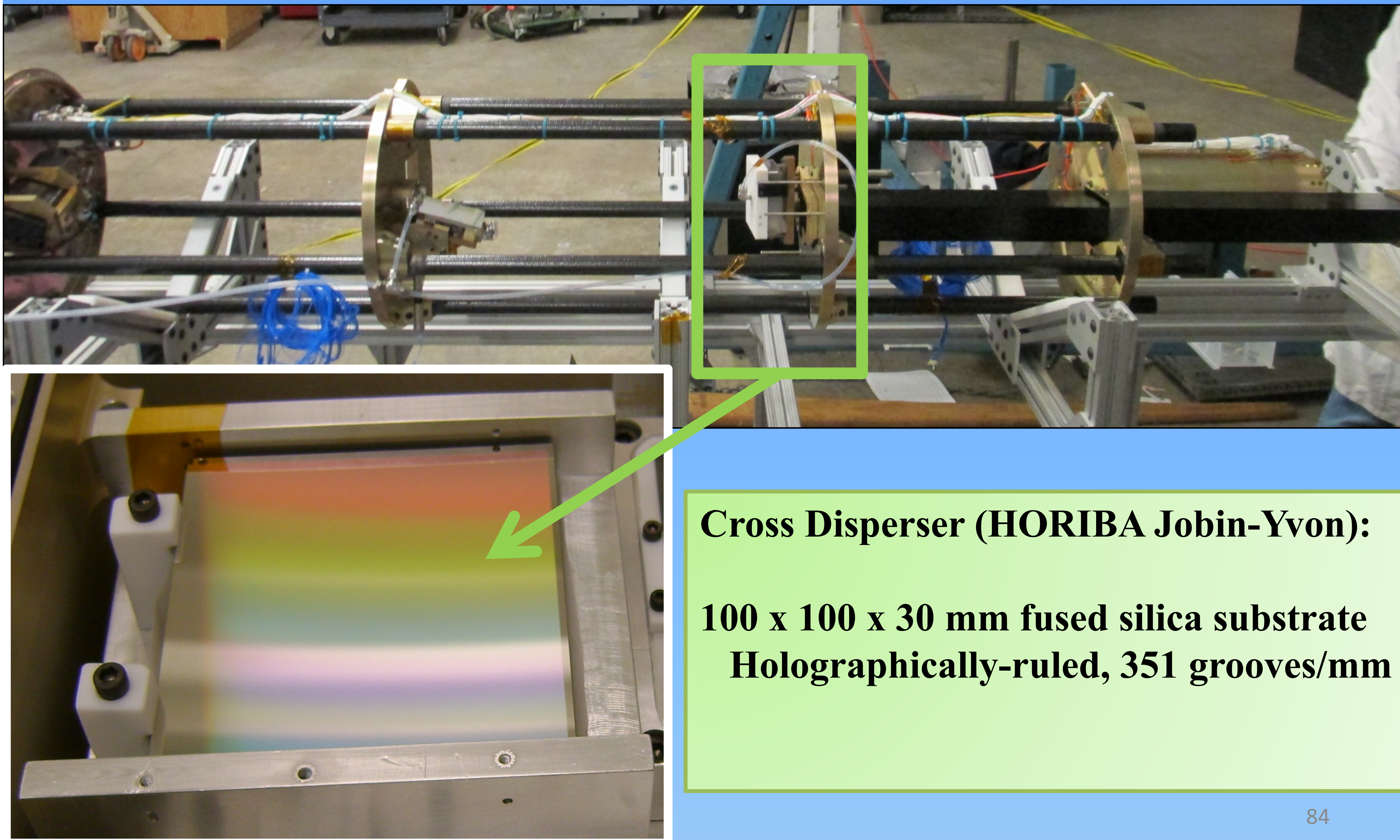
CHISL Technology Development

1) CHESS: (see Keri Hoadley's poster today/tomorrow, 9905-138) high-resolution ($R \approx 10^5$) echelle spectrograph





CHESS Payload



Cross Disperser (HORIBA Jobin-Yvon):

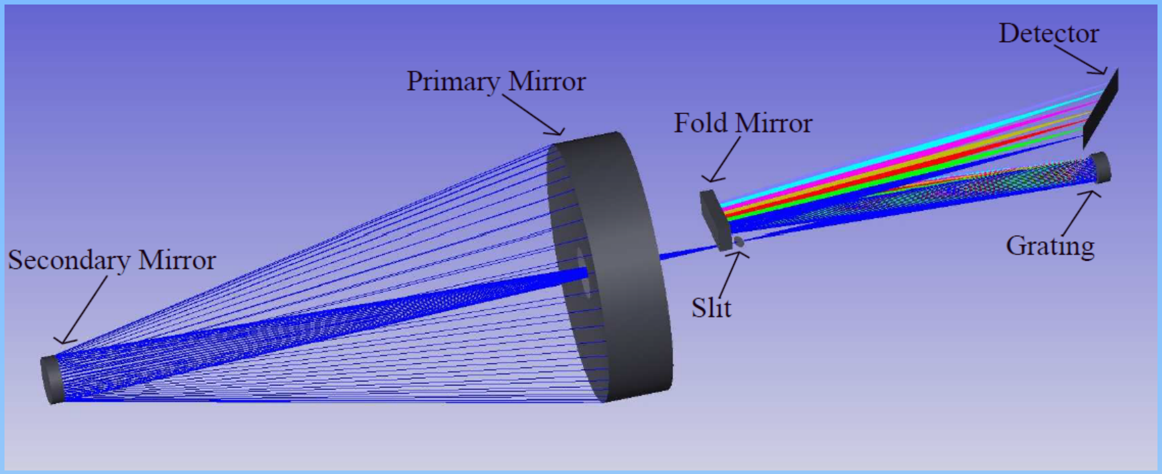
100 x 100 x 30 mm fused silica substrate
Holographically-ruled, 351 grooves/mm

4. CHISL Technology – Current Laboratory and Flight Testing

CHISL Technology Development

1) CHESS: (see Keri Hoadley's poster today/tomorrow, 9905-138)

2) SISTINE: (see Brian Fleming's Talk this afternoon, 9905-9). $R \approx 10{,}000$, sub-arcsecond imaging spectrograph, 1000 – 1600 Å

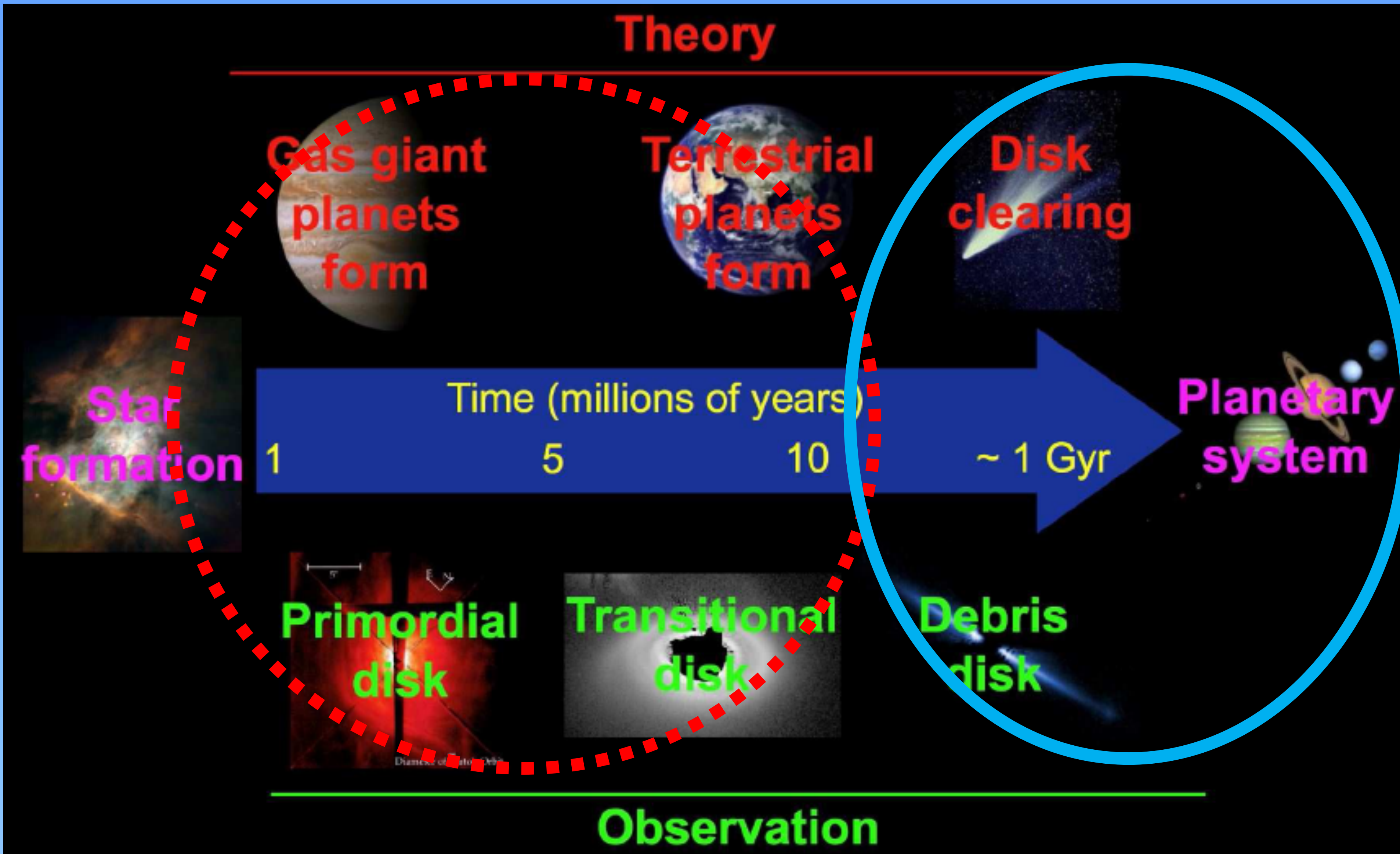


Summary – Part 1

1) HST-COS observations have enabled statistical studies of **both H_2 and CO** in the warm molecular atmospheres of protoplanetary disks for the first time.

2) H_2 fluorescence traces 0.1 – 3 AU (to 10 AU in some transitional disks) while CO fluorescence traces 2 – 10 AU. **H_2 disk inner radii increase with dust dissipation** and declining mass accretion rate.

3) CO and H_2 absorption line spectroscopy through inclined disks has revealed **CO/H_2 ratios ~10^{-4}**, suggesting that little CO chemical processing occurs in the first 2 Myr. **H_2O dissociation at ~1 AU** is the most likely explanation for the UV molecular continuum in PPD spectra.



A. Roberge et al. 2009 – Astro2010 White Paper

Outline

1. Circumstellar gas and dust are the building blocks of planetary systems. New molecular disk diagnostics probed using HST-COS

2. Structure, evolution, and composition of molecular gas at planet-forming radii (r < 10 AU) in protoplanetary environments

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3. High-energy (X-ray through UV) stellar irradiance regulates chemistry and evolution of potentially habitable planets – first panchromatic survey of M and K dwarf host stars (MUSCLES)

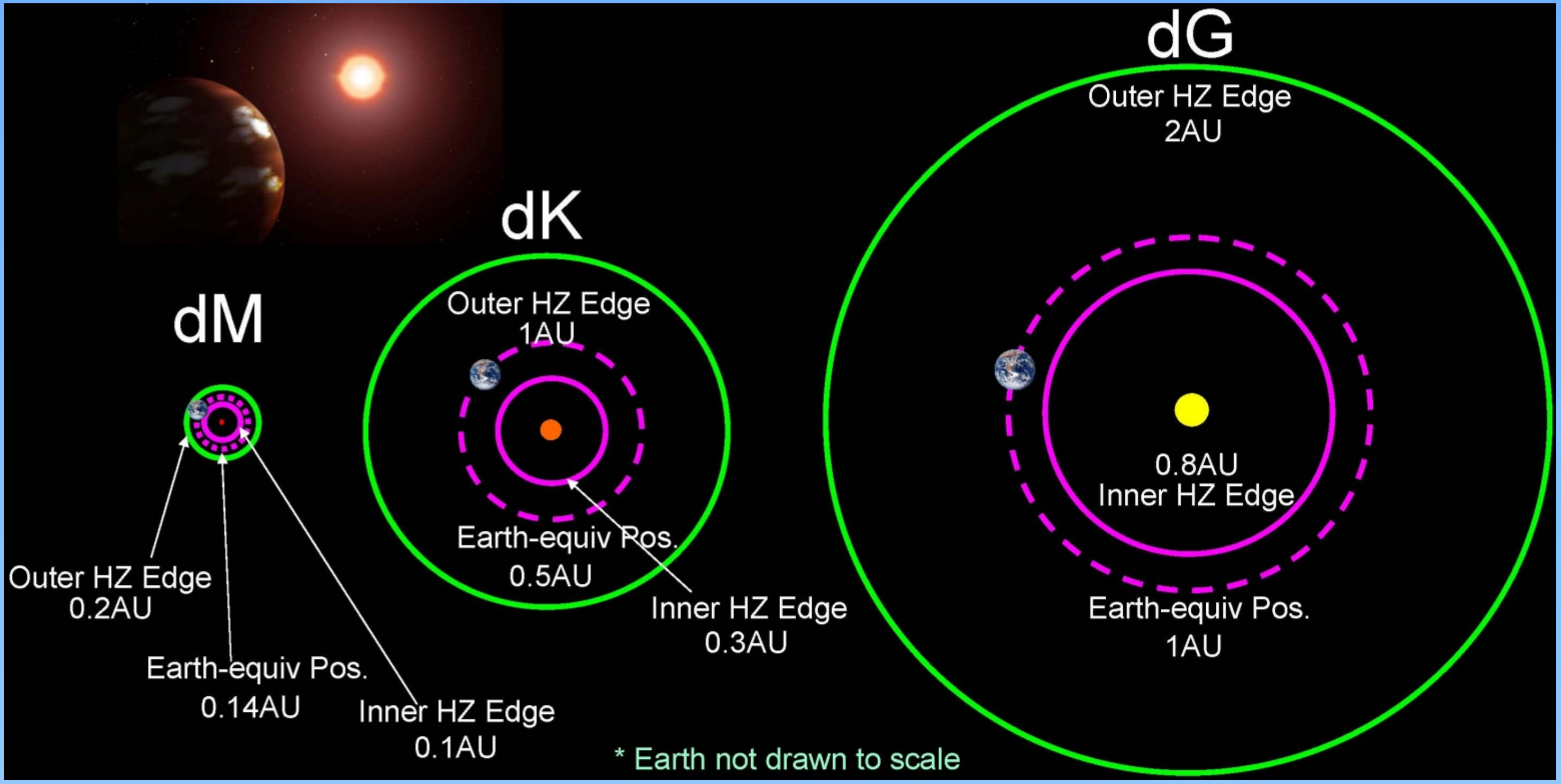
4. Quantifying the high-energy radiation environment, formation of "biosignature" species in Earth-like atmospheres, large UV/X-ray flares on optically inactive stars

The Energetic Radiation Environment in the Habitable Zones Around Low-Mass Exoplanet Host Stars

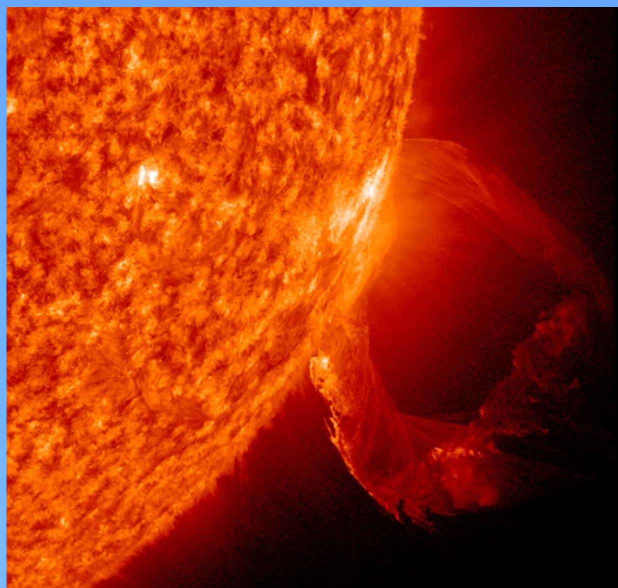
also starring:

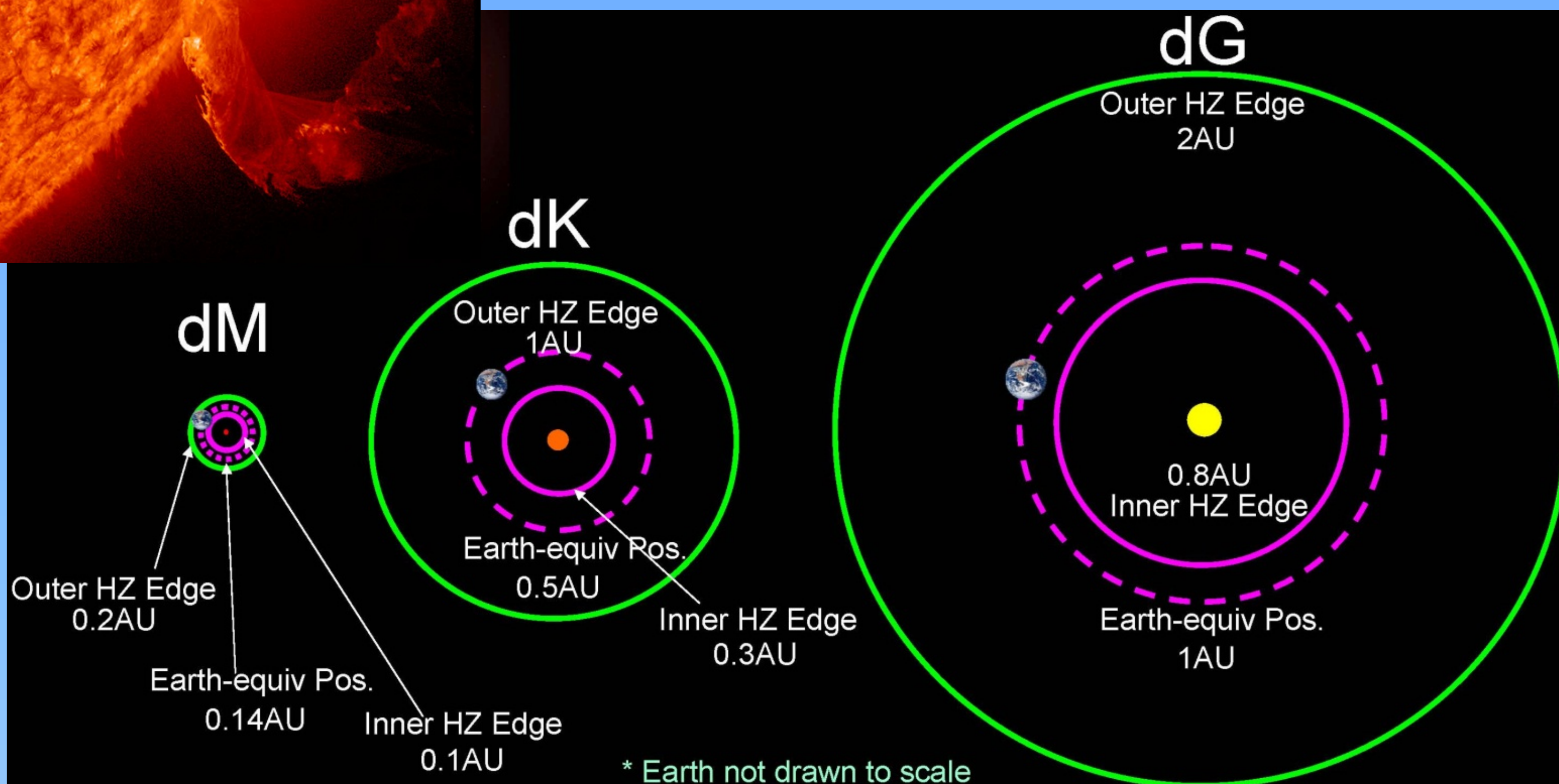
Tom Ayres – CU, Alex Brown – CU, Juan Fontenla - NWRA
Cynthia Froning – Texas, Suzanne Hawley – UW, Lisa Kaltenegger – Harvard/Cornell, Jim Kasting – Penn State
Jeff Linsky- CU, Pablo Mauas – Arg, Yamila Miguel - MPIA
Aki Roberge – NASA/GSFC, Sarah Rugheimer – Harvard/St. Andrews
John Stocke – CU, Feng Tian – LASP/Tsinghua, Mariela Vieytes - Arg
Lucianne Walkowicz – Princeton/Adler

Heating and Chemistry of Planetary Atmospheres

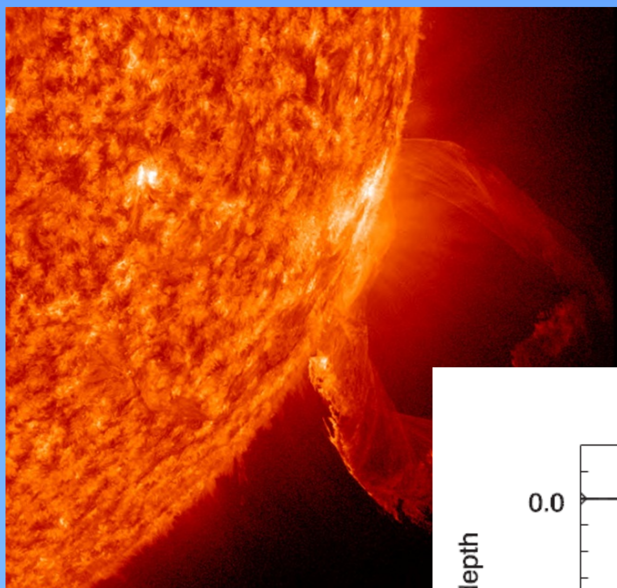


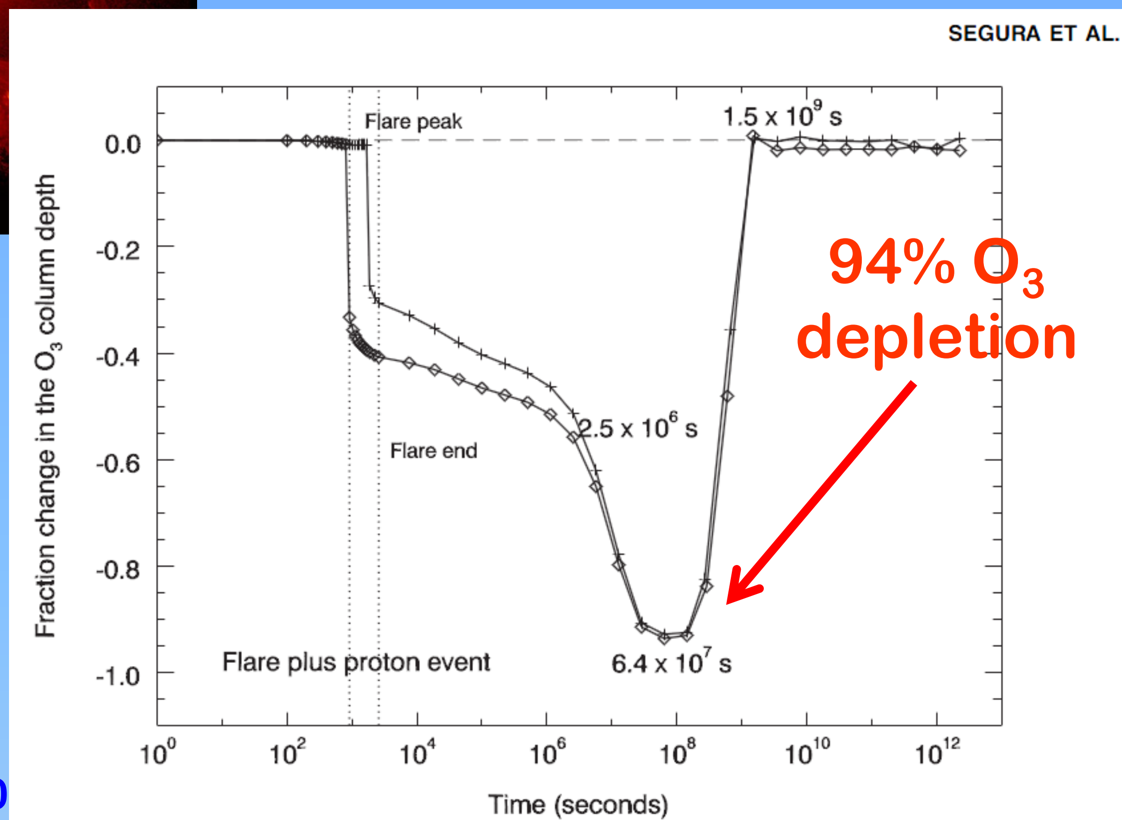
Heating and Chemistry of Planetary Atmospheres





