Probing Circumgalactic Cosmic Rays around the Milky Way via GeV-PeV gamma rays and neutrinos

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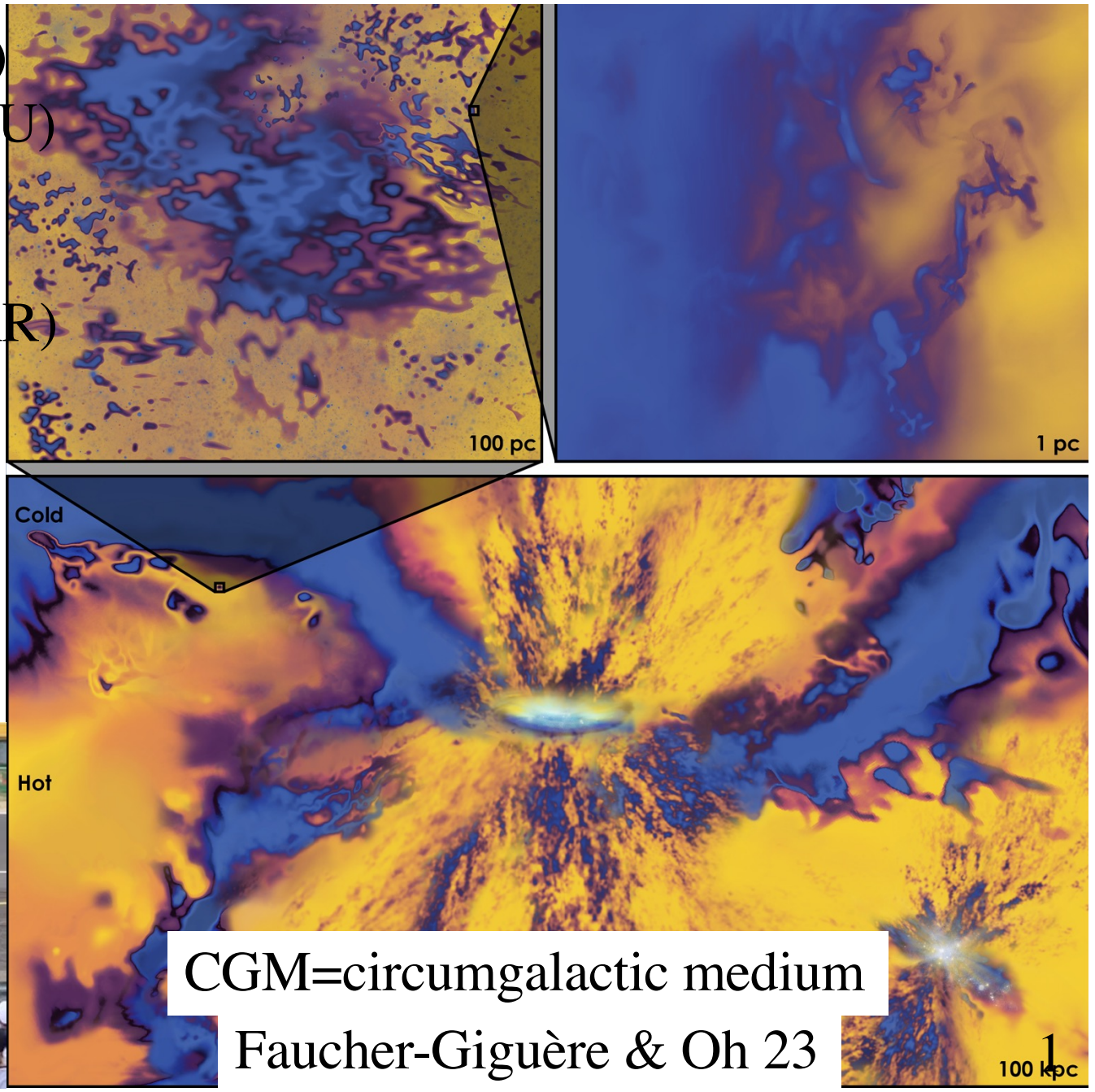
Kazumasa Kawata (ICRR)
Yutaka Ohira (U Tokyo)
Masahiro Nagashima
(Bunkyo U)

Papers in prep.



CGM=circumgalactic medium

Faucher-Giguère & Oh 23

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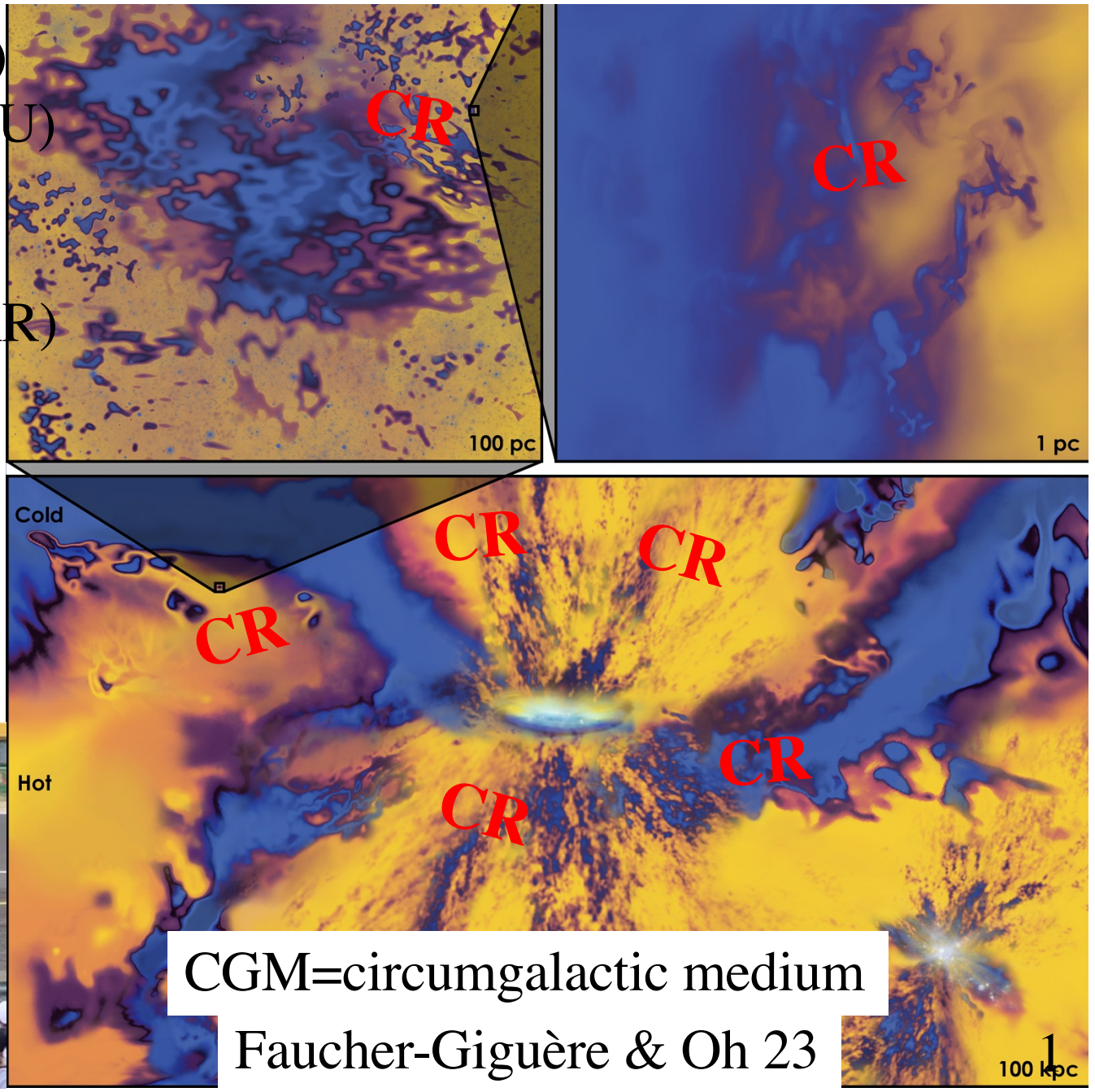

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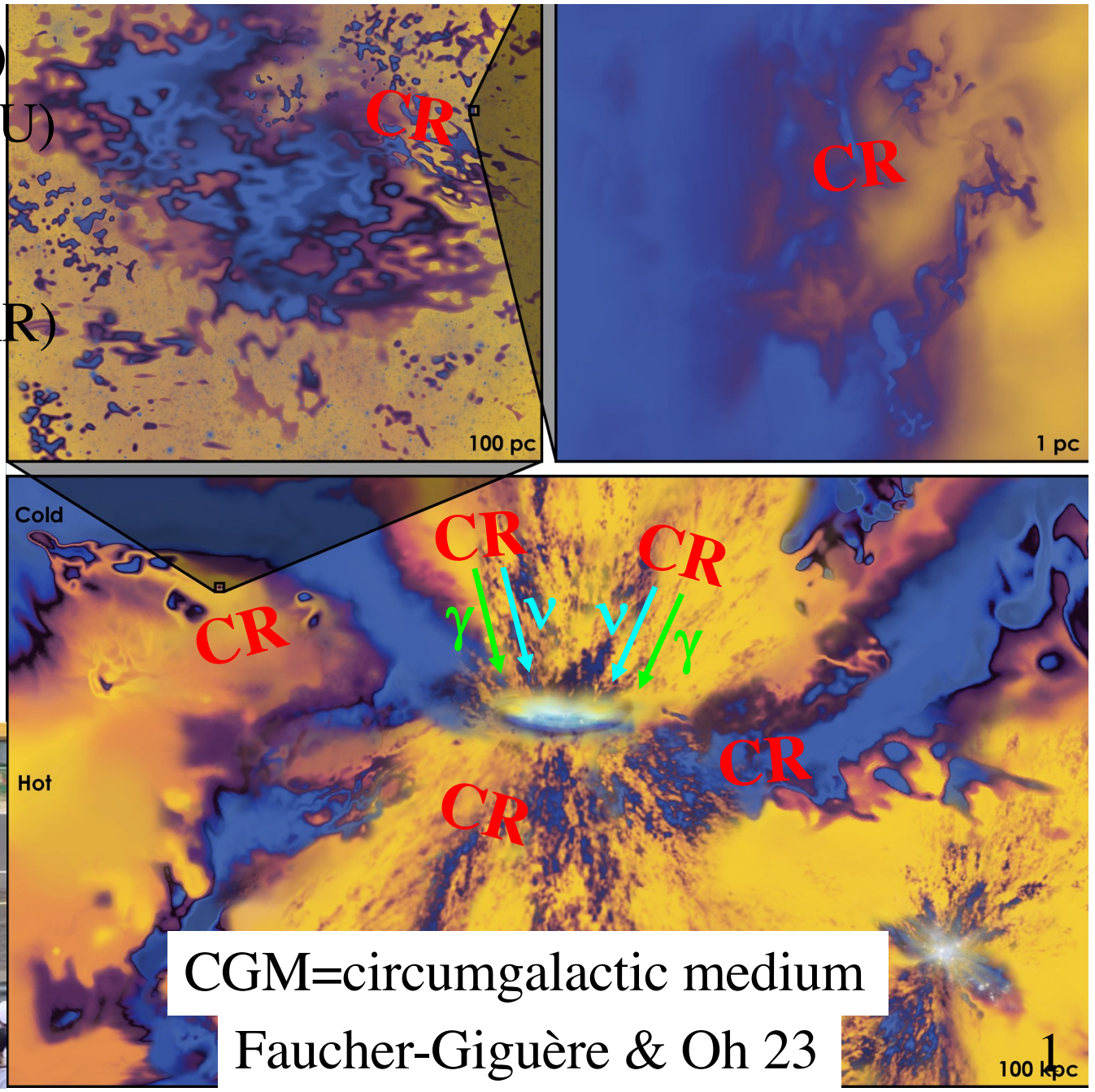

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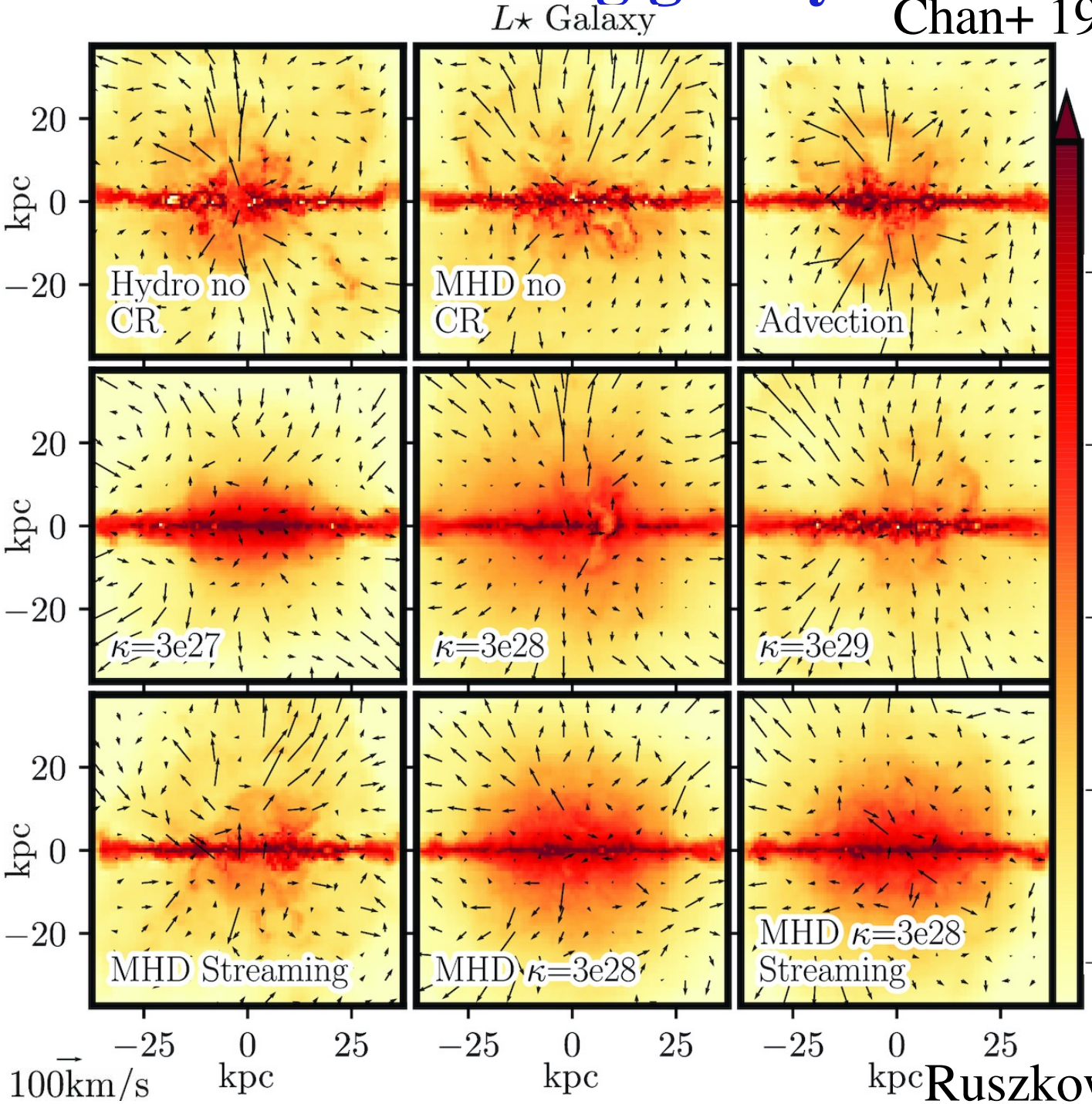
CR feedback during galaxy formation



