Dark Molecular Gas:
And Other Synergies Between Dust and Gas Tracers

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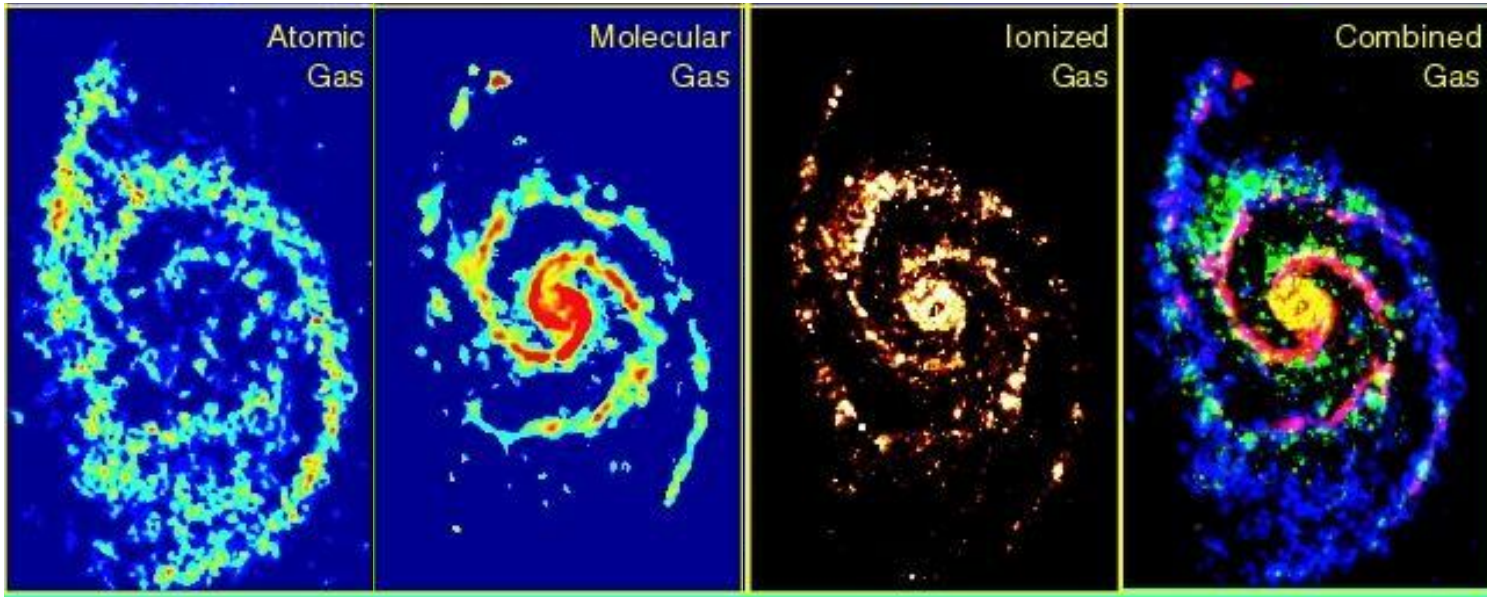
Outline

- Intro to Dark Molecular Gas
  - Inferred by 21-cm HI, CO & CMB dust
  - OH observations reveal CO-dark gas

- Brief reminder on Zeeman effect of Spectral Lines

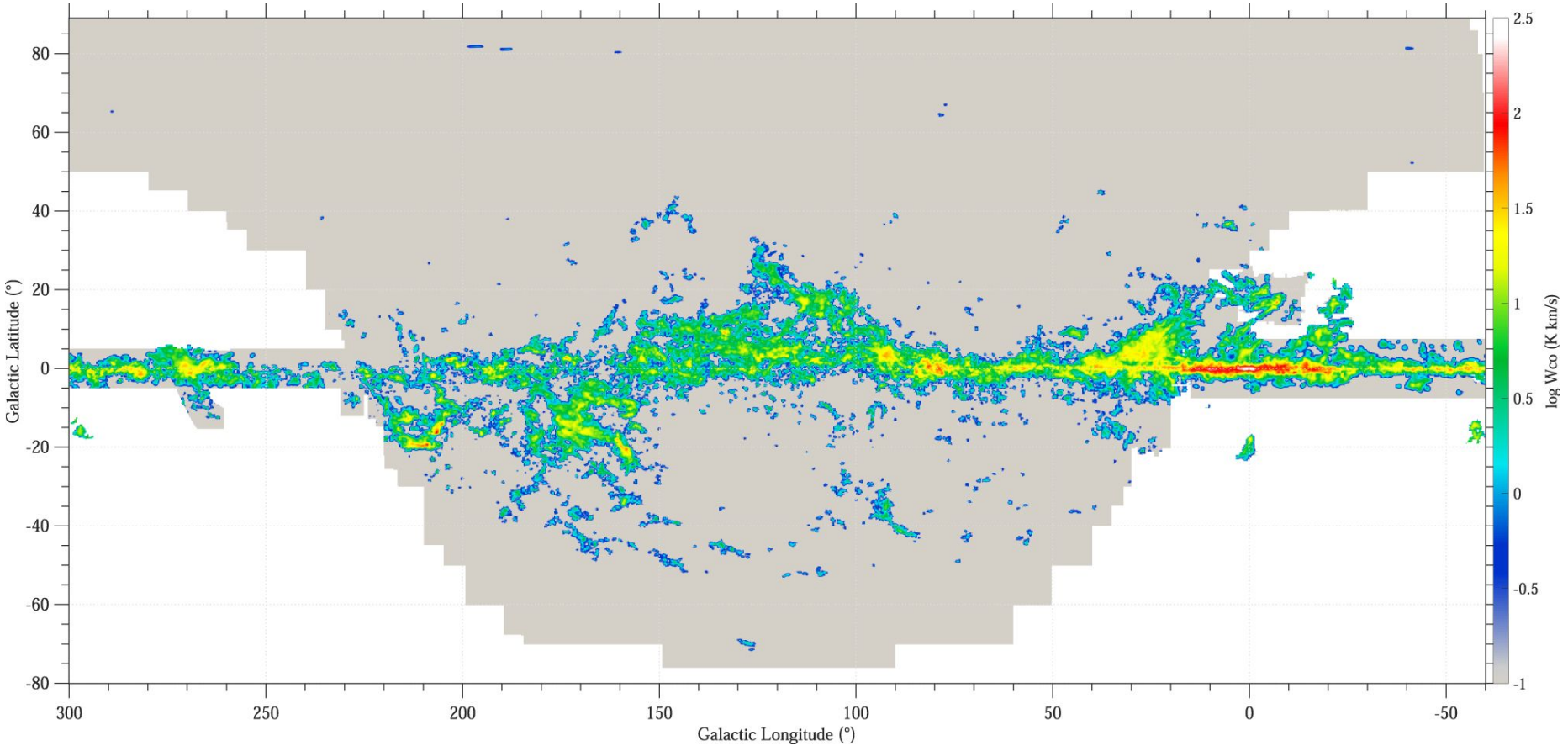
The Multi-Phase Interstellar Medium (ISM)



