The Atomic-to-Molecular Transition in the Milky Way & Beyond

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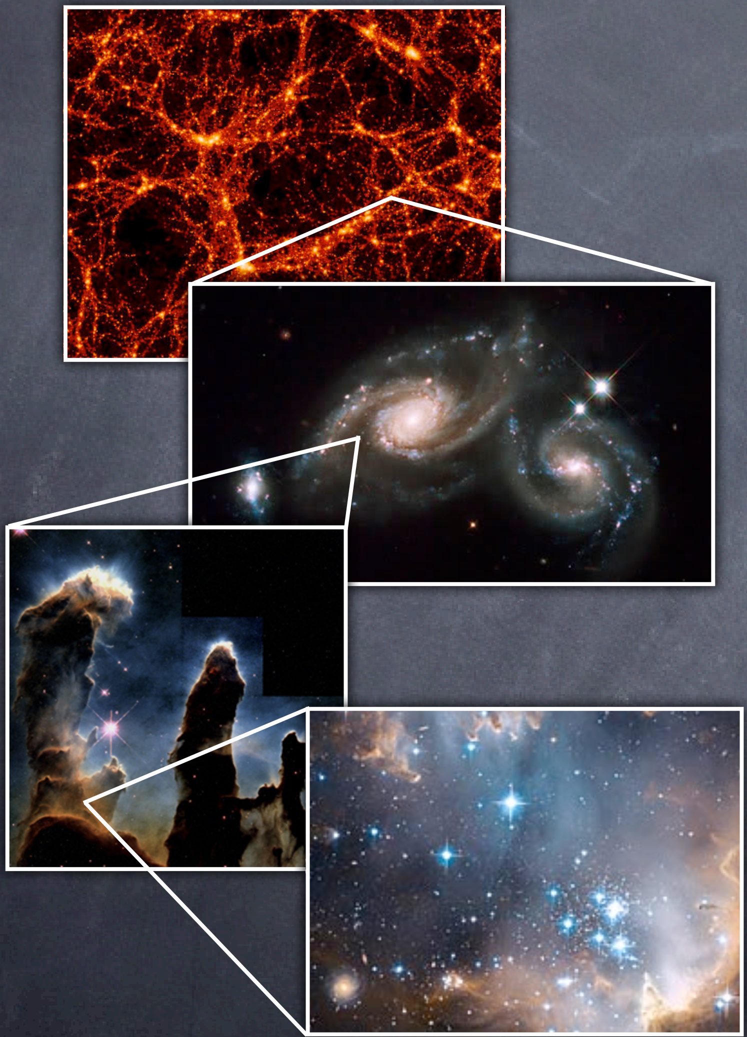
Outline

1. Background & Context
    - GASKAP: galaxy evolution from the local perspective
    - The atomic-molecular transition in galaxies
    - Supershells & molecular cloud formation
2. Supershells as Molecular Cloud Factories
    - Galactic supershells
    - Supergiant shells in the LMC
3. The SPLASH survey
    - OH as a tracer of transition-state gas
    - Project overview

"Galaxy Evolution Begins at Home"



- Big question in modern astrophysics: How do galaxies form and evolve?
- Much key physics takes place on small scales:
  - Complex & dynamic ISM
  - Star formation & feedback
  - Interaction between disks and halos
- Study this astrophysics in detail here at z=0.
- GASKAP to tackle this through HI and OH (18cm) observations of MW and Magellanic System.

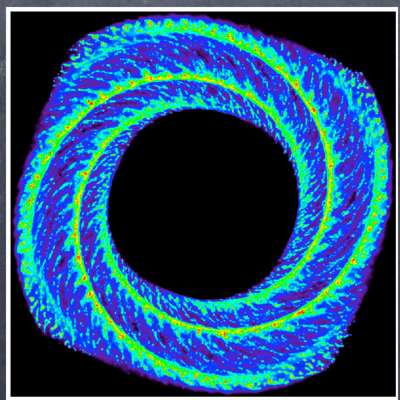
The Atomic-Molecular Transition

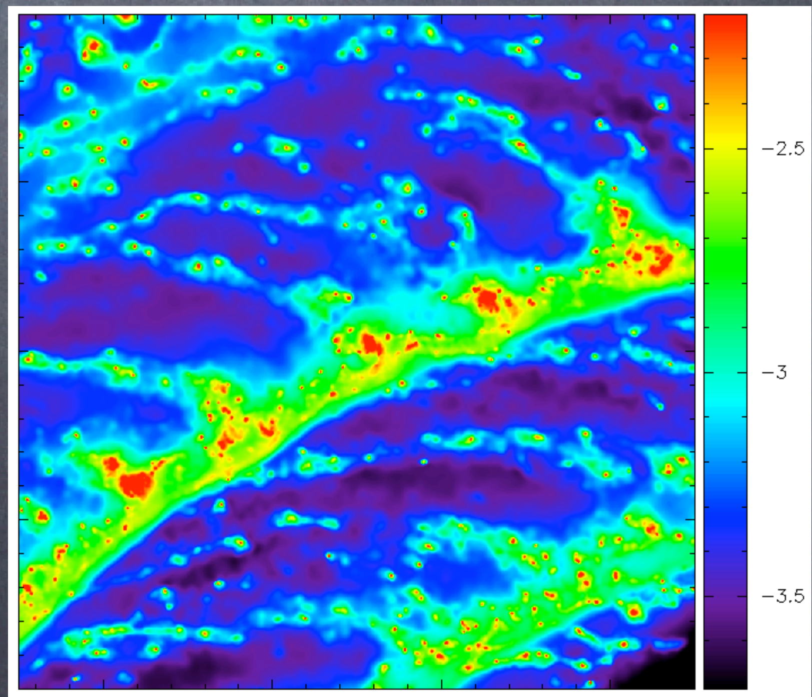
- Key GASKAP question: How do molecular clouds form out of the atomic medium?
  - Molecular clouds:
    - Coldest, densest phase of multi-phase ISM
    - Self-gravitating (or at least contain self-gravitating sub-structure)
    - The raw material for star formation
  - Questions:
    - How much of a galaxy can go molecular?
    - What environmental factors will drive it molecular?
    - On what timescales? Where?
    - How does this process proceed physically?

