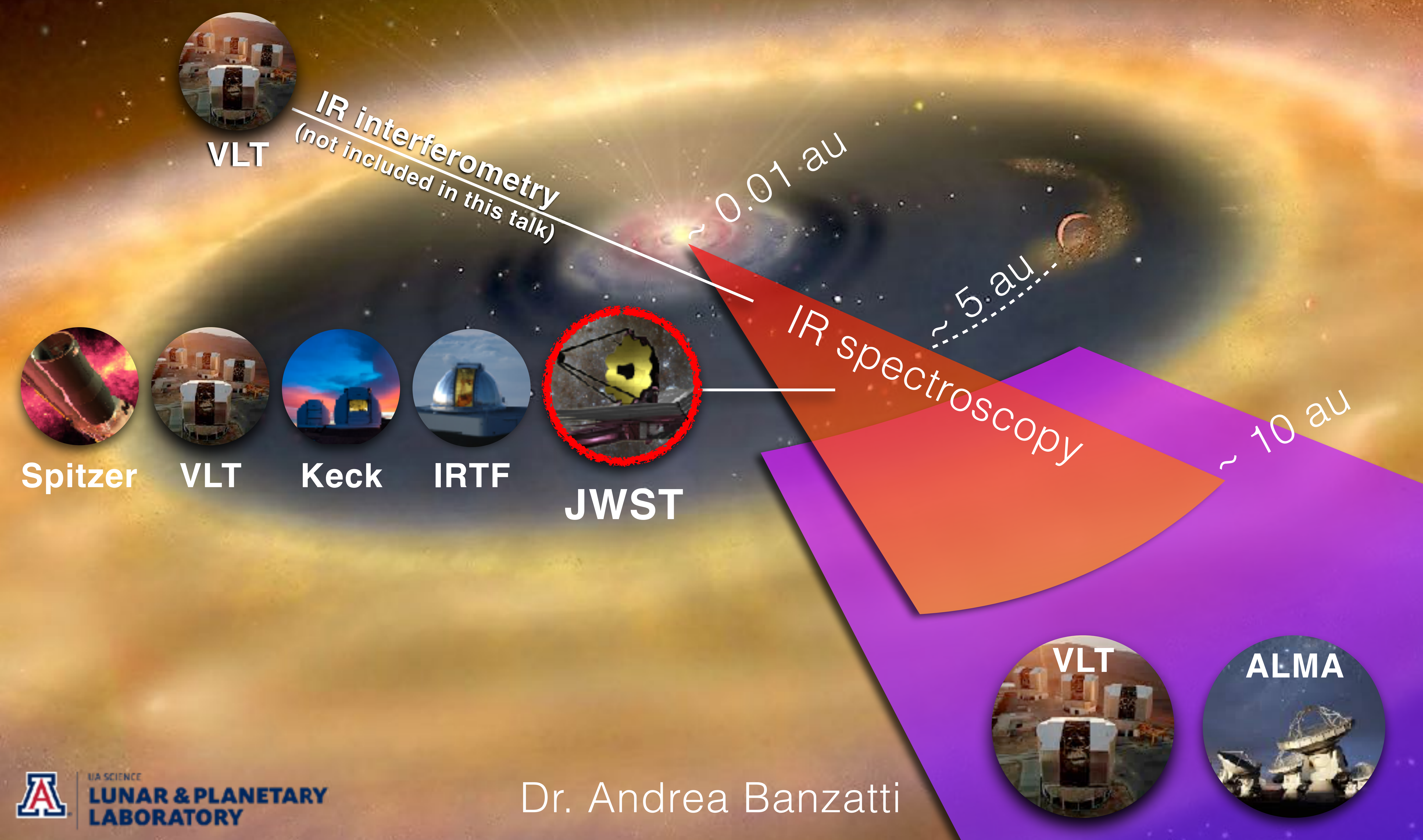
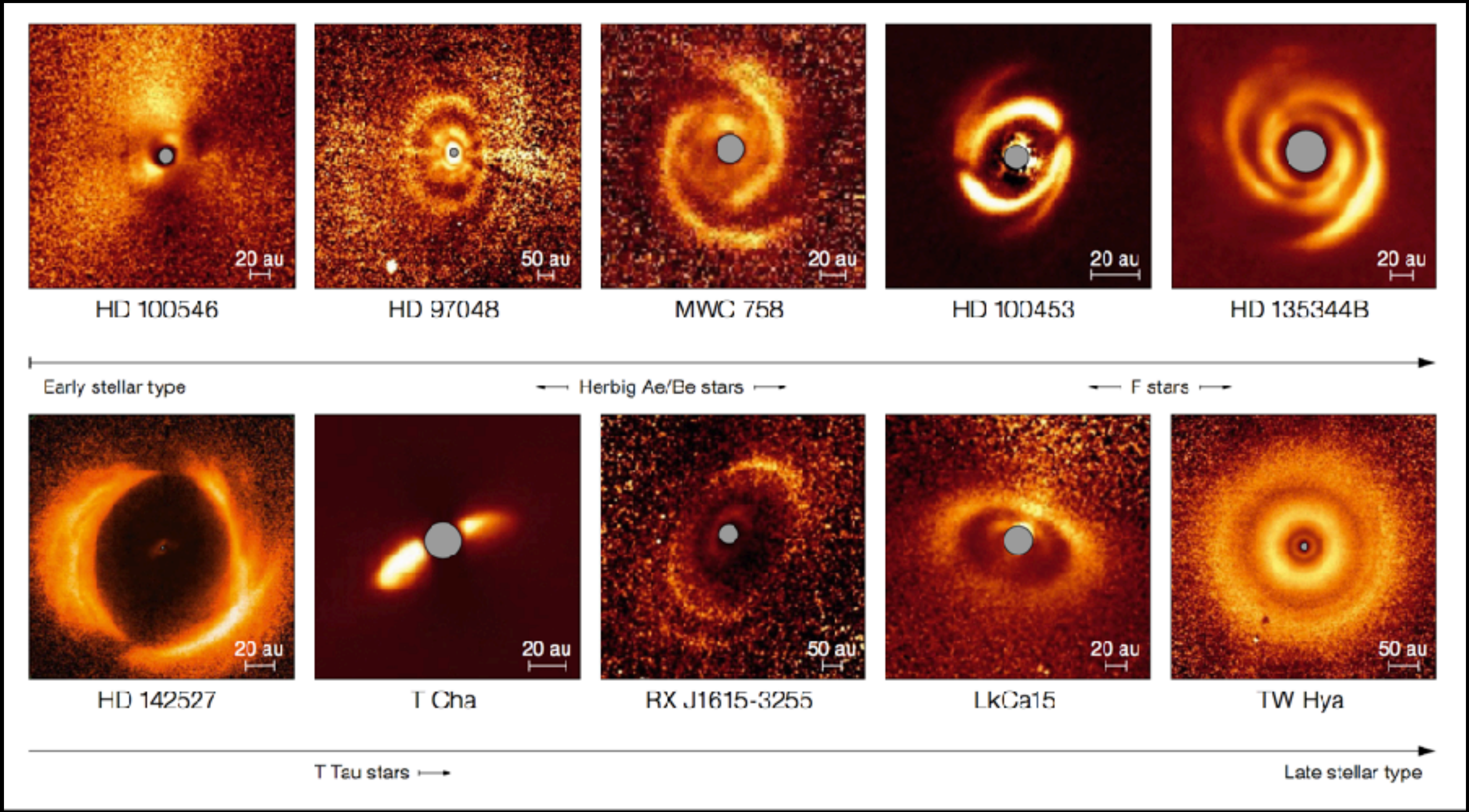
Revealing the evolution of disks at 0.01-10 au from high-resolution IR spectroscopy



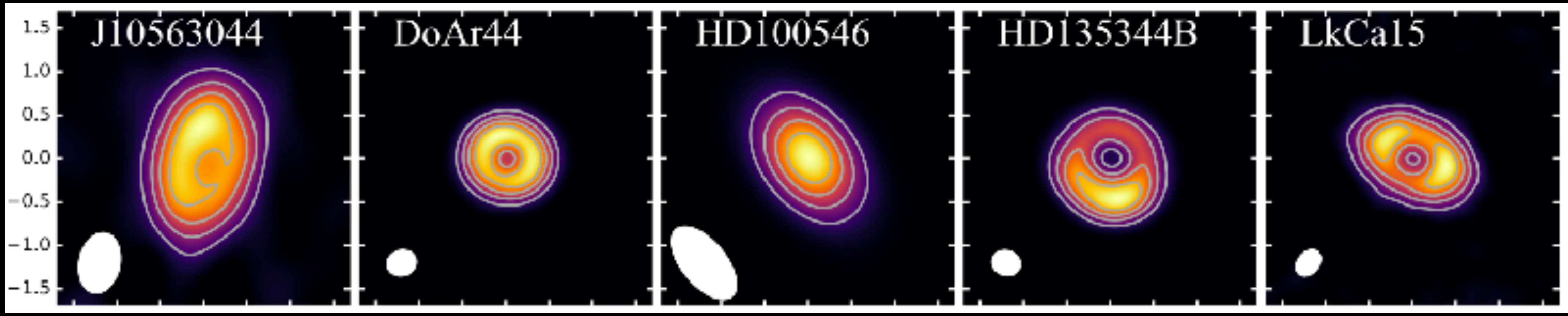
UA SCIENCE
LUNAR & PLANETARY LABORATORY

Dr. Andrea Banzatti

What happens in the “blind side”?



