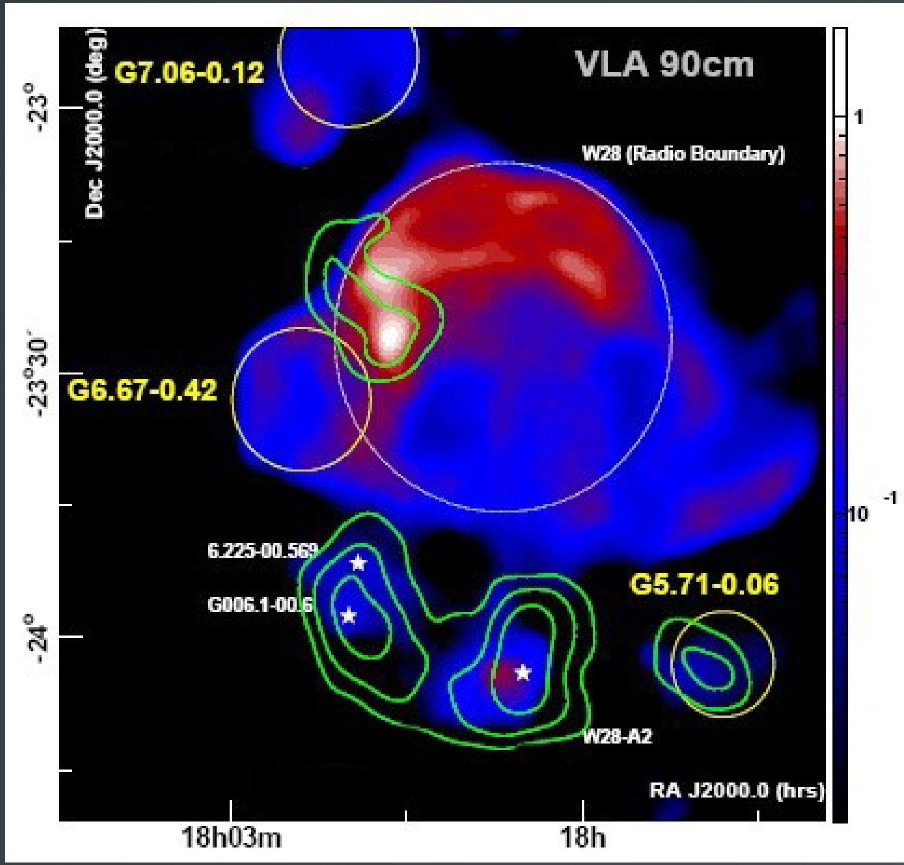
Tracing the target material of cosmic-rays towards gamma-ray sources with molecular line spectroscopy



Nigel Maxted, 2015
(LUPM Montpellier)

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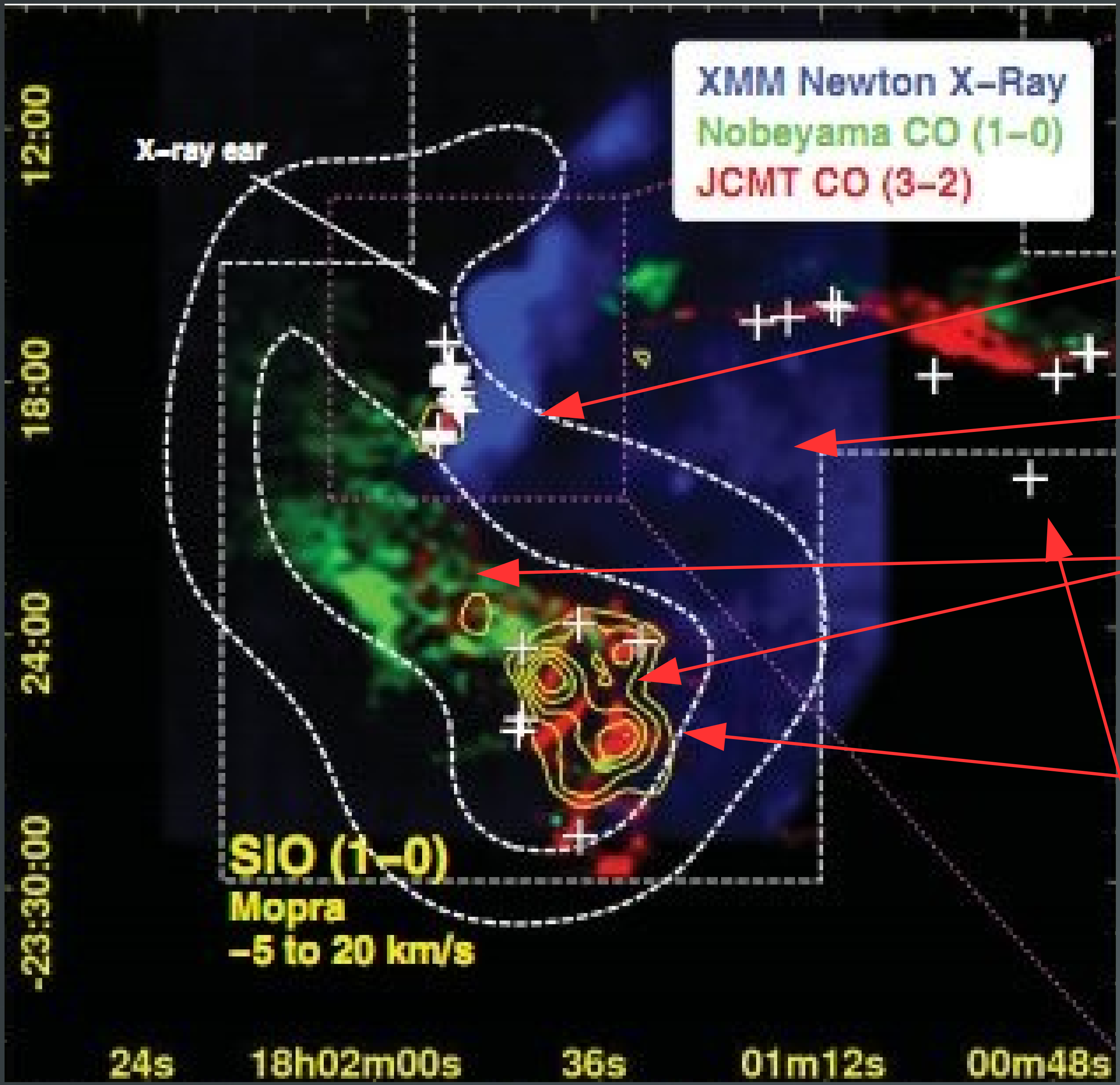


Nicholas et al 2012

White contours: TeV gamma-rays

Blue: Thermal X-rays

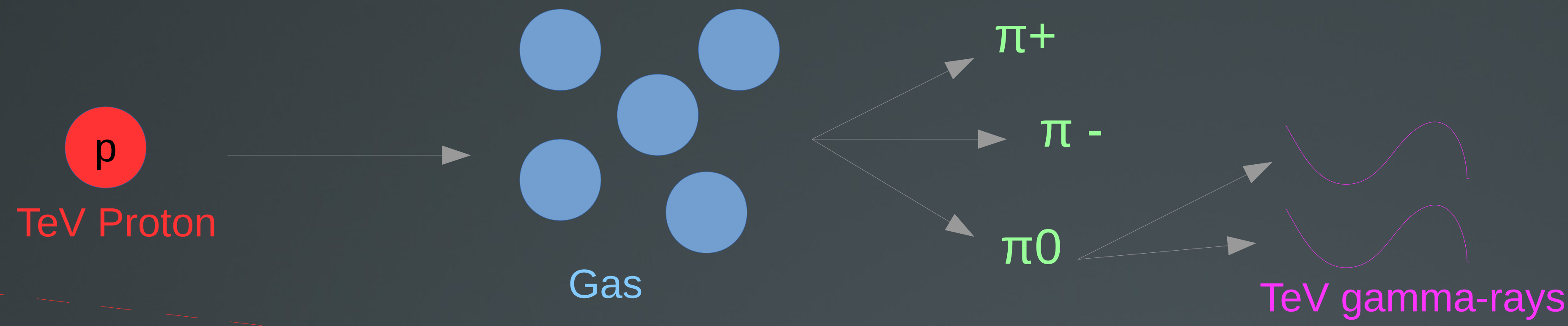
Green: CO(1-0)
Red: CO(3-2)