Atomic Gas is the reservoir for Molecular Gas. Traced by the HI 21cm Line → Molecules (H2, OH, CO, HCO+, HCN, etc) form from atoms… cool gas and regulates star formation → UV flux from hot, young stars ionize gas. → All components needed to understand galaxy formation and structure.

Figures from UMD Astro Webpage.

CO(J=1-0) as our workhorse tracer molecule for Molecular Gas (H2)



Dame 2022 – *A CO Survey of the Entire Northern Sky*

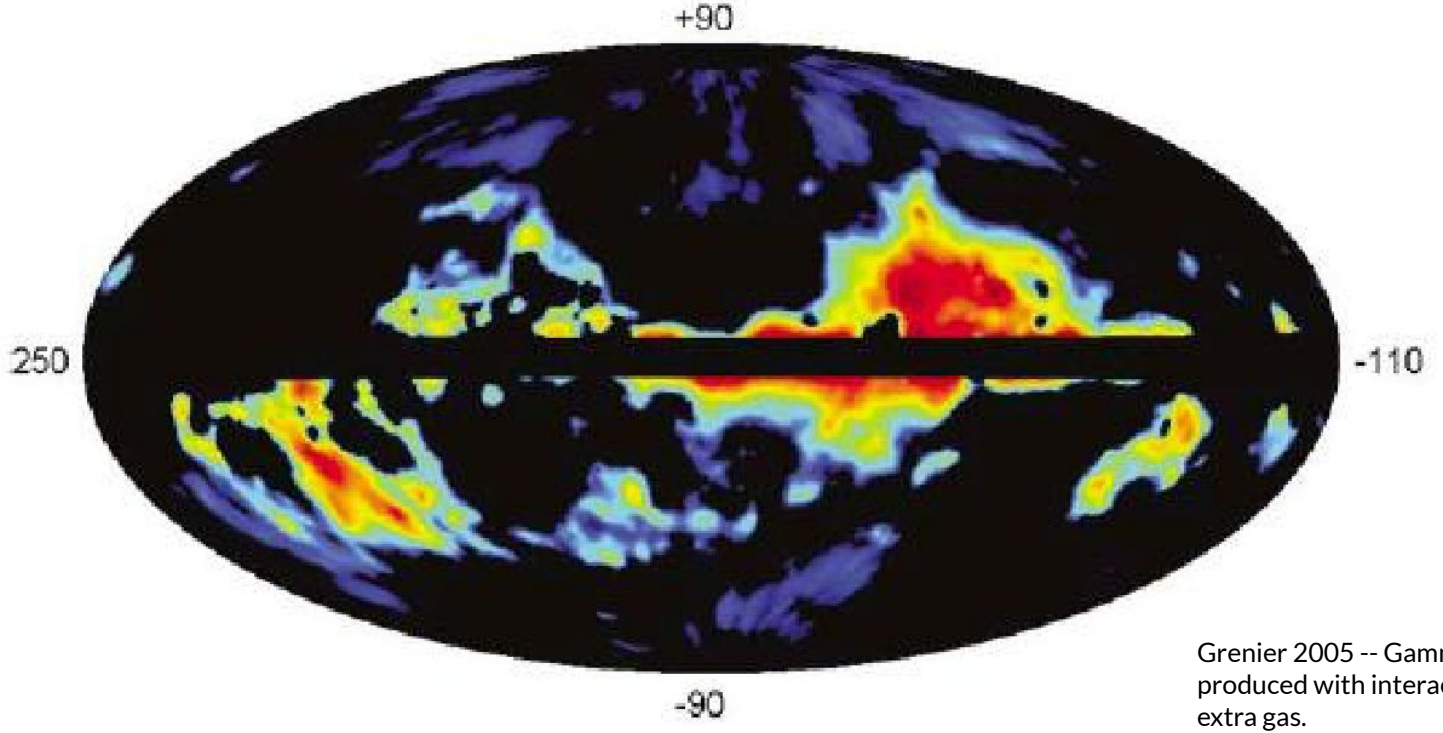
Why do we use CO(J=1-0)?

