Constraining Magnetic Fields at Galactic Scales

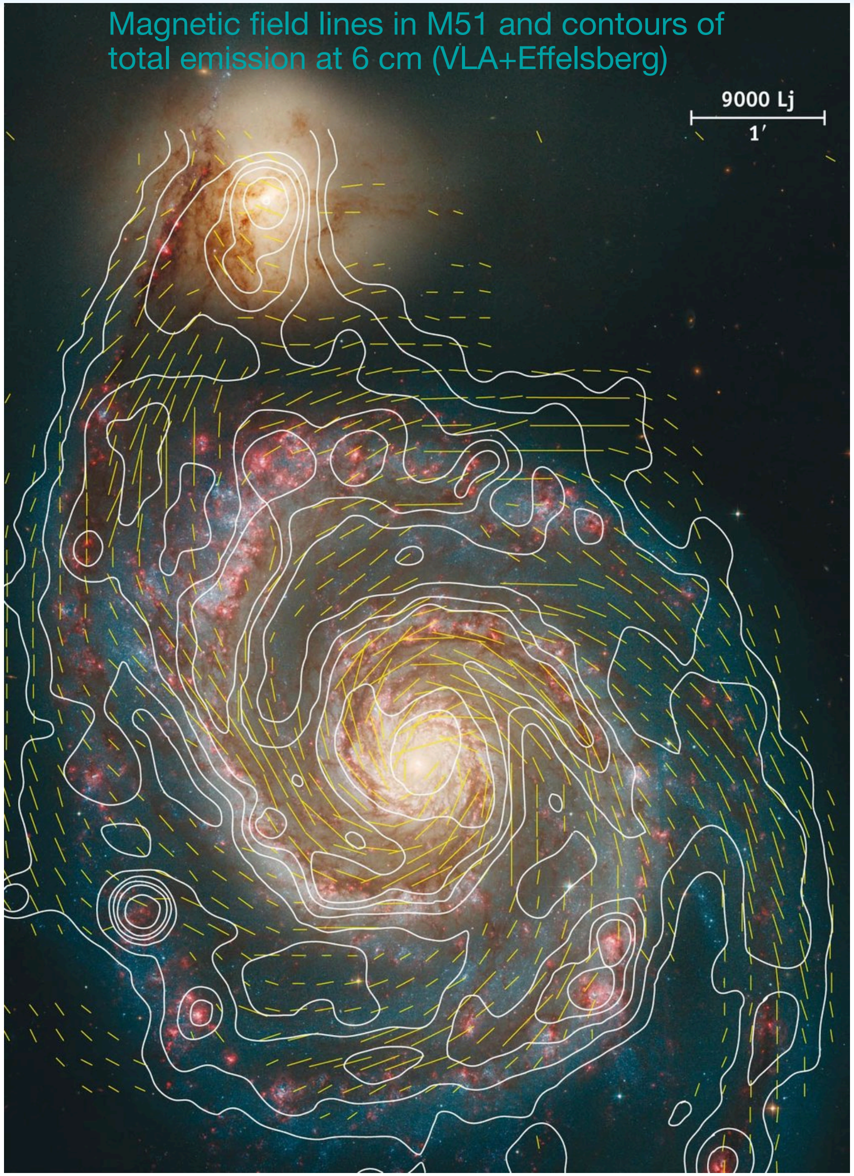
Tess Jaffe
NASA/Goddard

at ICRC
Berlin (virtually), 13 July 2021

Outline

1. What we're trying to do, why, and how.
2. What's wrong with the last ten years worth of work (including my own).
3. How we are going to do better and how the work being presented at this conference fits in.

External galaxies: one example



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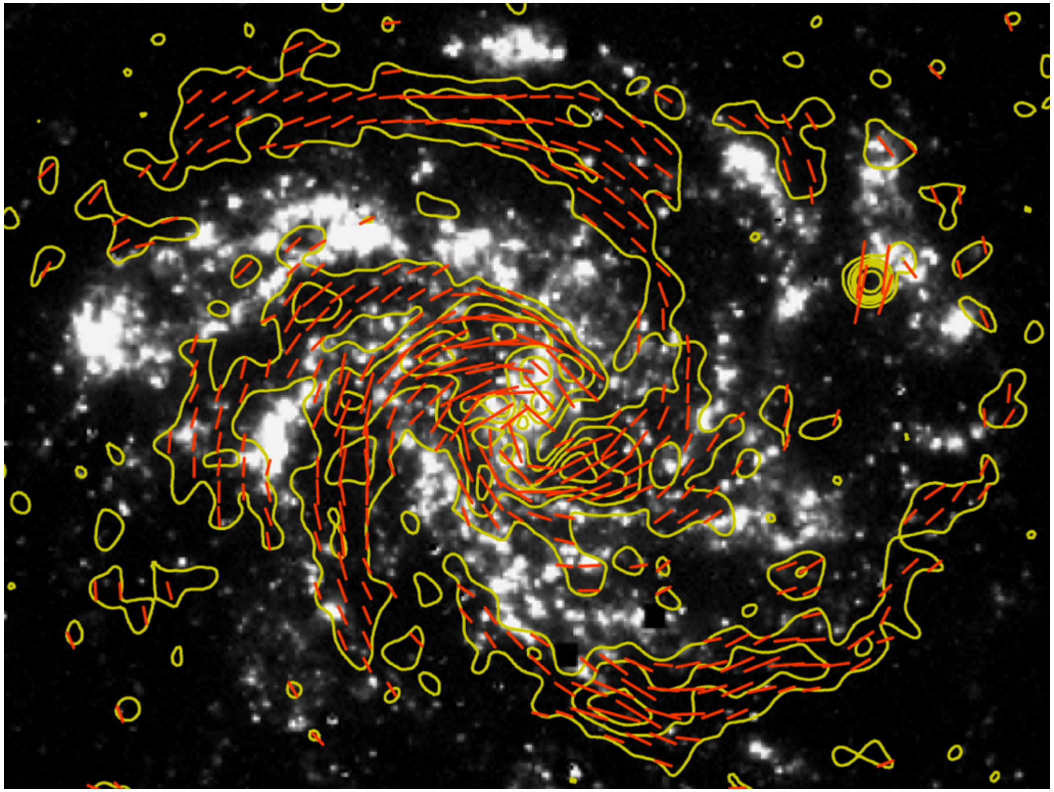
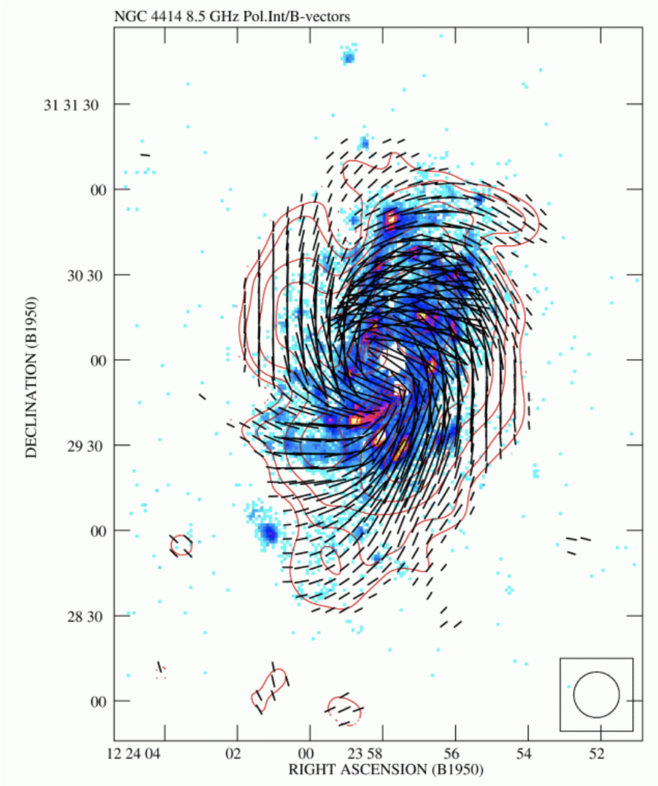
- First order: magnetic fields aligned with matter spiral structure. Can't be coincidental.
- But not always.
- Unfortunately, we cannot see our own galaxy like this.

Note that plots of polarization vectors are often rotated 90deg to show B-field direction

External galaxies: other examples





NGC6946 6cm PI over Hα (Copyright R. Beck, MPIfR)

(Soida et al. 2002)

A variety of morphologies observed, and we cannot assume a relationship with other matter tracers.

External galaxies: halo transition(s)?

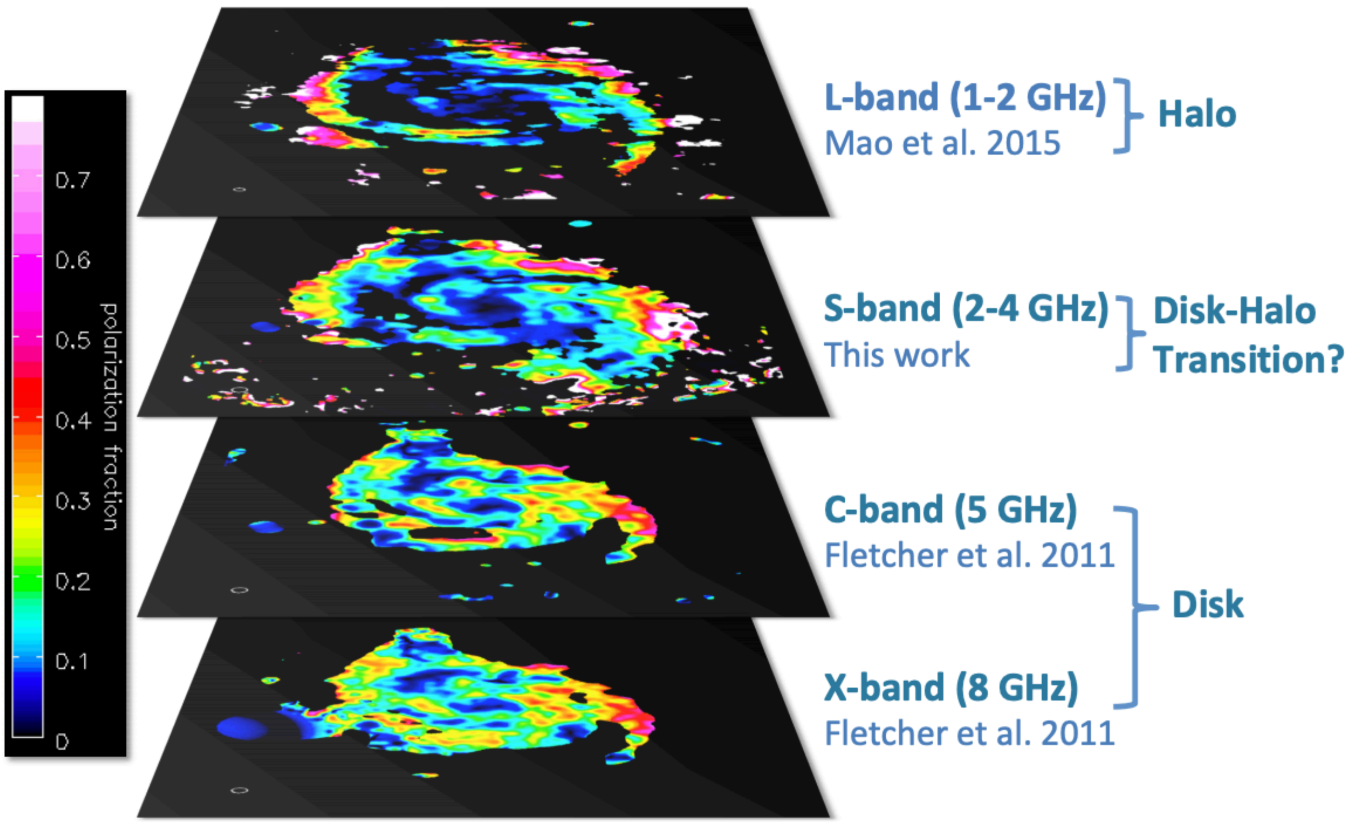
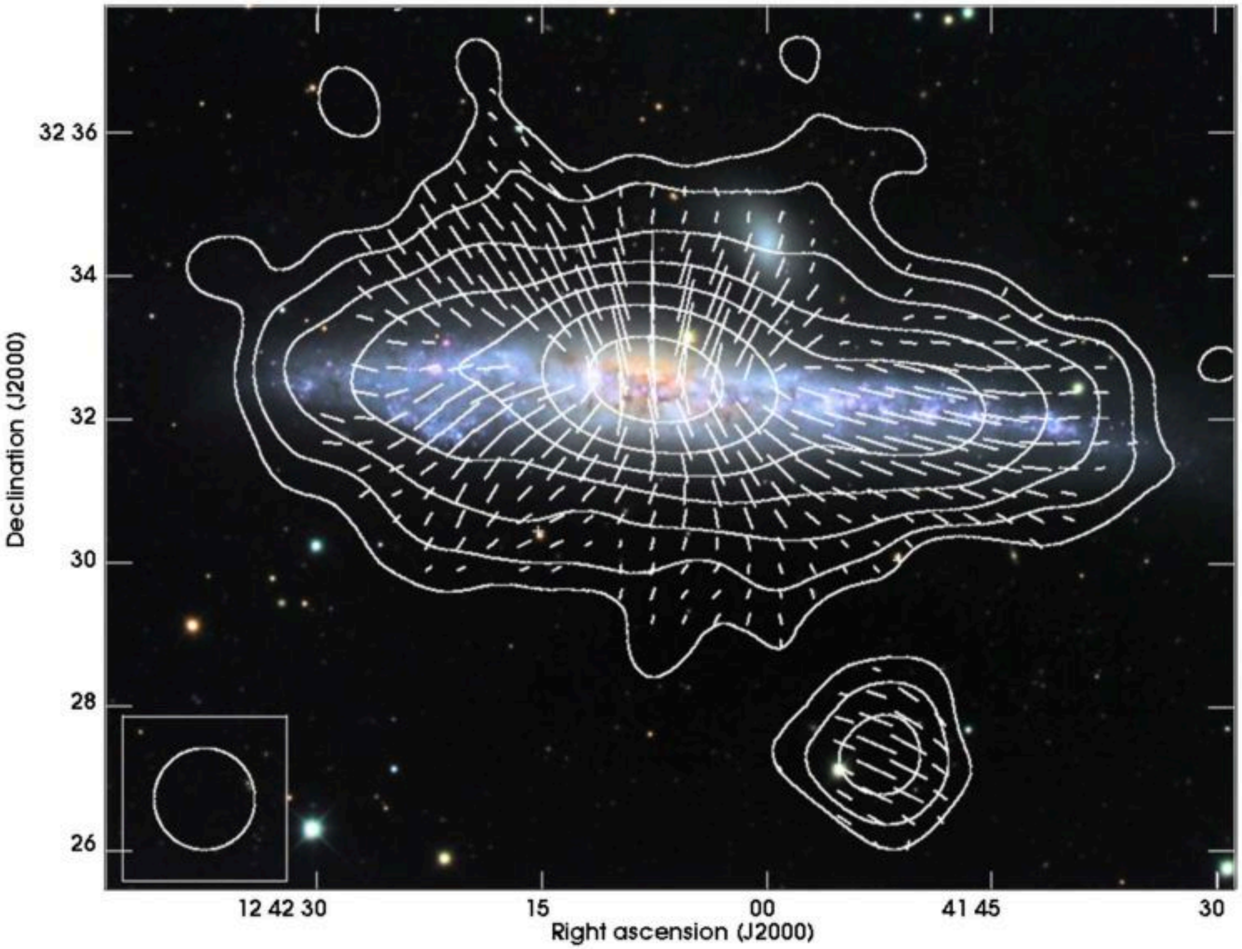


