# Summary

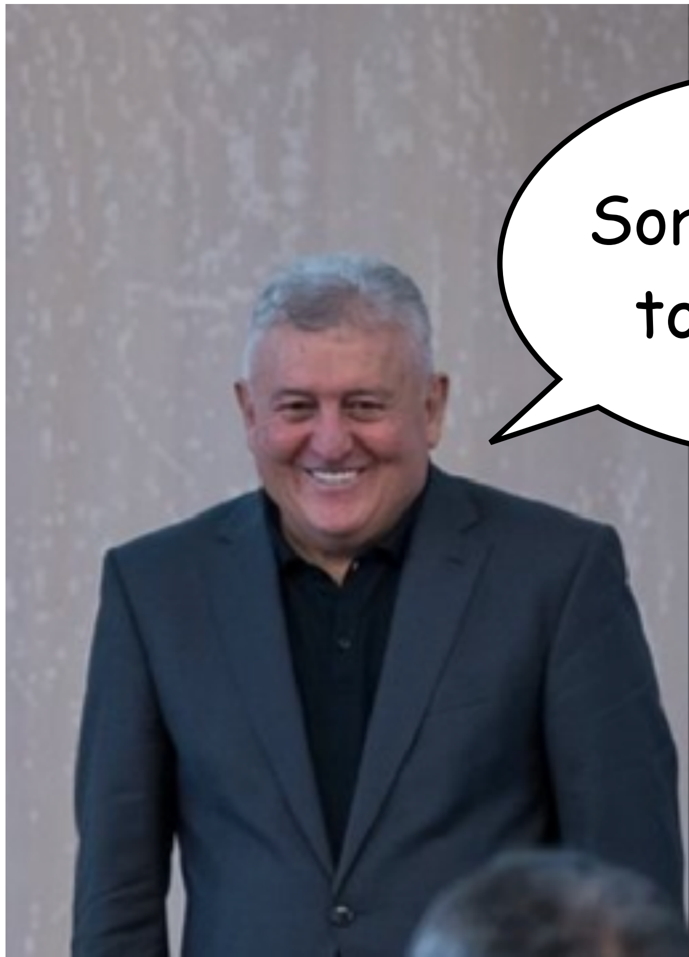
Stefano Gabici
APC, Paris

# Why me

# Why me

# Why me

# Why me


Sorry, I have to cancel…

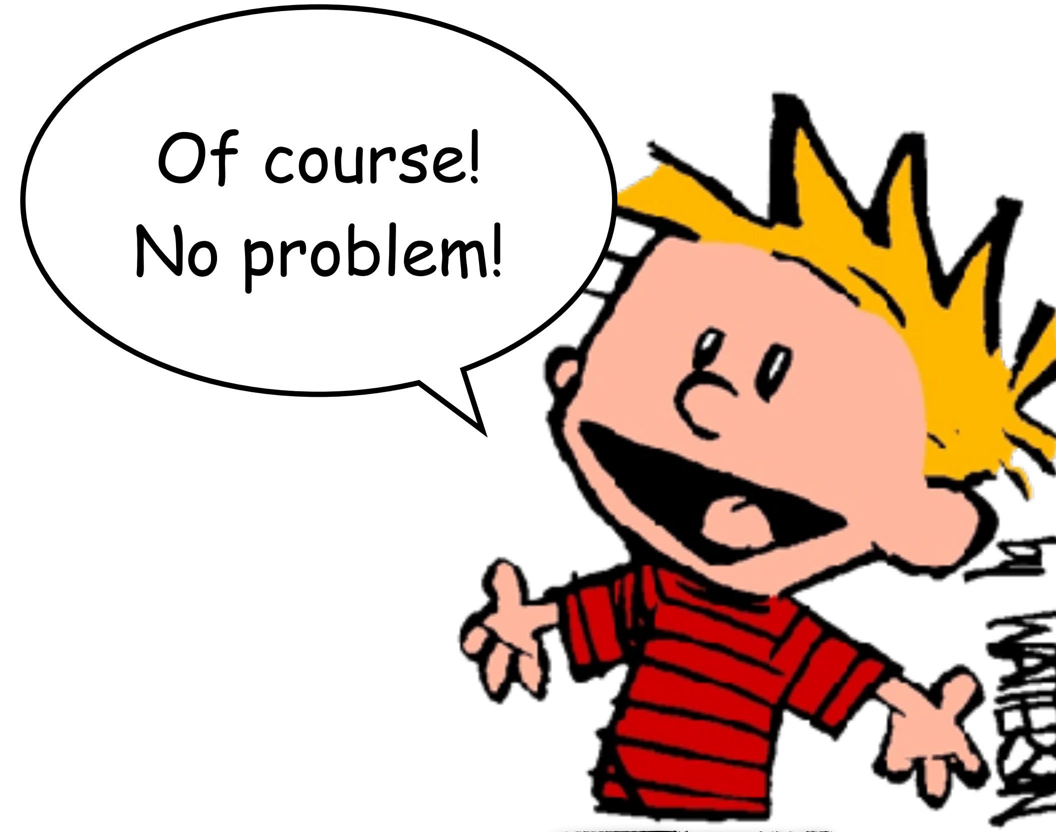

Stefano, can you do the summary talk?


Of course! No problem!

me

# Why me






me

the real me

# Dima's workshop: a long history

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2012 —> Dec 12th-14th

2016 —> Dec 7th-9th

2018 —> Dec 11th-14th

2020 —> Dec 7th-11th

2022 —> Dec 5th-7th

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always before the 15th

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never before the 5th

**2026 —> Dec 7th-11th**

# The real highlights

this was unexpected

the “Italian Friday session”

# Goal of this summary

[GOAL #1] propose a few questions (possibly intelligent ones) that might hopefully trigger a discussion

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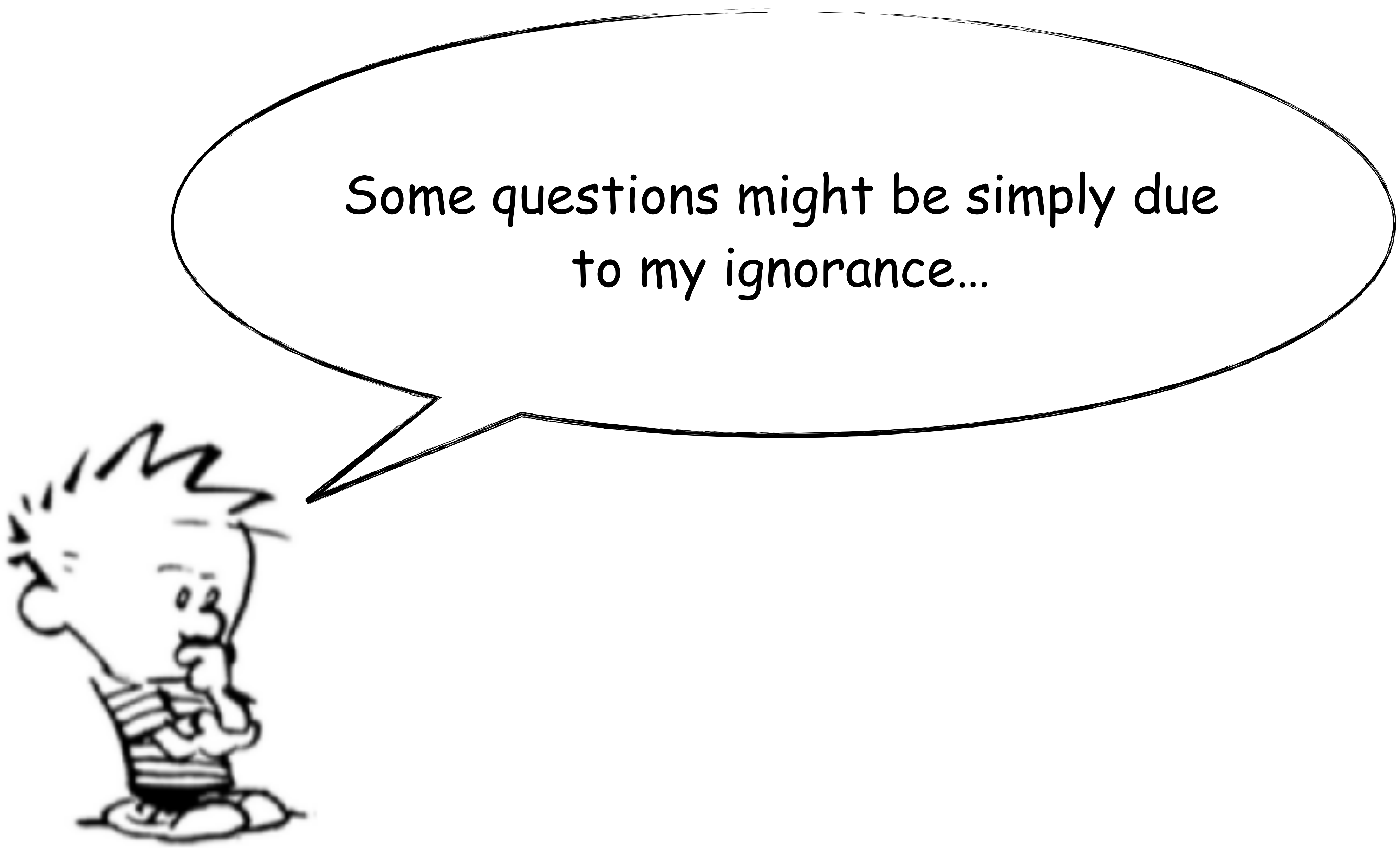


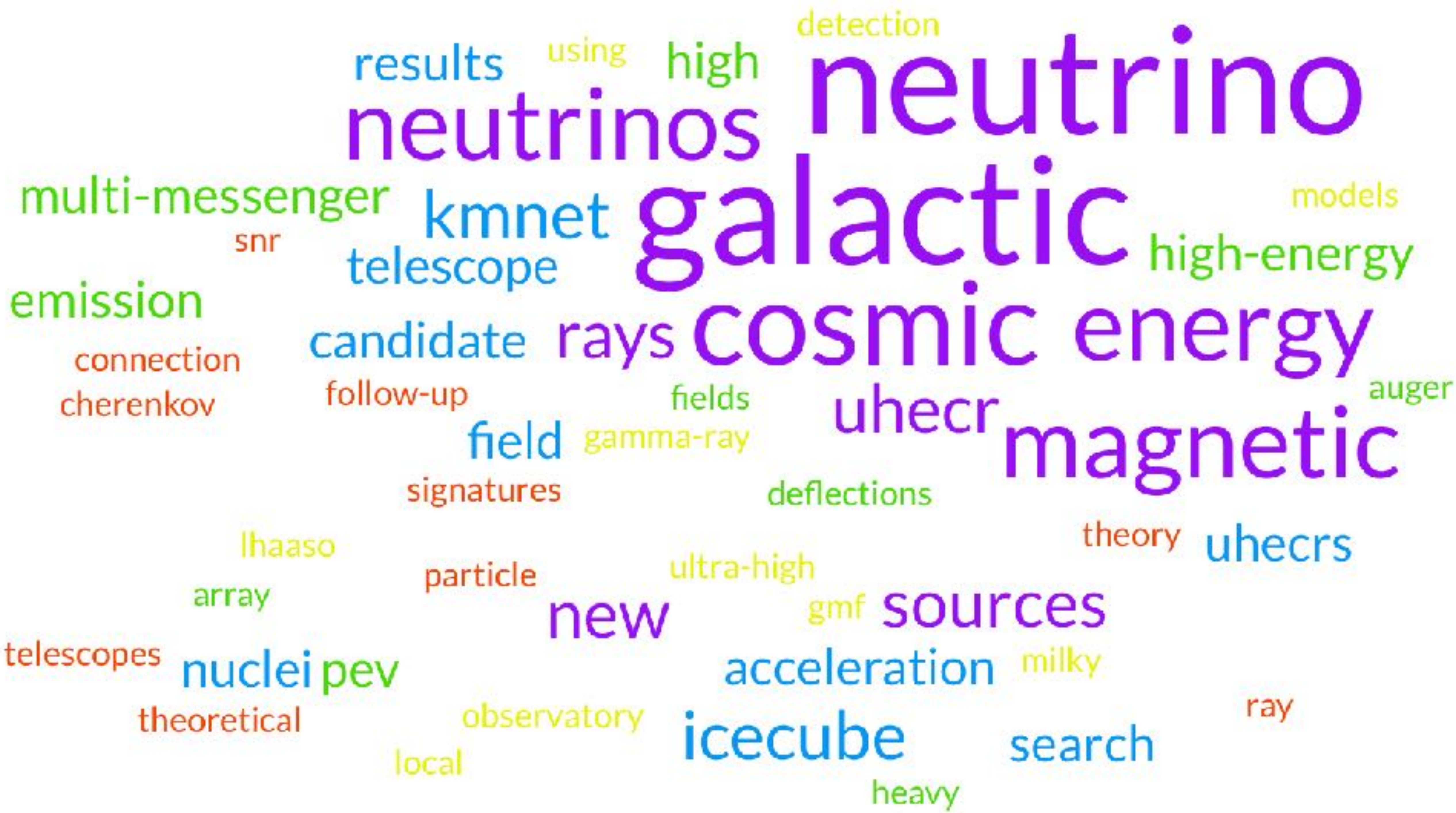
# Goal of this summary

[GOAL #1] propose a few questions (possibly intelligent ones) that might hopefully trigger a discussion

Some questions might be simply due to my ignorance...

[GOAL #2] keep it short (people will love it)

# Word cloud (from talks' titles)



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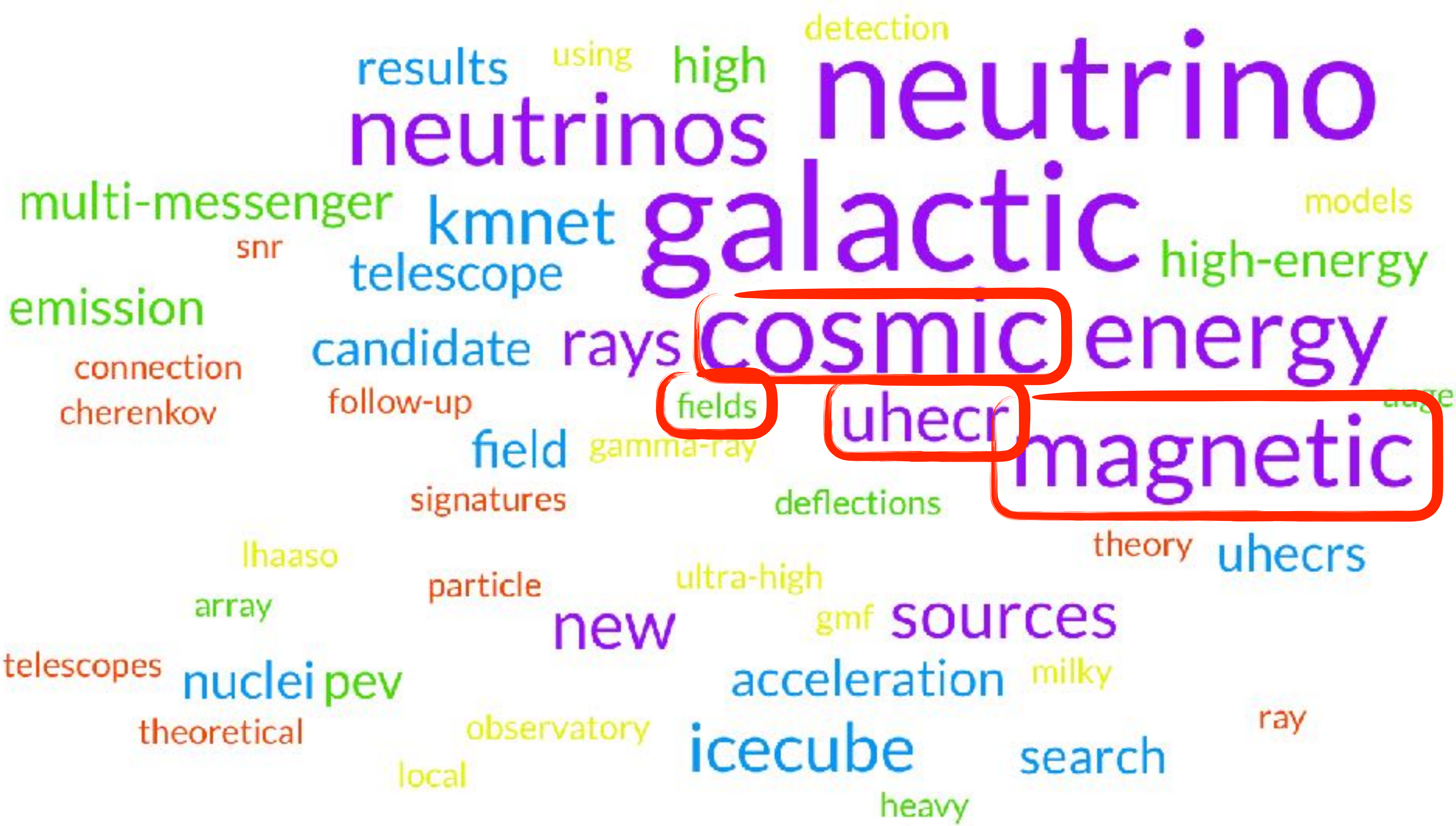
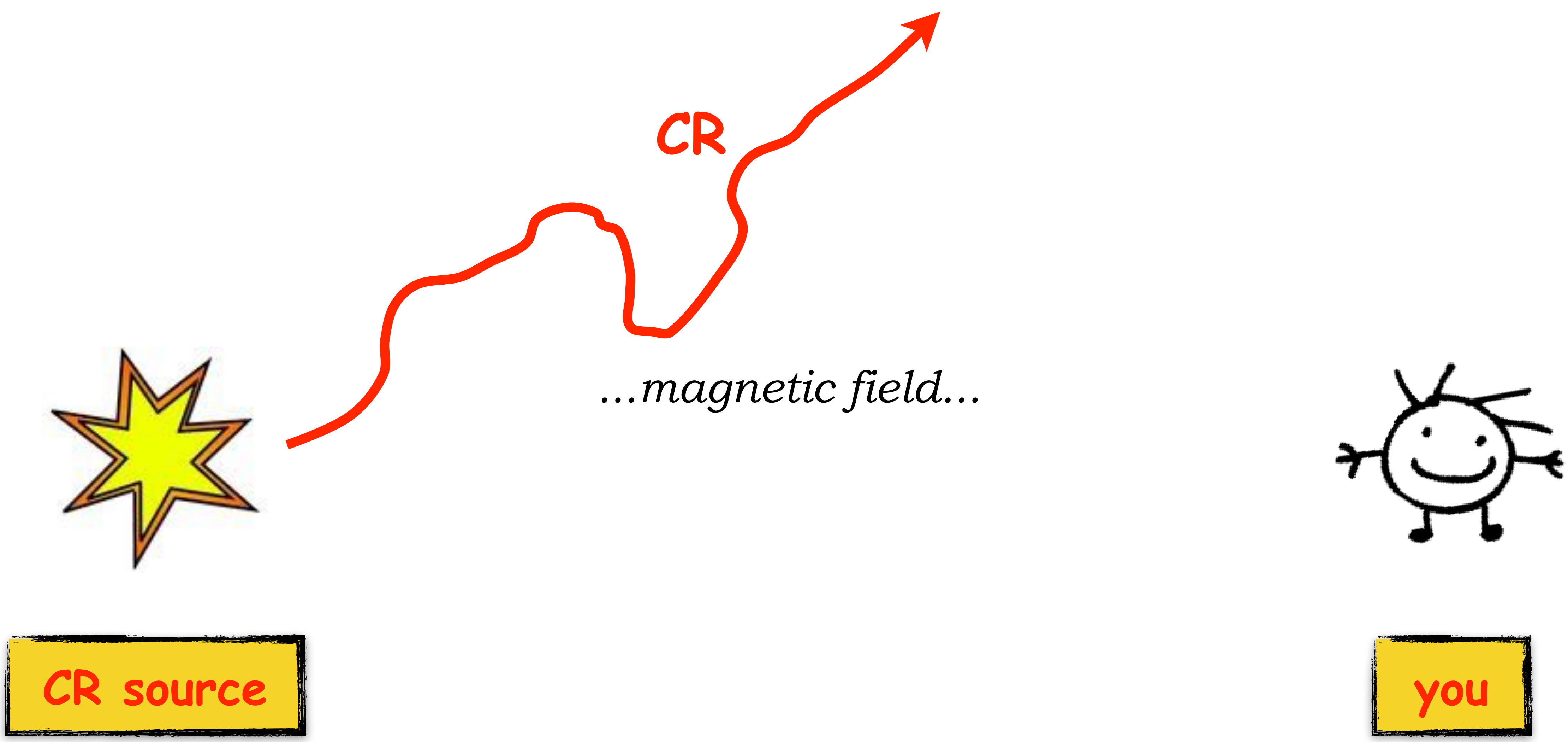


# Why are we still talking about CRs?



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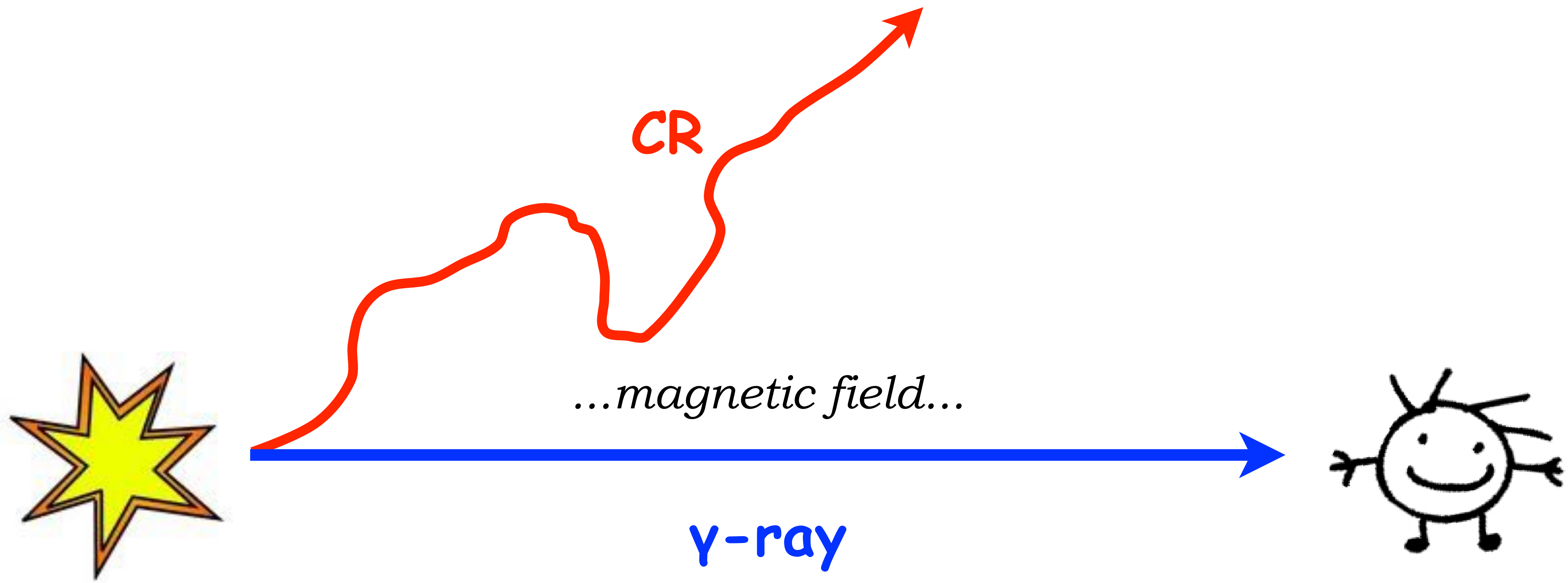
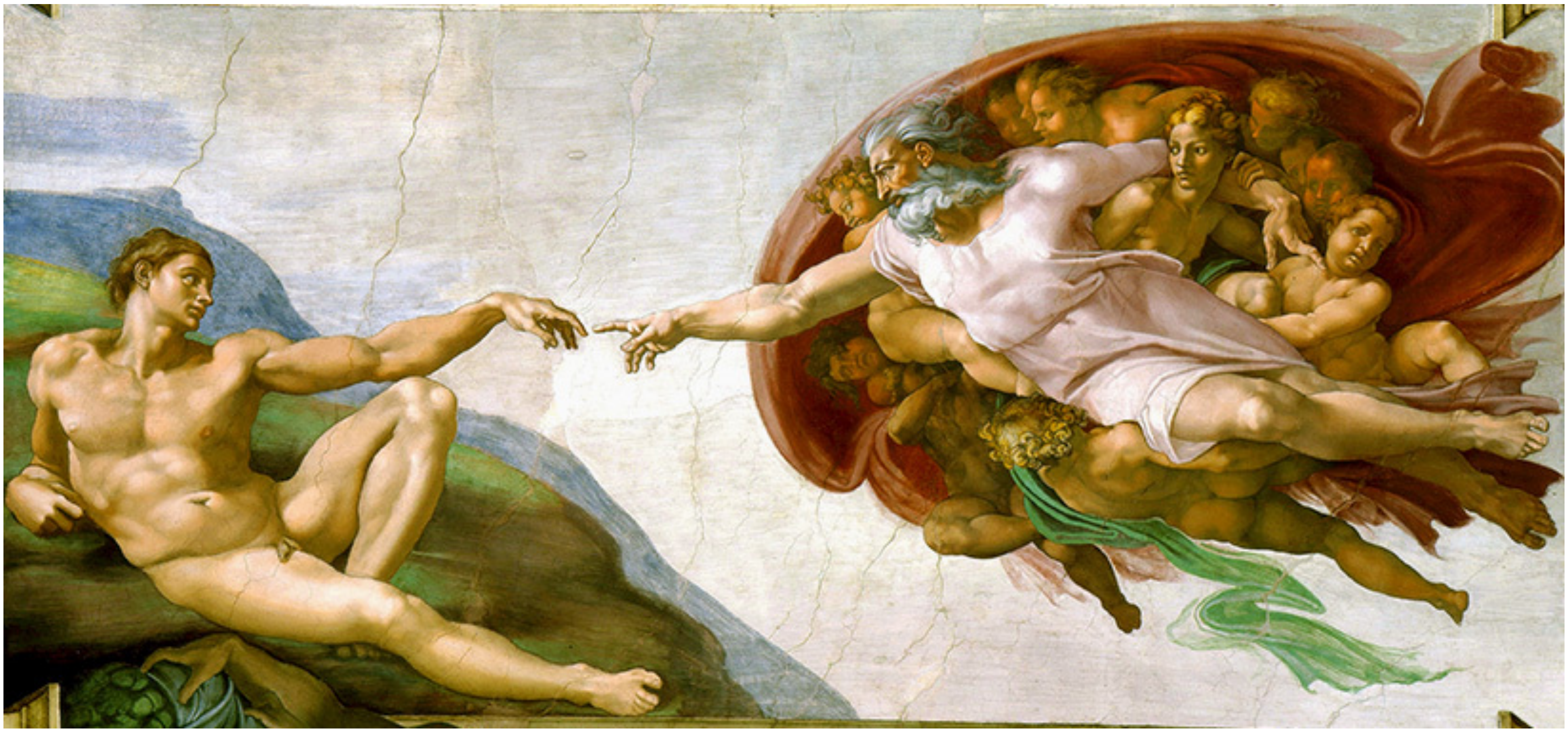



CR source

you

—> impossible (?) to do CR astronomy
—> must use indirect ways to pinpoint sources
—> γ-ray astronomy!

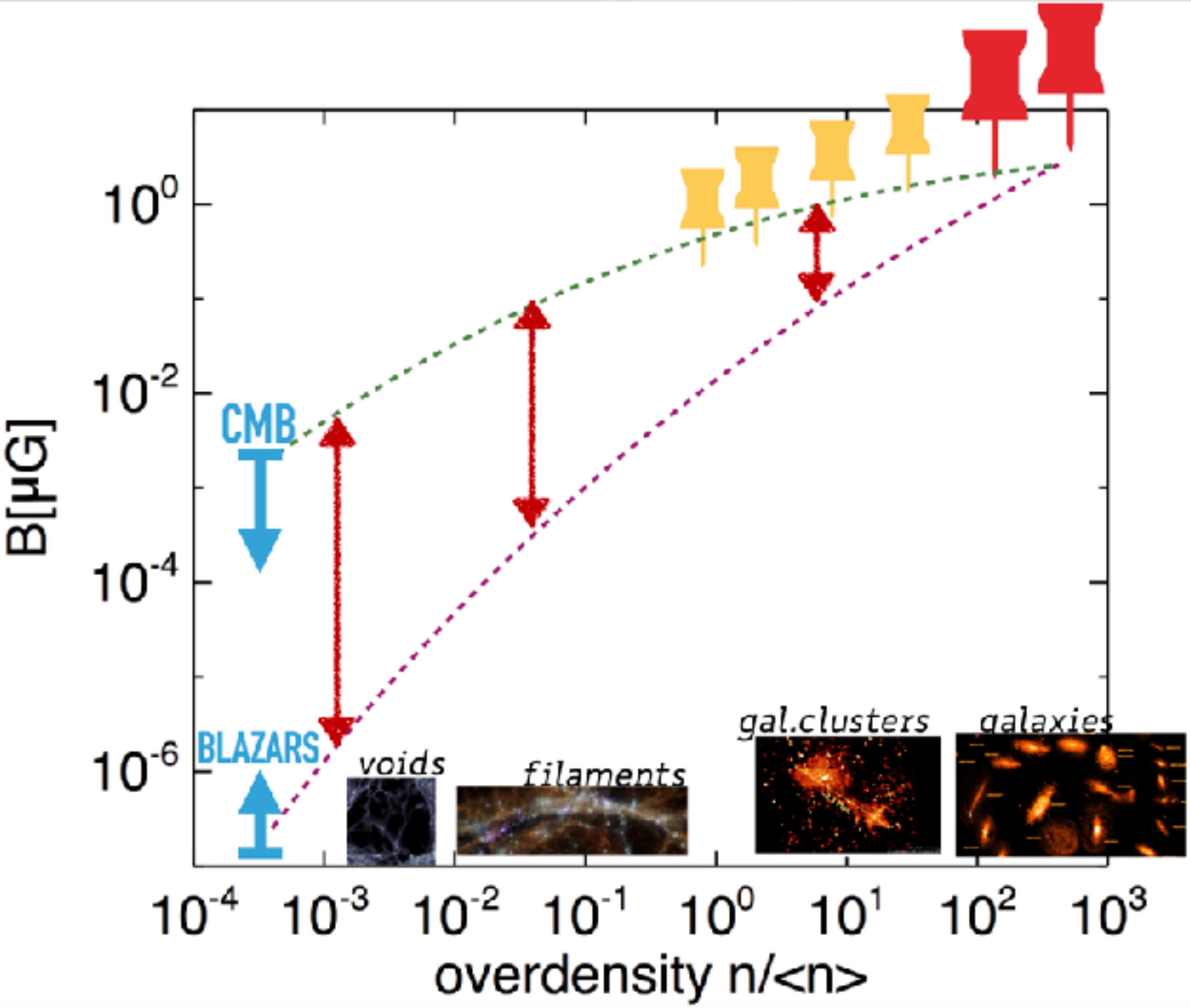
# Let's start from the beginning...



Origin of cosmic magnetism: primordial or astrophysical?

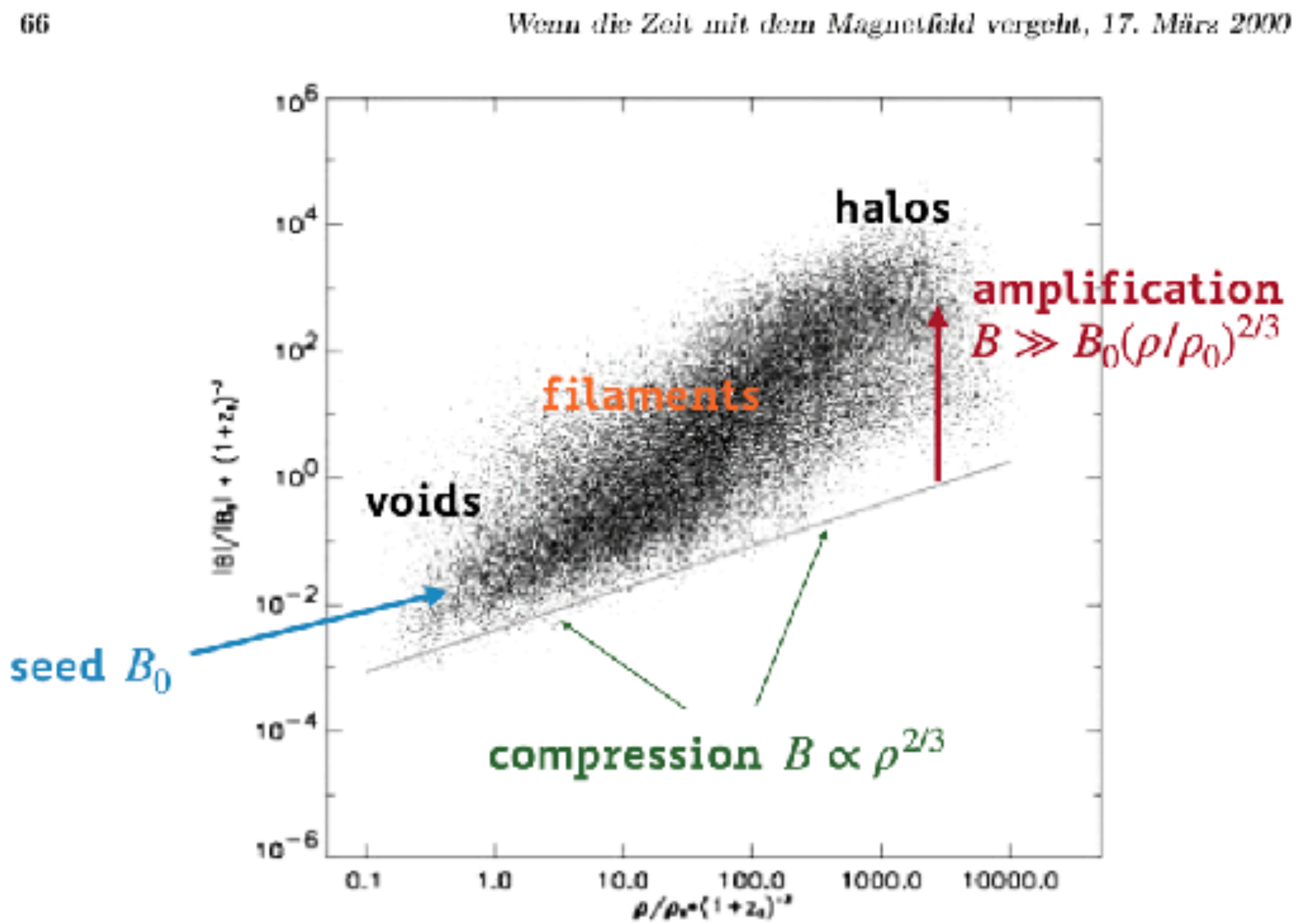
# Let's start from the beginning...

Vazza




Origin of cosmic magnetism: primordial or astrophysical?

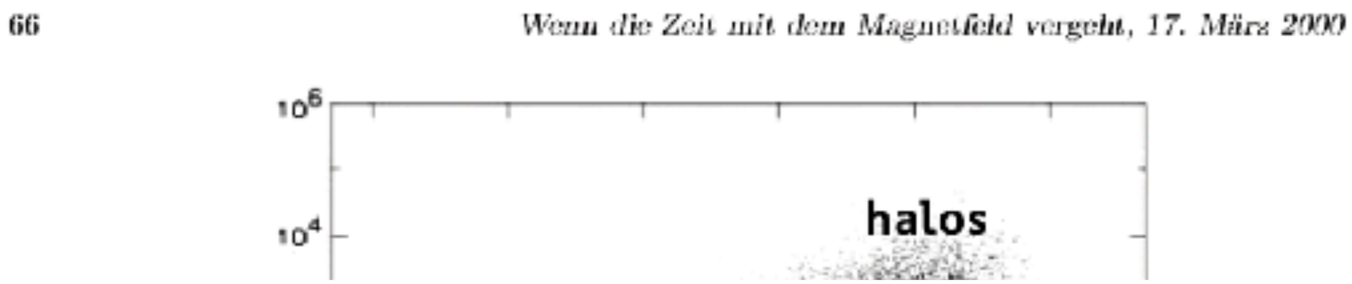
# Get away from galaxy clusters!



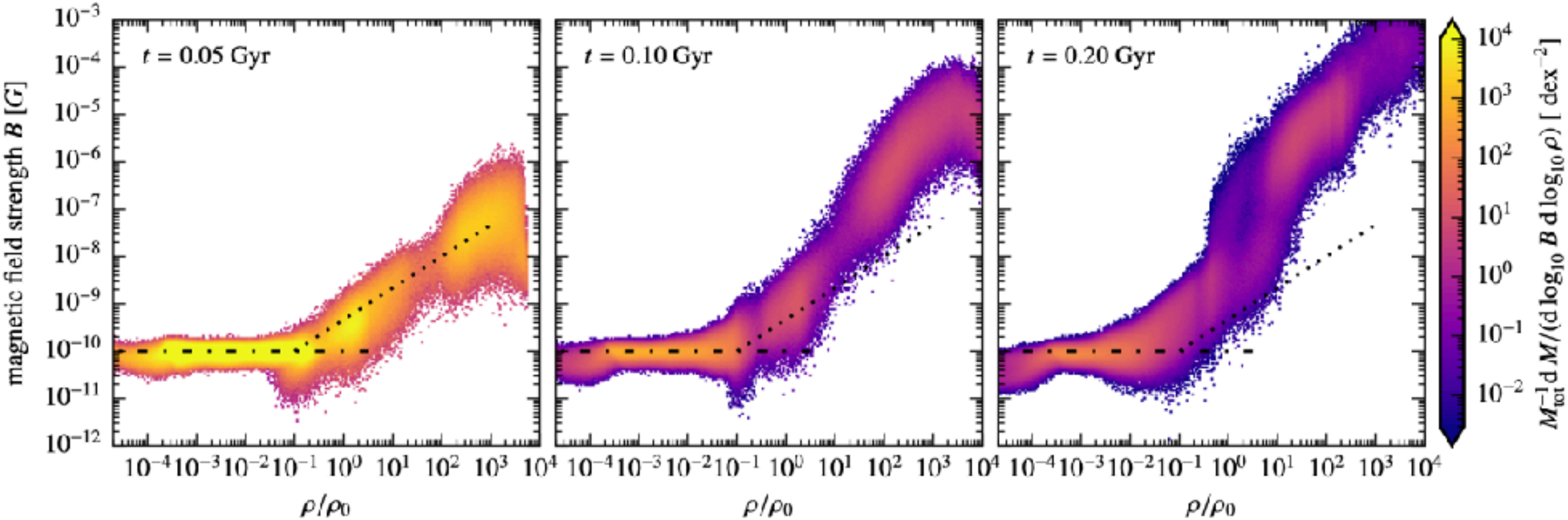

K. DOLAG (PHD THESIS 2000)

Vazza

# Get away from galaxy clusters!




Pfrommer

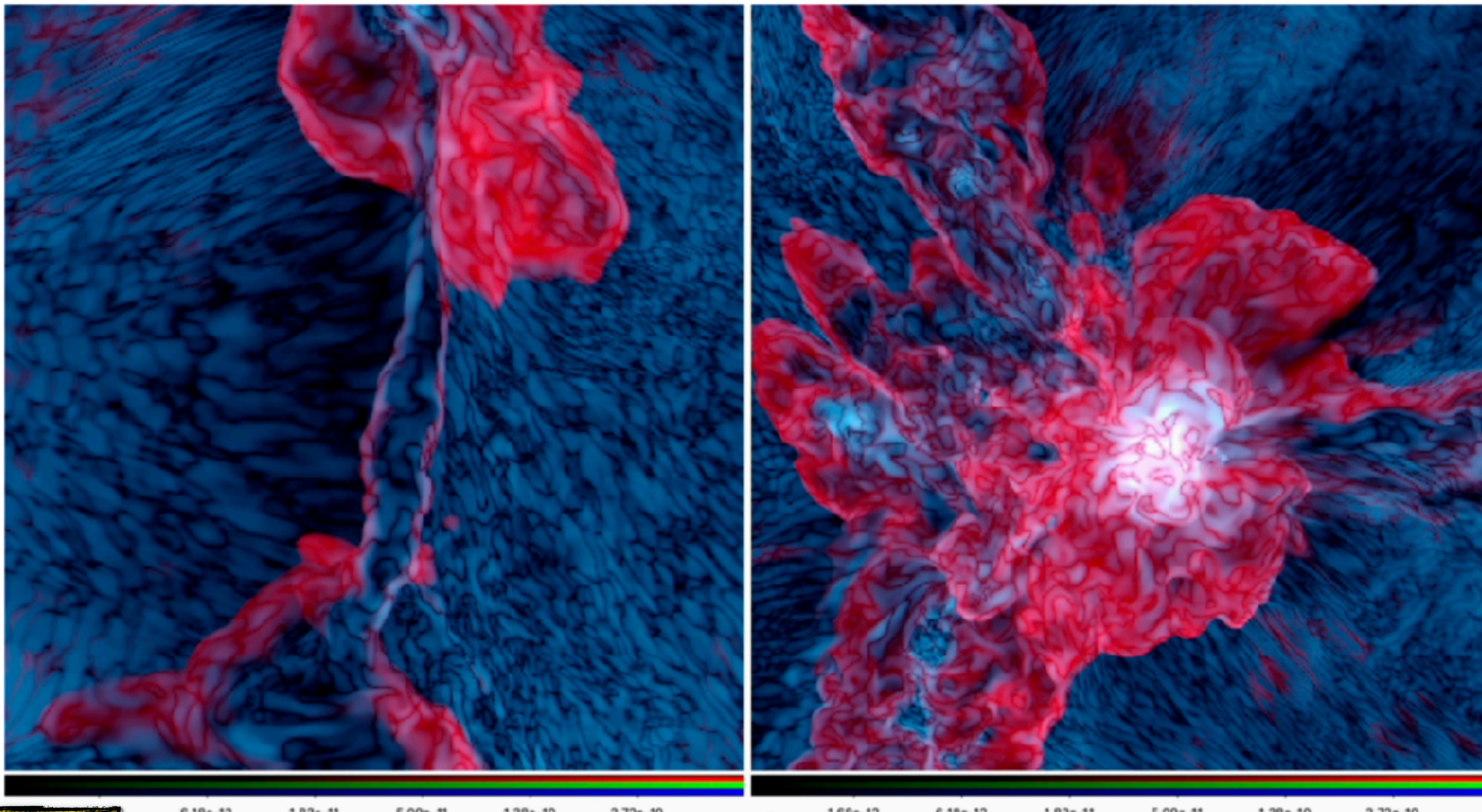



Vazza

# Get away from galaxy clusters!

**Filaments**: <u>no or little dynamo</u>, memory of seed $B_0$ is **preserved**

**Clusters**: <u>dynamo amplification</u>, memory of seed $B_0$ is **lost**




Vazza

red=gas temperature, blue/yellow= B-field amplitude

# Is it primordial?

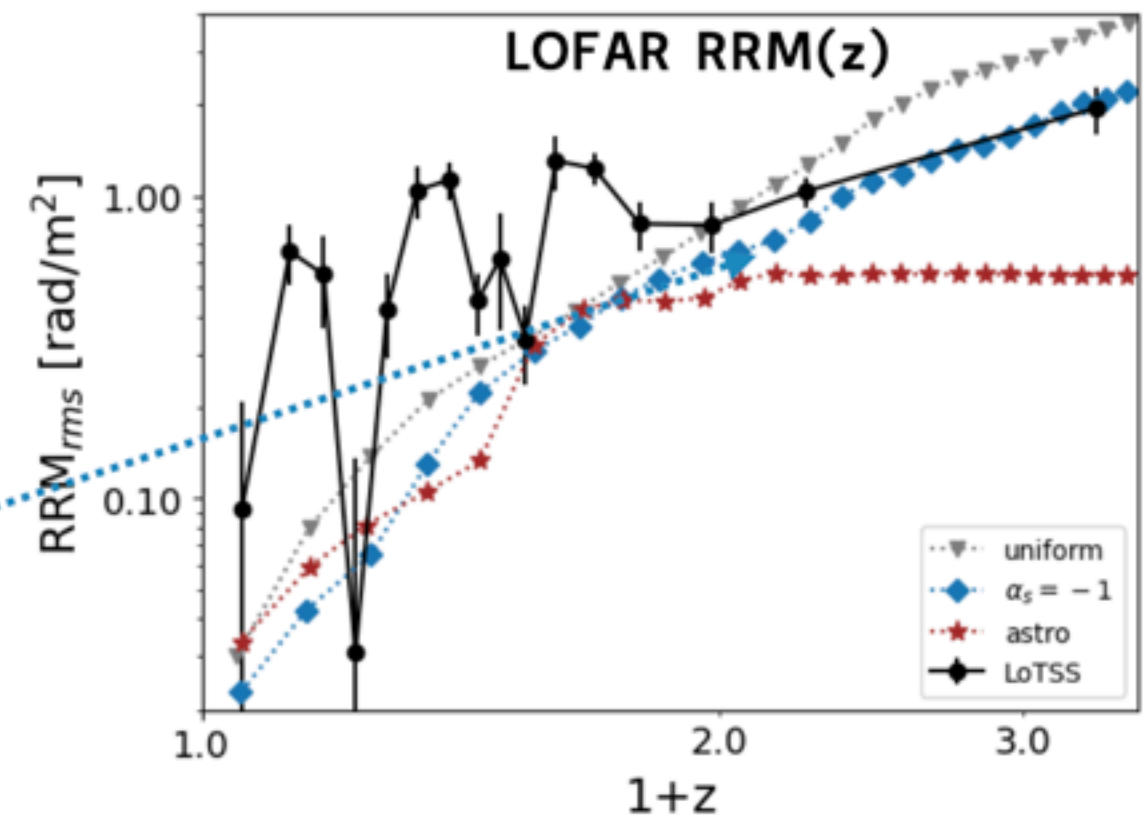
Vazza

~~Uniform B model (0.1nG)~~

Primordial model with $n_B$=-1

~~purely astrophysical seeding~~

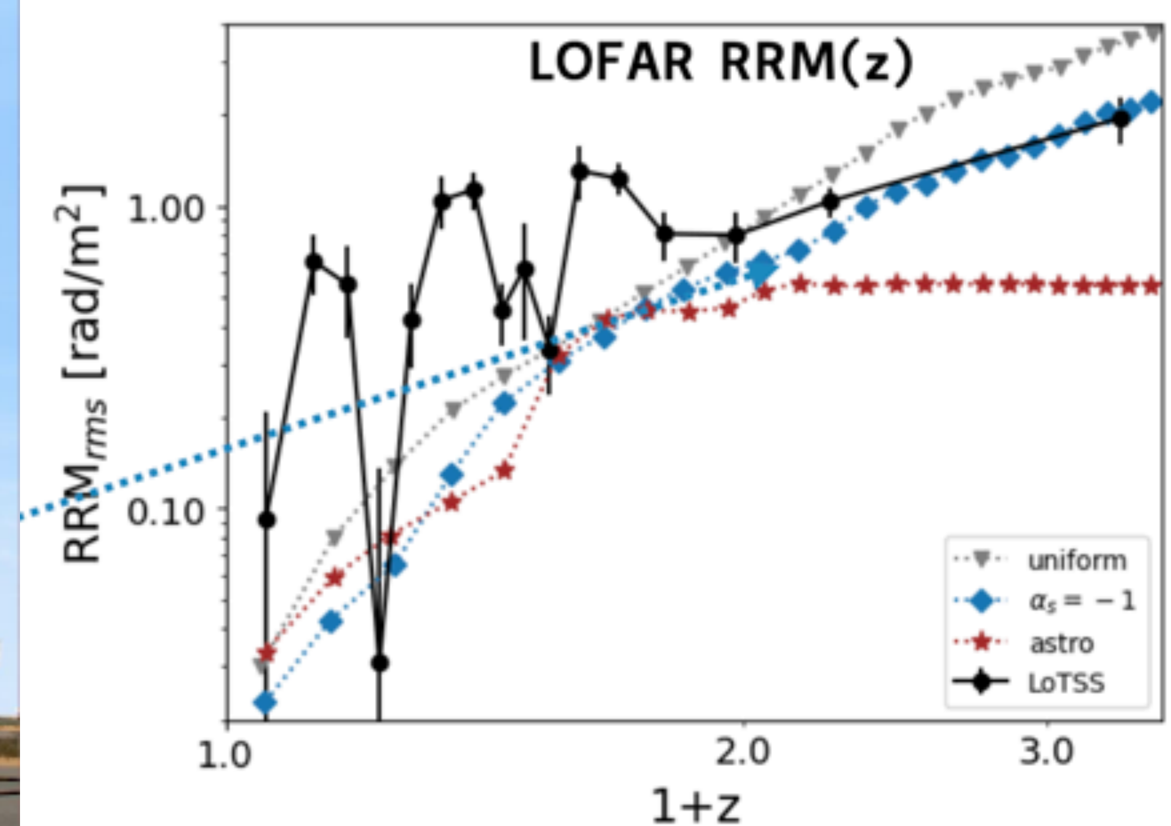
~~(AGN+stellar winds)~~




CARRETTI + 23, 24

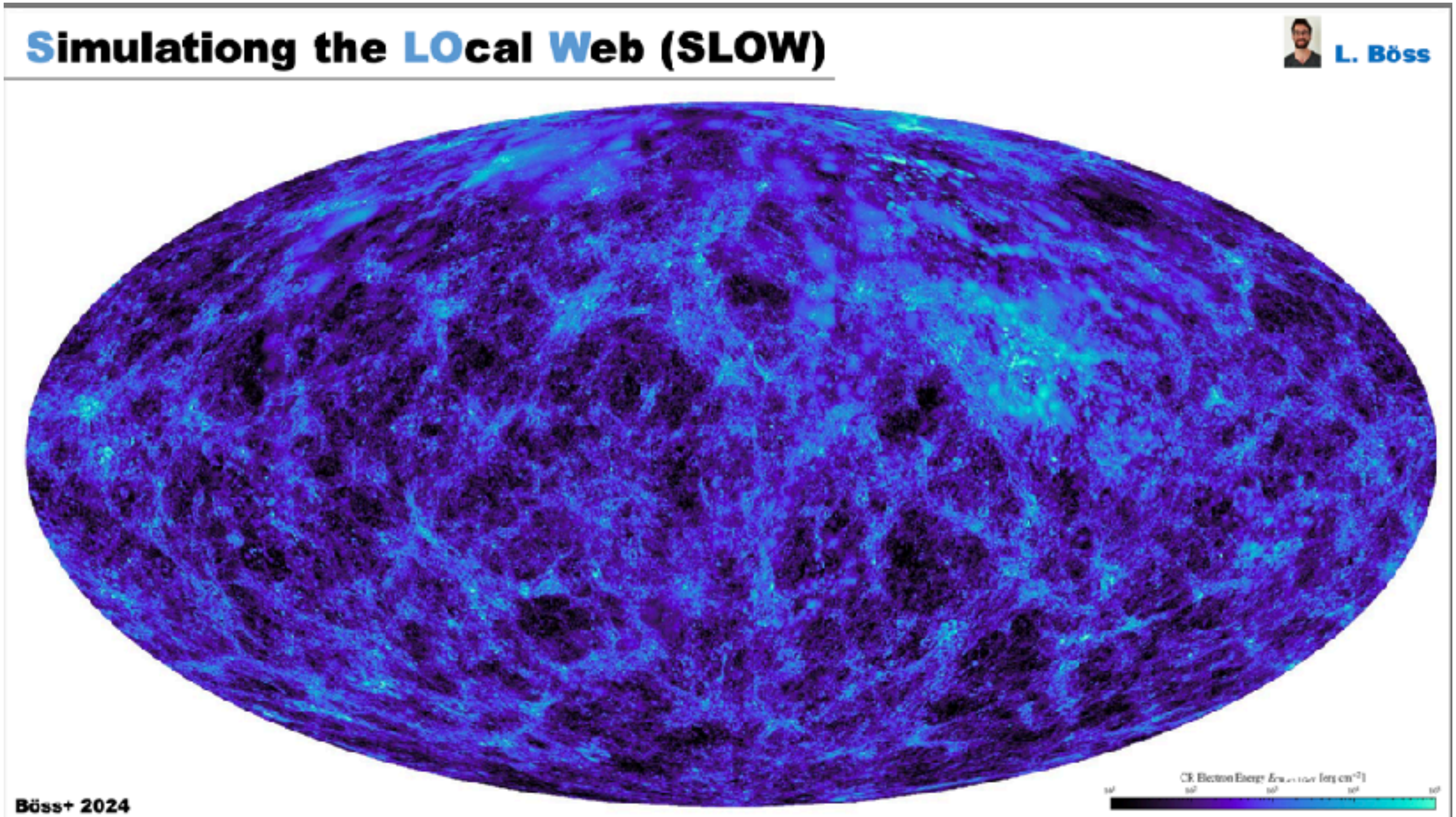
# Is it primordial?