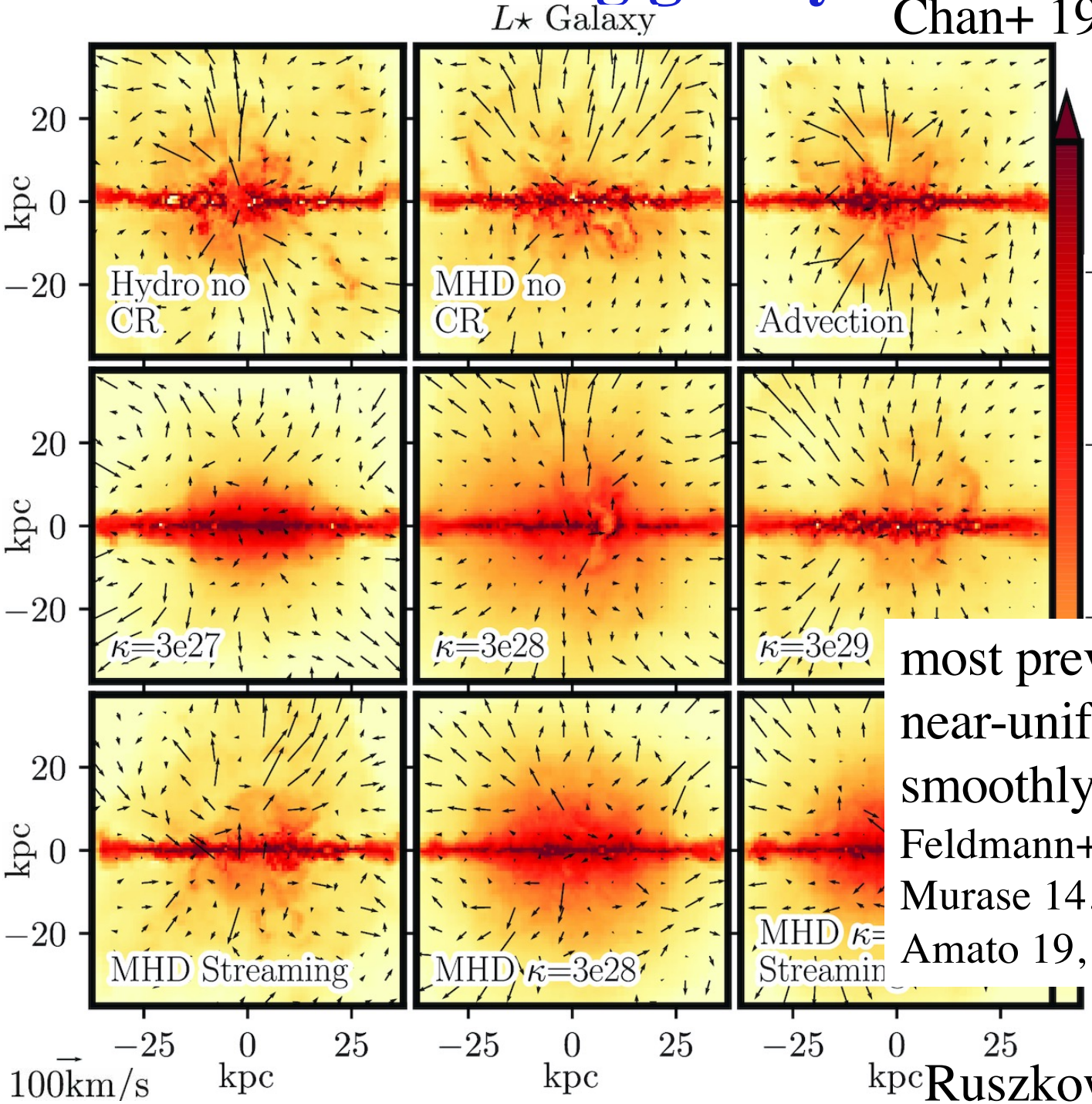
Chan+ 19

- 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



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- Depends strongly on assumed CR transport
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most previous studies assumed near-uniform emission from smoothly distributed gas

Feldmann+ 13, Taylor+ 14, Ahlers & Murase 14, Kalashev+ 16,22, Blasi & Amato 19, Liu+ 19, Recchia+ 21…

…

Ruszkowski & Pfrommer 23

cool CGM in Milky Way only component with reliable distances

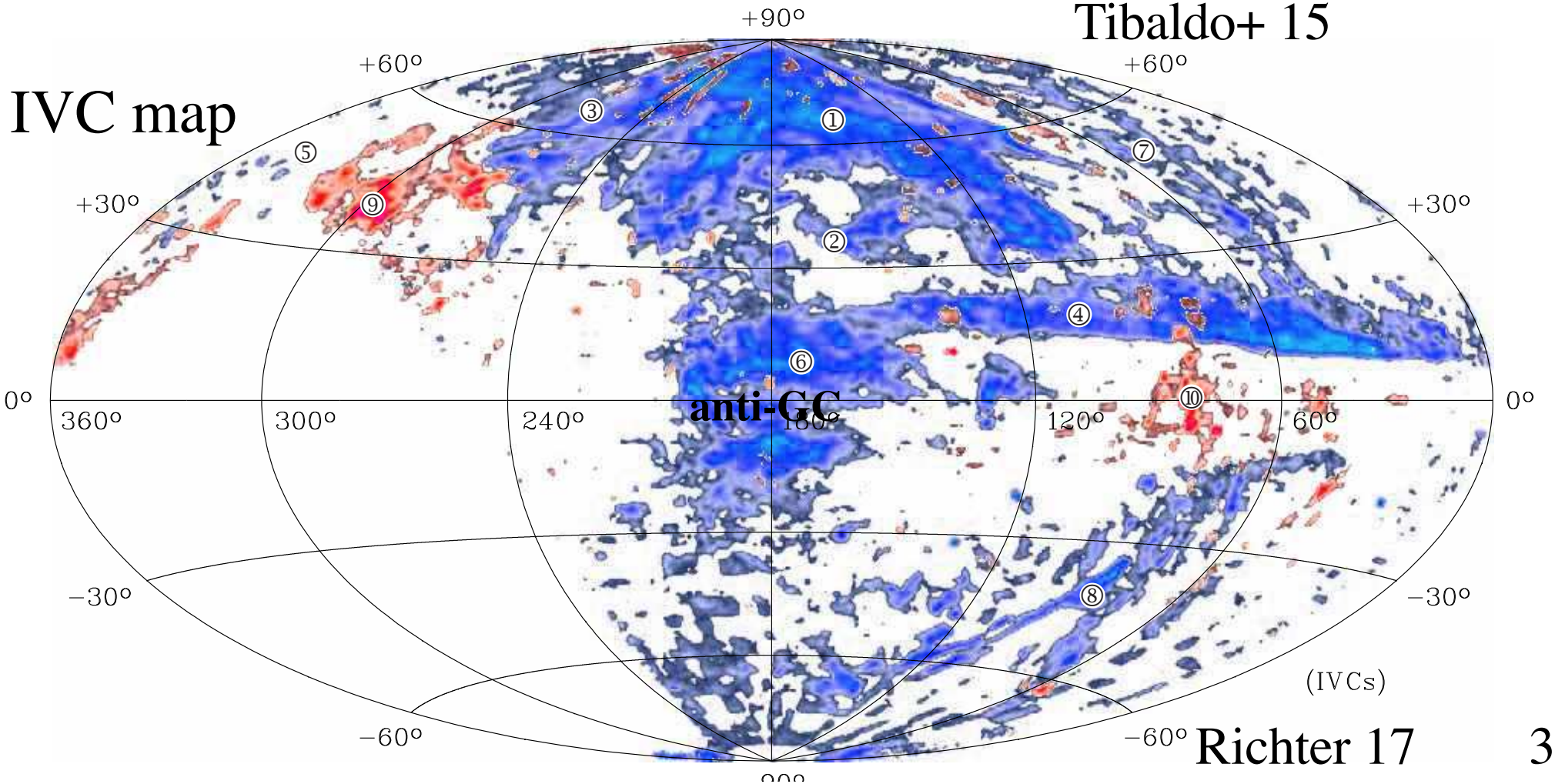
intermediate velocity clouds (IVCs): $|v_{dev}|$~40-90 km/s, D~1-2 kpc, Z~$Z_\odot$

some detected by LAT!

HI template fitting

Tibaldo+ 15

IVC map



Richter 17

cool CGM in Milky Way only component with reliable distances

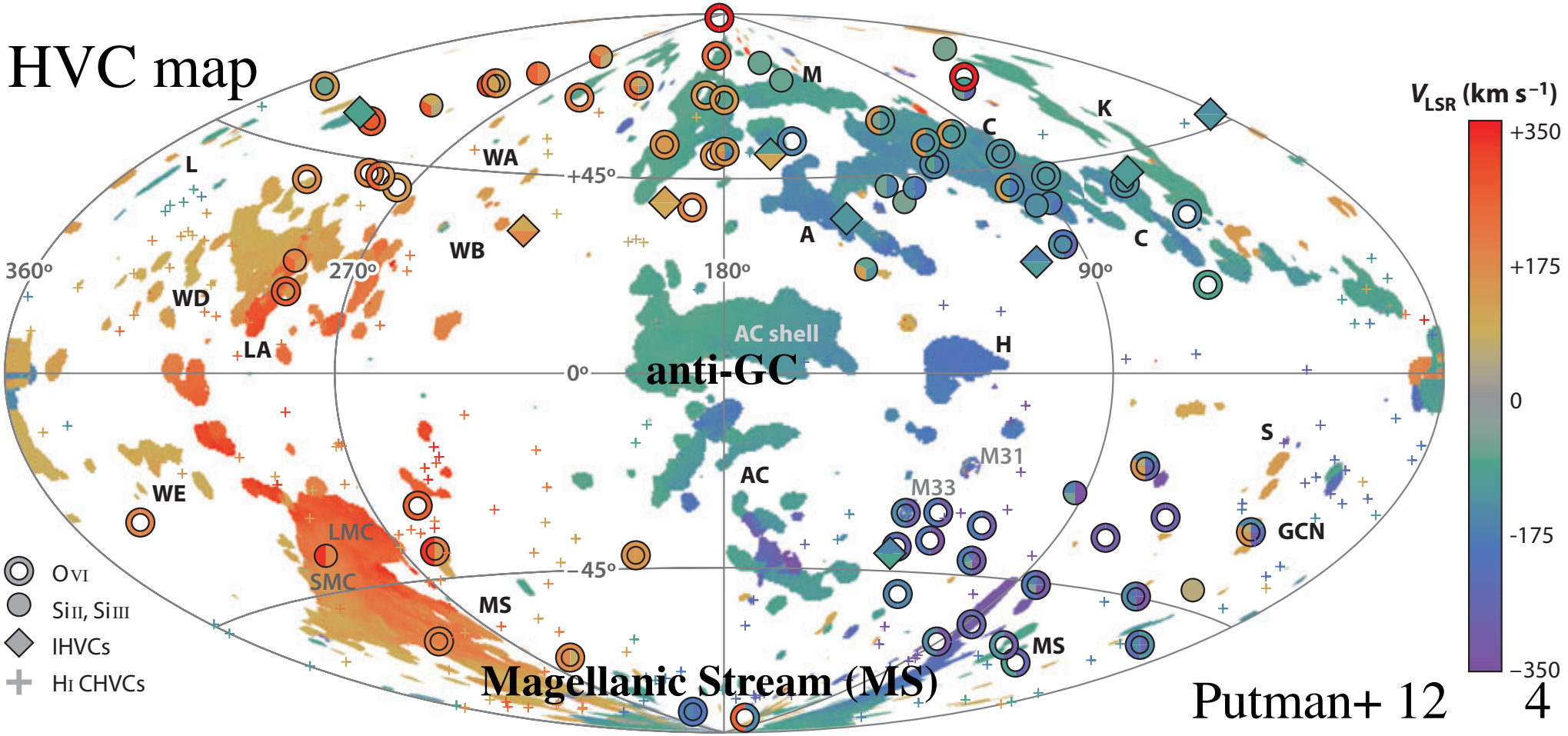
intermediate velocity clouds (IVCs): $|v_{dev}|$~40-90 km/s, D~1-2 kpc, Z~$Z_\odot$

