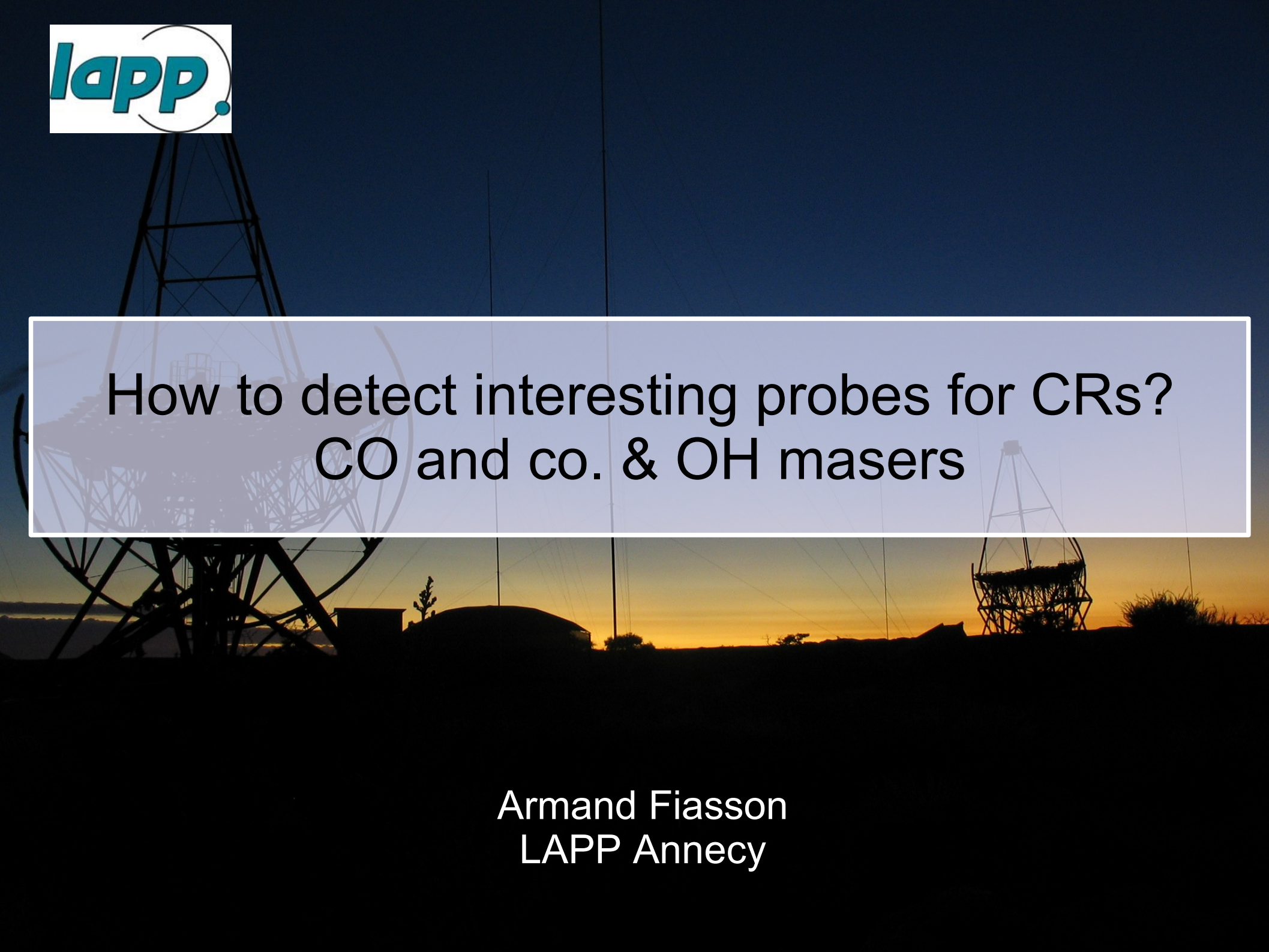
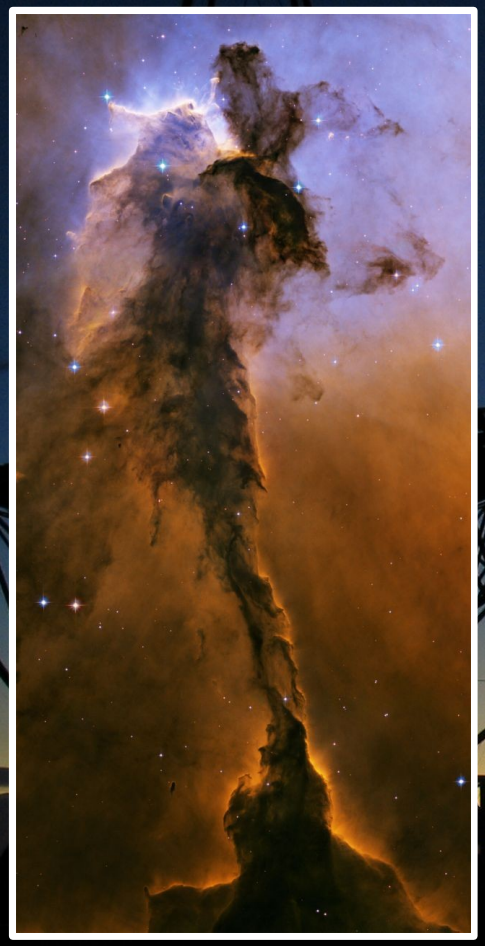


How to detect interesting probes for CRs? CO and co. & OH masers

Armand Fiasson
LAPP Annecy

Molecular Clouds - Introduction



The molecular clouds are major components of the ISM

- **Cold matter => T~10-20 K**
- **Neutral molecular matter: mainly H_2**
- **ISM phase with the highest density**
  - Density above a few 10 cm^{-3} up to 10^6 cm^{-3}

=> When integrated over 10 pc scale: Very massive target!!

What is the molecular cloud color?

Three type of transitions can be observed from molecular matter

- **Transitions between molecule electronic levels**
  - Most of them in the UV
- **Vibrationnal transitions**
  - Most of them in the IR
- **Rotationnal transitions**
  - Most of them in radio to millimetric
  - Not possible with electrically symetric molecules (no dipolar emission, only faint quadrupolar emission)

The nature of these clouds gives strong constraints on their visibility

- **T ~ 10-20 K => visibility in the range radio – millimetric wavelength**

  => Only the rotationnal lines can produce a visible emission
- **Main constituent = H_2**
  - No electric dipole => no rotationnal line

CO lines

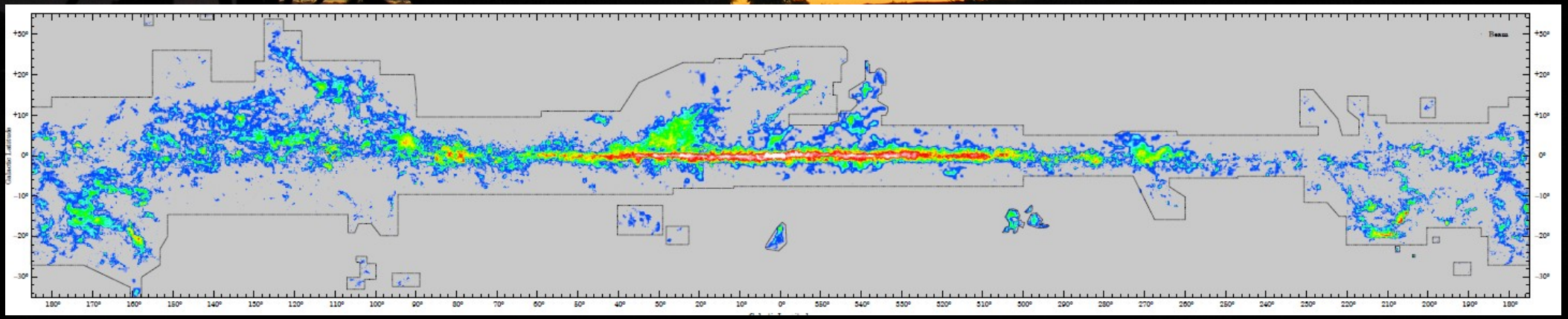
- **The molecule H_2 does not radiate from molecular cloud**

  => Other non symetric molecules present within the clouds have to be used

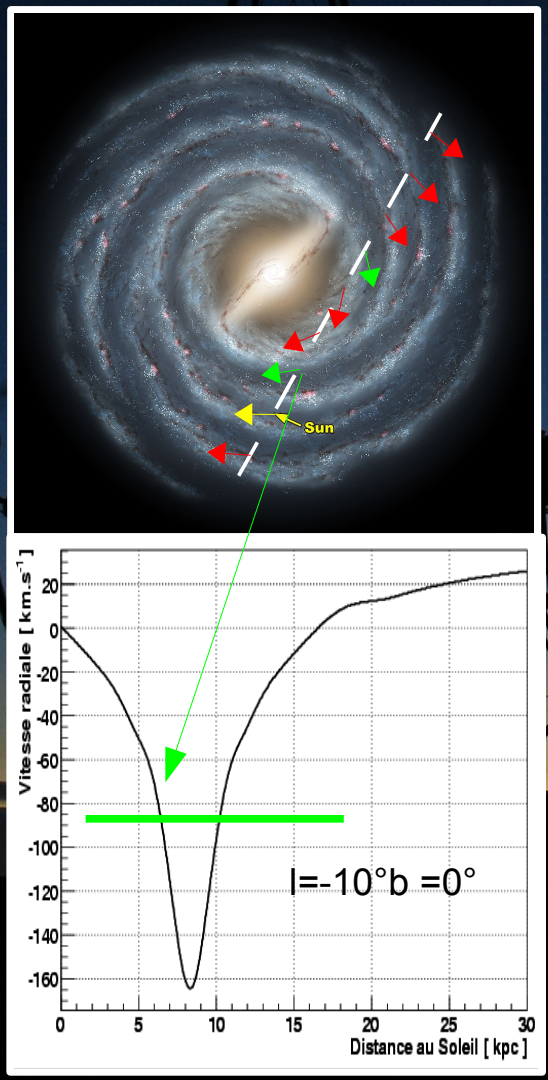
- **Several molecules/radicals have been detected within molecular lines: CH OH CN NH_3 ...**