Heating and Chemistry of Planetary Atmospheres



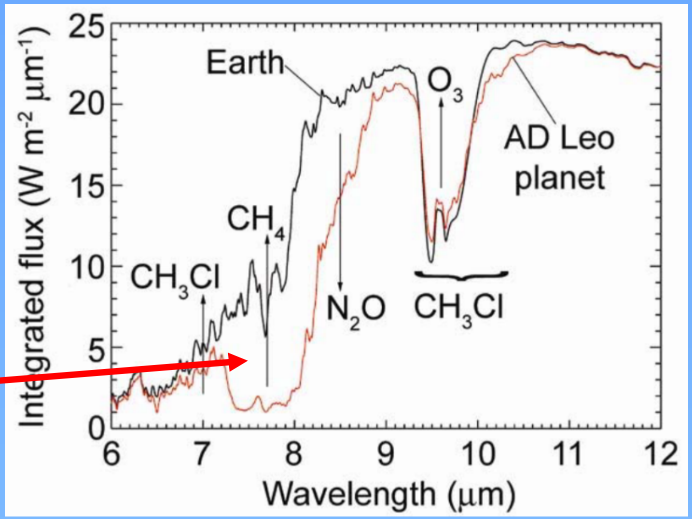


Segura+, AsBio, 2010

Exoplanet Atmospheres: Exo-Earths

- **Habitable planet candidates exist today**

Segura+, AsBio, 2005



- The EUV+FUV+NUV radiation fields of their host stars control the atmospheric heating/ stability and photochemical structure of their atmospheres – including formation of biomarkers (e.g., O_2, O_3, CO_2, CH_4)

- However, we have few constraints on the high-energy irradiance from "typical" (optically inactive) M and K dwarf planet hosts, neither observational nor theoretical

- **Modeling and interpretation of biomarkers require realistic inputs**

Observational Program

Measurements of the
Ultraviolet
Spectral
Characteristics of
Low-mass
Exoplanetary
Systems

(CU student Sarah LeVine)

PI – France. **CU graduate students Allison Youngblood and Parke Loyd**

Observational & Modeling Program

- **Optical & NIR** -
  - North: APO, LCOGT, South: El Leoncito, VLT
- **FUV (w/ Lyα) & NUV**
  - *Hubble Space Telescope*, **Cycle 22 Treasury**
- **LUV**
  - *Far-Ultraviolet Spectroscopic Explorer* + models
- **EUV**
  - Calculation based on new solar/stellar models and observed FUV line emission + *EUVE*
- **X-ray**
  - *Chandra, XMM-Newton, Swift*

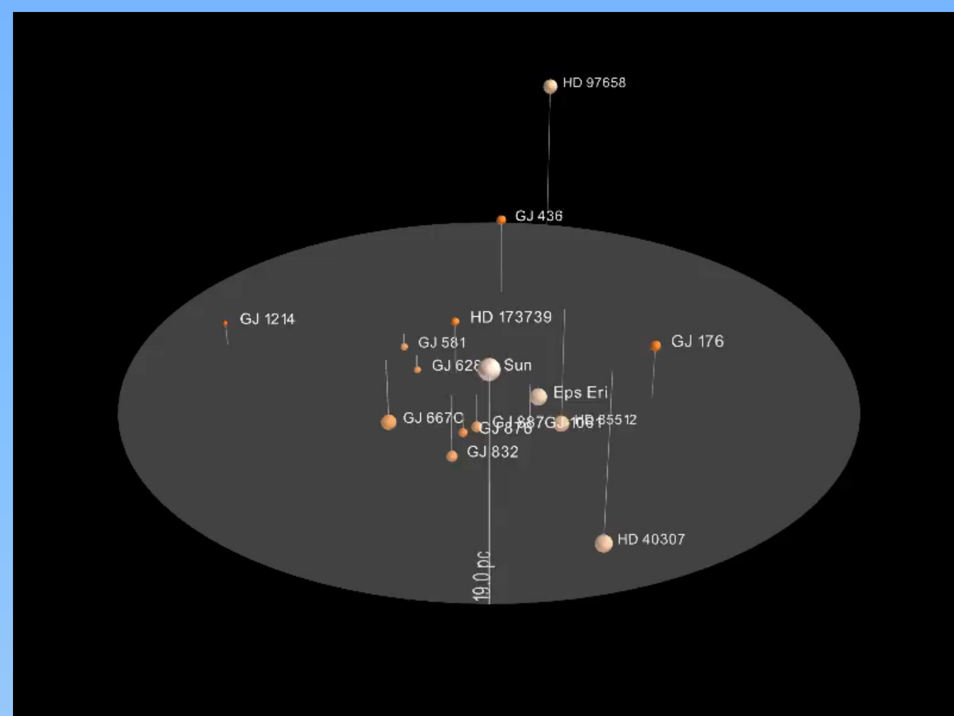
X-ray = 0.5 - 10 nm
EUV = 10 – 90 nm
LUV = 91 – 116 nm
FUV = 117 – 170 nm
NUV = 171 – 310 nm

PI – France

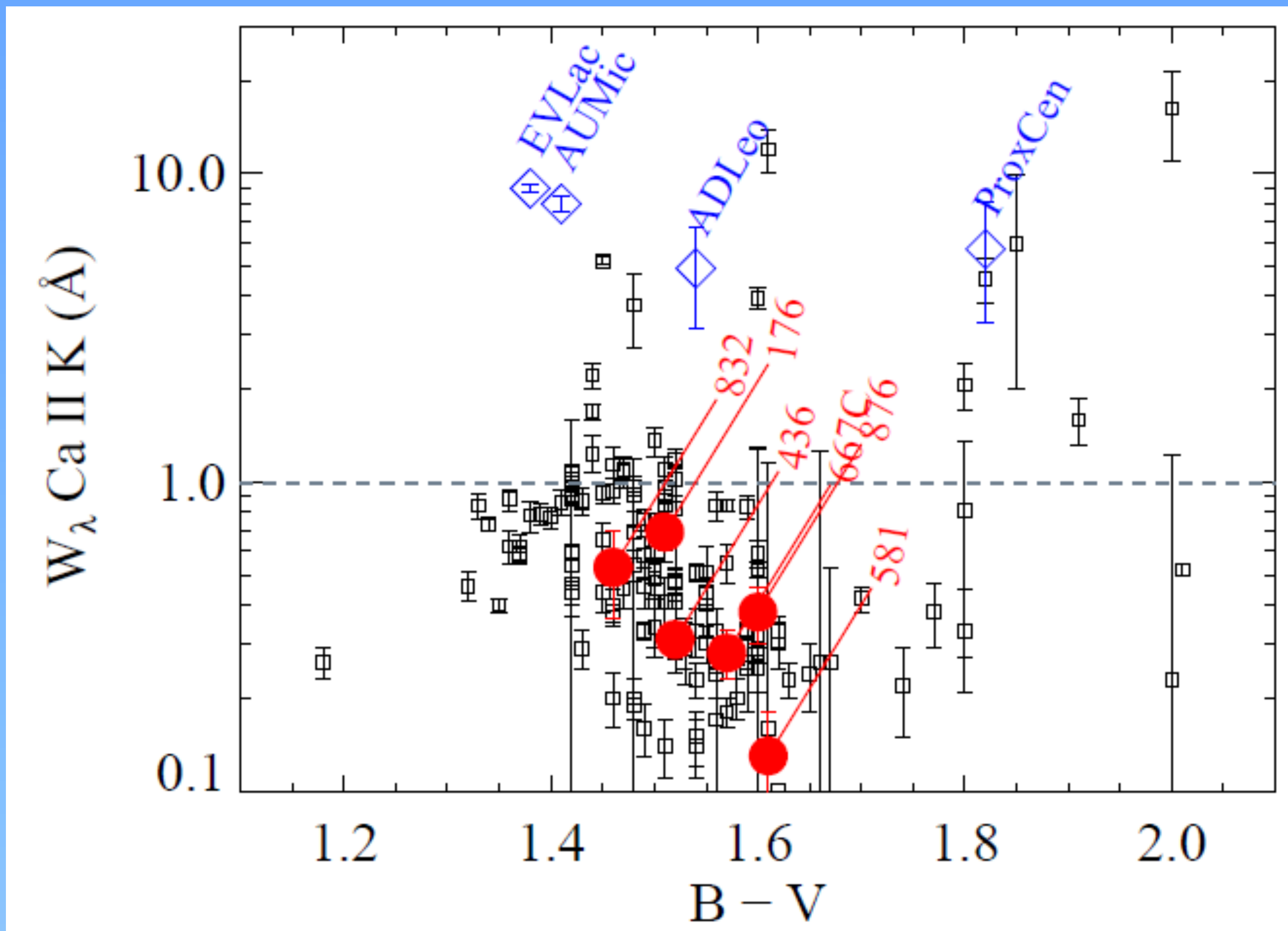
MUSCLES

MUSCLES Treasury Survey: 60% of K and M dwarf exoplanet hosts at d < 15 pc.

- What is the energetic radiation environment in the habitable zones of low-mass exoplanetary systems?
- Flares and activity on typical (`inactive') K & M dwarfs host stars
- Impact on atmospheric photo-chemistry and the production of molecular tracers



MUSCLES: “typical” M dwarfs

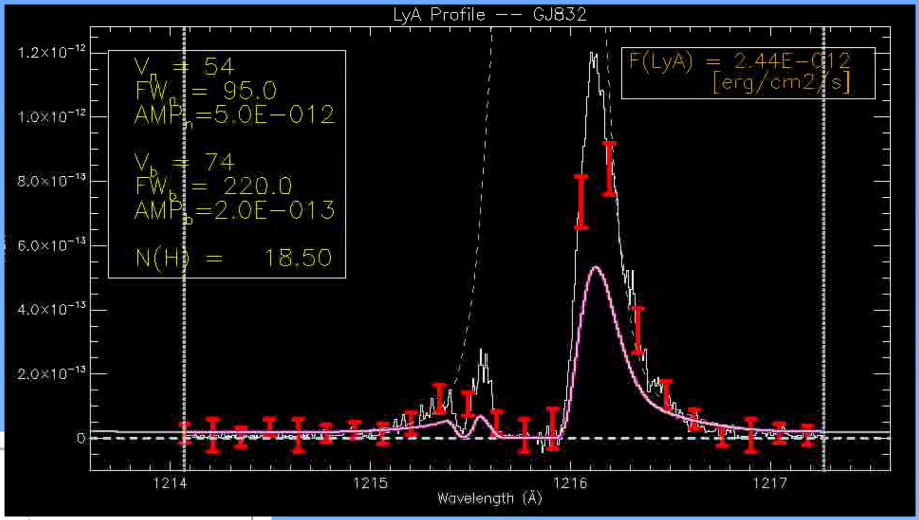


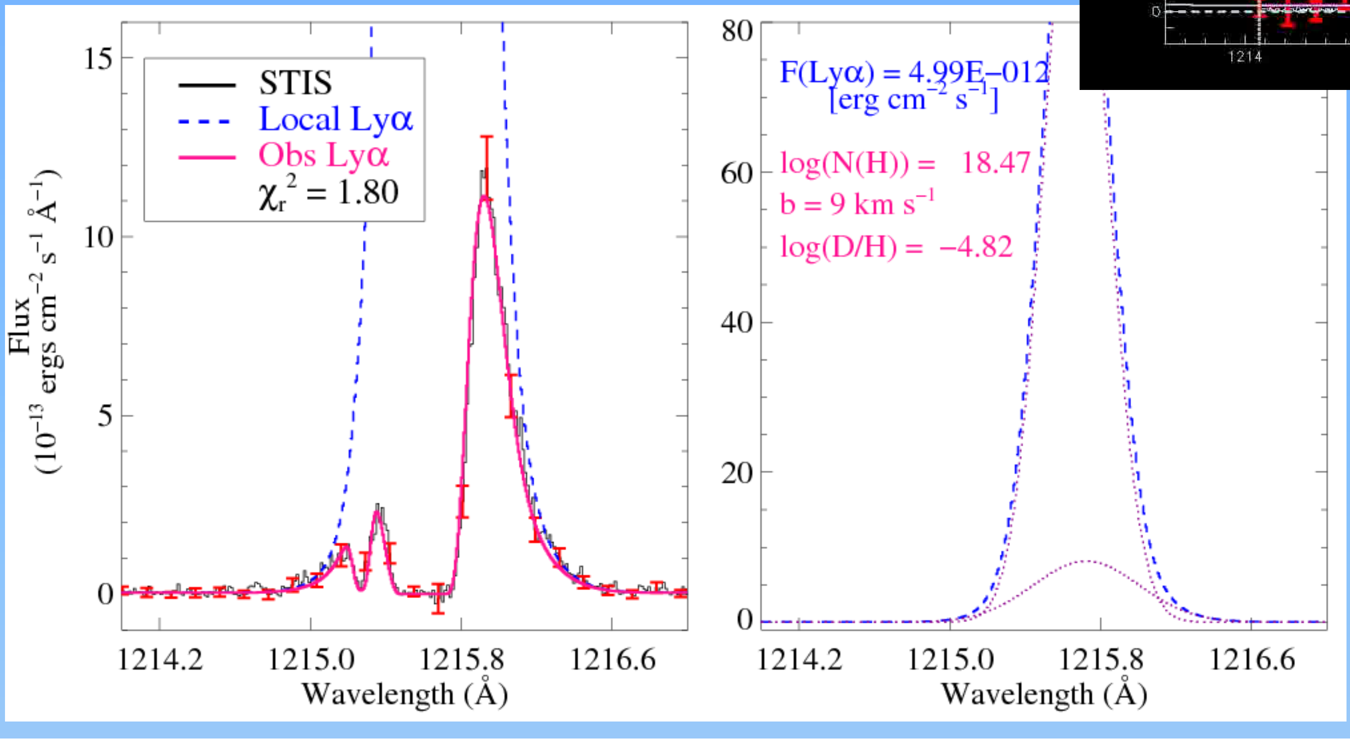
France et al. (ApJ-2016)

Compiling X-ray $\rightarrow$ NIR Stellar Irradiances

M dwarf Lyα

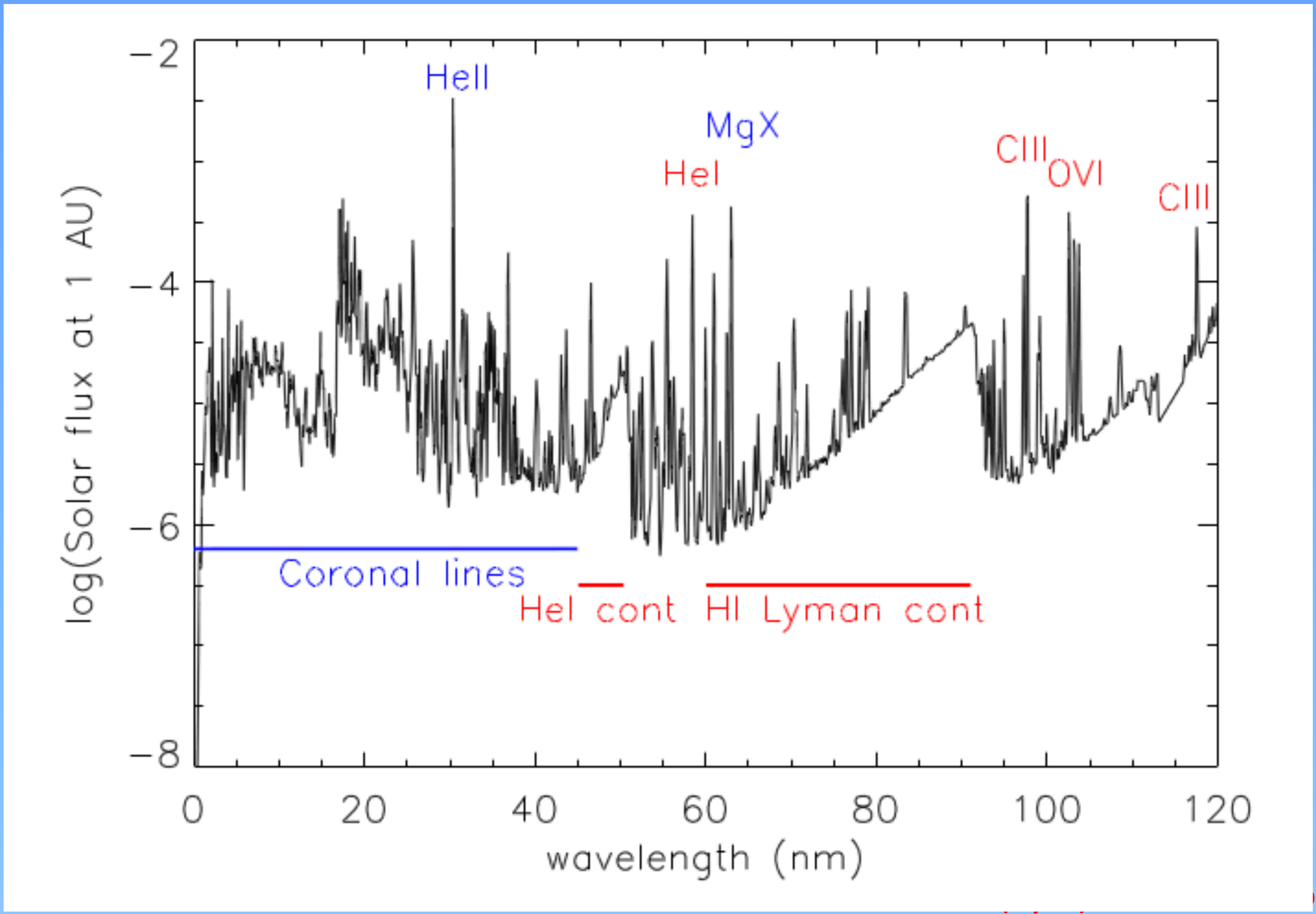
- Project MUSCLES: Lyα Reconstruction





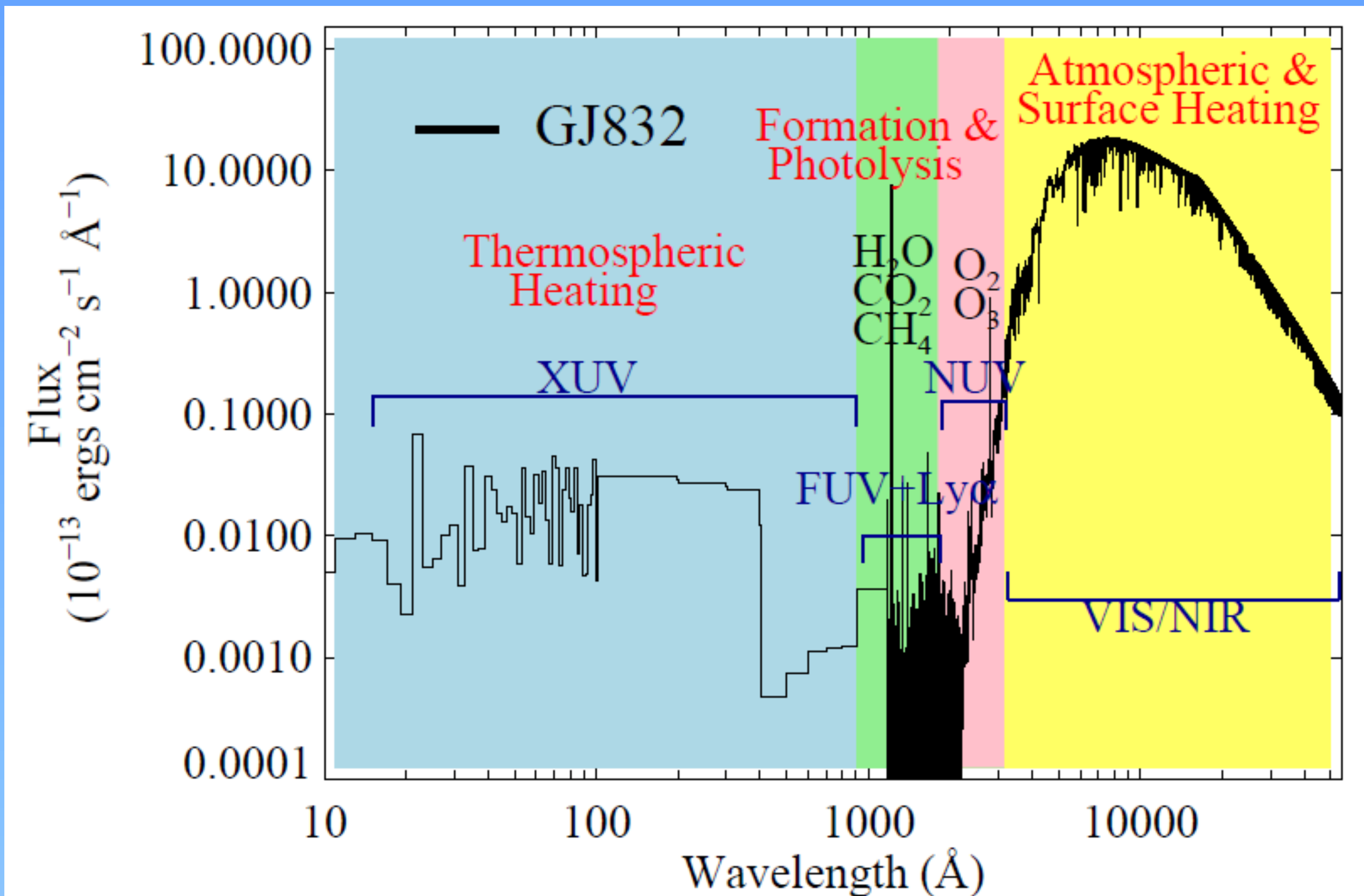
Youngblood et al. 2016
see also
France et al. (ApJ-2013)
Wood et al. (ApJ – 2005)

EUV Estimates: F(EUV) / F(Lyα)



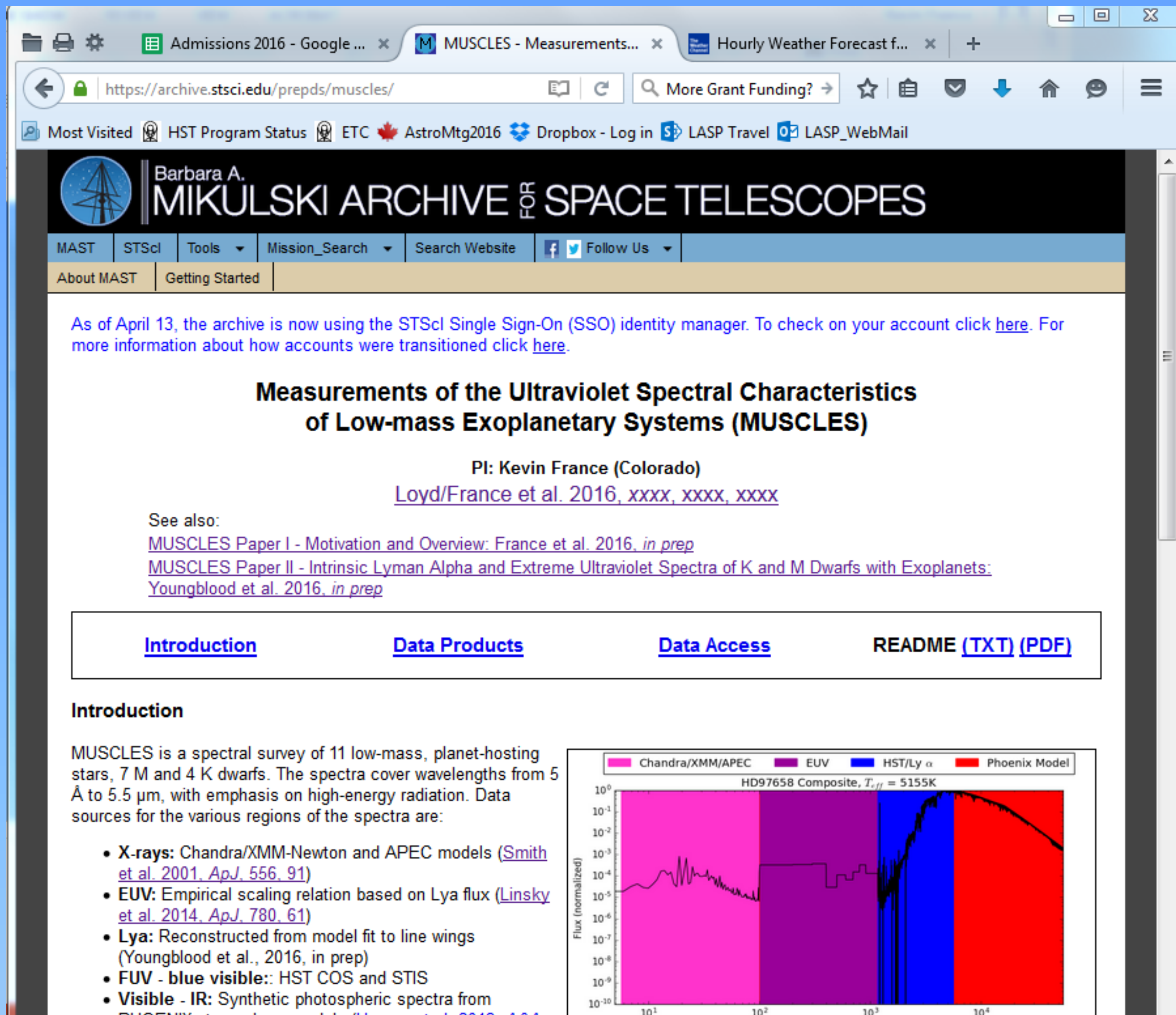
Youngblood et al. 2016
Linsky et al. 2014

