Gamma-Rays and the ISM (Mopra, ATCA, ASKAP... and others)

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SUB CRUCE LUMEN

CTA/MWL Meeting (Adelaide) Sept. 2016

Image Credit: NRAO

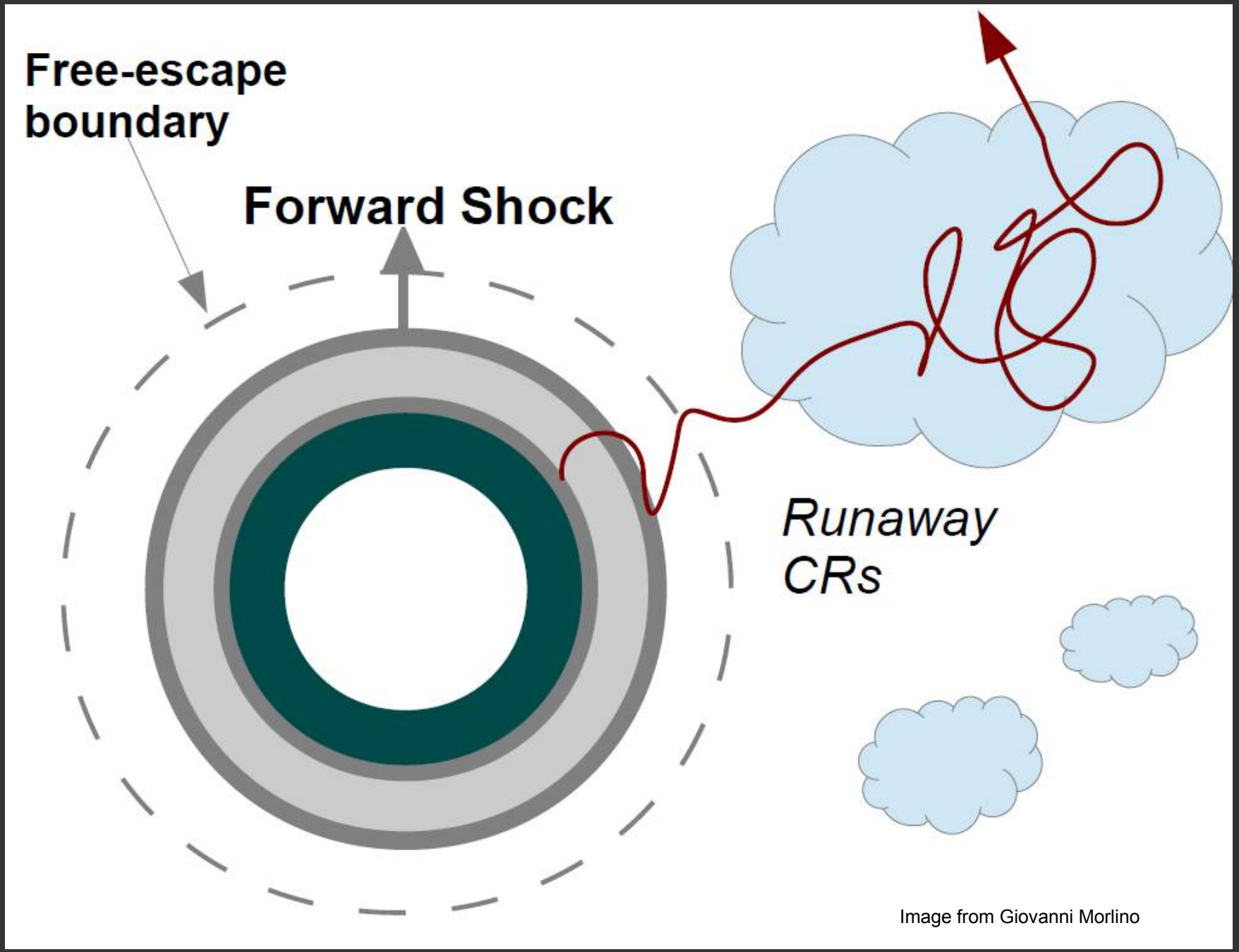
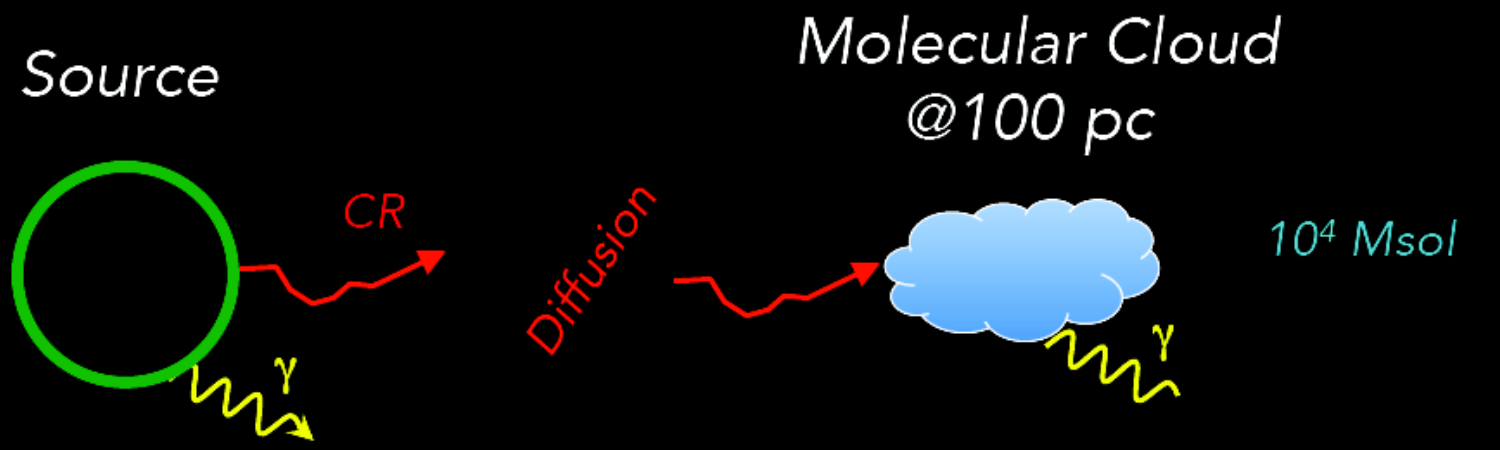
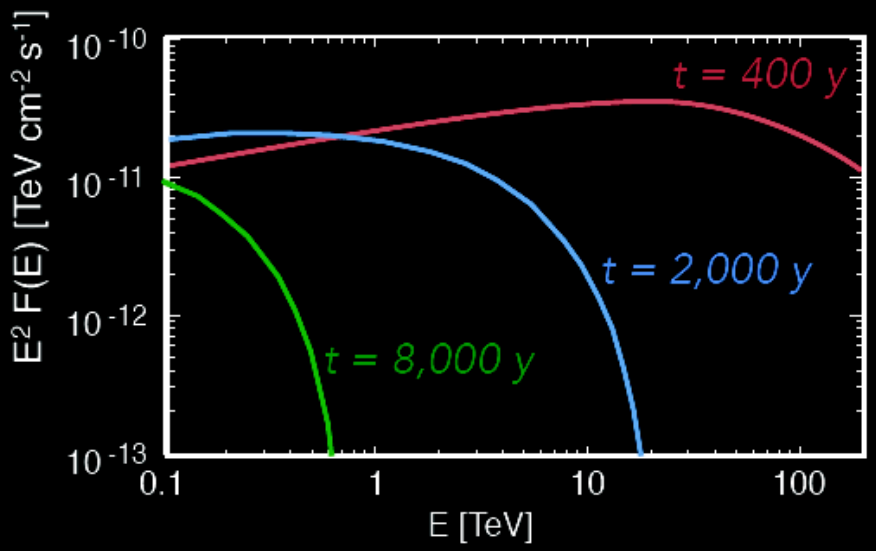


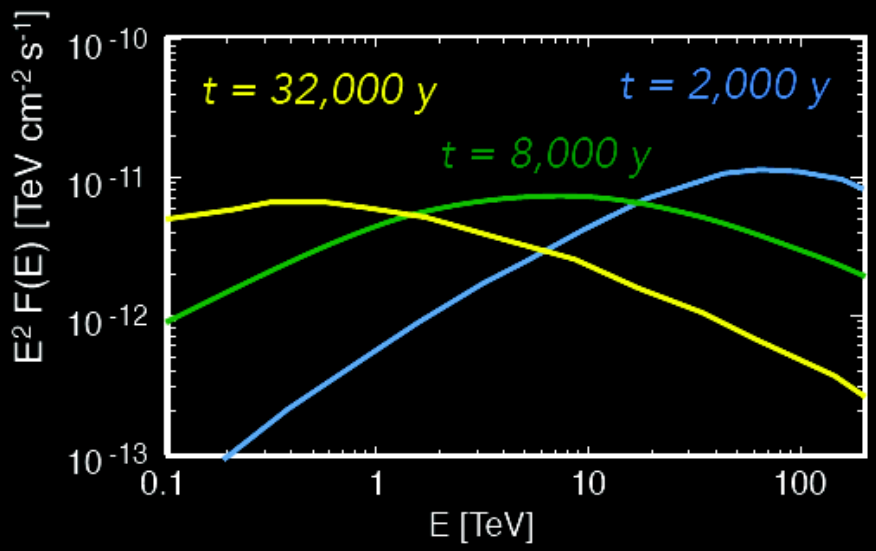
Image from Giovanni Morlino

Gamma-ray spectra from local and escaped CRs

e.g. Aharonian & Atoyan 1996







From Gabici & Aharonian (2007)

Slide from Richard White

Interstellar gas tracers & telescopes..

www.atnf.csiro.au/research/HI/sgps

HI (atomic H), OH, CS

CO

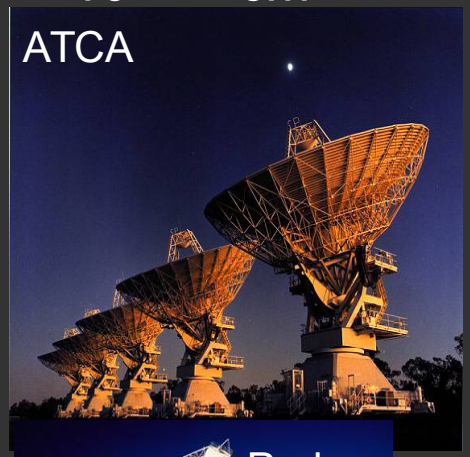
CO, NH_3, CS, SiO...

Gas density

$\sim 10^{1 \text{ to } 4}$ cm^{-3}

$\sim 10^{3}$ cm^{-3}

$>10^{3 \text{ to } 4}$ cm^{-3}



CSIRO

NANTEN
Submillimeter Observatory
なんてん電波天文台

国立天文台
NAOJ
National Astronomical Observatory of Japan

HEAT – THz (Antarctica)
[CI] + [CII]

Mopra Telescope

CSIRO

AUSTRALIA TELESCOPE NATIONAL FACILITY
CSIRO

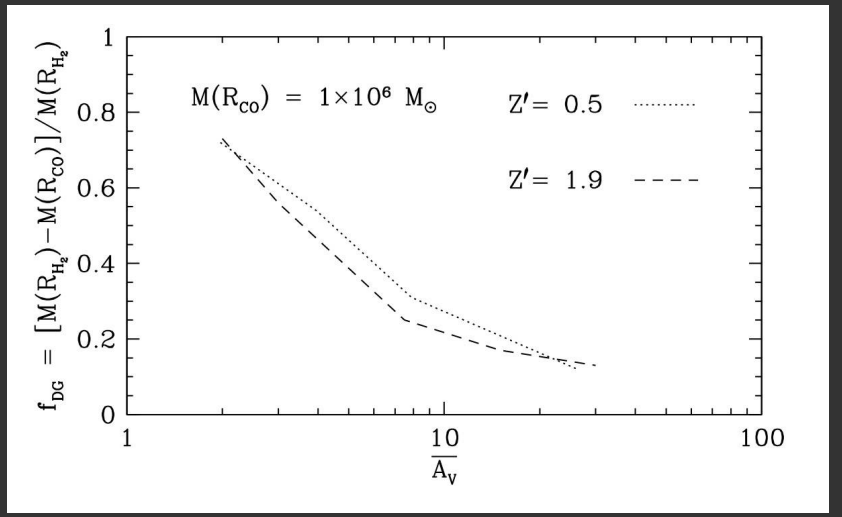
SCIENTIA
MANU ET MENTE

Missing Gas :"Dark" HI & H_2

Inferred by MeV/GeV gamma-ray observations
e.g. Greiner etal 2005, Ackermann etal 2011

Dark molecular gas has little/no CO, but carbon and OH present

Perhaps one-third of the molecular gas is "dark"?!
Wolfire, Hollenbach & McKee, 2010

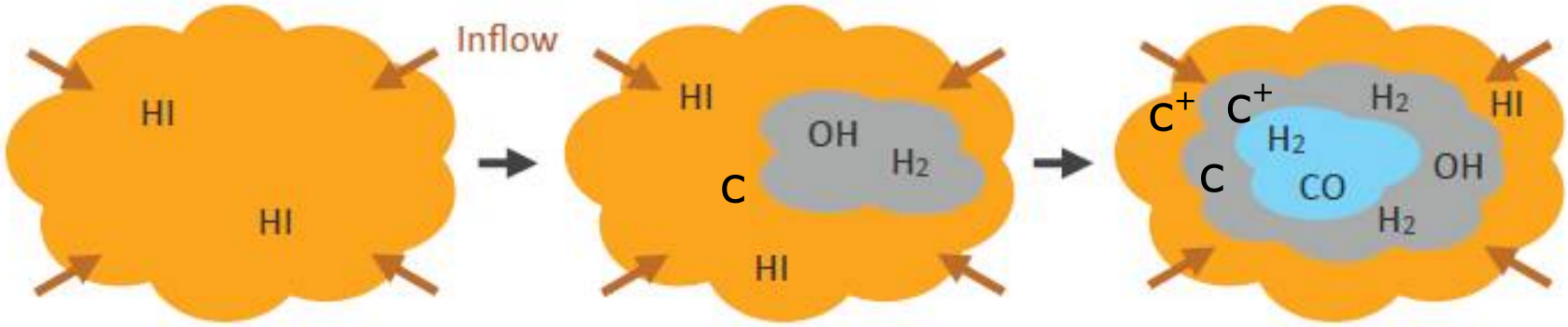


→ optically thick HI (Yasuo Fukui)

