

Gas towards Gamma-ray-Emitting Supernova Remnants

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On behalf of:

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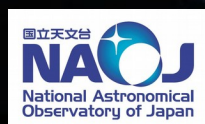
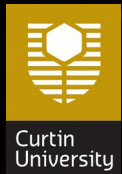
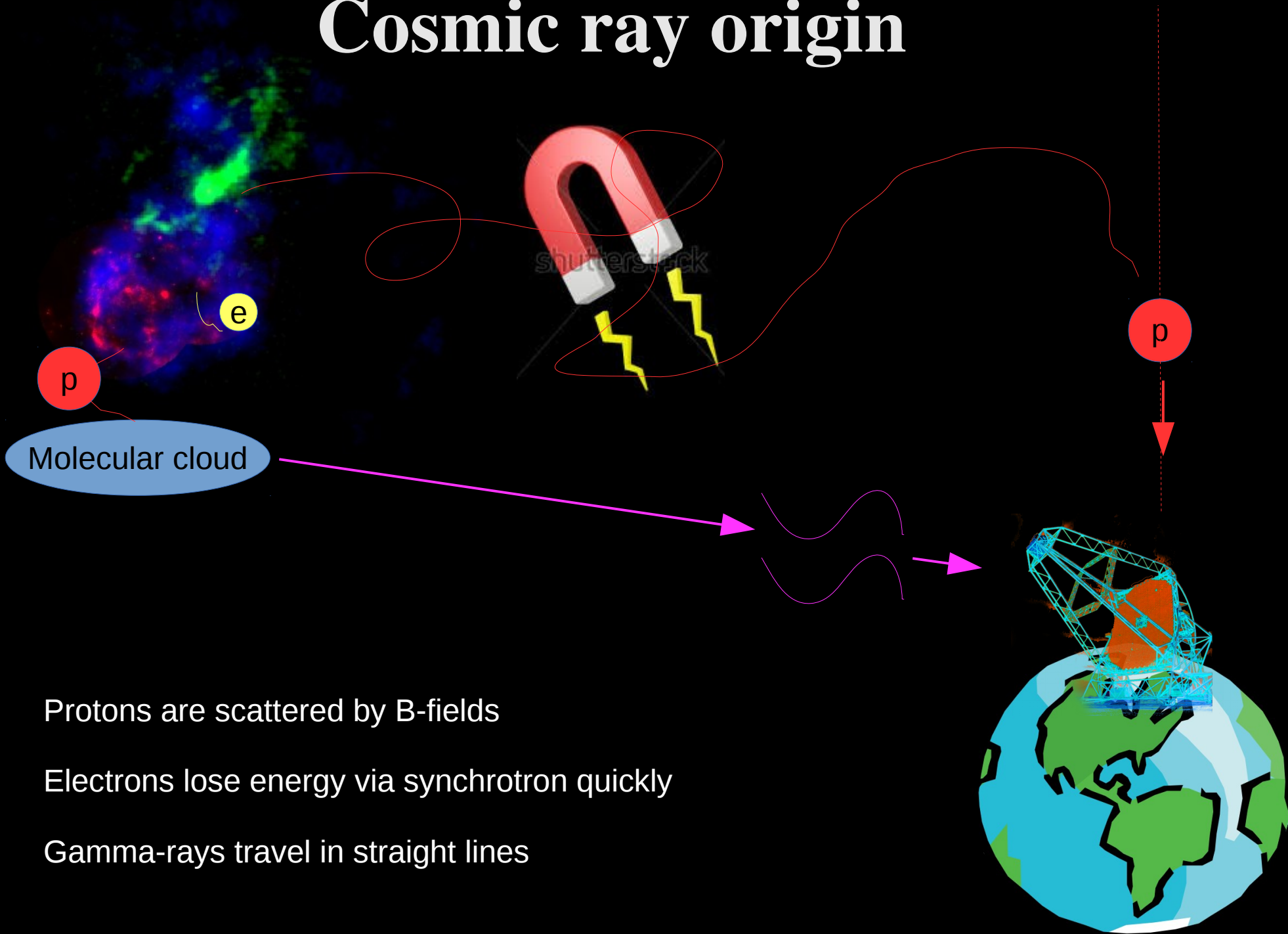


Image: HESS J1731-347
HESS gamma-ray
XMM-Newton Xray
Mopra CS(1-0)

[see Maxted et al., 2015, Maxted et al., in prep.]

Cosmic ray origin



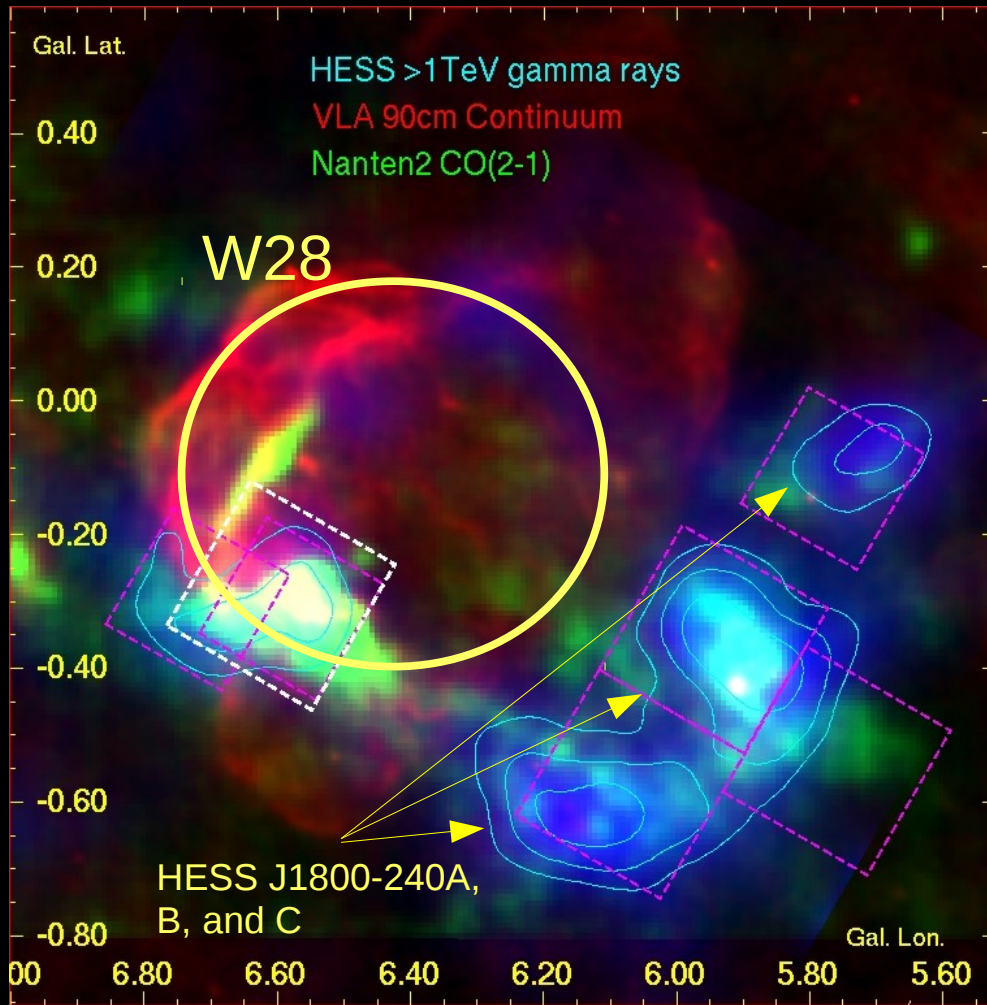
Protons are scattered by B-fields

Electrons lose energy via synchrotron quickly

Gamma-rays travel in straight lines

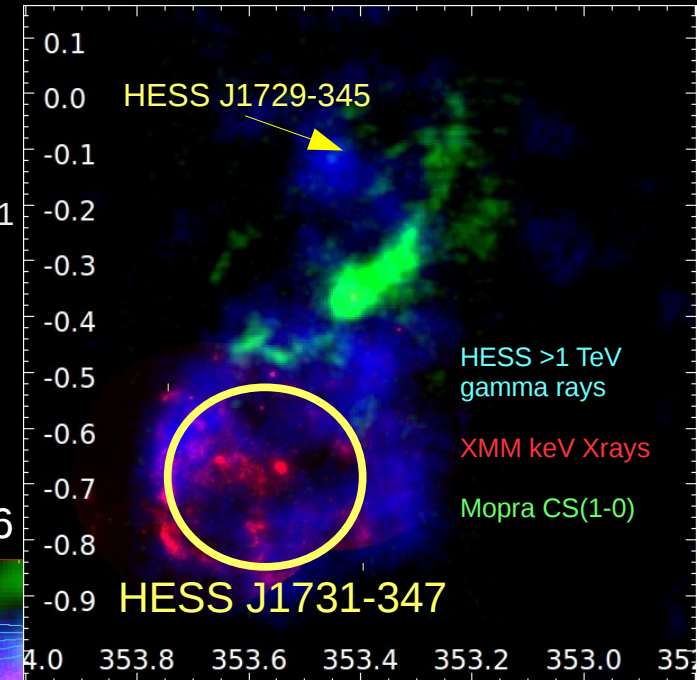
Gamma-ray emitting Supernova Remnants

W28



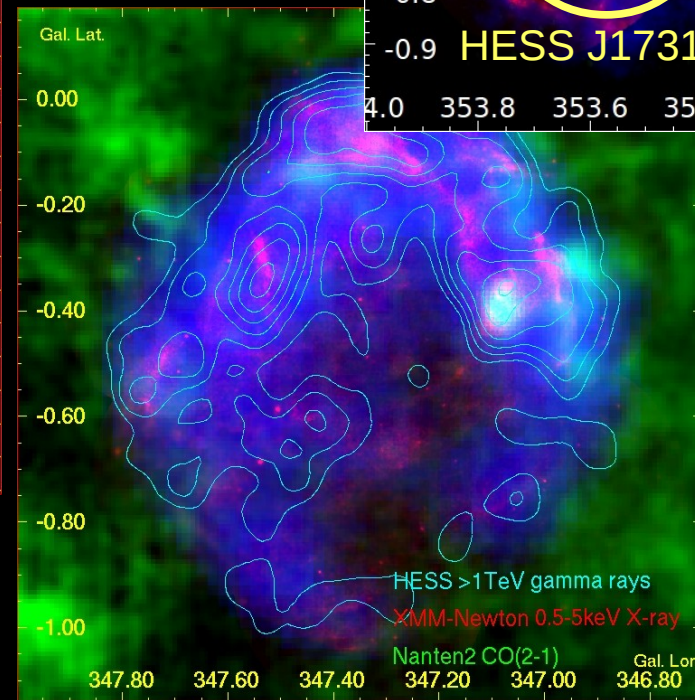
Dubner et al. 2000, Brogan et al. 2006, Fukui 2008,
Abdo et al 2010, Nakamura et al. 2014
Nicholas et al 2011, Nicholas et al 2012
Maxted et al *Submitted(2015)*

HESS J1731-347



Abramowski et al 2011
Bamba et al 2012
Maxted et al 2015
Maxted et al *in prep*

RX J1713.7-3946

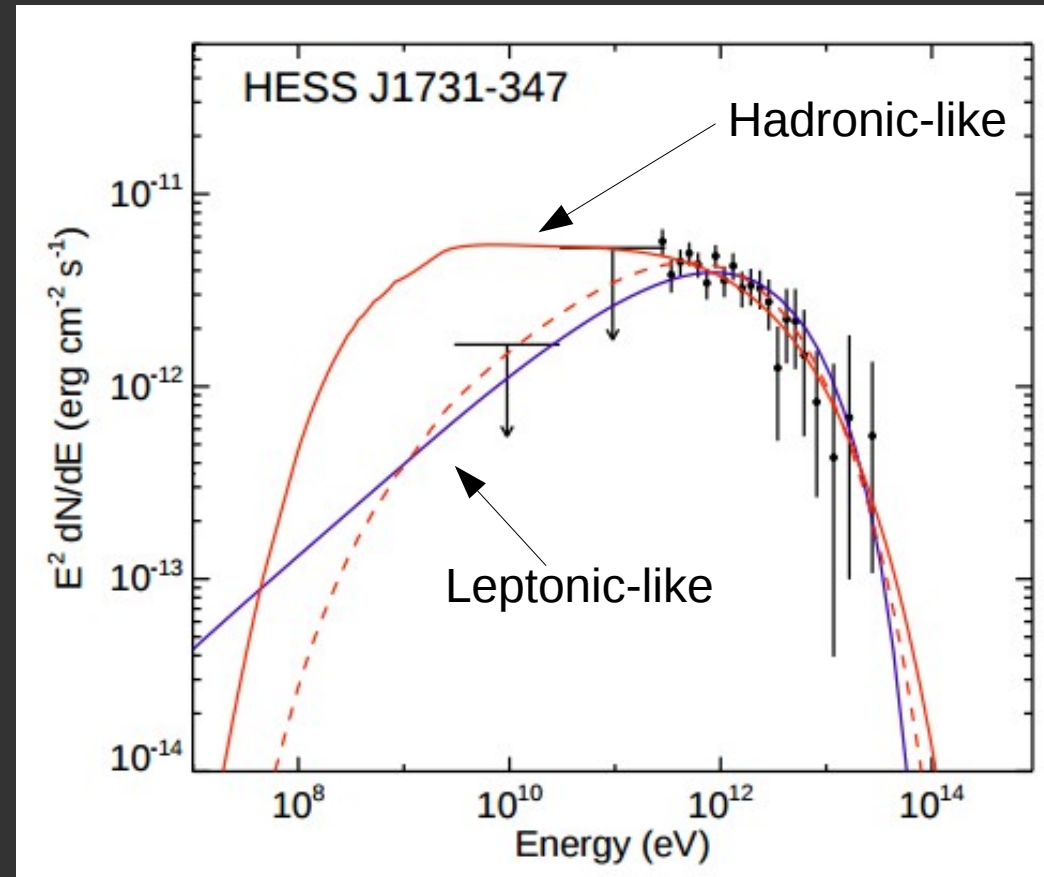


Aharonian et al 2006/07
Acero et al 2009
Fukui et al 2003
Moriguchi et al 2005
Maxted et al 2012
Maxted et al 2013

Young ($\sim 10^3$ yr) SNRs

Young SNRs, such as RX J1713.7-3946 and HESS J1731-347 have spectra which suggest leptonic gamma-ray emission (e.g. Acero et al 2015).

