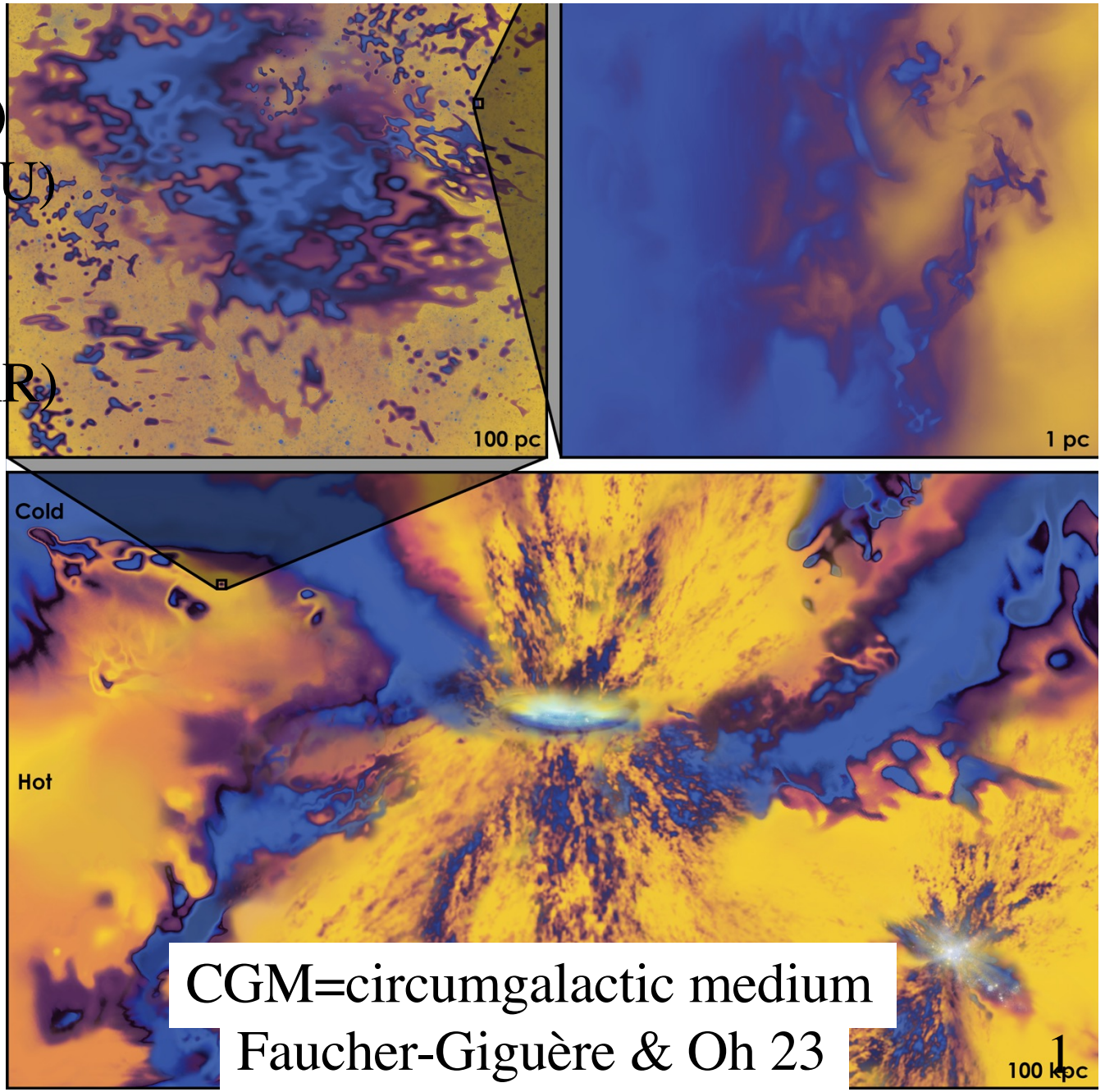
Probing Circumgalactic Cosmic Rays and Their Sources Around Milky Way

Susumu Inoue (Chiba U)
Naomi Tsuji (Kanagawa U)
Tsunefumi Mizuno
(Hiroshima U)
Kazumasa Kawata (ICRR)
Yutaka Ohira (U Tokyo)
Masahiro Nagashima
(Bunkyo U)

Papers in prep.



CGM=circumgalactic medium
Faucher-Giguère & Oh 23

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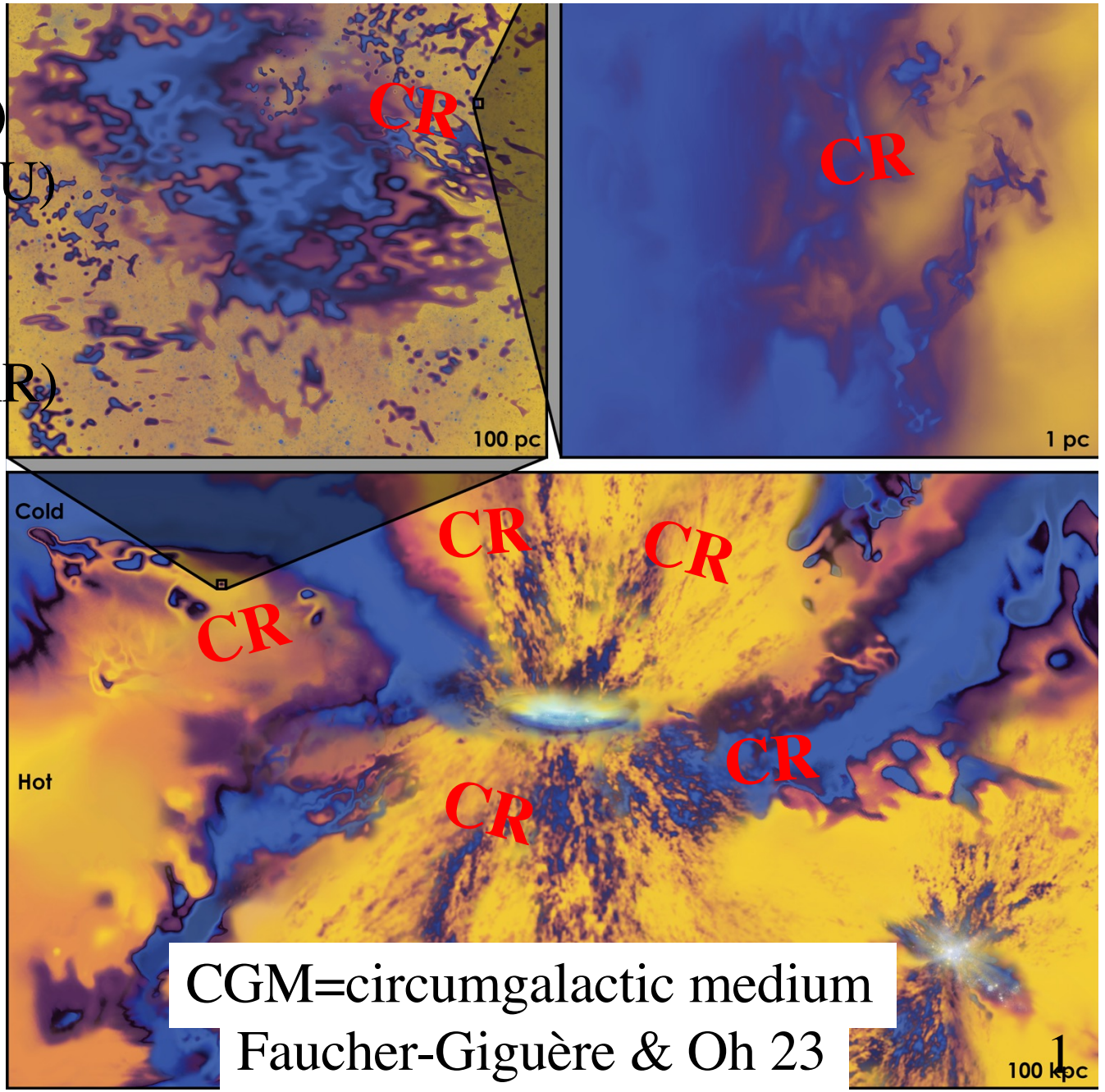

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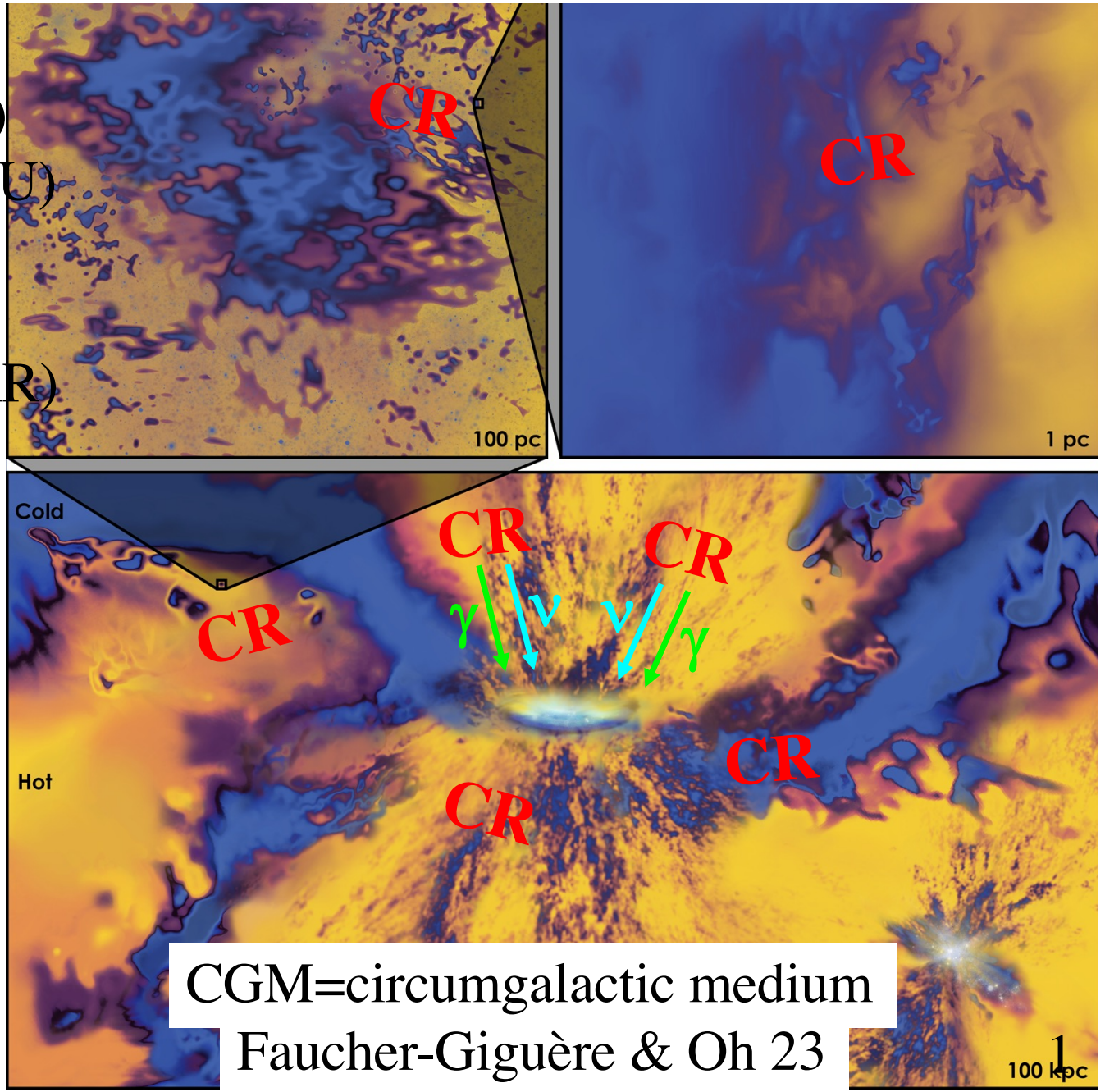

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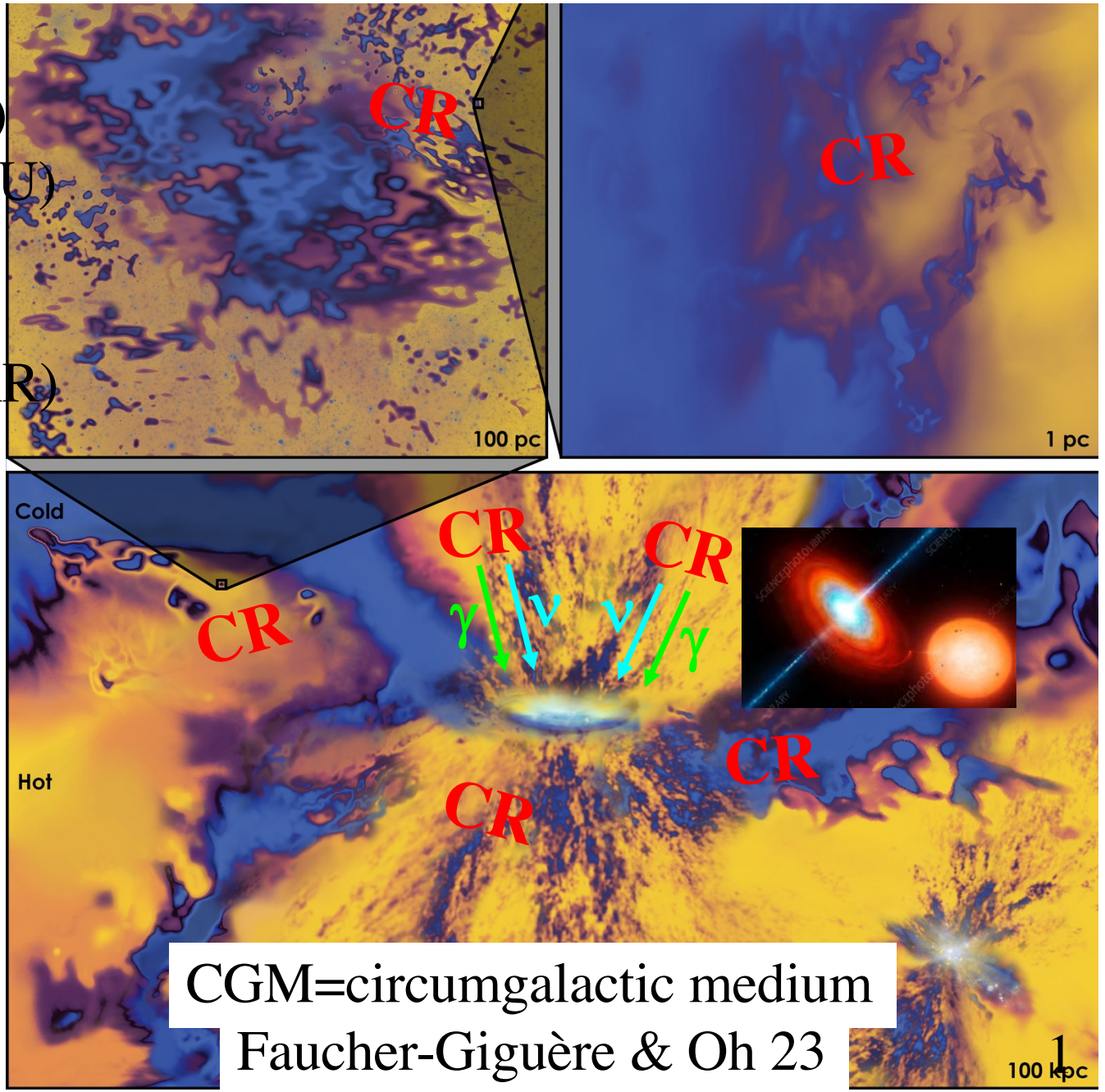

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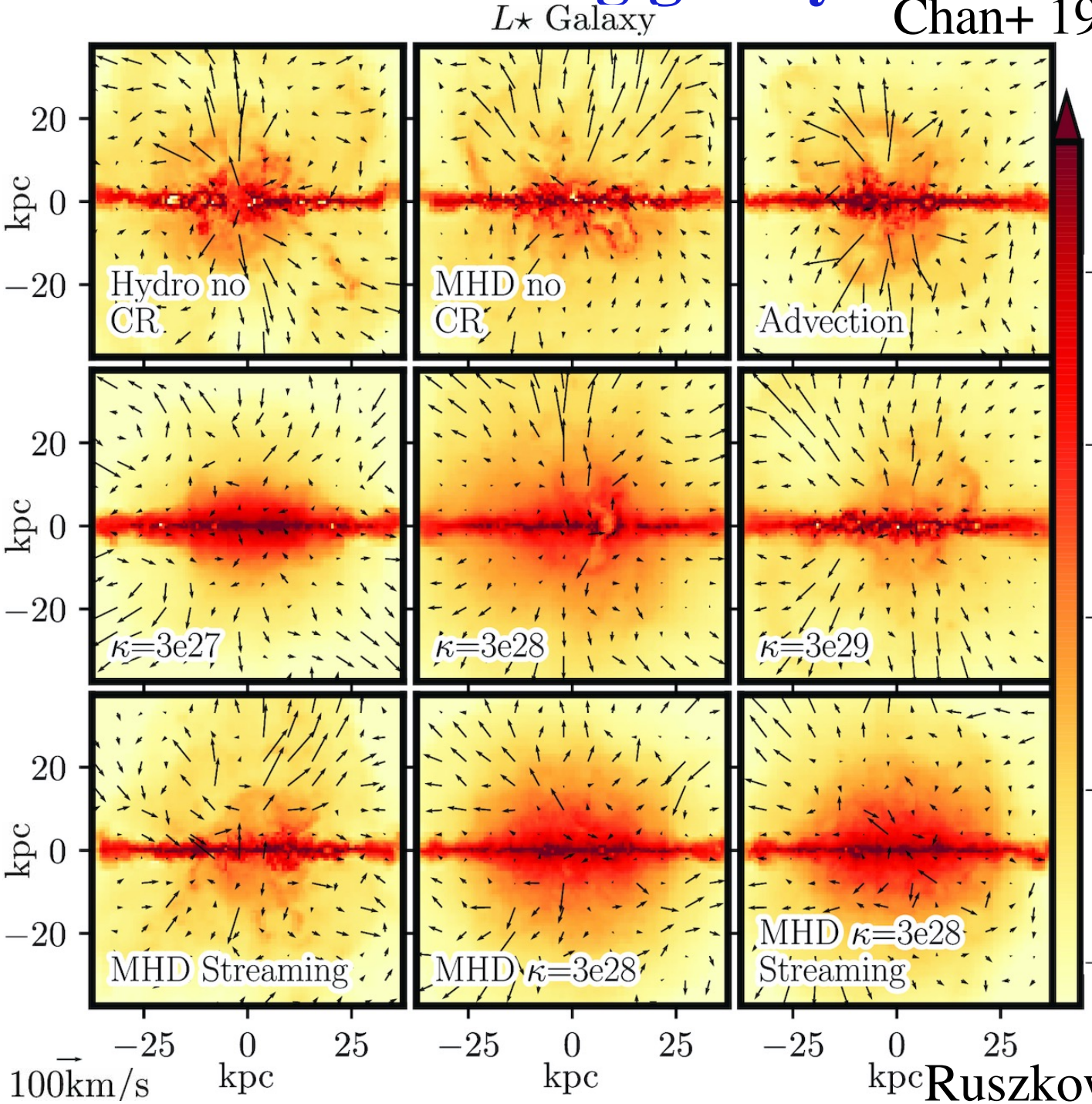
CR feedback during galaxy formation