- **Carbon monoxyde CO is the most abundant molecule after H_2**
  - Majority of C in gazeous phase is present as CO
  - Rotationnal lines in millimetric domain

    => Excitation by collision with H_2



Molecular Cloud Location

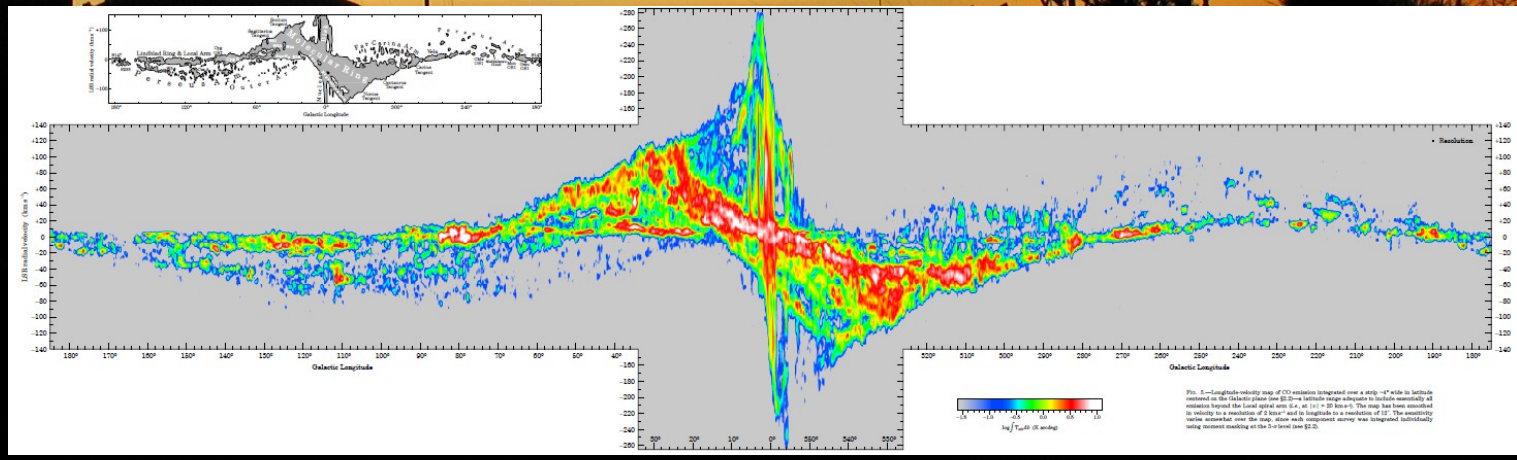


- **The clouds rotate around the Galactic Center**
  - Doppler effect of the lines

    => Can be converted in relative velocity
- **Rotation model predicts the relative velocity as a function of the distance to the Sun**

  But some degeneracy in the inner part of the Galaxy!

  => Distance between the Sun and the cloud quite well estimated



Molecular Cloud Mass

Line intensity is proportionnal to the cloud column density

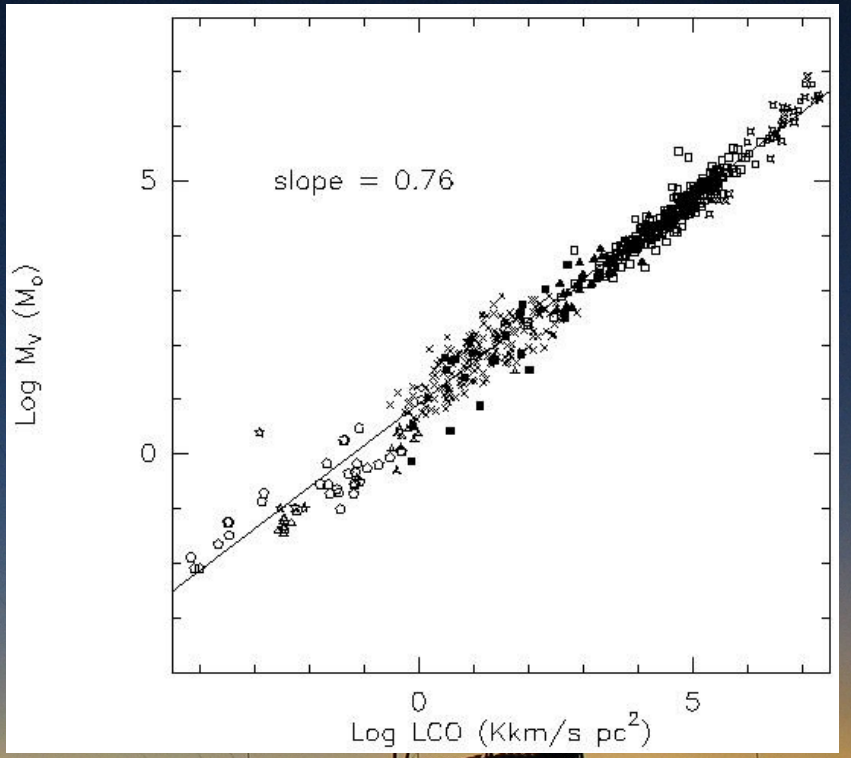
=> Cloud mass estimated assuming the Viriel equilibrium proportionnal to the CO line for closeby clouds

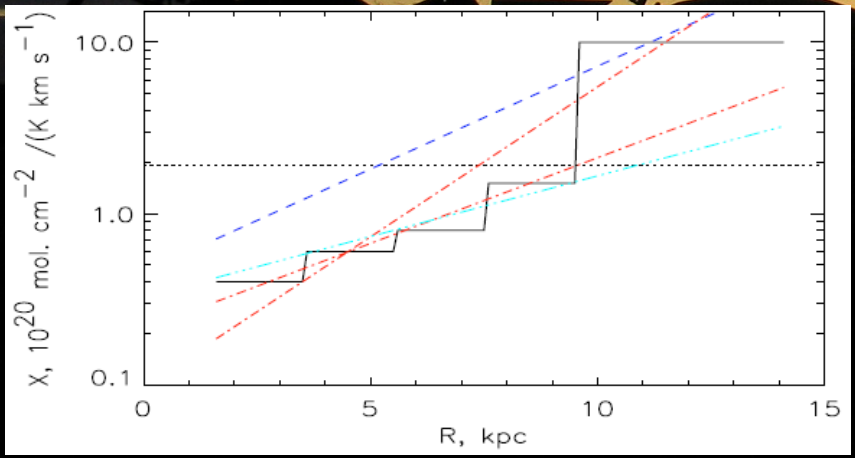
- But ^{12}CO is optically thick in most of the clouds

  => Use other CO isotope less abundant and optically thiner than ^{12}CO

- CS line also useful to look at dense clouds

  => also optically thinner than ^{12}CO





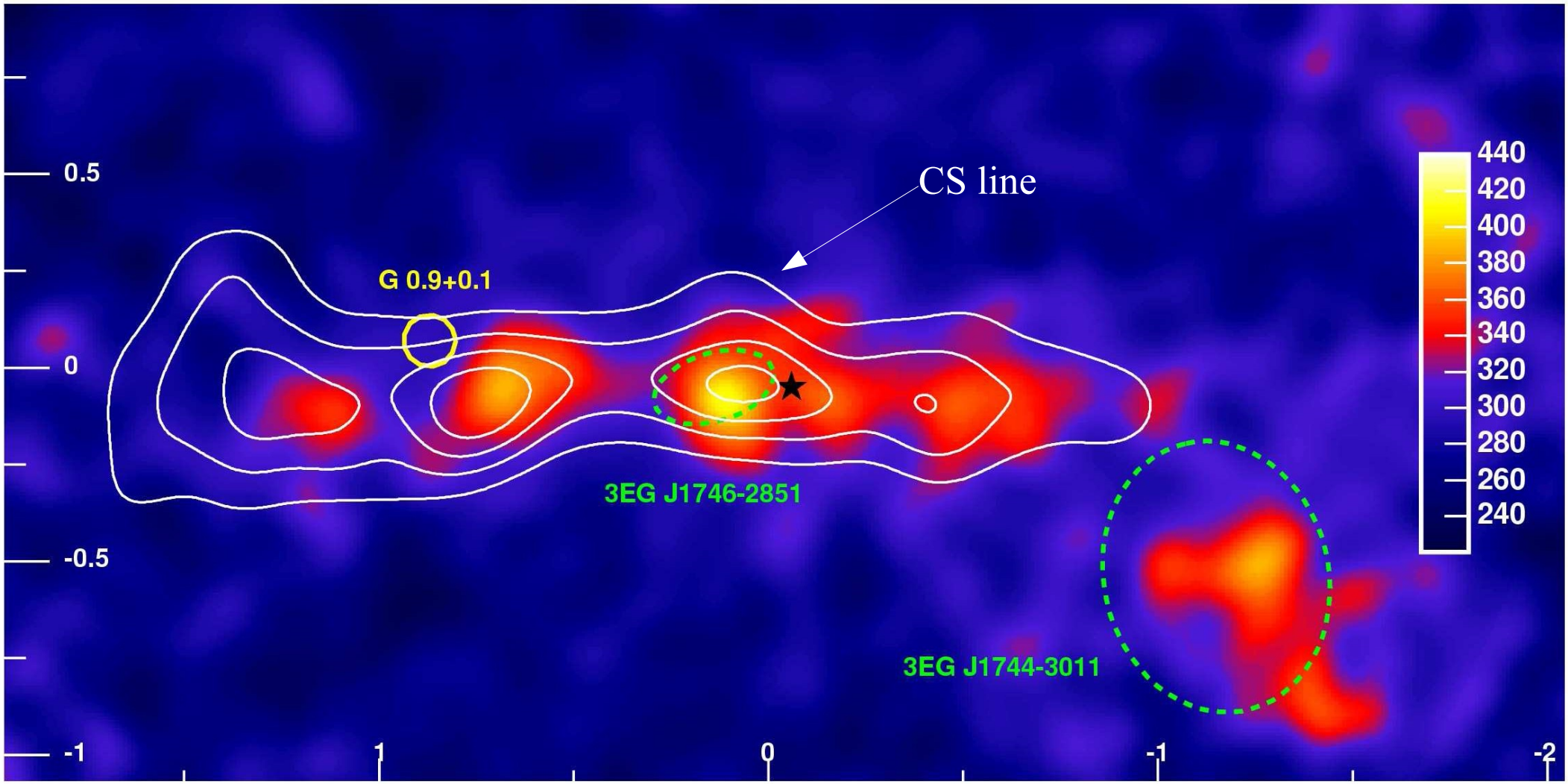
[Strong et al. 2004]