Yellow contours: SiO

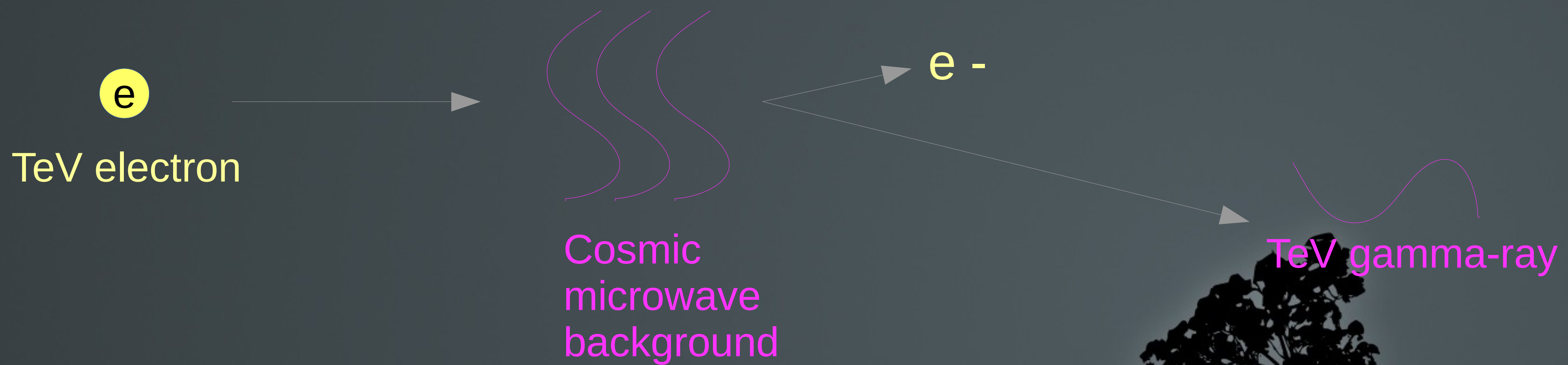
Crosses: OH masers

Gamma-ray emission from SNRS

p-p interaction:

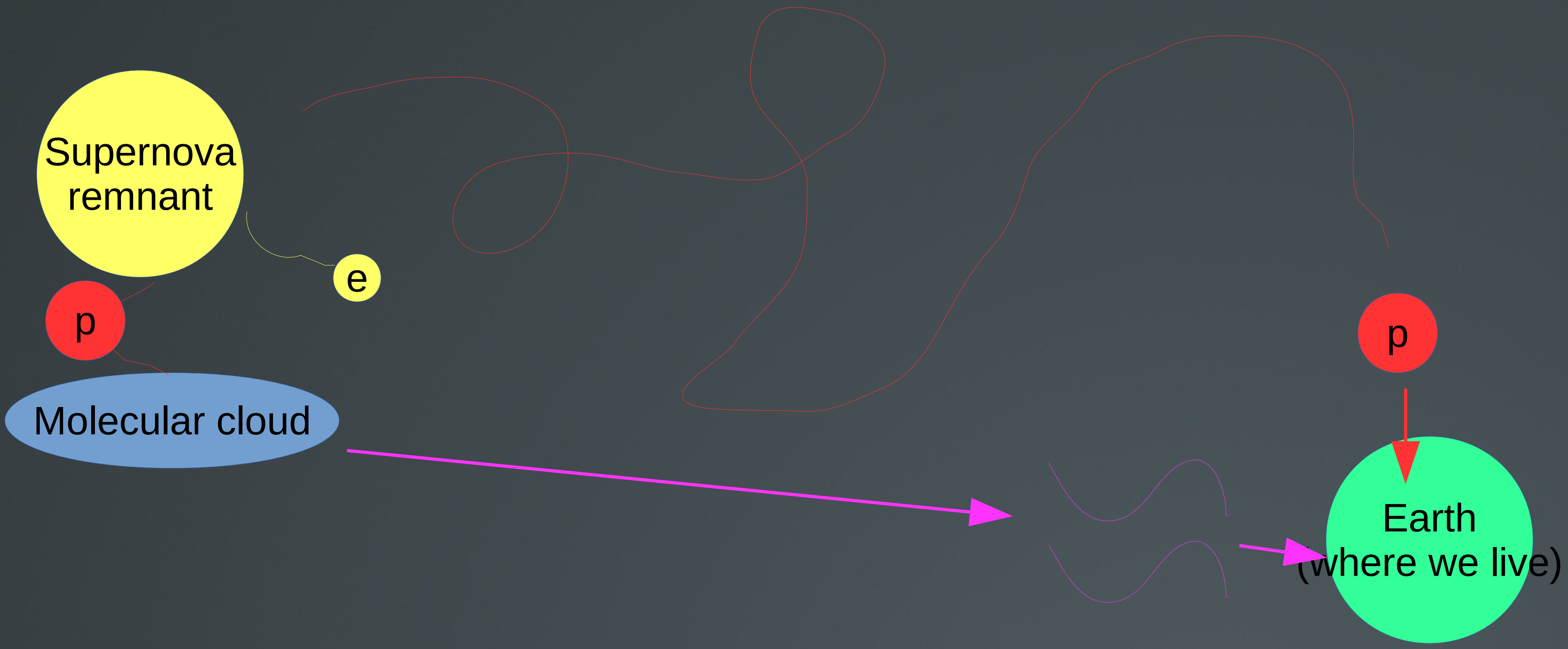


Inverse Compton Scattering:



Energy spectra?