5 Å – 5 µm Spectral Irradiance Database



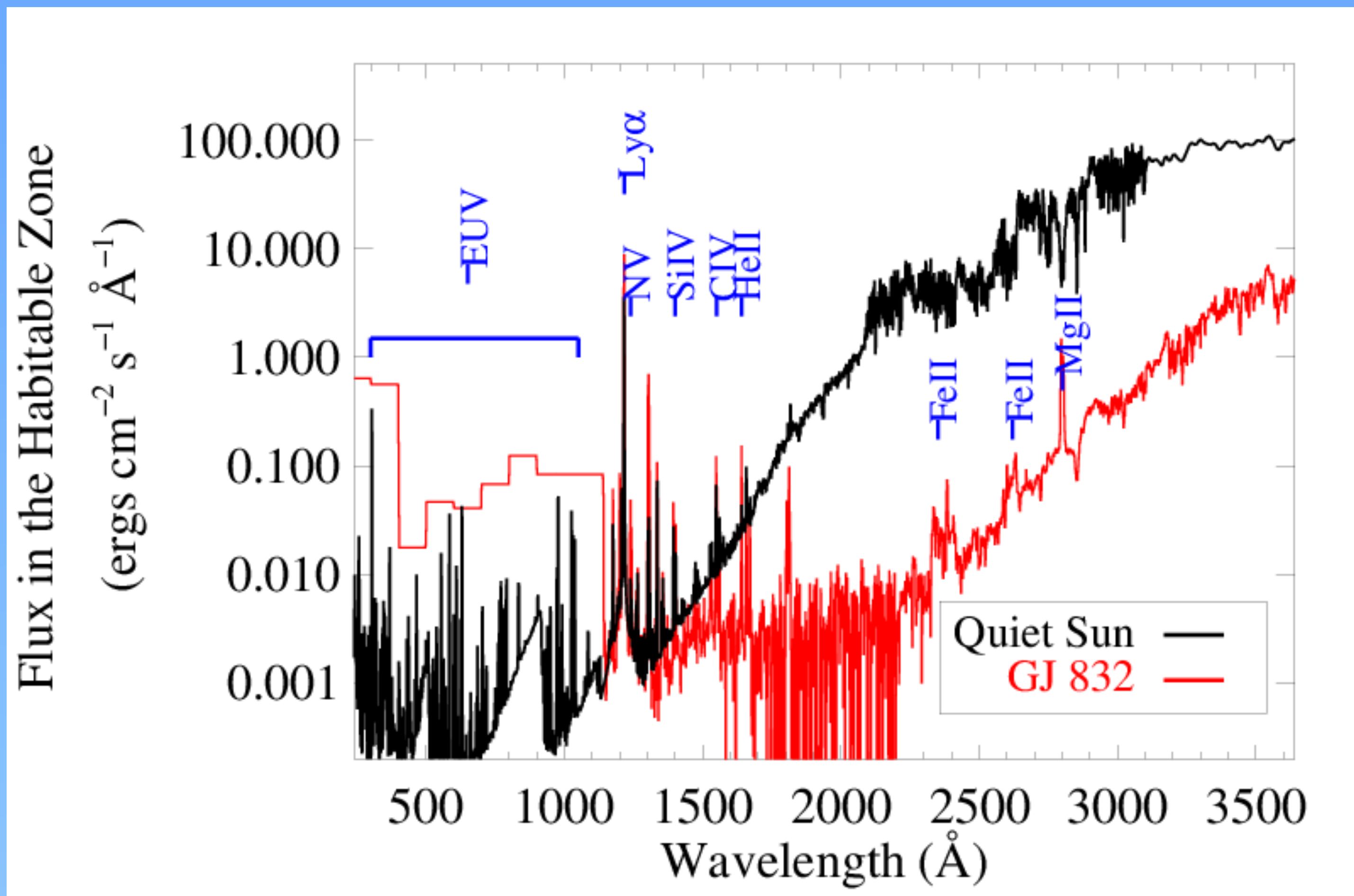
France et al. (ApJ-2016)
Loyd et al. (ApJ-2016 submitted)
Youngblood et al. (ApJ-2016 astro-ph)

https://archive.stsci.edu/prepds/muscles/



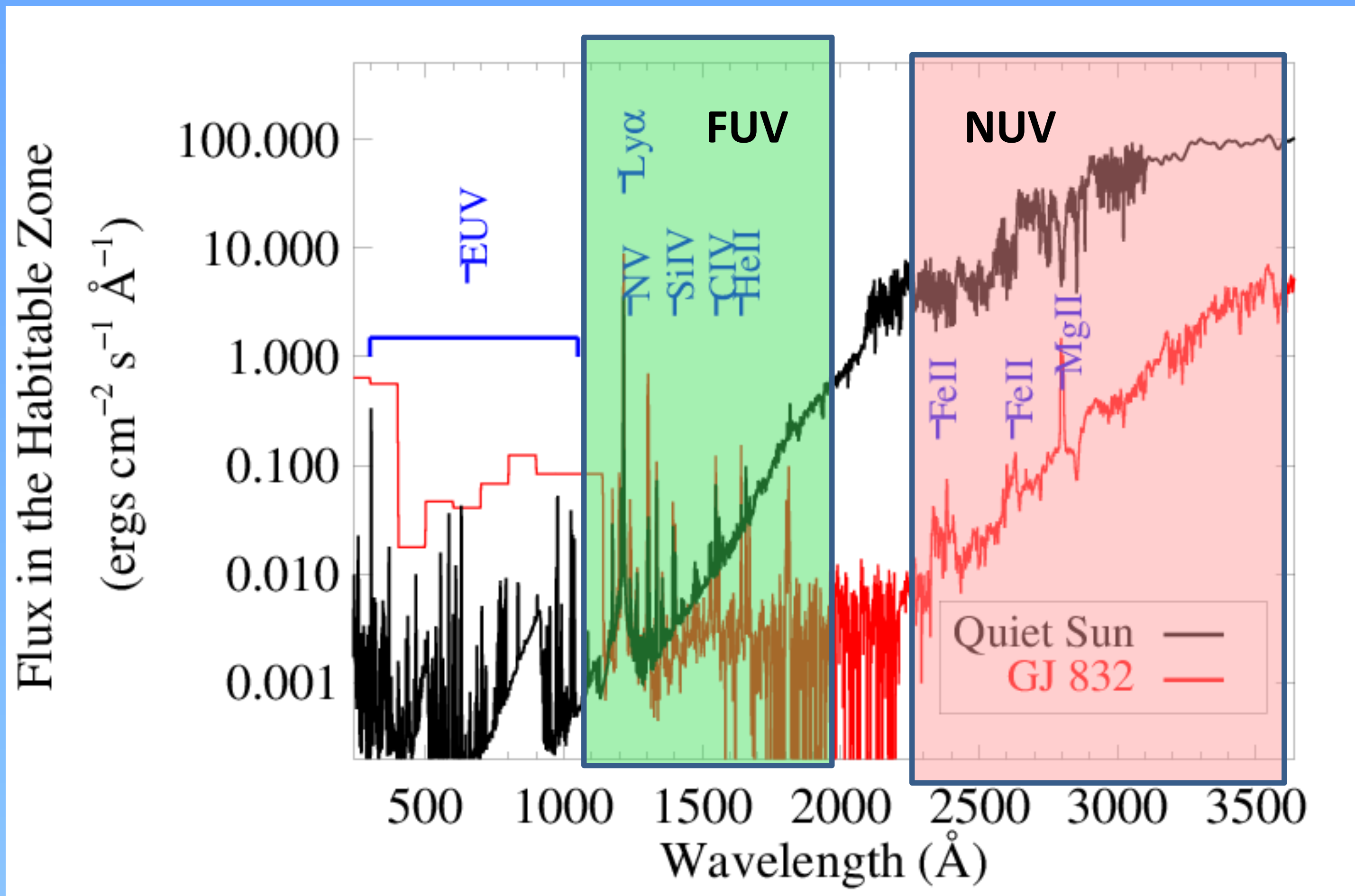
M dwarf FUV and NUV vs. Solar

- Project MUSCLES: GJ 832, UV Spectrum

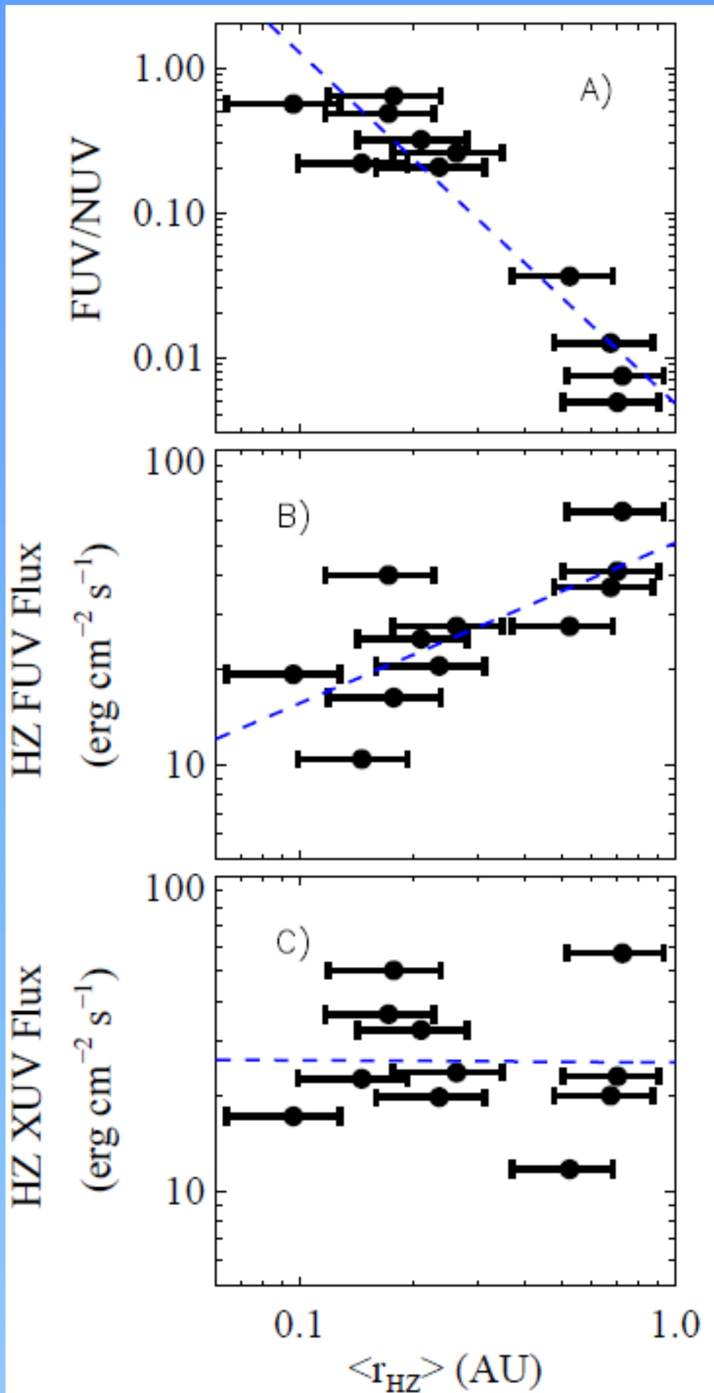


France et al. (ApJL-2012c, ApJ-2016)

FUV/NUV ratio



FUV/NUV – Atmospheric Oxygen Chemistry
Segura+, AsBio, 2010
Tian+, E&PSL, 2014



France et al. (ApJ-2016)

M -- FUV/NUV ~ 0.2 - 1

Sun -- FUV/NUV ~ 10^{-3}

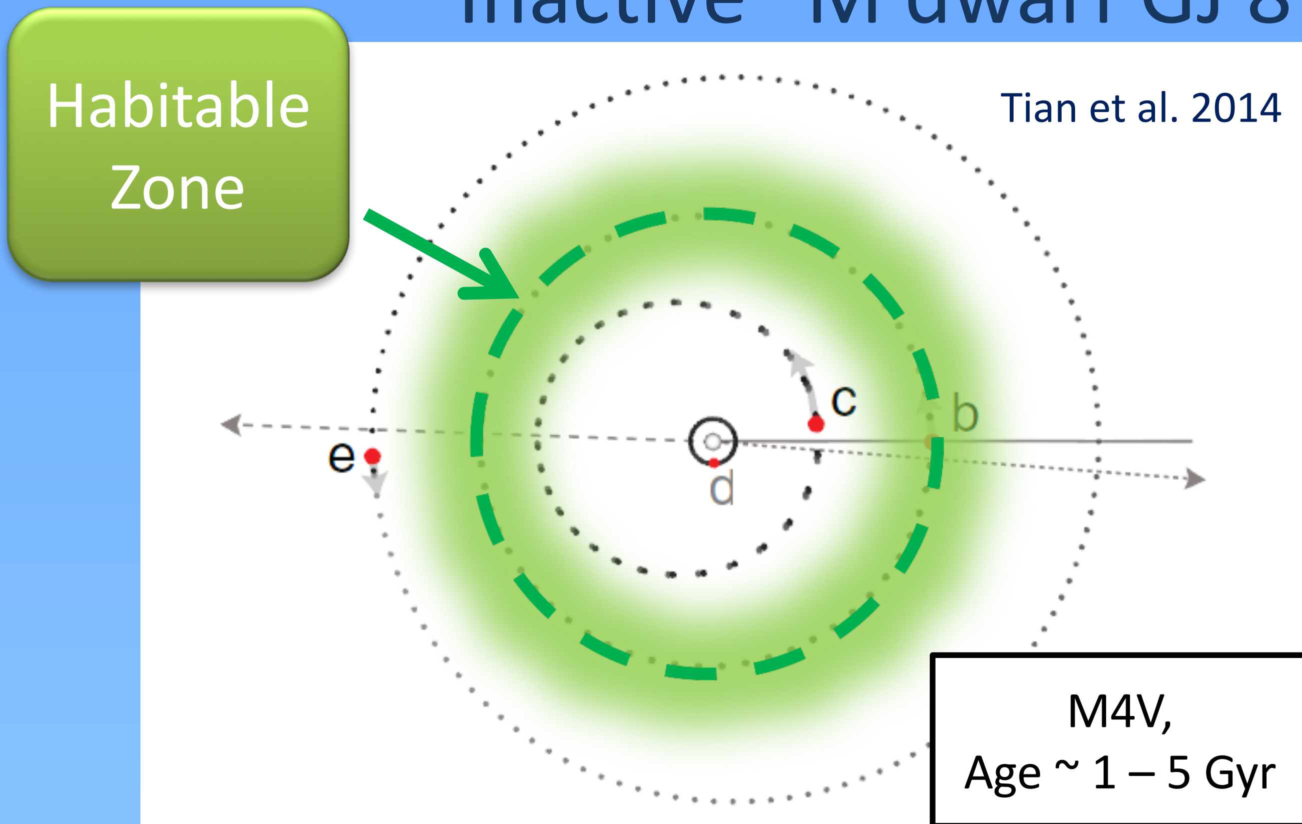
- **Potential abiotic production of O_2 and O_3 leading to "biosignatures imposters"**

F(FUV), F(XUV) in HZ $\approx$ 10 – 70 erg cm^{-2} s^{-1}

False Positive Biosignatures around M dwarfs
Segura+, AsBio, 2005; Hu et al. 2012
Tian+, E&PSL, 2014; Gao et al. 2015
Domagal-Goldman+ 2014, Harman+ 2015

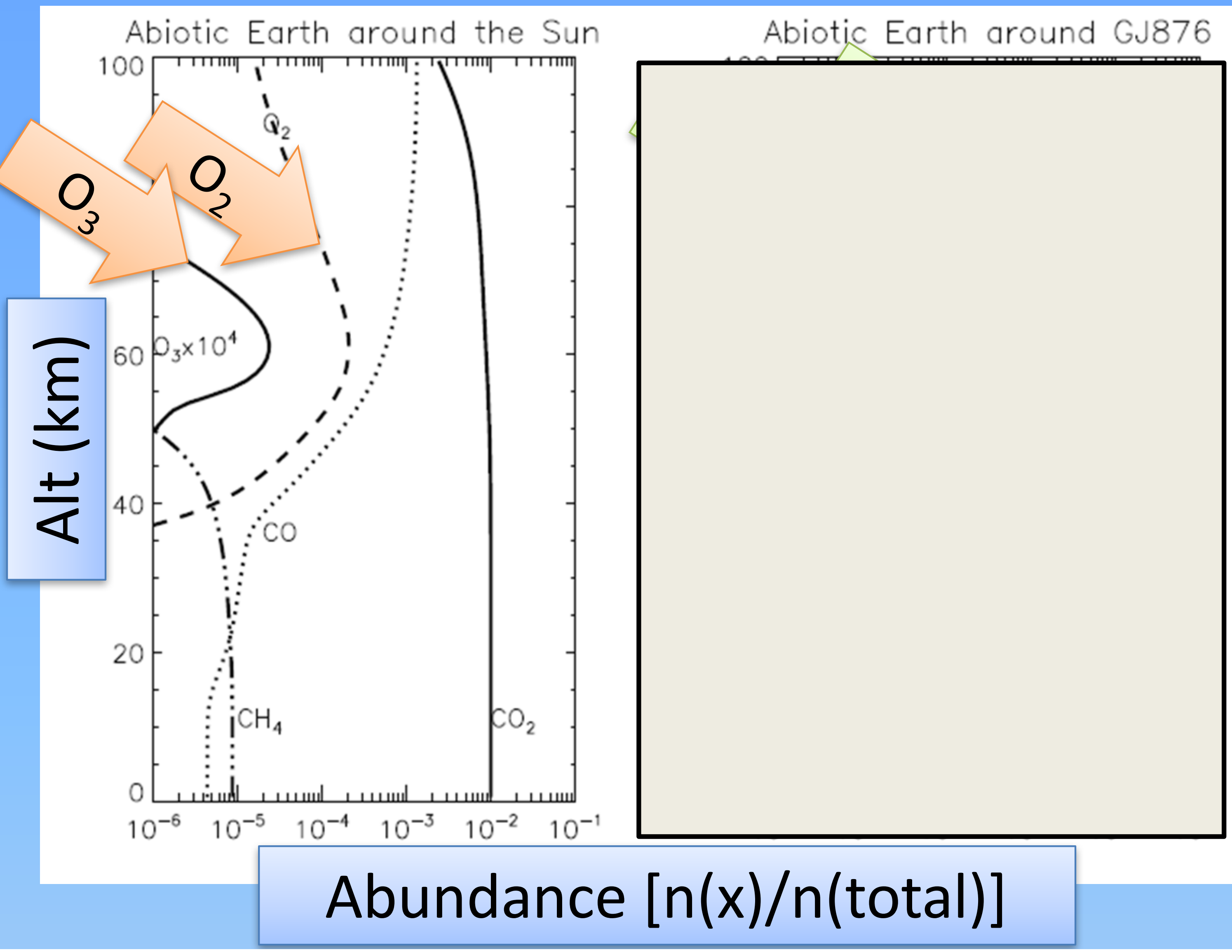
Potential Biomarkers on Exo-Earths

- Project MUSCLES: Initial Modeling Results, "Inactive" M dwarf GJ 876



Rivera et al. 2010
Tian et al. 2014
Harman et al. 2015

Potential Biomarkers on Exo-Earths

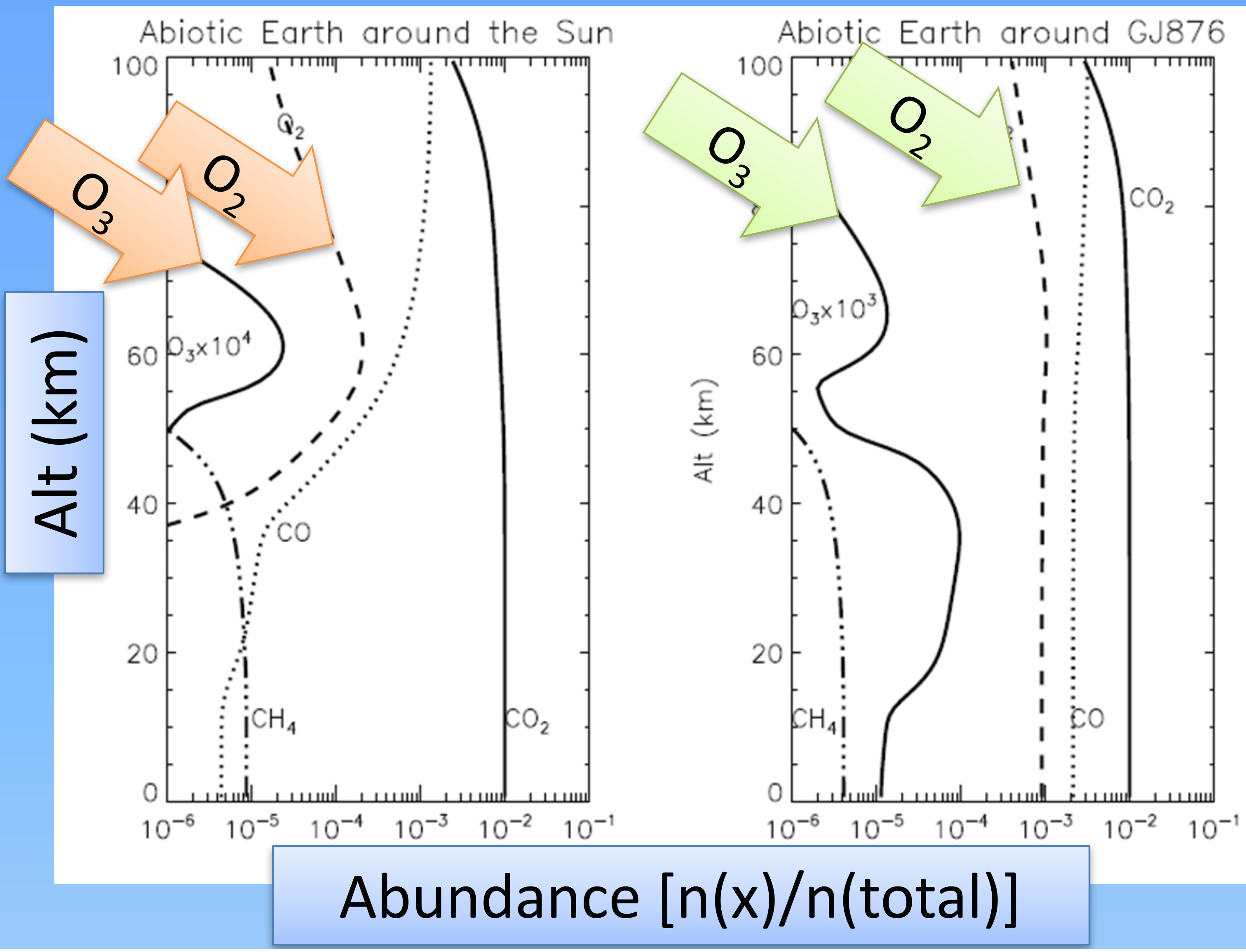


Tian, France et al. – 2014
Domagal-Goldman et al. 2014

(Kasting & Catling 2003; Segura et al. 2007)

Potential Biomarkers on Exo-Earths

Detectable Levels of O_2 and O_3
without an active biosphere



Tian, France et al. – 2014
Domagal-Goldman et al. 2014

(Kasting & Catling 2003;
Segura et al. 2007)