Proportionnality ratio X_{CO} is often assumed constant but should vary with radius to the Galactic center

- Should follow the cloud metallicity
- Variability needed to explain EGRET data

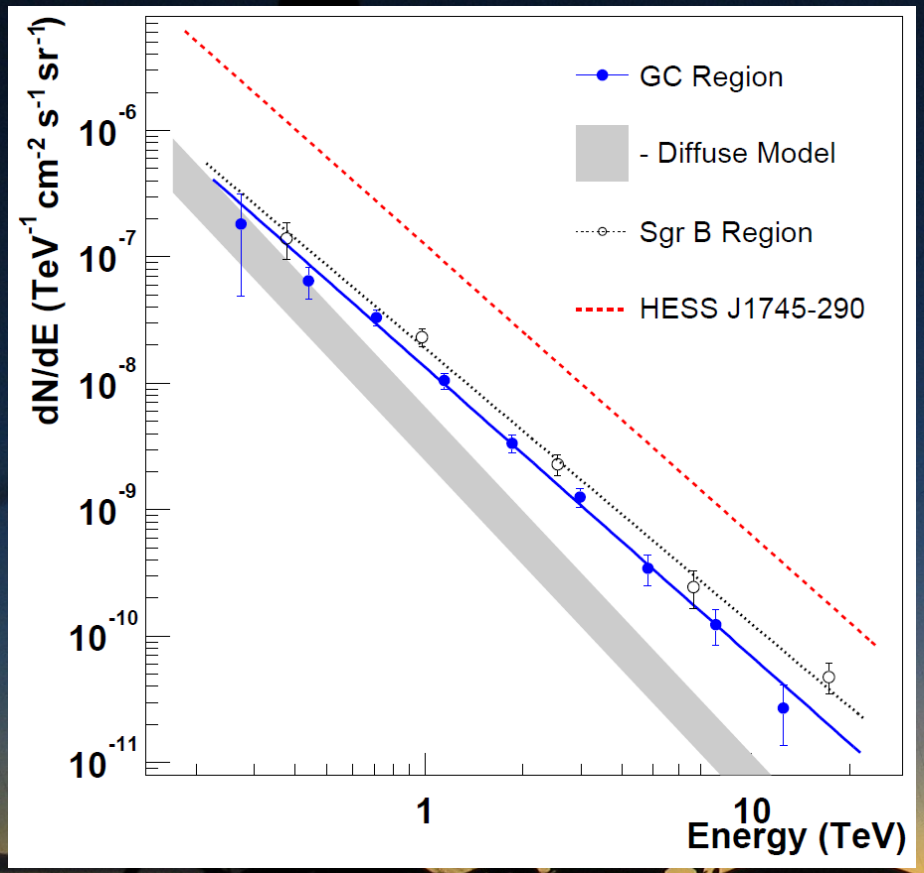
  => FERMI?

A nice correlation: The Galactic Center ridge



[Aharonian et al. Nature 439 695 2006]

The Galactic center ridge



- **Additionnal component to a diffuse model**

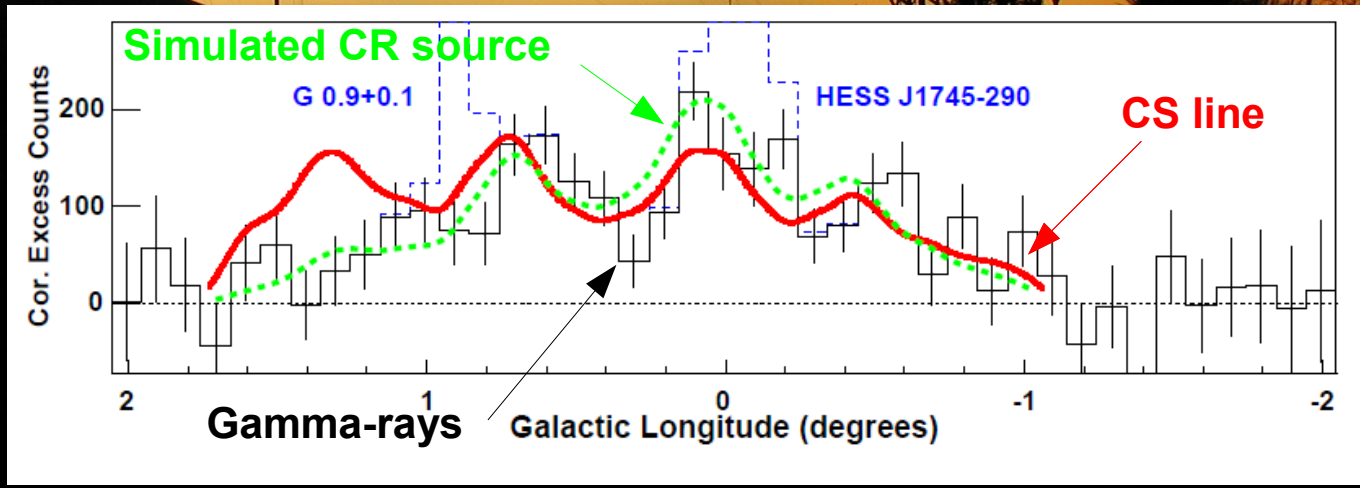
  => freshly accelerated particles

- **More likely protons**

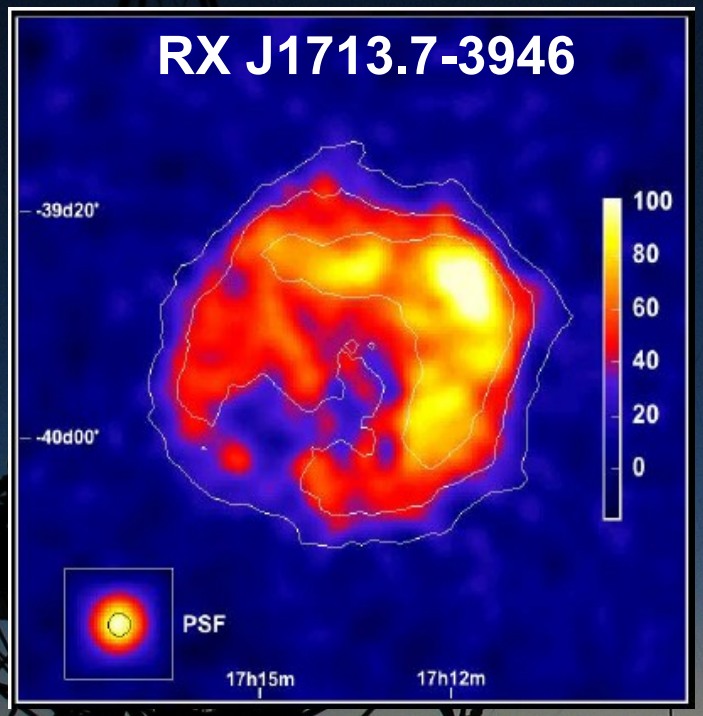
  => 1 SNR could explain the gamma-ray flux

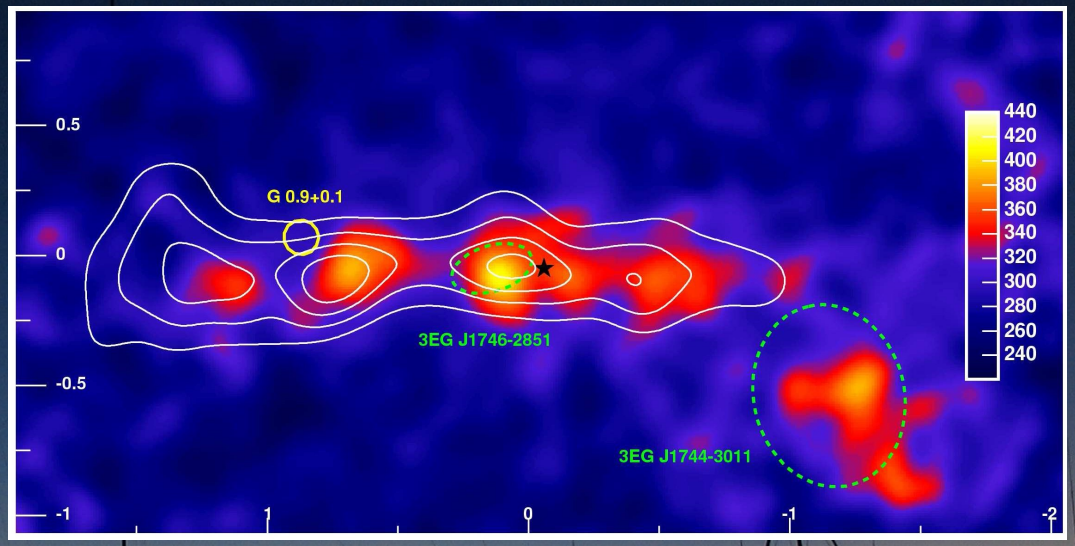
Nice correlation of molecular cloud with gamma-rays from freshly accelerated CR ...