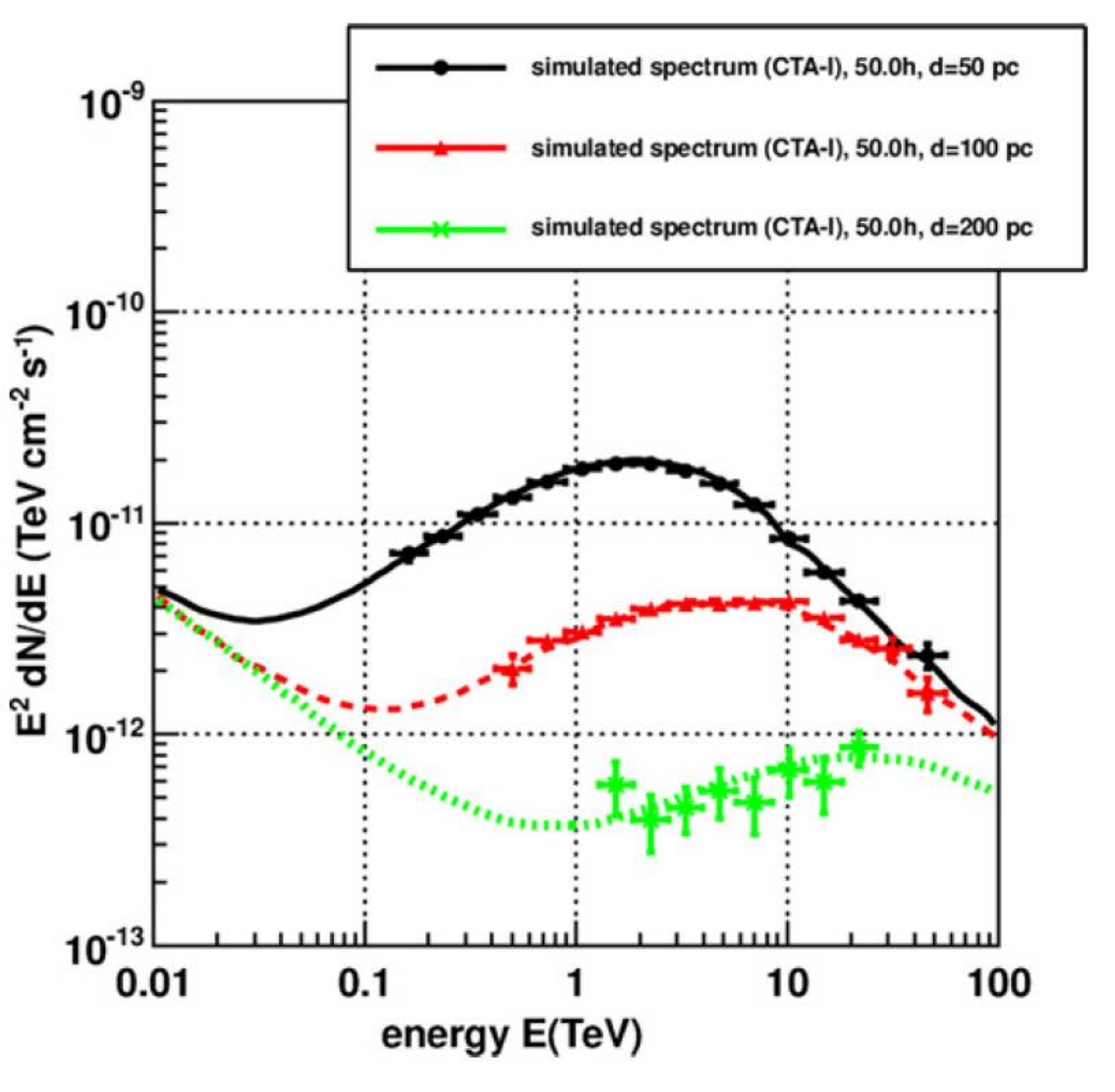
→ OH 1.6/1.7 GHz lines
(Parkes, ASKAP)

→ CI, C+ ~THz lines
(Nanten2, HEAT, STO2, SOFIA, STO2, DATE5,)

Graphic adapted from J. Dawson



CTA 50h Observation - CRs escaping accelerators Acero etal 2013



SNR age 2000 yr

Cloud mass 10^5 M_{sun}

d = 1 kpc

$D=10^{28}(E/10GeV)^{0.5}$ cm^2/s

PeV CRs escape first and arrive at the cloud first!

Probe for CR PeVatrons

But confusion guaranteed in Gal. Plane!

Need wide ISM surveys → Mopra, Nanten2, Nobeyma, ASKAP (S&N)

CR Diffusion *Into* Molecular Clouds

e.g. Gabici etal 2007, Inoue etal 2012

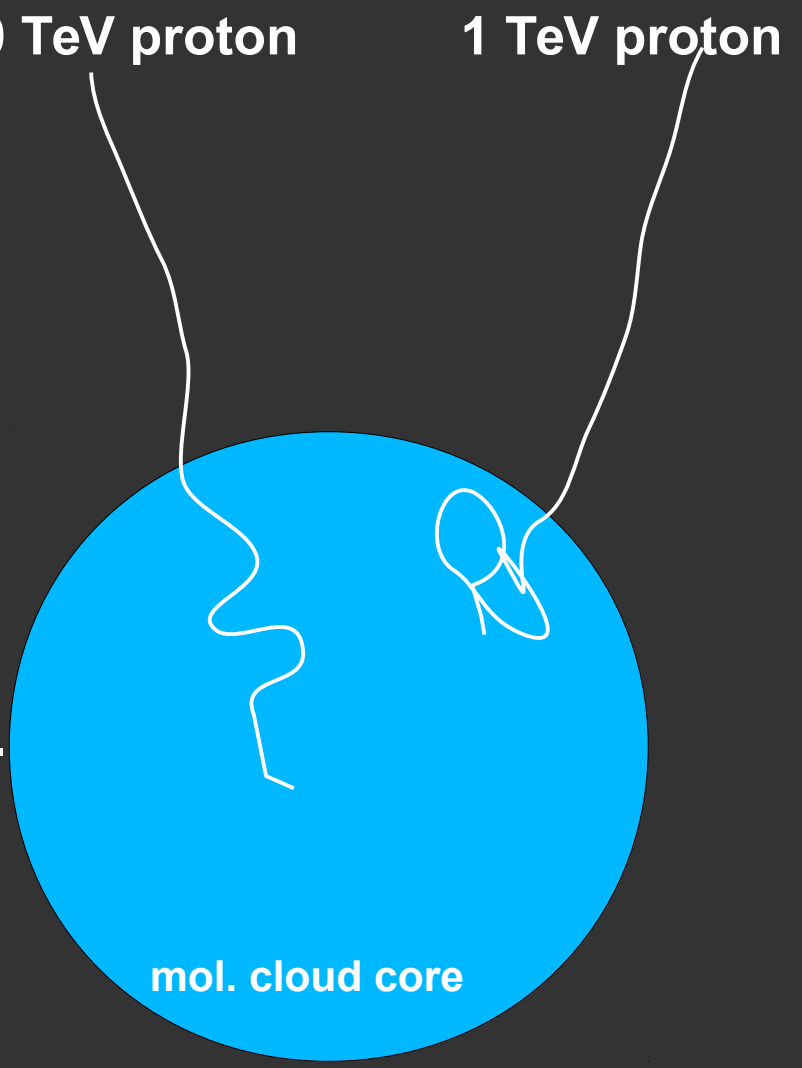
R = distance CR travels into molecular cloud core

R ~ sqrt[6 D(E_p, B) t]

$$D(E_P, B(r)) = \chi D_0 \left(\frac{E_P/\mathrm{GeV}}{B/3\,\mu\mathrm{G}} \right)^{0.5} \quad [\mathrm{cm}^2\,\mathrm{s}^{-1}],$$

$$B \sim 10(n/300\mathrm{cm}^{-3})^{0.65}\,\mu\mathrm{G}$$

Crutcher 2010



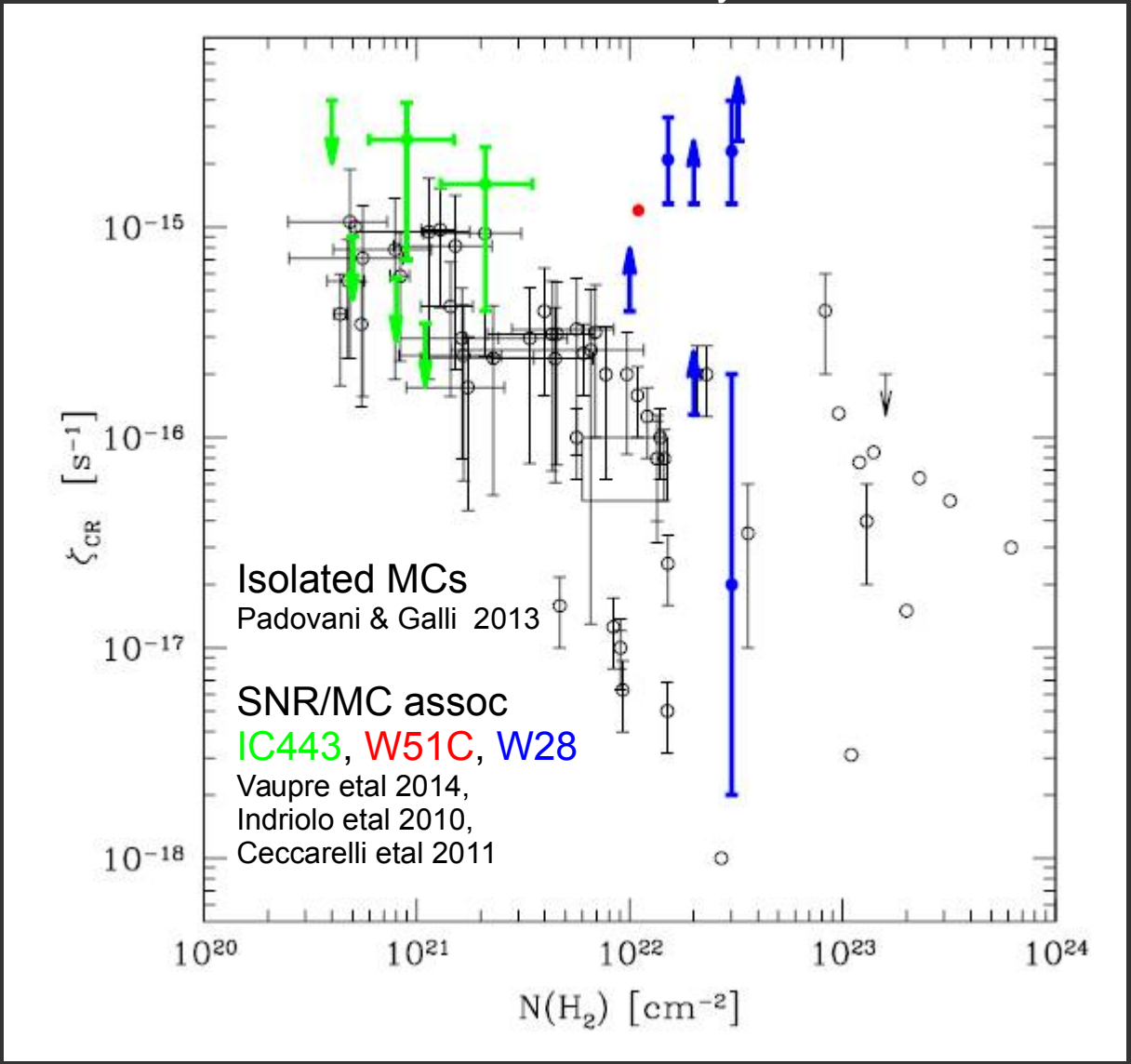
χ=diffusion suppression factor

→ Low energy CRs can't reach cloud core.
→ Harder TeV spectra from cores.
→ Depends on B-turbulence
(e.g. Morlino & Gabici 2015)
→ *Don't expect electrons to penetrate!!*
(due to sync. losses)

→ Need to map dense cloud cores ~1 arcmin or better

Sub-GeV CR penetration into MCs – Ionisation rates

Review by Gabici & Montmerle 2015

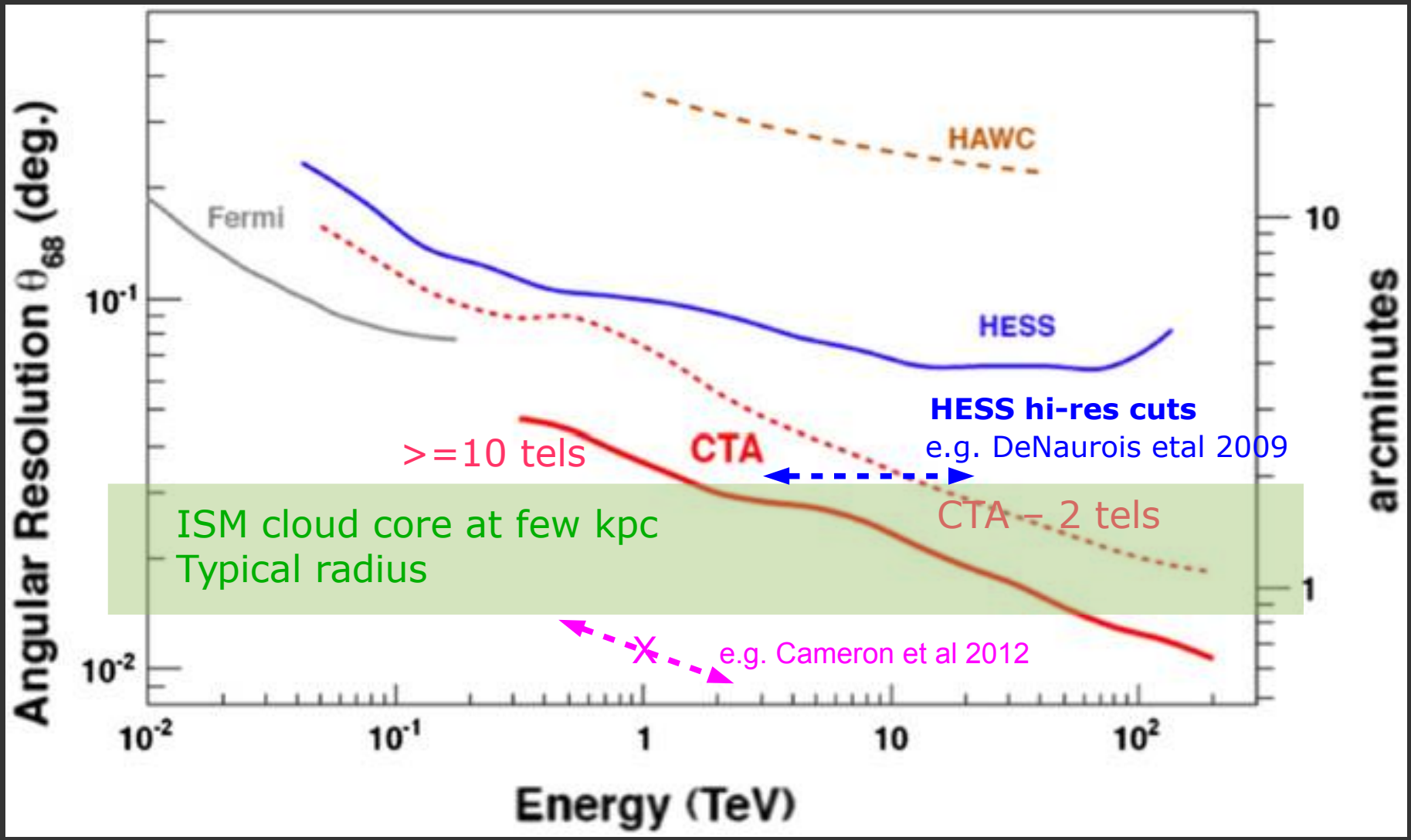


→ **low E CRs less penetrating in denser clouds**

→ **synergies with ionisation rate tracers: HCO+/DCO+ ; H_3^+ ; OH etc..**

Angular Resolution (HESS, CTA..)

