Tracing Cloud and Star Formation in the Milky Way and Nearby Galaxies with Heterodyne Spectroscopy

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CCAT-prime

Initial CCAT-prime science white paper (2017):
P. Schilke, D. Johnstone, R. Plume, E. Rosolowsky, R. Simon, F. Wyrowski

Astro2020 science white paper (astro-ph):
R. Simon, N. Schneider, F. Bigiel, et al.

Team members (preliminary):
UzK: work groups of J. Stutzki, P. Schilke, S. Walch
AIfA Bonn: work groups of F. Bertoldi, F. Bigiel
US/Canada: M. Fich, D. Johnstone, M. Nolta, T. Nikola, R. Plume, D. Riechers, E. Rosolowsky, G. Stacey, ...
Chile: A. Stutz, R. Herrera-Camus, U de Chile, Concepcion, Valparaiso, Diego Portales, ...
India: B. Mookerjea

Science theme

Galactic **Eco**logy (GEco, Bally, Schilke):
Study of the formation, growth, evolution, and dispersal of molecular clouds in the Milky Way, the Magellanic clouds, and other nearby galaxies through **submm spectroscopy** and photometry

This talk on behalf of

- A. Stutz, T. Nikola (co- session coordinators)
- Köln/Bonn/Cornell/Canada
- Participants of Chile meeting in 2019
- Others who already expressed their interest in prep. of this meeting and face-to-face splinter
- Others who will/should express their interest

Science questions

- How does the low density, diffuse ISM form molecular clouds, dense structures, and star forming cores?
- What are the roles of
  - Gravity and turbulence
  - Feedback
  - Converging flows, cloud-cloud collisions
    Supernovae, expanding HI shells
  - Shock compression at leading edges of spiral arms,
    the Galactic Bar for the CMZ
- How do the processes involved depend on environment?
- Synergy of observations **and** simulations is important

How do molecular clouds form and evolve?

- Mass flow onto galactic disks
- Clouds assemble from HI flows in the warm neutral medium
- Clouds are turbulent
  - Characteristics of turbulence
    - Observed line widths and shapes
    - complex structure seen in, e.g., dust continuum and line velocity channel maps
    - power law structure functions, fractal structure
    - Comparison to numerical simulations
  - Dissipation of turbulent energy → filaments
  - Fragmentation on smaller scales → cores and stars
    Feedback: Radiation, mechanical, SNe, …
- What drives supersonic turbulence?


Taurus/Herschel
(R. Hurt JPL-Caltech)

How do molecular clouds form and evolve? (continued)

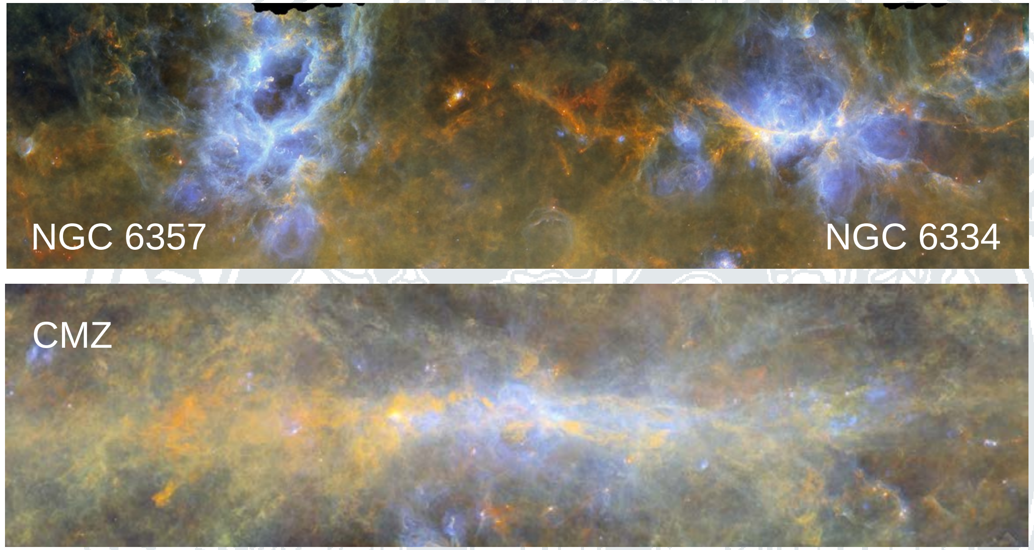
- Mass flow onto galactic disks
- Clouds assemble from HI flows in the warm neutral medium
- Clouds are turbulent
- What drives supersonic turbulence?
  - Magnetic fields,
  - Outflows,
  - HII regions,
  - Supernovae → may not be efficient enough
  - **Mass accretion:** no thorough investigation yet → CCAT-prime/GEco


Taurus/Herschel
(R. Hurt JPL-Caltech)

What kind of observations do we need?