Cosmic ray origin -theory

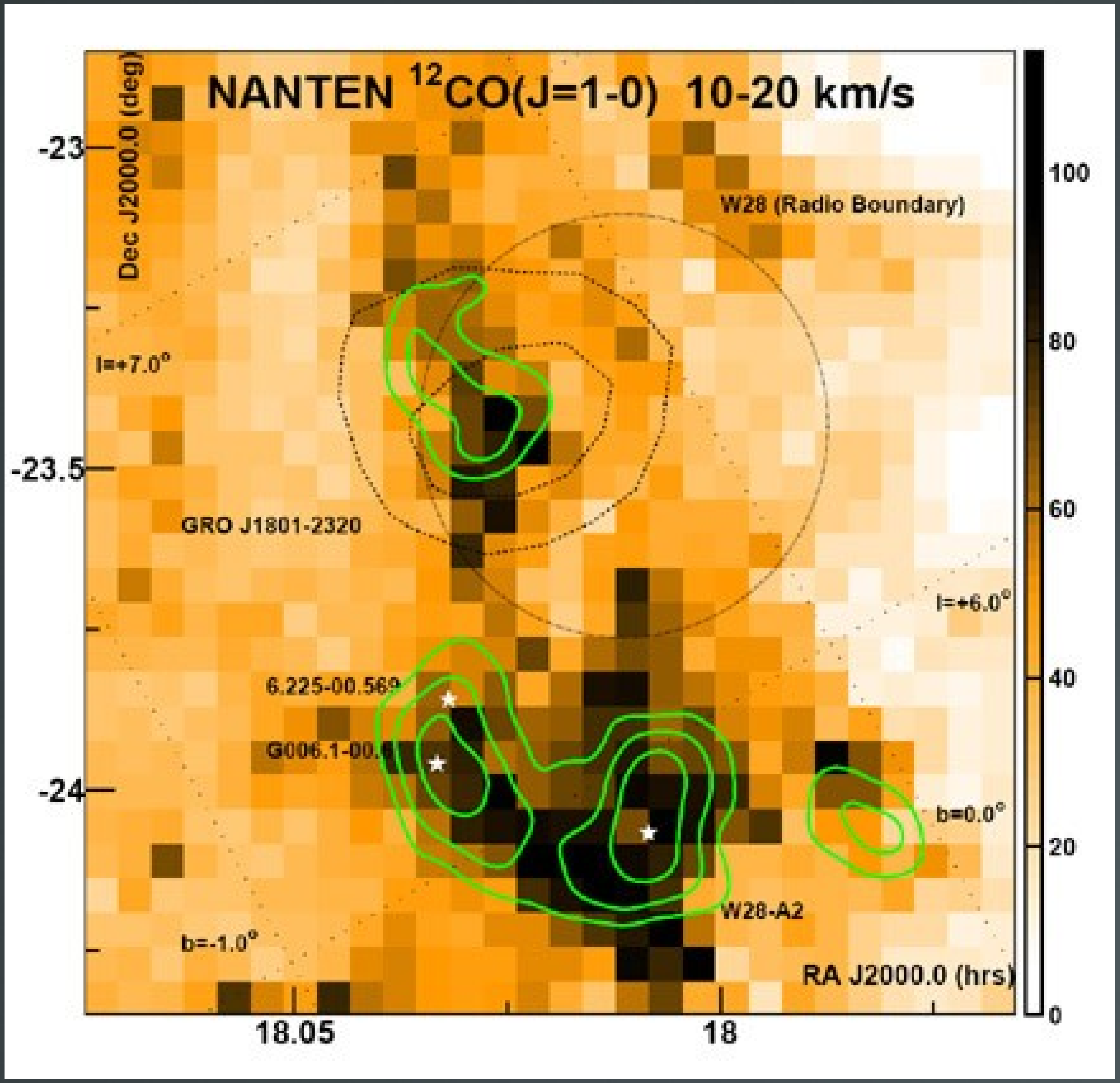


Protons are scattered by B-fields

Electrons lose energy via synchrotron quickly

Gamma-rays travel in straight lines

W28 Gamma-ray emission (and CO)



Fukui et al 2008

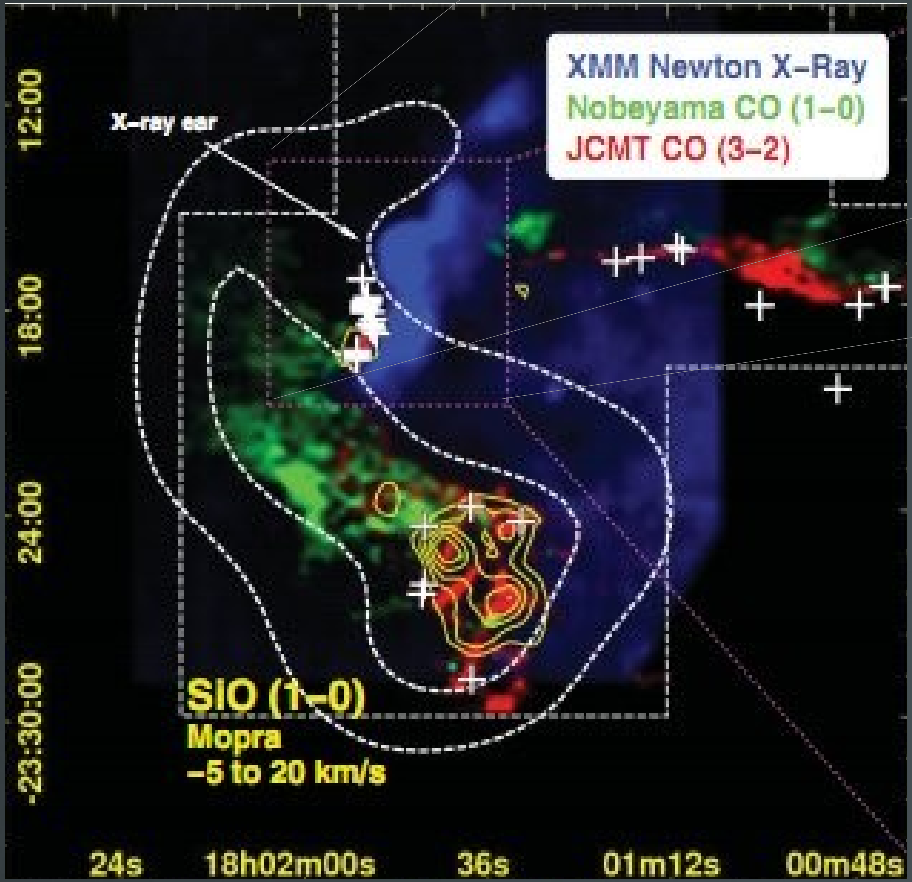
Good correlation between CO(1-0) emission and gamma-rays.

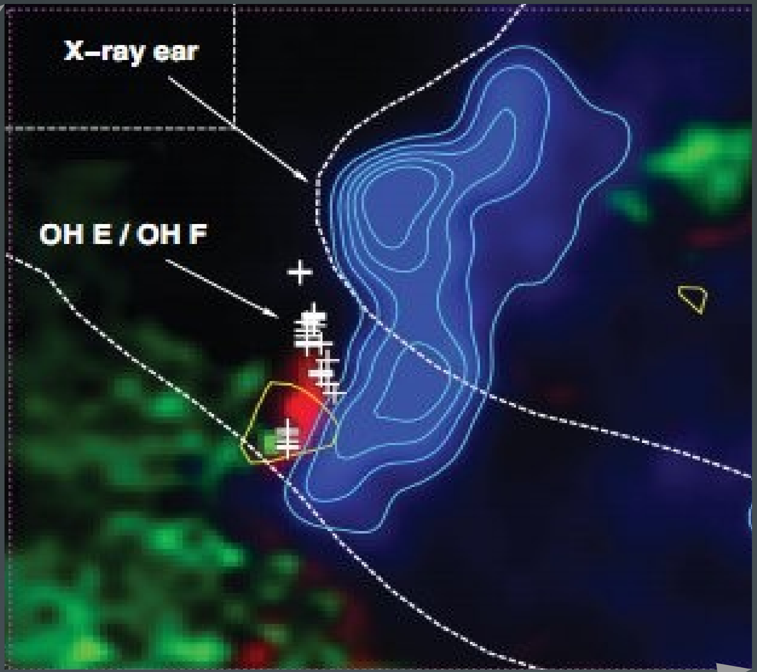
Suggestive of high energy protons (cosmic rays) interacting with gas.

Great evidence that W28 is a source of Cosmic rays!

There are some issues with this conclusion....