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

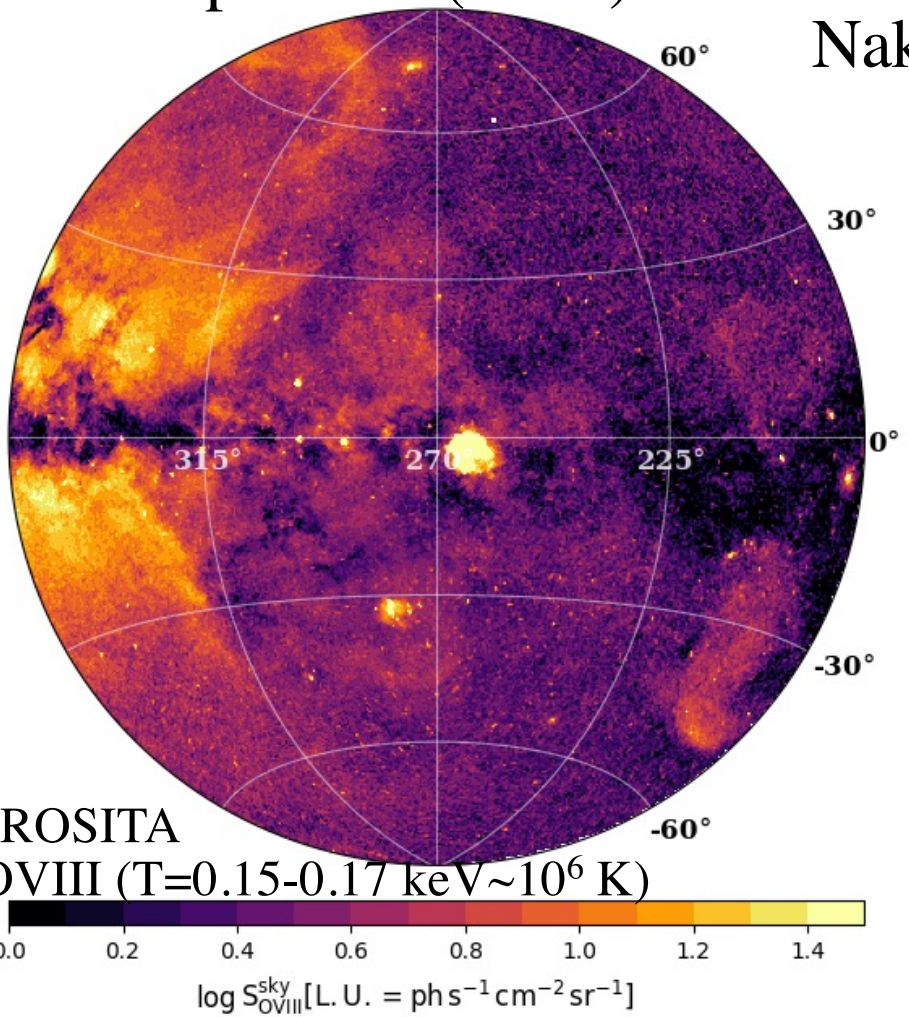


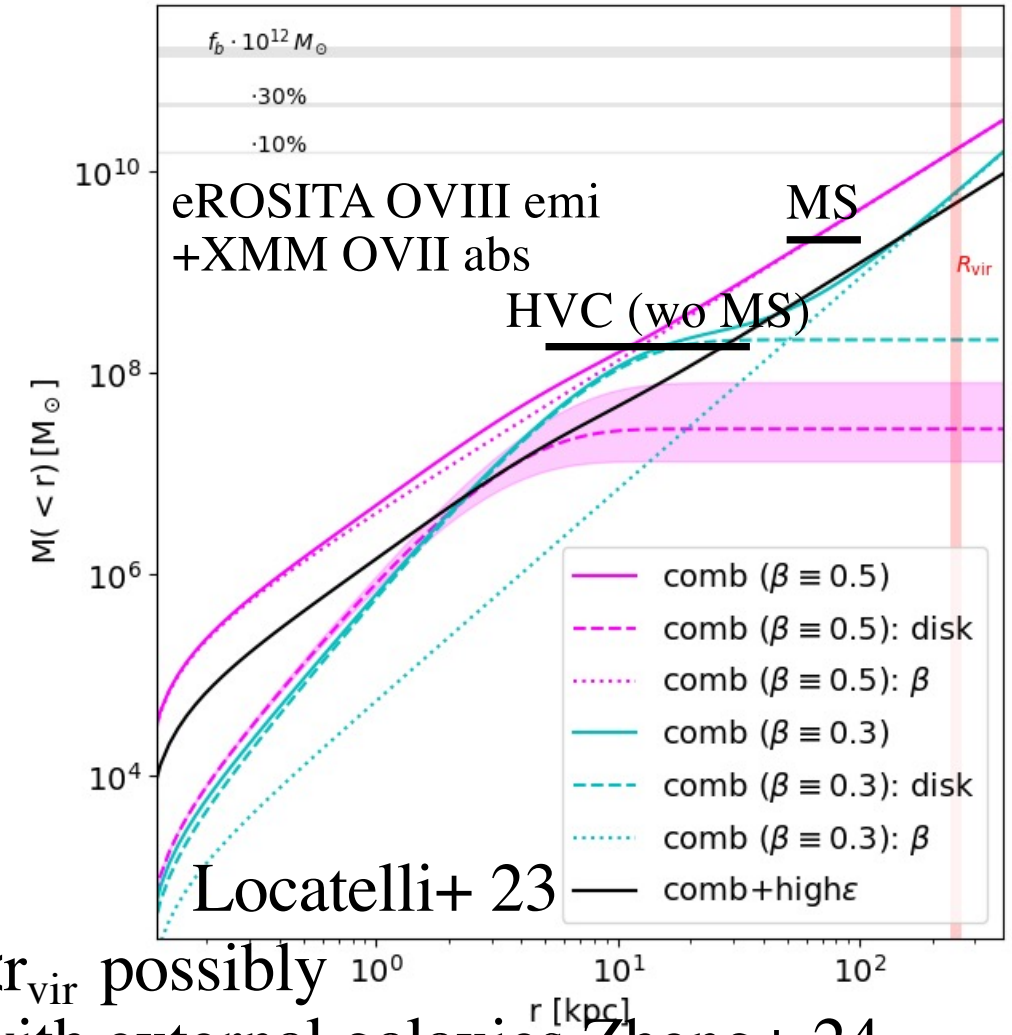
Putman+ 12

warm/hot CGM of Milky Way vs cool CGM

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

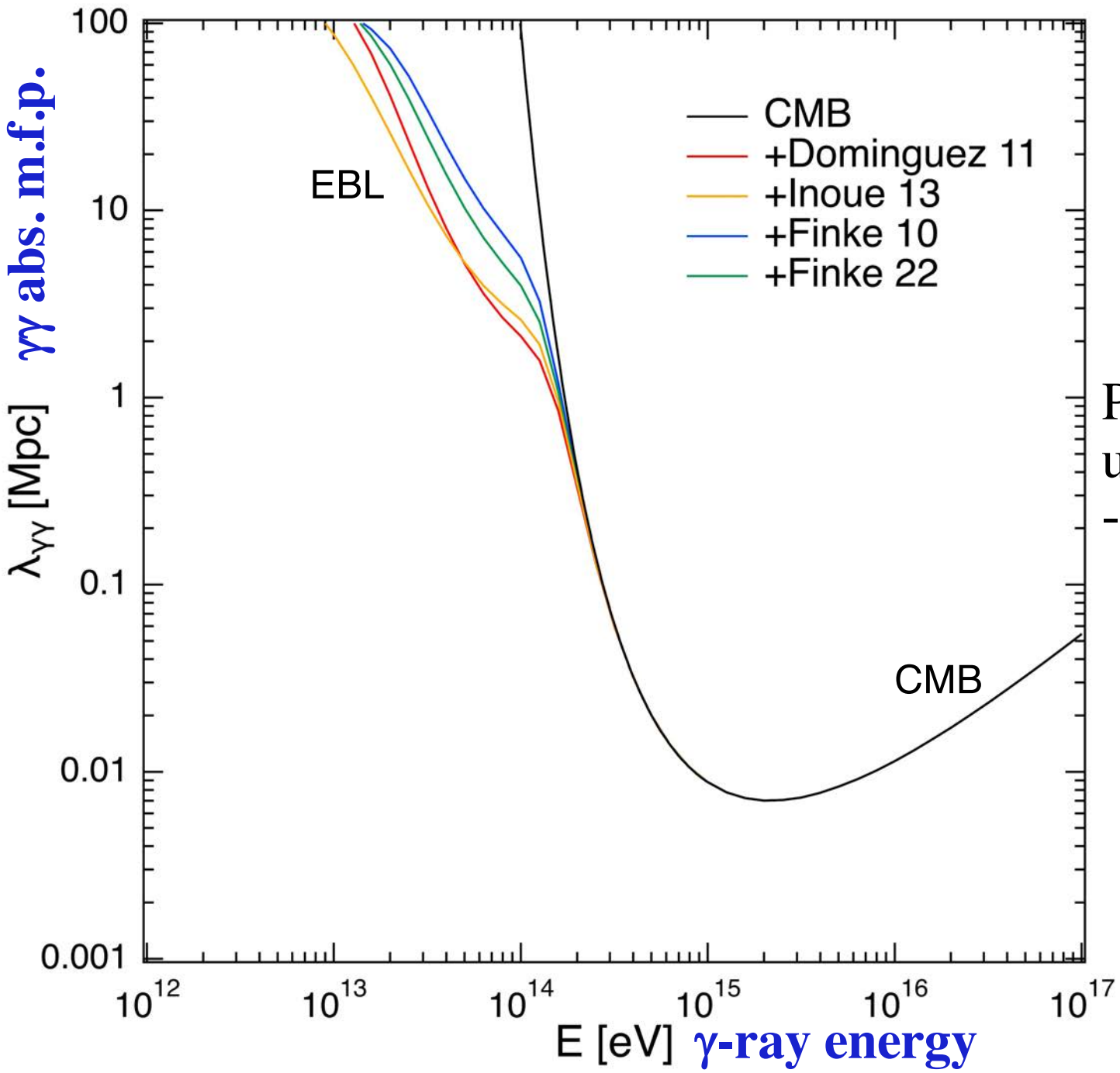
Nakashima+ 18, Kaaret+ 20, Locatelli+ 23





- eROSITA+XMM: hot CGM mass <r_{vir} possibly << $f_{bar,cosmic}$ 10^{12} $M_\odot$ -> consistent with external galaxies Zheng+ 24
  also FRB DM of MW Cook+ 23, Ravi+ 23; simulations Ayromlou+ 23…
- HVC HI+HII potentially significant mass fraction of entire CGM
  -> γ-ray + ν emission likely patchy, possibly correlated with cool gas

PeV γ rays: unique probe of Milky Way halo CRs



$\lambda_{\gamma\gamma}$~

400 kpc @0.2 PeV

70 kpc @0.3 PeV

30 kpc @0.4 PeV

10 kpc @0.8 PeV

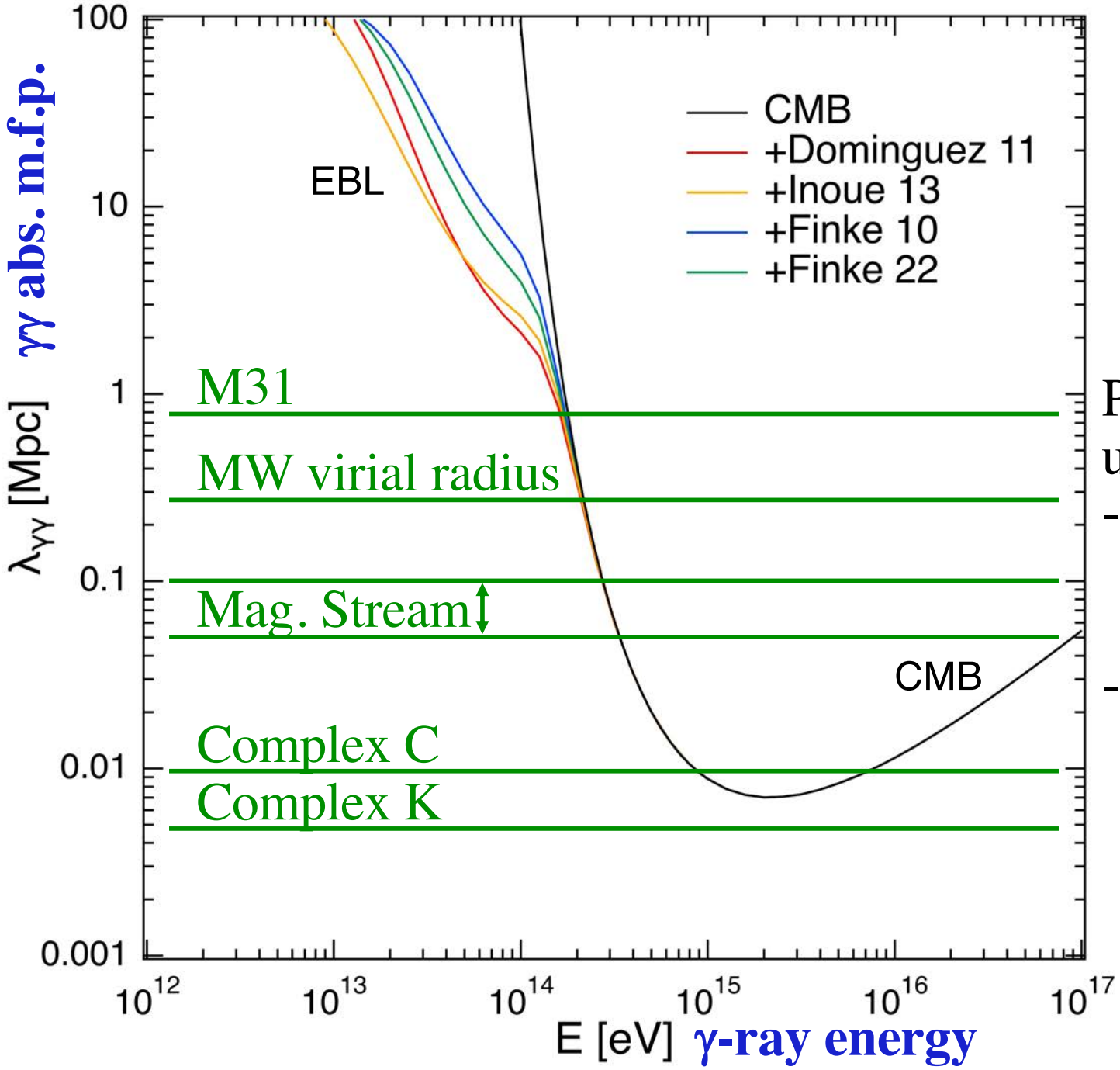
7 kpc @2-3 PeV

PeV=10^{15} eV

unlike GeV-TeV:

- extragalactic compt. filtered by γγ with EBL/CMB

PeV γ rays: unique probe of Milky Way halo CRs



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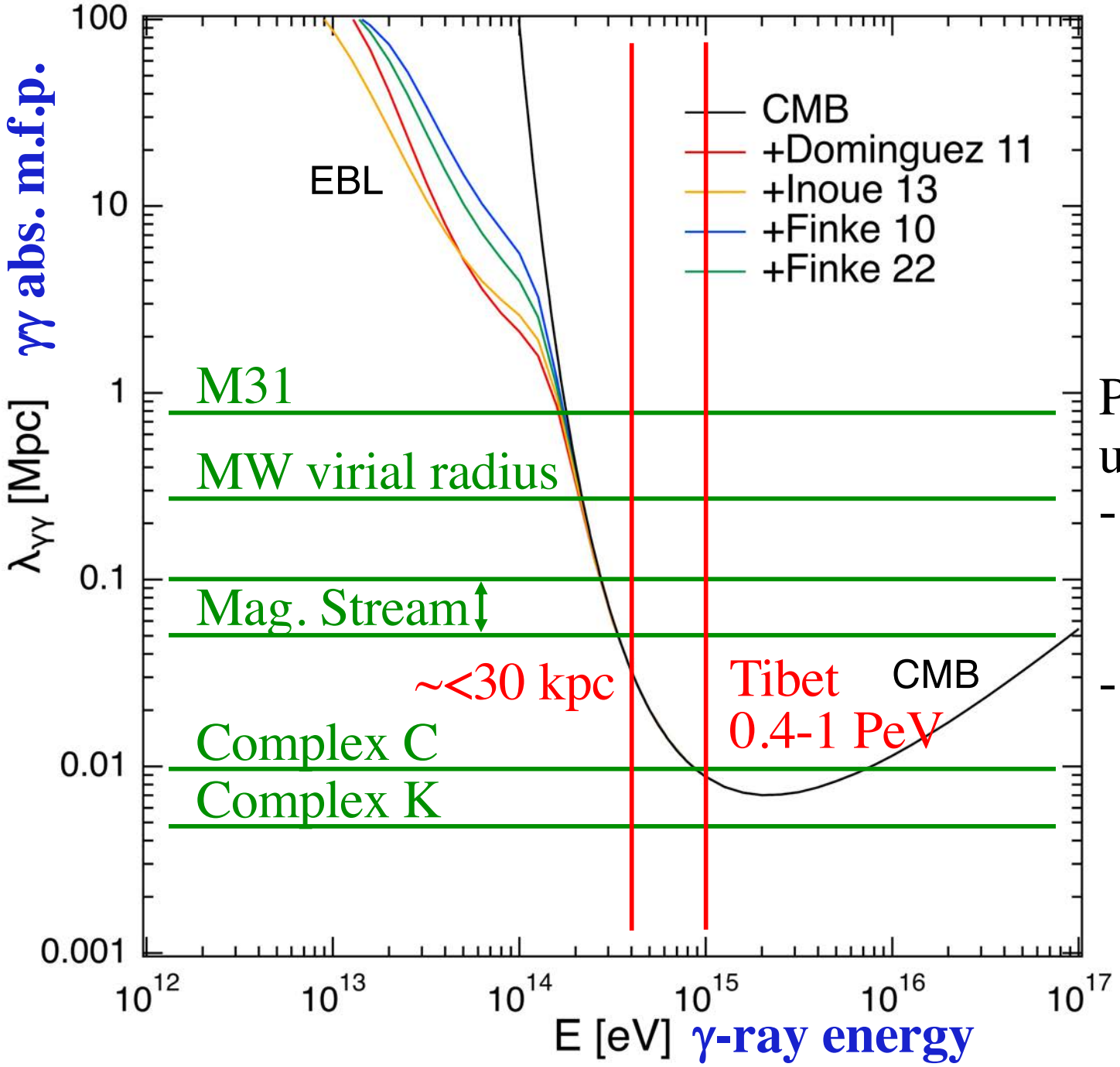