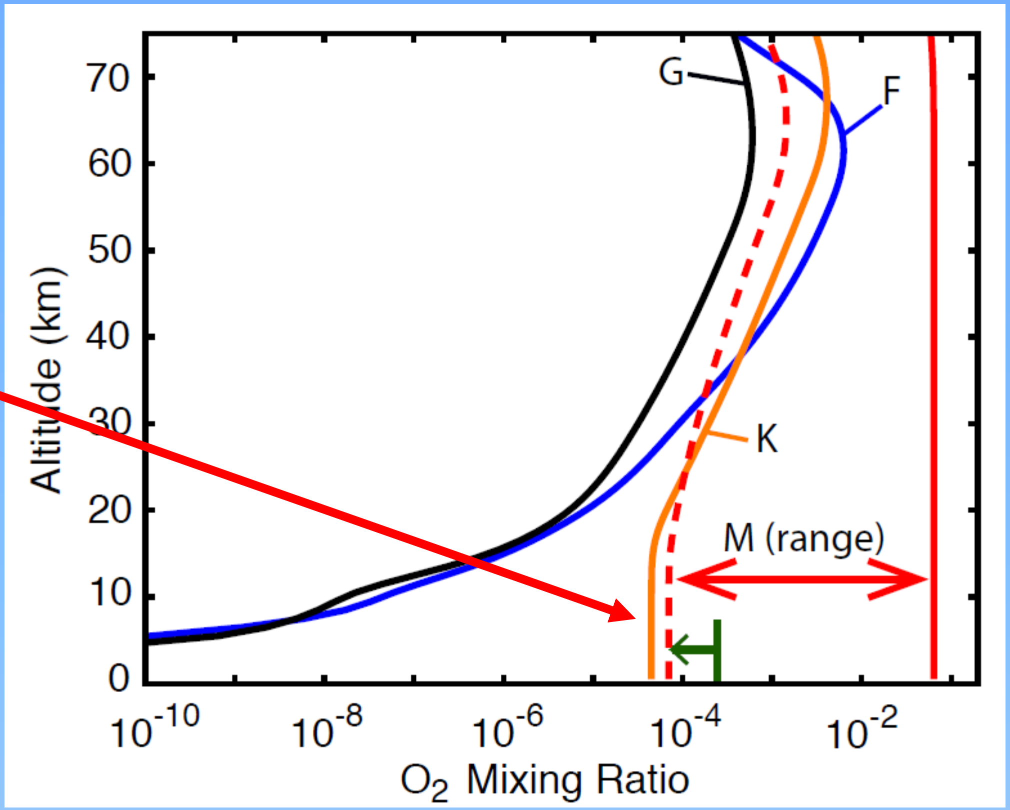
Atmospheric Impacts and Potential Biomarkers

- Older work: Segura et al. 2005, 2010; Hu et al. 2012

- Domagal-Goldman et al. (2014); possible abiotic O_3
- Rugheimer et al. (2015); FUV/ NUV irradiances from active/inactive stars vs. stellar models and Earth-like planet spectra

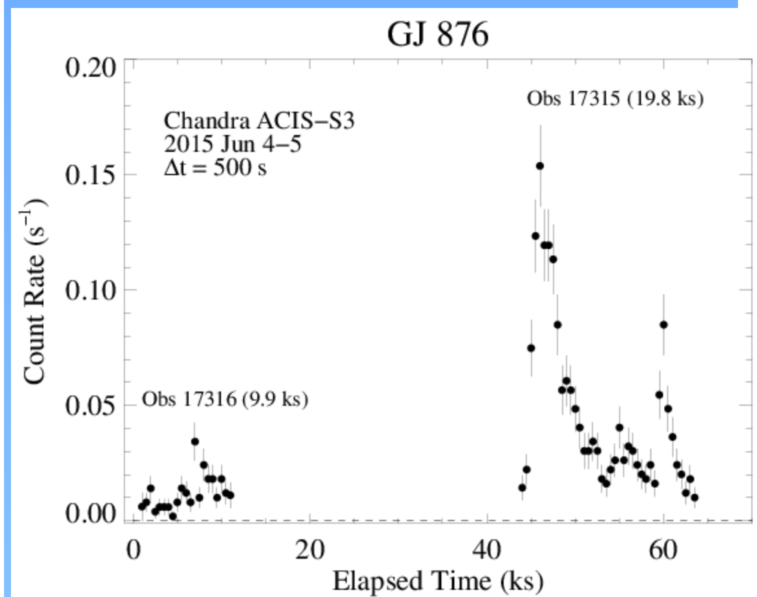
- Harman et al. (2015); prediction of abiotic O_2 and O_3

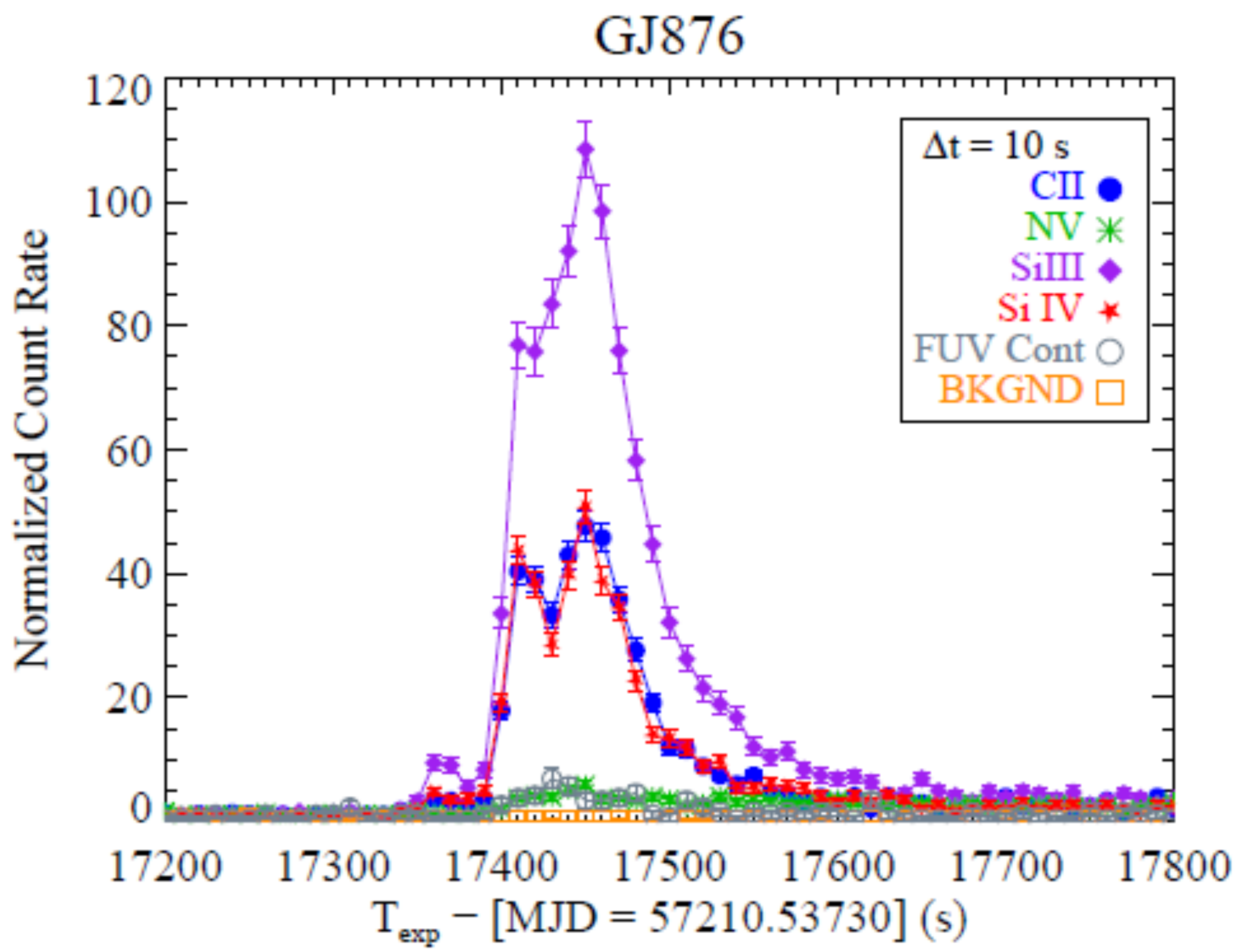
More to come!



UV variability in "inactive" M dwarf exoplanet host stars

- Optically Inactive dM4/5 GJ 876.

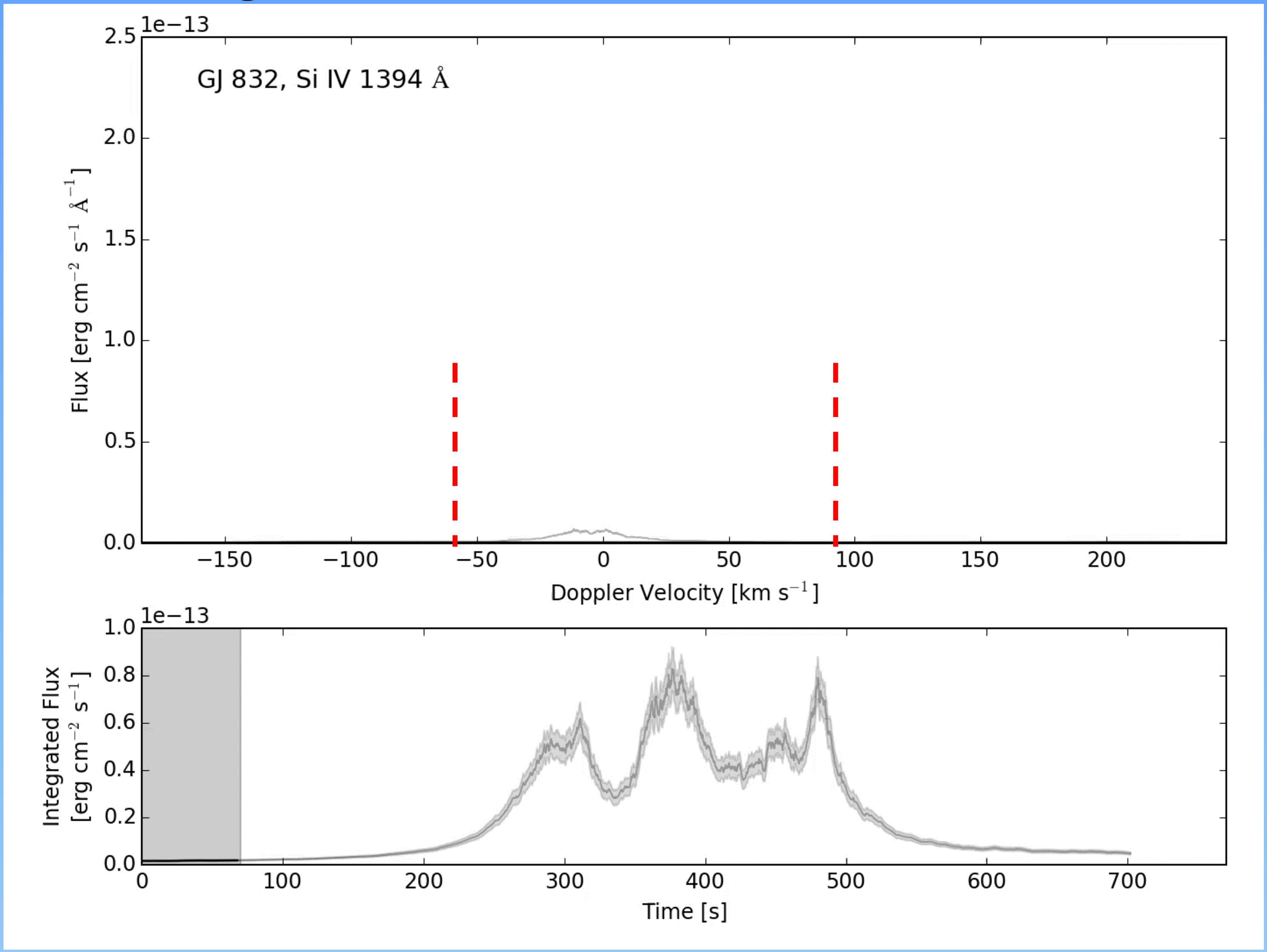




France et al. (ApJ-2016)
Loyd et al. (ApJ-2016 submitted)

MUSCLES Treasury, July 07 2015

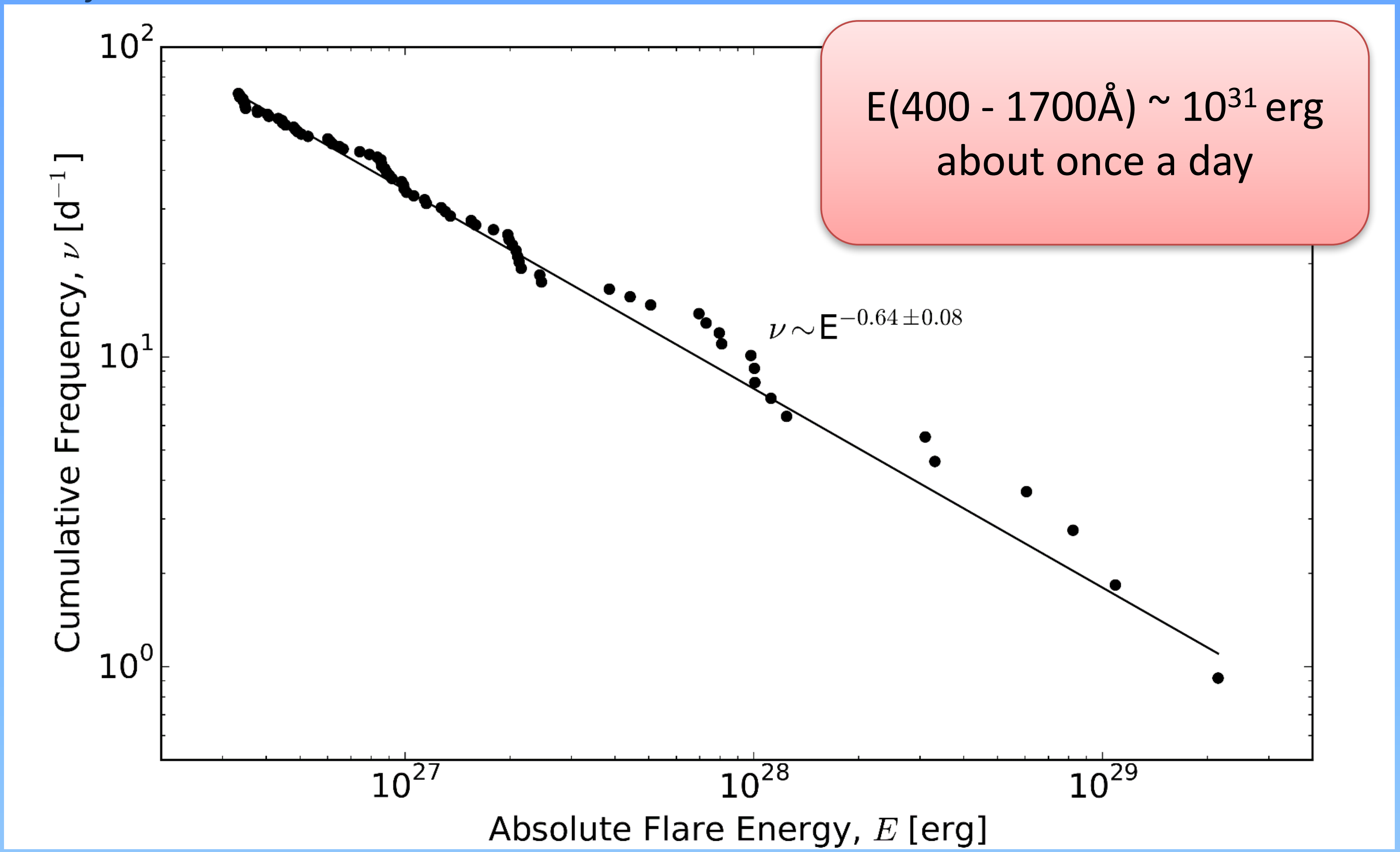
Velocity Profiles in M dwarf Flares



Loyd et al. (2016 – in prep)

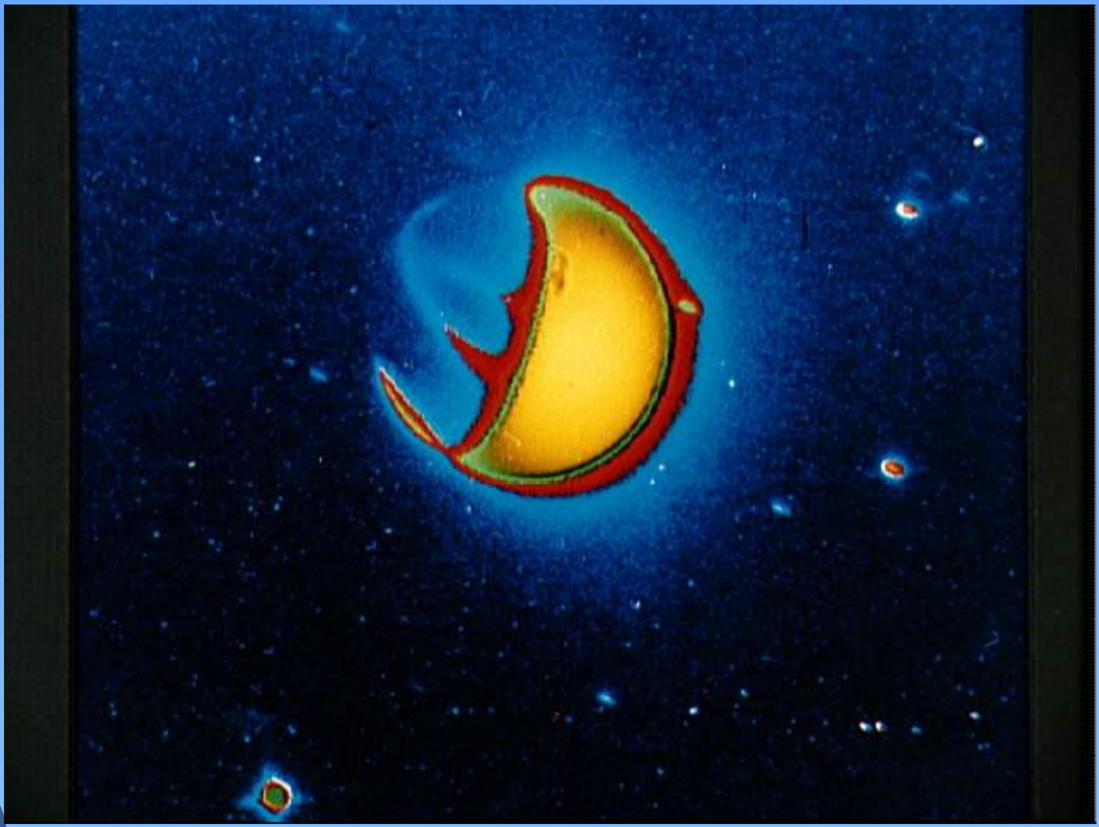
UV flare energy/duration distribution

- SiIV (*T_{form} ≈ 40,000 - 70,000 K)* Flare distribution



Loyd & France, ApJS 2014
Loyd et al. (2016 – in prep)

Earth-mass Planets around M and K dwarfs: The Production of (and eventual detection of) "Biomarker" Gases

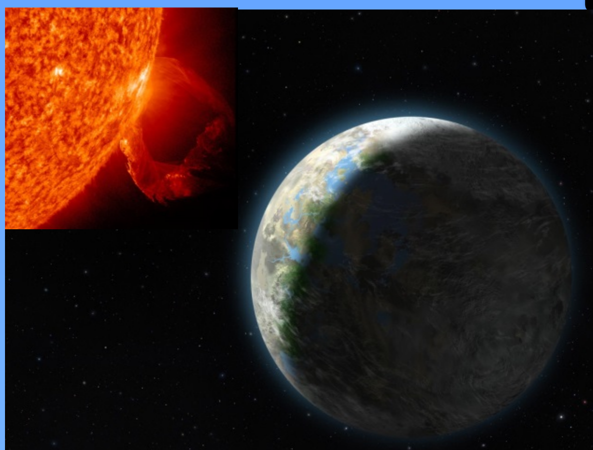


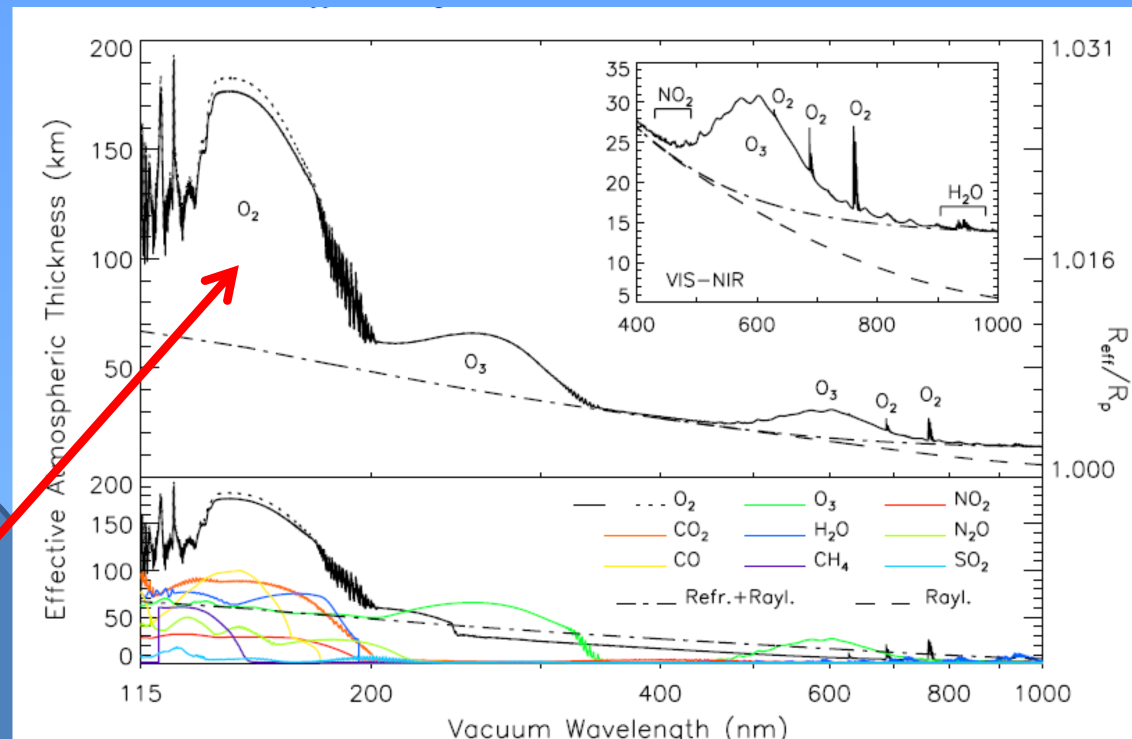
- Exo-Earth transits: they have extended atomic atmospheres too…

Kevin France

University of Colorado at Boulder

Earth-mass Planets around M and K dwarfs: The Production of (and eventual detection of) "Biomarker" Gases





BÉTRÉMIEUX & KALTENEGGER 2013

- (R_{planet}/R_*) for O_2, O_3, CO, CO_2, H_2, and H all peak in the UV, 100 - 400 nm.
- O_3 peak at 250 nm, O_2 peak at 160nm: habitable planets around F and A stars. (start discovery now)
- NEED: 8+ m primary, facility-class UV spectrograph, large photon-counting UV detectors

Kevin France

University of Colorado at Boulder

Summary

Summary – Part 2

1) **MUSCLES**: First panchromatic survey of the energetic radiation environment around M dwarf exoplanet host stars. High-level data products available on MAST for modeling community.

2) FUV/NUV ~ 0.2 -1 for M dwarfs, important for atmospheric chemistry and the production of possible **false-positive "biomarkers"**

3) **FUV and X-ray flares** (50 – 10000% increases on 10^2 – 10^3 second timescales) are present on ≥ half of **optically inactive** M dwarf exoplanet host stars observed to date. Impacts on atmospheres is work in progress.