Figure 1. Observed degree of polarization of M51 at different frequencies. All images have the same color scale and are smoothed to the same resolution of 15 arcsec (which corresponds to about 550 pc at the distance of M51). Note that the total intensity images used to calculate the degree of polarization were not corrected for thermal emission.

Kierdorf et al. (2018)

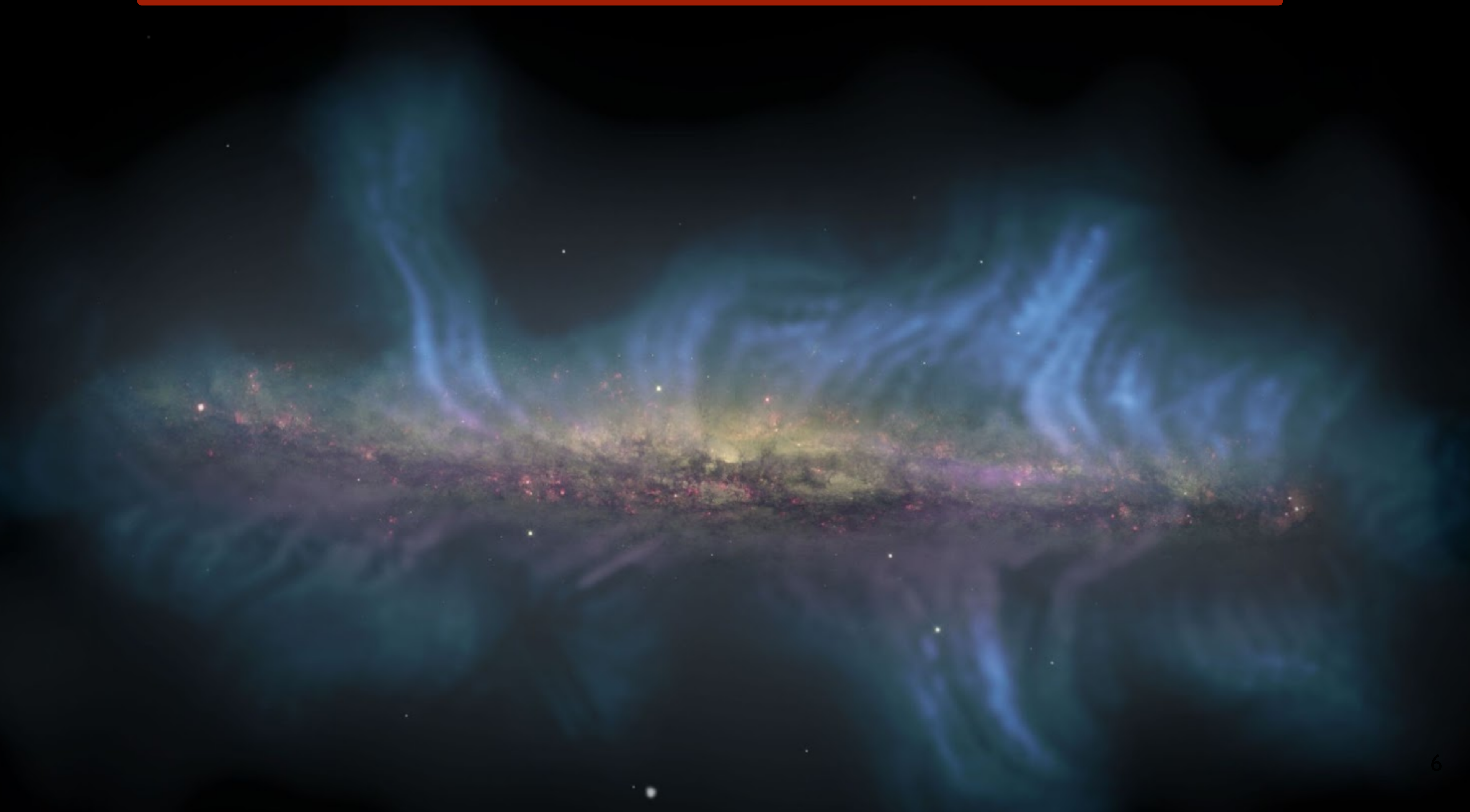
Particularly the axi- versus bi-symmetric spirals seen at different heights (Fletcher et al. 2011)

External galaxies: vertical field

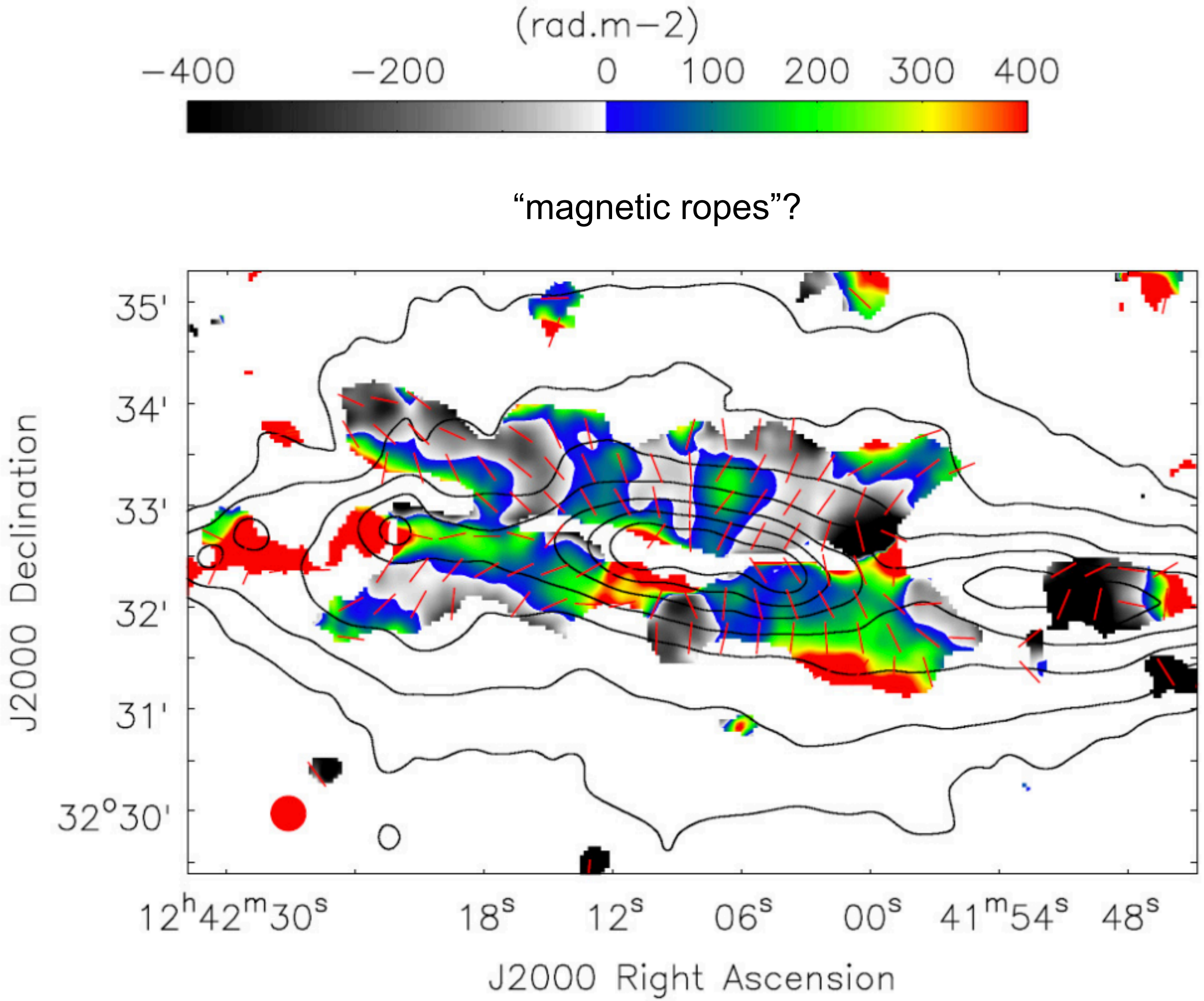


External galaxies: vertical field

See also Ralf-Jürgen Dettmar’s contribution on
Magnetic field structure in halos of star-forming disk galaxies