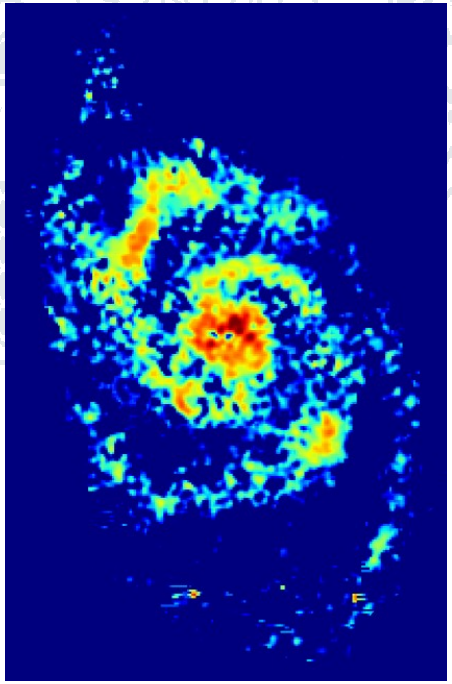
- Milky Way Galactic Plane and the Galactic Center
  - Large spatial (cloud) scales, high spatial resolution
  - Resolve structures within clouds (filaments, clumps, cores)
  - Resolve dynamics

  → Surveys in the continuum and spectral lines
- Nearby galaxies
  - Expand range of ISM conditions (metallicity, star formation rate)
    Calibration of CO, [CI], [CII] emissivities
  - Link between local universe and distant, high redshift galaxies
- Comparison with modelling/synthetic observations
  - MHD, chemistry, radiative transfer
  - Synthetic maps



Herschel/ESA HIGAL


Spitzer M51


SOFIA M51 [CII]

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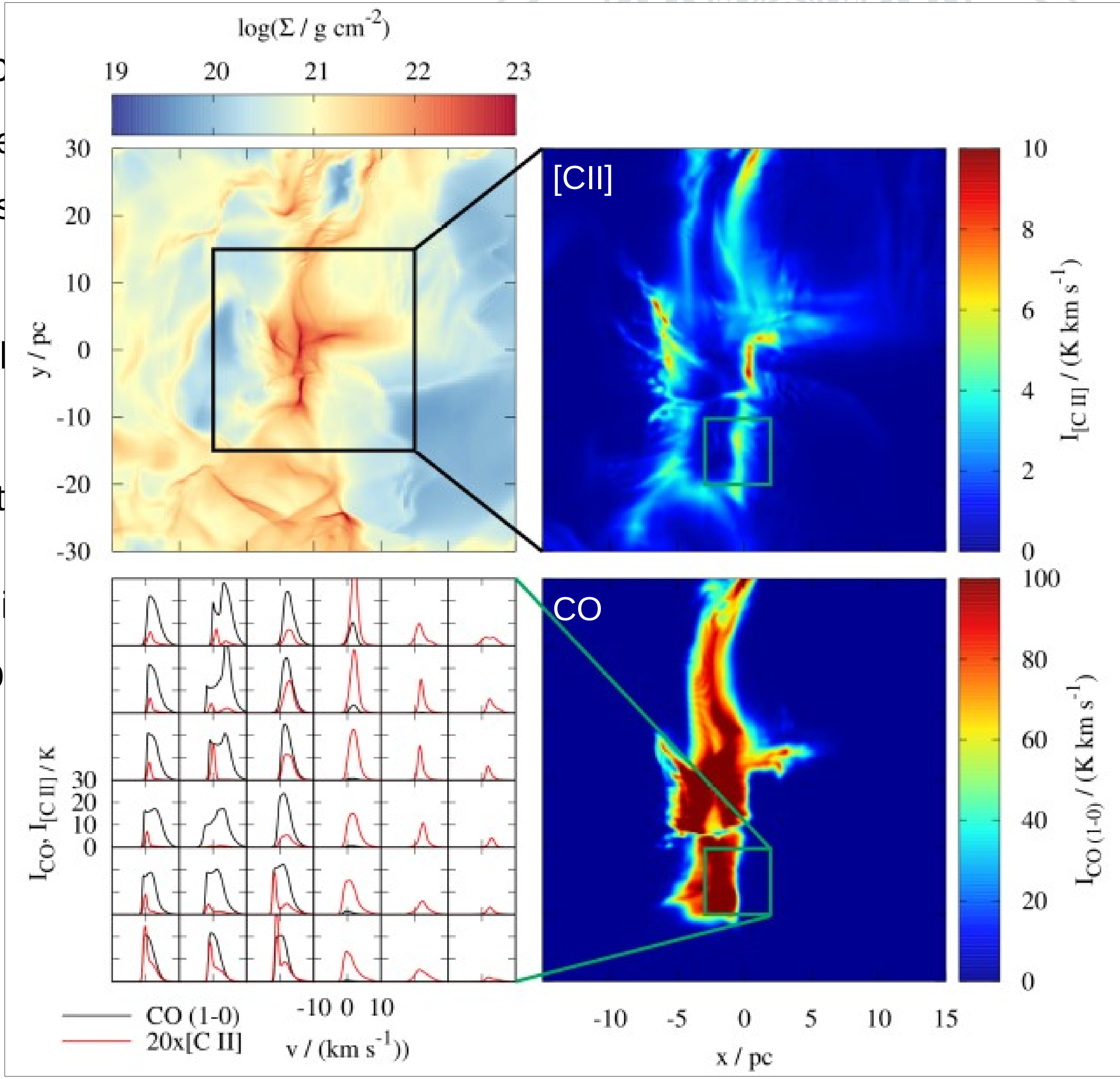
  - Synthetic maps:
    Example:
    continuum and spectra → SILCC-Zoom
    Seifried et al. 2017, Walch et al. 2015