X-rays



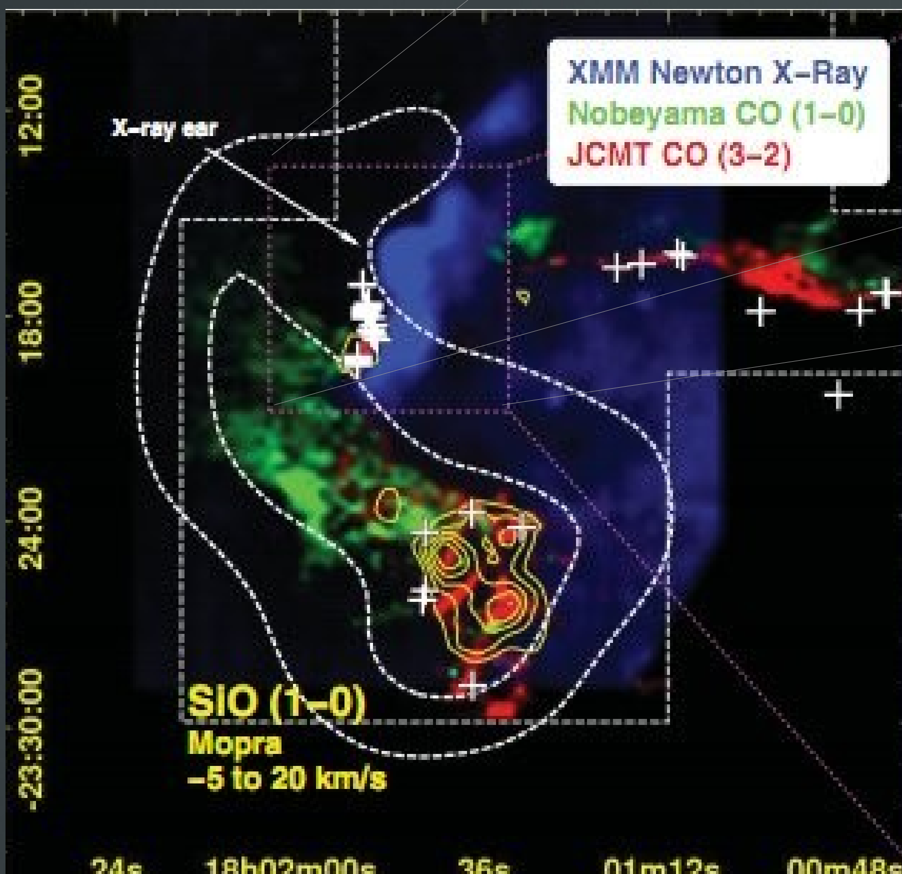


Nicholas et al 2012

Thermal X-rays (blue) are from high energy plasma

Seems to be at the cloud (green) boundary suggesting an interaction

CO Molecule

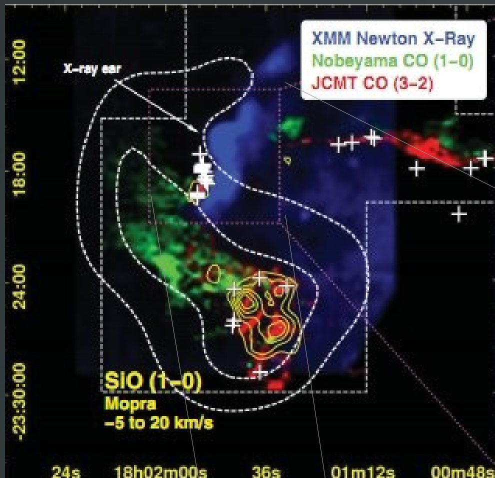


Nicholas et al 2012

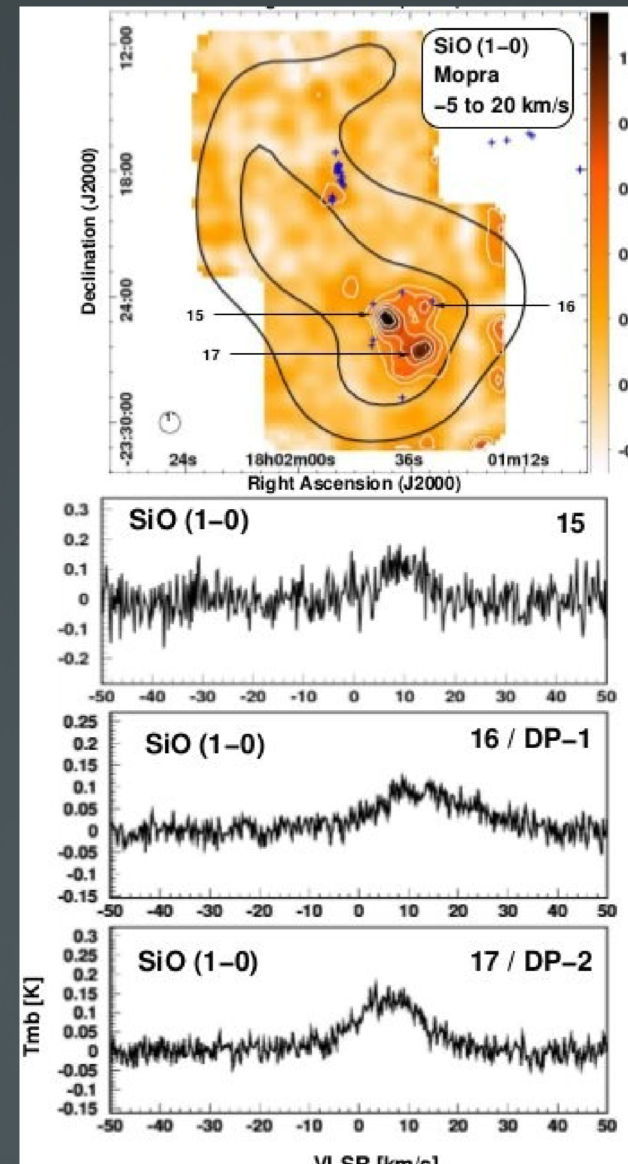
CO(1-0) shown in green
T~6 K

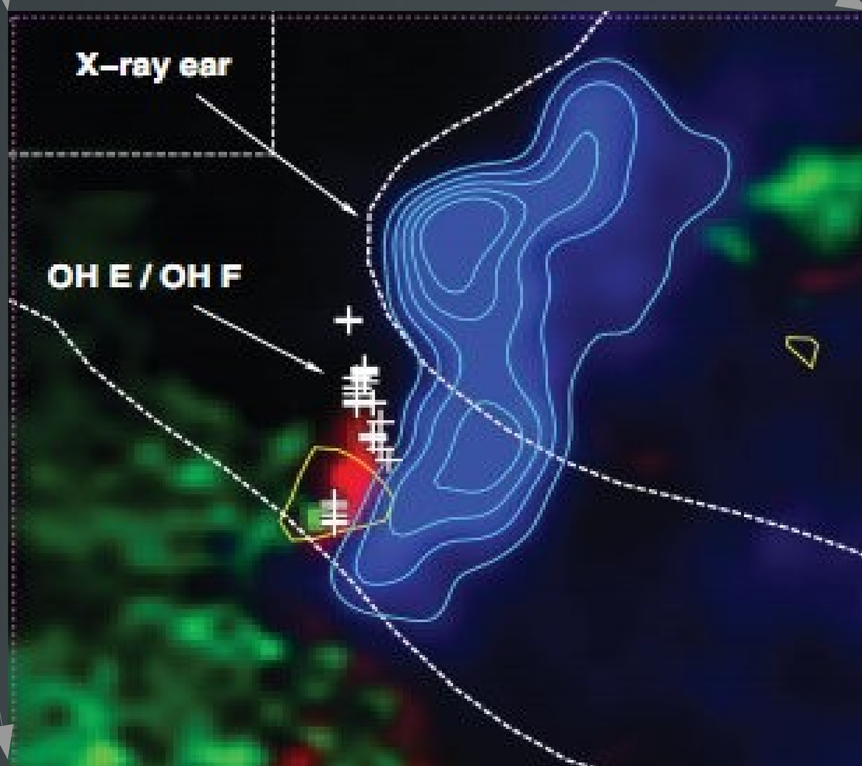
CO(3-2) shown in red
T~30 K

SiO -A shock tracer



Yellow contours are SiO(1-0) emission





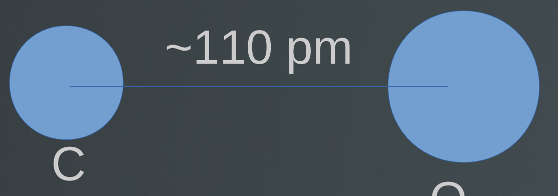
Nicholas et al 2012

CO vs SiO

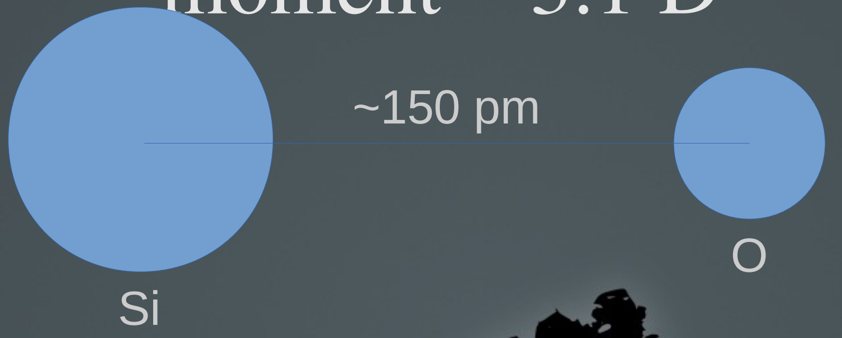
Since the shared electrons 'spend more time' with the atom with the highest electronegativity, there is a charge difference between atoms, hence a molecular dipole moment, $\mu = \delta d$ (half the charge difference * distance between bonds)