… but what is the source?



Which molecular clouds?





- **Supernova remnant associated with dense molecular clouds are our main target**
  - But the distance to SNR is poorly known

    =>physical associations are difficult to detect

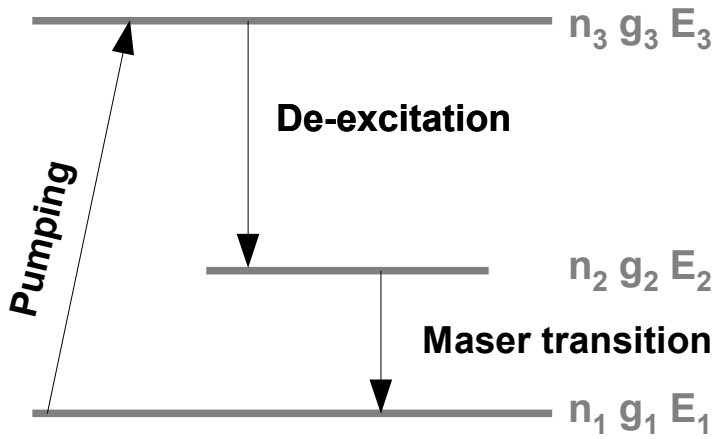
- **Necessity of good indicators of physical associations**

  => 1720 MHz OH masers are the corresponding tracers
  - Point at dense molecular probes in the vicinity of a SNR

What is a maser?

Maser = **M**icrowave **A**mplification by **S**timulated **E**mission of **R**adiation
« A maser is a device that produces coherent electromagnetic waves through amplification due to stimulated emission. » (Wikipedia)

=> Nothing more than a laser at lower frequency



n_i = level i population
g_i = level i degeneracy
E_i = level i energy

- **Thermal equilibrium:**

$$\frac{n_2 g_1}{g_2 n_1} = \exp\left(\frac{-h\nu}{KT}\right) \quad \Rightarrow \quad \frac{n_1}{g_1} > \frac{n_2}{g_2}$$

- **Equilibrium perturbed => pumping mechanism**

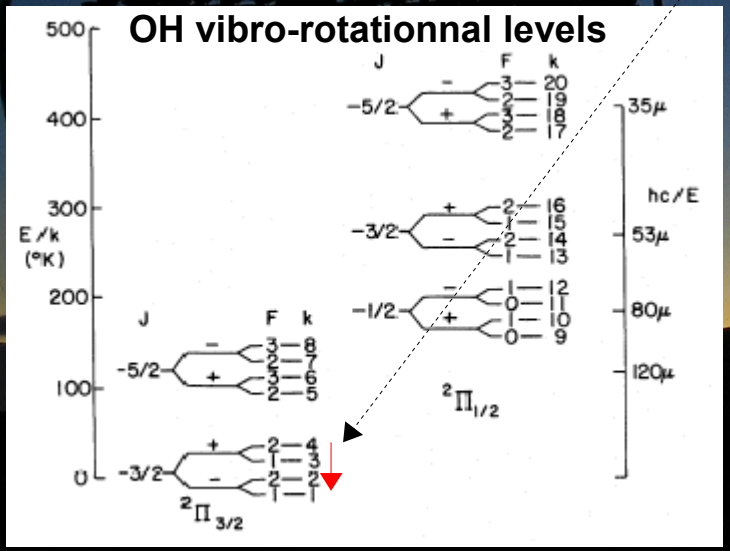
$$\frac{n_1}{g_1} < \frac{n_2}{g_2}$$

=> Stimulated emission & amplification of the radio field along the line of sight

Why this OH maser is interesting?

Two pumping mechanism for astrophysical masers:

- **Radiative pumping** => absorption of photons from the radiation field
- **Collisionnal pumping** => Vibro-rotationnal level excitation by collision with H_2



[Elitzur 1976]

<u>1720 MHz maser:</u> transition between sub-levels of the ground state

- **Collisionnal pumping is alone able to overpopulate this level**
  - Dipolar selection rules forbide decays from higher level to the 1720 MHz level
- **Radiative pumping involves higher level than the first excited level**
  - Overpopulates preferentially another level: 1612 MHz

    => frequently observed toward star forming regions

=> 1720 MHz OH masers occurs in molecular cloud shocked by a SNR

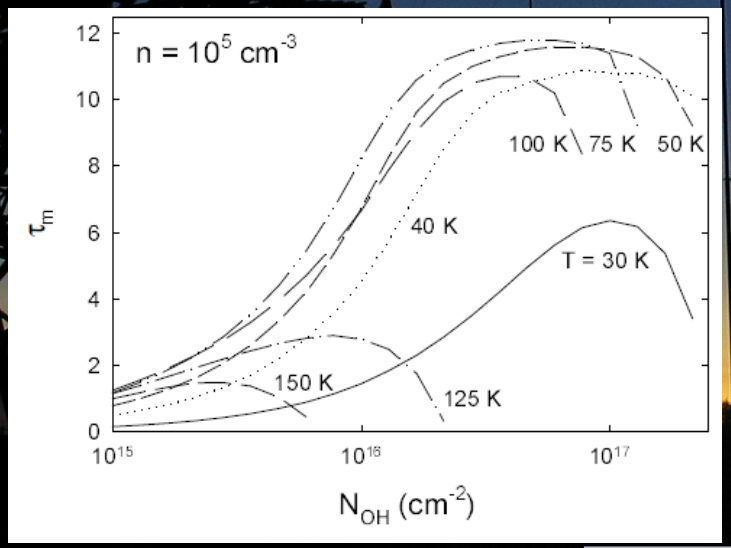
Which conditions are required?

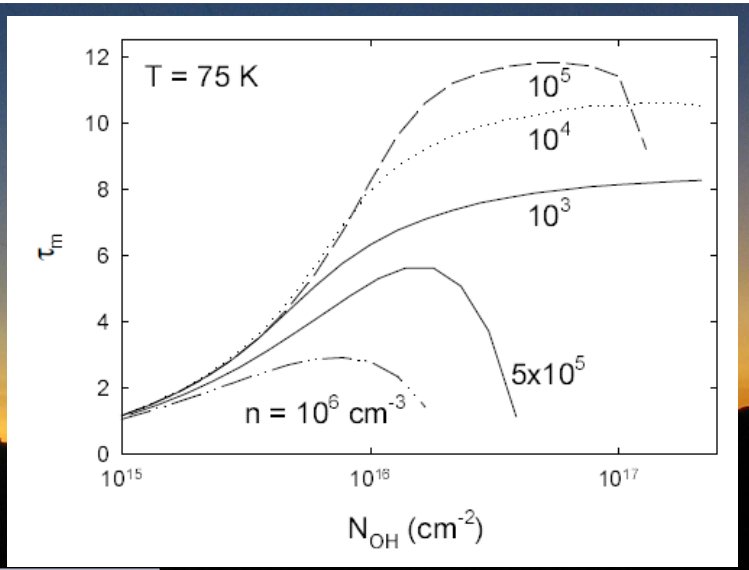
Very drastic conditions needed to produce 1720 MHz OH masers

- OH column density ~10^{16}-10^{17} cm^{-2}
- Moderated cloud temperature T<200K
- Cloud density preferably between 10^3 and $5x10^5$ cm^{-3}

→ Compatible with values measured in W28, IC443 ...

=> Outside of these conditions, the population inversion is suppressed





[Lockett et al. 1999]

=> 1720 MHz OH masers are encountered within dense molecular clouds
=> If a maser is detected => a shock is passing through the cloud
=> But absence of maser does not means no shock !

OH abundance into MCs

- **OH column density required for the maser emission is due to the shock itself**
  - Water formation induced by the shock
  - Photo-dissociation within the shocked medium

  => OH production

  [Wardle 1999]

- **Significant correlation observed with the Mixed-Morphology SNR class**

  => SNRs filled with thermal X-ray emission
  - X-ray produced by material swept and heated by the SNR shock

  [Yusef-Zadeh et al. 2003]

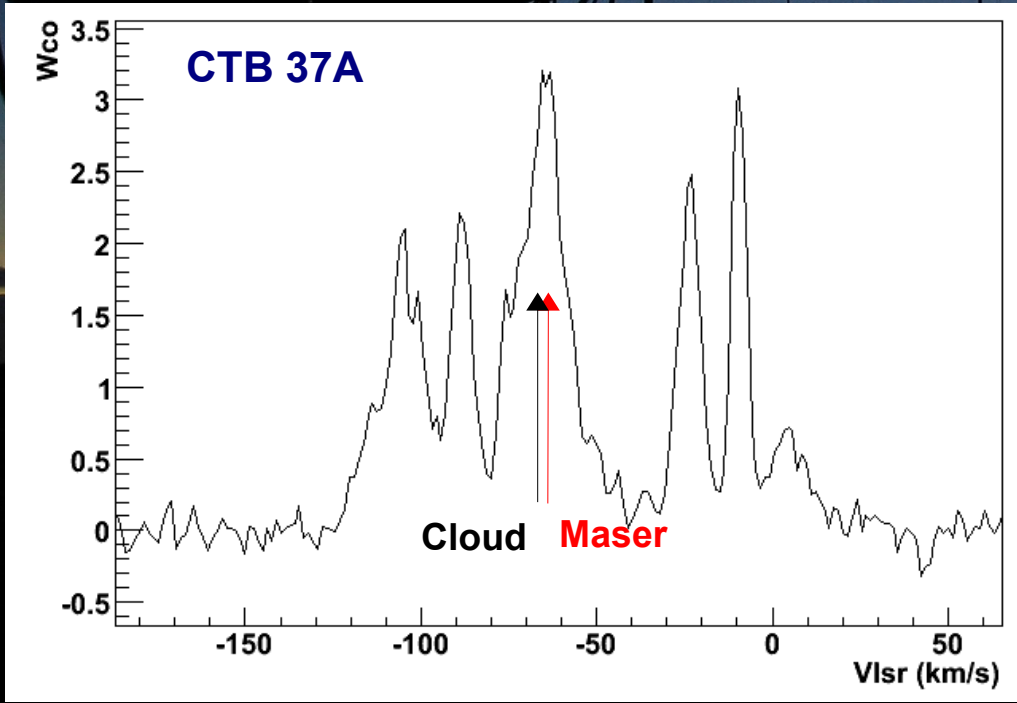
  => Additionnal confirmation that these masers are linked with dense material surrounding SNRs