CARRETTI + 23, 24

# Local Universe




Dolag

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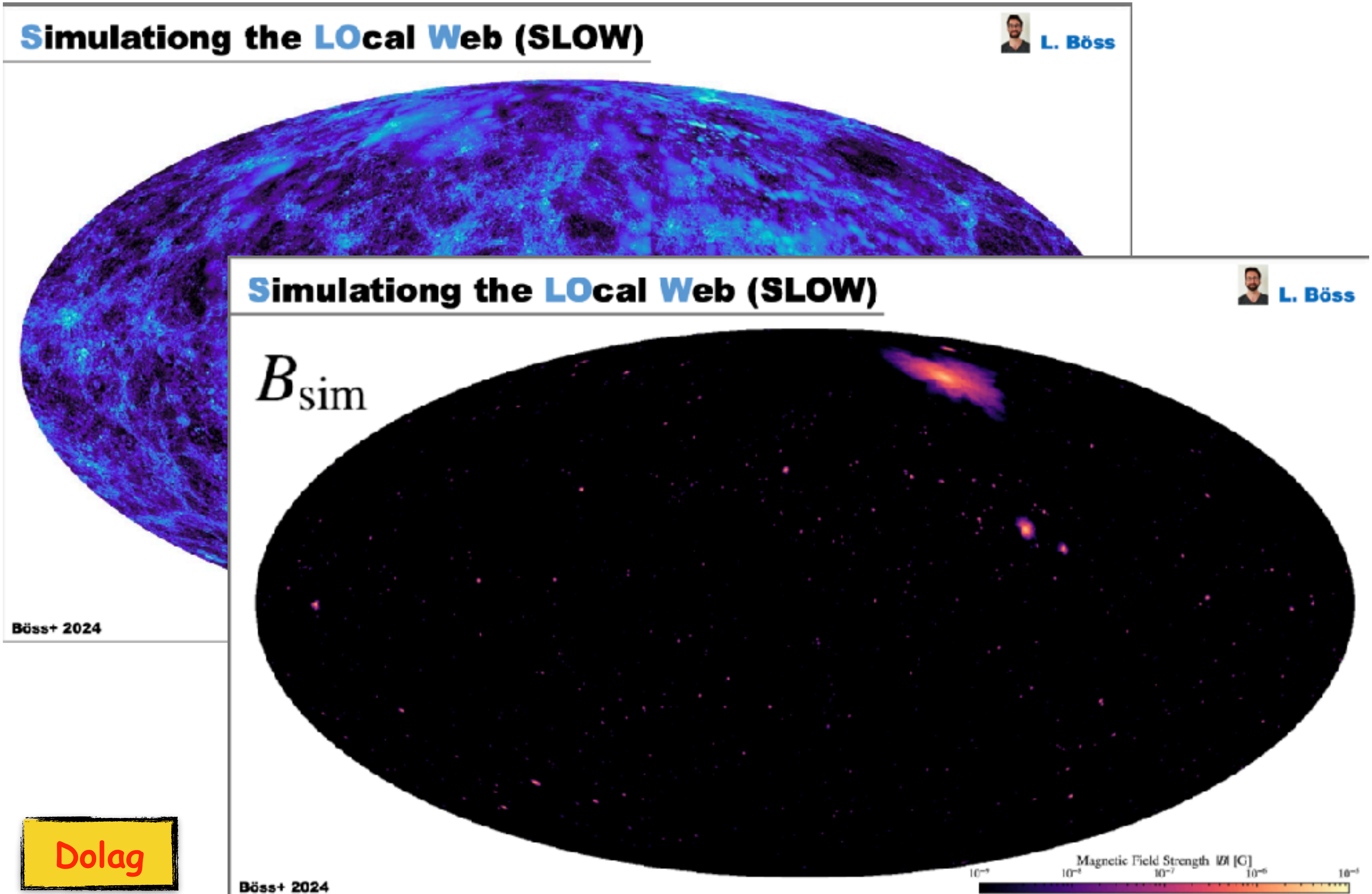


Dolag

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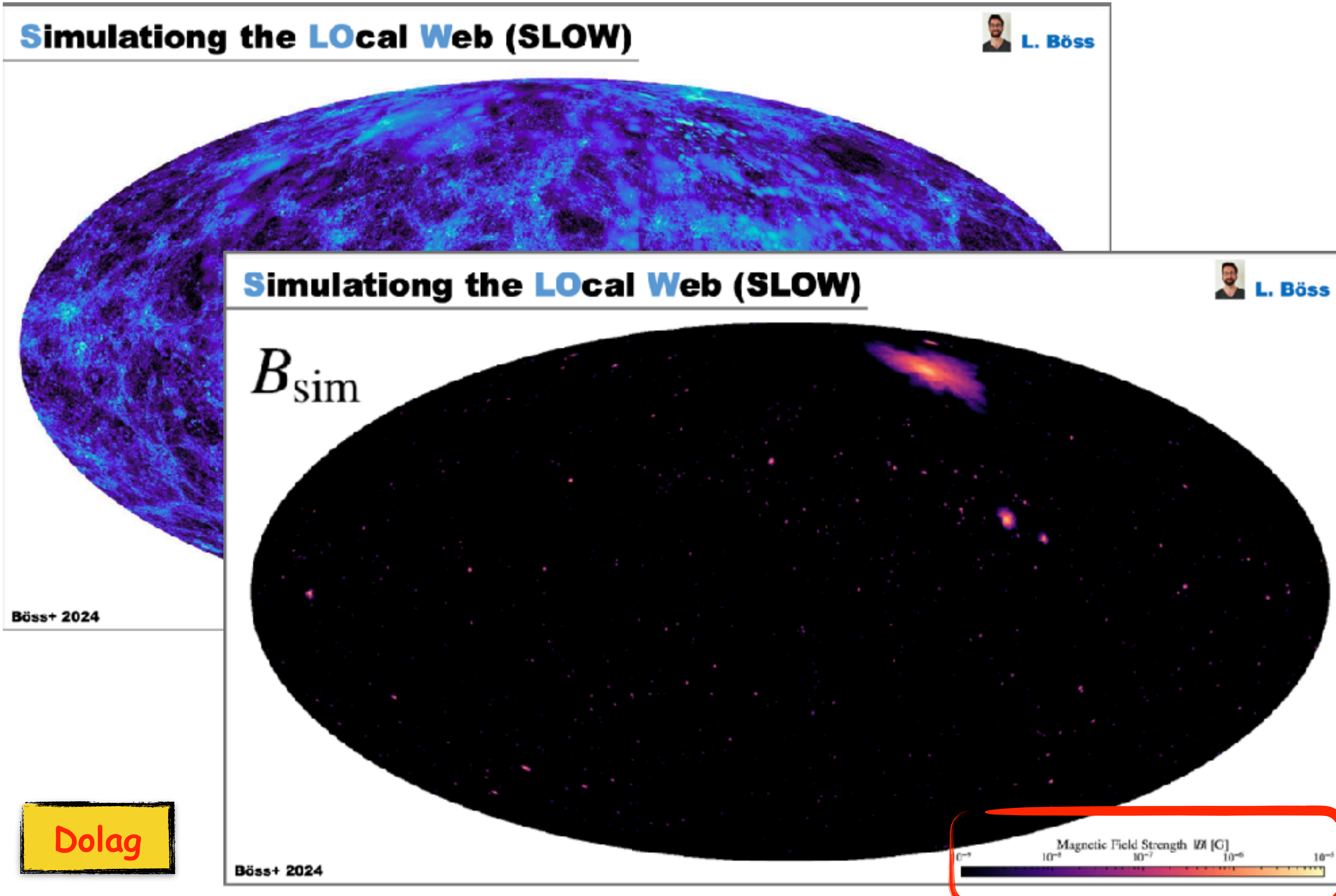
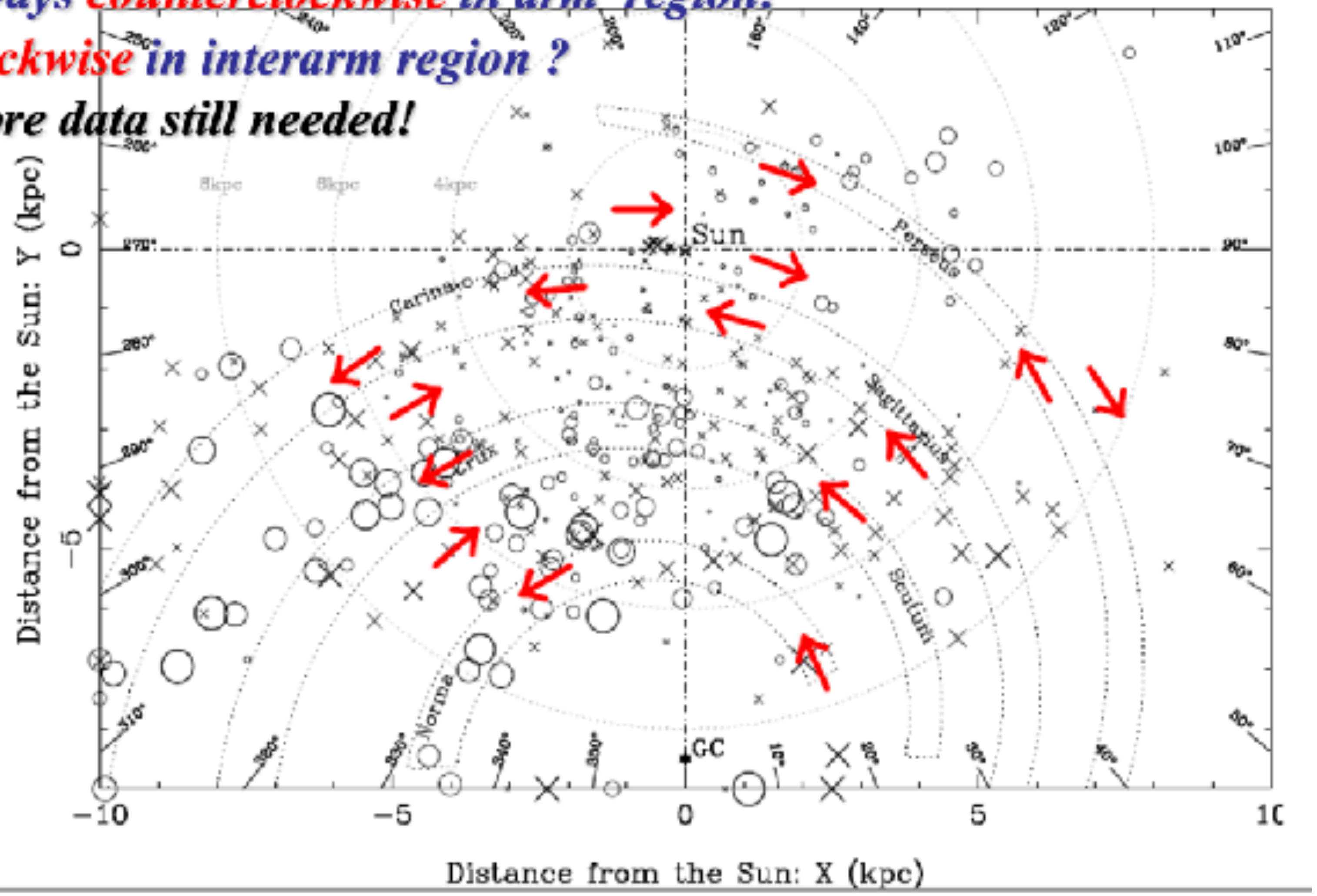



Dolag

# The Galaxy

- *always counterclockwise in arm region!*
- *clockwise in interarm region ?*
- *More data still needed!*




Han

# The Galaxy

- *always **counterclockwise** in arm region!*
- ***clockwise** in interarm region ?*
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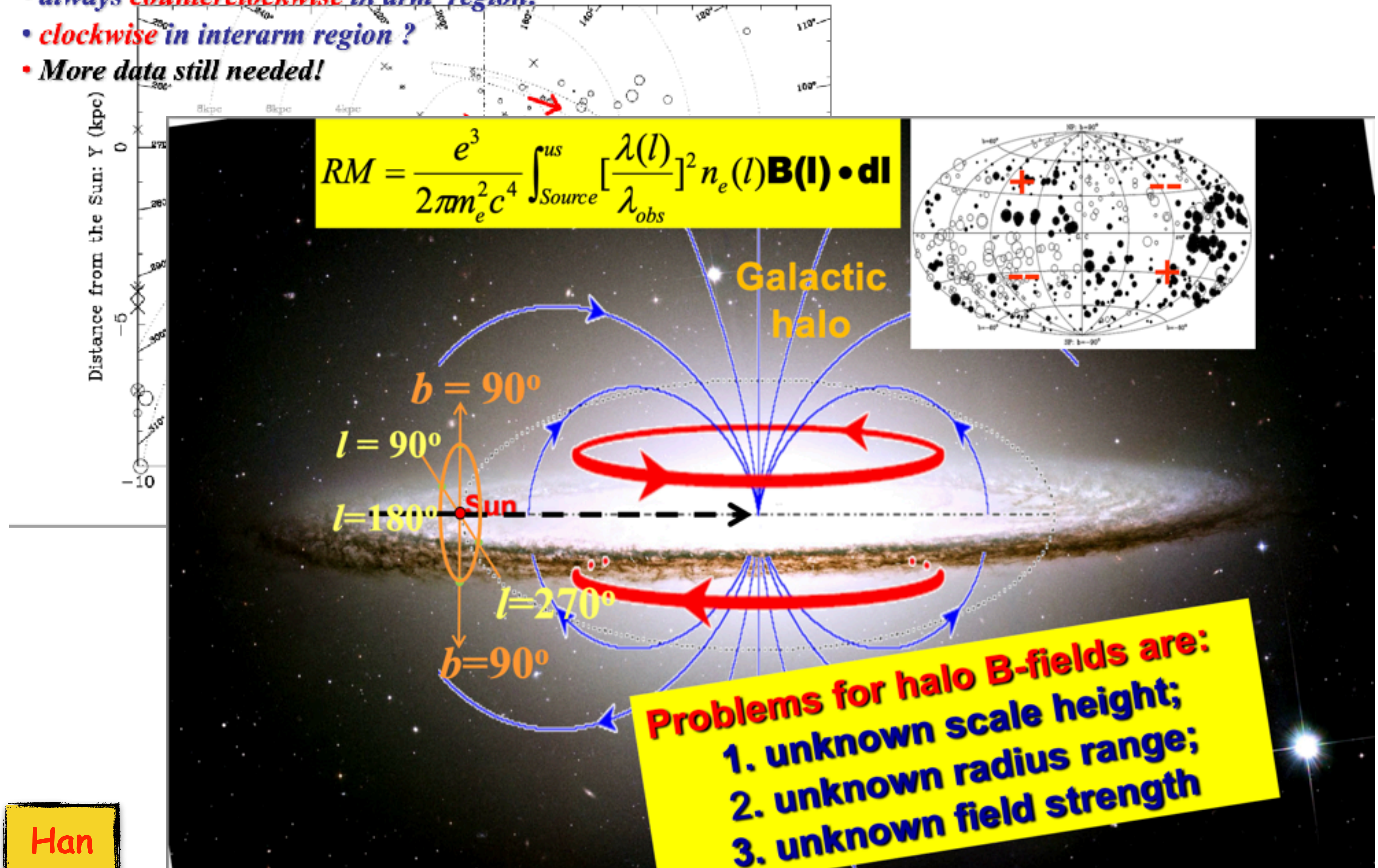
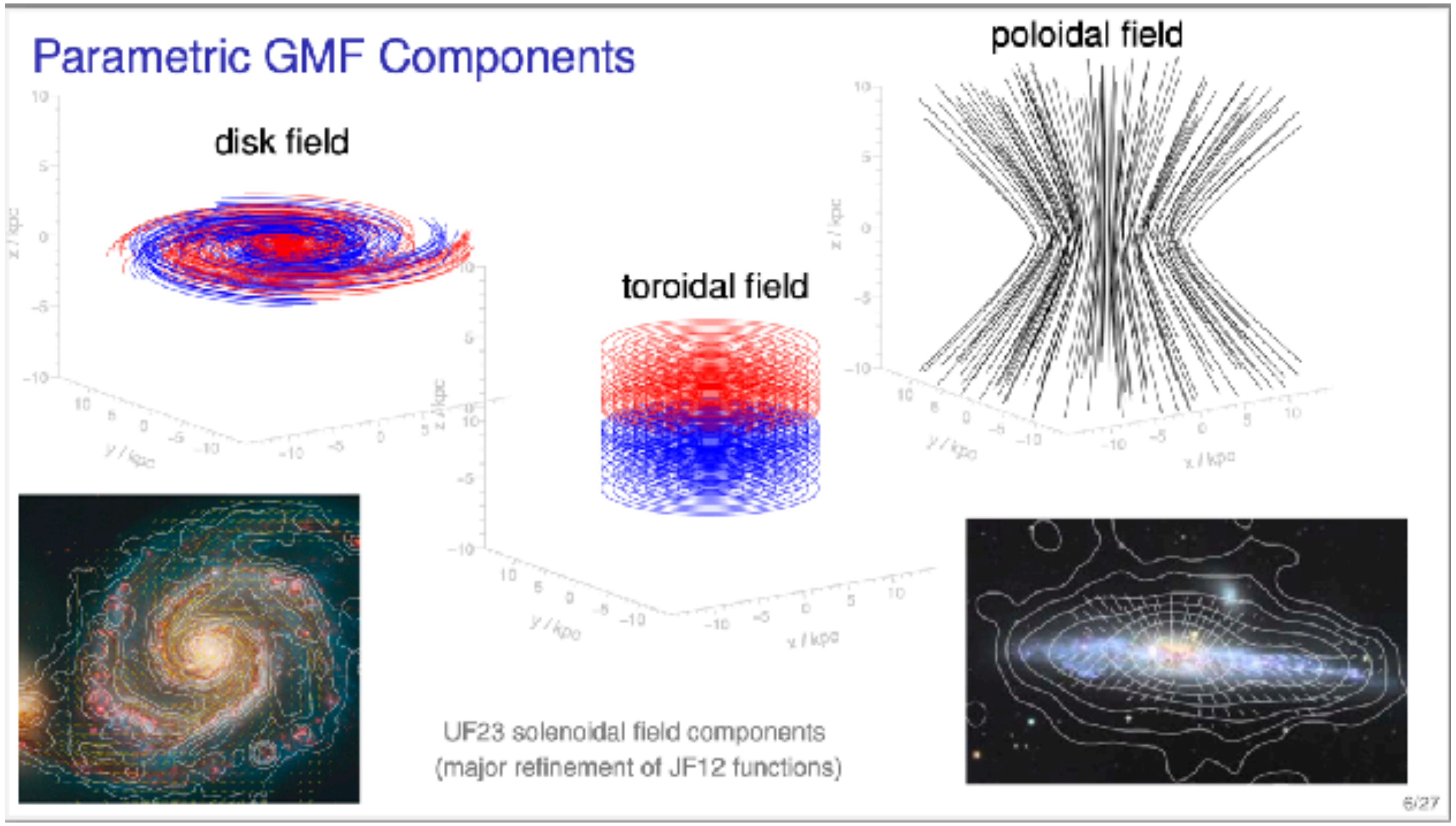


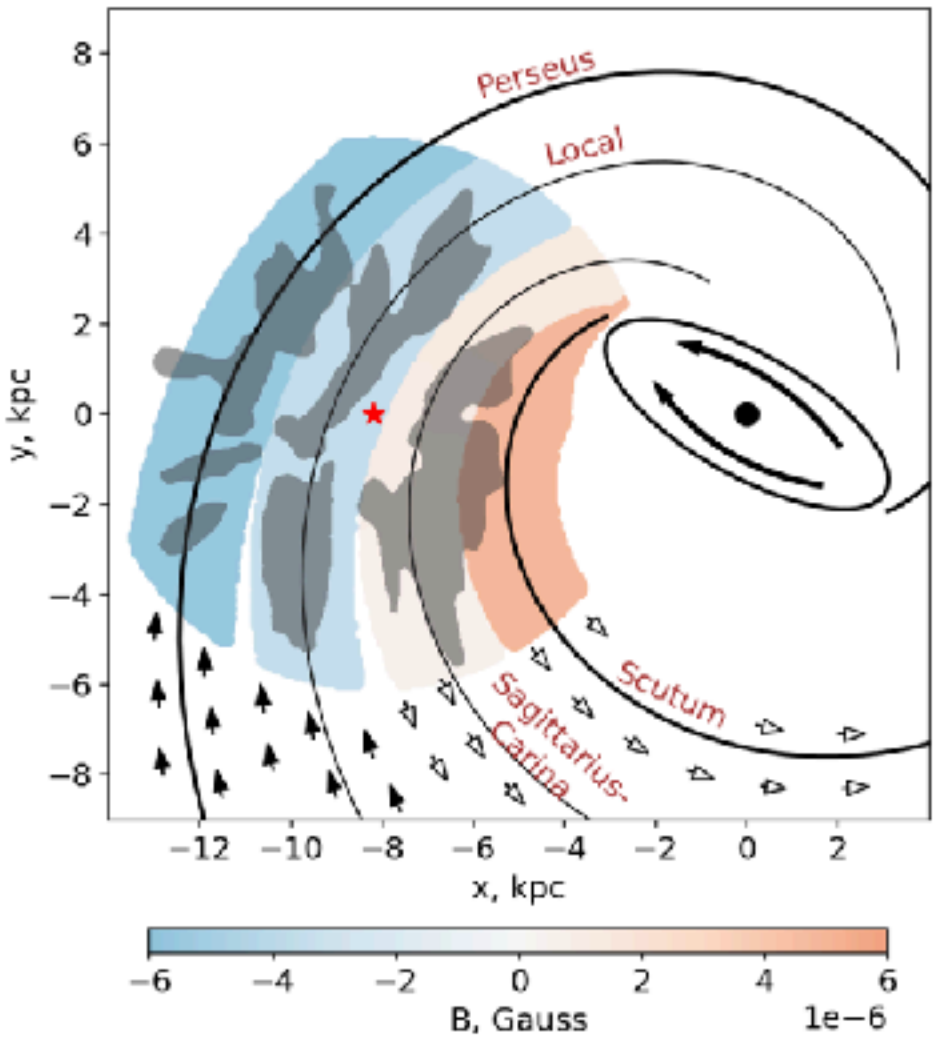

Han

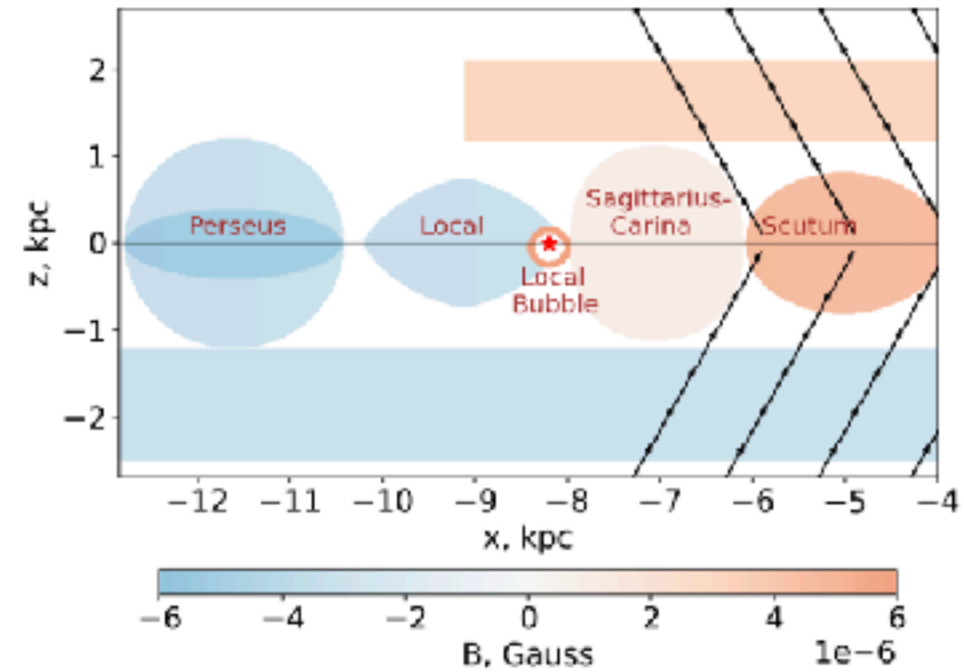
# The galactic halo

Unger

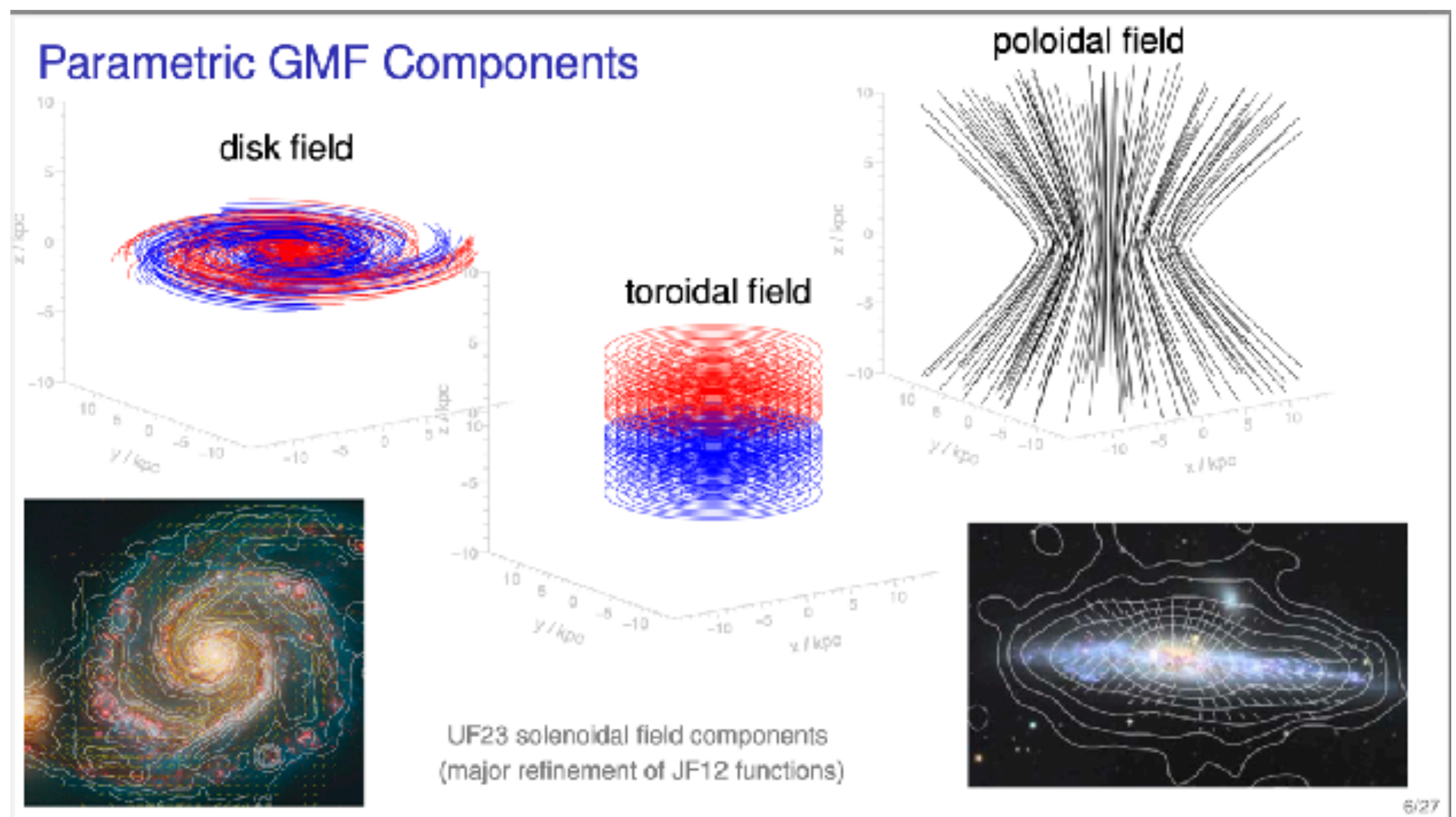


# The galactic halo



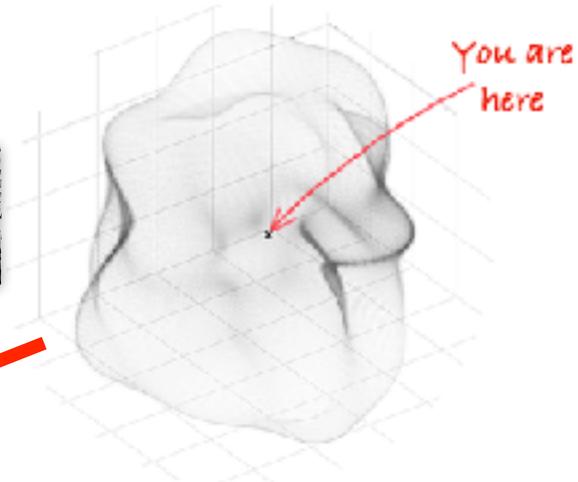

Korochkin

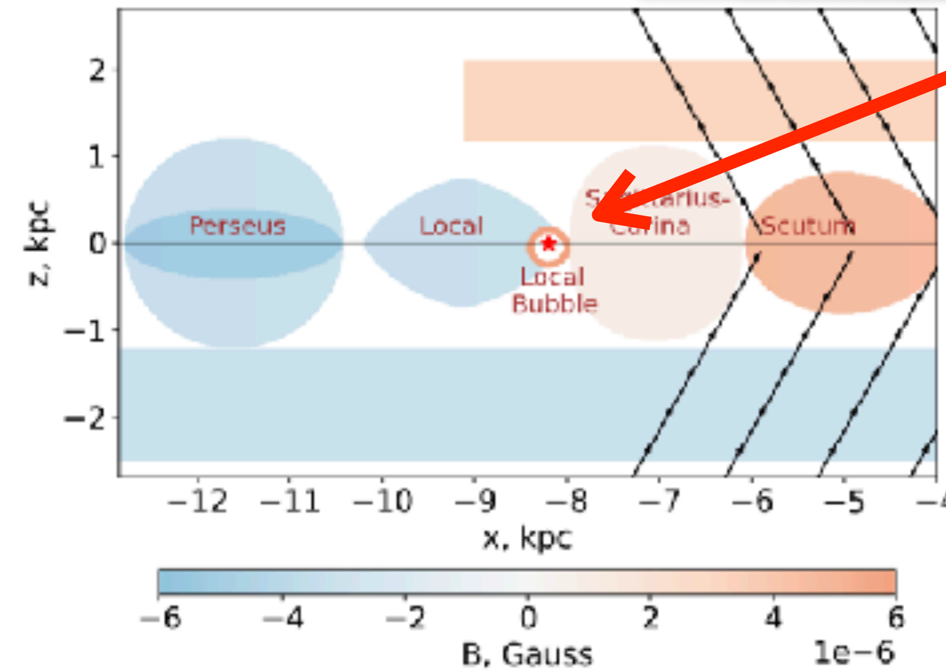


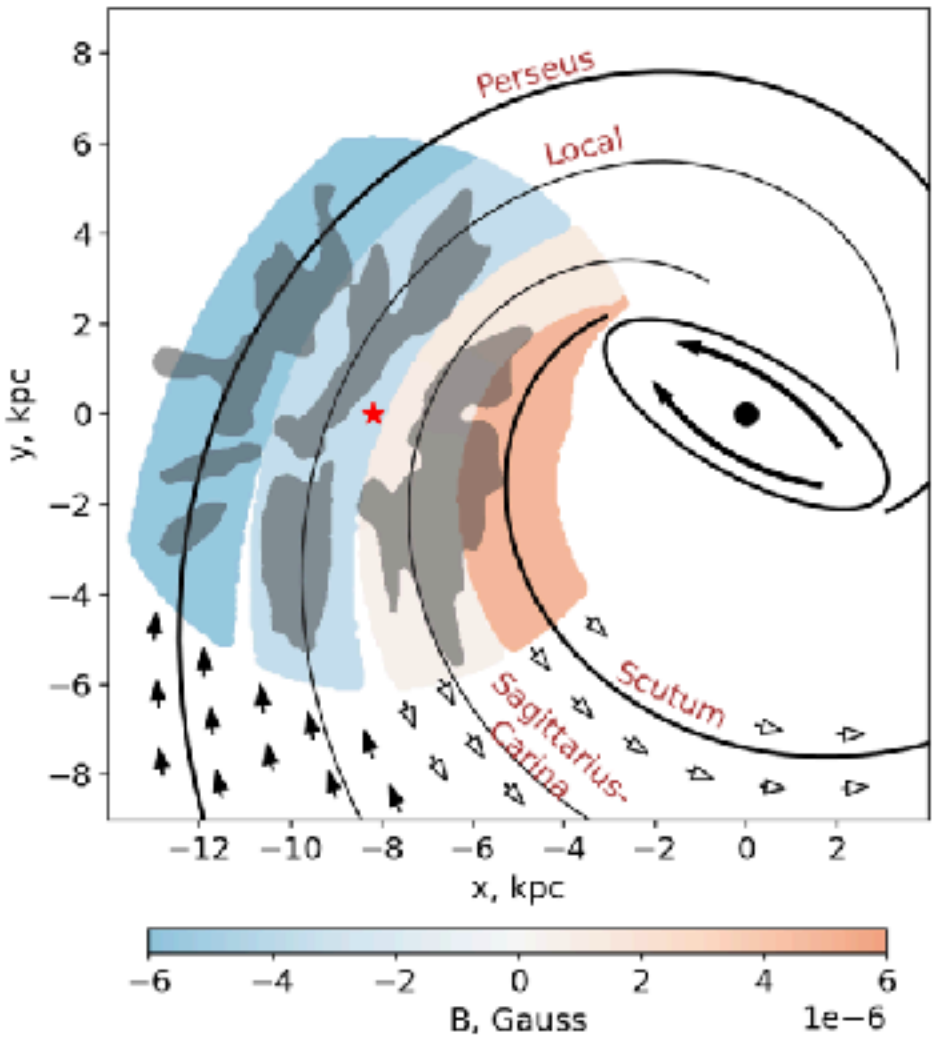

Unger

# The galactic halo

Pelgrims

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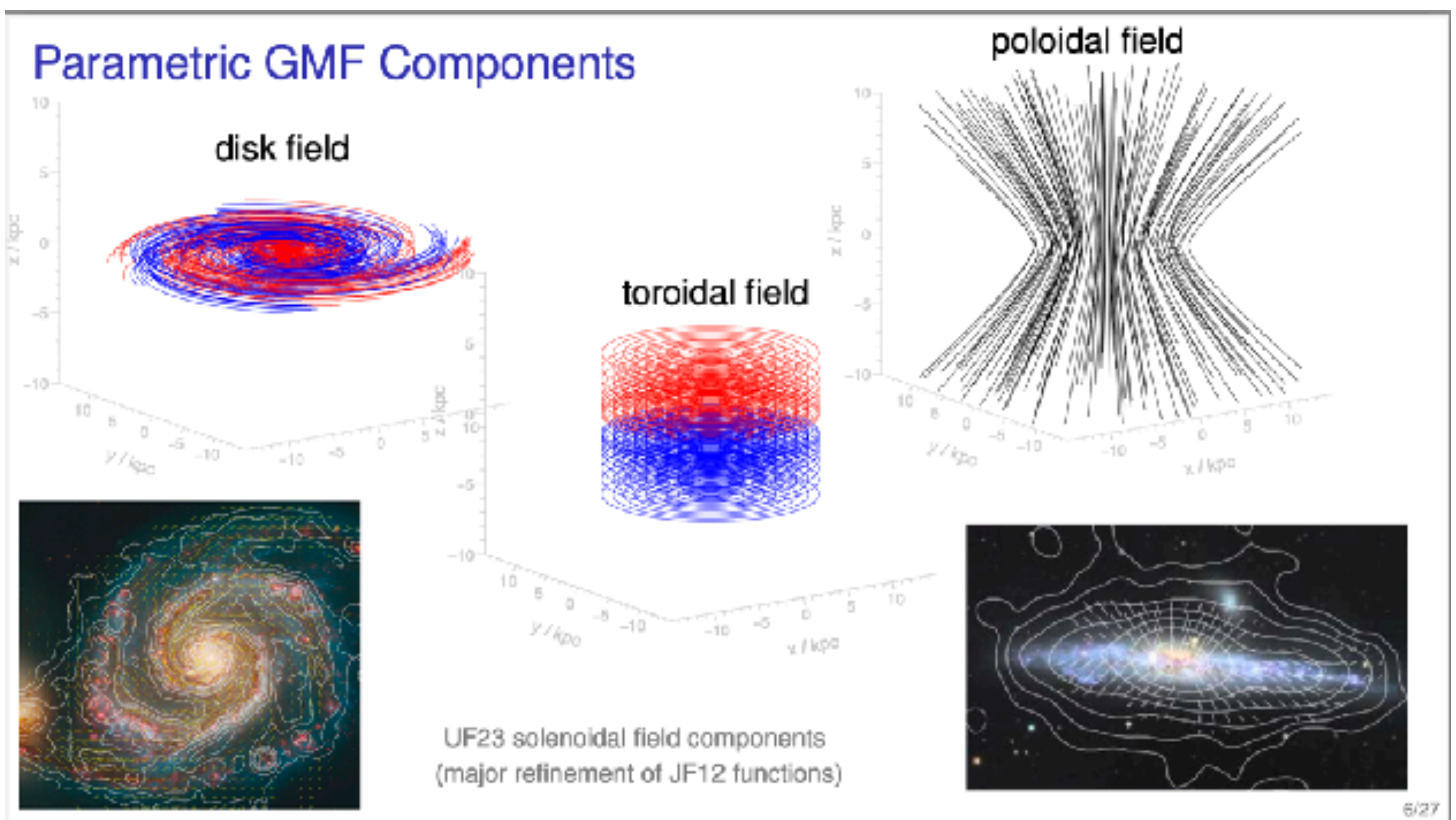

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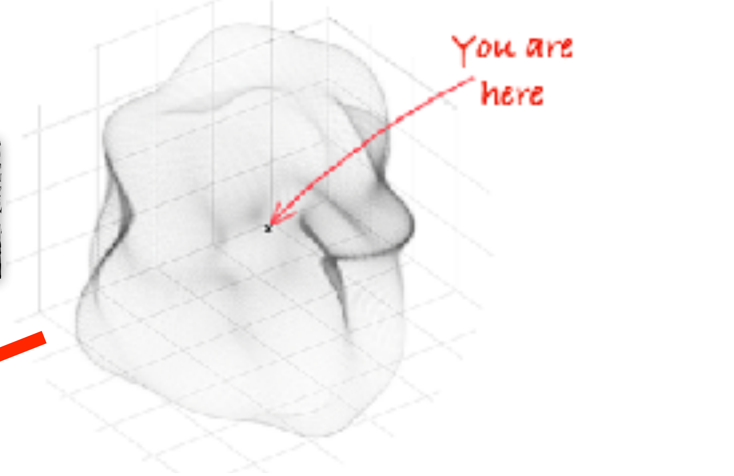


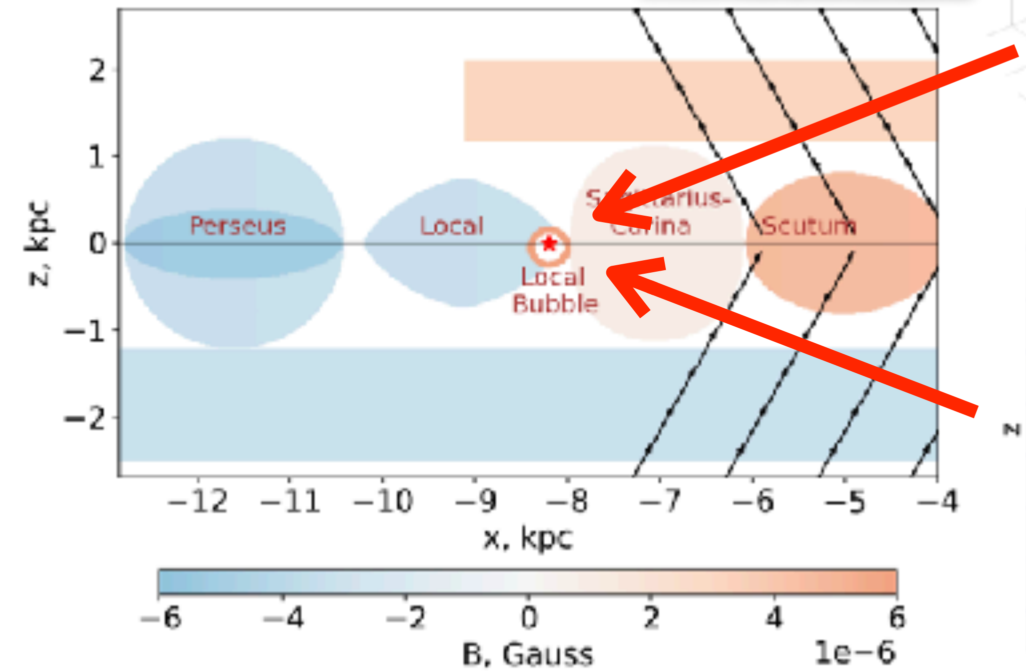


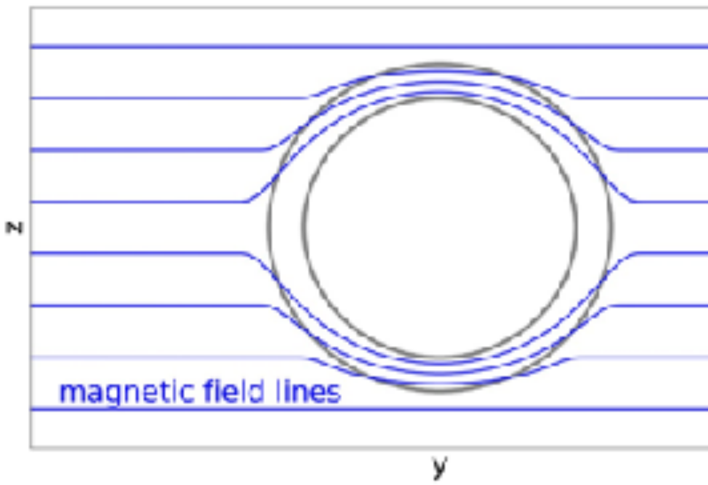


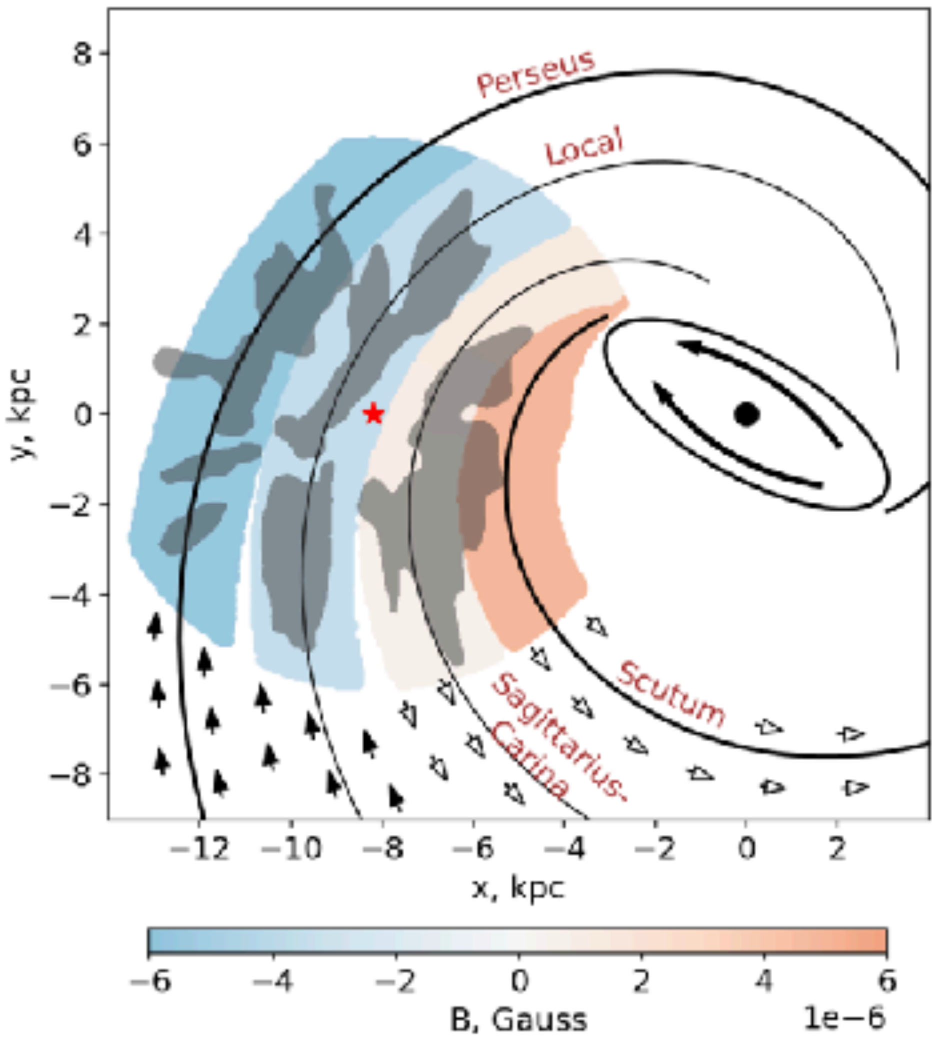


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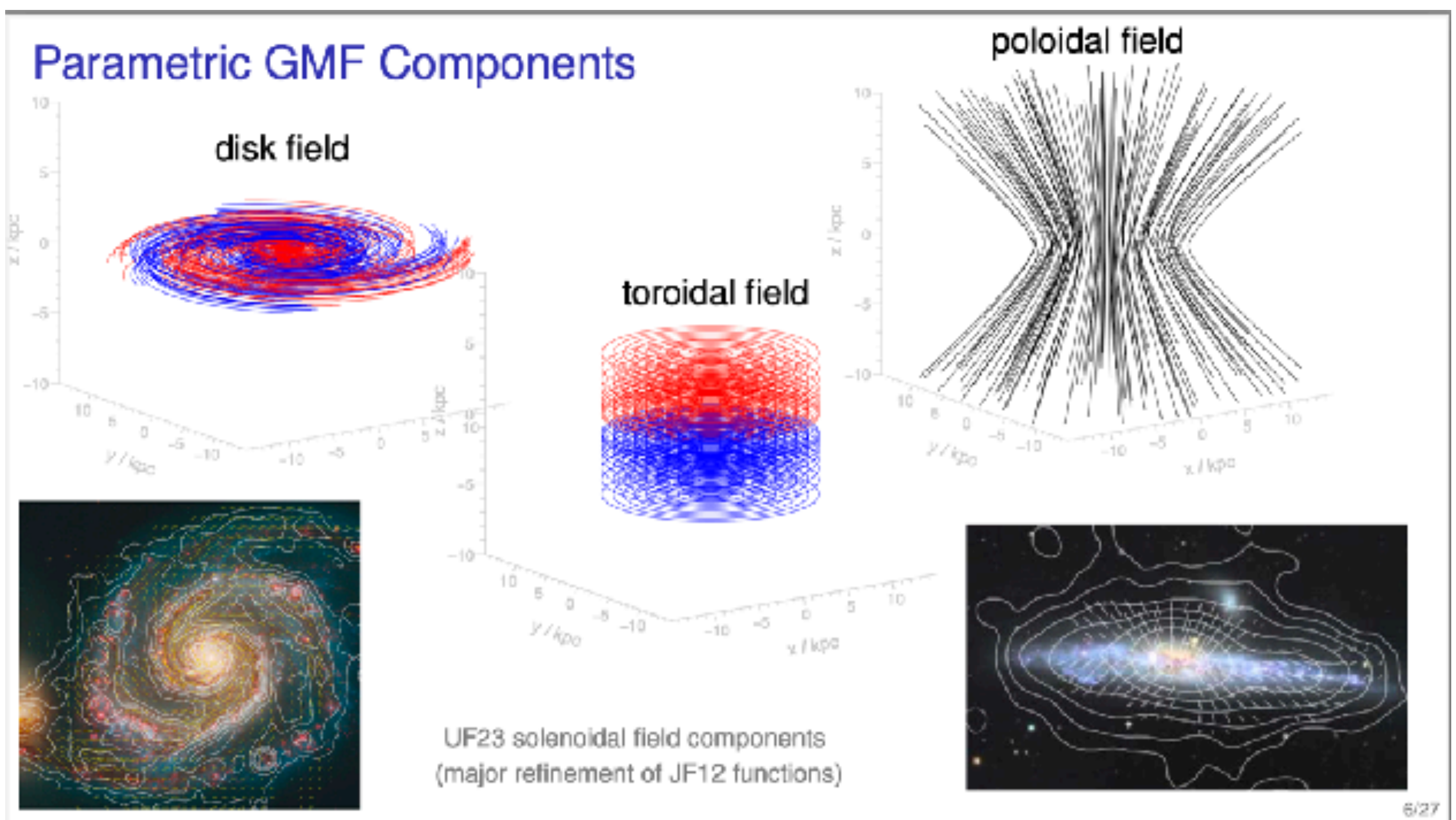


Unger

# The galactic halo

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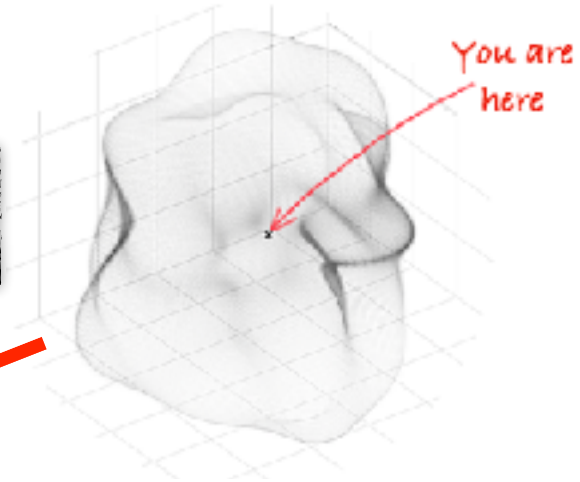
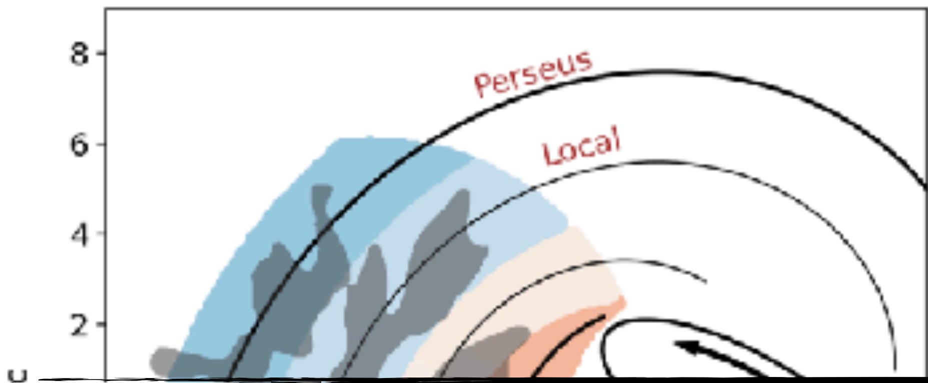
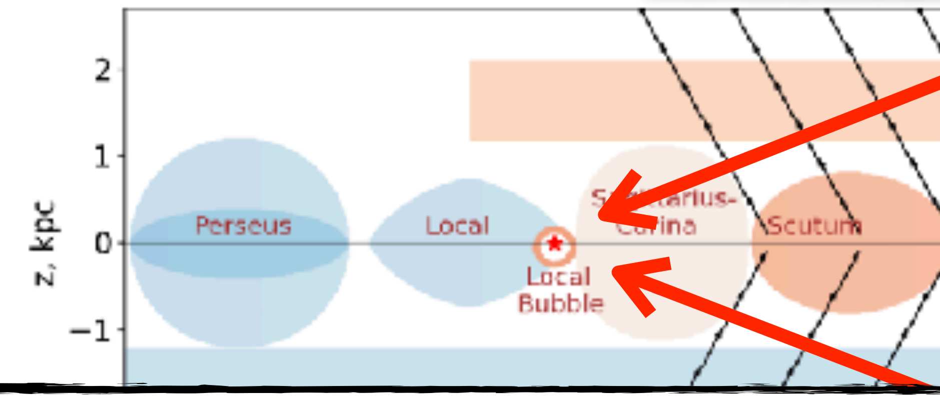
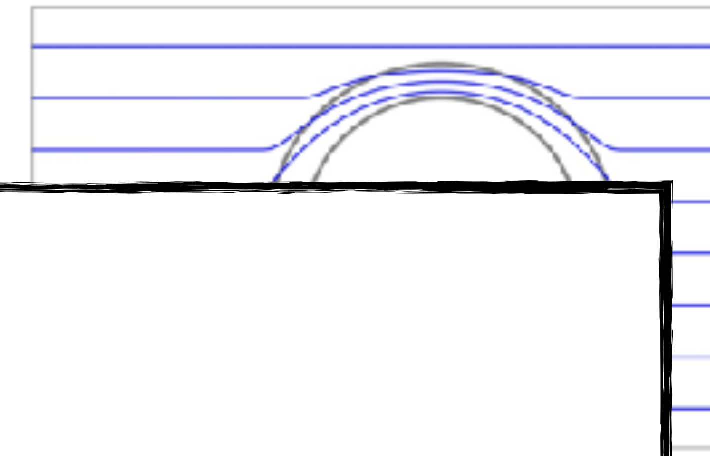


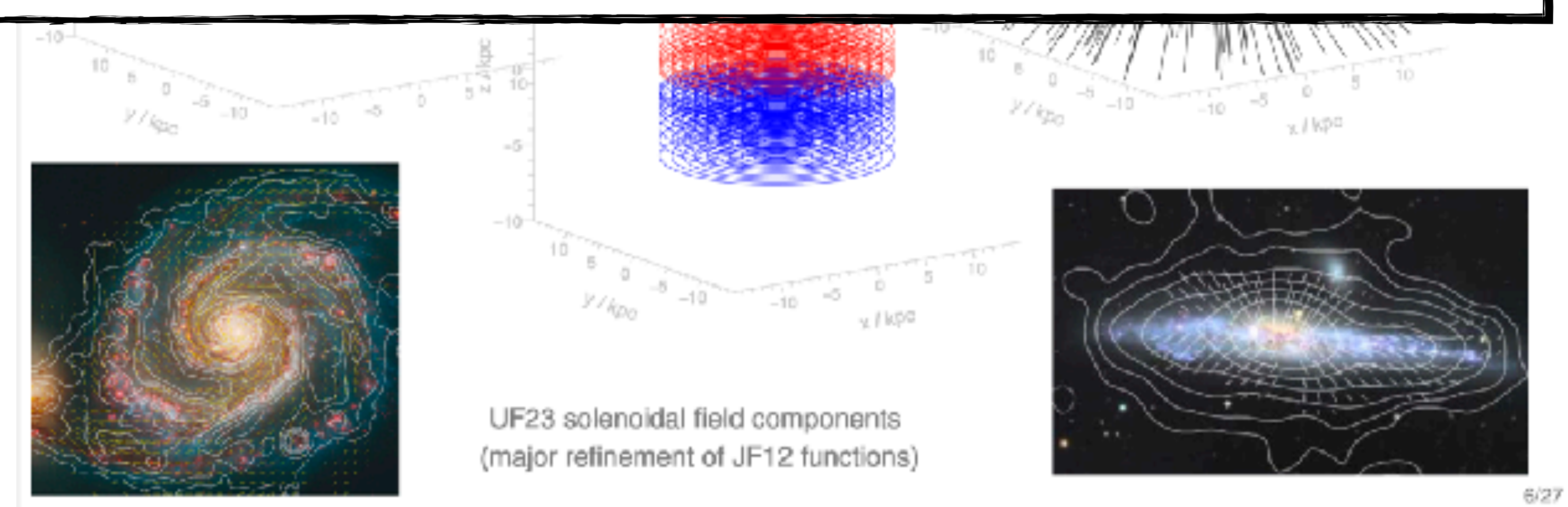
Draft version July 12, 2024
Typeset using LaTeX twocolumn style in AASTeX631

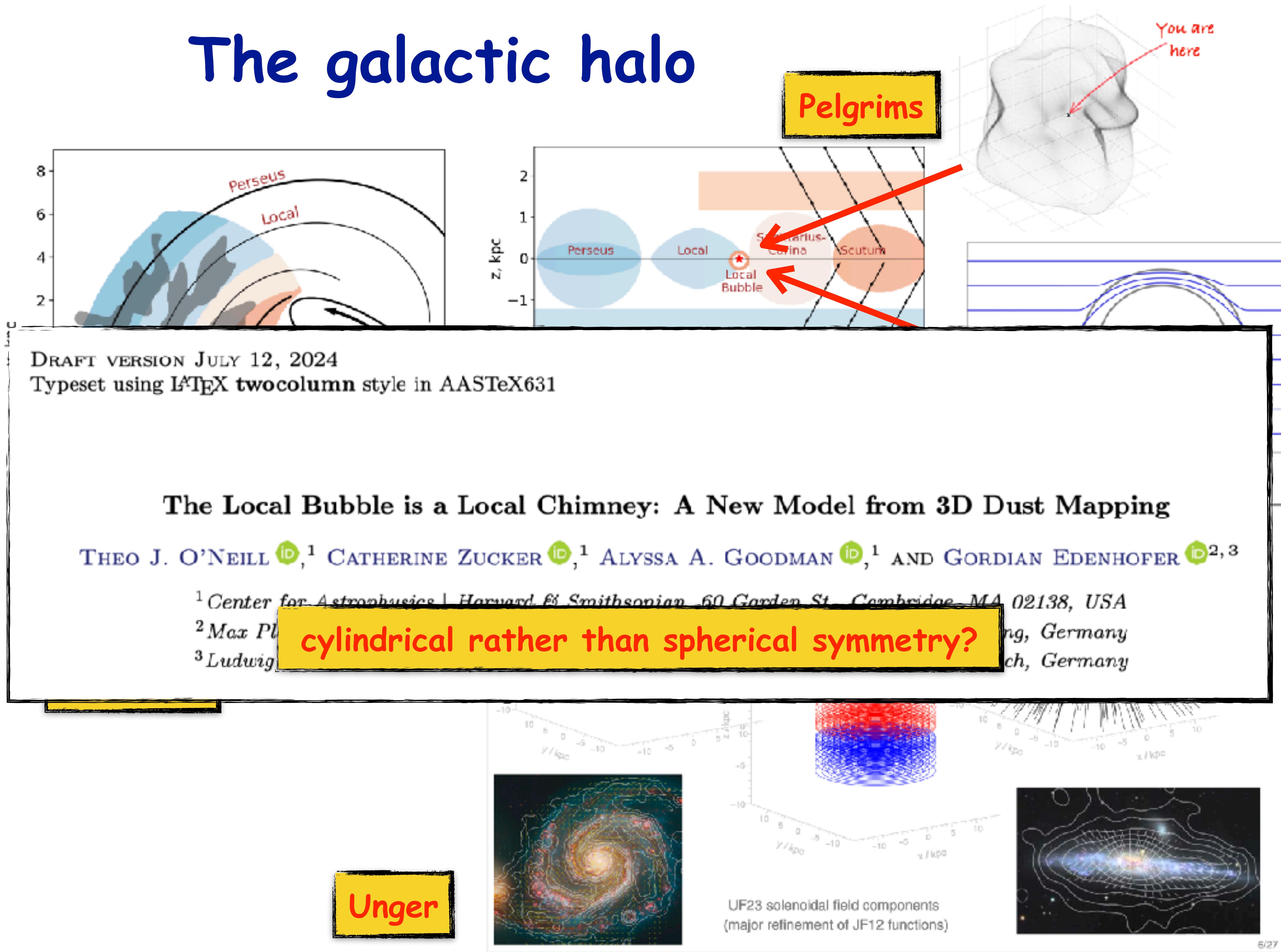
## The Local Bubble is a Local Chimney: A New Model from 3D Dust Mapping

Theo J. O'Neill[1] Catherine Zucker[1] Alyssa A. Goodman[1] and Gordian Edenhofer[2,3]

[1] Center for Astrophysics | Harvard & Smithsonian, 60 Garden St., Cambridge, MA 02138, USA
[2] Max Planck Institute for Astrophysics, Karl-Schwarzschild-Straße 1, 85748 Garching, Germany
[3] Ludwig Maximilian University of Munich, Geschwister-Scholl-Platz 1, 80539 Munich, Germany

Unger





The galactic halo
Pelgrims
You are here
Perseus
Local
Sagittarius-Carina
Scutum
Local Bubble
z, kpc
Draft version July 12, 2024
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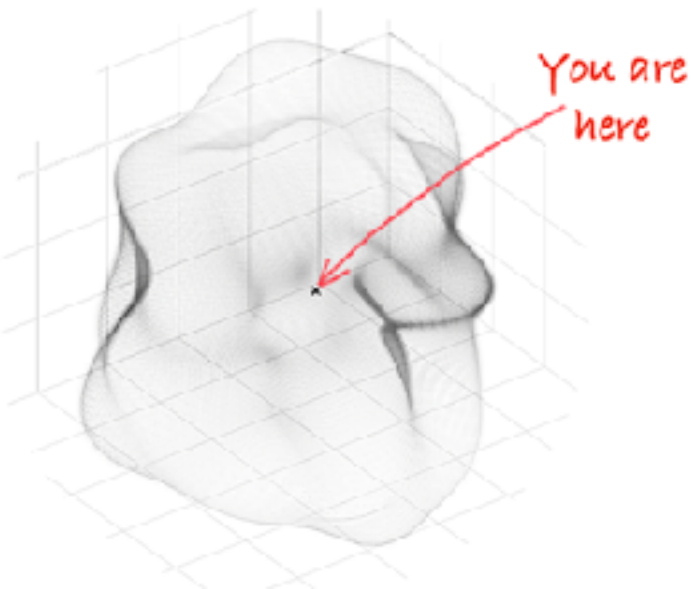
[1] Center for Astrophysics | Harvard & Smithsonian, 60 Garden St., Cambridge, MA 02138, USA
[2] Max Pl ... ng, Germany
[3] Ludwig ... ch, Germany
cylindrical rather than spherical symmetry?
Unger
UF23 solenoidal field components
(major refinement of JF12 functions)
6/27

# Many scales



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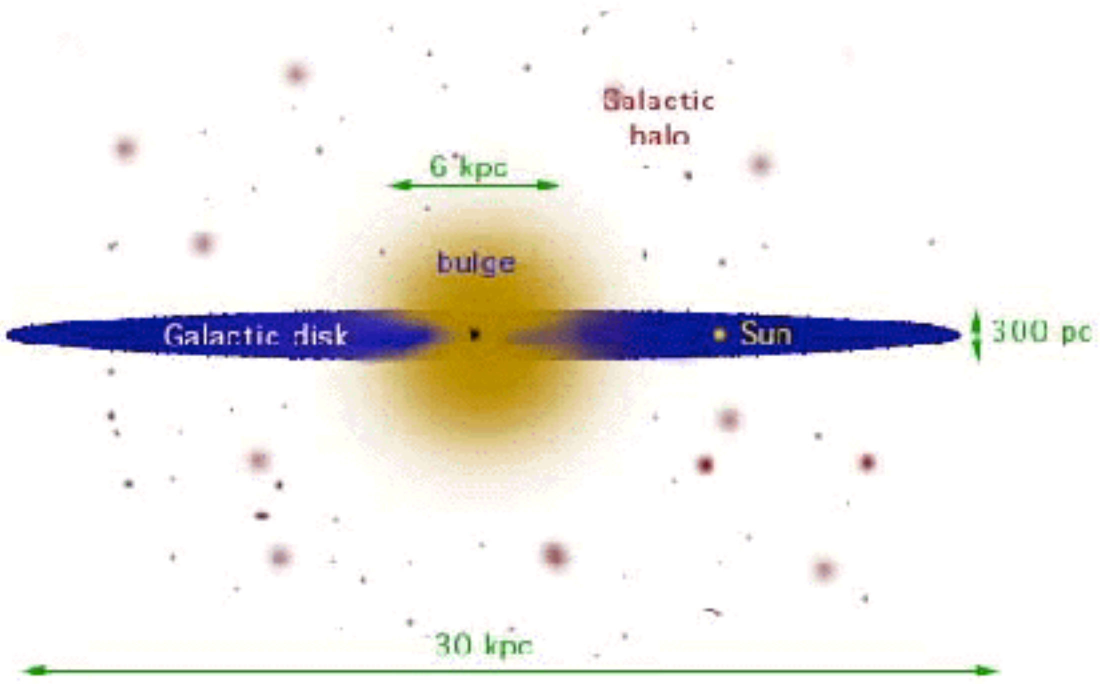
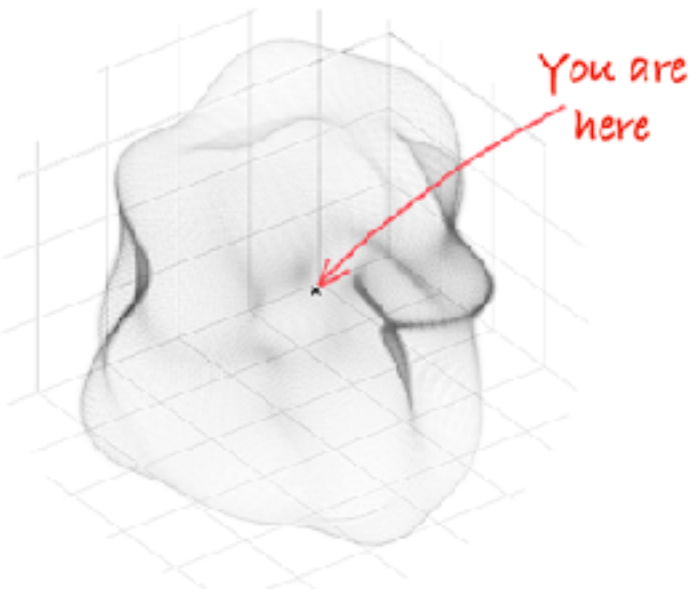