From Garufi et al. 2017, MSGR



Pinilla et al 2018

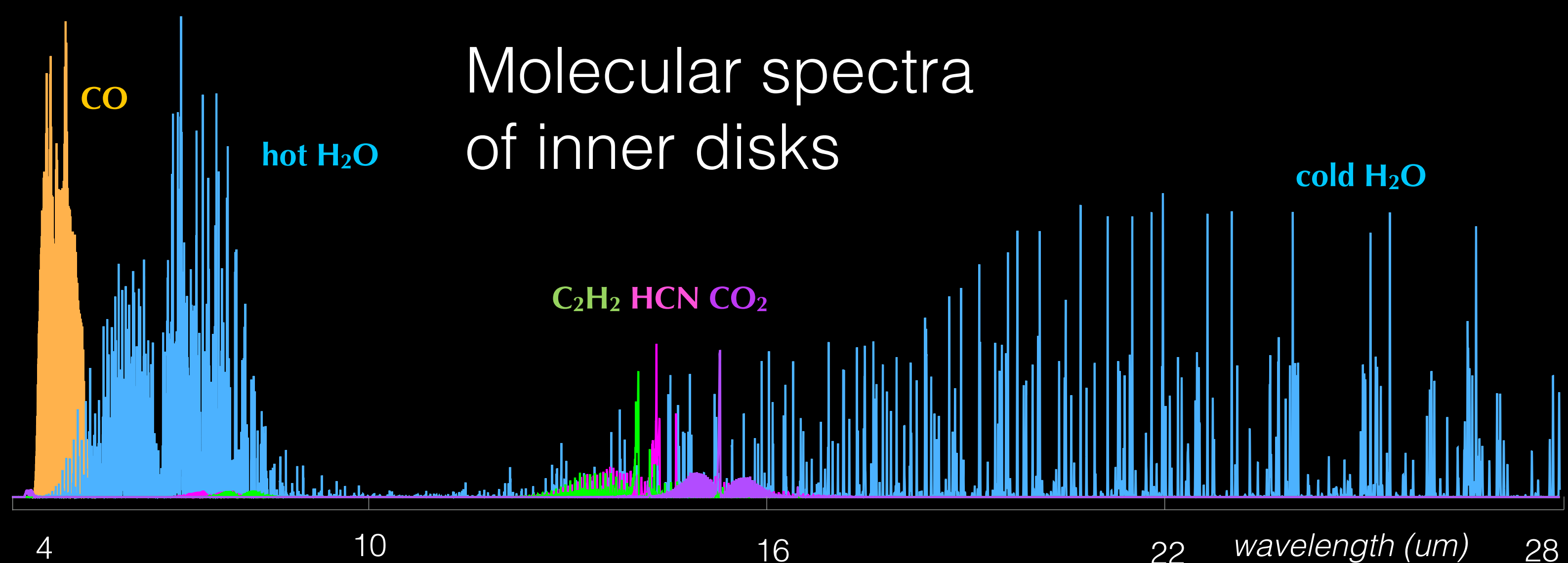
N/MIR molecular spectroscopy to study inner disks

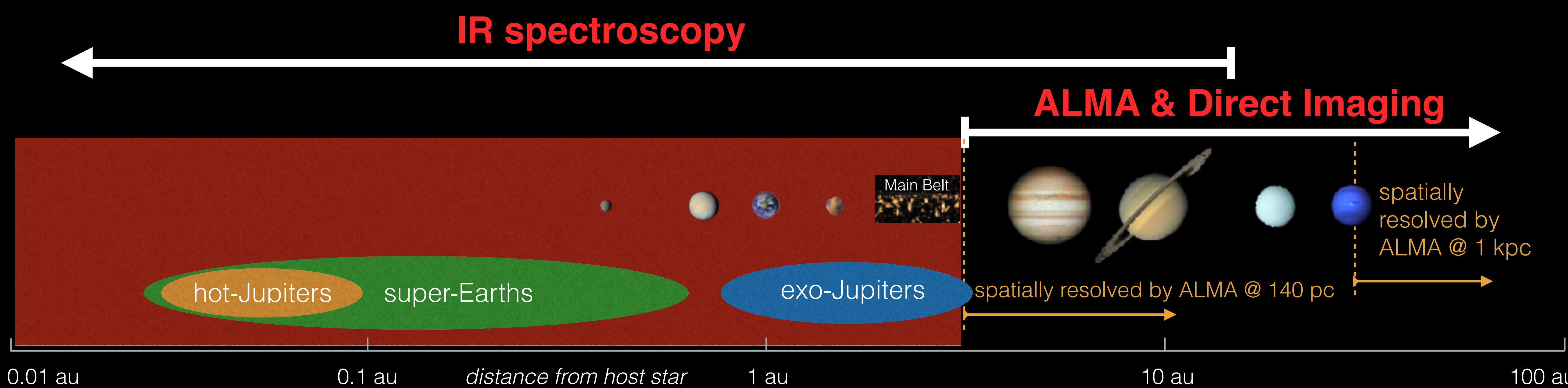
Wavelengths: ~2-40 micron (different ranges covered by different instruments)

Molecules: CO, H2O, OH, HCN, C2H2, CO2 (mostly, plus some other species)

Spectral Resolution: some very high (3 km/s), some only moderate (450 km/s) but large coverage

Science: structure (from gas kinematics), chemistry, evolution of planet-forming regions at < 10 au

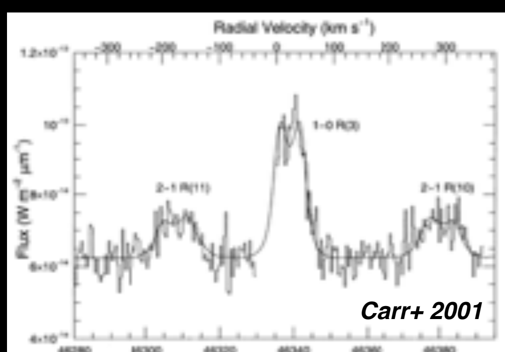




A brief history of N/MIR molecular spectroscopy of planet-forming regions

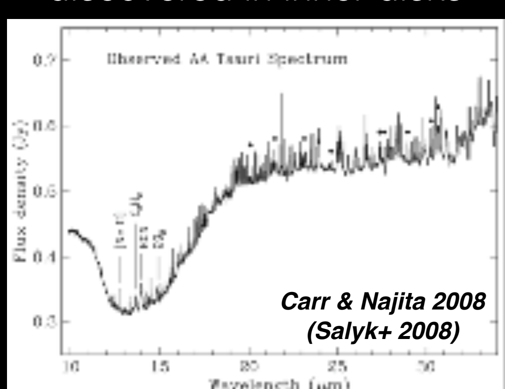
Mostly
small sample sizes
&/or
low spectral resolution

1990-2011:
CO gas NIR emission probes Keplerian inner disks



Carr, Najita, Blake, Brittain, Salyk

2008-2011:
Water and organics discovered in inner disks



Carr, Najita, Pontoppidan, Salyk, Fedele

Keck-NIRSPEC
1-5 um
R~25,000
~100 disks

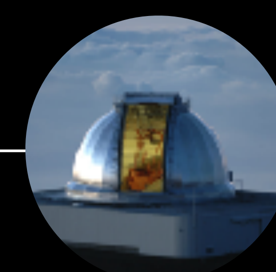
Spitzer-IRS
10-37 um
R~700
~100 disks

2008-today:
Large sample sizes (~100 disks)
high spectral resolution (R = 75,000 - 100,000)

Particularly promising:
combined datasets (wavelengths, tracers, molecules, samples) to obtain global view of evolving planet-forming regions