Acharyara etal 2013

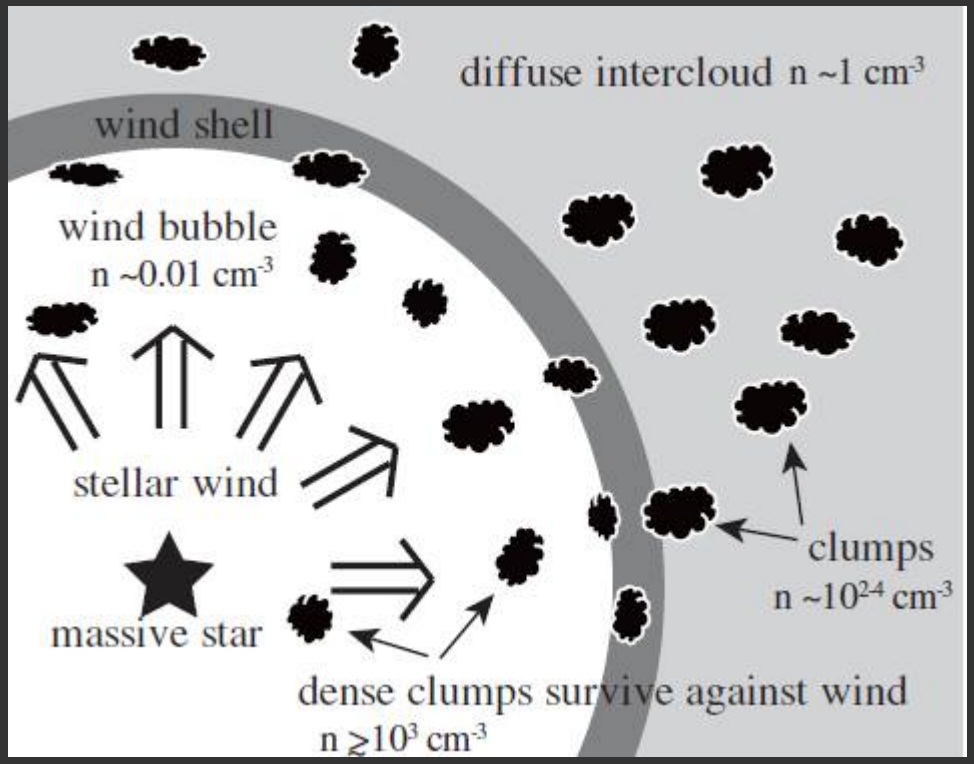


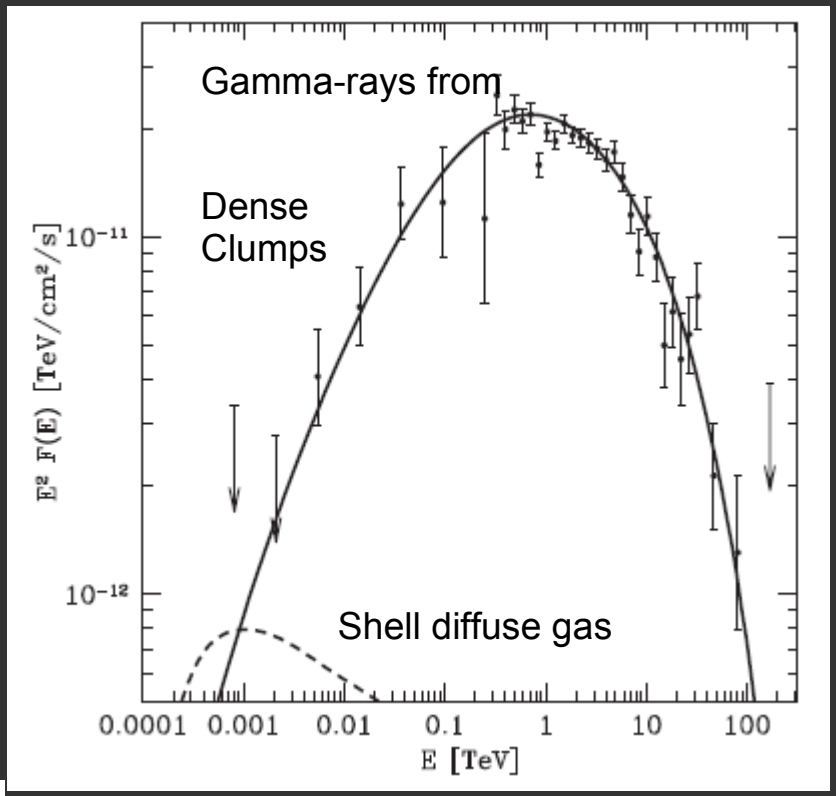
CTA MST-SCTs with small pixels and/or hi-res cuts → resolve cloud cores!

Hadronic Gamma-Rays from Clumpy ISM
SNR RXJ1713

Inoue et al. 2012

Gabici & Aharonian 2014





CR penetration depth

$$l_{\rm pd} \simeq (\kappa_{\rm d}\, t)^{1/2}$$

$$= 0.1\,\eta^{1/2} \left(\frac{E}{10\ {\rm TeV}}\right)^{1/2} \left(\frac{B}{100\ \mu{\rm G}}\right)^{-1/2} \left(\frac{t_{\rm age}}{10^3\ {\rm yr}}\right)^{1/2} {\rm pc}$$

$\eta = B^2/\delta B^2$

$\kappa_{\rm d} = 4\,\eta\, l_{\rm g}\, c/3\pi$ (Skilling 1975)

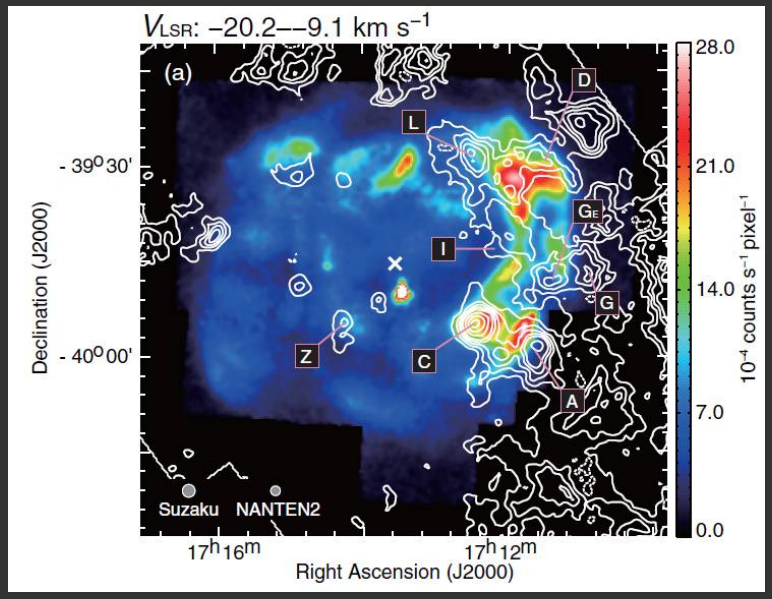
→ Dense clouds/clumps could play critical role in hadronic component

Dense Cores filter out external electrons! e.g. RXJ1713.7-3946:

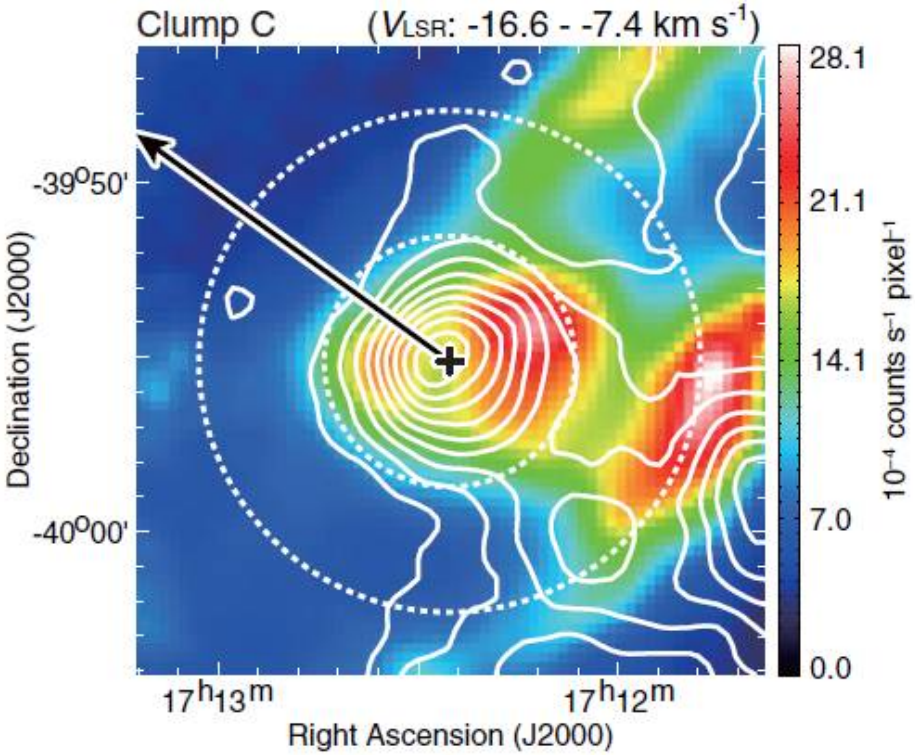
Sano etal 2013

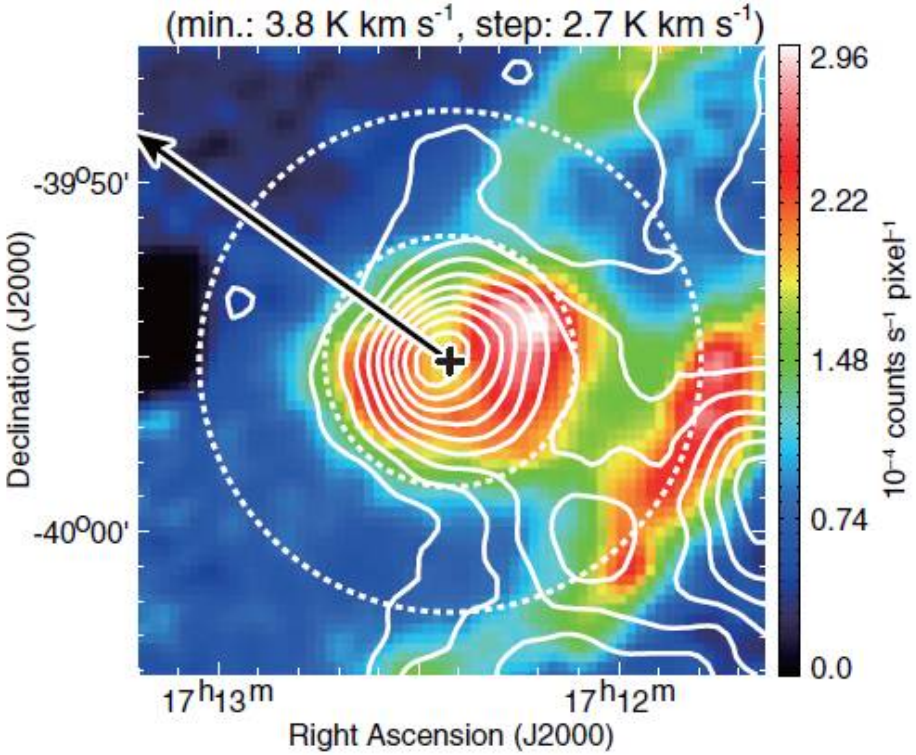
- CO(2-1) Nanten2 contours +X-ray images
- Synch cooling length < pc for
  30 TeV electrons, 6 keV X-rays,
  $n=10^5$/cc, B~400μG