    ➡ Answers determine how star formation will proceed.

The Atomic-Molecular Transition

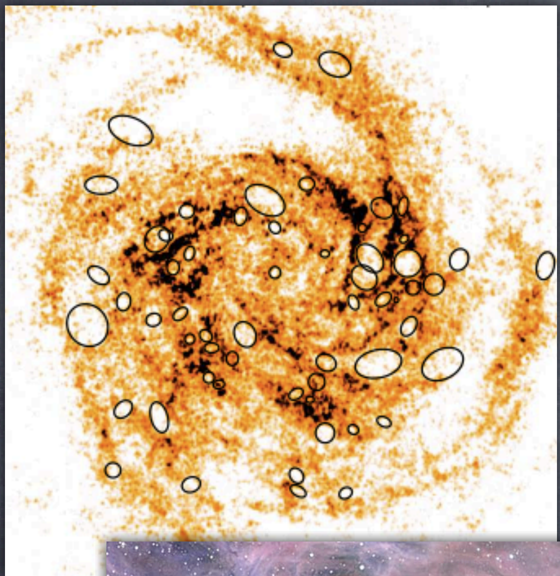
- Ingredients for molecular cloud formation:
  - High density (collisional formation) + High column density (UV-shielding)
- i.e. Gather up and compress material to drive it molecular, e.g:
  - Pile-up in spiral arm shocks
  - Build-up in stellar disk gravity field
  - Infall onto self-gravitating cloud complexes
  - Accumulation in colliding flows
  - etc.

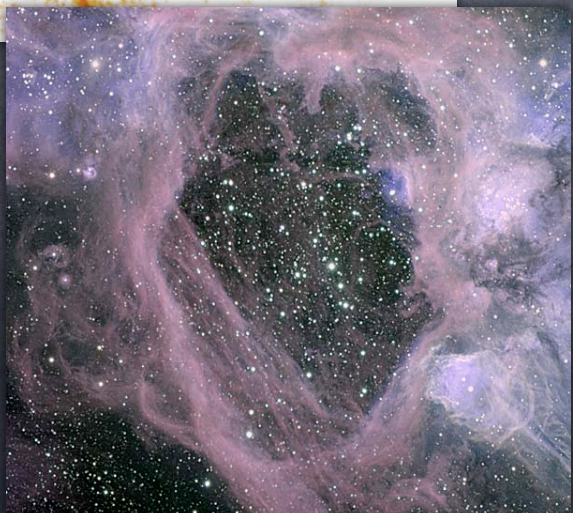




Simulations of molecular cloud formation in spiral arms by Clare Dobbs

Supershells & Molecular Cloud Formation





Top: HI shells in NGC6946A (Brinks et al. 2008)
Bottom: N44 superbubble (Gemini Observatory)

- Gaseous disks of star forming galaxies are riddled with the footprints of stellar feedback: gas piled up in over-dense shells.
- Supershells: R~100−1000 pc, E~$10^{51\text{-}53}$ erg

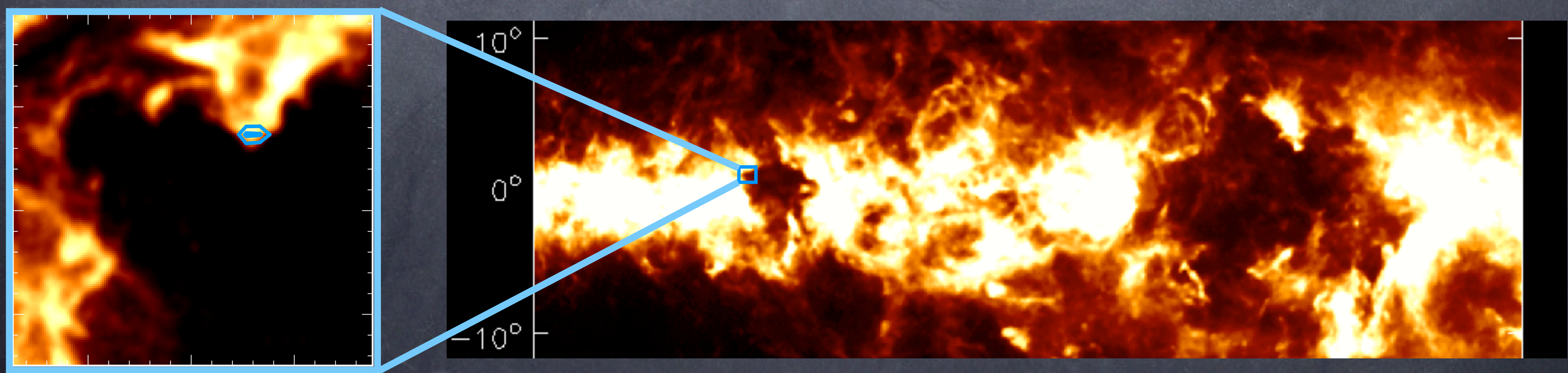
Q: Do supershells drive the ISM more molecular?

- Theoretically: Should be possible if conditions are right. Observationally: There are some fairly strong hints.
- But we need:
  (a) Solid observational proof
  (b) Numbers! *How important* is supershell-triggered formation to the molecular gas fraction of a galaxy?

Molecular Cloud Formation in Milky-Way Supershells

Observing the ISM in Supershells

- HI 21 cm line
  - Extended, large-scale atomic shell structure.
  - Interferometric mosaicing: parsec resolutions over kpc areas. Resolve small-scale structure throughout shell walls.
- $^{12}CO(J=1\text{–}0)$ @ 115 GHz
  - Pinpoint locations where gas is molecular & link to shell substructure.