Ie, ionic species ----> highest dipole moment,
Molecular Nitrogen, N_2-----> Zero dipole moment

- CO
- Electric dipole moment ~ 0.12 D



- SiO
- Electric dipole moment ~ 3.1 D



What effect does this difference in dipole moment have?

Cold, quiescent (star-less?) core

- CO freeze-out

  (eg. L1544, L1498, L1517B)

  (Caselli et al., 1999, Tafalla et al., 2002 ,2004)

- Usually just a drop by a factor of few though..

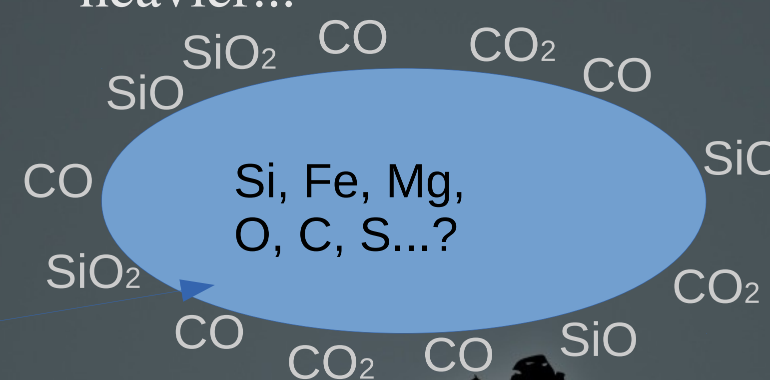
Grain composition not well constrained...
contains:
Fayalite (Fe_2SiO_4)
Fosterite (Mg_2SiO_4)
Olivine ($MgFeSiO_4$)
(Schilke et al., 1997)

- Total SiO freeze-out

  (eg. TMC-1, L1551, L34N, B335)

  (Ziurys, 1989)

- Remember that SiO is heavier...



Slightly warmer gas (say... 20-40 K)

- CO abundant in gas-phase.
- Prominent CO(1-0,2-1) emission (T~5.5,16.6 K, respectively)
- SiO not very abundant in gas-phase, still heavily depleted.

Hot Core (~100K)

- Higher-J CO transitions
- Increased (~10^{-8}-10^{-7}) SiO abundance observed in star-formation regions (~90K) Orion and NGC 7538 (Ziurys, 1989)
- Consistent with Si-release from grains and endothermic reactions:

  Si + O2 ⩾ SiO + ~

  Si + OH ⩾ SiO + ~

  with energy barrier of 111K (Langer & Glassgold, 1990)

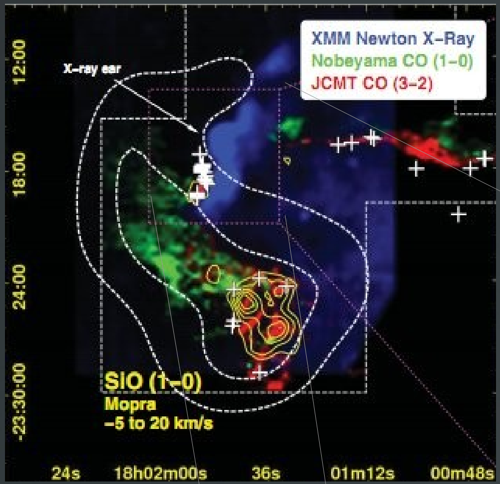
Shocked Core

- SiO released from grain-surface or Si released.
- Dust-dust and dust-gas collisions may release Si from grains (Gusdorf et al., 2008a/b, May et al., 2000)
- Dust-gas collisions may release whole SiO molecules from the outer mantle of dust grains (Schilke et al., 1997)
- Dust grains destroyed by X-ray emission (Martin-Pintado et al.,1999)