VLT-CRIRES (+)
1-5 um
R~100,000
~100 disks

VLT-VISIR 2.0
10-13 um
R~25,000
~50 disks

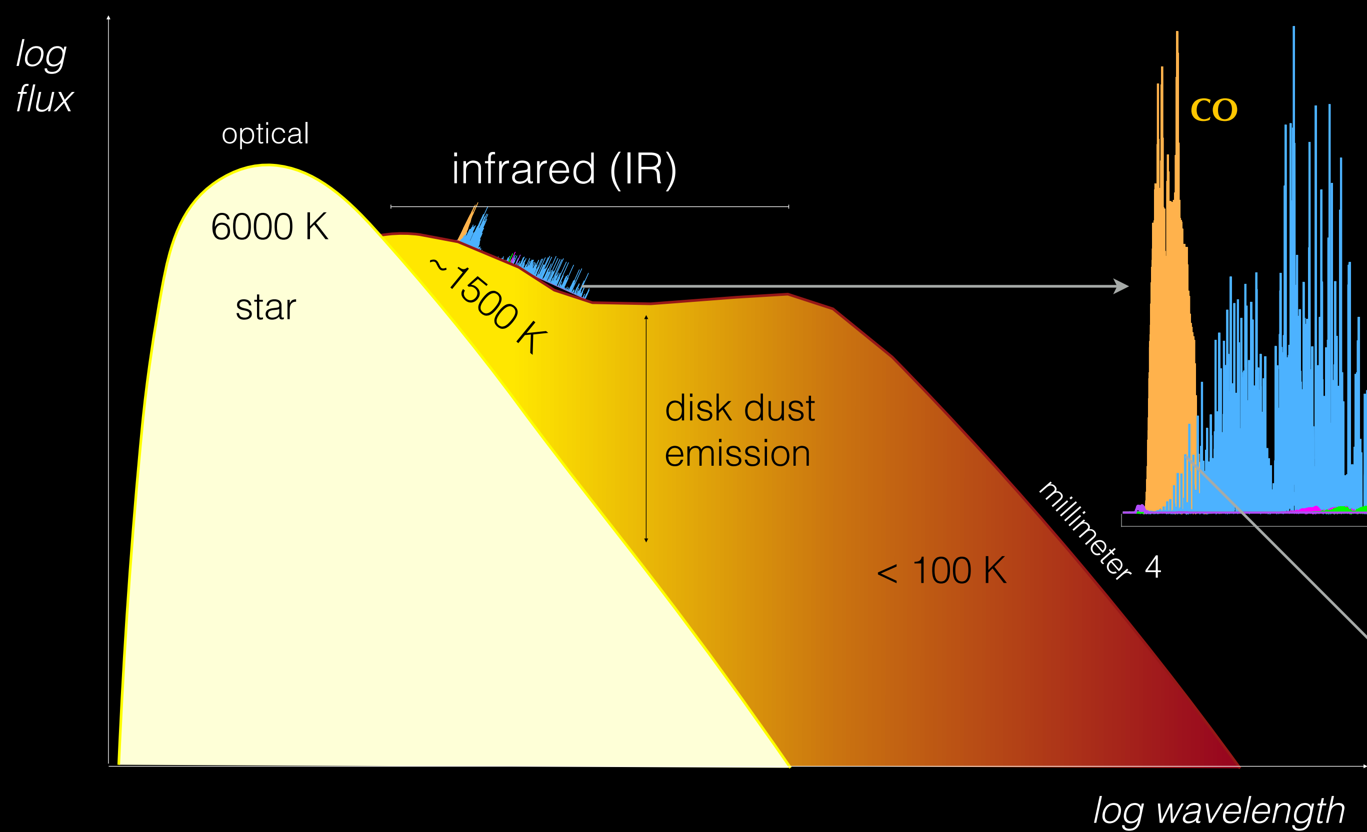


IRTF-ISHELL
1-5 um
R~75,000
>10 disks

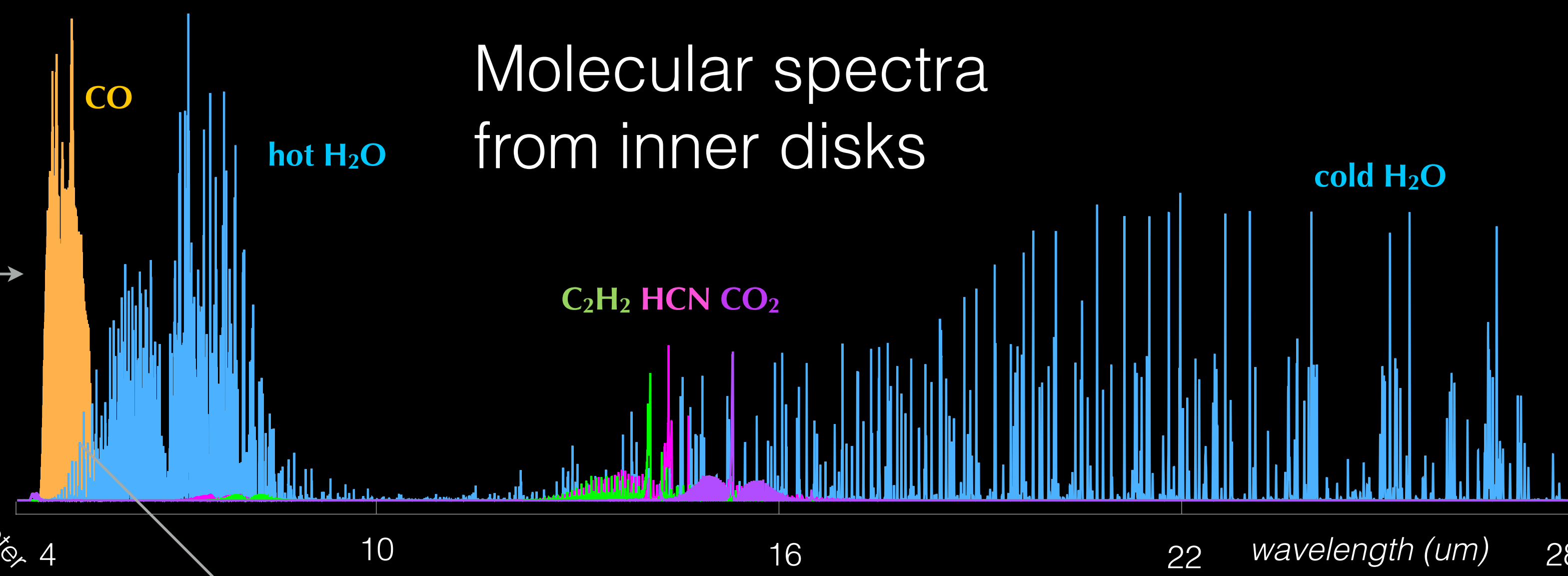
ORIGINS
Space Telescope

Some references:
Najita, Carr, Pontoppidan, Salyk, Brittain, Fedele, Carmona, Banzatti, Doppmann, Blake, Mandell, Pascucci, Brown, Herczeg, van der Plas, Bast, Hein Bertelsen, …