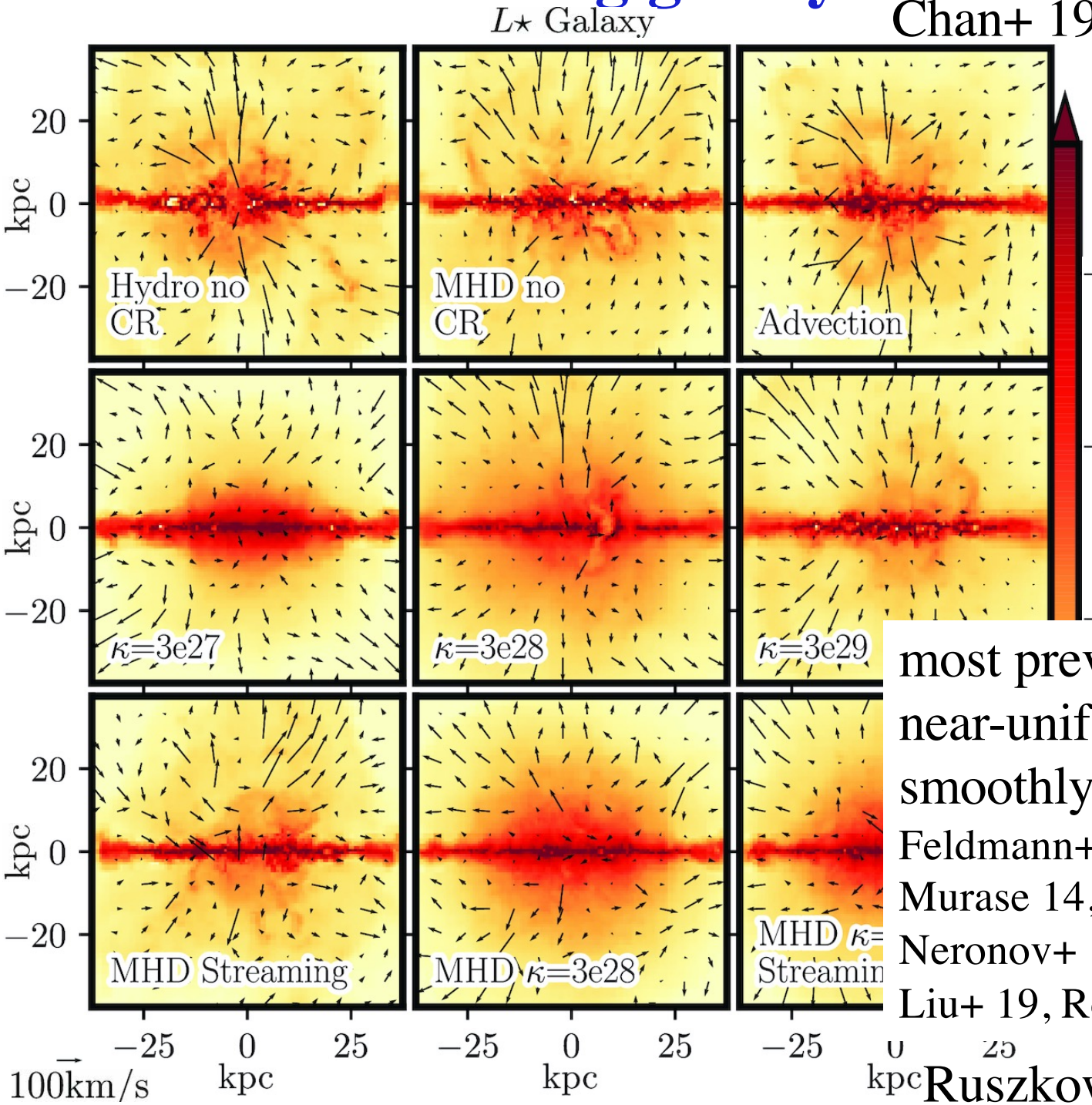
Chan+ 19

- CRs injected in disk, escape -> must exist in CGM
- Potentially large impact of p_{CR} on CGM, galaxy evol.
- Depends strongly on assumed CR transport
- Obs. constraints warranted

simulations
FIRE: Hopkins+
ChaNGa: Butsky+
AREPO/AURIGA: Pfrommer+
RAMSES: Dubois+
...

Ruszkowski & Pfrommer 23

CR feedback during galaxy formation



Chan+ 19

- CRs injected in disk, escape -> must exist in CGM
- Potentially large impact of p_{CR} on CGM, galaxy evol.
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most previous studies assumed near-uniform emission from smoothly distributed gas

Feldmann+ 13, Taylor+ 14, Ahlers & Murase 14, Kalashev+ 16,23, Neronov+ 18, Blasi & Amato 19, Liu+ 19, Recchia+ 21…

cool CGM in Milky Way only component with reliable distances

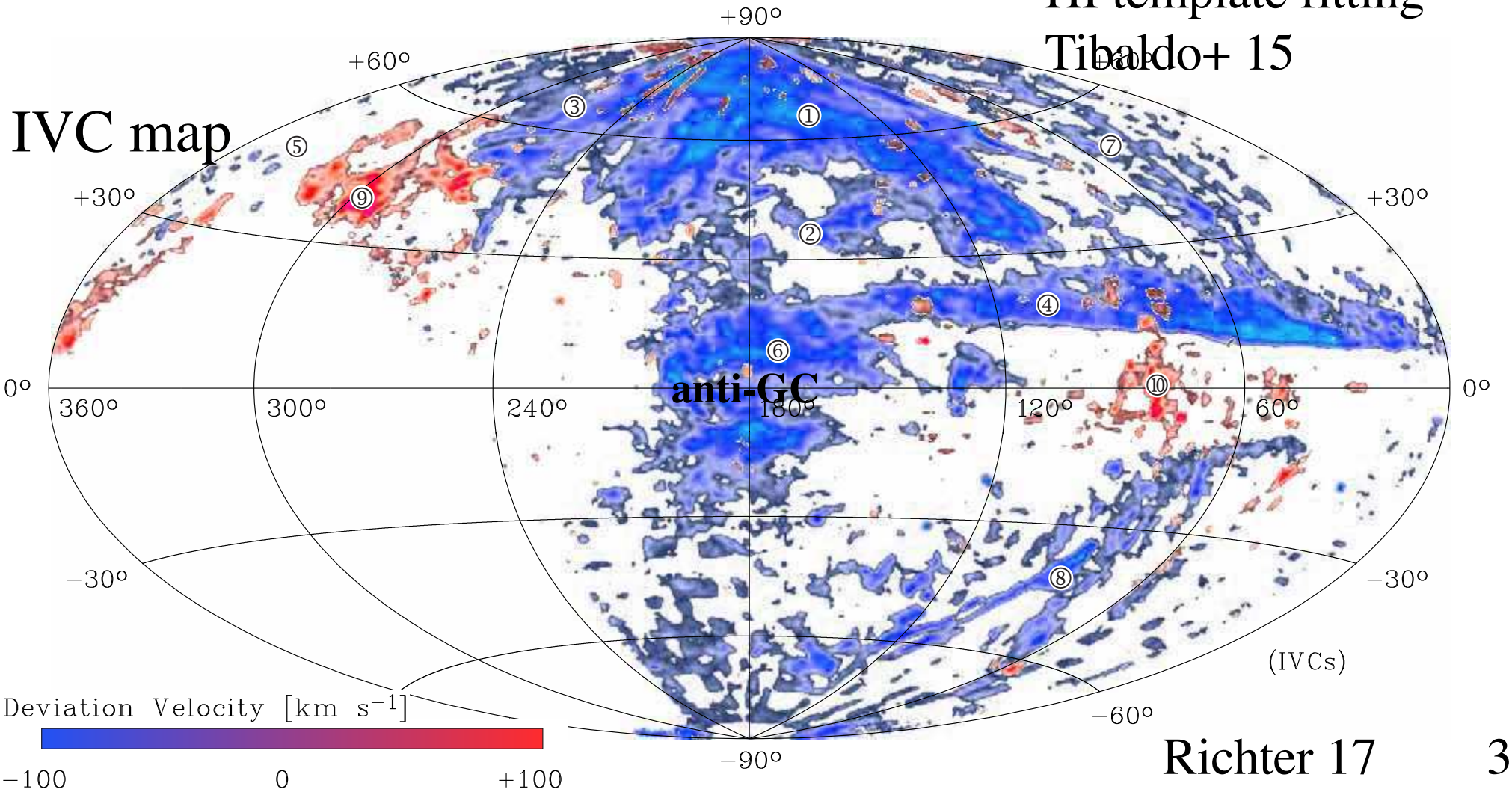
intermediate velocity clouds (IVCs): $|v_{dev}|$~40-90 km/s, D~1-2 kpc, Z~$Z_\odot$

some detected by LAT!

HI template fitting

Tibaldo+ 15

IVC map



cool CGM in Milky Way only component with reliable distances

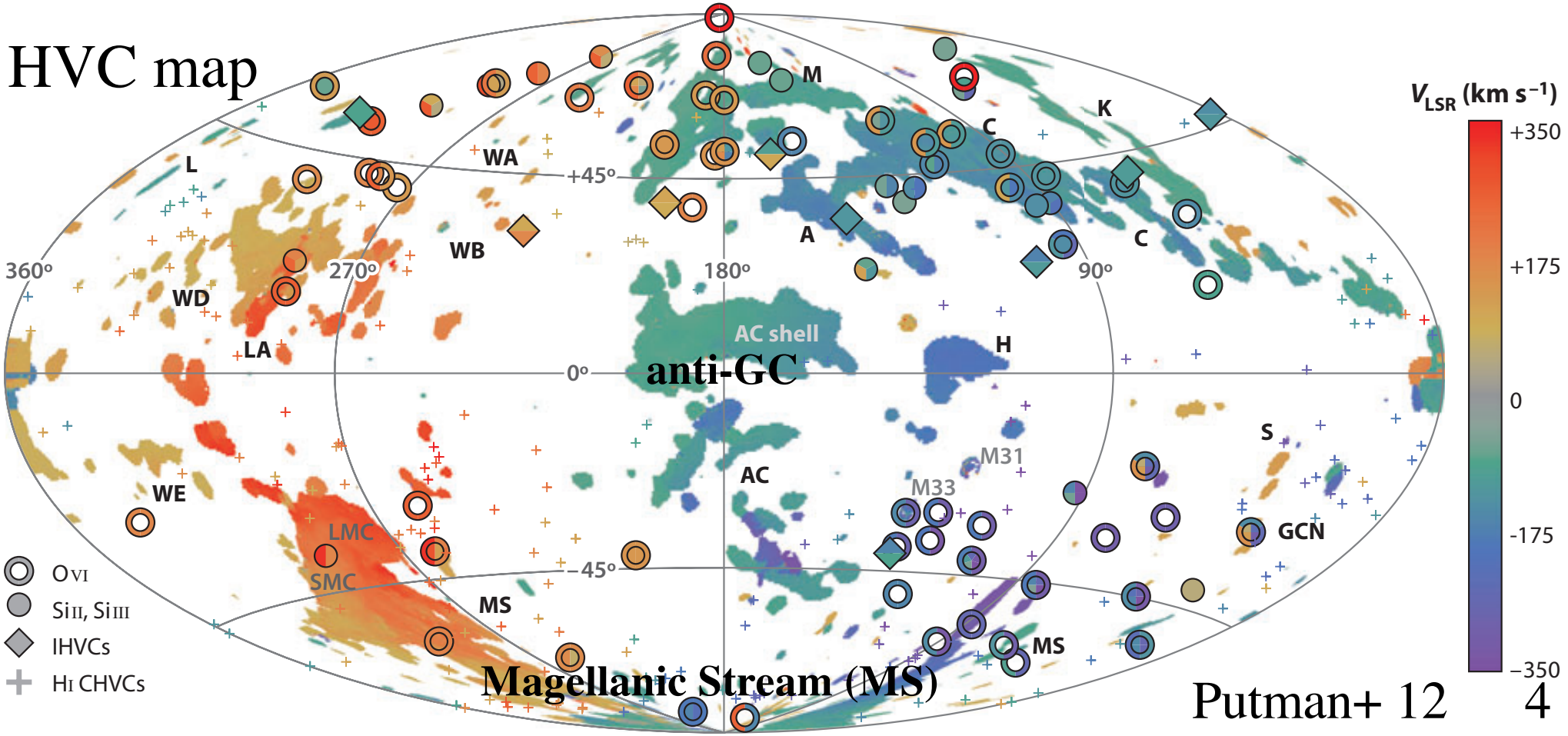
intermediate velocity clouds (IVCs): $|v_{dev}|$~40-90 km/s, D~1-2 kpc, Z~$Z_\odot$

high velocity clouds (HVCs): $|v_{dev}|$>90 km/s, D~3-12 kpc (MS 50-100 kpc

- HI+HII, $M_{HI+HII,HVC}$ >~2-4x $M_{HI,HVC}$ Z~<0.5$Z_\odot$
- HVCs (wo Mag. Stream): M_{tot} ~1.4x10^8 $M_\odot$
  Mag. Stream: M_{tot} ~2x10^9 $M_\odot$

not detected by LAT
Tibaldo+ 15

HVC map

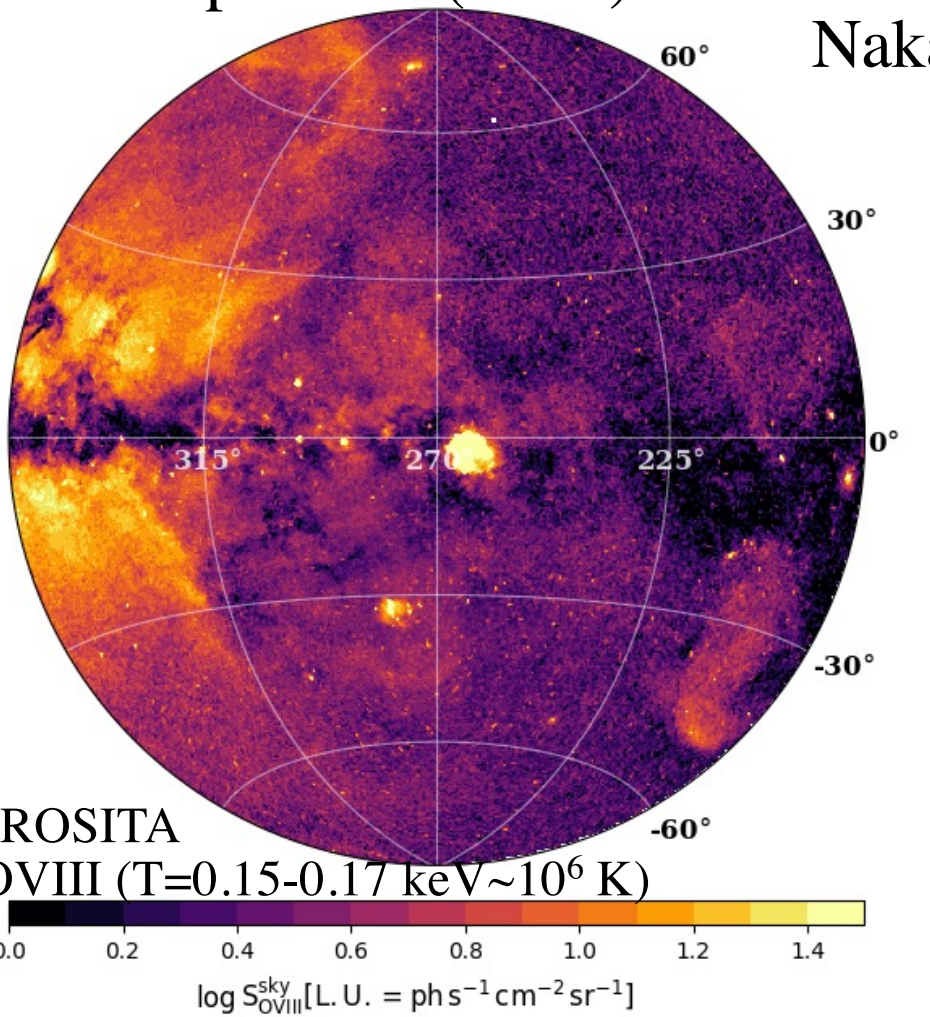


Putman+ 12

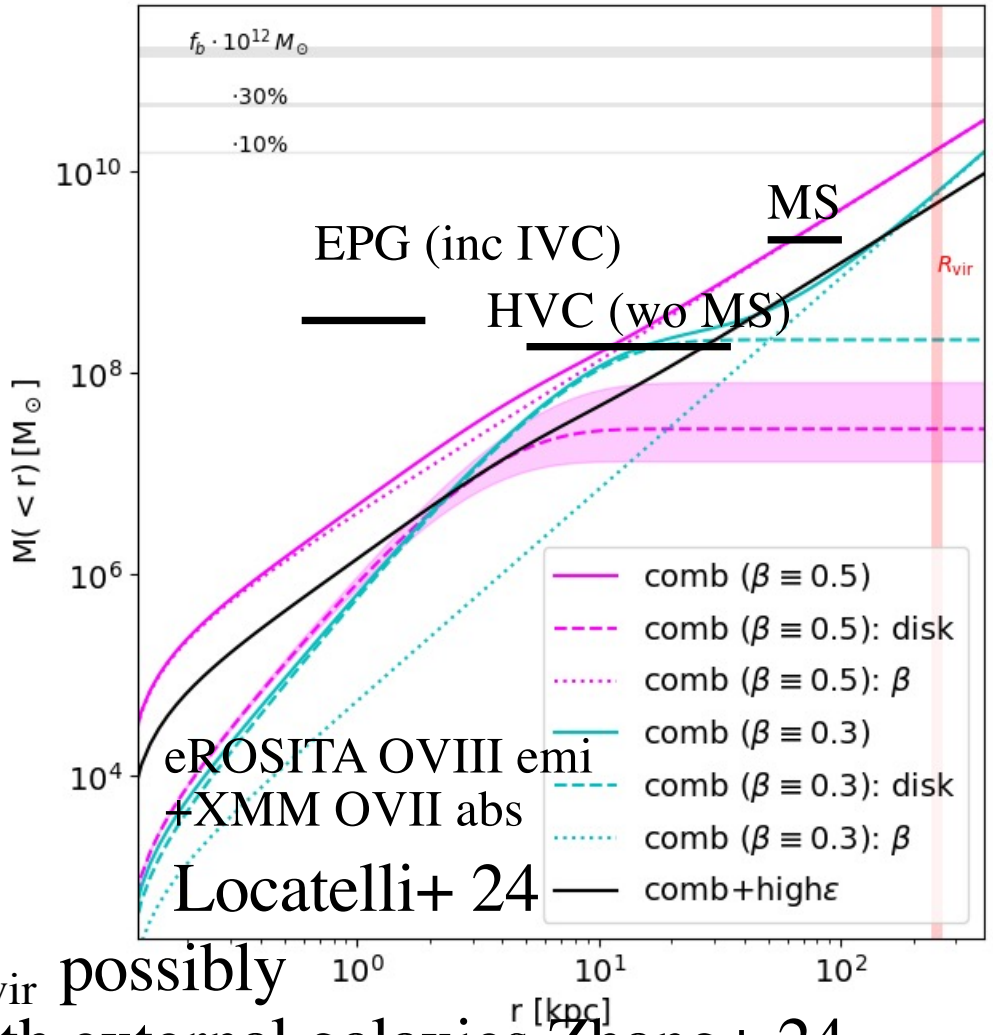
warm/hot CGM of Milky Way vs cool CGM

- outer spherical (virial) + inner disk-like (fountain?) components?