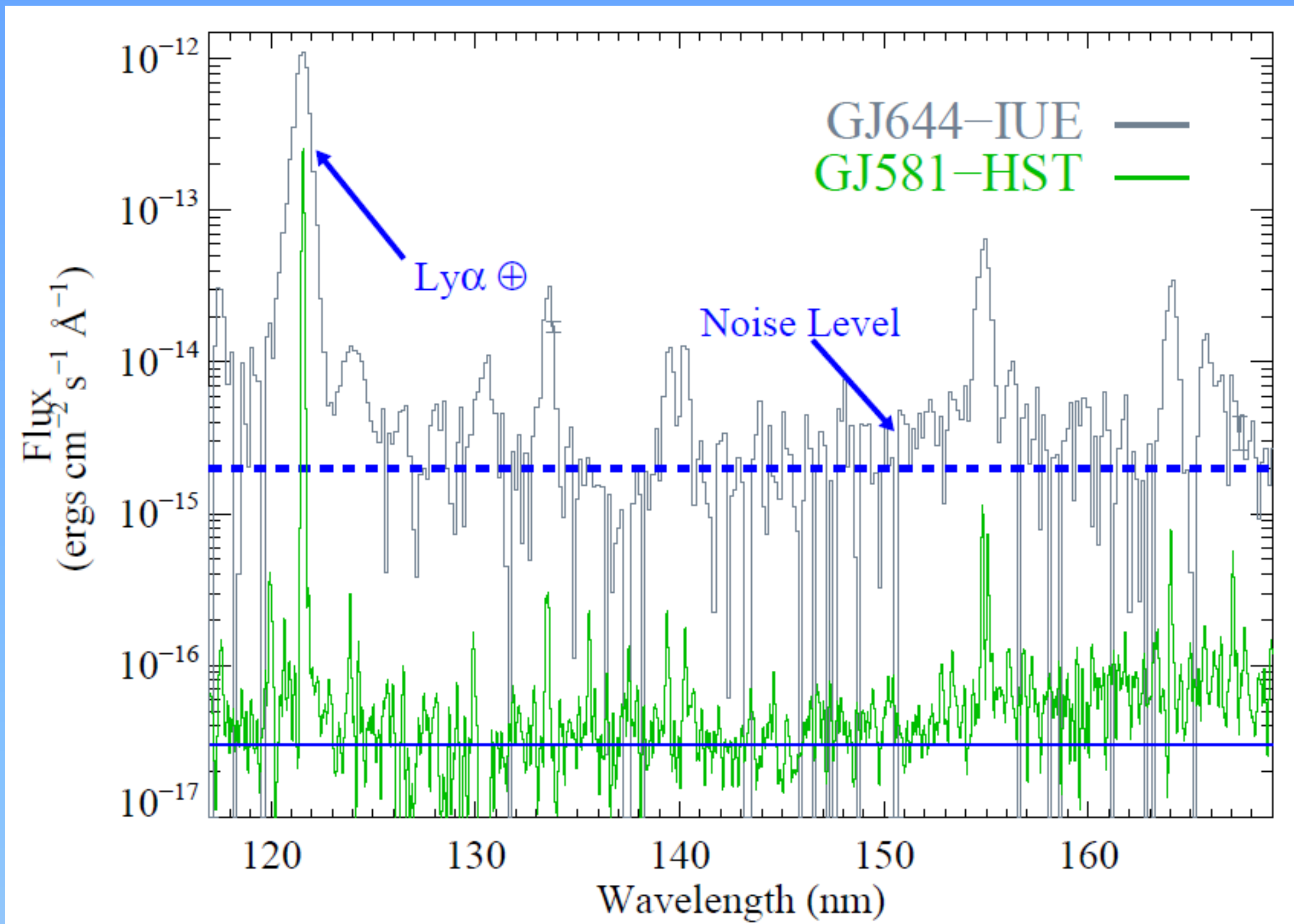

Thank you

MUSCLES

Table 1: MUSCLES Treasury Survey – Target List

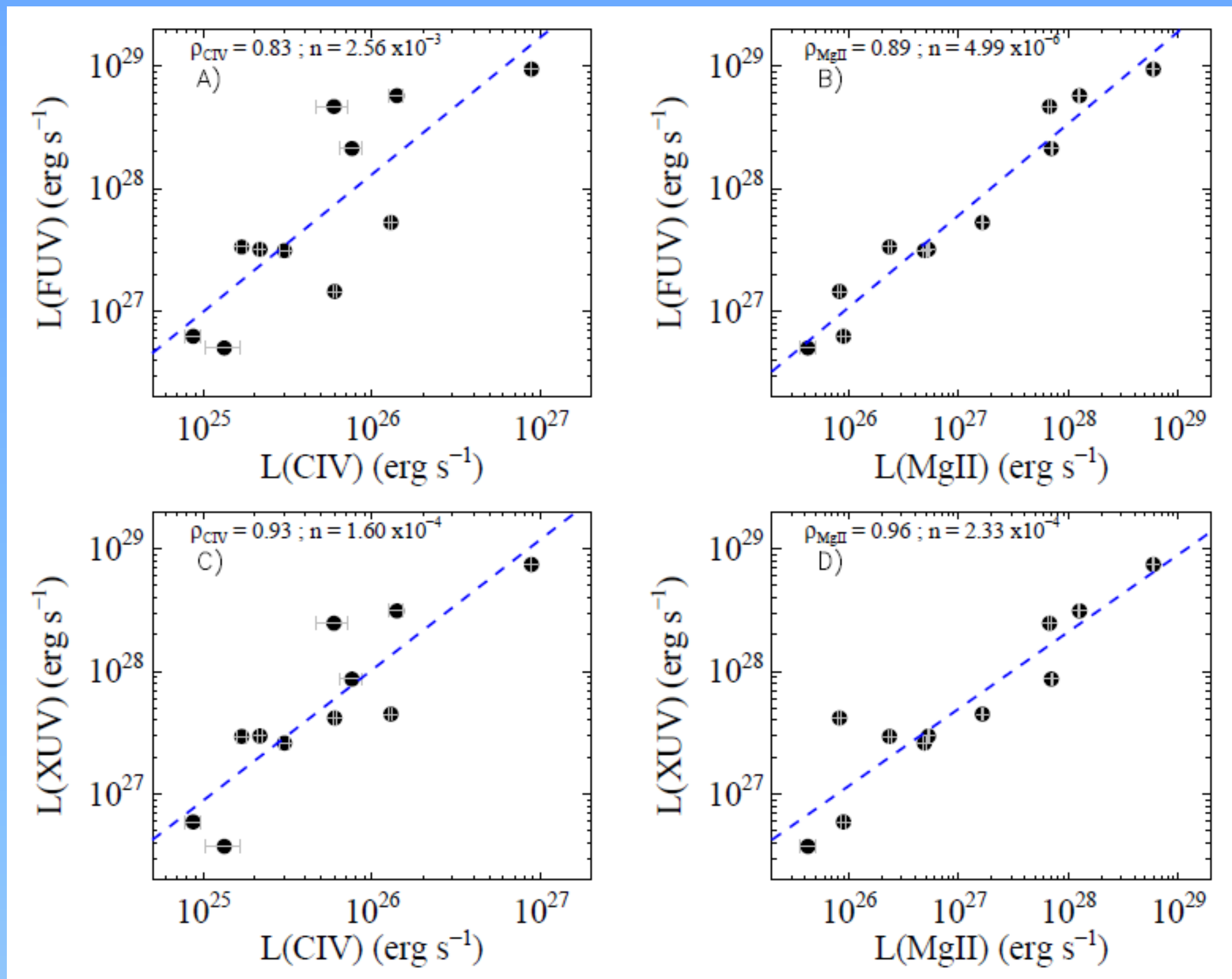
Star	Distance (pc)	Type	Exoplanet Mass $M \sin i$ (M_{Jup})	Semi-major Axis (AU)	*HST* T_{exp} (orbits)	X-ray Mode	X-ray T_{exp} (ks)
GJ 1214	13.0	M6	**0.020**	0.0143	15	*CXO*-GO15	[30]
GJ 876	4.7	M4	1.935, 0.61, **0.018**, 0.039	0.208, 0.130, 0.0208, 0.0208	10	*Chandra*	20 + 10
GJ 581	6.3	M3	0.050, **0.017**, **0.019**, **0.006**	0.041, 0.073, 0.218, 0.029	11	*CXO*-GO15	[50]
GJ 436	10.3	M2.5	0.073	0.0287	13	*Chandra*	20 + 10
GJ 176	9.4	M2.5	**0.026**	0.066	14	*Chandra*	20 + 10
GJ 667C	6.9	M1.5	**0.018**, **0.014**	0.049,0.123	11	*Chandra*	20 + 10
GJ 832	4.9	M1	0.64	3.4	10	*XMM*	10
HD 85512	11.2	K6	**0.011**	0.26	8	*CXO*-GO	[40]
HD 40307	12.9	K2.5	**0.013**, **0.021**, 0.030, **0.011**, **0.016**, **0.022**	0.047, 0.080, 0.132, 0.189, 0.247, 0.600	8	*CXO*-GO	[50]
ϵ Eri	3.2	K2	1.1 – 1.55	3.4	8	*XMM*	10
HD 97658	21.1	K1	**0.020**	0.080	9	*CXO*-GO	[50]
GJ 1061	3.7	M5	...	...	2		
GJ 628	4.3	M4	...	...	2		
HD 173739	3.6	M3	...	...	2		
GJ 887	3.3	M2	...	...	2		

M dwarf radiation fields: IUE is insufficient



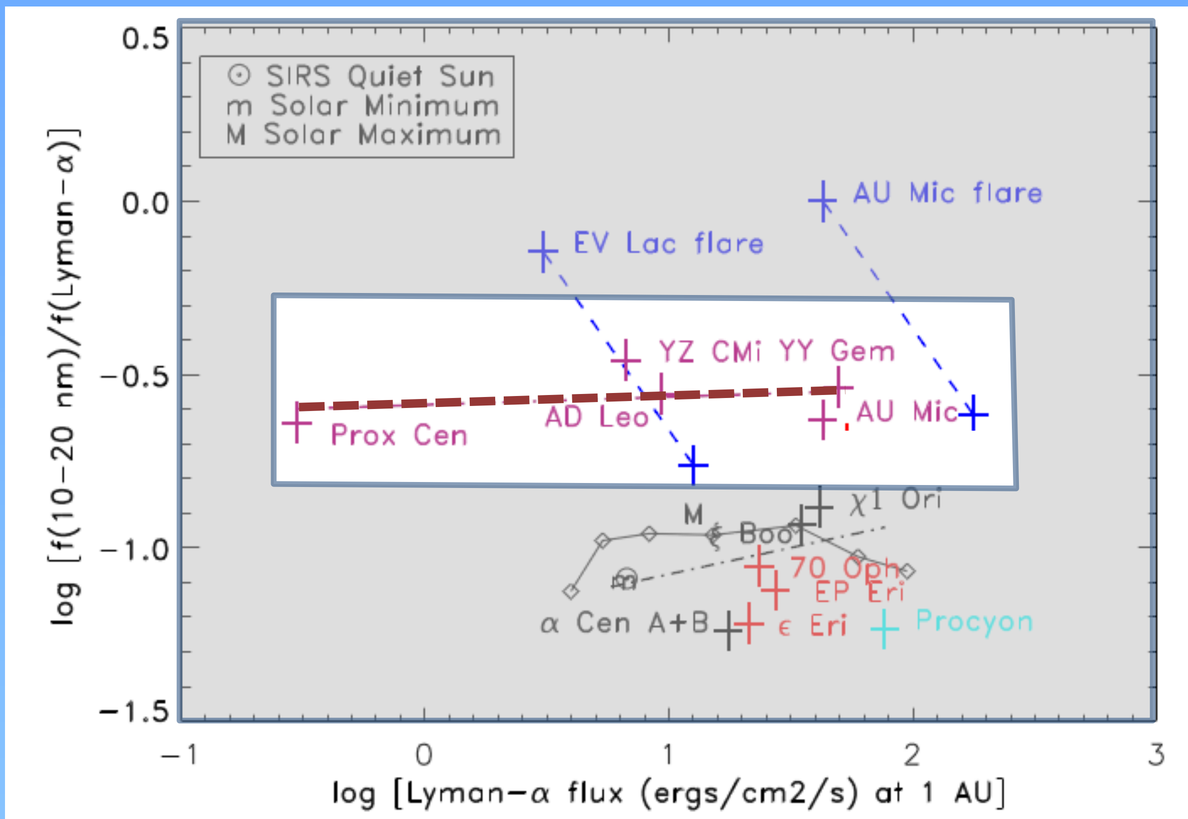
No MUSCLES? No problem.

•Correlations between broadband FUV and XUV fluxes and observed line fluxes provide first order irradiance estimates in the absence of complete observations



France et al. (ApJ-2016 astro-ph)

EUVE M dwarfs: F(EUV) / F(Lyα)



M-dwarf EUV calculations:

Based on *EUVE* data, M dwarf F(EUV)/F(Lyα) ratios agree with solar model, modulo an empirically constrained offset, e.g.,

$$\log\,(F(EUV)/F(Ly\alpha))_M \;=\; \log\,(F(EUV)/F(Ly\alpha))_\odot + \Delta F$$

$\Delta F(10 - 20\text{ nm}) = +0.37$ [16%]

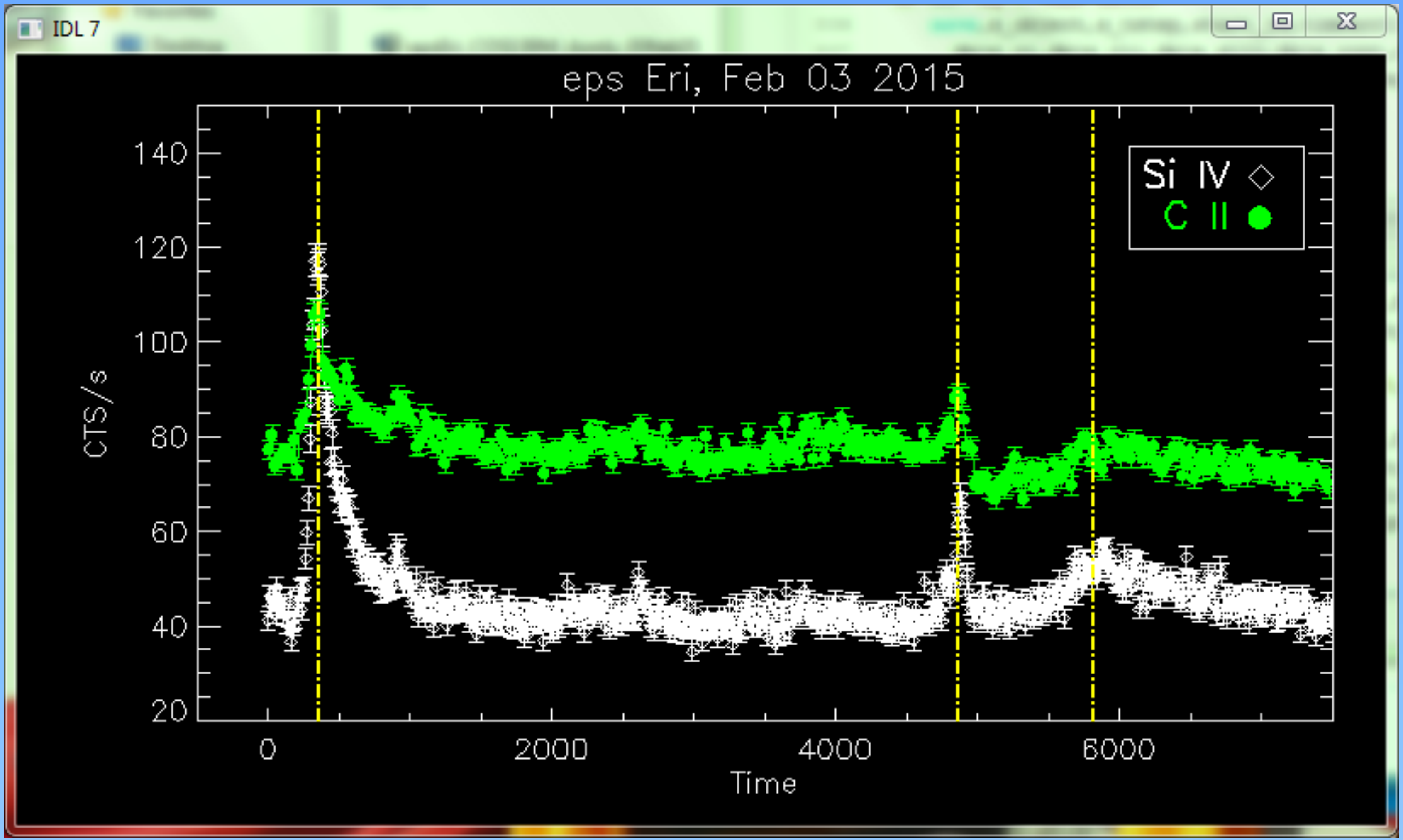
$\Delta F(20 - 30\text{ nm}) = -0.01$ [24%]

$\Delta F(30 - 40\text{ nm}) = -0.03$ [18%]

Youngblood et al. 2016
Linsky et al. 2014

UV variability in other exoplanet host stars

- K-dwarf ε Eri, FUV Flare. L_{FUV} increase ~ 3

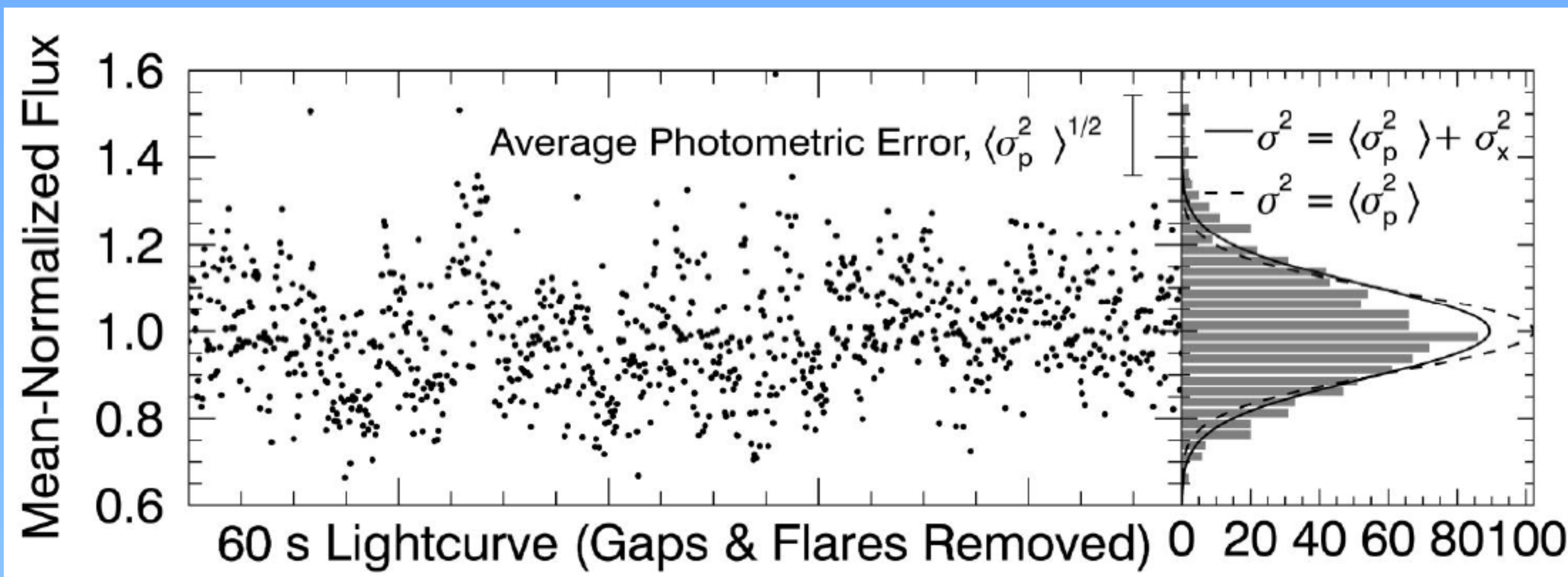


HST-COS, Feb 02 2015

UV variability in G, K, and M stars

- Stochastic Fluctuations = "excess" noise beyond photometric uncertainties, after removing flares.

- Likely microflares or smaller reconnection events



Loyd & France, ApJS 2014

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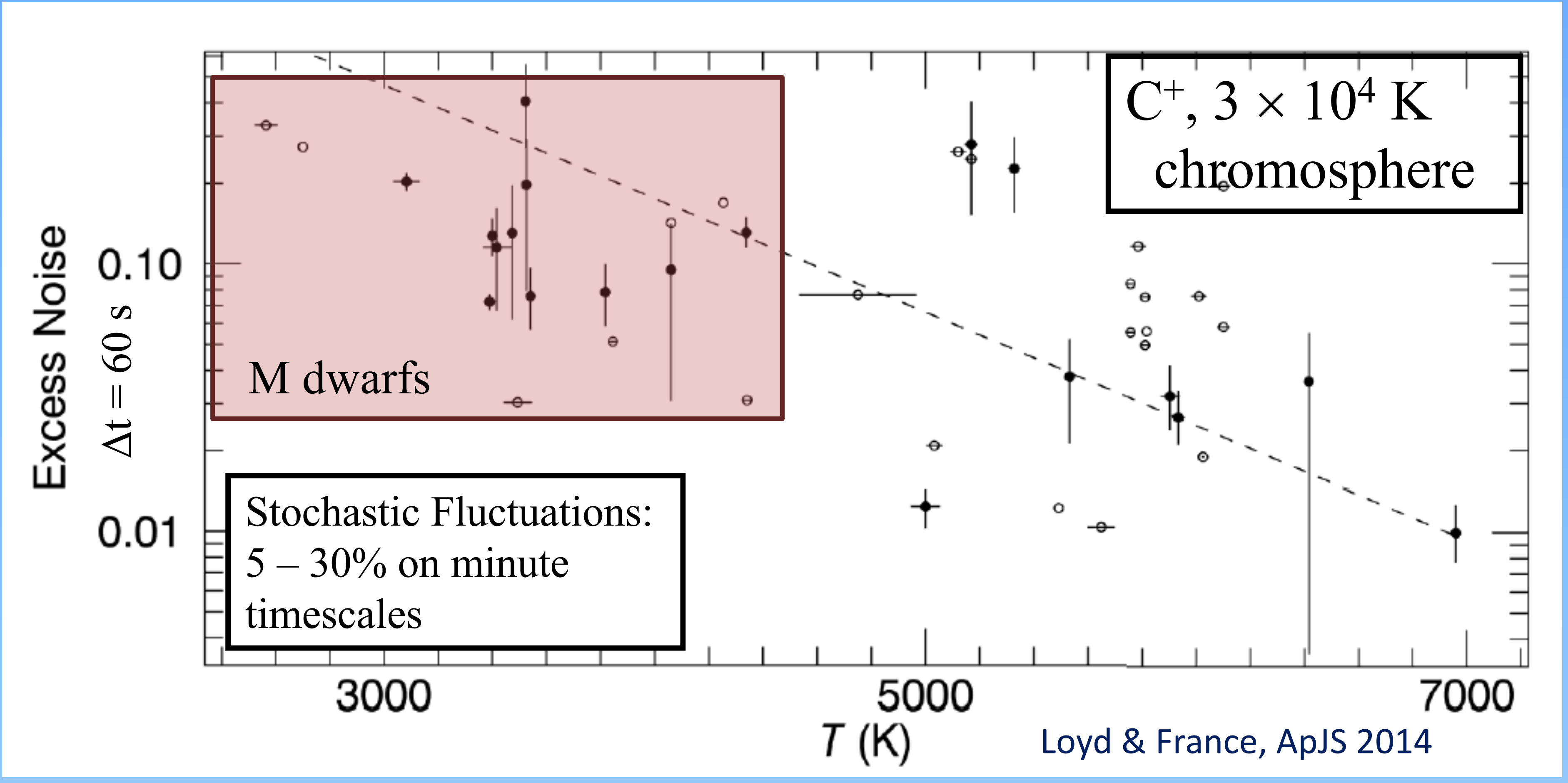


Loyd & France, ApJS 2014

Summary

1) Despite 2 – 3 Myr timescale for the end of accretion, many 1 – 10 Myr protoplanetary disks (CTTS + Herbig Stars) display a rich molecular layer at planet-forming radii (0.1 – 10 AU)

2) Fundamental band CO studies ($\lambda \sim 4.7\ \mu m$) provide the most detailed constraints on the temperature and kinematics of the 0.1 – 1.0 AU inner disk, including disk winds

3) H_2O, OH, and organic molecules are common inside 3 AU

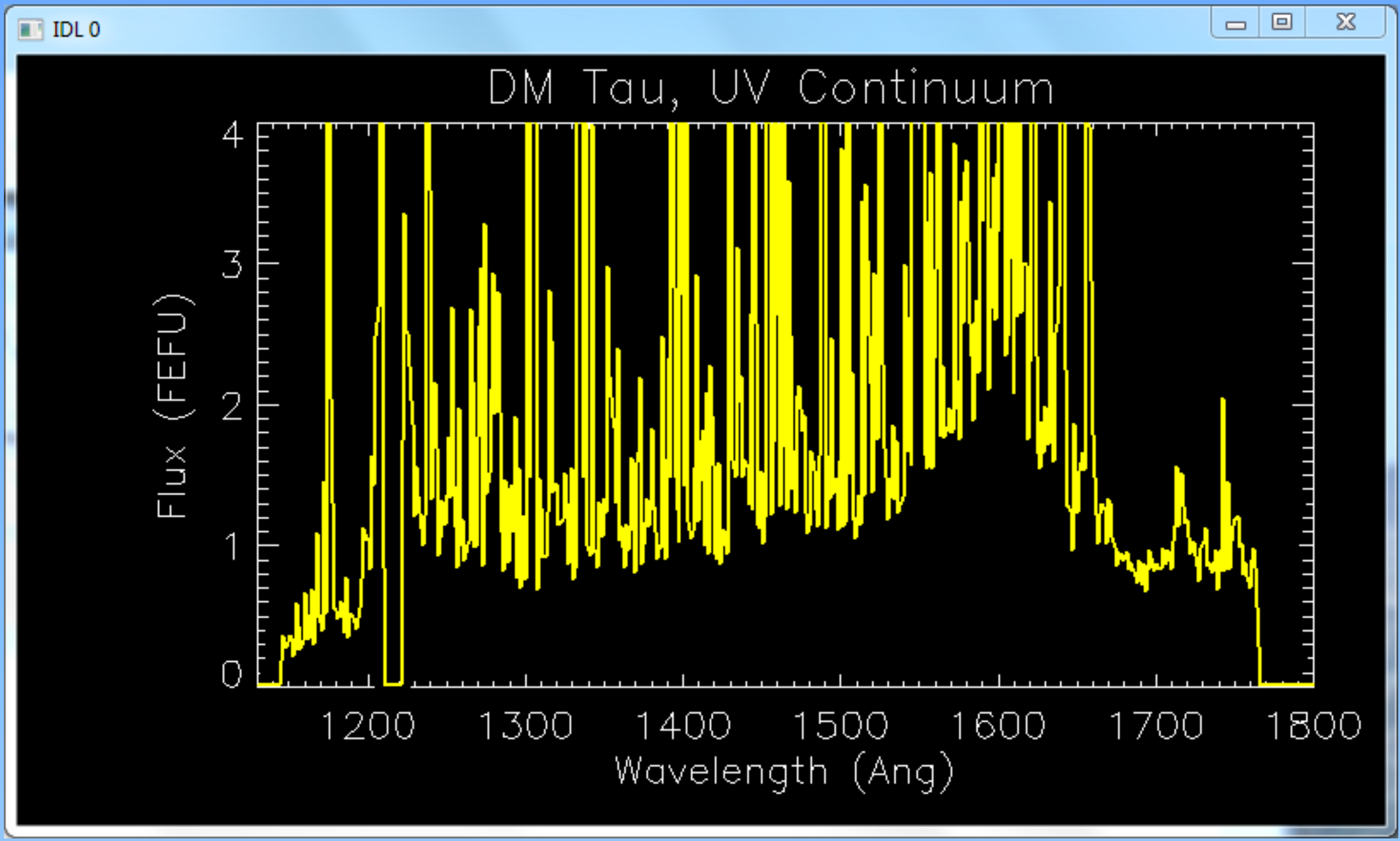
4) UV spectroscopy is a promising technique for the characterization of the photoexcitation of the inner disk surface (0.1 – 10 AU). Simultaneous coverage of CO and H_2 set a basis for gas-phase abundance and disk structure studies.