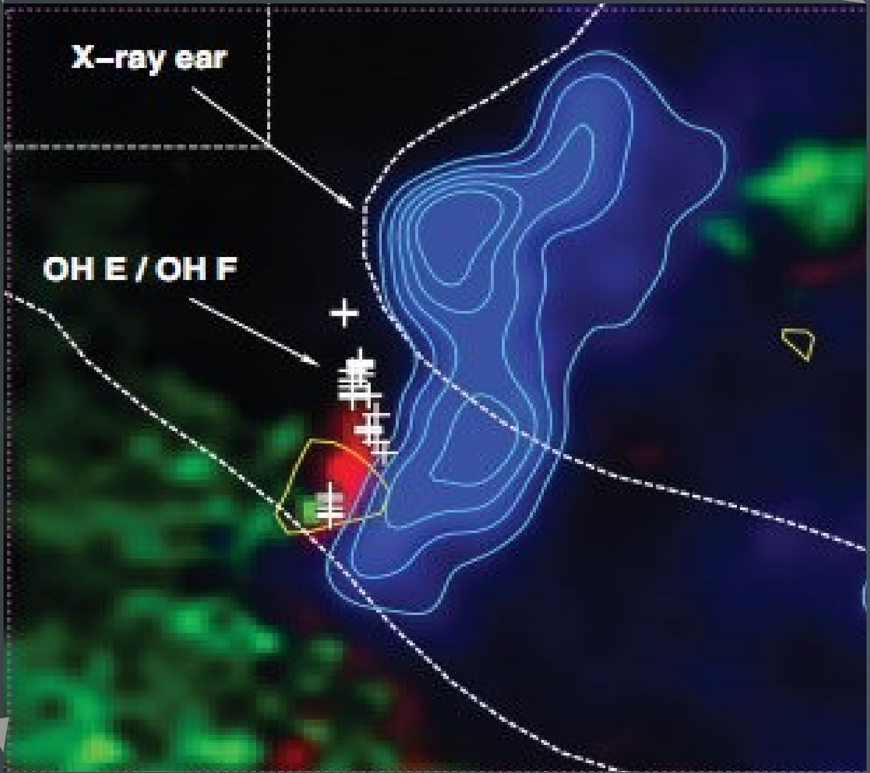
Mopra radio telescope, Australia

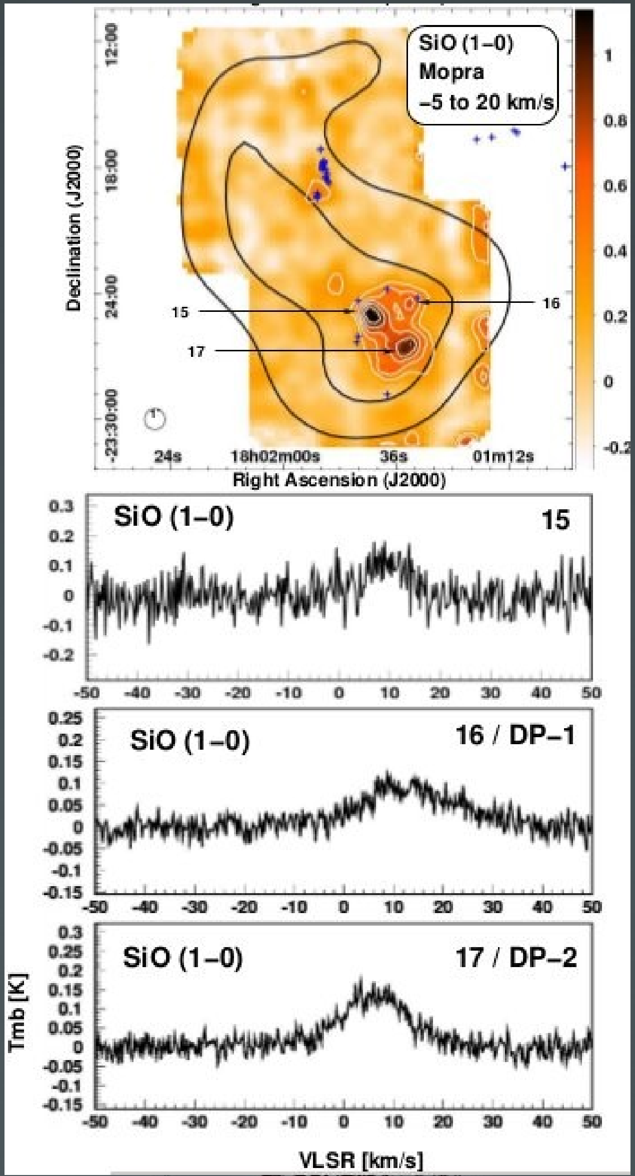
- CS(1-0)
- NH3(1,1)
- SiO(1-0)
- CO(1-0)
- CH3OH(7-6)
- HC3N
- H alpha lines
- + more

SiO -A shock tracer



Yellow contours are SiO(1-0) emission





Nicholas et al 2012

OH masers

- Shocks drive dissociation of H_2O molecules into OH
- And collisionally excite OH
- Seen towards SNRs: w28, IC443, CTB37A, W51, Sag A east, + more..

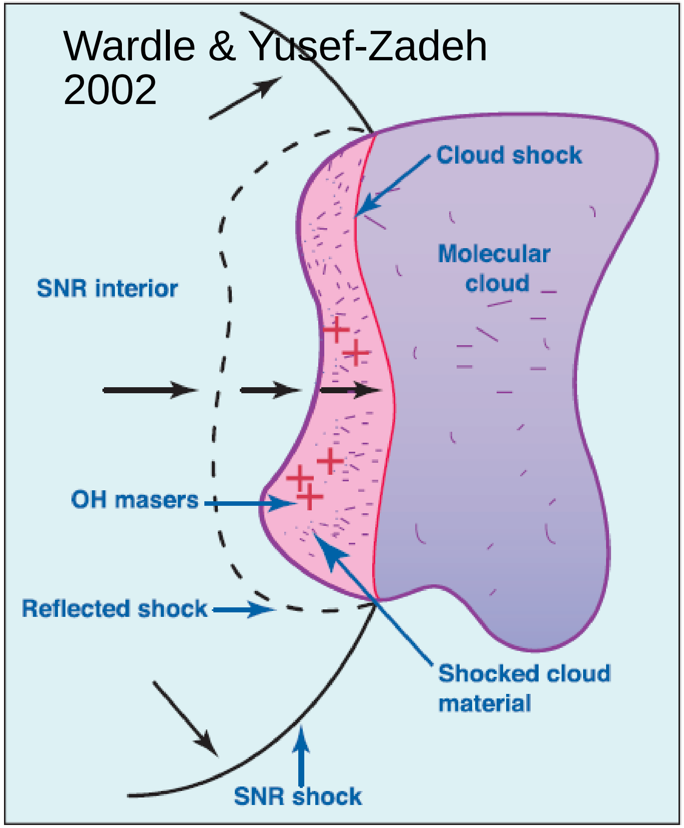
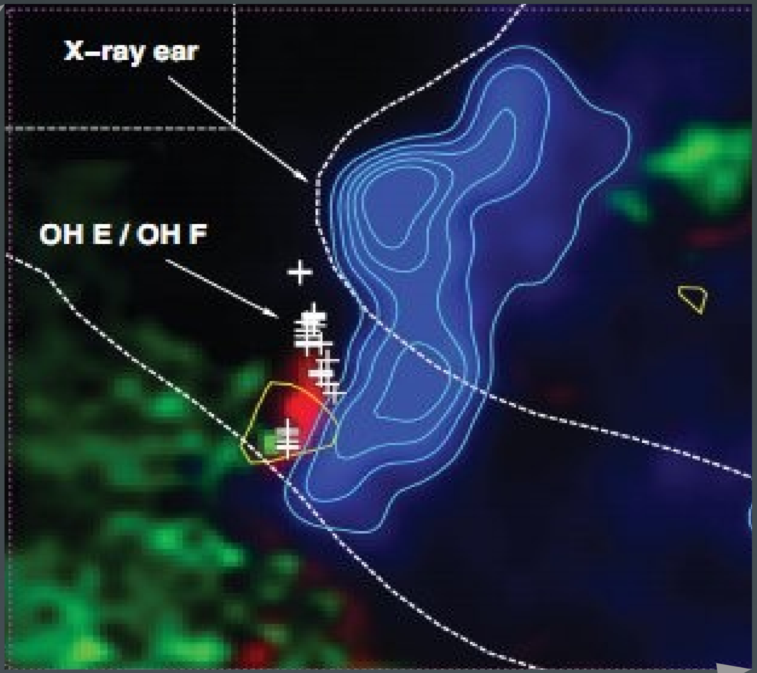
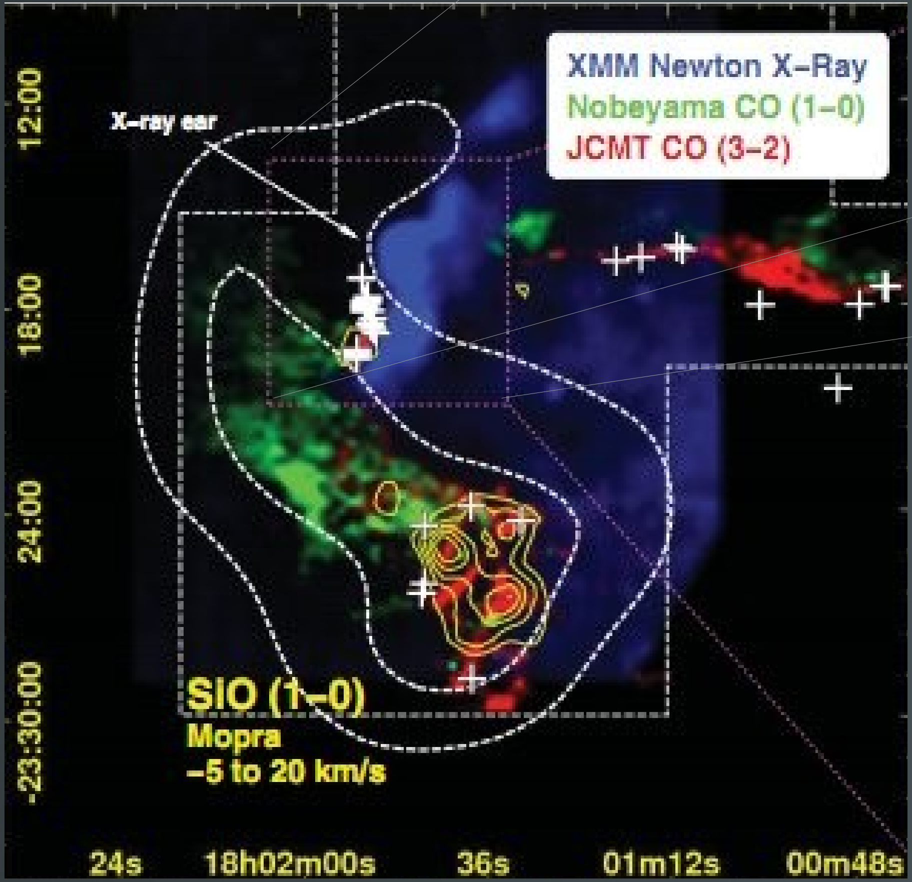


Fig. 1. Schematic of an expanding supernova remnant (SNR) interacting with an adjacent molecular cloud. Black arrows indicate velocity.