- Molecular Hydrogen (H2) is practically invisible in cold molecular clouds.
  - Need absorption measurements or fluorescence or hot gas.
- Almost singular reason – CO is *really* bright – so it's easy to observe!
- It's also abundant relative to H2 – stars make a lot of carbon and oxygen!

Limitations of CO as a bulk Molecular Gas Tracer

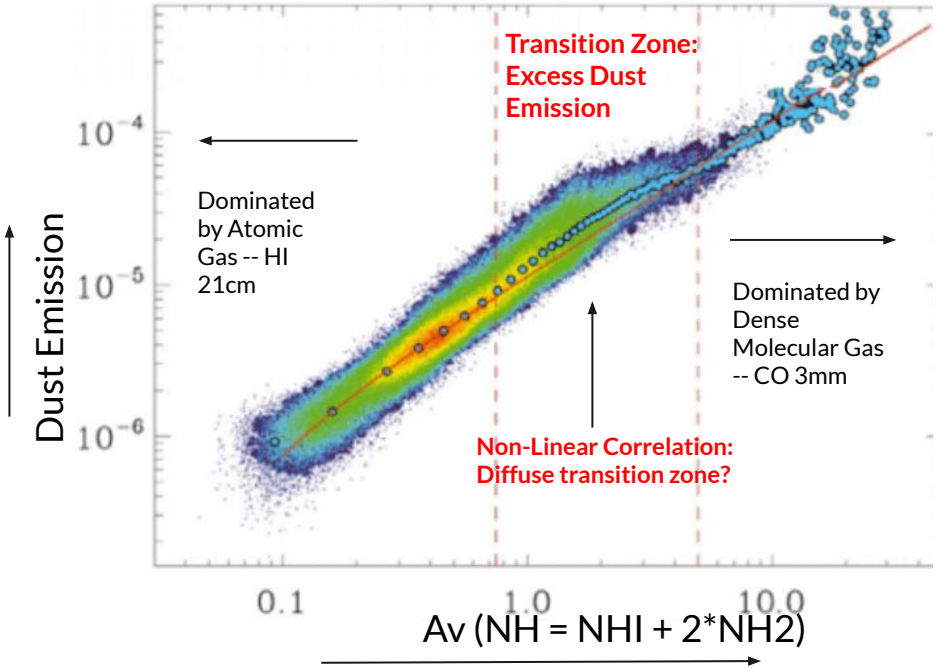
- Chemistry:
  - Efficient *formation* of CO (a *heavy* molecule) requires first formation of *lighter* molecules (e.g. where one component is H: OH, CH).
  - *Photodissociation* of CO happens rapidly without shielding in diffuse gas. (Av <1)
- Physics:
  - CO is not collisionally excited in diffuse gas (n < 500 cm^-3)
  - Spontaneous emission rate is large → bright but needs excitation to balance out.
- Observational:
  - The conversion between CO brightness and H2 ("X" factor) is highly uncertain, and varies with environment (e.g. metallicity).

The “Dark Gas” Observational Mystery

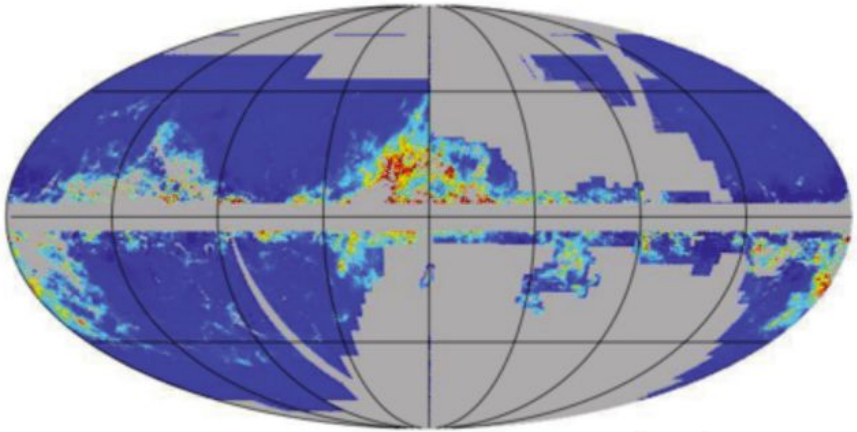


Grenier 2005 -- Gamma Rays produced with interactions with extra gas.

The “Dark Gas” Observational Mystery



IR Dust Emission -- dust correlates with gas.

