SNR Shock-Molecular Cloud Interactions

Masers as tracers of hadronic cosmic ray acceleration

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National Radio Astronomy Observatory

Atacama Large Millimeter/submillimeter Array
Expanded Very Large Array
Robert C. Byrd Green Bank Telescope
Very Long Baseline Array

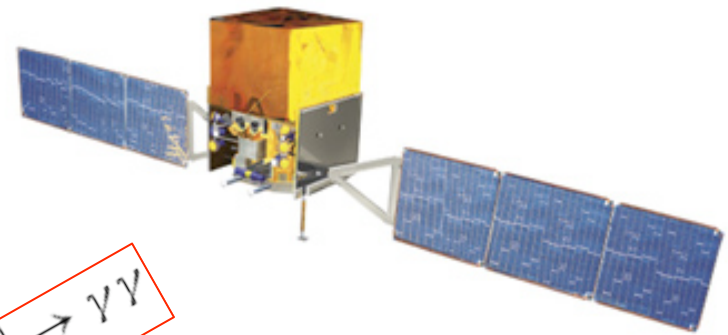
NRAO

Outline

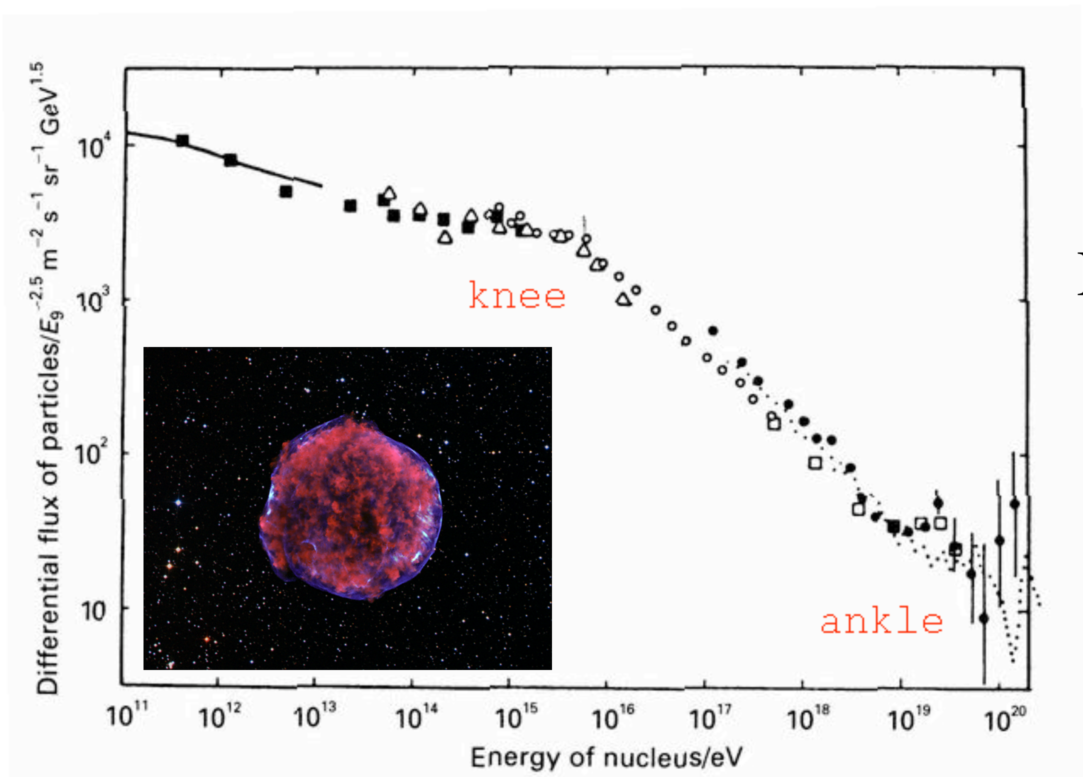
1. Why study the interaction of supernova remnant shocks with molecular clouds?
2. Observational challenges and the discovery of a "signpost" for supernova remnant interactions with molecular clouds.
3. The observational properties of the OH(1720 MHz) maser supernova remnant sample.
4. The theory. Maser excitation and post-shock OH production.
5. A new maser tracer of supernova remnant molecular shocks.

Current collaborators: *Ylva Pihlstrom, Lorant Sjouwerman, Mark Claussen*

Are Supernova Remnants the Sites of Hadronic Cosmic Rays?



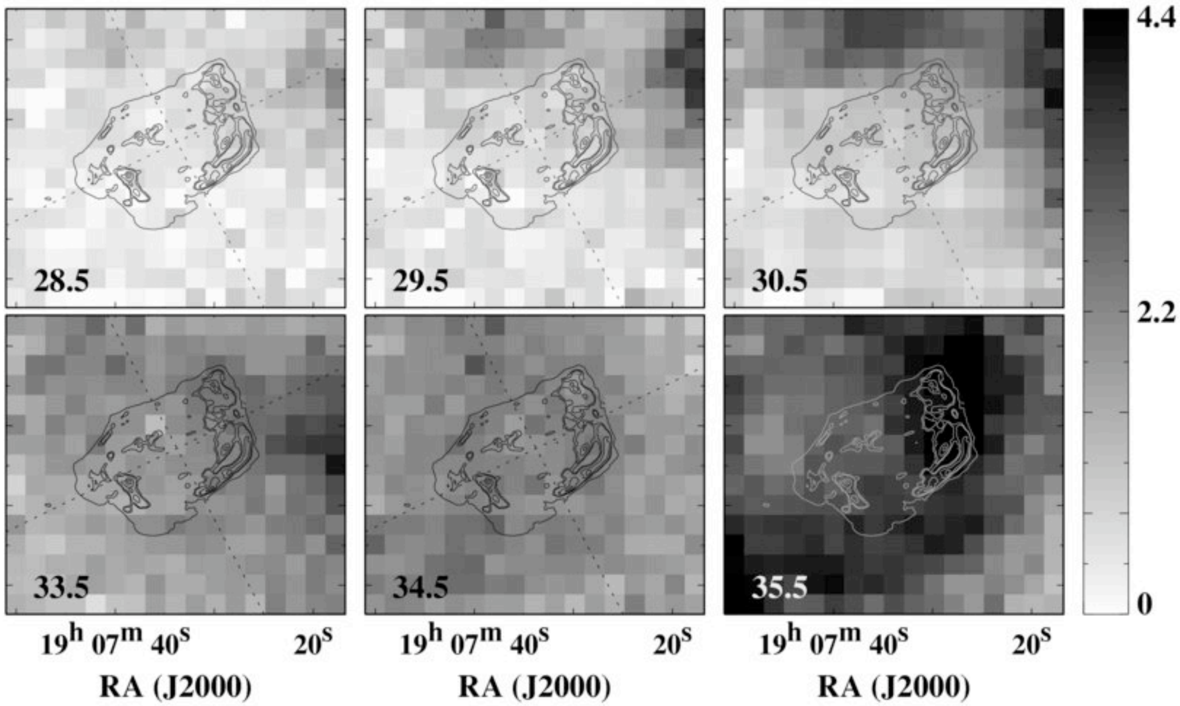
$$\pi^0 \rightarrow \gamma\gamma$$

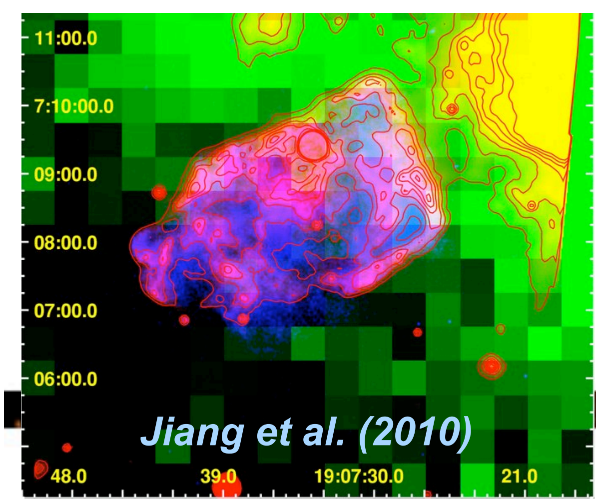


$$F(>100\ \mathrm{MeV}) \propto \varepsilon(t)\, E_{51}\, n_0\, d^{-2}$$

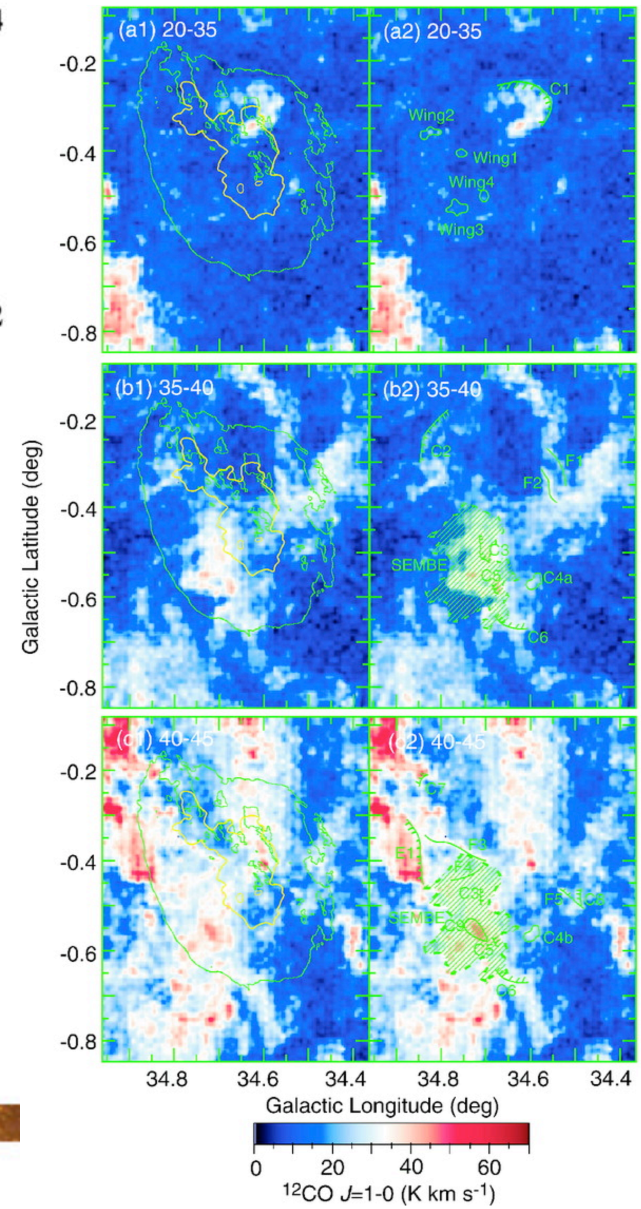
Distance (d) and density (n_0) are important but difficult parameters to measure.