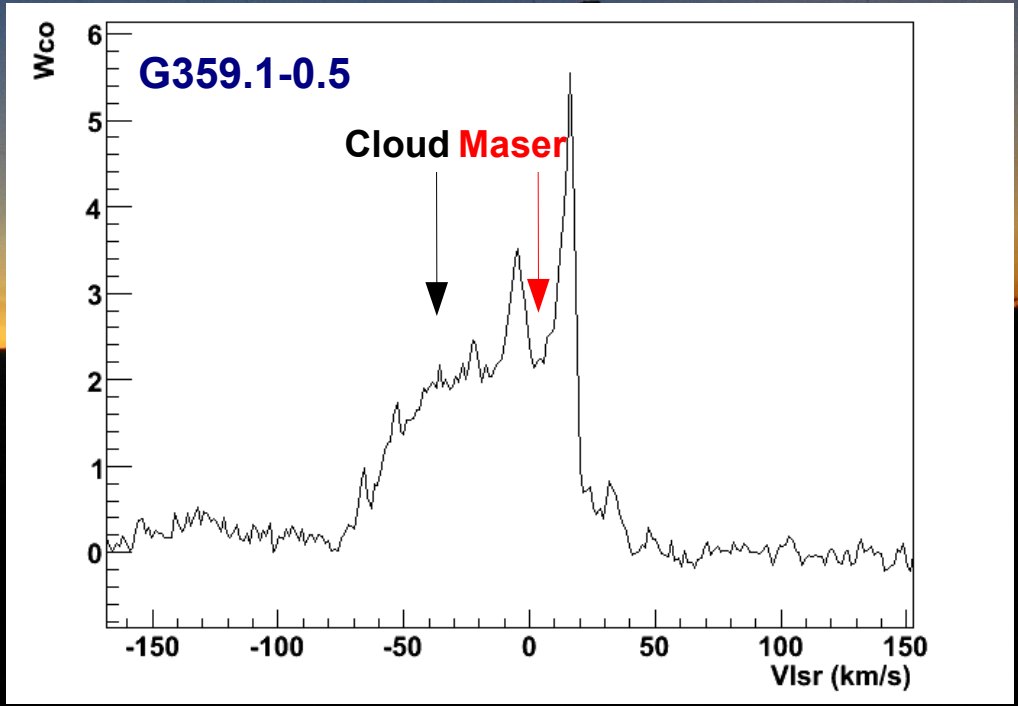
Maser radial velocity

- The radial velocity of the masers corresponds to the local velocity
- If the medium velocity is not affected by the shock, the velocity is the same as the parent cloud

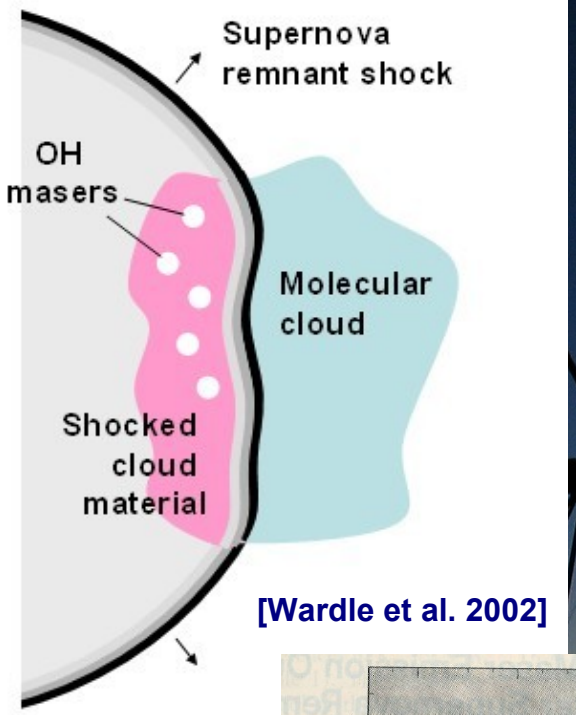
  => Very helpful to point at the right cloud among CO peaks along the line of sight

  … but sometimes not straightforward





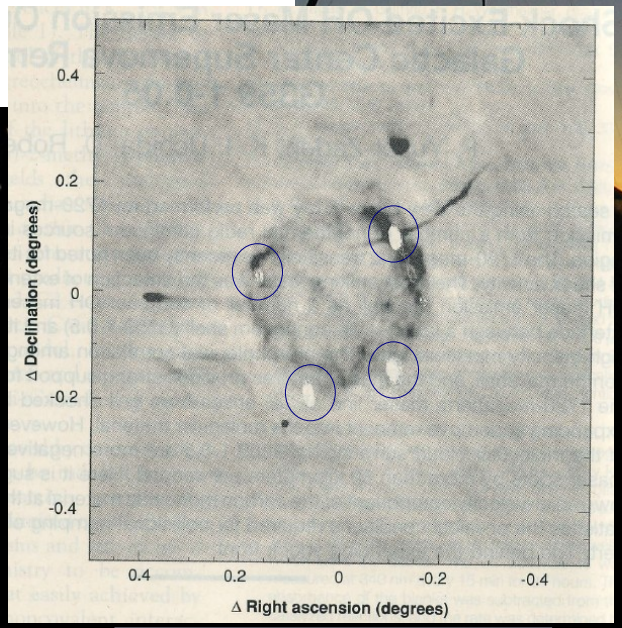
Where are located these masers?



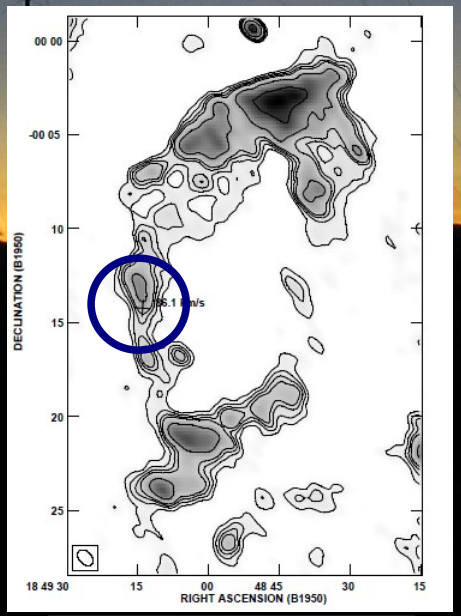
[Wardle et al. 2002]

- **Emission emitted from the material behind the shock**
- **Visible preferentially at the edge of the remnant**

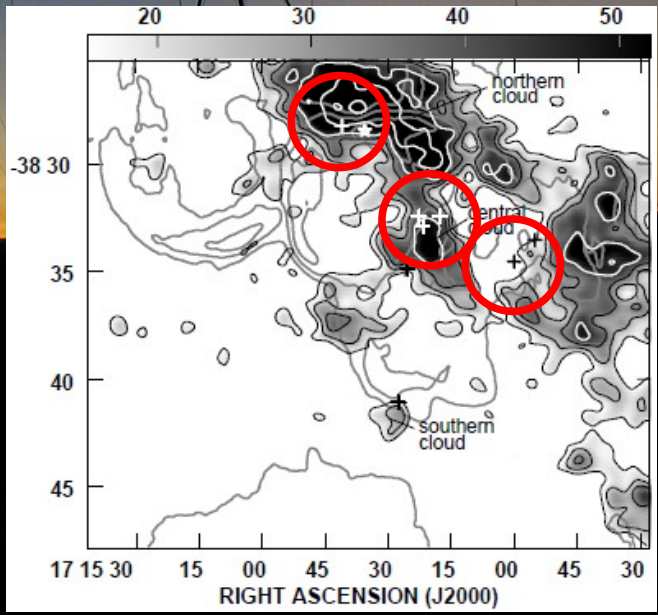
  => shock parallel to the line of sight
  - Column density of shocked material maximal
  - Velocity coherence maximal



[Yusef-Zadeh et al. 1995]



[Koralesky et al. 1998]



[Reynoso et al. 2000]

Are they frequent?

- **Several surveys have been led between 1995 and 2000**

  => Survey of a large fraction of Galactic SNRs (~200)

  => Around 10% are OH masers emitting

  Extract from Green et al. 1997:

  " The molecular gas acts as a dense target for the cosmic rays. Collisions between the two results in gamma-ray emission. In this context Table 3 – their survey - *can be viewed as a candidate list for conducting future searches of GeV or TeV emission in a search for the signature of cosmic ray acceleration "*

- **The detection of new maser emitting SNR are regularly announced by radioastronomers**
  - Galactic center region, W28 region...

  => Most of them have been observed by HESS

Frail et al. (1996)
Green et al. (1997)
Claussen et al. (1997)
Koralesky et al. (1998)
Yusef-Zadeh et al. (1999)

Caveats?