See also Uchiyama et al 2007



Suzaku 1–5 keV (left) and 5–10 keV (right) images



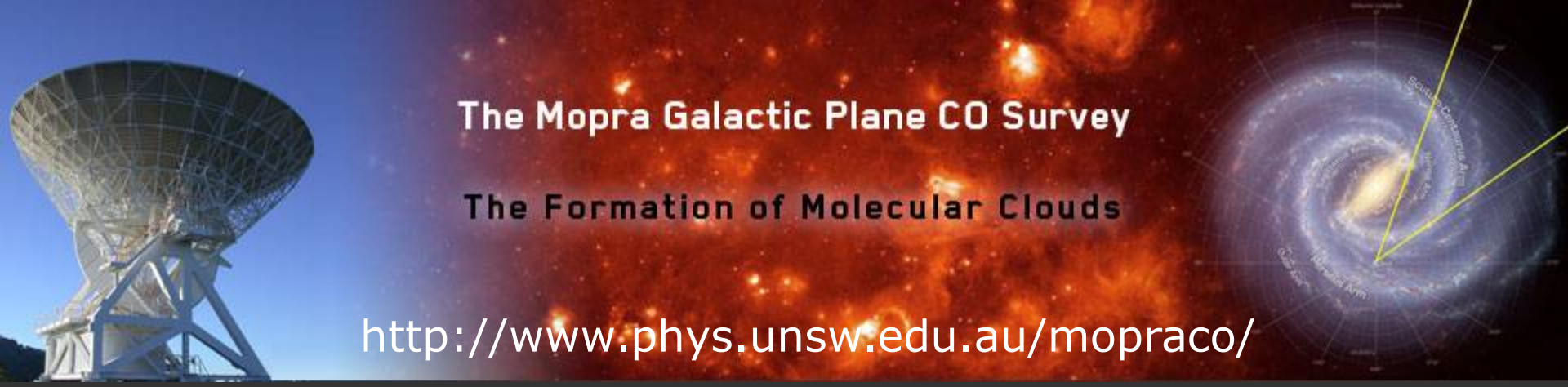


H.E.S.S. RX J1713.7-3946

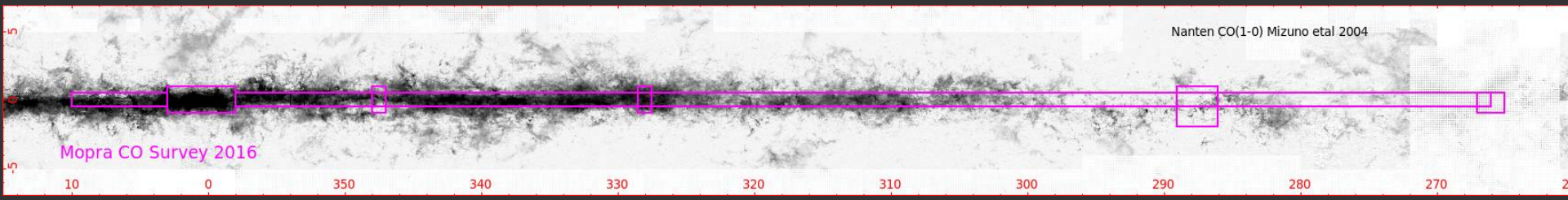
HESS Collab. in prep 2016

Year	2016
Live-time	164h
Energy	> 0.25 TeV
PSF (R_{68})	2.9 arcmin
γ's	31,000

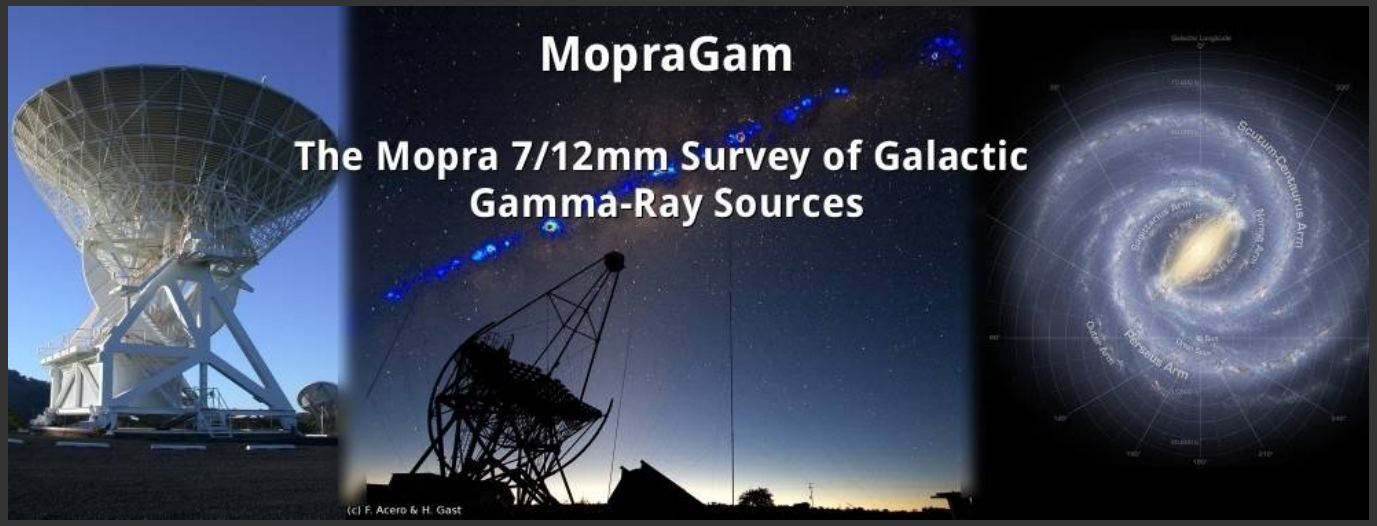
https://www.mpi-hd.mpg.de/hfm/HESS/pages/home/som/2016/09/



~35” beam @ ~0.1 km/s resolution (also 70” CO survey Barnes etal 2015)
CO(1-0), ^{13}CO(1-0), C^{17}O(1-0), C^{18}O(1-0)
l = 265 to 358; b = ±0.5deg mostly complete
extension to ±1.0deg l=2 to 10deg (compare to Dame etal 2000 ~8arcmin beam)



Data cubes publicly available once processed
l = 320 – 330 deg available now
Complementary to Nanten2 CO surveys over wider area
& Nobeyama CO survey (20” beam) in the north (Nishimura etal 2015)



http://www.physics.adelaide.edu.au/astrophysics/MopraGam/

Main ISM Tracers

CS(1-0), SiO(1-0), CH_3OH

Targets

Since 2012 observed over ~40 bright UnID TeV gamma and high energy sources (>1500 hrs)

→ Determine distance to cloud components (often difficult with CO)
→ Understand particle propagation
→ Disentangle hadronic/leptonic components
→ Some examples shown here (and see posters Maxted etal, Voisin etal)

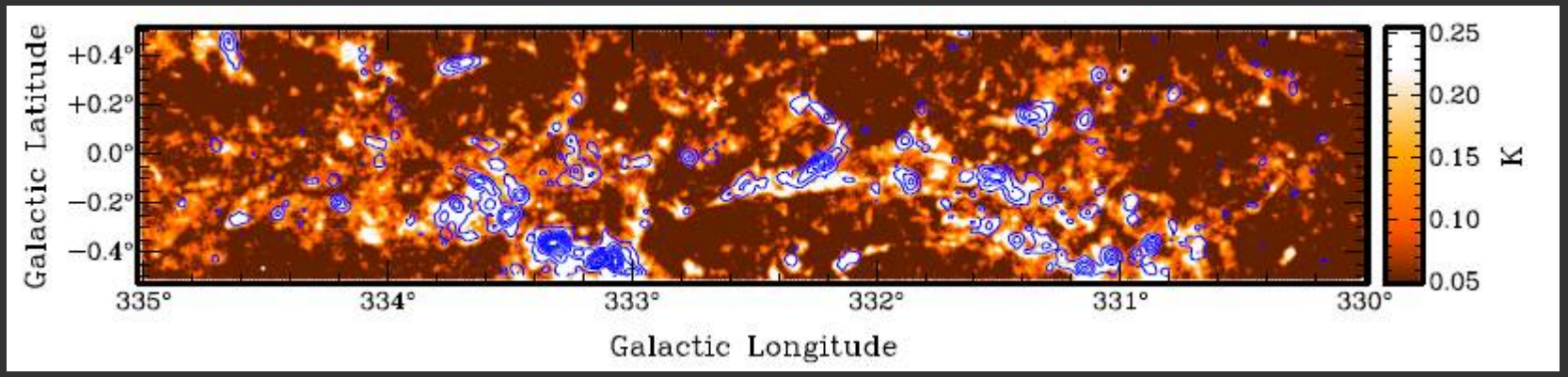
Coverage is limited to discrete sources → Systematic survey MALT45+

MALT45 7mm Survey with ATCA

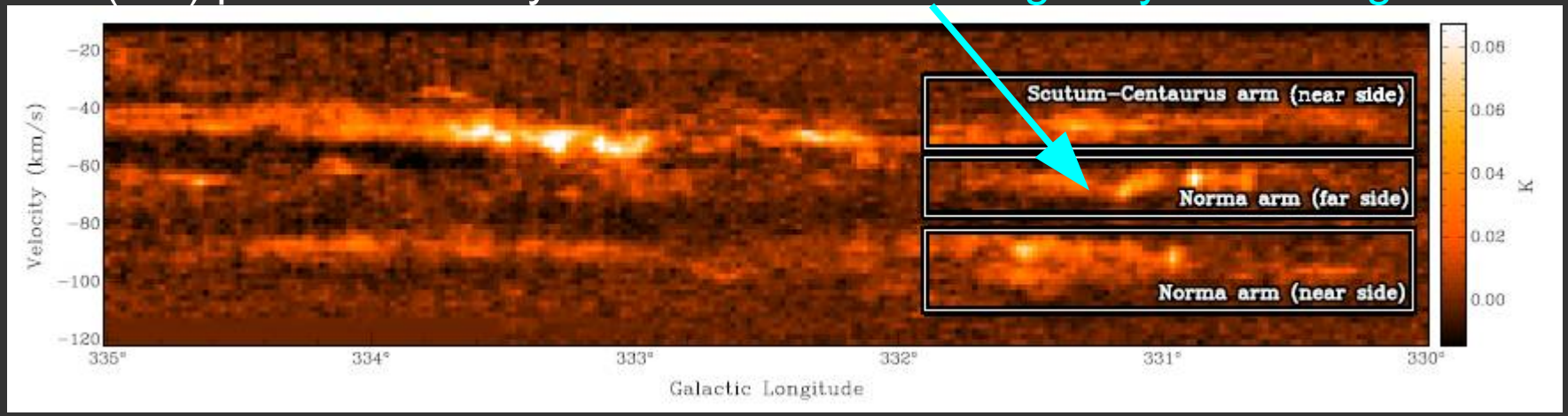
(Jordan etal 2013, 2015)

> 5x more sensitive than Mopra

CS(1-0) peak pixel image with HOPS NH3(1,1) contours



CS(1-0) position/velocity → can see far side of galaxy in dense gas!

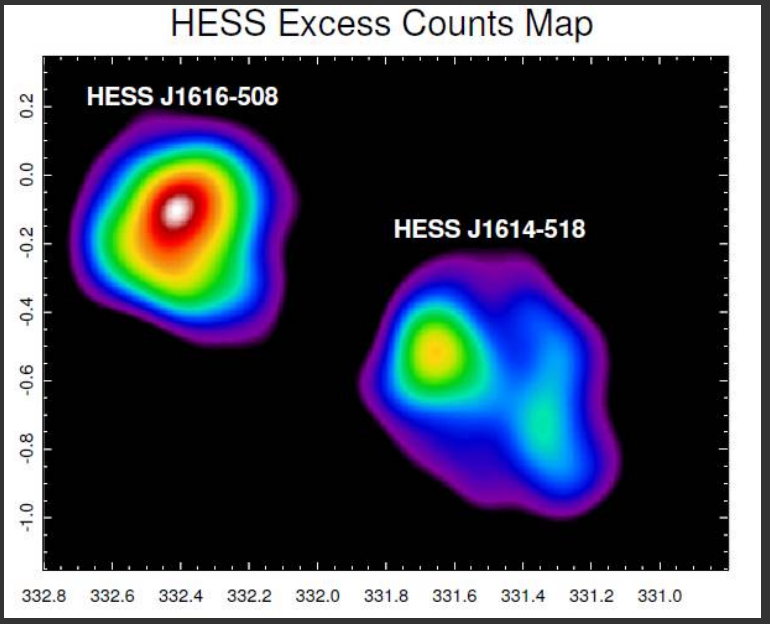


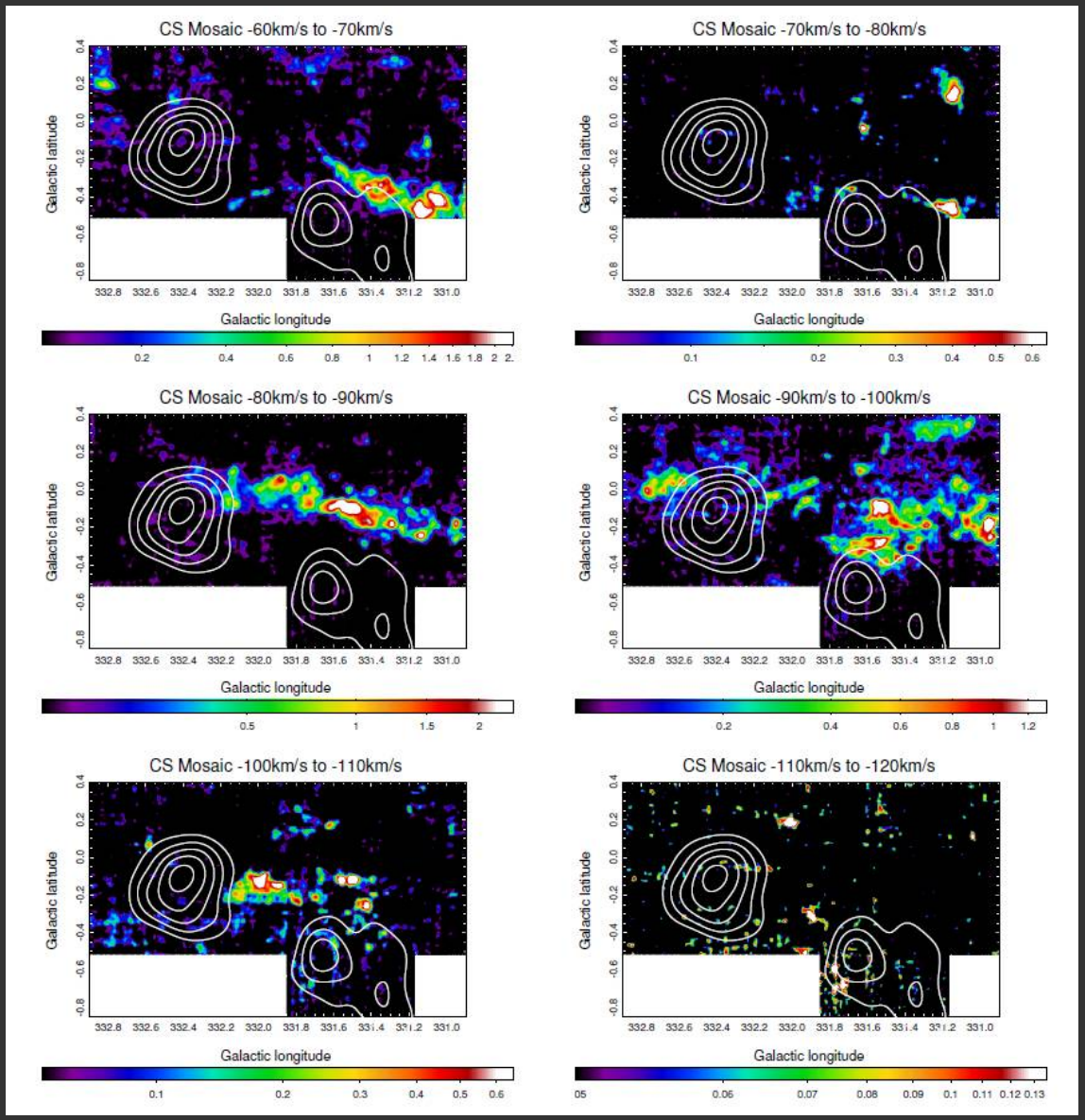
Proposal to extend to “Full Strength MALT 45” l = 300 to 360

→ dense gas ISM survey legacy for CTA

MALT 45 CS(1-0)
towards two TeV sources.