Traditional gas tracers of interactions





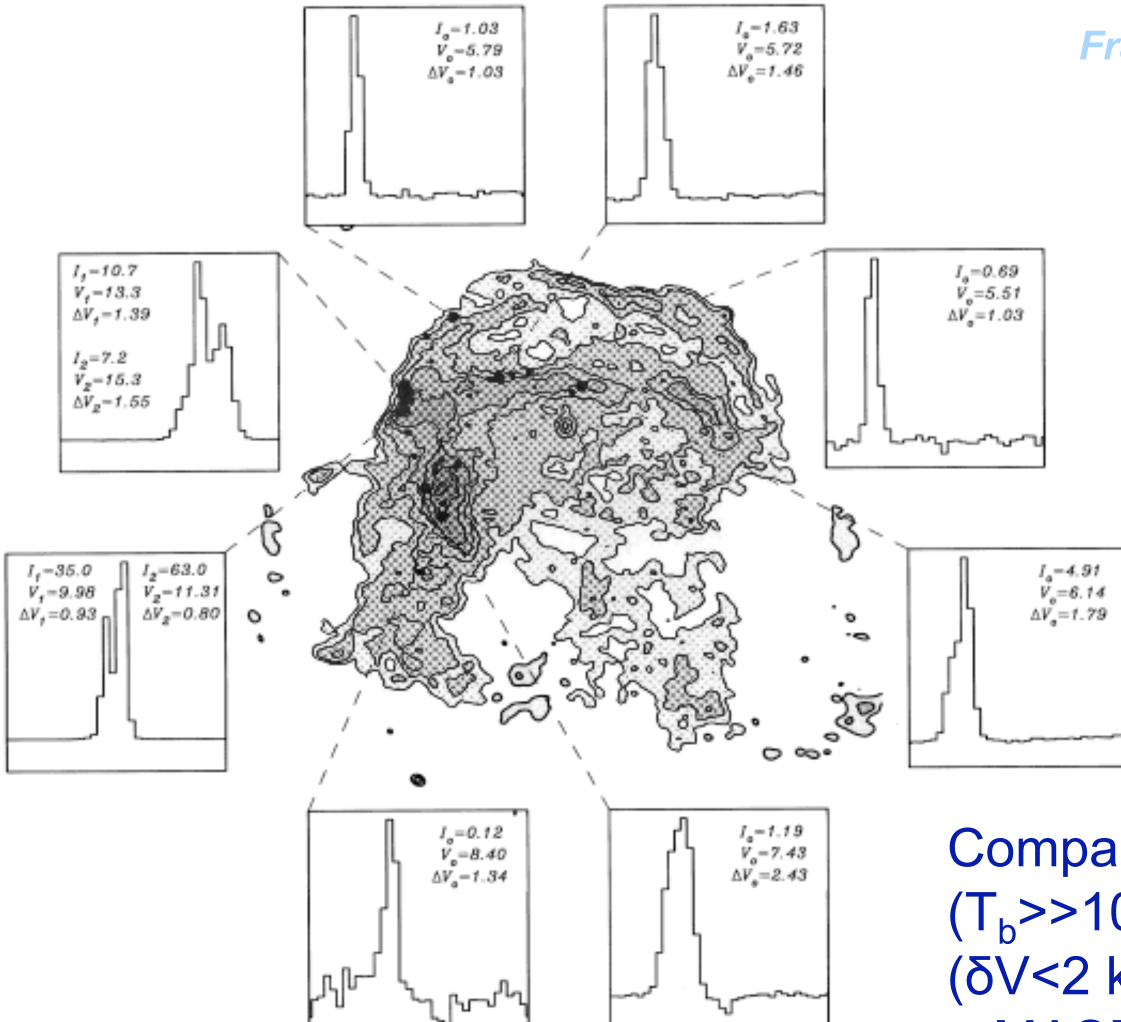
CO and HI suffer from line-of-sight velocity confusion in Galactic plane



Seta et al. (2004)

OH(1720 MHz) Emission Toward SNR W28

Frail, Goss & Slysh (1994)



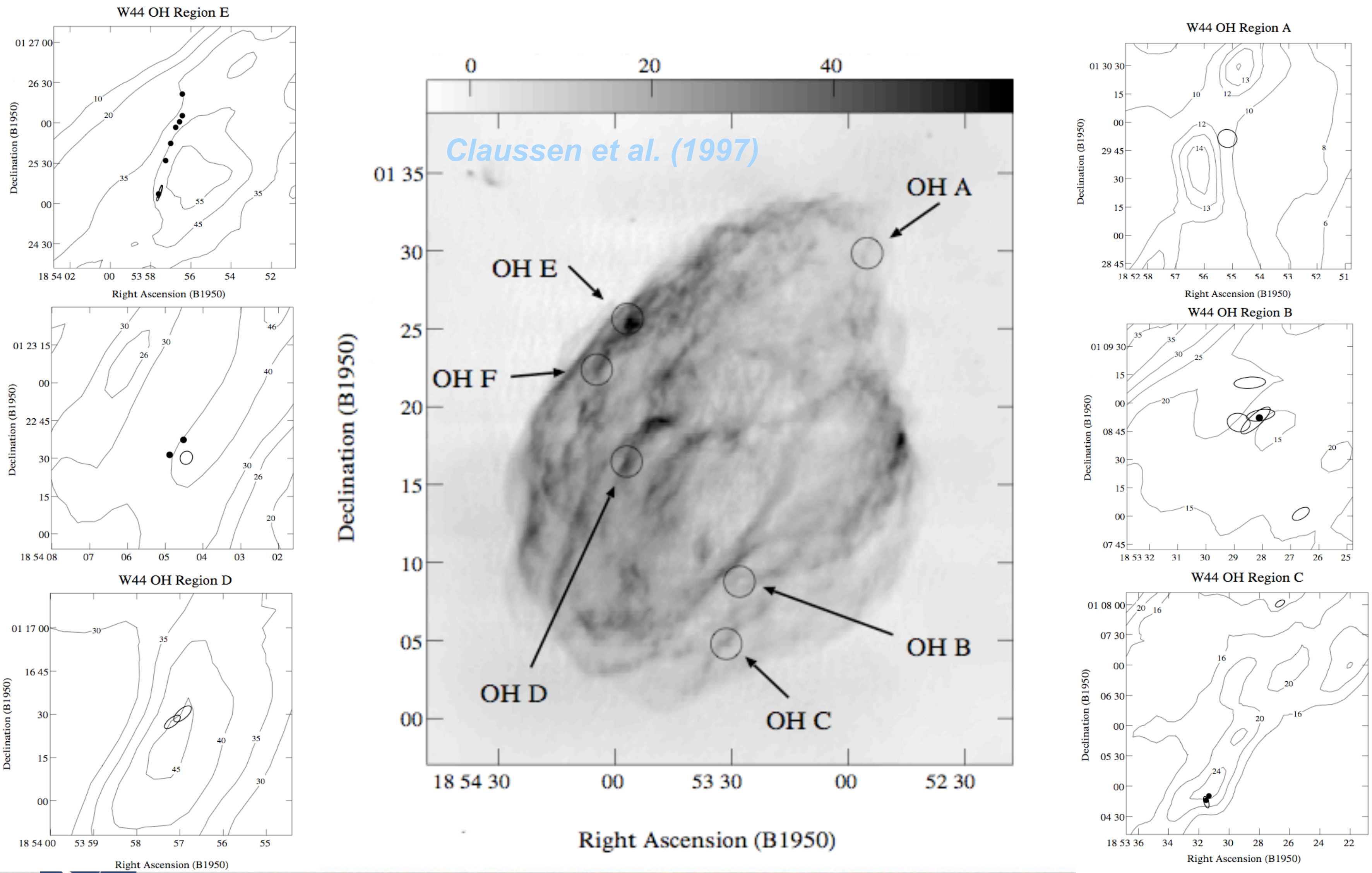
Compact, non-thermal (T_b>>10^4 K), narrow-line (δV<2 km s^{-1}) emission = MASERs

Galactic Surveys for OH Masers in SNRs

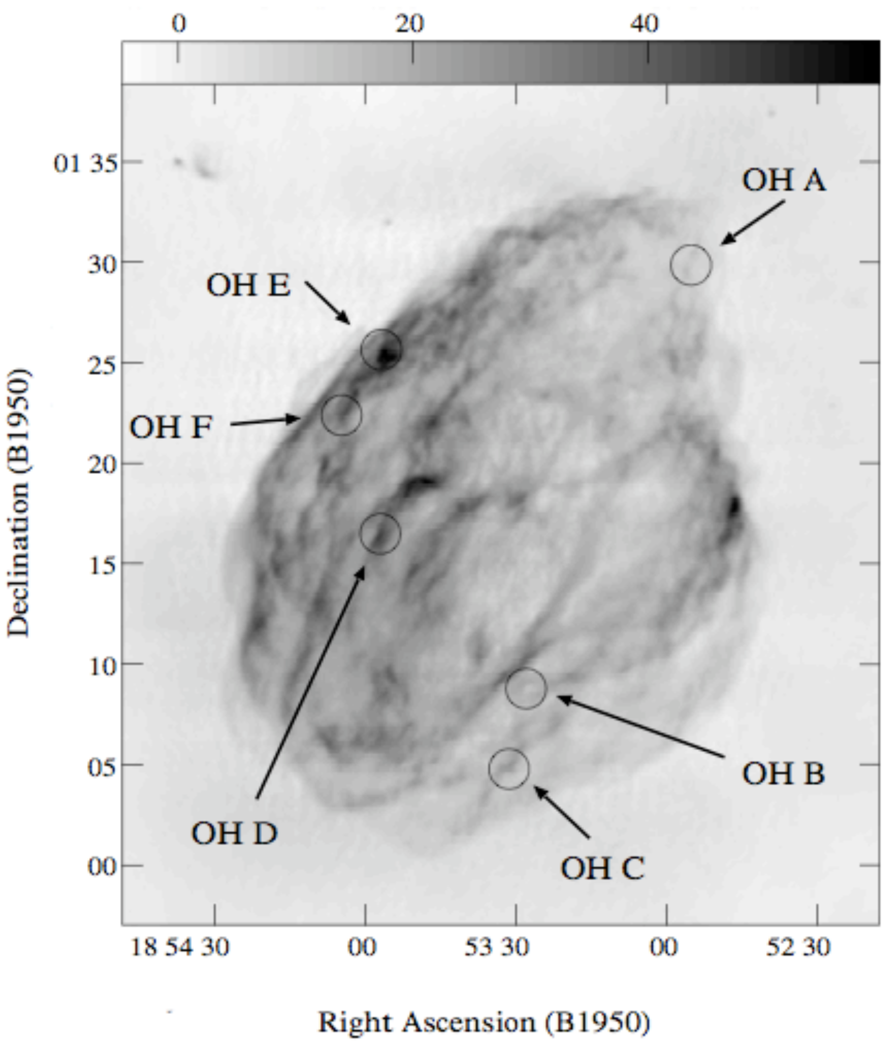
- Basic strategy: Single dish surveys with follow-up interferometric imaging of candidates.
- Advantage: Most of the known galactic SNR population could be observed quickly and efficiently.
- Weakness. Survey was sensitivity-limited and is confused by diffuse thermal OH.

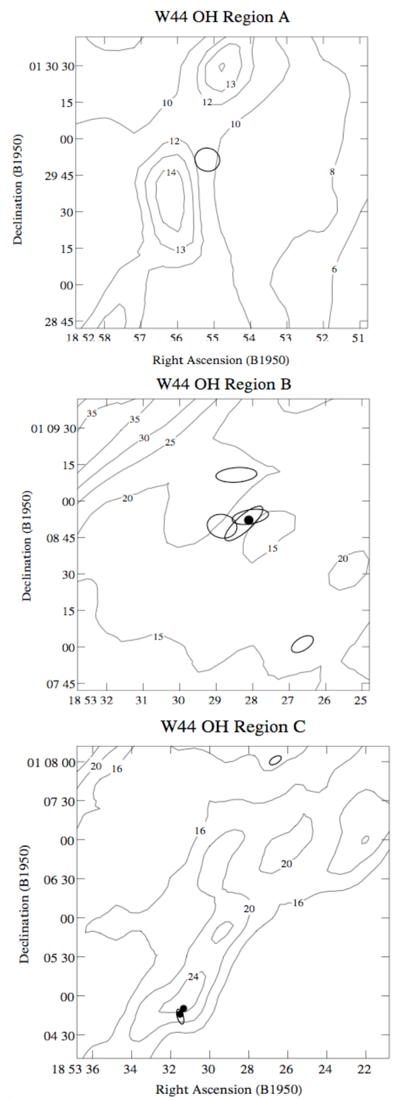
(1) Frail et al. (1996)
(2) Yuseh-Zadeh et al. (1996)
(3) Green et al. (1997)
(4) Sarma et al. (1997)
(5) Claussen et al. (1997)
(6) Koralesky et al. (1998)
(7) Yusef-Zadeh et al. (1999)
(8) Brogan et al. (2000)
(9) Hewitt & Yusef-Zadeh (2009)