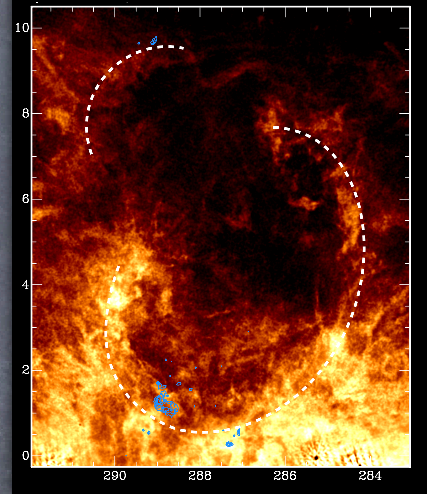
GASS (Galactic All-Sky Survey) HI data

Target Objects

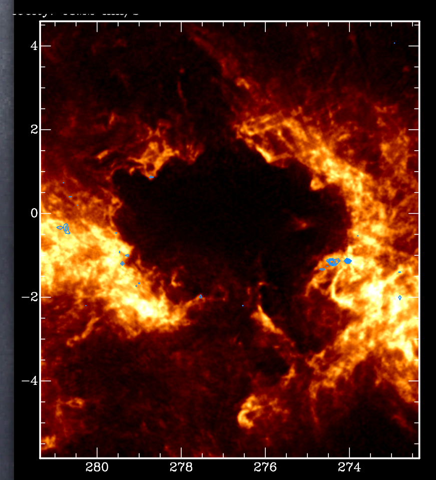
	GSH 287+04-17	GSH 277+00+36
Size (pc)	230 × 360	diameter: 610
Dist. (kpc)	2.6 ± 0.4	6.5 ± 0.9
R_{gal} (kpc)	~ 8	~ 10
M(HI) ($M_\odot$)	$7 \pm 3 \times 10^5$	$3 \pm 1 \times 10^6$
M(H_2) ($M_\odot$)	$2.0 \pm 0.6 \times 10^5$	$2.1 \pm 0.6 \times 10^5$
v_{exp} (km s^{-1})	~ 10	~ 20
Age (yr)	$\sim 10^7$	$< 2 \times 10^7$
Evolution	Young chimney	Evolved chimney

Dawson et al. (2008a, 2008b, 2011), McClure-Griffiths et al. (2003)