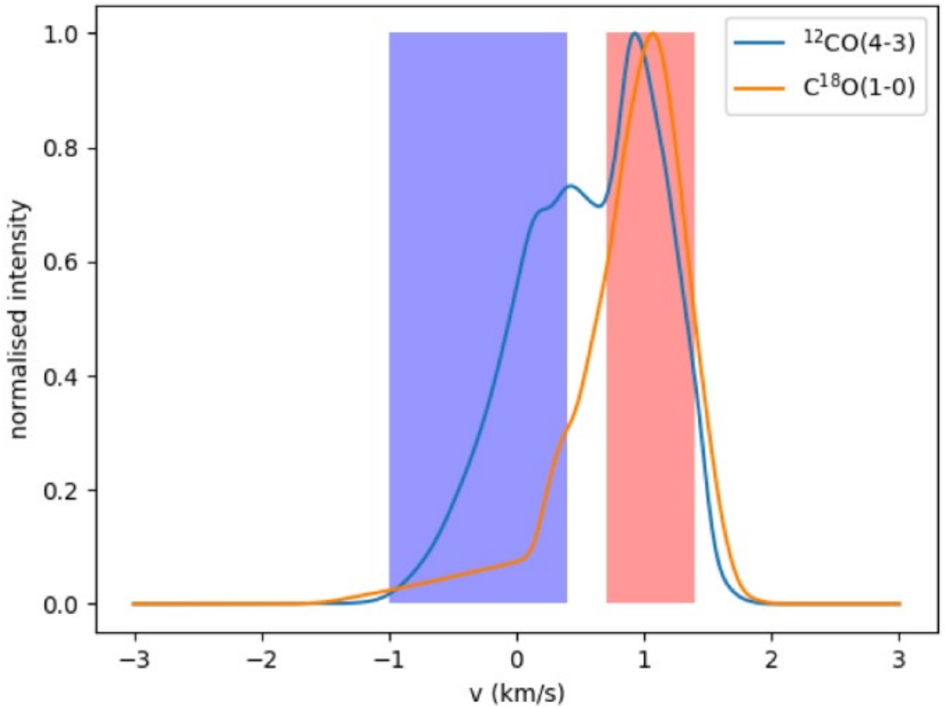
What kind of observations do we need?

- Mass accretion: Cloud formation
  - HI 21 cm:
    But: broad lines, line of sight confusion
  - Low-J CO lines: cold, moderately dense molecular gas (H_2)
    But: CO formation lags behind that of H_2 → "CO-dark" molecular gas
  - Cloud mass accretion of low density H_2 gas best traced by [CI] (Clark et al. 2019)
    → **Only low-J CO and [CI] together viable tracers of cloud mass (in formation)**
- Turbulence dissipation: Structure formation
  - Low-velocity shocks

    Mid-J CO lines are best tracers (J_{upper} = 4 – 7)