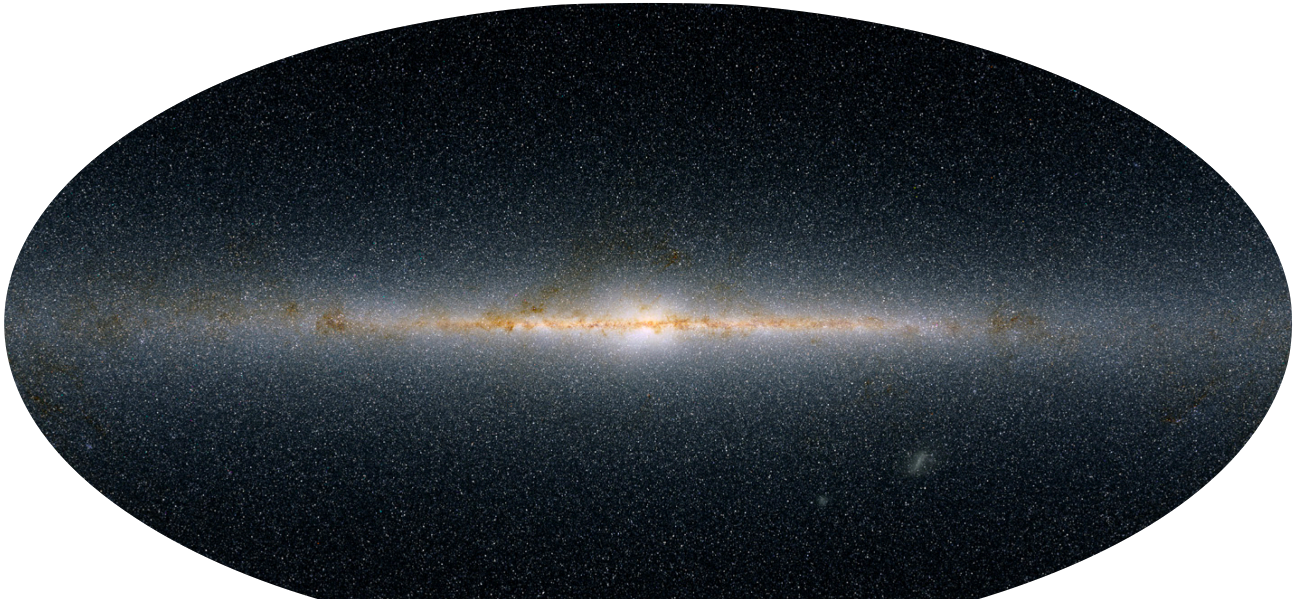


External galaxies: vertical field

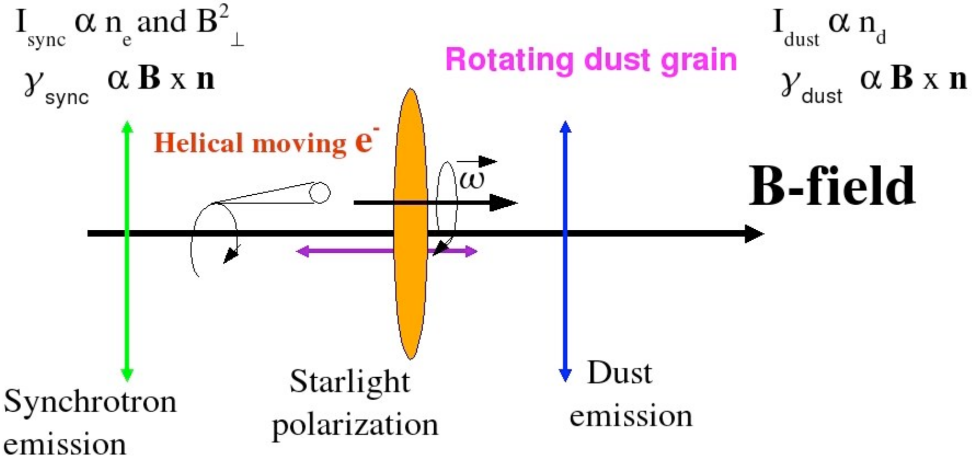


Mora-Partiarroyo et al., *A&A*, 2019, CHANG-ES XV: Large-scale magnetic fields in the halo of NGC 4631
See also Krause et al. 2020 (A&A 639, A112)

Our view of the Milky Way: optical

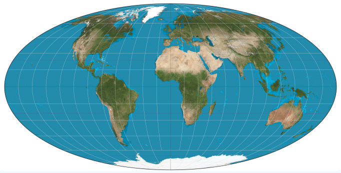


Courtesy of 2MASS/UMass/IPAC-Caltech/NASA/NSF

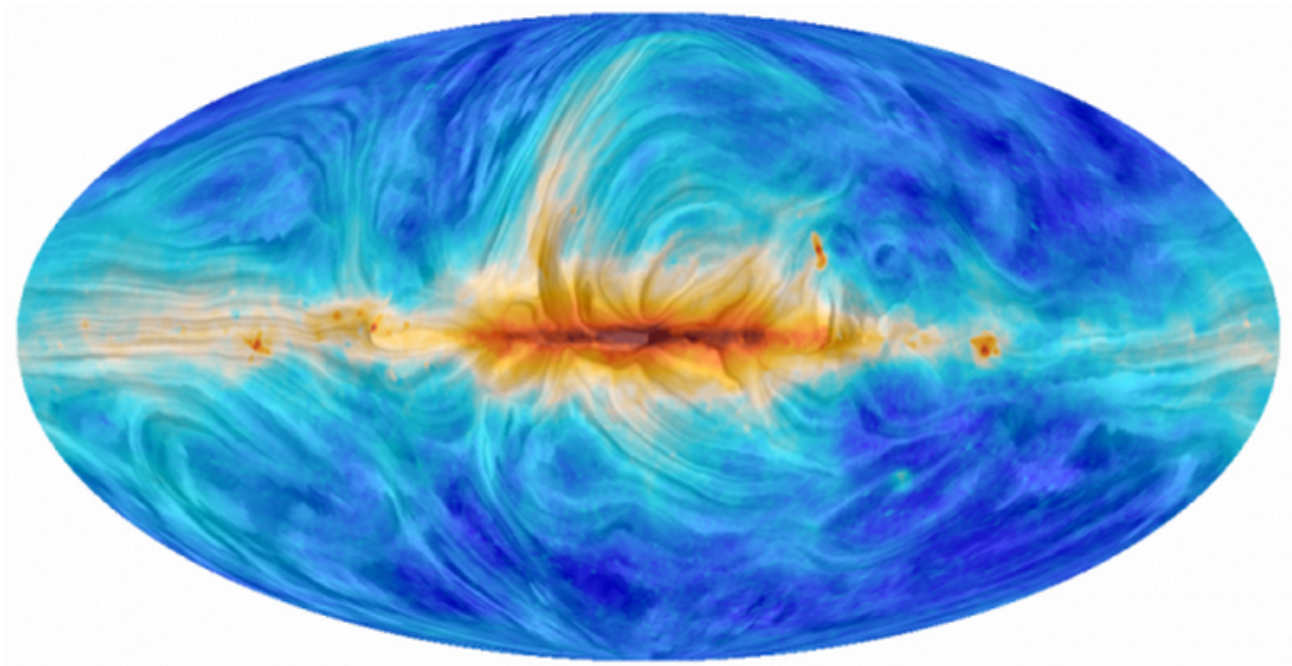


(Courtesy J.F. Macías-Pérez)

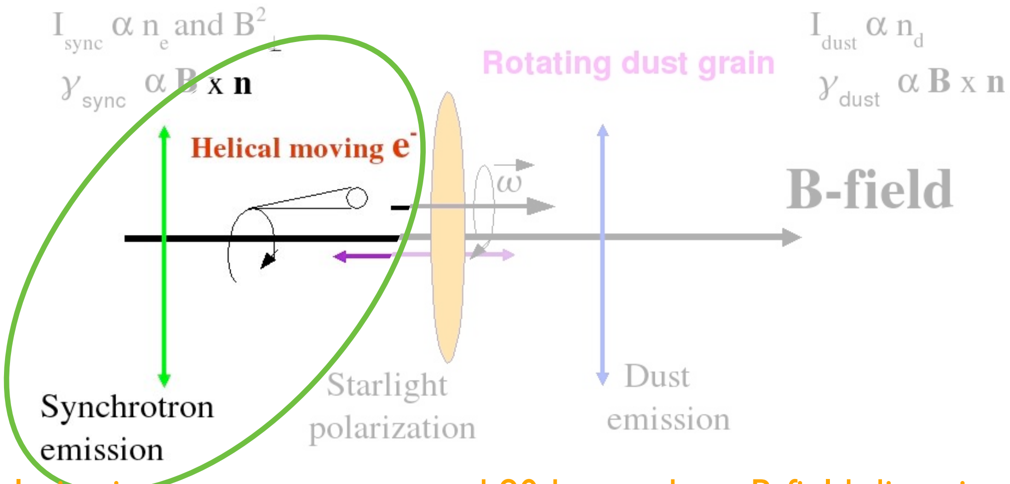
Atlas



Polarized synchrotron emission: radio to microwave

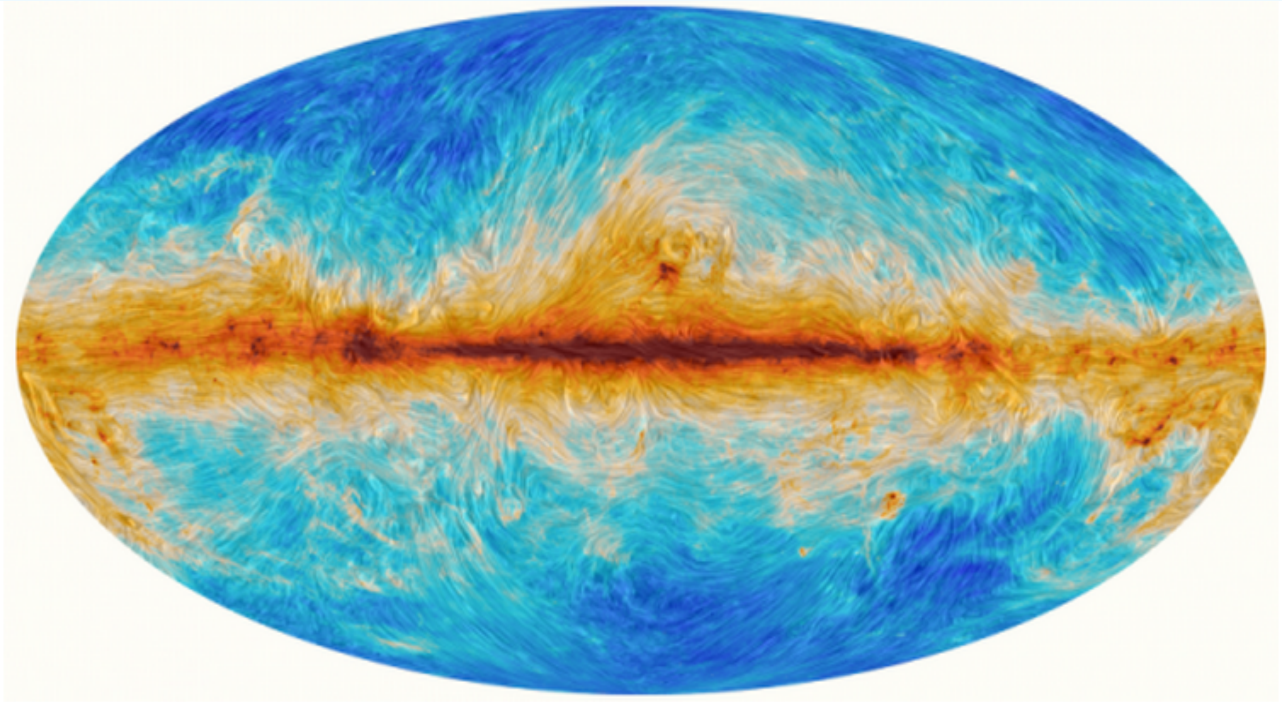


30 GHz polarized synchrotron (ESA, Planck Collaboration)

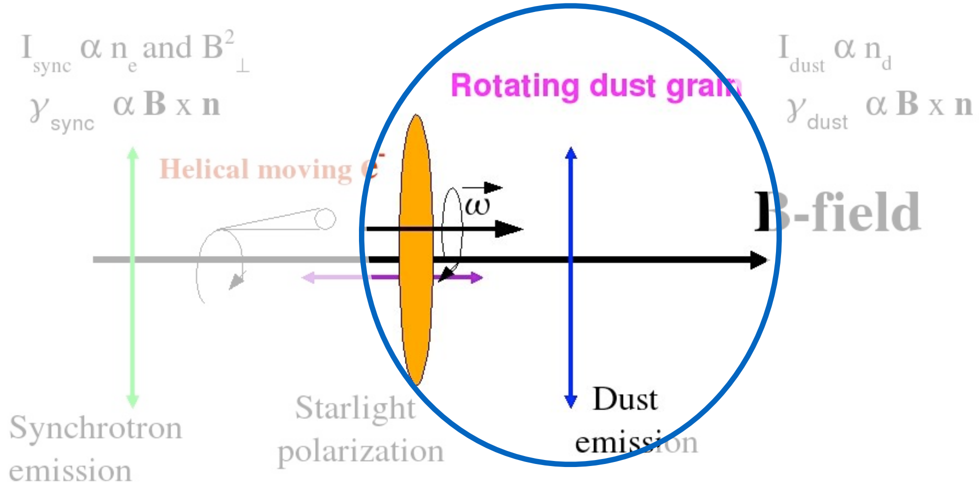


Note that plots of polarization vectors are rotated 90deg to show B-field direction