Nakashima+ 18, Kaaret+ 20, Locatelli+ 23



eROSITA
OVIII (T=0.15-0.17 keV~10^6 K)



eROSITA OVIII emi
+XMM OVII abs
Locatelli+ 24

eROSITA+XMM: hot CGM mass <r_{vir} possibly << $f_{bar,cosmic}$ 10^{12} $M_\odot$ -> consistent with external galaxies Zhang+ 24, also SZ: Schaan+ 20, Hadzhiyska+ 24;

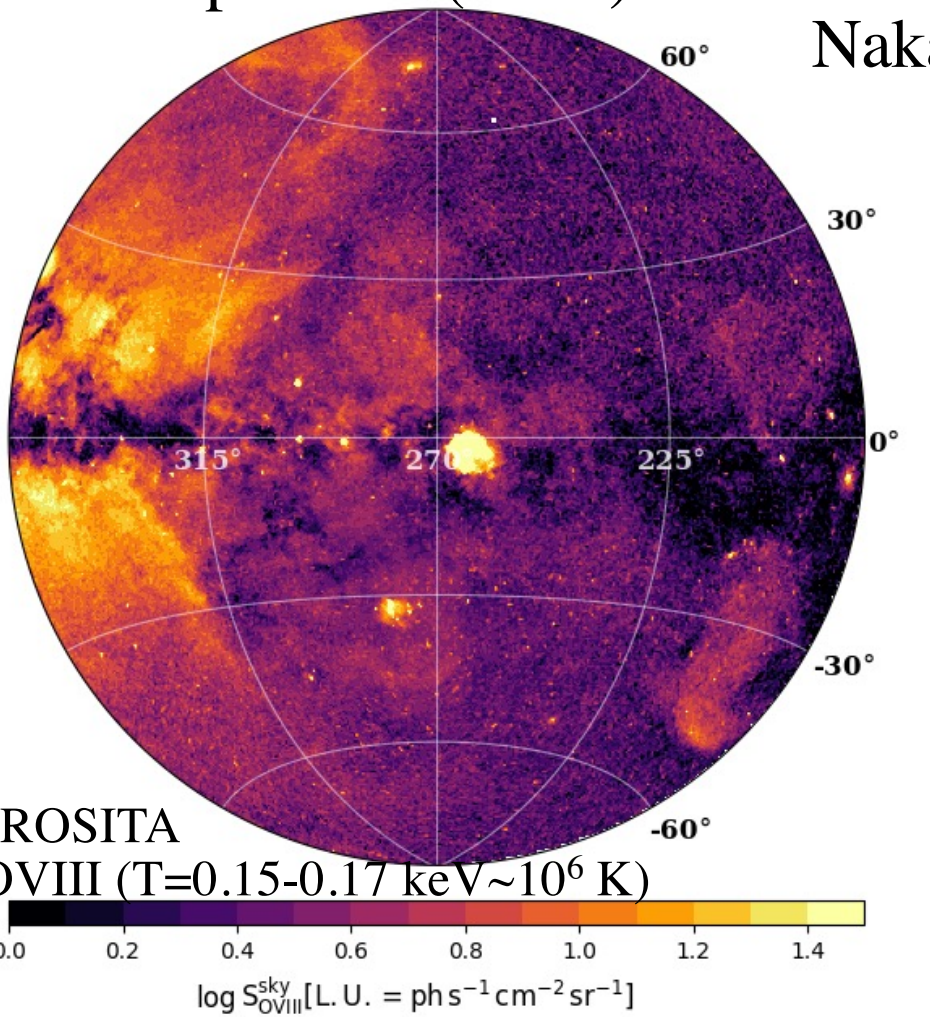
FRB DM of MW: Cook+ 23; FRB DM of external galaxies Connor+ 24;

simulations: IllustrisTNG, EAGLE, SIMBA e.g. Ayromlou+ 23…

warm/hot CGM of Milky Way vs cool CGM

- outer spherical (virial) + inner disk-like (fountain?) components?

Nakashima+ 18, Kaaret+ 20, Locatelli+ 23



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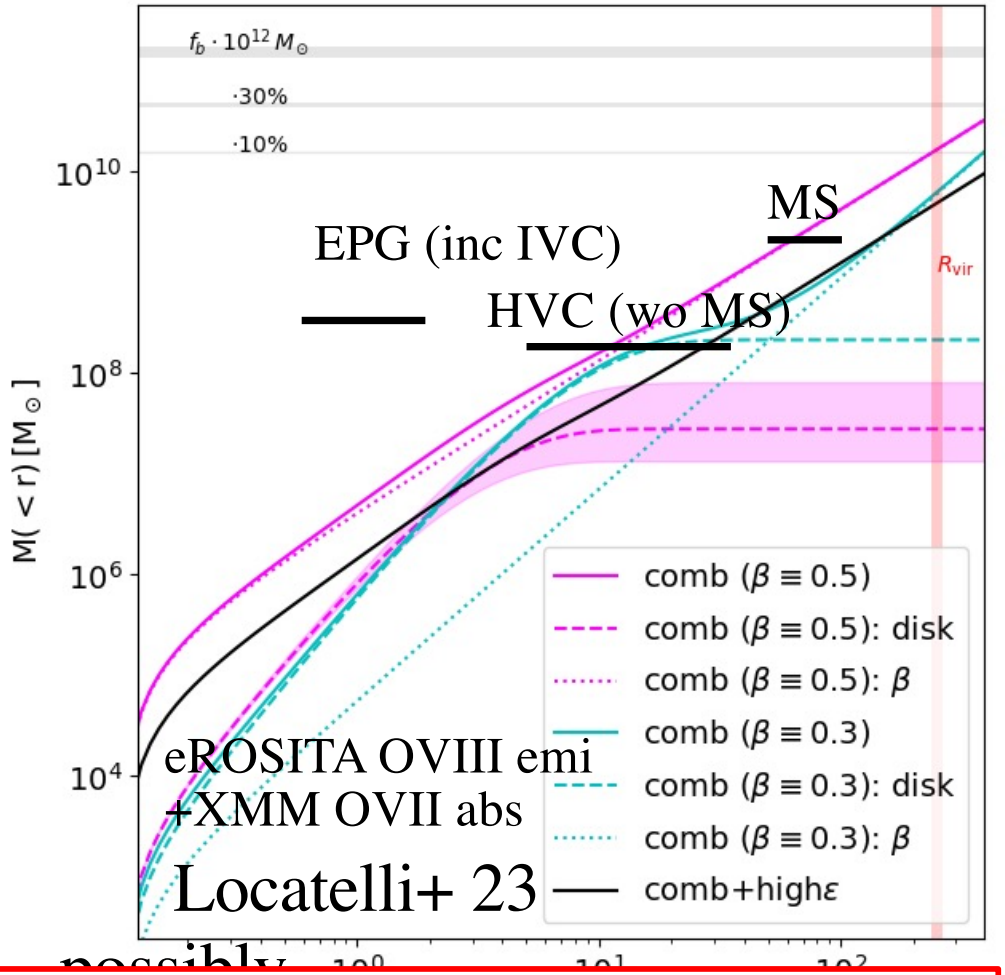
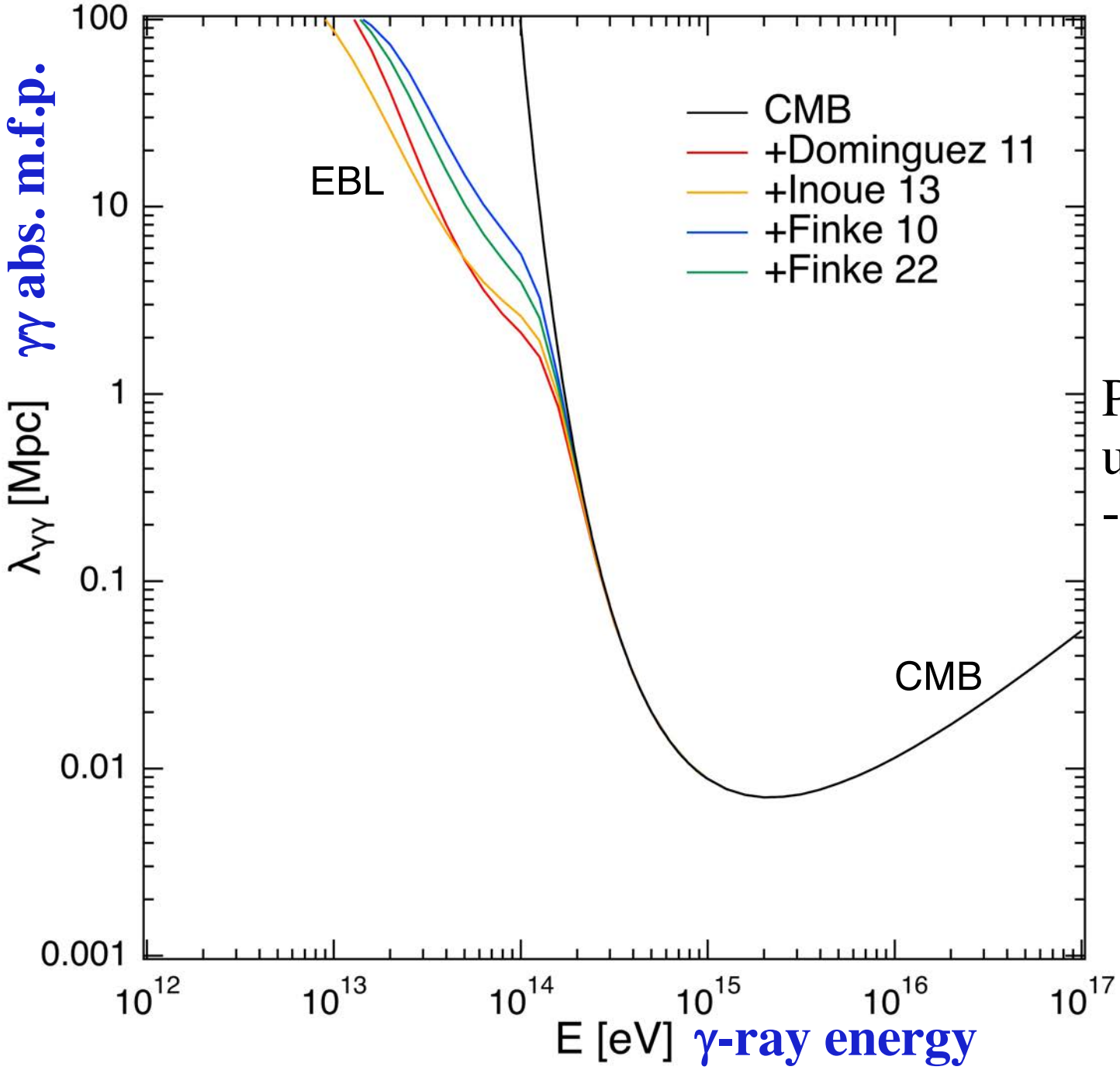


eROSITA OVIII emi
+XMM OVII abs
Locatelli+ 23

eROSITA + XMM: hot CGM mass <r ... possibly

IVC/HVC HI+HII potentially significant mass fraction of entire CGM
-> γ-ray + ν emission likely patchy, potentially correlated with cool gas

PeV γ: unique probe of MW circumgalactic CRs



$\lambda_{\gamma\gamma}$~

400 kpc @0.2 PeV

70 kpc @0.3 PeV

30 kpc @0.4 PeV

10 kpc @0.8 PeV

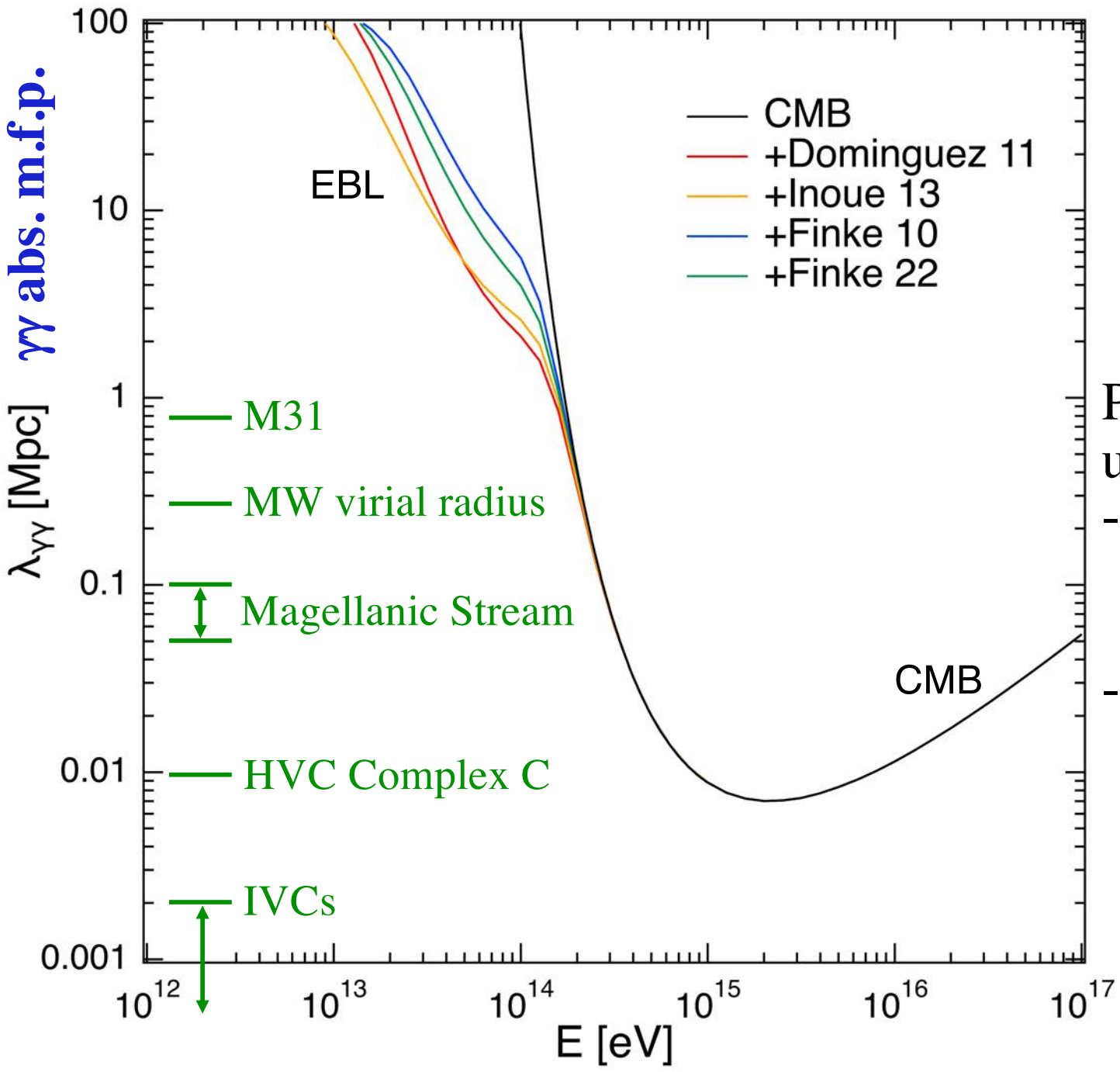
7 kpc @2-3 PeV

PeV=10^{15} eV

unlike GeV-TeV:

- extragalactic compt. filtered by γγ with EBL/CMB

PeV γ: unique probe of MW circumgalactic CRs



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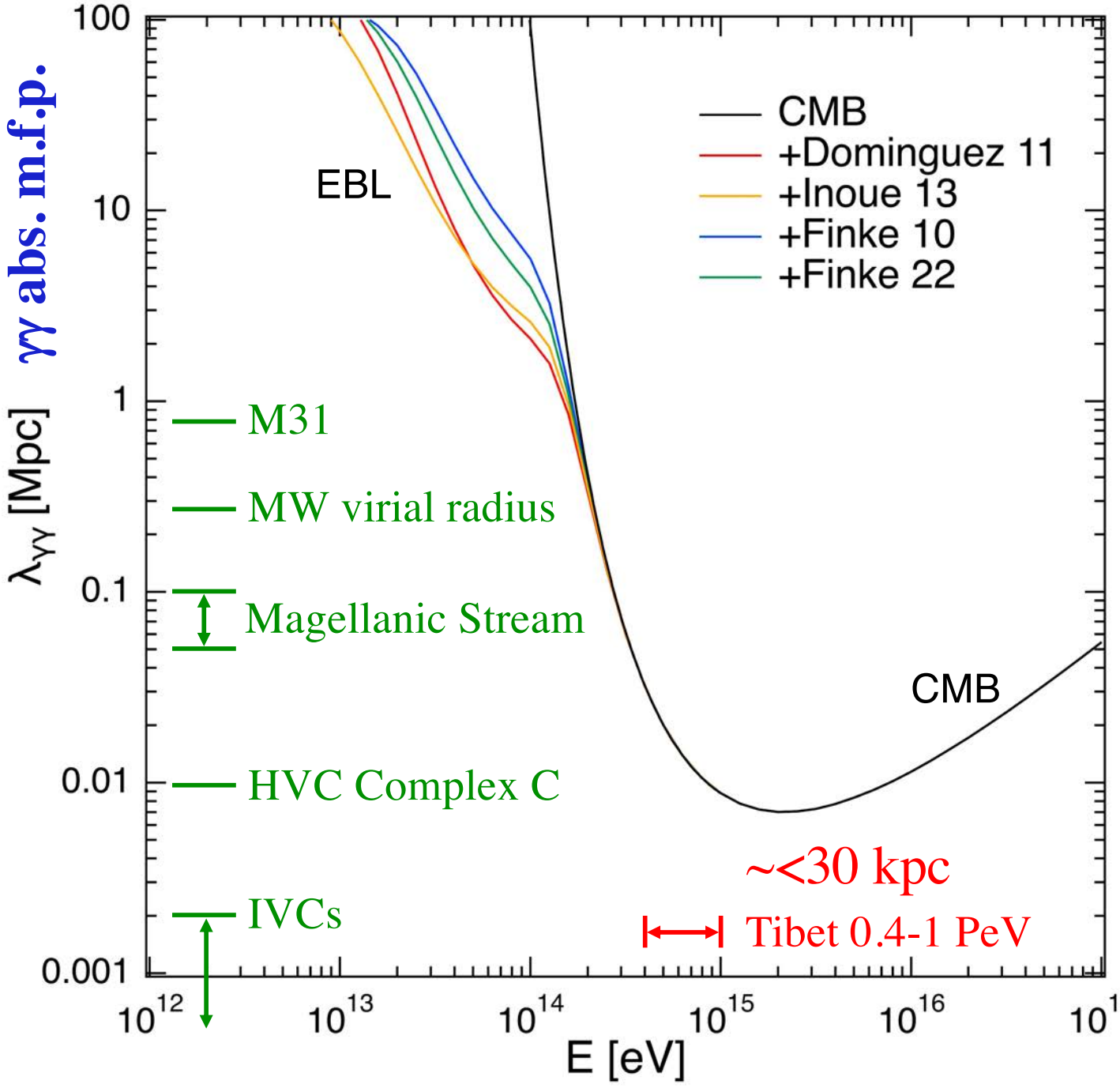

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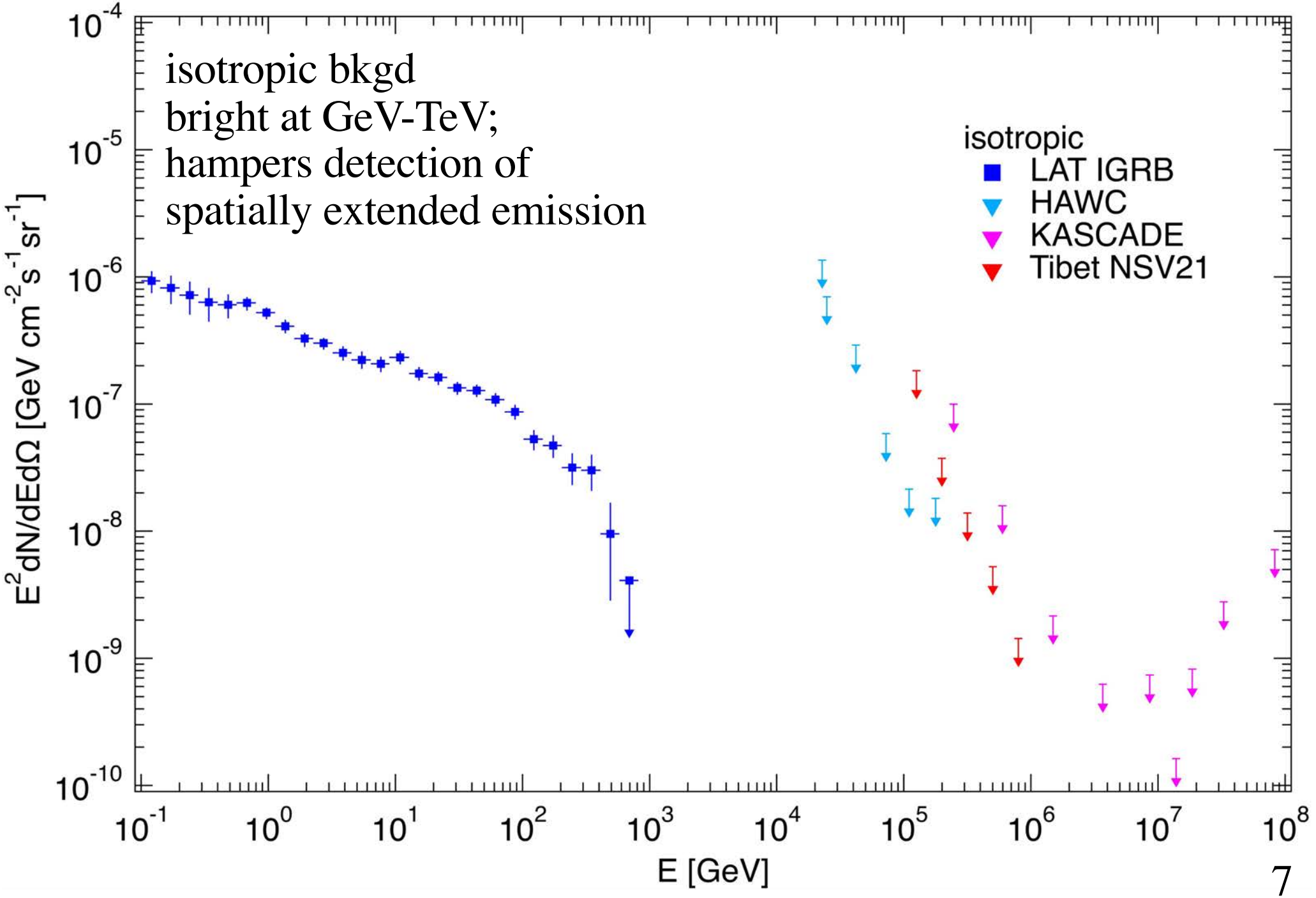
Nice for probing circumgalactic CRs!