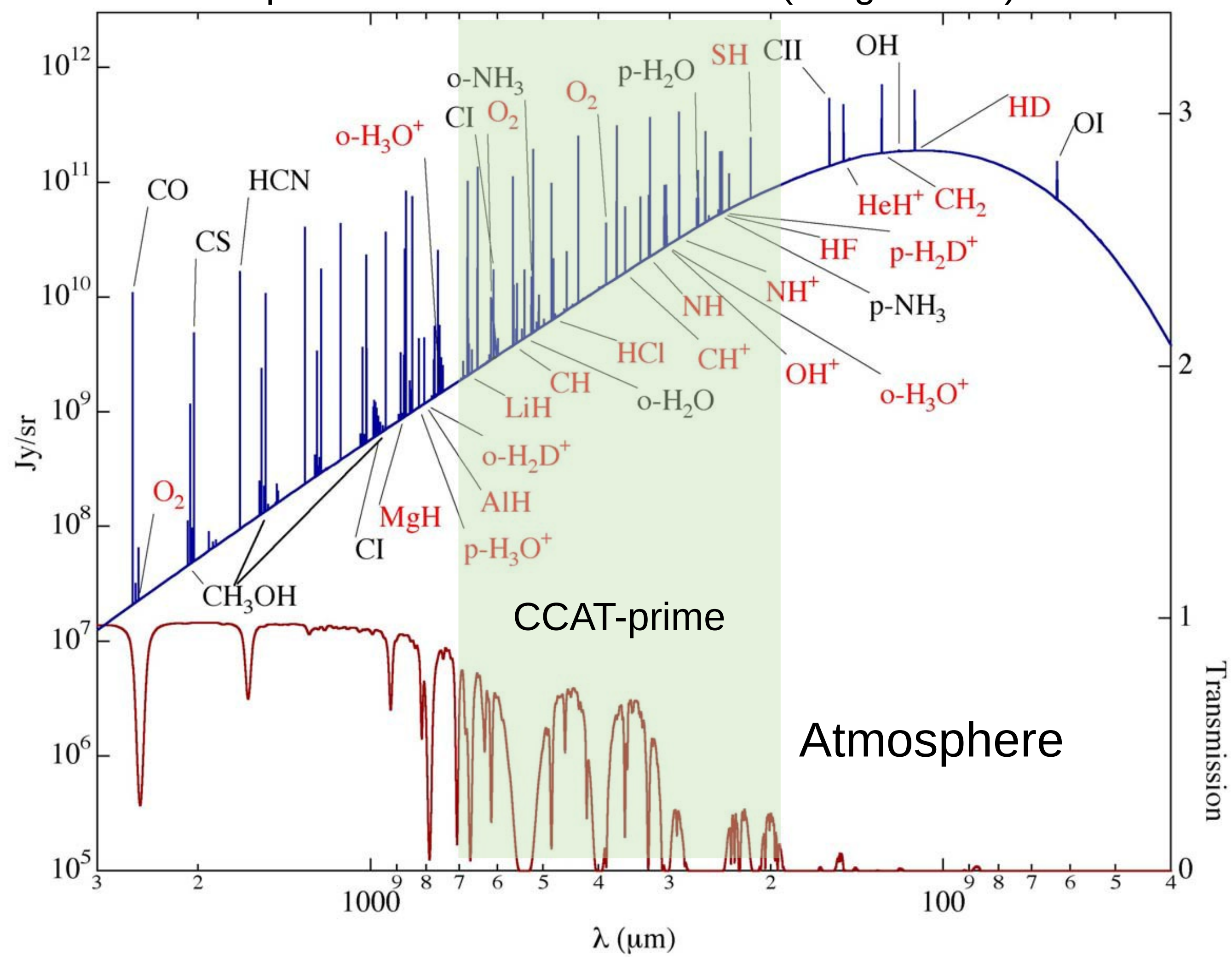
    Study of the Musca filament underway

Based on filament simulations by Clarke et al. 2018

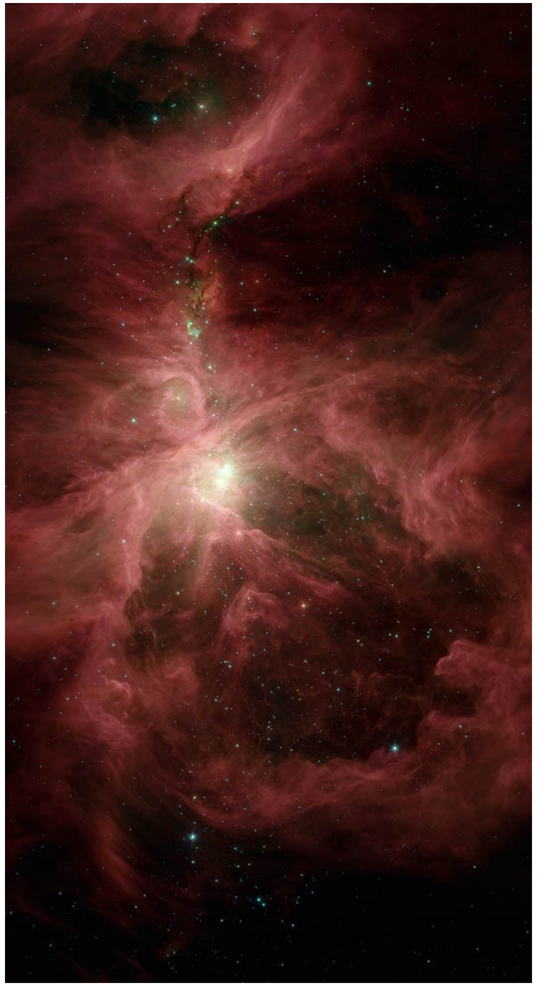


- Feedback
  - Heating
    - Radiation: HII regions, Photon Dominated Regions (PDR): photoelectric effect
    - Cosmic-/X-rays
    - Winds, outflows
    - Low- and high-velocity shocks
  - Cooling:
    predominantly in (sub)mm, far-, mid-IR
    - Dust continuum:
      Herschel, Spitzer, ATLASGAL, …
    - Spectral lines:
      - [CII] 158 µm, [OI] 63 µm: SOFIA
      - mid- to high-J CO:
        APEX, SOFIA, ASTE, NANTEN2