Following Green et al., OH masers seems the perfect indicator for observation with ground based telescope to search for CR acceleration but …

Some caveats to keep in mind:

- **OH masers indicate physical association between the SNR shock and the cloud**
  - The shock propagation is affected by the dense material

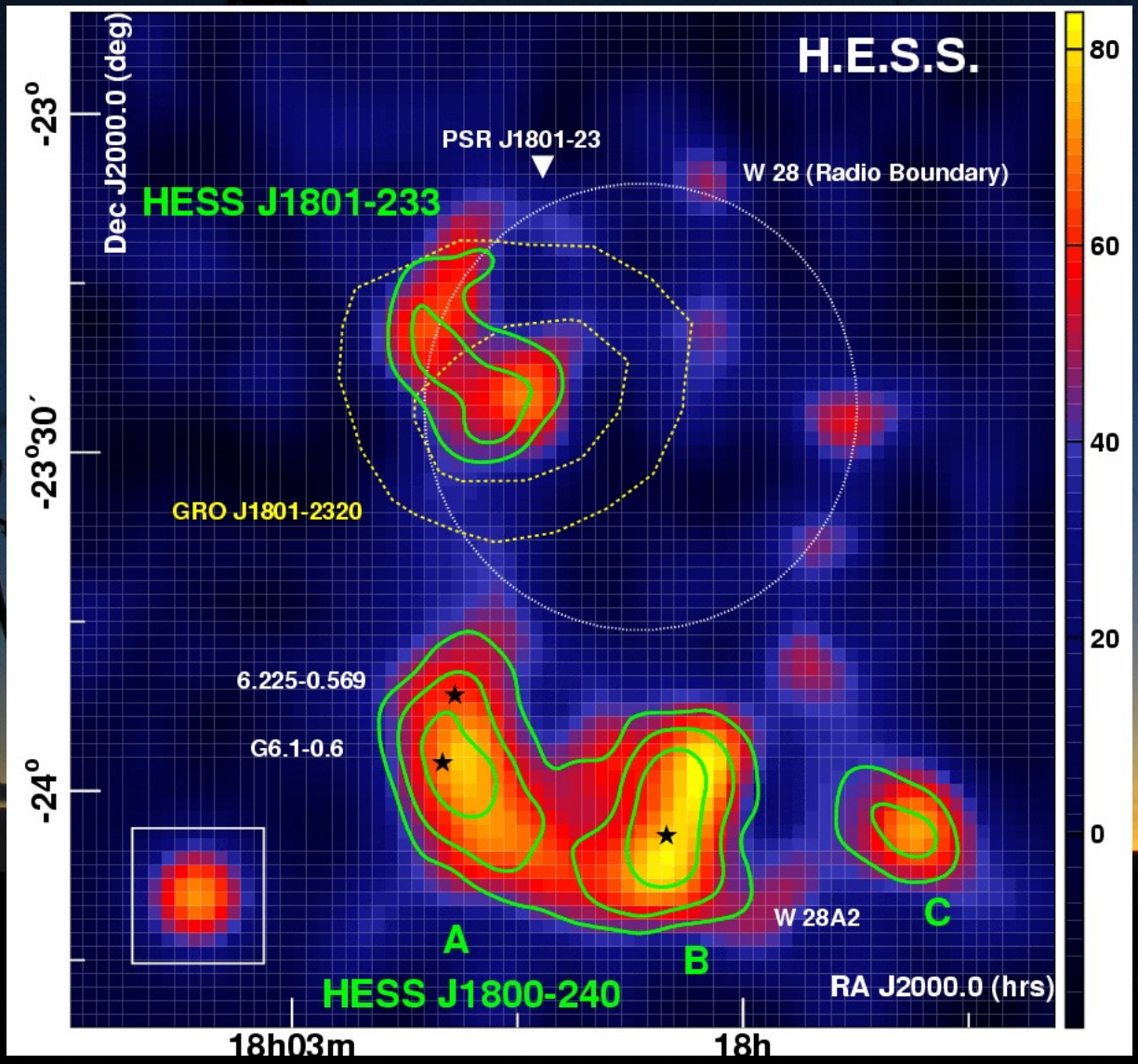
    => What about the CR acceleration efficiency ??
  - The SNR morphology is often unusual due to the inhomogeneous medium

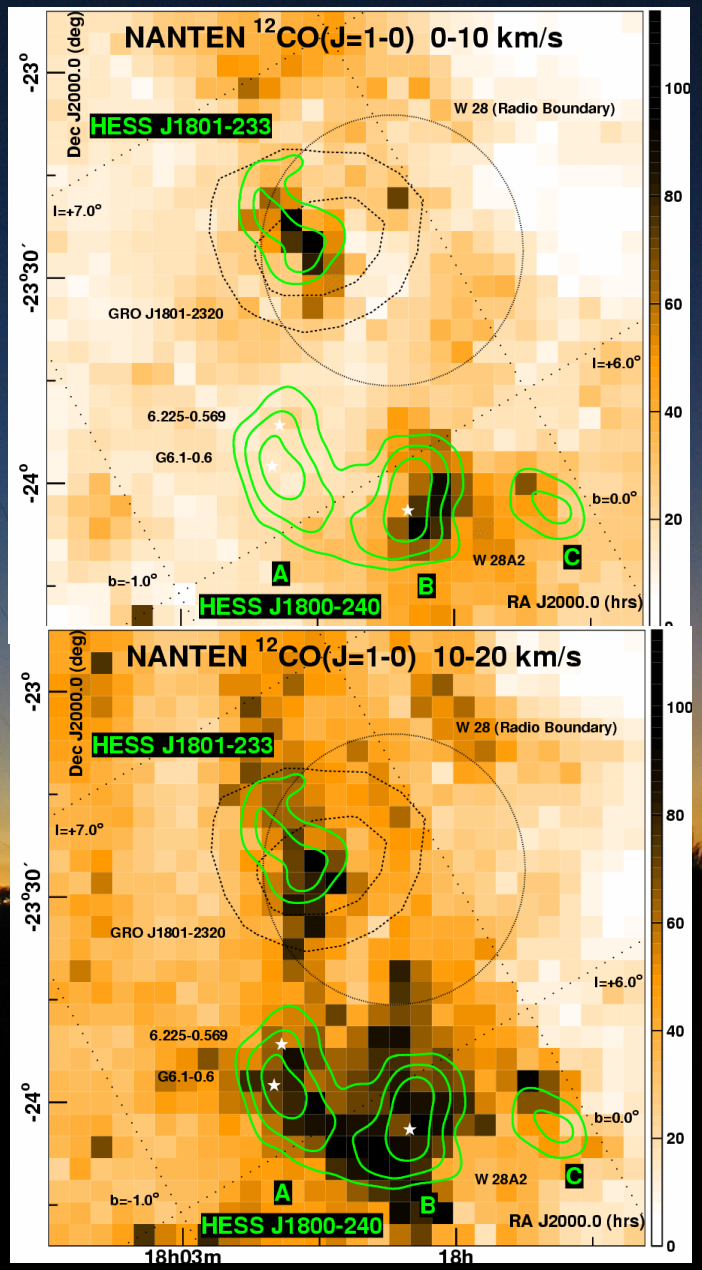
    => Probably not the better candidates for comparison with theoretical predictions

- **Maser emitting SNRs appears to be rather evolved SNRs with age ~ 10 kyr**
  - More energetic particle should have escaped from the remnant