Polarized dust emission: submm

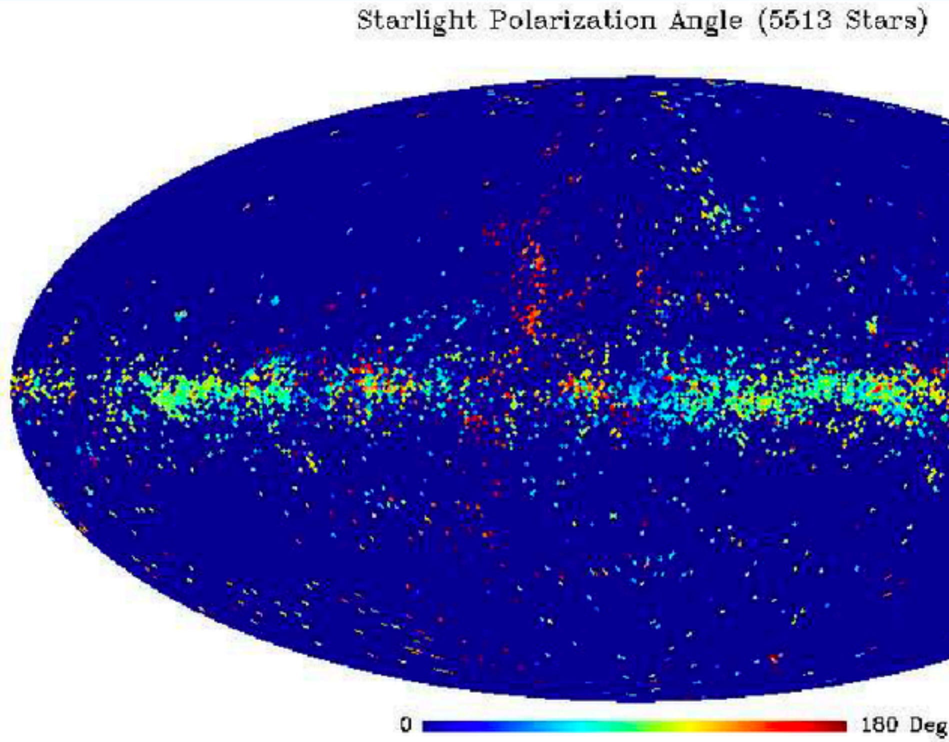


353 GHz polarized dust (ESA, Planck Collaboration)

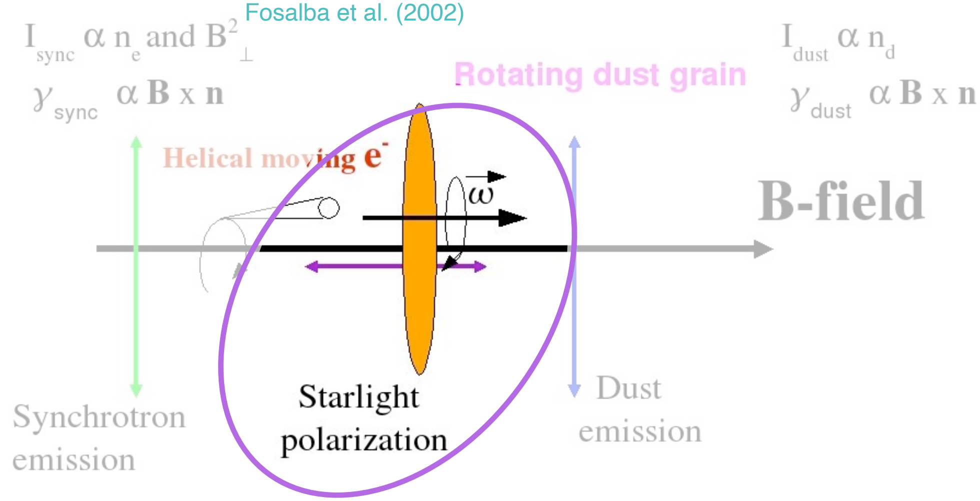


Note that plots of polarization vectors are rotated 90deg to show B-field direction

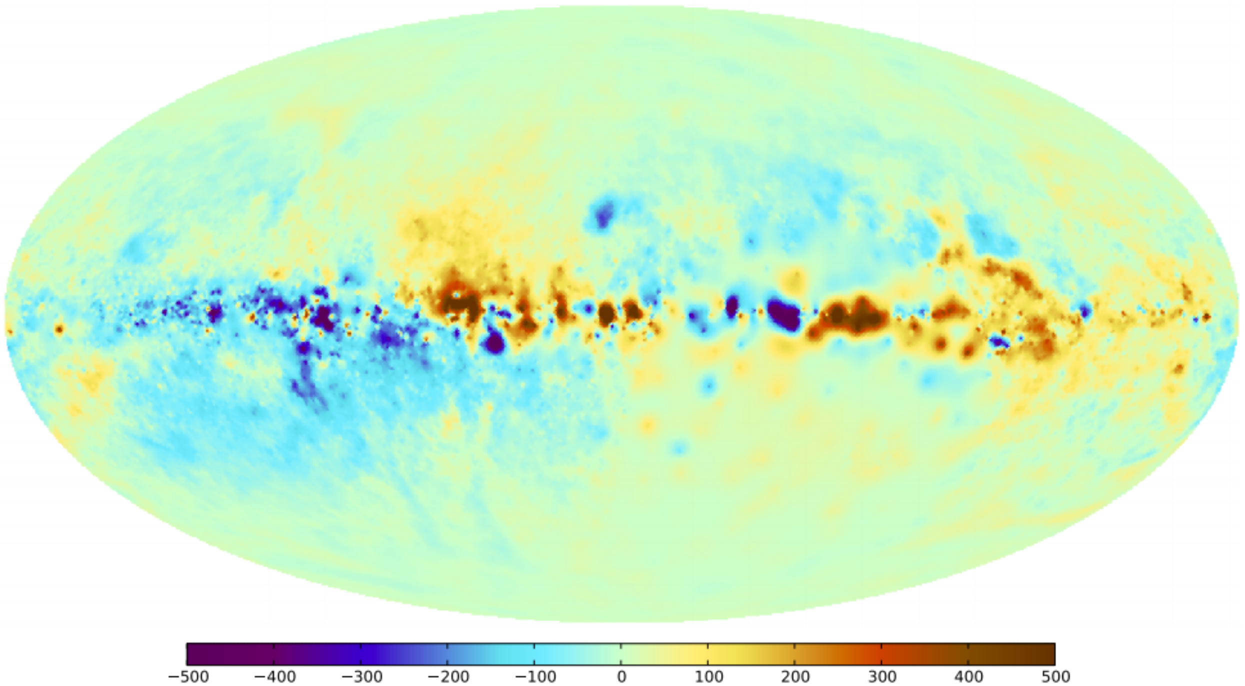
Starlight polarization: optical



Fosalba et al. (2002)



Faraday rotation: radio



Faraday depth (rad/m²)
(Oppermann et al. 2012)

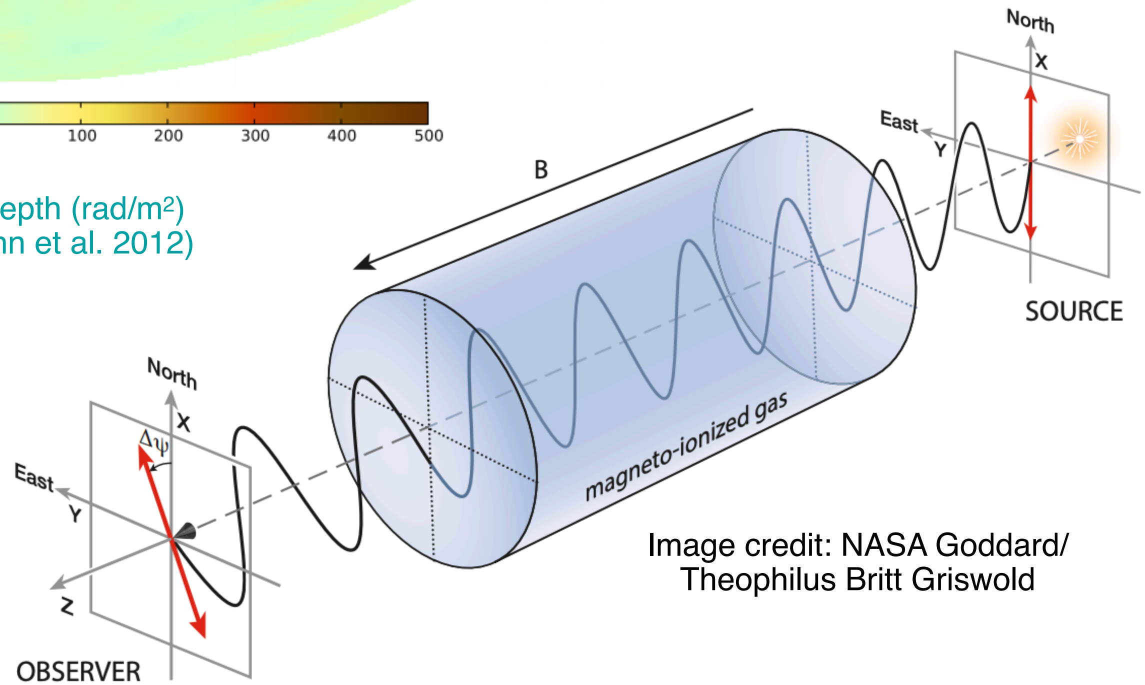
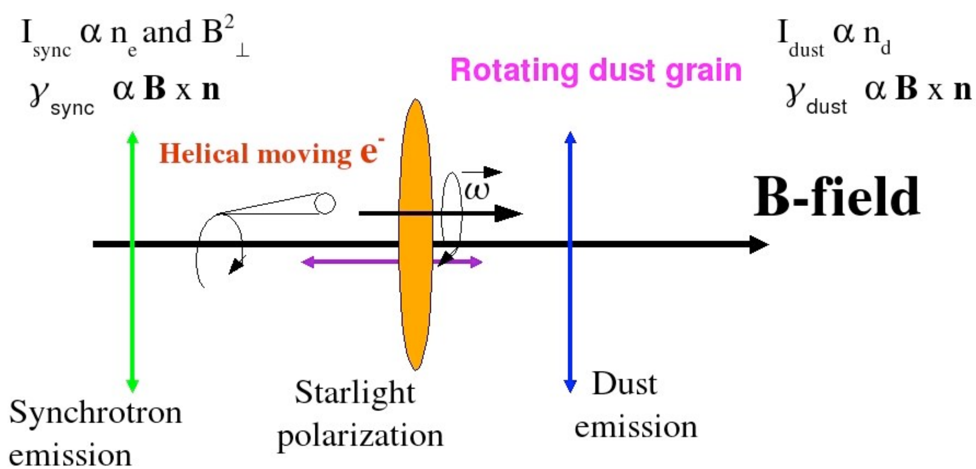
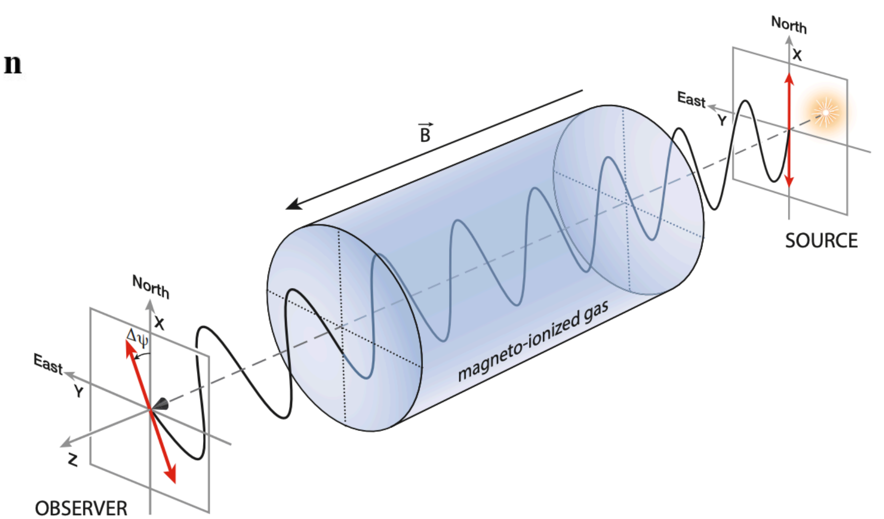


Image credit: NASA Goddard/
Theophilus Britt Griswold

- Synchrotron emission: $I(\nu) \propto \int_{LOS} n_{CRE} B_{\perp}^2 dl$ i.e. traces component ***perpendicular*** to LOS
- Faraday rotation measure: $RM \propto \int_{LOS} n_e B_{\parallel} dl$ i.e. traces component ***parallel*** to LOS, **3D** with pulsar distances
- Thermal (vibrational) dust emission: $f(B_{\perp}, n_d, T_d, S_{IRF} \ldots)$ traces component ***perpendicular*** to LOS but depends on dust environment, grain sizes and shapes, alignment mechanisms....
- Starlight polarization: $f(B_{\perp}, n_d, \ldots)$, ***perpendicular*** component, ***3D*** with star distances.