S. Pointon
(MPhil thesis 2015)

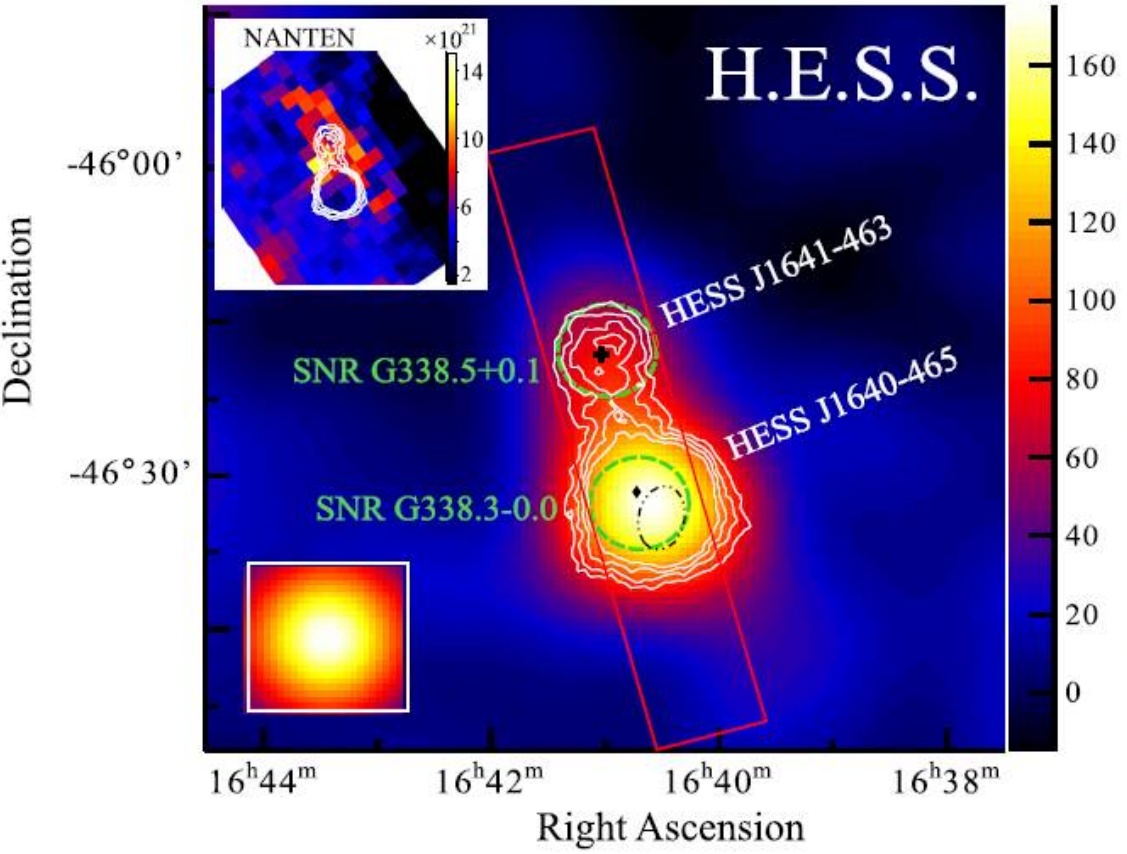


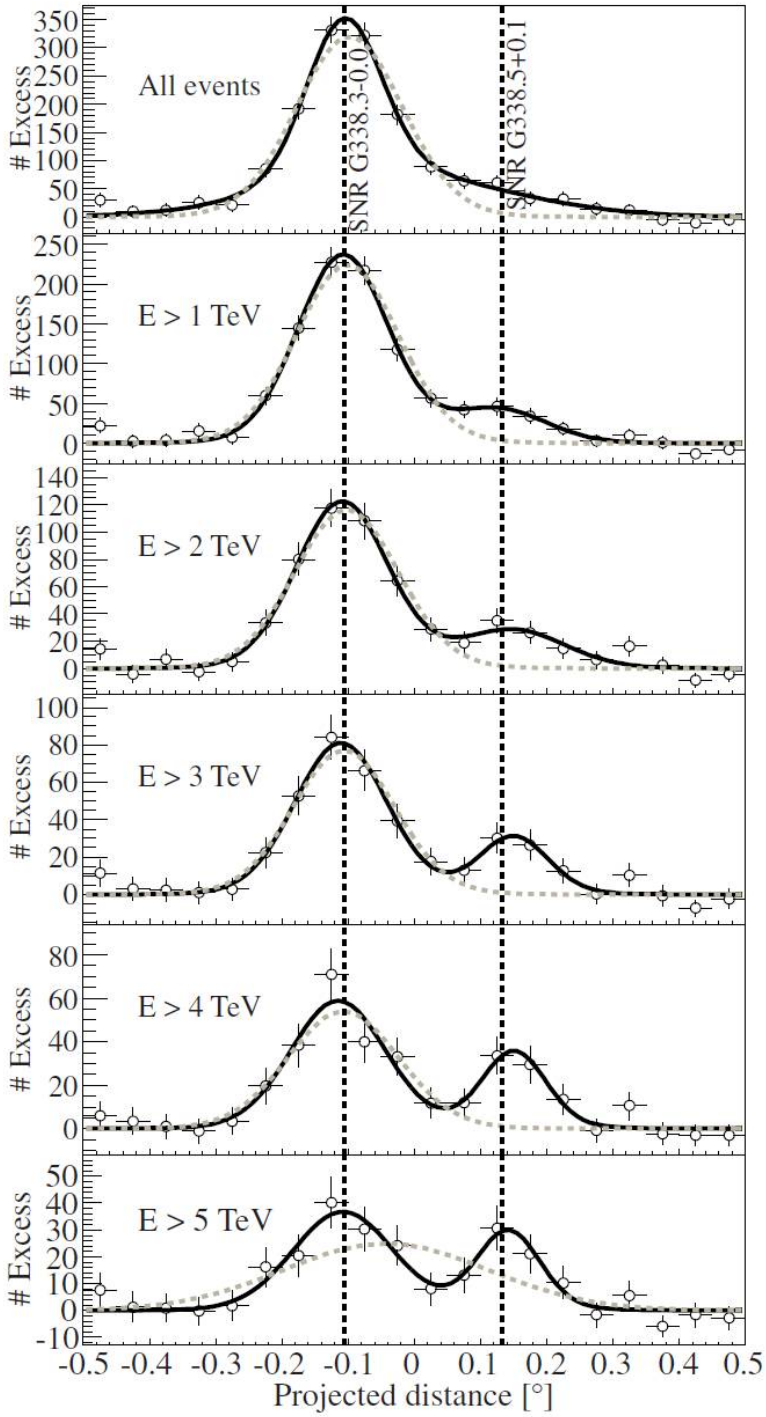


MALT45 data
(Jordan etal 2015)

+ Mopra CS(1-0) extension to south

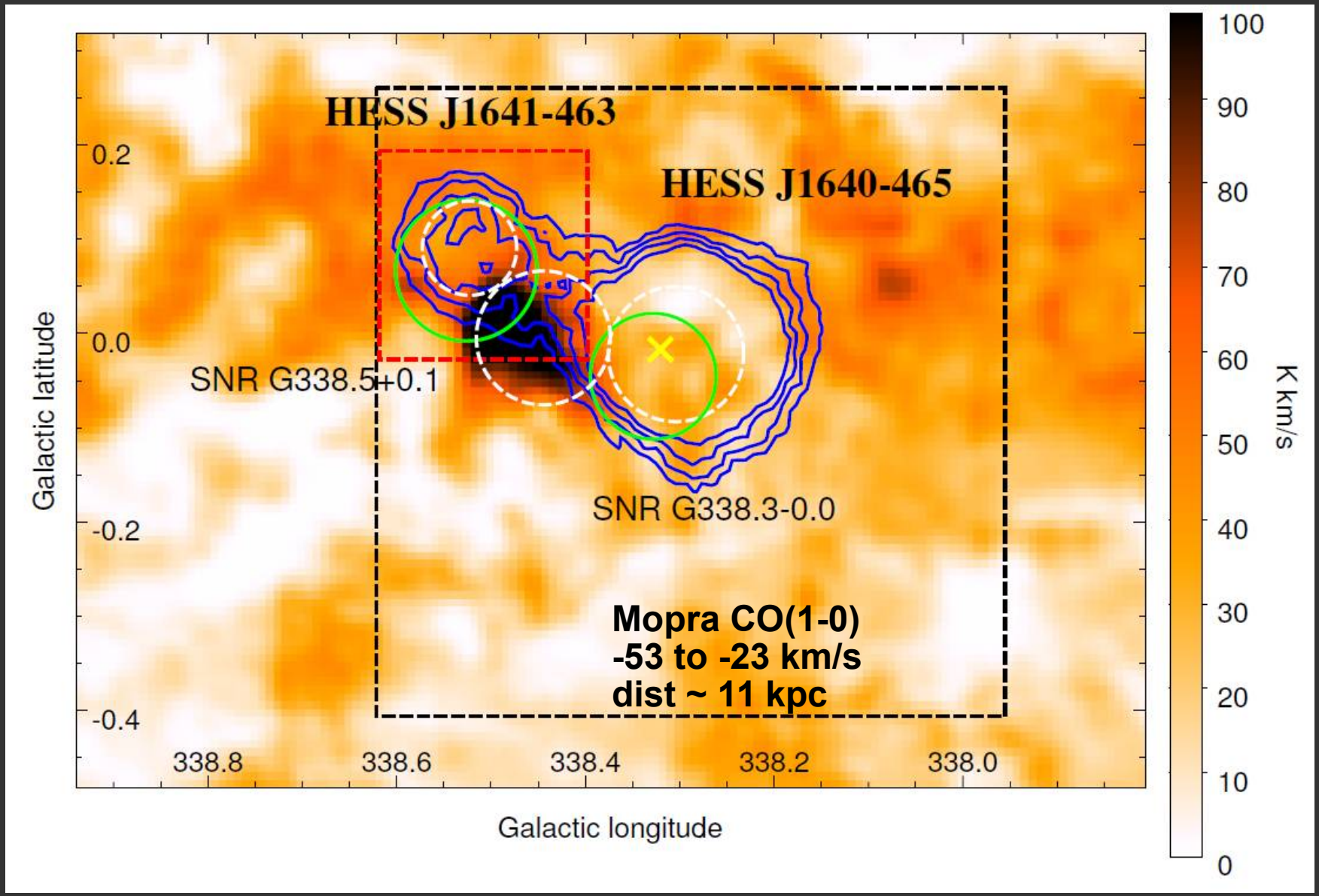
HESSJ1641-463
A Galactic PeVatron?





Does HESSJ1641 result from cosmic-rays escaping SNR G338.3?

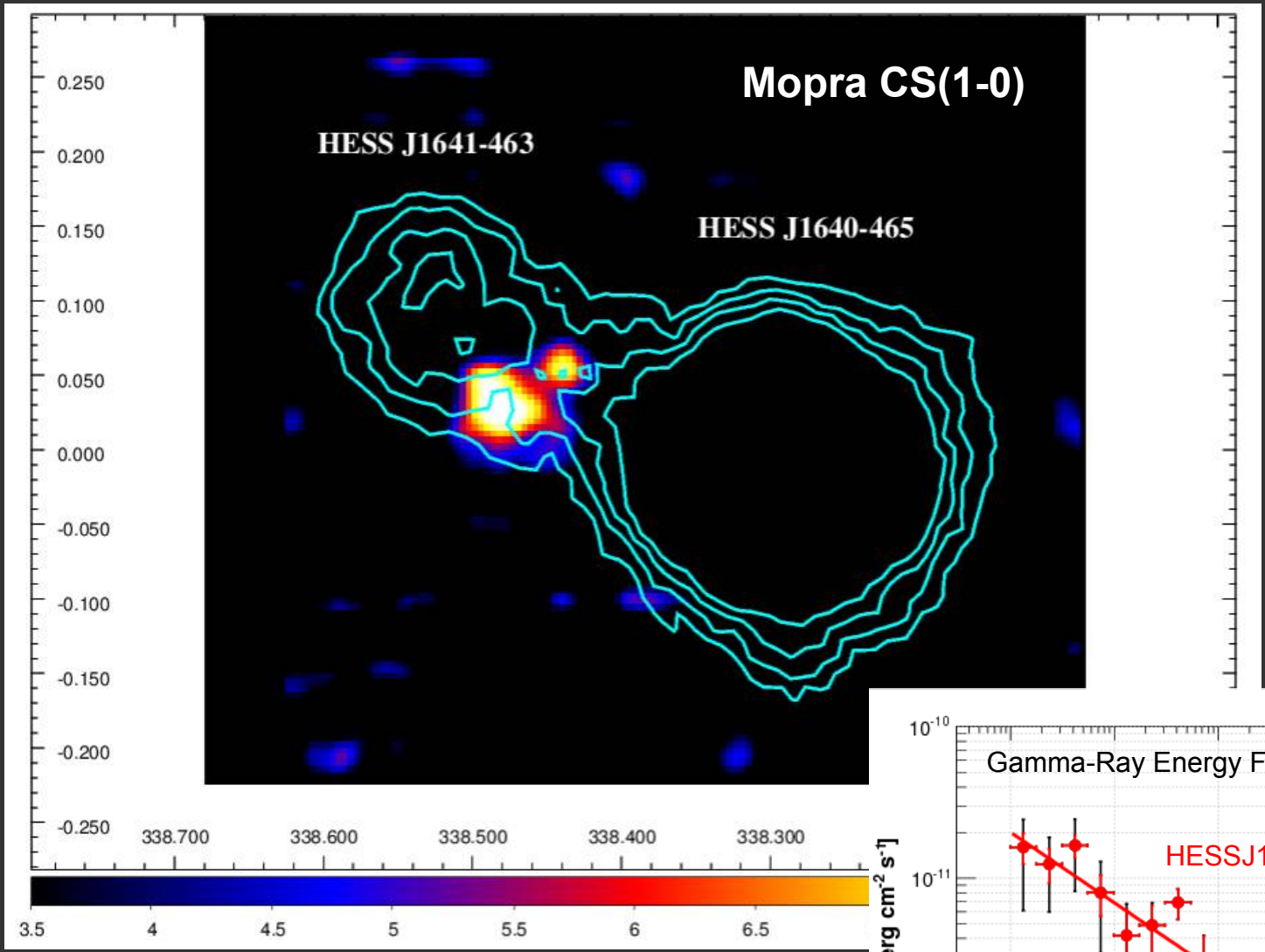
Hard-spectrum source HESSJ1641
(HESS Coll. 2015)