Galactic
halo
6 kpc
bulge
Galactic disk
Sun
300 pc
30 kpc

You are
here

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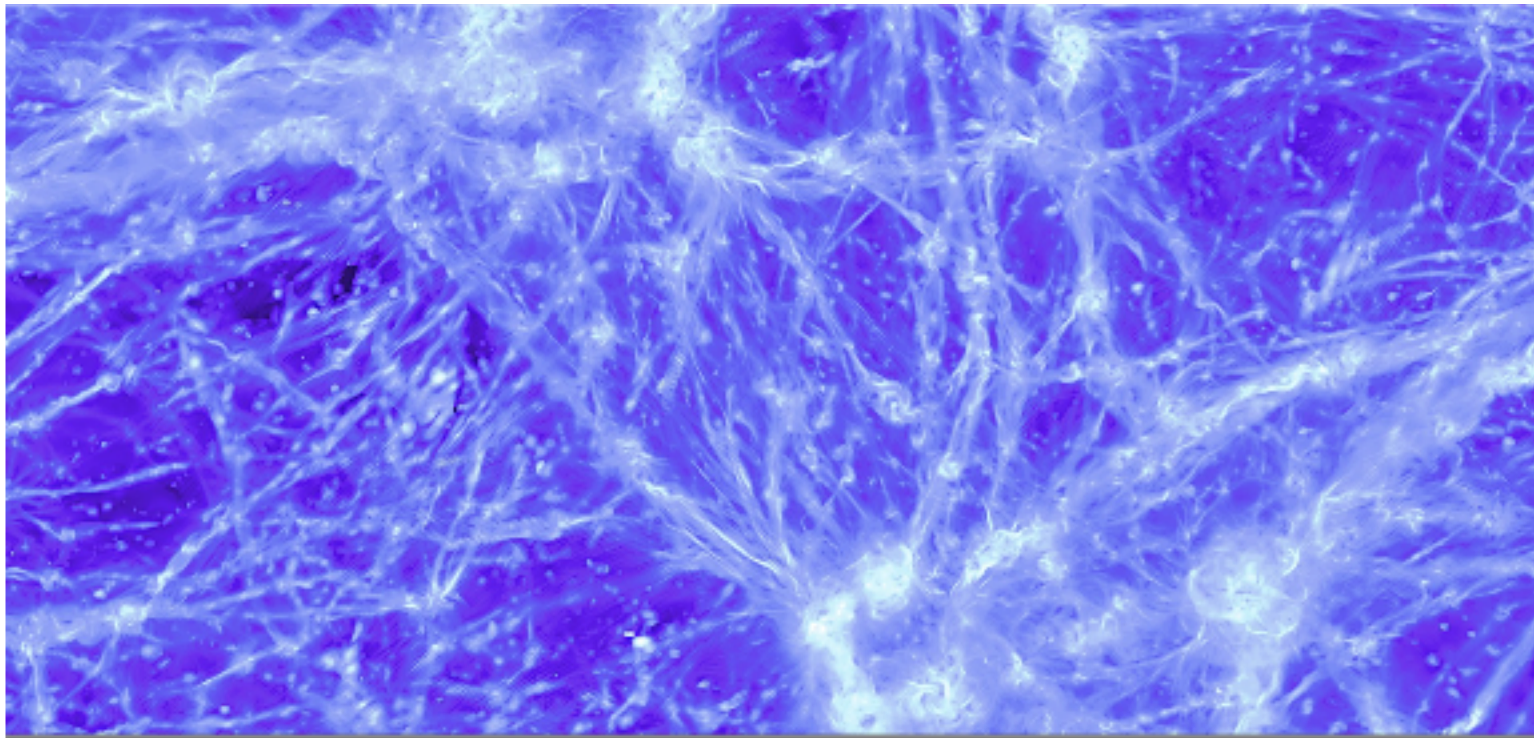
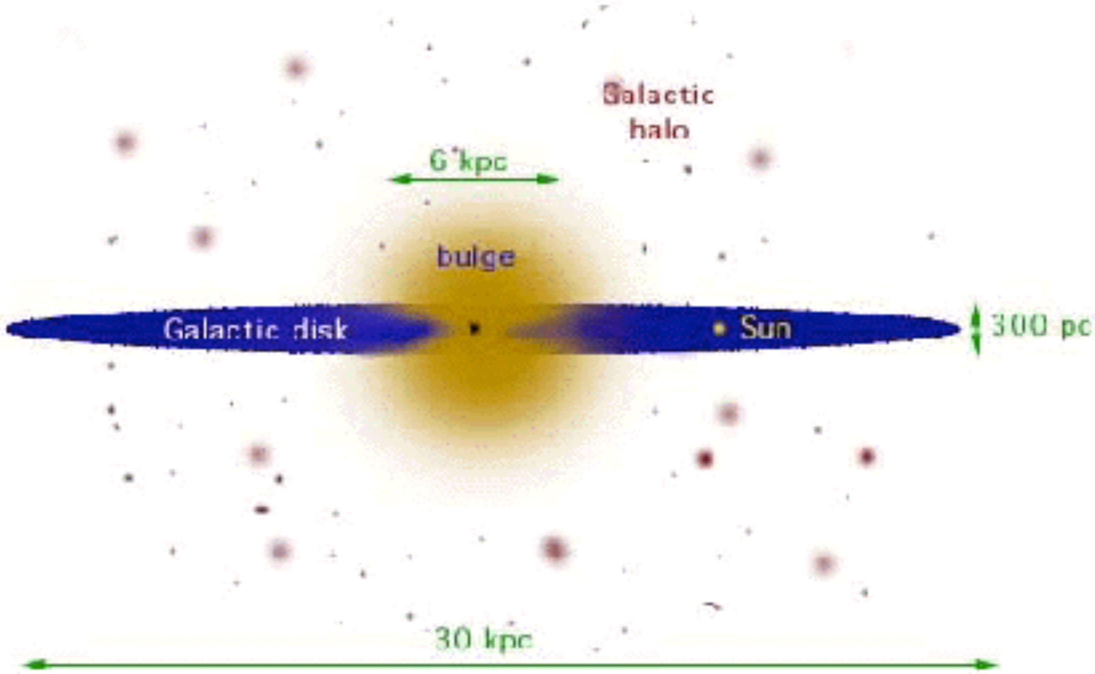
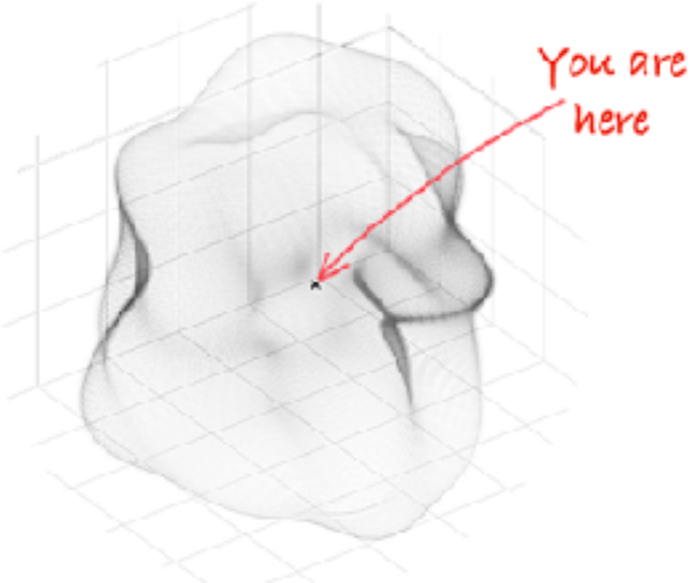



Galactic
halo
6 kpc
bulge
Galactic disk
Sun
300 pc
30 kpc


You are
here

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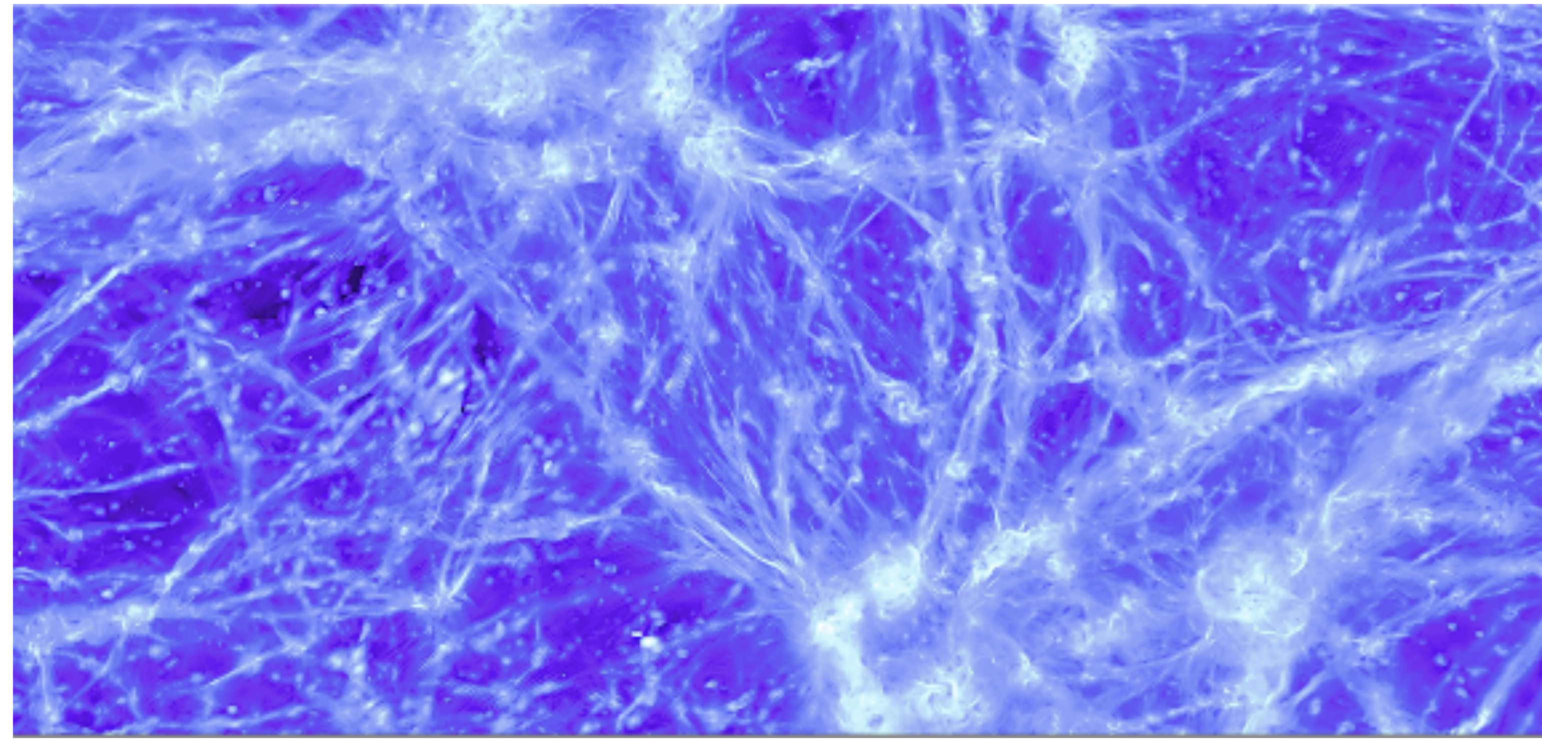
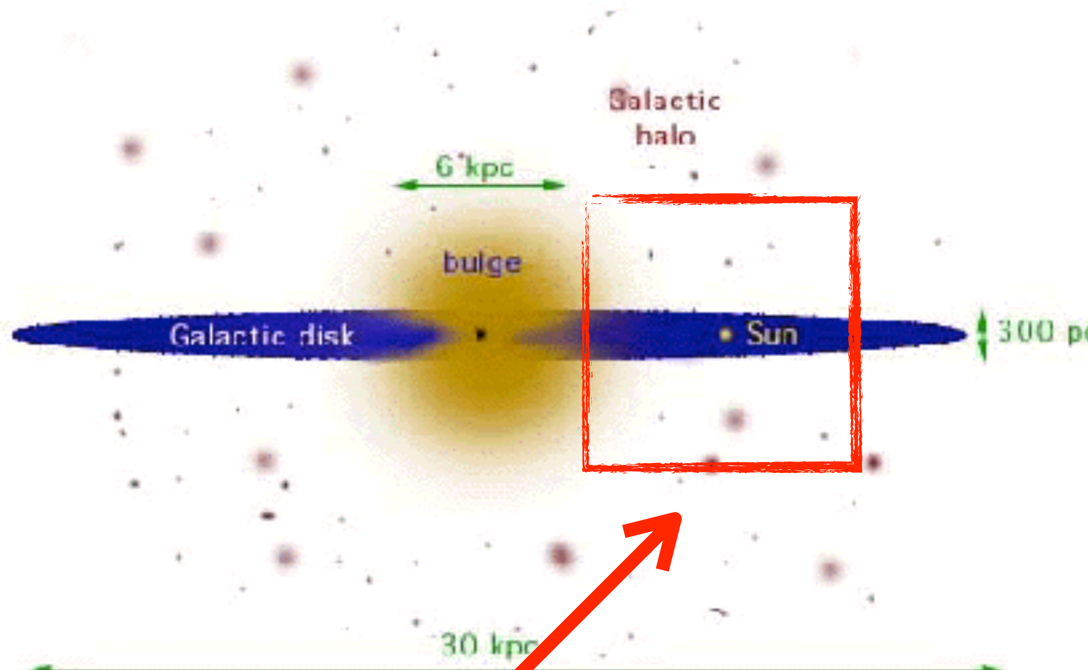
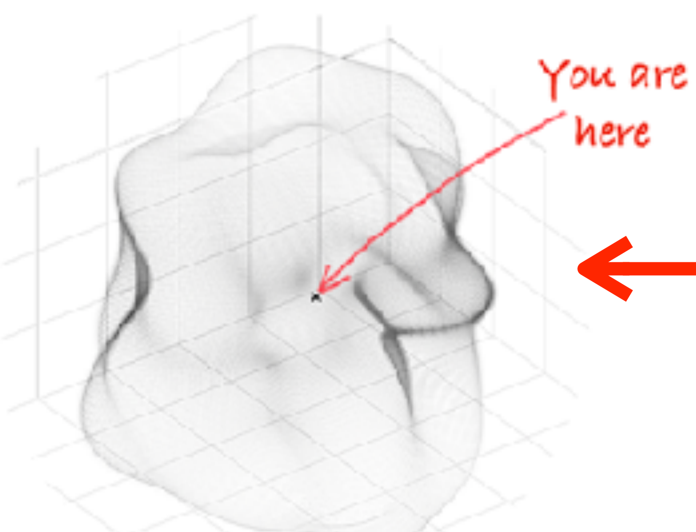
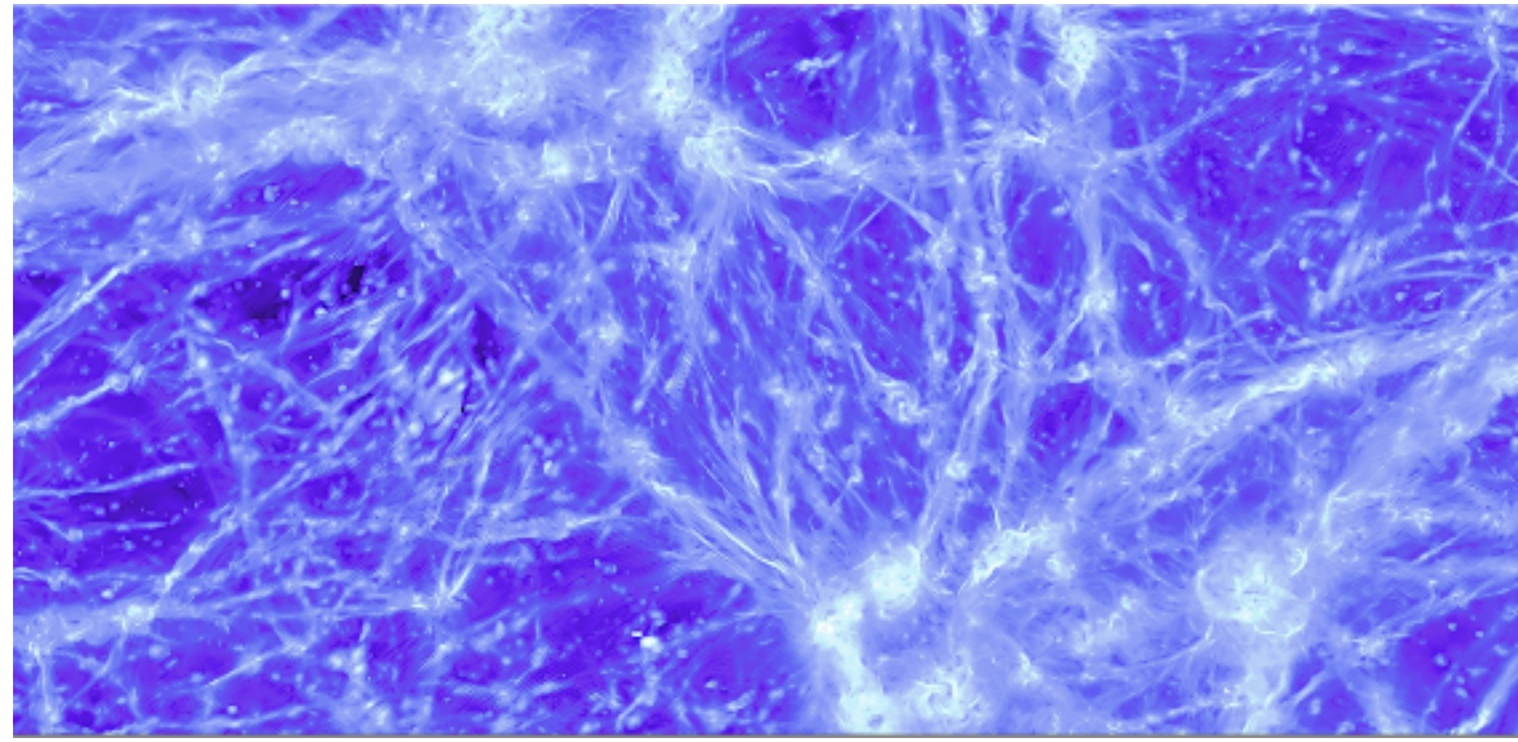




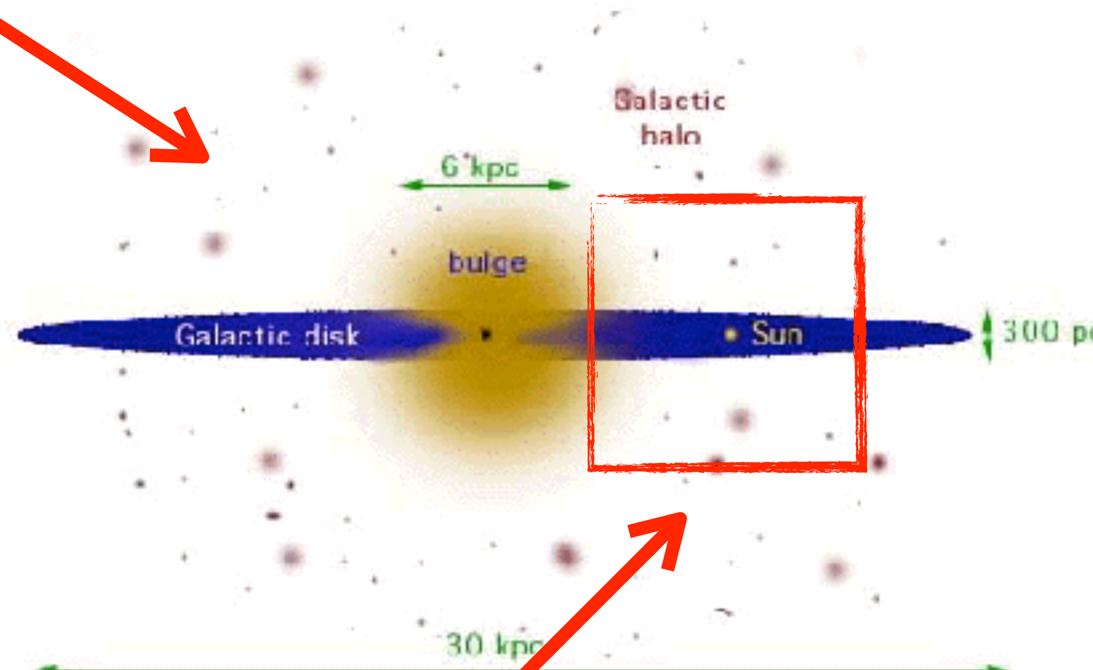



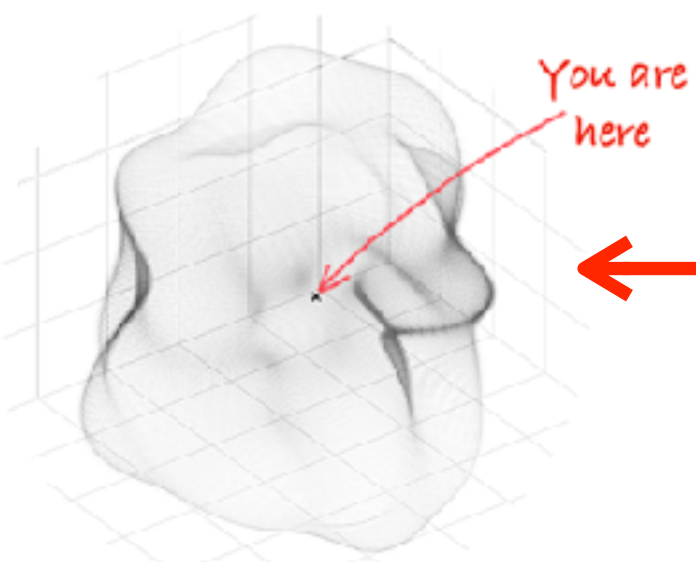

Galactic CR

# Many scales



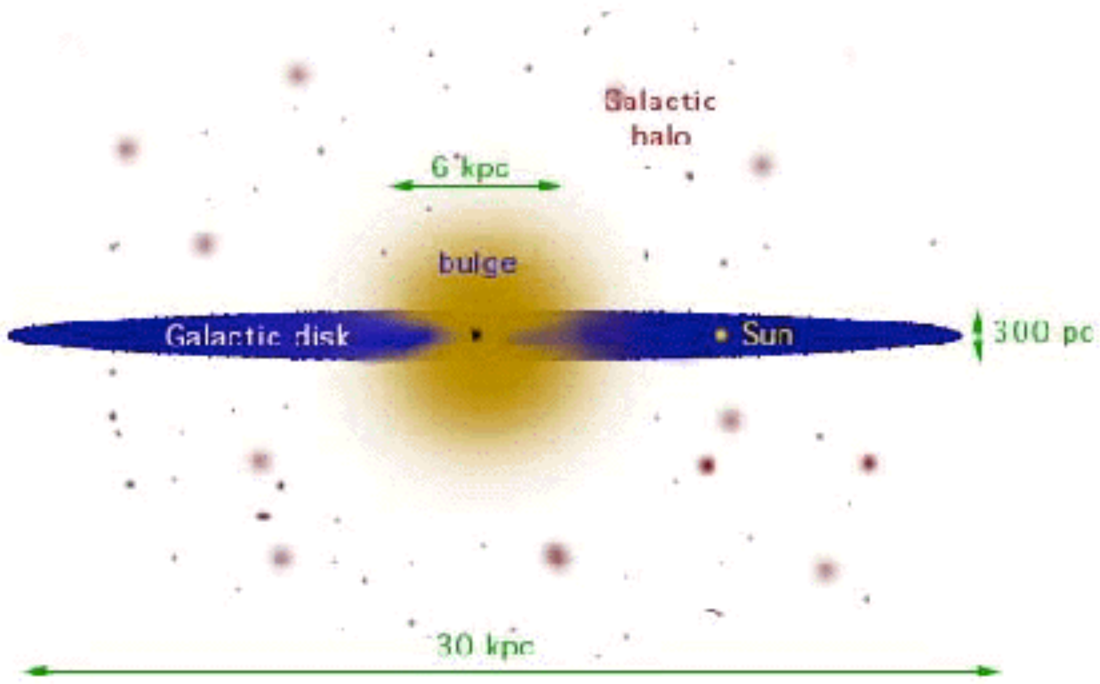
extragalactic CR

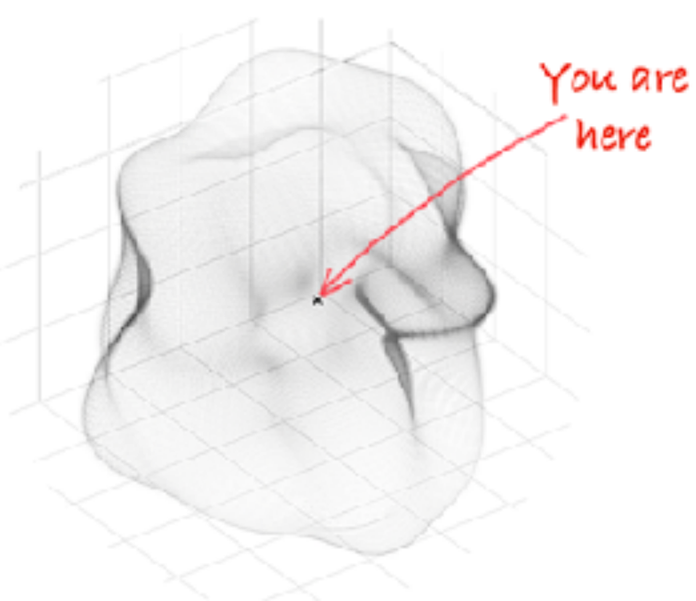



Galactic CR

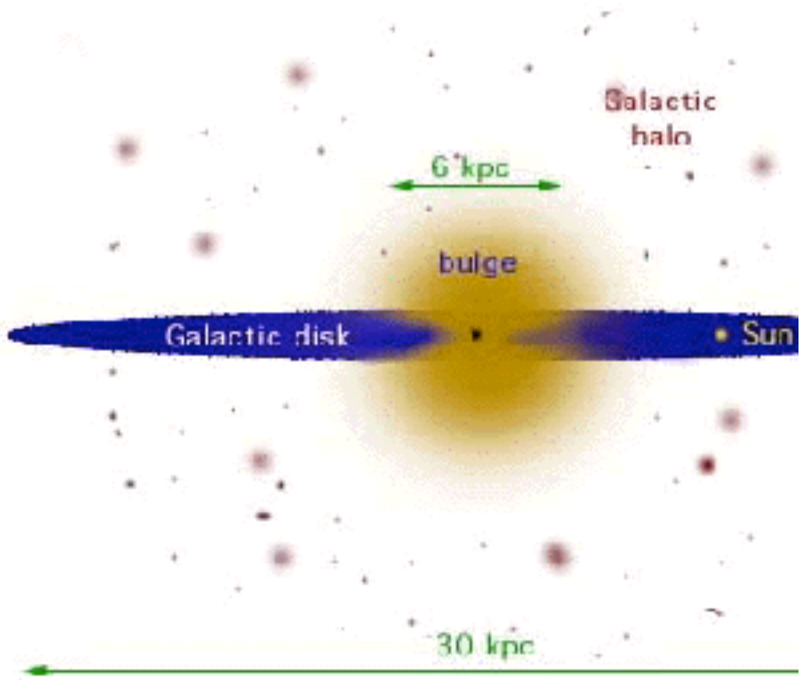
# Small and large scales are decoupled

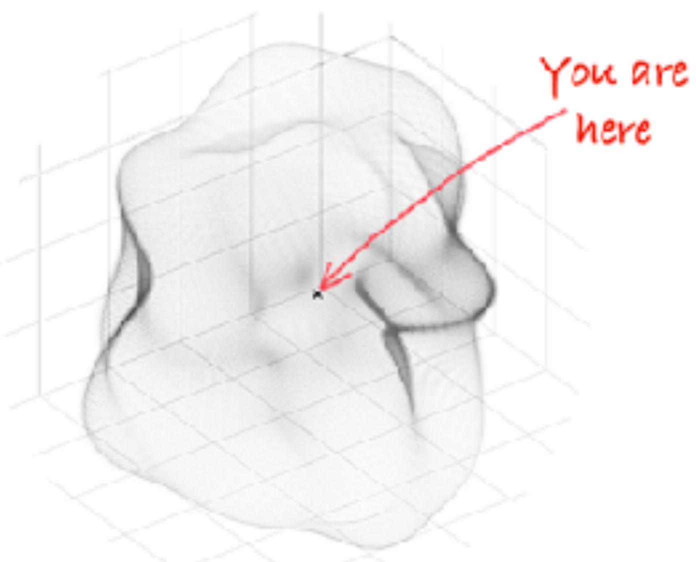


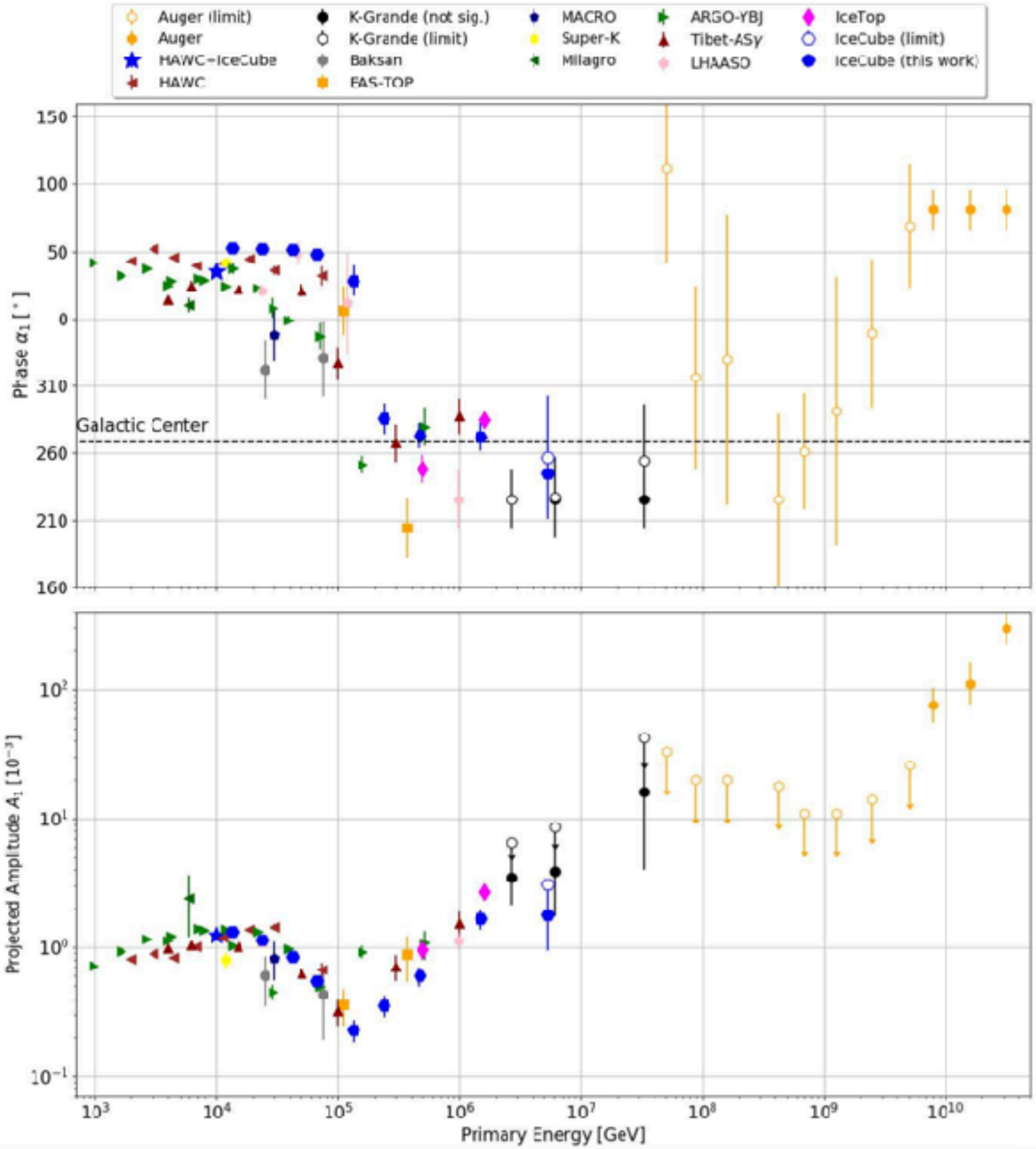



# Small and large scales are decoupled

Soldin



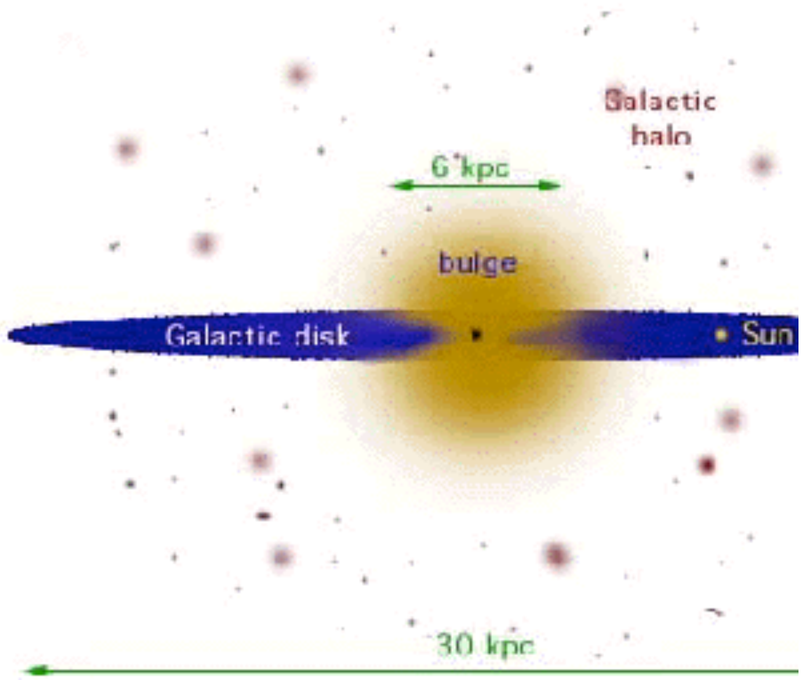



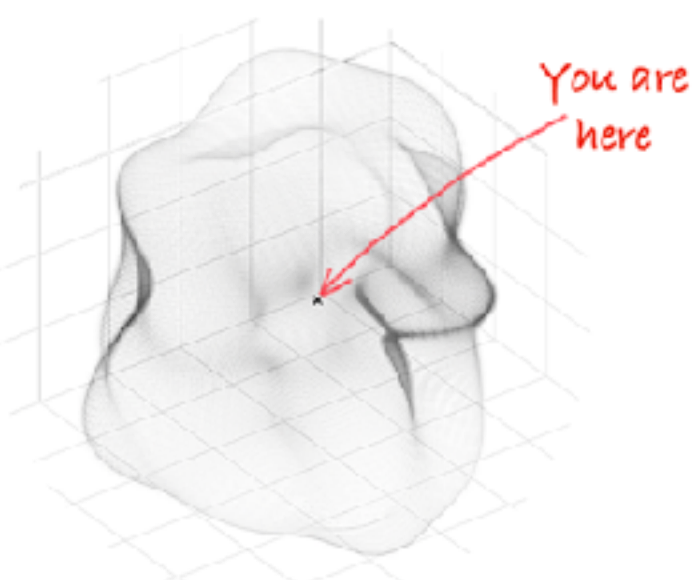



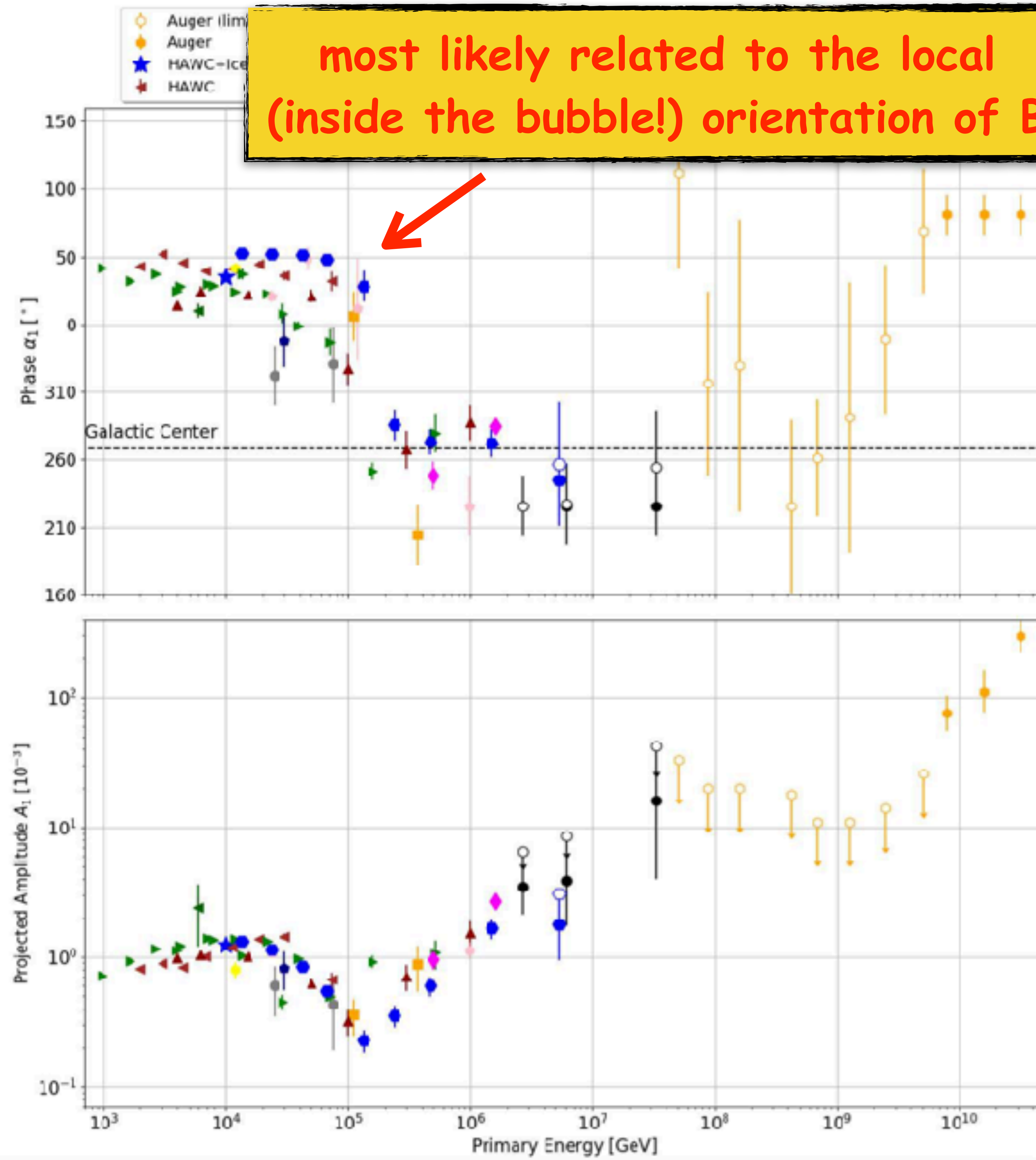
# Small and large scales are decoupled

Soldin

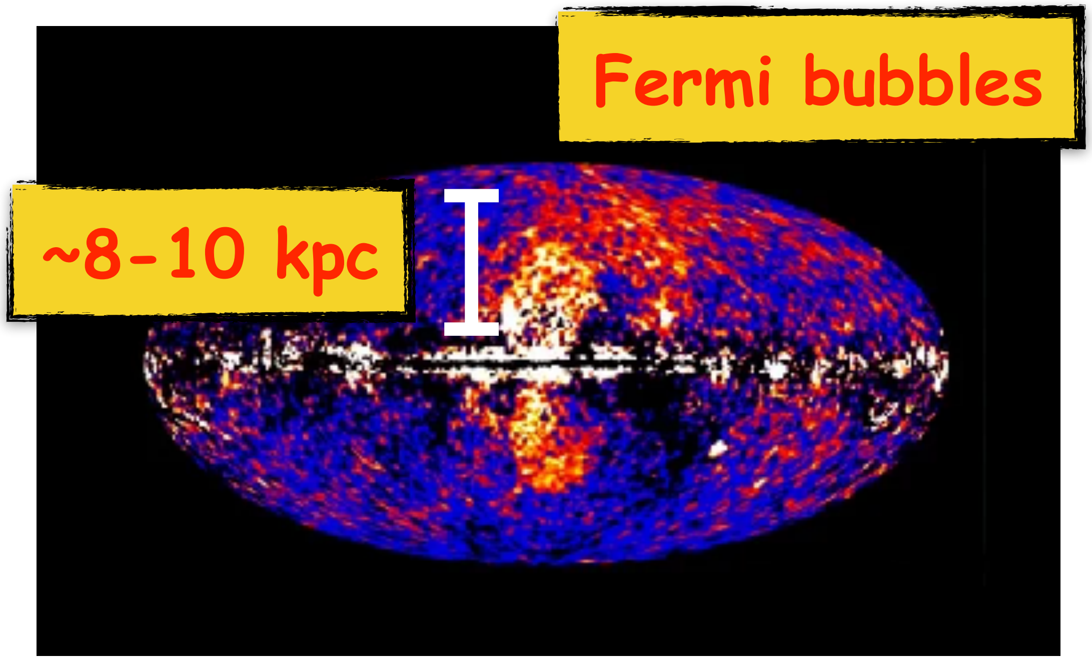
most likely related to the local (inside the bubble!) orientation of B



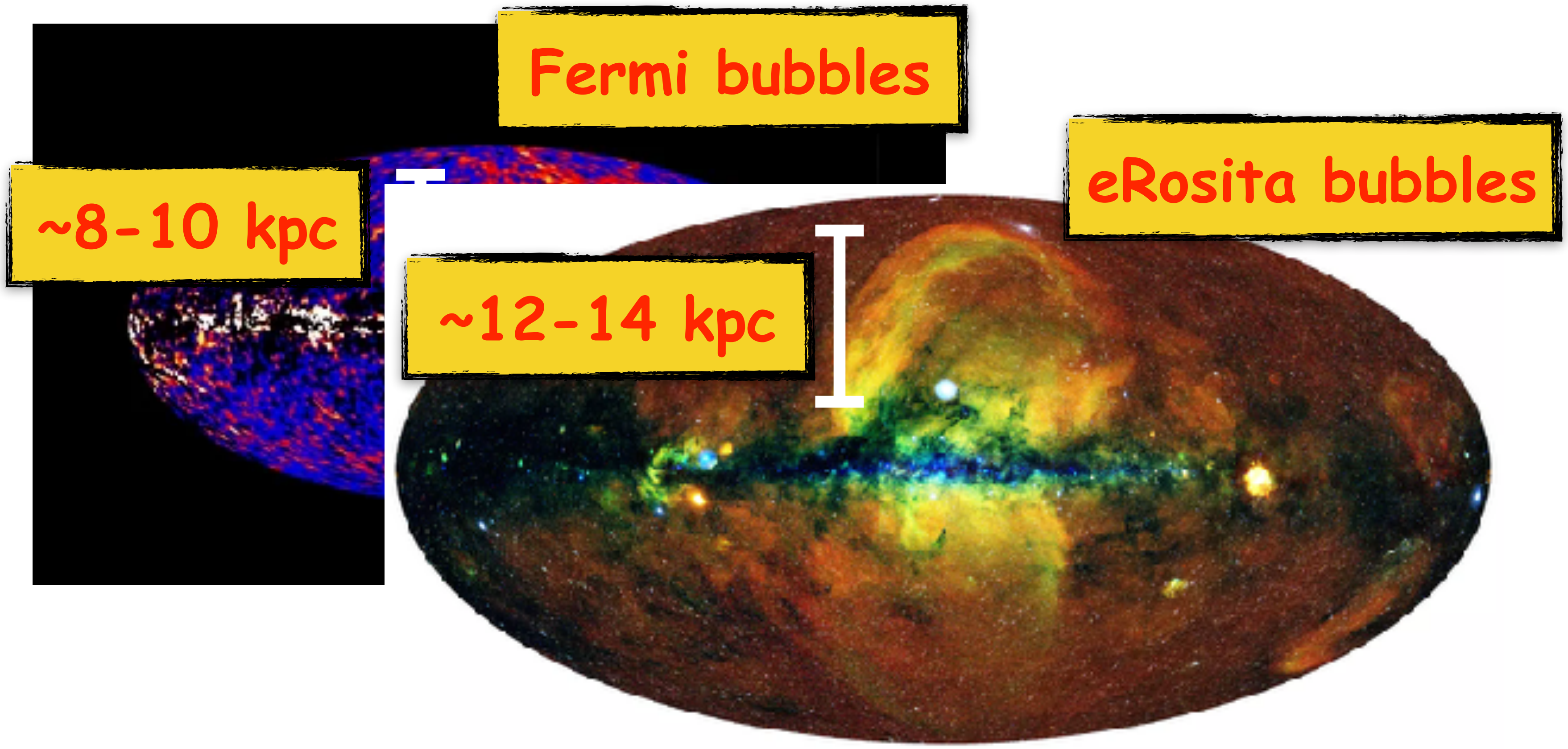



# Do we know the intermediate scales?



# Do we know the intermediate scales?



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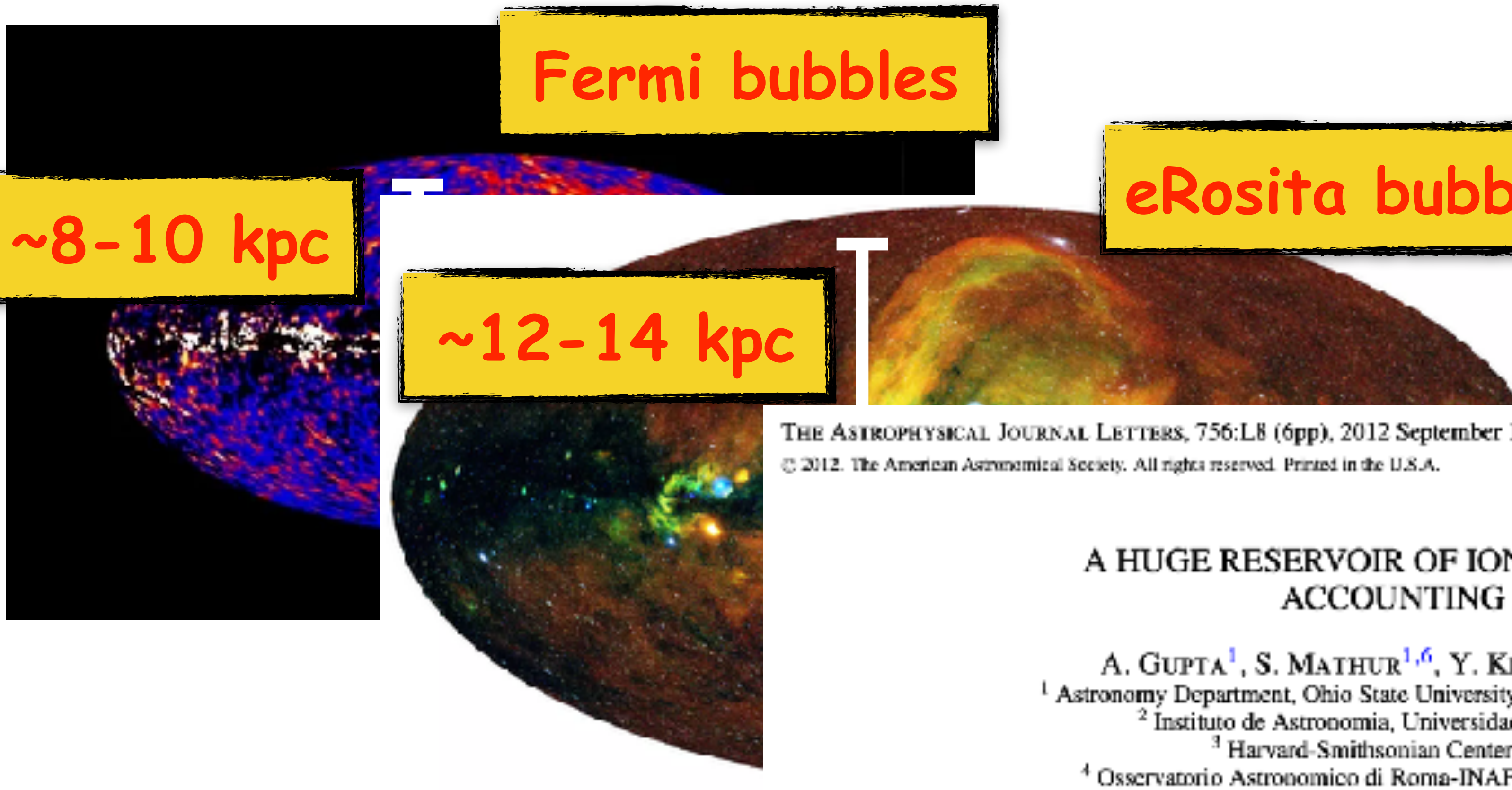


The Astrophysical Journal Letters, 756:L8 (6pp), 2012 September 1
doi:10.1088/2041-8205/75


A HUGE RESERVOIR OF IONIZED GAS AROUND THE MILKY WAY: ACCOUNTING FOR THE MISSING MASS?

A. Gupta[1], S. Mathur[1,6], Y. Krongold[2], F. Nicastro[3,4], and M. Galeazzi[5]
[1] Astronomy Department, Ohio State University, Columbus, OH 43210, USA; agupta@astronomy.ohio-state.edu
[2] Instituto de Astronomia, Universidad Nacional Autonoma de Mexico, Mexico City, Mexico
[3] Harvard-Smithsonian Center for Astrophysics, Cambridge, MA 02138, USA
[4] Osservatorio Astronomico di Roma-INAF, Via di Frascati 33, I-00040 Monte Porzio Catone, RM, Italy
[5] Physics Department, University of Miami, Coral Gables, FL 33124, USA
*Received 2012 May 8; accepted 2012 July 10; published 2012 August 9*

ABSTRACT

Most of the baryons from galaxies have been "missing" and several studies have attempted to map the circumgalactic medium (CGM) of galaxies in their quest. We report on X-ray observations made with the *Chandra X-Ray Observatory* probing the warm-hot phase of the CGM of our Milky Way at about $10^6$ K. We detect O VII and O VIII absorption lines at $z = 0$ in extragalactic sight lines and measure accurate column densities using both K$\alpha$ and K$\beta$ lines of O VII. We then combine these measurements with the emission measure of the Galactic halo from literature to derive the density and the path length of the CGM. We show that the warm-hot phase of the CGM is massive, extending over a large region around the Milky Way, with a radius of over 100 kpc. The mass content of this phase is over ... than that i... baryonic mass i... ss of the Ga...

R ~ 100 kpc

M ~ $10^{10}$ Msun

*Key w...*: halo – inte... X-rays: galaxies

*Online-only material:* color figures

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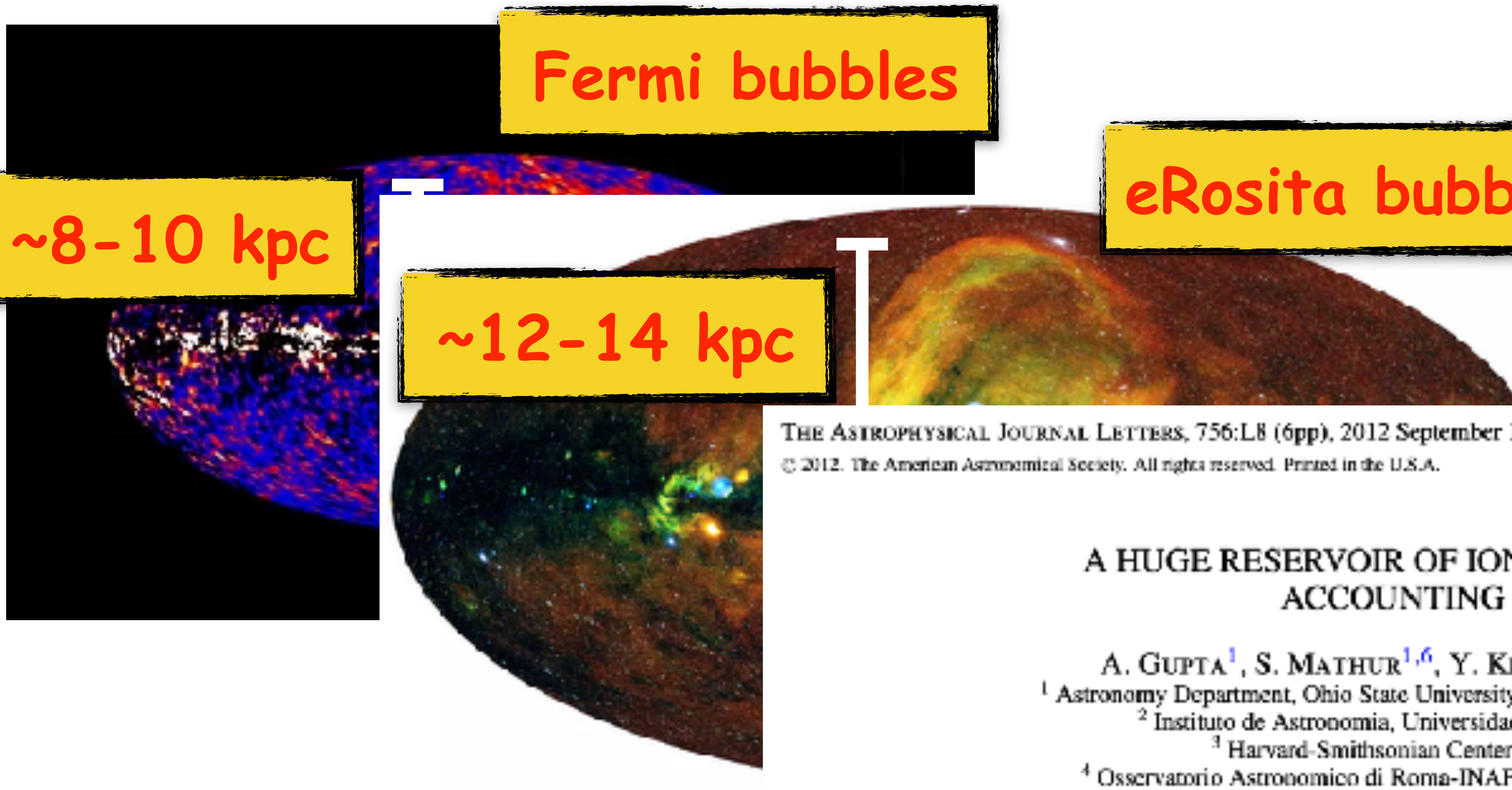


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Faint gamma-ray halo of R ~ 120-200 kpc around Andromeda detected by Fermi (Karwin+ 20)

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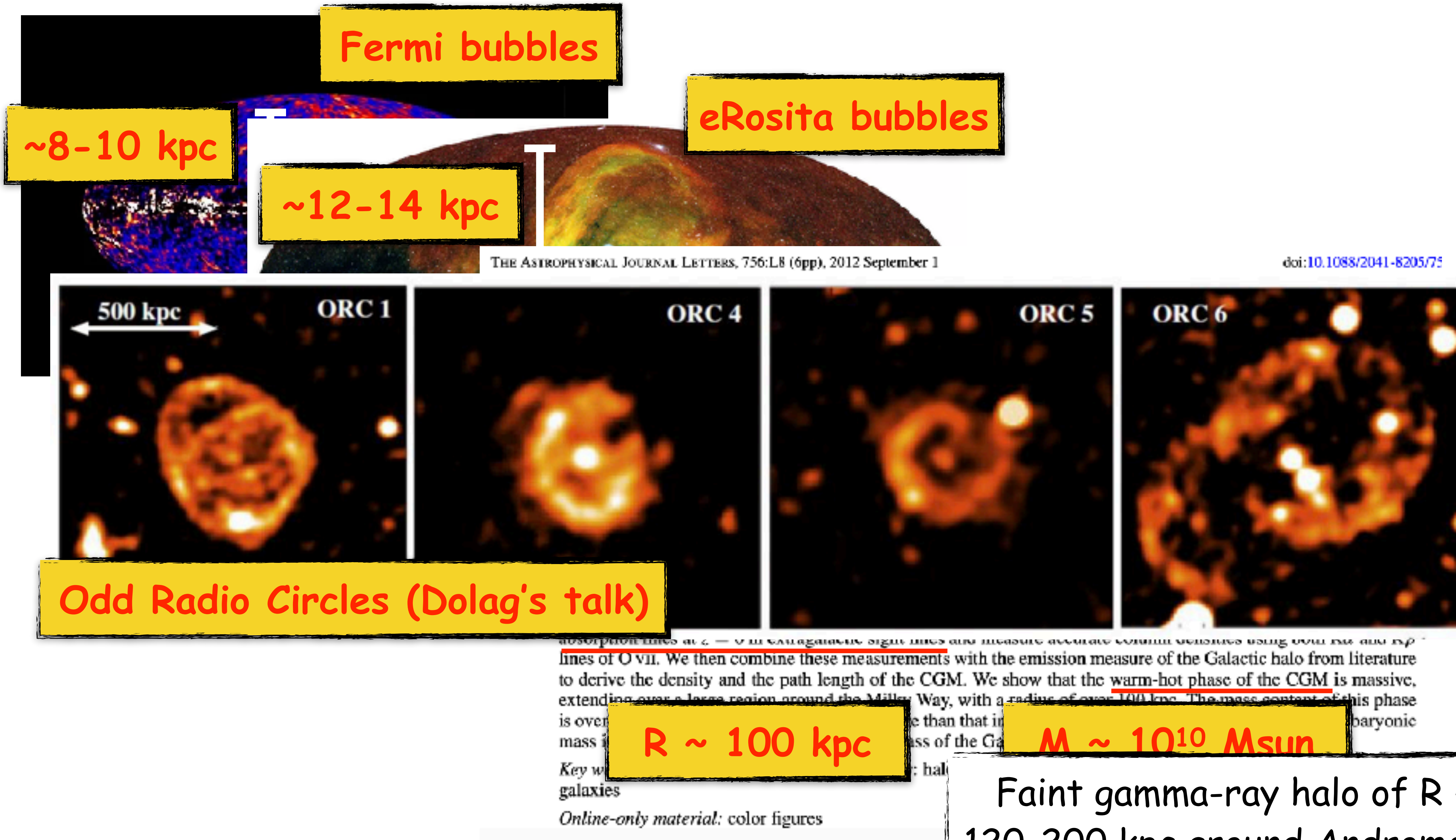


