Revealing the evolution of exoplanet-forming disks at 0.01-10 au
IR spectroscopy to study inner disks

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

**Molecules**: CO, H$_2$O, OH, HCN, C$_2$H$_2$, CO$_2$ (mostly, plus some other species)

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

**Science**: structure, chemistry, evolution of planet-forming regions at < 10 au
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)
I use:  
- infrared spectra  
- optical spectra  
- ultraviolet spectra  
- radio images  

to unveil how disks evolve and exoplanet are formed.

Observing  
Gas & Dust evolution at 0.01-10 au in protoplanetary disks

A synergetic, high-spectral-resolution, panchromatic approach to study the evolution of inner disks.

**Optical spectroscopy:**
Outflows, winds, and disk dispersal
(e.g. Hartigan et al. 1995, Simon et al. 2016, Banzatti et al. in prep.)

Ilaria Pascucci (University of Arizona)  
Suzan Edwards (Smith College)  
Uma Gorti (NASA Ames, SETI Institute)  
Min Fang (University of Arizona)  
Lile Wang (Princeton)

**Infrared spectroscopy:**
Molecular gas composition & thermo-chemical evolution

Klaus Pontoppidan (Space Telescope Science Institute)  
Ewine van Dishoeck & Arthur Bosman, Simon Bruderer (Leiden, MPE)  
Geoff Blake (Caltech)  
Colette Salyk (Vassar)  
Mihkel Kama (Cambridge)  
Antonio Garufi (Madrid)  
Inga Kamp (Groningen)  
Stefano Antonellini (Belfast)  
Sean Brittain (Clemson)  
John Rayner (Hawaii)  
Christian Rab (Groningen)  
+ the VISIR2.0 “PP Disks as chemical factories” team

**UV spectroscopy:**
Residual H$_2$ gas in transitional disks
(e.g. France et al. 2012, Hoadley et al. 2015, Banzatti et al. in prep.)

Kevin France (University of Colorado)  
Keri Hoadley (Caltech)  
James Owen (Imperial College London)  
Nicole Arulanantham (University of Colorado)

**Infrared & Optical**

Spitzer-IRS  
VLT-CRIRES  
Gemini-TEXES  
IRTF-ISHELL  
Keck-NIRSPEC  
Magellan-MIKE  
Keck-HIRES

**UV**

HST-COS
High-res. 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
- CRIRES on VLT (8-m)
- ~30 nights of data (currently the sharpest view of planet-forming inner disks)

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

- $^{12}$CO v1
- $^{12}$CO v2
- NC
- FWHM -> emitting radius
- RATIO -> vibrational temperature

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

The high-velocity gas is gone

NC

BC

SC

RATIO —> vibrational temperature
FWHM —> emitting radius

12CO v1

12CO v2

12CO v1

12CO v2

(Banzatti & Pontoppidan 2015)

Primordial (full) disks
Partly devoid gaps
Devoid inner gaps
Debris disks

Stellar masses:
○ = 1 M☉
○ = 2 M☉
○ = 3 M☉

(end of primordial gas)
(UV pumping regime)
(Beta Pic (upper lim.))
(SR21)
(HD141569)
(HD100546)
(SA0206462)
(HD135344B)

(Banzatti & Pontoppidan 2015)
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$_2$O, OH), to study the thermo-chemical structure and evolution

Measurements:
- CO/H$_2$O

Models:
- imprints planet core composition
- imprints planet atmosphere composition

(Banzatti et al. 2017)
The powerful synergy of gas and dust tracers

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

(Banzatti et al. 2018)
Connecting jets, winds, and disk dispersal

Data: Optical spectroscopy (Keck-HIRES, Magellan-MIKE)
Resolution: high (Δv ~ 7-9 km/s)
Sample size: > 50 disks, spanning evolutionary stages
Goals: resolve kinematics of different outflow components in [OI], link outflow and disk evolution, determine processes of inner disk depletion

(Banzatti et al. 2018, in prep; also Fang et al. 2018, in prep)