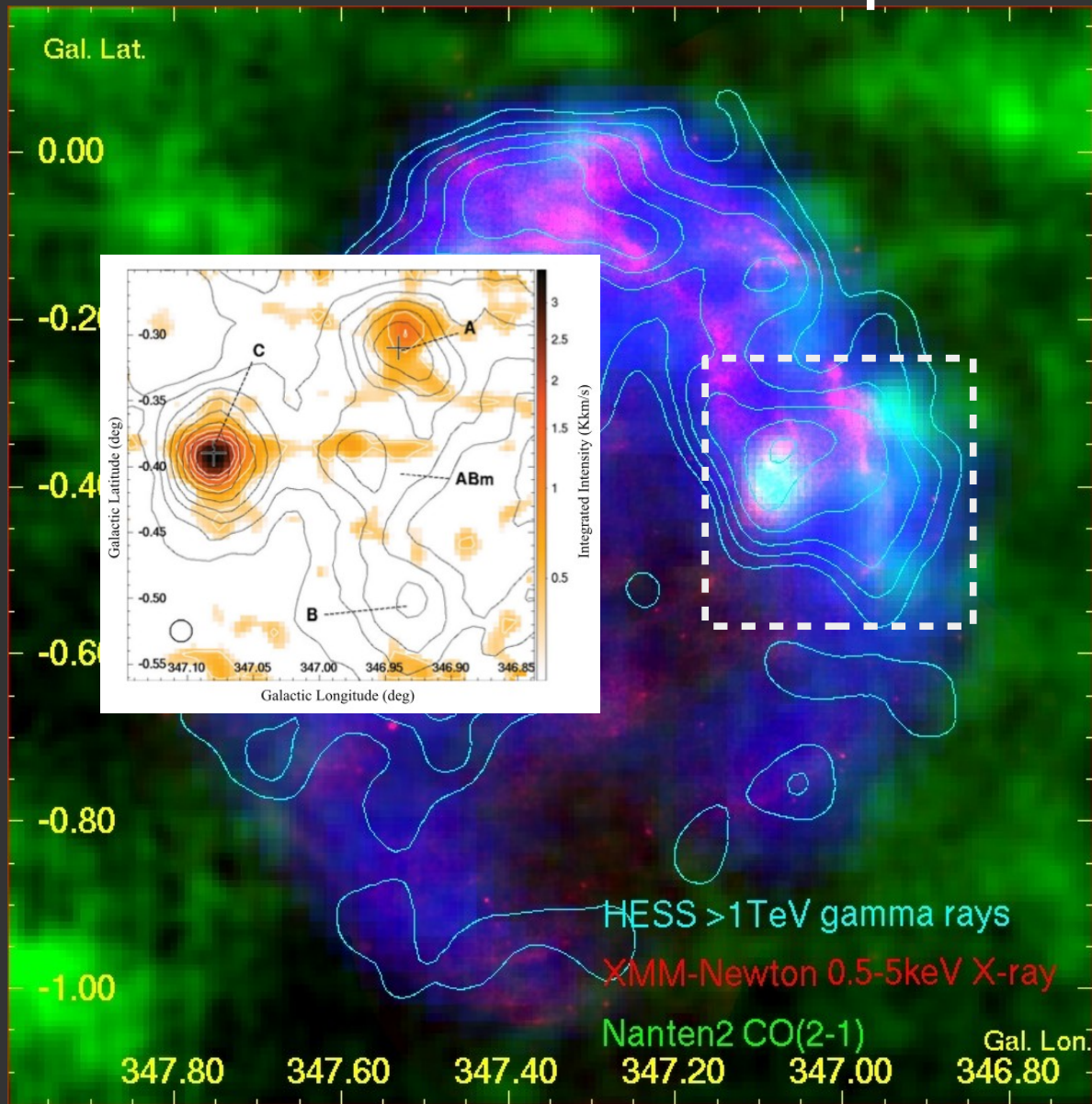
But some argue that the existence of dense clumps might lead to a lack of a distinct 'pion bump' in gamma-ray spectra (e.g. Gabici & Aharonian 2014/2015).



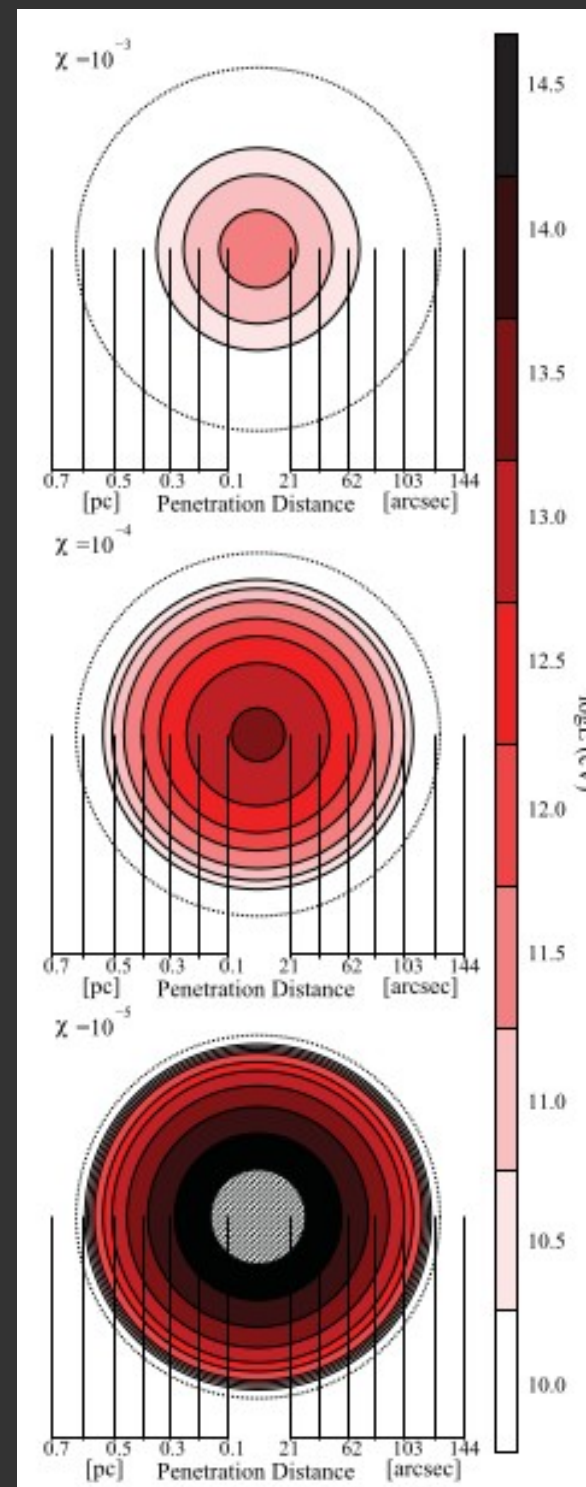
Acero et al 2015

RX J1713.7-3946

Diffusion into clumps?

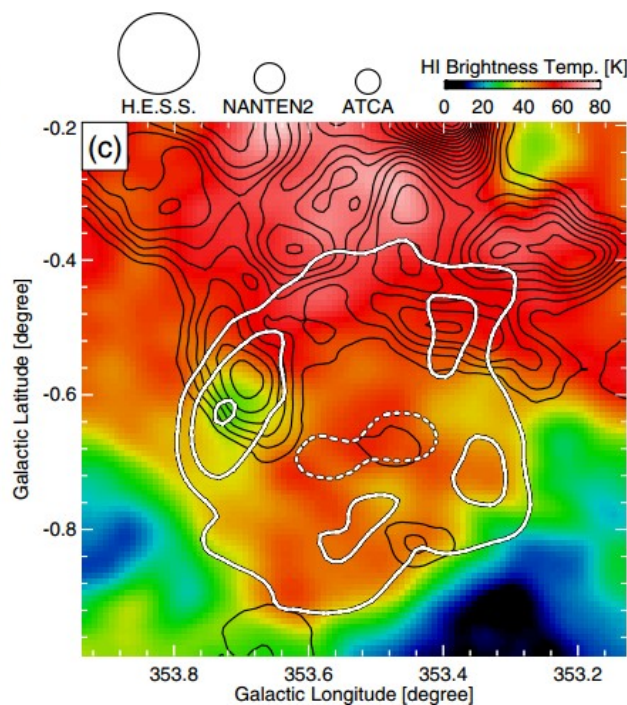
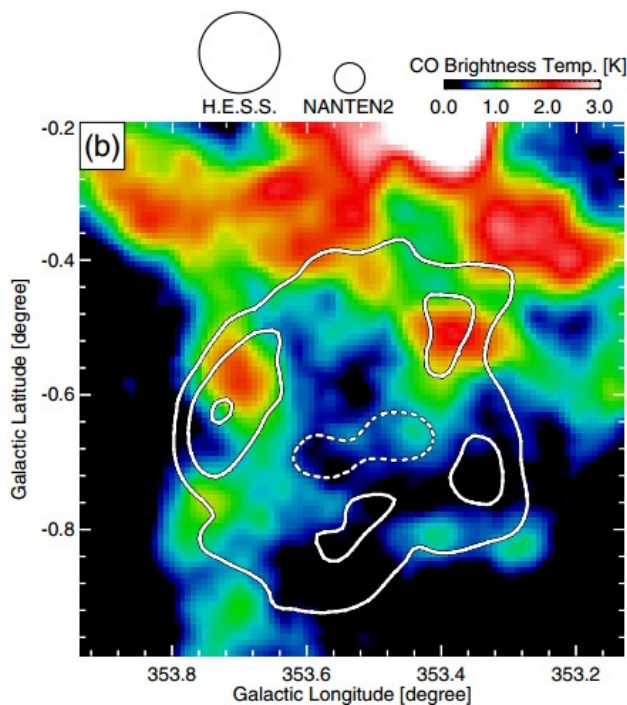


Maxted et al 2012

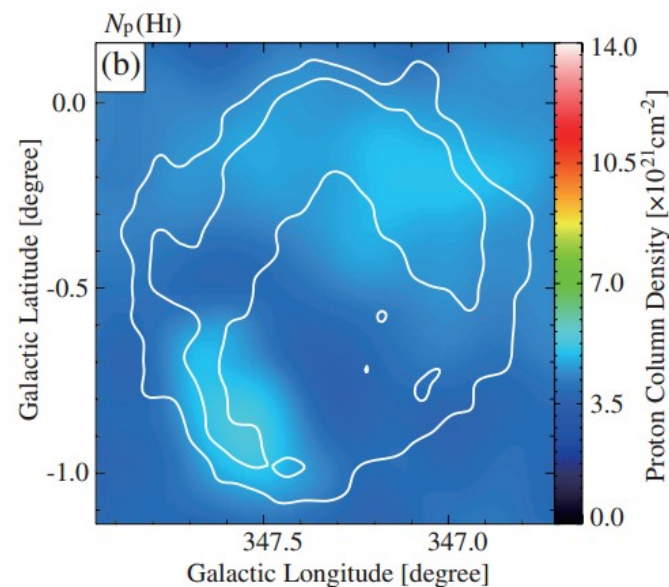
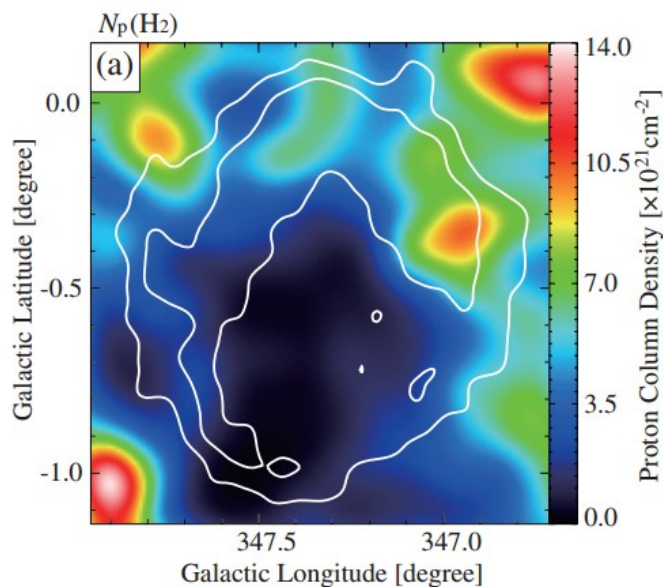


HESS J1731-347 & RXJ1713.7-3946

CO and HI

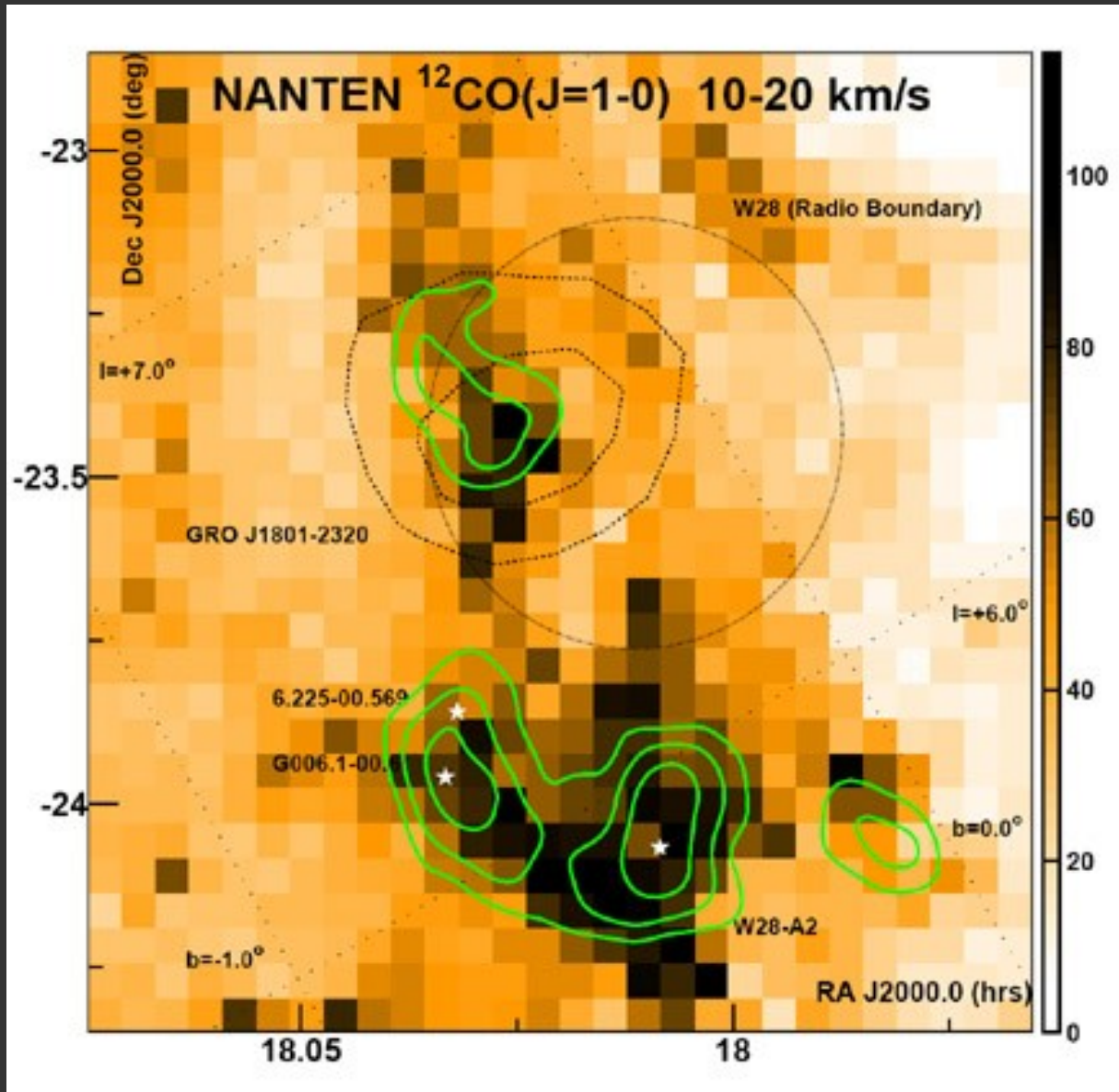


HESS J1731-347
Fukuda et al 2014



RXJ1713.7-3946
Fukui et al 2012

W28 Gamma-ray emission (and CO)



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!

Mopra surveys of W28



Mopra,
Warrumbungles, Australia

Mopra 7 mm survey of the northern cloud W28 interaction region.

Targeted transitions include:

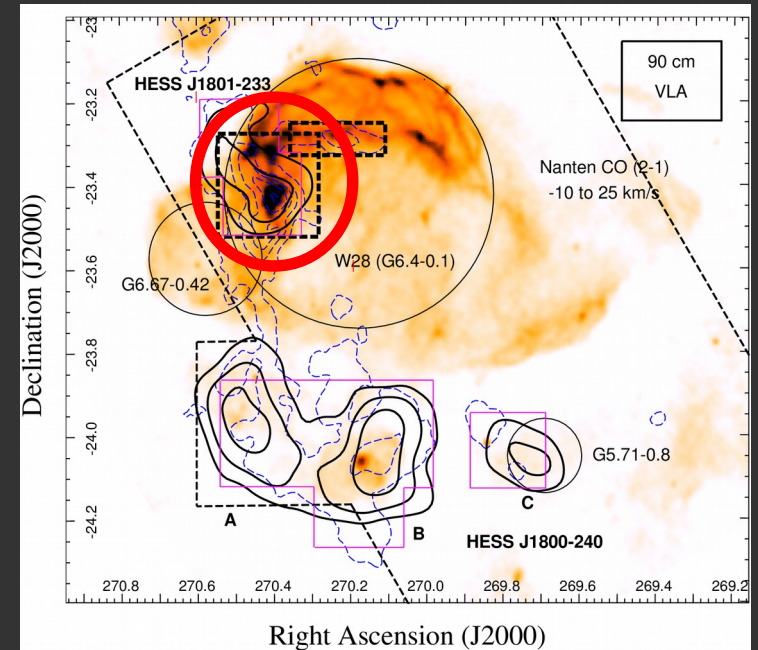
| | |
|-----------|----------|
| CS(1-0) | C34(1-0) |
| 13CS(1-0) | SiO(1-0) |
| CH3OH | HC3N |

~1' angular resolution
~0.2 km/s velocity resolution

7mm

12mm

Nicholas et al., 2012



A new Mopra 12mm survey of the northern cloud W28 interaction region.