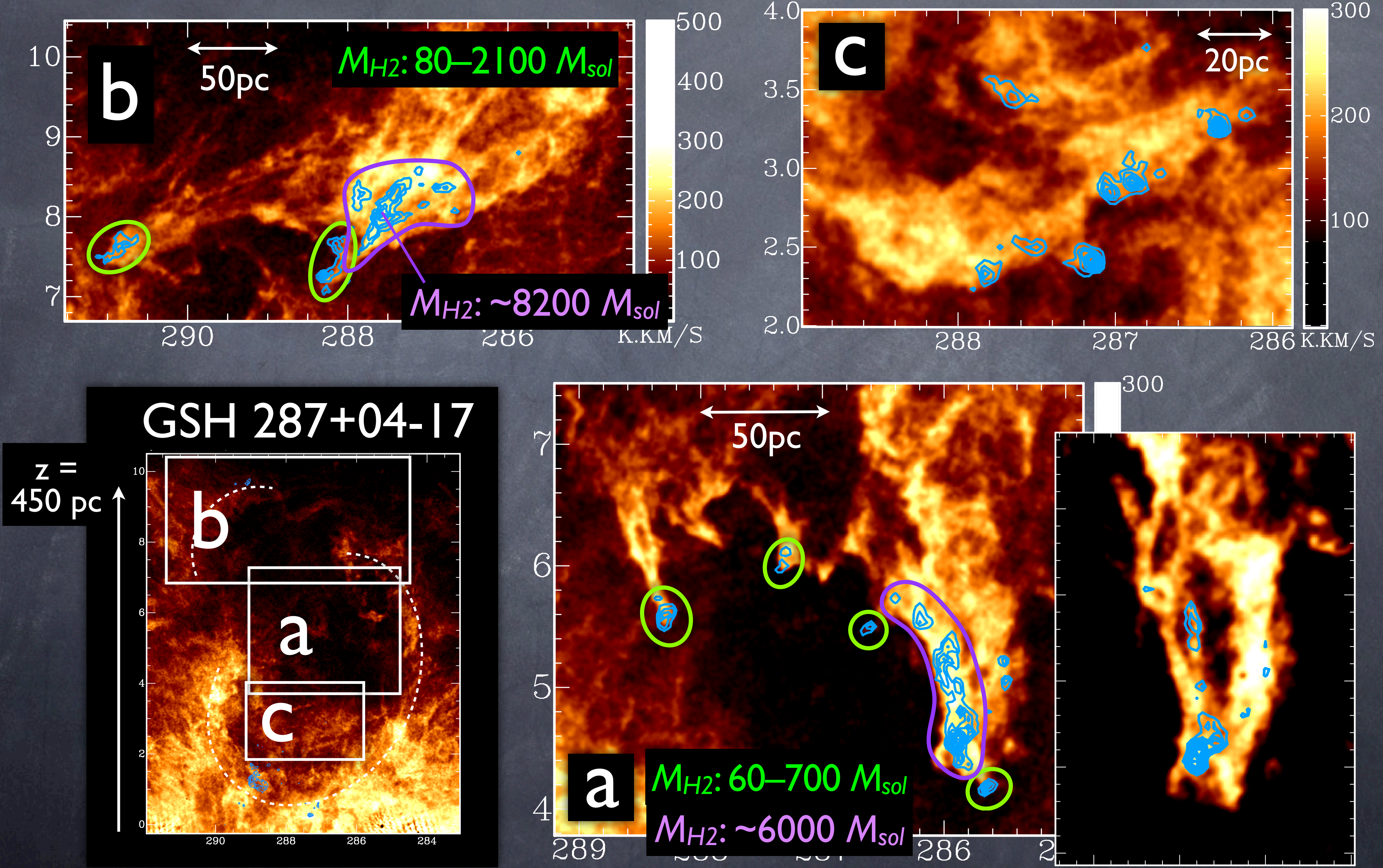
GSH 287+04-17



GSH 277+00+36



Details of the Supershell Walls



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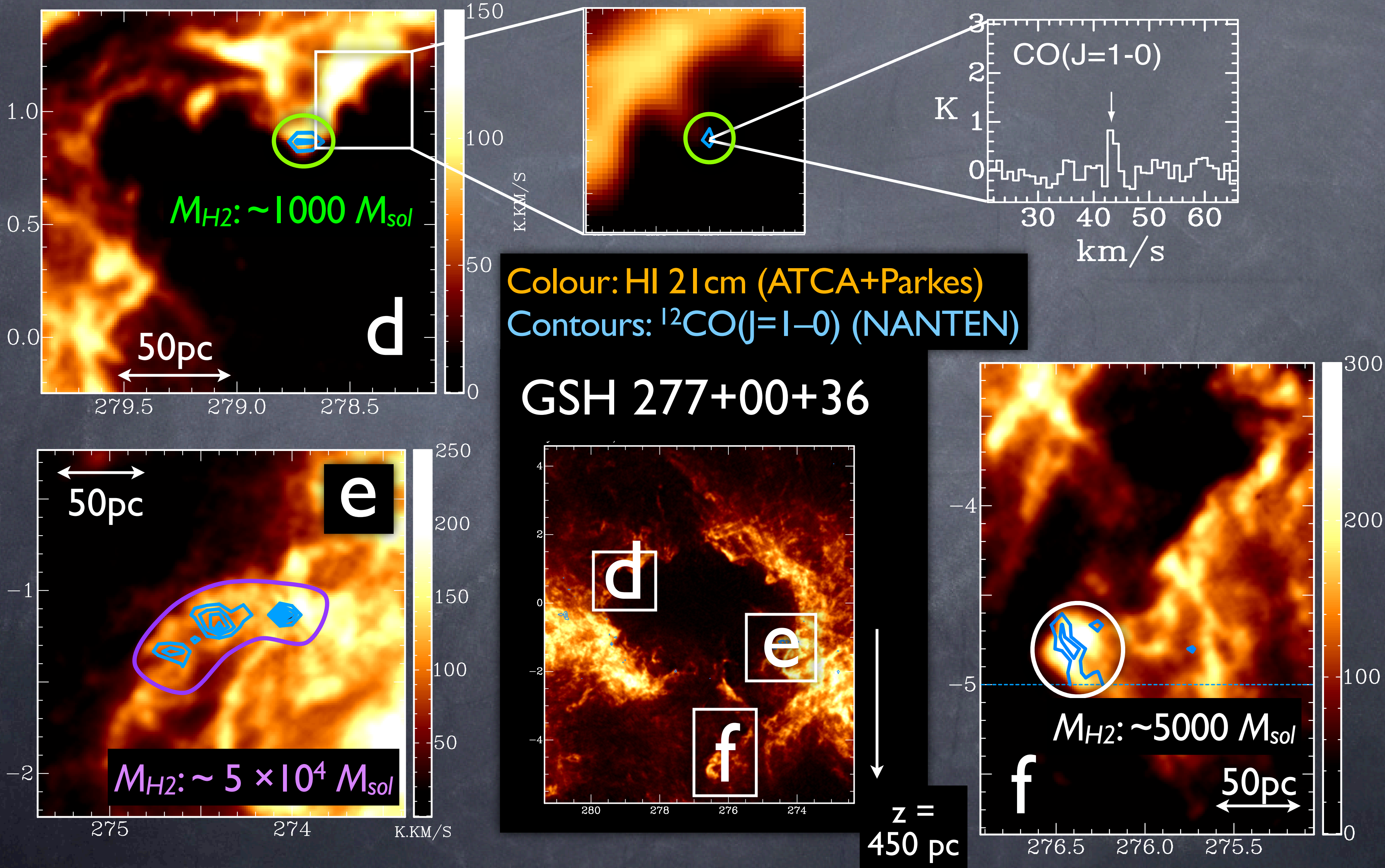
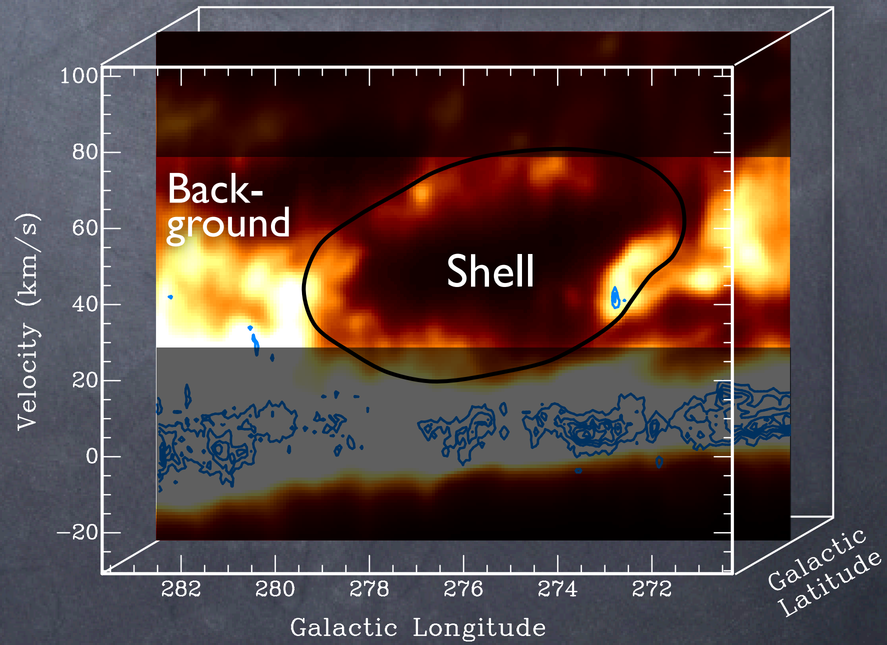


Enhanced Molecular Fraction

- Test for molecular gas formation: compare molecular gas fraction in:
  - (a) The volumes of space affected by the shells (including voids!)
  - (b) Nearby regions outside their zone of influence

$$M_{\mathrm{H}_2} \propto 2.0 \times 10^{20} \int T_v(\mathrm{CO})\, dv$$
$$M_{\mathrm{HI}} \propto 1.8 \times 10^{18} \int T_v(\mathrm{HI})\, dv$$

$$f_{mol} = \frac{M_{\mathrm{H}_2}}{M_{\mathrm{HI}} + M_{\mathrm{H}_2}}$$



- Conceptually simple, but challenging in the Galactic Plane. Choose regions carefully...