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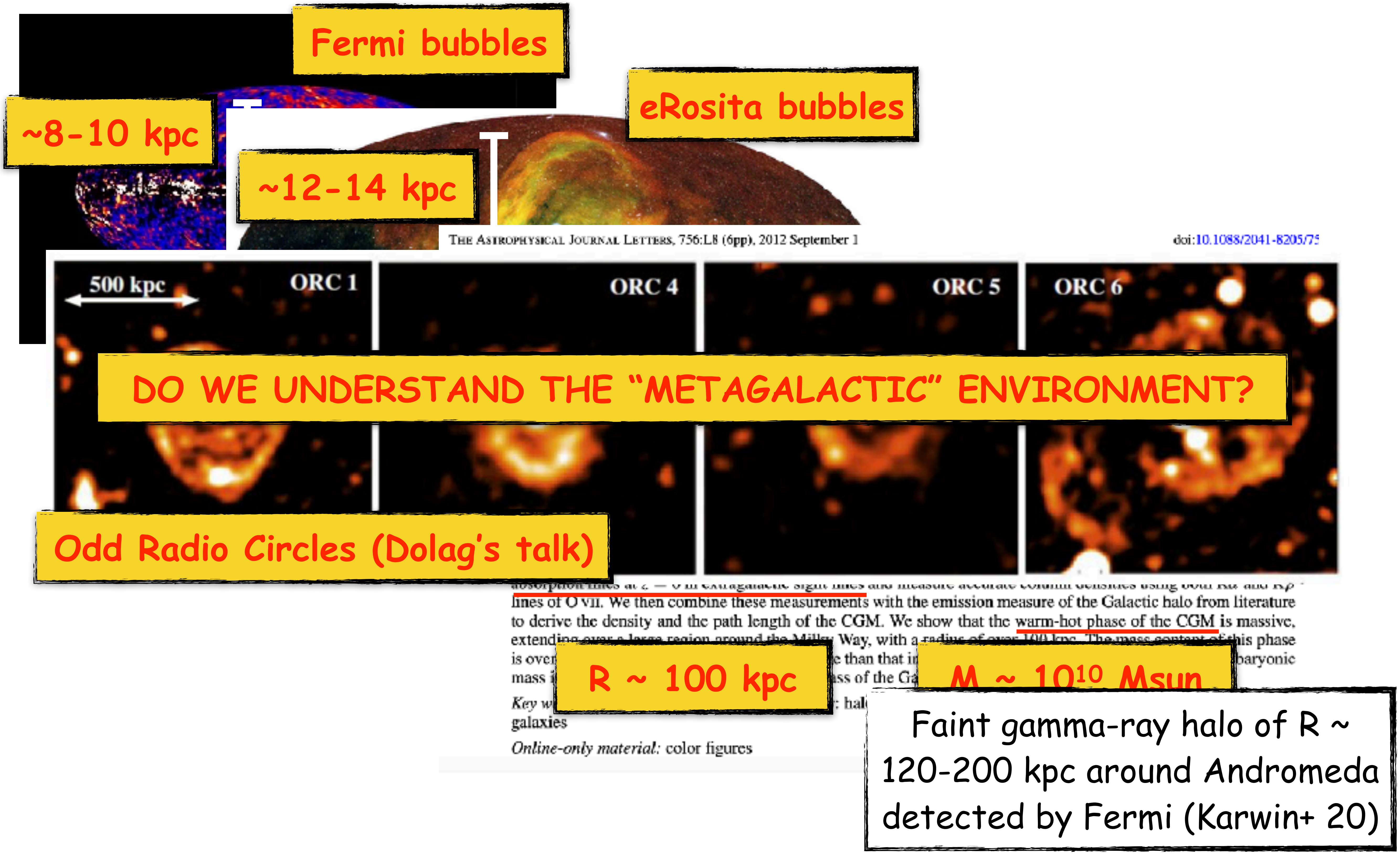
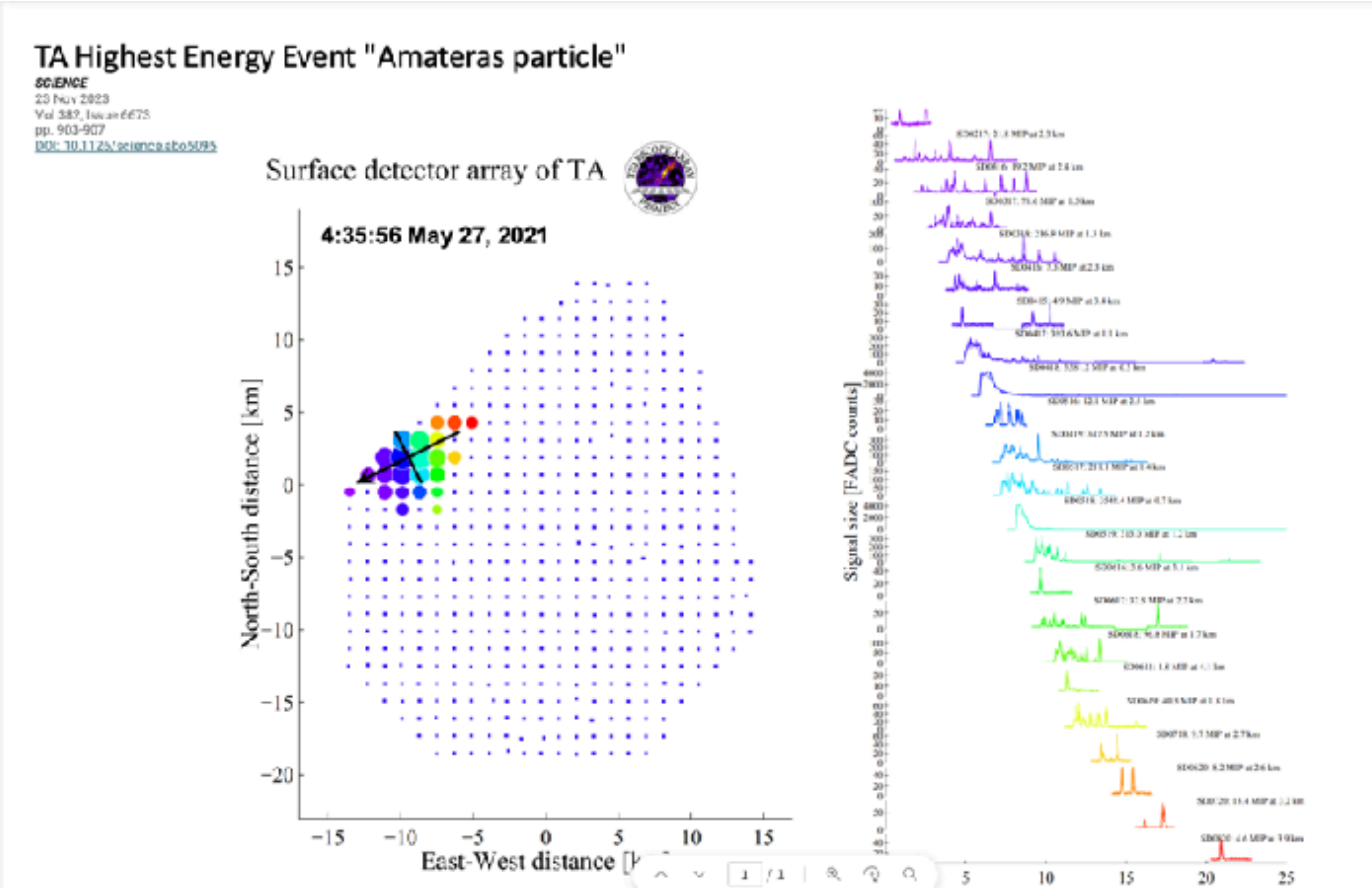


# Amaterasu particle

Tsunesada



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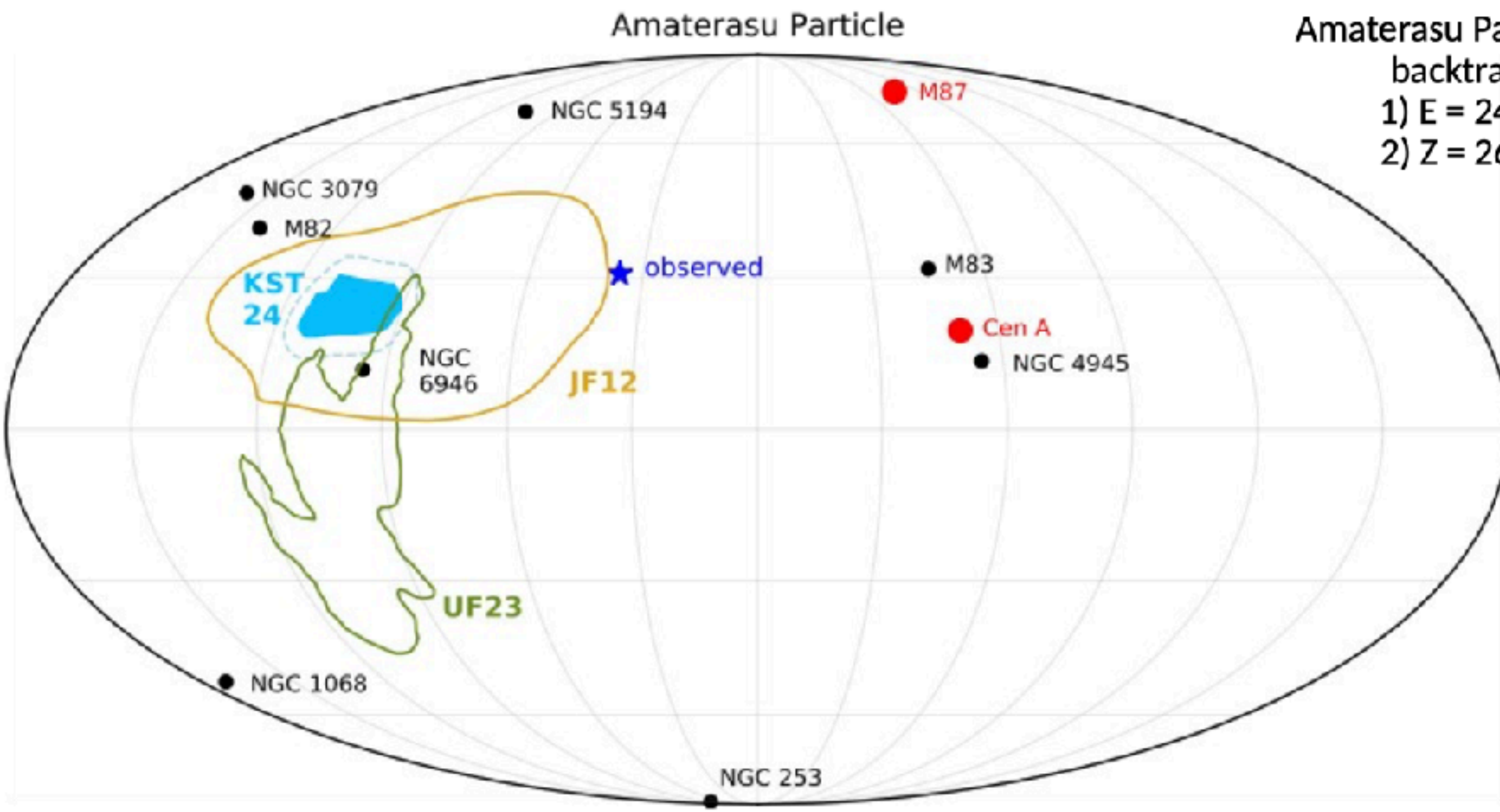
Tsunesada

TA Highest Energy Event "Amateras particle"

SCIENCE
23 Nov 2023
Vol 382, Issue 6673
pp. 903-907




Amaterasu Particle KST24 backtracking:
1) E = 244 EeV
2) Z = 26 (iron)

Kuznetsov 2023,
Unger&Farrar 2023,
Bourriche&Capel 2024

Korochkin

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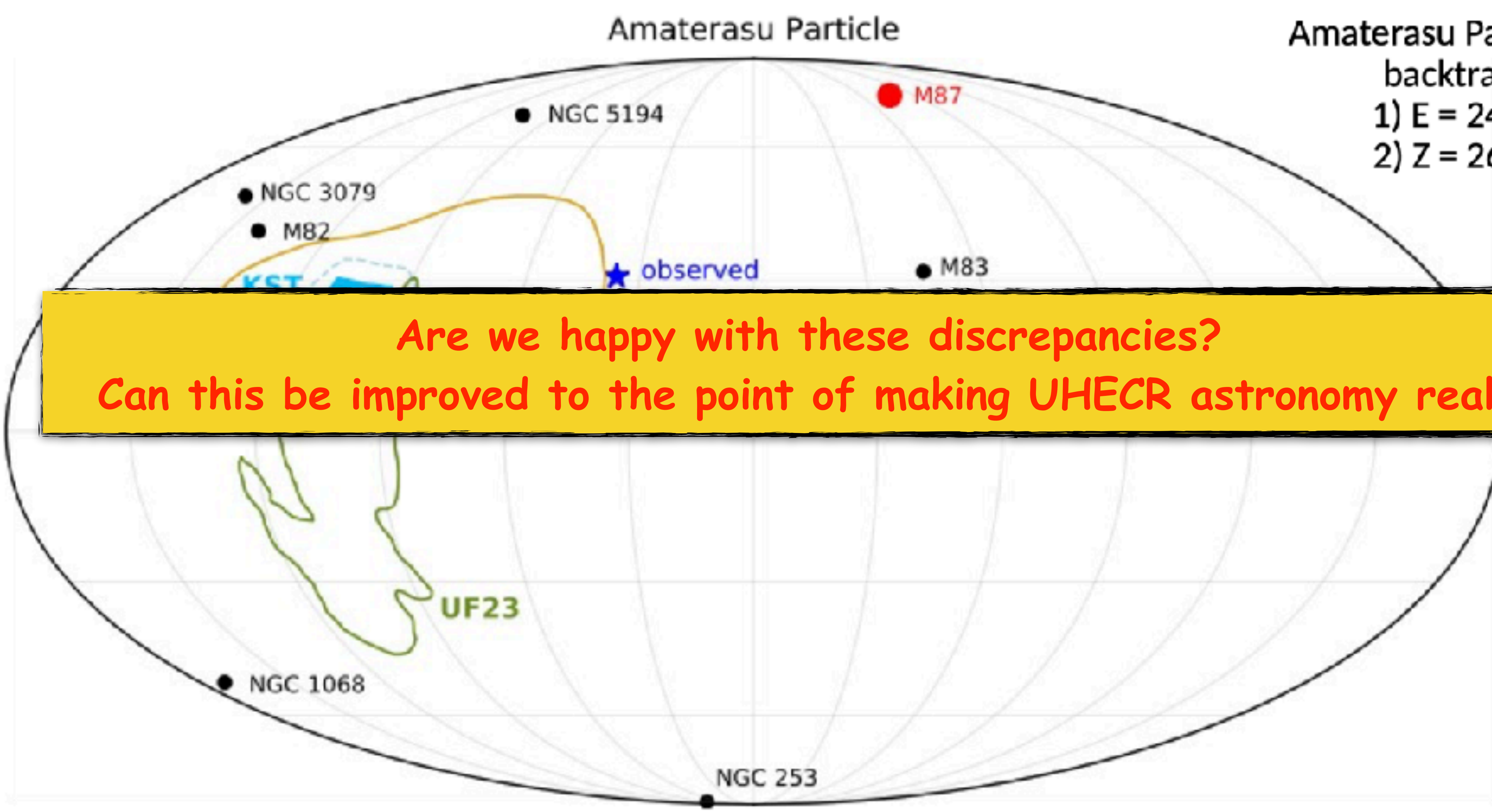


Amaterasu Particle KST24 backtracking:
1) E = 244 EeV
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Are we happy with these discrepancies?
Can this be improved to the point of making UHECR astronomy real?

Kuznetsov 2023,
Unger&Farrar 2023,
Bourriche&Capel 2024

Korochkin

# Difficult to pinpoint sources

**all these observations can be explained if UHECR sources follow the large-scale structure**

Mollerach & Roulet 2015, Phys. Rev. D, 92, 06301 (2015)
Tinyakov, & Urban, J. Exp. Theor. Phys., 120, 533 (2015)
Globus & Piran, ApJL, 850, L25 (2017)
Tinyakov & di Matteo MNRAS 476 (2018)
Globus, Piran, Hoffman, Carlesi, Pomarede MNRAS 484 (2019)
Ding, Globus, Farrar ApJL 913 L13 (2021)
Allard, Aublin, Baret, Parizot A&A 664 A120 (2022)
Bister & Farrar ApJ 966 71 (2024)
Bister, Farrar, Unger ApJL 975 L21 (2024)
The Pierre Auger Collaboration, arXiv:2408.05292

Bister

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[Do we know anything that does NOT follow the LSS?]

Bister

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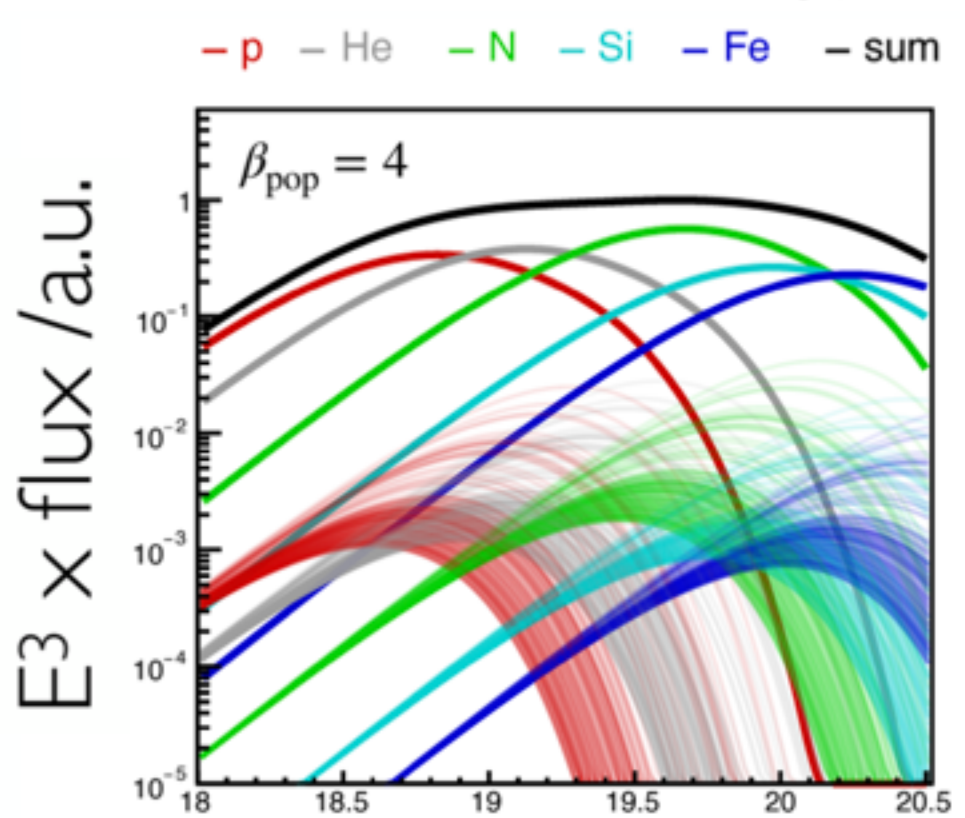


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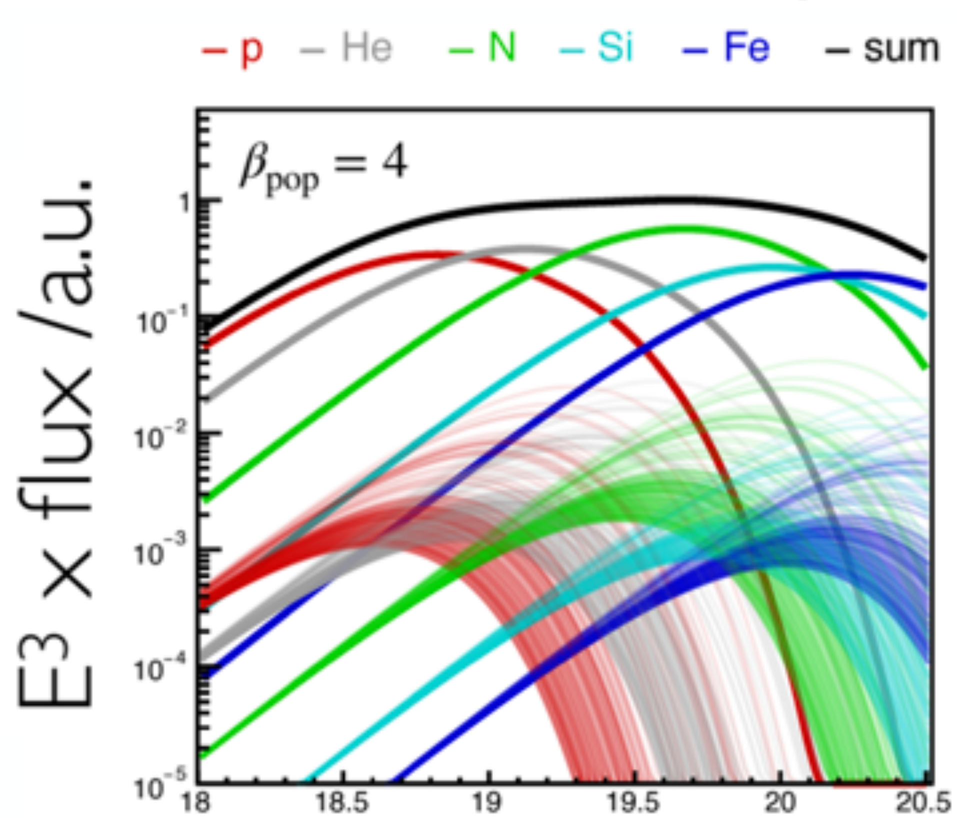
[Do we know anything that does NOT follow the LSS?]

**can be described by:**

1) population of extragalactic sources dominating from ankle energy
2) following Peters cycle (acceleration ∝ Z)
3) very hard injection spectrum
4) not too strong source evolution
5) almost identical sources

Bister

# Difficult to pinpoint sources

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The Pierre Auger Collaboration, arXiv:2408.05292

[Do we know anything that does NOT follow the LSS?]

what can produce this?

y:

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Bister

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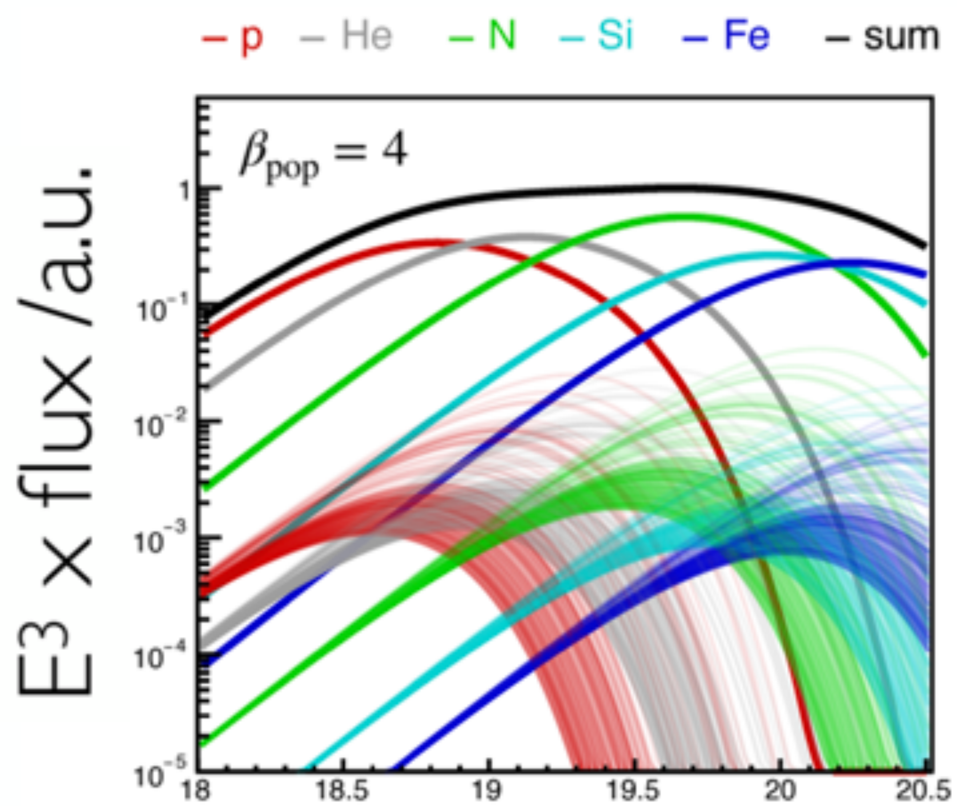


- **need source number density ~$10^{-4}$ Mpc$^{-3}$** for compatibility with dipole and quadrupole amplitudes with UF23
- **cosmic variance again dominant over differences between GMF models**

see also Allard, Aublin, Baret, Parizot A&A 664 A120 (2022)

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Bister

# Auger and TA

# Auger and TA

uncertainties of
interaction codes

Ostapchenko

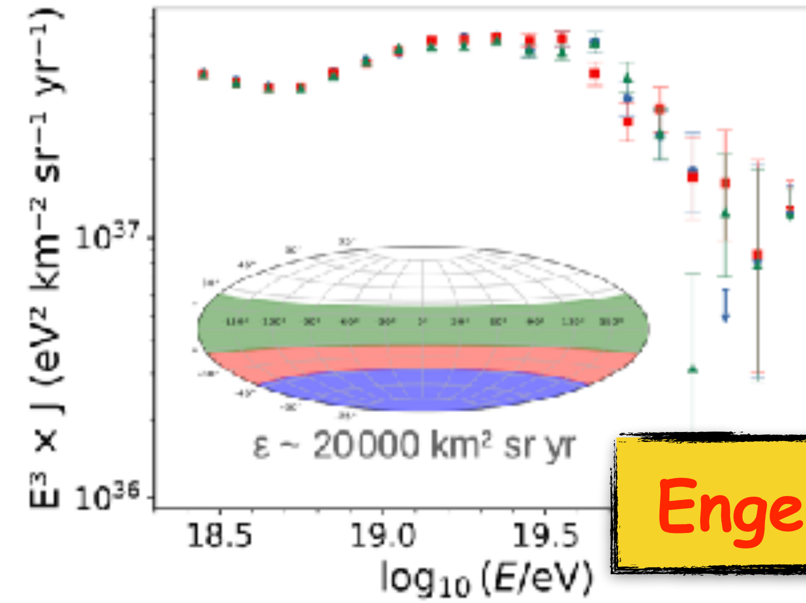
Pierog

# Auger and TA

uncertainties of interaction codes

**Ostapchenko**

**Pierog**




**Engel**

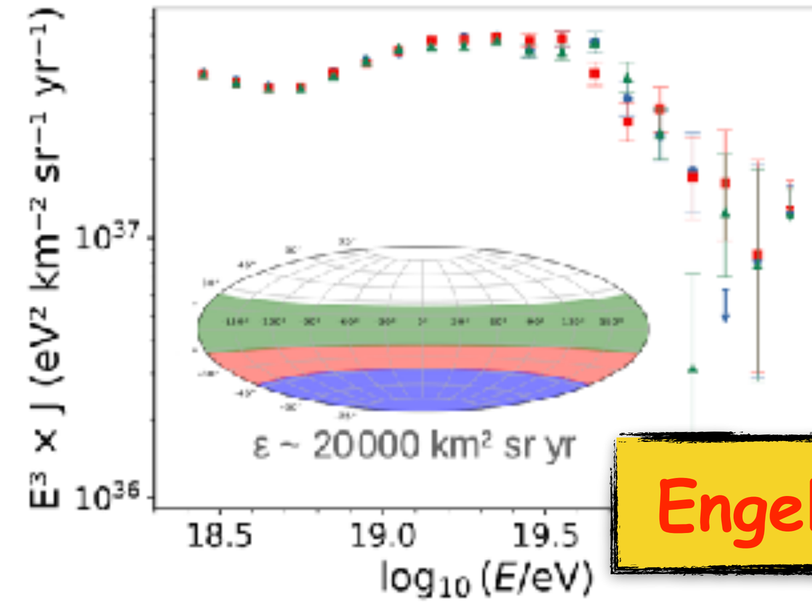
**No declination dependence found beyond the expectation from dipole**

# Auger and TA

uncertainties of interaction codes

**Ostapchenko**

**Pierog**

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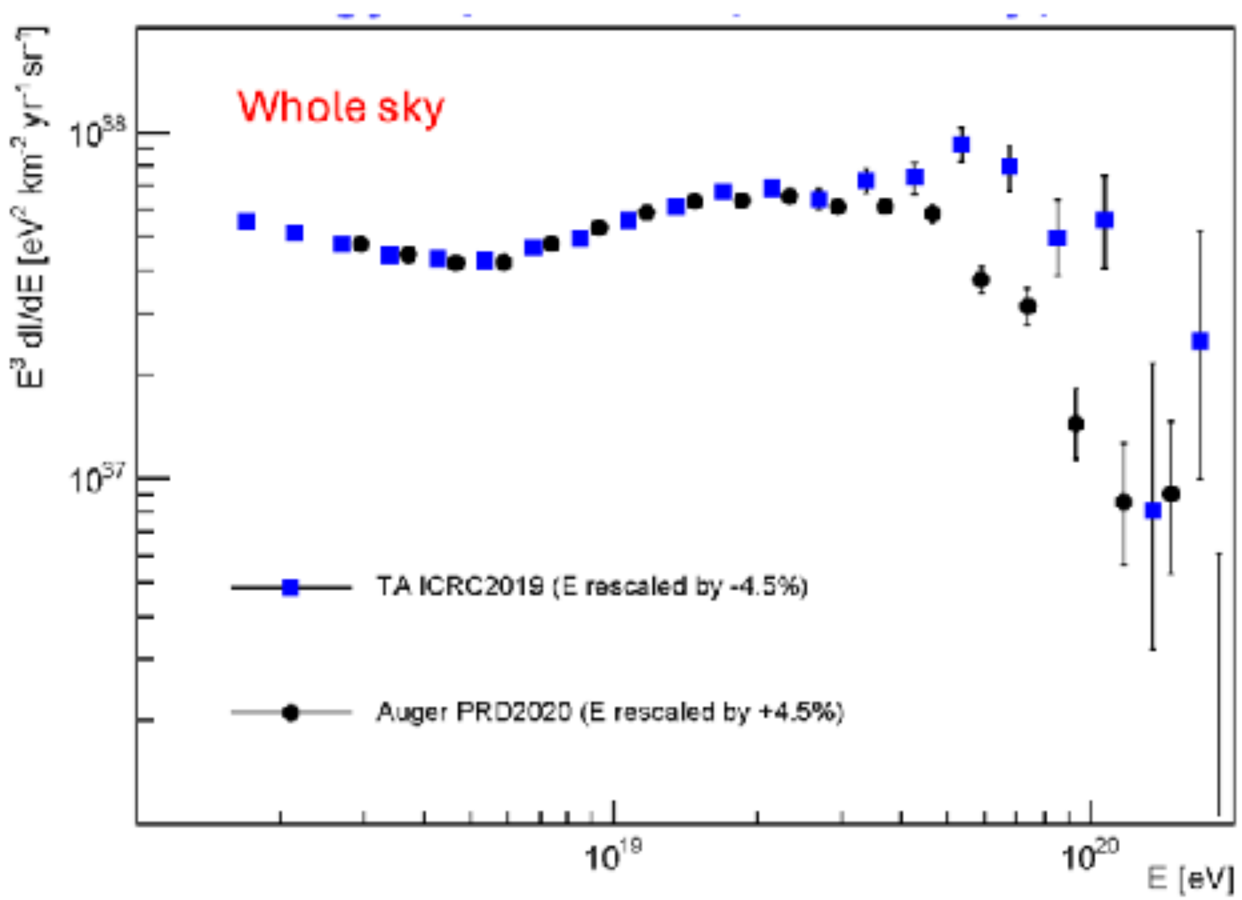


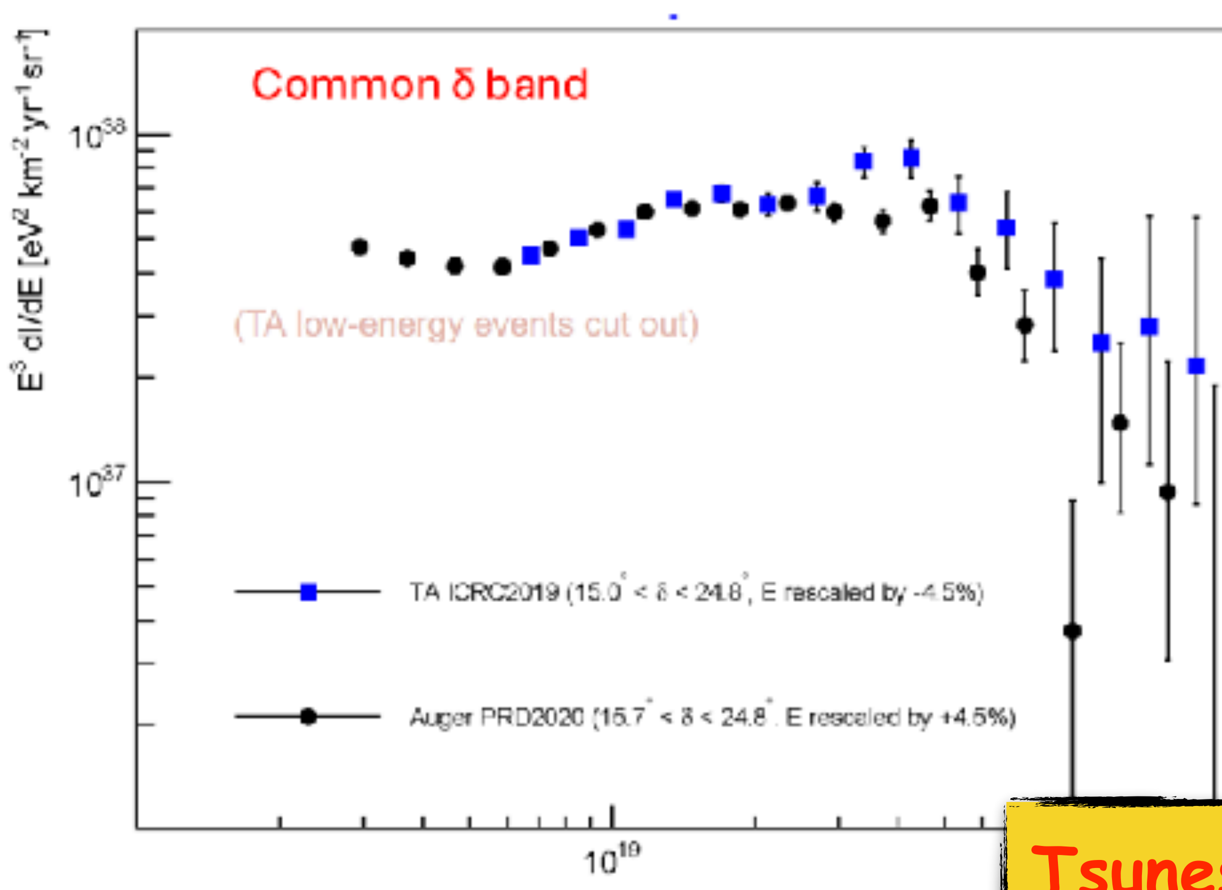


**Tsunesada**

# Auger and TA

uncertainties of interaction codes

Ostapchenko

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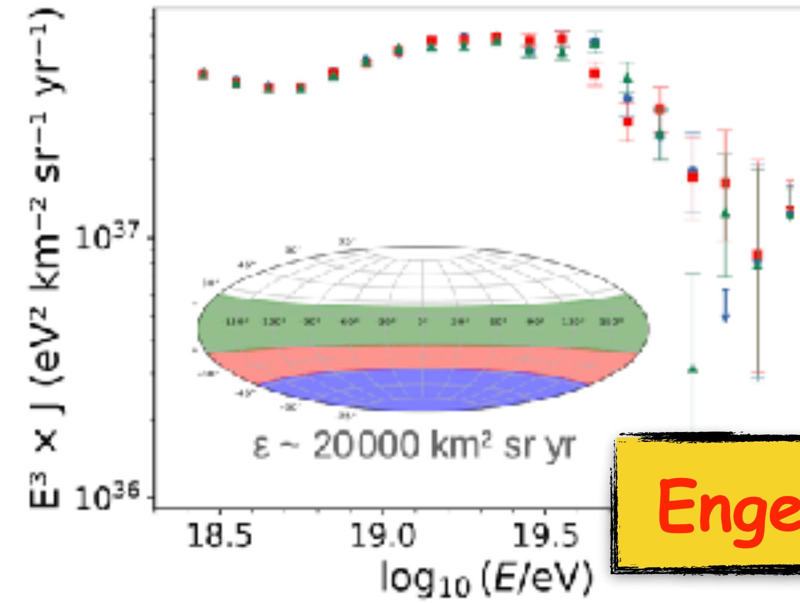
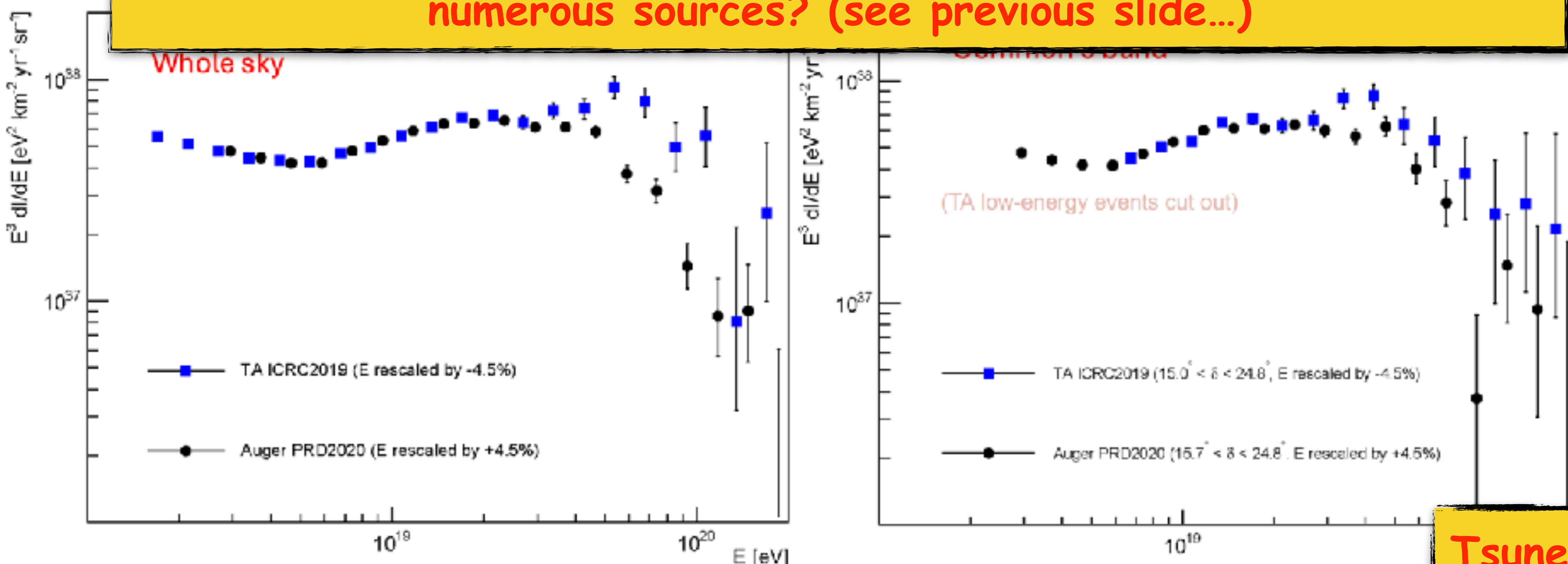



Engel

No declination dependence found beyond the expectation from dipole

How can this be consistent with the requirement of relatively numerous sources? (see previous slide…)




Tsunesada

# The usual suspects...

## Summary: Source candidates & key constraints

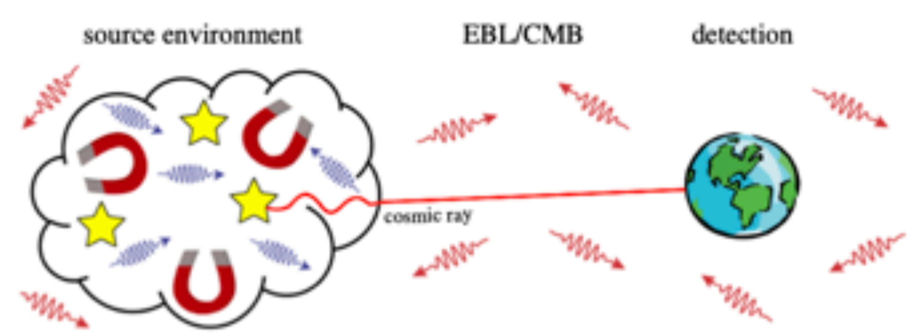
| | Powerful AGN | long GRBs | TDEs | Accretion Shocks | BNS mergers |
|---|---|---|---|---|---|
| $n_S \gtrsim 10^{-3.5}$ $Mpc^{-3}$ | [✘] | [✘] | ? | ? | ✔ |
| UHECR energy injection | ✔ | ✘ | ? | ? | [✔] |
| Ordinary galaxy | ✘ | ✘ | ✔ | [✘] | ✔ |
| Universal $R_{max}$ | ✘ | ✘ | ✘ | ✘ | ✔ |
| Highest energy events? | ✘ | ✘ | ✘ | ✘ | ✔ |

Farrar

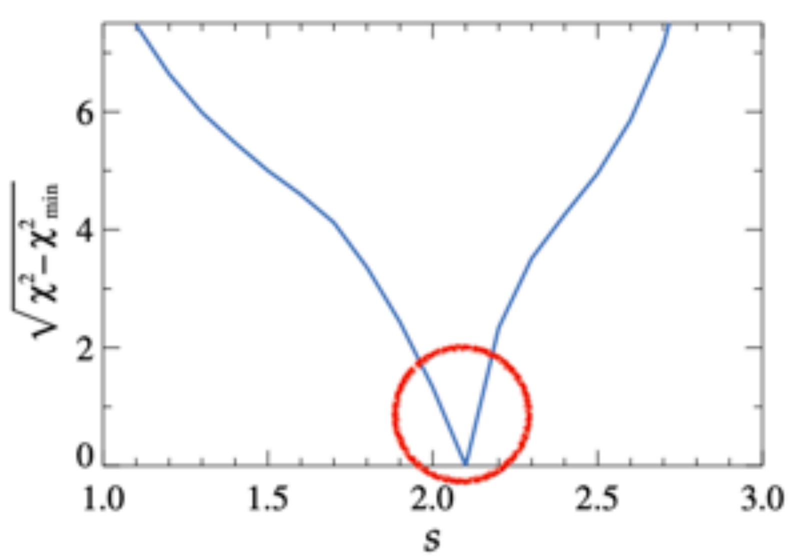
# The usual suspects…

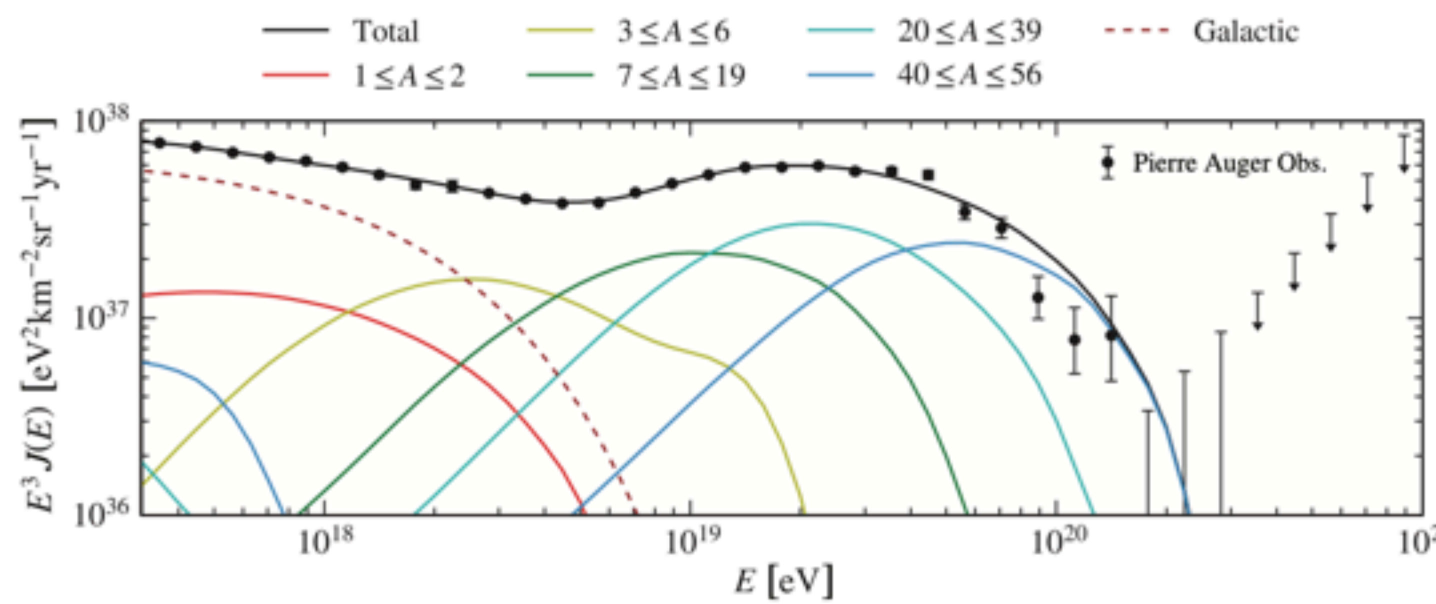
## Summary: Source candidates & key constraints

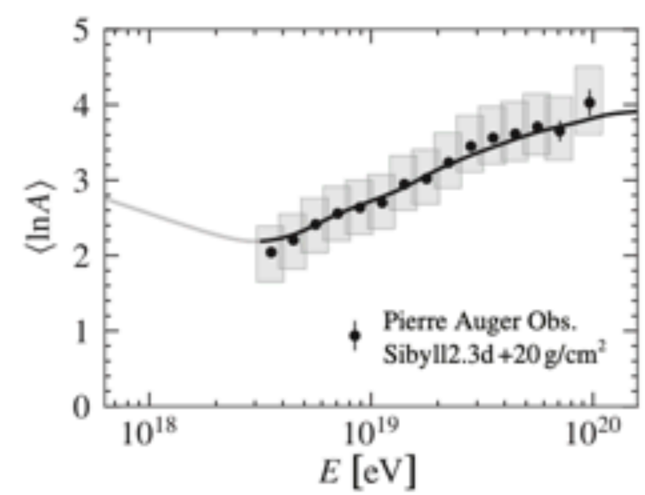
### Particle acceleration via magnetized turbulence: fitting to UHECR data

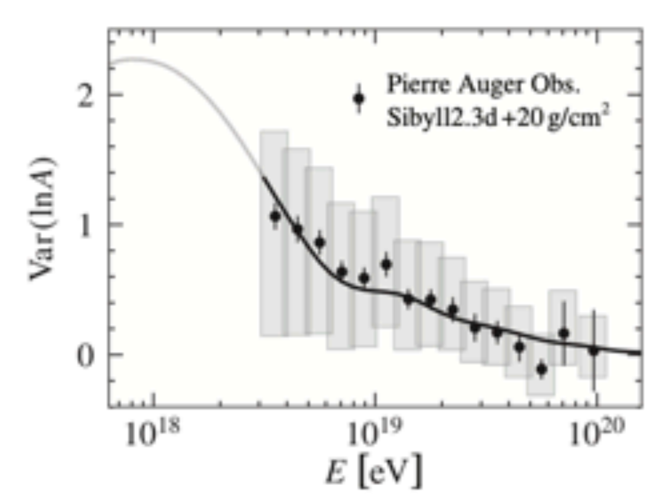



Particle interaction and propagation according to Unger, Farrar, Anchordoqui 2015 (see also Muzio and Farrar 2023)



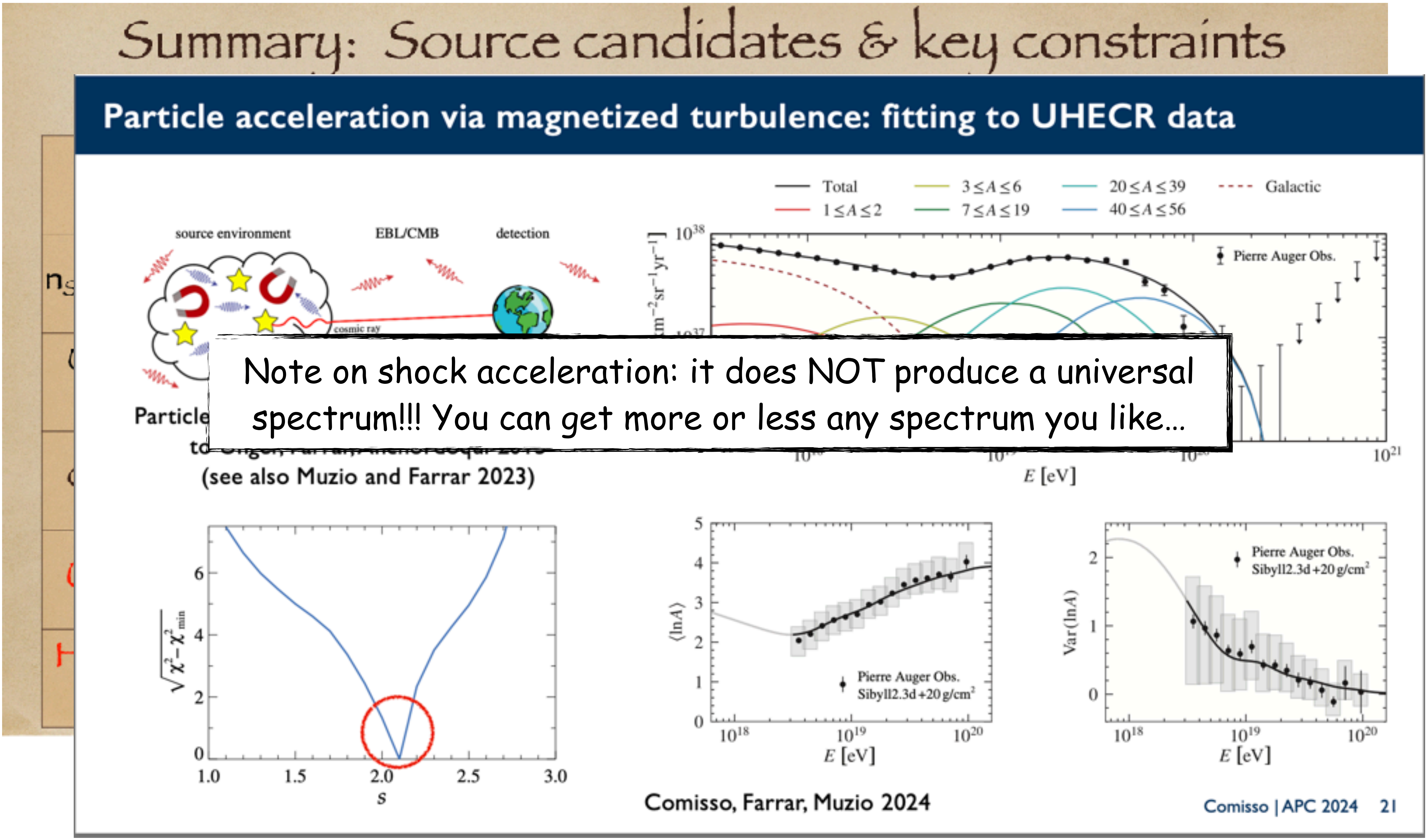

Comisso, Farrar, Muzio 2024



Comisso

Farrar

# The usual suspects...

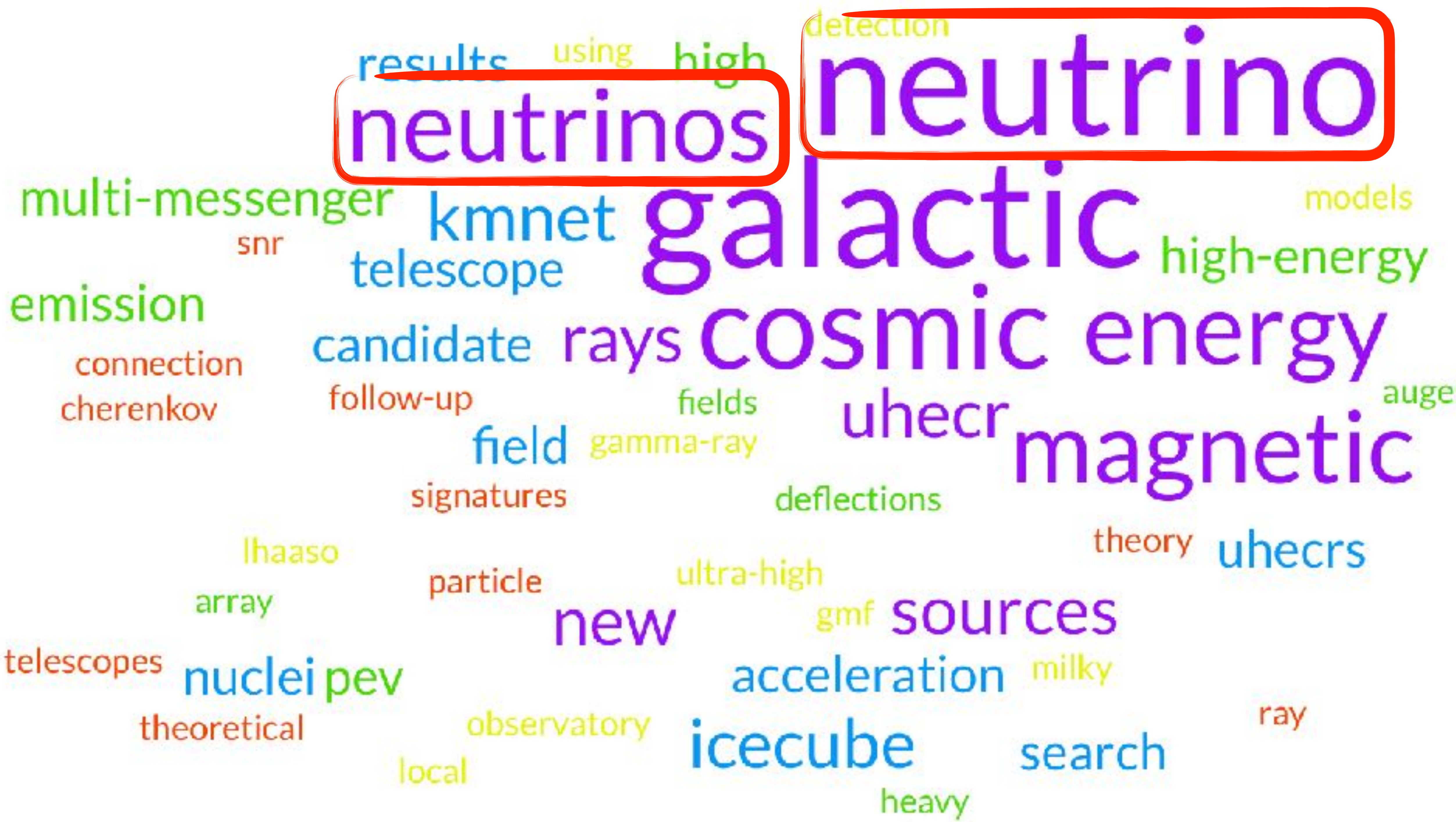



Note on shock acceleration: it does NOT produce a universal spectrum!!! You can get more or less any spectrum you like...