Transitions targeted:

| | |
|----------|----------|
| NH3(1,1) | NH3(2,2) |
| NH3(3,3) | NH3(4,4) |
| NH3(6,6) | NH3(9,9) |

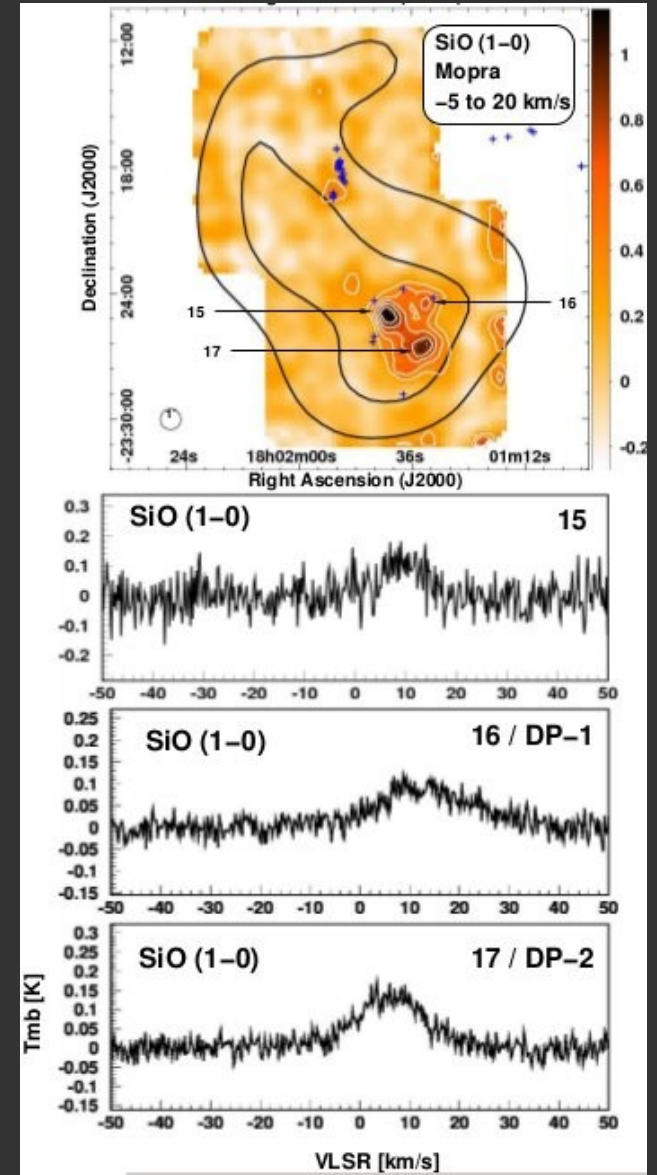
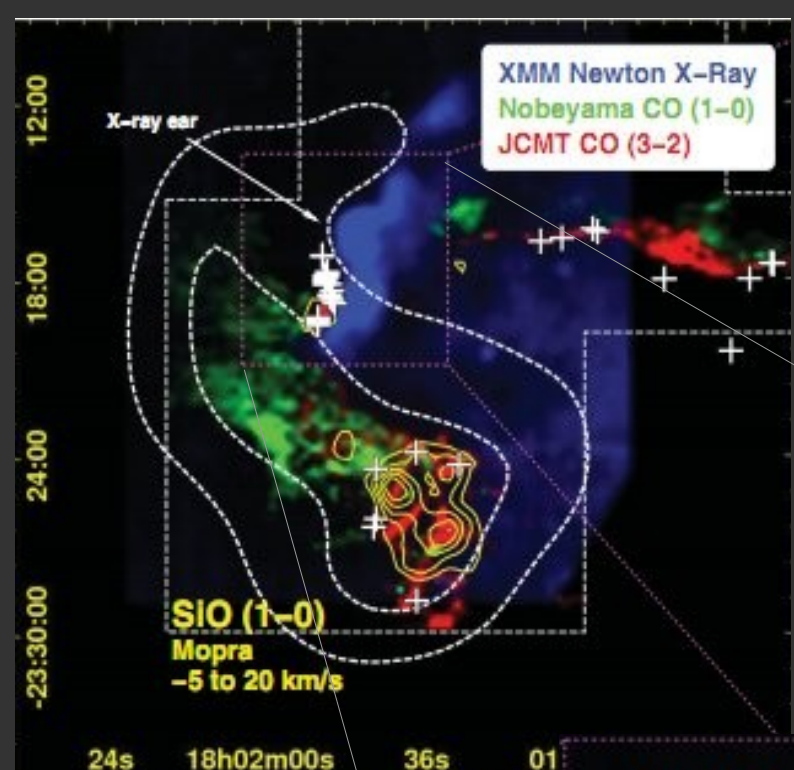
~2' angular resolution
~0.4 km/s velocity resolution

Maxted et al., submitted (2015)

7mm

SiO - A shock tracer

Yellow contours are SiO(1-0) emission

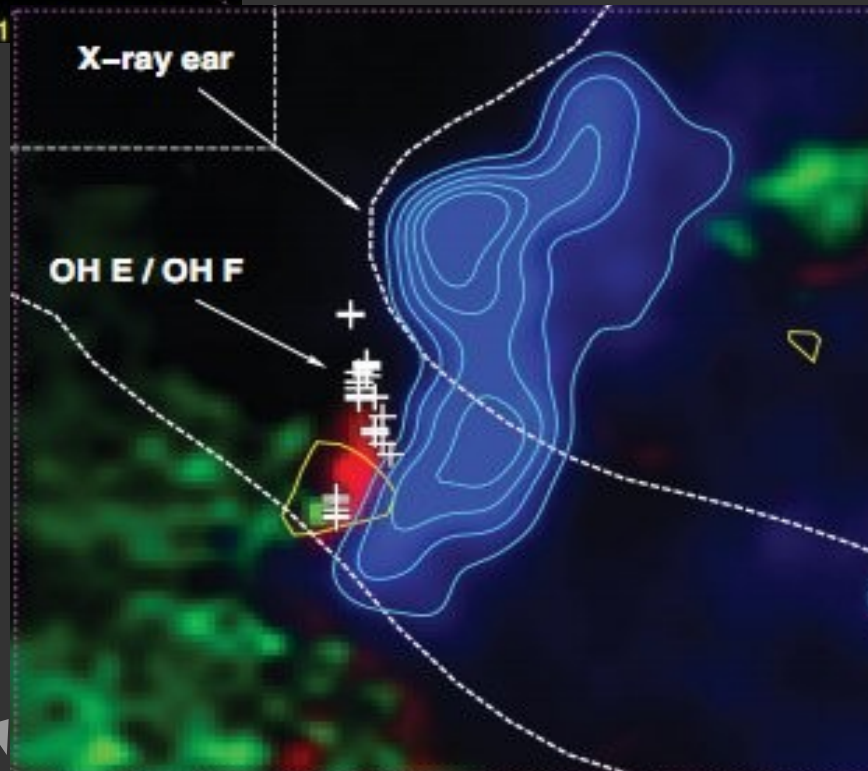


Thermal X-rays (blue) are from high energy plasma

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

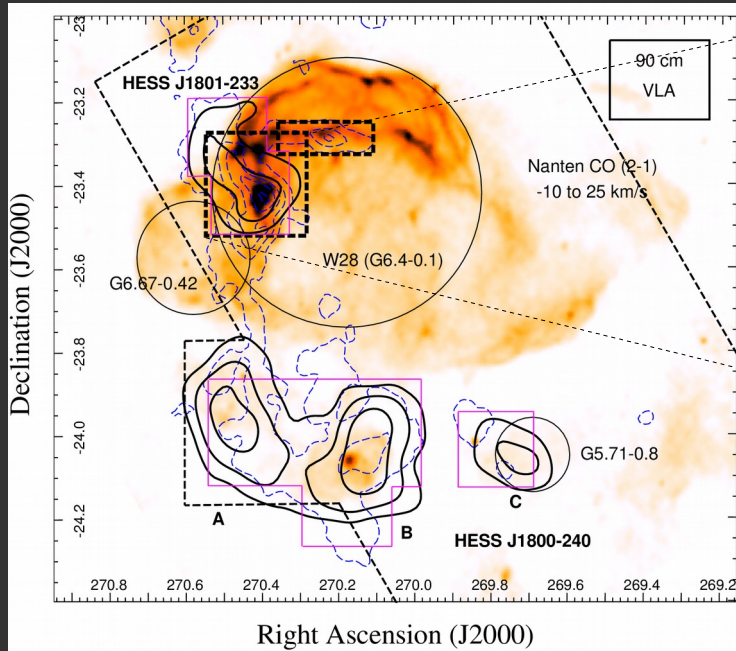
CO(3-2) shown in red
T~30 K

White crosses: OH masers



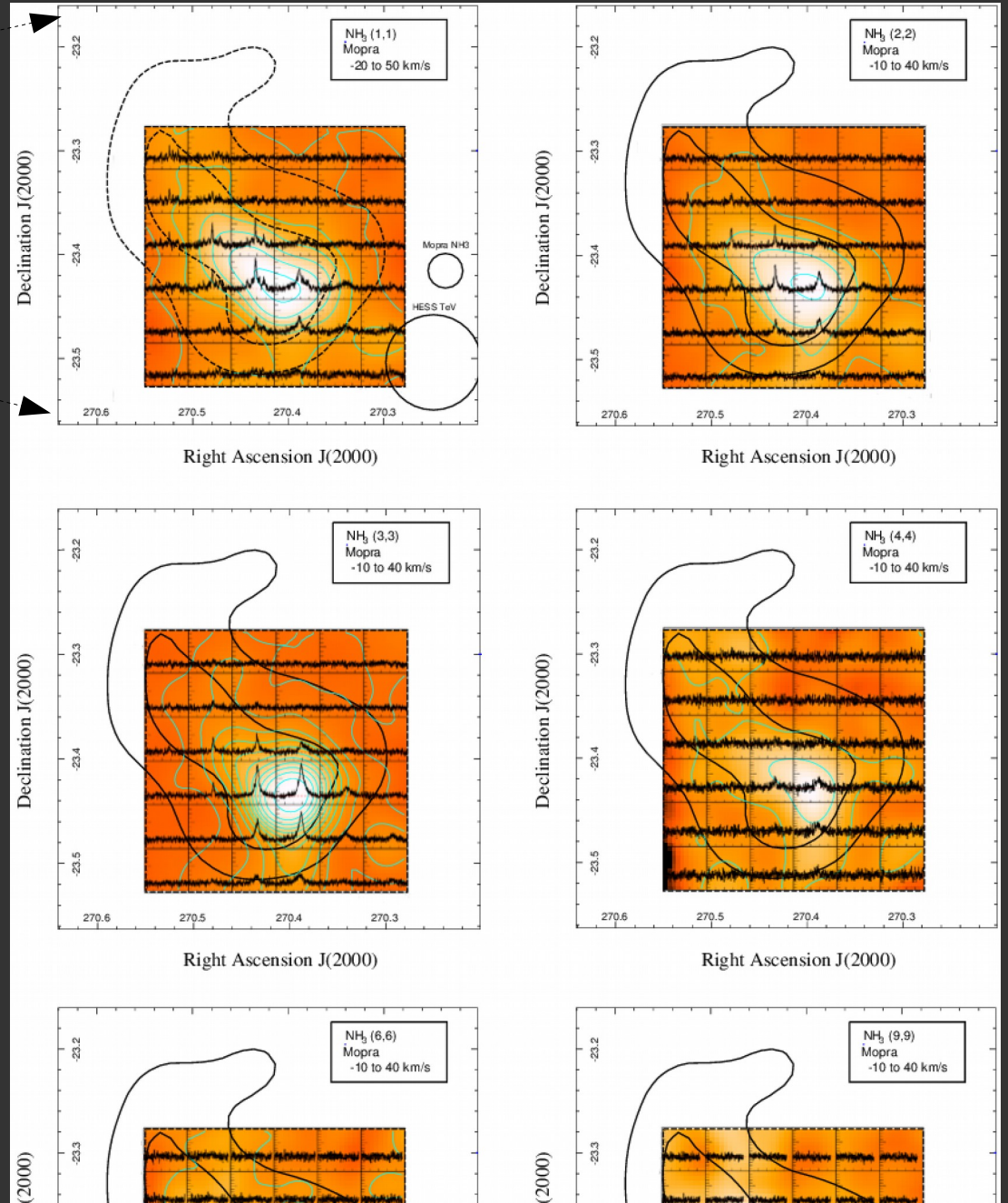
W28 NH3 study

12mm



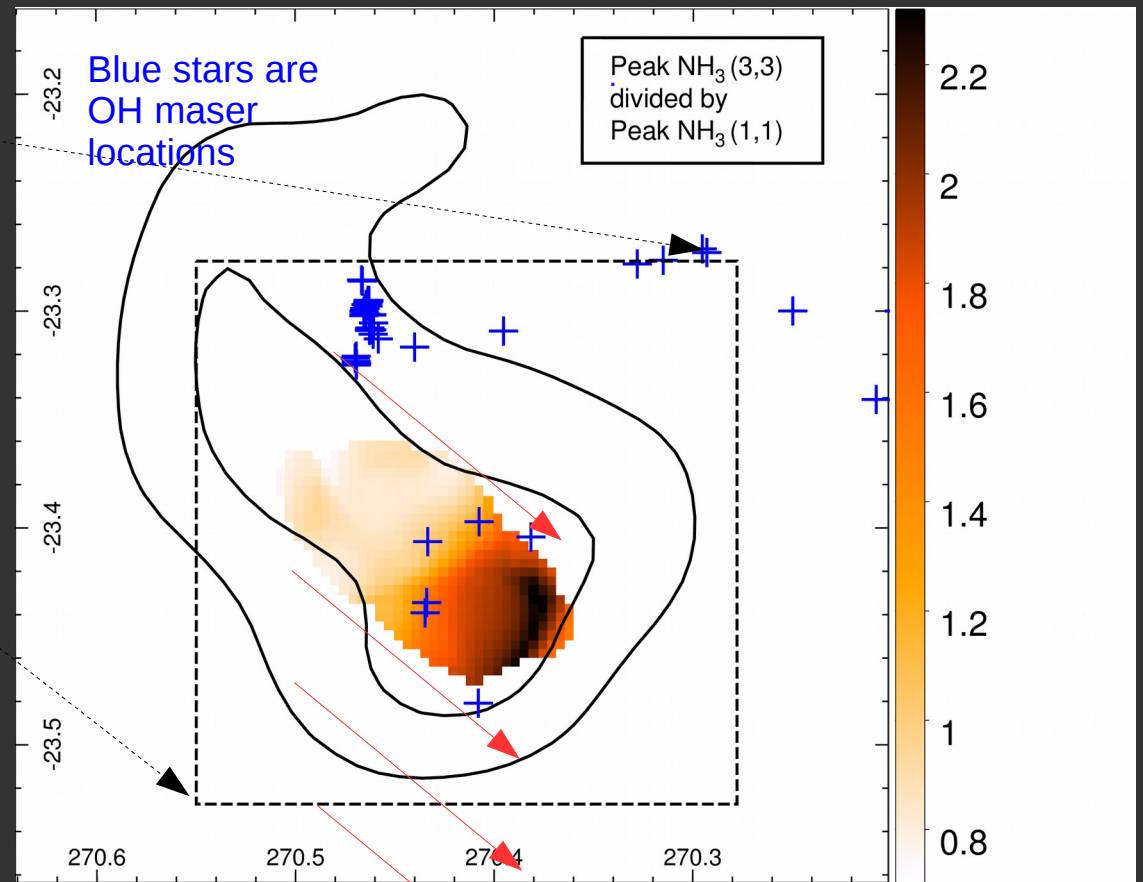
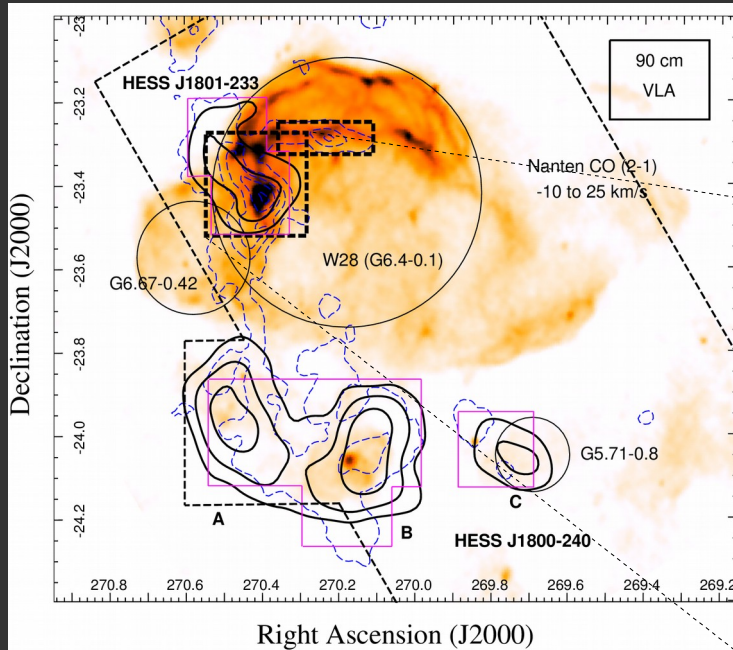
Unprecedented spectral detail