Molecular Gas in the 0.1 – 10 AU Circumstellar Environments Around Young Stars

Mahalo

Composition of Protoplanetary Disks: Indirect Observations of H_2O at ~1 AU?

- COS enables robust FUV continuum characterization for the first time



Composition of Protoplanetary Disks: Indirect Observations of H_2O at ~1 AU?

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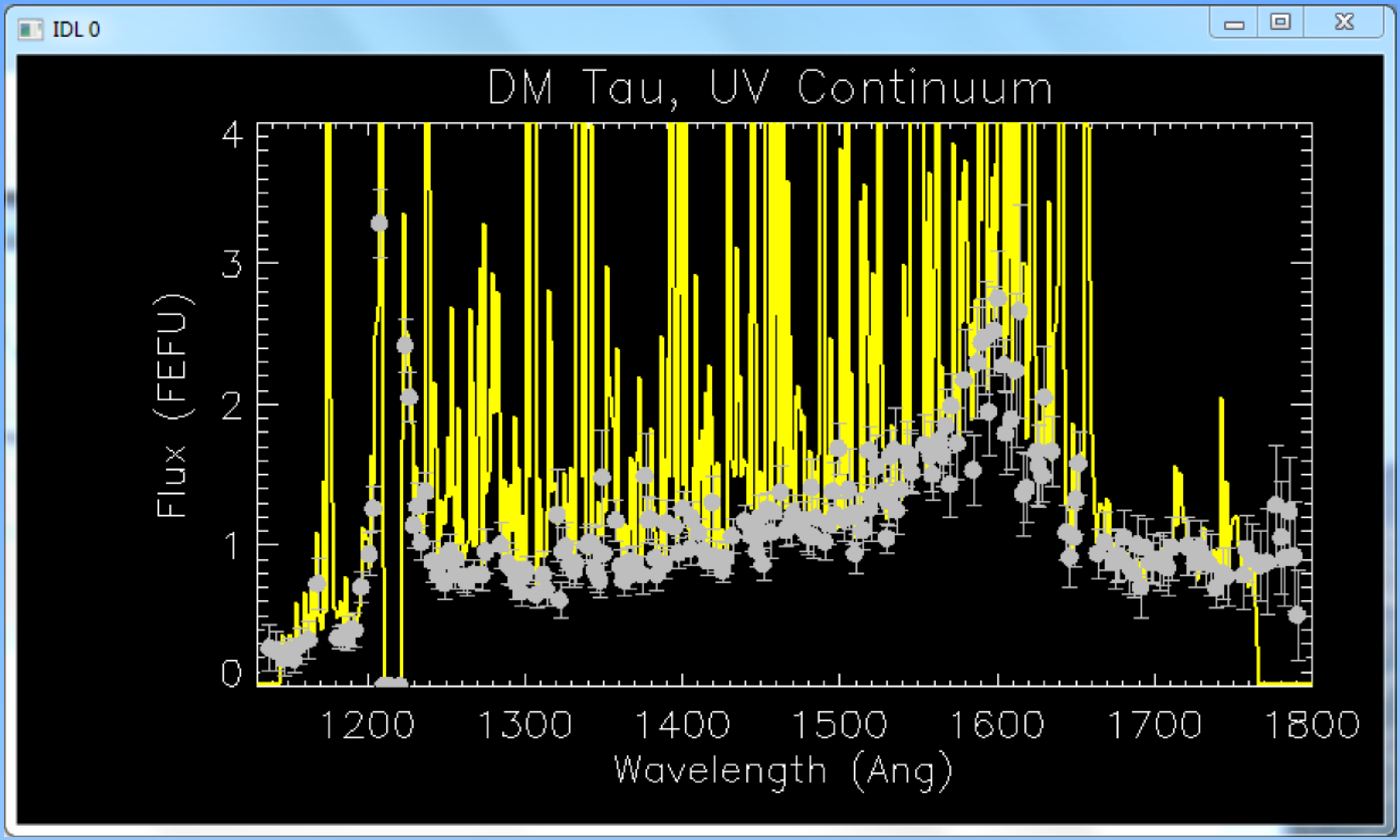
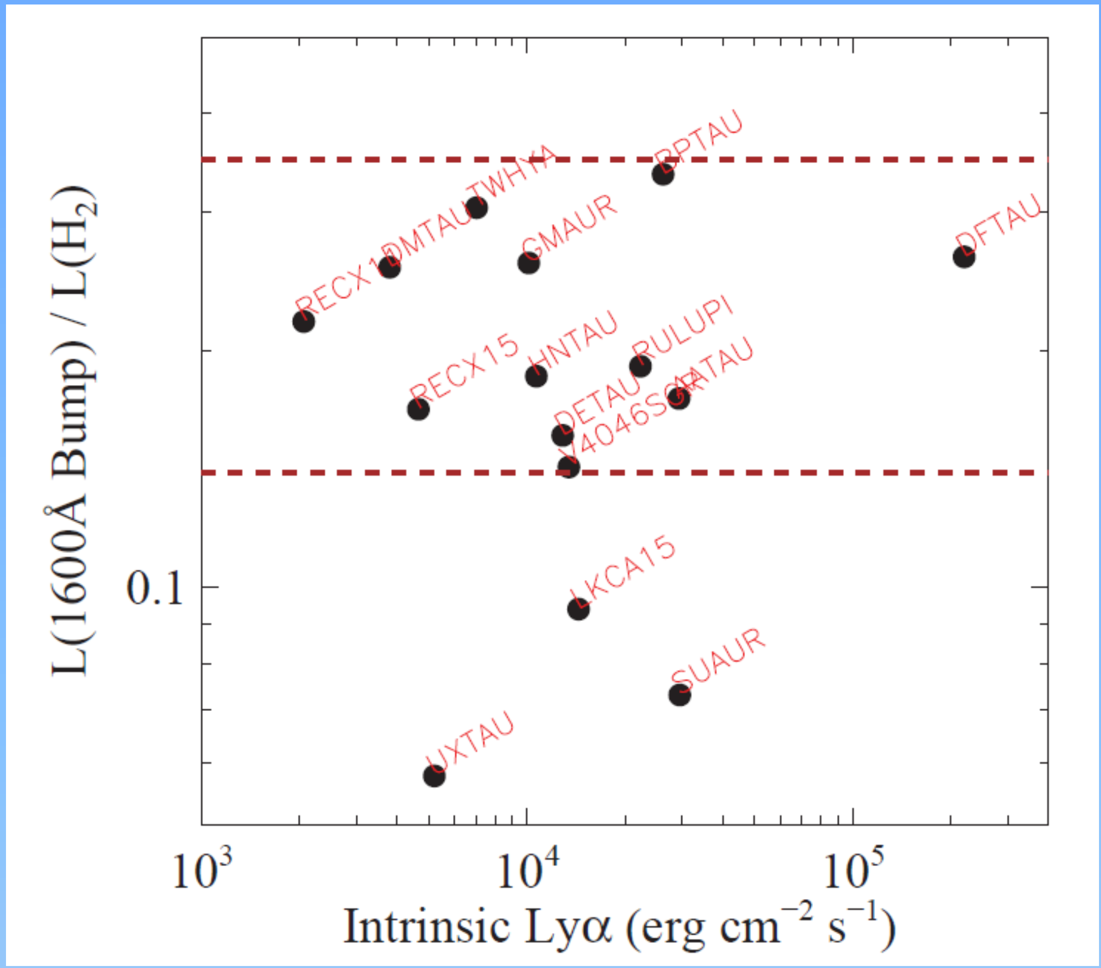


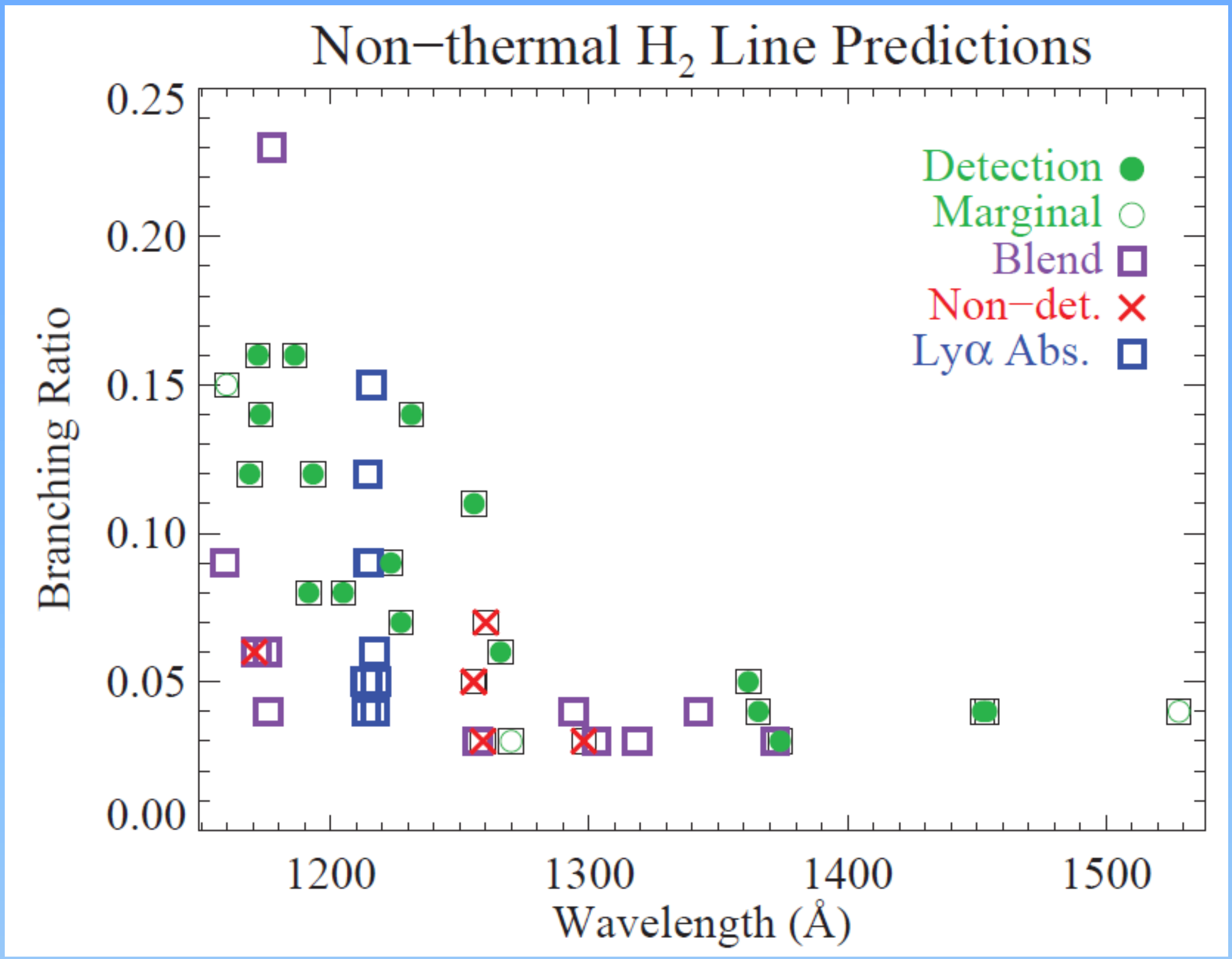
Composition of Protoplanetary Disks: Indirect Observations of H_2O at ~1 AU?

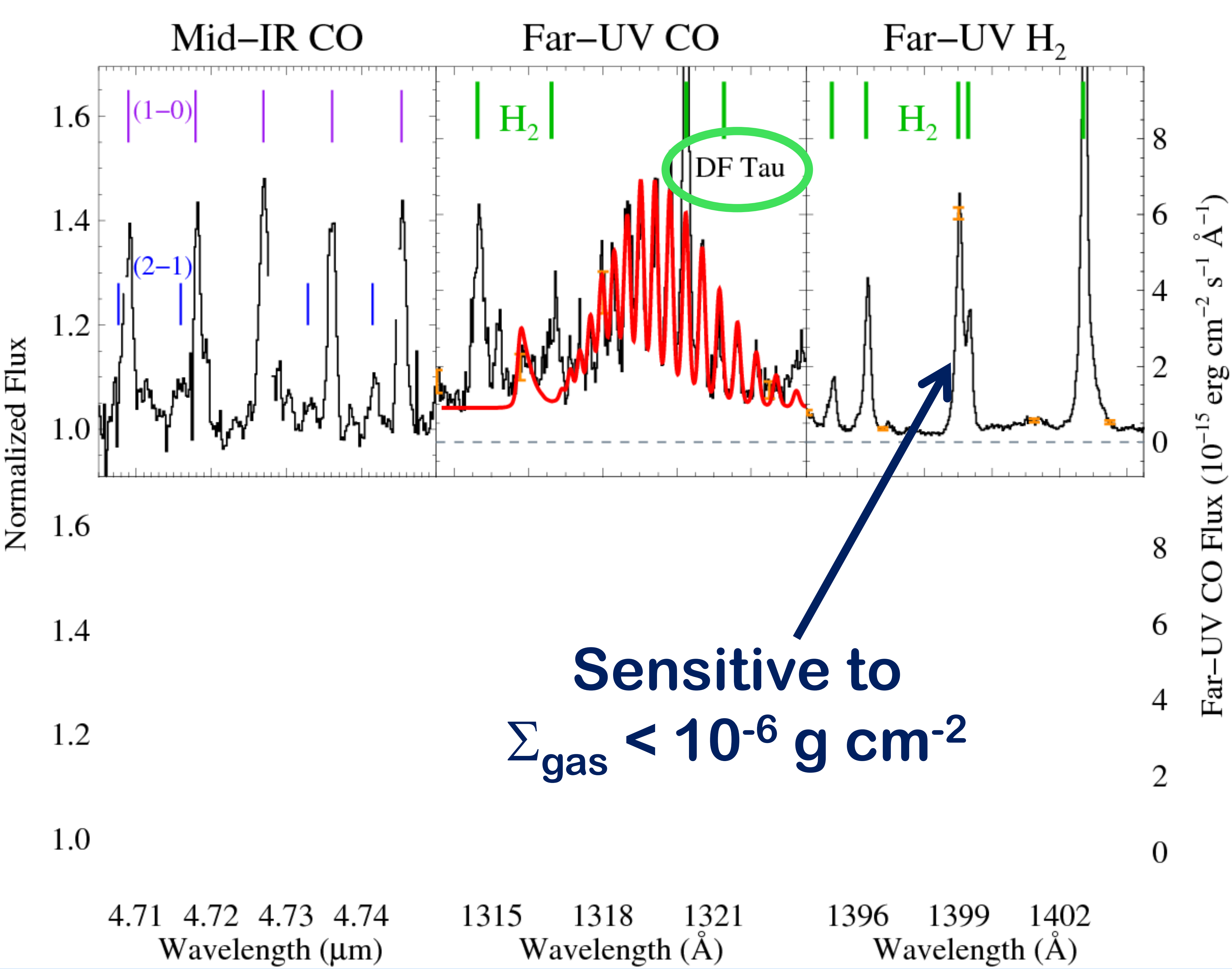
- "1600Å Bump" Measurement and Correlations
- 10 – 30% of Lyα pumped H_2 luminosity(!), must tie in to Lyα



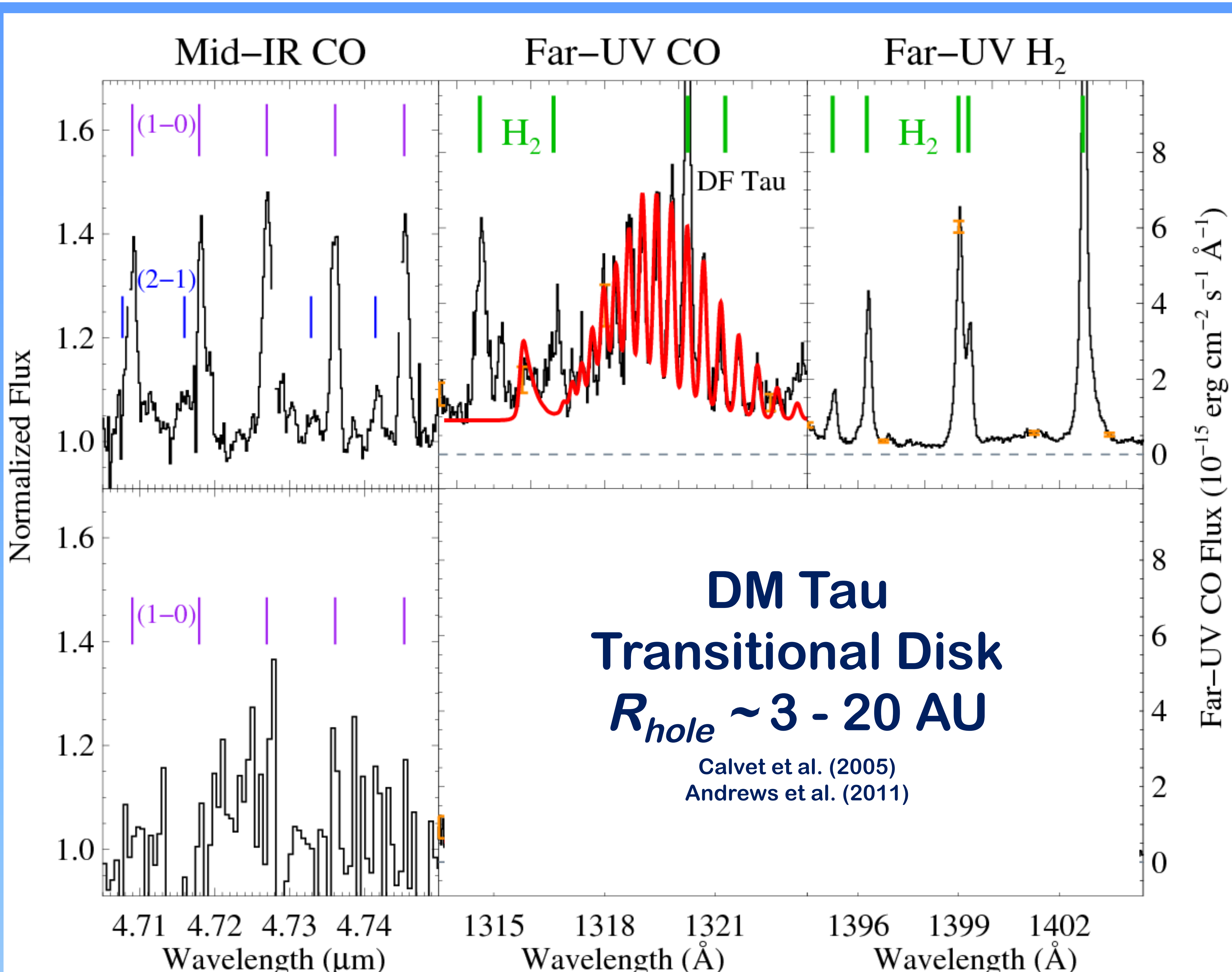
Composition of Protoplanetary Disks: Indirect Observations of H_2O at ~1 AU?