How to get spatial information at 0.01-10 au

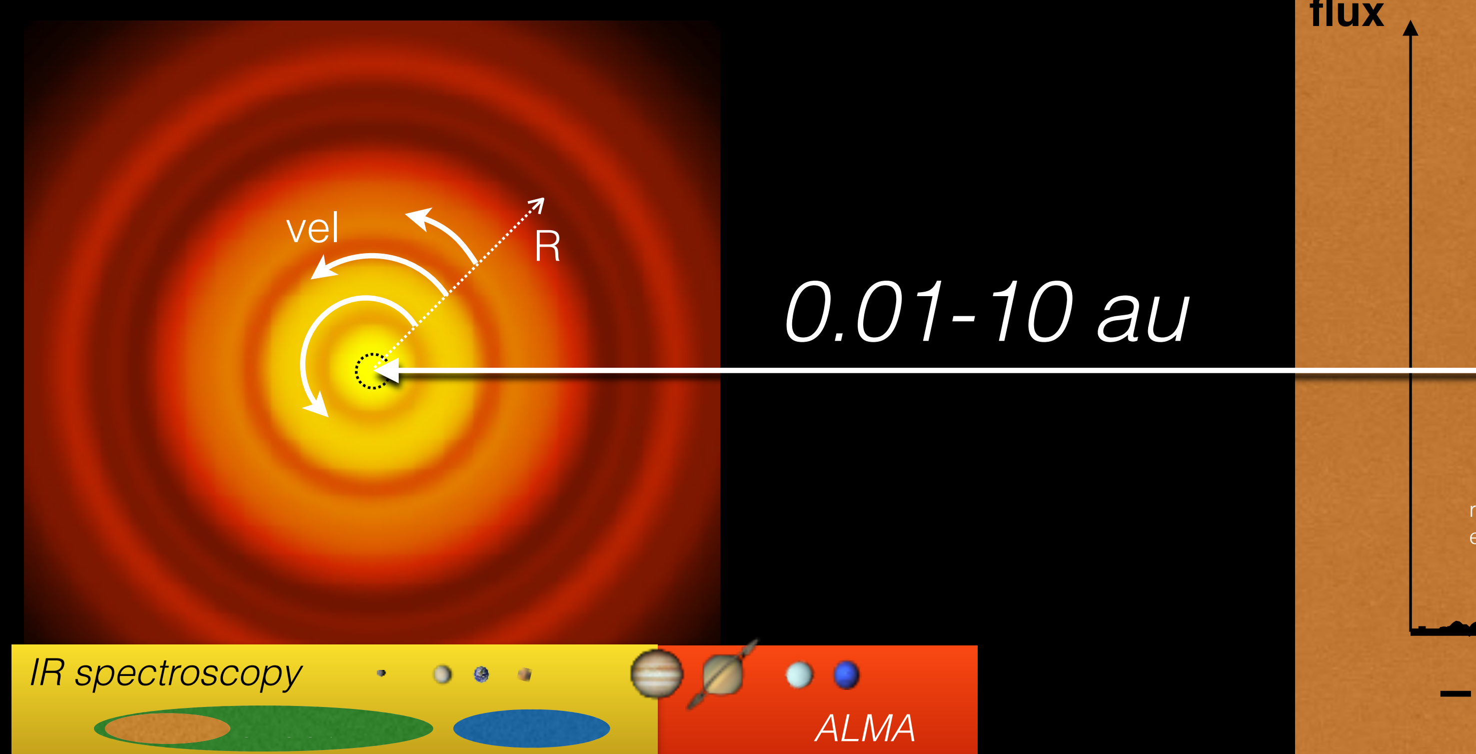


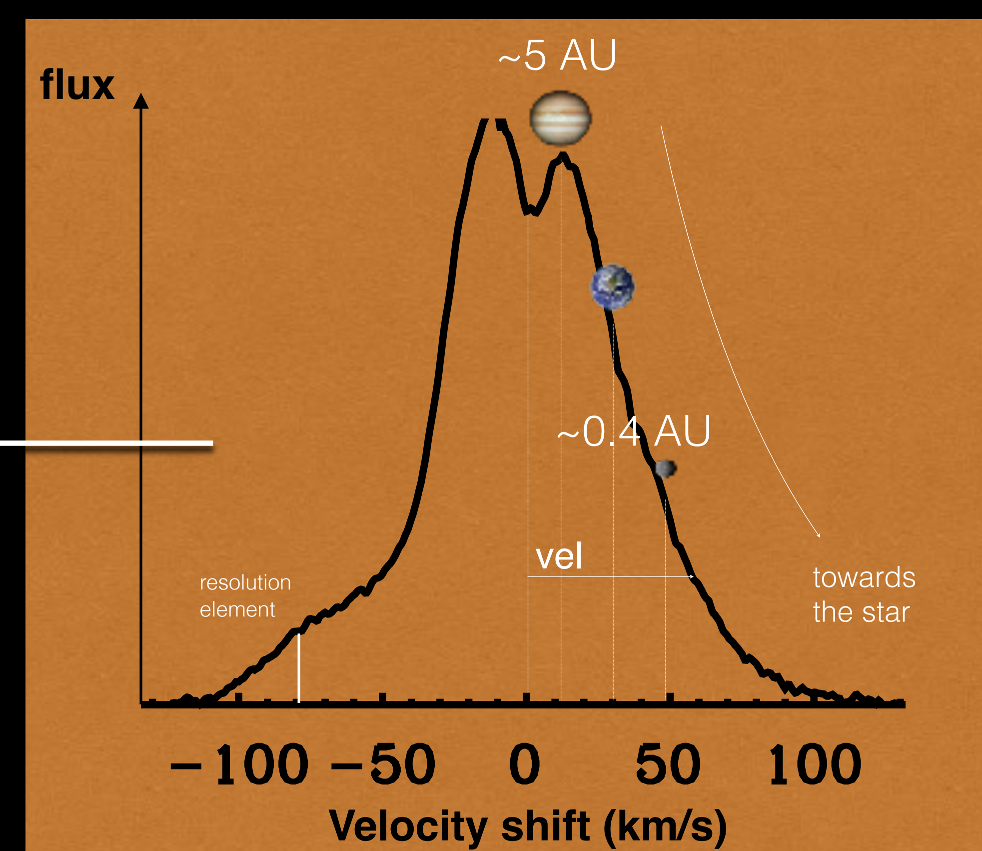
Molecular spectra from inner disks



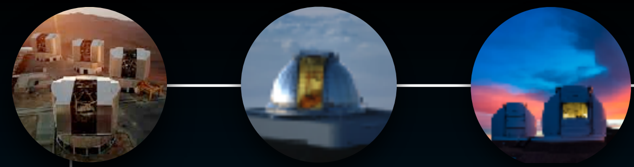
(e.g. Carr & Najita 2008; Salyk et al. 2011; Banzatti et al. 2012, 2013, 2017)

Doppler broadening of CO emission lines:





(e.g. Brittain et al. 2007; Pontoppidan et al. 2011; Banzatti et al., 2015a,b, 2017)

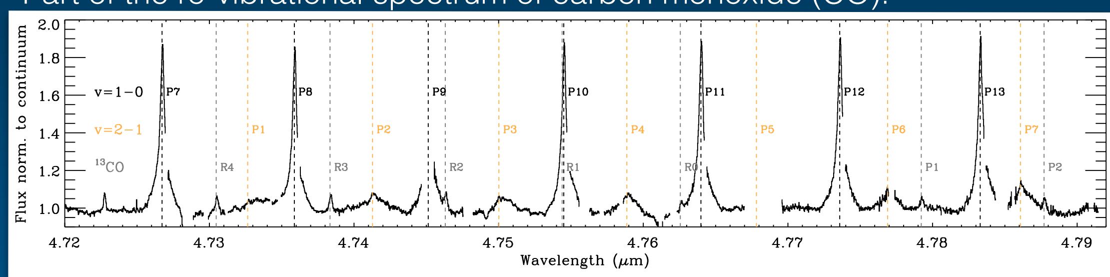


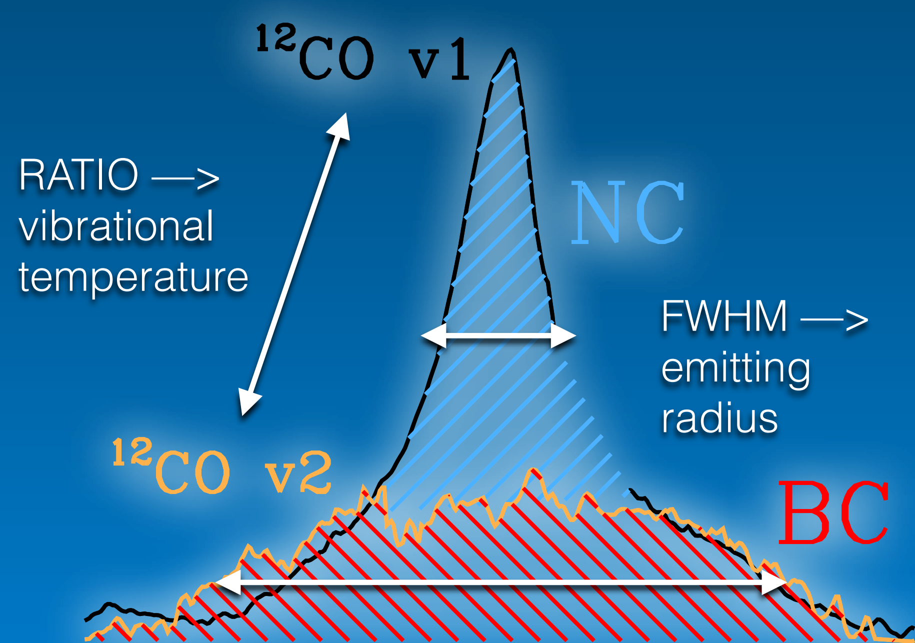
High-res. CO spectra to study inner disks

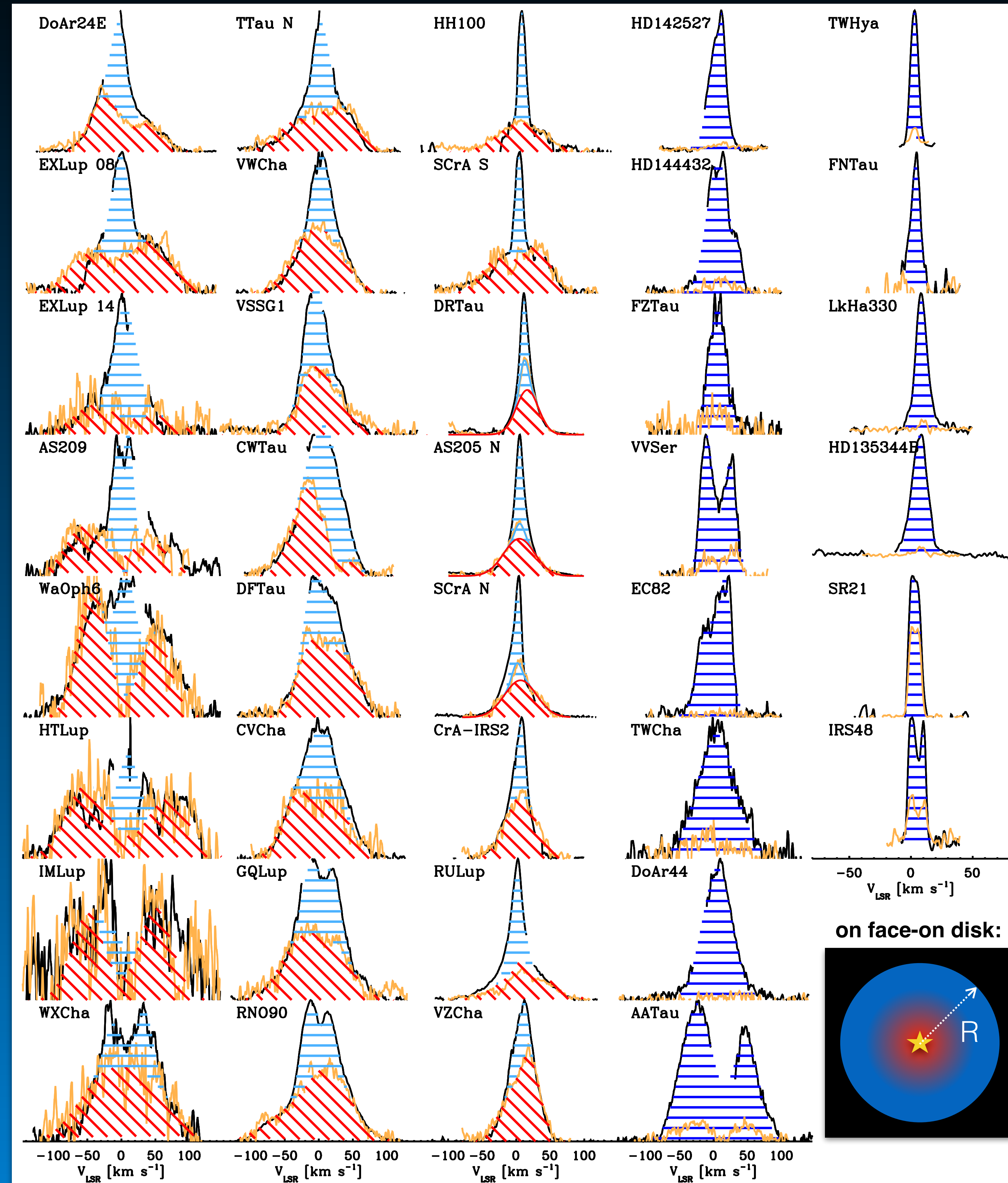
Data: IR spectroscopy (VLT-CRIRES, IRTF-iSHELL)
Resolution: high (Δv ~ 3-15 km/s)
Sample size: > 50 disks, spanning evolutionary stages
Goals: resolve gas kinematics and radial structure at < 5 AU, detect gas-depleted zones, measure gas temperature and density, reconstruct inner disk evolution phases