Maxted et al., submitted (2015)



W28 NH3 study

12mm



Transition Energies

NH₃(1,1) : 22.7 K

NH₃(3,3) : 123 K

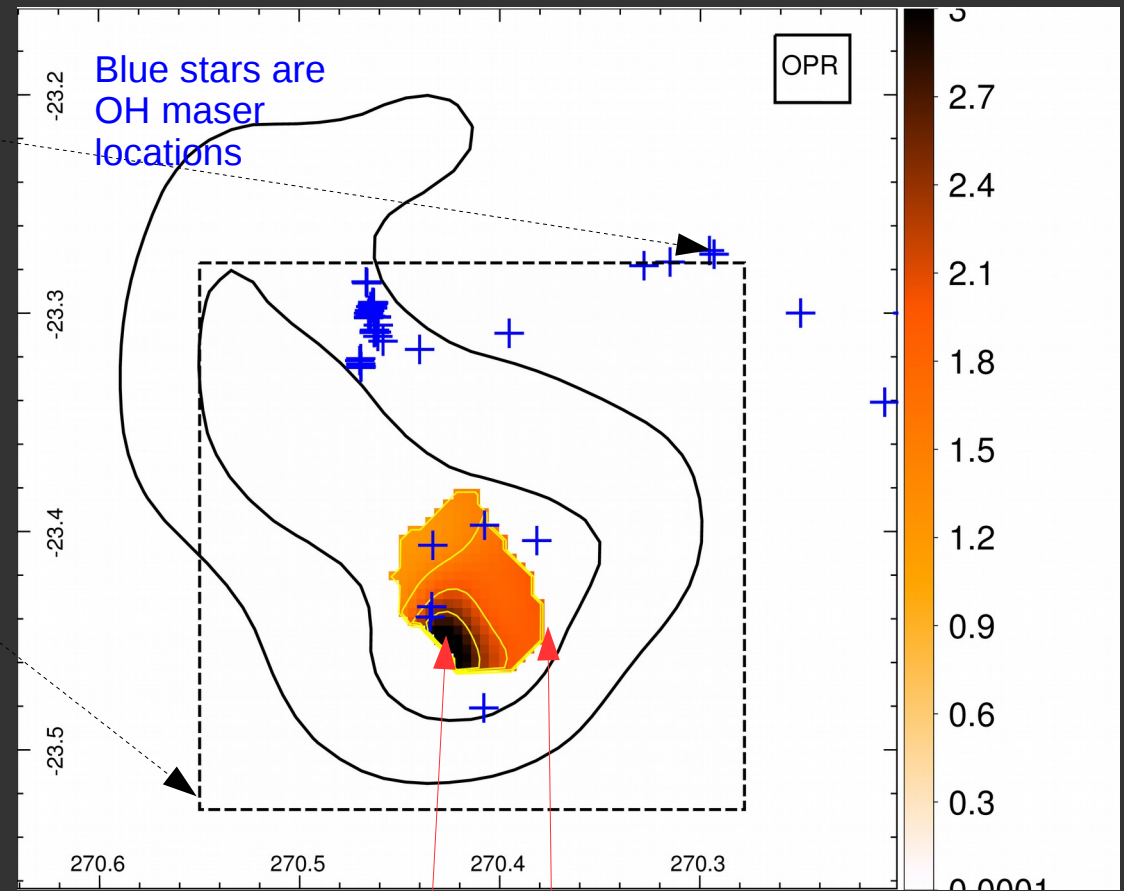
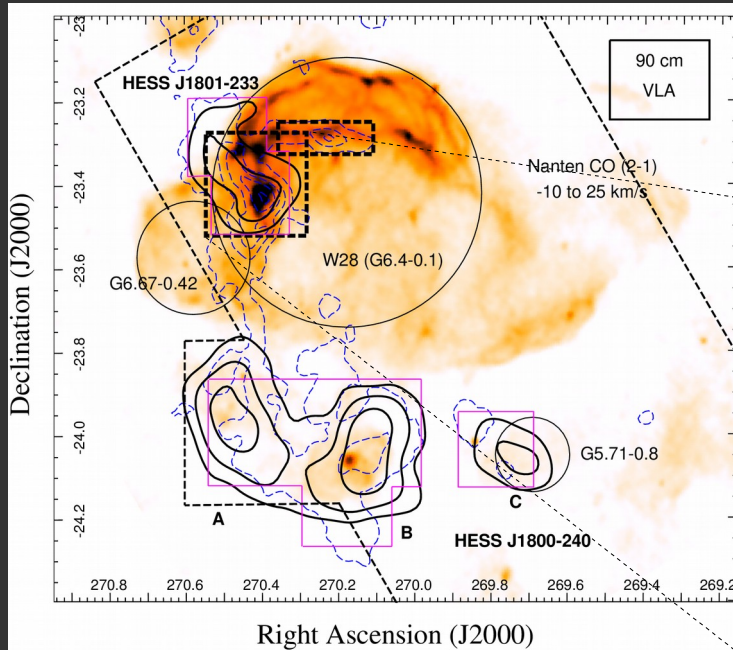
Maxted et al., submitted (2015)

Increasing
NH₃(3,3) / NH₃(1,1)
ratio

W28
shock

W28 NH3 study

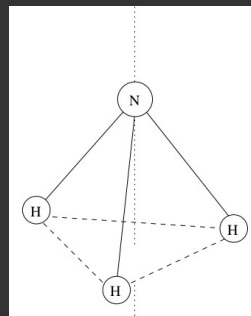
12mm



Ortho-para-NH3 ratio can be calculated in the region exhibiting NH3(3,3), (4,4) and (6,6) emission lines

Variation of ortho/para ratio: $\sim 1.5 - 3$

Maxted et al., submitted (2015)



o-NH₃ p-NH₃ ratio 12mm

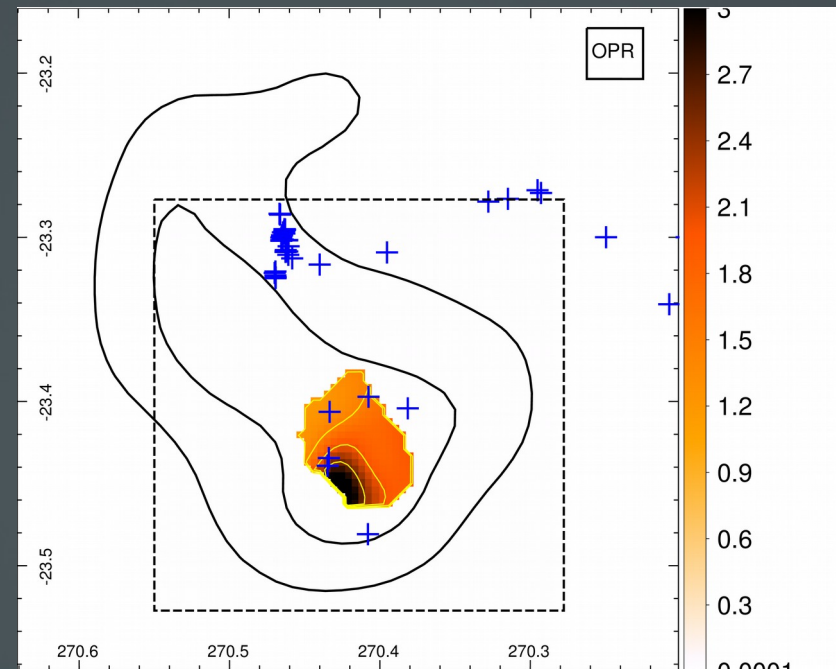
*OPR ~ 1 : suggestive of gas-phase NH₃ formation (Faure et al. 2013),

*OPR > 1 : suggestive that NH₃ is released from dust grains (Umemoto et al. 1999)

In W28, OPR $\sim 1.5-3$, suggesting that NH₃ molecules are being released from dust grains. Is the W28 shock responsible?

If so, this technique is yet another method of tying a SNR to a gas cloud.

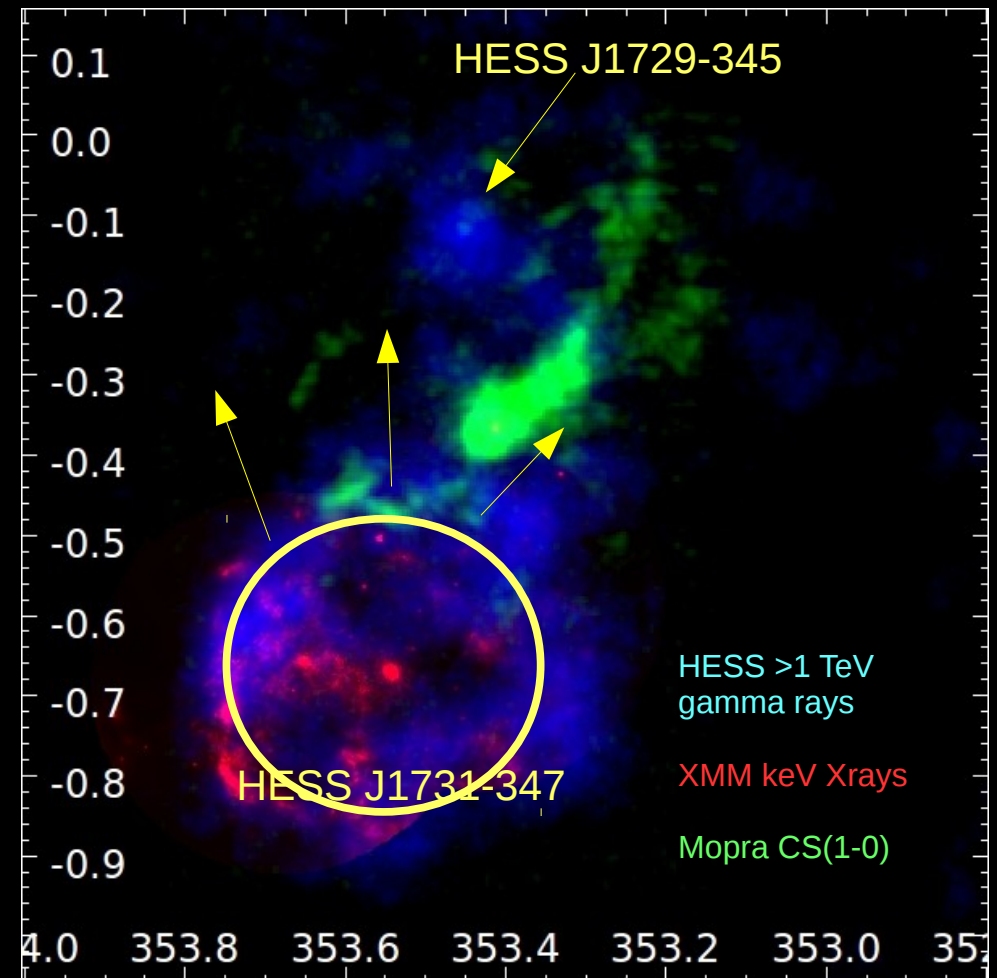
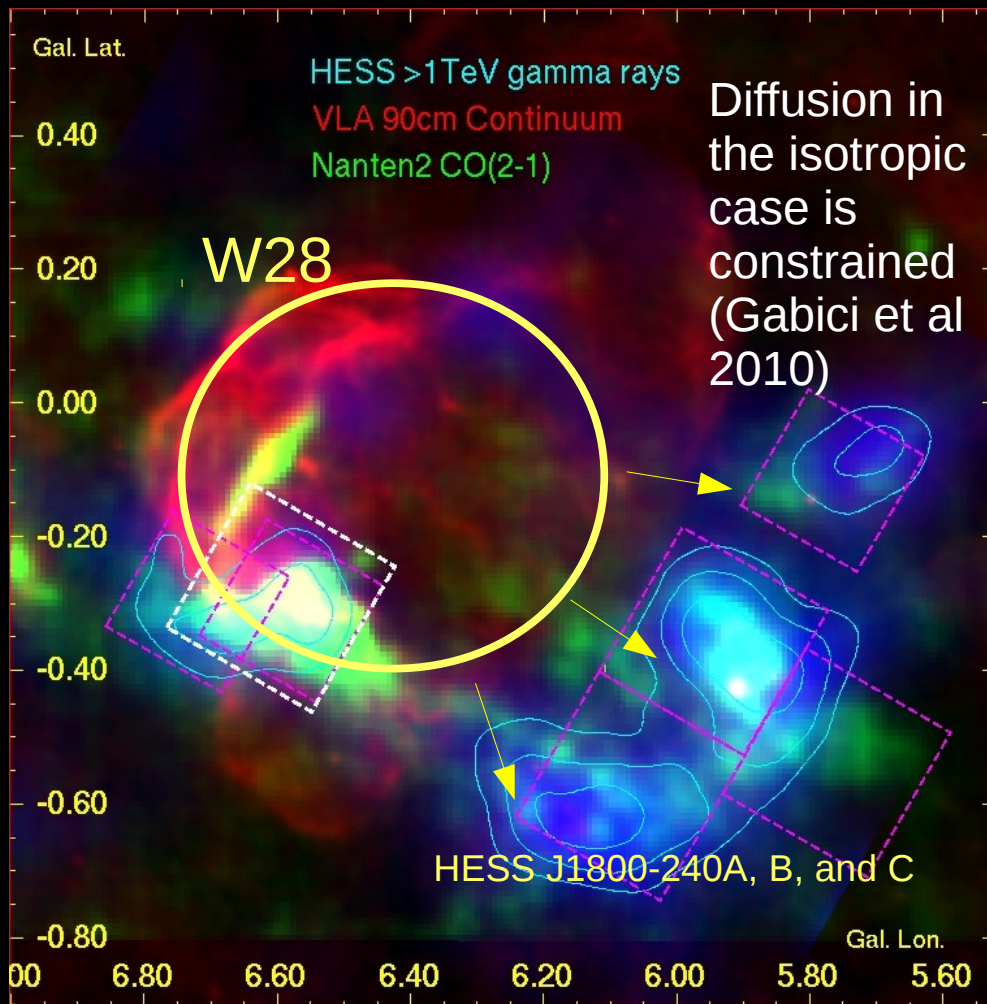
Maxted et al., submitted (2015)



Suppressed Diffusion away from CR sources

W28

HESS J1731-347



Dubner et al. 2000, Brogan et al. 2006, Fukui 2008,

Abdo et al 2010, Nakamura et al. 2014

Nicholas et al 2011, Nicholas et al 2012

Maxted et al *Submitted*(2015)