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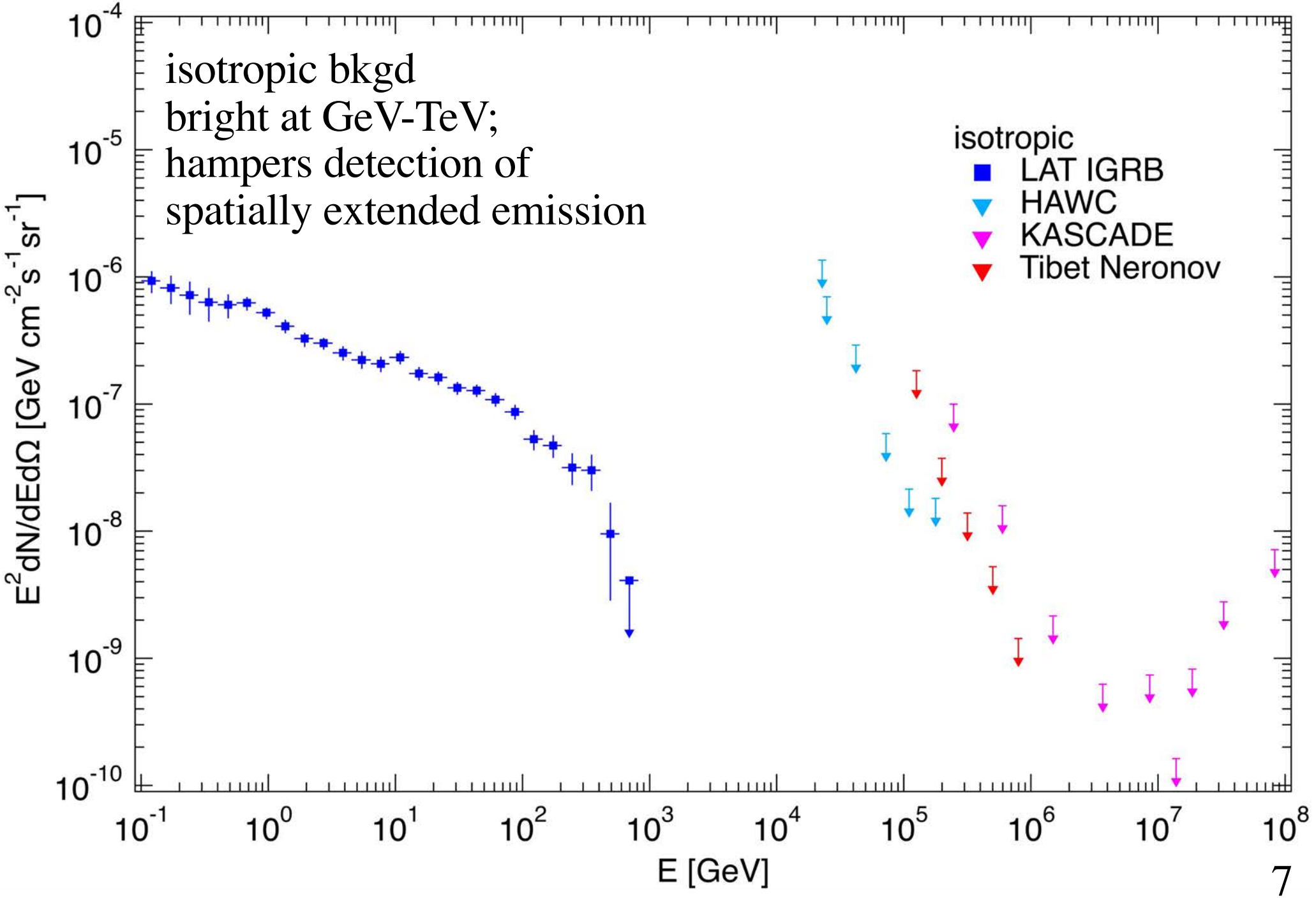
Nice for probing circumgalactic CRs!

diffuse gamma-ray emission



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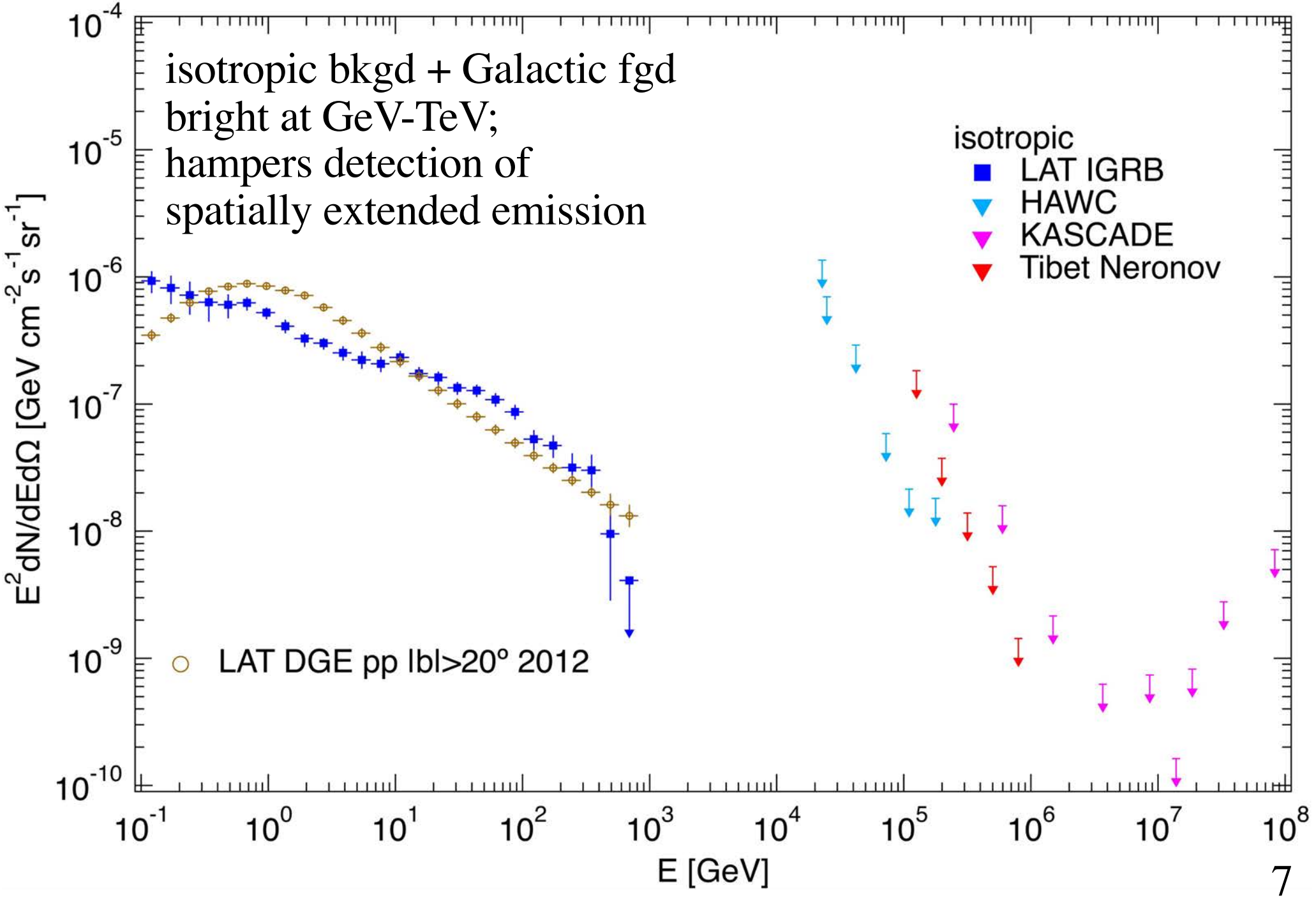

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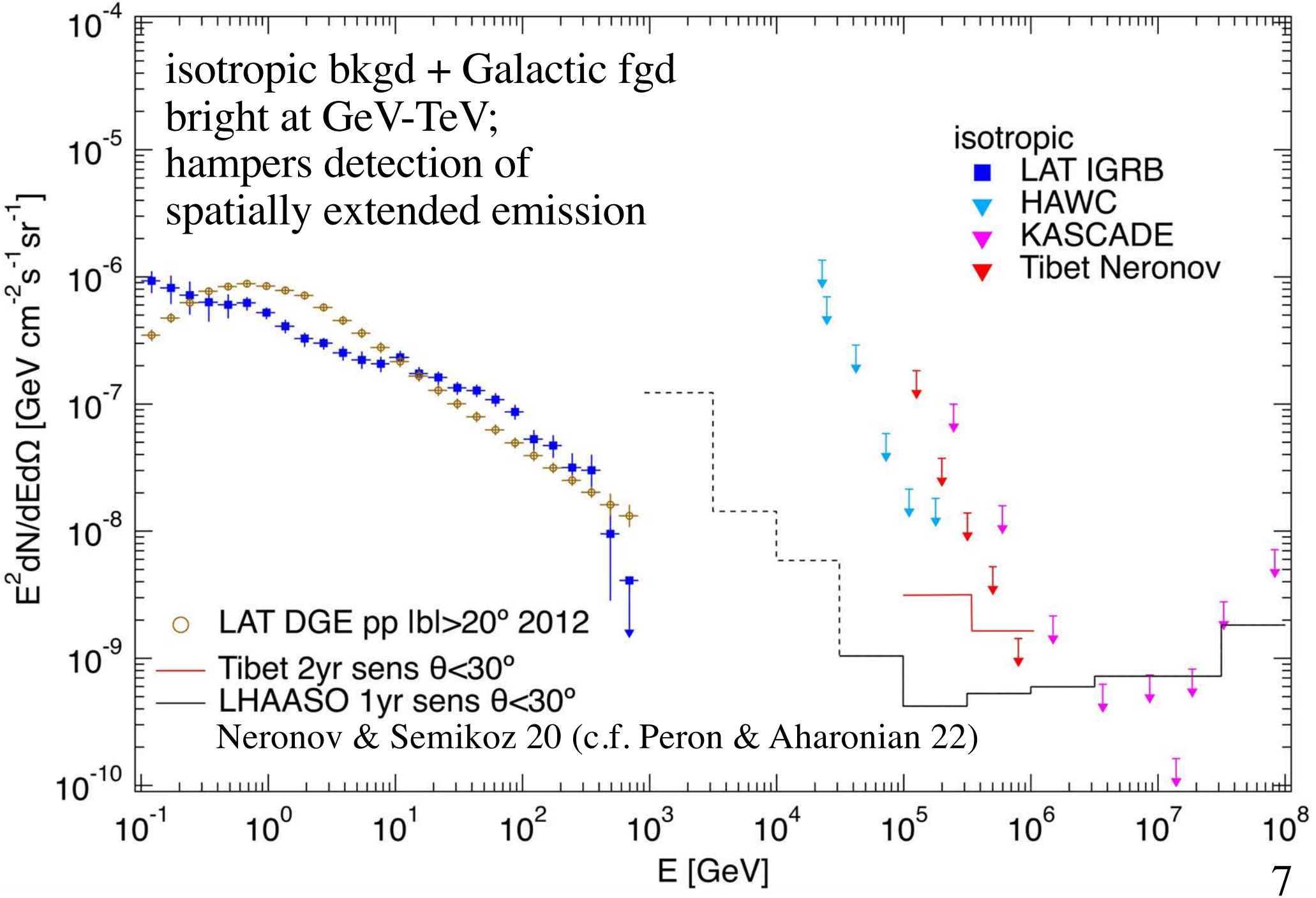

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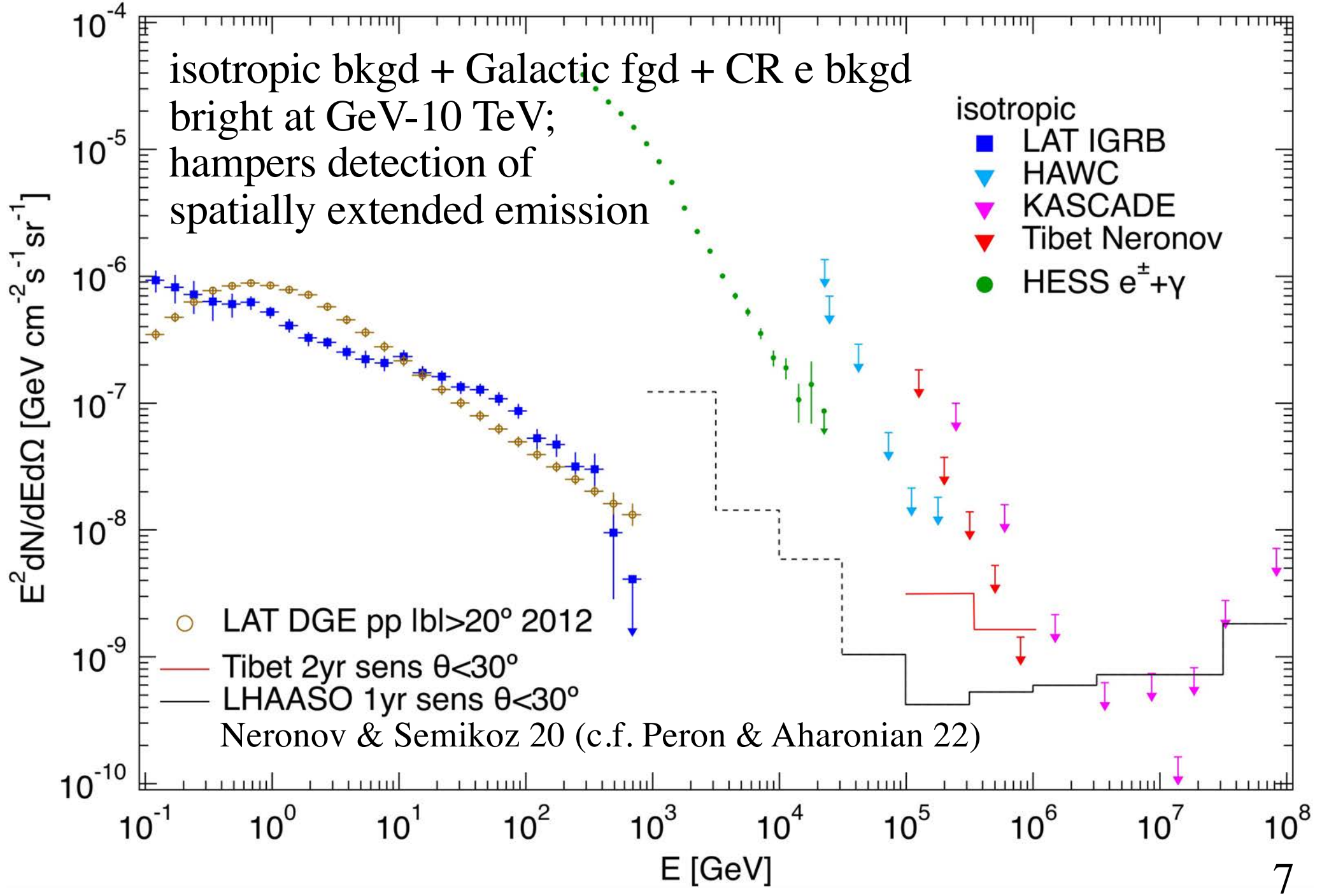