Spectrum of a molecular cloud (Bergin 2008)

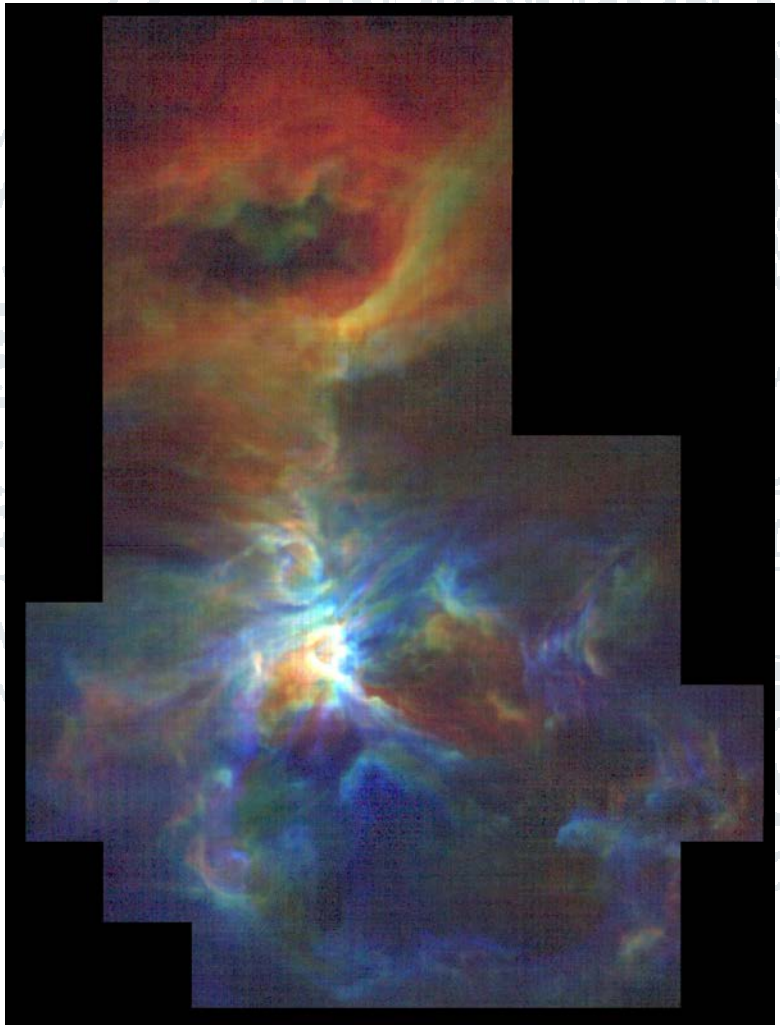


Example: Orion A → CCAT-prime comparable angular and spectral resolution



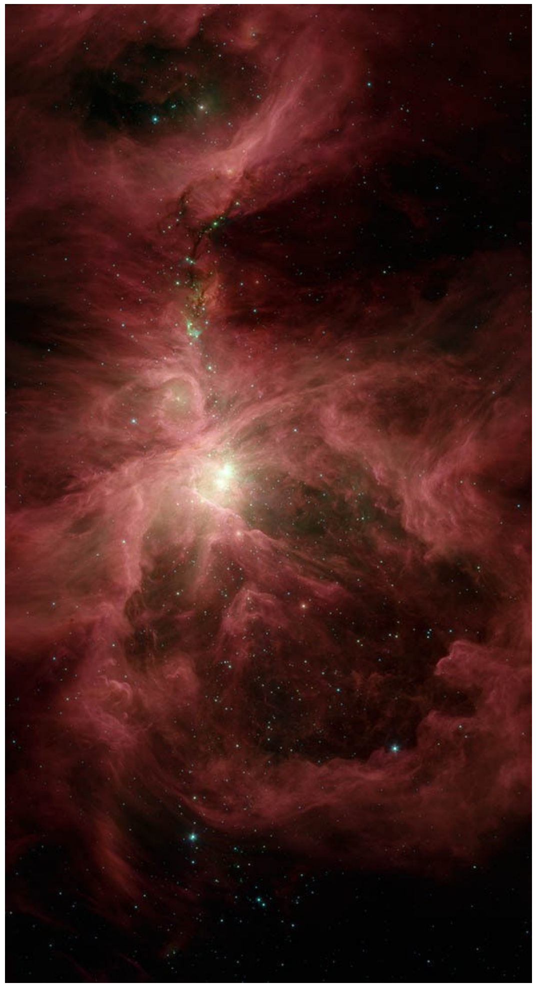
Spitzer mid-IR continuum
IRAC

Herschel far-IR continuum
SPIRE, PACS



[CII] 158 μm spectral line
SOFIA/upGREAT
(Pabst et al. 2019)