detectability of diffuse γ-ray emission



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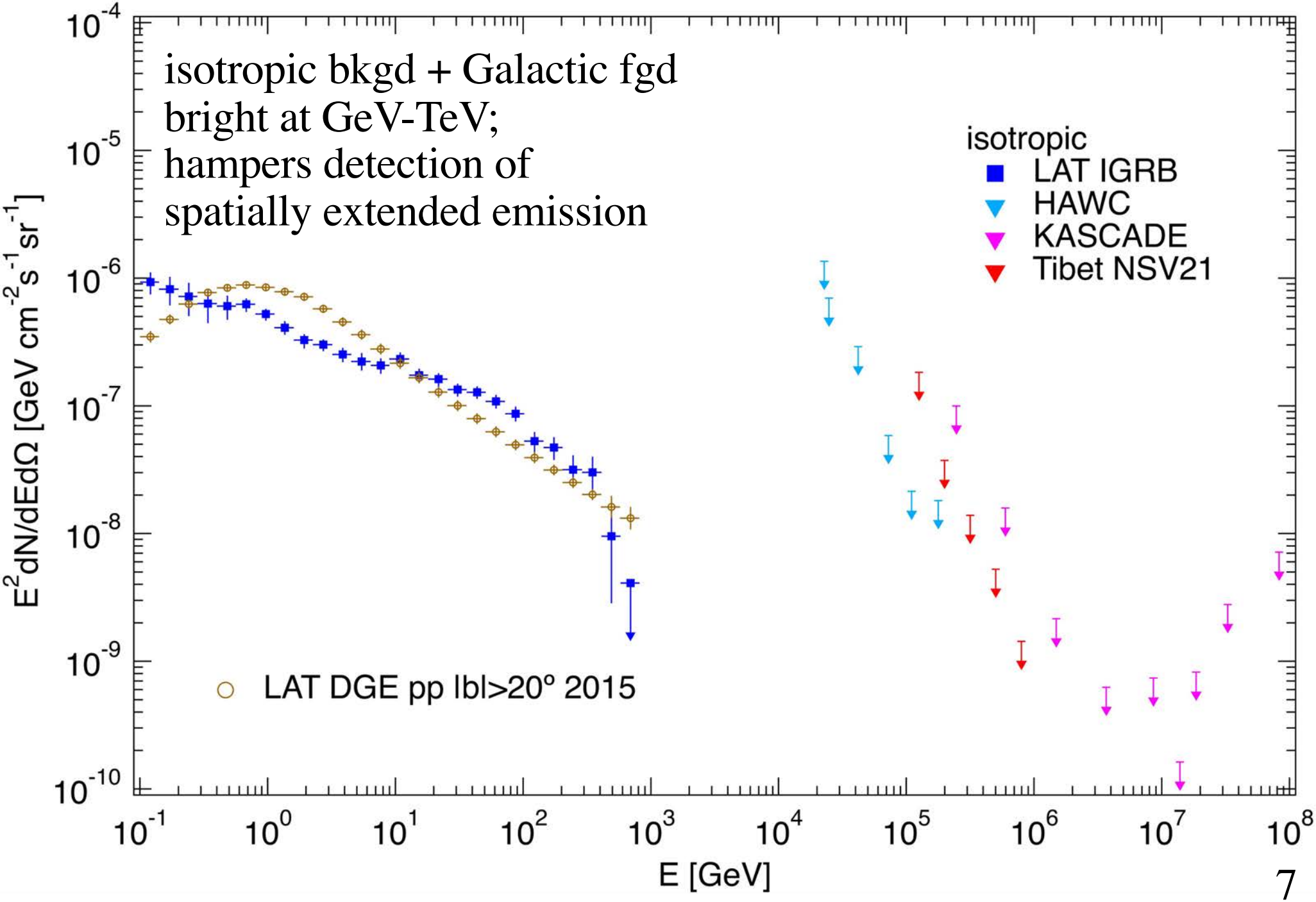

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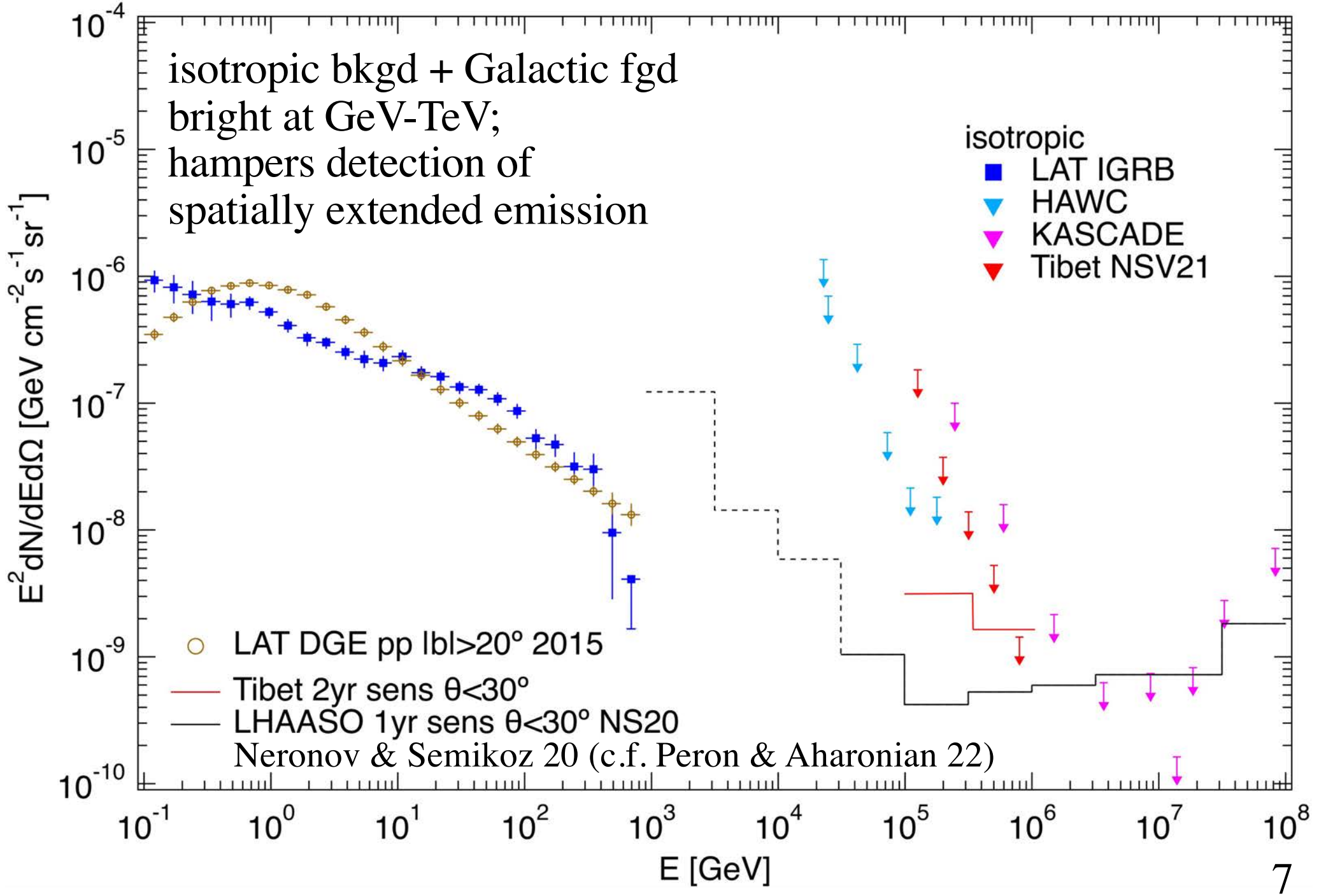

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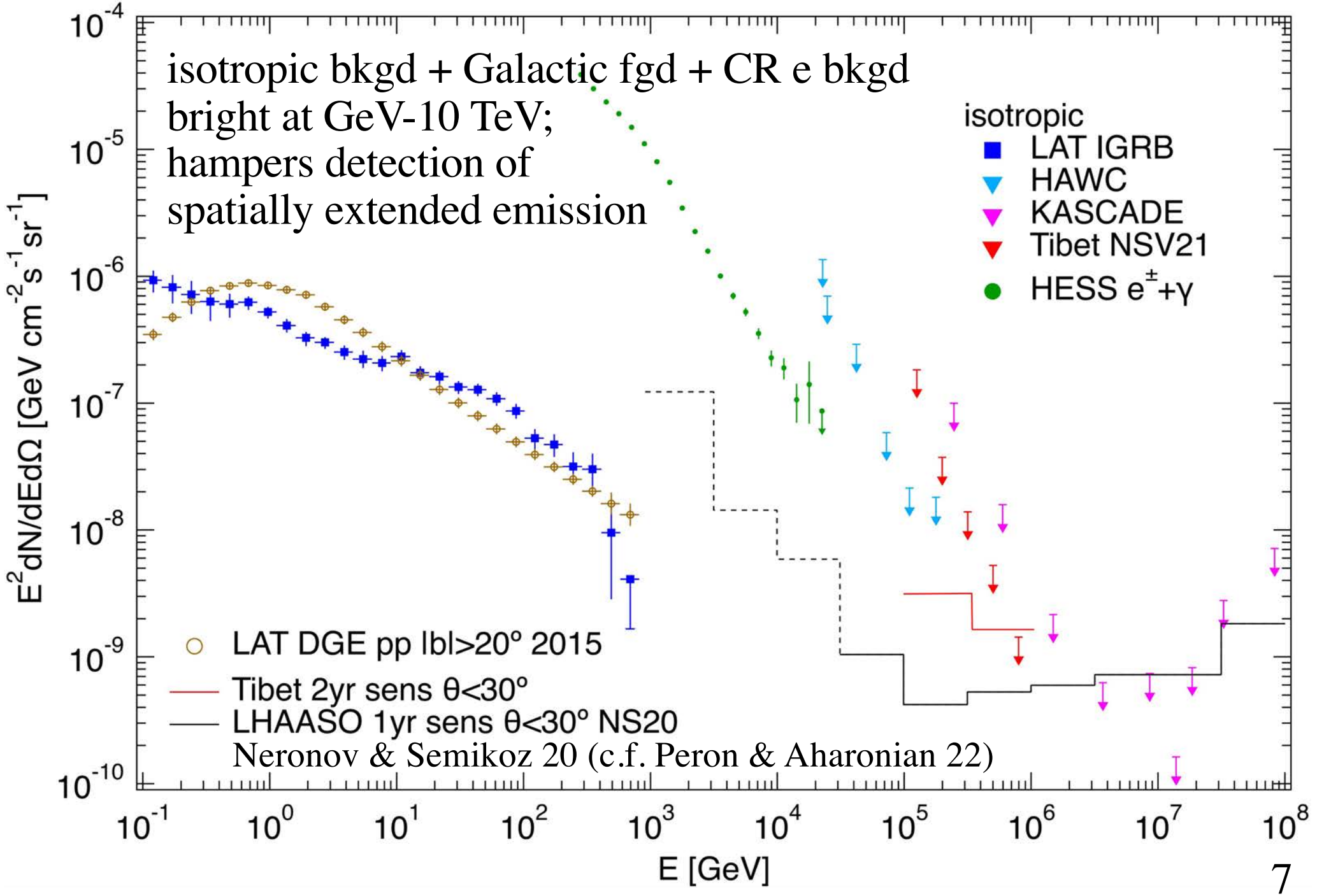

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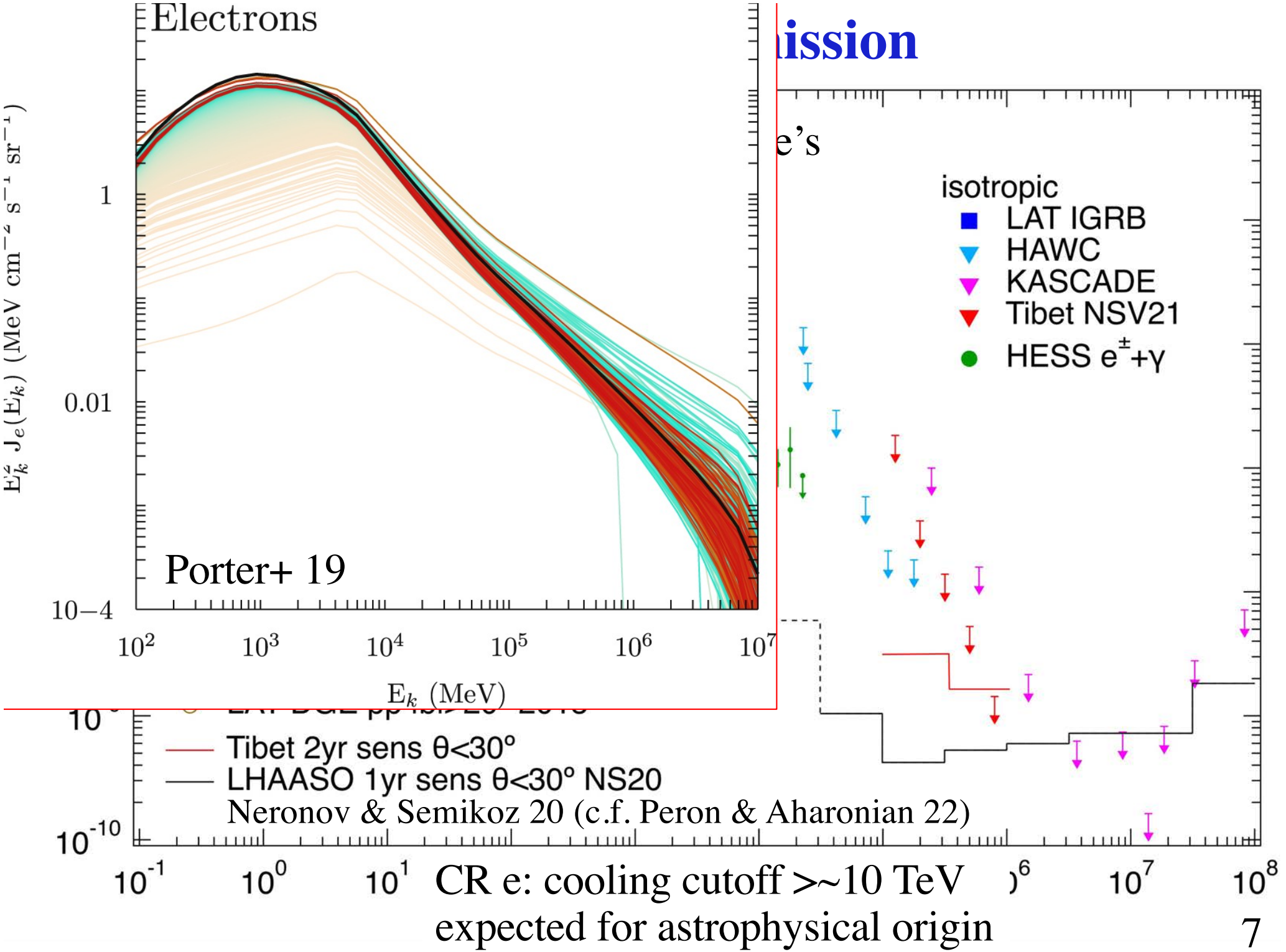
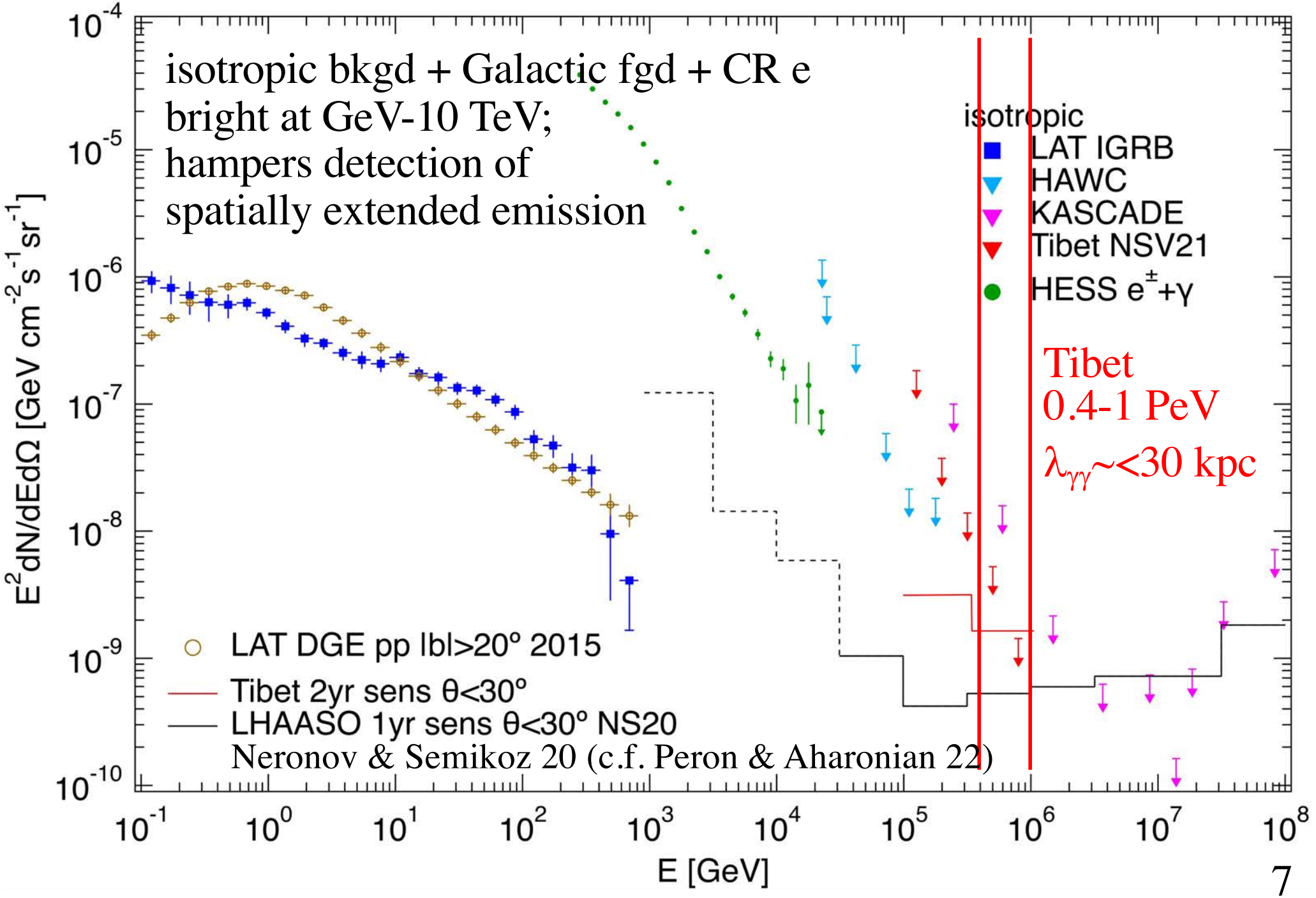