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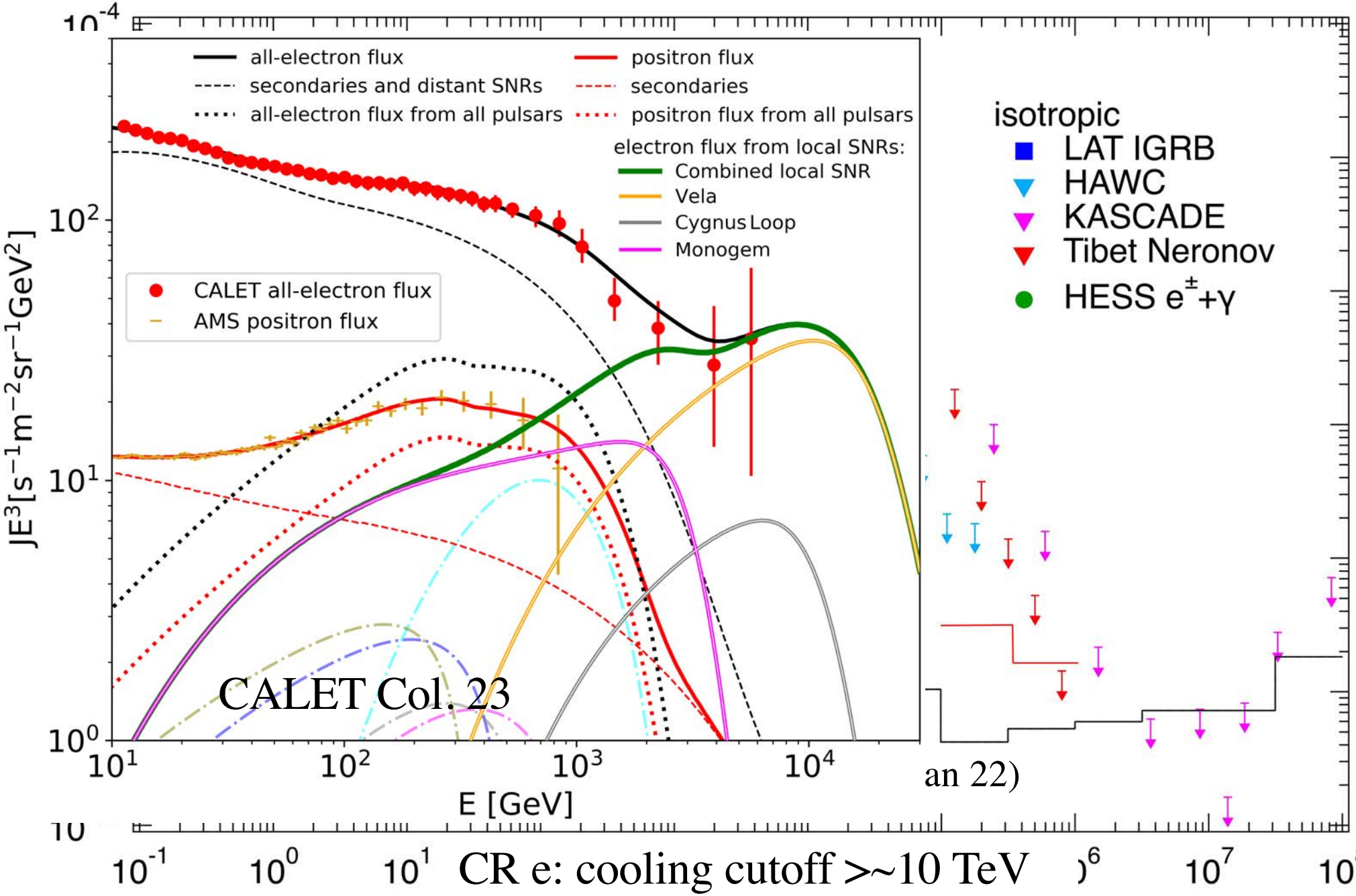
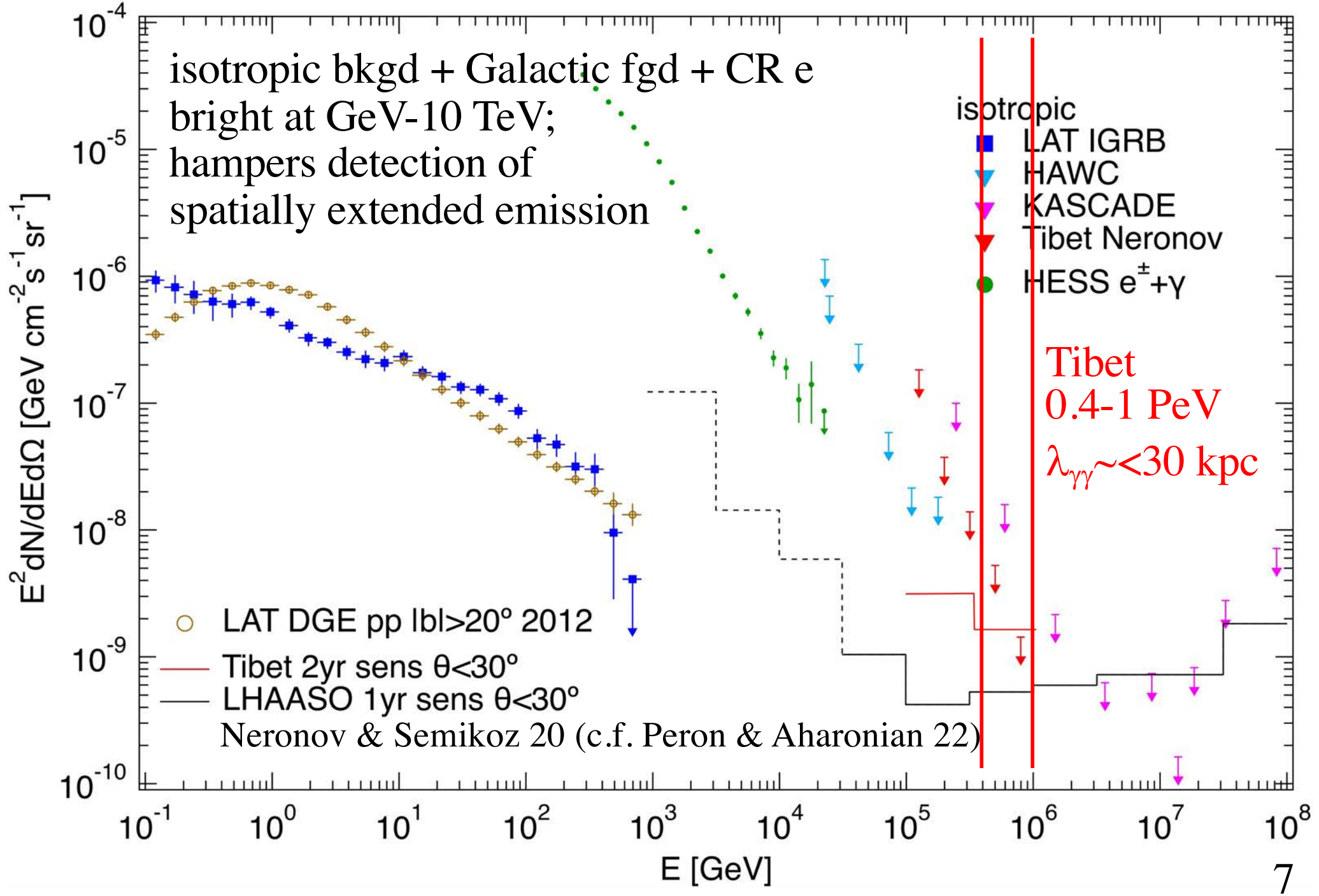


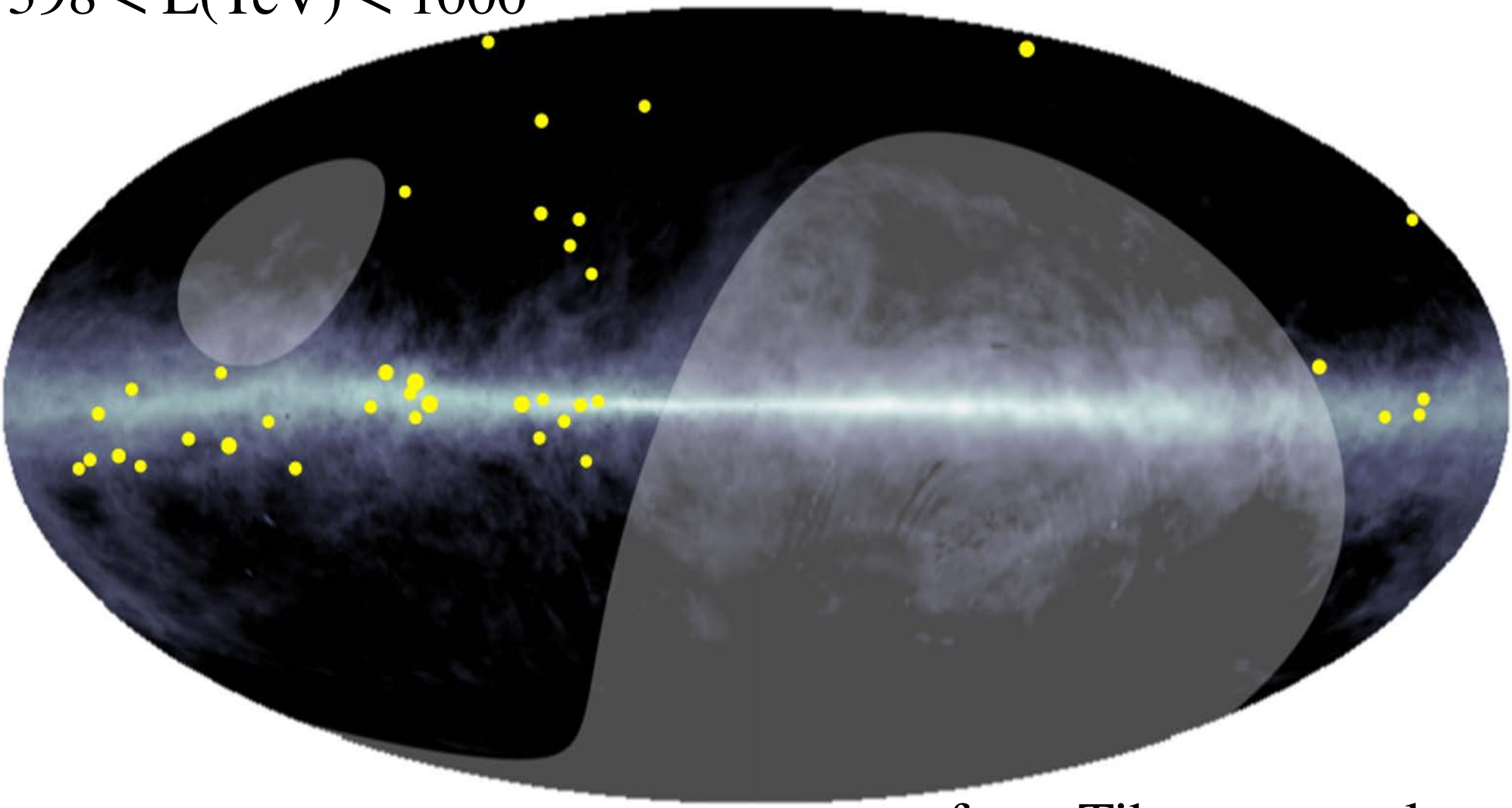
CR e: cooling cutoff >~10 TeV
expected for astrophysical origin