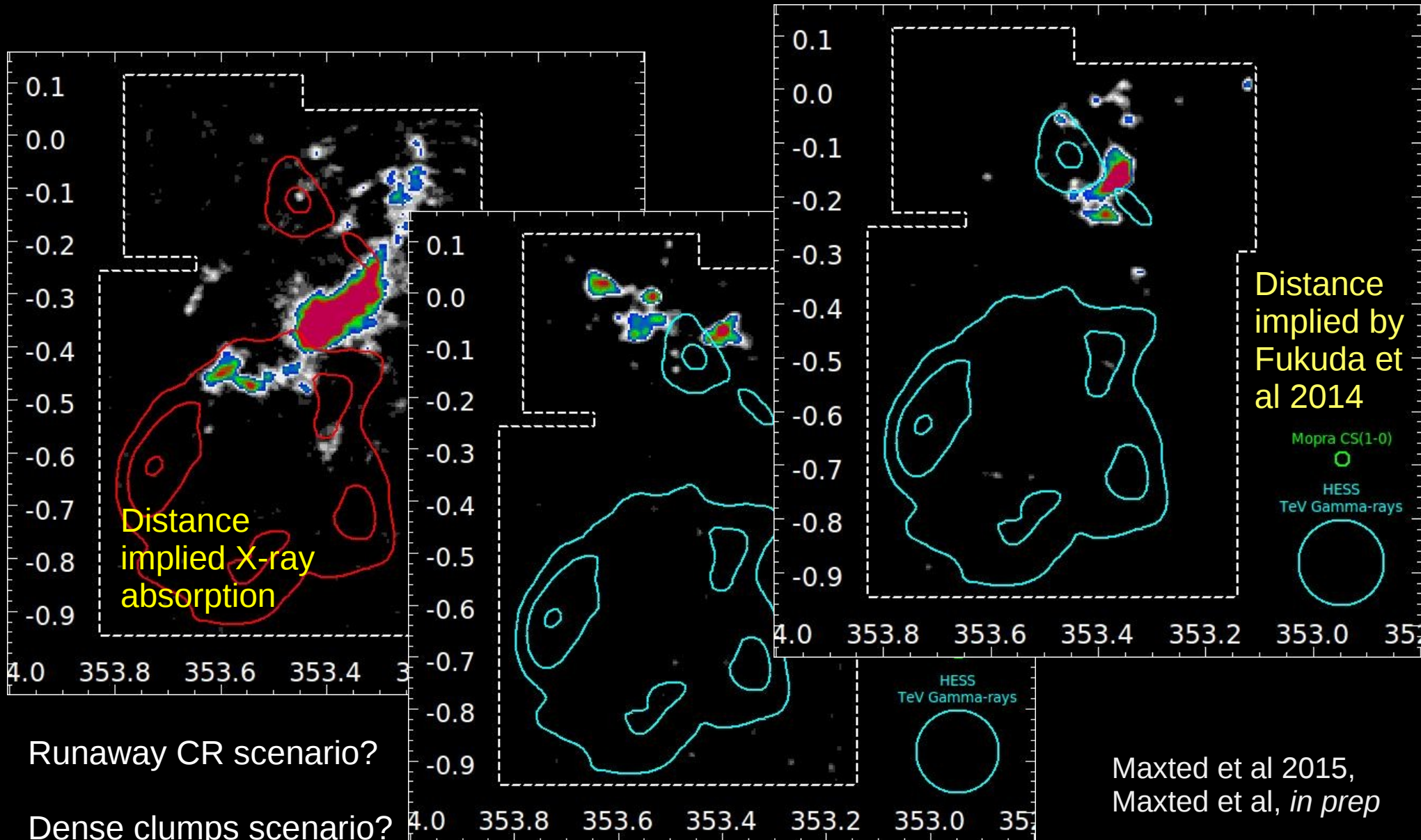
Abramowski et al 2011

Bamba et al 2012

Maxted et al 2015

Maxted et al *in prep*

HESS J1731-347 CS(1-0) emission



Runaway CR scenario?

Dense clumps scenario?
-not molecular clumps?

Maxted et al 2015,
Maxted et al, *in prep*

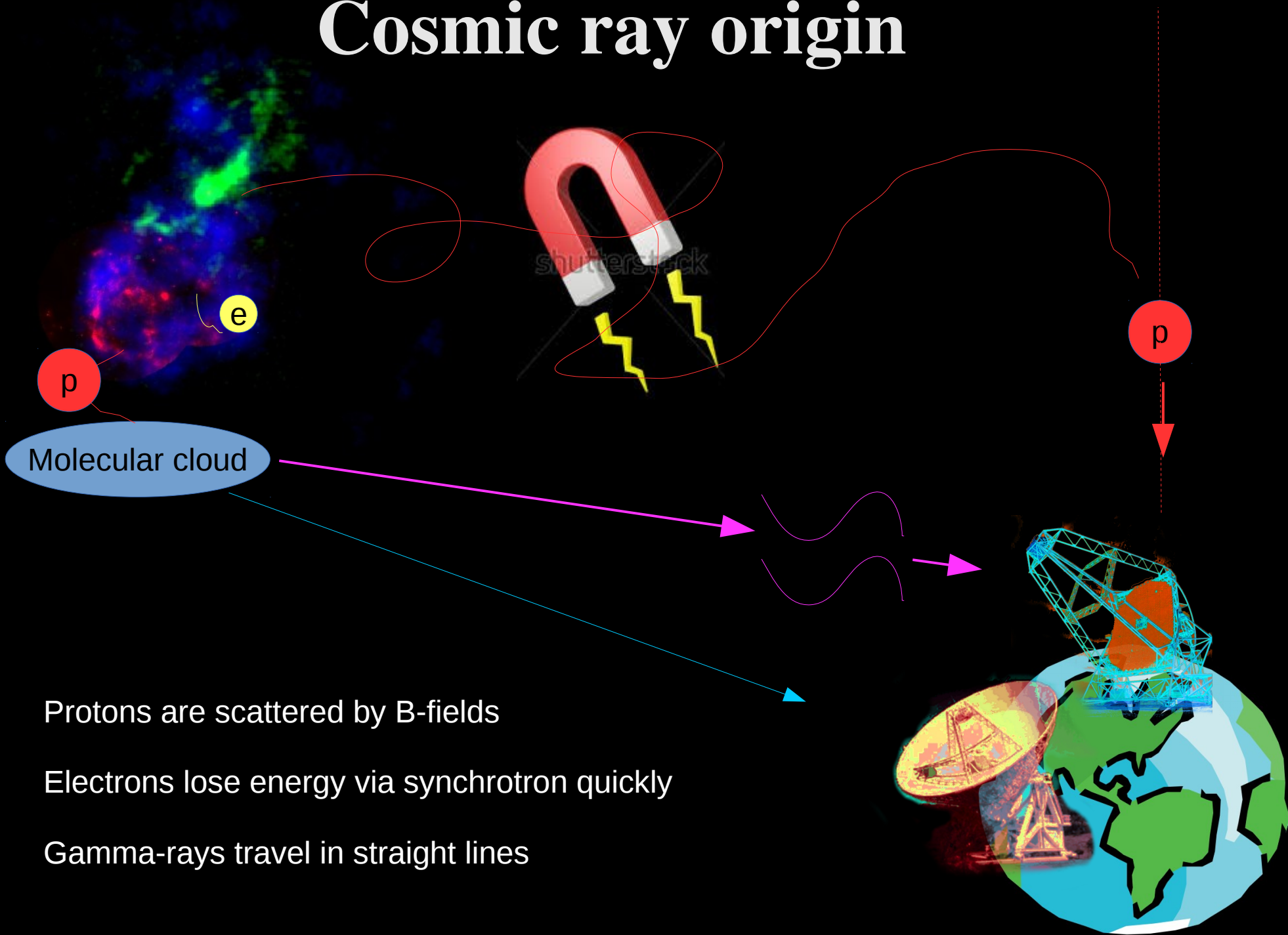
Thank you



Back-up Slides



Cosmic ray origin



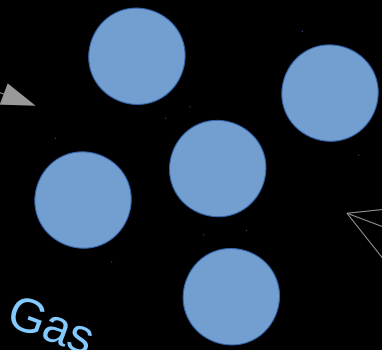
Molecular cloud

- Protons are scattered by B-fields
- Electrons lose energy via synchrotron quickly
- Gamma-rays travel in straight lines

Gamma-ray emission from SNRS

p-p interaction:

p
TeV Proton



π^+

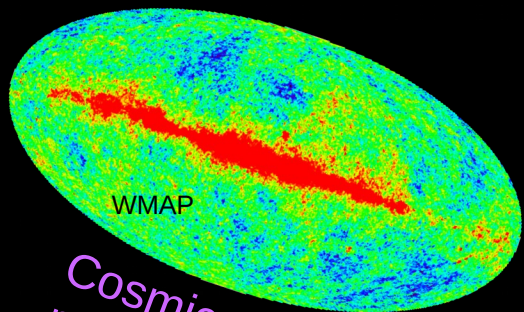
π^-

π^0

TeV gamma-rays

Inverse Compton Scattering:

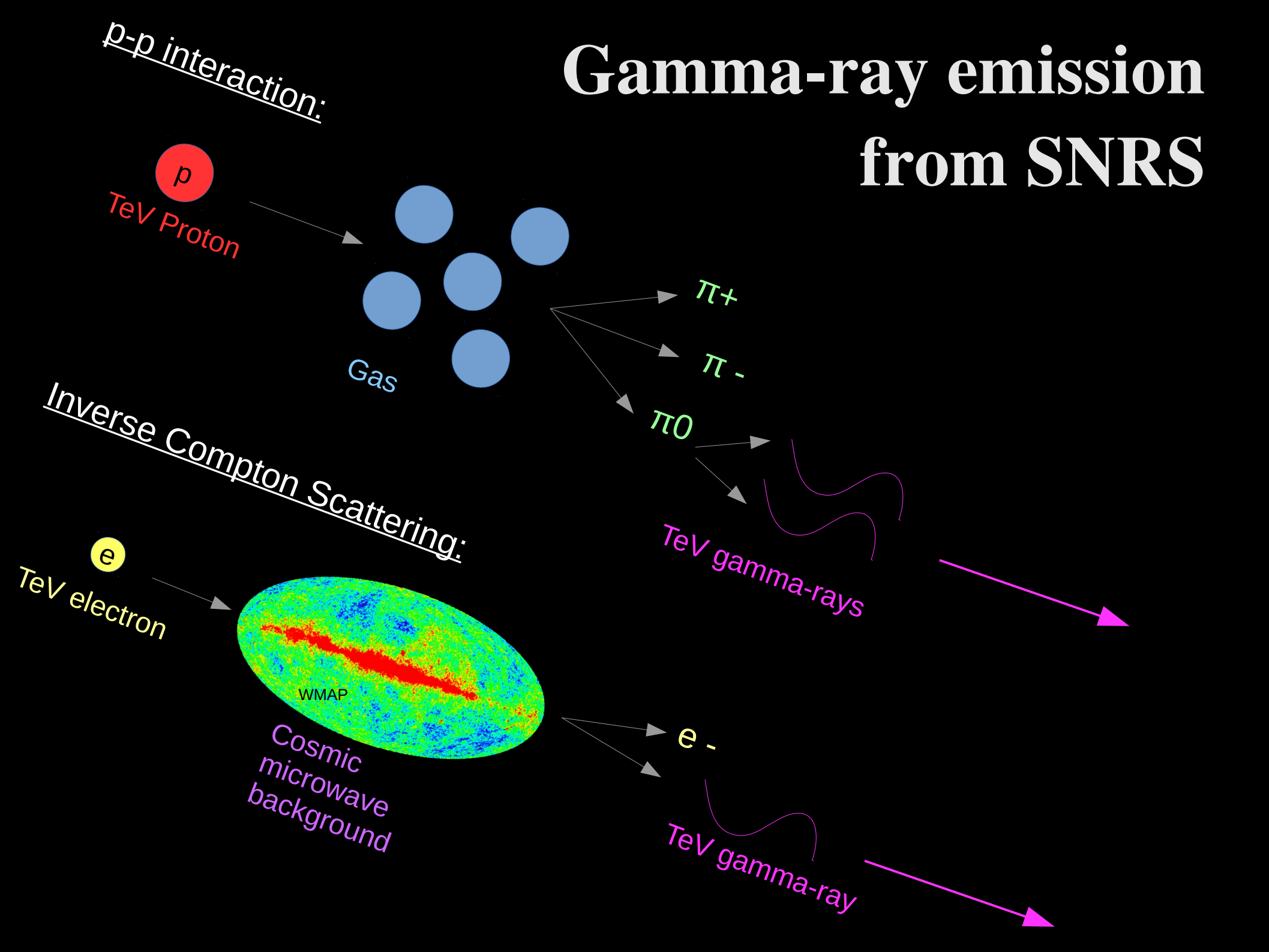
e^-
TeV electron



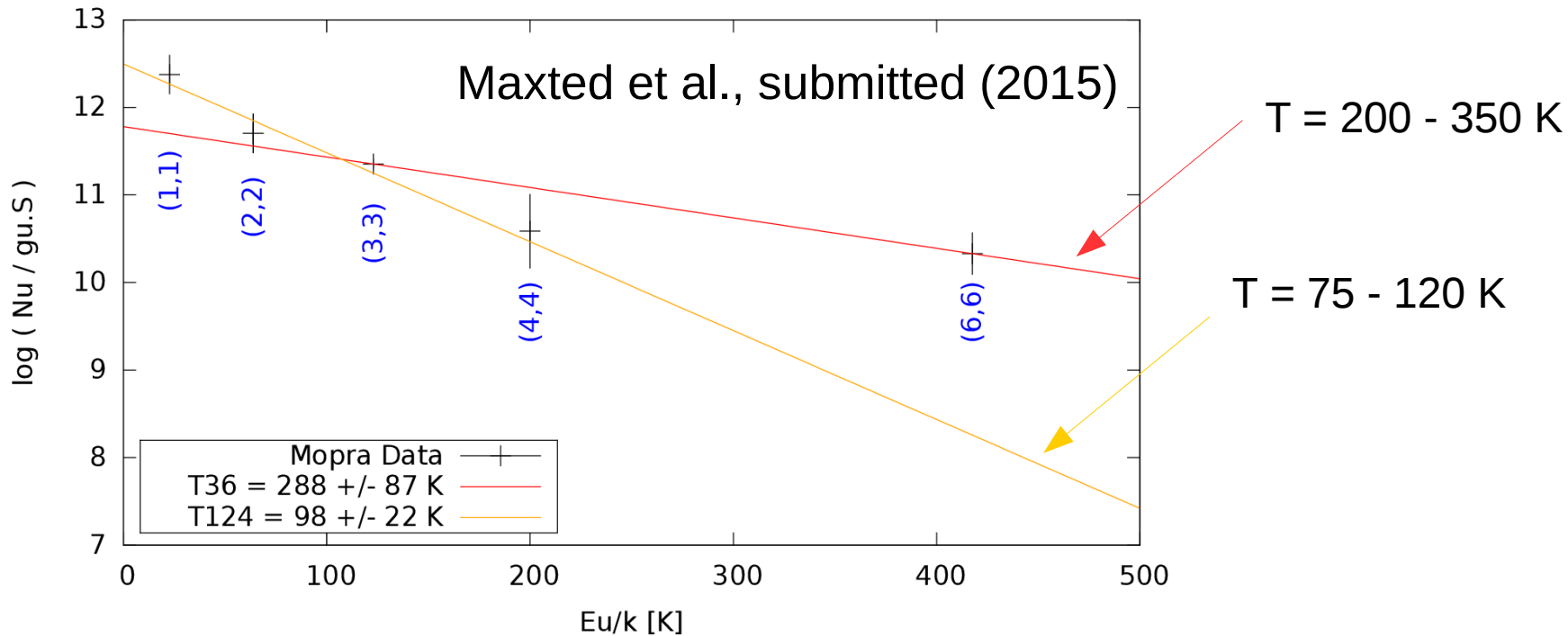
Cosmic microwave background

e^-

TeV gamma-ray



A new NH₃ survey of W28

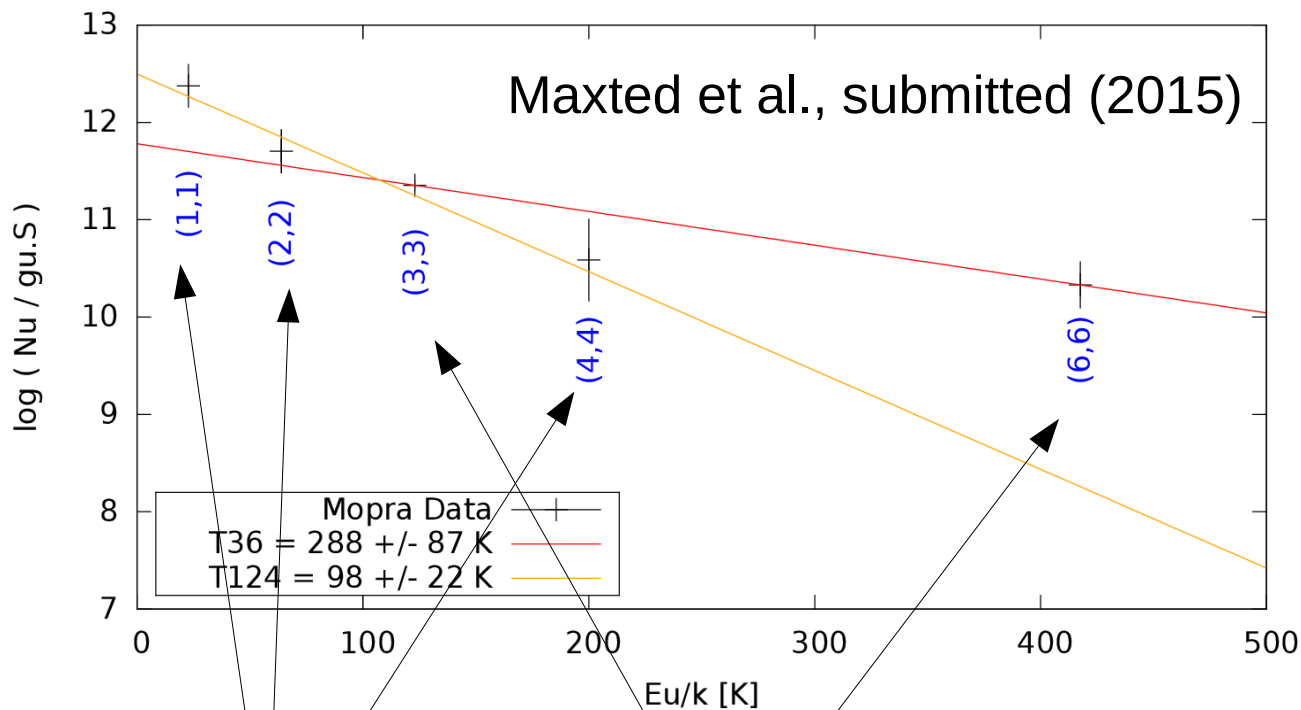


LTE rotational temperatures very high!