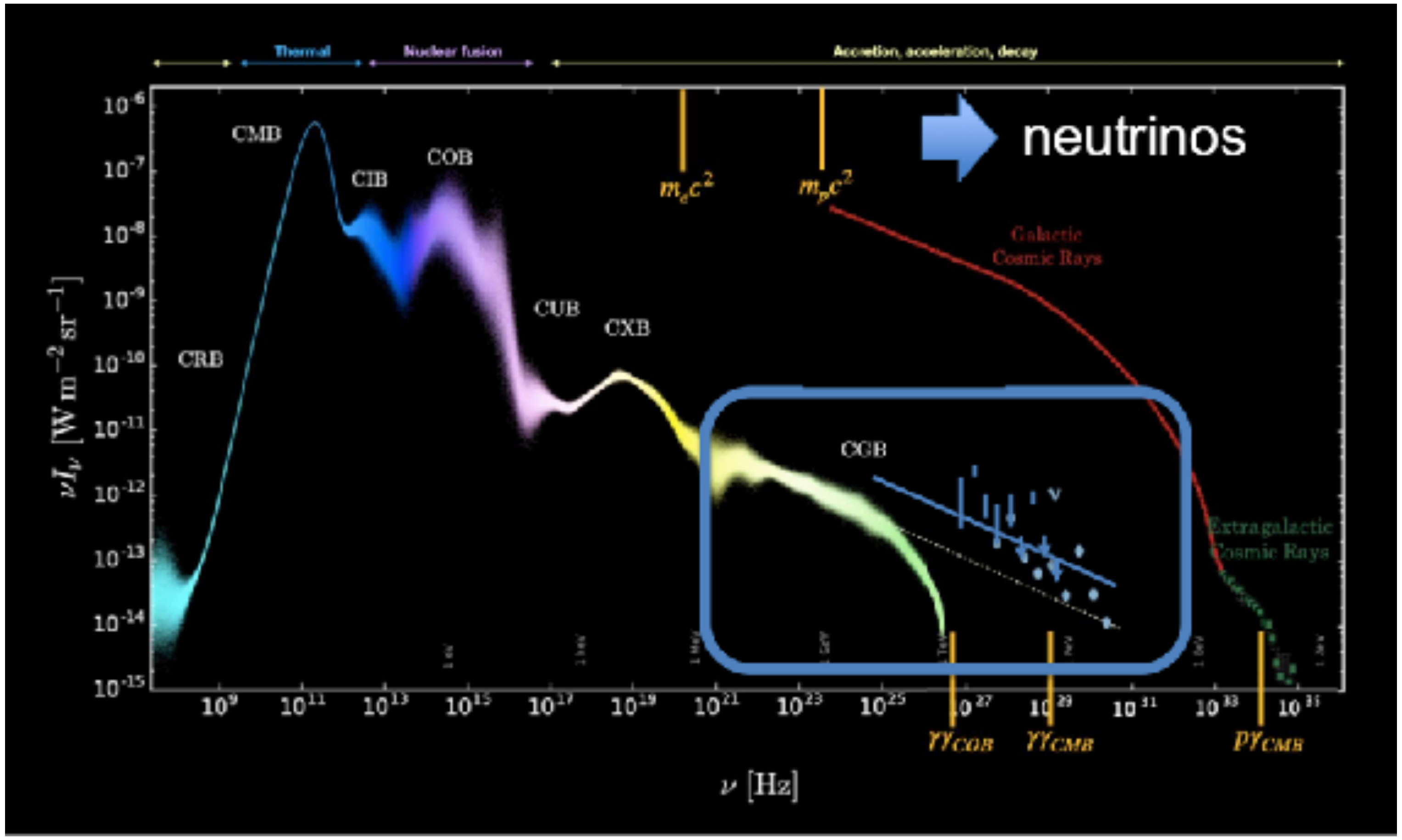
Comisso

Farrar

# Word cloud (from talks' titles)



# Diffuse neutrinos




Halzen

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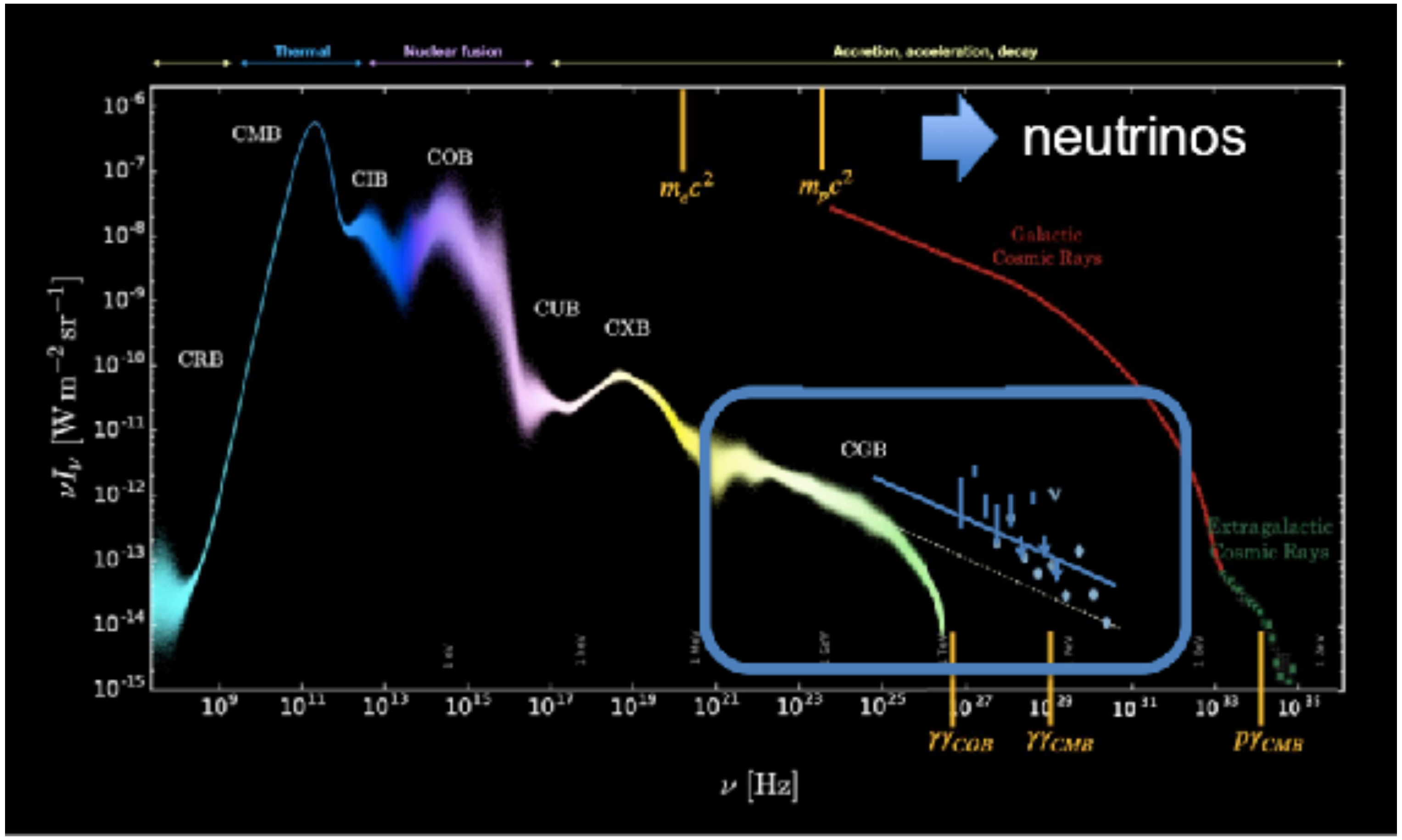


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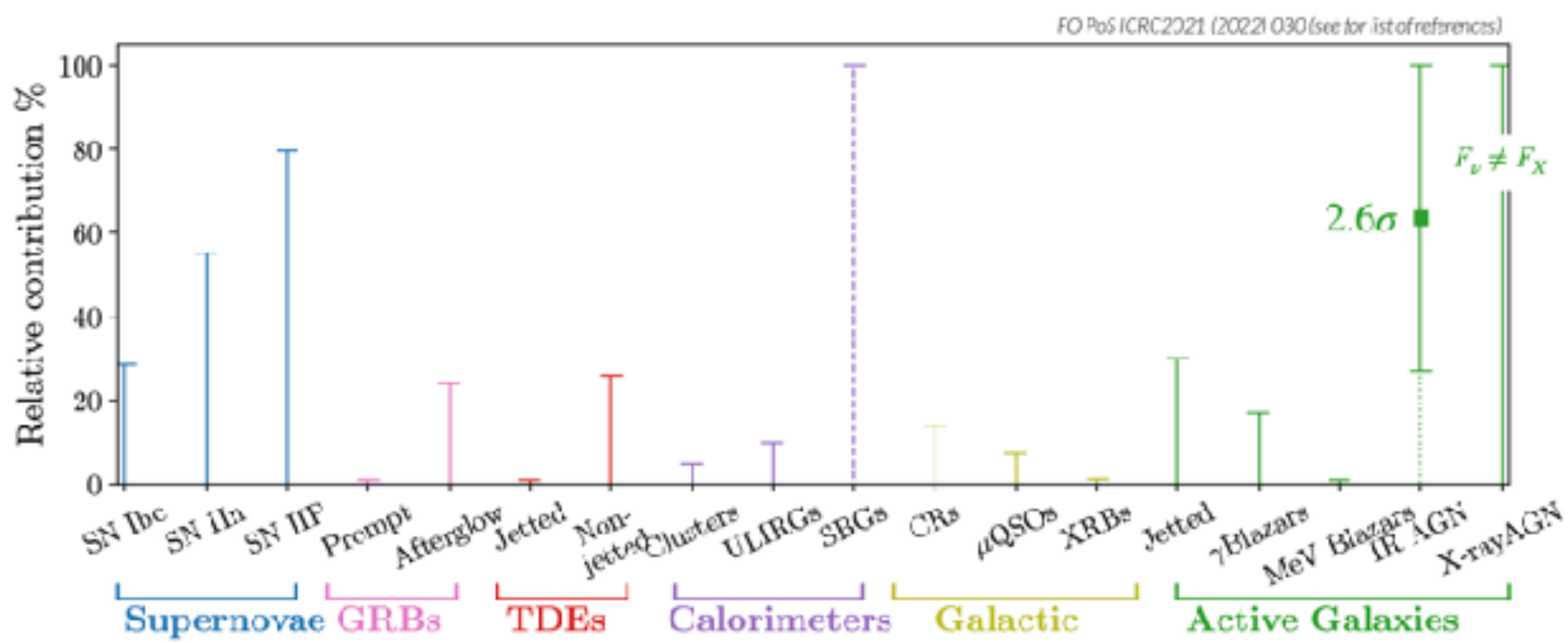


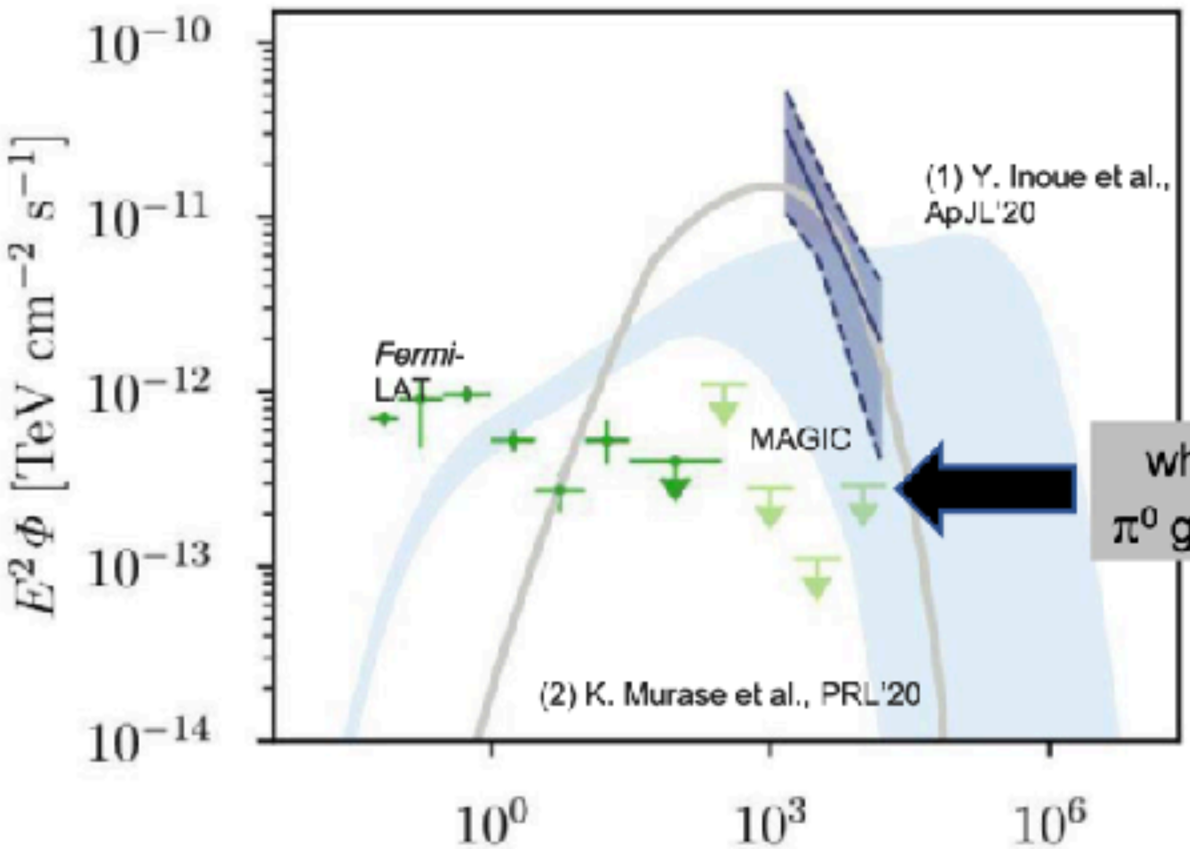

Oikonomou

# Sources!

Halzen

a gamma ray for every neutrino?

NGC 1068: an obscured cosmic accelerator




where are the $\pi^0$ gamma rays ?

The emergence of a new class of sources: high X-ray active galaxies

→ 2024: IceCube Search for Neutrino Emission from X-ray Bright Seyfert Galaxies
Northern sky NGC 4151 and CGCG 420-015
arXiv:2406.07601

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Halzen

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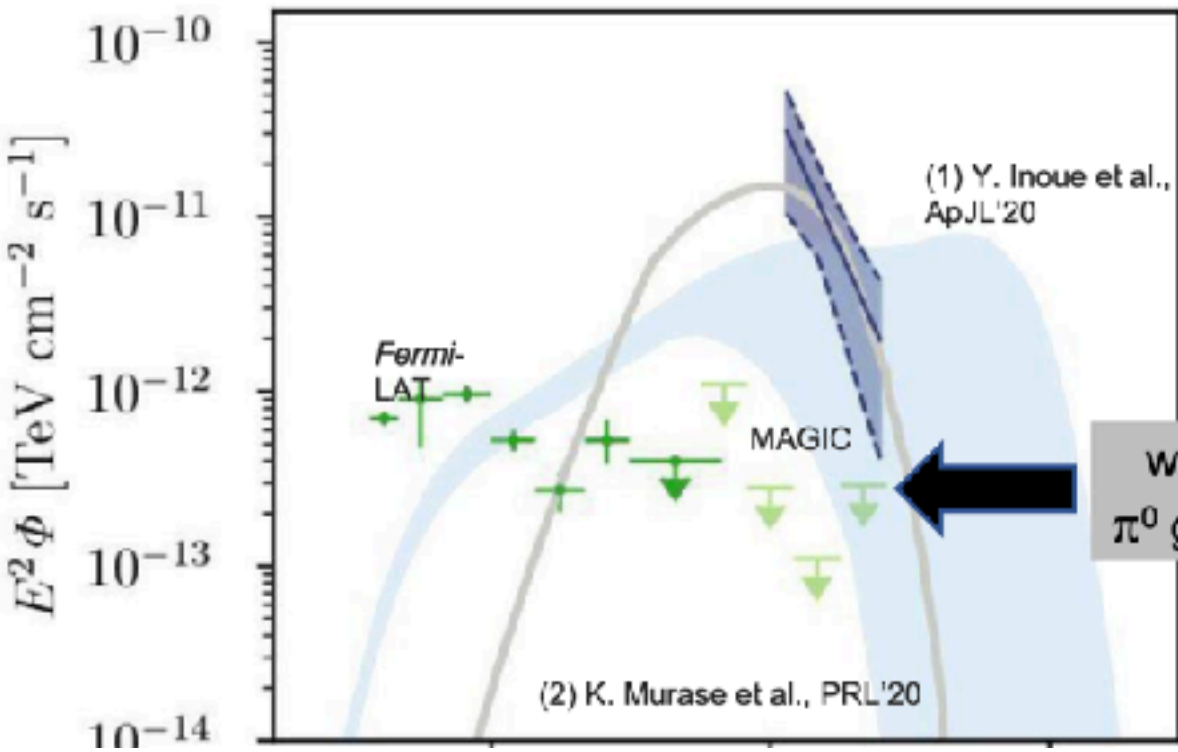


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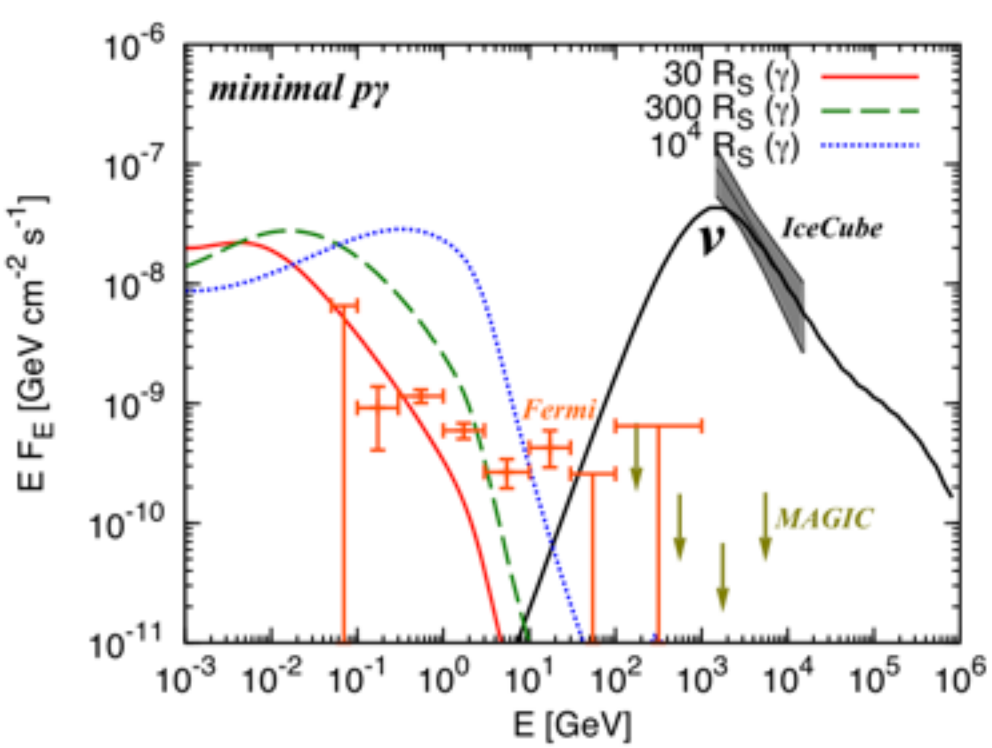


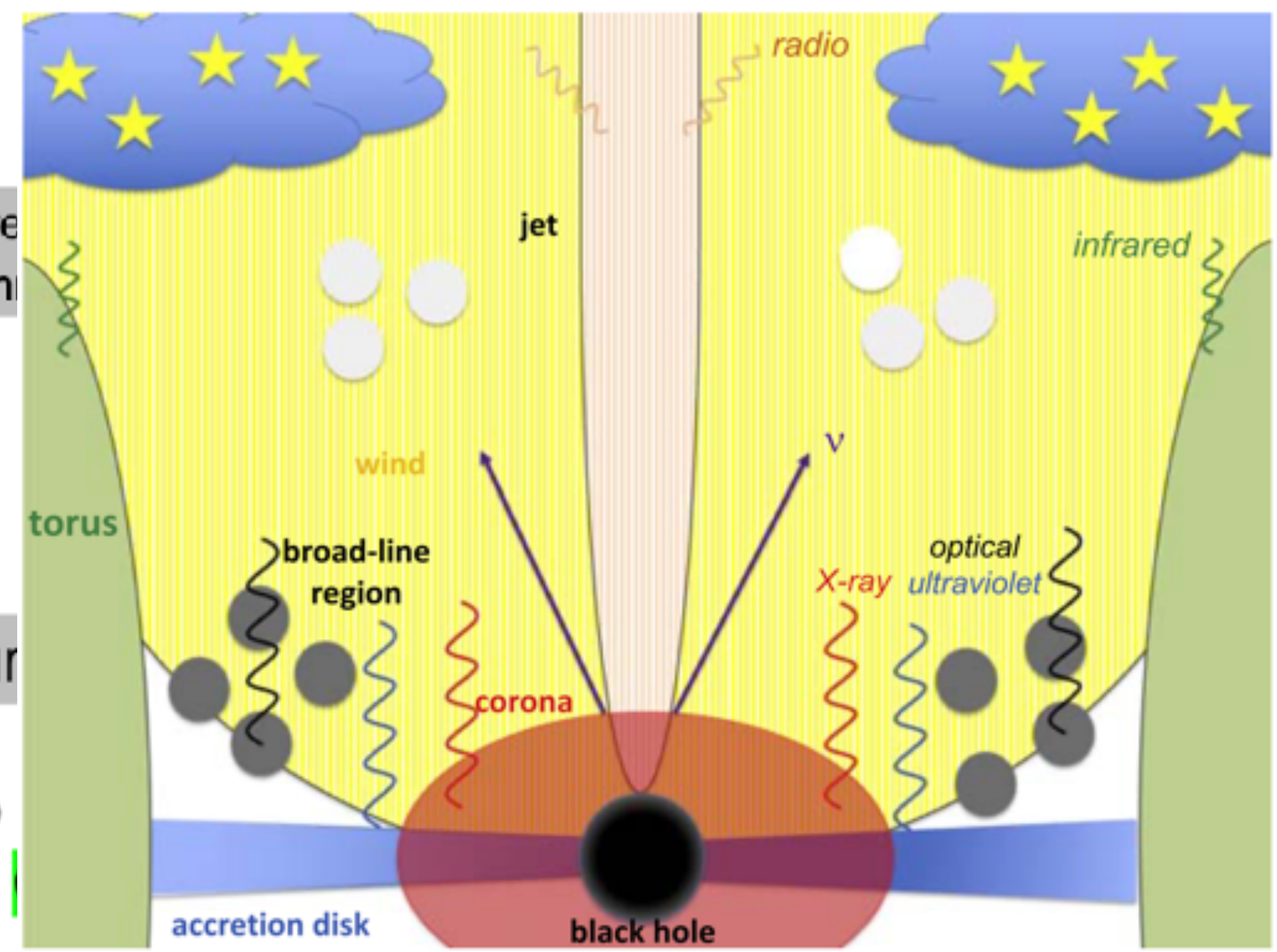


Murase

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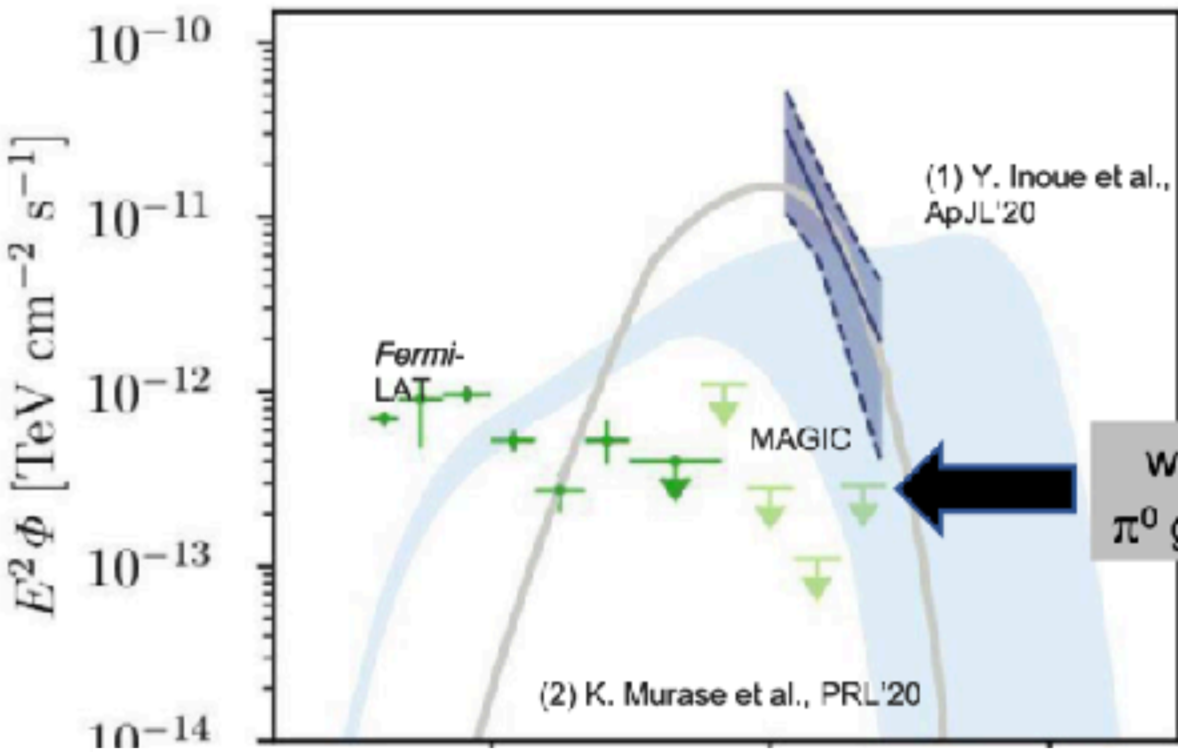


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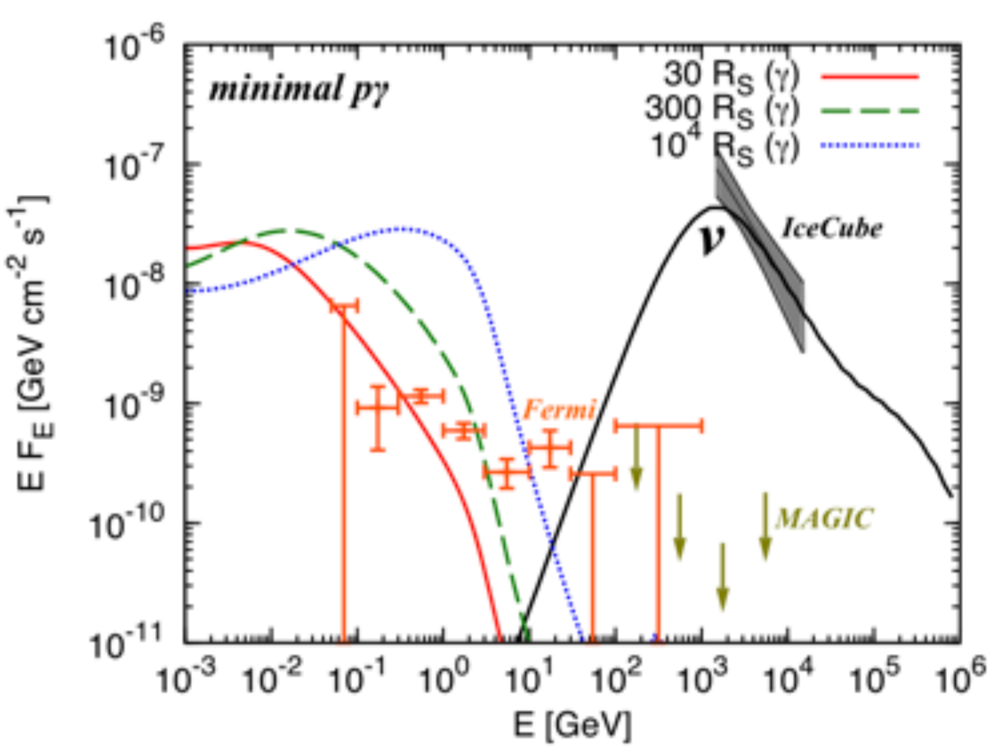


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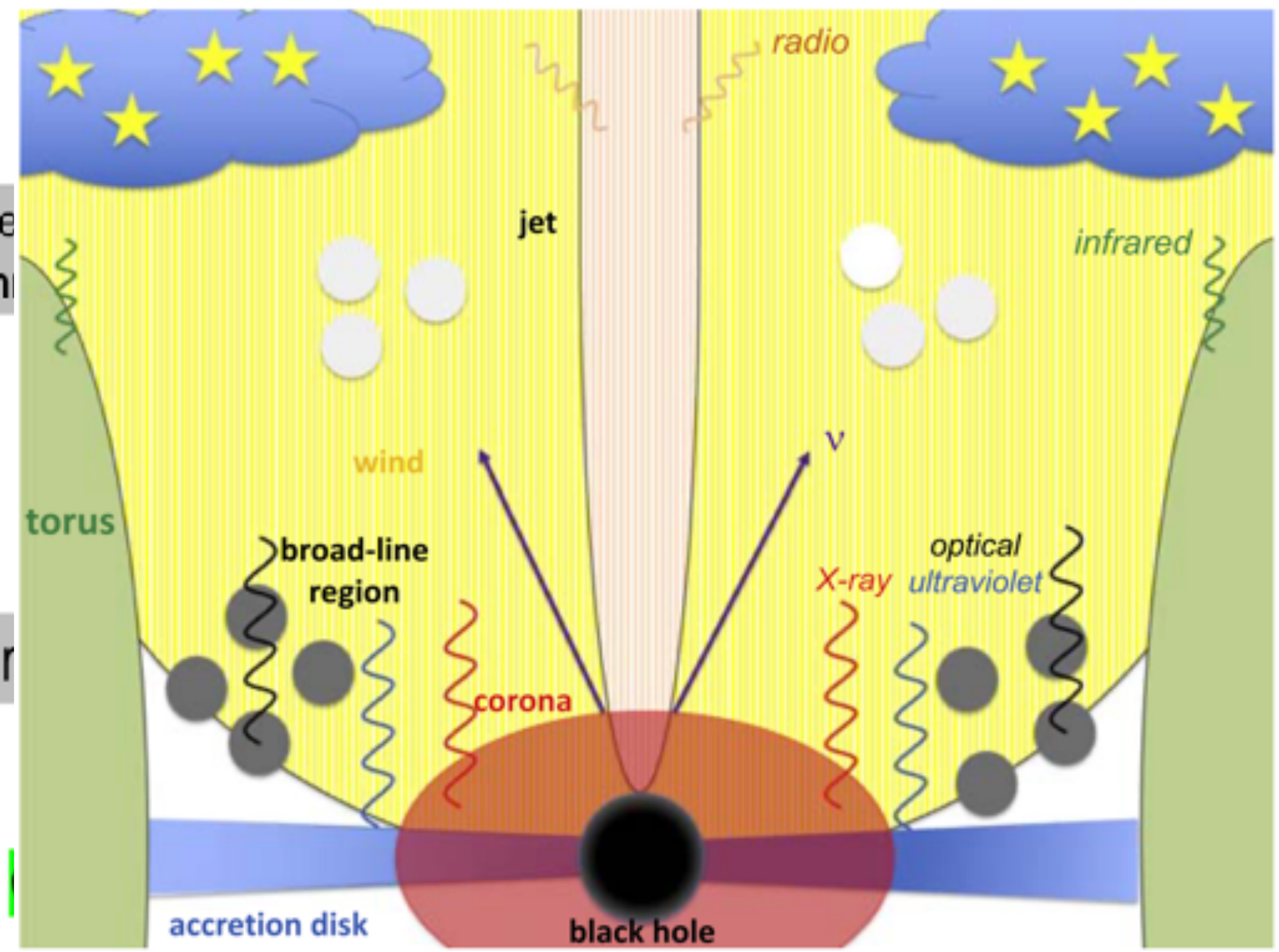
Waxman —> critical discussion and alternatives




Murase

# Hidden sources are old stuff

1979

NEUTRINOS AS A PROBE FOR THE NATURE OF

AND PROCESSES IN ACTIVE GALACTIC NUCLEI

R. Silberberg and M. M. Shapiro
Laboratory for Cosmic Ray Physics
Naval Research Laboratory
Washington, D. C. 20375, U.S.A.

ABSTRACT

There are several classes of galaxies with compact nuclei and huge energy outputs ($10^{42}$ to $10^{47}$ erg/sec) from these nuclei. Such objects are the quasars, radio-galaxies, Seyfert galaxies of class 1 and Seyferts of class 2. A large or dominant non-thermal energy component has been established for the first three. Seyferts of class 2, however, are so heavily obscured by dust and gas that their non-thermal nature is not established. It is shown that neutrino astronomy would help ascertain the nature of class 2 Seyferts. Various mechanisms have been proposed for energy generation in galactic nuclei: ultra-massive black holes, giant stars (spinars), and dense clusters of stars with frequent supernovae. The nature of the radio lobes and jets is still obscure: are they ejected plasmoids, or effects of particle beams or ejected fragmented spinars? How neutrino astronomy might help to choose the appropriate model among alternatives such as these will be explored.

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alternative

**Eichler's comment (1979)**

Berezinsky (1977) has pointed out that optical photons emitted at a scale of $\sim 10^{15}$ cm in a galactic nucleus could serve as a target against which high-energy protons convert some of their energy to charged pions through the reaction

$$p + \gamma \rightarrow n + \pi^{+} . \qquad (10)$$

Here we add that *X*-radiation could serve the same purpose and could interact with protons having energy as low as $\sim 3 \times 10^{13}$ eV. Consider that the X-ray

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*Mon. Not. R. astr. Soc.* (1981) 194, 3–14

## On high-energy neutrino radiation of quasars and active galactic nuclei

V. S. Berezinsky *Institute for Nuclear Research, Academy of Sciences of the USSR, Moscow, USSR*
V. L. Ginzburg *P. N. Lebedev Physical Institute, Academy of Sciences of the USSR, Moscow, USSR*

Received 1980 February 26

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nuclei and huge energy outputs ($10^{42}$ to $10^{47}$ erg/
from these nuclei
galaxies, Seyfert
class 2. A large
ponent has been
ferts of class 2, however, are so heavily obscure
dust and ga
established
would help
Various mec
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holes, gian
stars with
radio lobes
ejected pla
ejected fra
might help
alternative

Eichler's comment

Berezinsky (1977) has pointed
photons emitted at a scale of ~1(
nucleus could serve as a target a
energy protons convert some o
charged pions through the reactio

$$p + \gamma \rightarrow n + \pi^+ . \qquad (10)$$

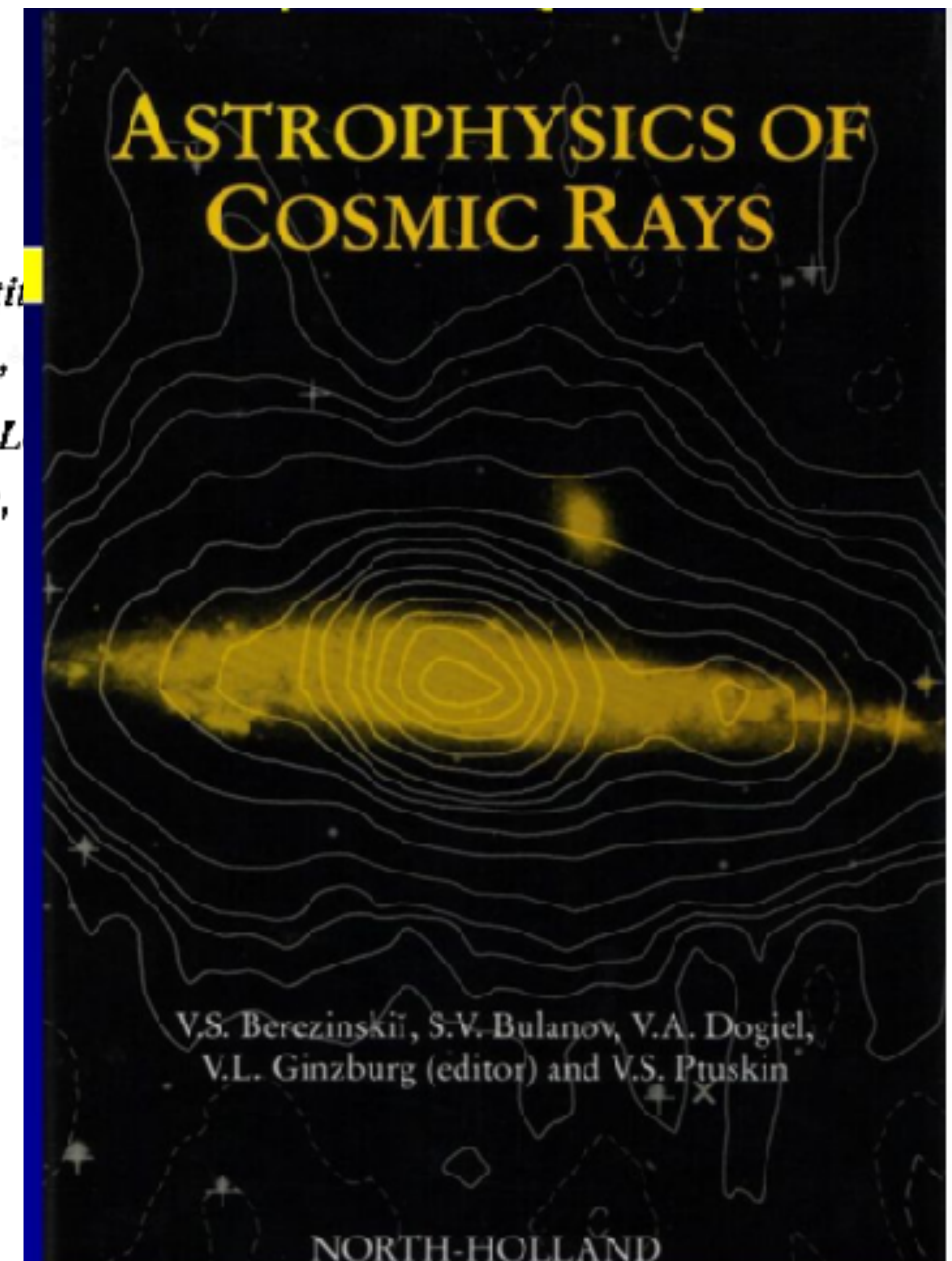
Here we add that X-radiation could serve the same purpose and could interact with protons having energy as low as ~3 × $10^{13}$ eV. Consider that the X-ray

*Mon. Not. R. astr. Soc.* (1981) 194, 3–14

## On high-energy neutrino radiation of quasars and active galactic nuclei

V. S. Berezinsky *Insti*
*Sciences of the USSR, Moscow,*
V. L. Ginzburg *P. N. L*
*Sciences of the USSR, Moscow,*

Received 1980 February 26



# Hidden sources are old stuff

NEUTRINOS AS A PROBE FOR THE NATURE OF

AND PROCESSES IN ACTIVE GALACTIC NUCLEI

R. Silberberg and M. M. Shapiro
Laboratory for Cosmic Ray Physics
Naval Research Laboratory
Washington, D. C. 20375, U.S.A.

1979

ABSTRACT

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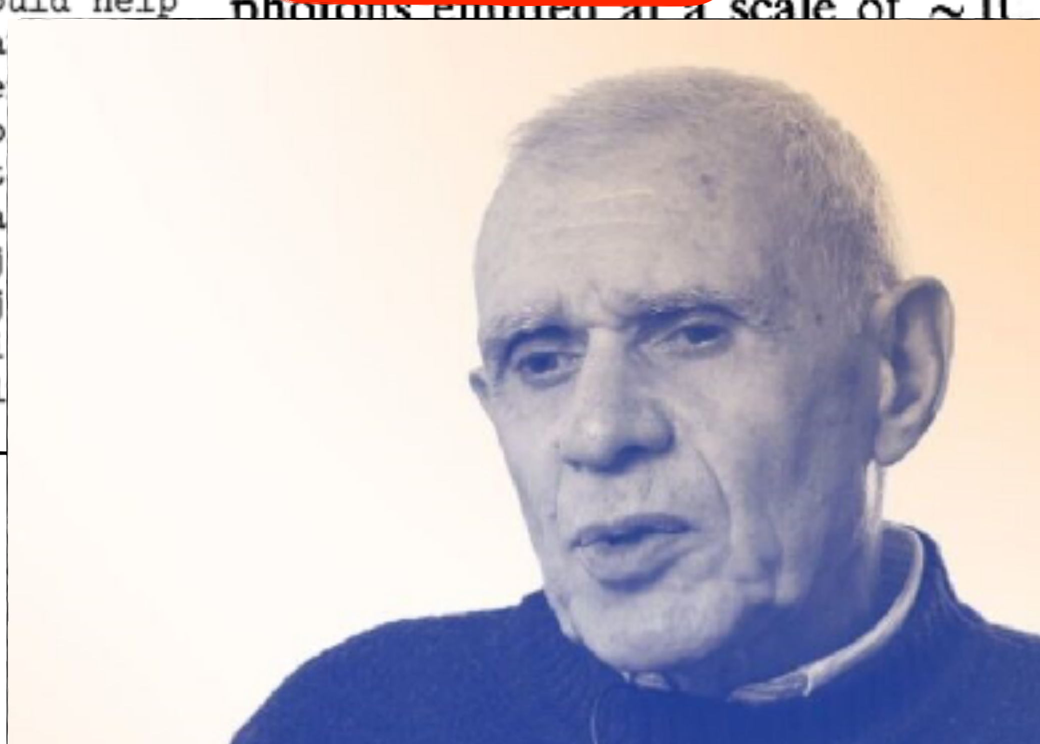
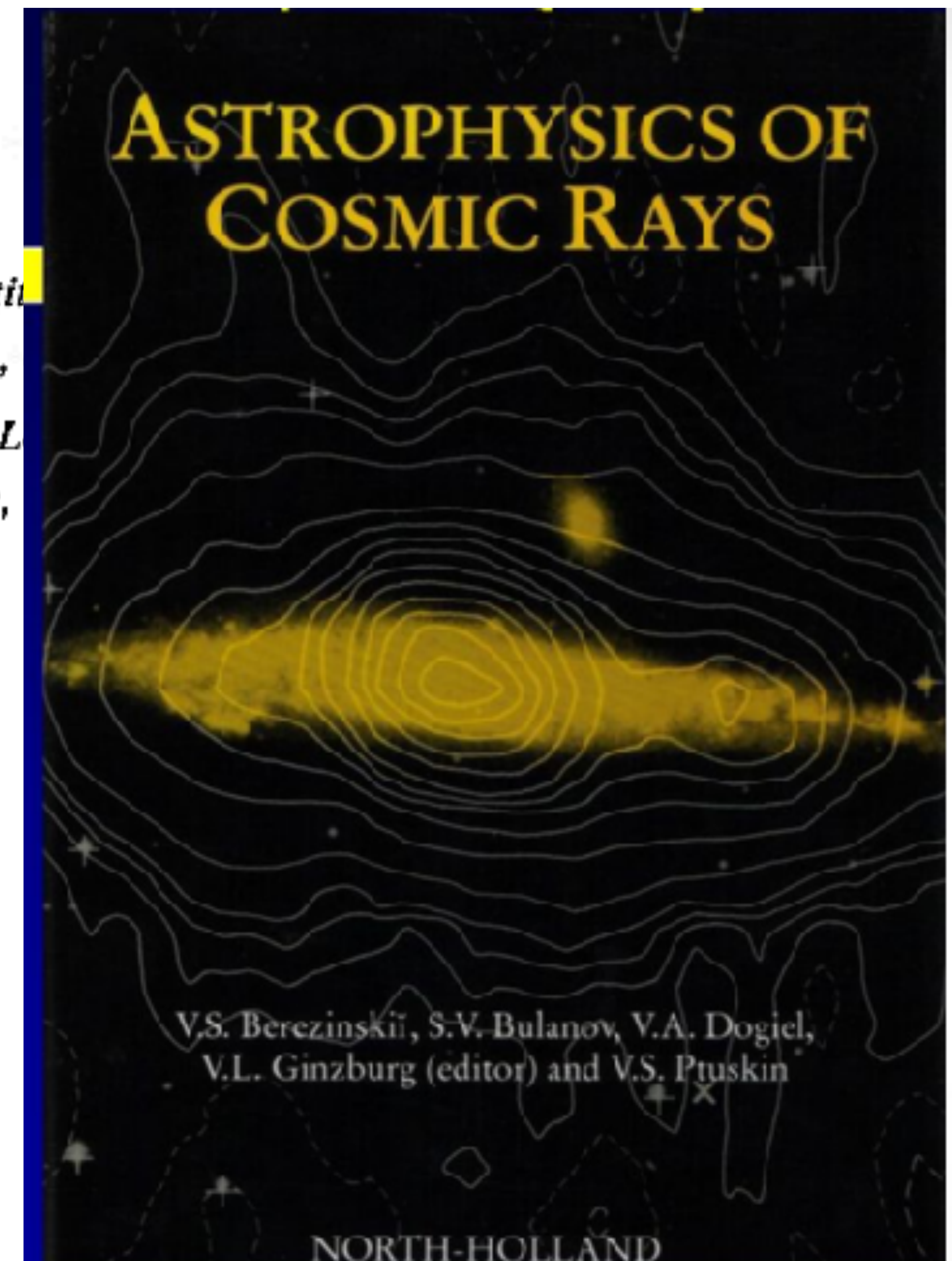
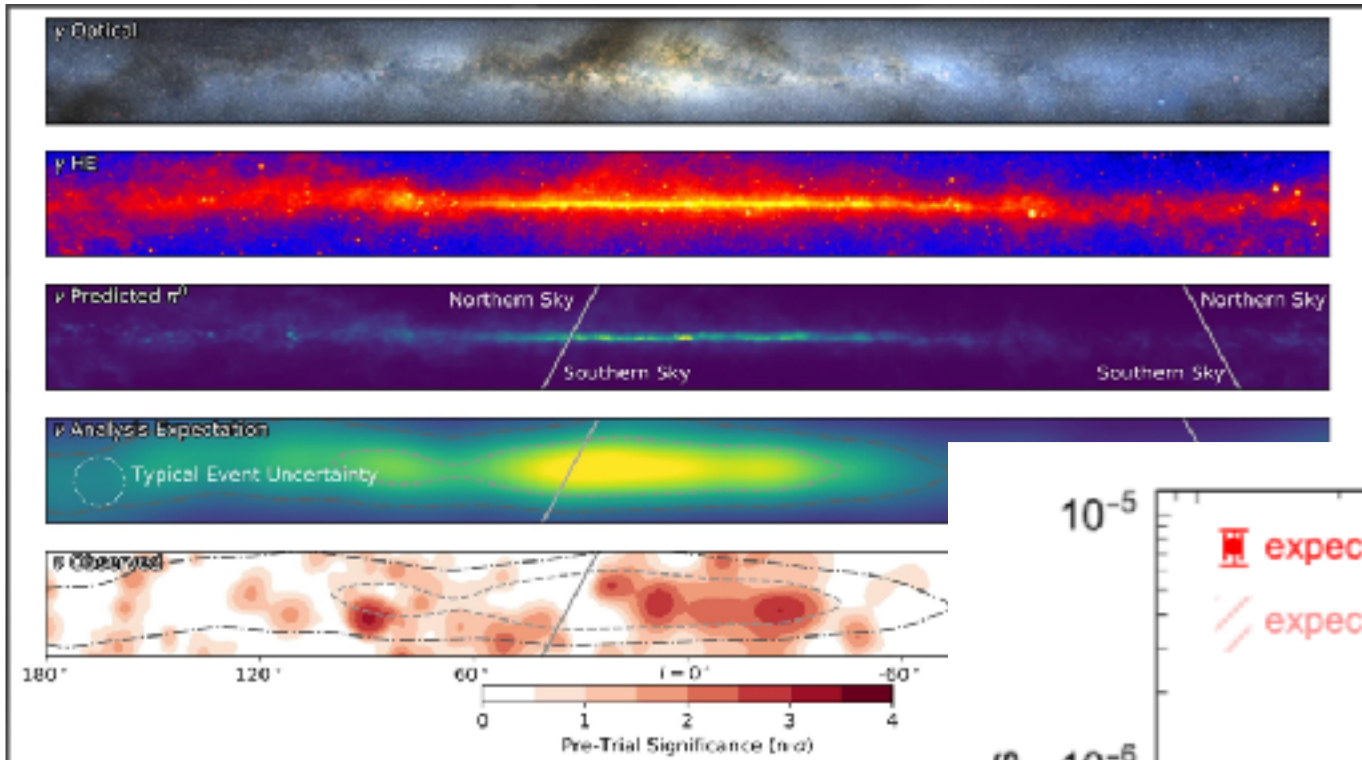
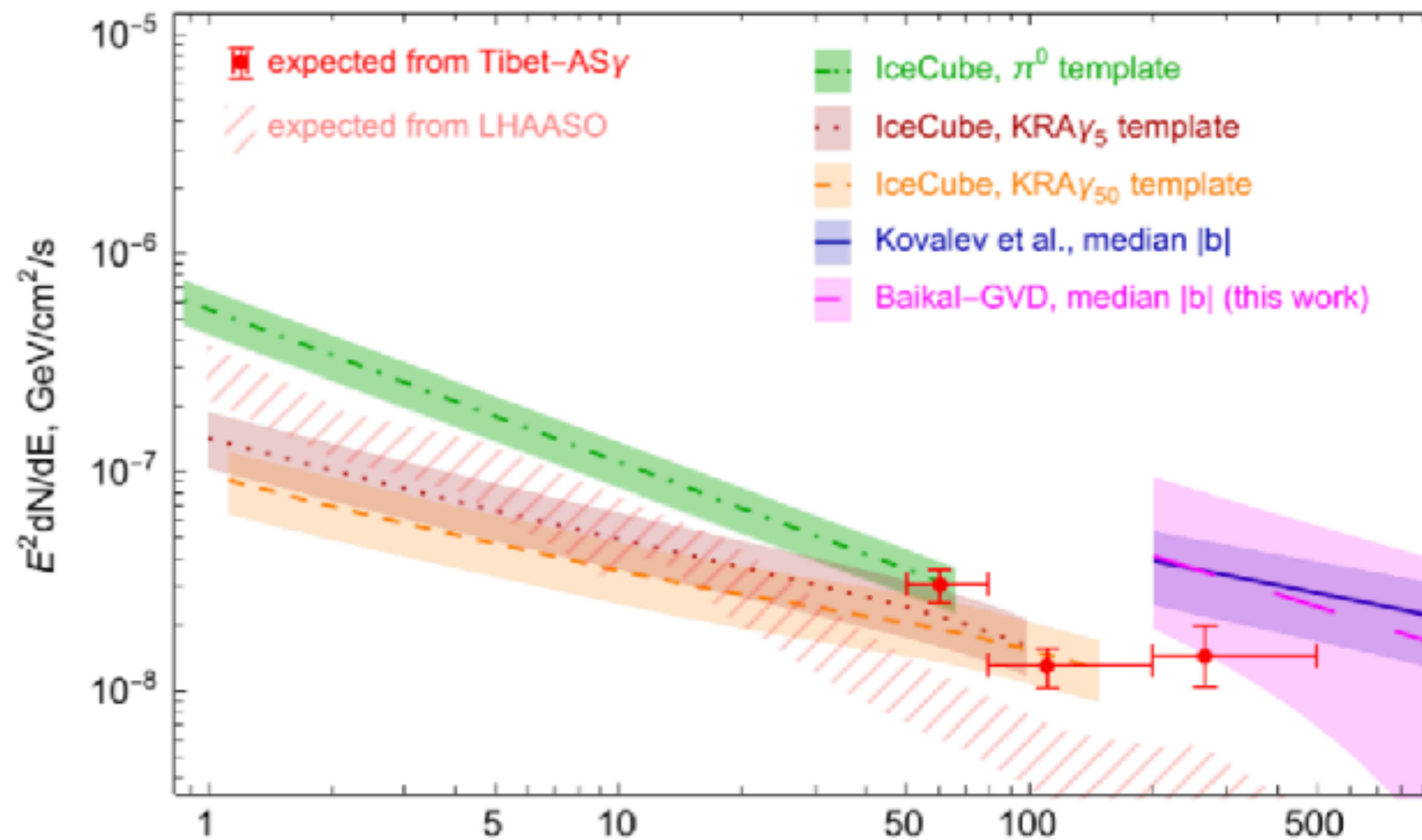




# Diffuse emission from the Galactic disk




Dvornicky




Halzen

Kurahashi Neilson

ANTARES —> Kouchner

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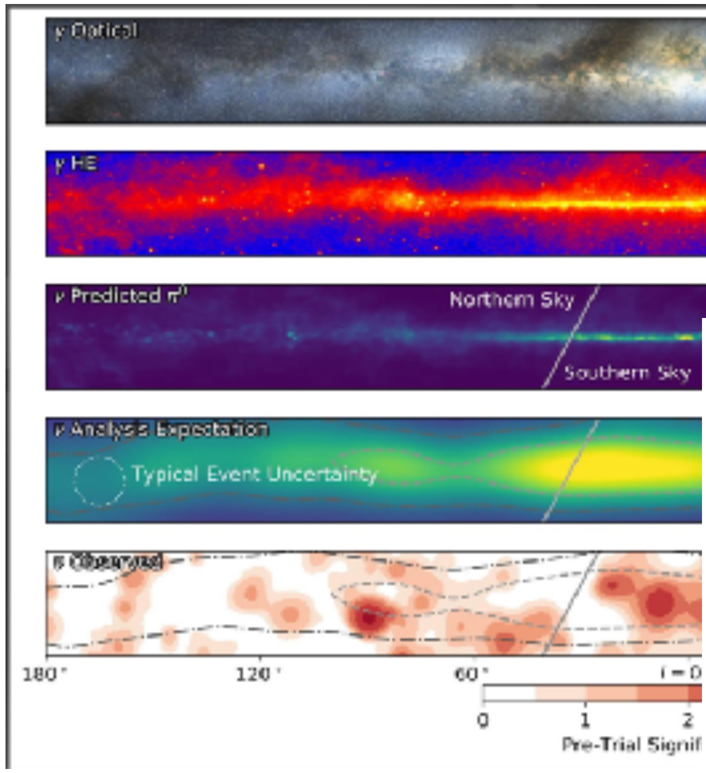
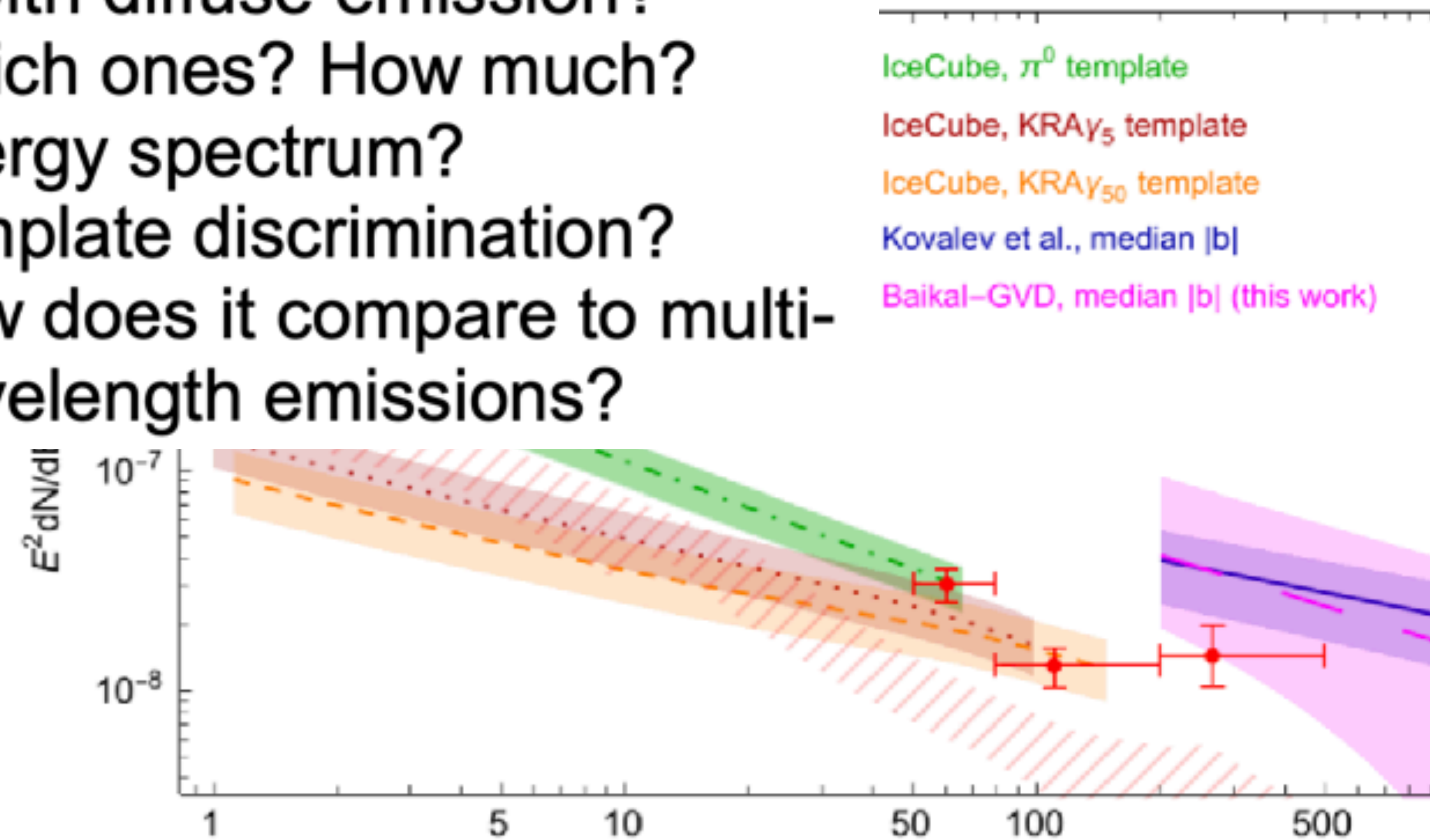



- Are there point sources mixed in with diffuse emission?
- Which ones? How much?
- Energy spectrum?
- Template discrimination?
- How does it compare to multi-wavelength emissions?