Several observing programs
(mostly a LP by vDishoeck &Pontoppidan)
CRIRES on VLT (8-m)
~30 nights of data
(more than 24 papers published to date)

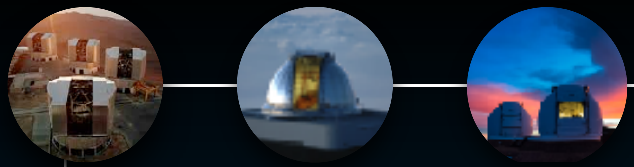
Part of the ro-vibrational spectrum of carbon monoxide (CO):





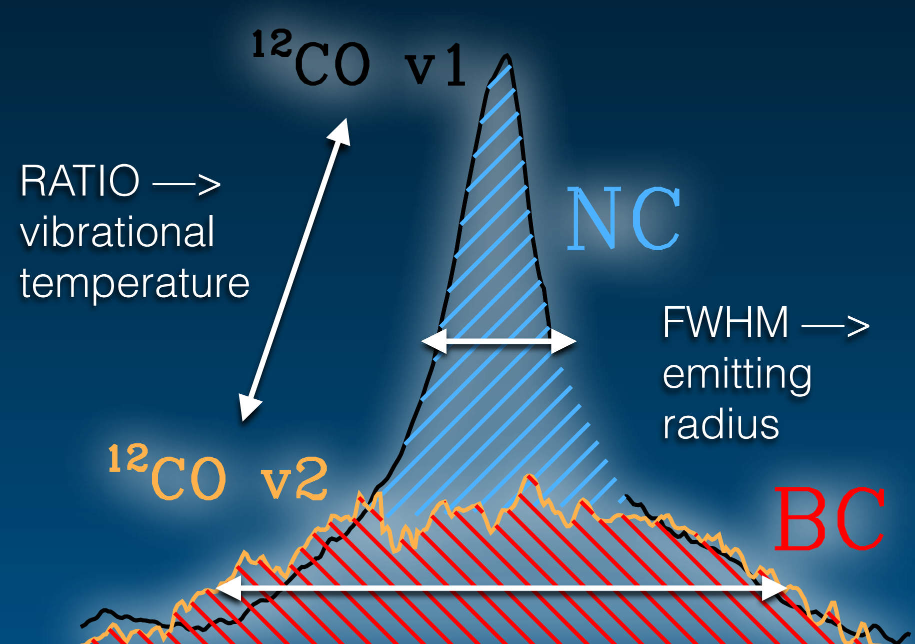


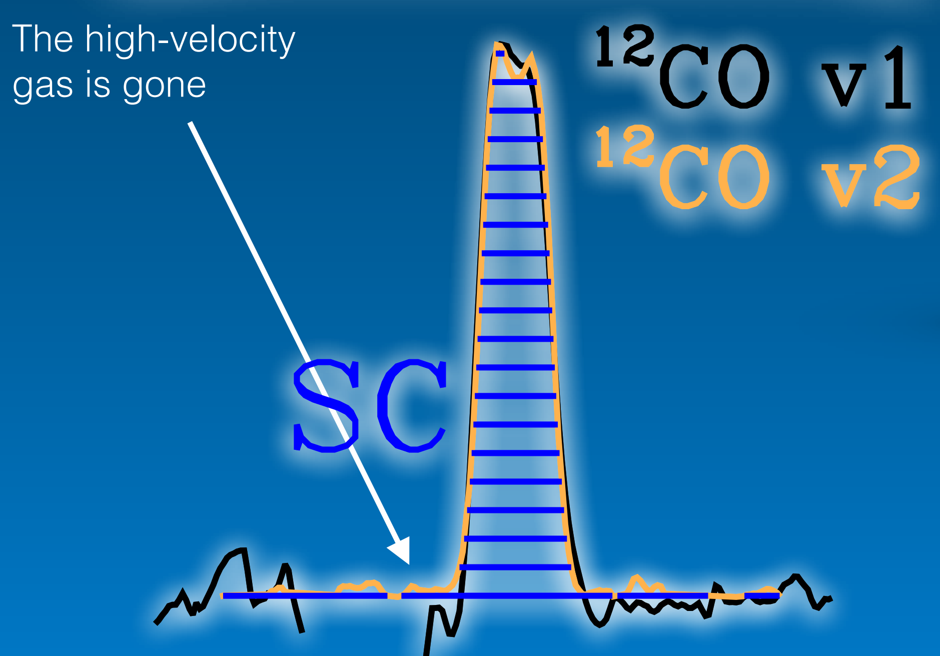
Banzatti et al. 2015a, 2017, 2018, Banzatti & Pontoppidan 2015



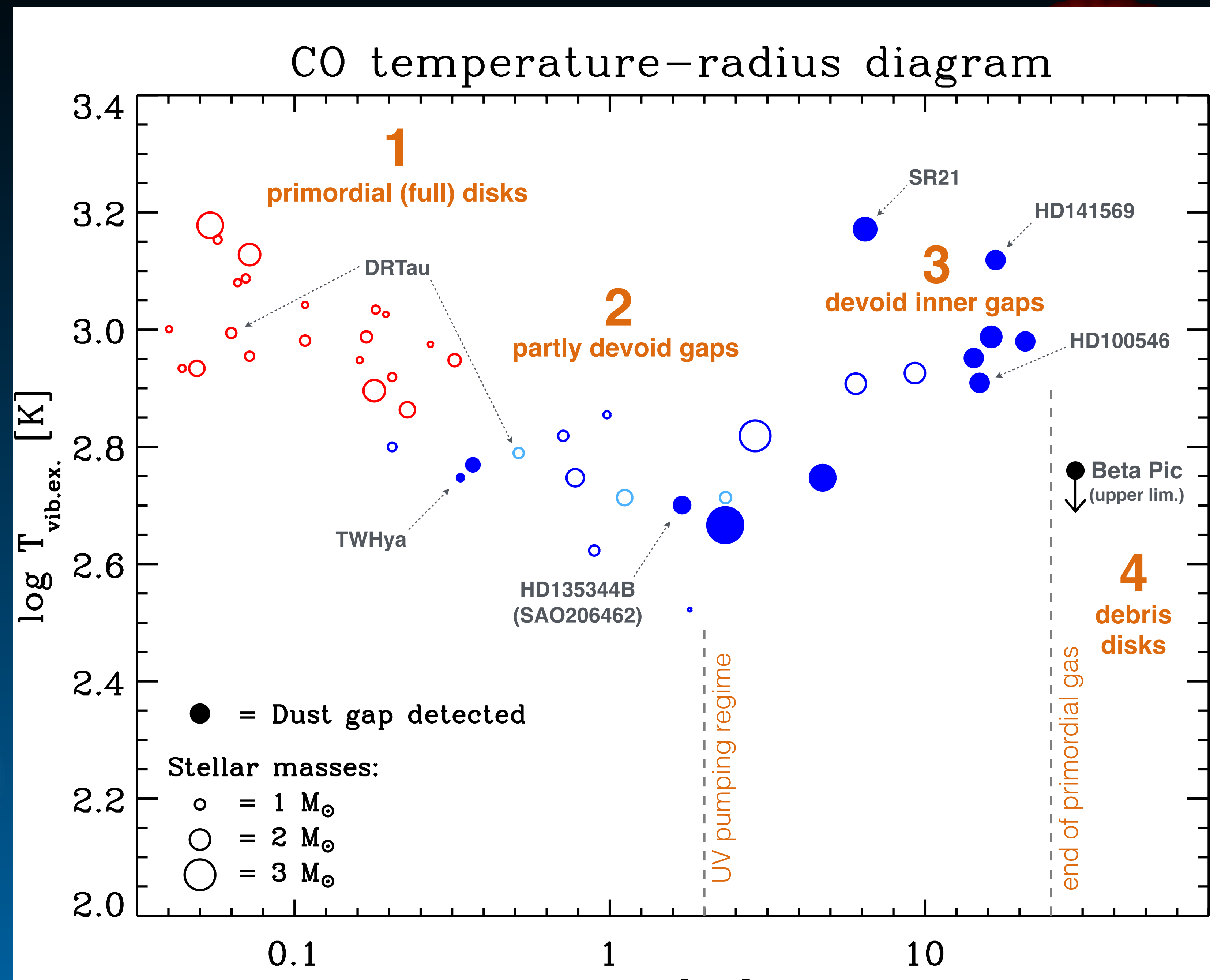
Gas temperature and evolution/depletion

Data: IR spectroscopy (VLT-CRIRES, IRTF-iSHELL)
Resolution: high (Δv ~ 3-15 km/s)
Sample size: > 50 disks, spanning evolutionary stages
Goals: resolve gas kinematics and radial structure at < 5 AU, detect gas-depleted zones, measure gas temperature and density, reconstruct inner disk evolution phases