Enhanced Molecular Fraction

GSH 287+04-17

$$[\,f_{mol}\,]_{\rm shell} = 0.22 \pm 0.06$$
$$[\,f_{mol}\,]_{\rm backgr} = 0.11 \pm 0.05$$
= 2.0

in-shell enhancement in molecular fraction

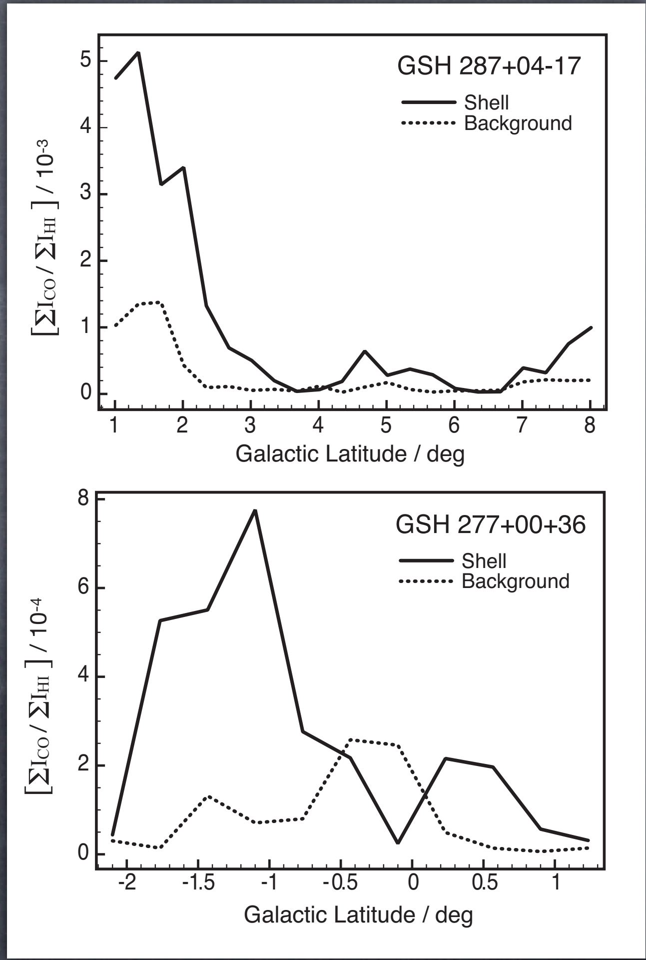
GSH 277+00+36

$$[\,f_{mol}\,]_{\rm shell} = 0.068 \pm 0.016$$
$$[\,f_{mol}\,]_{\rm backgr} = 0.020 \pm 0.006$$
= 3.4

Direct observational support for molecular cloud formation in supershells

Suggests formation of new material > destruction of old If true on large scales has profound implications for role played by supershells in evolution of Galactic ISM. !!

f_{mol} with galactic latitude

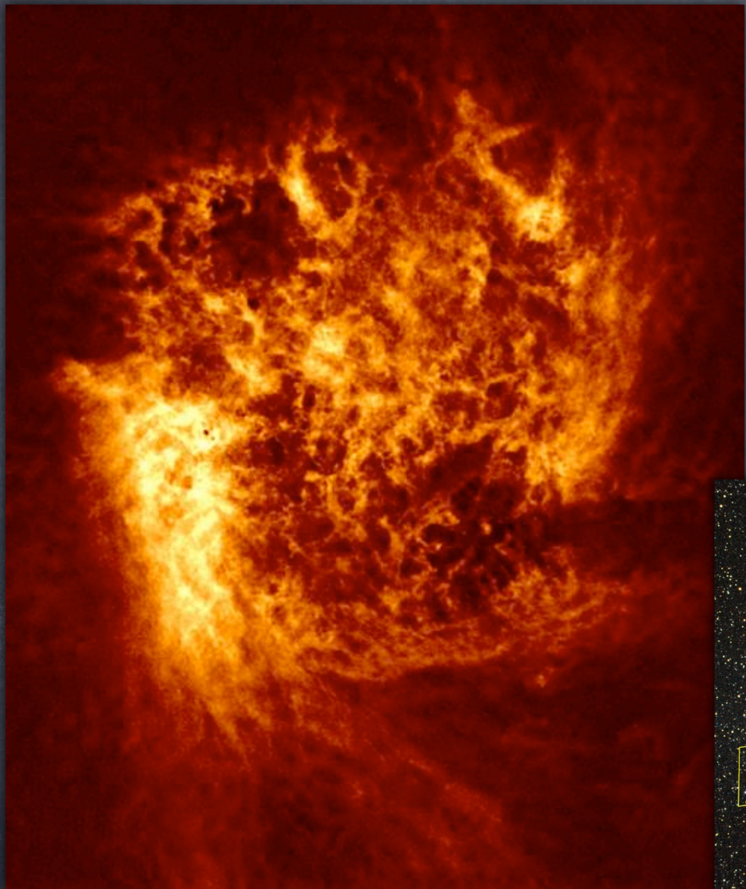


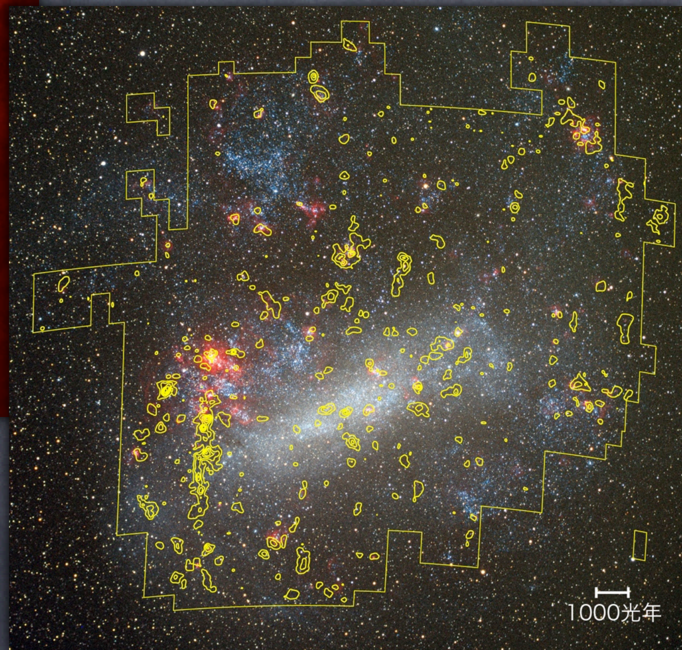
Dawson et al. (2011)