Example: Orion A → CCAT-prime comparable angular and spectral resolution



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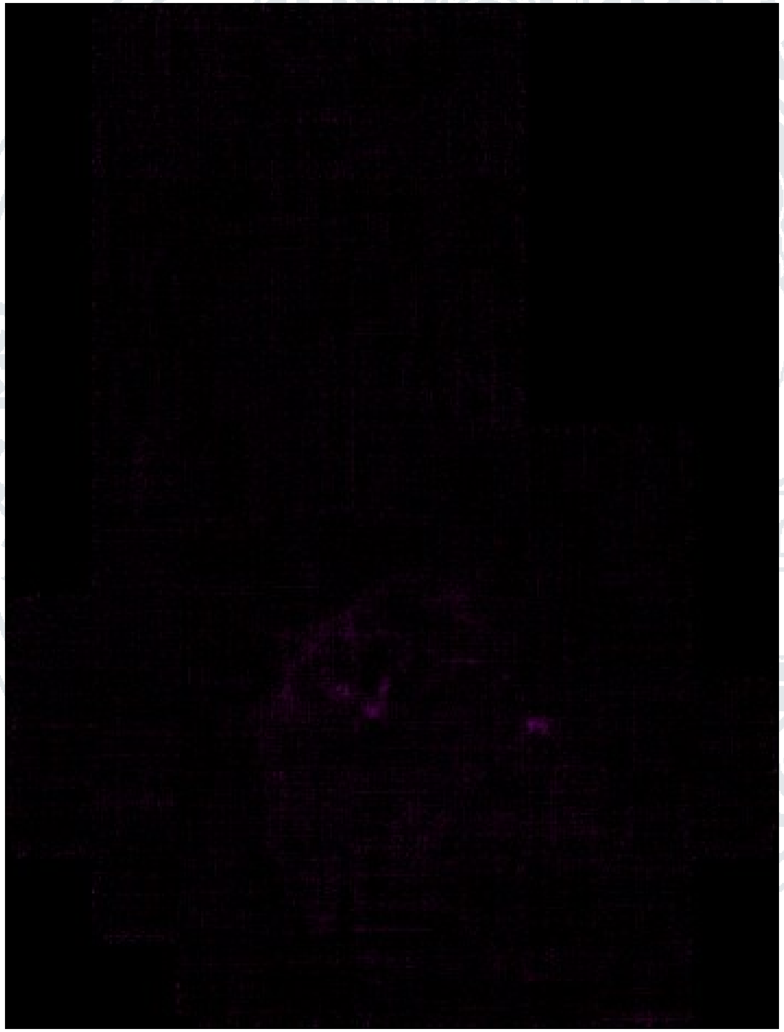


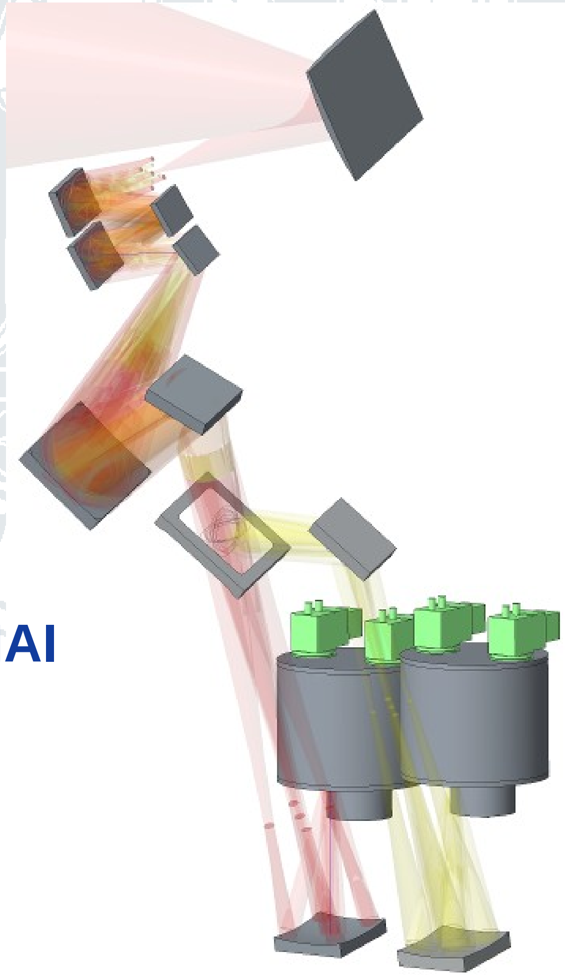
[CII] 158 µm spectral line
SOFIA/upGREAT, R. Higgins
(Pabst et al. 2019)