Galactic Surveys for OH Masers in SNRs



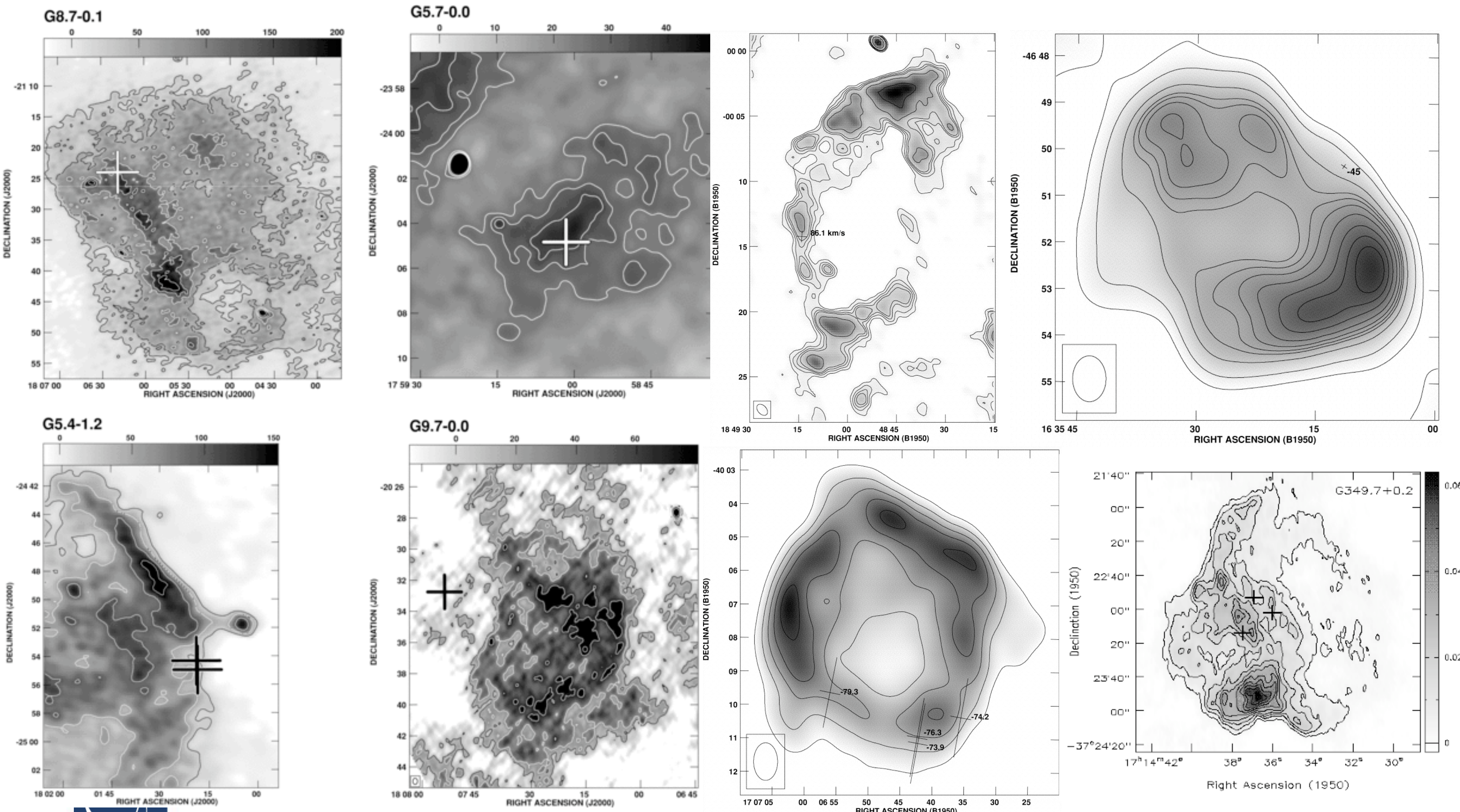
Galactic Surveys for OH Masers in SNRs





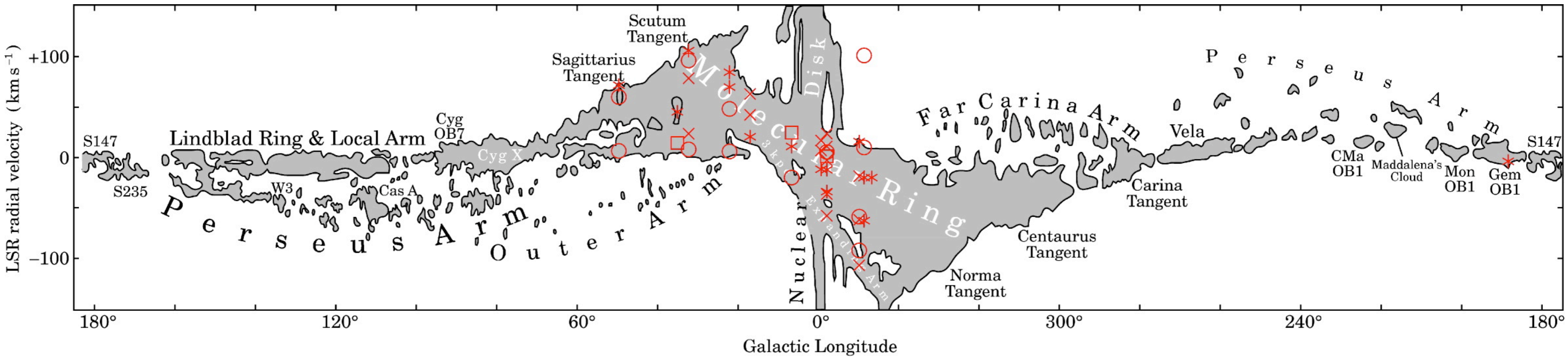
- Masers are located on or near peaks of synchrotron emission
- Masers are at similar velocities with small dispersion
- SNRs with OH tend to be “mixed morphology” SNRs in the X-rays with soft (T<1 keV), thermal spectral

Galactic Surveys for OH Masers in SNRs



Galactic Surveys for OH Masers in SNRs

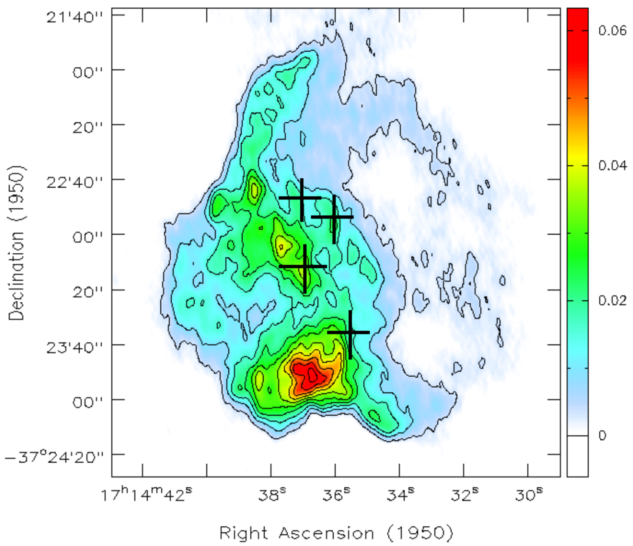
Hewitt, Yusef-Zadeh, & Wardle (2008)

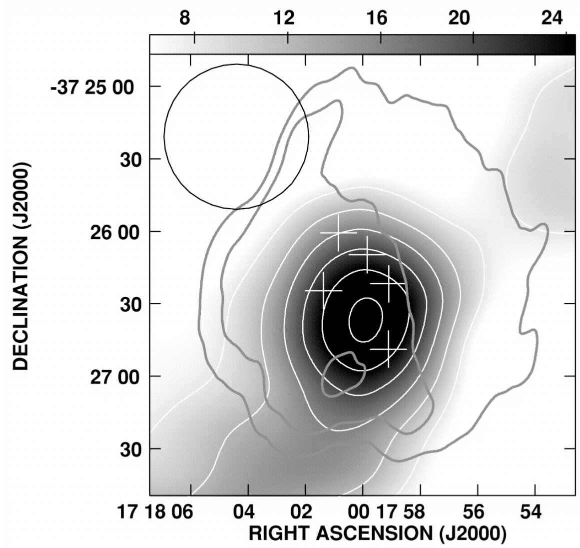


- About 10% of all SNRs have OH(1720 MHz) masers
- SNRs are preferentially found in the inner galaxy (molecular ring)
- SNRs with OH(1720 MHz) masers trace the broad scale distribution of molecular gas in our galaxy