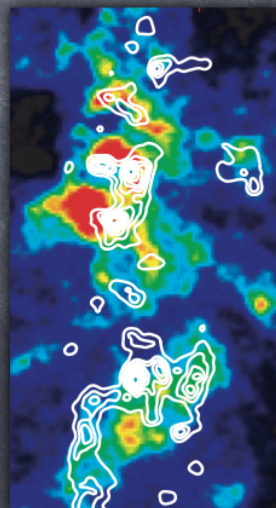
Molecular Cloud Formation in Supergiant Shells in the LMC

The Large Magellanic Cloud

- Nearest star-forming galaxy, *d* ~ 50 kpc
- Nearly face-on → nice target for studying relationship between atomic and molecular clouds
- Excellent CO & HI data available.





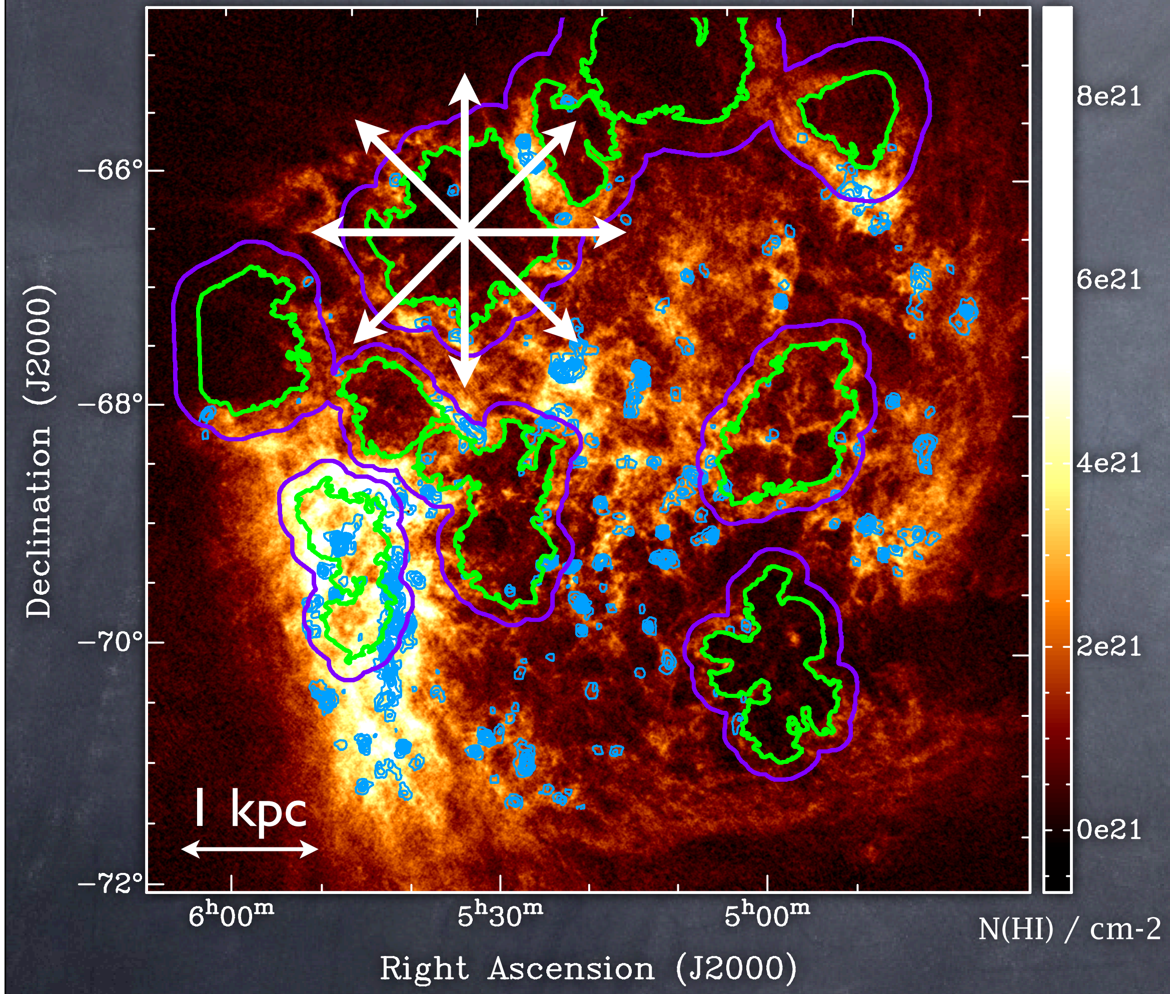


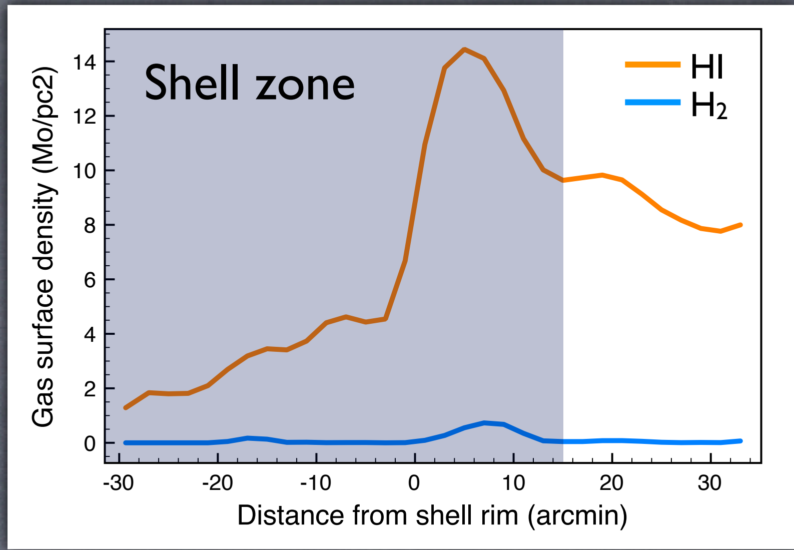
Top: The LMC in HI (Kim et al. 2003)