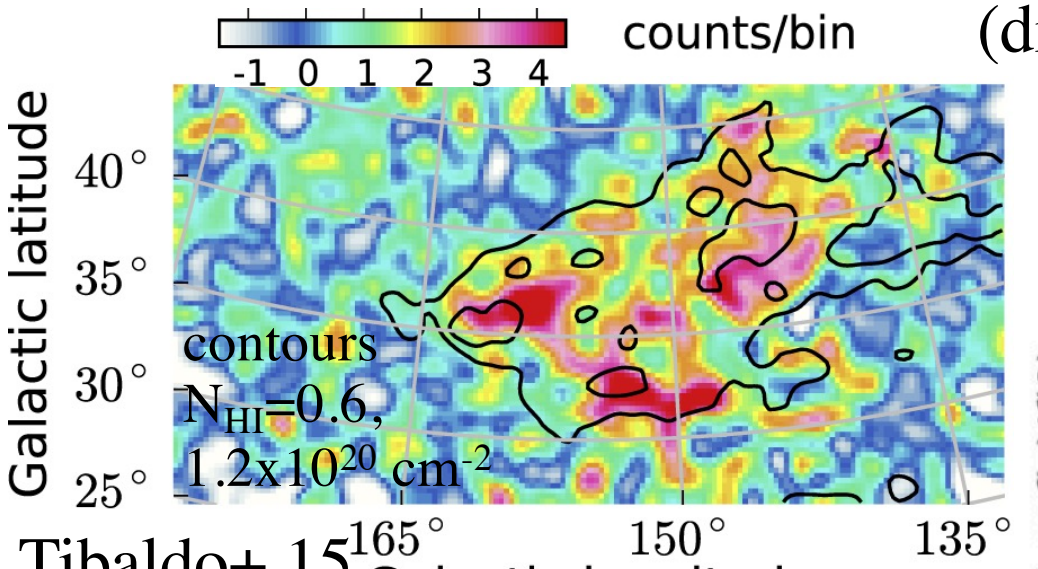
CR e: cooling cutoff >~10 TeV
expected for astrophysical origin

detectability of diffuse γ-ray emission

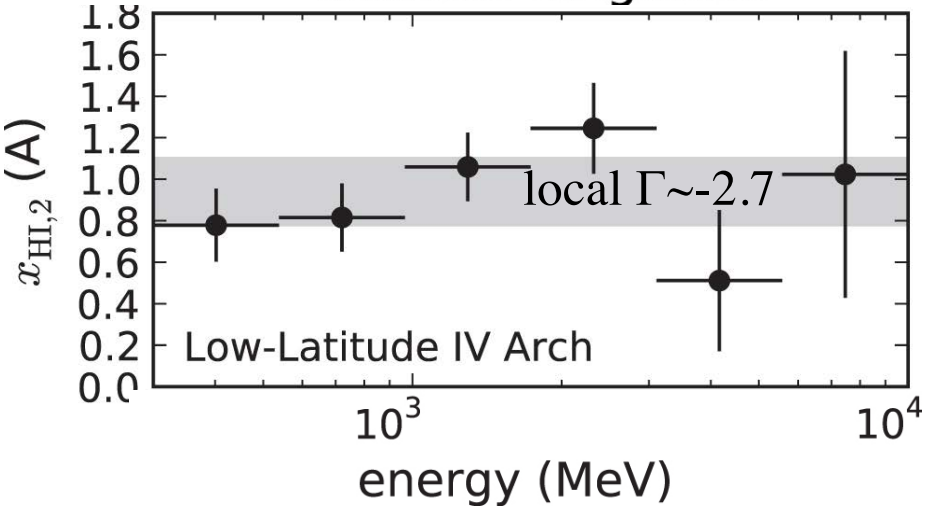


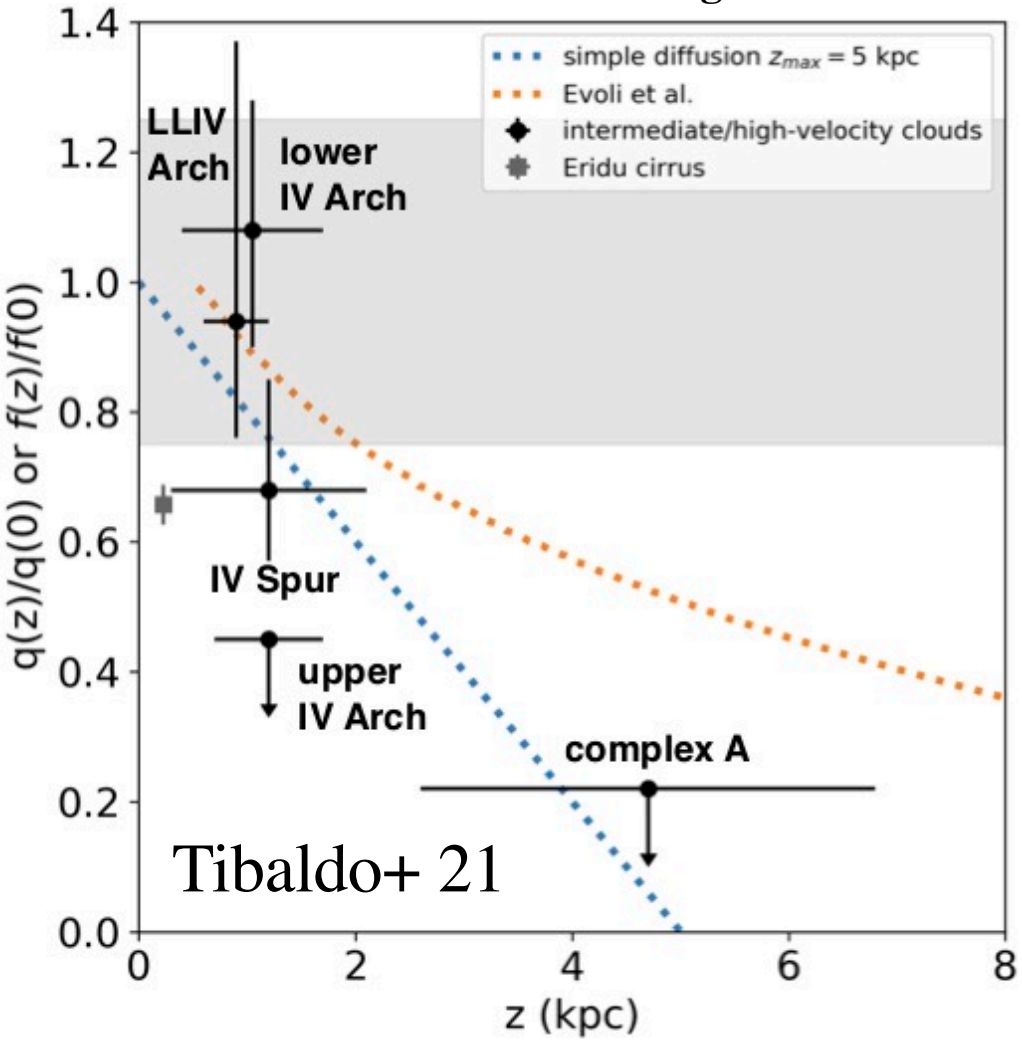
GeV detections of IVCs

evidence of CRs at z~1-2 kpc (disk-halo interface) $p_{CR}+p_{gas} \rightarrow \pi^0 \rightarrow \gamma$



Tibaldo+ 15





- significant detection of 3 IVCs at z~1-2 kpc
- spectra consistent with local CR (but with large errors)
- upper limits for a HVC at z~5 kpc -> decrease of ρ_{CR} vs z?
  NB Complex A at R~15 kpc

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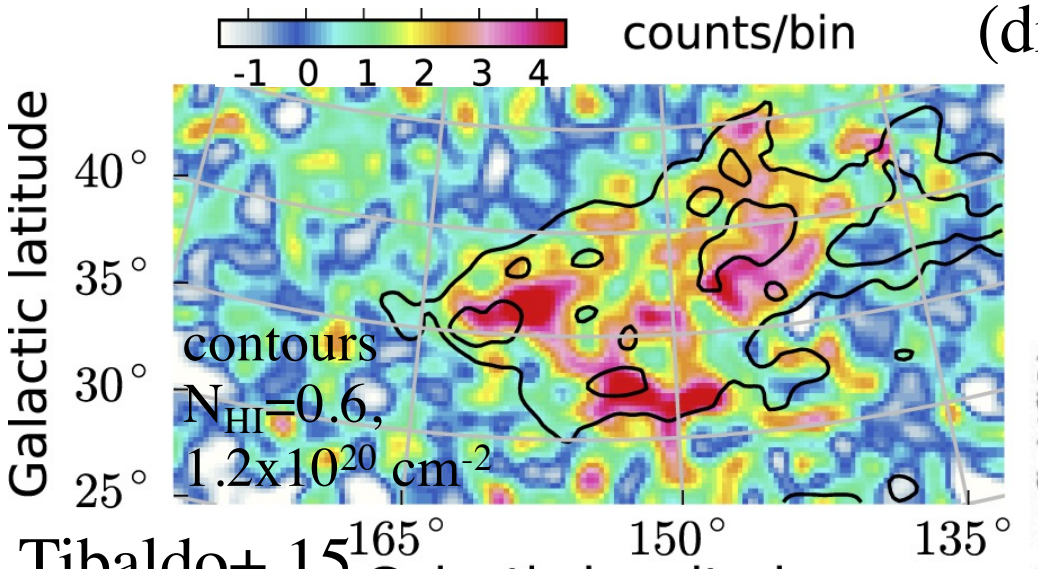
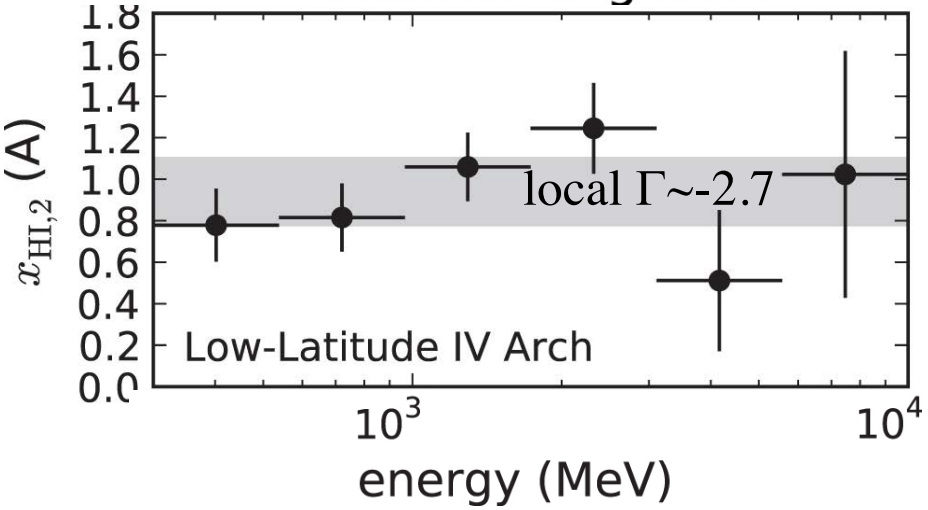
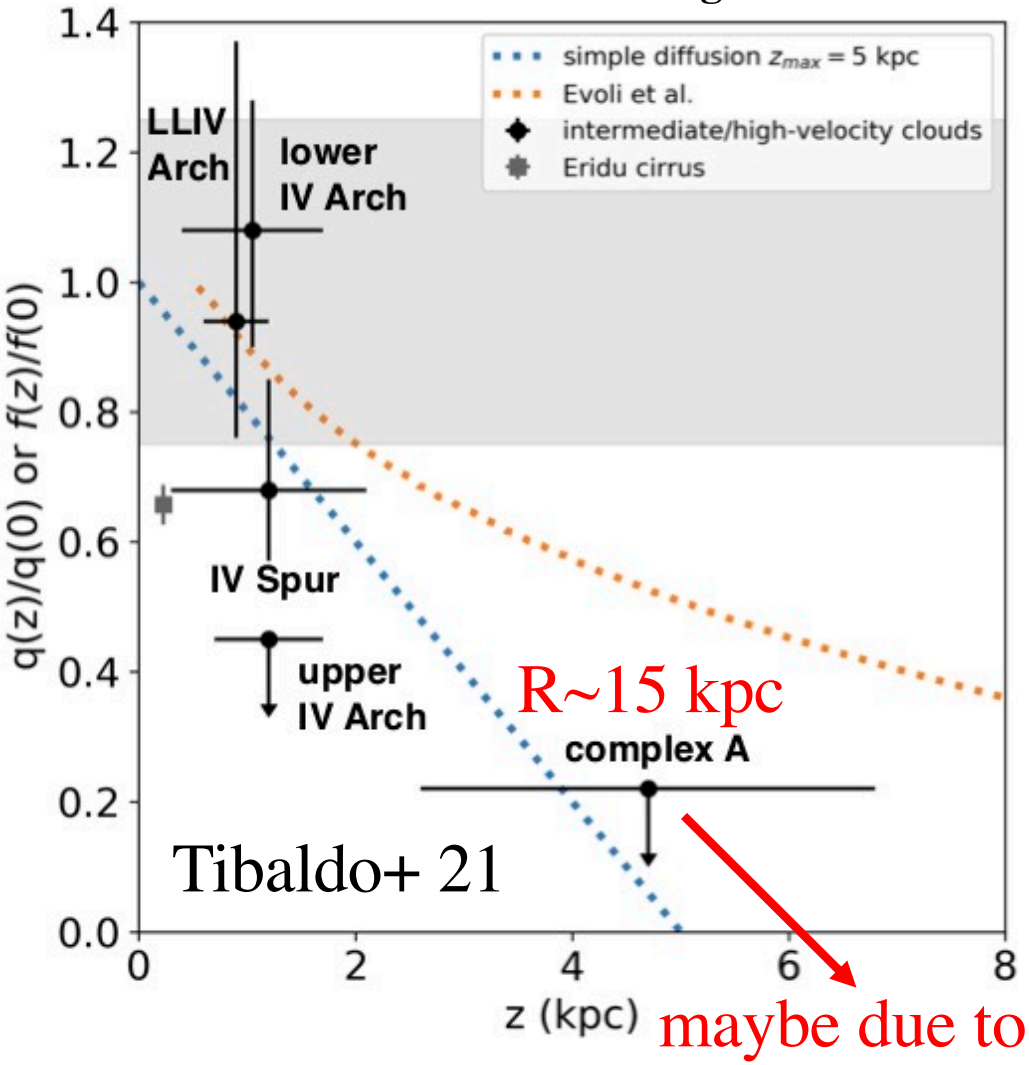


Tibaldo+ 15





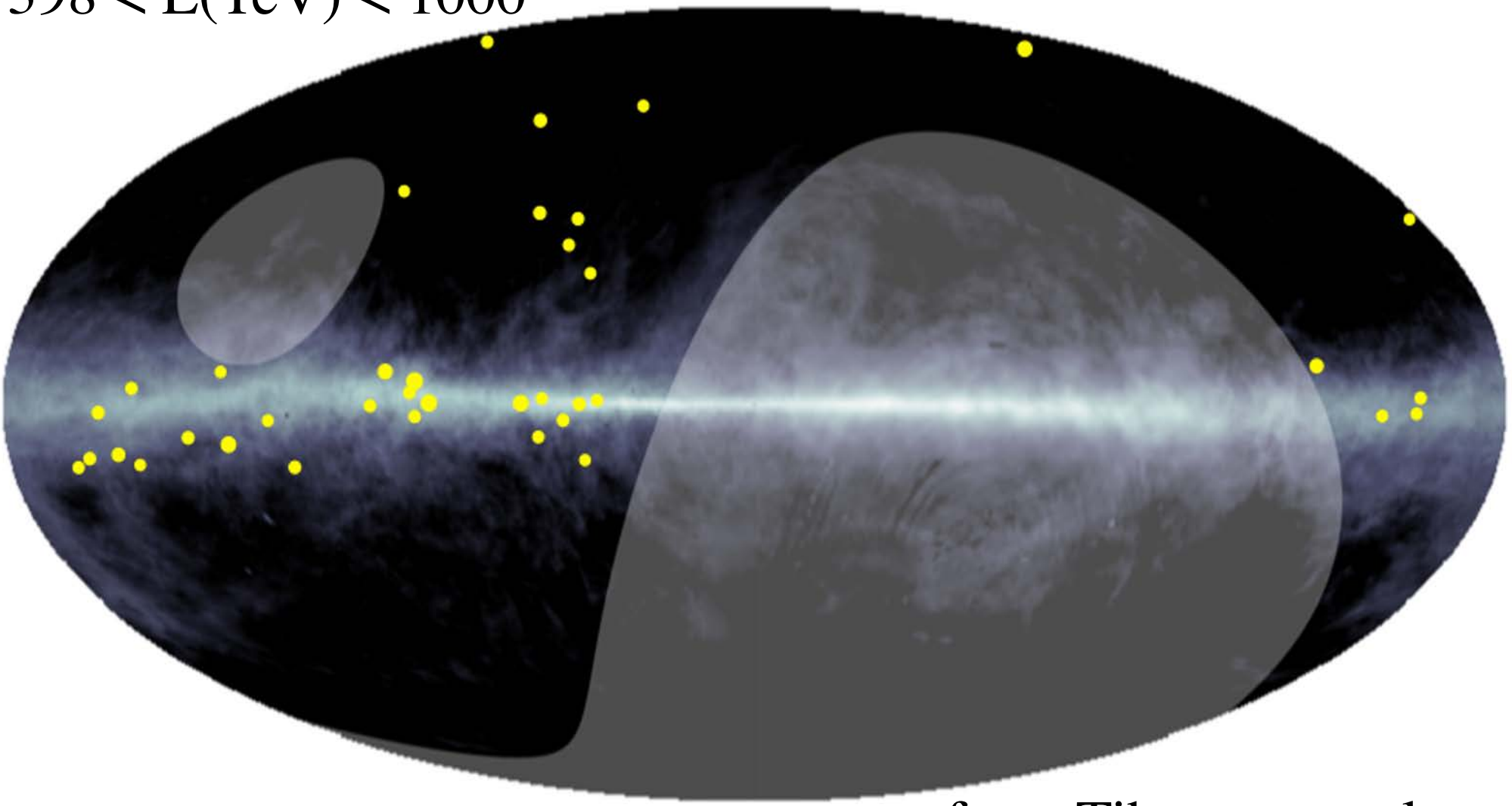
Tibaldo+ 21

maybe due to large R, not z

- significant detection of 3 IVCs at z~1-2 kpc
- spectra consistent with local CR (but with large errors)
- upper limits for a HVC at z~5 kpc -> decrease of ρ_{CR} vs z?
  NB Complex A at R~15 kpc