    => Probably not the better candidates to have a look at the highest energy

The W28 field



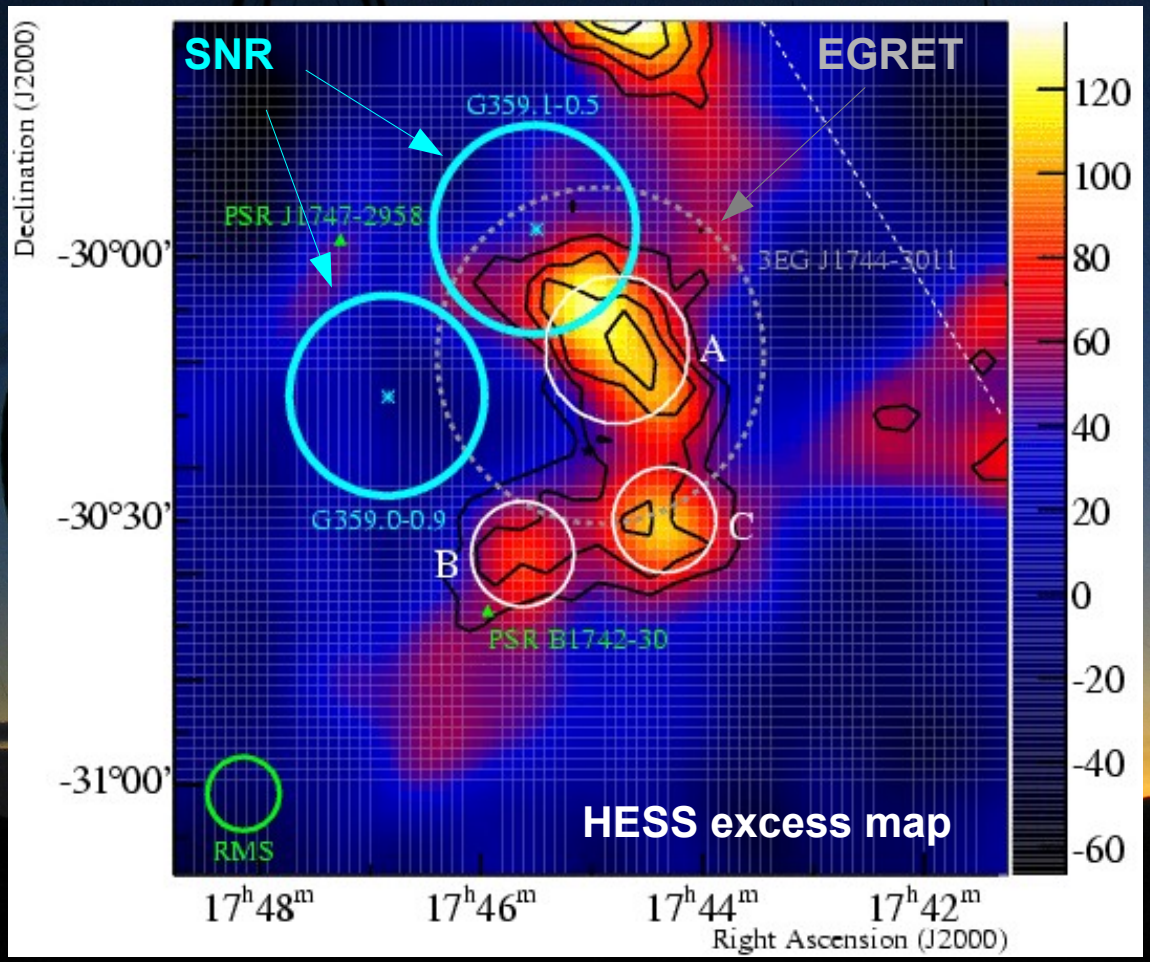


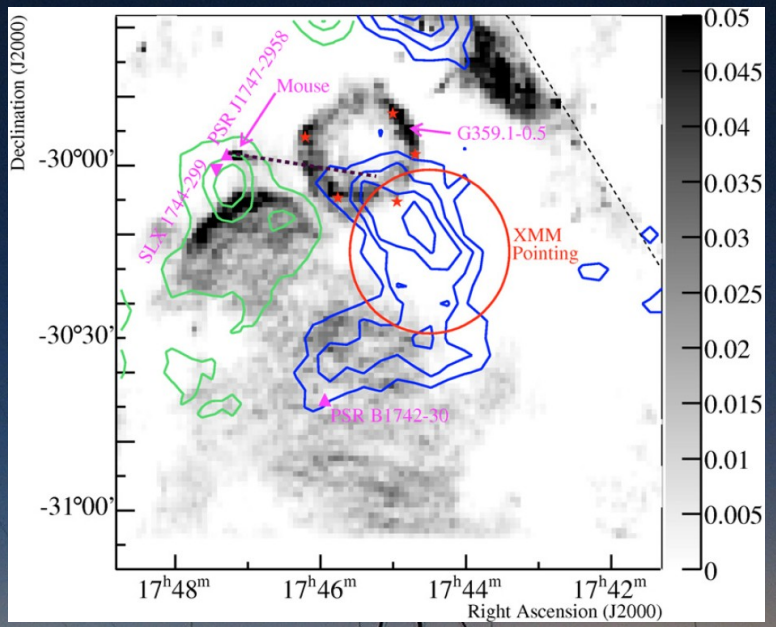
- **Two SNR/MC associations possibly detected**

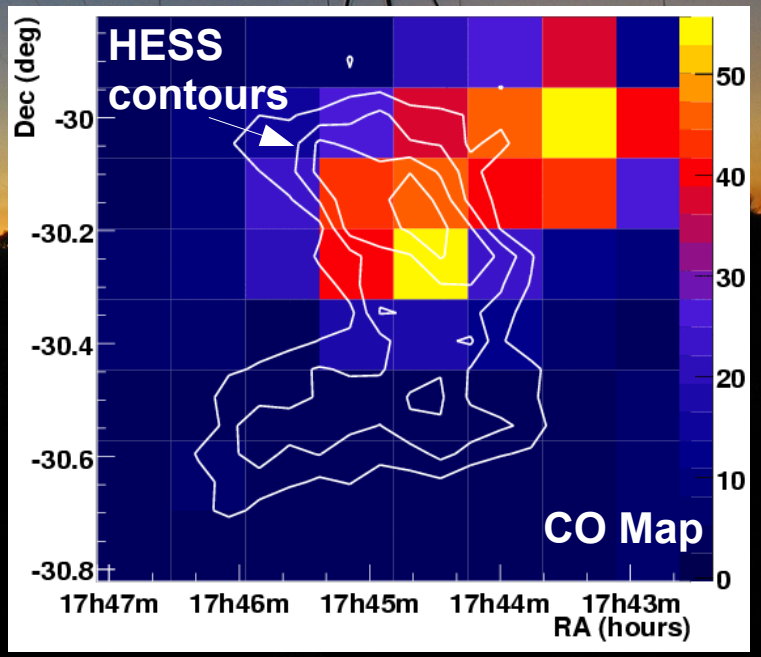
  => One OH maser recently detected toward C region

[Aharonian et al. 2008]

HESS J1745-303 & G359.1+0.5





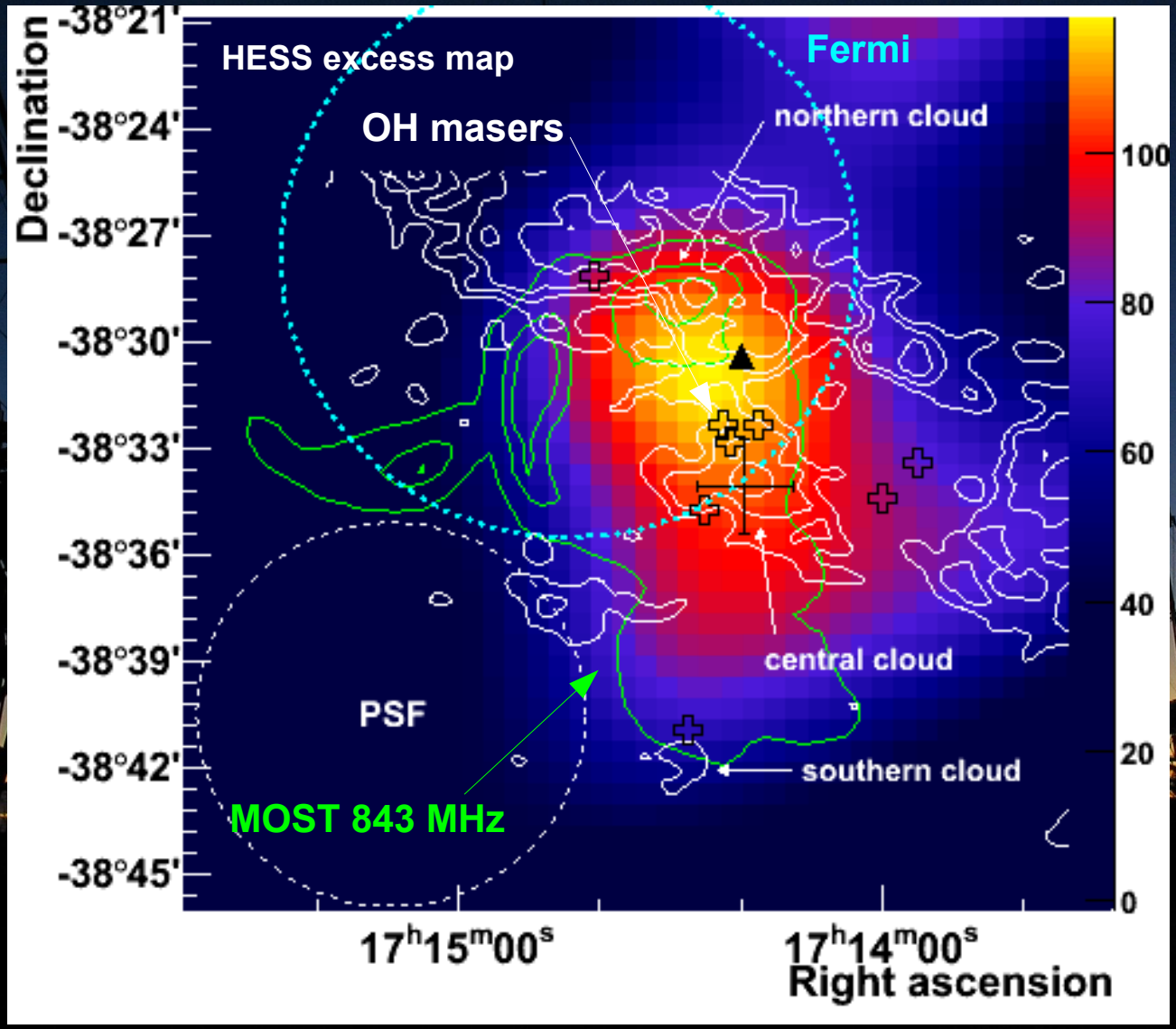


- **Unidentified source close to the Galactic Center**

  => A region seems likely associated with G359.1-0.5

[Aharonian et al. 2008]