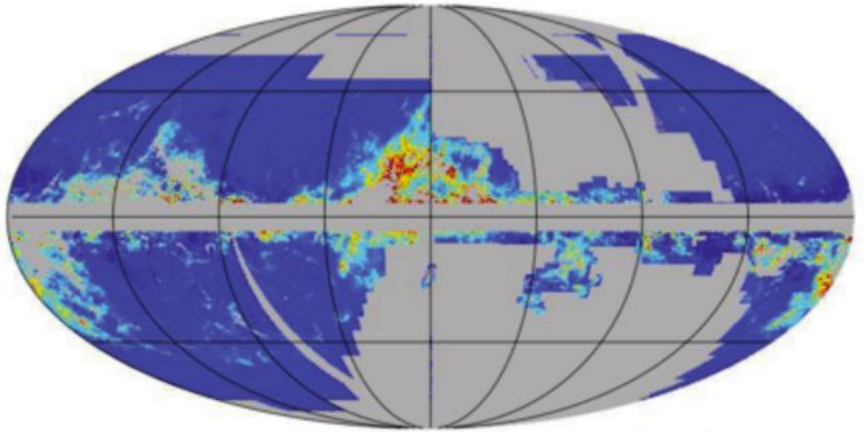


Planck Collaboration et al. (2011), 536, A19

Open Questions on Dark Gas

- What is it? *(Mostly solved? H2!)*
  - Is it Saturated Atomic Hydrogen, or Molecular Hydrogen?
  - Murray et al 2018 (and others), high resolution HI data showed it's **primarily not atomic**.
  - The rest must be **molecular**.
- How much? (*Depends on who you ask…)*
  - Wrong baryonic mass estimate of galaxy?
  - C+ says 30%, Gamma Rays say 100-200%, more H2.
- Where? (Work in progress!)
  - Very large volume.
  - Phase distribution very uncertain, Gamma rays and dust lack radial velocity measurements (need a spectral line!).
- What is the physical environment? (Diffuse, hot?)
  - How does it influence star formation rate/history in the regions without CO?

Excess IR Dust Emission -- dust correlates with gas.

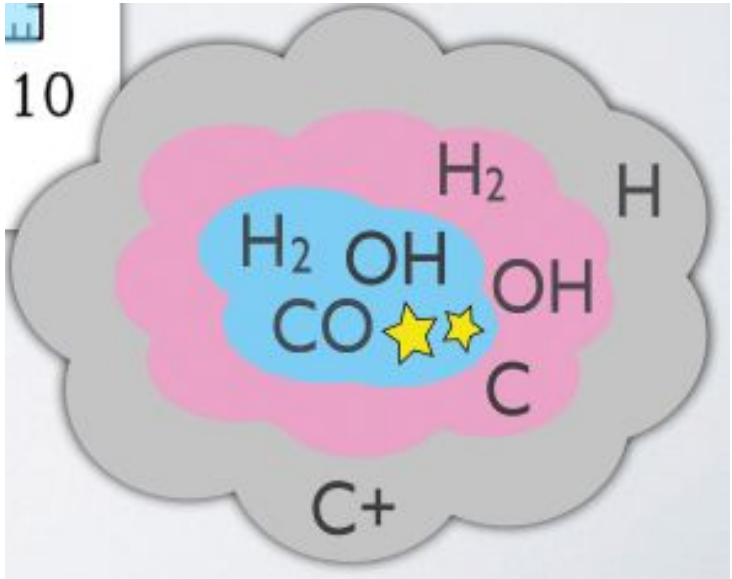


Planck Collaboration et al. (2011), 536, A19

Blind 18cm OH Surveys with the Green Bank Telescope (2015-)

The ‘Onion’ Model and ‘PDR’ Schematic:

Cartoon courtesy of Jo Dawson



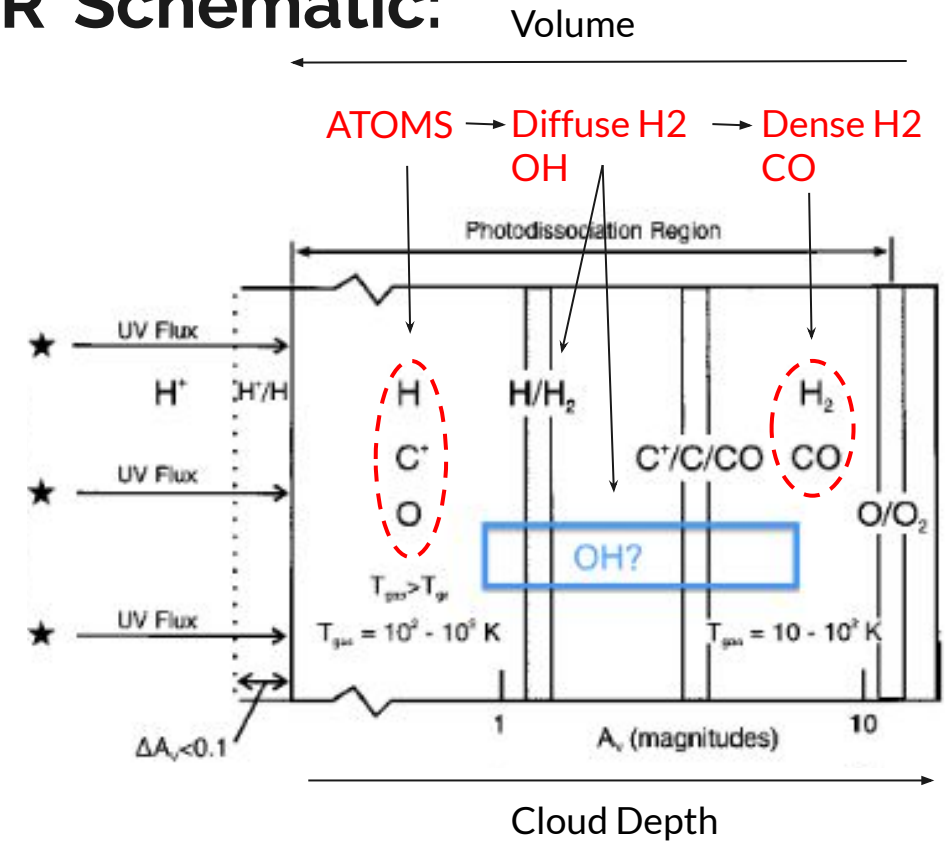
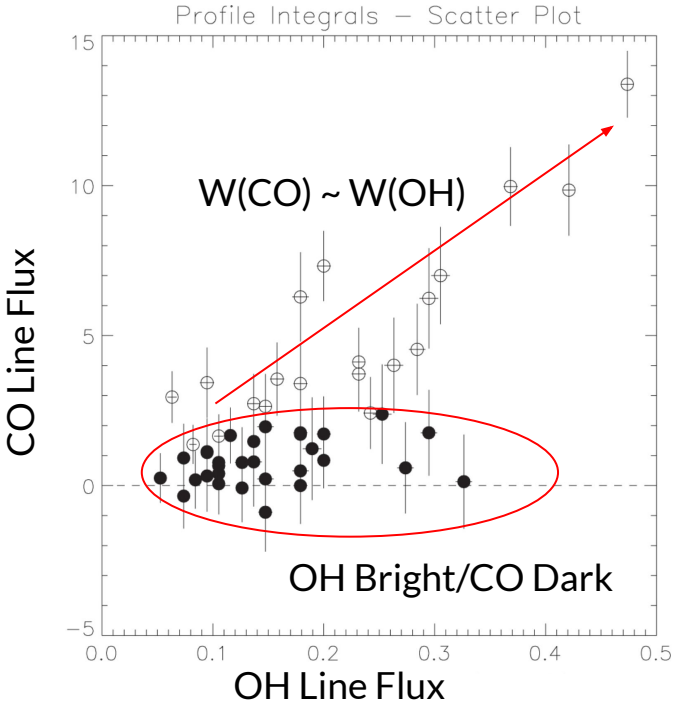
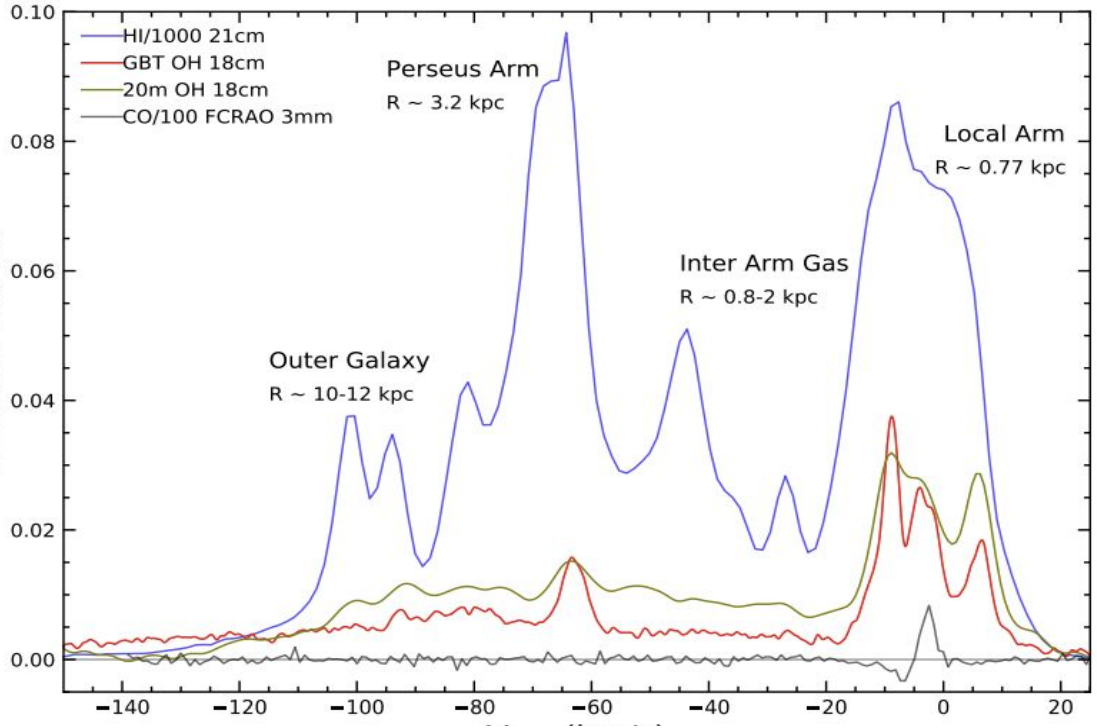


Figure Adapted from Li 2015, who adapted it from Tielens 2005.