Tibet ASγ events sky map

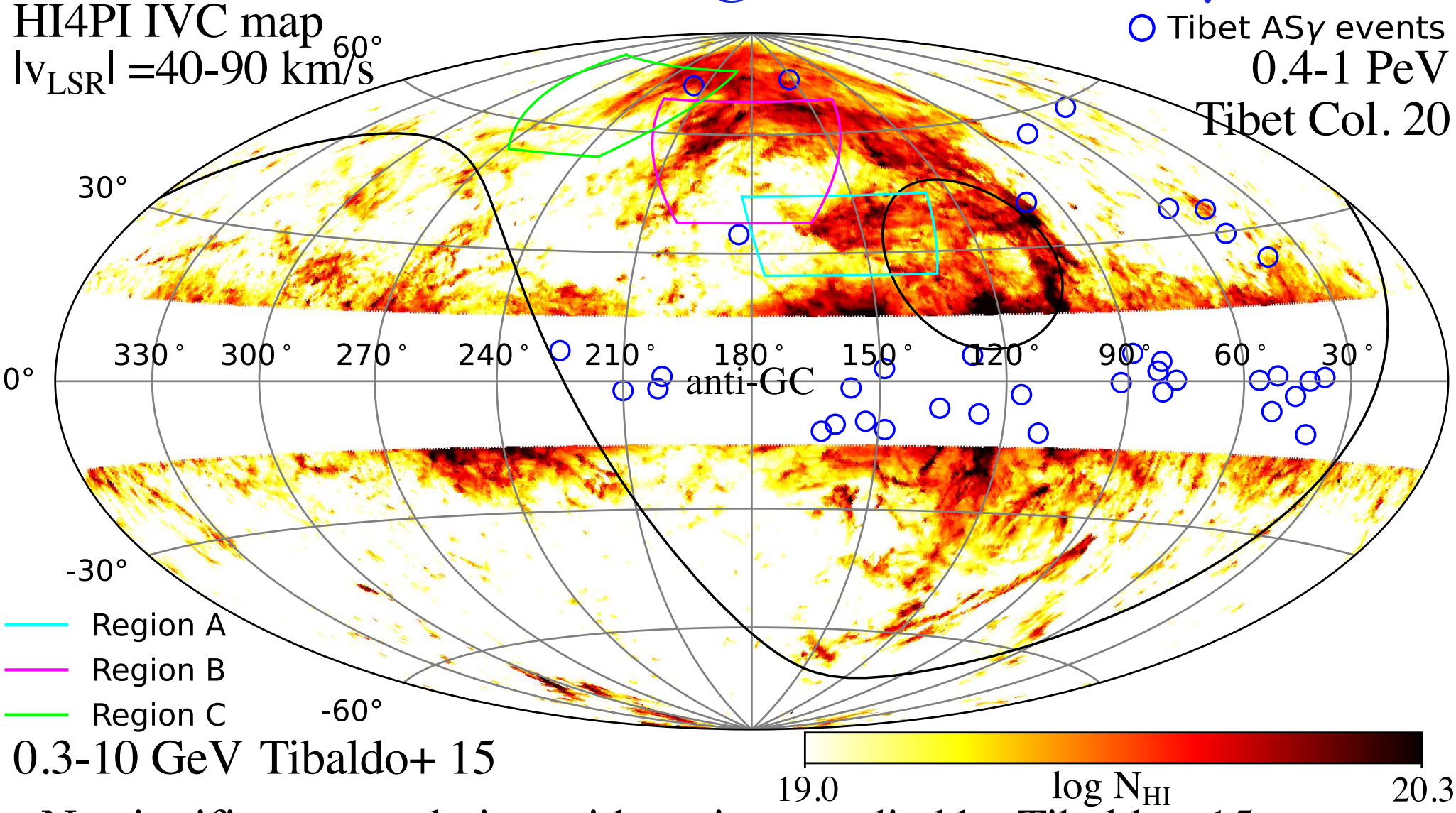
398 < E(TeV) < 1000



from Tibet press release

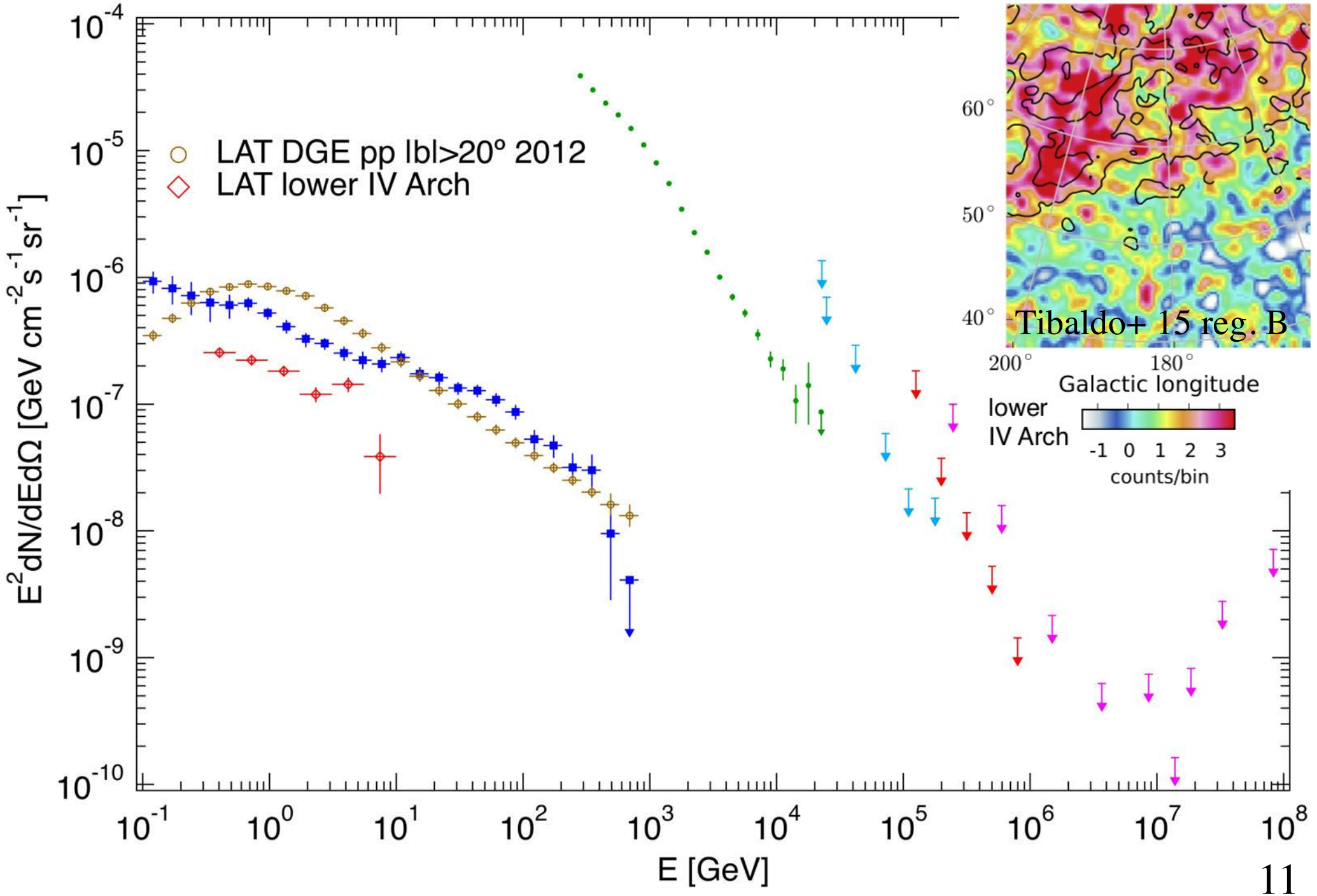
Tibet high b events: consistent w. CR background, but also with real γ rays

IVCs vs GeV-detected regions vs Tibet ASγ events



- No significant correlation with regions studied by Tibaldo+ 15
  -> upper limits on PeV CRs in some IVCs (z~1-2 kpc)
- Some events nearby - potential signal?

IVCs: probing GeV-PeV CRs at disk-halo interface



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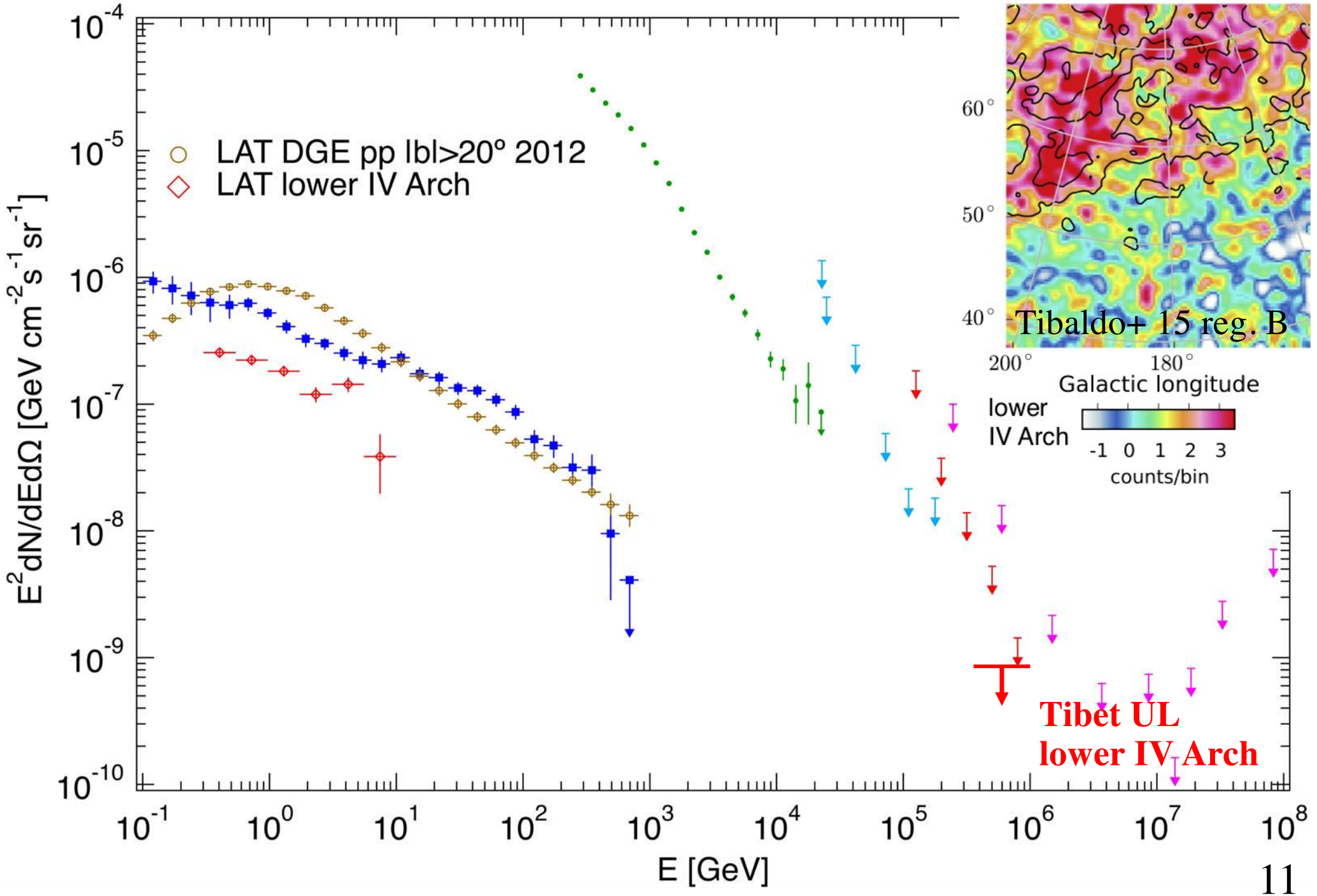

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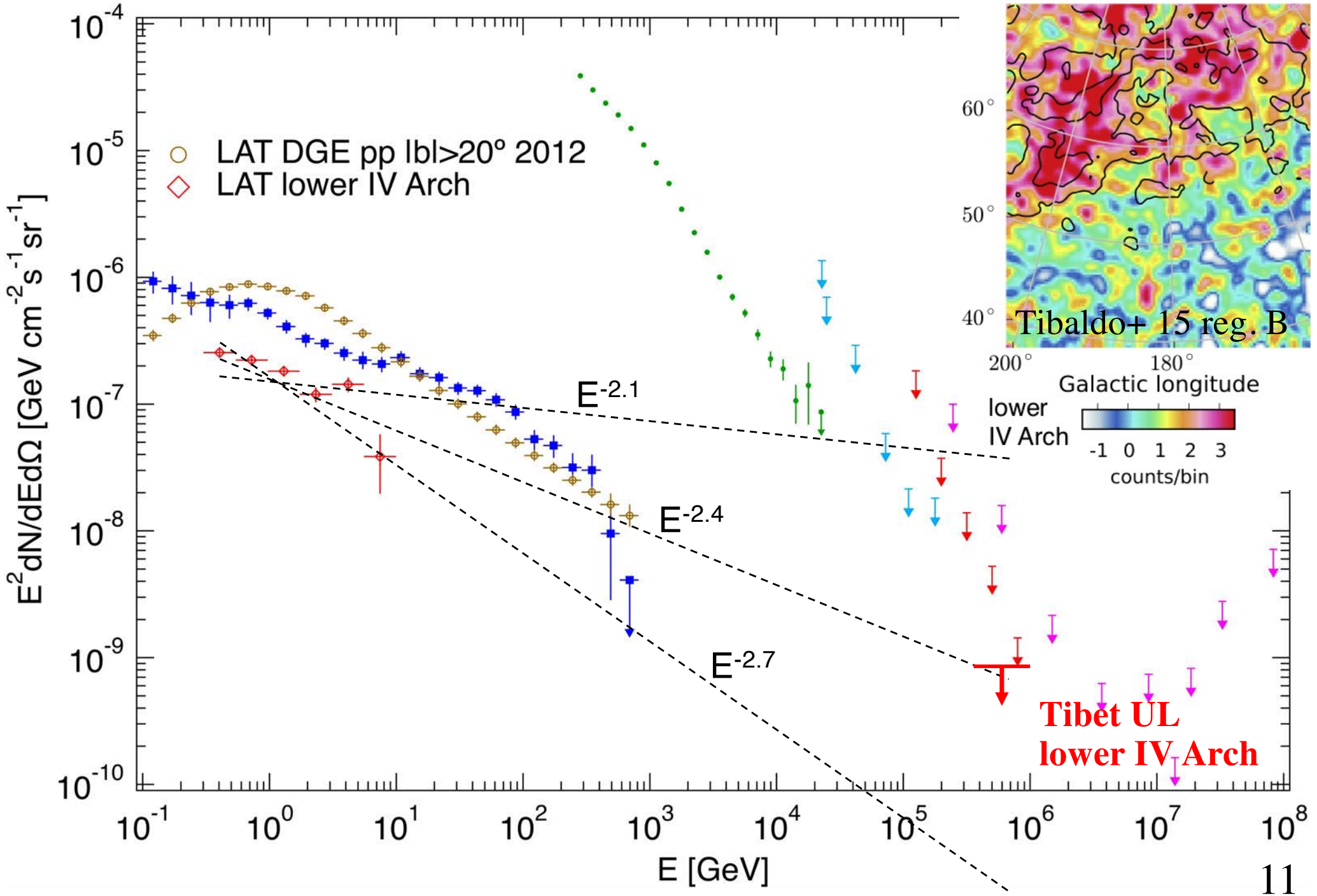

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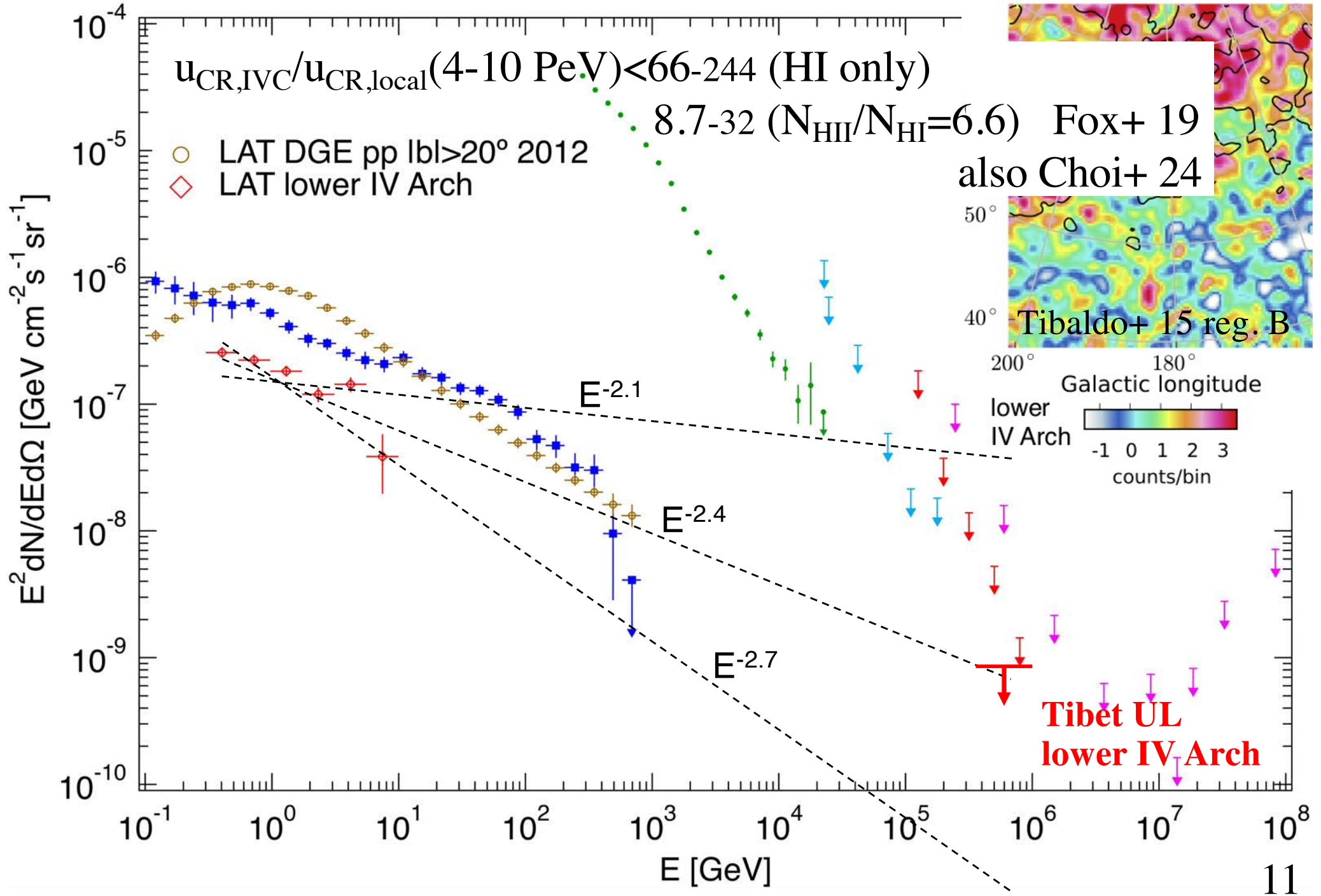