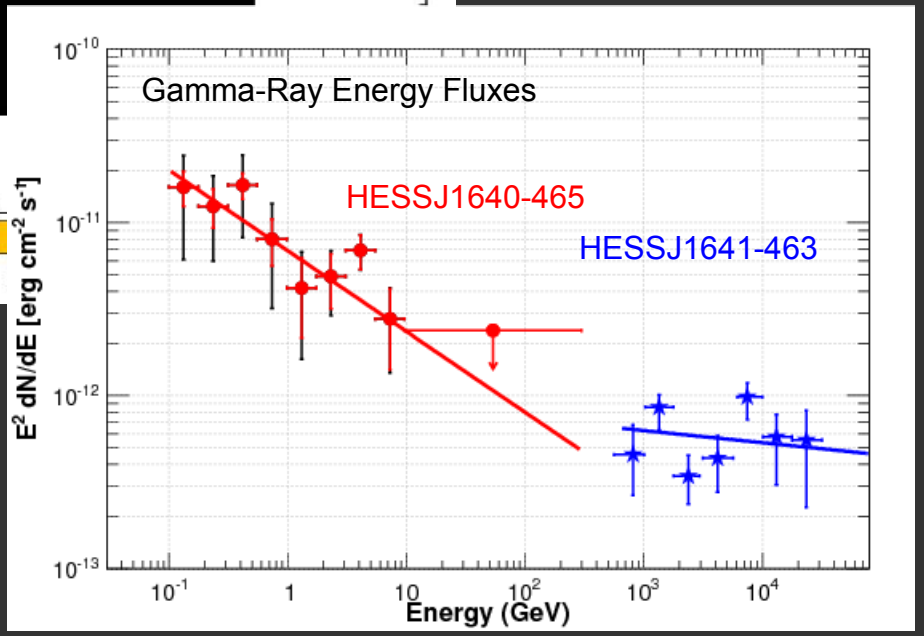


ISM studies by Lau etal 2016 (HESSJ1640 ISM – Supan et al 2016)

→ ISM density >200/cc towards TeV sources and 'bridge'

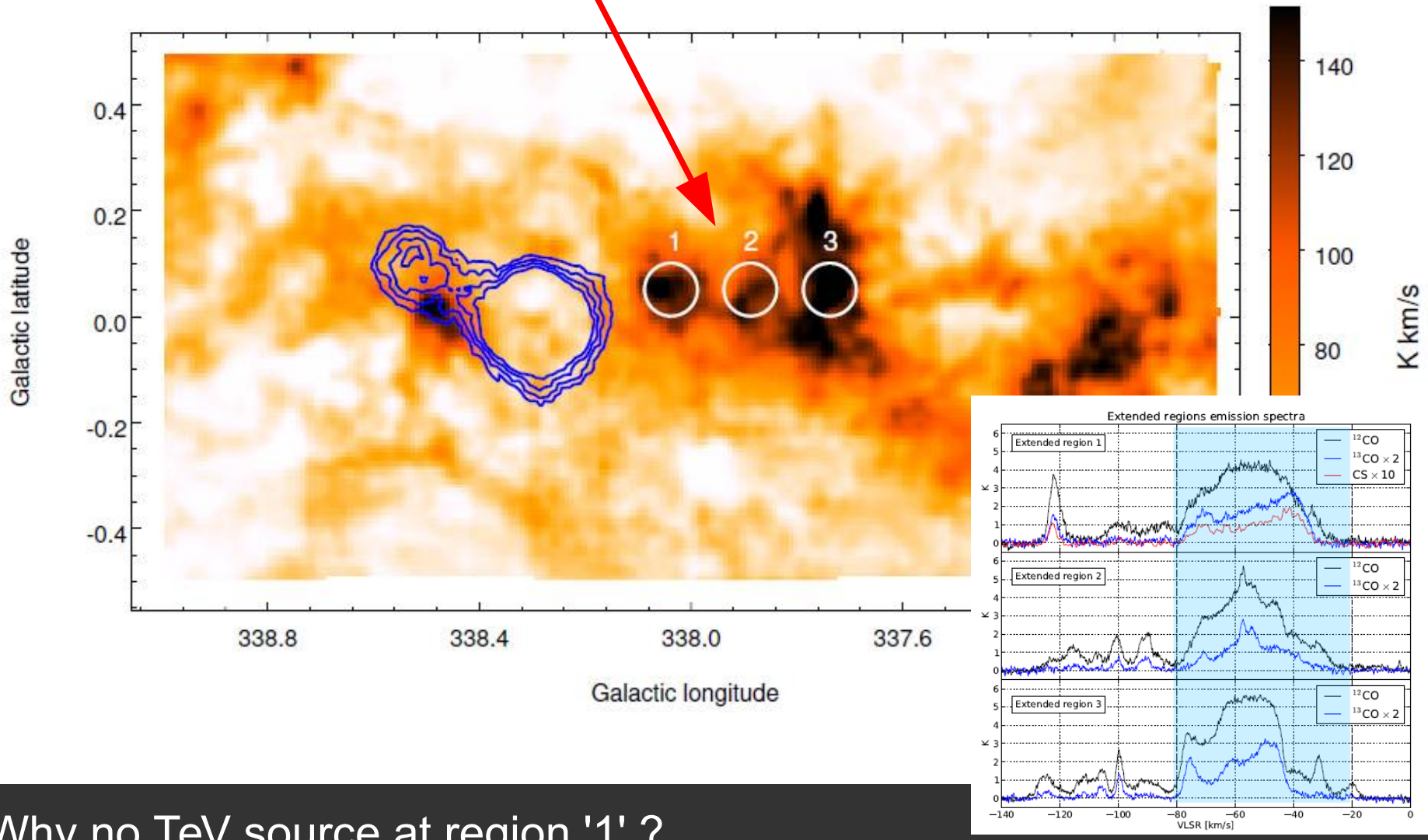
→ Hadronic: CR density ~100 for HESSJ1641; >350 for HESSJ1640



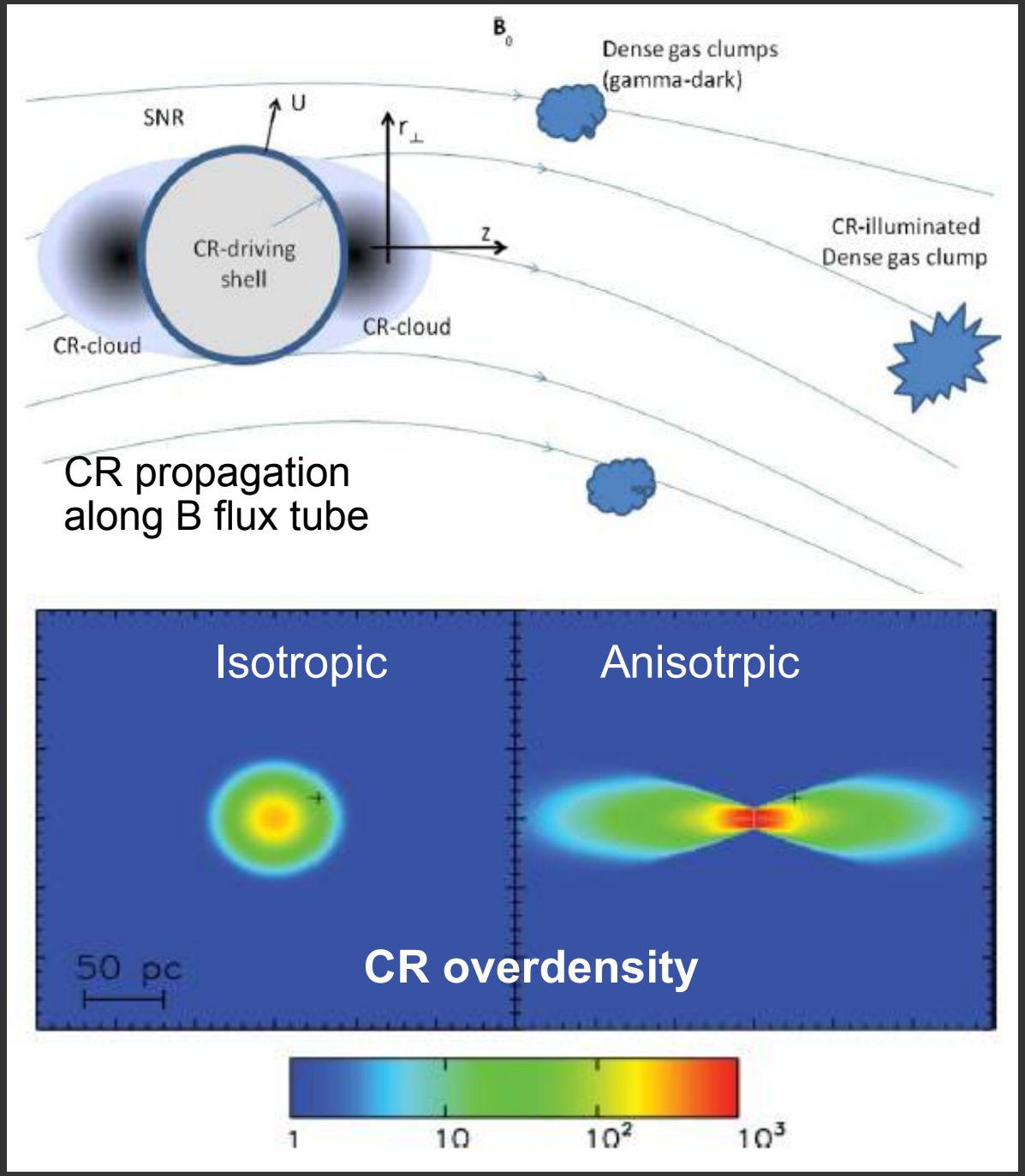


- Dense gas (>10^4/cc) bridge between TeV sources
→ Can filter low-E CRs from SNR G338.3

What about this huge ISM cloud to Galactic west?



Why no TeV source at region '1' ?
→ Cloud slightly in fore/background?
Only need ±50 pc distance to reduce CR density (e.g. Aharonian & Atoyan 1996)



CR diffusion – not necessarily Isotropic!

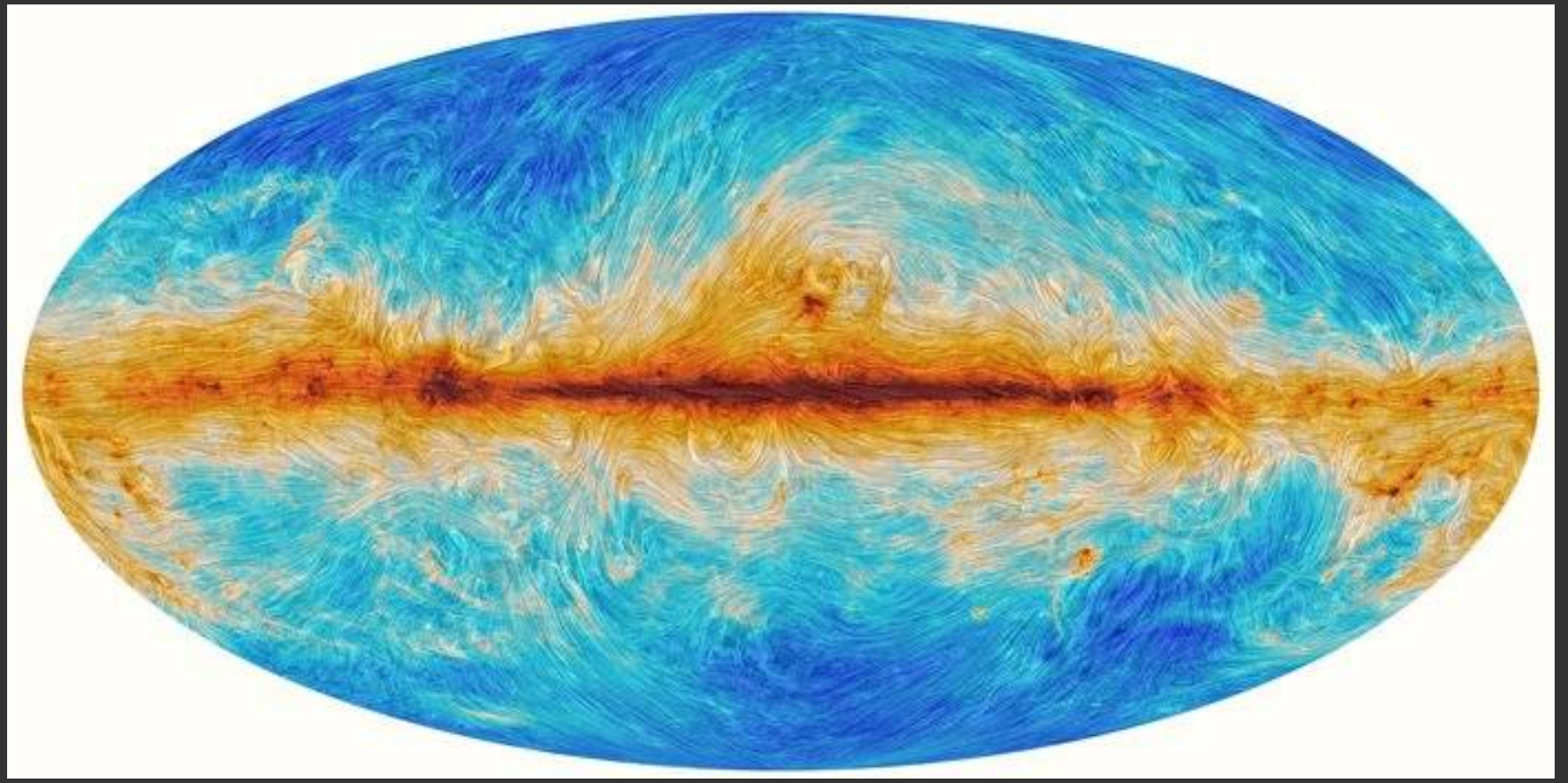
Malkov etal 2013
Nava & Gabici 2013

→ Nearby clouds will see different CR densities

→ Need detailed maps of ISM gas + B-field direction

Planck map of B-field direction (dust polarisation)

http://www.esa.int/spaceinimages/Images/2015/02/Polarised_emission_from_Milky_Way_dust



Note: In Gal. plane this is dominantly the ***foreground B-field direction***.
Next Step: ASKAP POSSUM (Faraday rotation measures in great detail)