Dvornicky

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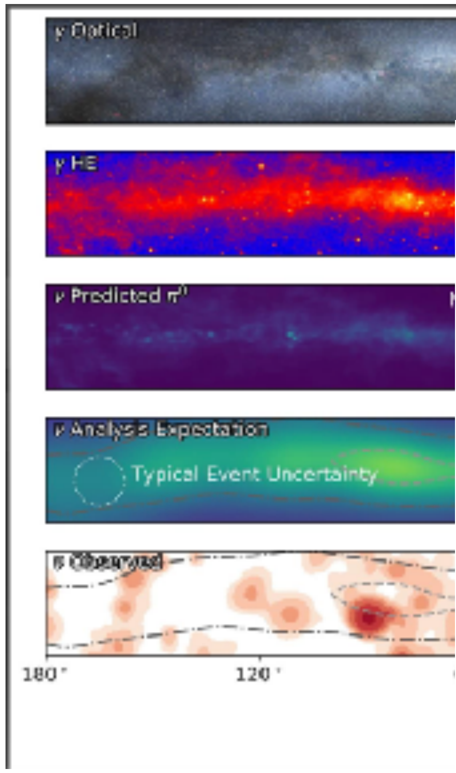


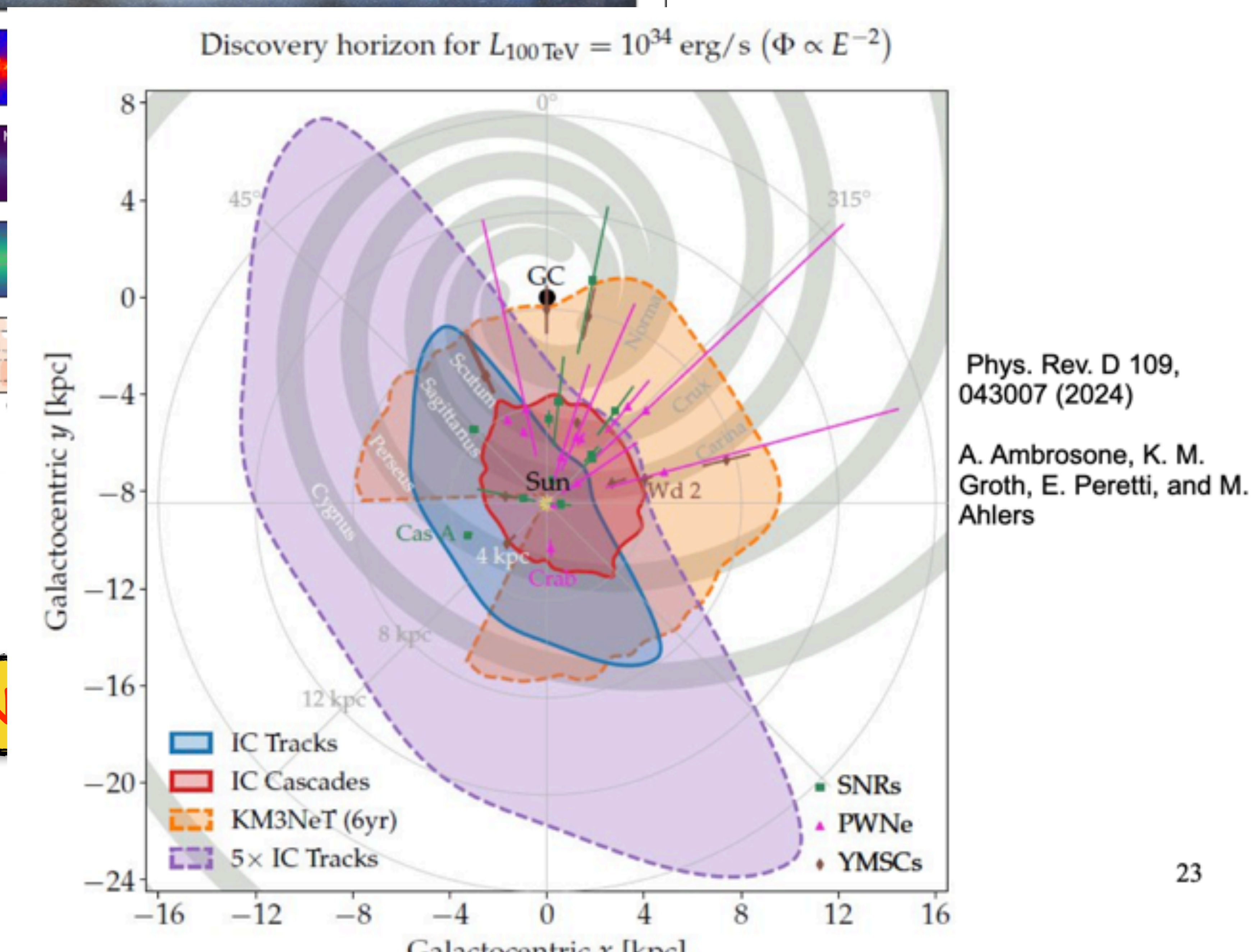


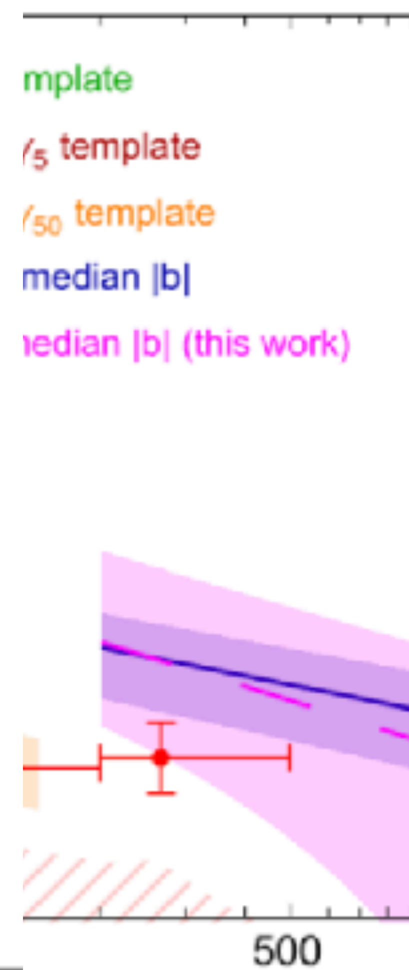


Dvornicky

Halzen

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ANTARES —> Kouchner

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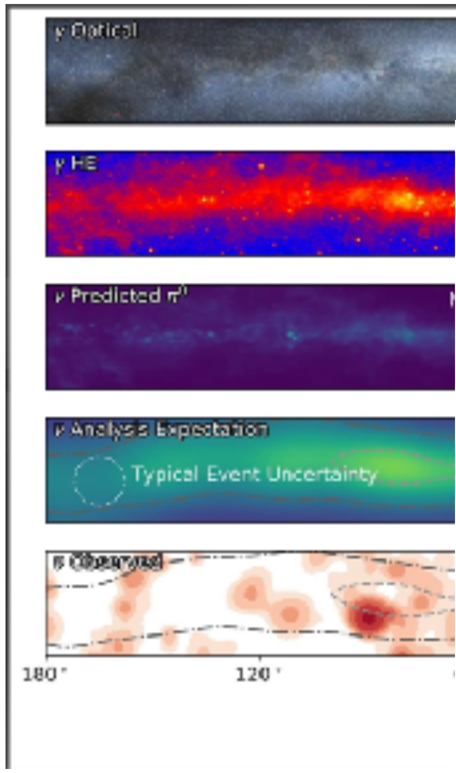


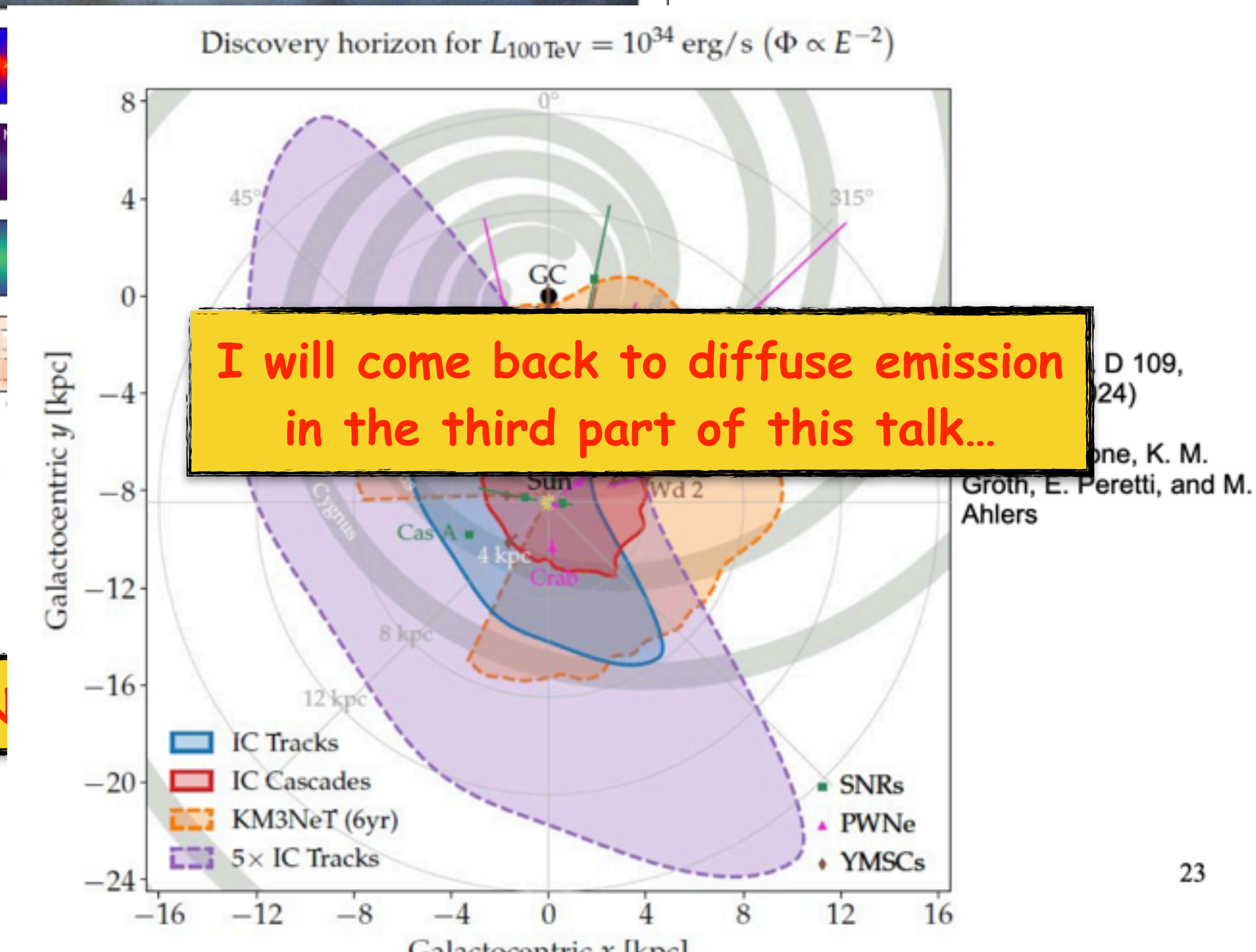


I will come back to diffuse emission in the third part of this talk…

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one, K. M.
Groth, E. Peretti, and M.
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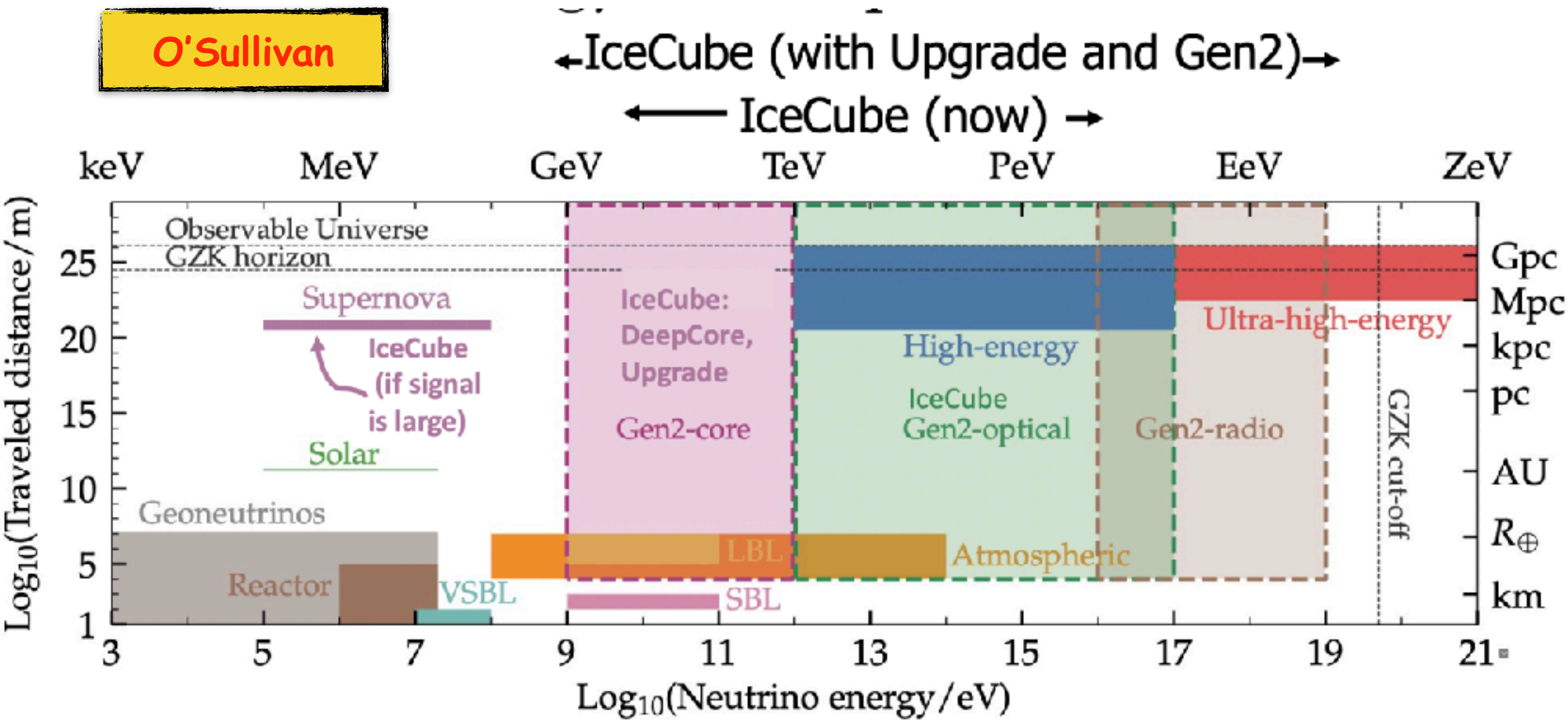
ANTARES —> Kouchner

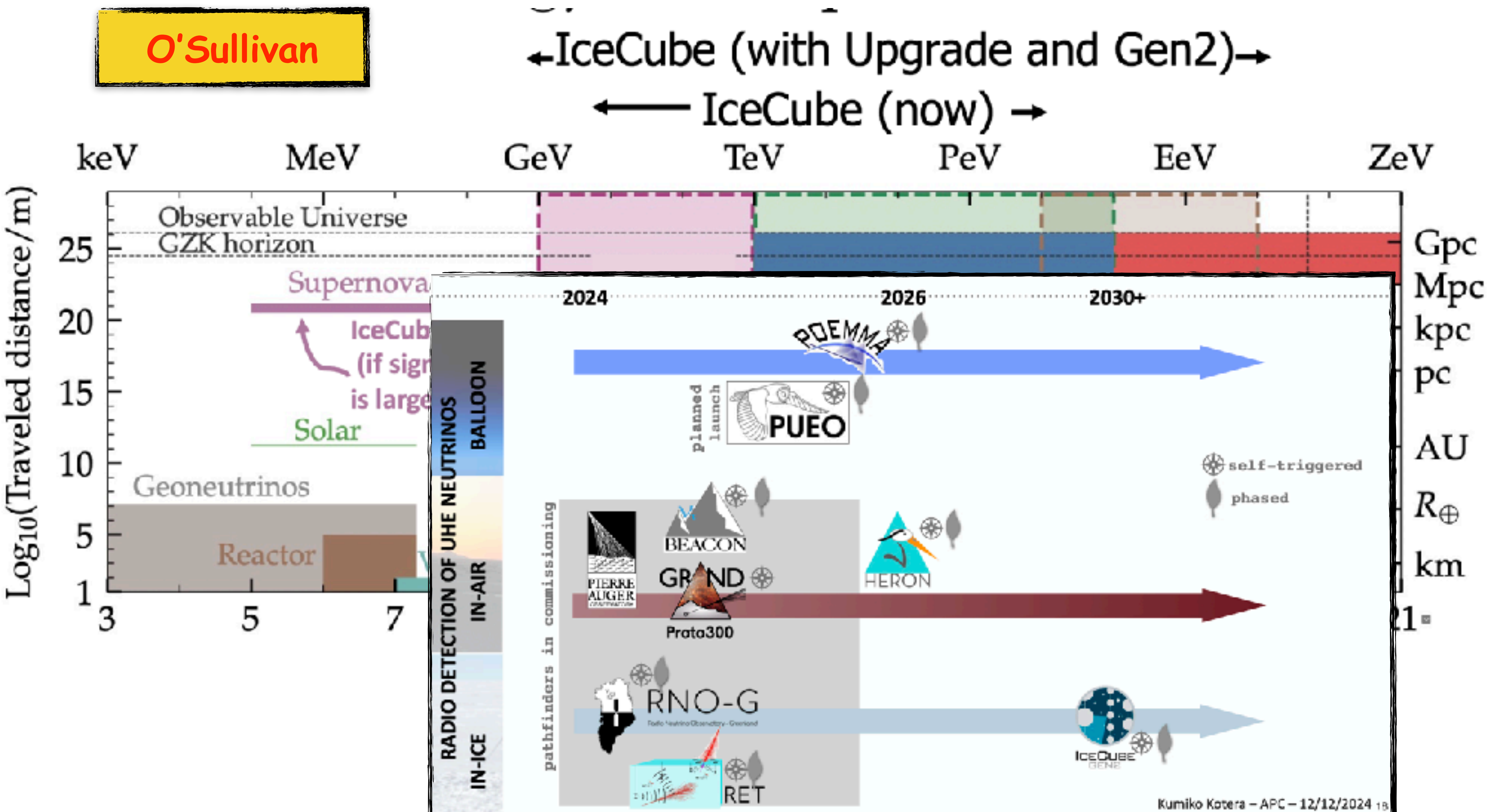
# The future of neutrino astronomy

O'Sullivan



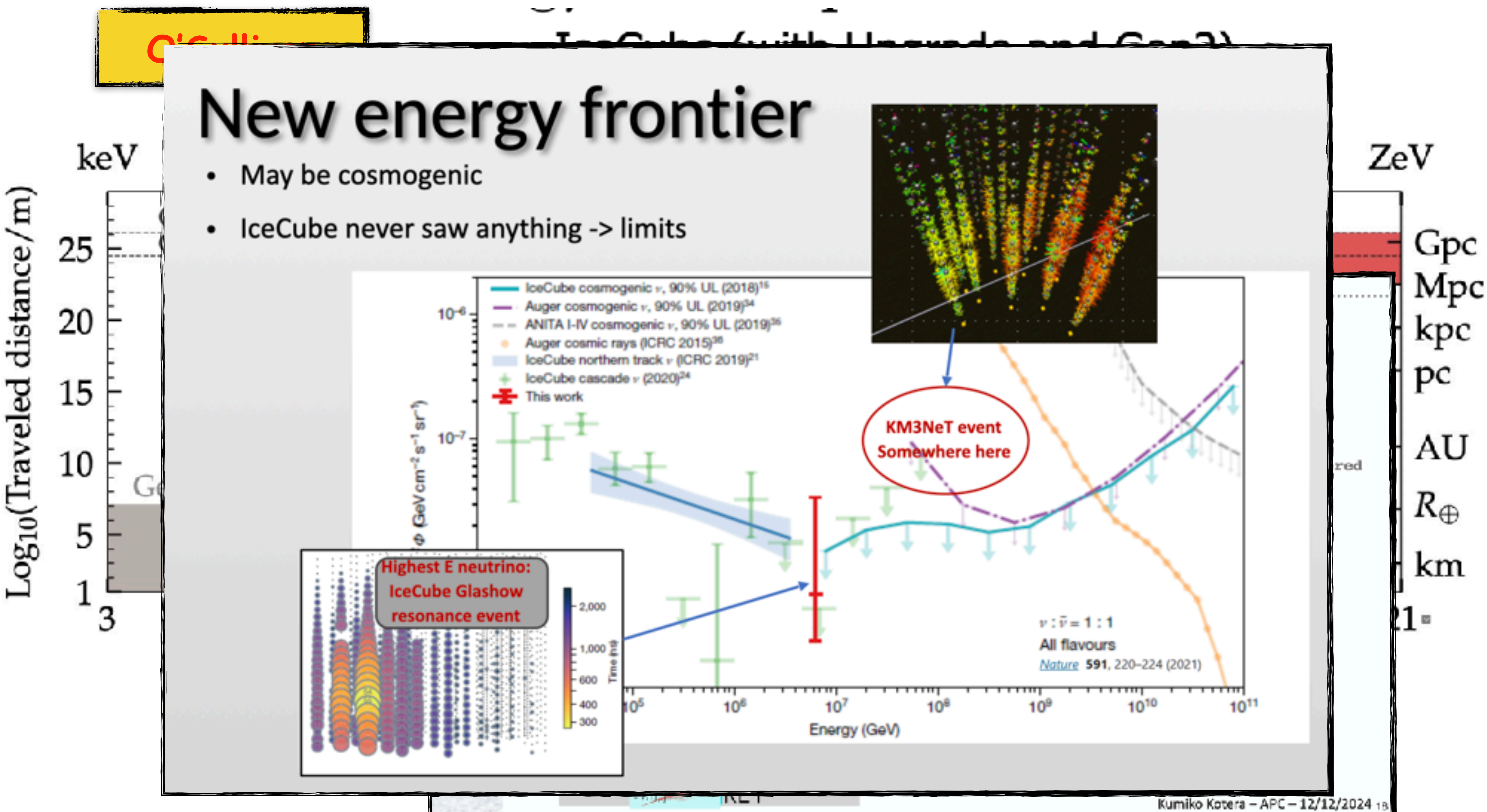
# The future of neutrino astronomy

O'Sullivan




Kotera

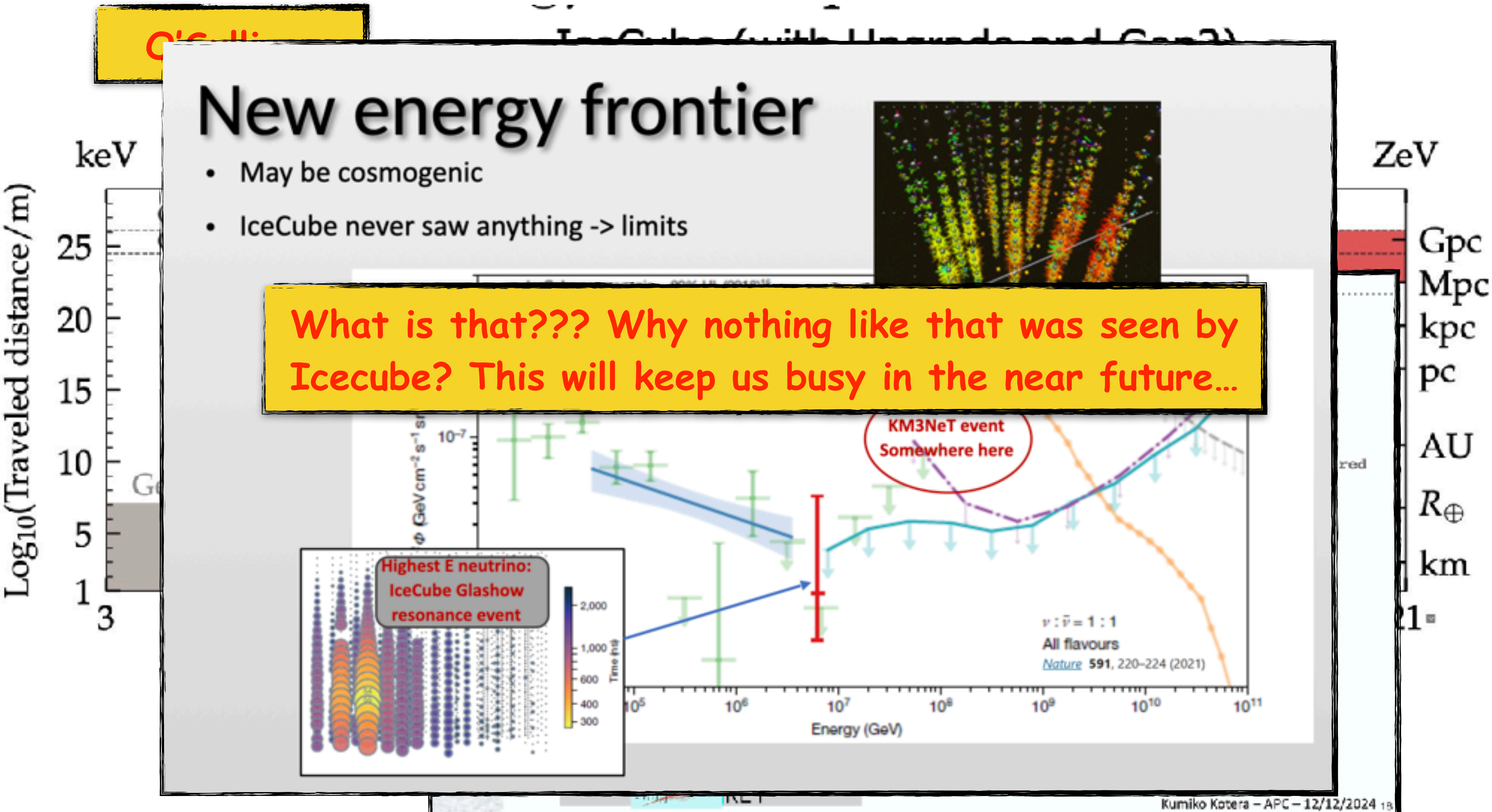
# The future of neutrino astronomy




Heijboer

Kotera

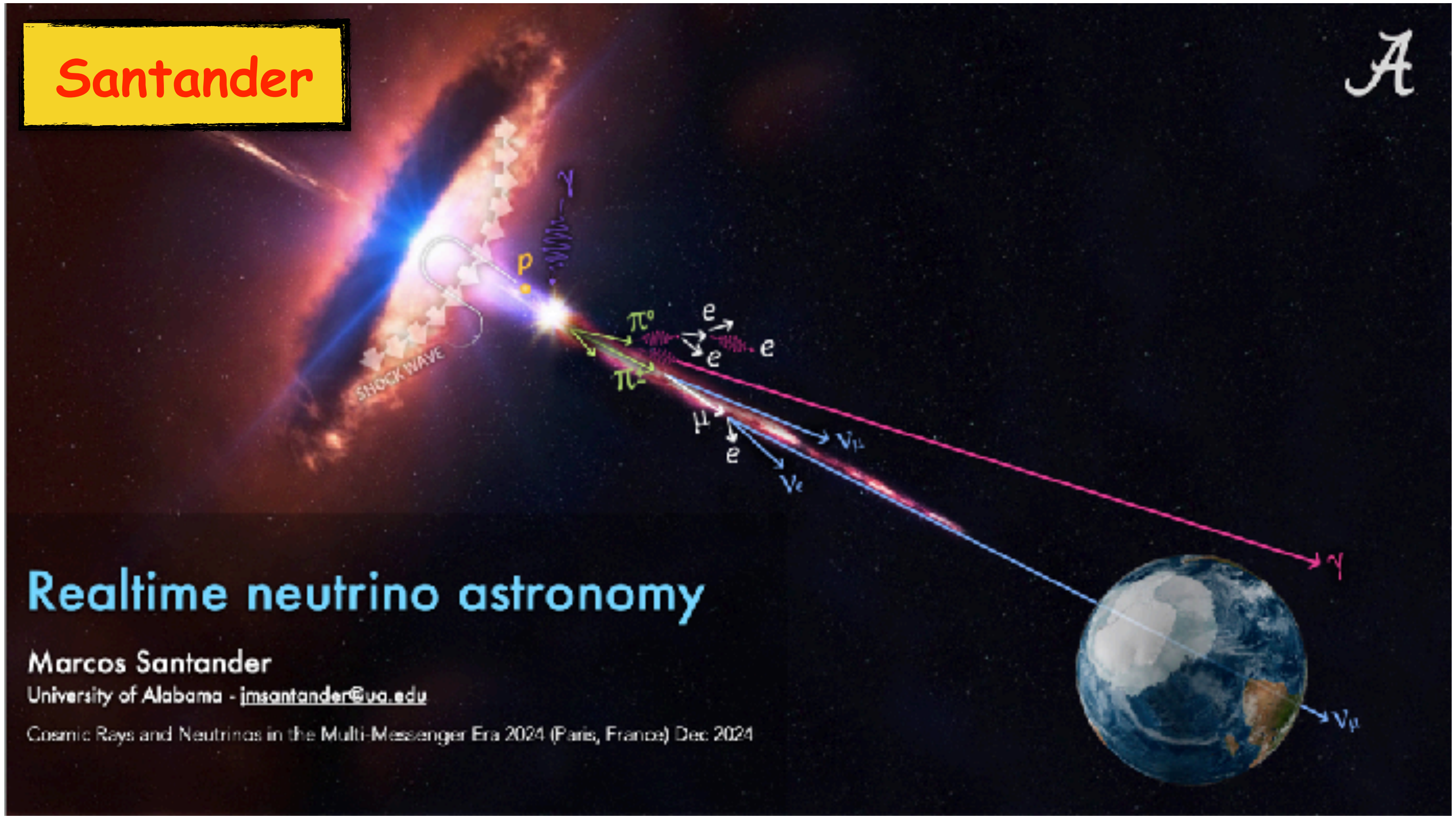
# The future of neutrino astronomy




Heijboer

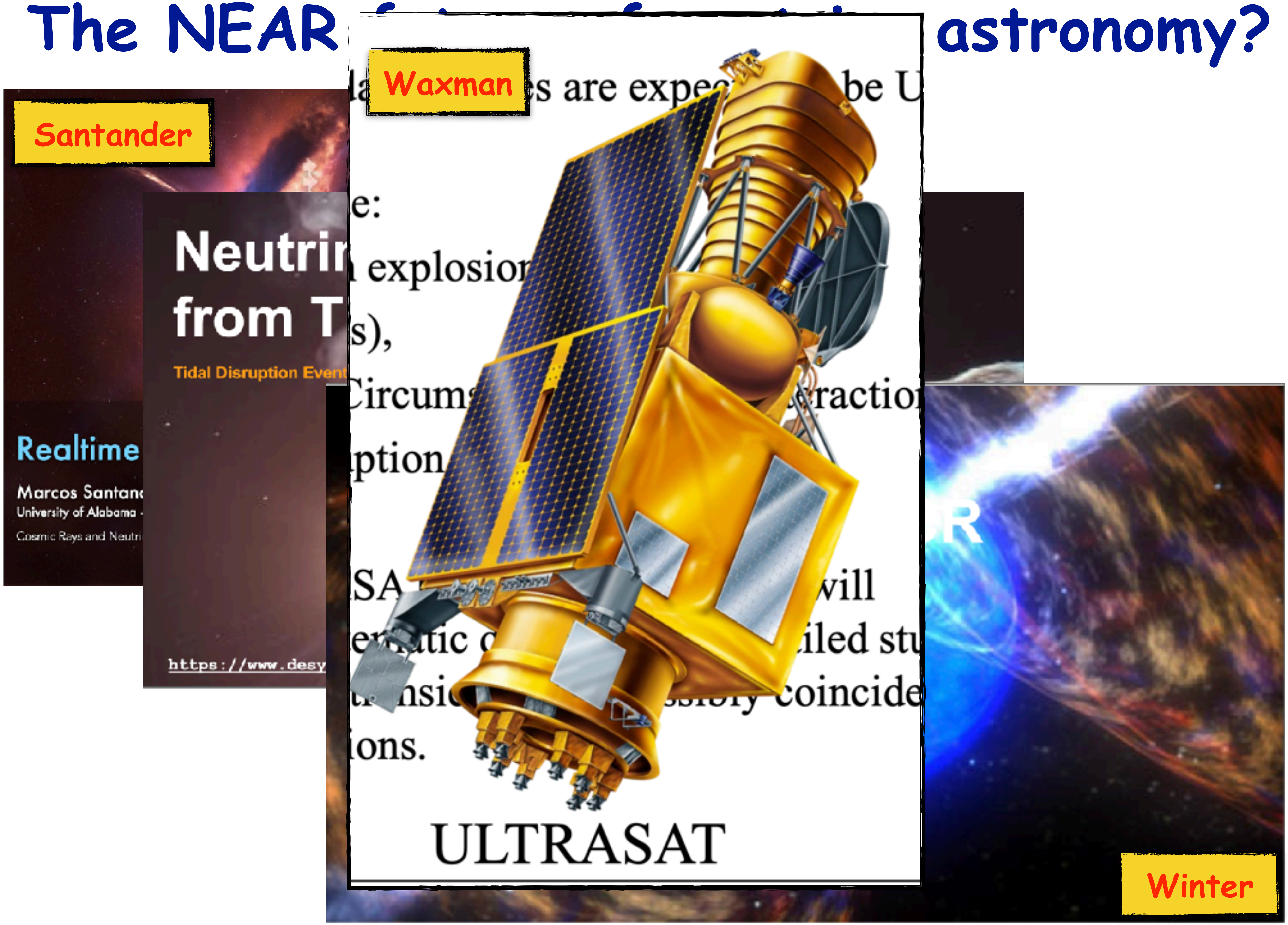
Kotera

# The NEAR future of neutrino astronomy?

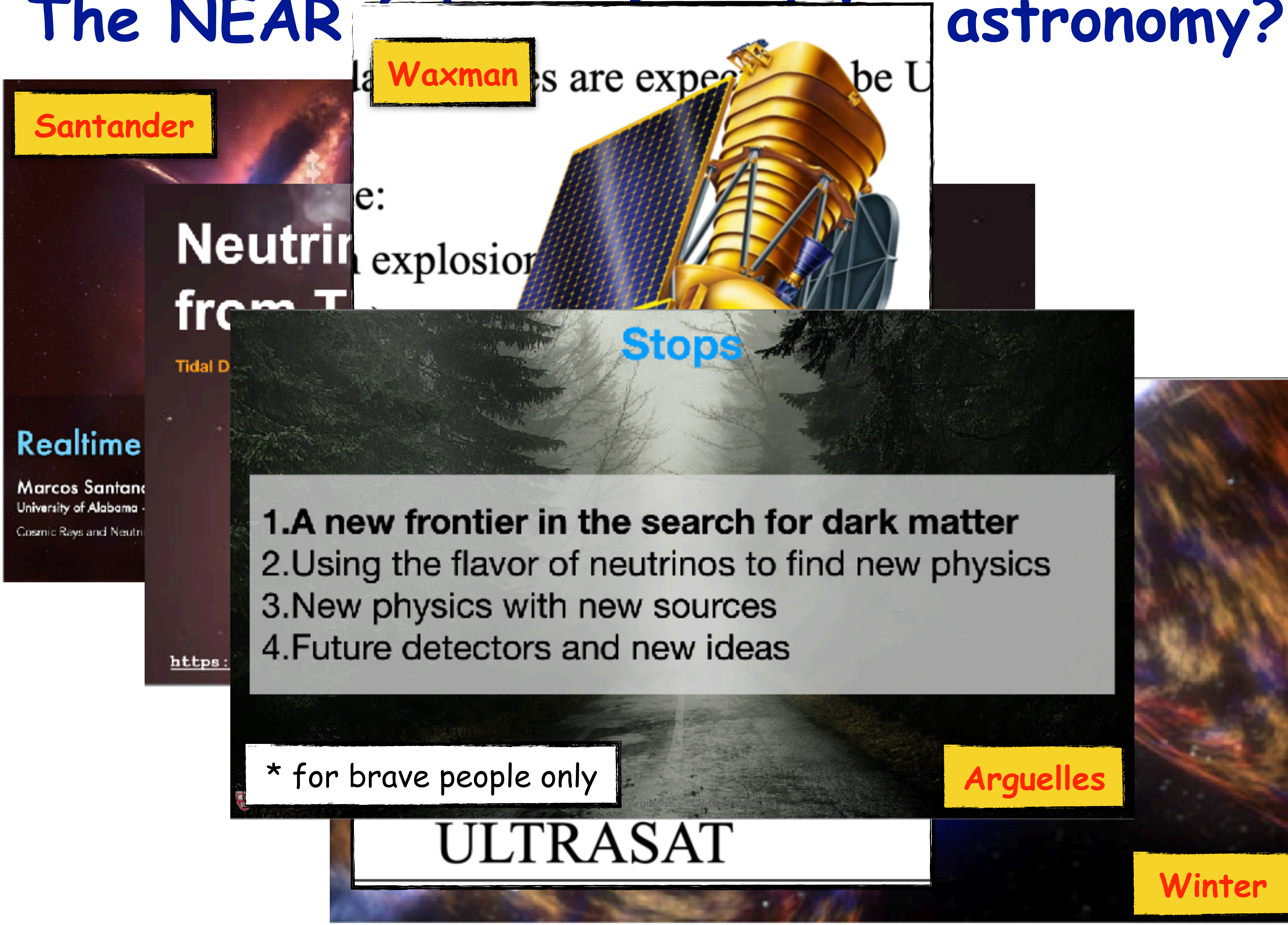


# The NEAR future of neutrino astronomy?

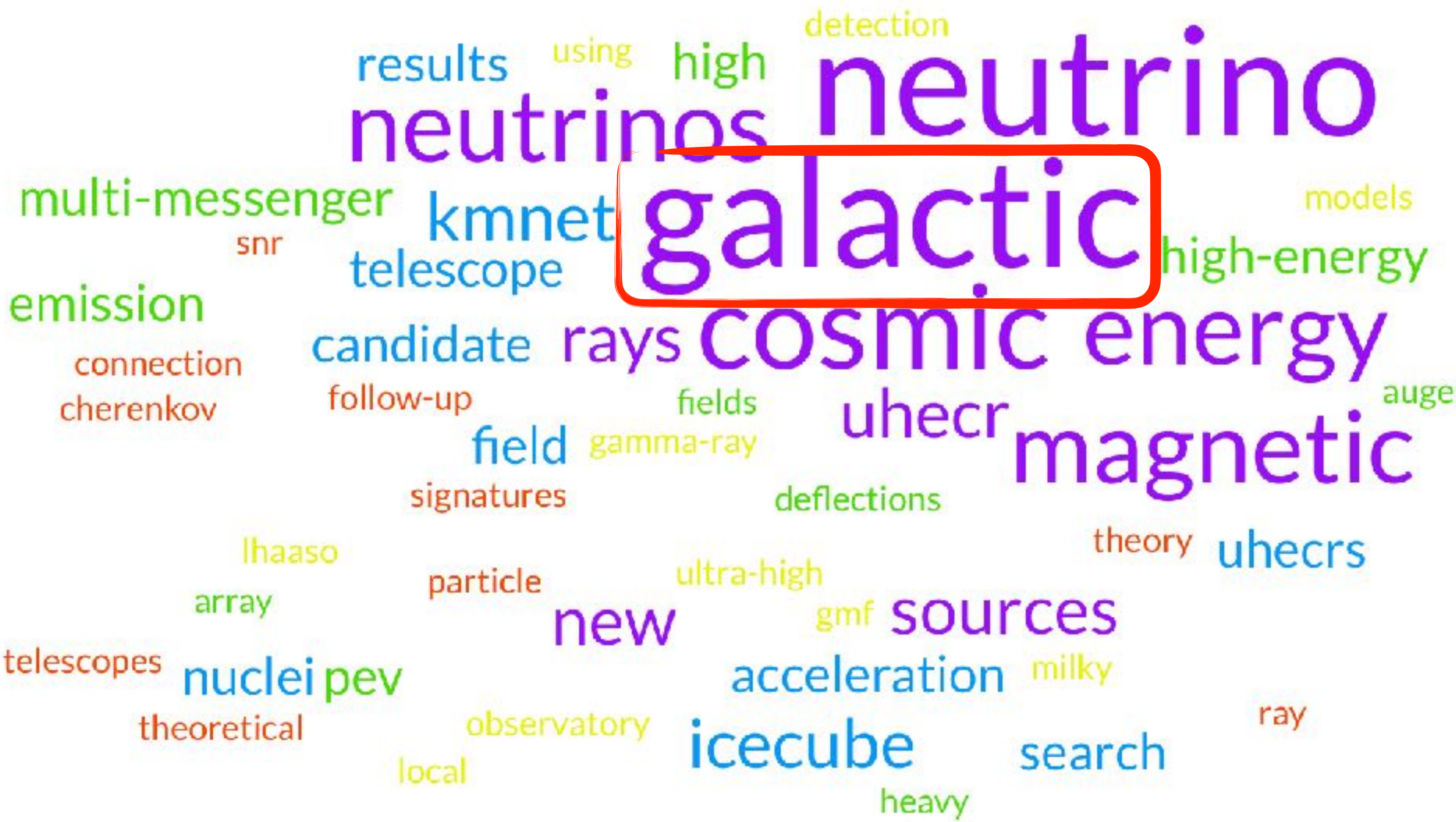
# The NEAR … astronomy?



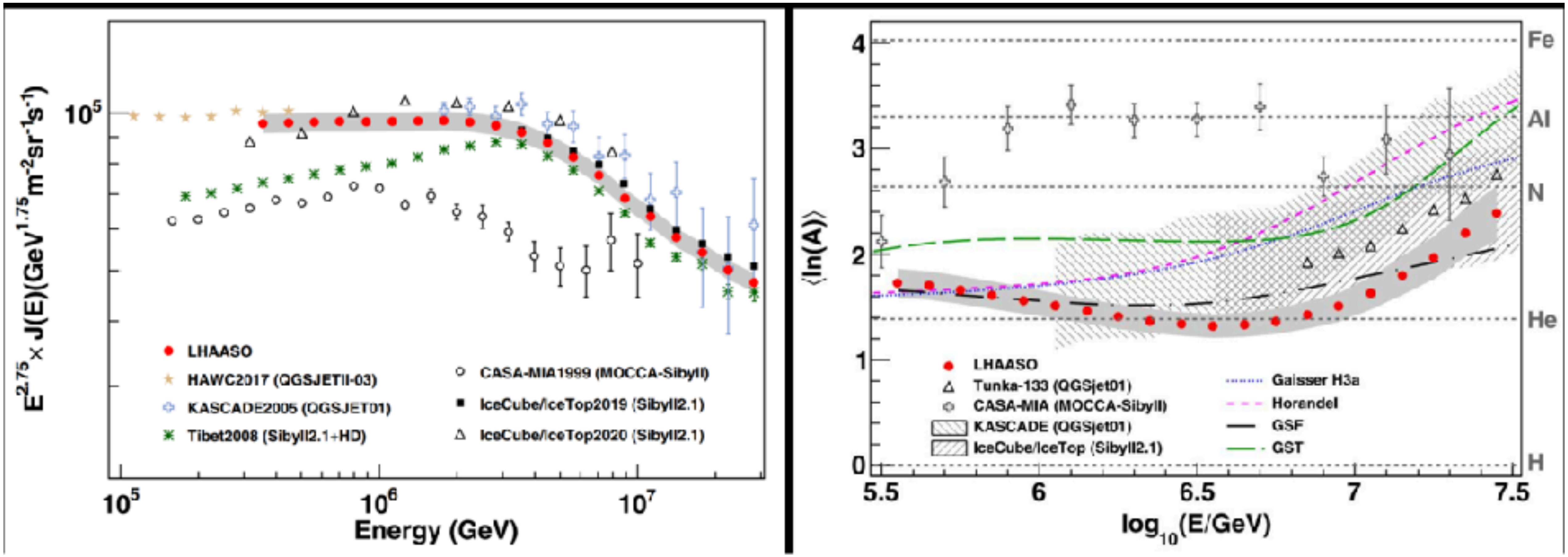
# The NEAR astronomy?



# Word cloud (from talks' titles)



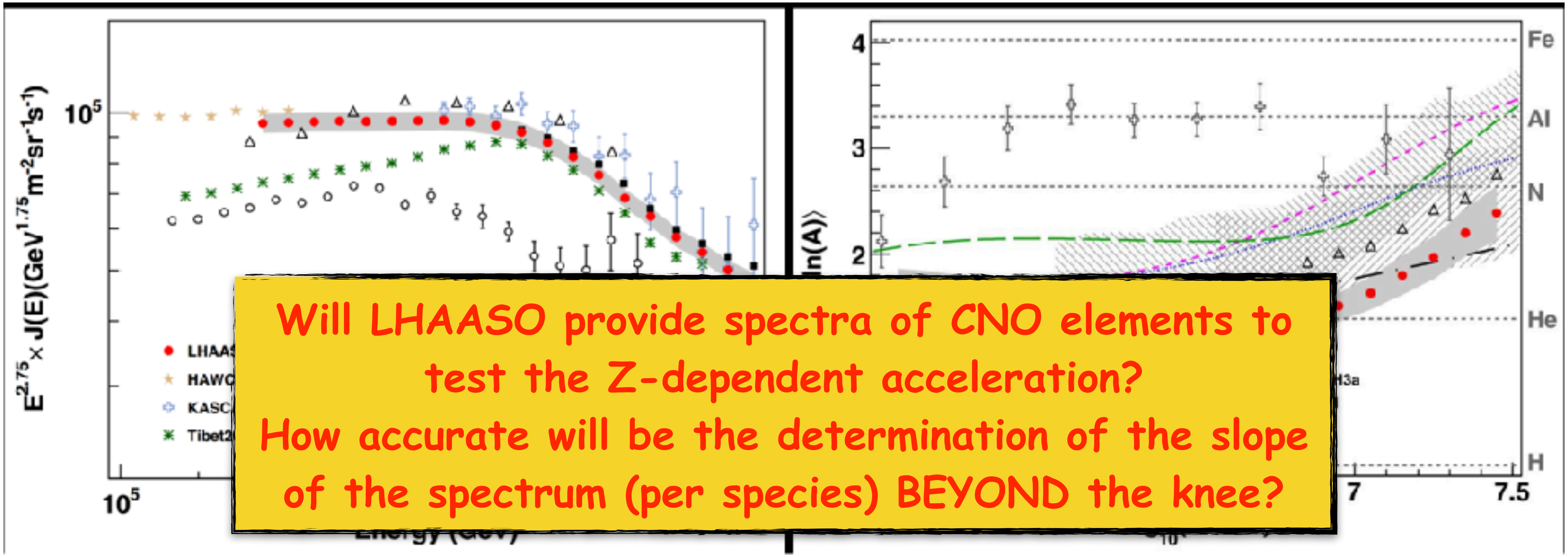
# The CR knee




- The CR knee is attributed to P and He with rigidity-dependent cutoff energy
- An ankle-like structure due to Fe at 9.2 PeV is discovered

He

# The CR knee




Will LHAASO provide spectra of CNO elements to test the Z-dependent acceleration?
How accurate will be the determination of the slope of the spectrum (per species) BEYOND the knee?

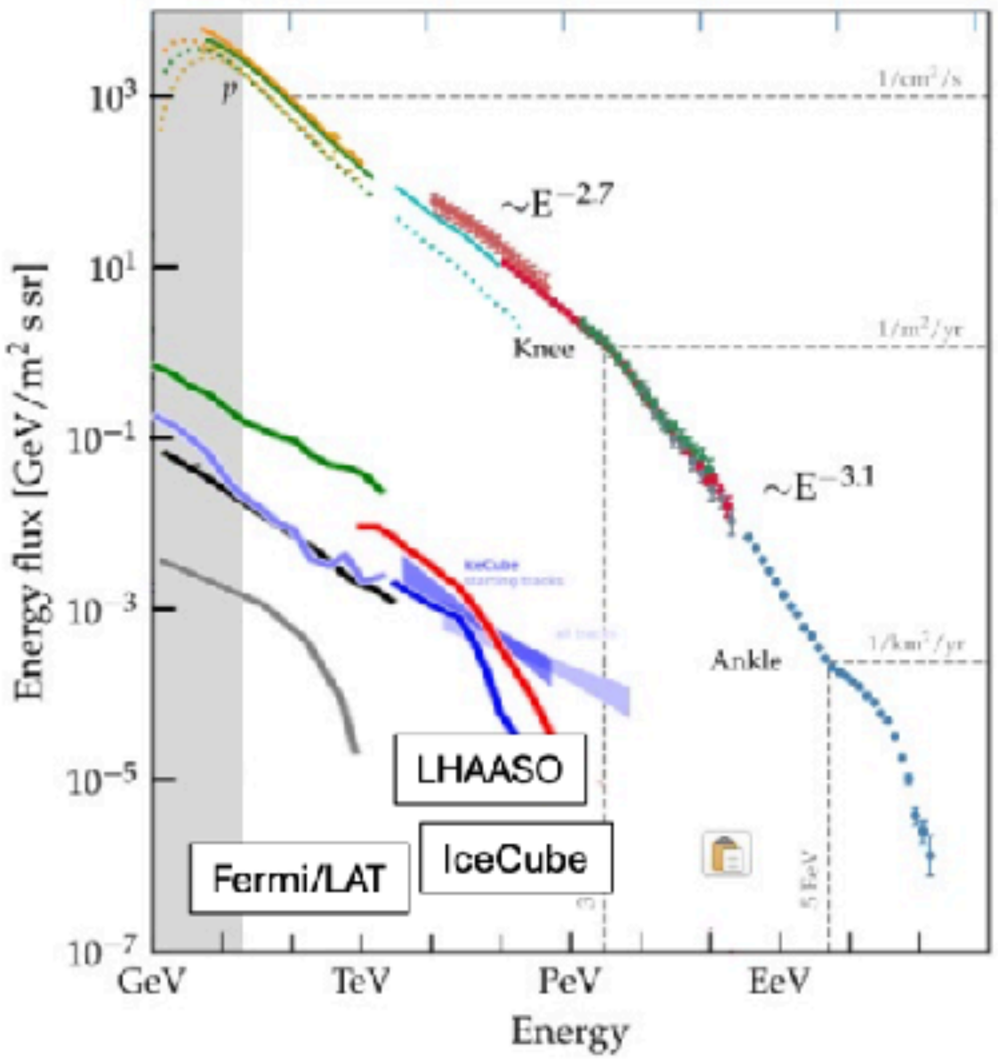
- The CR knee is attributed to P and He with rigidity-dependent cutoff energy
- An ankle-like structure due to Fe at 9.2 PeV is discovered

He

Neronov

# Diffuse emission

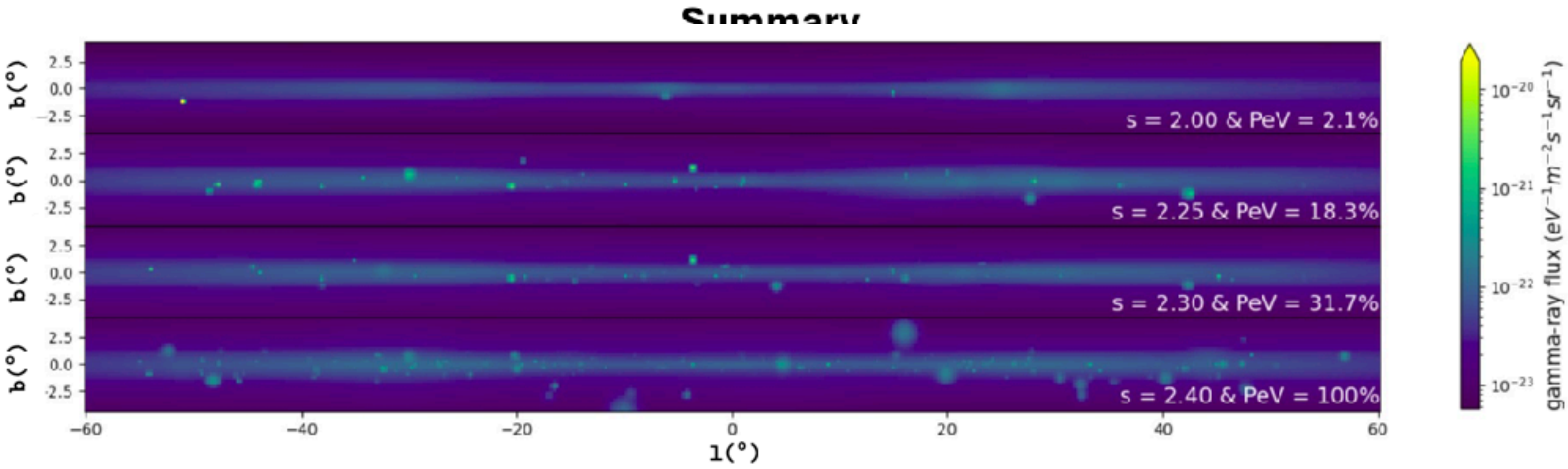
## Summary

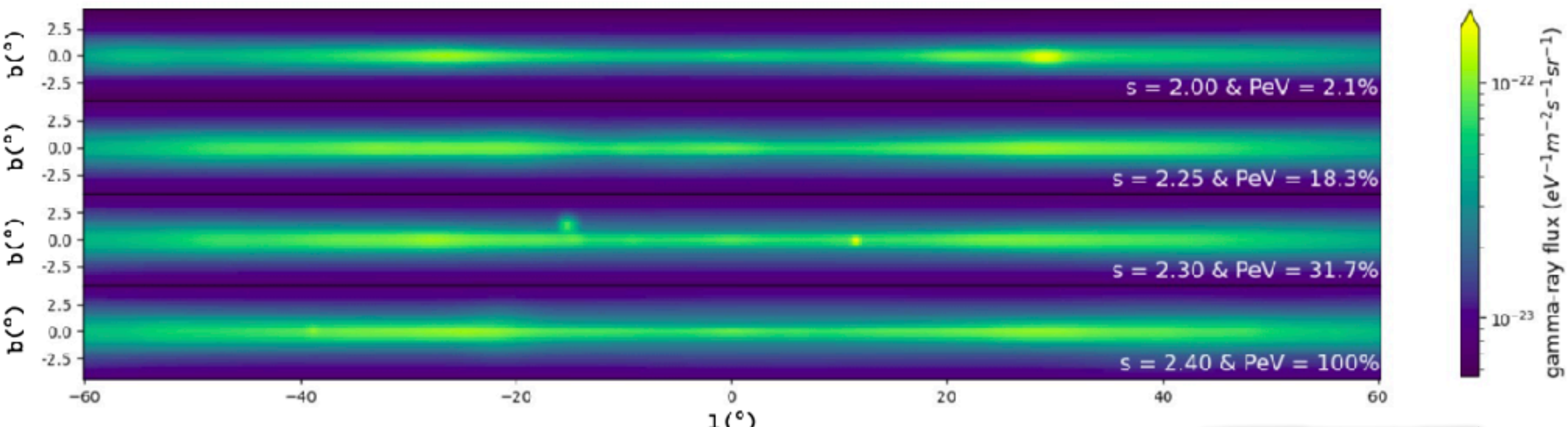



High-quality gamma-ray data up to PeV and complementary neutrino data start to provide a possibility to answer the questions

- What is the average spectrum of cosmic rays in the Milky Way?
- Does it have a PeV "knee" feature?
- Is the knee at the same energy everywhere?
- What source(s) are responsible for the knee?

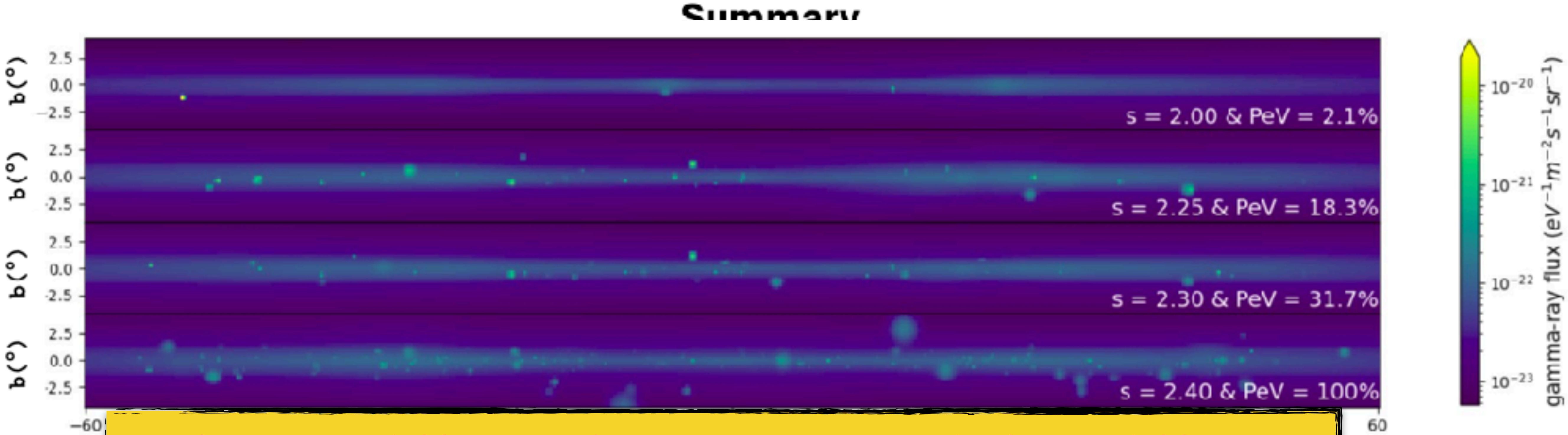
# Diffuse emission



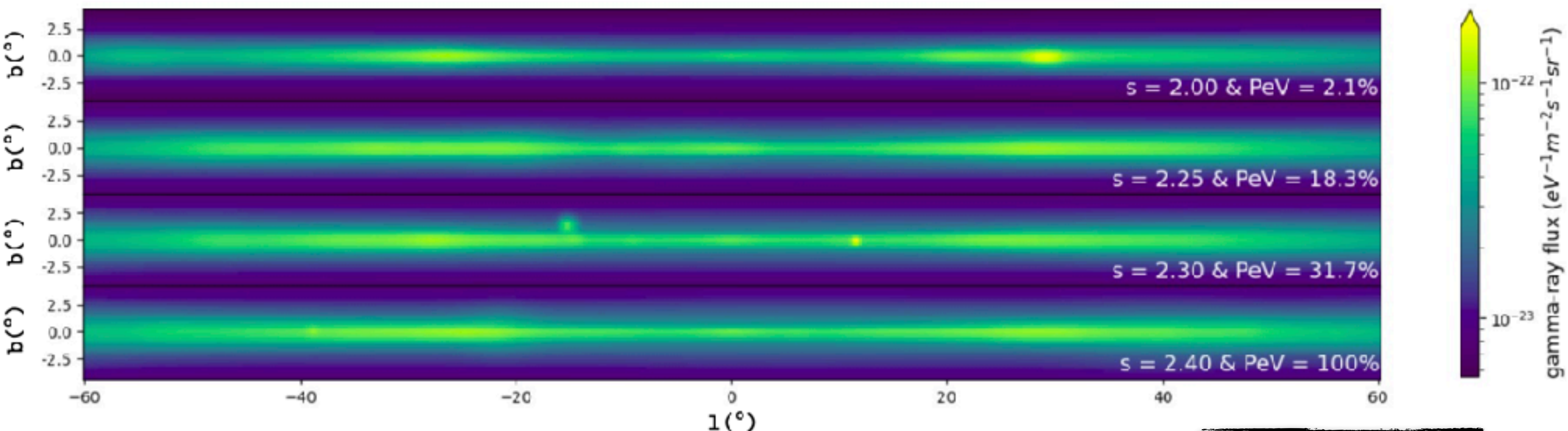



# Diffuse emission

Neronov




Clumpy or diffuse? What is a source and why is diffuse?

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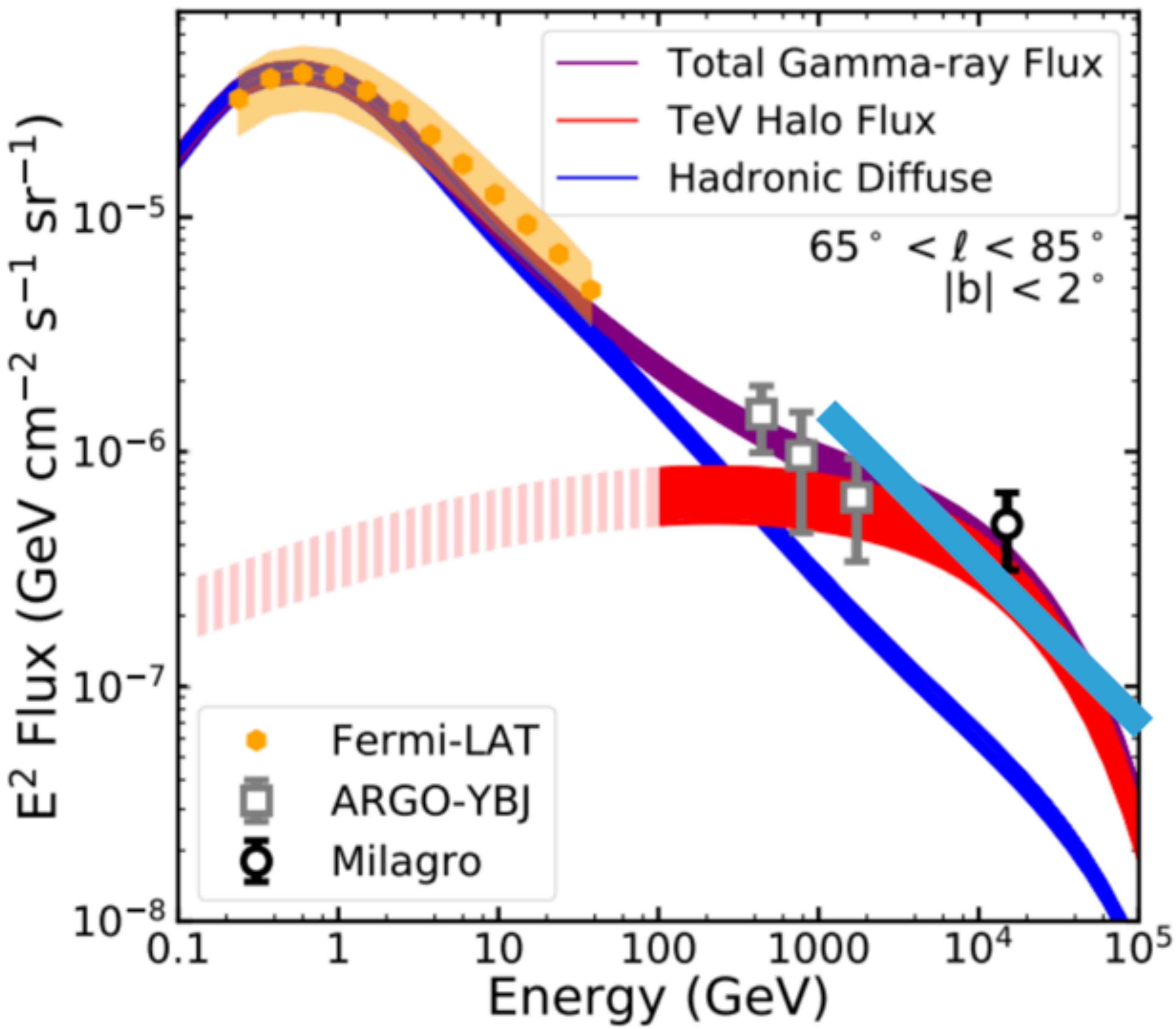
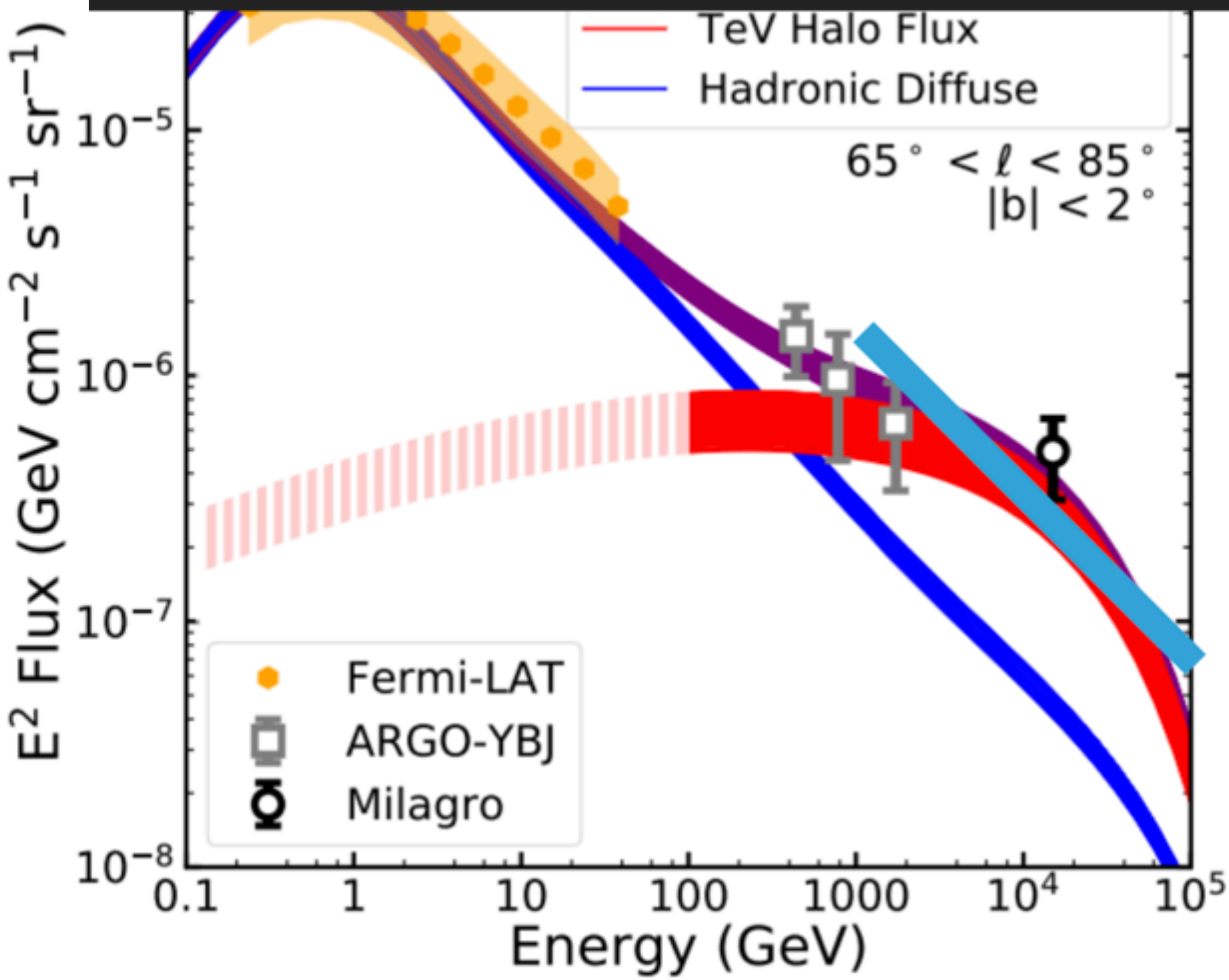
# TeV halos make the diffuse emission?




Linden

# TeV halos make the diffuse emission?

- TeV halos are a common feature around middle-aged (and possibly young and recycled pulsars).