- "1600Å Bump" mechanism: **H_2O + Lyα -> H_2^* + O**
  - **H_2^* + Lyα -> observed line and continuum spectra**
- Electron-impact does not fit, Lyα-pumped H_2O fragments do

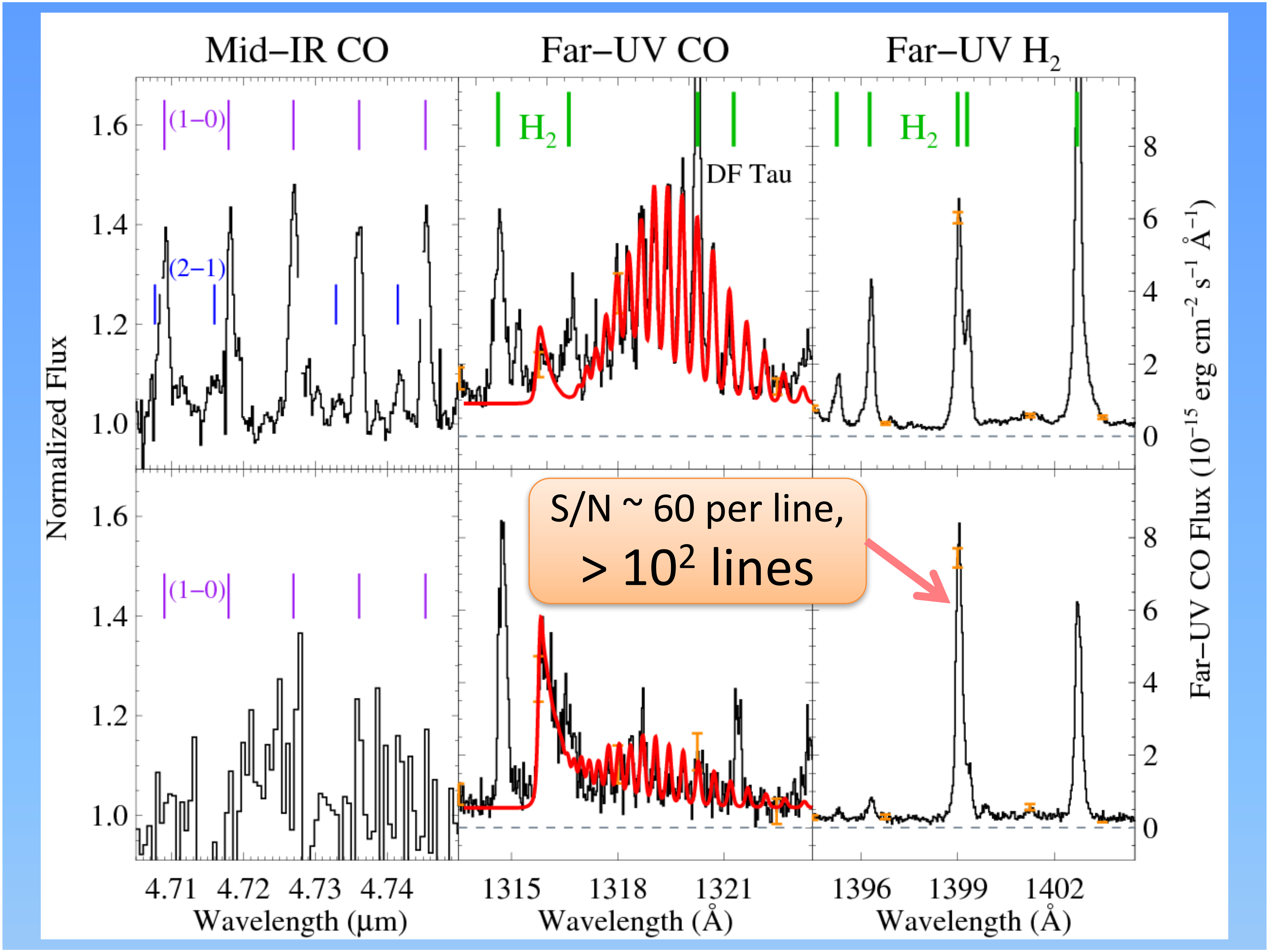




Mid–IR CO
Far–UV CO
Far–UV H_2
(1–0)
(2–1)
H_2
DF Tau
Normalized Flux
Far–UV CO Flux (10^{-15} erg cm^{-2} s^{-1} Å^{-1})
Wavelength (μm)
Wavelength (Å)
Wavelength (Å)
Sensitive to
Σ_{gas} < 10^{-6} g cm^{-2}

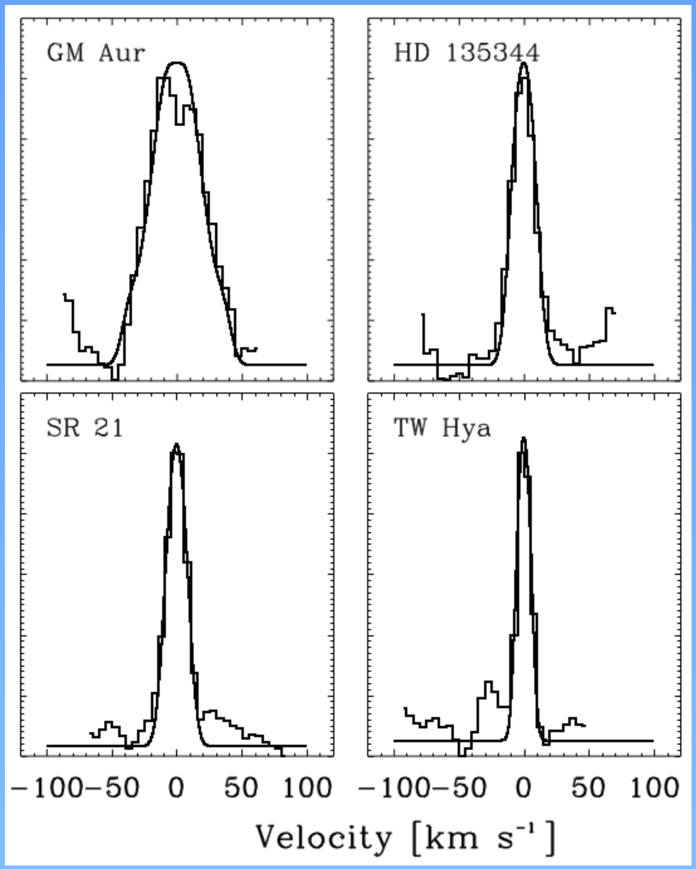


Mid–IR CO
Far–UV CO
Far–UV H2
(1–0)
(2–1)
H2
DF Tau
Normalized Flux
Far–UV CO Flux (10^-15 erg cm^-2 s^-1 Å^-1)
Wavelength (μm)
Wavelength (Å)
DM Tau
Transitional Disk
Rhole ~ 3 - 20 AU
Calvet et al. (2005)
Andrews et al. (2011)



Mid–IR CO
Far–UV CO
Far–UV H$_2$
(1–0)
(2–1)
H$_2$
DF Tau
S/N ~ 60 per line,
> 10^2 lines
Normalized Flux
Far–UV CO Flux (10^{-15} erg cm^{-2} s^{-1} Å^{-1})
Wavelength (μm)
Wavelength (Å)
Wavelength (Å)

Molecules at *r* < 10 AU



Salyk et al. 2009

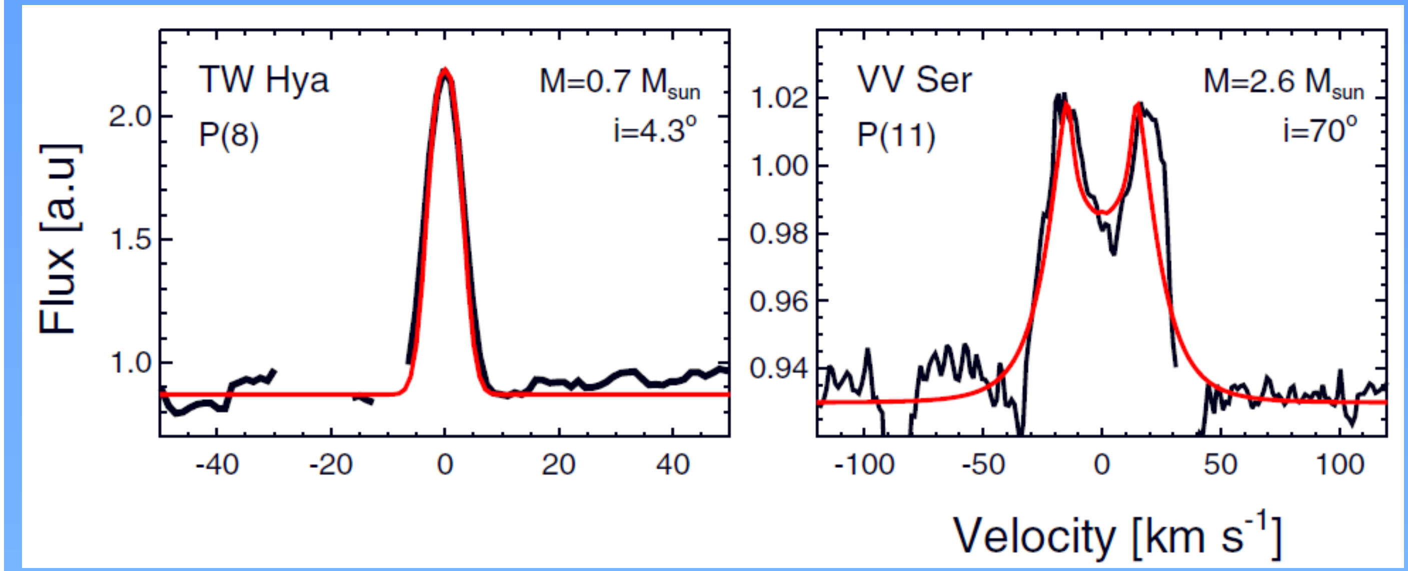
λ ~ 4 - 5 μm CO fundamental emission

High-resolution mid-IR ground-based spectrographs:

1) NIRSPEC (*R* ~ 25,000)
2) CRIRES (*R* ~ 90,000)

CO Rovibrational Emission

Bast et al. 2011

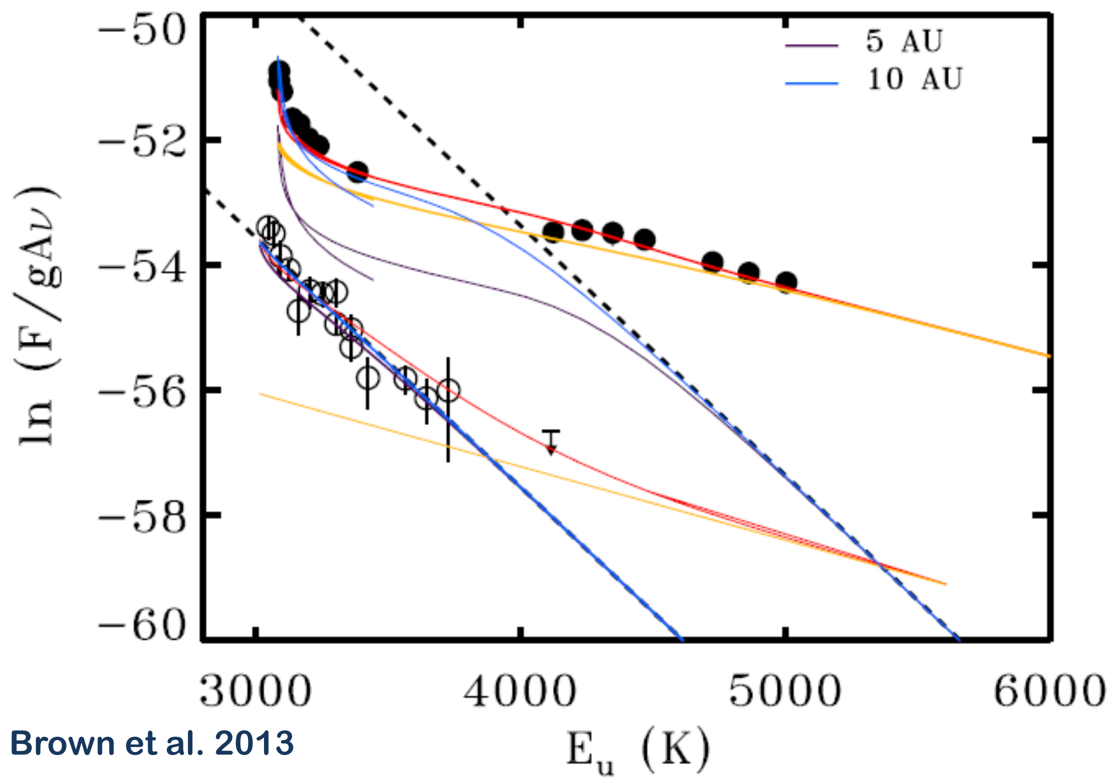


Inferred Spatial Distributions:

1) **Line Profiles & Astrometry**
2) Temperature Distributions

- **Keplerian Disk**
  (requires inclination & M_*)
- Disk + Wind
  (spectroastrometry desirable)

CO Rovibrational Emission



Brown et al. 2013

- **Rotational Excitation Diagrams**
  (optical depth effects)

- Isotopic Fractions and Vibrational Excitation
  (UV radiation field, grain opacities)

T_{rot} (IR-CO) = 300 – 1500K
(warm molecular layer near/ interior to 1 AU)

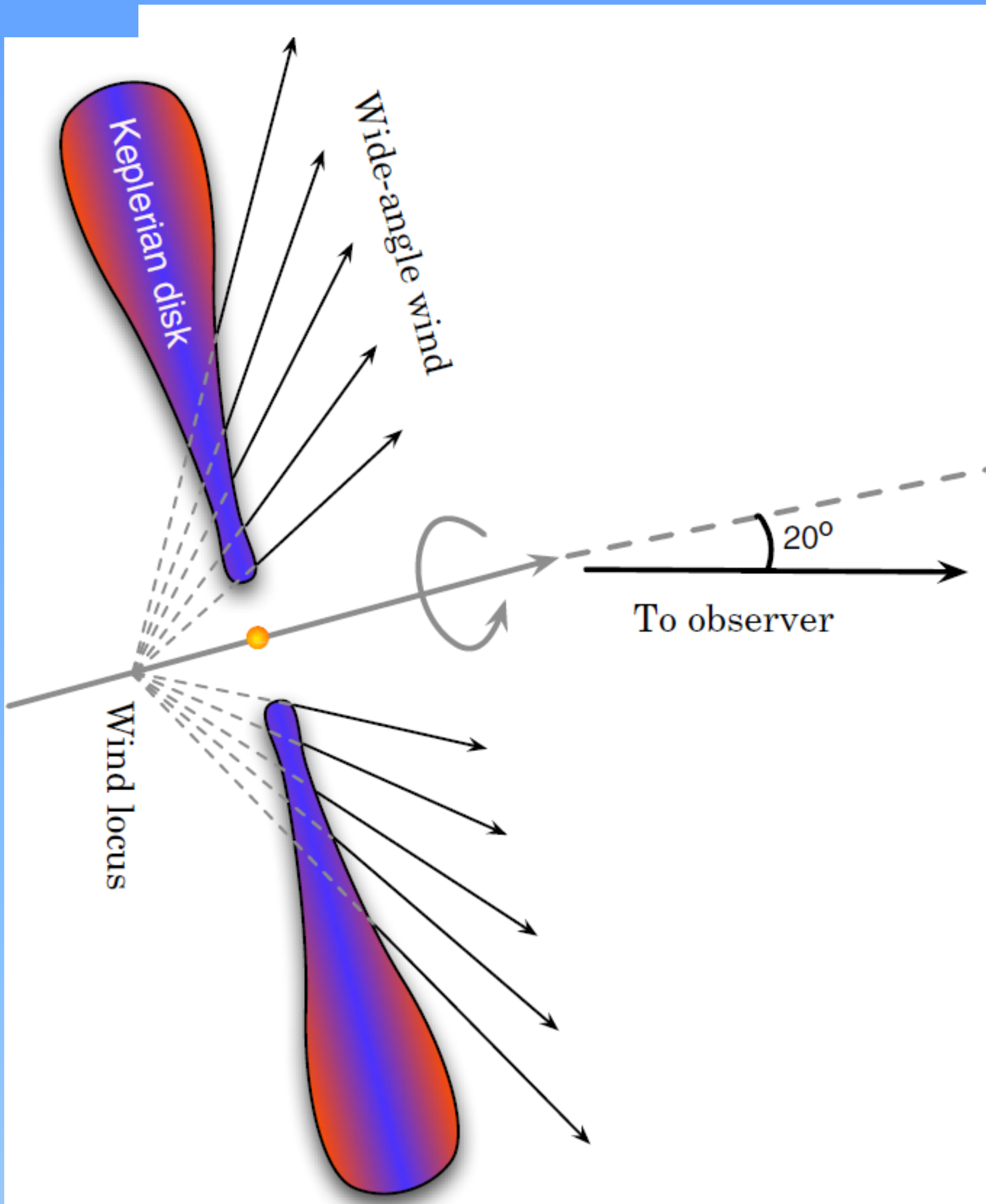
Inferred Spatial Distributions:

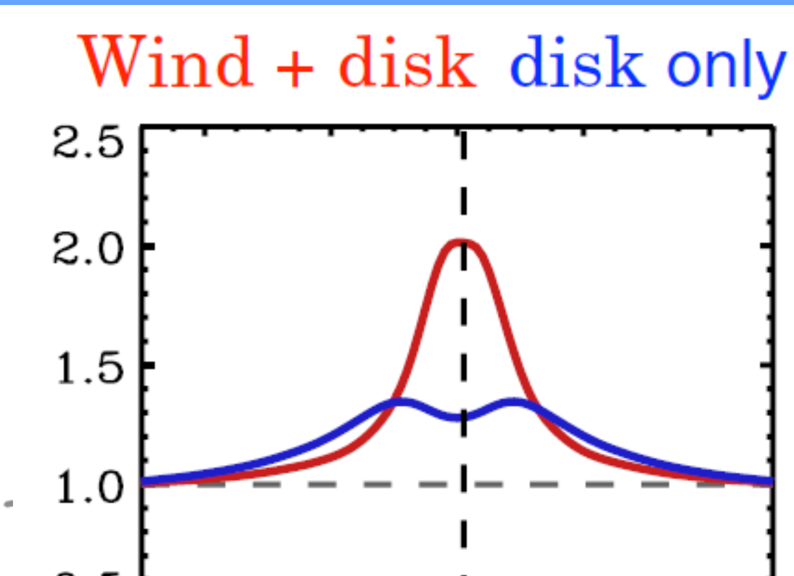
1) Line Profiles & Astrometry
2) **Temperature Distributions**

Najita et al. 2003
Salyk et al. 2007-2011
Brown et al. 2013

CO Rovibrational Emission

Pontoppidan et al. 2011

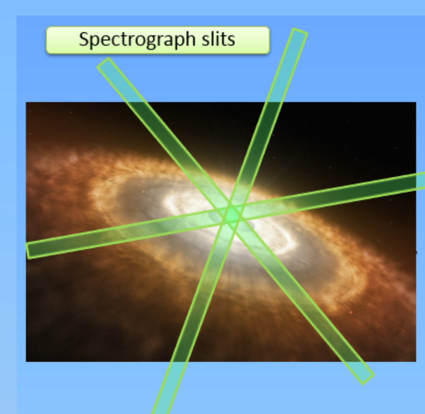




Inferred Spatial Distributions:

1) Line Profiles & Astrometry

2) Temperature Distributions

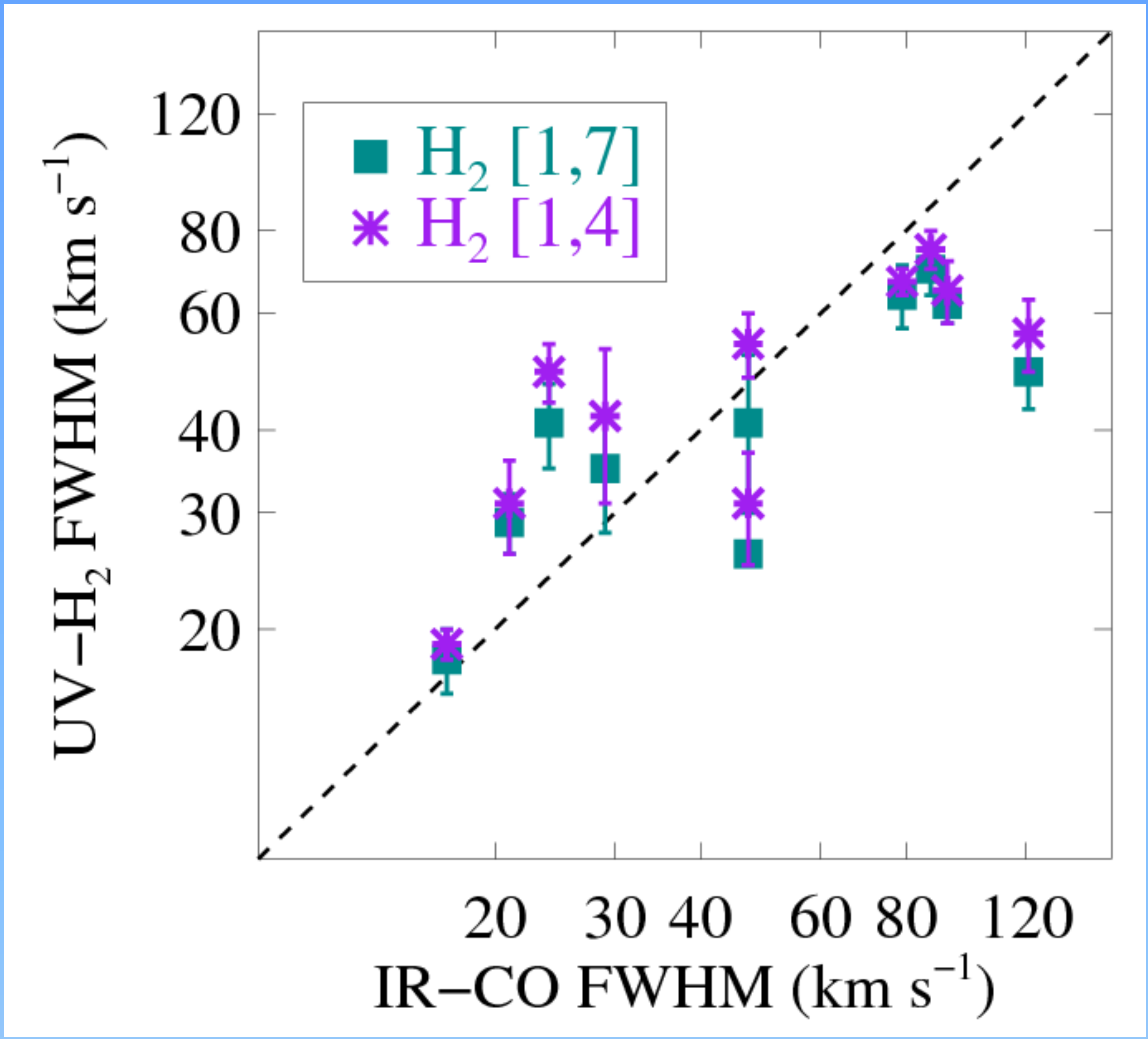


Molecules in Protoplanetary Disks: Ultraviolet Emission from the Inner Disk

- UV-H_2: Most targets dominated by single, symmetric H_2 line profile at the stellar radial velocity:
  1. Disk surface origin, likely wind component
  2. T_{rot}(UV-H_2) = 2500 $\pm$ 1000 K
  3. **$R_{UV\text{-}H2}$ = 0.1 – 3 AU** ; M_{H2}(2500K) ~ 10^{-6} – 10^{-4} $M_{\oplus}$

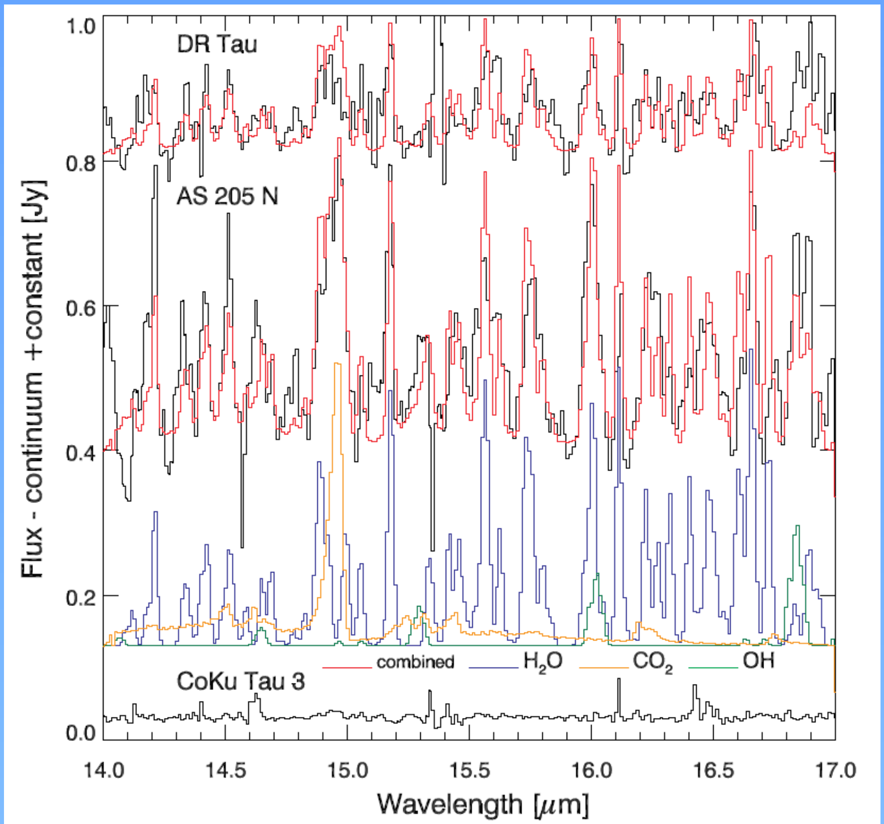
- UV-CO: Narrower lines, no evidence for broad component
  1. Disk surface origin
  2. T_{rot}(UV-CO) = 400 $\pm$ 300 K
  3. **$R_{UV\text{-}CO}$ = 2.0 – 10 AU** ; M_{H2}(500K) ~ 10^{-2} – 10^{-1} $M_{\oplus}$

Molecules in the Inner Disk: Ultraviolet-Infrared Relationship



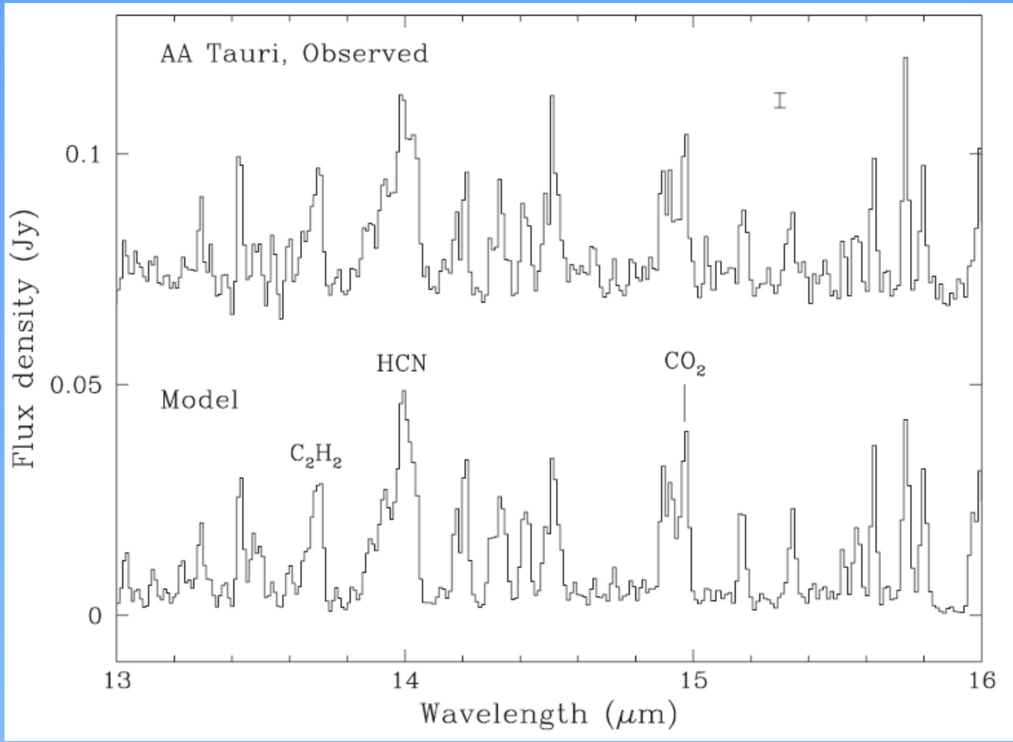
France et al. (2012b), Salyk et al. (2011), Bast et al. (2011), Brown et al. (2013)