diffuse gamma-ray emission



Tibet ASγ events sky map

398 < E(TeV) < 1000

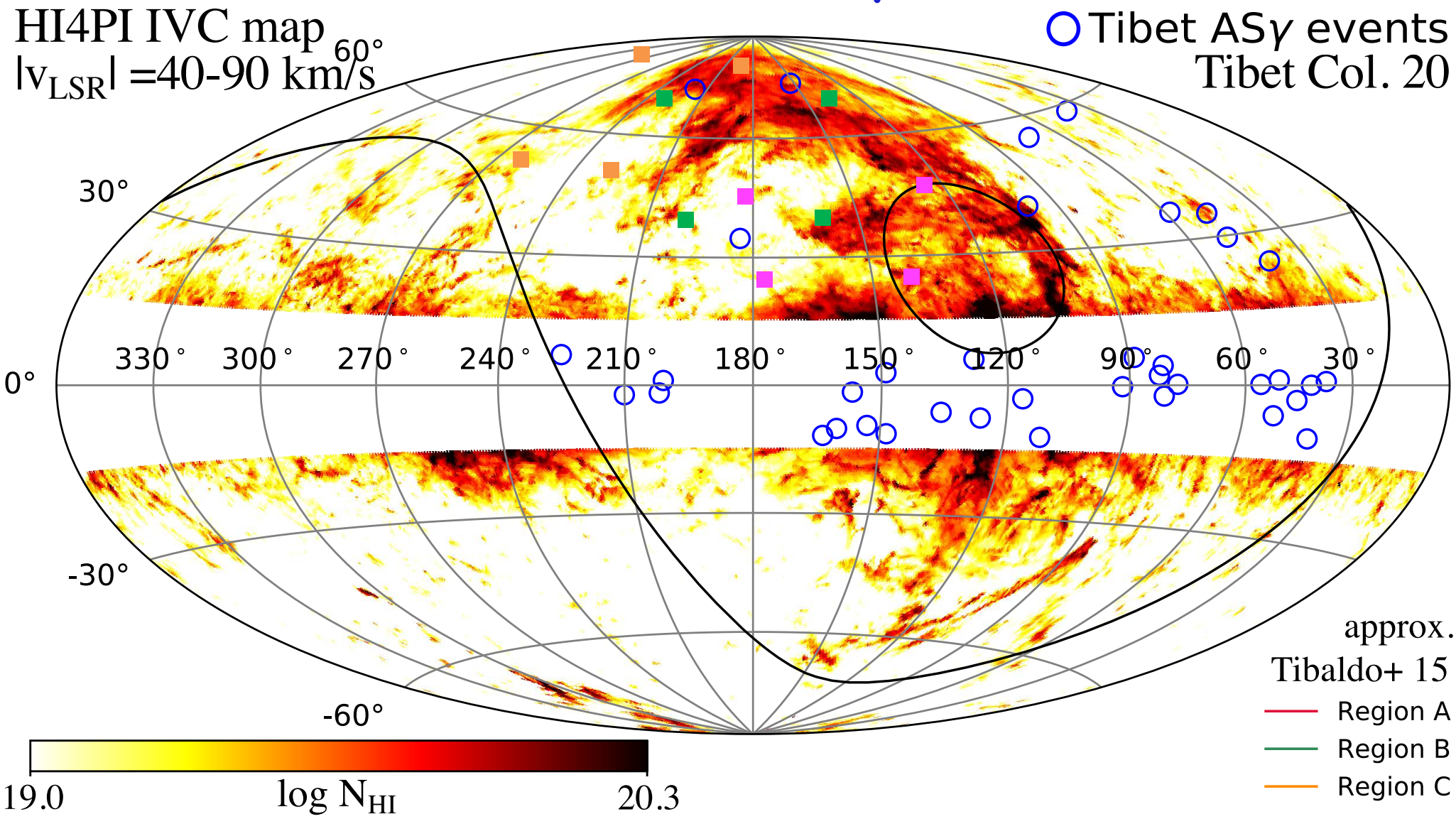


from Tibet press release

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

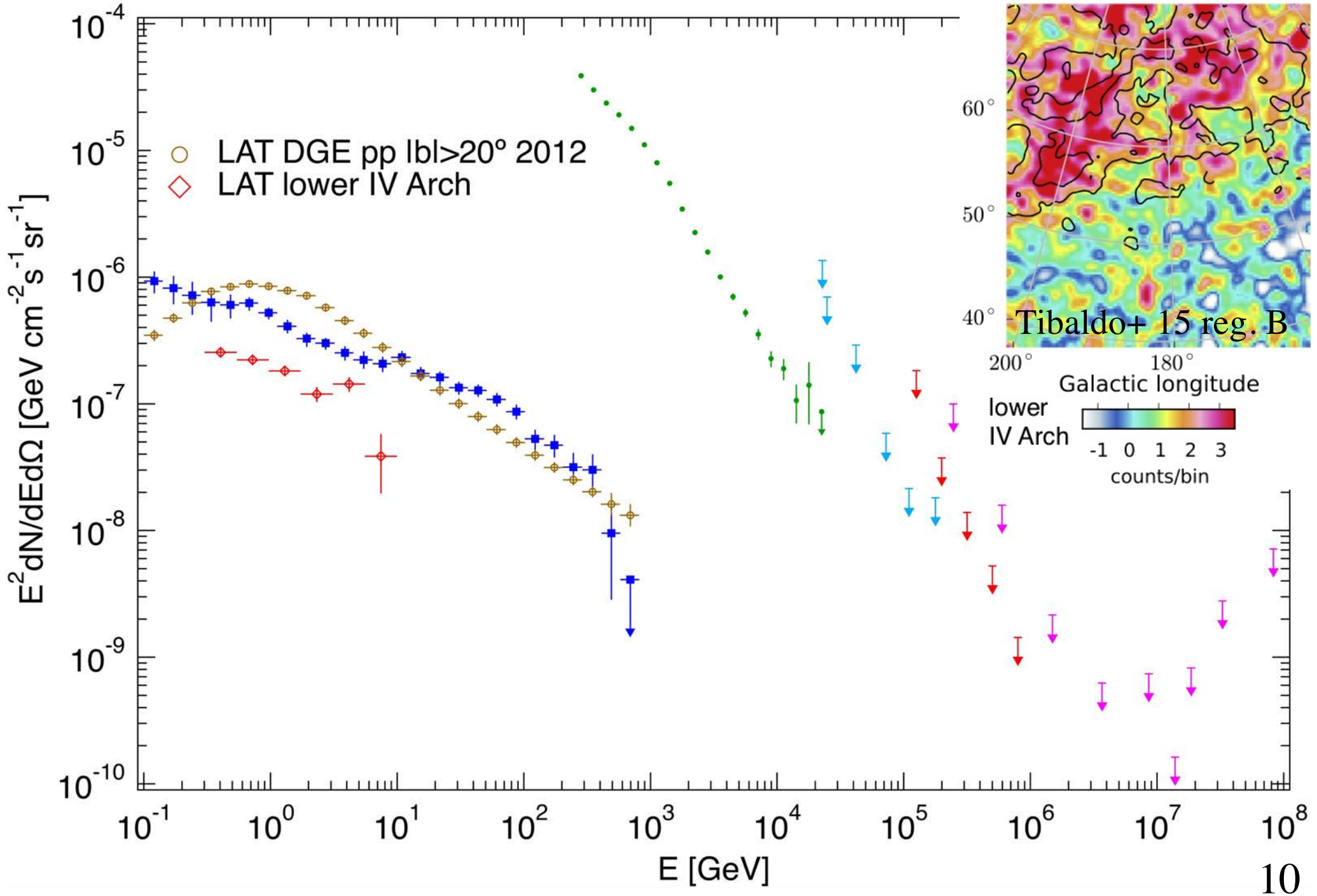
IVCs vs Tibet ASγ events

0.4-1 PeV



- No Tibet events within regions studied by Tibaldo+ 15 (despite some events nearby) -> upper limits on PeV CRs in some IVCs (z~1-2 kpc)

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



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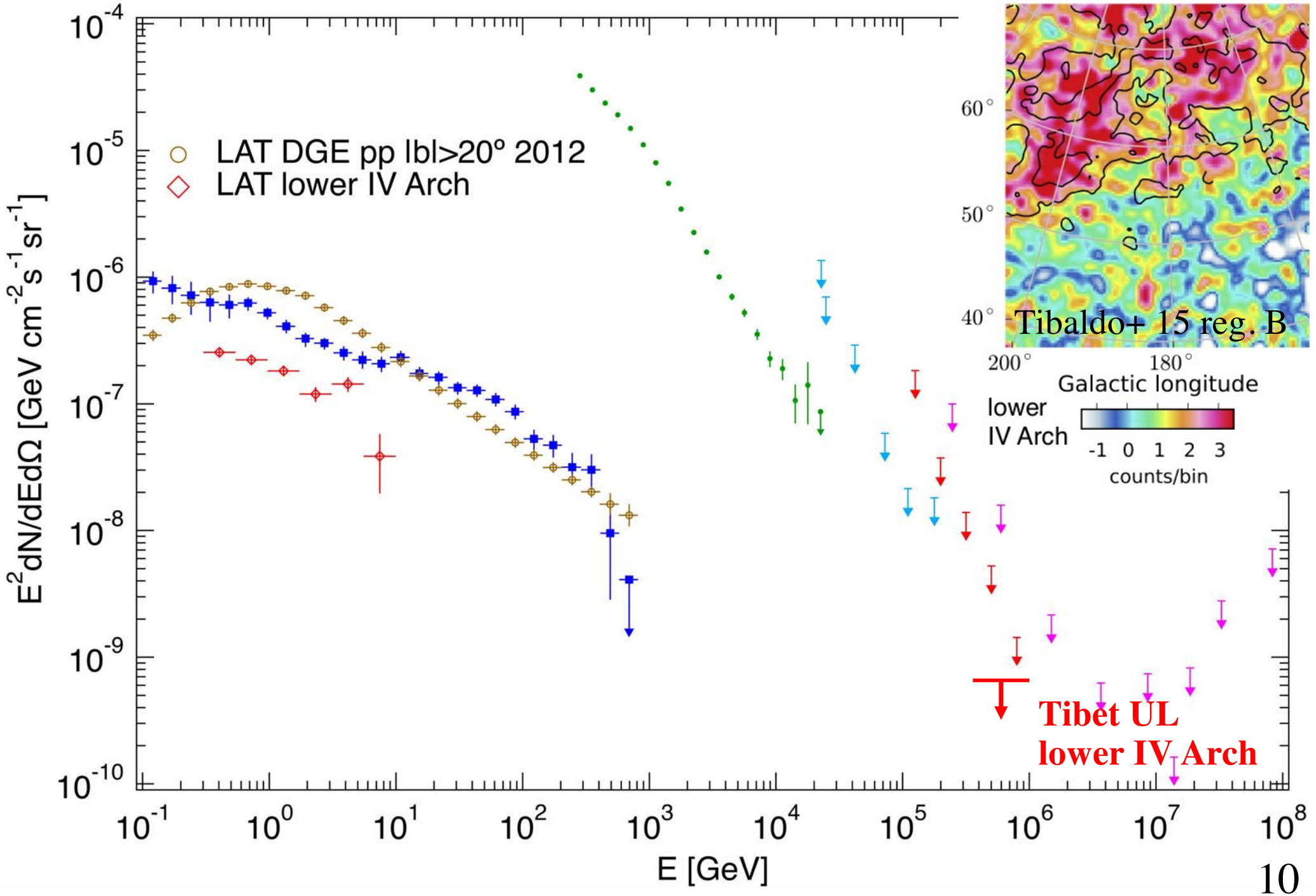

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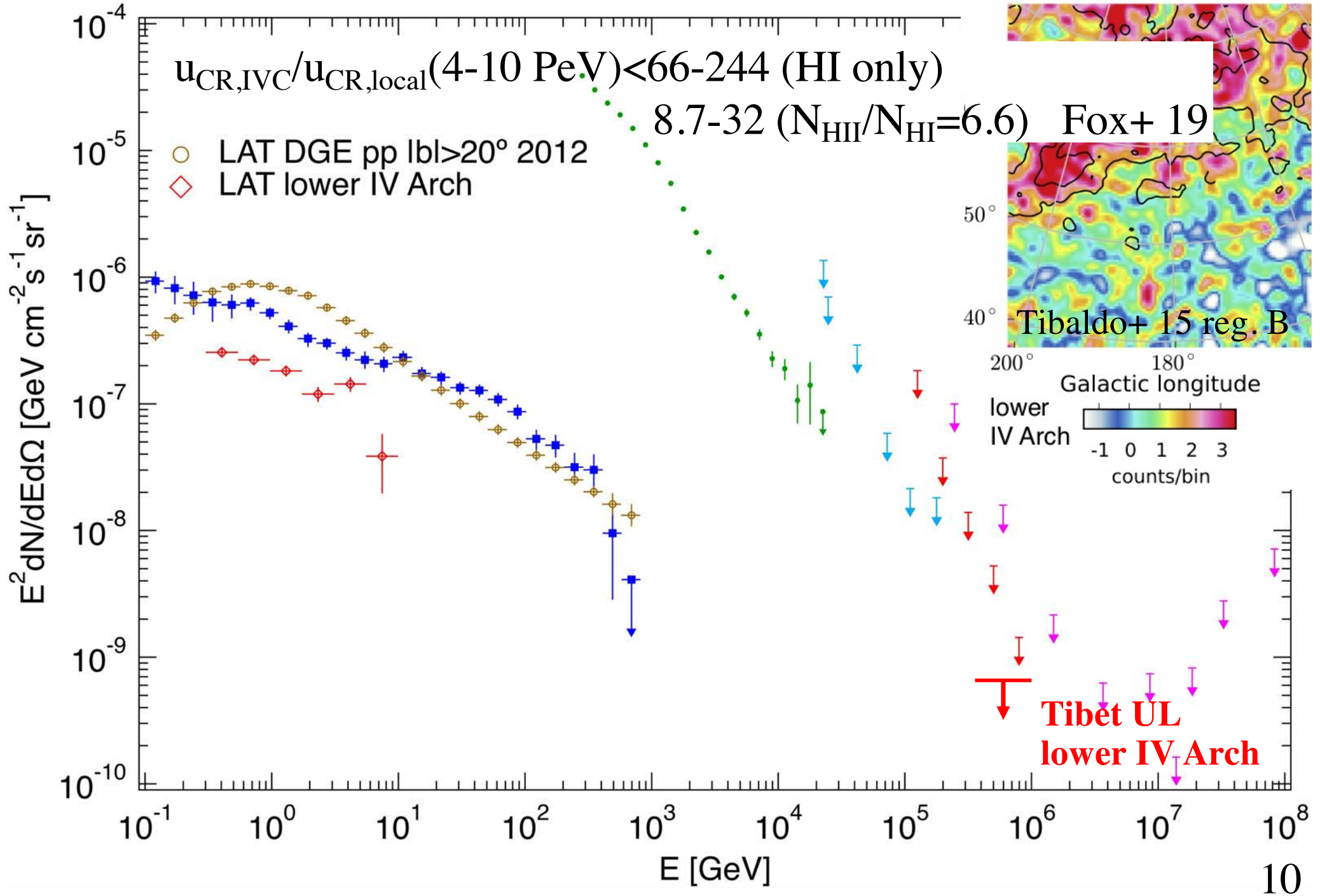