(Courtesy J.F. Macías-Pérez)



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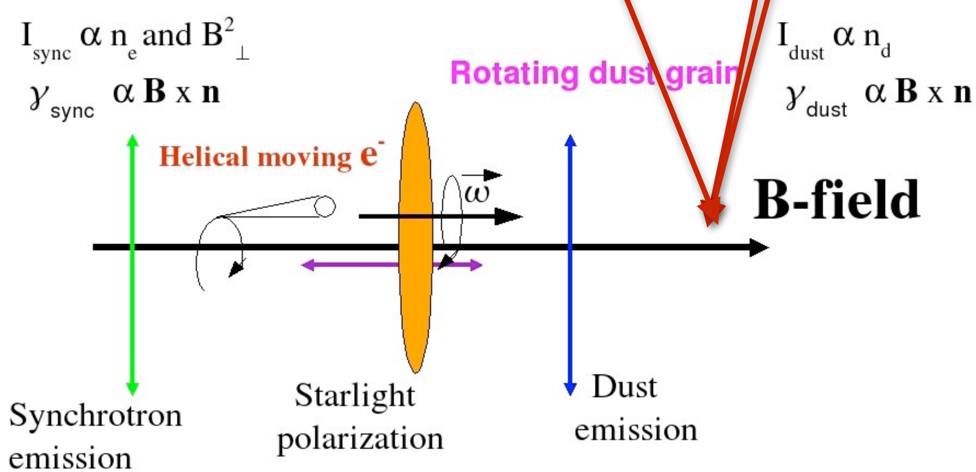

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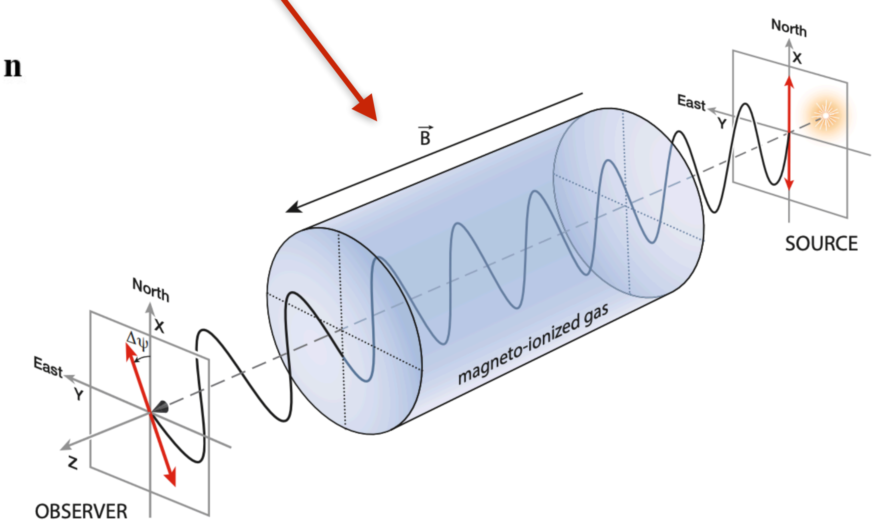

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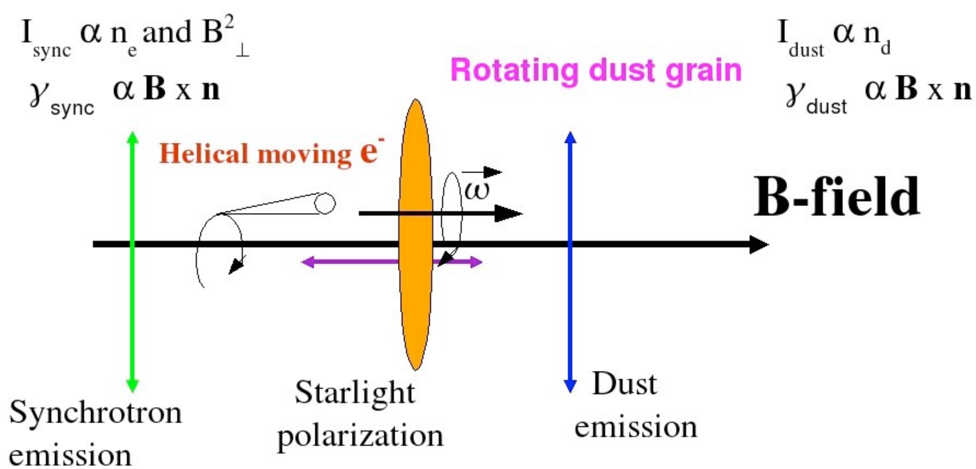
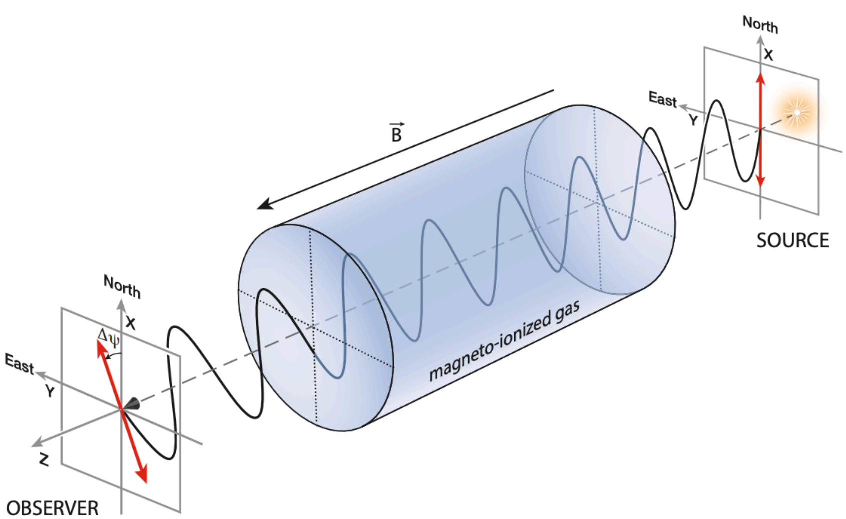


(Courtesy J.F. Macías-Pérez)



- <u>Synchrotron emission</u>: $I(\nu) \propto \int_{LOS} n_{CRE} B_{\perp}^2 \, dl$ i.e. traces component ***perpendicular*** to LOS

Problem I: Spatial distribution of CRs

- <u>Faraday rotation measure</u>: $RM \propto \int_{LOS} n_e B_{\parallel} dl$ i.e. traces component ***parallel*** to LOS, **3D** with pulsar distances

- <u>Thermal (vibrational) dust emission</u>: $f(B_{\perp}, n_d, T_d, S_{IRF} \ldots)$ traces component ***perpendicular*** to LOS but depends on dust environment, grain sizes and shapes, alignment mechanisms....

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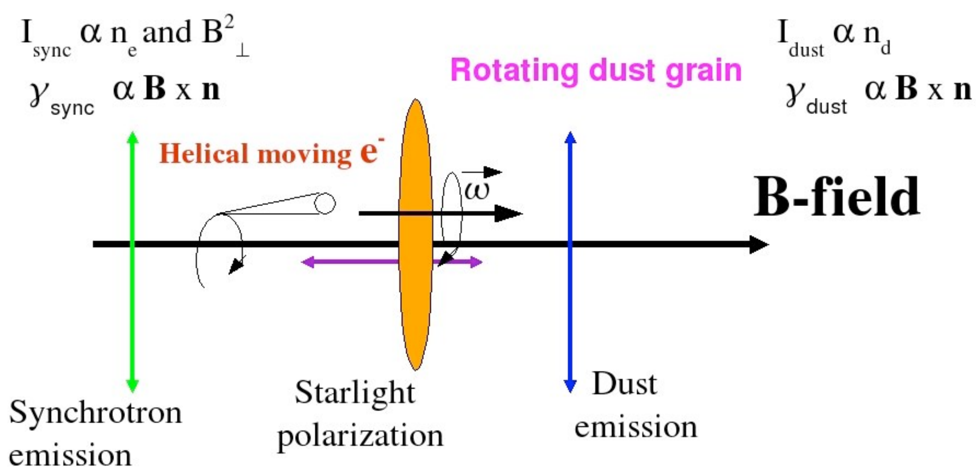

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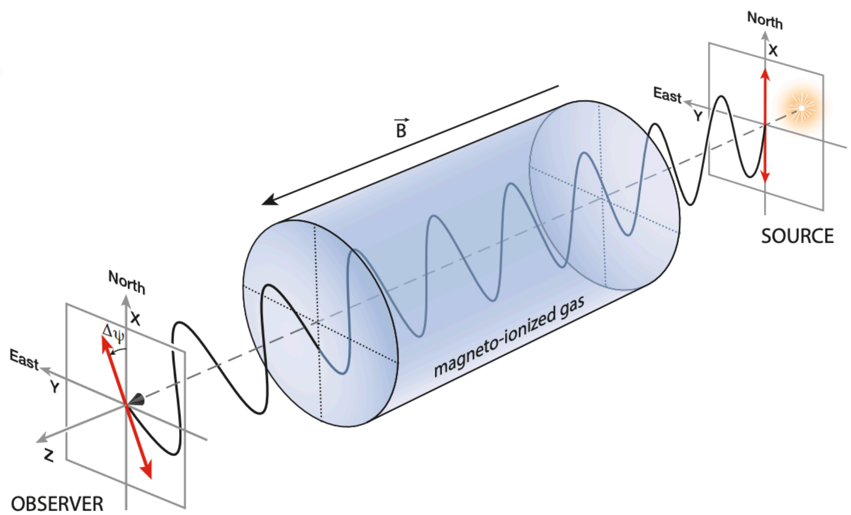

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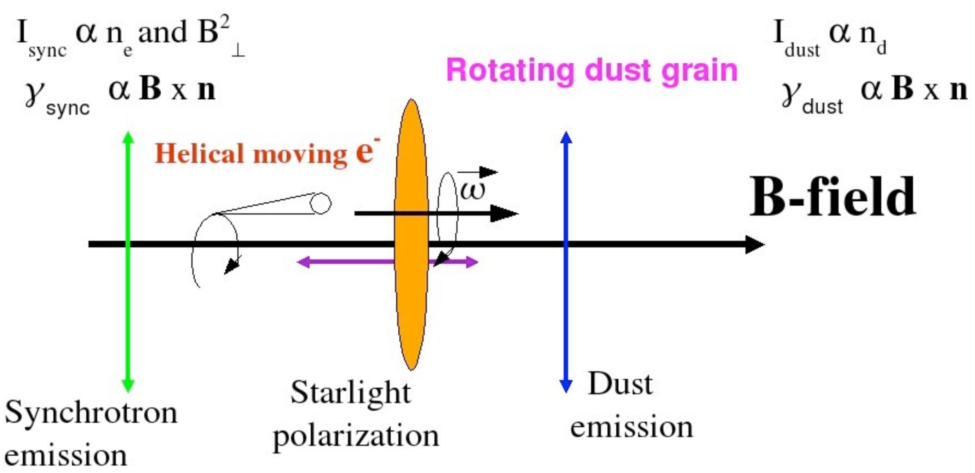

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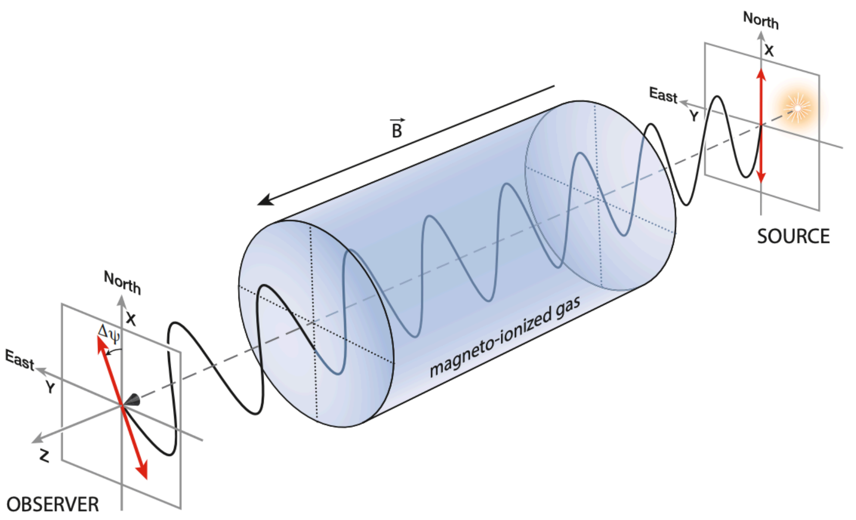

Problem II: Spectral distribution of CRs

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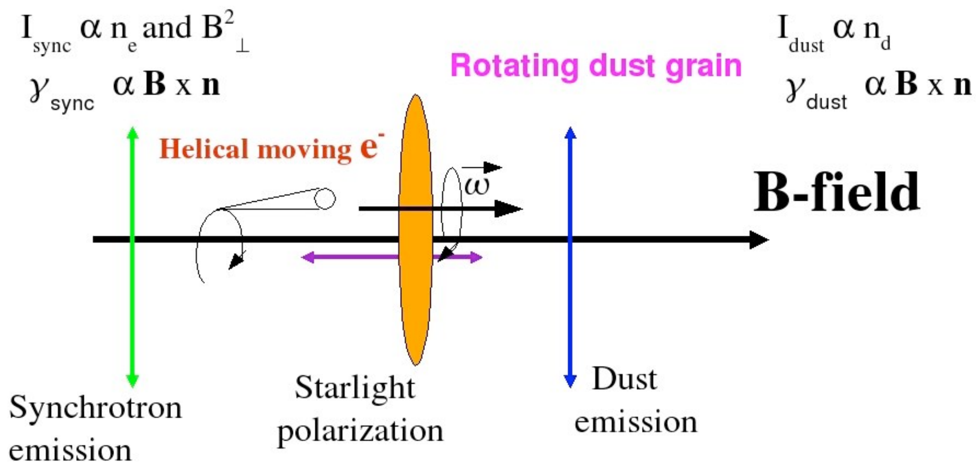
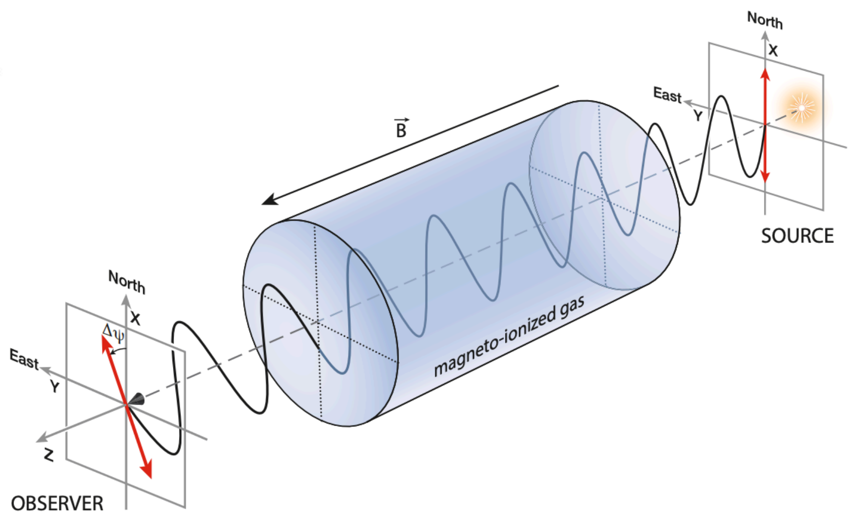