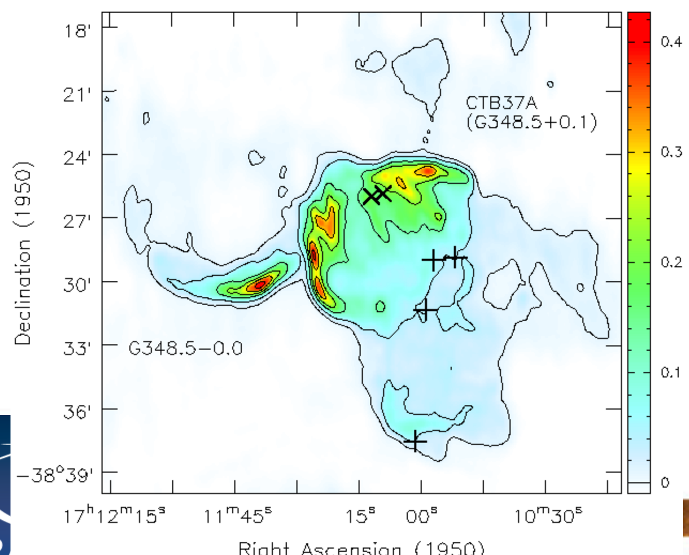
The Maser/Molecular Cloud Connection

G349.7+0.2



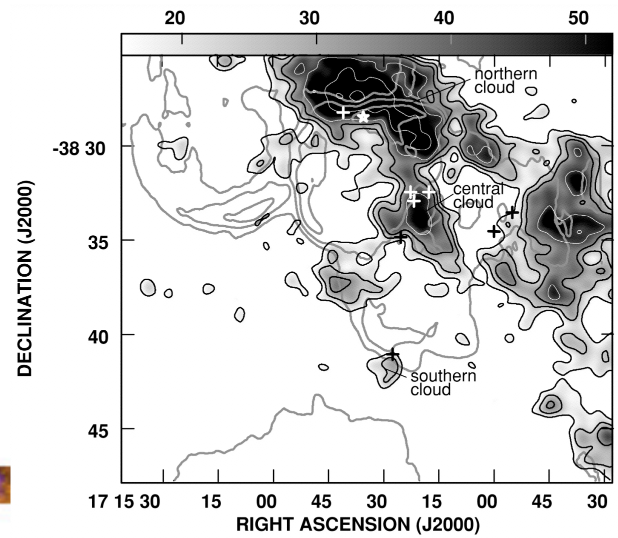


CTB 37A



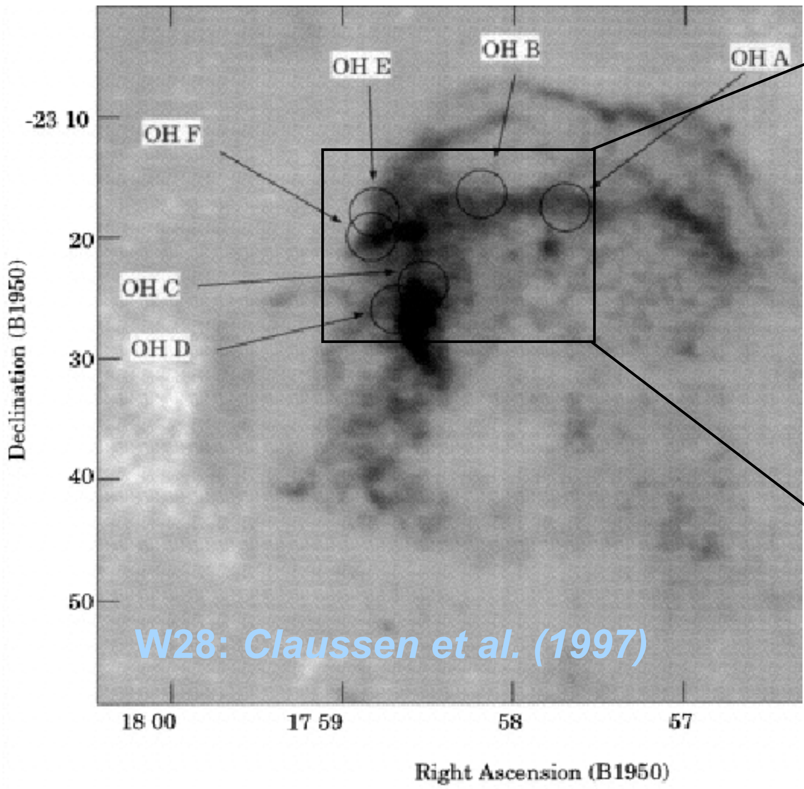
Greyscale: CO (1-0) emission

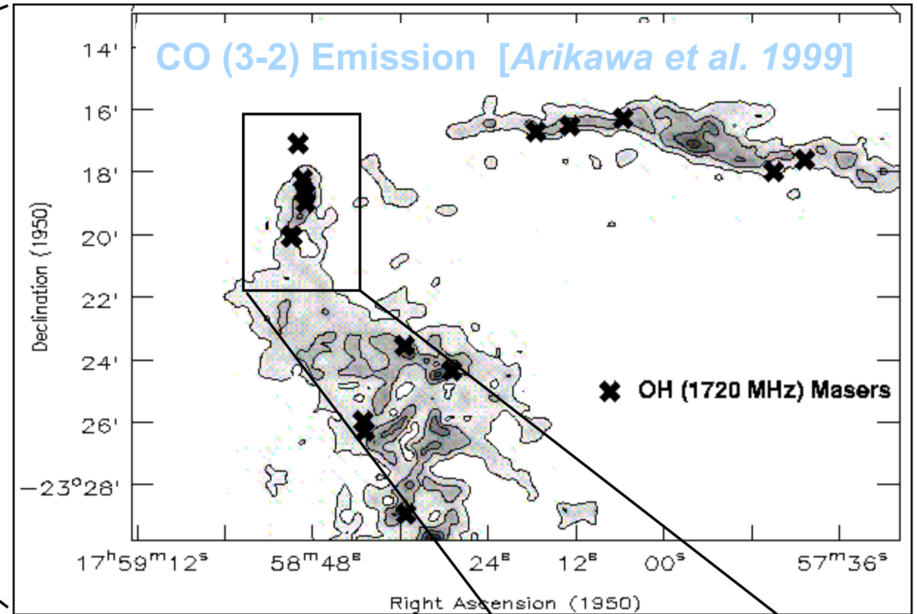
Reynoso & Mangum (2000)

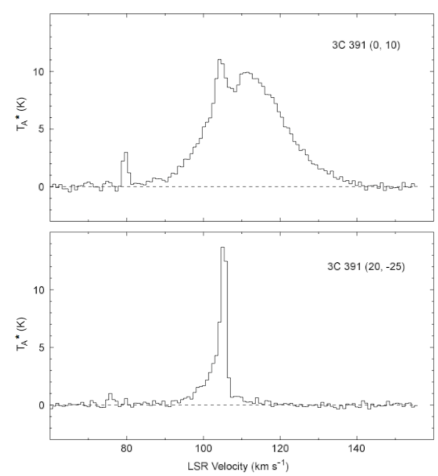


Slide taken from C. Brogan presentation

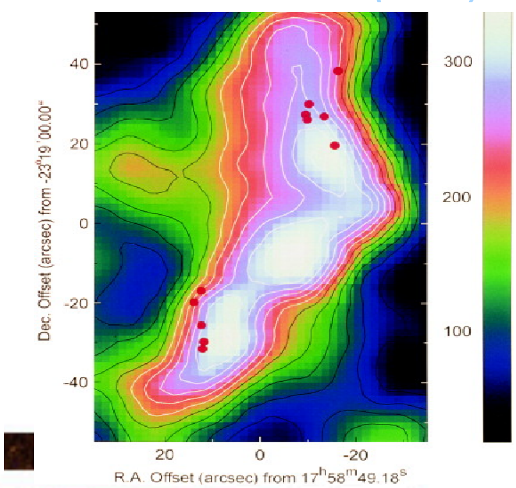
The Maser/Molecular Cloud Connection







Frail & Mitchell (1998)



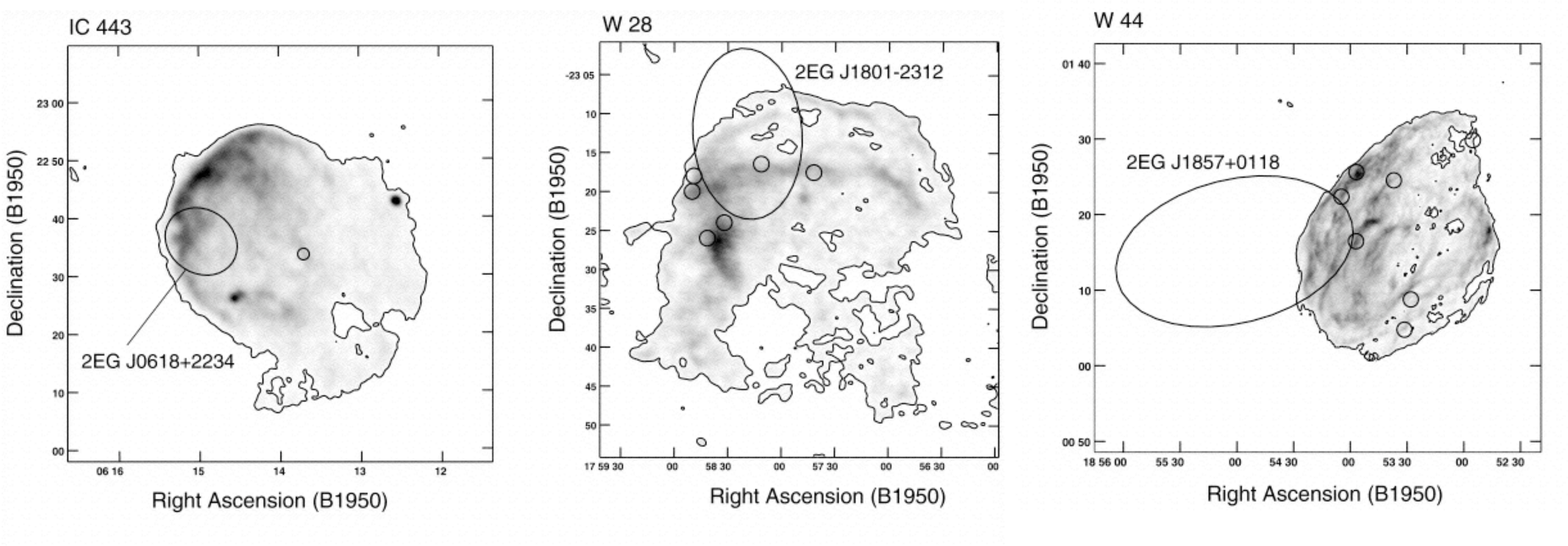
The Maser/Gamma-Ray Connection

Claussen et al. (1997)

"it is noteworthy that the three remaining SNR/EGRET coincidences are also our three best examples of a SNR/molecular cloud interaction, as traced by the detection of the OH(1720 MHz) maser transition. …remaining 14 SNRs all are more distant than 5 kpc and thus we would not expect these SNR detected as discrete EGRET sources given its sensitivity (Drury et al. 1994). However, they are important candidates for future searches and their detection at Gev or TeV energies would be a convincing proof of cosmic ray acceleration theories."

NRAO

The Maser/Gamma-Ray Connection



Claussen et al. (1997)

See talks by Gallant, Brandt, Chaves, Méhault and many more.

OH(1720 MHz) Masers as a signpost

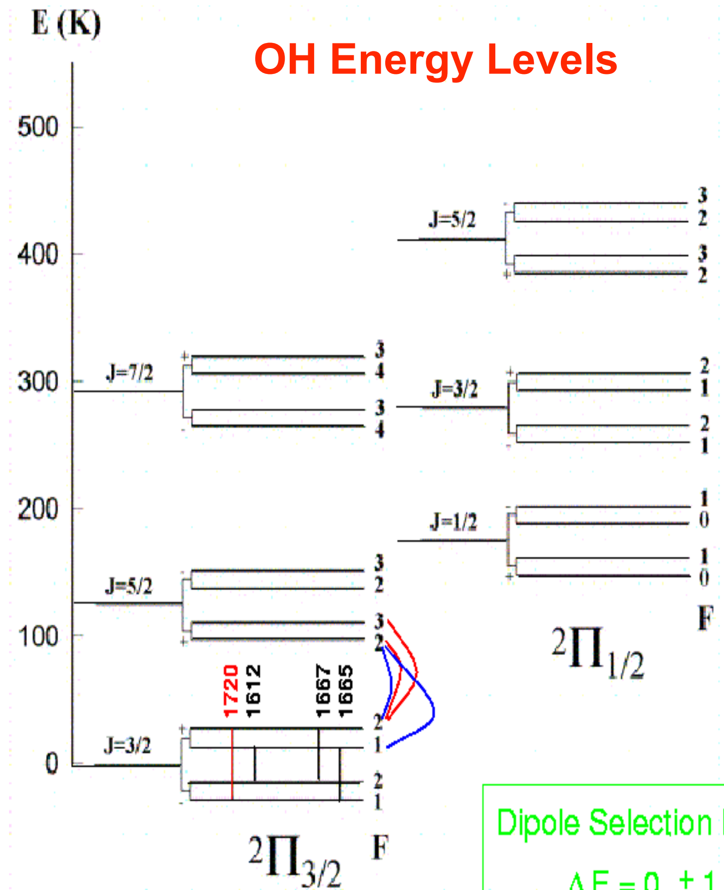
- Masers are located on or near peaks of synchrotron emission
- Masers are at similar velocities with small dispersion
- SNRs with OH tend to be "mixed morphology" SNRs in the X-rays with soft (T<1 keV), thermal spectral
- Masers associated toward 10% of all supernova remnants
- Masers are in close proximity to molecular gas which show signs of shock interactions with the supernova remnant
- Magnetic pressure is comparable to the hot gas interior to the supernova remnant
- Early indications that masers also trace gamma-ray emission

Distance-Ordered List of OH SNRs

(l,b)	RA (J2000)	Dec. (J2000)	d_{kpc} (kpc)	# masers	γ-rays?	Name
189.1, +3.0	06 17 00	+22 34	1.5	6	Y	IC443
6.4,−0.1	18 00 30	-23 26	2.0	41	Y	W28
34.7,−0.4	18 56 00	+01 22	2.5	25	Y	W44
5.7,−0.0	17 59 02	−24 04	3.2	1	P	
8.7,−0.1	18 05 30	−21 26	3.9	1	**Y**	W30
9.7,−0.0	18 07 22	−20 35	4.7	1	N	
359.1,−0.5	17 45 30	−29 57	5.0	6	P	
5.4,−1.2	18 02 10	−24 54	5.2	2	N	Milne 56
49.2,−0.7	19 23 50	+14 06	6.0	2	Y	W51C
357.7,+0.3	17 38 35	−30 44	6.4	5	N	
357.7,−0.1	17 40 29	−30 58	>6	2	N	MSH 17-39
348.5,+0.1	17 14 06	−38 32	8	10	**Y**	CTB 37A
32.8,−0.1	18 51 25	−00 08	5.5/8.5	1	N	Kes 78
0.0,+0.0	17 45 44	−29 00	8.5	7	Y	SgrAEast
1.0,−0.1	17 48 30	−28 09	8.5	1	N	
1.4,−0.1	17 49 39	−27 46	8.5	2	N	
31.9,+0.0	18 49 25	−00 55	9.0	2	**Y**	3C 391
337.0,−0.1	16 35 57	−47 36	11	3	N	CTB 33
21.8,−0.6	18 32 45	−10 08	5.2/11	1	N	Kes 69
346.6,−0.2	17 10 19	−40 11	5.5/11	5	N	
349.7,+0.2	17 17 59	−37 26	>11	5	**Y**	
16.7,+0.1	18 20 56	−14 20	2.2/14	1	N	
337.8,−0.1	16 39 01	−46 59	12.3	1	P	Kes 41