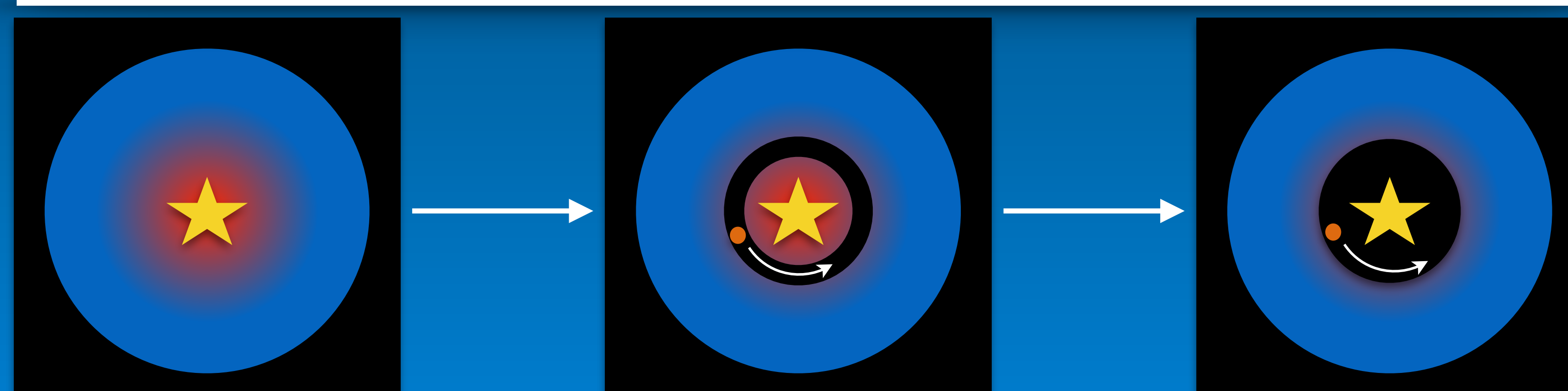




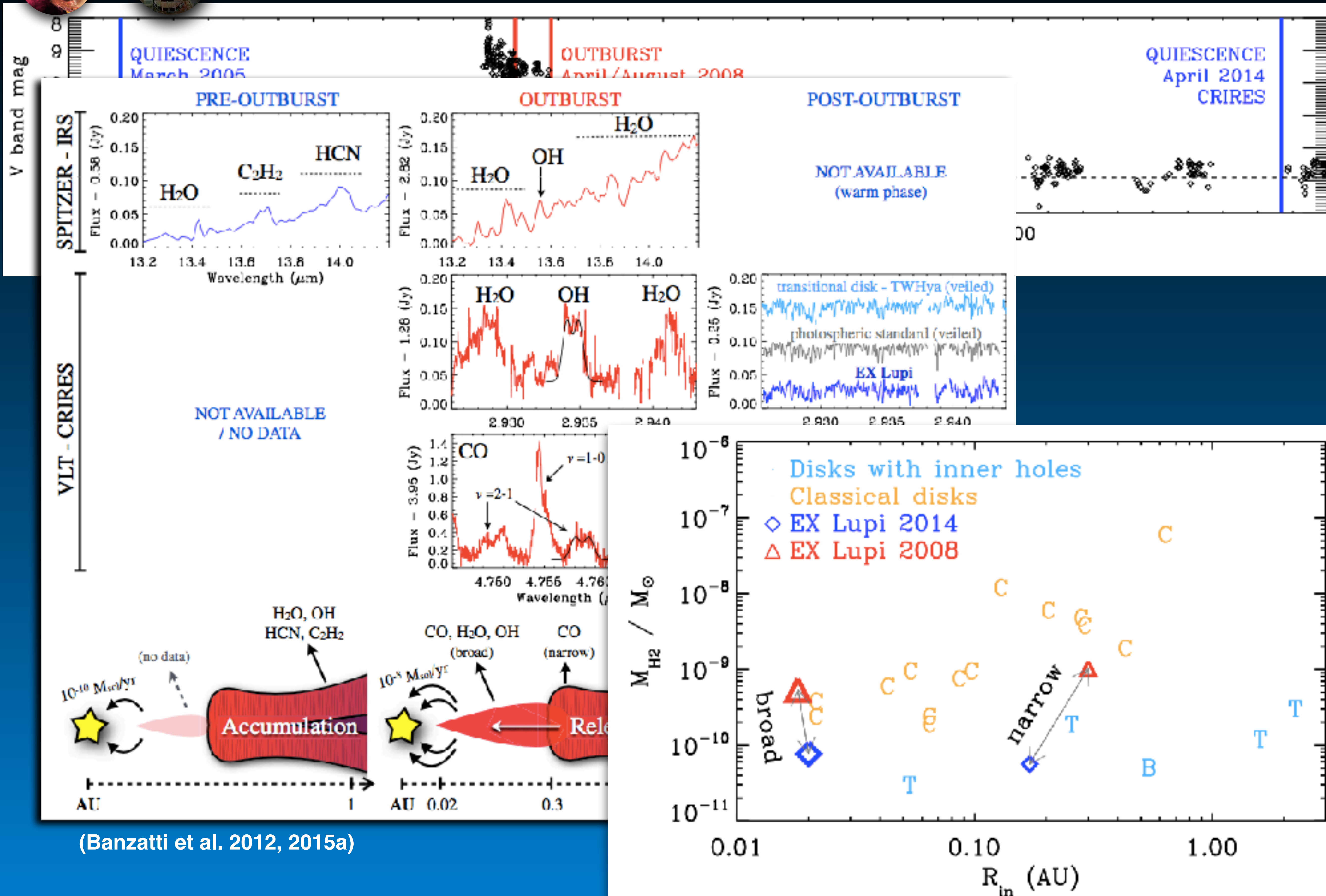
(Banzatti & Pontoppidan 2015)



(Banzatti & Pontoppidan 2015)



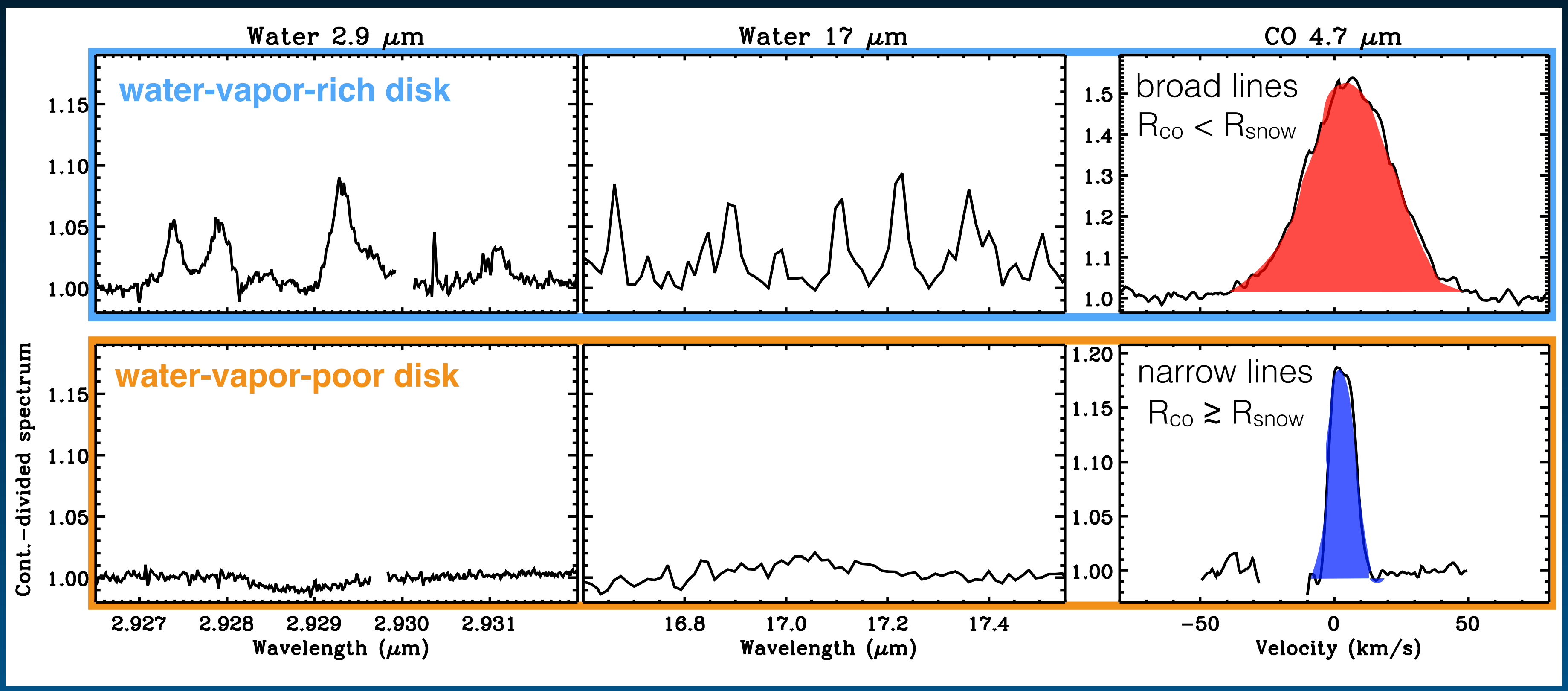
Intermezzo: the interesting case of EXLupi…