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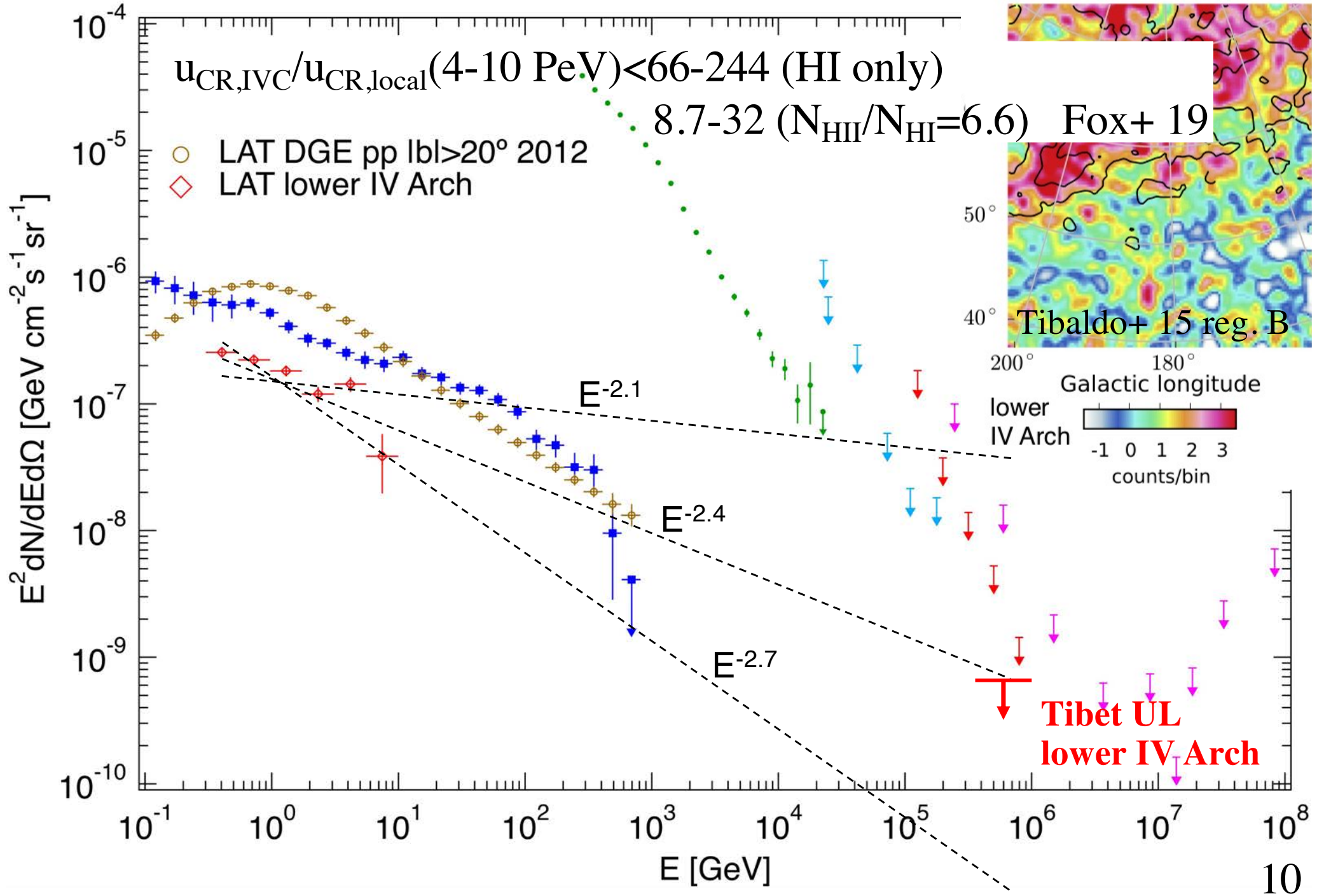

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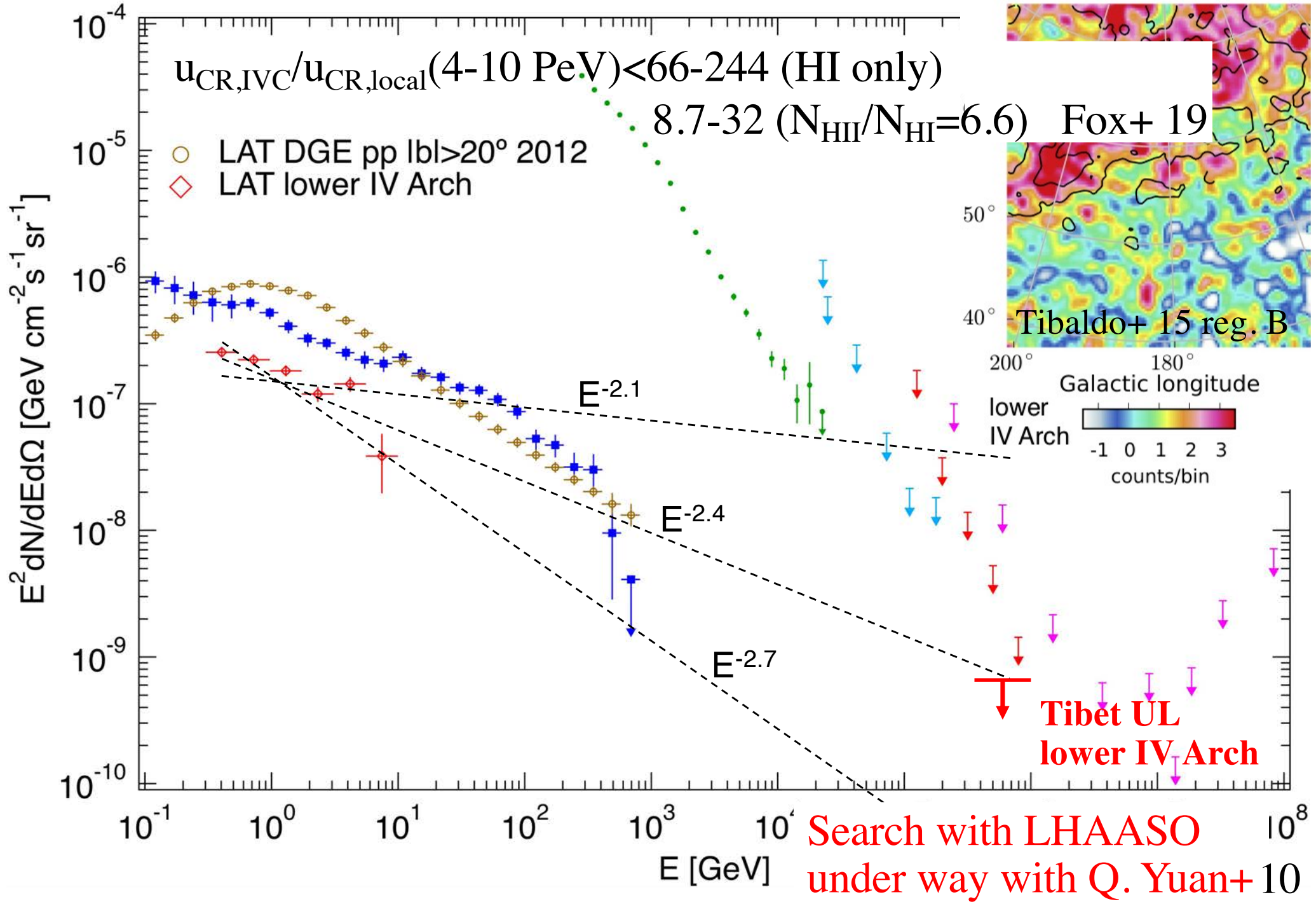
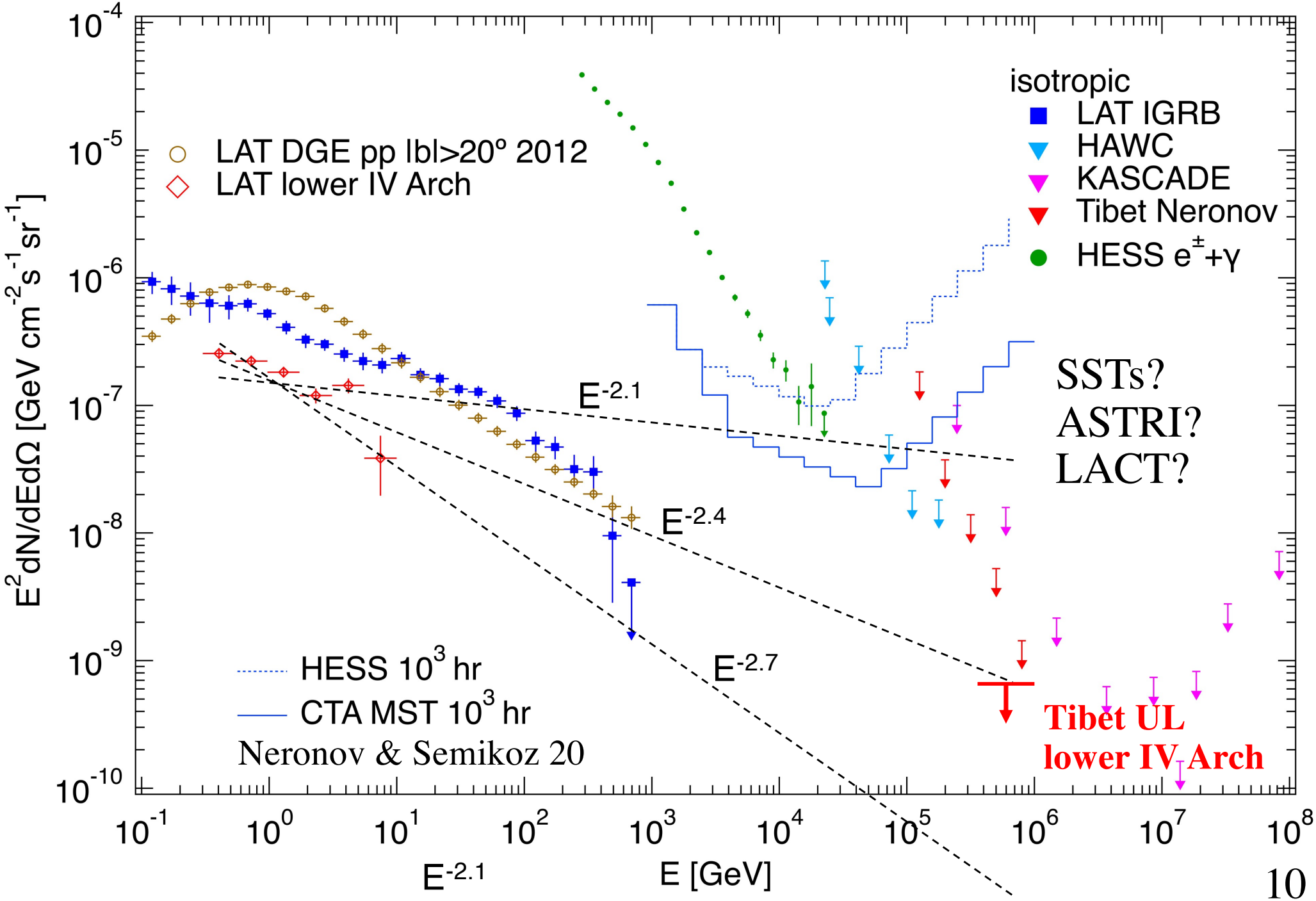


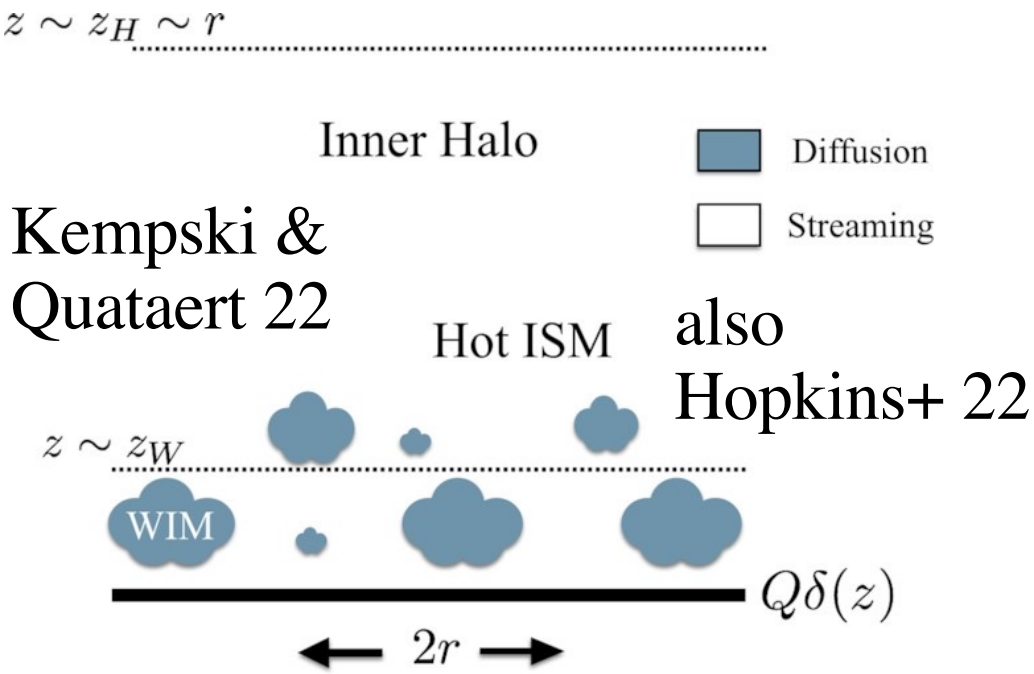
Search with LHAASO under way with Q. Yuan+

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



probing GeV-PeV CRs at z~1-2 kpc: implications

- Unlike phenomenological models of CR propagation (e.g. GALPROP), theoretically motivated models predict different modes at ~GeV (self-confinement) and ~PeV (extrinsic turbulence)
- Between z~0 and z~1-2 kpc, potentially significant differences due to different wave damping processes in cool and warm/hot phases



Kempski & Quataert 22

also Hopkins+ 22

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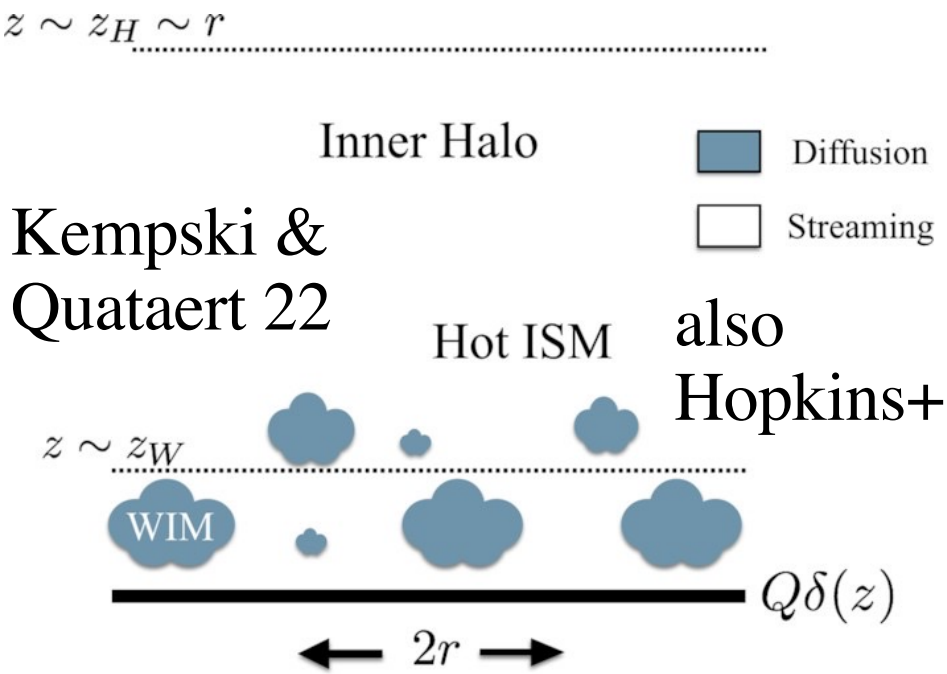
- Some simulations predict significant spectral hardening at z~few kpc



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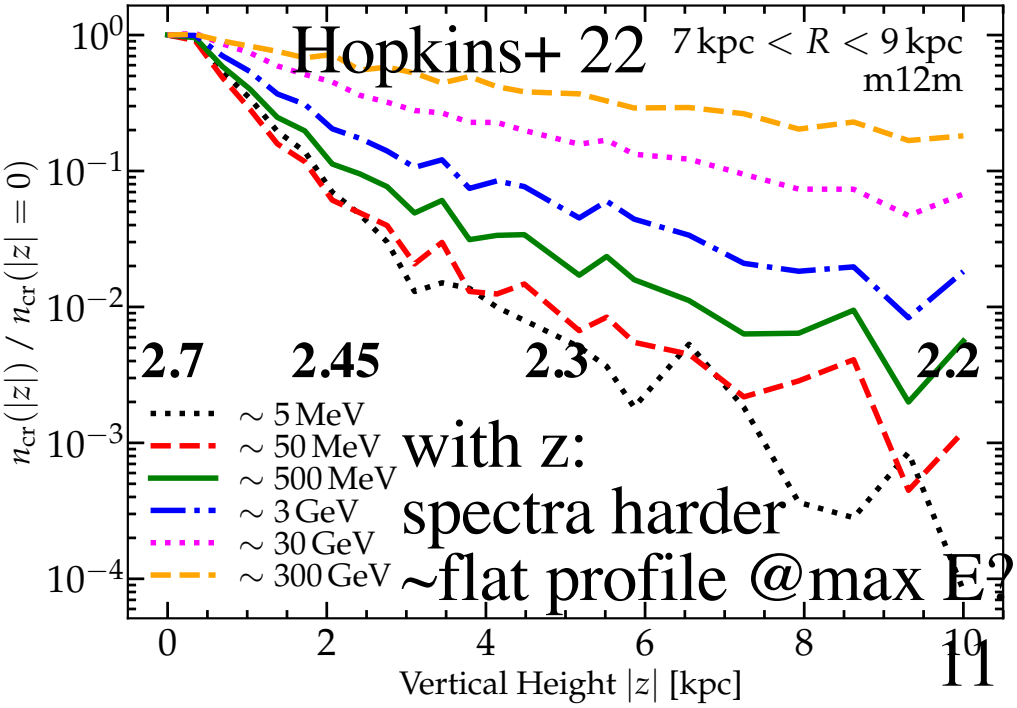

with z:
spectra harder
~flat profile @max E?