The OH (1720 MHz) Maser Excitation

- MASER = Microwave Amplification of Stimulated Emission of Radiation
- OH is an abundant ISM molecule
- Spin orbital coupling splits OH into two rotational ladders
- Rotational levels are slit by lambda doubling and spin orbital coupling
- Four ground state transitions
  - Main lines (1665 , 1667 MHz)
  - Satellite (1612, 1720 MHz)



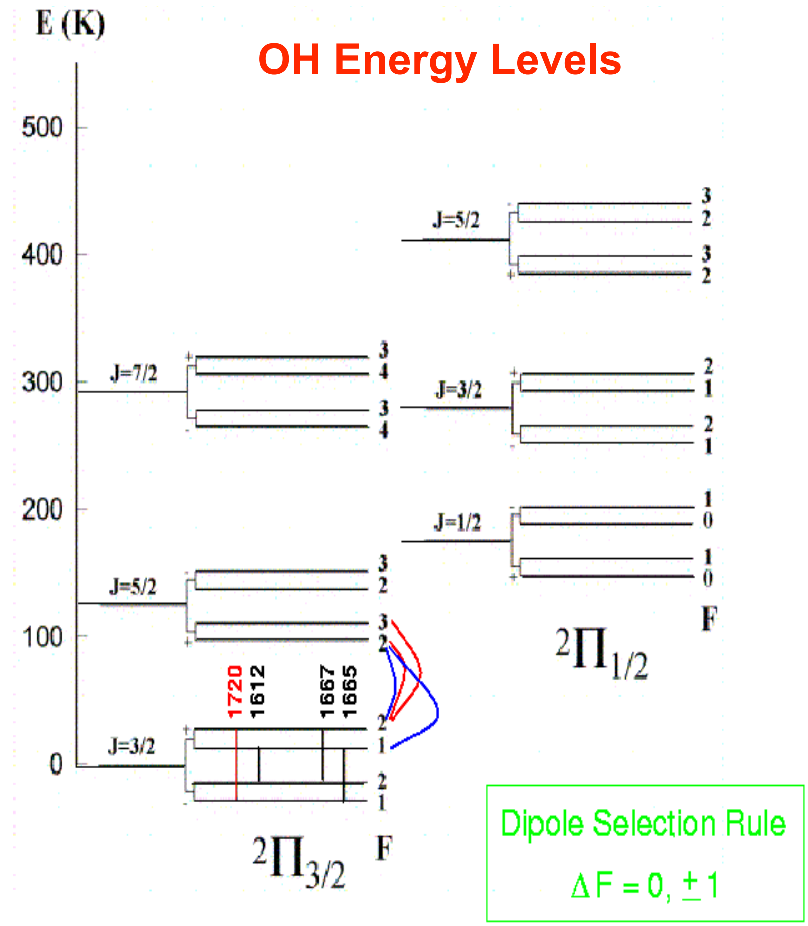
Dipole Selection Rule

$\Delta F = 0, \pm 1$

The OH (1720 MHz) Maser Excitation

- 1665 MHz 1667 MHz masers are associated with star formation
- 1612 MHz masers associated with evolved stars (Miras, OH/IR)
- Both inversions are radiatively pumped (via FIR photons)

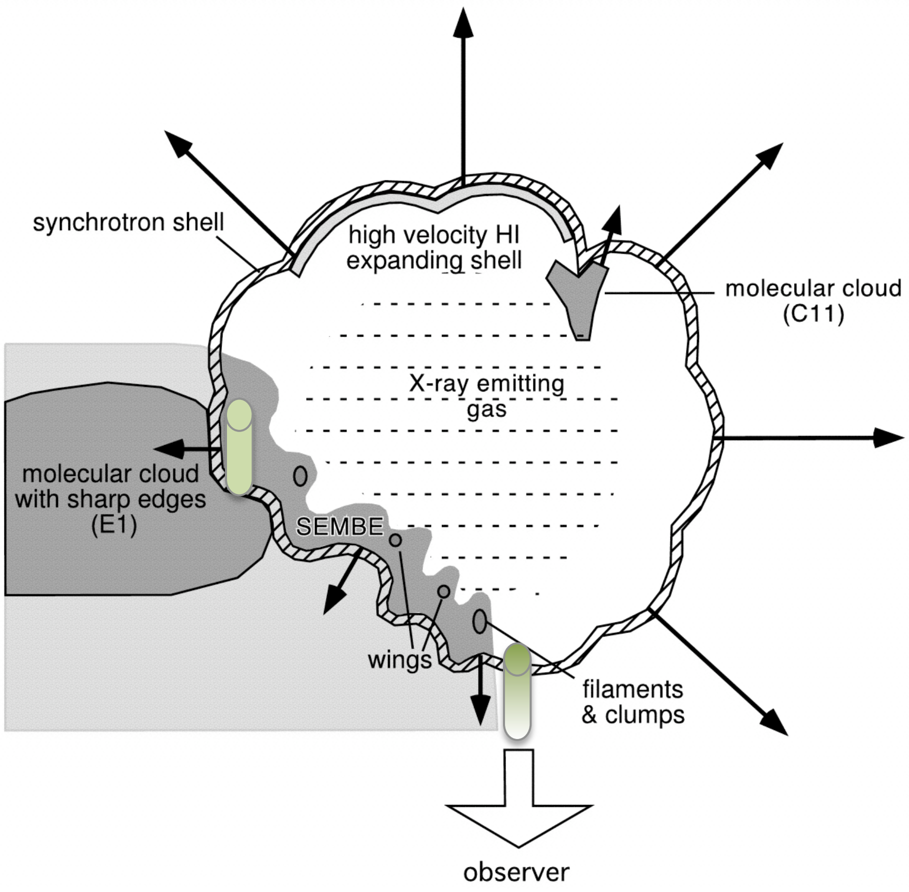
- But the 1720 MHz inversion is <u>collisionally</u> pumped
- FIR radiation *depopulates* the inversion of the 1720 MHz line



Velocity Coherence and Masers

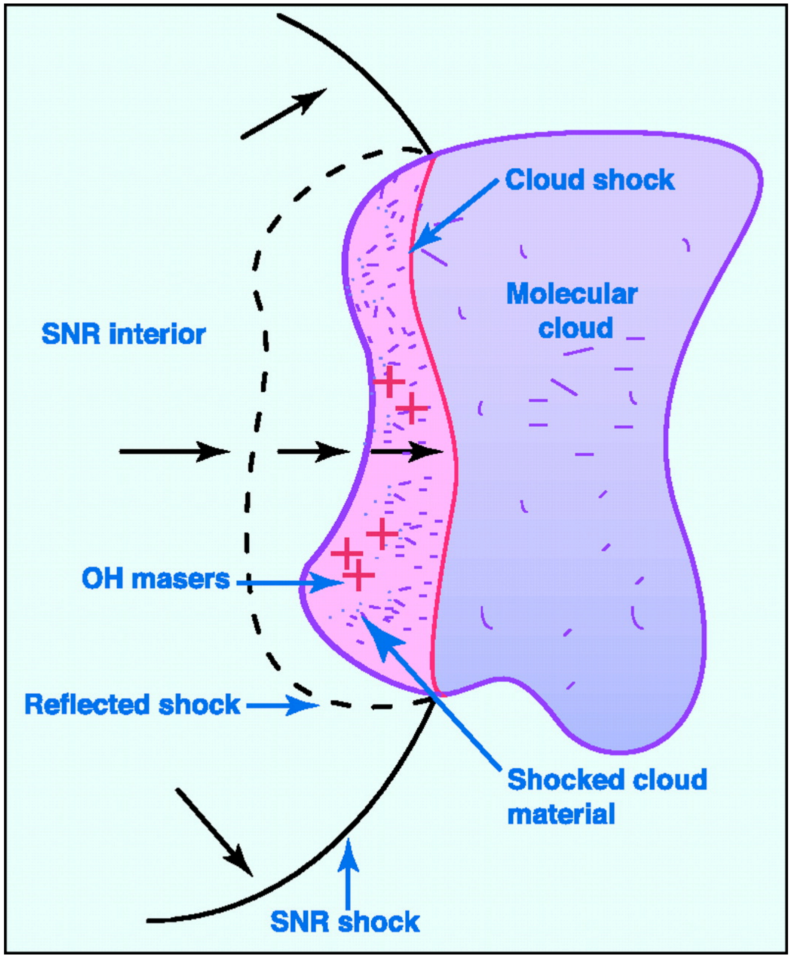
Seta et al. (2004)

- Masers need large columns of molecules with small velocity gradients (Doppler shifts destroy coherent amplification)
- Masers will occur where the line-of-sight velocity gradiant is small i.e. dV/dR~0
- Masers favor edge-on shock geometry such that $V_{maser} \sim V_{MC} \sim V_{SNR}$
- Thus maser velocities yield kinematic distances to the SNR



Maser as Tracers of SNR/MC Interactions

- A supernova remnant drives a slow shock into an adjacent molecular cloud
- OH is produced in post-shock gas through photo-dissociation of H_2O by either X-rays or CR
- OH at T=50-150 K and $n_0=10^4$-10^5 cm^{-3}
- Masers are excited along paths transverse to the line-of-sight
- Masers give estimates of the SNR distance, cloud gas density and magnetic field.

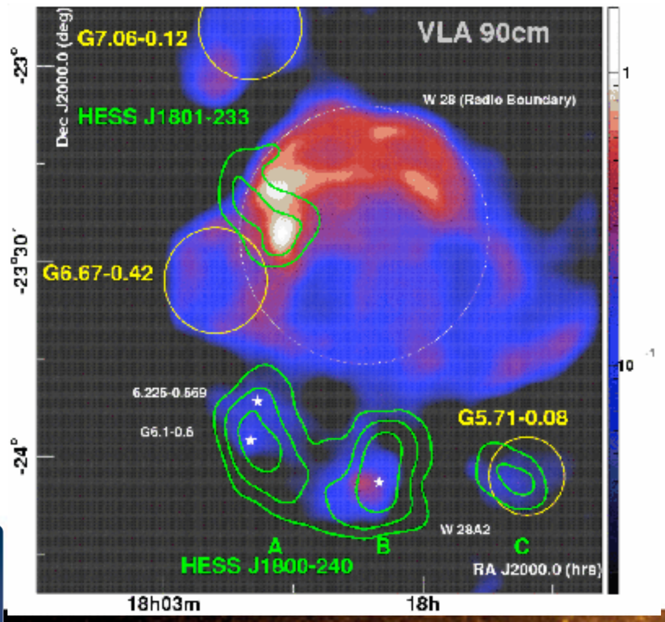


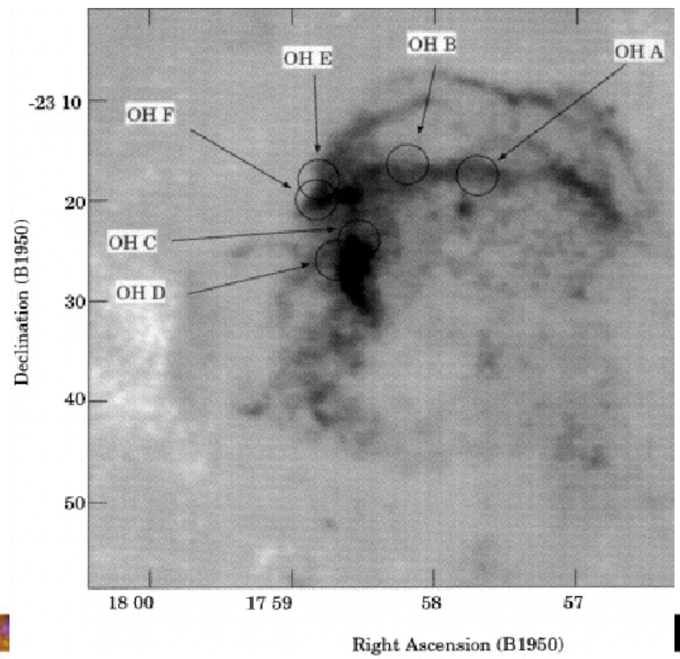
Wardle and Yusef-Zadeh (2002)