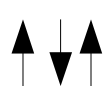
Non-LTE analyses suggest mis-matched kinetic temperatures for :

- * 70 - 90 K for para-NH₃ transitions
- * >135 K for ortho-NH₃ transitions

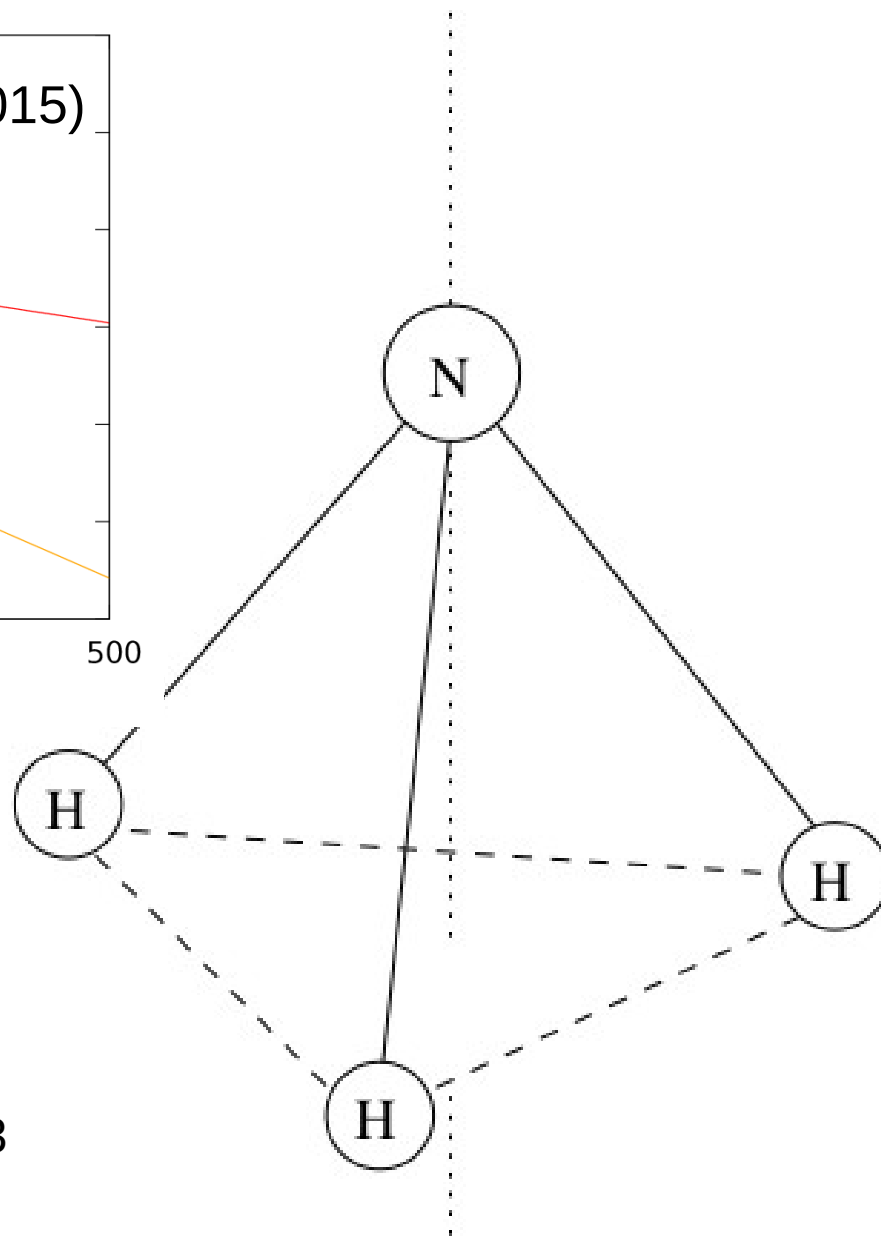
A new NH₃ survey of W28



Para-NH₃ transitions

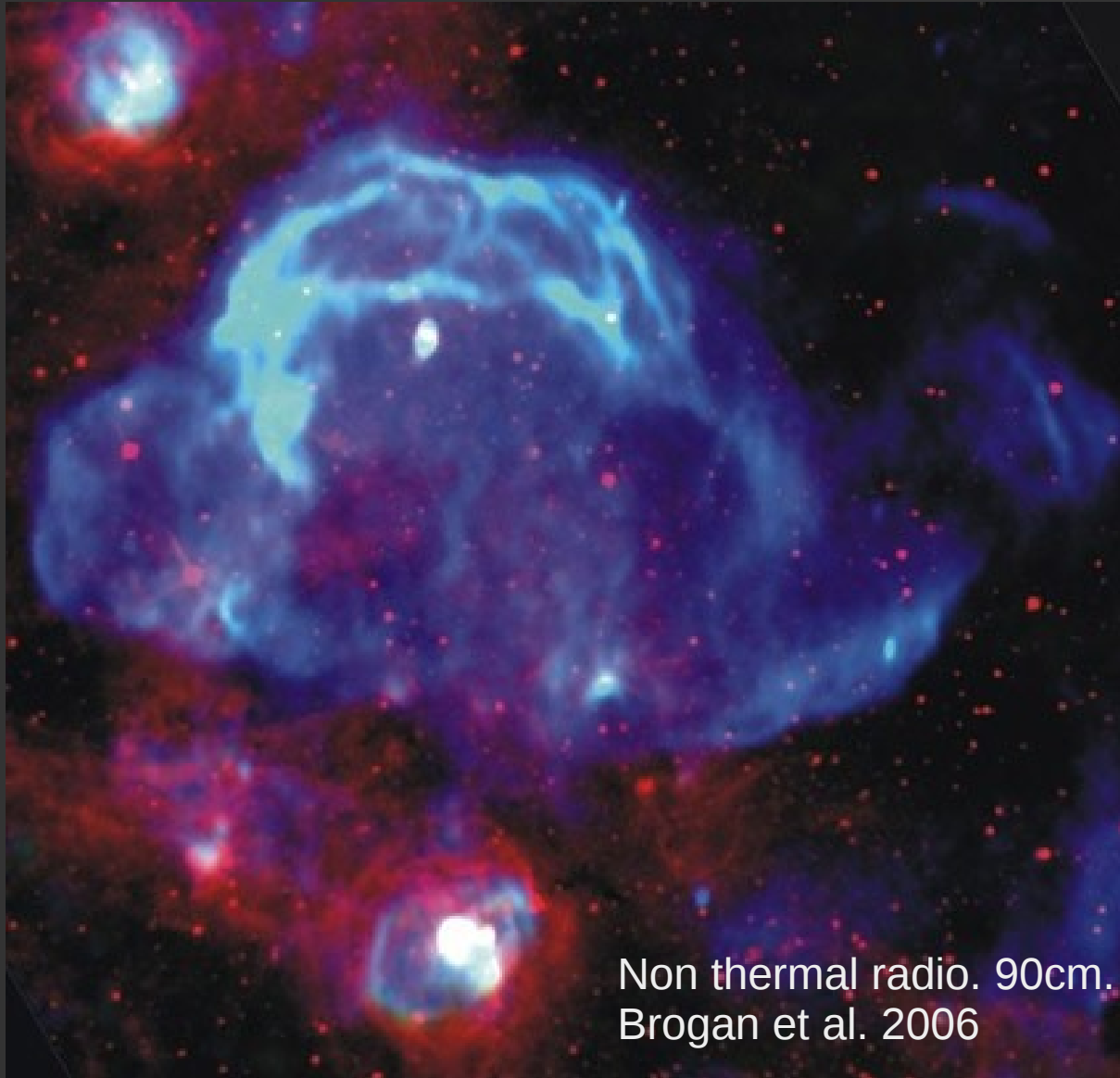


Ortho-NH₃ transitions



Method to calculate ratio of ortho-NH₃ to para-NH₃ presented in Umemoto et al. 1999