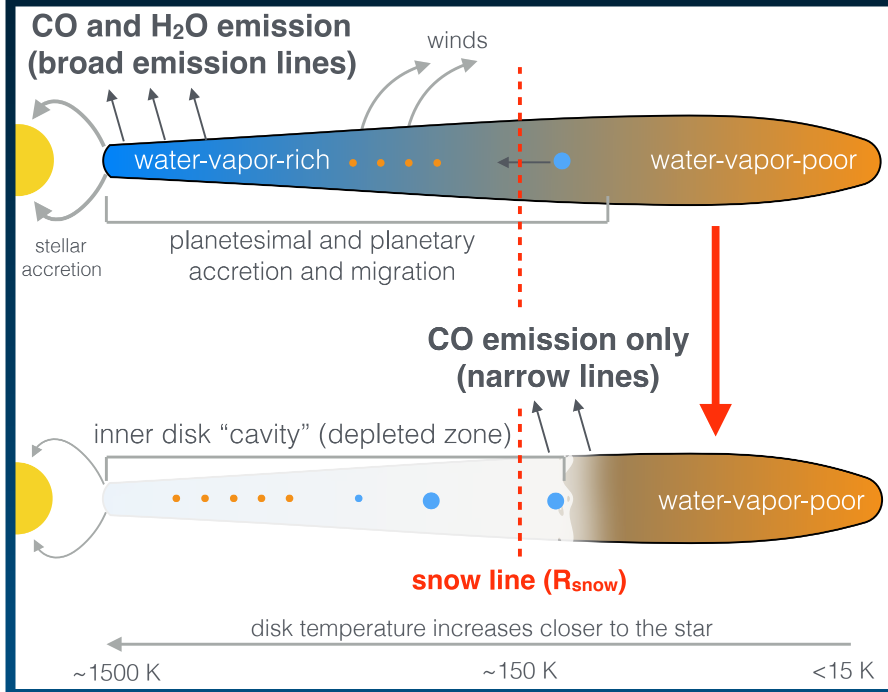


(Banzatti et al. 2012, 2015a)

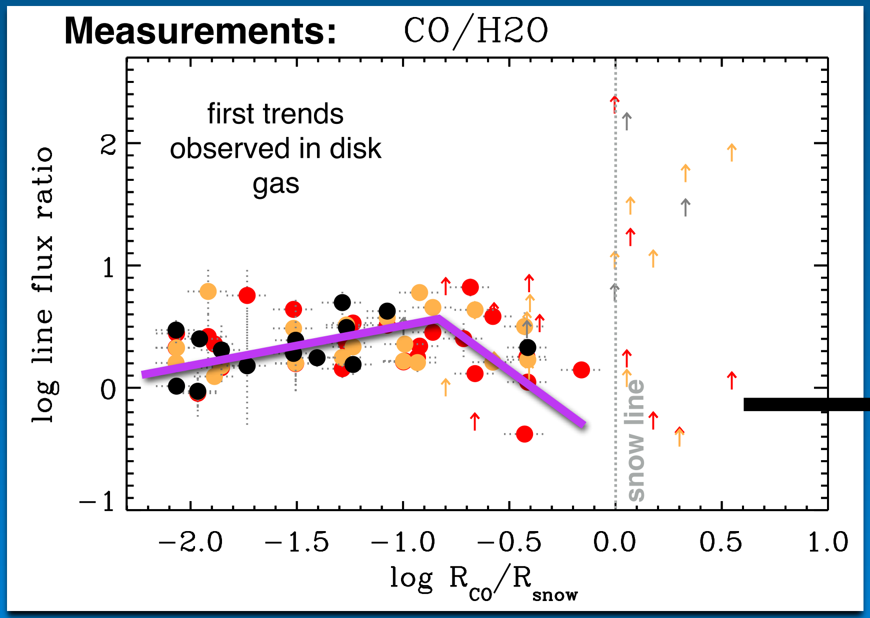
Water vapor evolution and chemical gradients

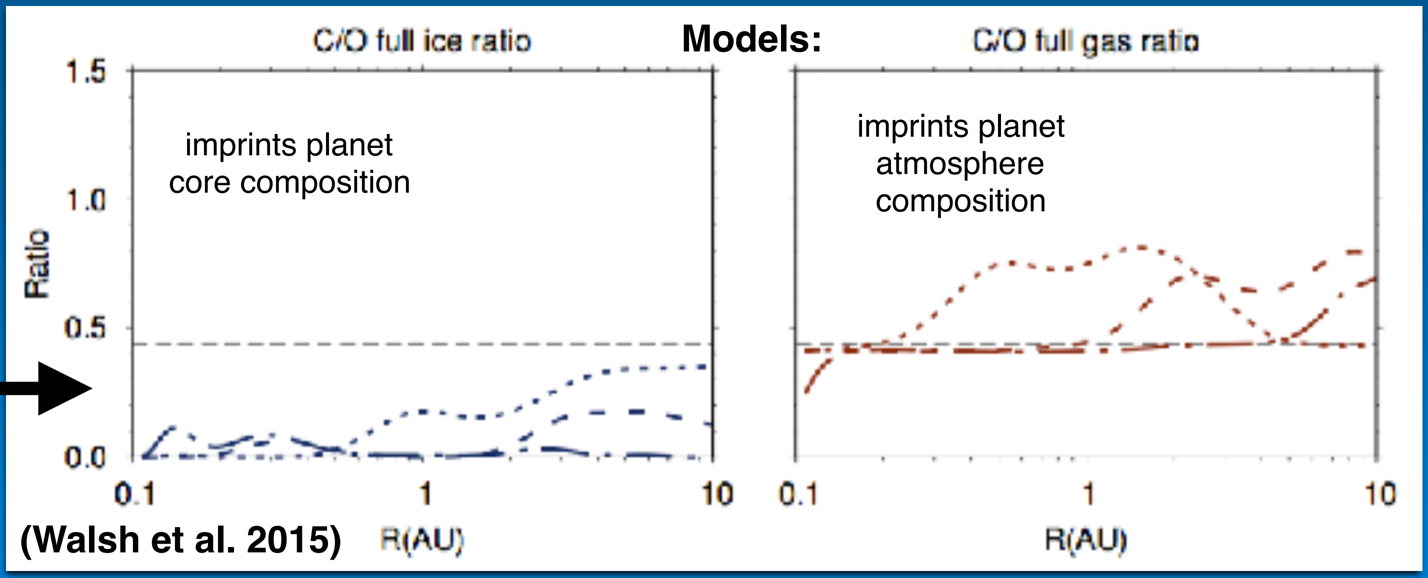
Data: IR spectroscopy (VLT-CRIRES, Spitzer-IRS)
Resolution: low + high (Δv ~ 3-450 km/s)
Sample size: > 50 disks, spanning evolutionary stages
Goals: combined analysis of multiple molecular tracers (CO, H_2O, OH), to study the thermo-chemical structure and evolution





(Banzatti et al. 2017)