OH Masers Are Not Infallible

- Only 10% of galactic SNRs have OH(1720 MHz) masers
- OH masers are excited over a relatively narrow range of n_o and T
- No line ratio diagnostics available to derive n_o and T directly
- The <u>absence</u> of masers tells us nothing (e.g. W28, IC 443)

Aharonian et al.(2008)

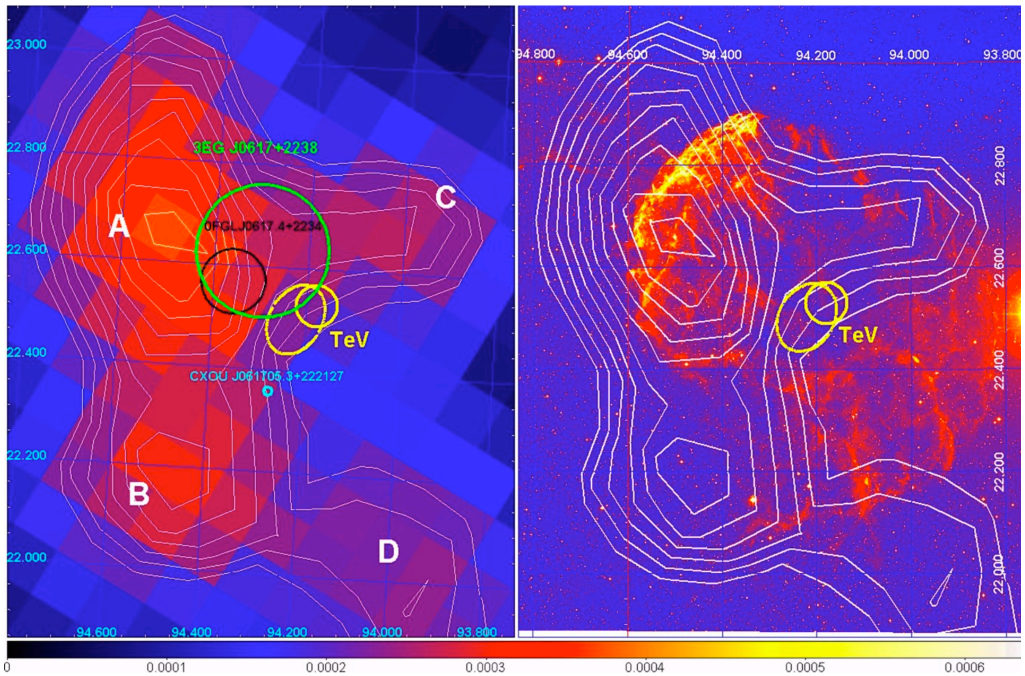




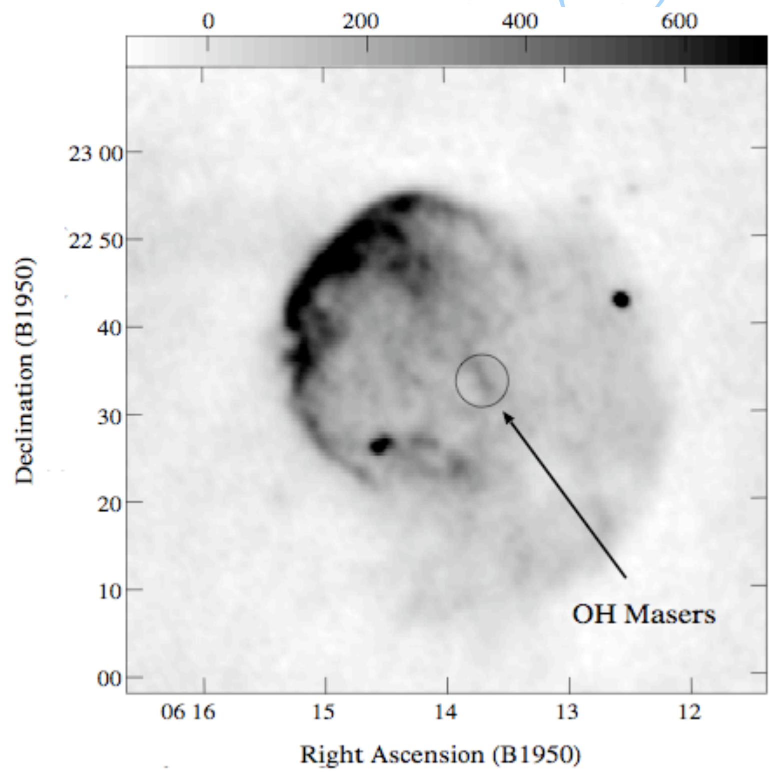
Claussen et al. (1997)

OH Masers Are Not Infallible

Tavani et al. (2010)



Claussen et al. (1997)



Can we find a new maser shock tracer?

The Methanol (CH_3OH) Maser Line

From Simon Ellingsen talk

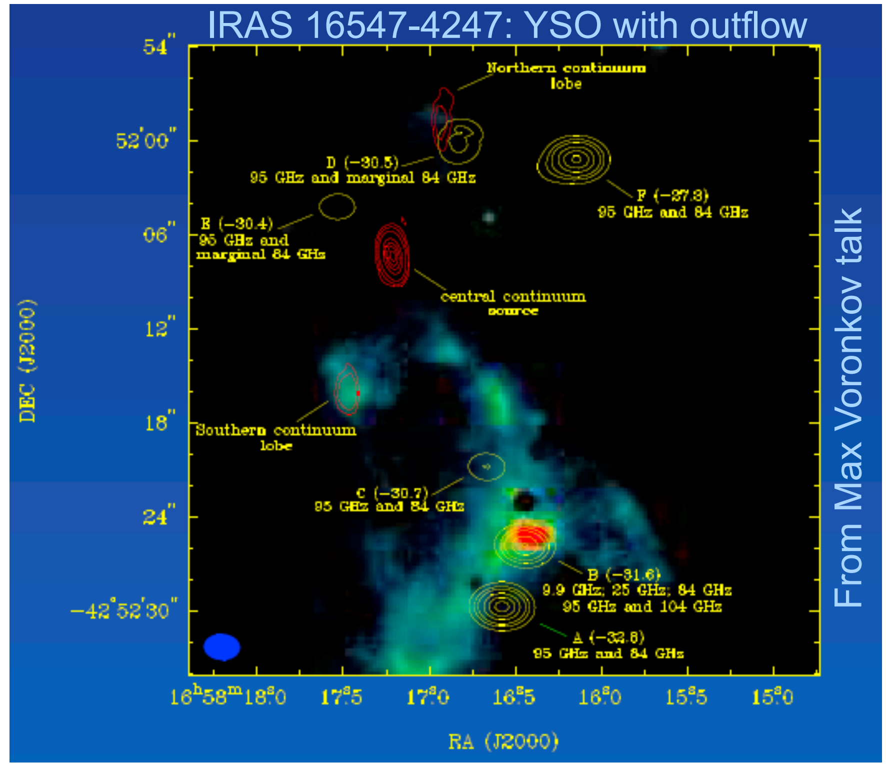
- Methanol called the molecular "weed" of star formation regions
- Divides into two distinct classes by excitation mechanism
- Class II
  - Most common. 500+ known
  - Radiatively-pumped (IR)
  - 36, 44, 84 and 95 GHz lines
  - Very bright and compact
  - Trace high mass SF <u>only</u>
  - Near OH and H_20 masers

Class I
Class II

NRAO

The Methanol (CH_3OH) Maser Line

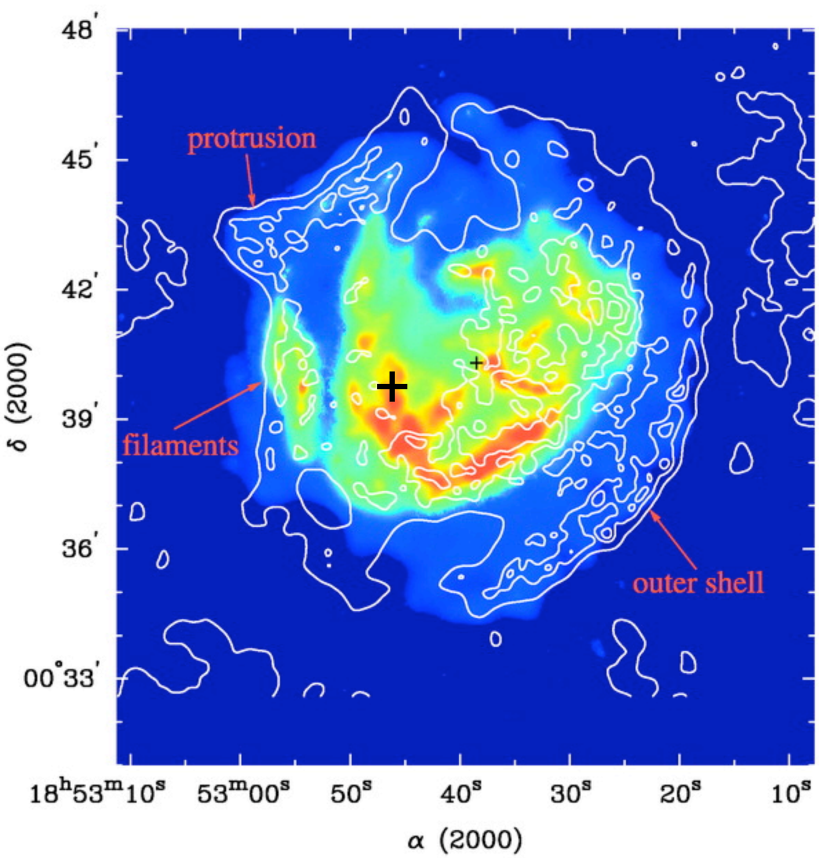
- Class I
  - Less studied, few unbiased surveys, most toward Class II
  - Collisionally-pumped maser
  - Trace both high and low SF
  - Hints that they trace earlier phases in SF than Class II
  - Associated with shocked outflows interacting with molecular gas
  - Different transitions are excited over a wide range of n_o and T

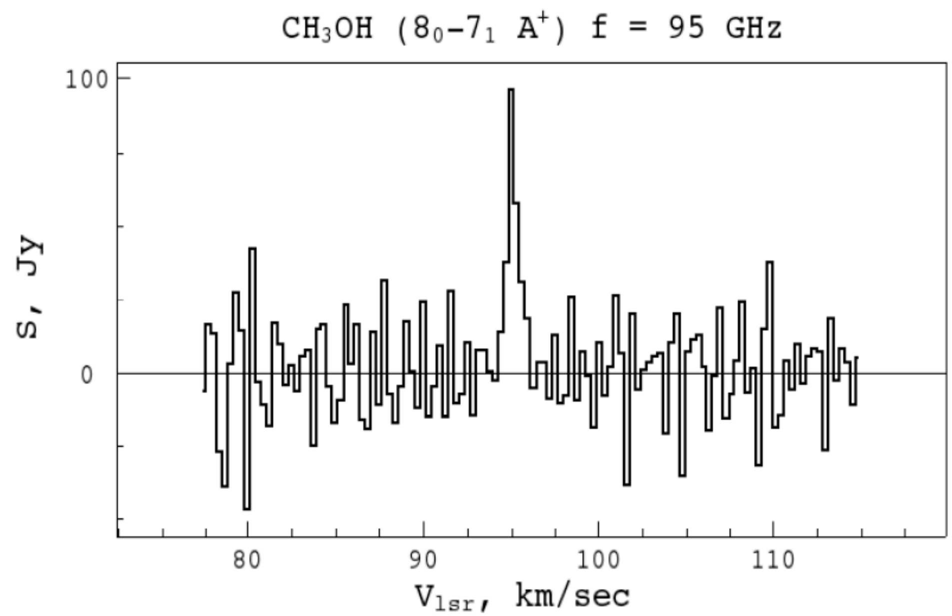


A possible new and versatile maser shock tracer?