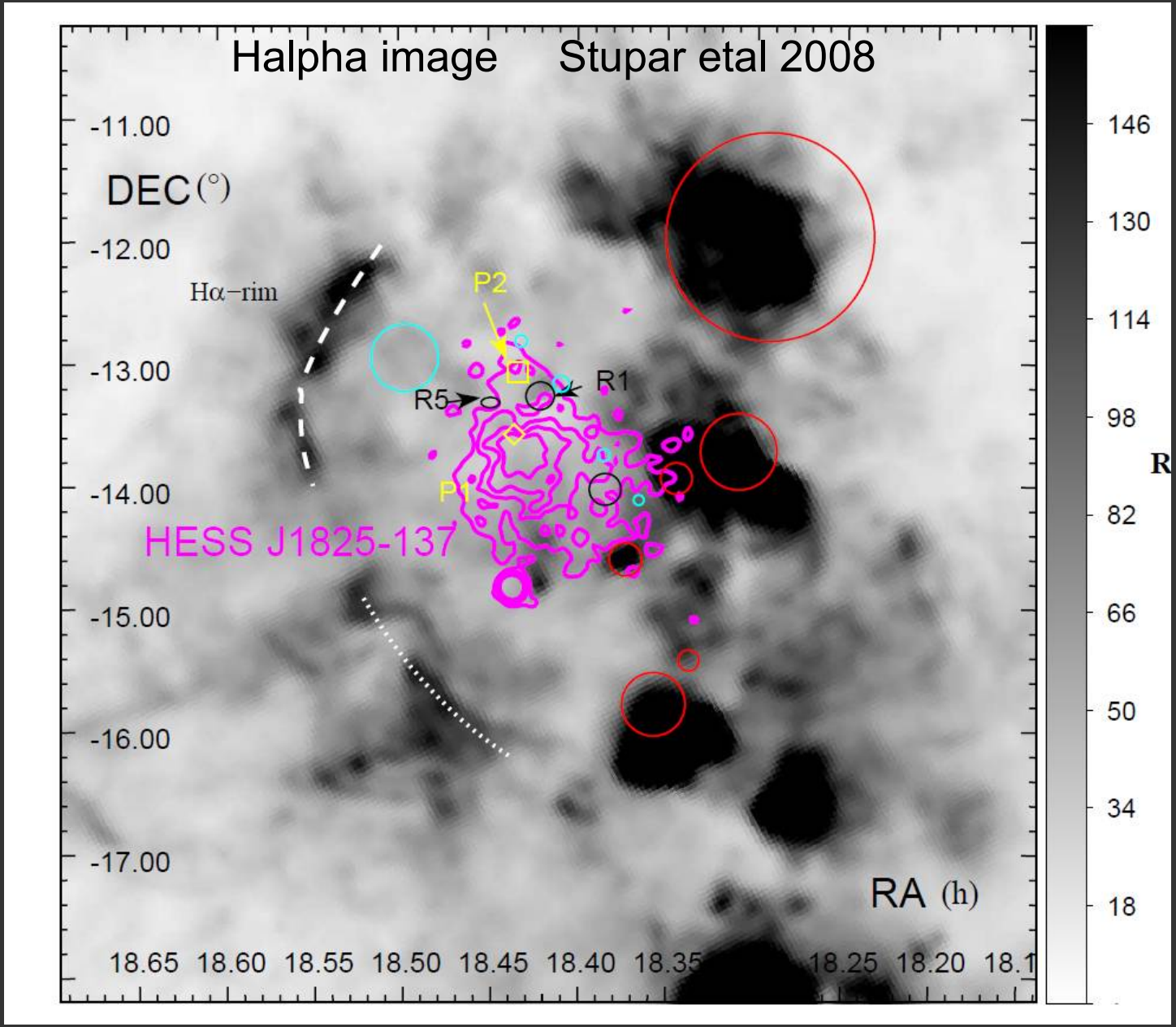
H-alpha: Looking for shocked gas around old SNRs

ISM study towards HESSJ1825 & HESSJ1826

Voisin etal 2016

TeV-bright pulsar powered nebula (J1825)

Northern TeV emission (J1826) overlap with dense ISM → cosmic-rays escaping SNR?



Gamma Rays & ISM

- ISM gas is an essential ingredient in understanding gamma-ray sources

→ What accelerates the particles?
→ What types of particles are accelerated?

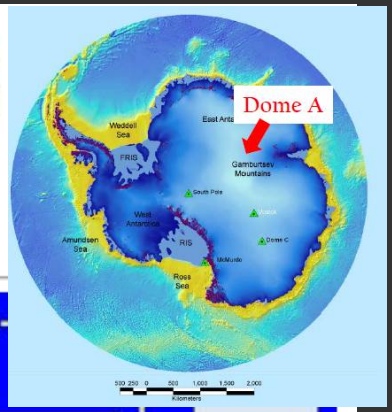
- Critical requirements of ISM surveys
→ (sub)arcmin CO surveys (Mopra, Nobeyama..)
→ wide CO coverage (Nanten2)
→ dense gas (Mopra, ATCA, ASKAP)
→ atomic gas (ASKAP)
→ dark gas (ASKAP, HEAT, DATE5....)

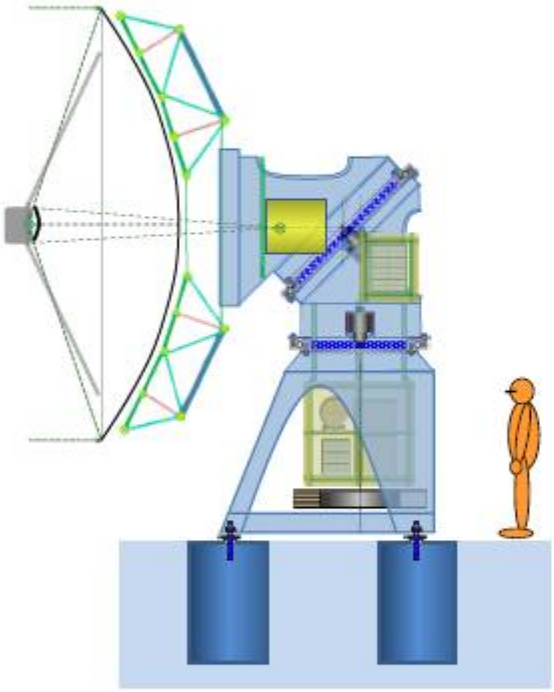
→ angular resolution perfectly matched with CTA (& hi-res deep HESS obs)
→ CTA needs these new ISM surveys..

Backup ….

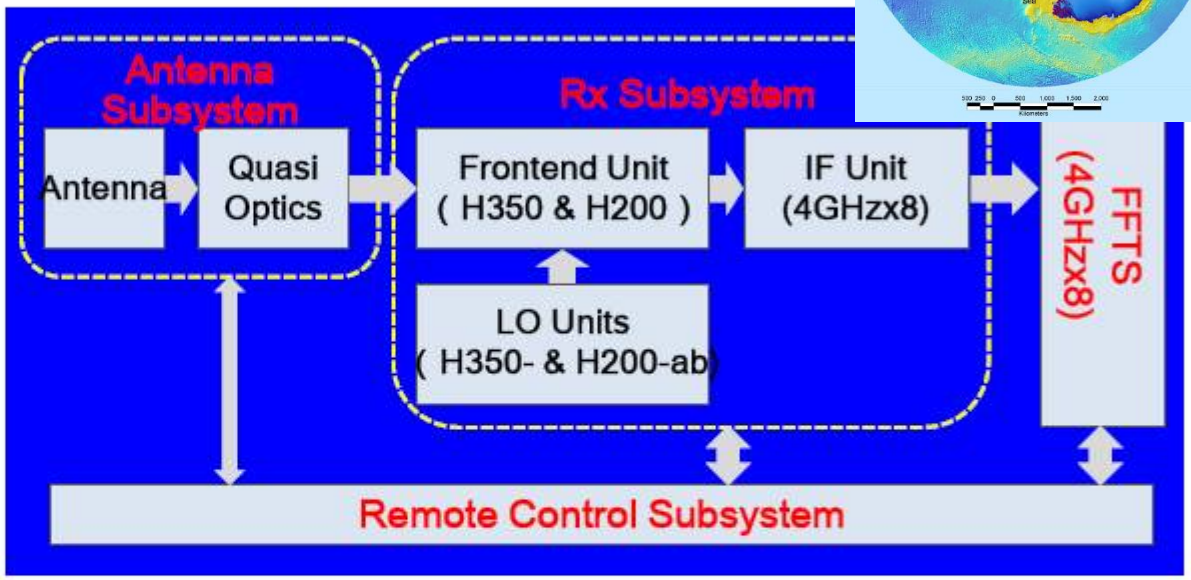
Dome A 5m THz Telescope (DATE5)

Led by CAS, China





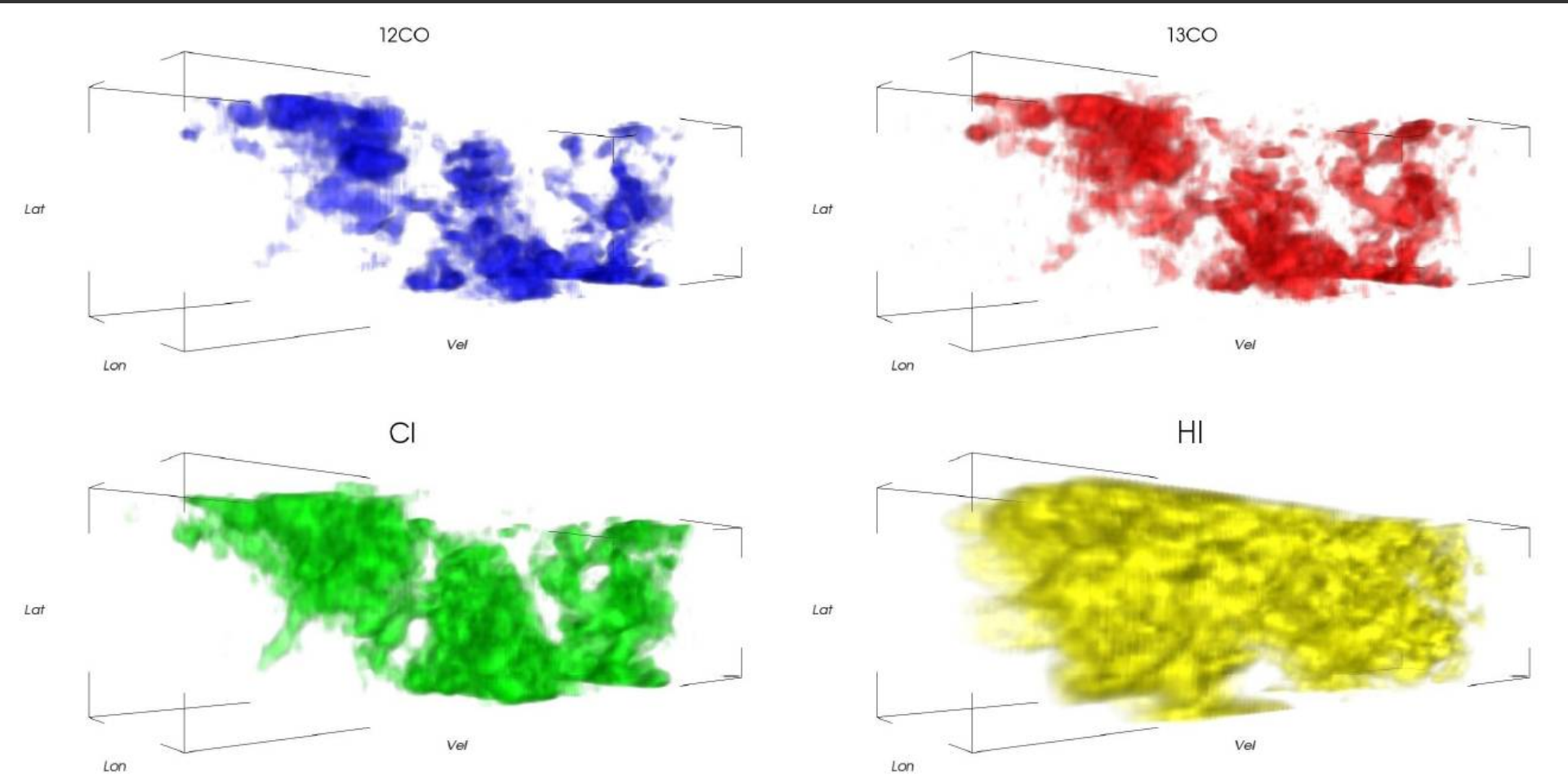
preliminary design of DATE5



Antenna	Cassegrain
Diameter	5m, with rms accuracy <10μm
Receiver	1x4 superconducting SIS & HEB mixer
Band	350μm & 200μm
IF BW	4GHz x 4 beams x 2 bands
FOV	5′×5′ (200μm)
Pointing	≤2"

CI, CO, HI towards G328 region (1x1 deg) (Burton et al 2013, 2015)

CI (2-1) – HEAT 2' beam
CO(1-0) – Mopra 30” beam
HI – Parkes/ACTA 2' beam



3D pixel (voxel) analyis → 50% increase in CI / ^{13}CO ratio at cloud edges.