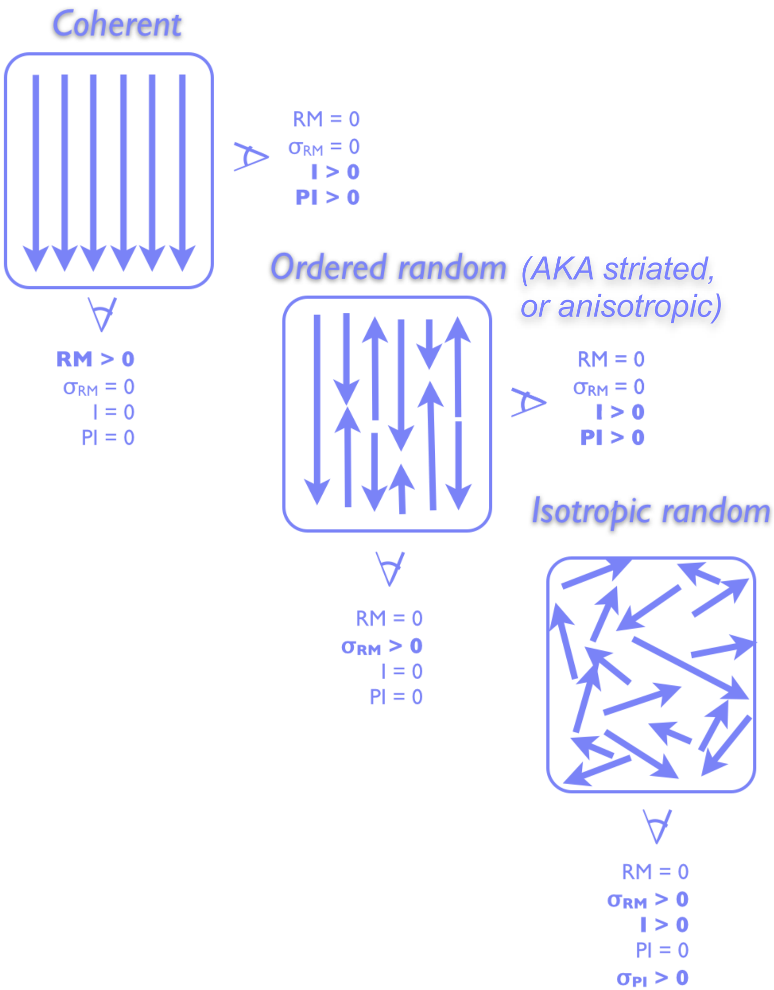
(Courtesy J.F. Macías-Pérez)



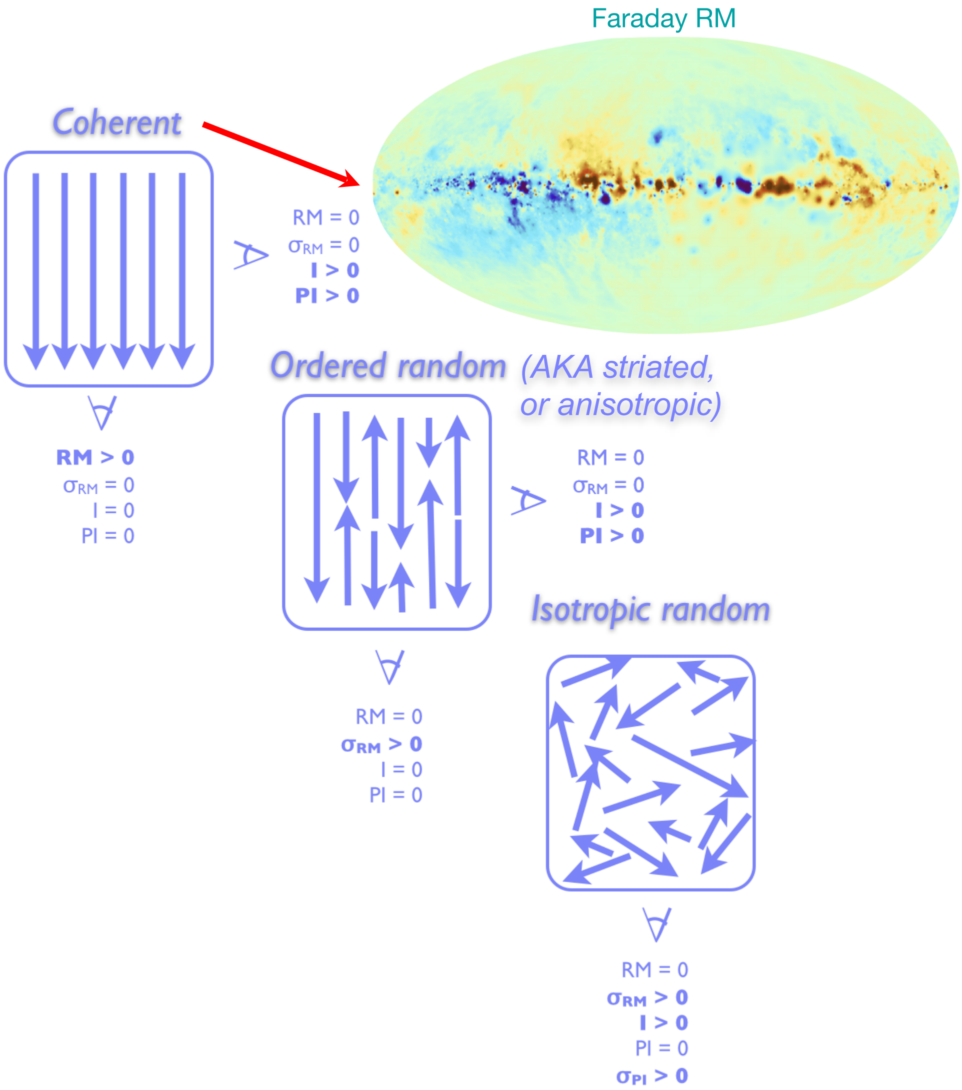
Milky Way

- So where are we in the Milky Way?
- We have all these potential morphological complexities in *B*.
- Challenges:
  - We are in the disk and looking through it.
  - Unique challenge of projection onto full-sky.
  - Dependencies on other uncertain astrophysical processes.
- Advantages:
  - More 3D info.
  - Better spatial resolution.