OH masers



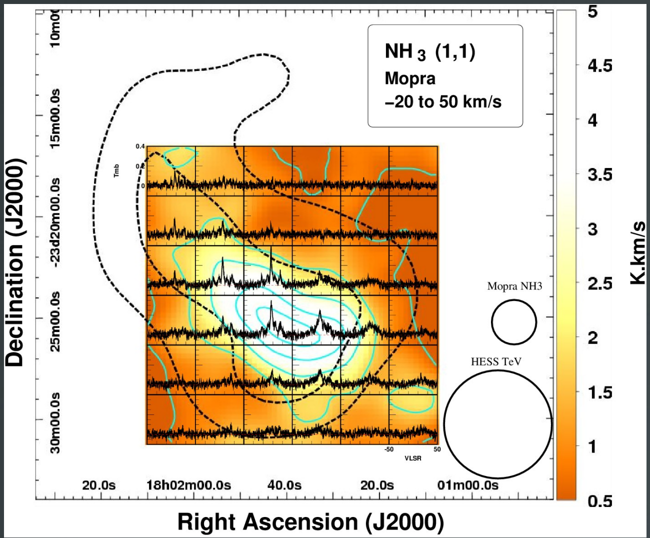


Nicholas et al 2012

White crosses: OH masers

Future work

Specifically for W28:

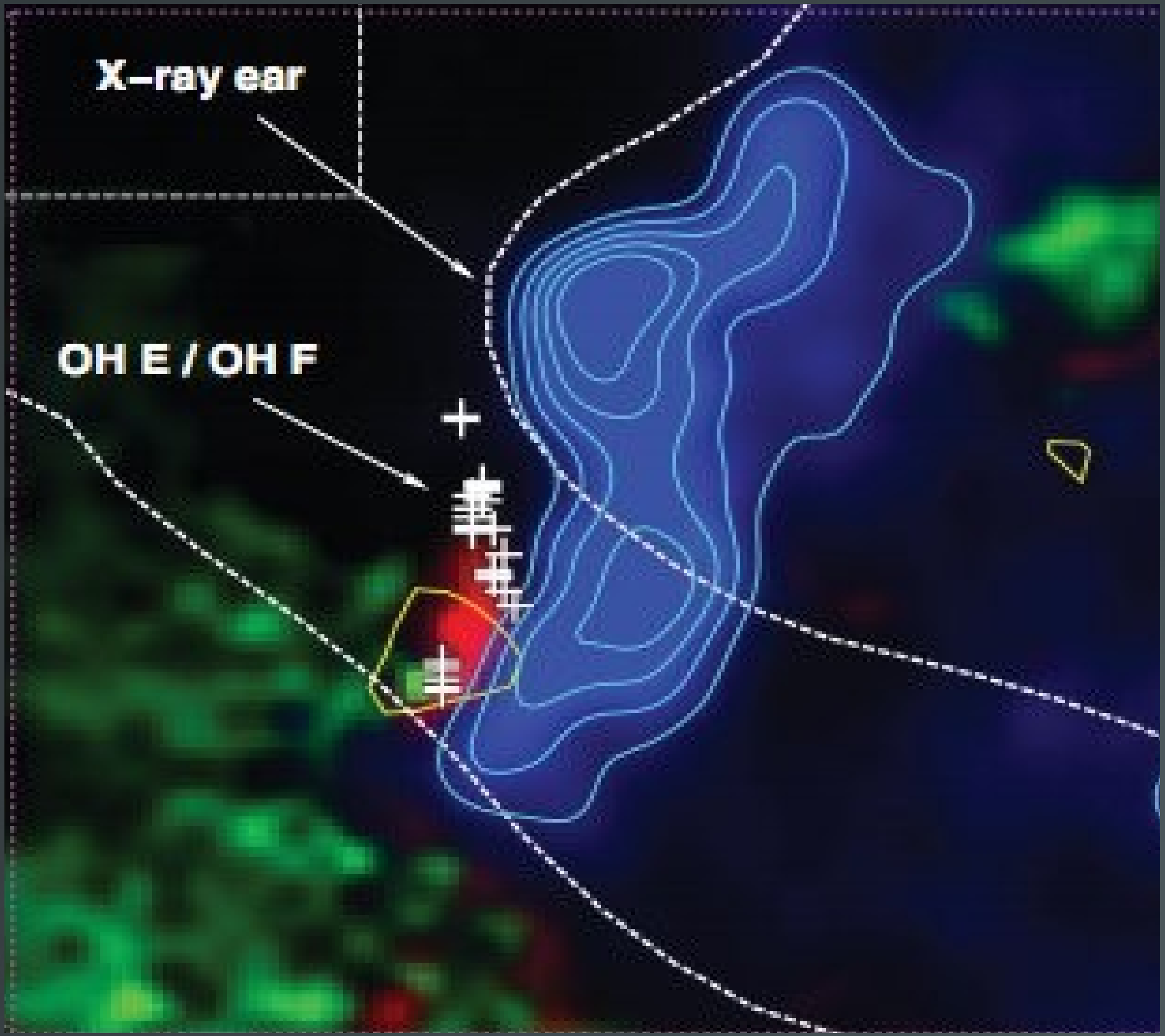


Maxted et al, in prep.

Generally:

- Scrutinise the entire population of gamma-ray supernova remnants.
- Calculate upper limits for SiO and OH maser emission towards SNRs with non-detections.
- Investigate the relation between SNR age and molecular emissions.

Summary



A supernova remnant is seen in radio continuum and X-rays.

A molecular cloud traced is by CO(1-0) emission.

Shocked gas is indicated by OH masers and SiO(1-0) emission.

Shock heating of gas is seen by CO(3-2) emission.

A generally good correspondence between gas and gamma-ray emission is observed, suggesting emission from p-p interactions.

W28 is a cosmic ray source?

Thank you

Back-up Slides

Gamma-ray spectra

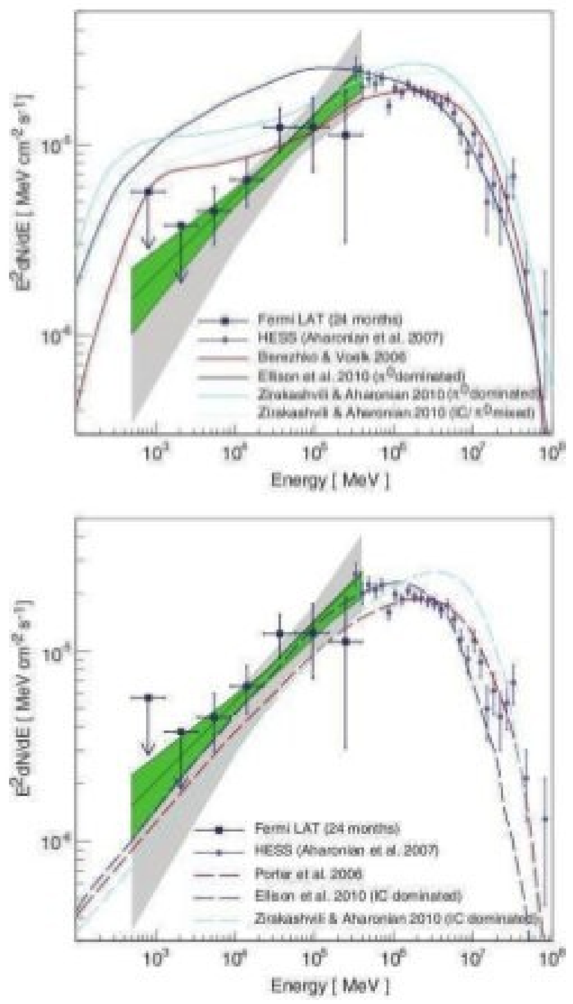


Figure 1.6: Two Spectral Energy Distributions (SEDs) taken from Abdo et al. (2011). Images include HESS and Fermi gamma-ray data points. The top image includes hadron-dominated SED models (authors indicated) predicted from HESS data, whereas the the bottom image includes lepton-dominated SED models (authors indicated) predicted from HESS data. The modeled SEDs pre-date the Fermi data-points, so may be considered predictions for the level of gamma-ray emission in the ~1-100 GeV range.