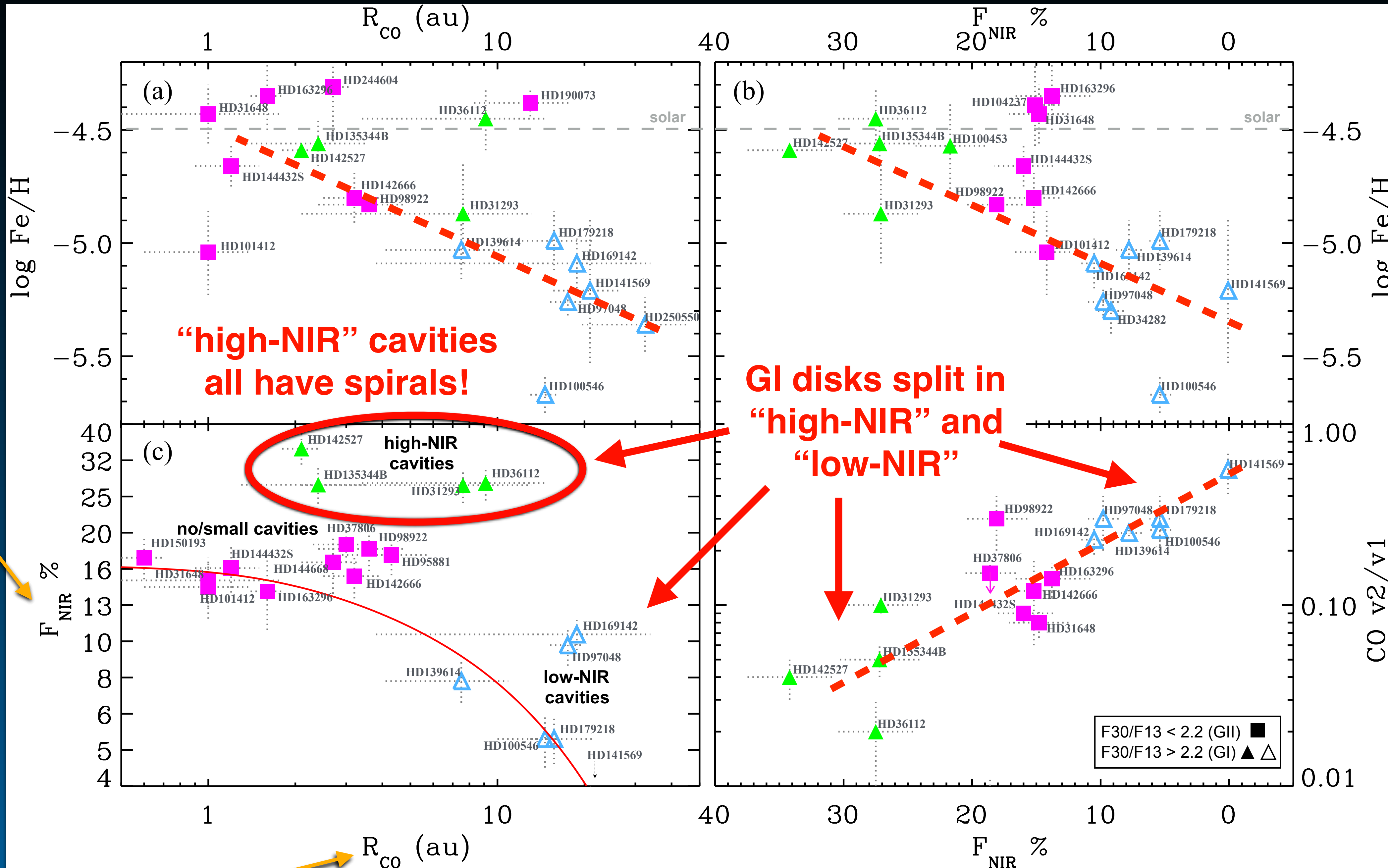


The powerful synergy of gas and dust tracers

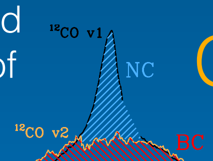
high-res optical spectroscopy of stellar photosphere (Folsom+ 2012, Kama+ 2015)

DUST

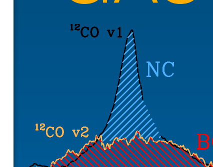
optical-to-IR photometry



GAS

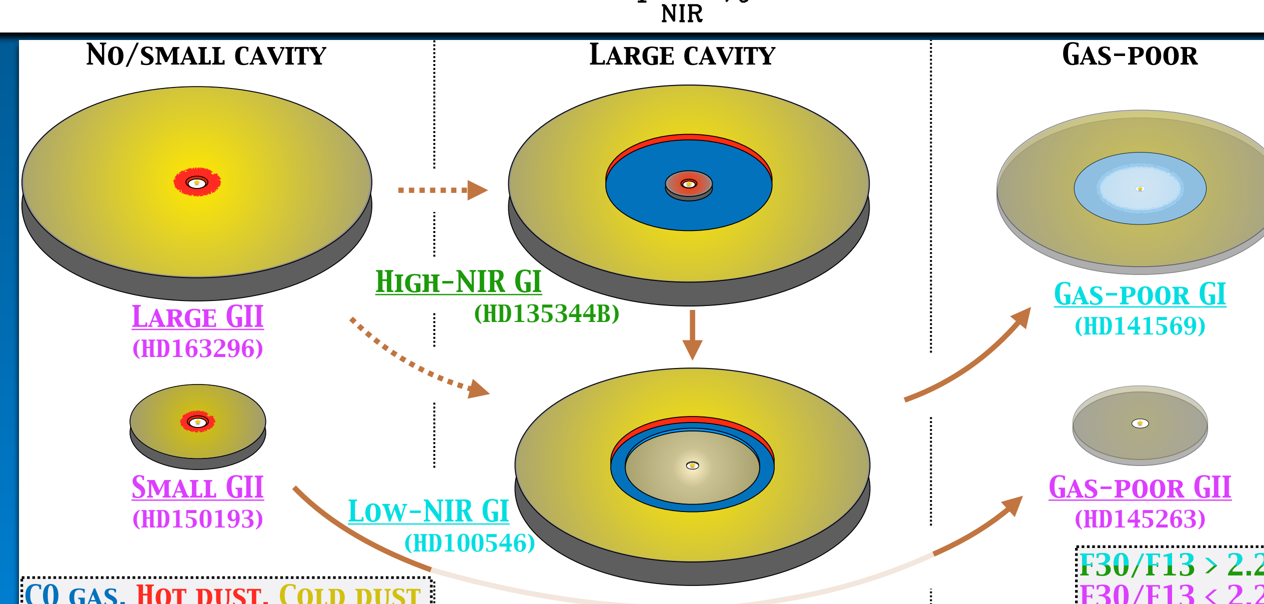


high-res infrared spectroscopy of disk molecular emission



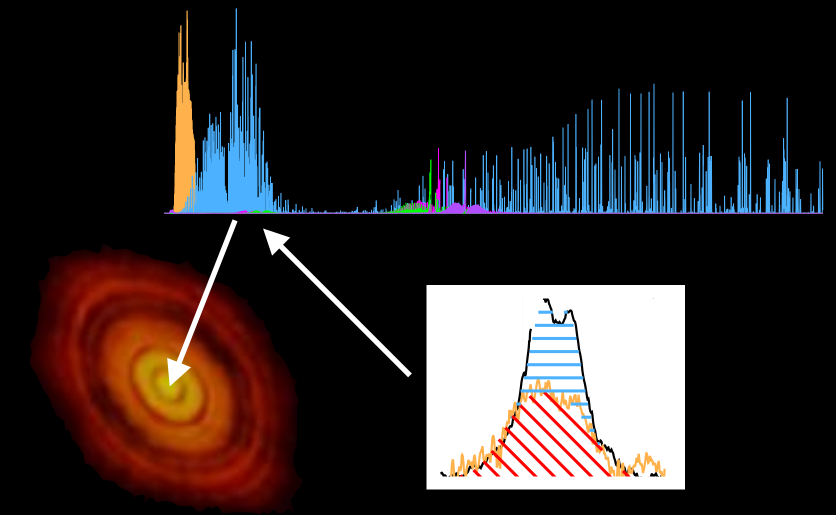
GAS

(Banzatti, Garufi, Kama et al. 2018)



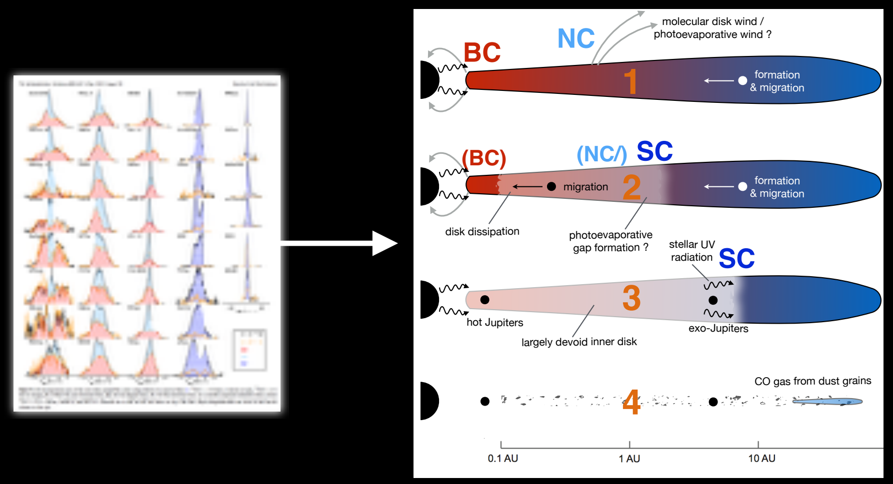
The evolution and depletion of gas & dust are tightly connected in inner disks

Summary



Molecular spectroscopy at infrared wavelengths provides a unique probe of protoplanetary disks at ~0.05 - 10 au, complementary to imaging (limited to > ~5 au @ 140 pc)

By combining high spectral resolution (R = 25,000 -100,000), multiple molecules (CO, H_2O, OH), large samples (50-100 disks), and multiple disk tracers (gas, dust, winds), we are working our way towards obtaining a global view of the evolution of inner planet-forming disks.



An escalation of discoveries in recent years:

1) CO kinematics and excitation reveal the formation and evolution of inner disk cavities
2) as inner disks evolve, H_2O is depleted in the terrestrial planet zone
3) dust and molecular gas are depleted simultaneously, by planet-formation processes or disk winds (?)
4) next: links between complementary techniques, to link evolving inner disks and exoplanet populations…..