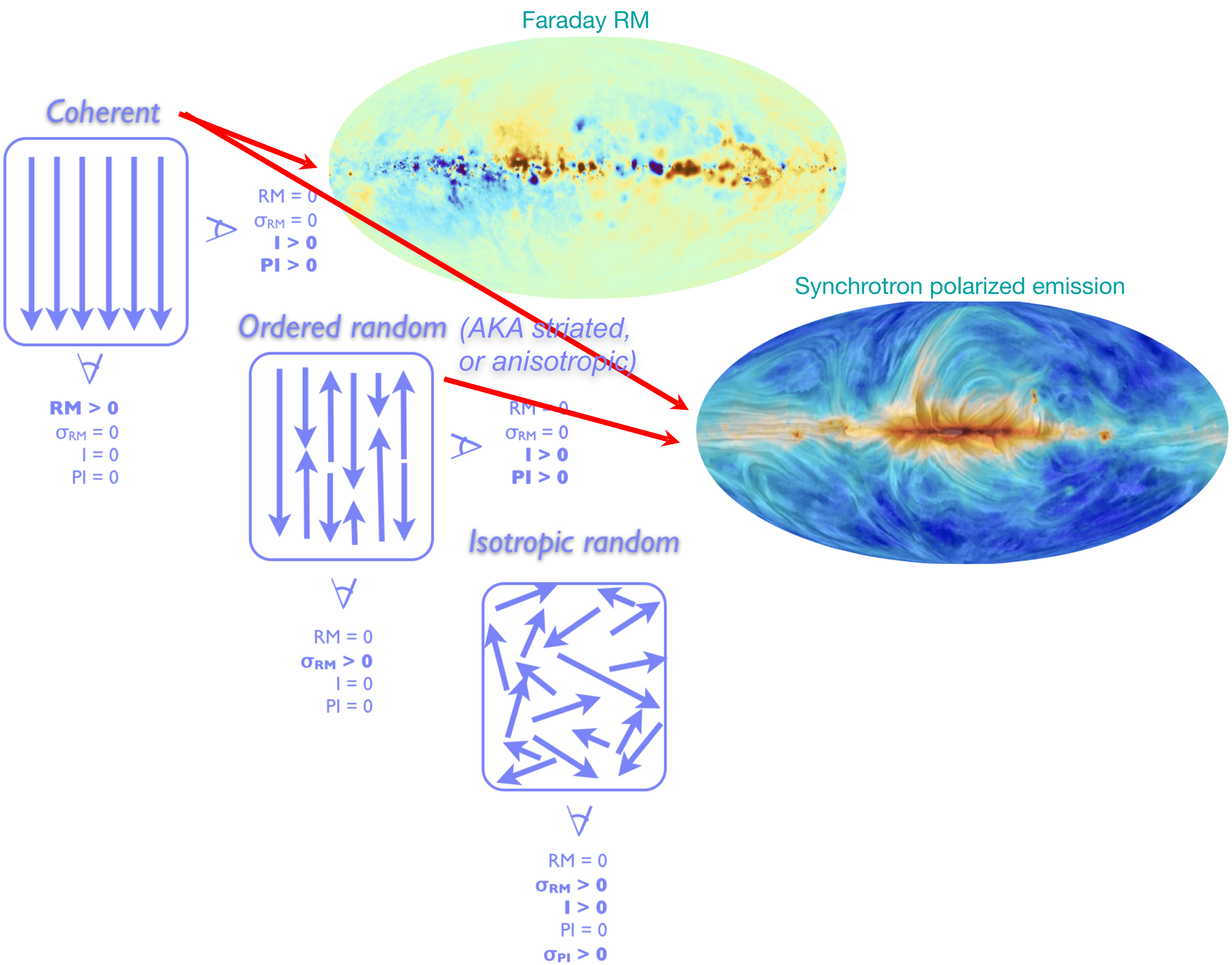
Components of the GMF



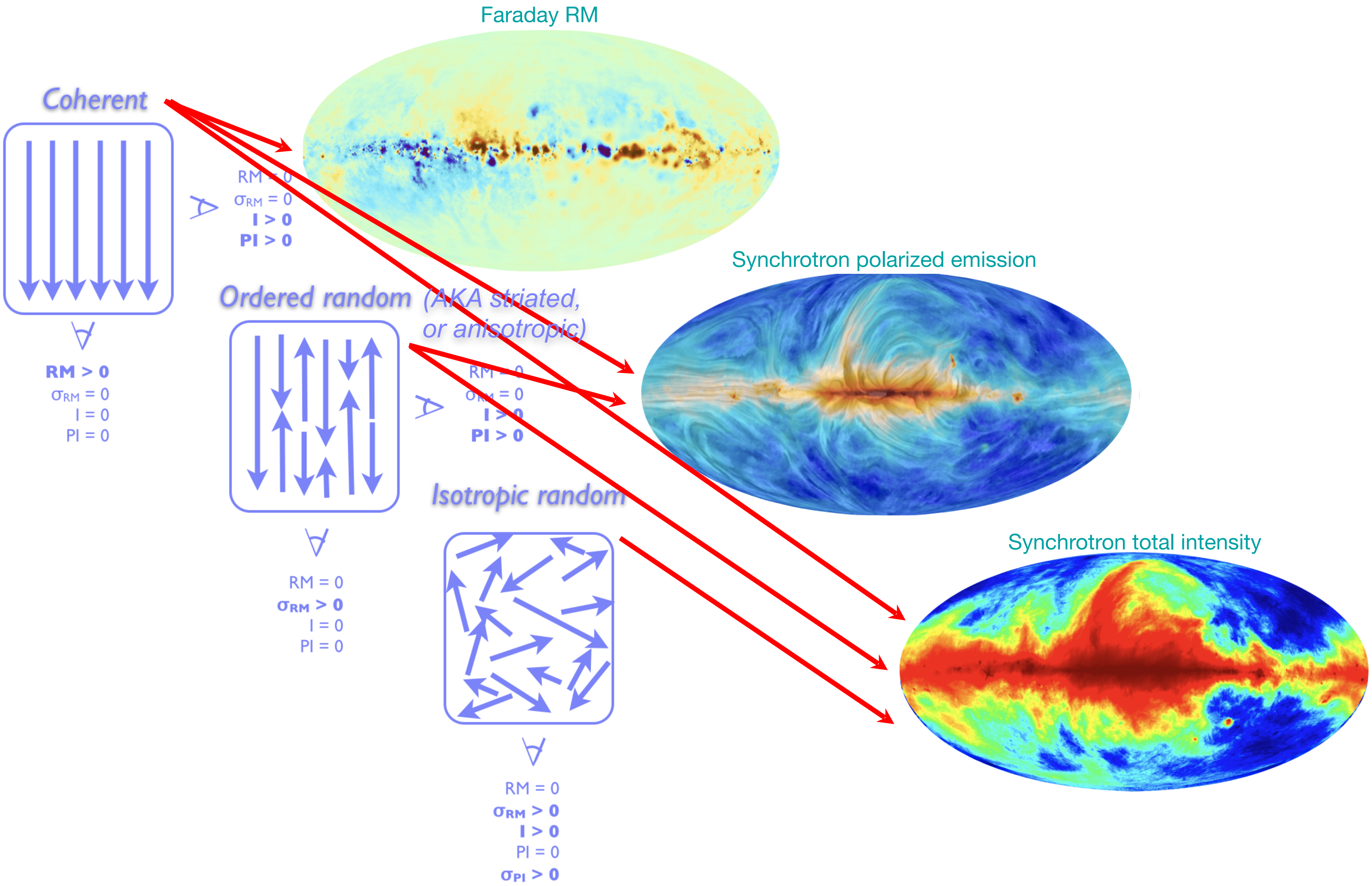
Components of the GMF



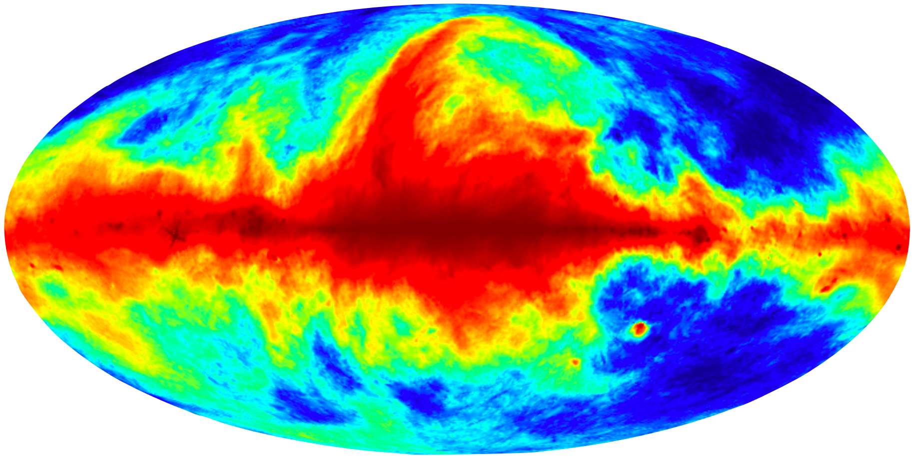
Components of the GMF

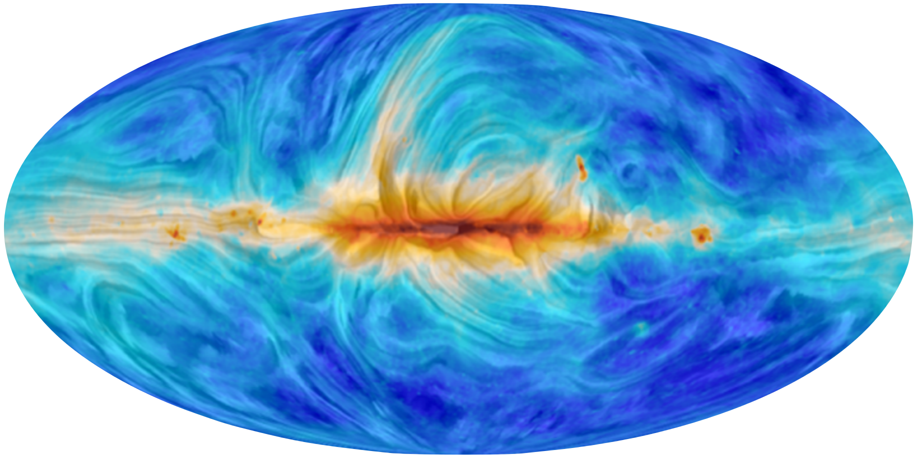


Components of the GMF



Problem II in synchrotron emission


408 MHz total intensity emission (Haslam et al. 1982 and Remazeilles et al. 2014)


30 GHz polarized synchrotron (ESA, Planck Collaboration)

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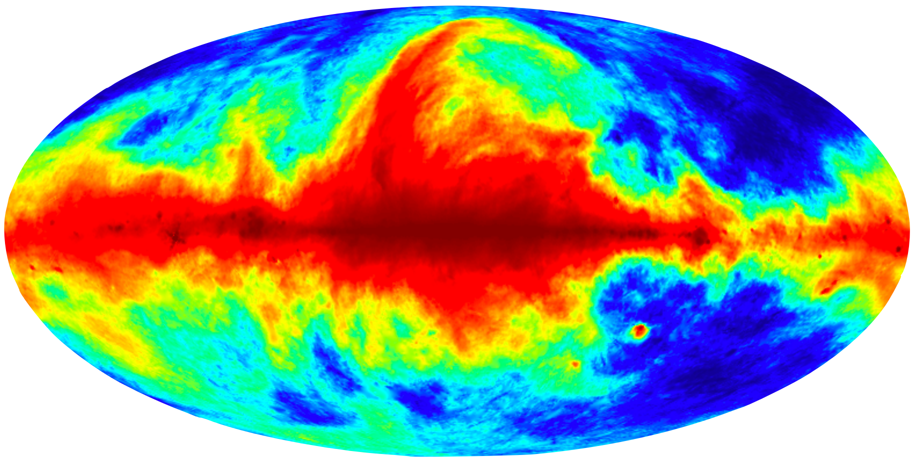

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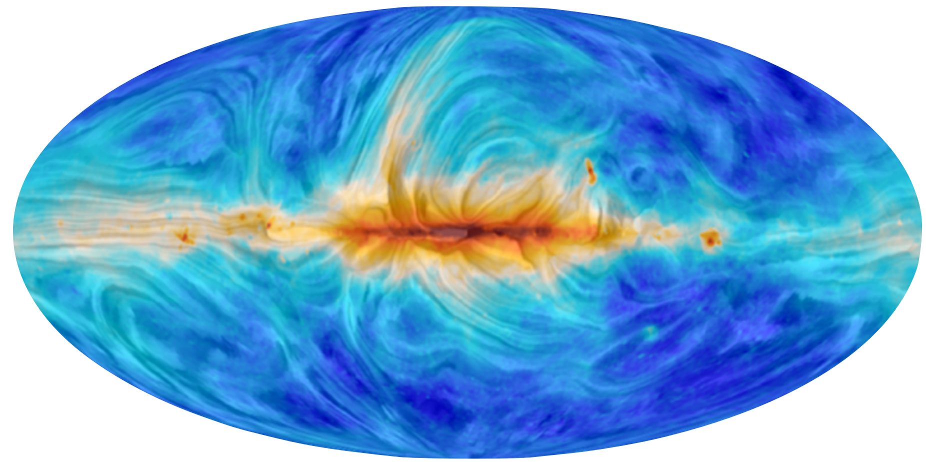

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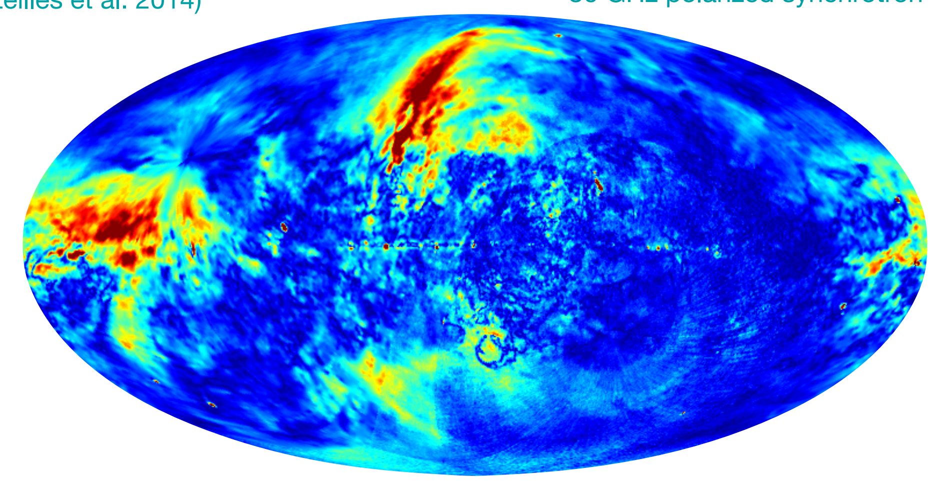
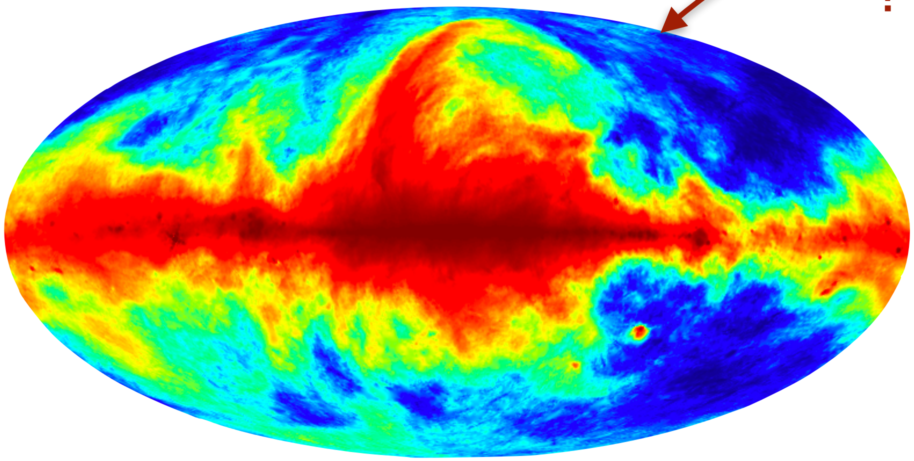


1.4 GHz polarized synchrotron (Reich 1982, Wolleben et al. 2006, Testori et al. 2008)

Problem II in synchrotron emission

$\frac{PI_{\nu_1}}{I_{\nu_2}}$ => $N_{CRE}(\gamma) \propto \gamma^p$ where $p \propto f(\gamma) \propto f'(\nu)$

?