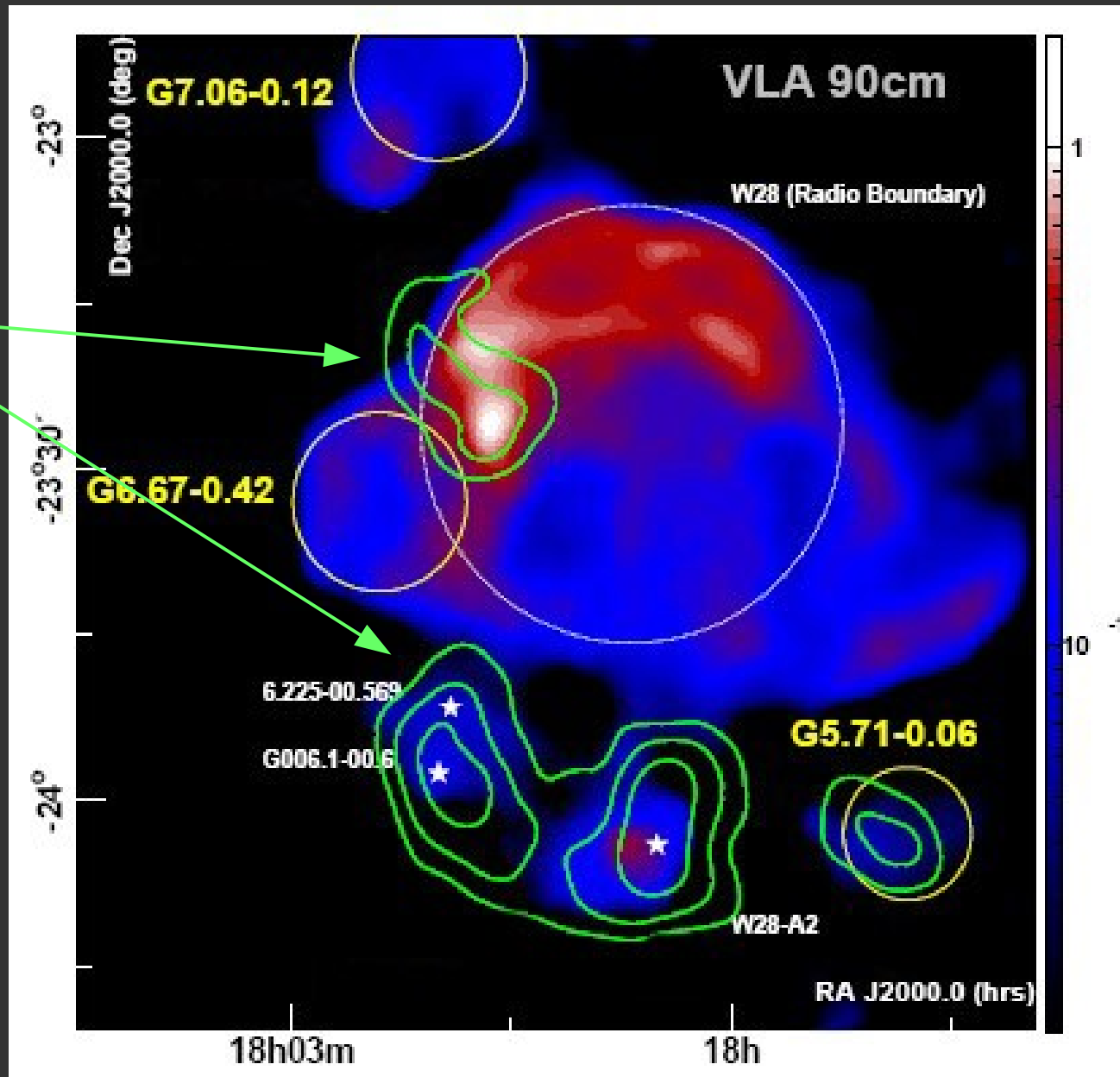
Supernova remnant W28



Non thermal radio. 90cm.
Brogan et al. 2006

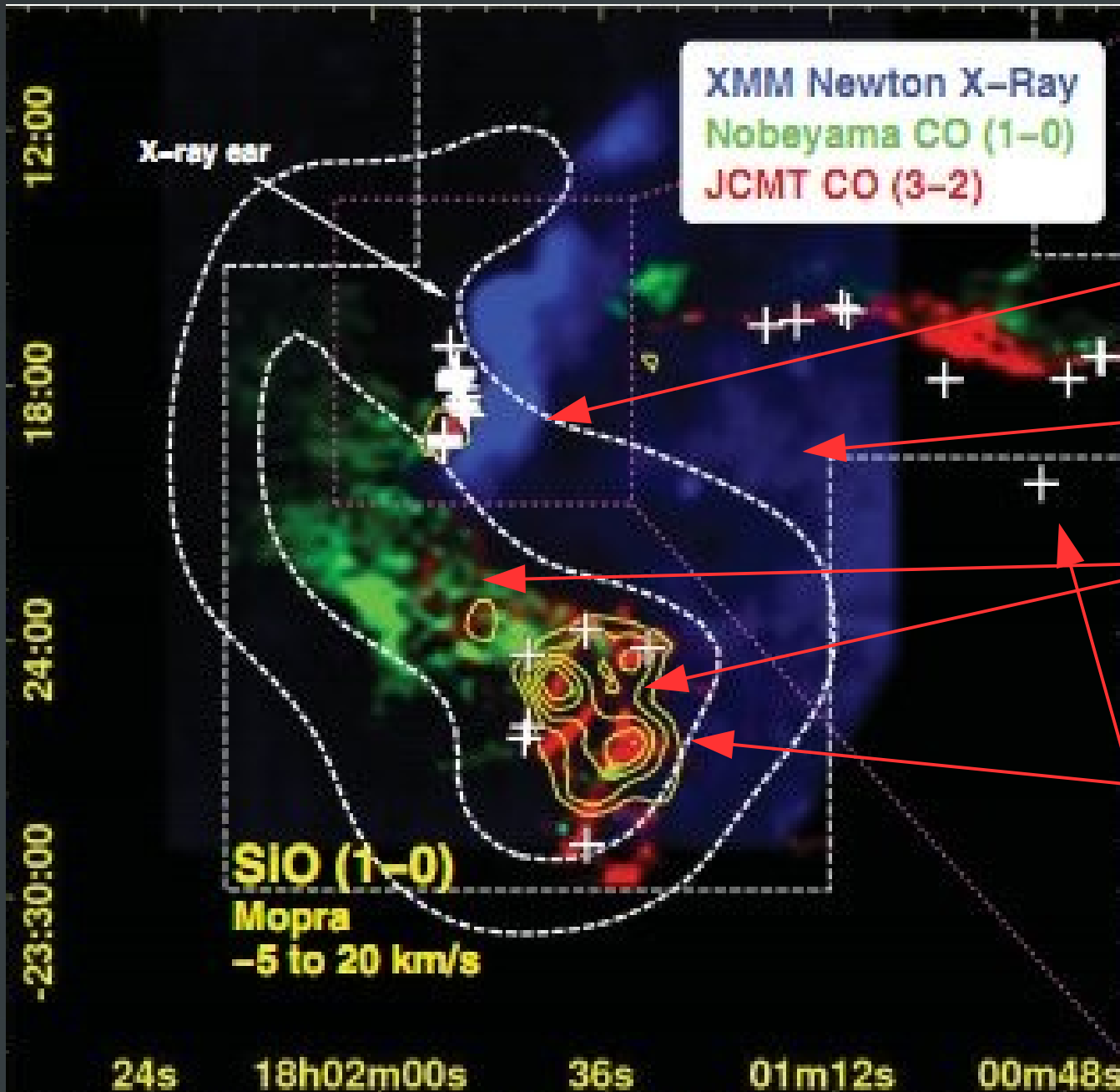
Supernova remnant W28

HESS TeV
gamma-rays



Non-thermal radio. Dubner et al. 2000, Brogan et al. 2006

Contents



White contours: TeV
gamma-rays

Blue: Thermal X-rays

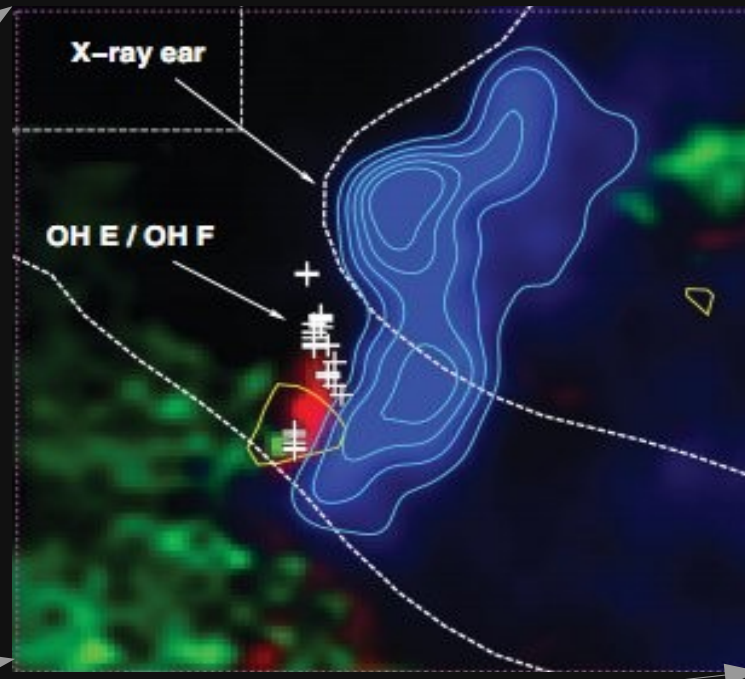
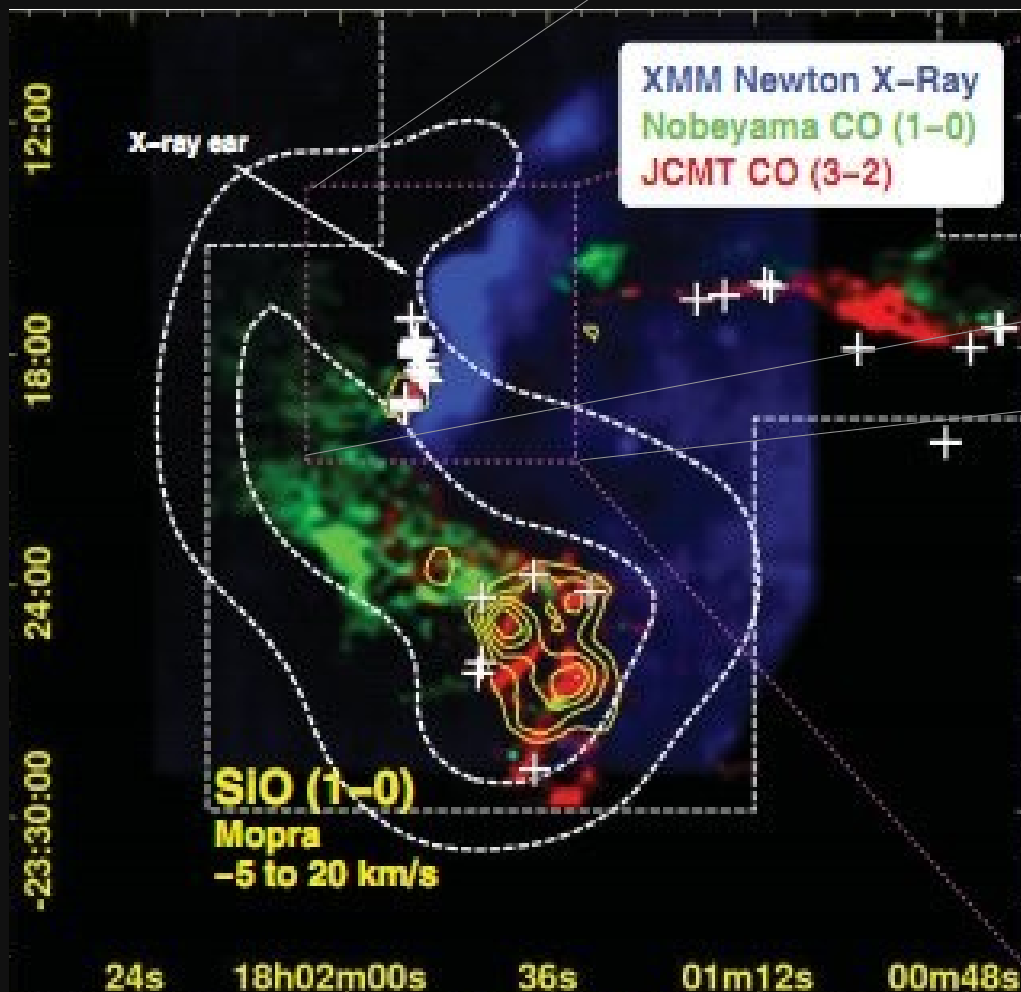
Green: CO(1-0)
Red: CO(3-2)

Yellow contours: SiO

Crosses: OH masers



W28: Multi-wavelength



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

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

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

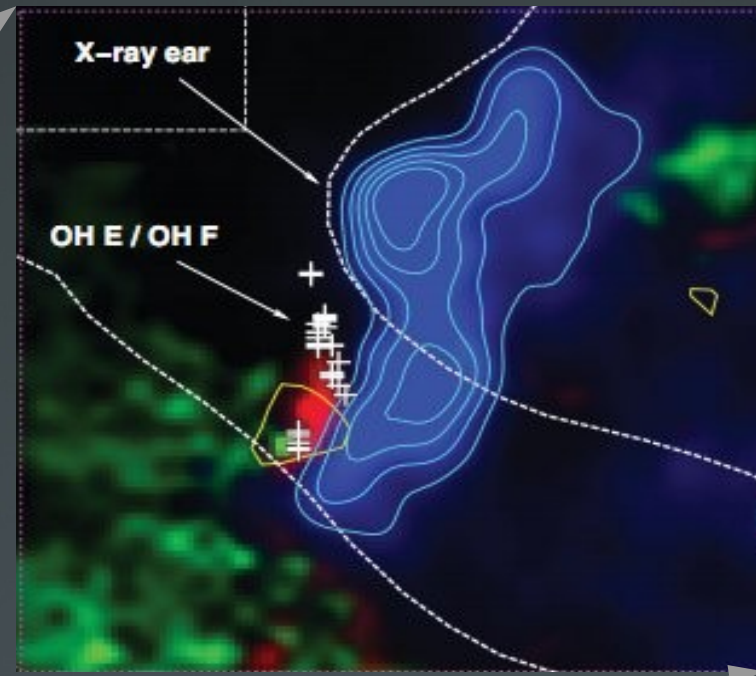
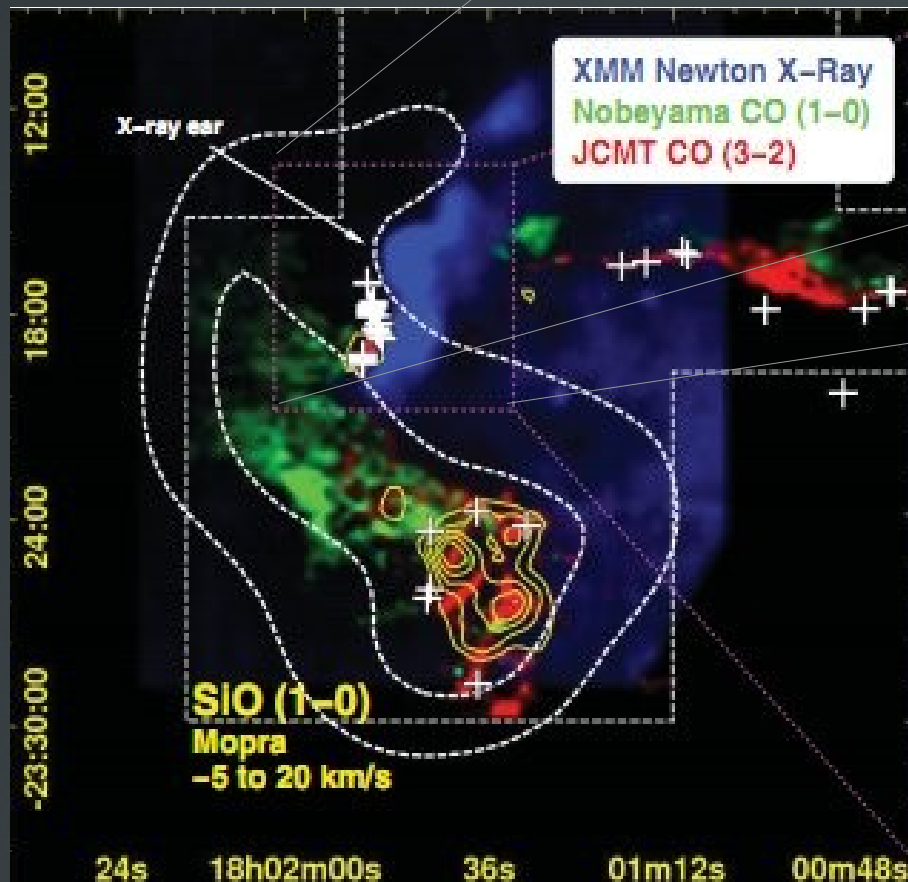
White crosses: OH masers

Nakamura et al. 2014

Arikawa et al. 1999

Claussen et al. 1997

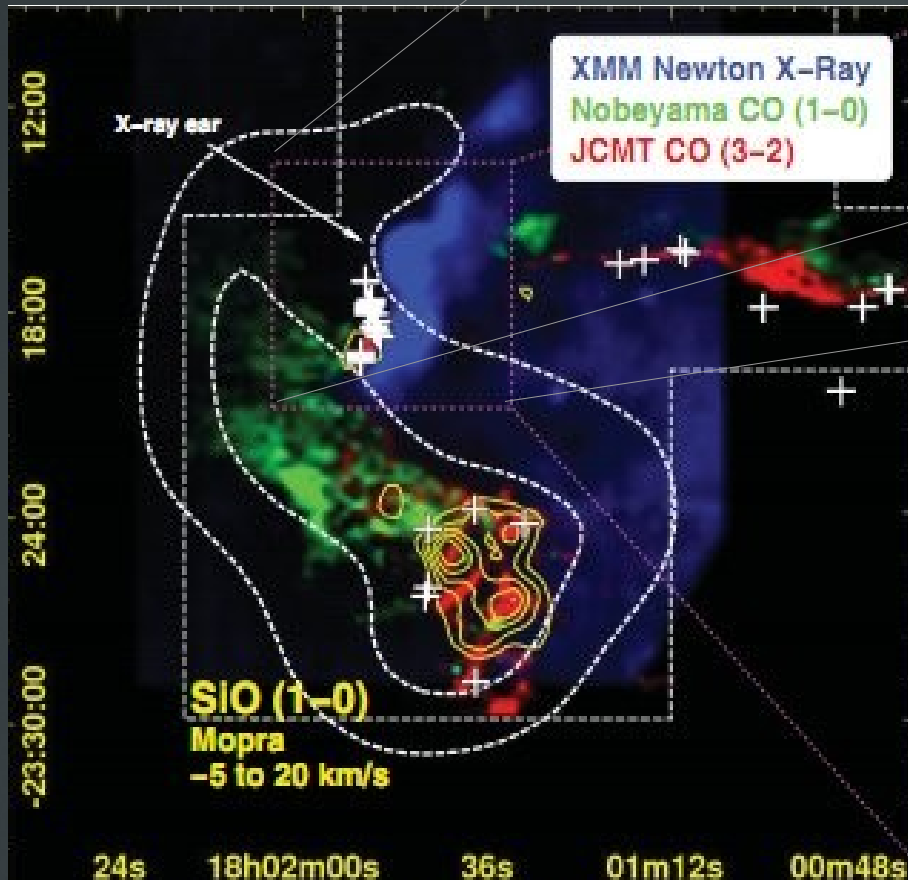
X-rays



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

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

CO Molecule



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

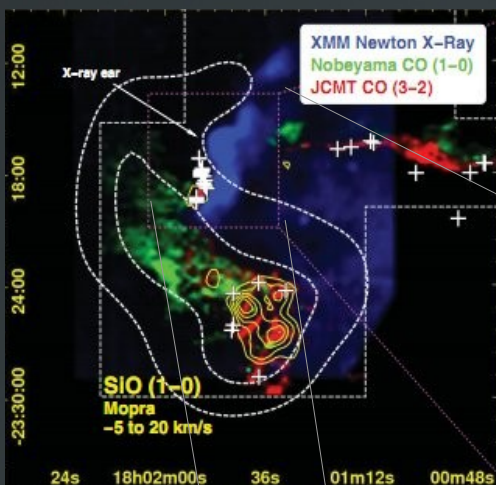
CO(3-2) shown in red
T~30 K

Arikawa et al. 1999

Nicholas et al 2012



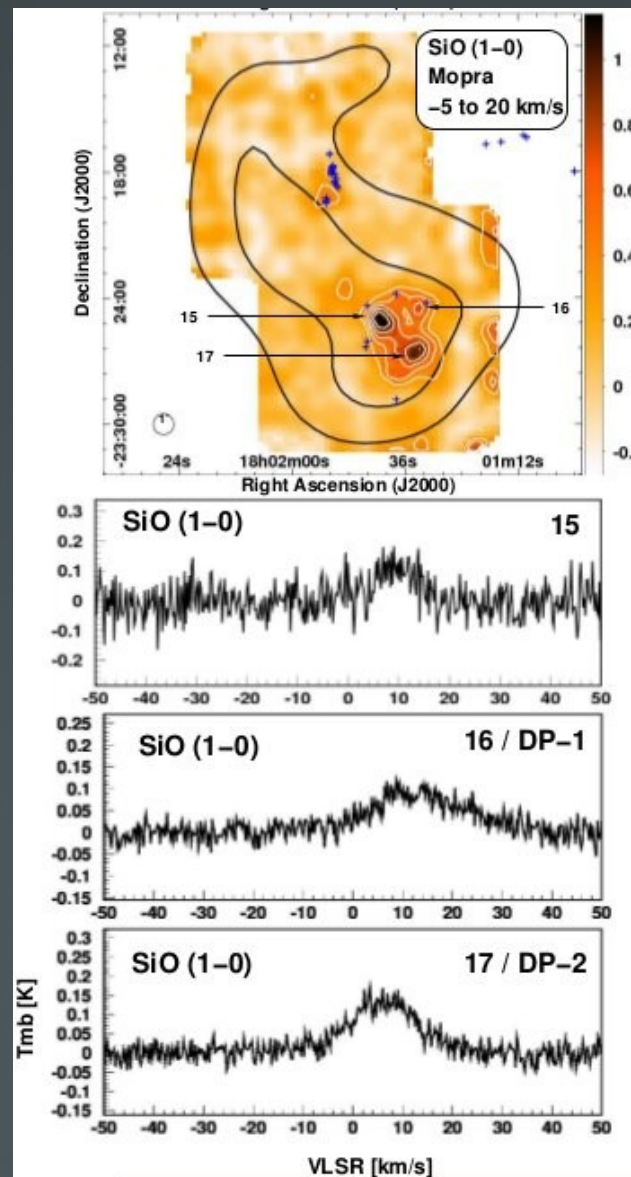
SiO - A shock tracer



Yellow contours are SiO(1-0) emission



Nicholas et al 2012



CO vs SiO

- CO
 - Low electric dipole moment
 - Critical density for emission $\sim 1.10^3 \text{ cm}^{-3}$
 - High abundance everywhere except cold, starless cores.
 - Good general H₂ tracer
- SiO
 - High electric dipole moment
 - Critical density for emission $\sim 6.10^4 \text{ cm}^{-3}$
 - Si and SiO released from dust grains in energetic environments
 - Si is manufactured into SiO at high ($\sim 100\text{K}$) temperatures
 - Good shock-tracer