When do our molecules emit?

- Things to consider:
  - The chemistry of the environment. How does molecular abundance vary?
  - What is the phase of the molecule?
  - Will the molecule become excited?
  - Will the molecule de-excite RADIATIVELY?

OH

The former case of a non-dissociative shock propagating through high density material (10^4-$10^5\,cm^{-3}$) is considered to be particularly promising (Frail et al., 1998). This involves a high-temperature (~1 000 K) post-shock region that produces a significant column density of OH (Draine et al., 1983). As the gas cools (to ~400 K) OH is converted into H_2O, but the high OH column density can be maintained if conditions are right for the simultaneous destruction of H_2O molecules, possibly caused by X-ray emission from the inner SNR region (Wardle et al., 1998, 1999). This would allow for a population of OH molecules to be kept at a temperature of 100-200 K in the post-shock region.

1720 MHz OH masers are expected to be most intense perpendicular to the direction of the shock-motion because the column density of the shock-excited, population-inverted OH molecules is largest here, while the velocity-dispersion of the emitters is smallest. It follows that the line-of-sight velocity of these masers generally represent the systemic velocity of gas associated with the object that injected the shock.

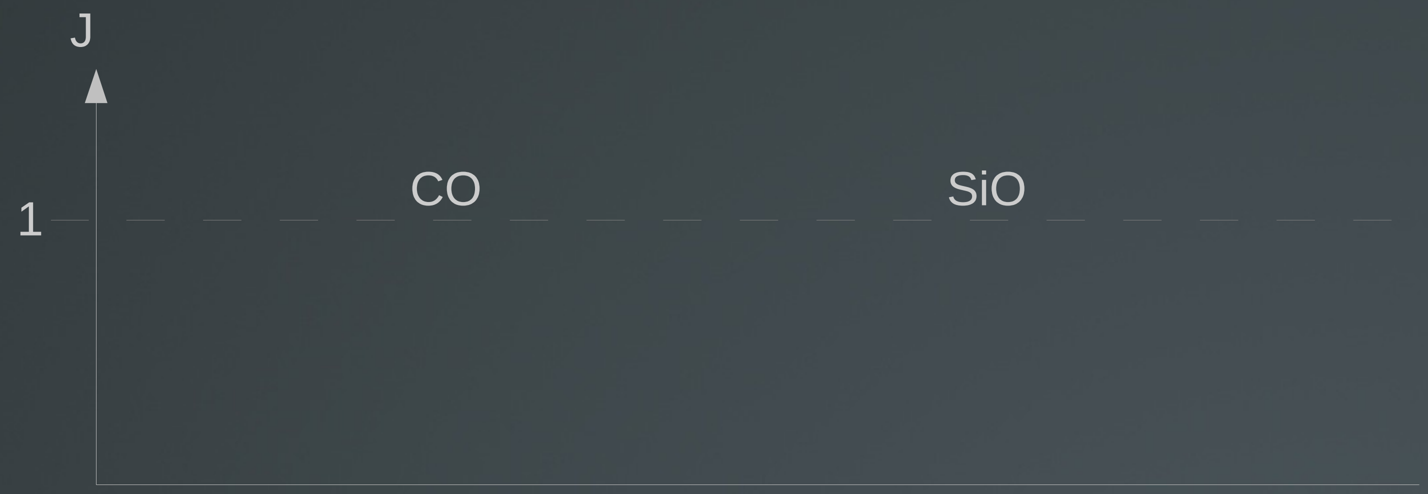
Maxted et al 2013

CO vs SiO

- CO
- Low electric dipole moment
- Critical density for emission ~1.10^{3} cm^{-3}
- High abundance everywhere except cold, starless cores.
- Good general H2 tracer

- SiO
- High electric dipole moment
- Critical density for emission ~6.10^{4} cm^{-3}
- Si and SiO released from dust grains in energetic environments
- Si is manufactured into SiO at high (~100K) temperatures
- Good shock-tracer

2 Excited Molecules



- Some amount of time will pass before these 2 different molecules in the J=1 state will decay.

  How much time??

Einstein A-coefficient from state i to j for linear molecule

$$A_{ij} = \frac{64\pi^4}{3c^3}\frac{\nu_{ij}^3}{h}|\mu|^2$$

Dipole moment

Frequency

- Describes the rate (/s) of decay.
- Spontaneous decay rate proportional to (frequency)^3 and (Dipole moment)^2

CO(J=1-0) vs SiO(J=1-0)

- CO(J=1-0)
- Electric dipole moment ~ 0.12 D
- Frequency ~115 Ghz
- $A_{10}\ \alpha\ v^3\mu^2$

$A_{10} \sim 7.45 * 10^{-8}$ /s

- SiO(J=1-0)
- Electric dipole moment ~ 3.1 D
- Frequency ~43 Ghz
- $A_{10}\ \alpha\ v^3\mu^2$

$A_{10} \sim 3.05 * 10^{-6}$ /s

Therefore, SiO(J=1) decays (with emission) ~40 times faster than CO(J=1).

$$A_{ij} = \frac{64\pi^4}{3c^3}\frac{\nu_{ij}^3}{h}|\mu|^2$$

Collisions

- Once a molecule is collisionally excited (let's ignore radiation...), spontaneous decay (A_{10}) must compete with collisional de-excitation (C_{10}).
- Note that if the kinetic temperature is larger than the transition energy (~5 K, usually is), C_{01} is generally comparable, but larger than C_{10}
- Define a point where spontaneous decay is as likely as collisional de-excitation,
    - A ~ C, Or A/C ~1
        - $C_{10} = k_{10}(T) \cdot n_H$

          (/s) (cm^3/s) (cm^{-3})

Collisions

- So at the point where $A_{10} \sim C_{10}$,

  $A_{10}/C_{10} \sim 1$

  $A_{10} / (k_{10}\ n_H) \sim 1$

- Rearrange to get the 'Critical density'

  $n_H \sim A_{10} / k_{10}$

  where $k \sim \sigma\ v$, v is M-Boltzmann, $v \sim \mathrm{sqrt}(2kT/m)$

CO(J=1-0) vs SiO(J=1-0)

- CO(J=1-0)

  $A_{10} \sim 7.45 * 10^{-8}$ /s

- $k_{10} = \sigma v = \sigma.\mathrm{sqrt}(2kT/m)$

  $k_{10} \sim 5.10^{-11}$ cm^3/s

- Critical density

  $\sim 1.10^3$ cm^{-3}

- SiO(J=1-0)

  $A_{10} \sim 3.05 * 10^{-6}$ /s

  $k_{10} \sim 5.10^{-11}$ cm^3/s

- Critical density

  $\sim 6.10^4$ cm^{-3}

Therefore, all else being equal, CO(1-0) emission is characteristic of smaller density than SiO(1-0) emission (in thermal cases, at least)

What about abundance?

- C is ~7 times more abundant than Si, but this certainly doesn't mean [CO]/[SiO]~7
- [CO]/[H_2]~10^{-5}, [SiO]/[H_2]~10^{-12} -10^{-7}...?
- We don't just care about abundance, but we care about GAS-PHASE abundance