OH has shown abundant “CO-Dark” Molecular Gas

Allen et al. 2015





Busch et al. 2021

Test Case: The Chamaeleon Molecular Cloud

- Giant molecular clouds, local molecular clouds and high latitude molecular clouds are all great targets for CMBS4!

- Why? Primarily:
  - High angular resolution (<1')
  - Wide FOV and deep sensitivity.
  - CMB signal is faint

- Many complementary datasets exist/will exist, primarily:
  - 21-cm HI (GASKAP, MeerKAT, GMRT, SKA)
  - CO (NANTEN, ALMA, IRAM 30m)
  - Gamma Rays (Fermi-LAT)

(0th Order)First, measure:

$$\tau_\nu = \frac{I_\nu}{B_\nu(T)} = \sigma_\nu N_{\rm H} = \kappa_0 \left(\frac{\nu}{\nu_0}\right)^\beta R_{\rm DG}\,\mu_{\rm H} N_{\rm H}$$

Dust Optical Depth ~ N(H)
(we could also use dust radiance or extinction)

And since:

$$N_{\rm H} = N_{\rm HI} + 2N_{\rm H_2}$$

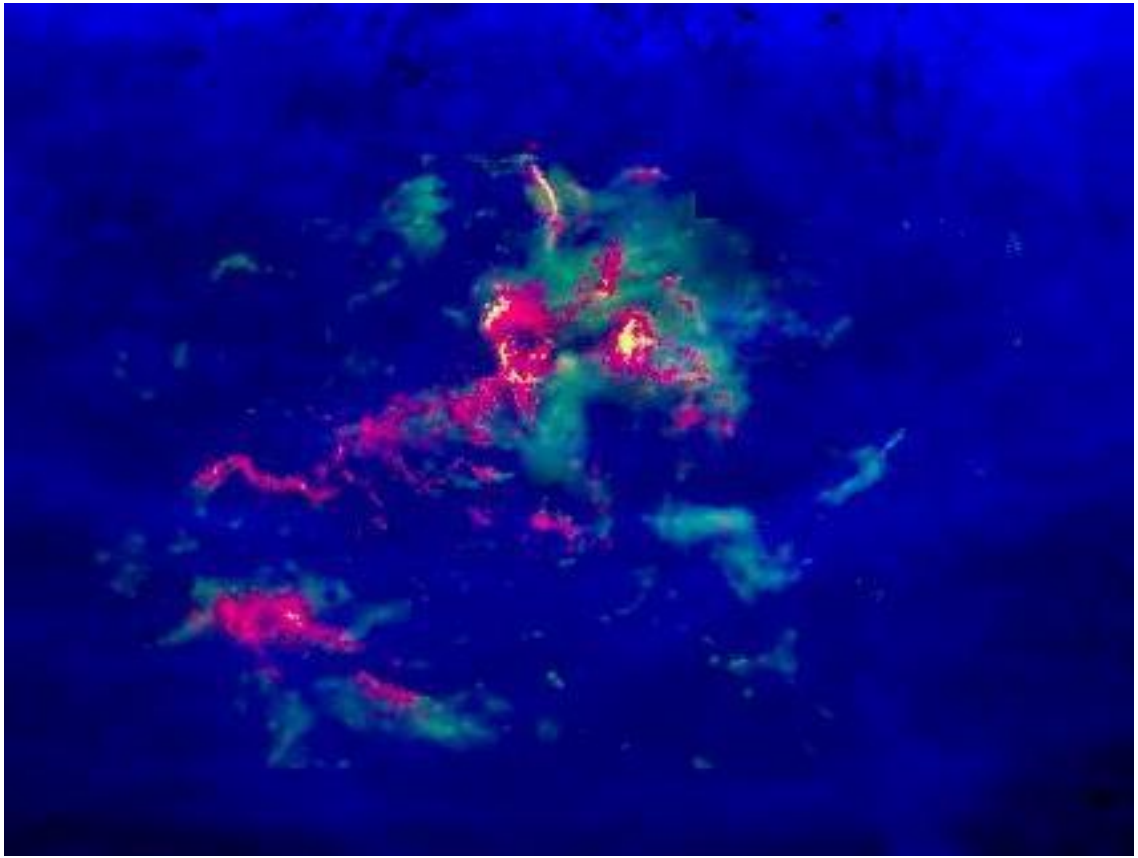
Use an HI map, then:

$$N_{\rm H_2} = (N_{\rm H} - N_{\rm HI})/2$$

Planck Collaboration, Fermi Collaboration, Ade, P. A. R., Aghanim, N., Aniano, G., Arnaud, M., & Ashdown, M. 2015, A&A, 582, A31