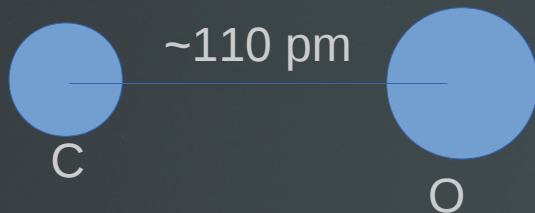
CO vs SiO

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, N₂-----> Zero dipole moment

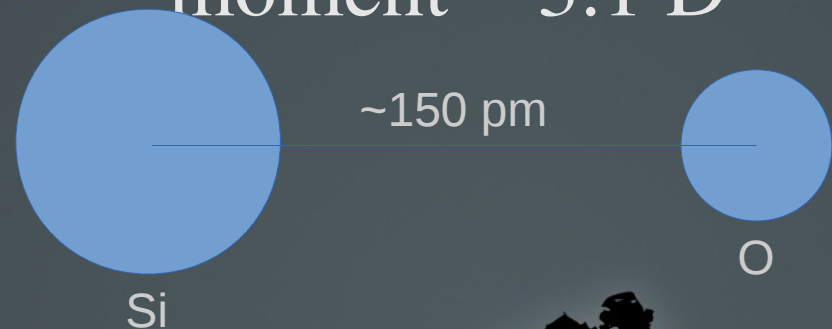
- CO

- 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)

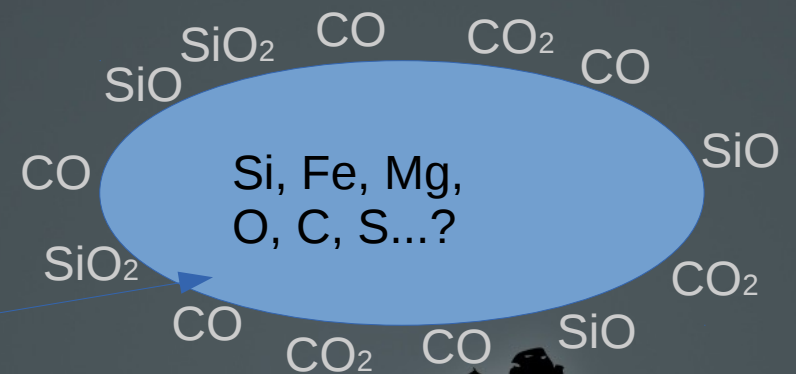
(Schilke et al., 1997)



- 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 ($\sim 10^{-8}$ - 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:



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

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..

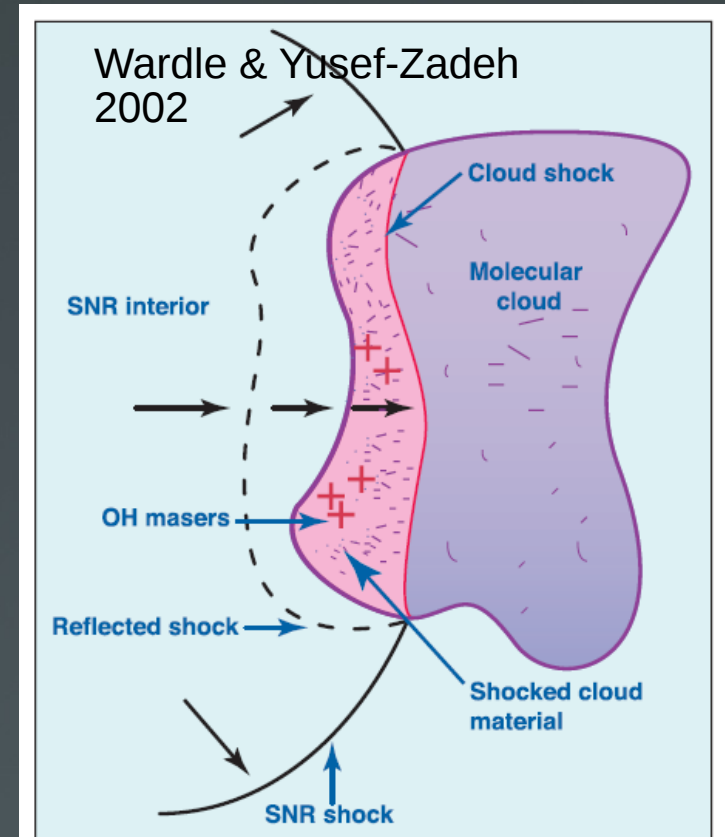
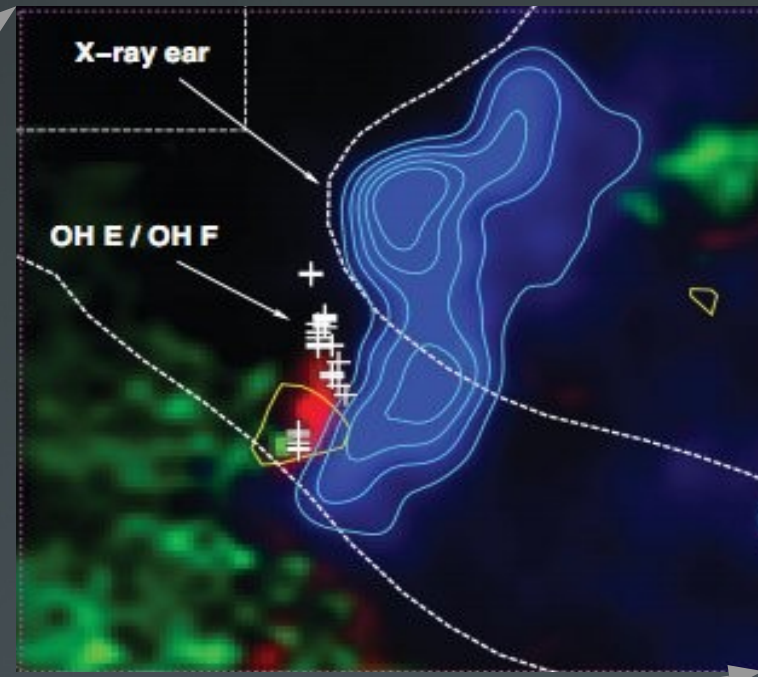
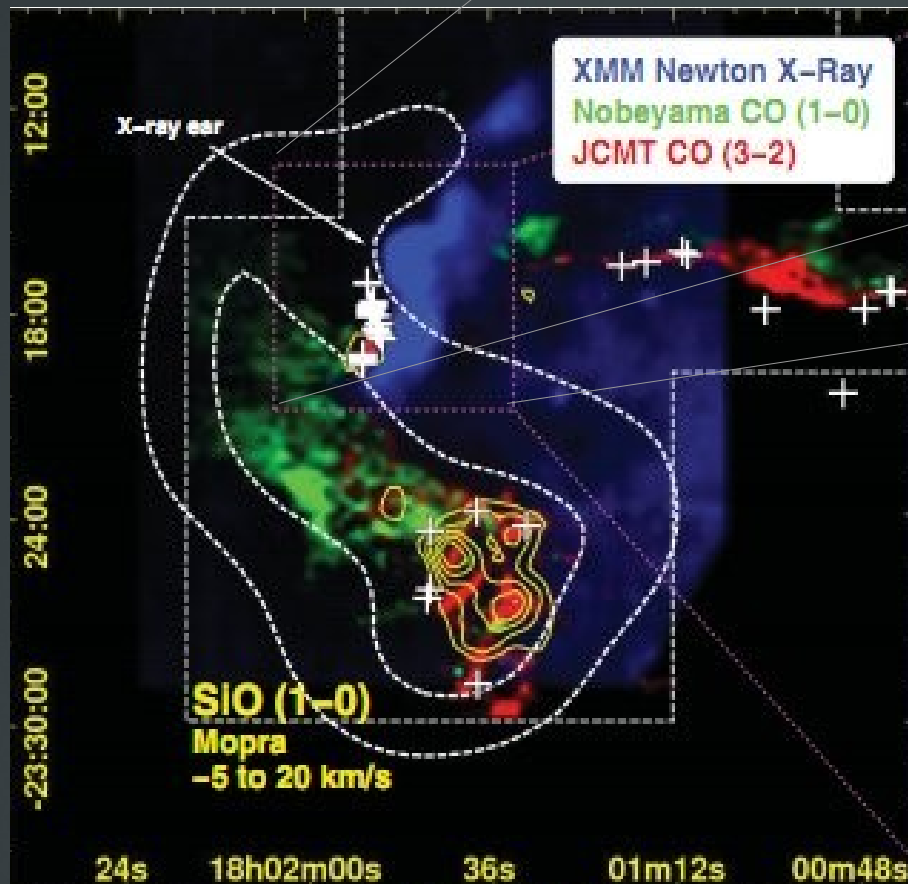


Fig. 1. Schematic of an expanding supernova remnant (SNR) interacting with an adjacent molecular cloud. Black arrows indicate velocity.

OH masers



White crosses: OH masers



OH

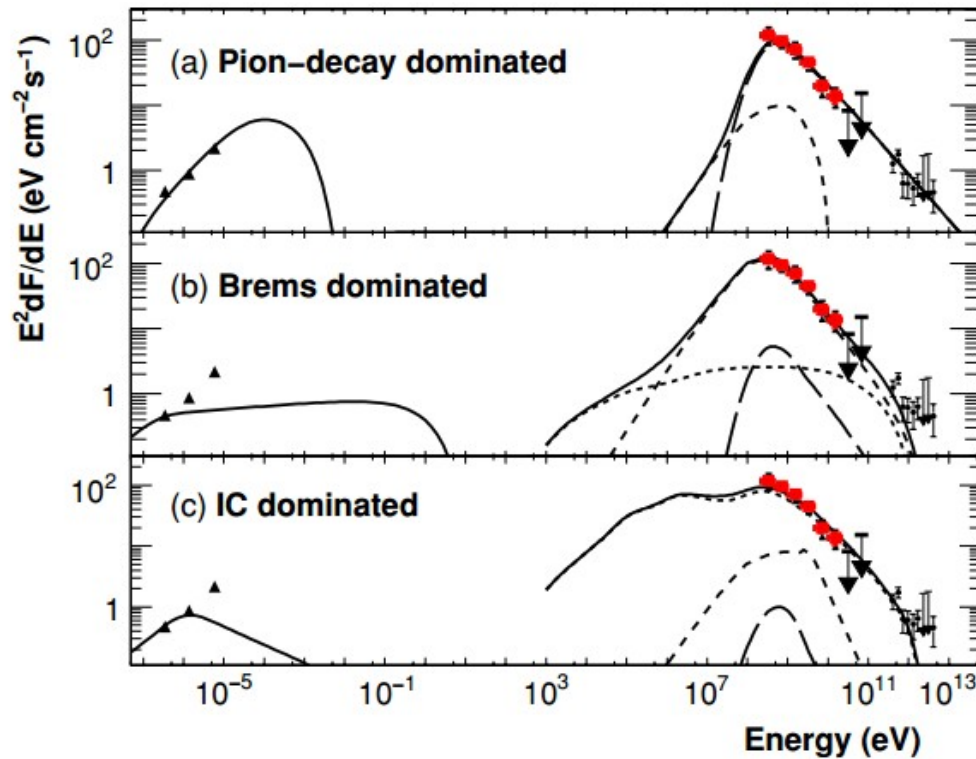
The former case of a non-dissociative shock propagating through high density material (10^4 - 10^5 cm^{-3}) is considered to be particularly promising (Frail et al., 1998). This involves a high-temperature (~ 1000 K) post-shock region that produces a significant column density of OH (Draine et al., 1983). 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



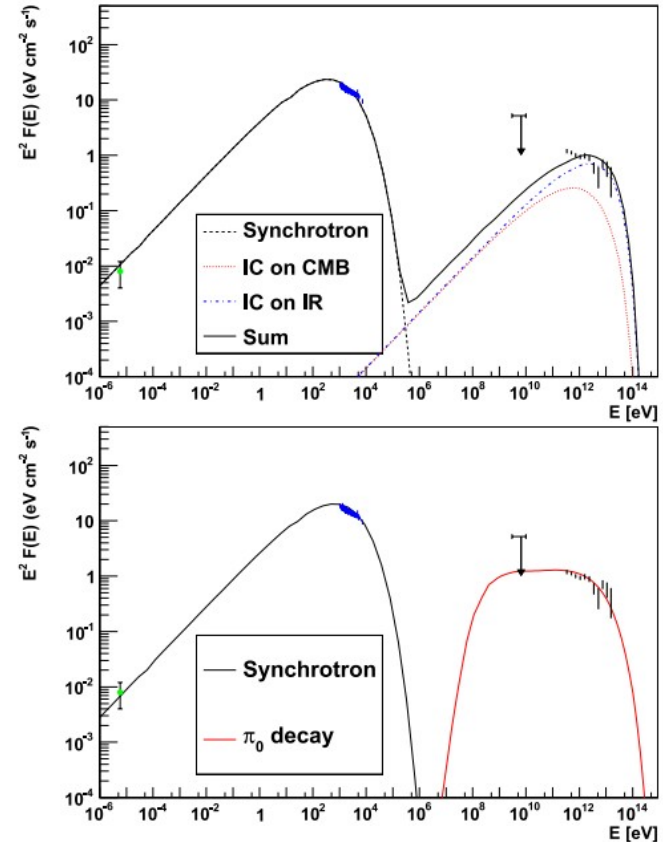
The W28 (north) & HESS J1731-347 Spectra



Abdo et al (Fermi collab.), 2010

Difficult to distinguish gamma-ray mechanism in some older remnants.

Other old remnants exhibit hadronic interactions (e.g. Ackermann et al 2011)

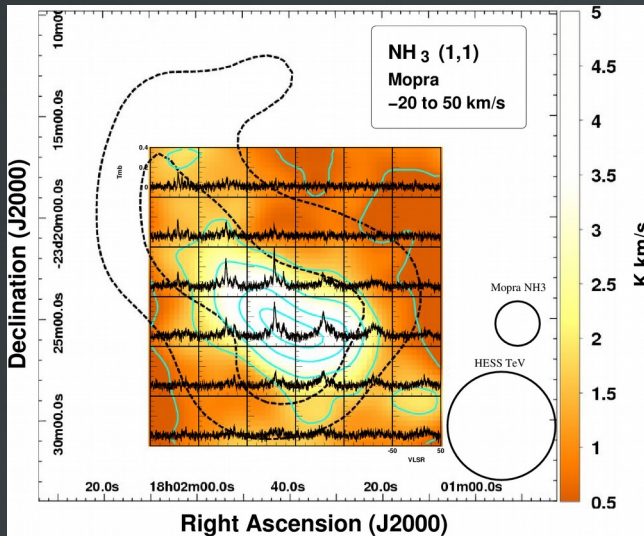


Abramowski et al (HESS collab.), 2011

Difficult to distinguish gamma-ray mechanism in some newer remnants, but a leptonic mechanism is often favoured

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?