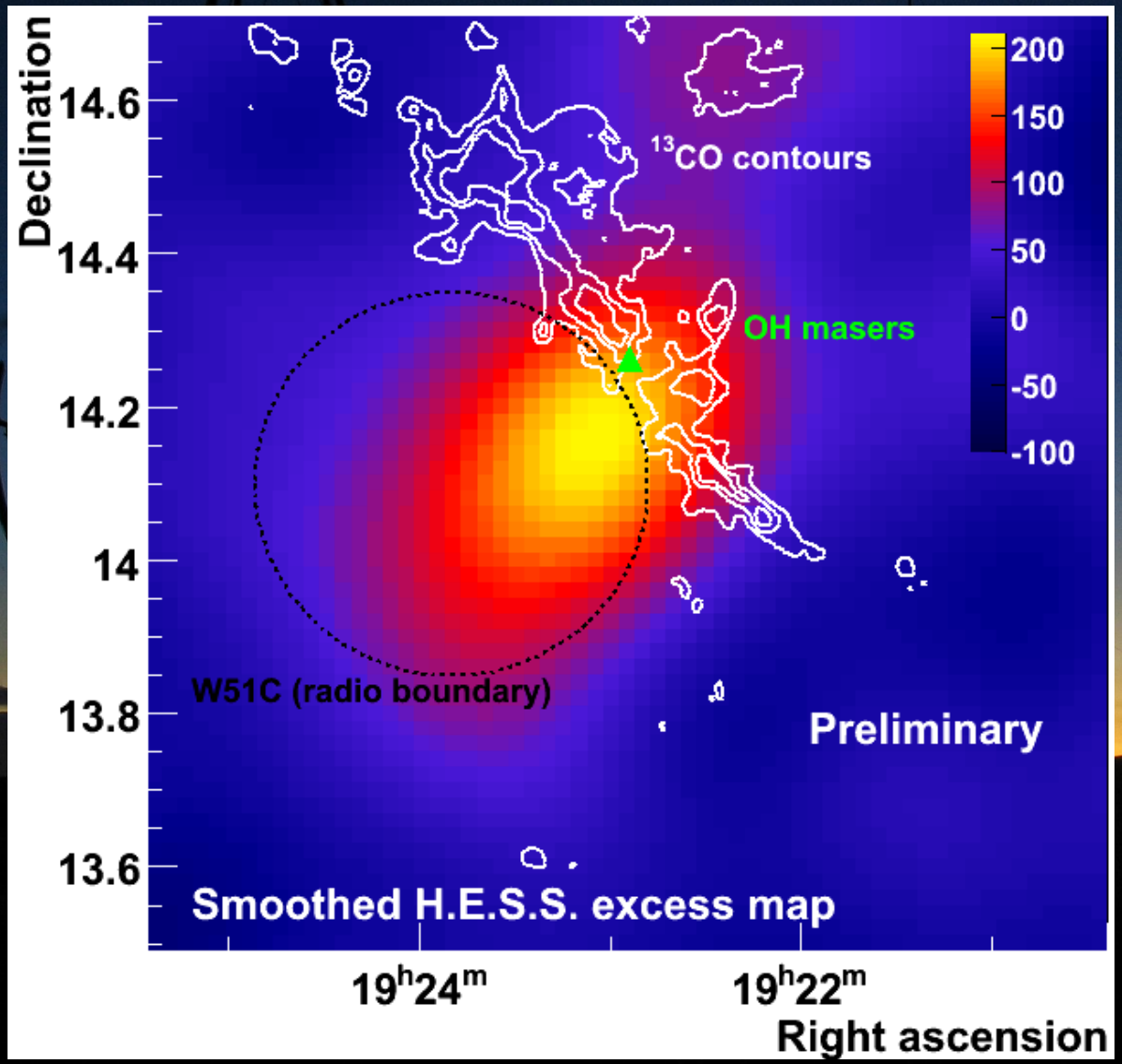
HESS J1714-385 & CTB 37A



[Aharonian et al. 2008]

- HESS source coincident with dense shocked molecular clouds
- But a PWN origin is also possible

HESS J1923+141 & W51C



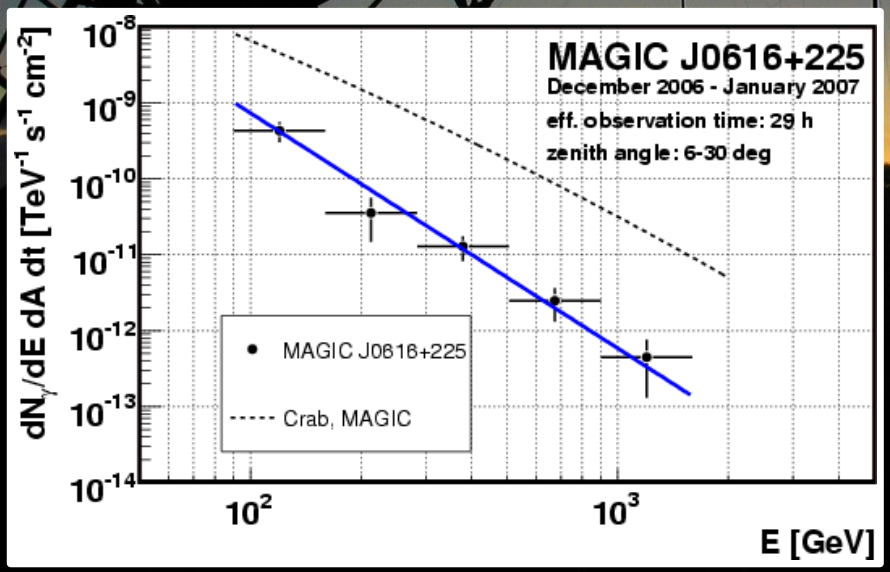
- **New source announced in various conferences this fall/winter**
- **Several possible origins**
  - PWN
  - Shocked molecular cloud
  - Star forming region
- **Source possibly multiple**
  - Two hotspots visible with the most sensitive analyses

=> the new data analysis is under progress

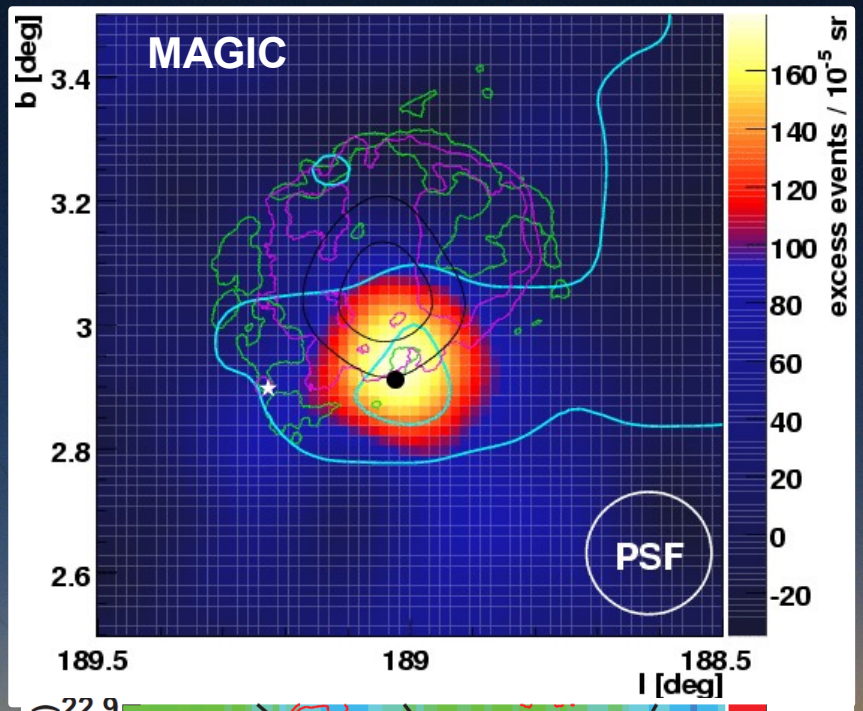
[Fiasson et al. ICRC 2009]

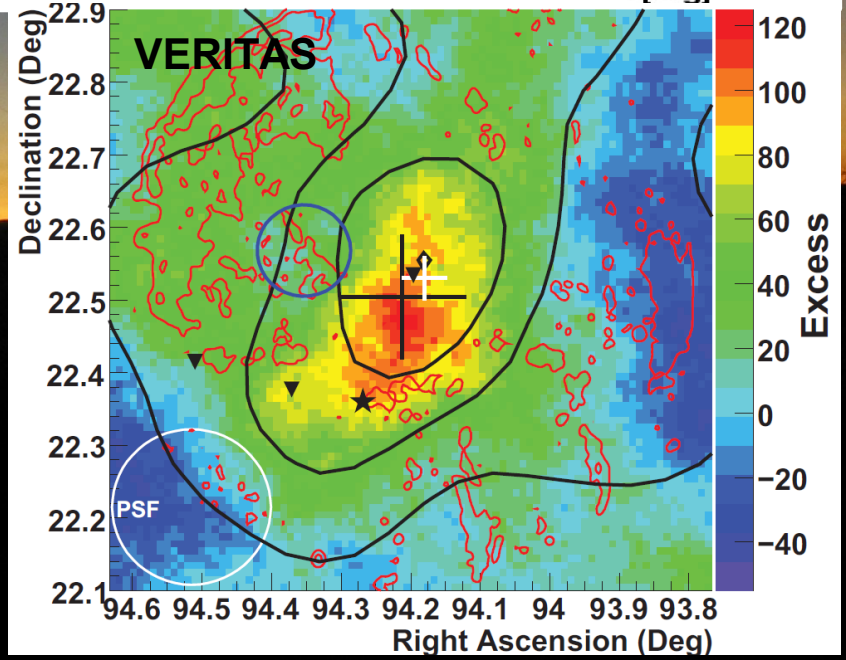
IC 443

- **IC 443**
  - One of the most famous SNR/MC associations
  - Several OH Masers
- **MAGIC (70 GeV – qq 10 TeV) & VERITAS**
  - Excess coincident with the cloud and the masers
  - Spectrum steeper than expected Γ = 3.1 ± 0.3
- **No non thermal X-rays associated with the source**



[Albert et al. 2007]





[Acciari et al. 2009]

Summary

- **CO and CS lines are the most used tracers for molecular clouds**
  - The H_2 is not visible at radio/mm wavelenghts
  - CO and CS emit at these frequencies
  - The line intensity is roughly proportionnal to the cloud mass
- **1720 MHz OH masers are very reliable indicators of SNR/MC associations**
  - Produced within shocked dense molecular clouds
  - Maser velocity very useful to point to the good MC

  => The radio surveys have shown that around 10% of the SNRs (>20) are maser emitting
- **Several detection of VHE gamma-ray emission towards molecular clouds**
  - Associations already detected with HESS: W28, G359.1-0.5, CTB 37A, W51 ...
  - Plus another confirmed association detected by MAGIC & VERITAS: IC 443
- **At least 4 emissions are associated with a bright FERMI source**

  => additionnal argument in favor of a hadronic origin

  Growing class of confirmed GeV and TeV sources