What kind of observations do we need? Summary

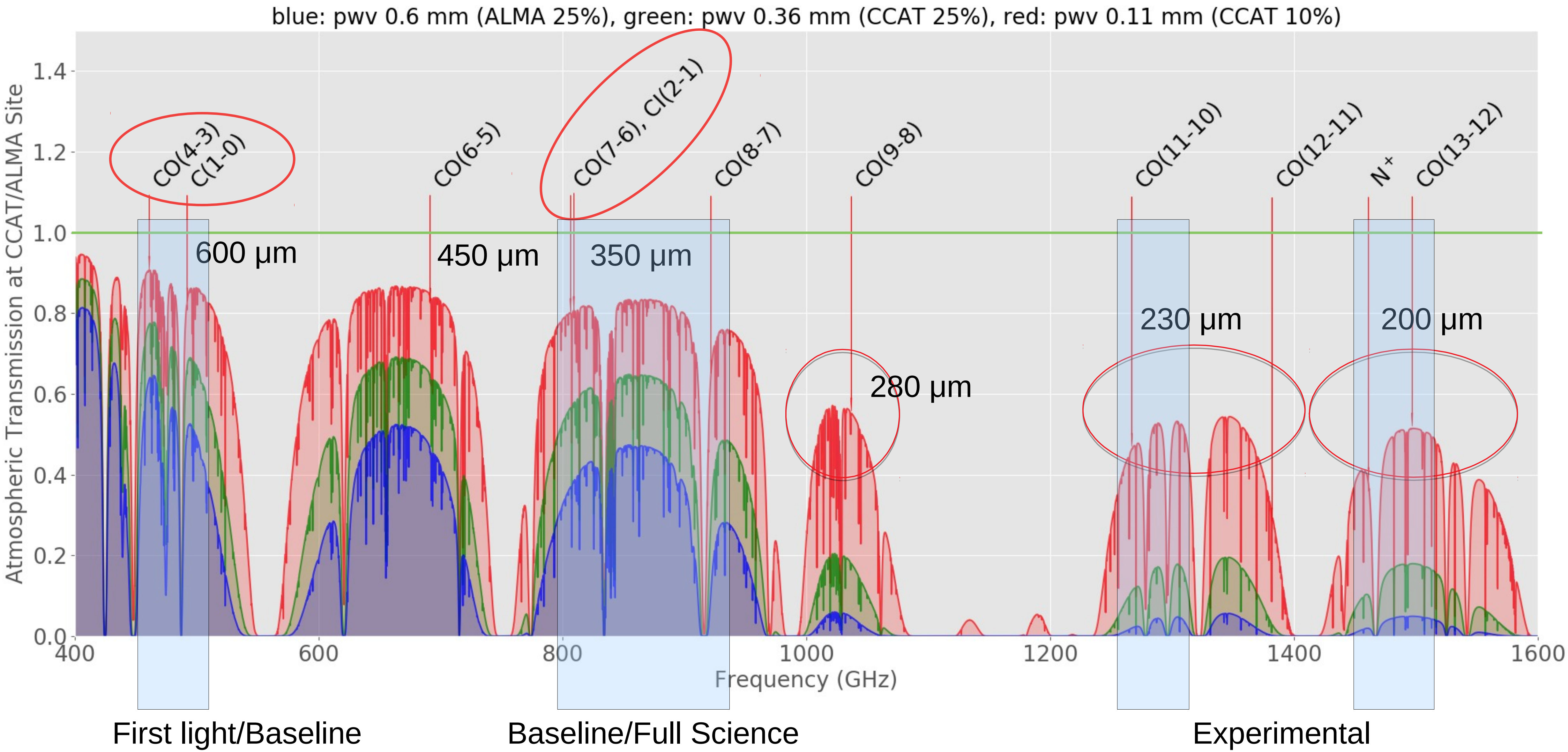
- Large scale, unbiased surveys
  - Cover whole clouds, from cloud edges to filaments and active star forming regions
  - Different environments
    physical conditions (temperature, pressure, radiation field),
    metallicity, cosmic rays, star formation rate, …
- Continuum observations
  - Herschel (HIGAL), Spitzer (GLIMPSE, MIPSGAL), APEX (ATLASGAL), WISE, …
- Spectral line observations
  - Low-J CO: Cold molecular gas, FCRAO, Mopra, Nobeyama, …
  - Atomic carbon lines:
    CO-dark molecular gas, PDRs: Missing
  - Mid-J CO lines:
    Filament formation, active gas (PDRs, shocks, outflows, winds): Missing

    Plus experimental high frequency heterodyne channels: CO high-J, N^+, ...