Methanol maser detection toward Kes 79

Sun et al. (2004)

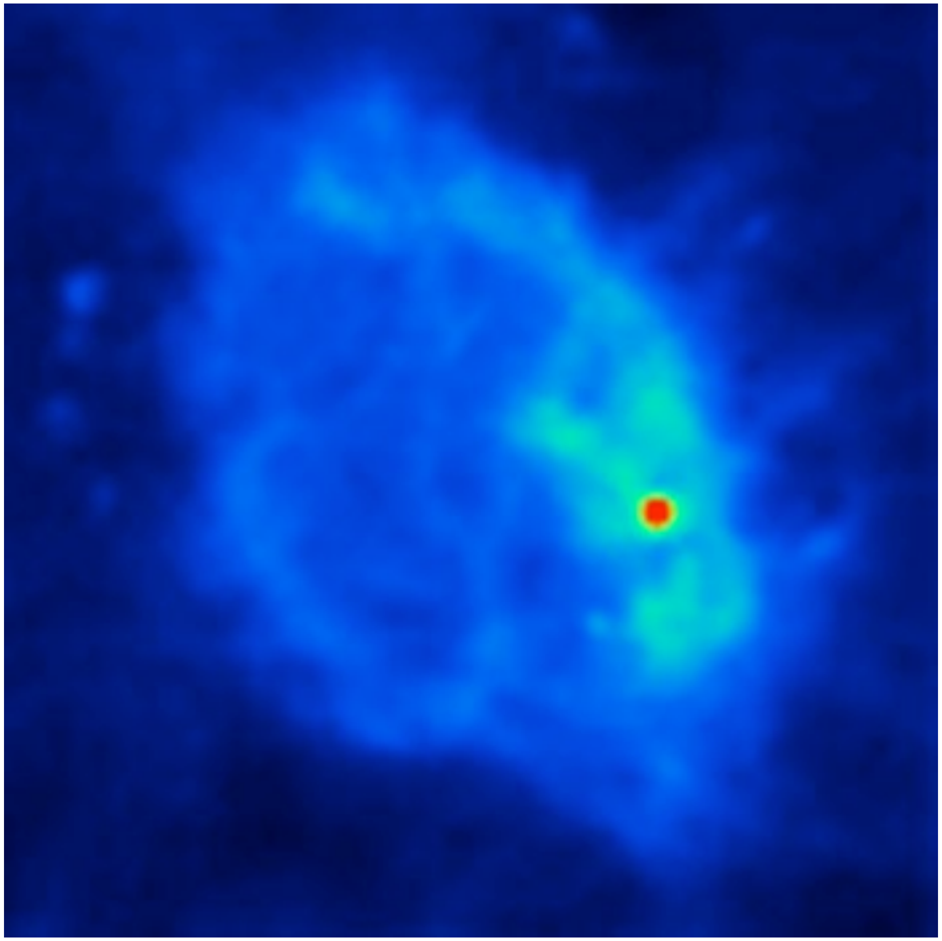


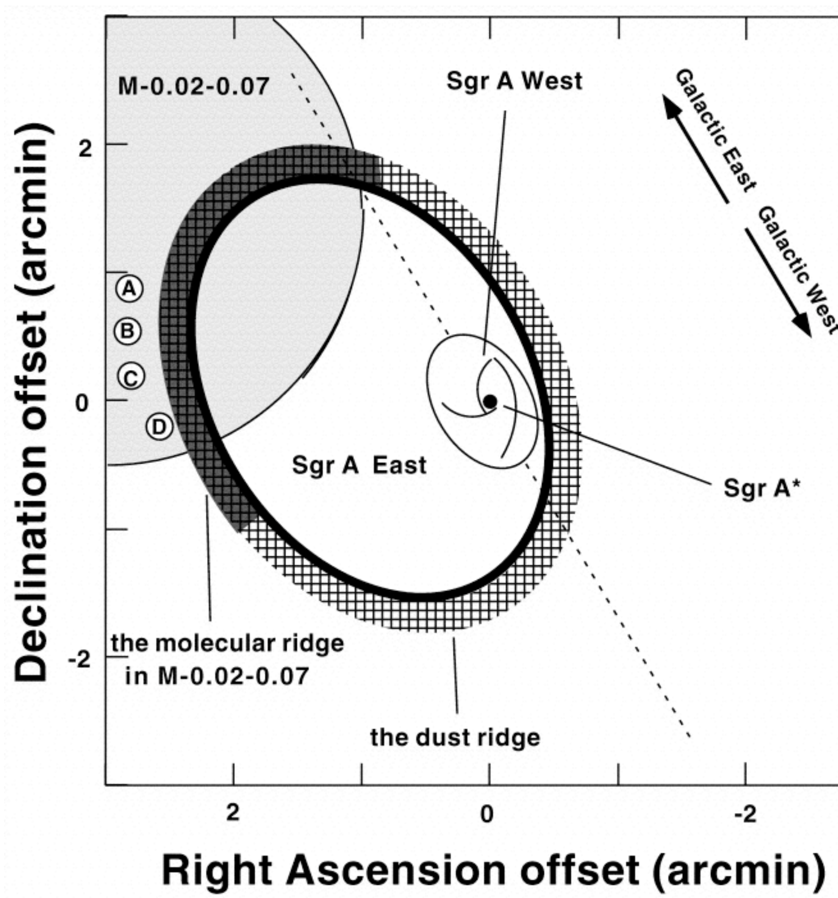


Zubrin & Shulga YSC'15 Proceedings of Contributed Papers
(eds. Choliy V. Ya., Ivashchenko G.), pp. 41-43

- RT22 detection of narrow line at 95 GHz (V=95 km/s)
- At same velocity of CO gas
- Unable to confirm with ARO 12-m and VLA

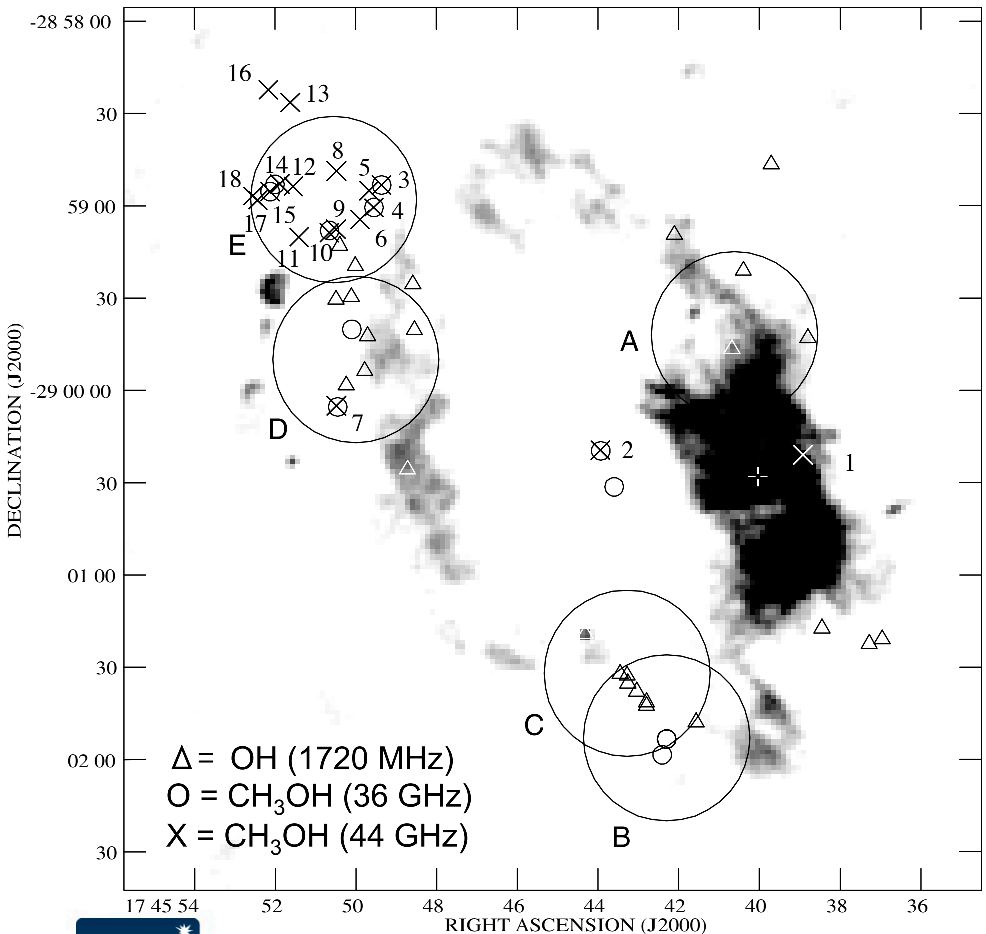
Methanol at the Galactic Center

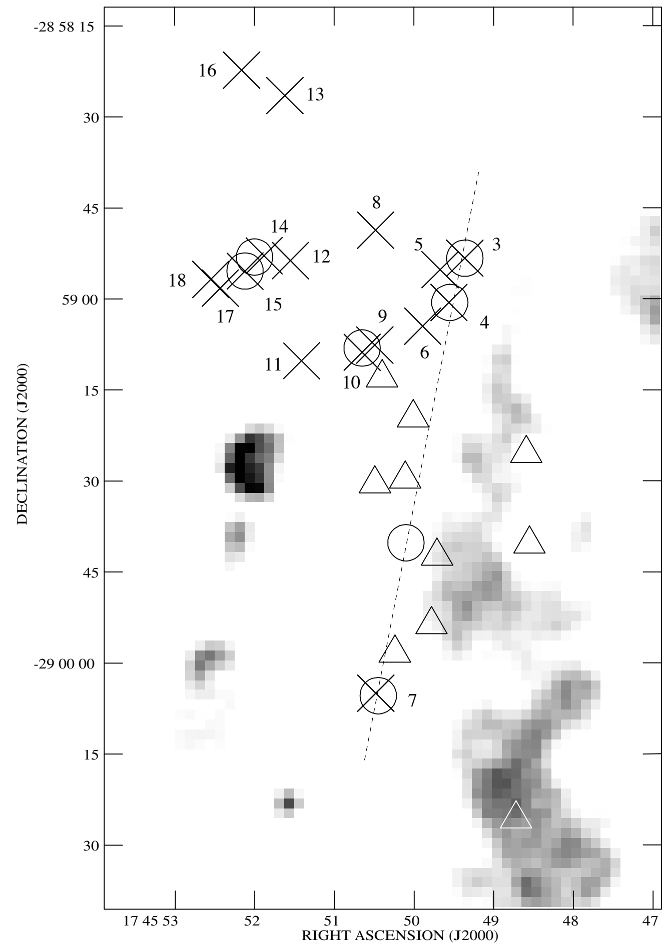




Maeda et al. (2002)