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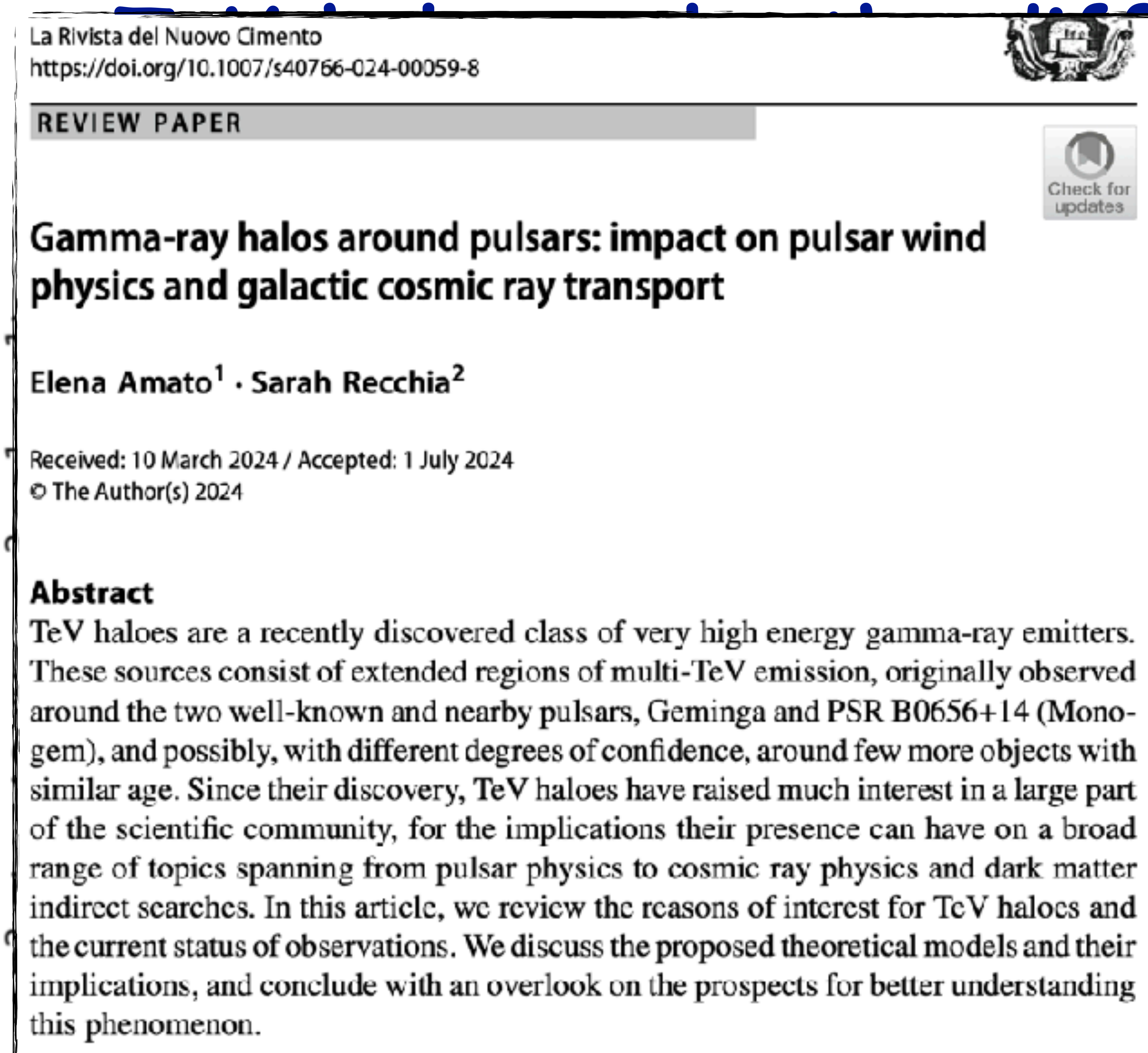


La Rivista del Nuovo Cimento
https://doi.org/10.1007/s40766-024-00059-8

REVIEW PAPER

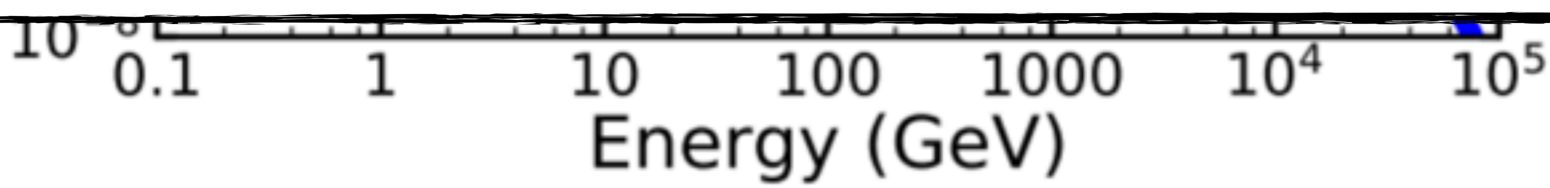
Check for updates

## Gamma-ray halos around pulsars: impact on pulsar wind physics and galactic cosmic ray transport

Elena Amato[1] · Sarah Recchia[2]

Received: 10 March 2024 / Accepted: 1 July 2024


**Abstract**
TeV haloes are a recently discovered class of very high energy gamma-ray emitters. These sources consist of extended regions of multi-TeV emission, originally observed around the two well-known and nearby pulsars, Geminga and PSR B0656+14 (Monogem), and possibly, with different degrees of confidence, around few more objects with similar age. Since their discovery, TeV haloes have raised much interest in a large part of the scientific community, for the implications their presence can have on a broad range of topics spanning from pulsar physics to cosmic ray physics and dark matter indirect searches. In this article, we review the reasons of interest for TeV haloes and the current status of observations. We discuss the proposed theoretical models and their implications, and conclude with an overlook on the prospects for better understanding this phenomenon.




Linden

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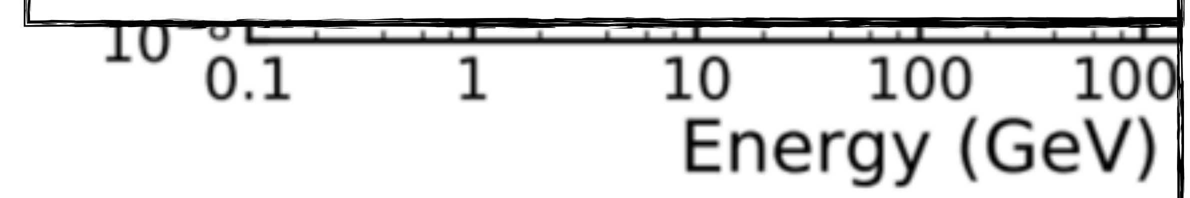


A&A 665, A132 (2022)
https://doi.org/10.1051/0004-6361/202243481


Astronomy & Astrophysics

### Are pulsar halos rare?

#### Modeling the halos around PSRs J0633+1746 and B0656+14 in the light of *Fermi*-LAT, HAWC, and AMS-02 observations and extrapolating to other nearby pulsars

Pierrick Martin[1], Alexandre Marcowith[2], and Luigi Tibaldo[1]

[1] IRAP, Université de Toulouse, CNRS, CNES, 31028 Toulouse, France
e-mail: pierrick.martin@irap.omp.eu
[2] Laboratoire Univers et Particules de Montpellier (LUPM) Université Montpellier, CNRS/IN2P3, CC72, Place Eugène Bataillon, 34095 Montpellier Cedex 5, France

Received 4 March 2022 / Accepted 8 June 2022

**ABSTRACT**

*Context.* Extended gamma-ray emission, interpreted as halos formed by the inverse-Compton scattering of ambient photons by electron-positron pairs, is observed toward a number of middle-aged pulsars. The physical origin and actual commonness of the phenomenon in the Galaxy remain unclear. The conditions of pair confinement seem extreme compared to what can be achieved in recent theoretical models.
*Aims.* We searched for scenarios minimizing as much as possible the extent and magnitude of diffusion suppression in the halos in J0633+1746 and B0656+14, and explored the implications on the local positron flux if they are applied to all nearby middle-aged pulsars.
*Methods.* We used a phenomenological static two-zone diffusion framework, and compared its predictions with *Fermi*-LAT and HAWC observations of the two halos, and with the local positron flux measured with AMS-02.
*Results.* While strong diffusion suppression of two to three orders of magnitude at ~100 TeV is required by the data, it is possible to find solutions with diffusion suppression extents as small as 30 pc for both objects. If all nearby middle-aged pulsars develop such halos, their combined positron flux including the contribution from Geminga would saturate the ≳100 GeV AMS-02 measurement for injection efficiencies that are much smaller than those inferred for the canonical halos in J0633+1746 and B0656+14, and more generally with the values typical of younger pulsar wind nebulae. Conversely, if positrons from other nearby pulsars are released in the interstellar medium without any confinement around the source, their total positron flux fits into the observed spectrum for the same injection efficiencies of a few tens of percent for all pulsars, from objects a few thousand years in age that power bright pulsar wind nebulae to much older objects like J0633+1746 and B0656+14.
*Conclusions.* It seems simpler to assume that most middle-aged pulsars do not develop halos, although the evidence supporting this scenario depends on the actual properties of the local pulsar population and on the uncertain physics driving the formation and evolution of halos. The occurrence rate of the phenomenon could be as low as ~5–10%, and the local positron flux in the ~0.1–1.0 TeV range would thus be attributed to a few dozen nearby middle-aged pulsars rapidly releasing pairs into the interstellar medium, with a possible contribution over part or most of the range by J0633+1746, and at higher energies by B0656+14.

**Key words.** astroparticle physics – pulsars: general – cosmic rays – gamma rays: ISM

Linden

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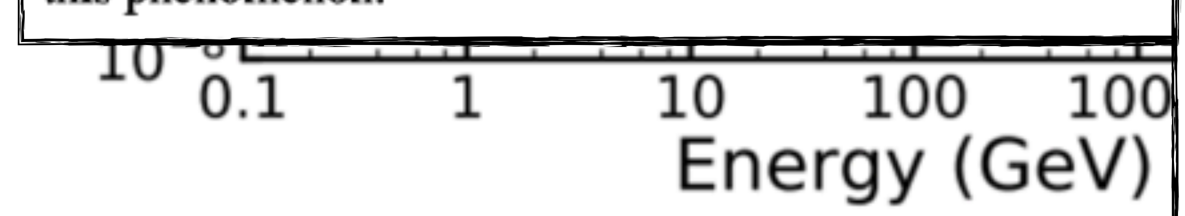
How many TeV halos?

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**Key words.** astroparticle physics – pulsars: general – cosmic rays – gamma rays: ISM

# Are SNRs PeVatrons?

## X-ray polarization overview

SNR are still surprising objects!

| | Age (yr) | B field | P.F. | Orientation B-field | Ref. |
|---|---|---|---|---|---|
| Cas A | ~350 | ~250 μG | ~5% | radial | Vink+ '22 |
| Tycho | 452 | ~200 μG | ~10% | radial | Ferrazzoli+ '23 |
| SN1006 | 1018 | ~80 μG | ~20% | radial | Zhou+ '23 |
| RX J1713 | ~1500 | ~20 μG | 26%—30% | tangential | Ferrazzoli+ '24 |
| Vela Jr | ~3000 | ~10 μG | 10%—20% | tangential | Prokhorov+ '24 |

- Radial vs tangential: age (or B-field?) dependence in X-rays

Vink

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- In general not PeVatrons:
  - Not observationally (at best $E_{max}$~100 TeV)
  - SNRs V<5000 km/s, B~10 μG, 1000 yr:

$$E_{\rm max} \approx 3 \times 10^{14} \eta^{-1} \left( \frac{B_0}{10\ \mu{\rm G}} \right) \left( \frac{V_{\rm s}}{5000\ {\rm km/s}} \right)^2 \left( \frac{t}{500\ {\rm yr}} \right)\ {\rm eV}$$

Vink

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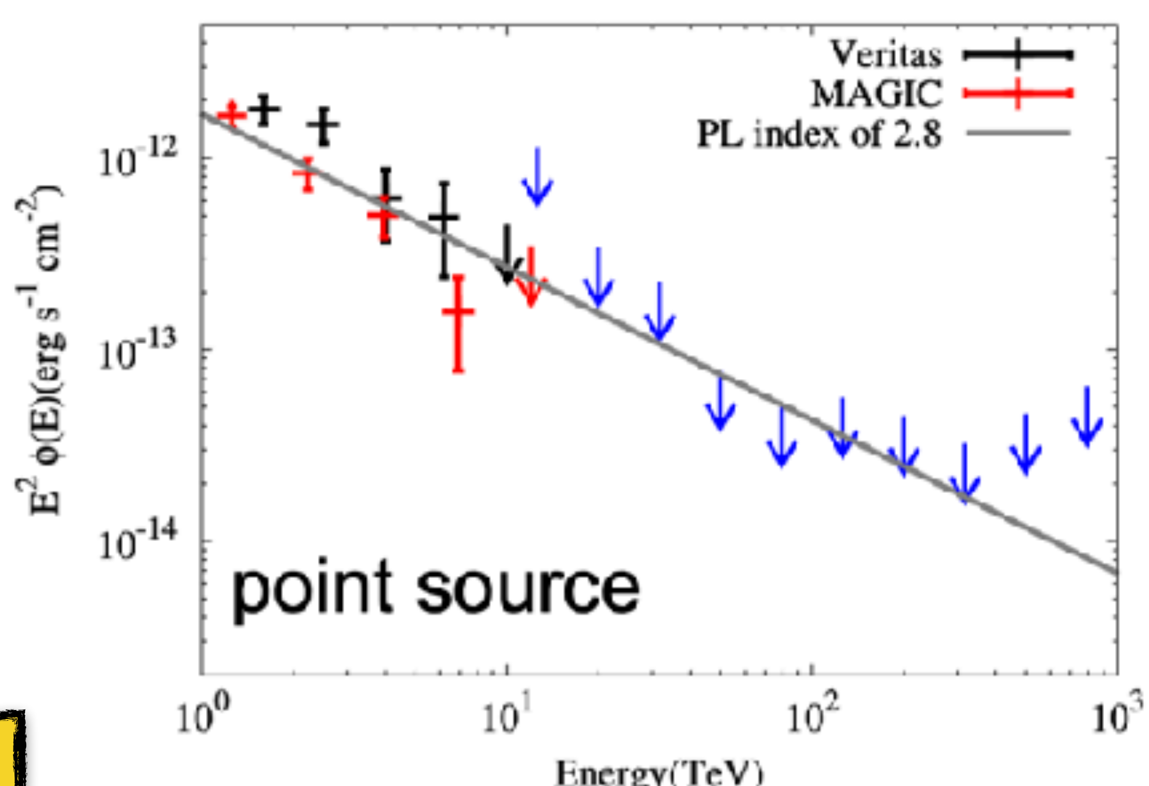
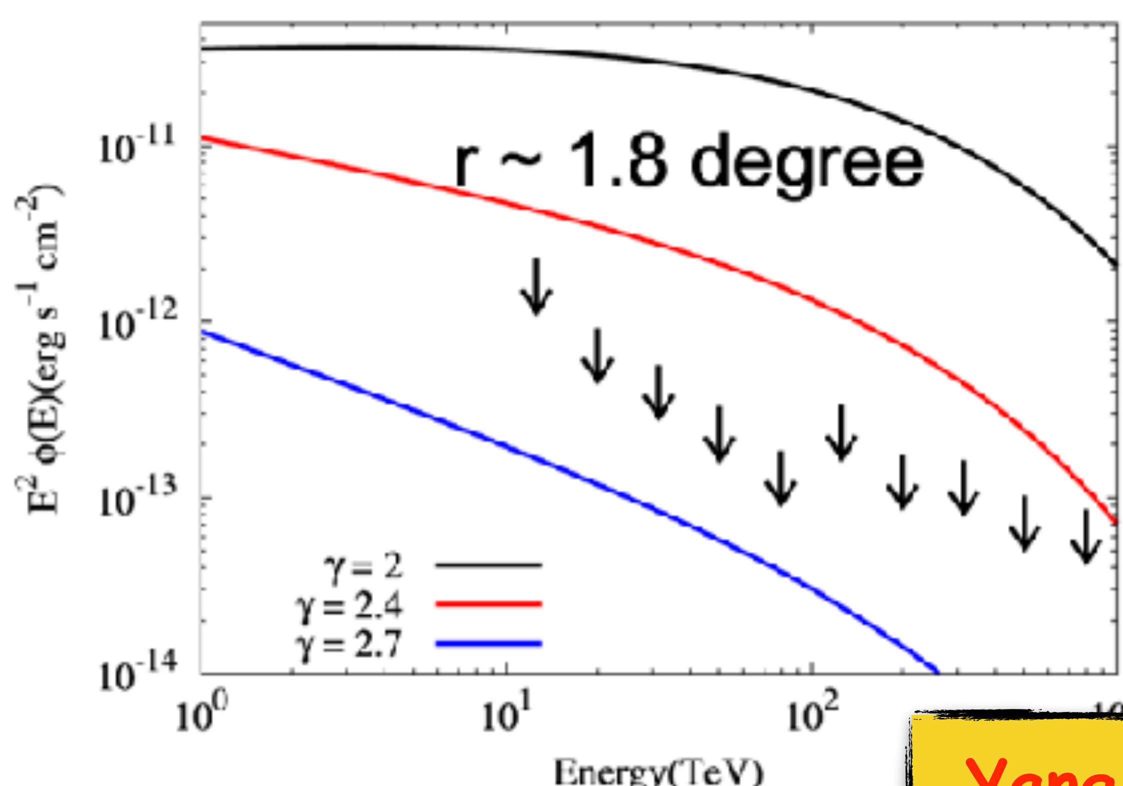
  - Not observationally (at best $E_{max}$~100 TeV)



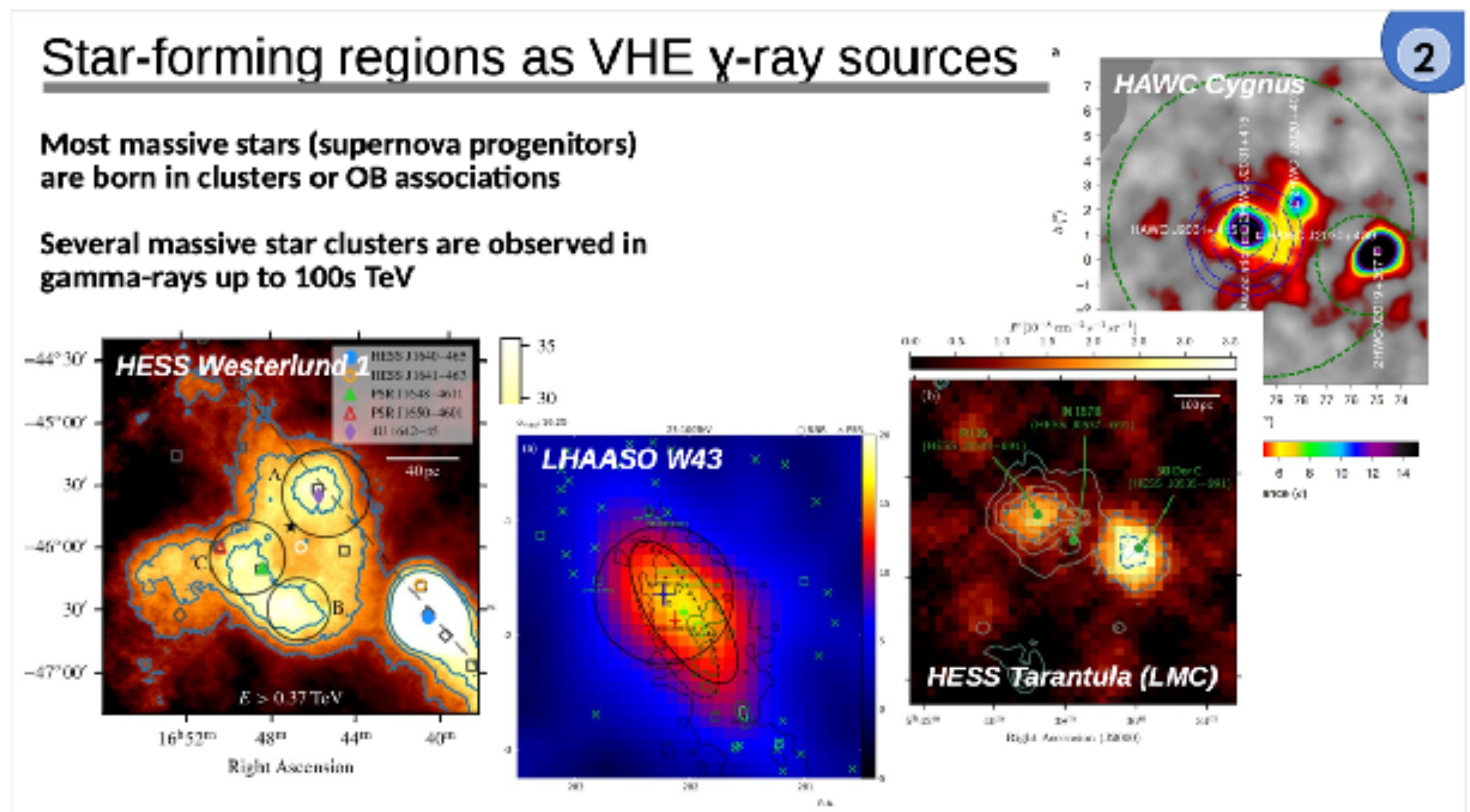




Vink

Yang

# Where are PeVatrons?*

Vieu



# Where are PeVatrons?*

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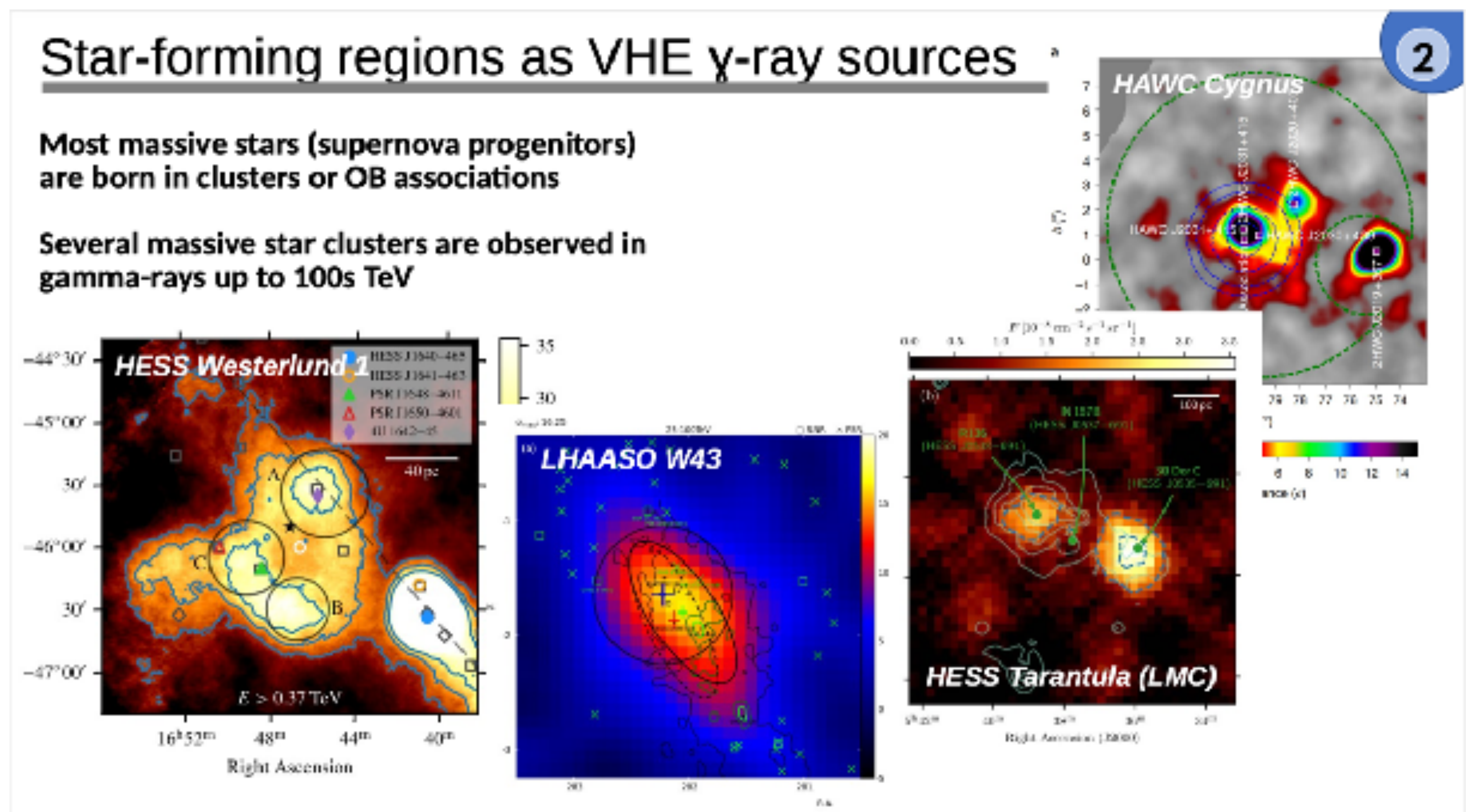
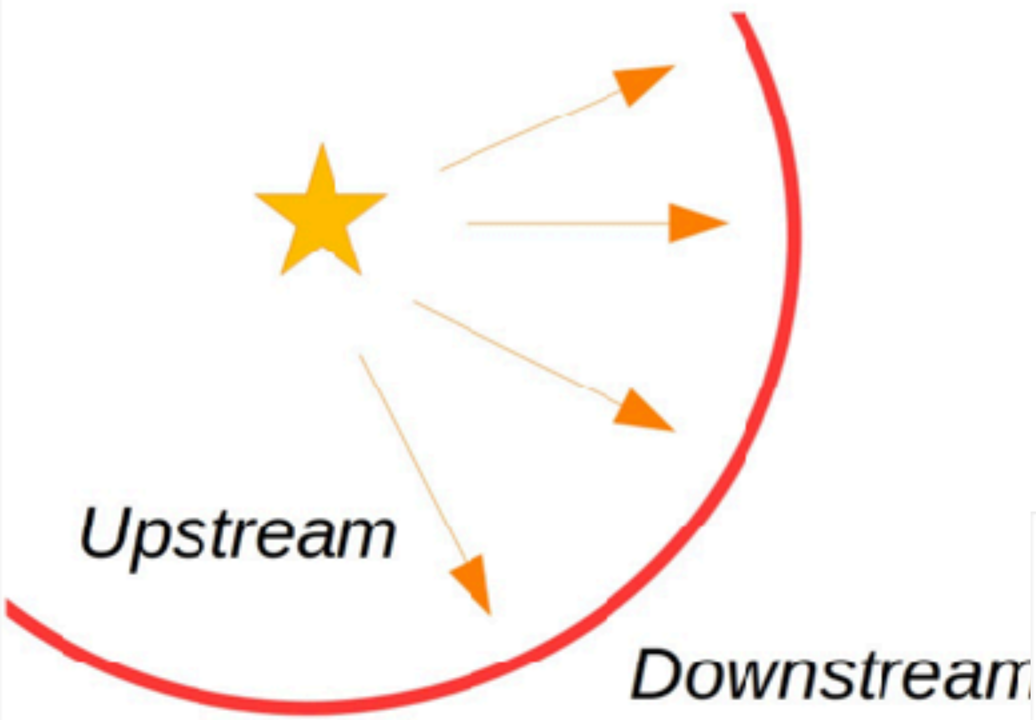



* in fact, the spectrum of Galactic CRs extends WELL BEYOND the knee!

# Where are PeVatrons?*

## Maximum energy in stellar wind cavities

Vieu




Adiabatic losses upstream => $E_{max} < V_w B R$

Super-Alfvénic stellar wind => $B << V_w \, sqrt(4 \pi \rho)$

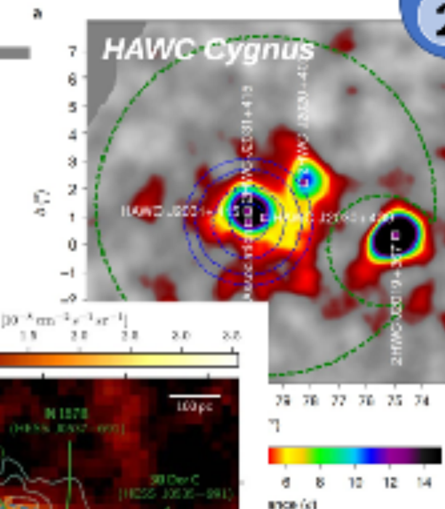
=> $E_{max} << sqrt(2 V_w L_w)/c \sim 100$ TeV

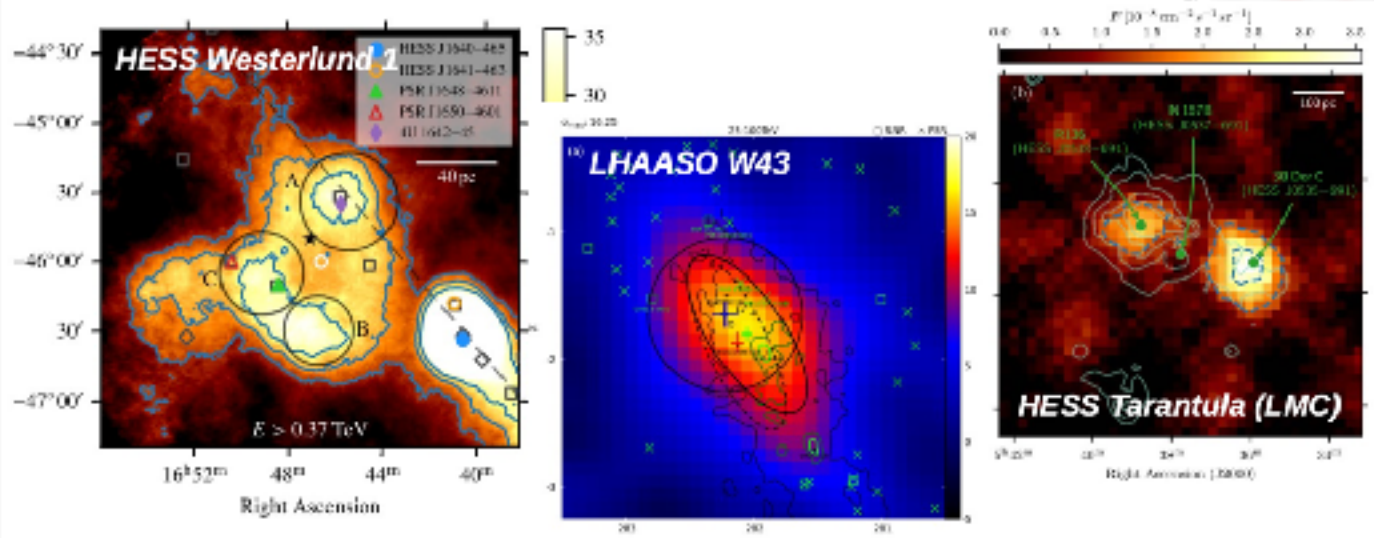
### Star-forming regions as VHE γ-ray sources

2

Most massive stars (supernova progenitors) are born in clusters or OB associations

Several massive star clusters are observed in gamma-rays up to 100s TeV

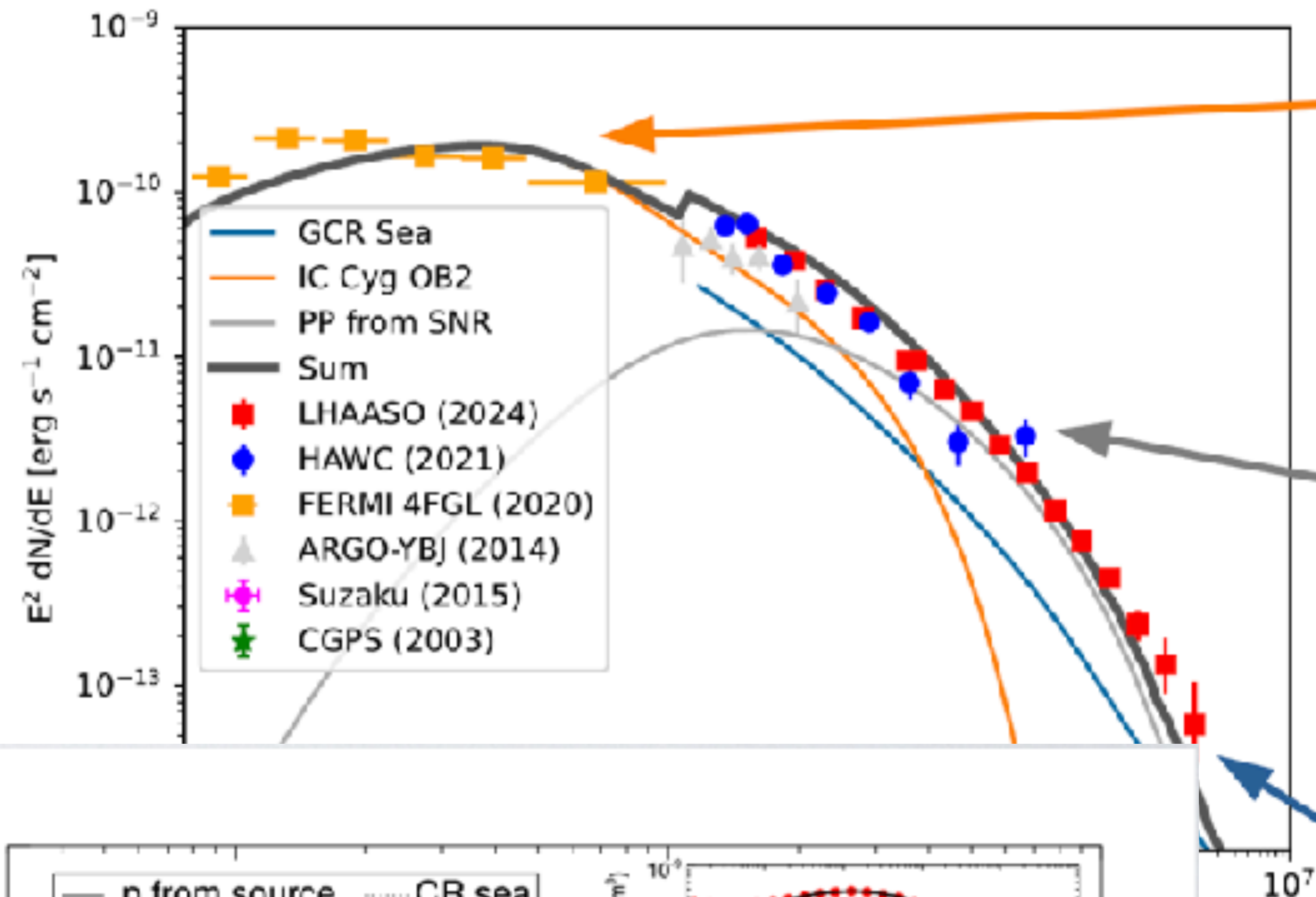



* in fact, the spectrum of Galactic CRs extends WELL BEYOND the knee!

# Cygnus?

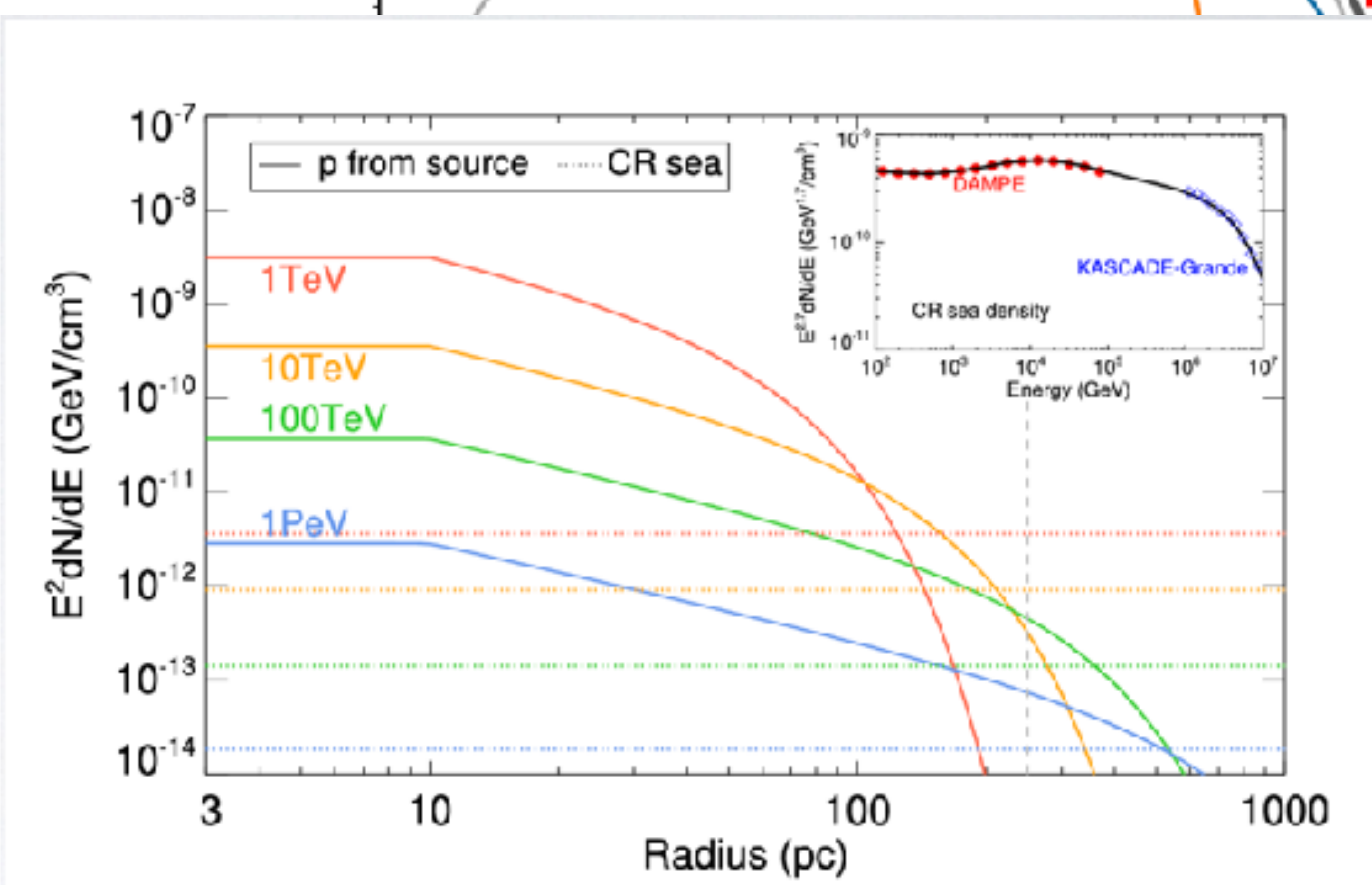
Vieu




**$e^-$ accelerated at individual WTS**
IC on cluster FUV field
$n = 0.05\ cm^{-3}$
$B \sim 10\ \mu G$
$P_{e-} = 0.005 \times P_{OB2}$

**Relic p from past clustered SN**
Explosion 200 kyr ago
Energy ~ 5e51 ergs
γ-ray production on Cygnus Mcs
$E_{max}$ protons = 2 PeV

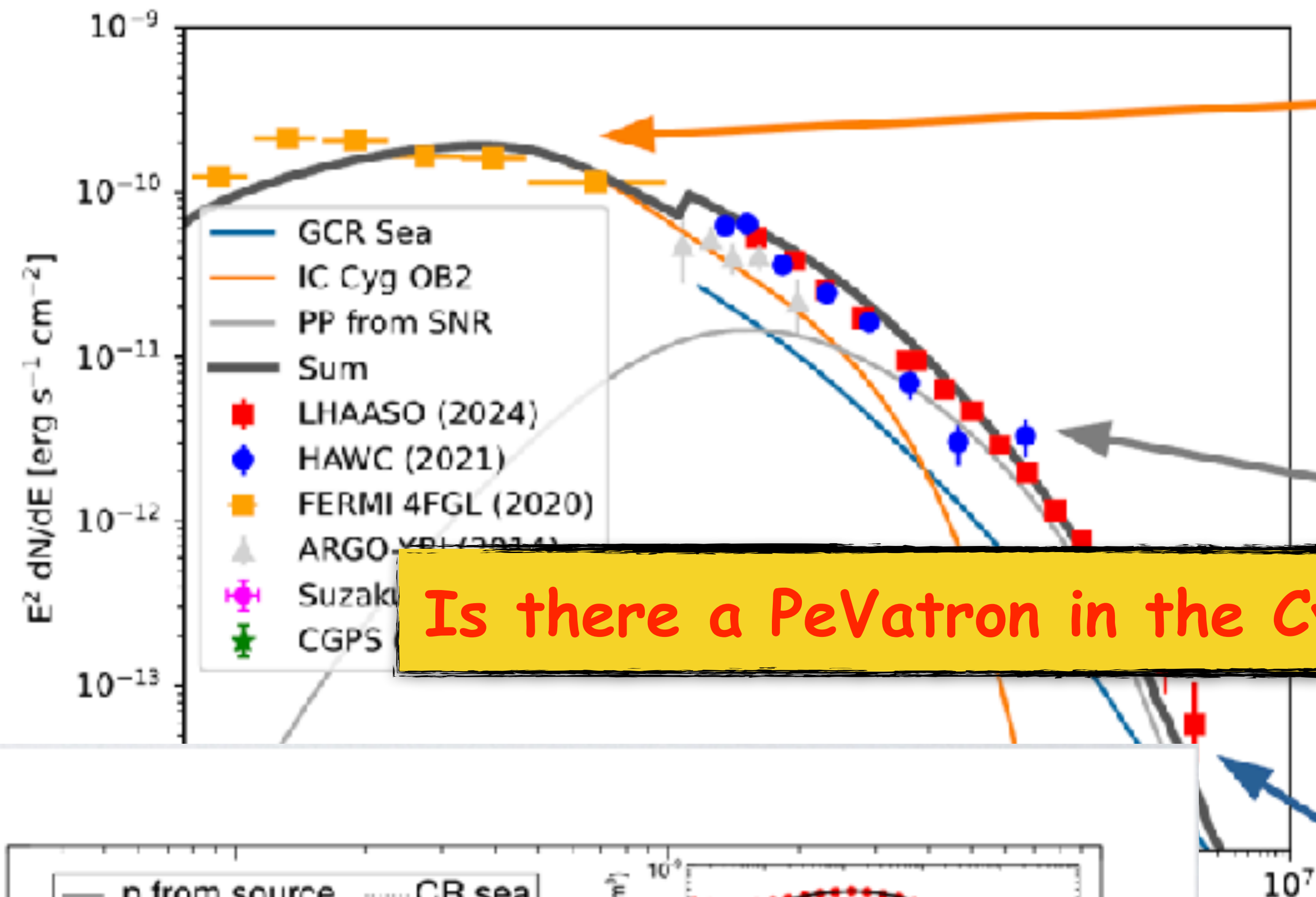
**UHE contamination**
GCR sea (Schwefer+22)
Cygnus X-3




Yang

# Cygnus?

Vieu

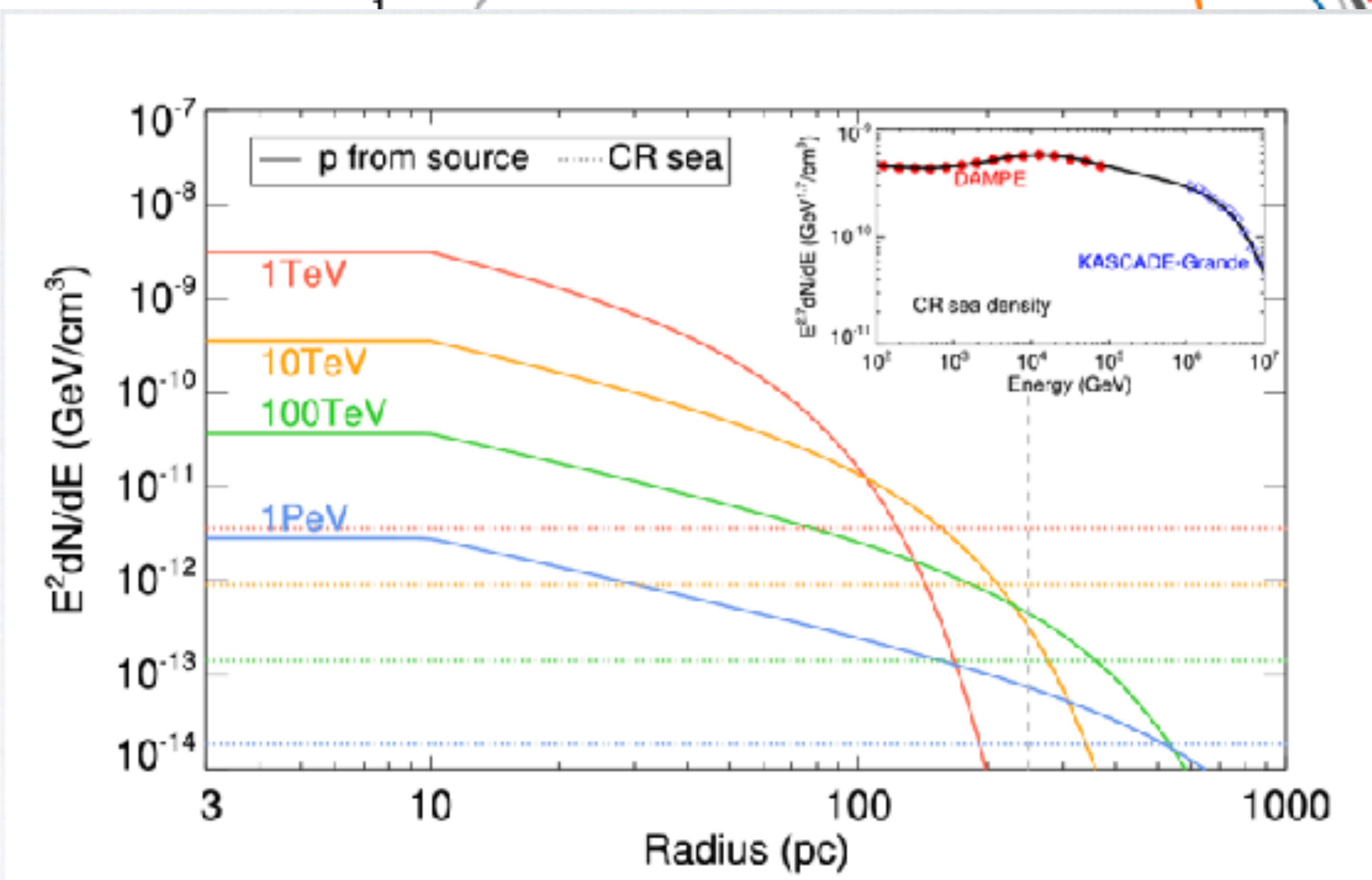



**e⁻ accelerated at individual WTS**
IC on cluster FUV field
$n = 0.05\ cm^{-3}$
$B \sim 10\ \mu G$
$P_{e-} = 0.005 \times P_{OB2}$

**Relic p from past clustered SN**
Explosion 200 kyr ago
…rgs
…on Cygnus Mcs
$E_{max}$ protons = 2 PeV

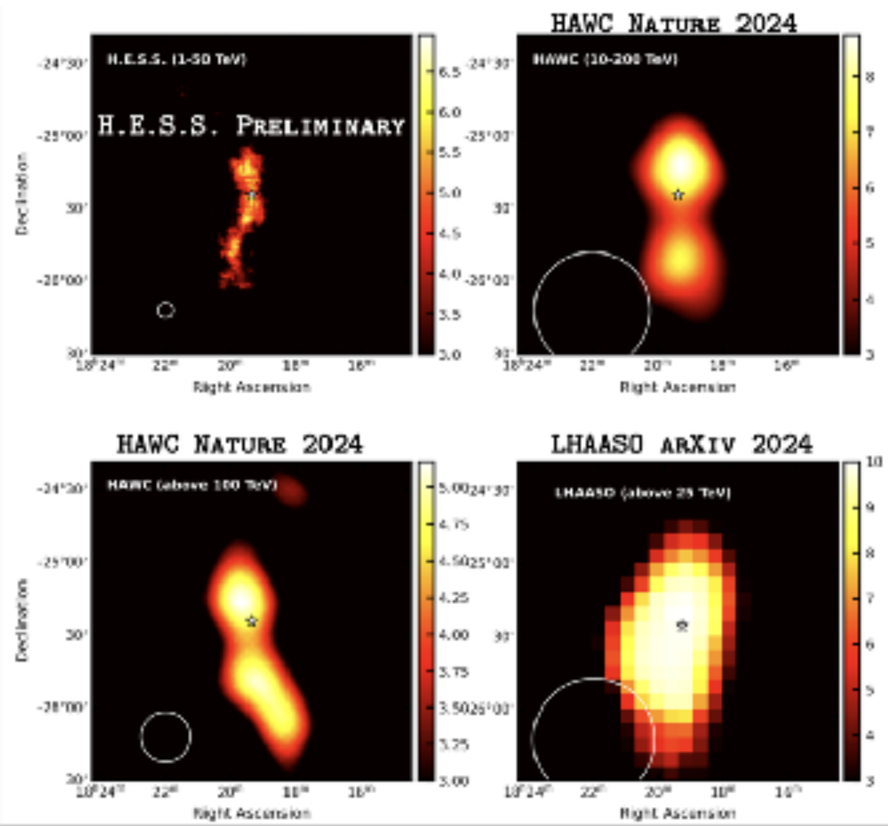
**UHE contamination**
GCR sea (Schwefer+22)
Cygnus X-3

**Is there a PeVatron in the Cygnus region?**



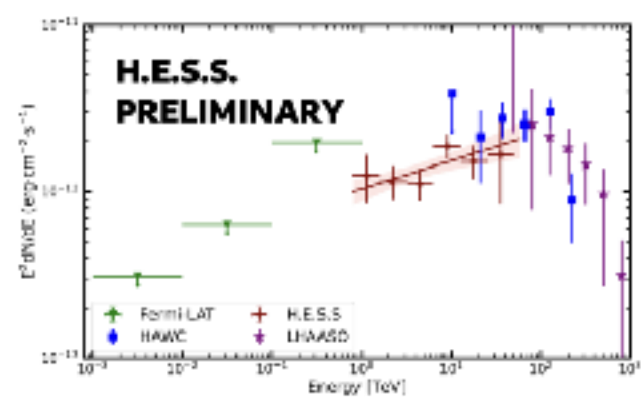

Yang

# Microquasars?

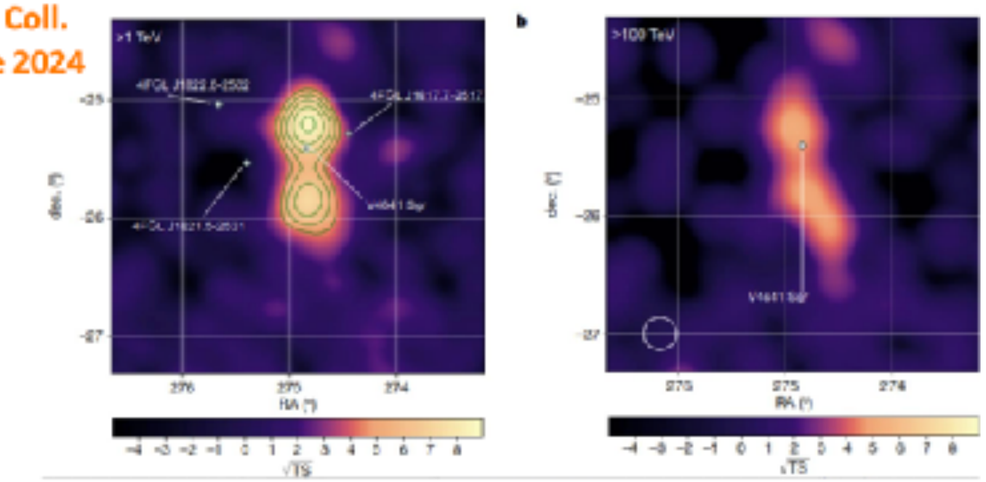


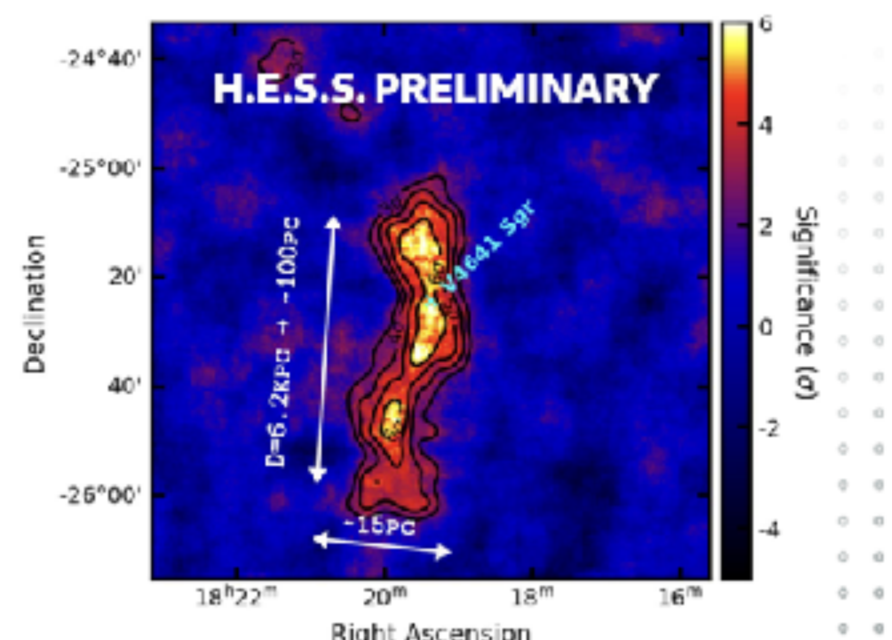

LHAASO detected photons up to 800 TeV from V4641 Sgr !!

LHAASO Collaboration 2410.08988




HAWC Coll. Nature 2024



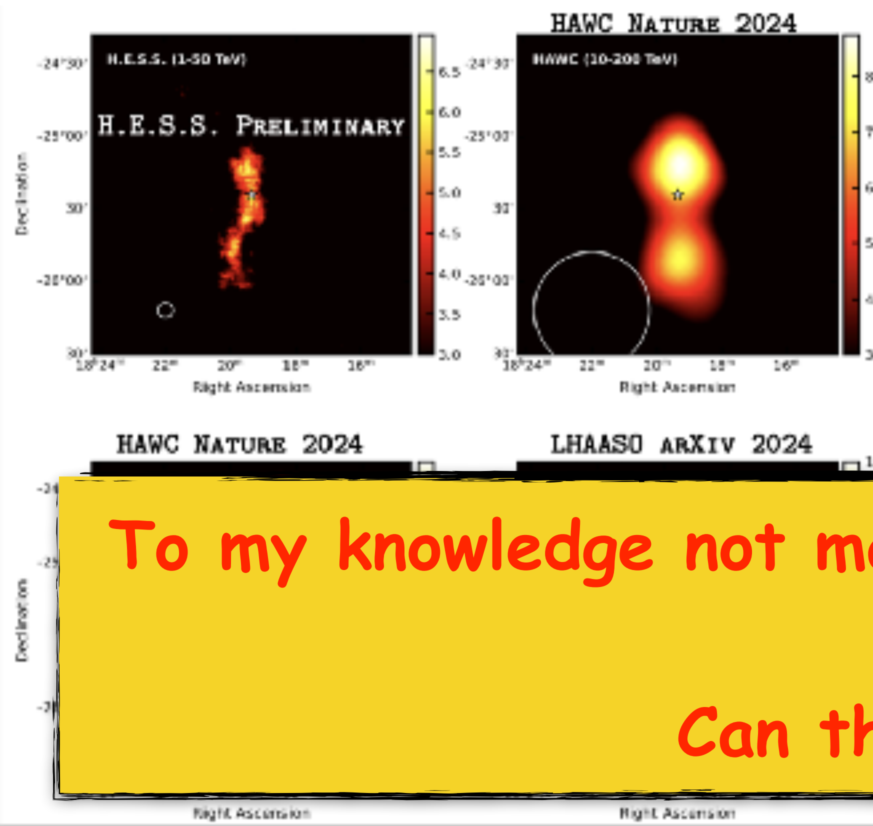



$$E_{\text{Hillas}} \approx 10Z\left(\frac{B}{20\mu\text{G}}\right)\left(\frac{u_1}{0.26c}\right)\left(\frac{R}{1.6\text{pc}}\right)\text{PeV}$$

Yang

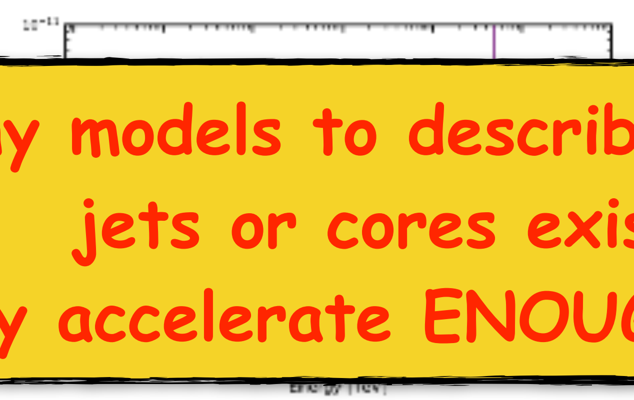
Hinton

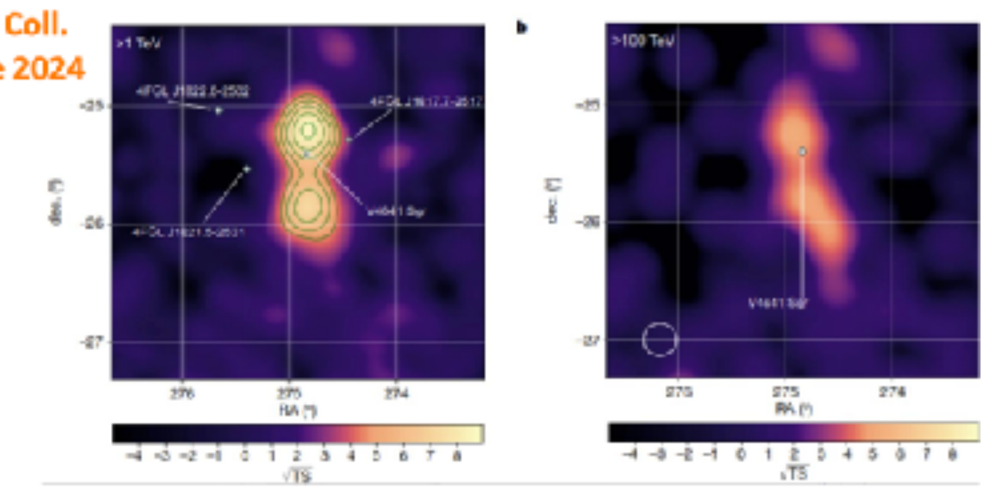
# Microquasars?

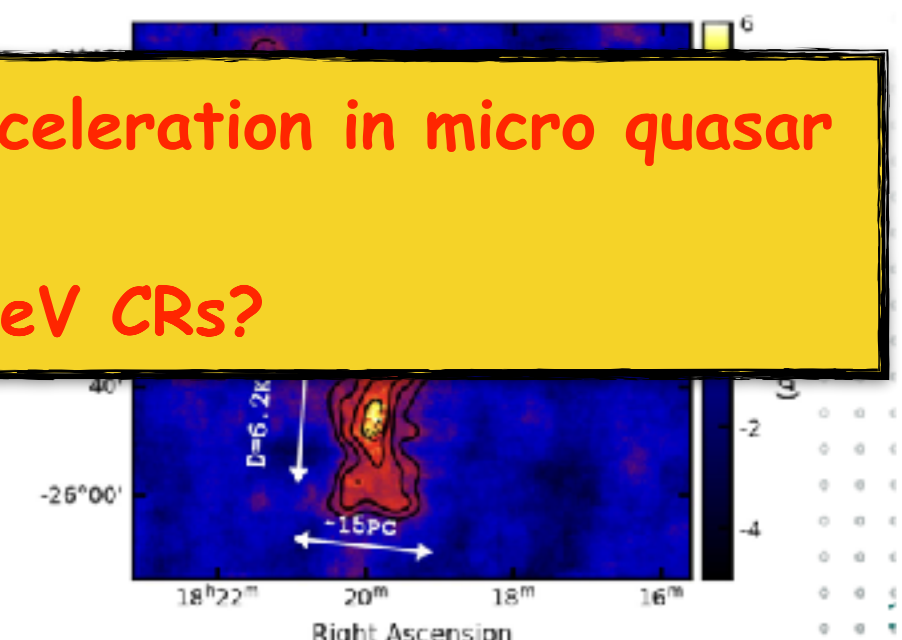



LHAASO DETECTED PHOTONS UP TO 800 TeV FROM V4641 Sgr !!