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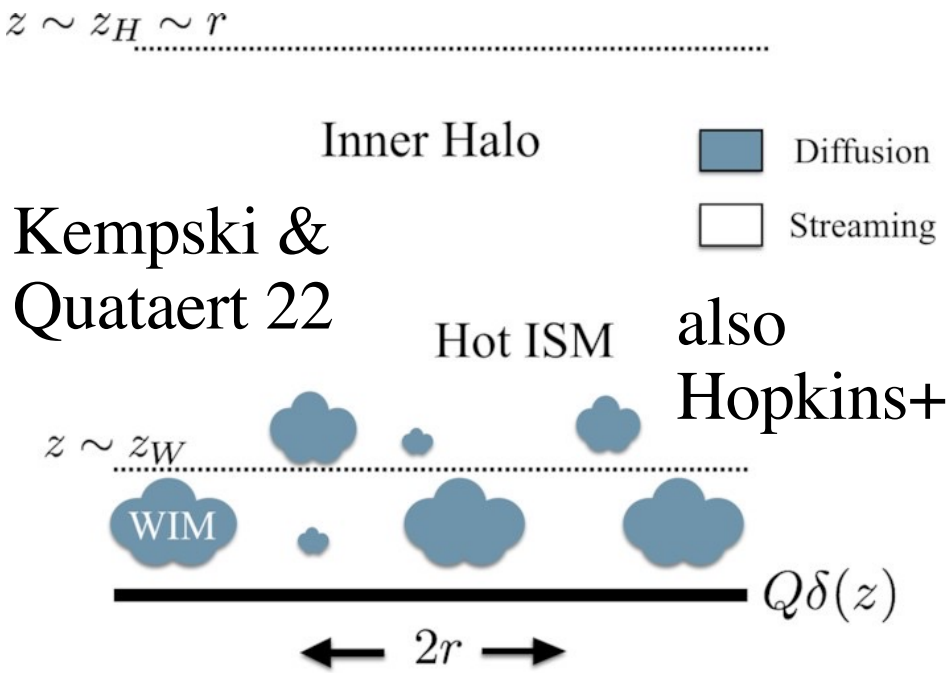
- Between z~0 and z~1-2 kpc, potentially significant differences due to different wave damping processes in cool and warm/hot phases
- Some simulations predict significant spectral hardening at z~few kpc
- Relevant IVCs consistent with Galactic fountain outflows Marasco+ 22
  -> launching site of Galaxy-wide (CR-driven) winds?
  -> transient CR enhancement via buoyant bubbles? Recchia+ 21



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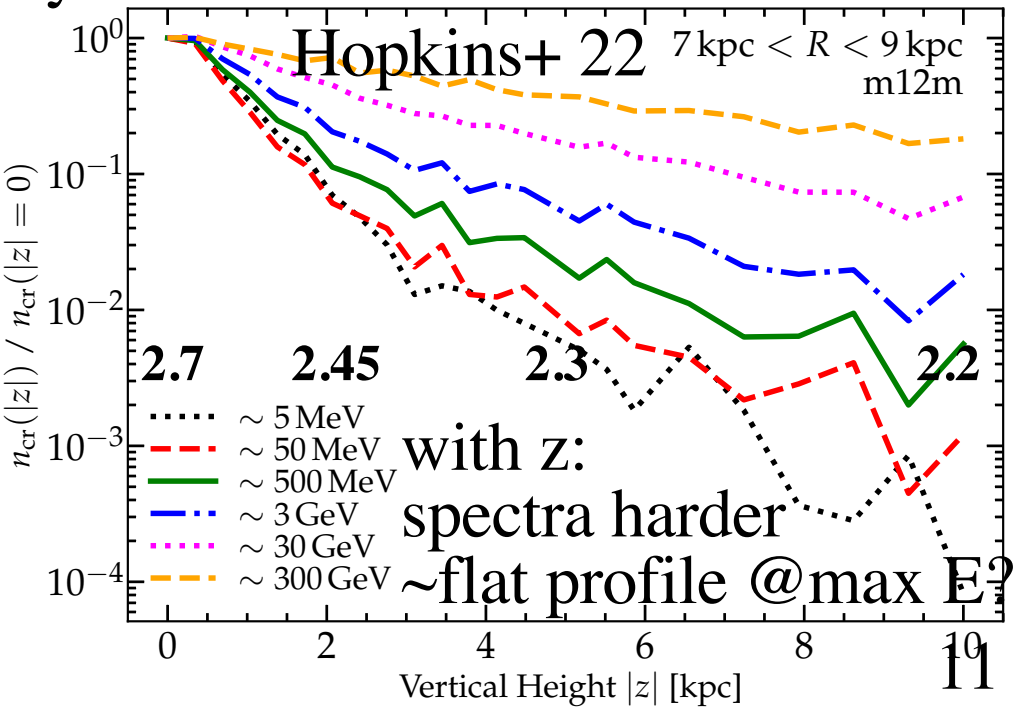

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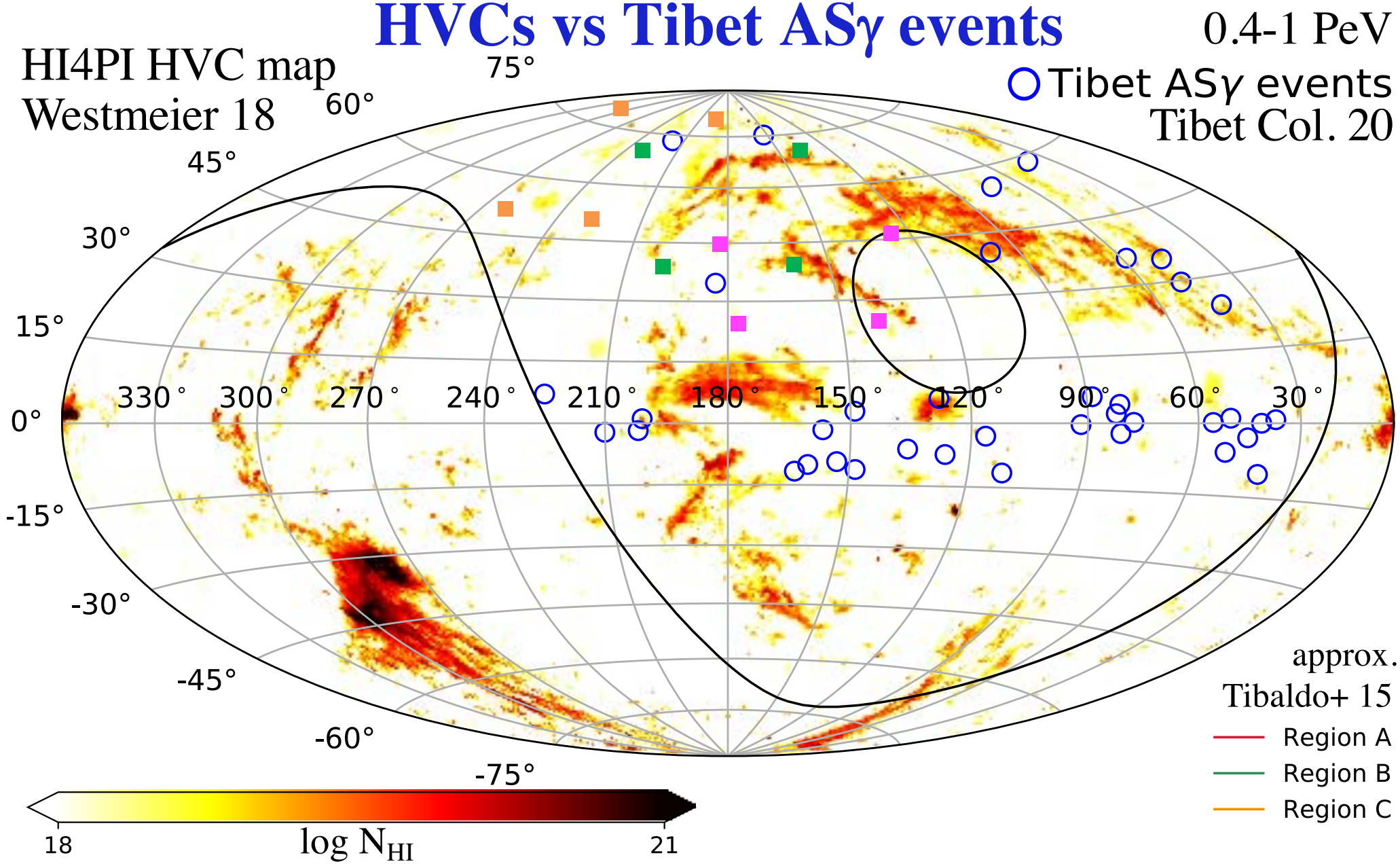
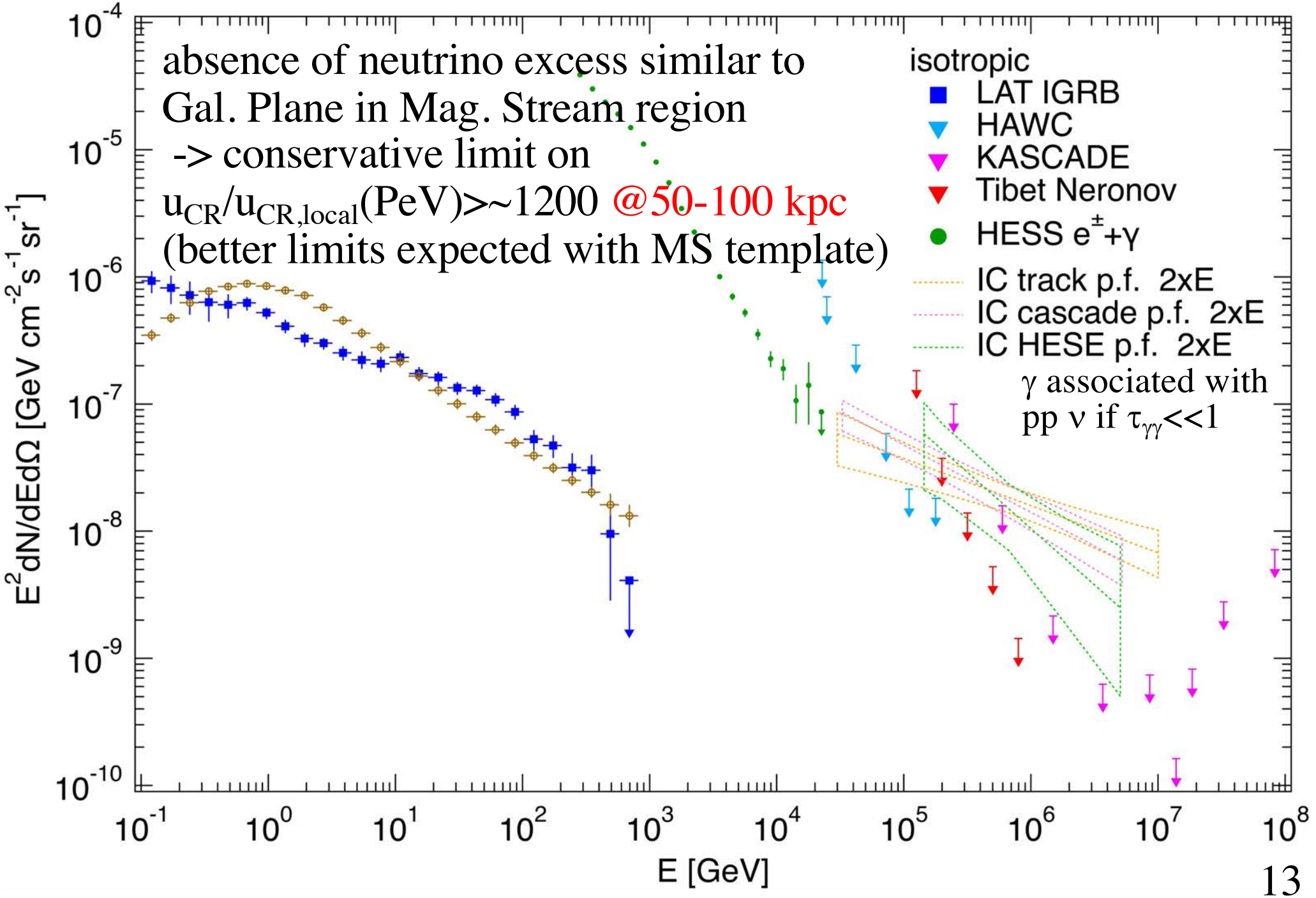
HVCs vs Tibet ASγ events



- No statistically significant correlations Tibet events vs HVCs (z~2-8 kpc)
  -> $u_{CR,HVC}/u_{CR,local}$(4-10 PeV)~<250 $(f_{tot/HI}/4)^{-1}$
  constrains non-standard scenarios Fujita+ 17, Merten+ 18, Recchia+ 21

neutrinos: probing CRs in the outer halo



summary: Probing MW CGCRs with GeV-PeV γ, ν

- CRs in CGM potentially crucial for evolution of Milky Way but many unknowns. Observational probe needed. γ-rays from halo likely patchy, possibly correlated with cool gas.

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

- Tibet high b events vs IVC/HVC correlation search: Not significant so far -> Limits on CRs escaping from disk, CRs in inner halo. Study with LHAASO under way. Potential new insight into CR propagation, (CR-driven)winds.

- 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.