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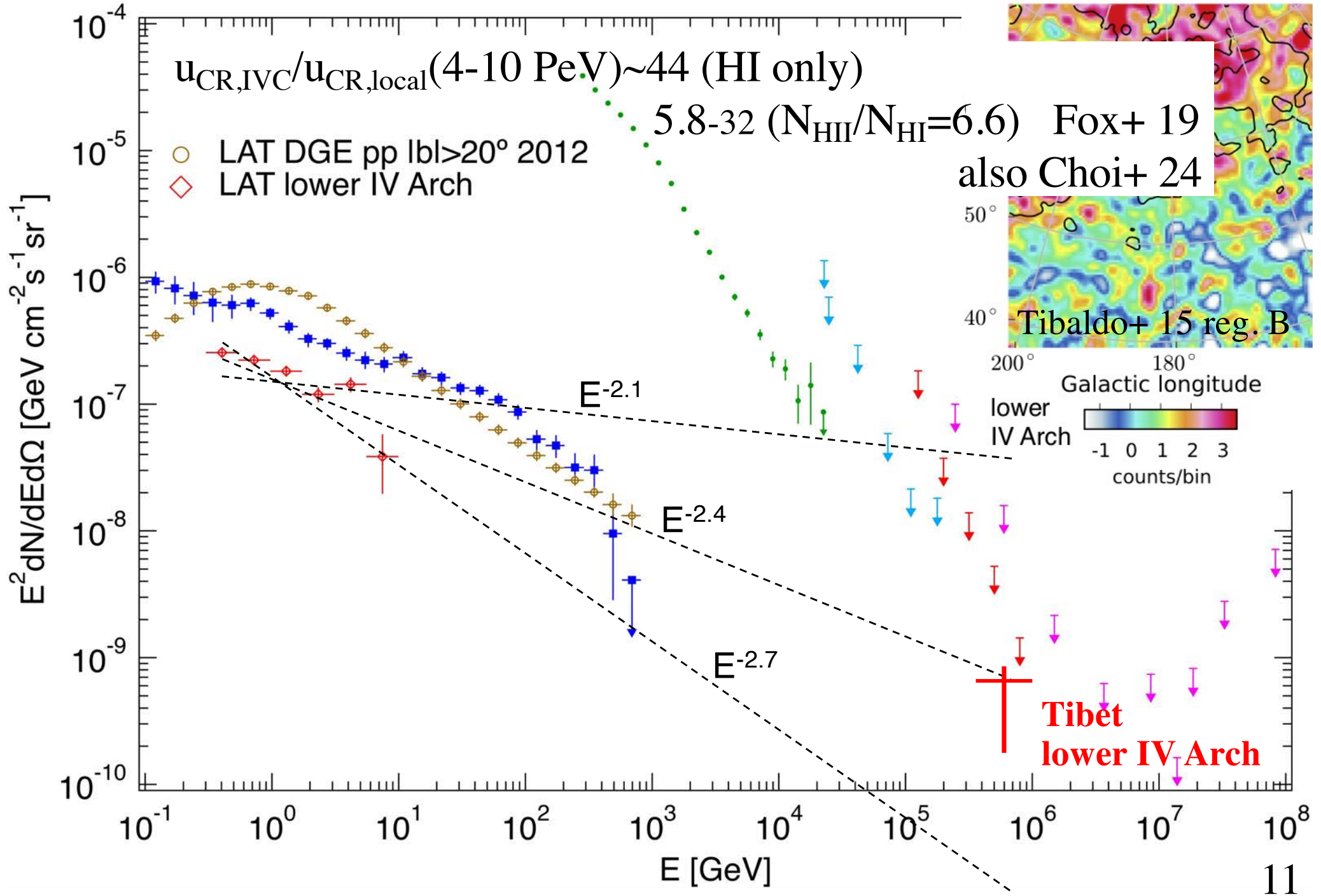
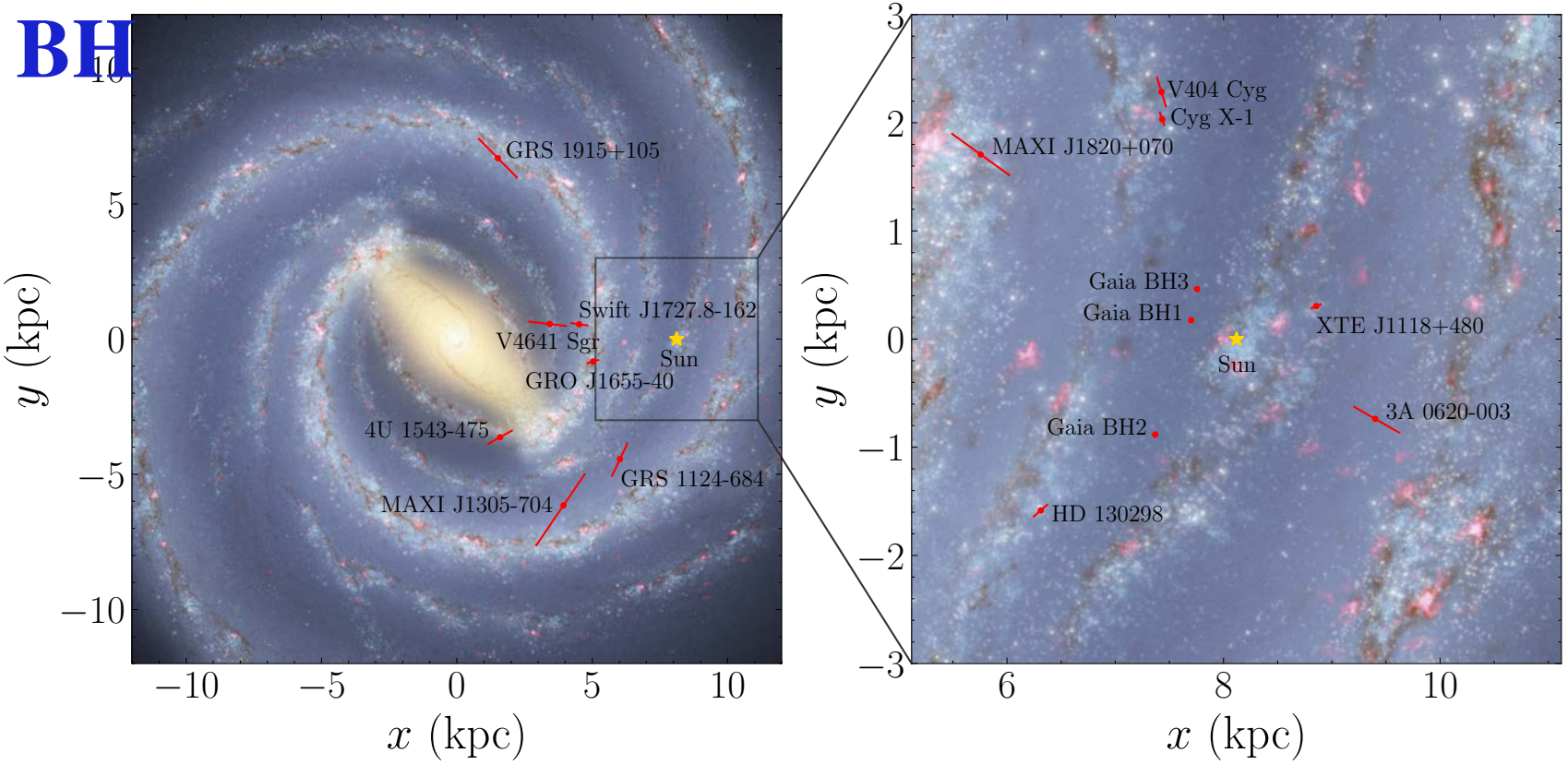
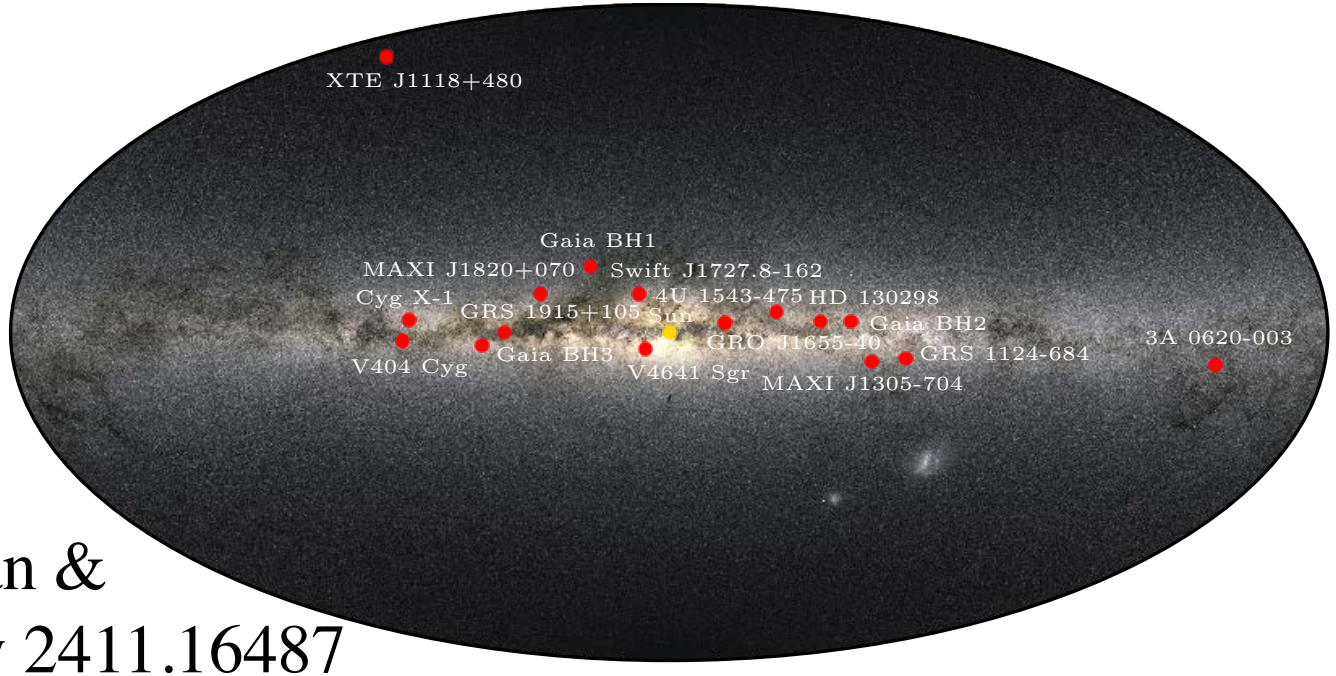


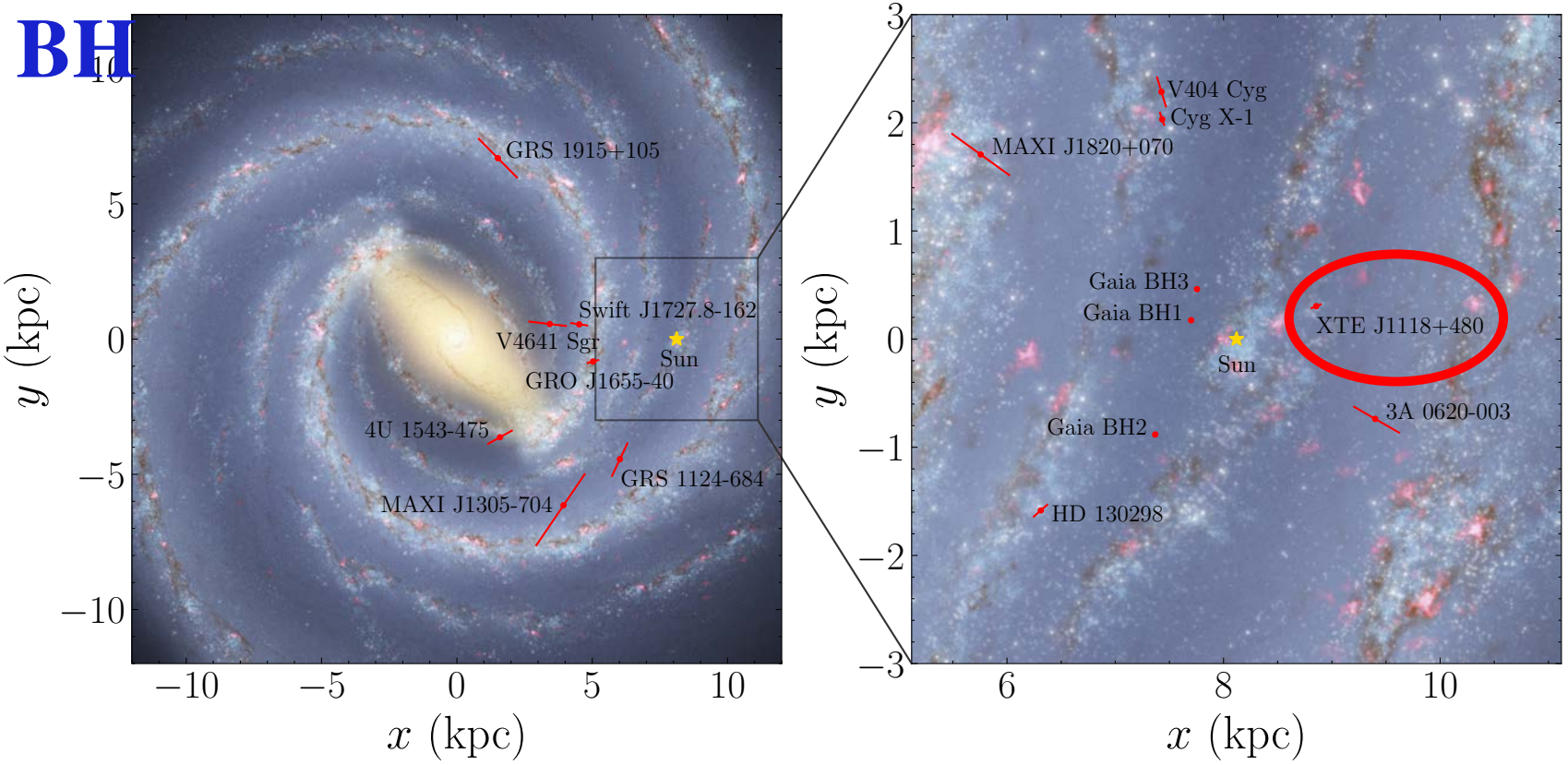
Galactic BH sky map





Nagarajan & El-Badry 2411.16487

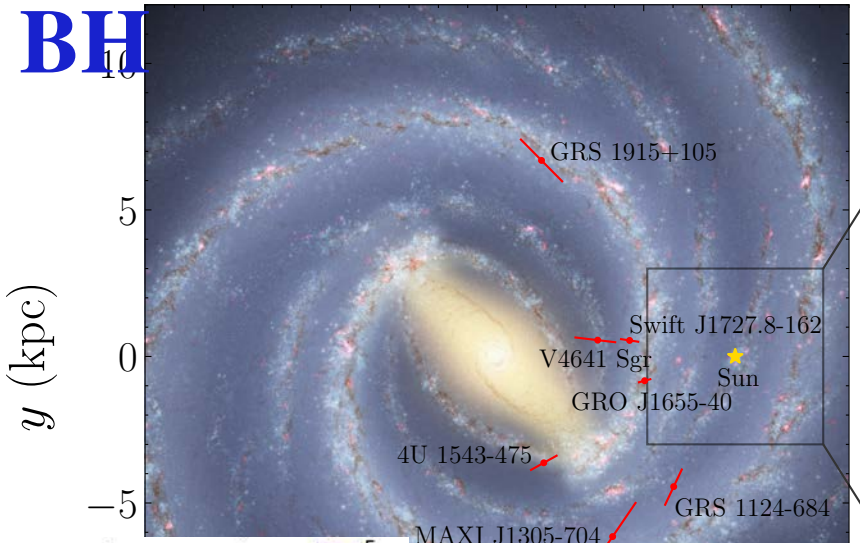
Galactic BH sky map

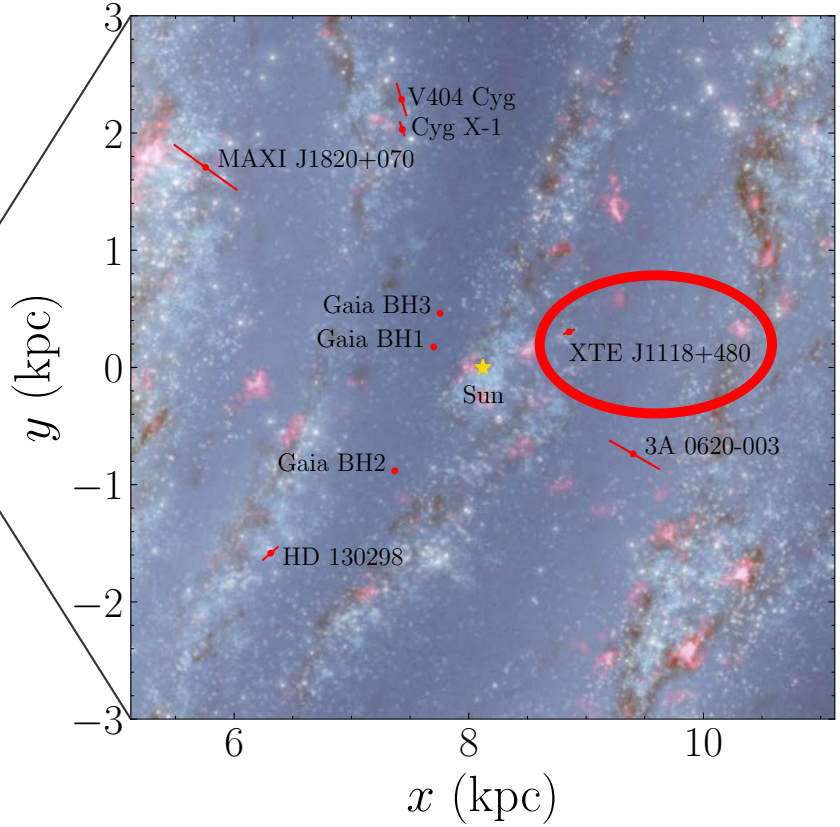


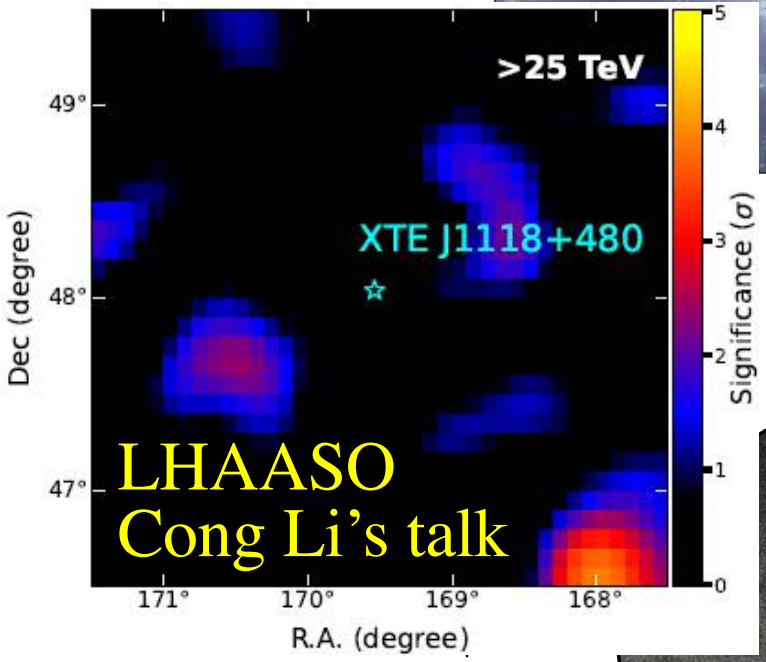
XTE J1118+480
l=158 b=62.3
D~1.7 kpc

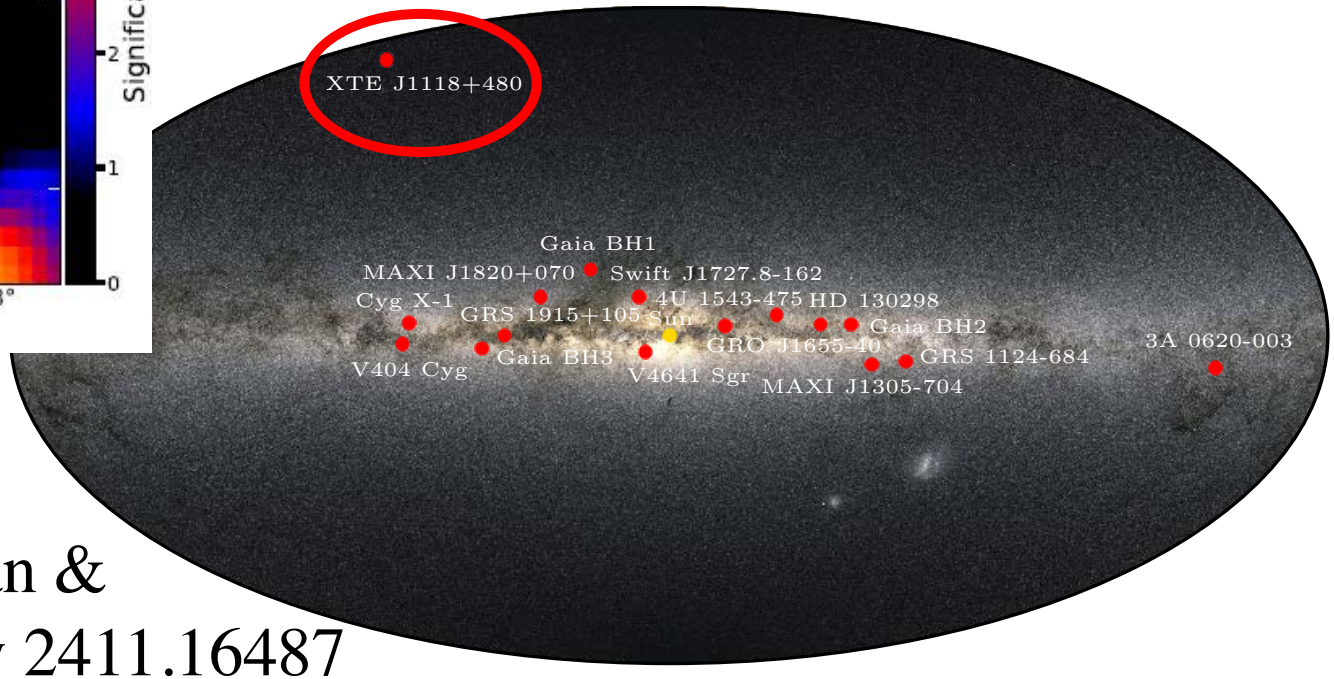
Nagarajan &
El-Badry 2411.16487

Galactic BH sky map









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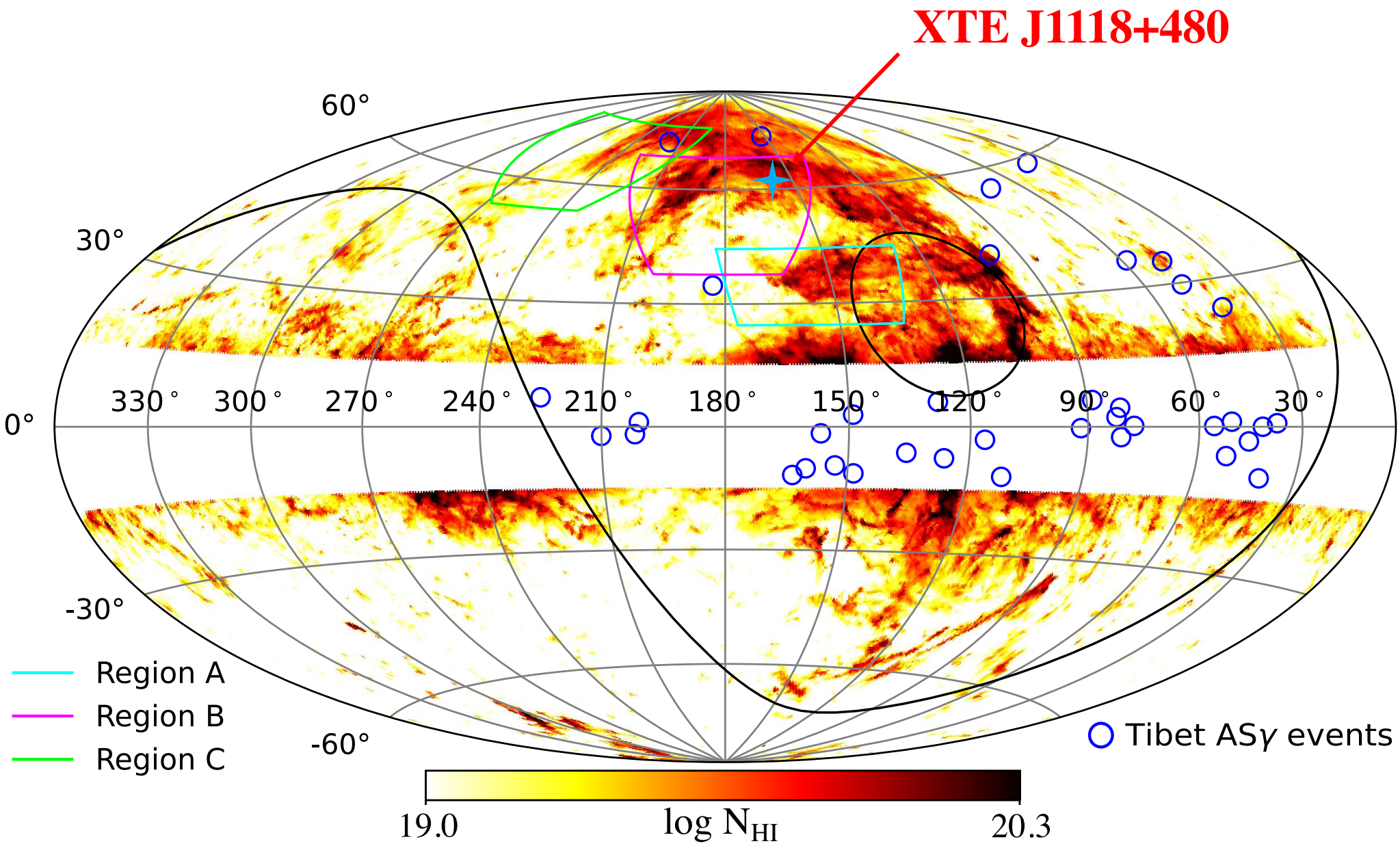
IVCs vs GeV-detected regions vs Tibet ASγ events



high-b microquasar XTE J1118+480: past pevatron activity?