Right: Optical image overlaid with CO contours (Fukui et al 1999)

CO and HI in the 30 Dor region (Ott et al. 2008)

Supergiant shells in the LMC





Global analysis:

$$[\ f_{mol}\ ]_{\mathrm{shells}} = 0.037 \pm 0.001$$

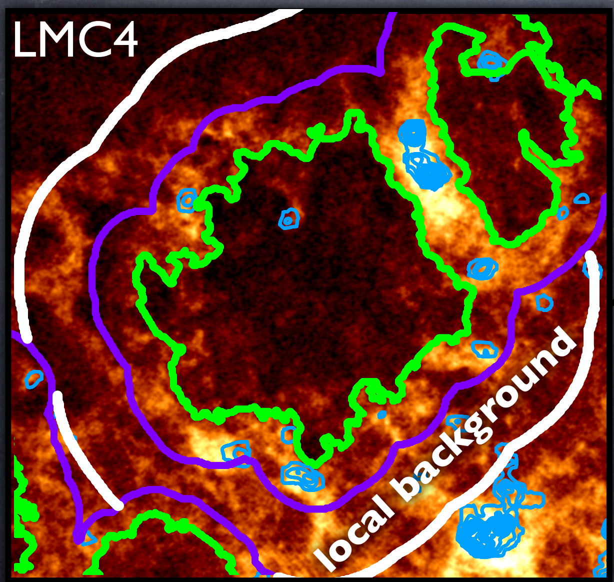
$$[\ f_{mol}\ ]_{\mathrm{backgd}} = 0.037 \pm 0.001$$

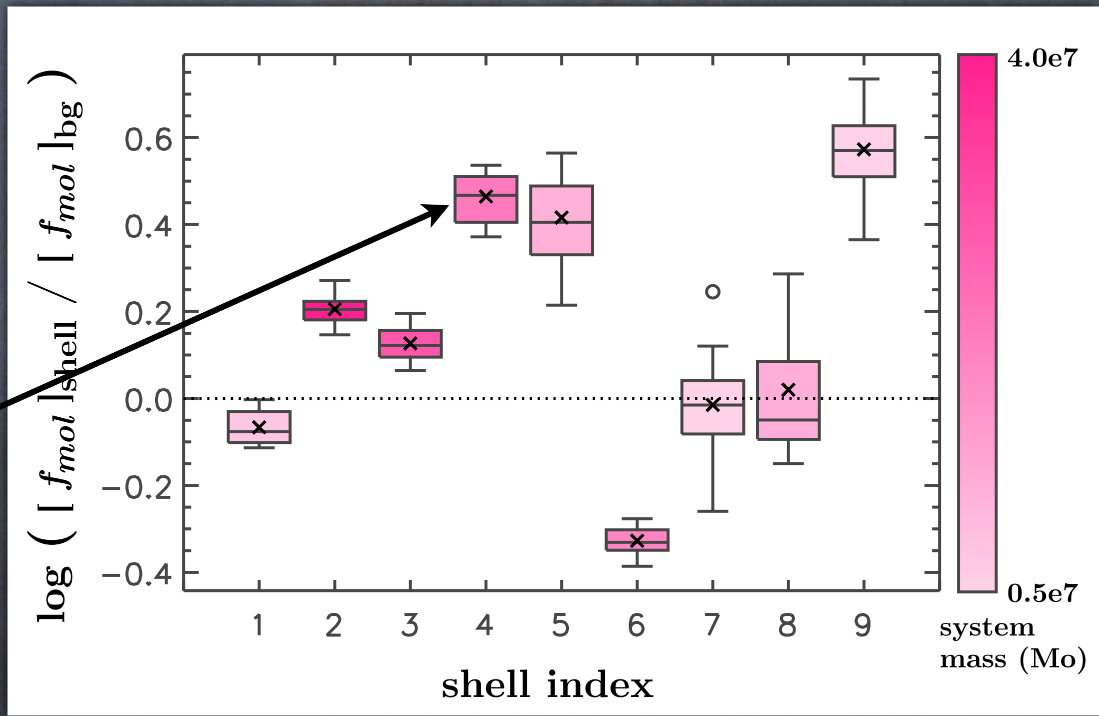
➡ No measurable enhancement over galaxy as a whole

Colour: HI 21cm (ATCA+Parkes data; Kim et al. 2003)
Contours: $^{12}CO(J=1\text{–}0)$ (NANTEN data; Fukui et al. 1999)

Supergiant shells in the LMC

- Compare shell zones with local environments (< 500 pc from inner rim)
  - ➡ Majority of systems do show evidence of ISM being more molecular in shell zones than outside.
- Supergiant shells **do** drive the ISM more molecular, though not the dominant driver.