Test Case: The Chamaeleon Molecular Cloud

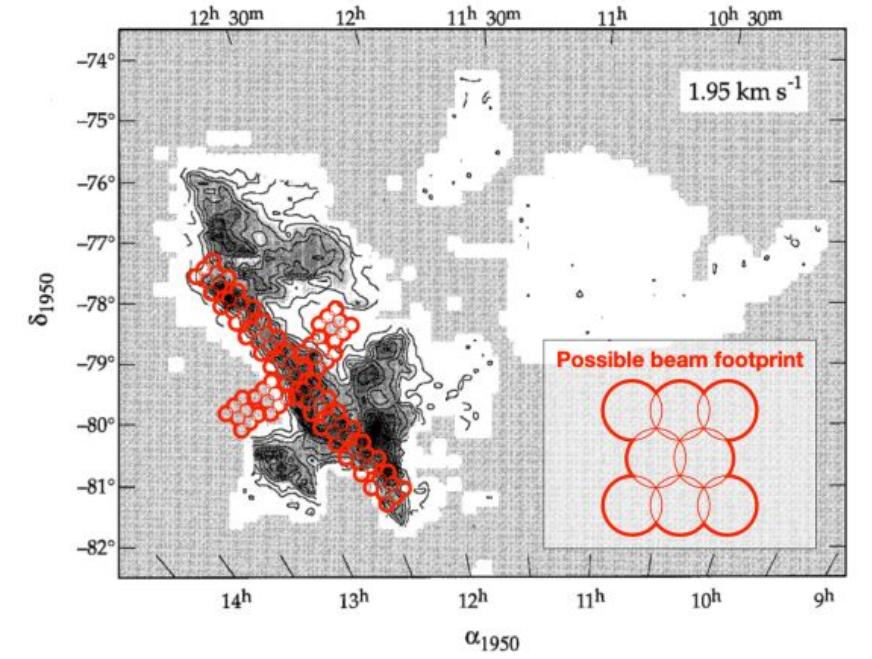
- Dark Gas mass ~ double CO-bright gas mass
- The Dark Gas is *primarily* H2.
- Many open questions:
  - Variation with?:
    - Dust temp
    - Grain size
    - CO “X” Factor
    - Chemistry?
    - “Clumpiness”
- What are the properties *globally*?



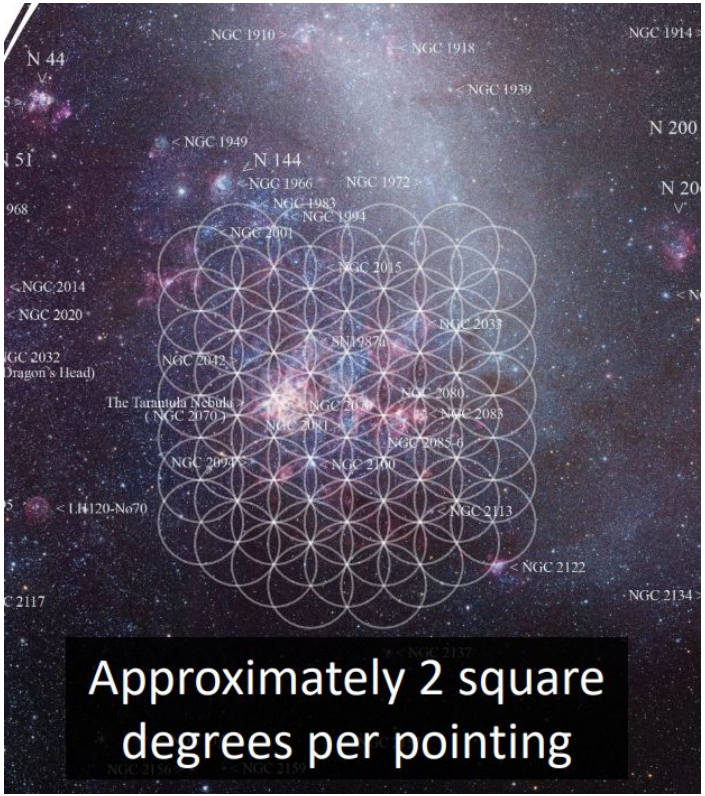
Blue (*HI*), Red (*CO*), Teal (*Dark Neutral Medium*)

Liszt, Gerin and Grenier A&A, 627, 5, 2019

Future Consideration: Phased Array Feeds will enable extensive sensitive OH mapping!



24 hour OH mapping proposal for one side of Cham. (with a single beam this would take > 200 hours!)



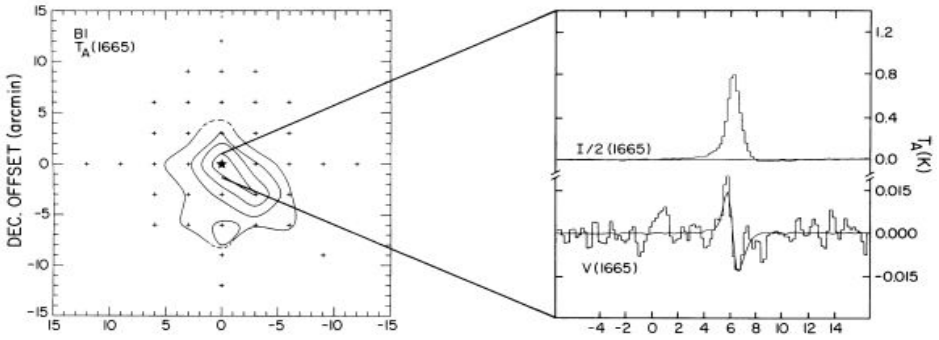
CryoPAF Science Presenation from Anita Petzler (CSIRO)