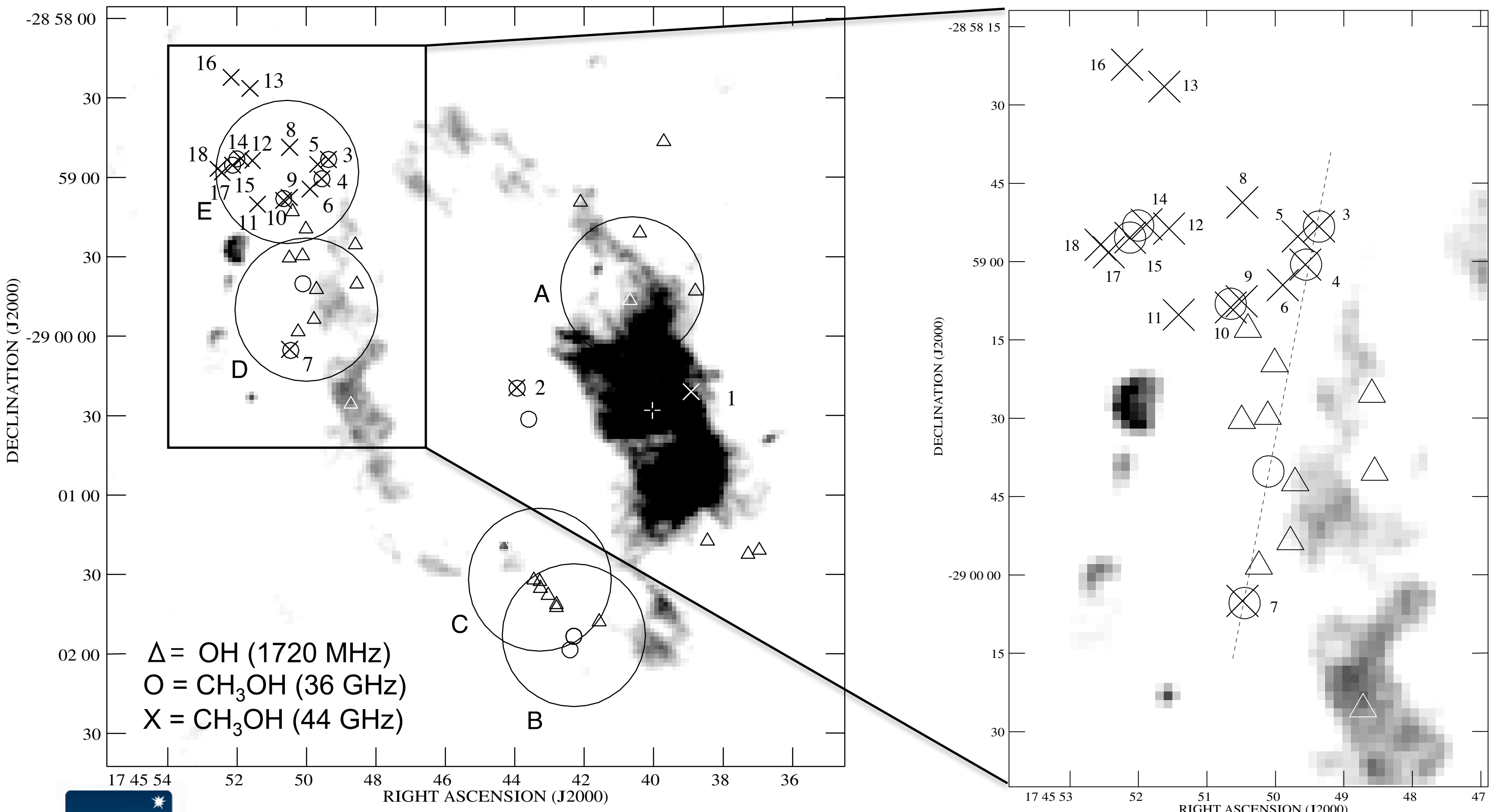
Methanol at the Galactic Center





Pihlstrom, Sjouwerman and Fish (2011)

Methanol at the Galactic Center



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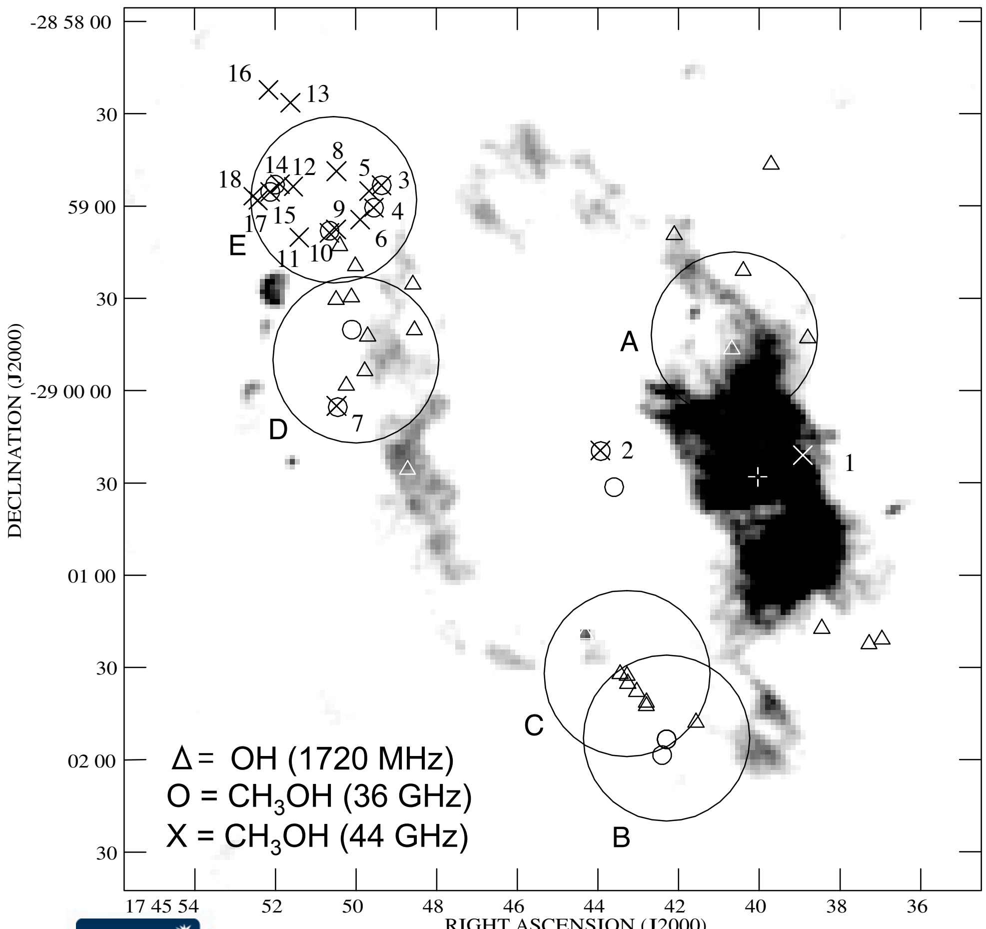
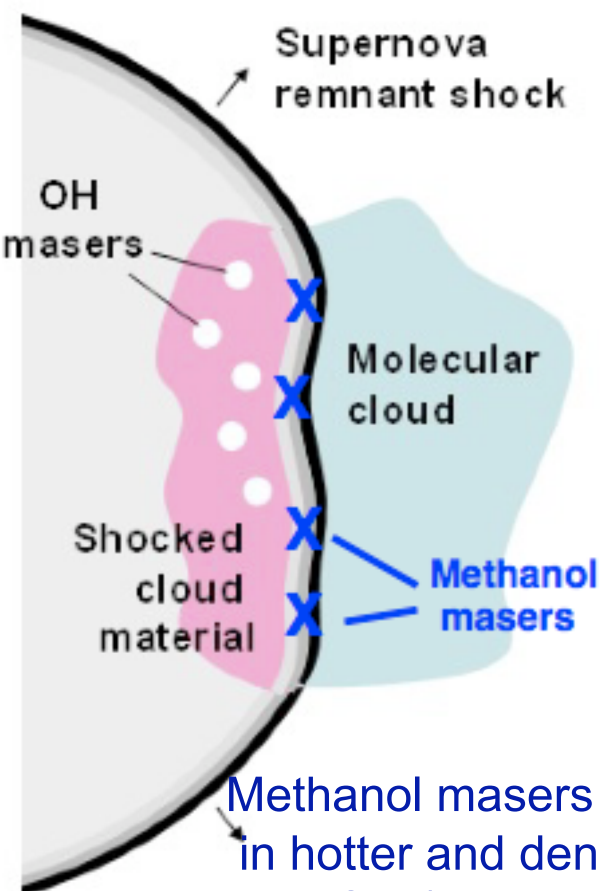
Methanol at the Galactic Center



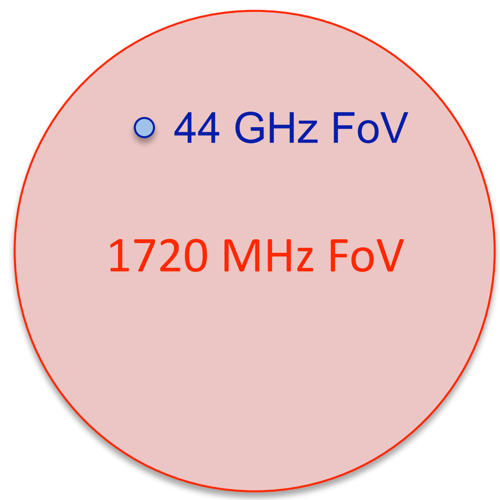


Methanol masers excited in hotter and denser gas than OH (closer to shock?)

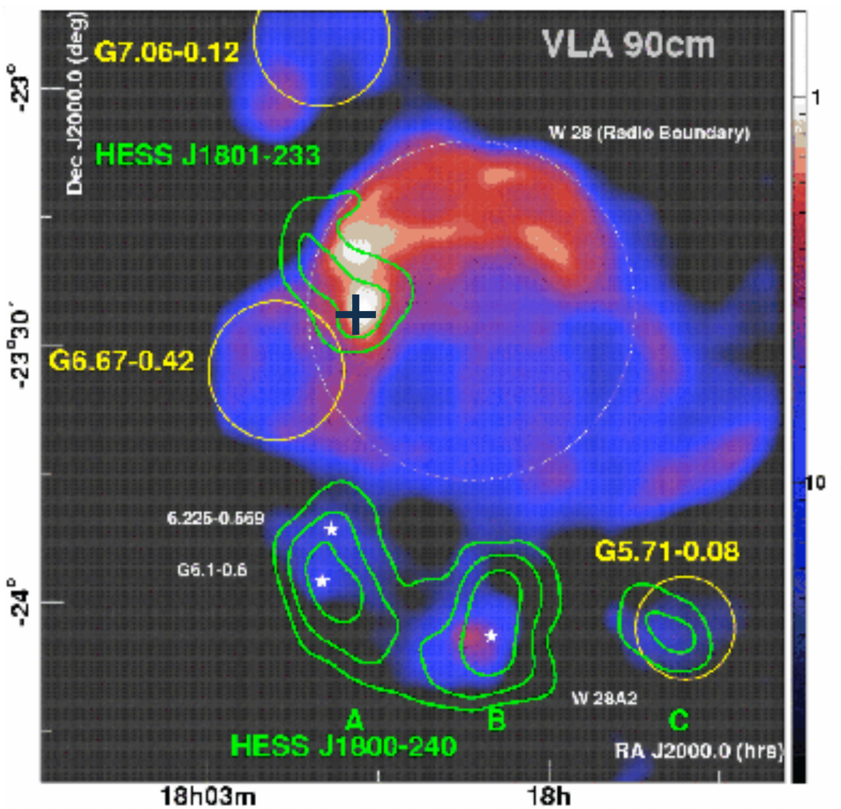
Methanol Maser Survey of SNRs

- VLA search at both 36 GHz and 44 GHz
- 21 supernova remnants searched
- Focus on OH maser sites and some TeV, GeV and CO peaks
- Biased survey. Field of view is small.
- Observing finished. Data reduction started.

- Preliminary results



Methanol Maser Survey of SNRs



Aharonian et al.(2008)

- One CH_3OH (44 GHz) maser detected toward W28 OH-D
  - Samples T=80-200 K, $n_o=10^5$-10^6 cm^{-3}
- Few OH masers in this location
- Located at the peak of TeV detections
- Looks promising as a probe

Conclusions

1. OH(1720 MHz) masers are an excellent tracer of the interaction of supernova remnant shocks with molecular clouds?
2. OH masers act as "signposts" when looking for GeV/TeV evidence of hadronic cosmic-ray acceleration.
3. OH masers give us useful constraints on distance, density and magnetic fields for testing acceleration models.
4. Class I methanol masers hold out the possibility of being more powerful maser tracer of supernova remnant molecular shocks.