CHAI



Atmospheric conditions: Cerro Chajnantor opens up the submm and THz windows



CHAI windows

Galactic Ecology with CHAI, survey details

Survey	Line	Size (sq.deg)	rms (K)	Δv (km/s)	Beam ('')	Percentile/ pwv (mm)	Time (h)	Days (8 h)
Gal. Plane	CI(1-0)	200	0.25	0.5	26	50/0.6	1000	125
	CO(4-3)	200	0.25	0.5	26		400	50
LMC	[CI](1-0)	64	0.10	1	26	50/0.6	1000	125
	CO(4-3)	64	0.10	1	26		395	50
SMC	[CI](1-0)	20	0.10	1	26		310	40
	CO(4-3)	20	0.10	1	26		125	16
Gould Belt	CO(7-6)	30	0.25	0.25	16	25/0.28	480	60
	^{13}CO(8-7)	30	0.25	0.25	14		335	42
Zoom-ins	[CI](2-1)	50	0.25	0.5	16	25/0.28	362	45
Experim.	CO(11-10)	1	0.25	0.5	10	10/0.2	1200	150
	CO(13-12)	1	0.25	0.5	8		305	38
Nearby Gal.	**Line**	**Size (sq.arcmin)**	**rms (K)**	**Δv (km/s)**	**Beam ('')**	**pwv (mm)**	**Time (h)**	**Days (8 h)**
	[CI](1-0)	10	0.01	1	26	0.60	4.5	--
	CO(4-3)	10	0.03	1	26	0.60	1.7	--
	[CI](2-1)	10	0.006	1	16	0.28	17.5	--
	CO(7-6)	10	0.02	1	16	0.28	1.7	--

Other Galactic science topics

- Protostellar variability → Talk by Doug Johnstone “Time Domain Astrophysics“
- Compact THz sources (~10% of the total time, experimental)
  - In competition with SOFIA
    - Angular resolution factor ~2.4 better for CCAT-prime
    - Point source sensitivity better for CCAT-prime below a certain system temperature
      This happens for pwv < 0.4 mm (25% of the time)
    - Absorption towards continuum point sources (H_2D^+, …)
    - Compact emission of highly excited lines (high-J CO)

Preparations for CCAT-prime/CHAI surveys

- Synergy with other obervational programs
  - Continuum: Herschel, Spitzer
  - Spectral lines: FCRAO, IRAM, Nobeyama, Mopra, JCMT, APEX, SOFIA, ...
    - Collaborative Research Center 956: Conditions and Impact of Star Formation (U Köln/Bonn, MPIfR)
    - DFG/ANR program GENESIS (S. Bontemps, R. Simon, N. Schneider)
Cloud formation: Musca filament
    - SOFIA legacy program FEEDBACK ([CII] and [OI], A. Tielens, N. Schneider, R. Simon)
- Modelling
  - MHD simulations, synthetic observations
  - PDR modelling in feedback regions

Preparations for CCAT-prime/CHAI surveys

- Planning of observations
  - Selection of survey regions (Milky Way and nearby galaxies)
  - Constraints: Science, visibility, weather (water vapor), ...
  - Scheduling
- Data handling
  - Cologne/Bonn heritage (KOSMA, NANTEN, Herschel/HIFI, APEX, SOFIA)
    - Heterodyne receivers and observing software
    - Data reduction and analysis
  - Data observing software and pipeline development (KOSMA/NANTEN/Herschel/APEX/SOFIA heritage)
  - CCAT-prime software group, bi-weekly zoom meetings
    - Data rates
    - Storage capacity (on site, transfer off the mountain, home institutes)
  - Data centers in Canada and at UzK
    - Storage and servers for pipelining and data access

Preparations for CCAT-prime/CHAI surveys: GEco community (so far...)

Involves Chilean community

Universität zu Köln
Thomas Bisbas, Christof Buchbender,
Ronan Higgins, Yoko Okada,
Volker Ossenkopf, Markus Röllig,
Alvaro Sanchez-Monge, Peter Schilke,
Nicola Schneider, Daniel Seifried,
Robert Simon, Jürgen Stutzki, Steffi Walch

India: Bhaswati Mookerjea

AIfA/MPIfR Bonn
Frank Bertoldi, Frank Bigiel,
Reinhold Schaaf, Friedrich Wyrowski, ...

Cornell/Canada
Mike Fich, Doug Johnstone, Thomas Nikola,
Mike Nolta, Rene Plume, Dominik Riechers,
Erik Rosolowsky, Gordon Stacey, ...

Chile
Manuel Aravena, Stefano Bovino,
Leonardo Bronfman, Guido Garay,
Pablo Garcia, Rodrigo Herrera-Camus,
Liu Hongli, Eduardo Ibar, Paulina Lira,
Manuel Merello, Rodrigo Reeves,
Monica Rubio, Amelia Stutz, ...

Involve everybody in the detailed planning

- No face-to-face meeting yet...
- Biweekly Zoom meetings ramp up soon
- Identify targets and refine science
- First light
- Potential first papers
- Distribute work
- Proposal

Friday session!

Preparations for CCAT-prime/CHAI surveys

- First light science
  - “Poster Child“ targets: prominent molecular clouds (Orion, ...), Galactic Center, Magellanic clouds
  - Low frequency only, smaller receiver array
- Baseline and full science
  - Extend to large scale surveys
  - Full CHAI capability
    - Larger receiver arrays
    - High frequency zoom ins
- Data products
  - Calibrated data cube mosaics
  - Quality assessment
    Sophisticated reduction (atmospheric calibration, removal of instrumental effects: PCA)
  - Complementary data
  - Modelling related to the surveys

CCAt-prime on the summit of Cerro Chajnantor