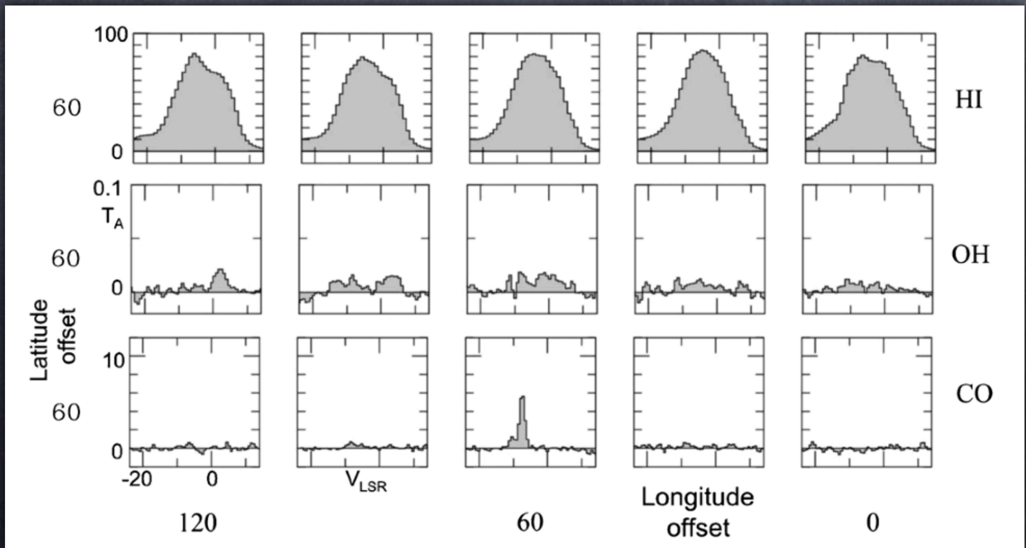




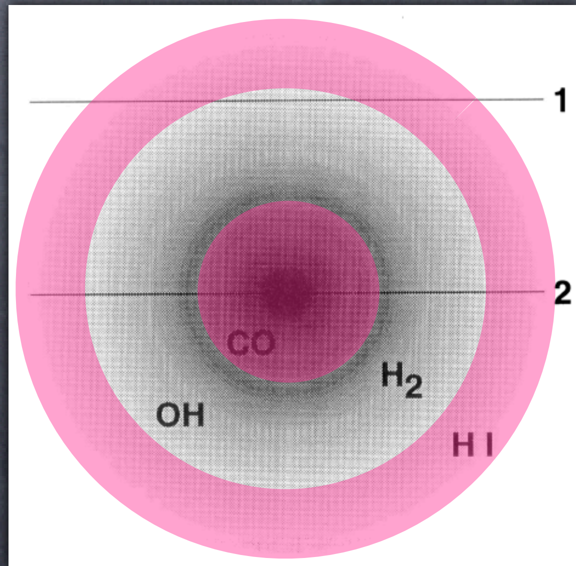
SPLASH: Probing Transition-State Gas in the Milky Way

Limitations of CO and HI

- To form comprehensive picture, need tracers that follow neutral ISM through all stages of its evolution.
- Shielding requirements for CO: $A_V \gtrsim 1$ → restricted to dense, highly-molecular regions → misses diffuse H_2.
- HI and CO alone miss up to 50% of mass in neutral gas complexes! *(Grenier et al. 2005, Dawson et al. 2011)*
- OH 18 cm lines (1612, 1665, 1667, 1712 MHz) a promising alternative...



Allen et al. (2012)



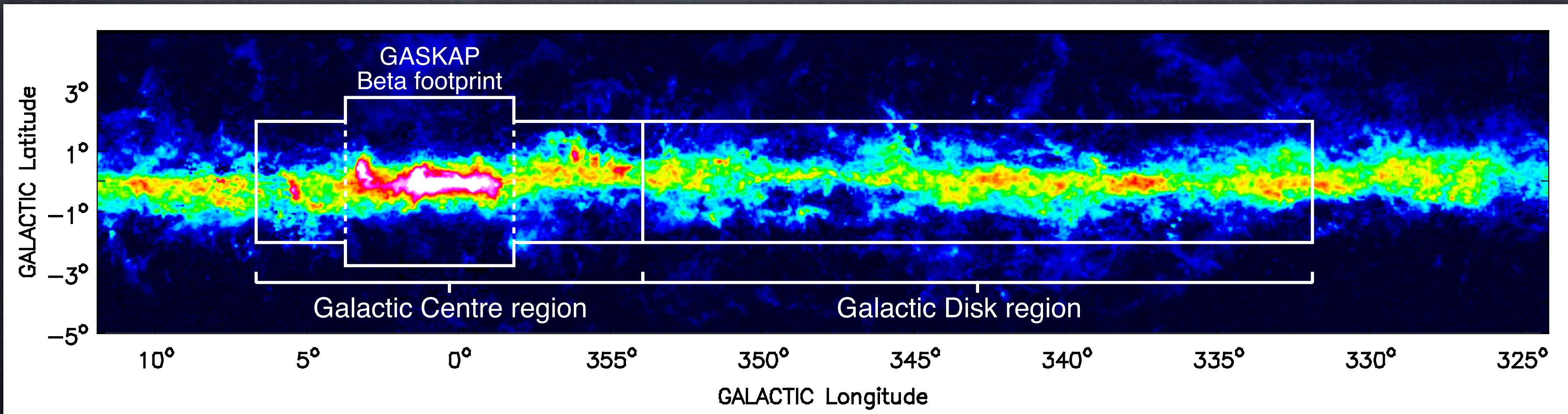
Schematic of molecular cloud (Liszt & Lucas 1996)

OH as a Tracer of "Missing" gas

- OH 18 cm emission from diffuse gas is a versatile probe but challenging to observe.
- Versatile:
  - Seen in both emission & absorption
    - ➡ Directly solve for T_{ex} and τ
    - ➡ Potential to resolve near-far distance ambiguity
  - Intensity ratios sensitive to thermal state of gas → diagnose departures from LTE.
- Challenging:
  - Peak T_b ~ 100 mK → 10–100 x weaker than CO!

SPLASH

- **S**outhern **P**arkes **L**arge **A**rea **S**urvey in **H**ydroxl
- Phase 1: ~1800 hours over 2 years
- Observe Galactic Centre and inner 30 deg of Plane to sensitivity of σ ~ 25 mK
- First fully-sampled large-scale survey in OH
- Order of magnitude more sensitive than previous surveys (needed for diffuse OH)



SPLASH

- Distribution:
  - Scale height?
  - Degree of concentration in spiral arms?
  - Relative to traditional tracers
- Gas properties:
  - Thermal & excitation states...
  - Mass, density, column density...

Atomic-molecular transition in Milky Way

- New map of th
- Deep, unbiasse CASS maser team!)
- Complementa
  - GASKAP: High resolution, moderate sensitivity, interferometer → OH absorption, masers, resolves out extended structure.
  - SPLASH: Low resolution; high sensitivity; single dish → diffuse, extended emission, provide short-spacing correction for GASKAP

Observations commence May 2012

Summary

- Transition from atomic to molecular ISM key part of galaxy evolution.
- Evidence that accumulation of ISM in supershells contributes to the production of molecular gas in both the Milky Way and the LMC.
- In LMC, their effect is secondary to other dominant drivers. As yet unknown for the Milky Way.
- The SPLASH survey will seek transition-state gas traced in OH in the Galactic Plane.