H_2O & organics



Salyk et al. 2008

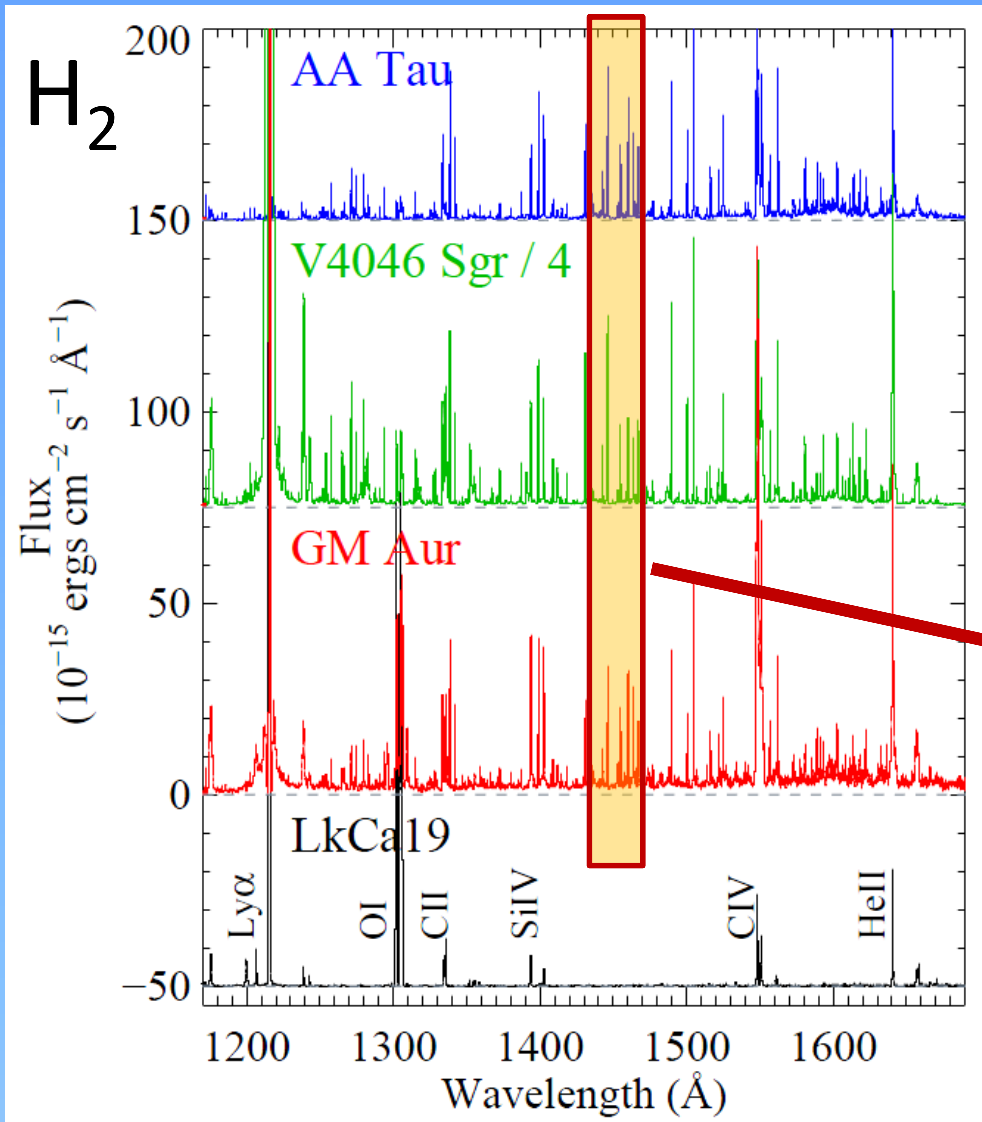
Warm, Inner disk origin



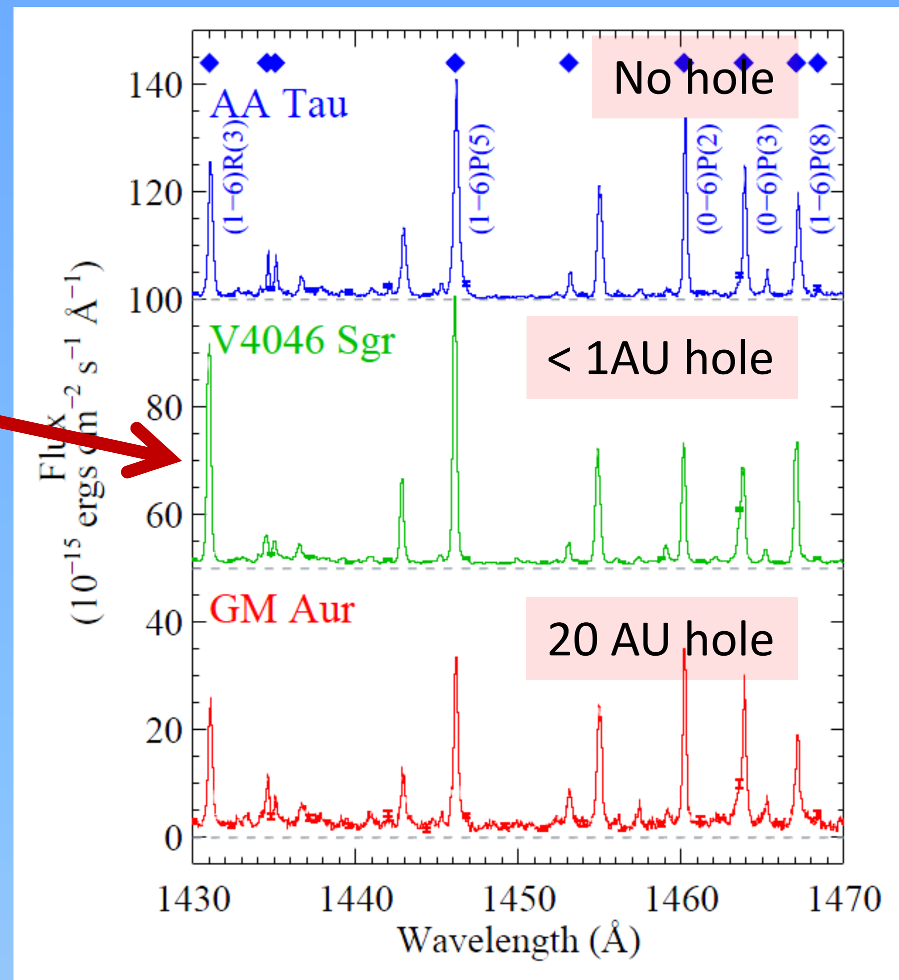
Carr & Najita et al. 2008

Molecule	*T* (K)	*N* (10^{16} cm^{-2})	*R** (AU)
H_2O	575 ± 50	65 ± 24	2.1 ± 0.1
OH	525 ± 50	8.1 ± 5.2	2.2 ± 0.1
HCN	650 ± 100	6.5 ± 3.3	0.60 ± 0.05
C_2H_2	650 ± 150	0.81 ± 0.32	0.60†
CO_2	350 ± 100	0.2 –13	1.2 ± 0.2
CO	900 ± 100	49 ± 16	0.7 ± 0.1

Molecules in Protoplanetary Disks: Ultraviolet Emission from the Inner Disk

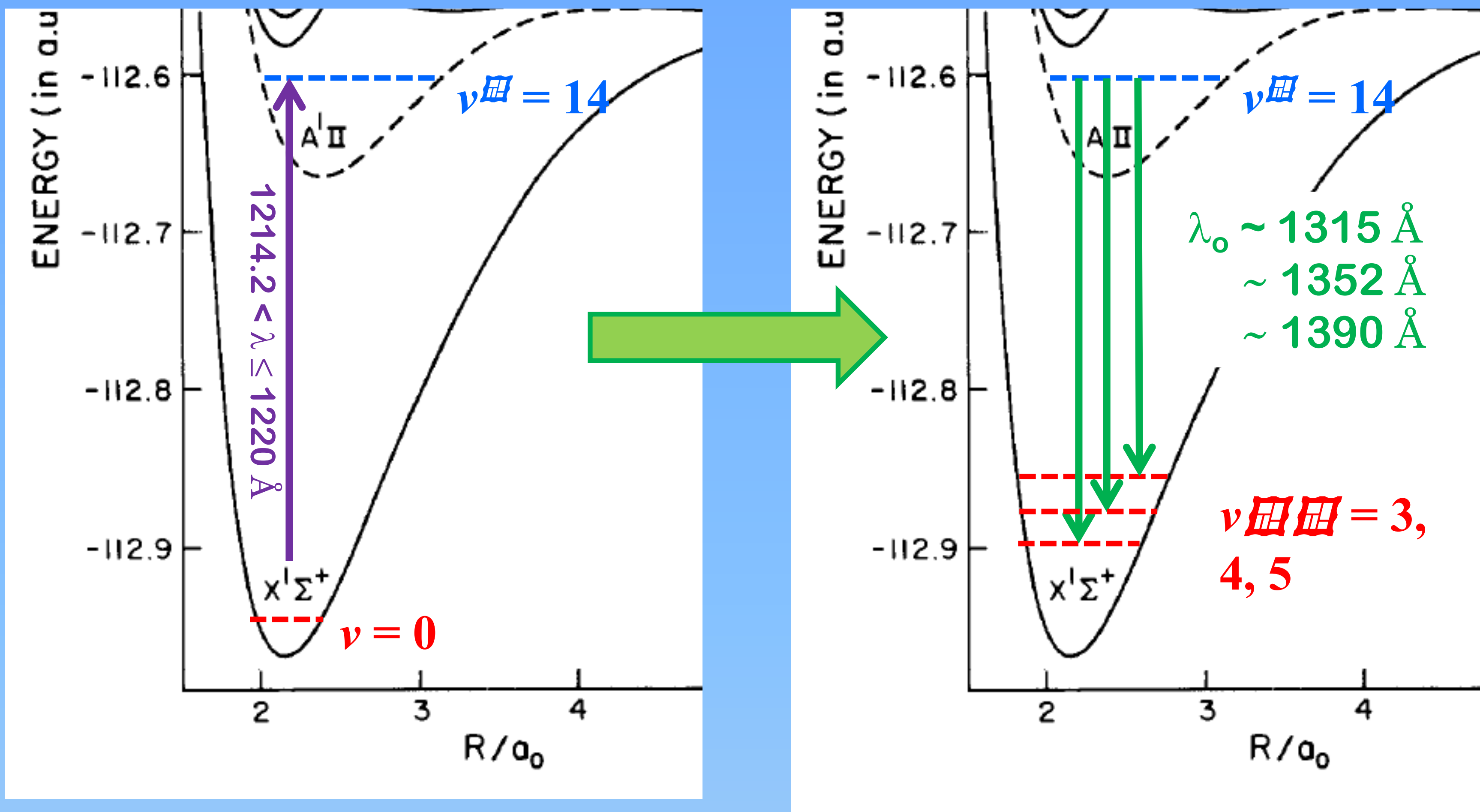


10s – 100s of photo-excited H_2 lines in every gas-rich disk spectrum

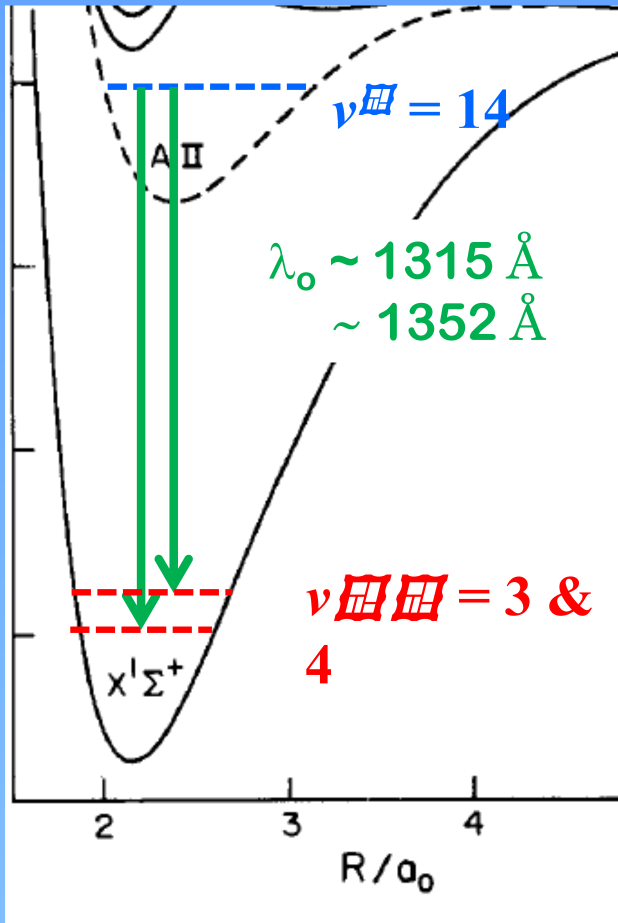


UV-H_2 and UV-CO

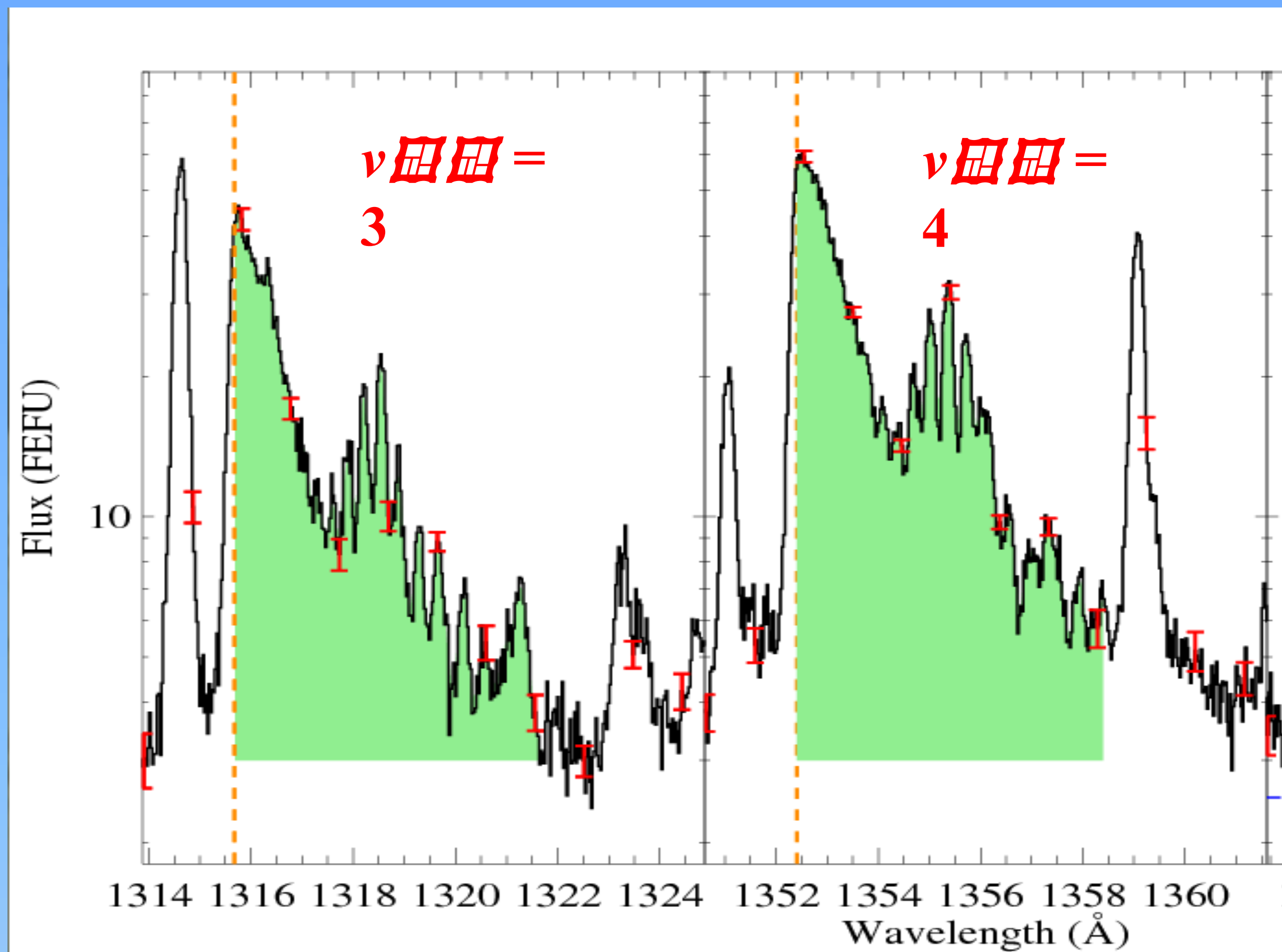
CO Fluorescence



UV-H_2 and UV-CO



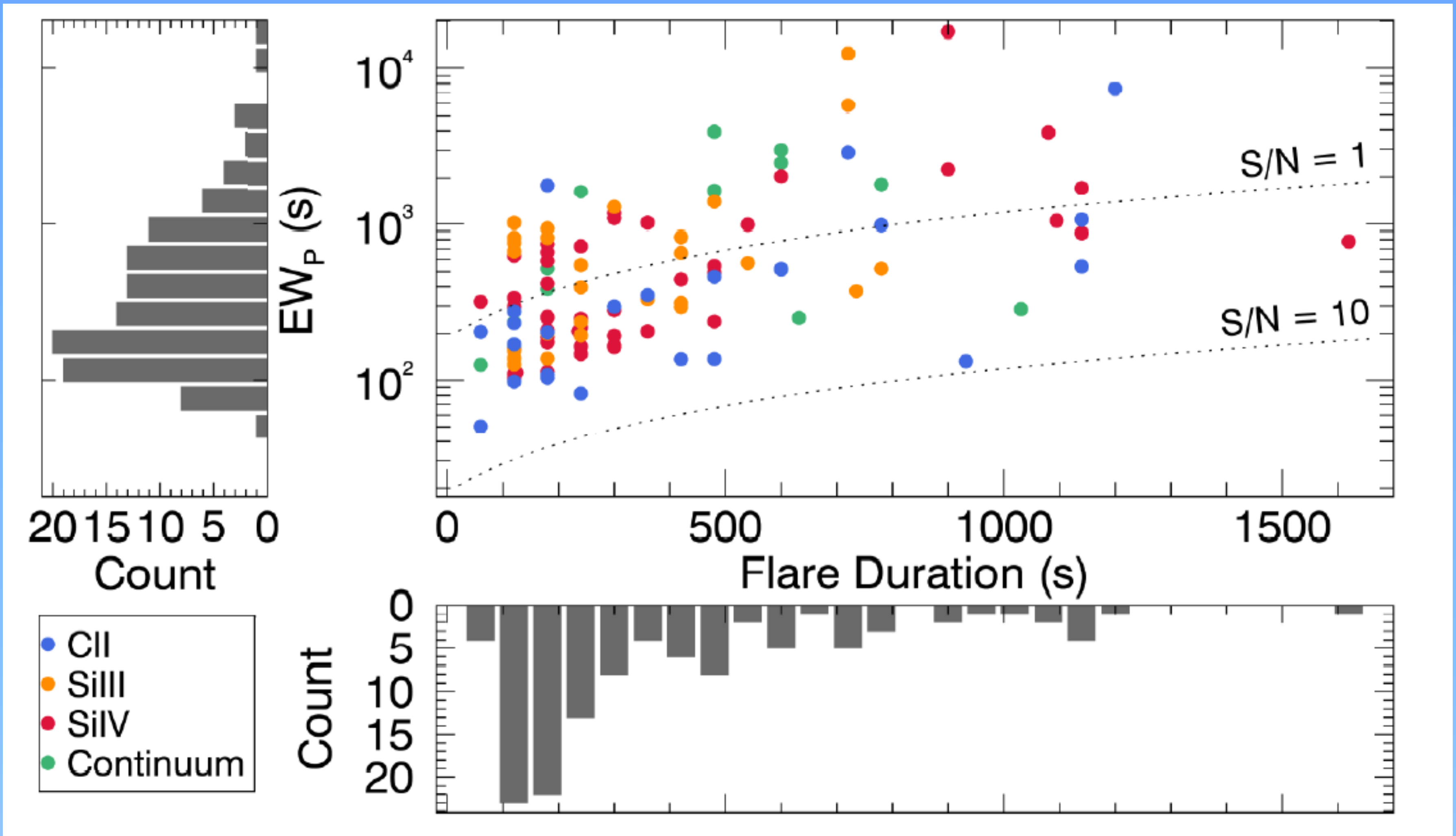
Strong detections of photo-excited CO in ~ 60% of our gas-rich disk targets



France et al. (2011b)

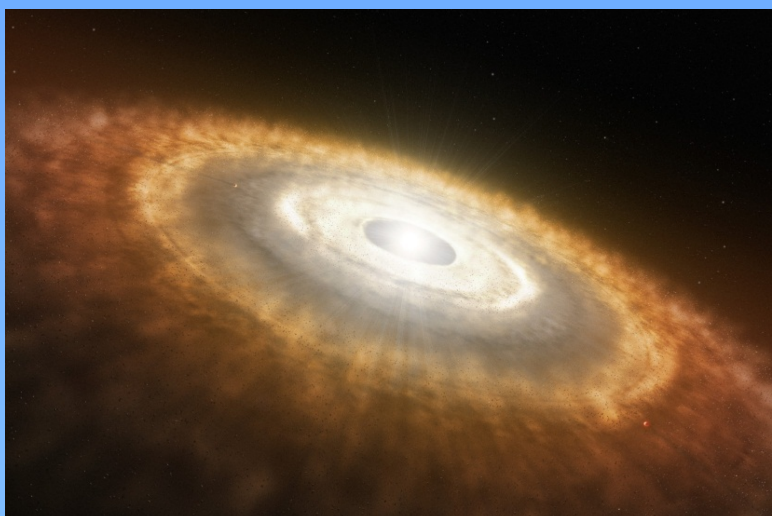
UV variability in G, K, and M stars

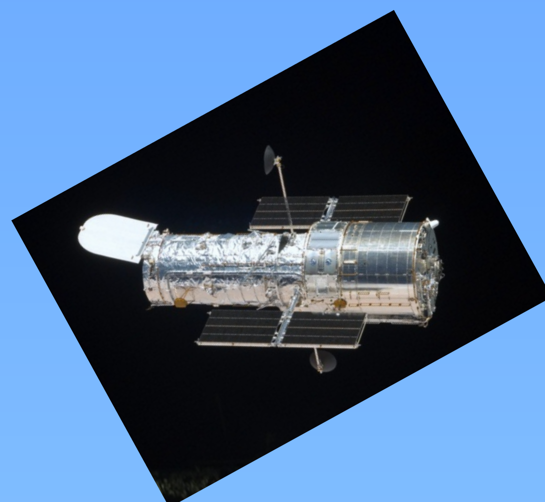
- UV Flare statistics

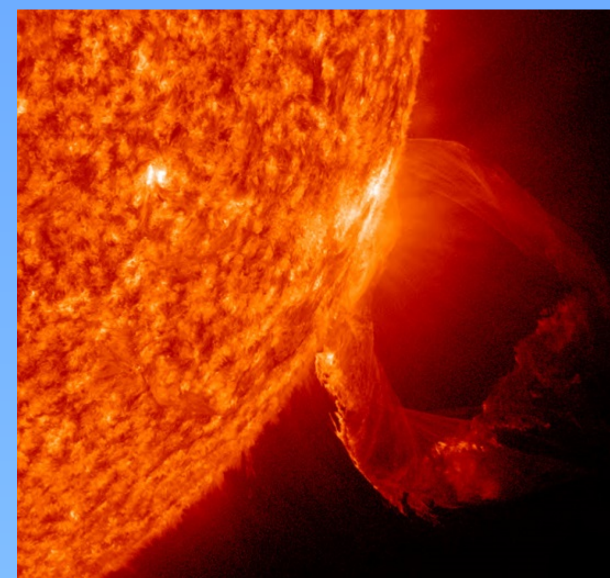


Loyd & France, ApJS 2014

Hubble's Ultraviolet View of Protoplanetary Disks and Exoplanetary Environments







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