Tibet events possibly associated with IVCs

$$R_{\rm Tibet} \sim \theta_{\rm Tibet} d_{1118} \sim 0.9\,{\rm kpc}$$

$$U_{4-10{\rm PeV}} \sim 2.3\times10^{-16} - 1.7\times10^{-15}\,{\rm erg\,cm^{-3}}$$

CR diffusively escaping from microquasar

$$D_{\rm disk}(E_p) \sim 10^{28}\,{\rm cm^2 s^{-1}} \left(\frac{E_p}{3\,{\rm GeV}}\right)^{1/3} \text{ assume}$$

$$R_{\rm dif} \sim (6 D_{\rm disk}(E_p) T)^{1/2} \sim 0.8\,{\rm kpc} \left(\frac{E_p}{6\,{\rm PeV}}\right)^{1/6} \left(\frac{T}{3\times10^4\,{\rm yr}}\right)^{1/2}$$

$$U_{\rm p} \sim \frac{3 L_p T}{4\pi R_{\rm dif}^3} \sim 1.2\times10^{-15}\,{\rm erg\,cm^{-3}} \left(\frac{L_p}{10^{38}\,{\rm erg\,s^{-1}}}\right) \left(\frac{T}{3\times10^4\,{\rm yr}}\right)^{-1/2}$$

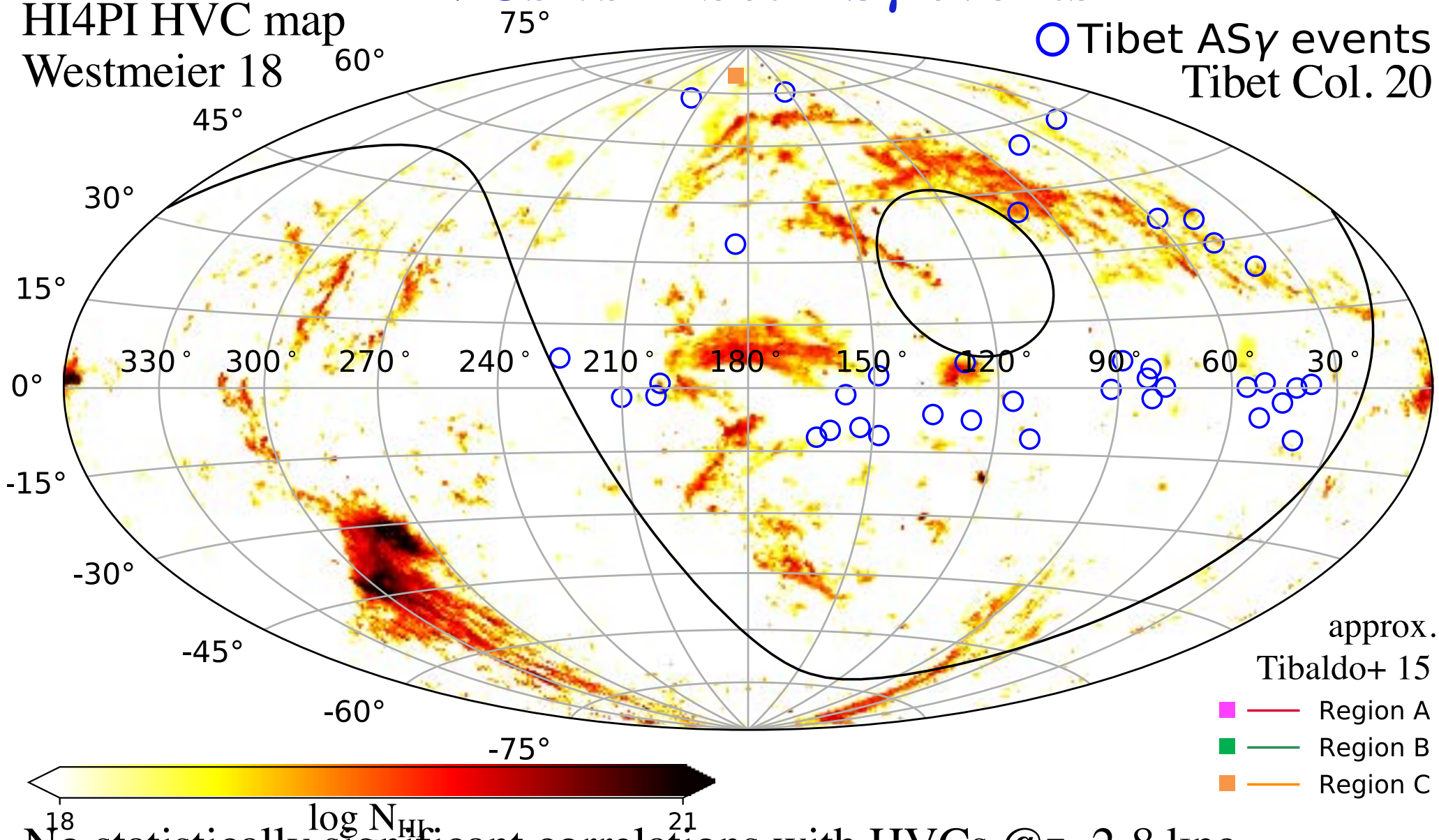
potential contribution to directly observed CRs?

$$R_{\rm dif} \sim (6 D_{\rm disk}(E_p) T)^{1/2} \sim 1.7\,{\rm kpc} \left(\frac{E_p}{6\,{\rm PeV}}\right)^{1/6} \left(\frac{T}{1.1\times10^5\,{\rm yr}}\right)^{1/2}$$

potentially other high-b microquasars

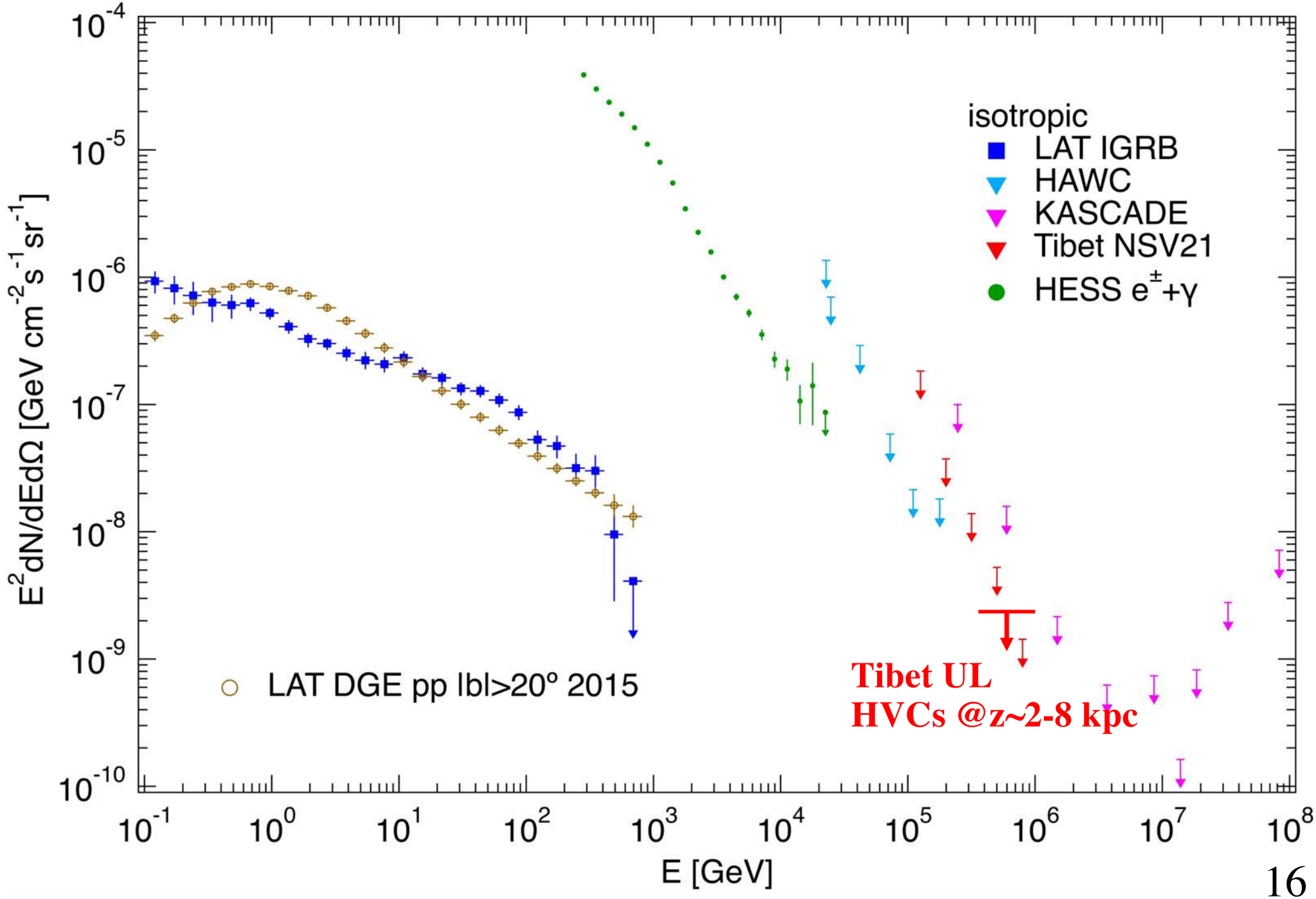
-> LHAASO!

HVCs vs Tibet ASγ events

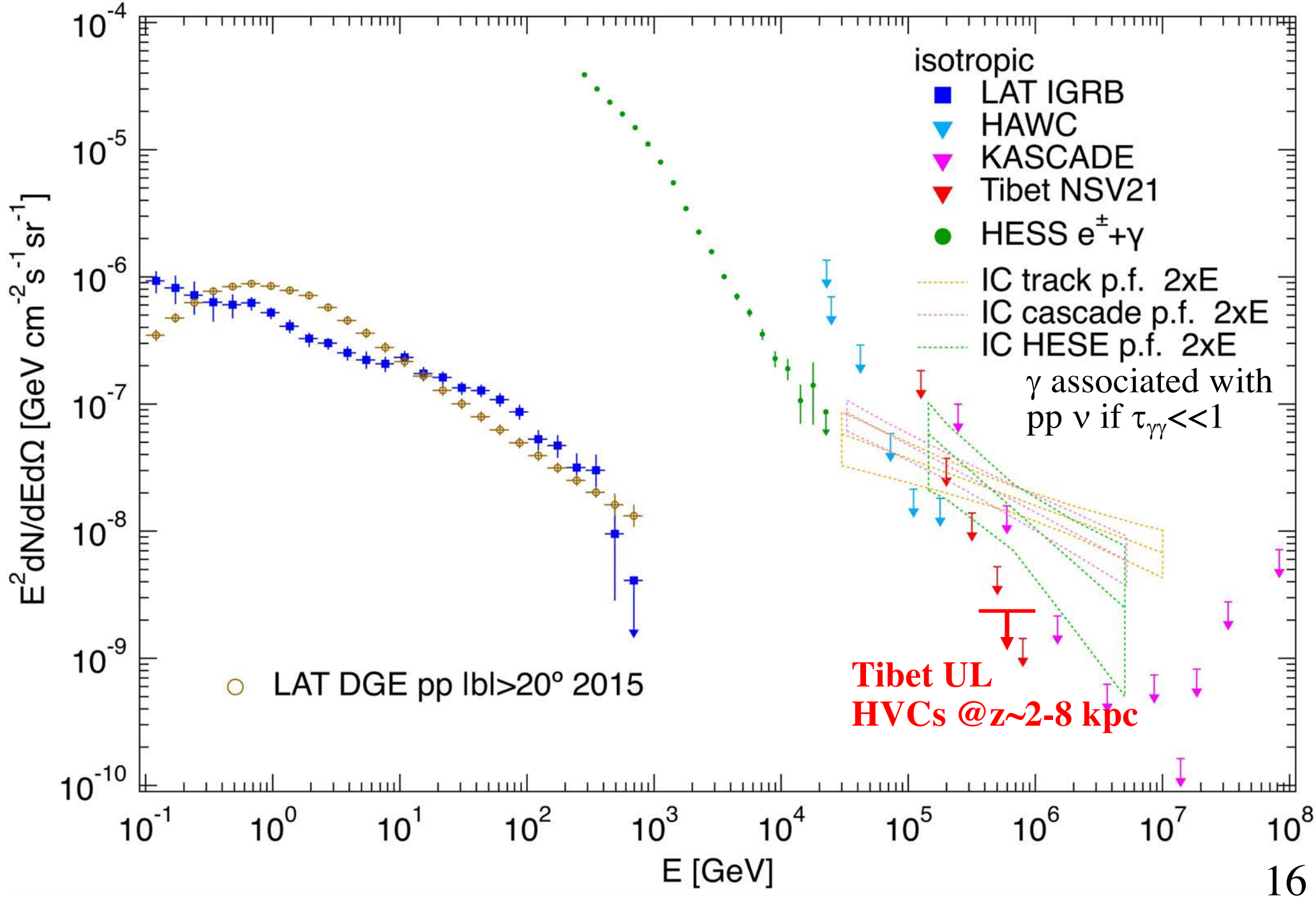


No statistically significant correlations with HVCs @z~2-8 kpc
-> $u_{CR,HVC}/u_{CR,local}$(4-10 PeV)~<250 $(f_{tot/HI}/4)^{-1}$ -> constrains models for PeV CRs - GWTS: Jokipii+ 87, FB: Cheng+ 12, SB: Aerdker + 25…
diffuse neutrinos: Taylor+14, Neronov+ 18, Recchia+ 21…

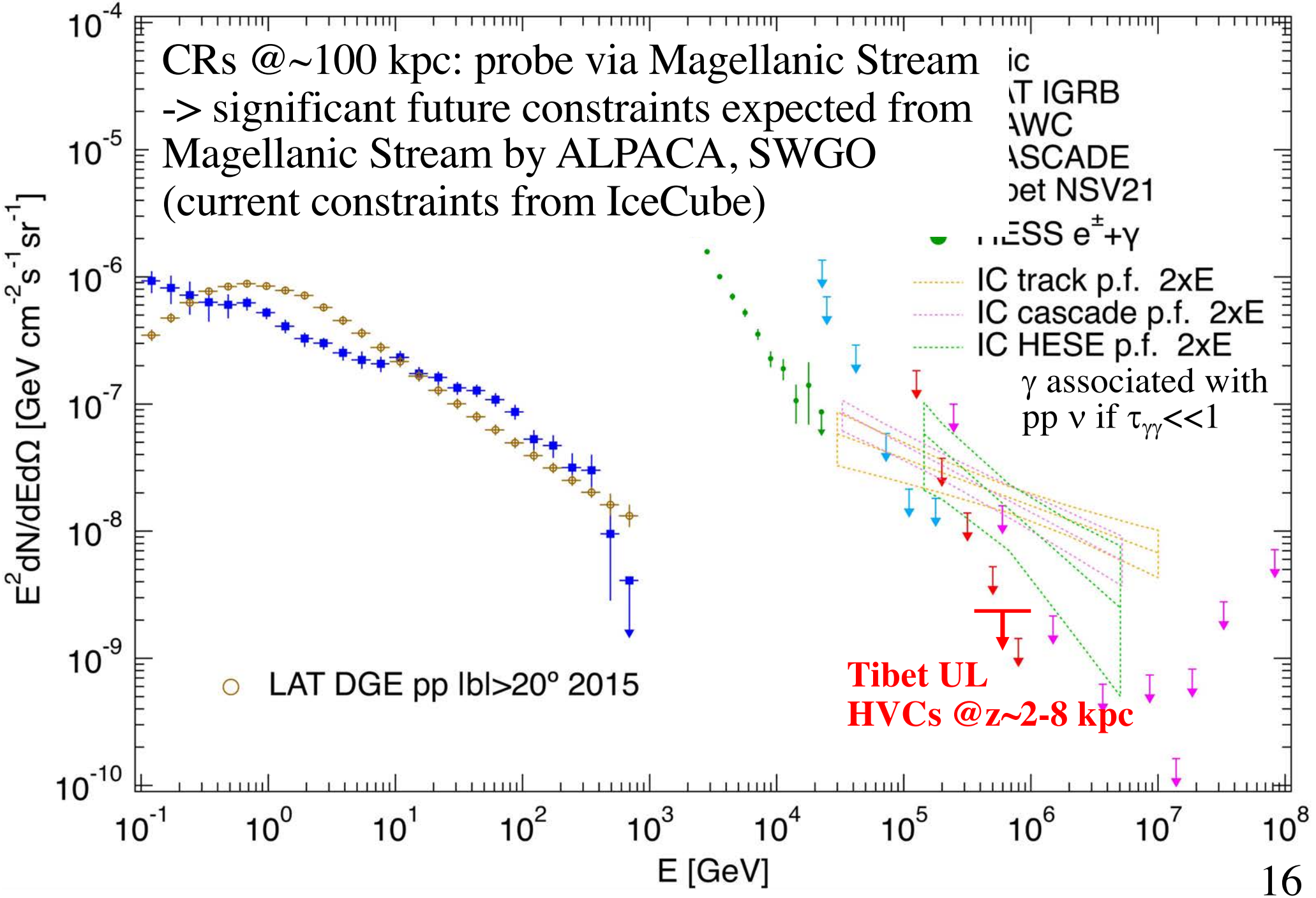
neutrinos: probing CRs in the outer halo



neutrinos: probing CRs in the outer halo



neutrinos: probing CRs in the outer halo



summary: Probing MW CGCRs and their sources

- CRs in CGM expected but many unknowns.
  Observational probe needed. γ-rays, ν from CGM likely
  patchy, potentially correlated with cool gas.

- PeV γ-rays advantangeous over GeV-TeV because:
  Extragalactic γ shielded. E-dependent γγ horizon covers
  interesting CGM scales. CR elec. bkgd suppressed by cooling.

- Tibet high b events vs IVC/HVC correlation search:
  Not significant so far -> Constraints on CRs in inner halo,
  high b microquasars, kpc-scale models for PeV CRs.
  Discussion for LHAASO with Q. Yuan et al. under way.
  Potential new insight into CR propagation.

- For CRs in outer halo, neutrinos offer meaningful constraints.
  Future constraints via PeV γ from South (ALPACA, SWGO).

- Challenging for IACTs, but potentially crucial additional info.