ASKAP - Australian Square Kilometre Array Pathfinder

http://www.atnf.csiro.au/projects/askap

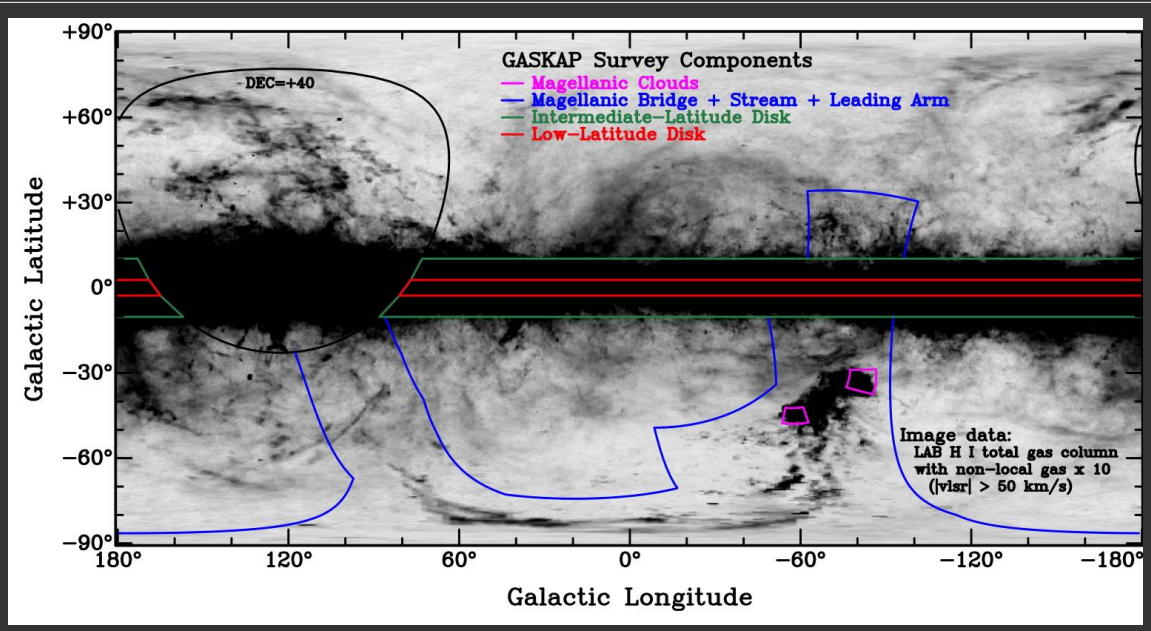
Number of dishes	36
Dish Diameter (m)	12
Dish Area (m^2)	113
Total Collecting Area (m^2)	4072
Aperture Efficiency	0.8
System Temperature (K)	50
Field-of-view (deg^2)	30
Frequency Range (MHz)	700-1800
Instantaneous Bandwith (MHz)	300
Maximum number of channels	16384
Maximum Baseline (km)	6

Phased array feeds (PAFs) *30-beams*
> 5 deg FoV.
- All dishes built; All PAFs by 2016
- Continuum survey, HI & OH lines, B-field strength & turbulenc, transients
→ Many key science projects

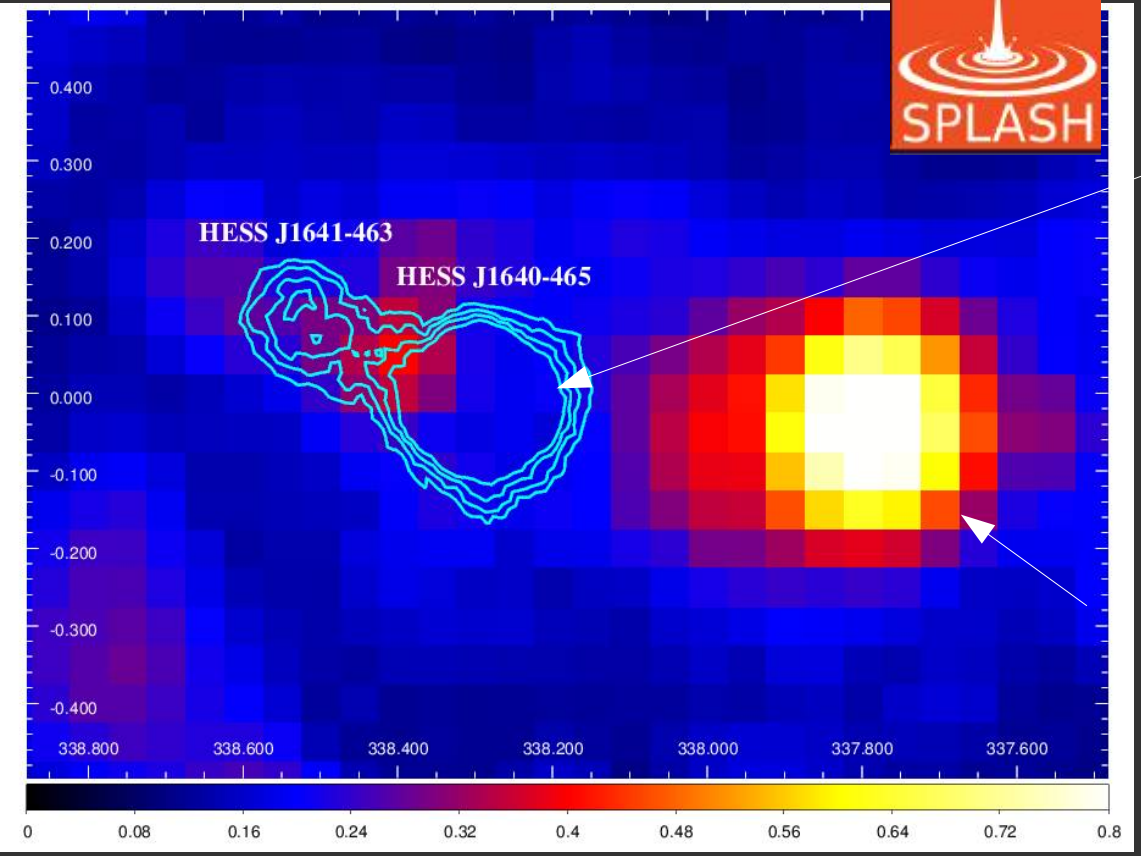
GASKAP

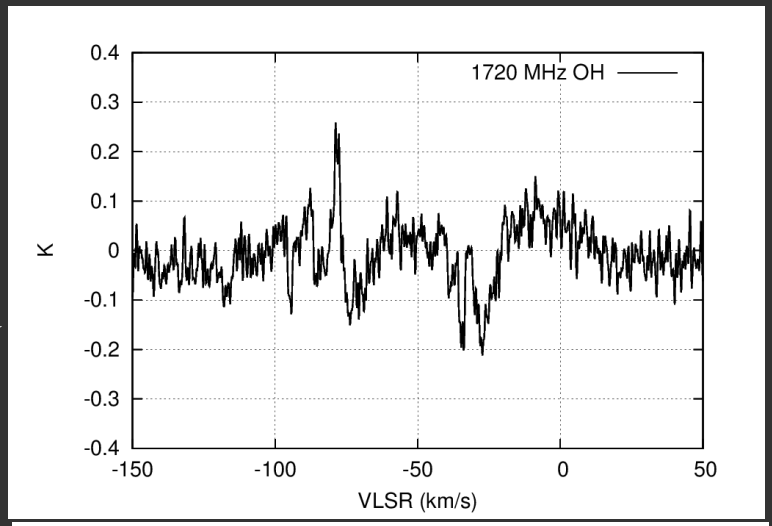
www.atnf.csiro.au/research/GASKAP/

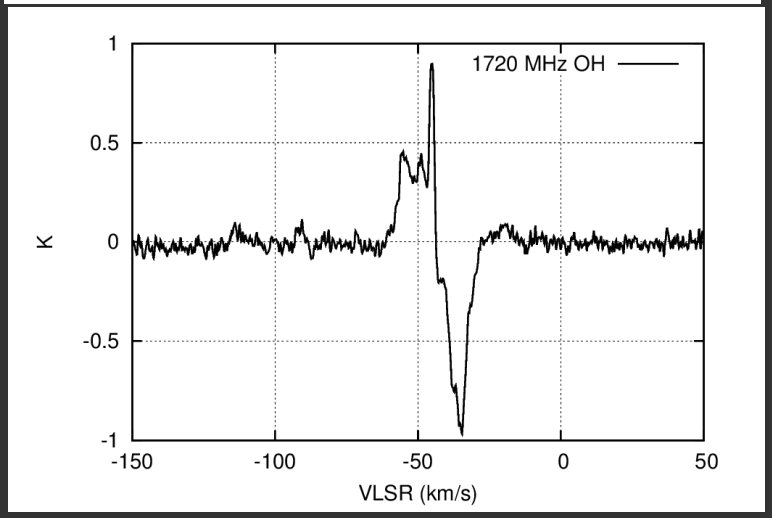
Key HI/OH survey
- 30 arc-sec resolution



Parkes SPLASH 1720 MHz OH
(Dawson et al 2013, 2014)

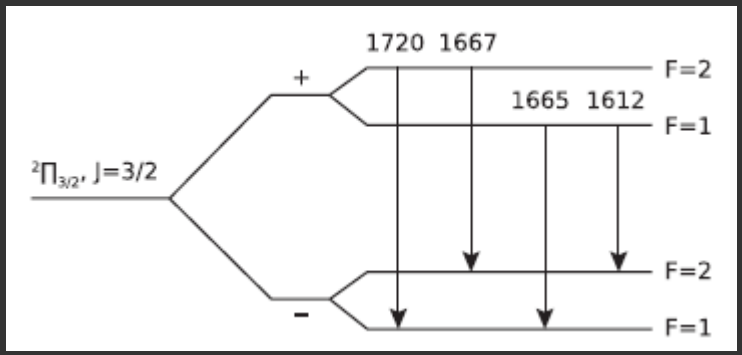






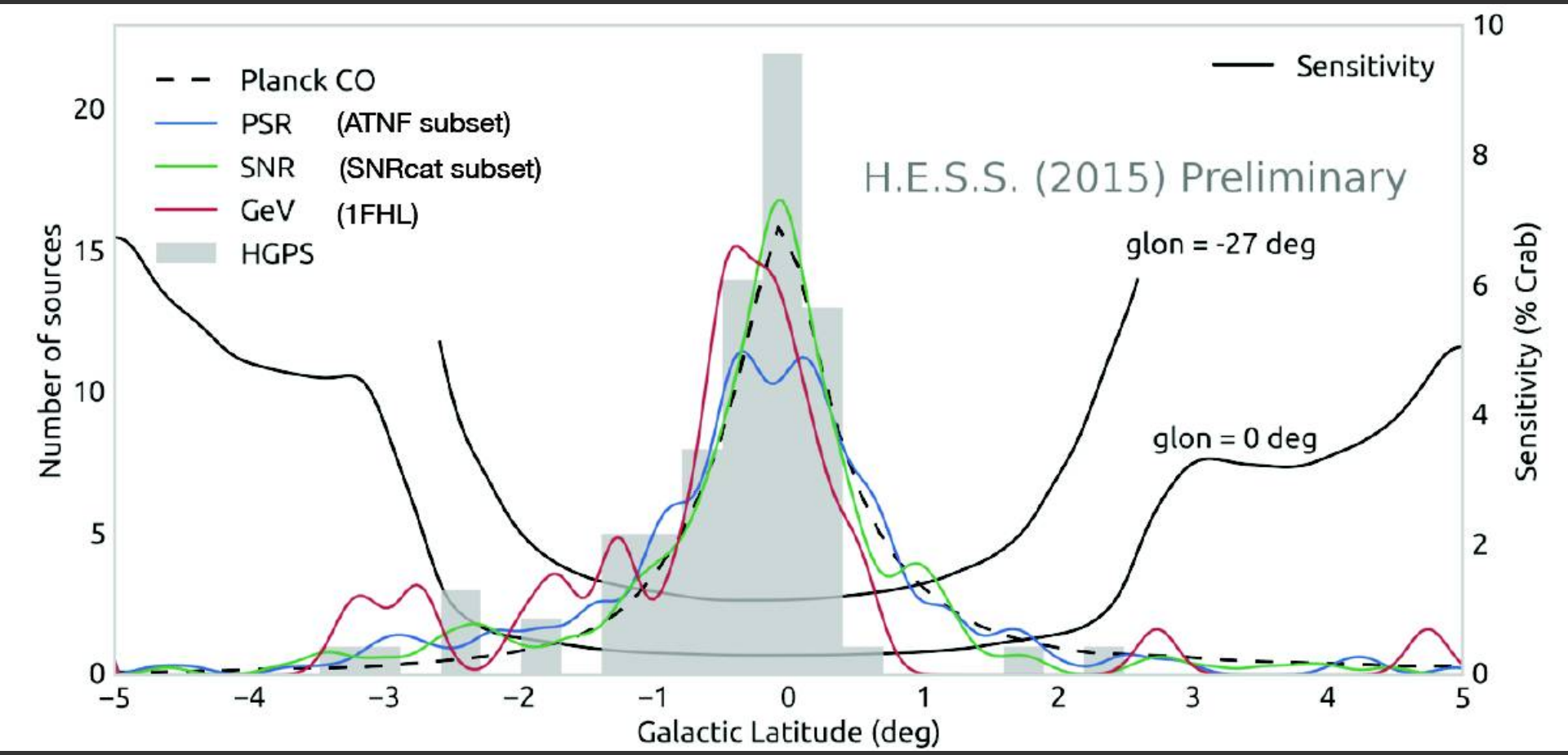
Aims: Search for SNR pumped 1720 MHz lines (ie those without other OH transitions 1667, 1665, 1612 MHz)

Search for OH without CO
– Parkes beam (12') too big
→ ASKAP 30” beam

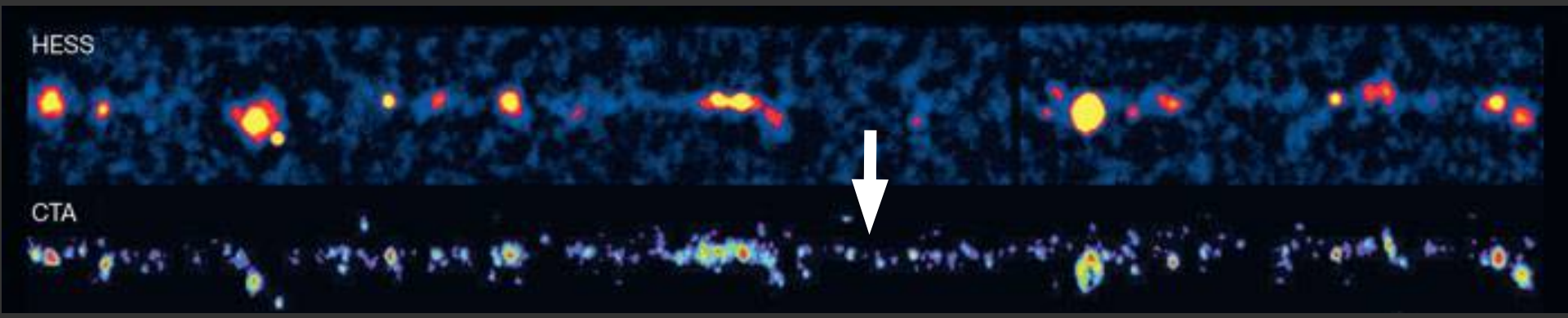


Deil et al 2015

Latitude Distribution - HGPS Sources et al.



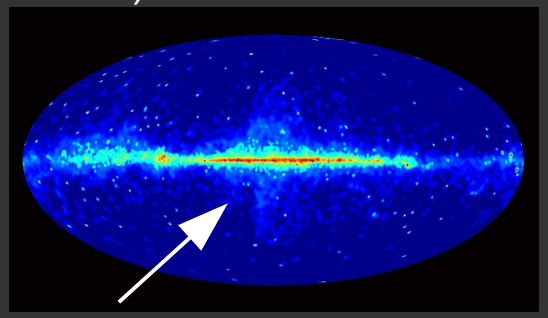
Galactic Plane TeV Surveys : HESS → CTA



Funk et al 2012

- CTA will provide Galactic Plane TeV Gamma-ray maps
  on ~1-3 arc-min scales
  (~0.5 arc-min possible – high quality cuts)

- >3 sources per deg^2 |b|<0.2° |l|<30° (Dubus etal 2013)



- Diffuse TeV components visible?
  from CR 'sea' – maybe
  local CR accelerator enhancements – yes

Confusion guaranteed (same as for Fermi-LAT at GeV energies!)

- Mapping the ISM on arc-min scales over the plane will be essential
Mopra (CO, CS), Nanten2 (CO), ASKAP (HI, OH), THz (CI, C+)