LHAASO Collaboration 2410.08988






To my knowledge not many models to describe acceleration in micro quasar jets or cores exist.
Can they accelerate ENOUGH PeV CRs?

$$E_{\rm Hillas} \approx 10Z \left(\frac{B}{20\mu{\rm G}}\right) \left(\frac{u_1}{0.26c}\right) \left(\frac{R}{1.6{\rm pc}}\right) {\rm PeV}$$

Yang

Hinton

# Leptonic PeVatrons also!

☞ Galactic sources are relatively small:

$$\frac{R}{d} \sim 0.2^\circ \frac{(R/10\mathrm{pc})}{(d/3\mathrm{kpc})}$$

i.e., likely all extended sources seen by LHAASO include the source and its vicinity

Khangulyan

$$t_{\rm syn} > \frac{\eta \epsilon_{\rm max}}{ceB} \rightarrow \epsilon_{\rm max} < \left(\frac{t_{\rm syn}}{cR\eta}\right) eBR$$

$$\epsilon_{\rm max} < 30\mathrm{PeV}\,\eta^{-1/2} \left(\frac{B}{5\mu\mathrm{G}}\right)^{-1/2}$$

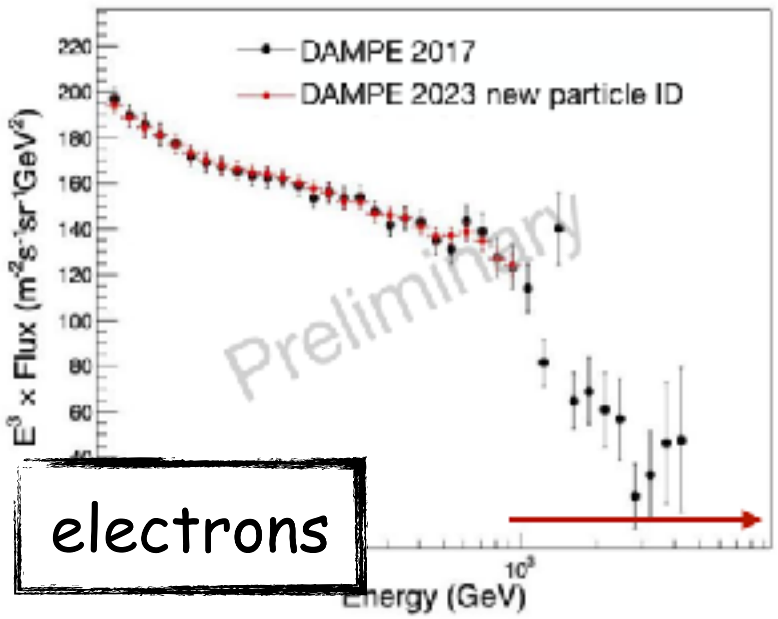
even more difficult to identify proton PeVatrons?

# Let's move to lower energies…

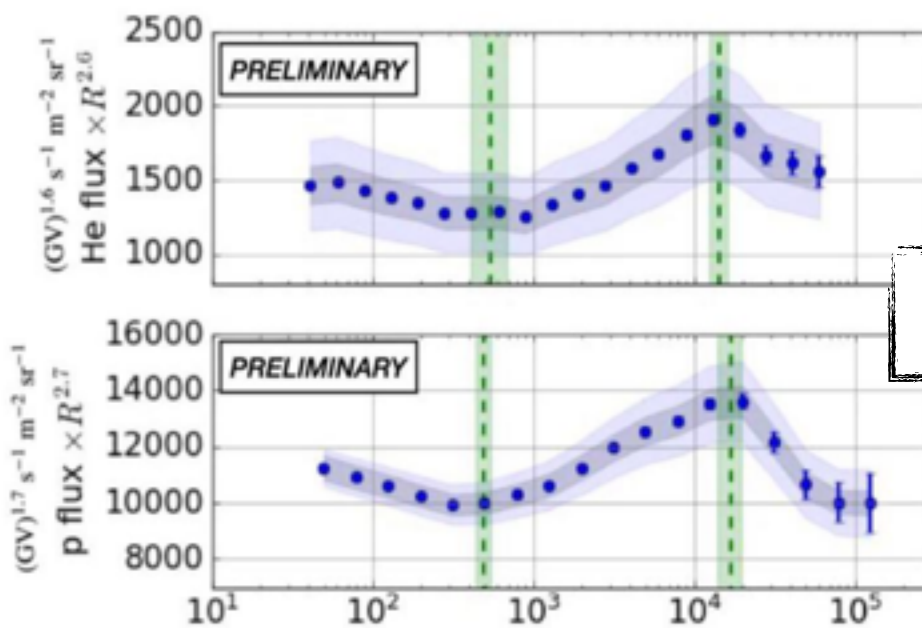
DAMPE

# Breaks everywhere!

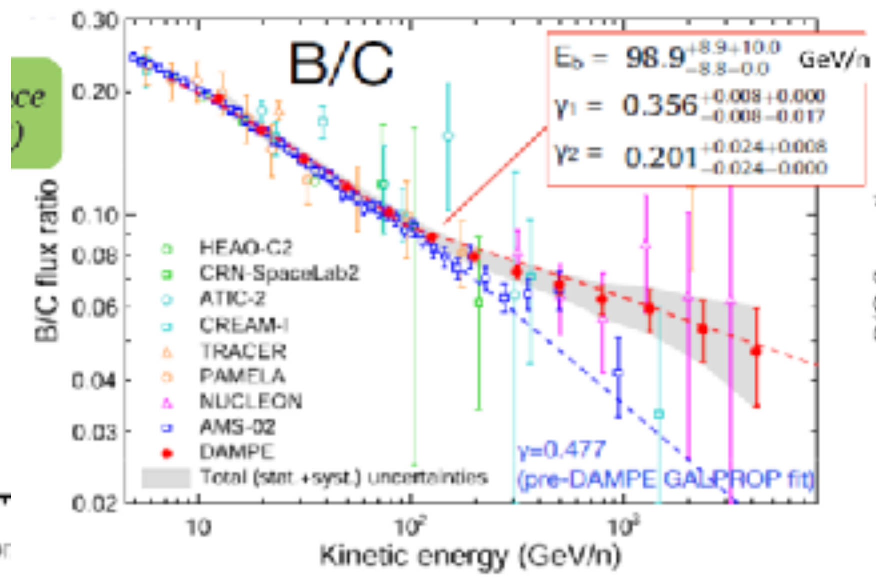
Alemanno

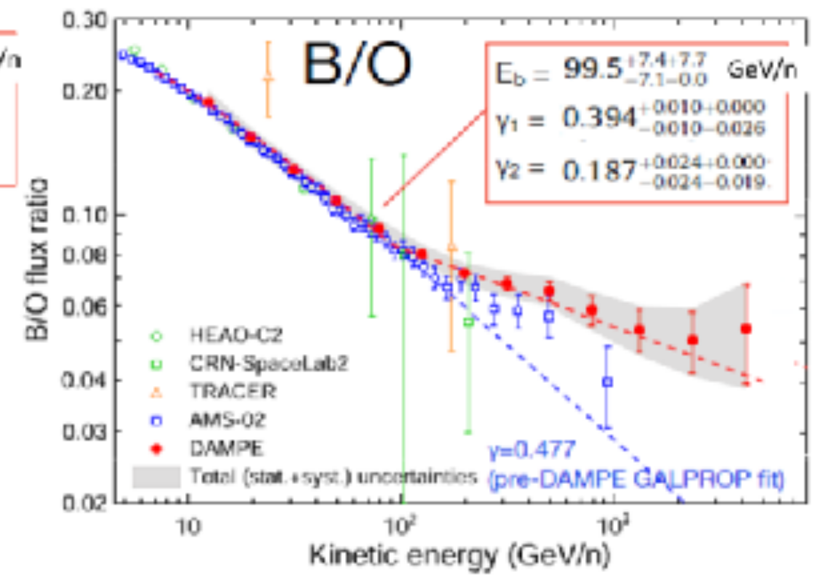



electrons

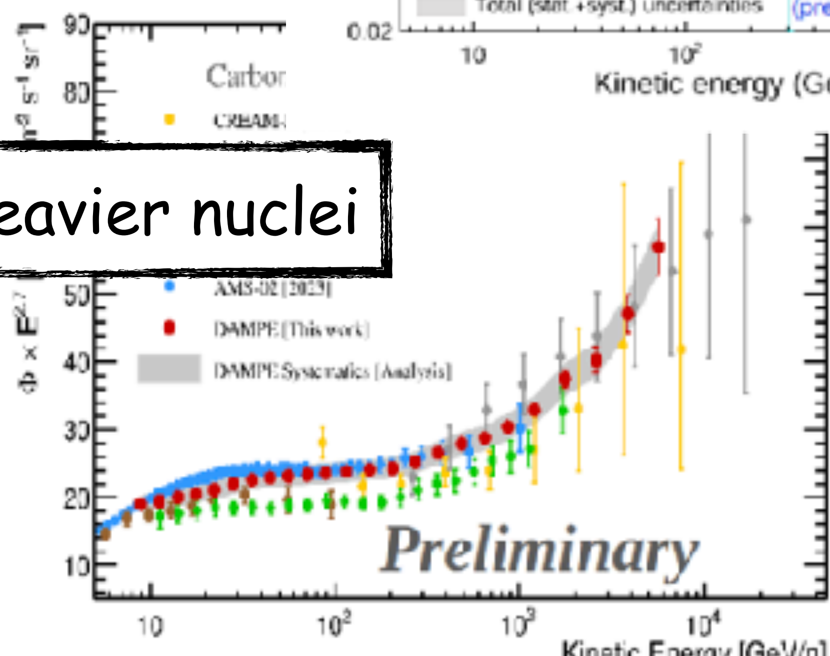



H and He

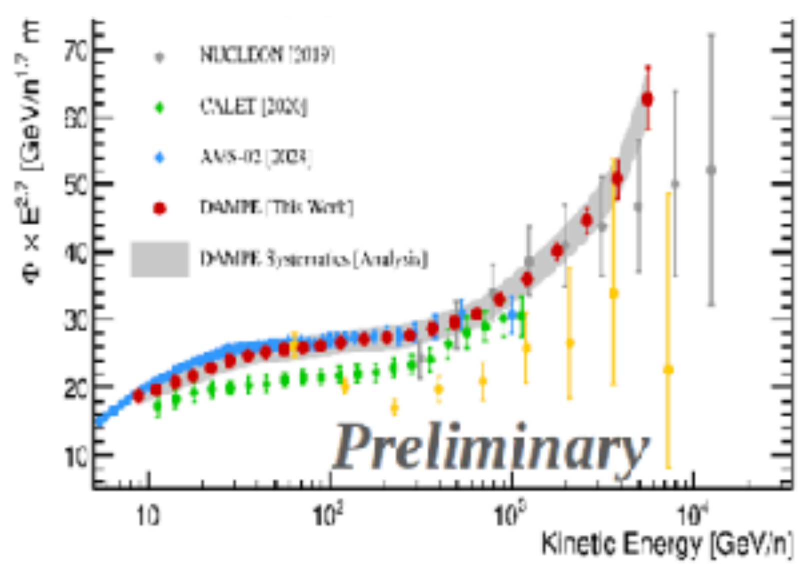


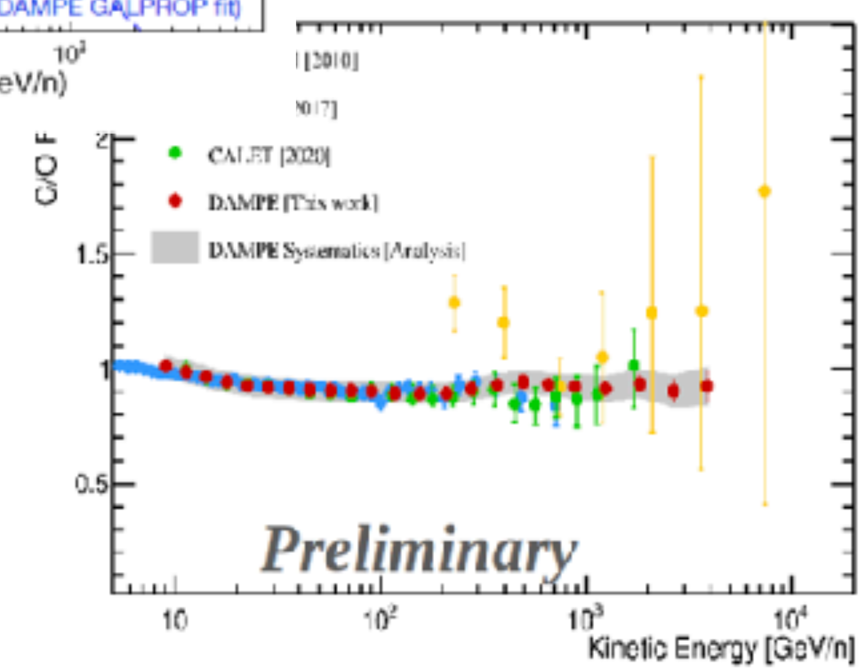




secondary /primary




heavier nuclei

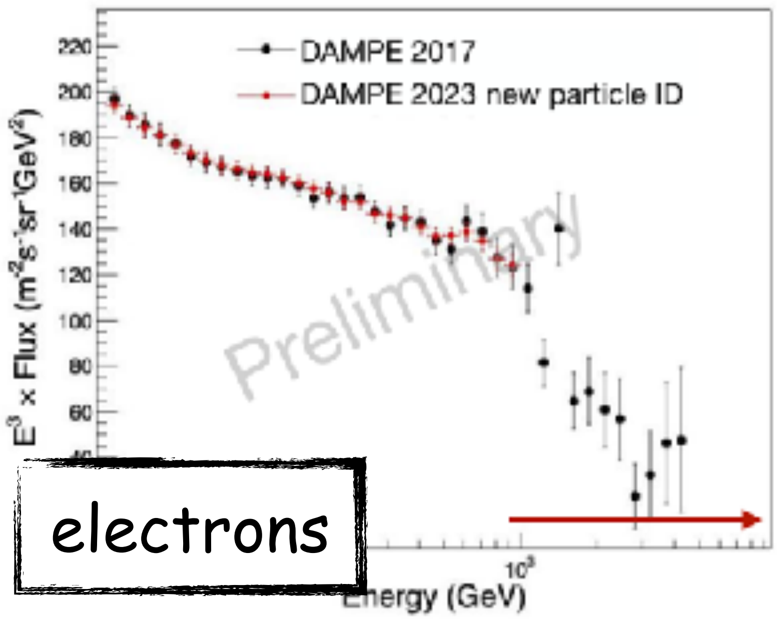


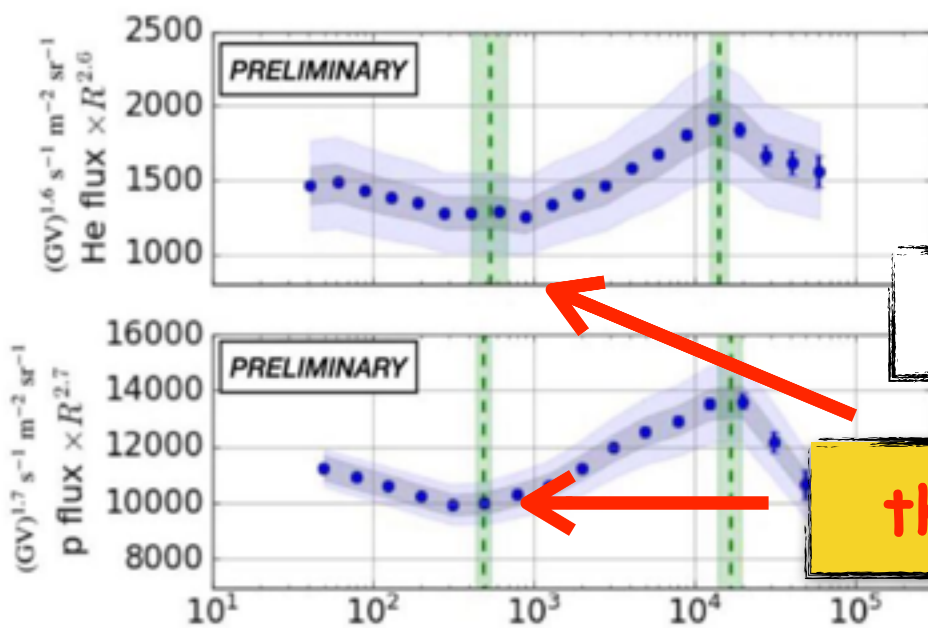
DAMPE

# Breaks everywhere!

Alemanno

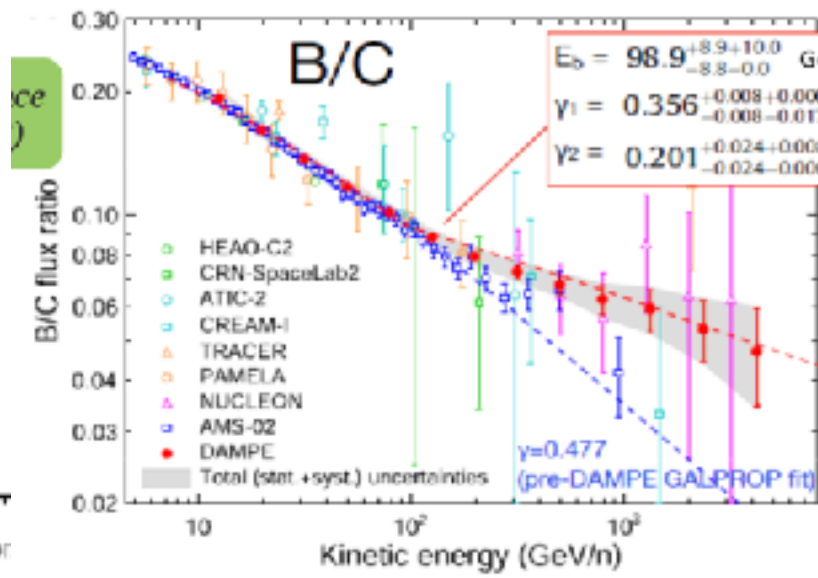


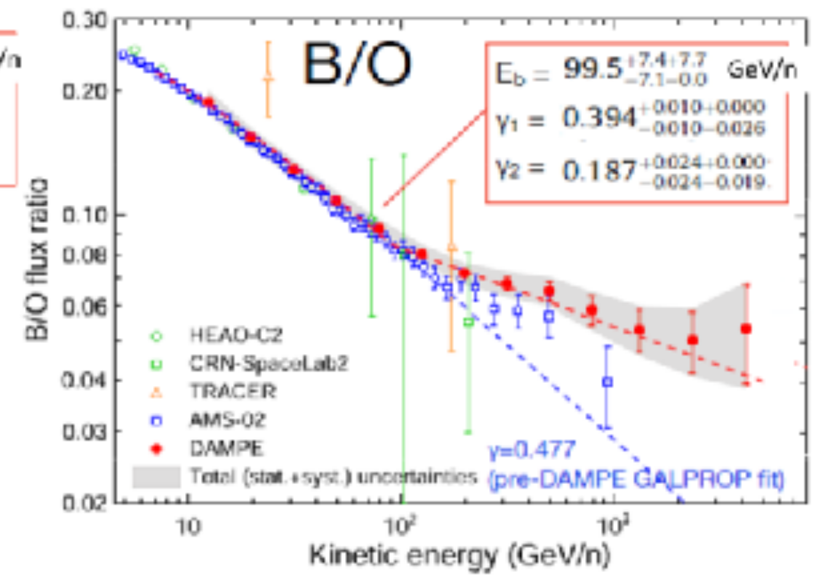

electrons



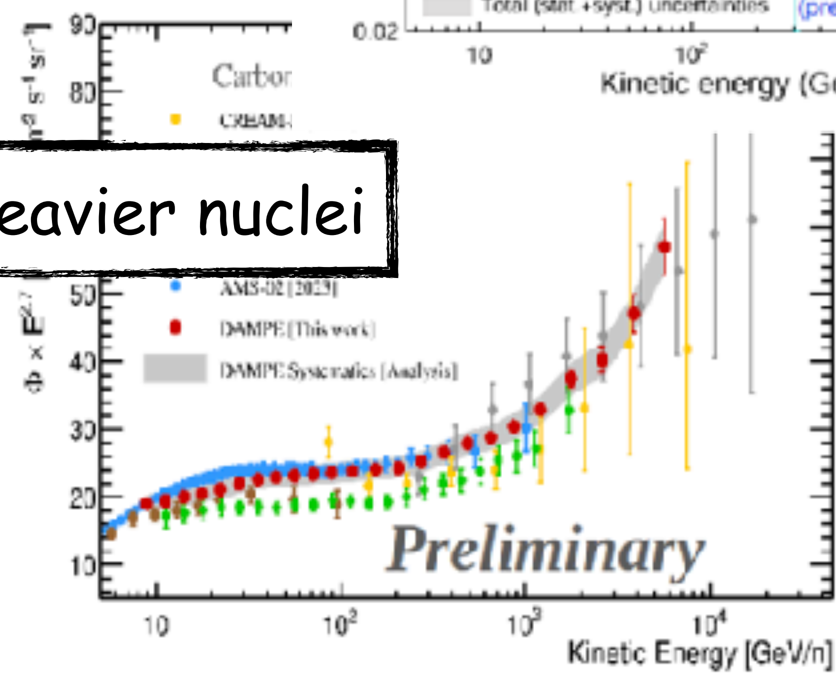

H and He

this is due to transport

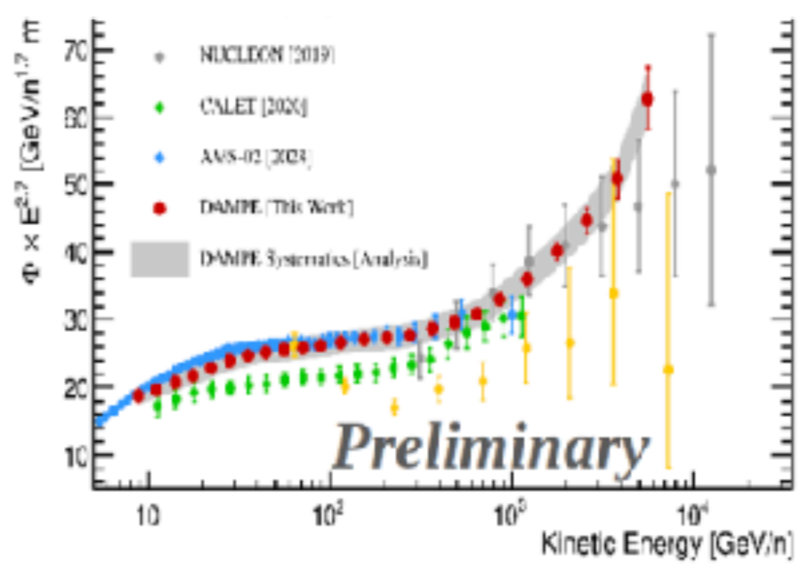


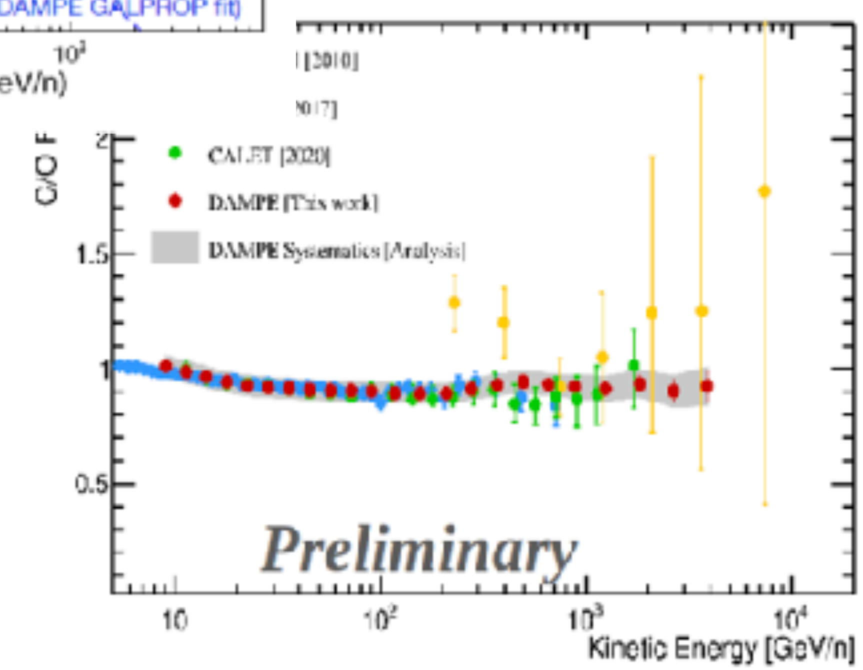




secondary /primary




heavier nuclei

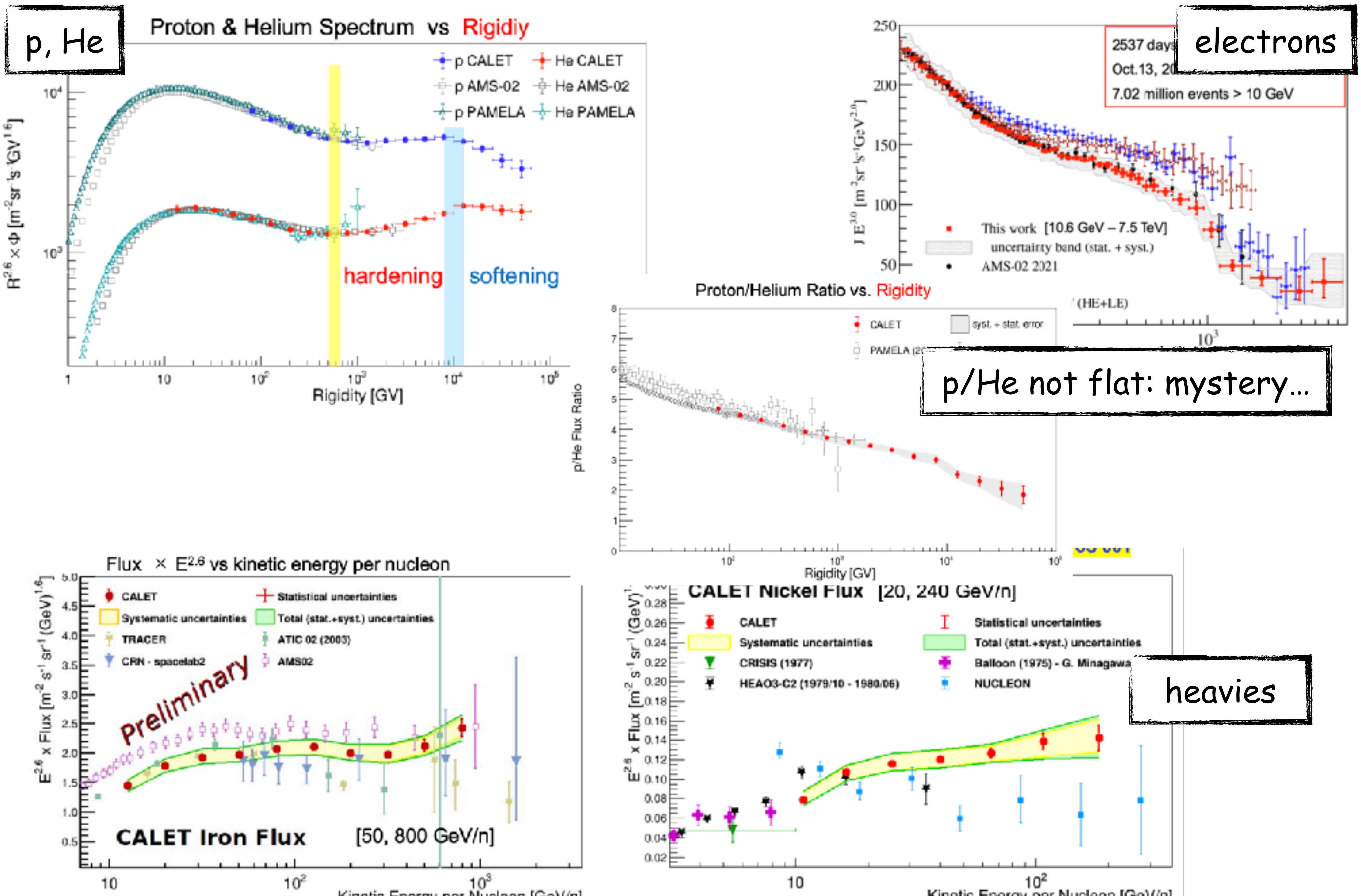


CALET

# Breaks everywhere!

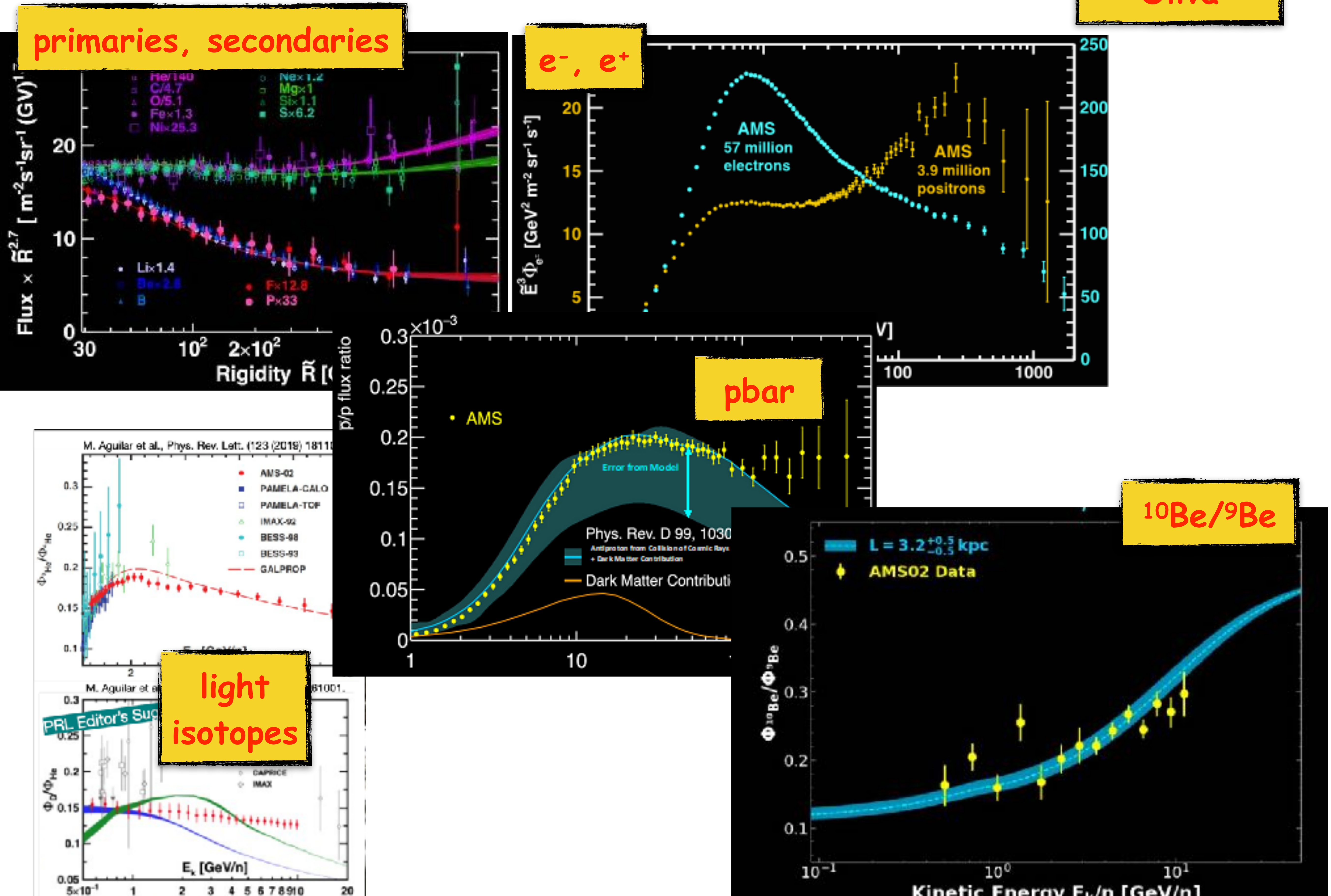
Maestro



AMS-02

# Breaks and more

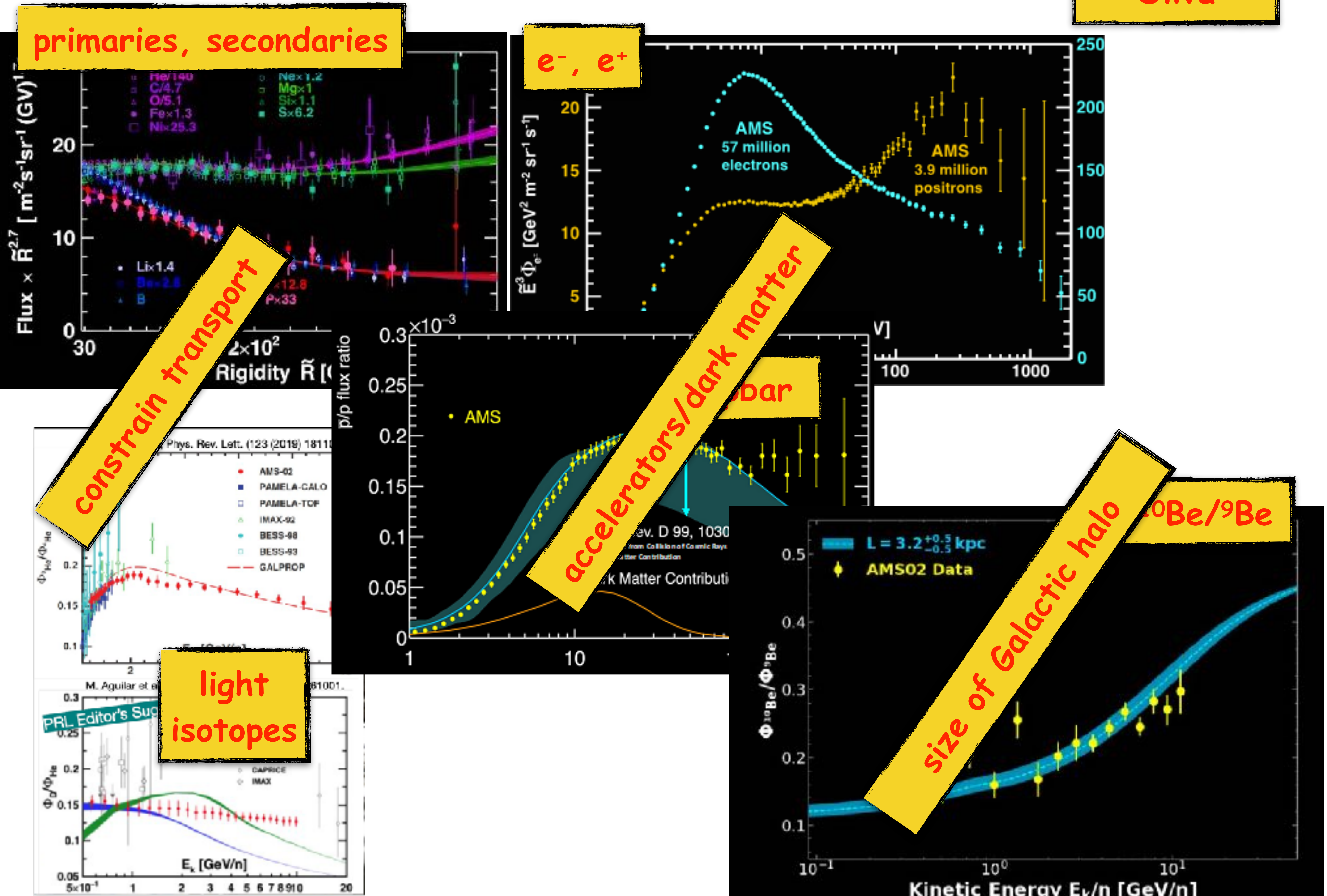
Oliva



# Breaks and more

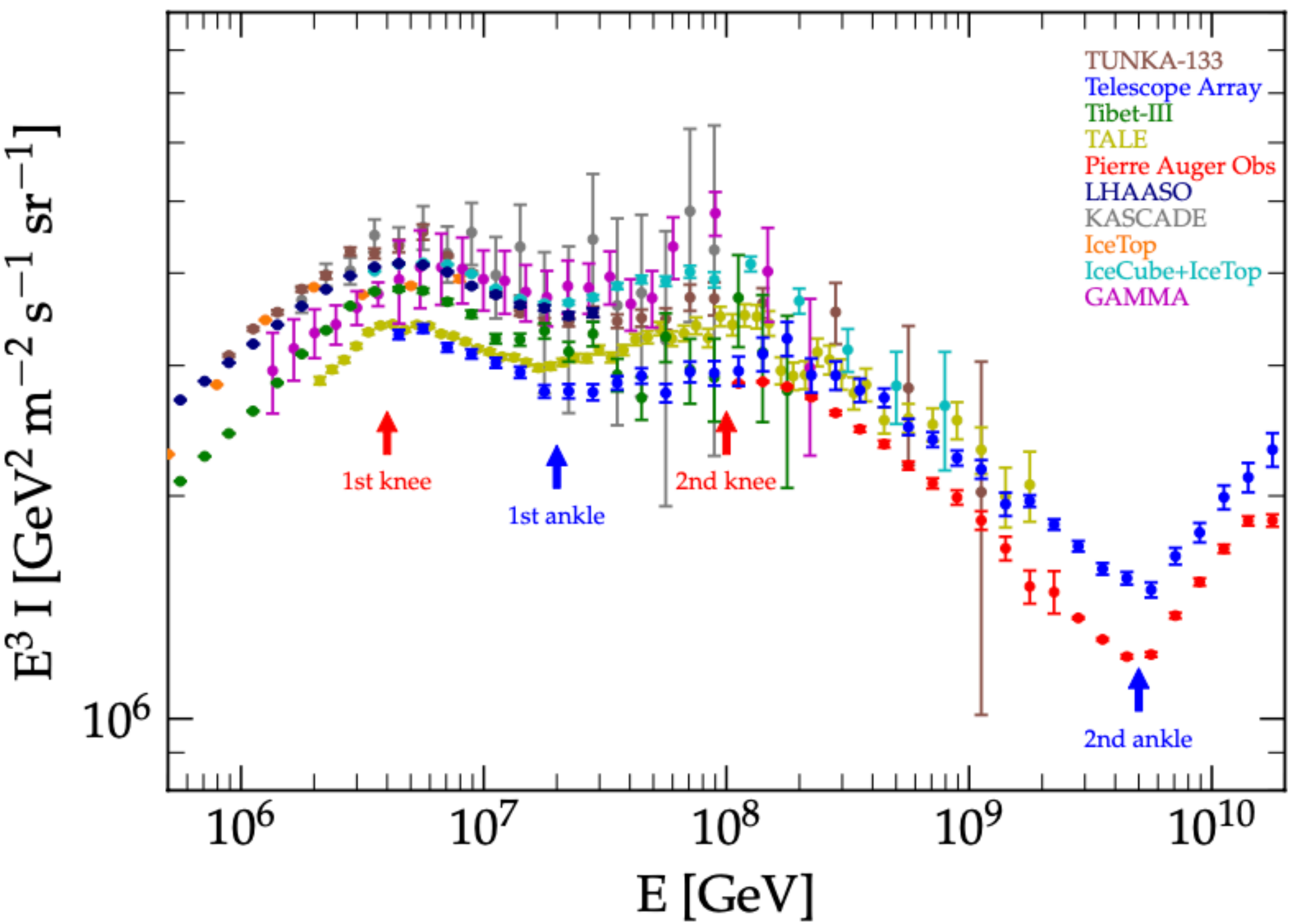
AMS-02

Oliva



# Explanations?

Evoli



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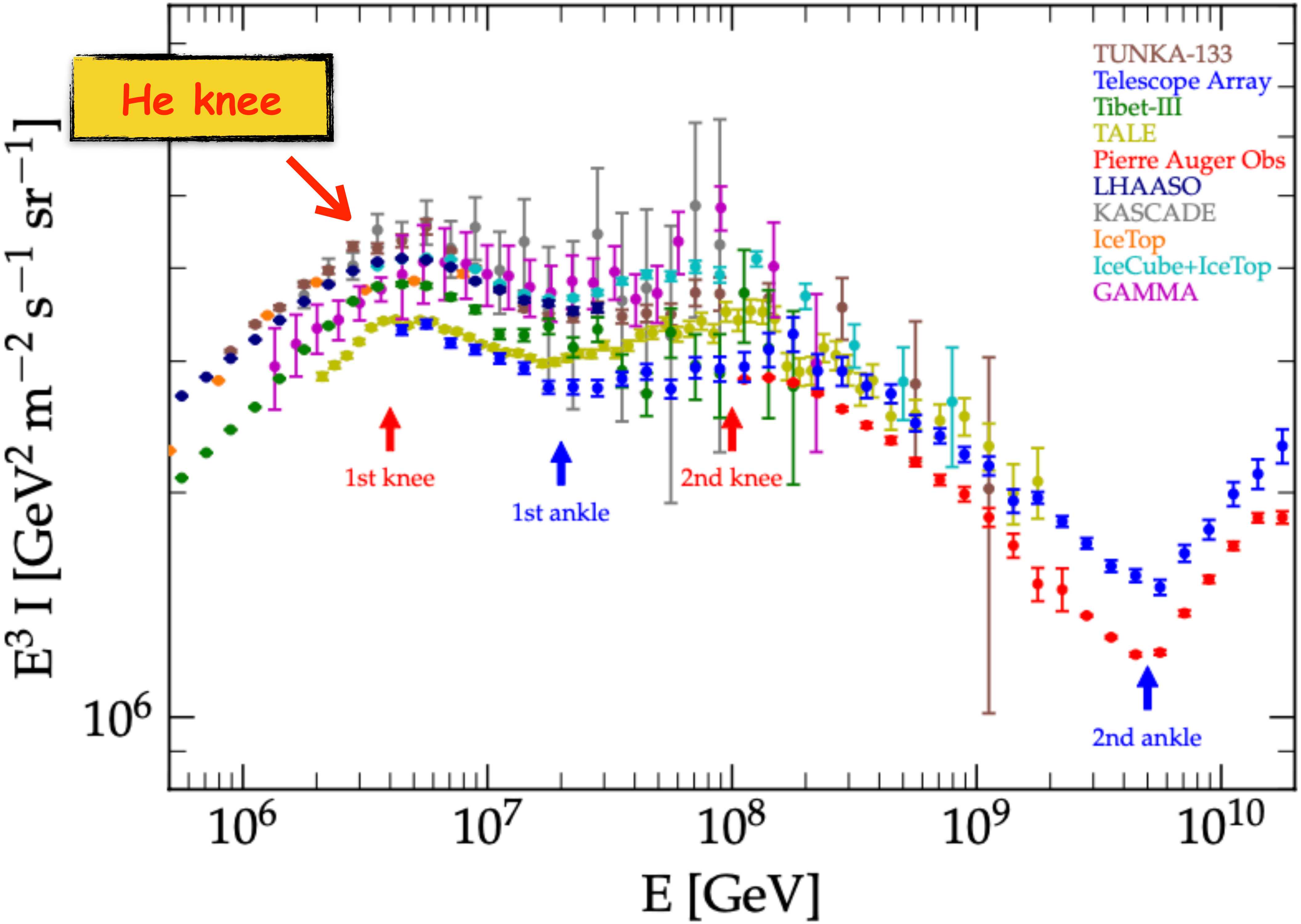
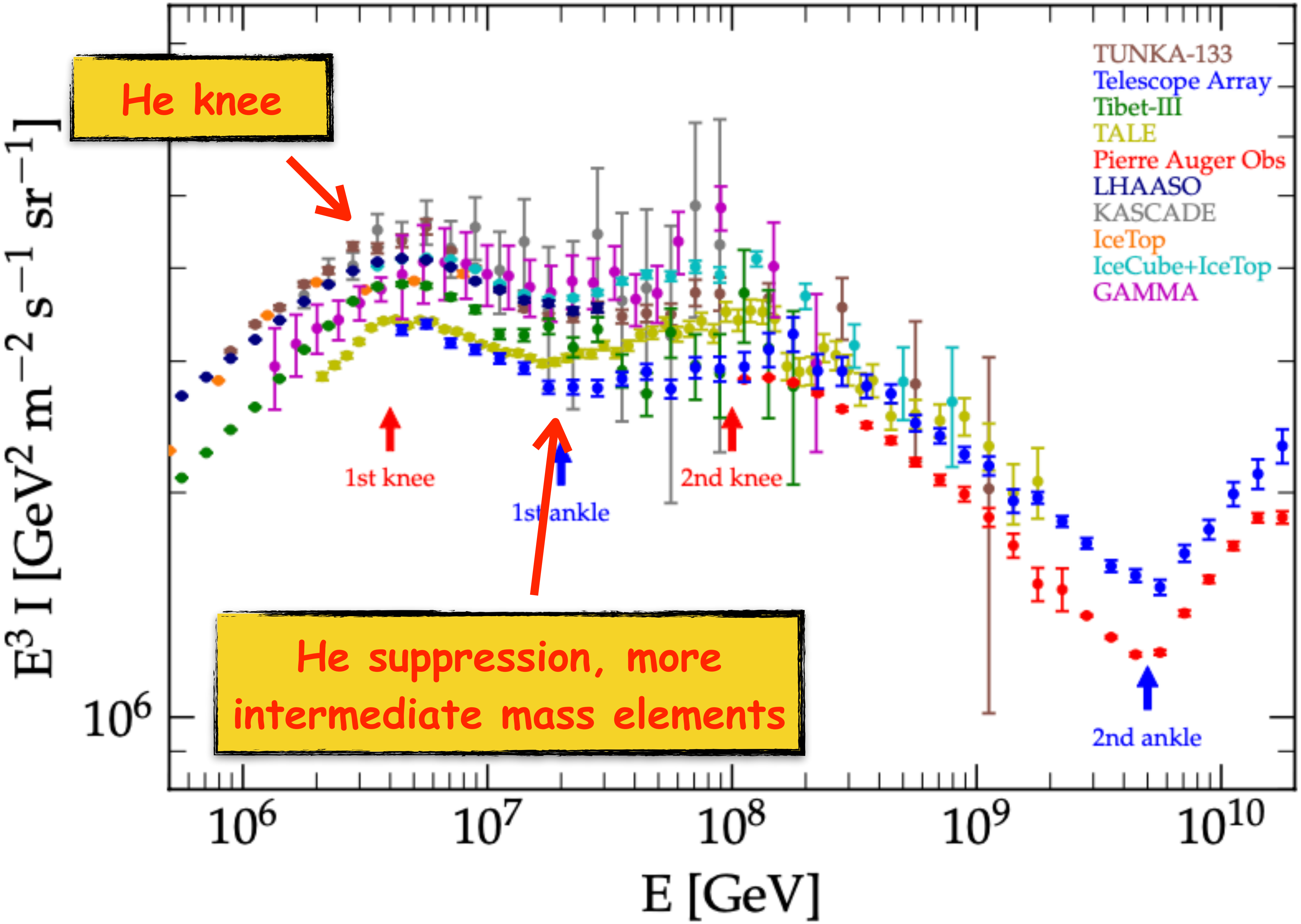
Evoli



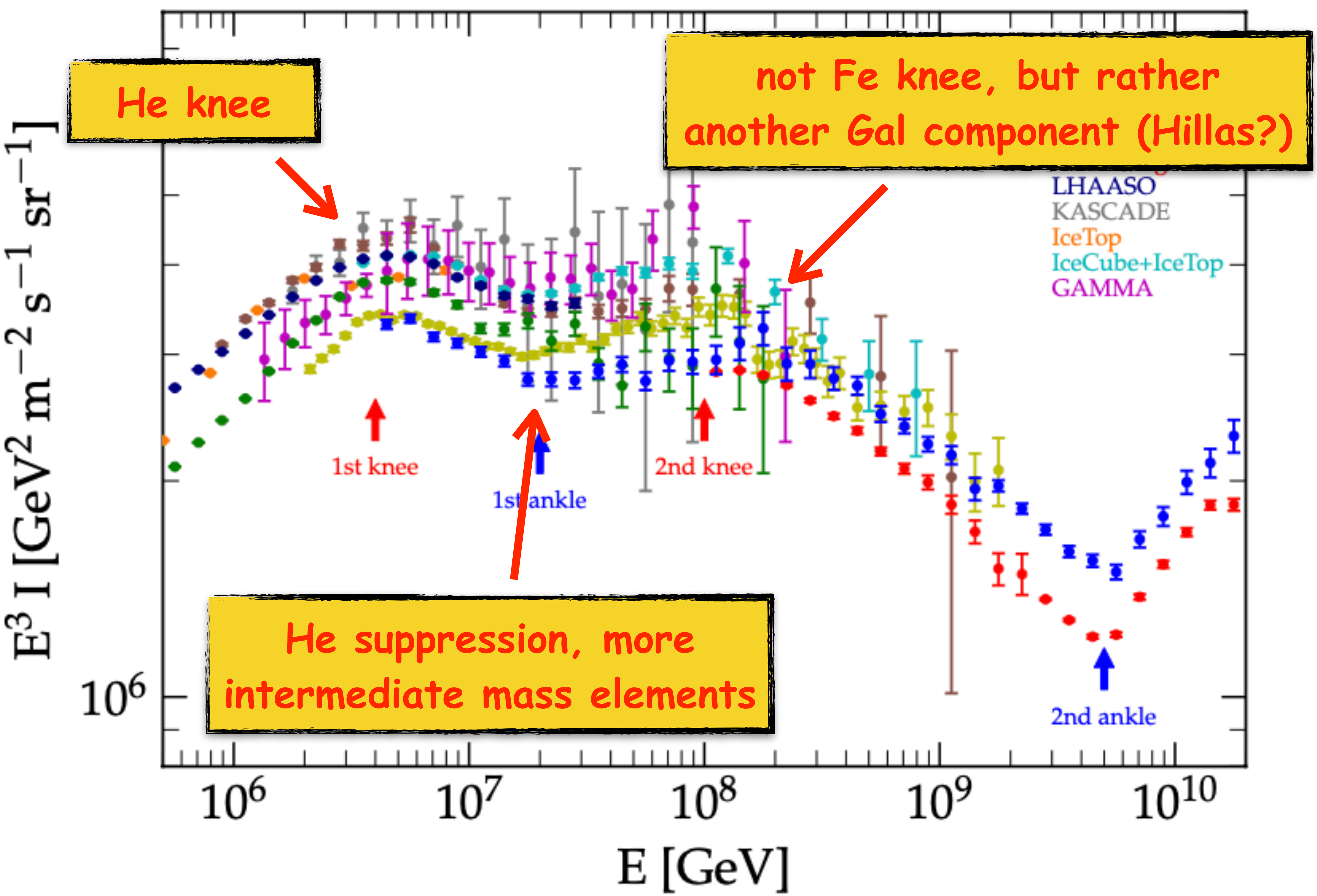
# Explanations?

Evoli



# Explanations?

Evoli



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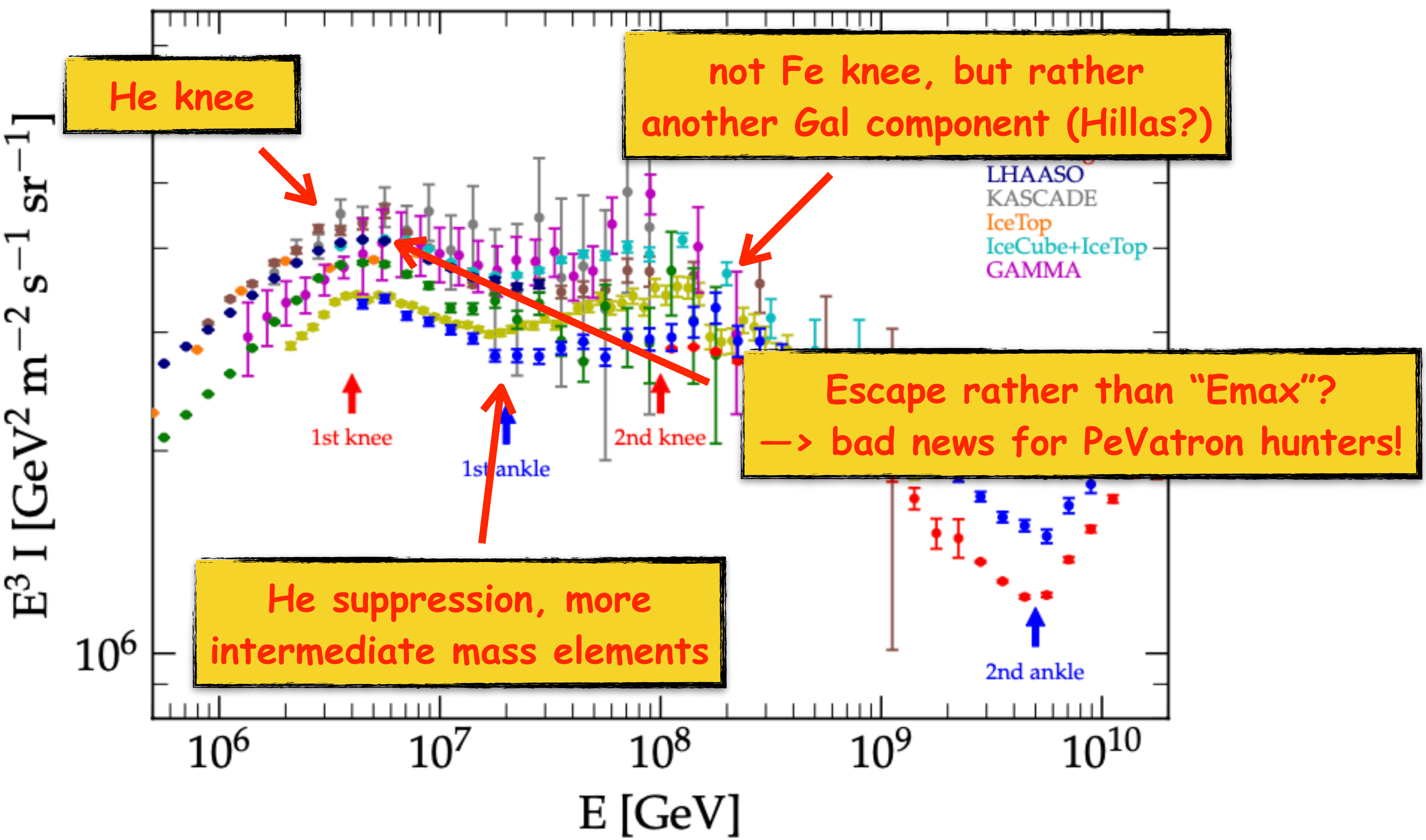
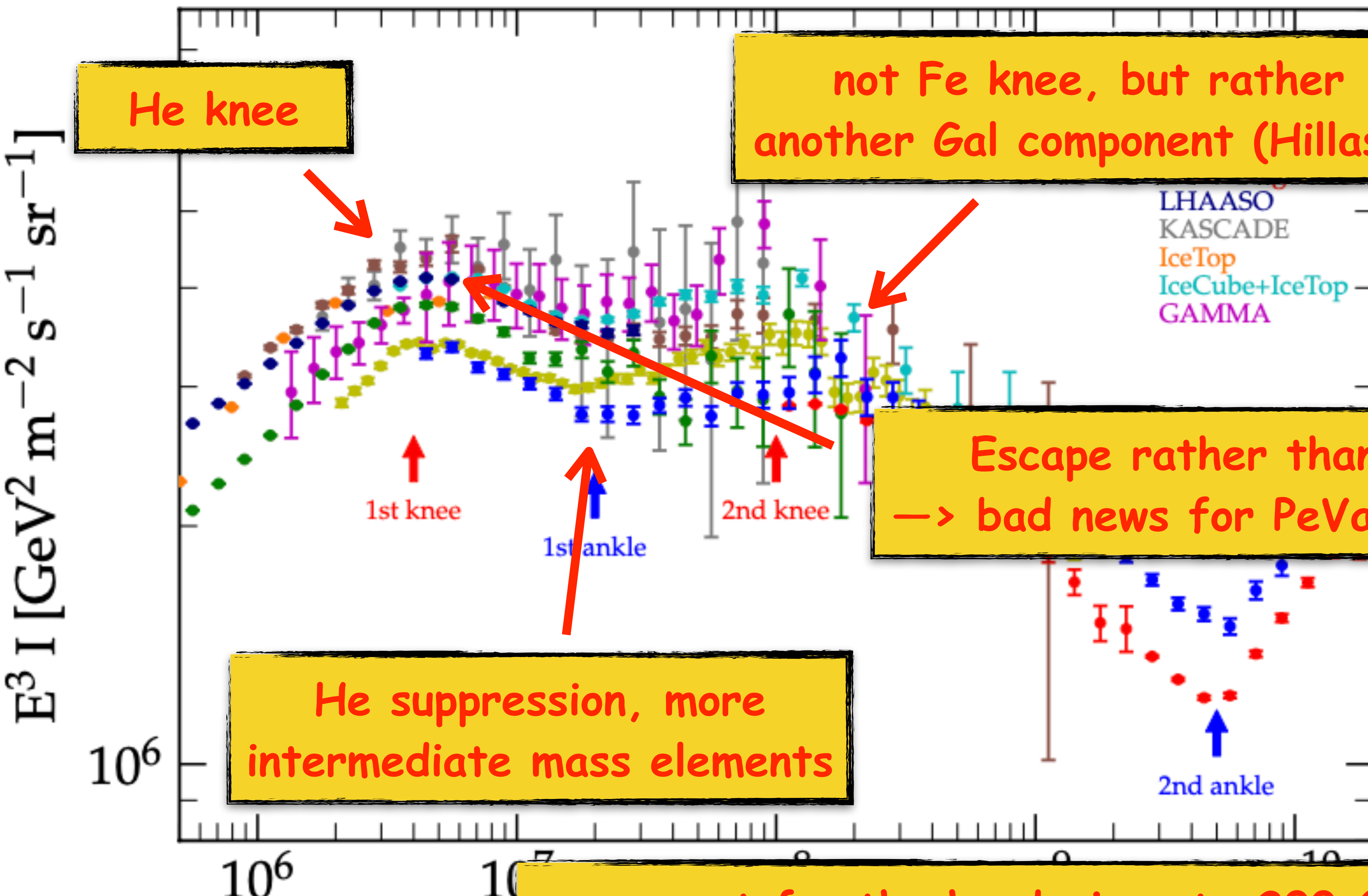
Evoli



# Explanations?

Evoli




He knee

not Fe knee, but rather another Gal component (Hillas?)

Escape rather than "Emax"?
—> bad news for PeVatron hunters!

He suppression, more intermediate mass elements

except for the hardening at ~200 GV all other features deserve more studies

- What is the shape of the local bubble? (chimney?) —> transport of Galactic CRs
- Do we understand the “metaGalaxy”? [O(100) kpc] —> UHECR propagation?
- Can we improve models of B-fields to make UHECR astronomy real?
- Very few or very many UHECR sources? Why must the spectrum be so hard?
- Extragalactic neutrinos: Seyferts or not?
- What is the very energetic event seen by KM3NeT? Why Icecube never detected anything like that?
- Will LHAASO test the scenario of a Z-dependent knee? Will it measure the slope of the spectrum (per species) BEYOND the knee?
- Can we see the knee in diffuse gamma rays?
- How clumpy is the VHE diffuse emission? What is a source and what is diffuse?
- AreTeV Halo common or not?
- Where are PeVatrons? [in fact, Where are super-PeVatrons???]
- Is there a PeVatron in the Cygnus region?
- Microquasars as PeVatrons? Should we develop more models for acceleration at micro quasars? Can they explain PeV CRs?
- Are leptonic PeVatrons making our hunt for proton PeVatrons more difficult?
- Do we understand all the breaks in the CR spectrum? [No, we need more studies for all the features except for that @ O(200) GV]
- p and He different slope: why?
- Secondary/Primary, isotopic ratios, etc… Is this information fully exploited?