Briefly, Zeeman Splitting of Spectral Lines

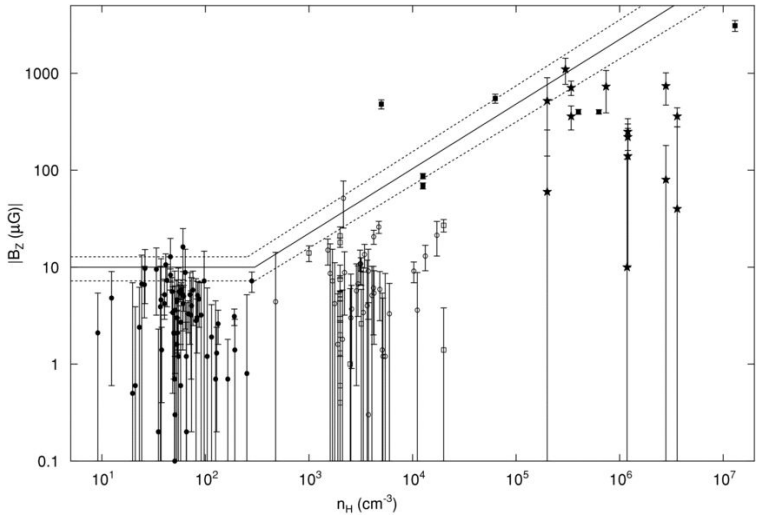
- Zeeman Splitting of a spectral line is a very reliable method to measure magnetic field strength.
  - In Line-of-Sight!
  - Not very many detections (HI, CH, OH)…
  - Incredibly difficult measurement.

- CMB Dust Data can obtain estimate of plane of sky B field (DCF method?) & B orientation data.

- 3D Magnetic Field strength information is *possible* in the future!



Goodman 1989



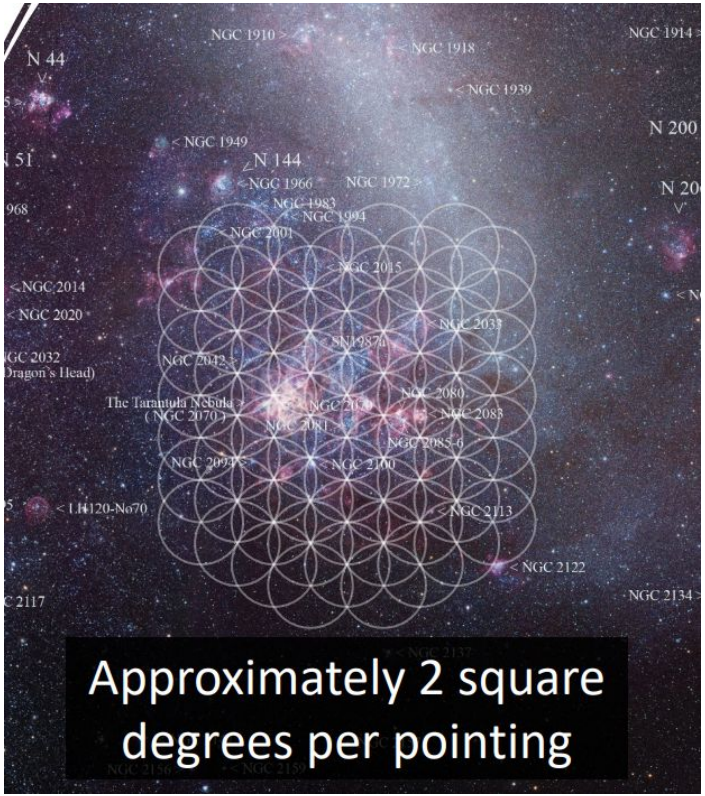
Crutcher 2010

Large-Scale OH Zeeman Splitting Survey?

- However, with new PAFs (>40 beams) (on both GBT and Parkes):
  - And a lot of work to characterize the beam squint, polarization leakage, beam response…
  - Hundreds of hours of integration time…

- We can conduct a “shallow” (2 hour x pointing) survey for N(OH) in Molecular Clouds
  - Then conduct a “deep” (100 hours) survey for Zeeman splitting towards high N(OH) in many clouds.
  - Map of 3D magnetic field strength?!
  - →Science? (profit???)

- This timeline may actually align with the timeline of CMBS4…



CryoPAF Science Presenation from Anita Petzler (CSIRO)

Conclusions

- CMB Dust Data can trace total (atomic + molecular) Hydrogen column in our Galaxy.
  - ***This is super interesting and very useful!***
  - Many open problems in tracing ‘CO-Dark’ Molecular Gas, Chemistry and dust evolution.
  - CMB S4 dust data will be: 1) Higher resolution (<1’ from 10’) 2) More sensitive (tradeoff, lower freq–not in space)

- Planck + Fermi-LAT already did a test case study towards Chamaeleon.
  - We should this type of work more.
  - Esp. with an eye towards collecting many gas tracers from complementary telescopes (OH, CH, CO, HCO+, HI)
  - The ‘CO-Dark’ multiphase medium needs a lot of work!

- In ~5 years it *may* be possible to routinely map clouds in 18cm OH or 9cm CH with a PAF on a single-dish telescope, allowing for maps of LOS B field across clouds to be compared to Plane-of-Sky B field from CMB dust data.

Thanks!