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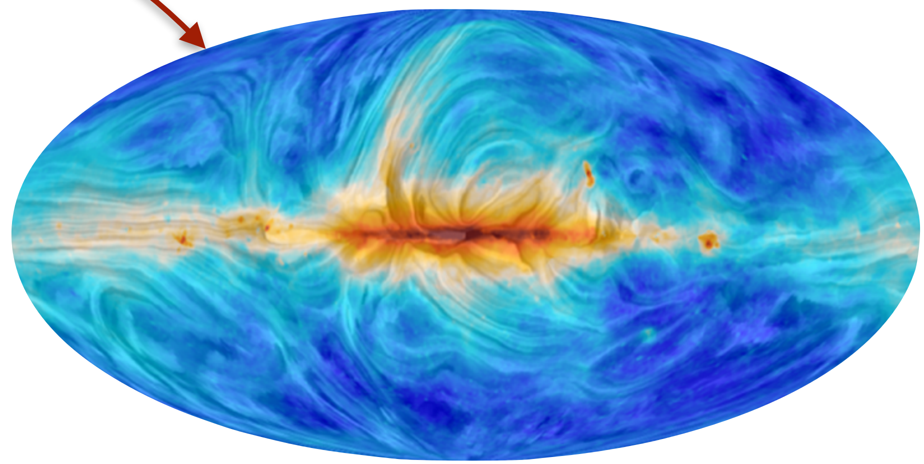

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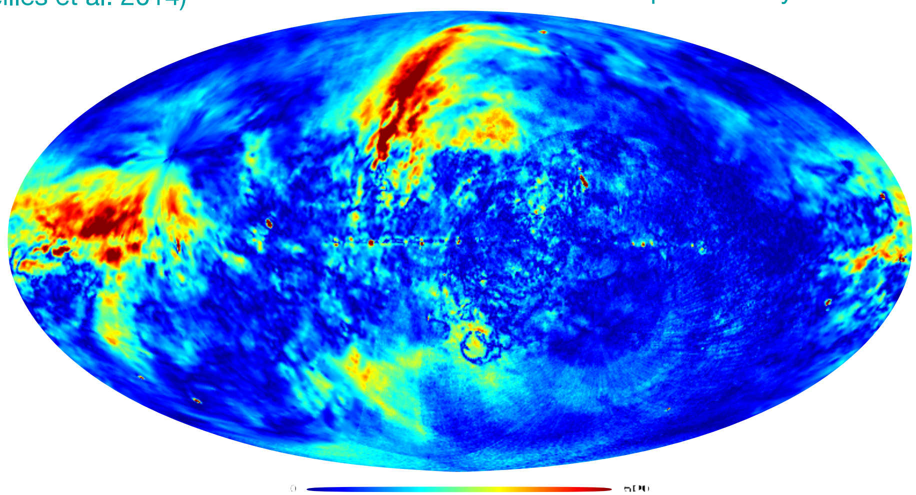


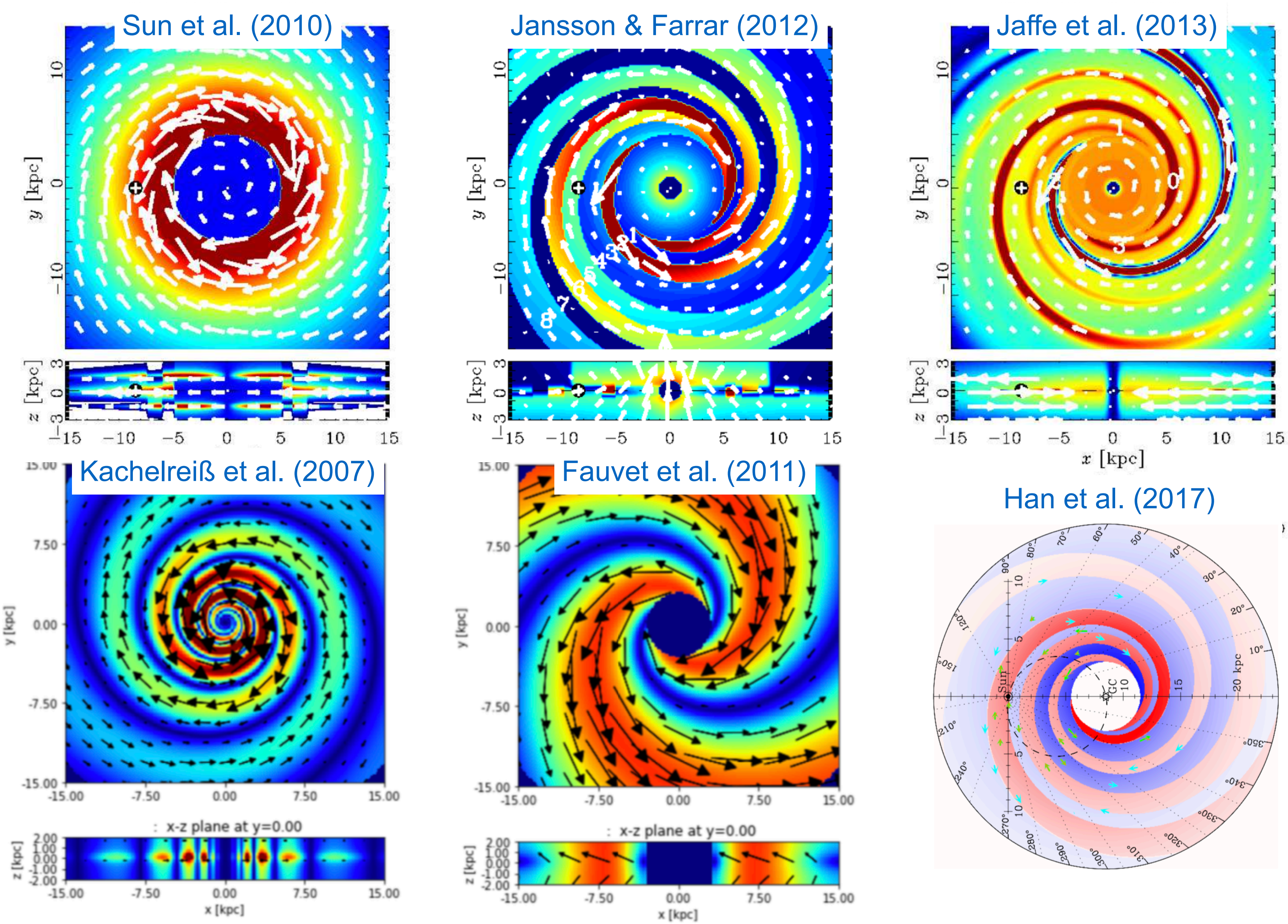
1.4 GHz polarized synchrotron (Reich 1982, Wolleben et al. 2006, Testori et al. 2008)

A few of the problems with the state of the art

- **Very different models all roughly match the same(ish) observables.**
  - *(degeneracies all over the place)*
- **None is very connected to physics.**
  - *(this can be done better now)*
- **A Bayesian model comparison has not been done.**
  - *(this is hard but do-able now)*
- **And don’t even ask about the treatment of the turbulence.**
  - *(this is annoying and needs thought)*

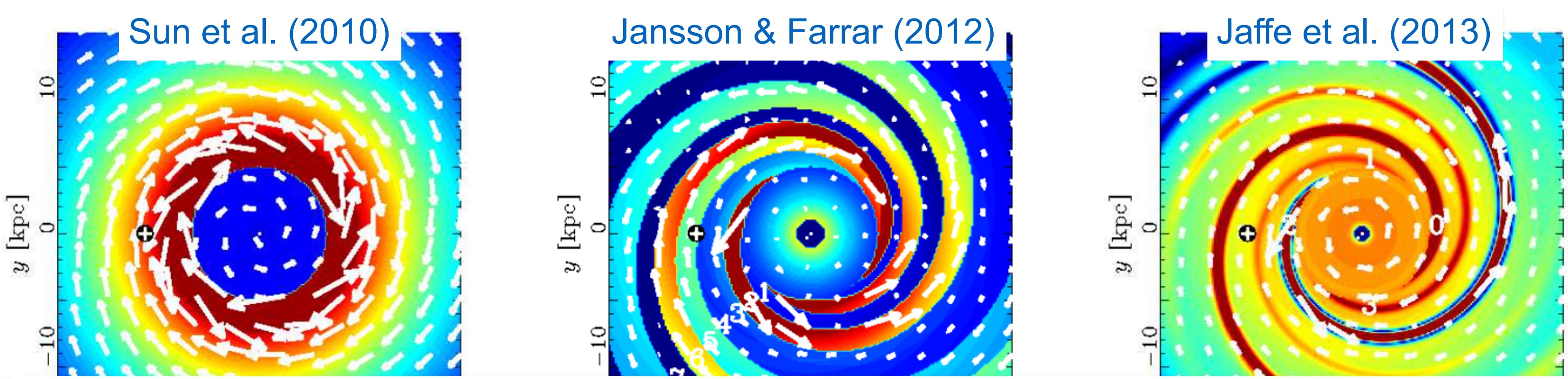
The state of the art

- Very different morphologies can roughly match the same(ish) observables.

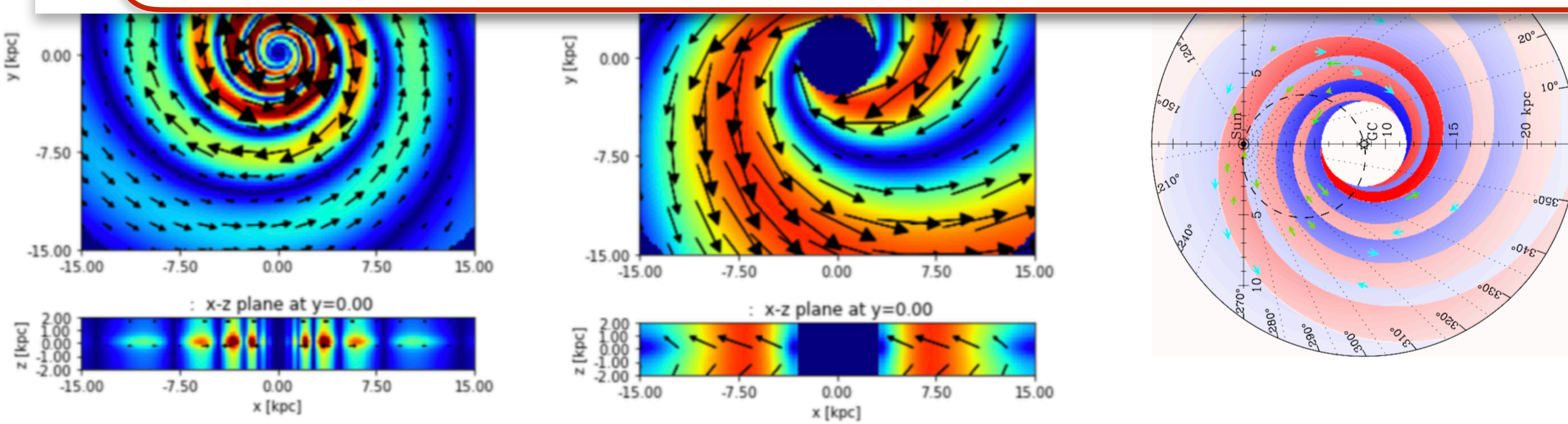


The state of the art

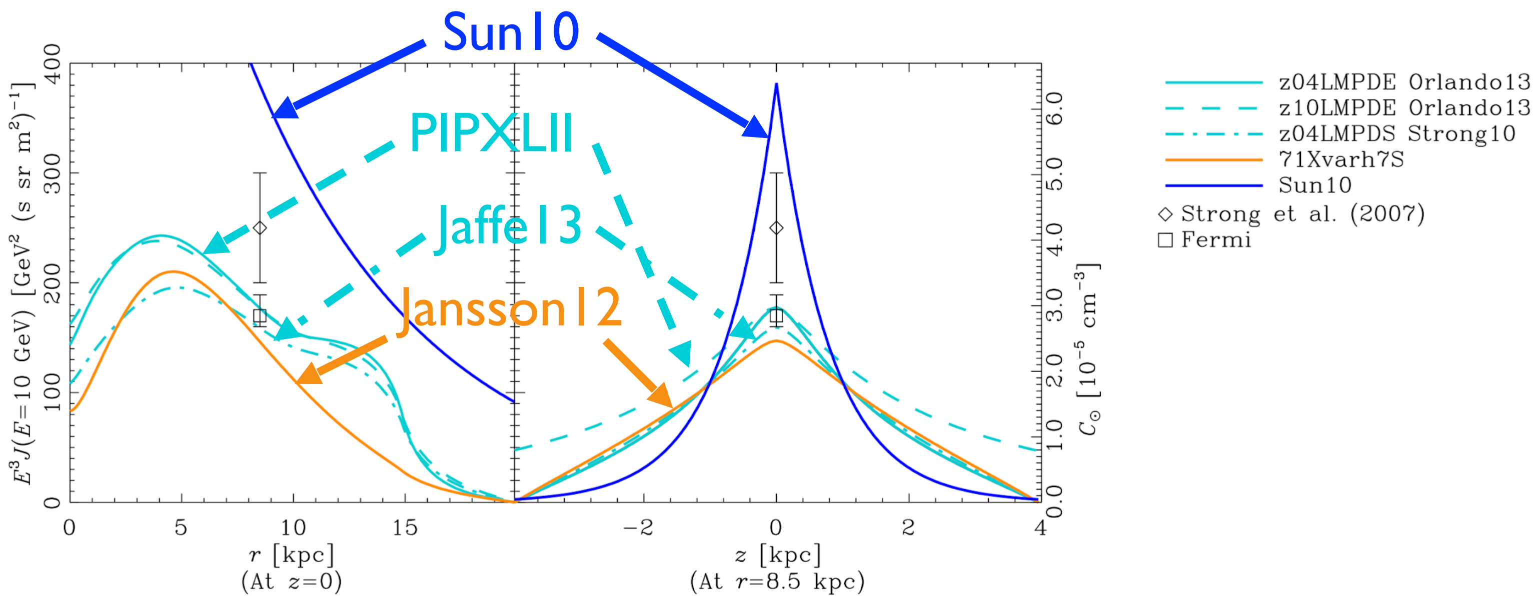
- Very different morphologies can roughly match the same(ish) observables.



- **Insufficient distance information:** current sampling of Galactic pulsars leaves significant uncertainty as to where the coherent field features lie along the LOS.
- **Uncertain CR spatial distribution**: likewise, few 3D tracers of CR density and therefore synchrotron emissivity is degenerate between CRs and **B**.
- **Uncertain CR spectral distribution**: introduces a degeneracy between field components due to combination of varying spectrum and Faraday effects.

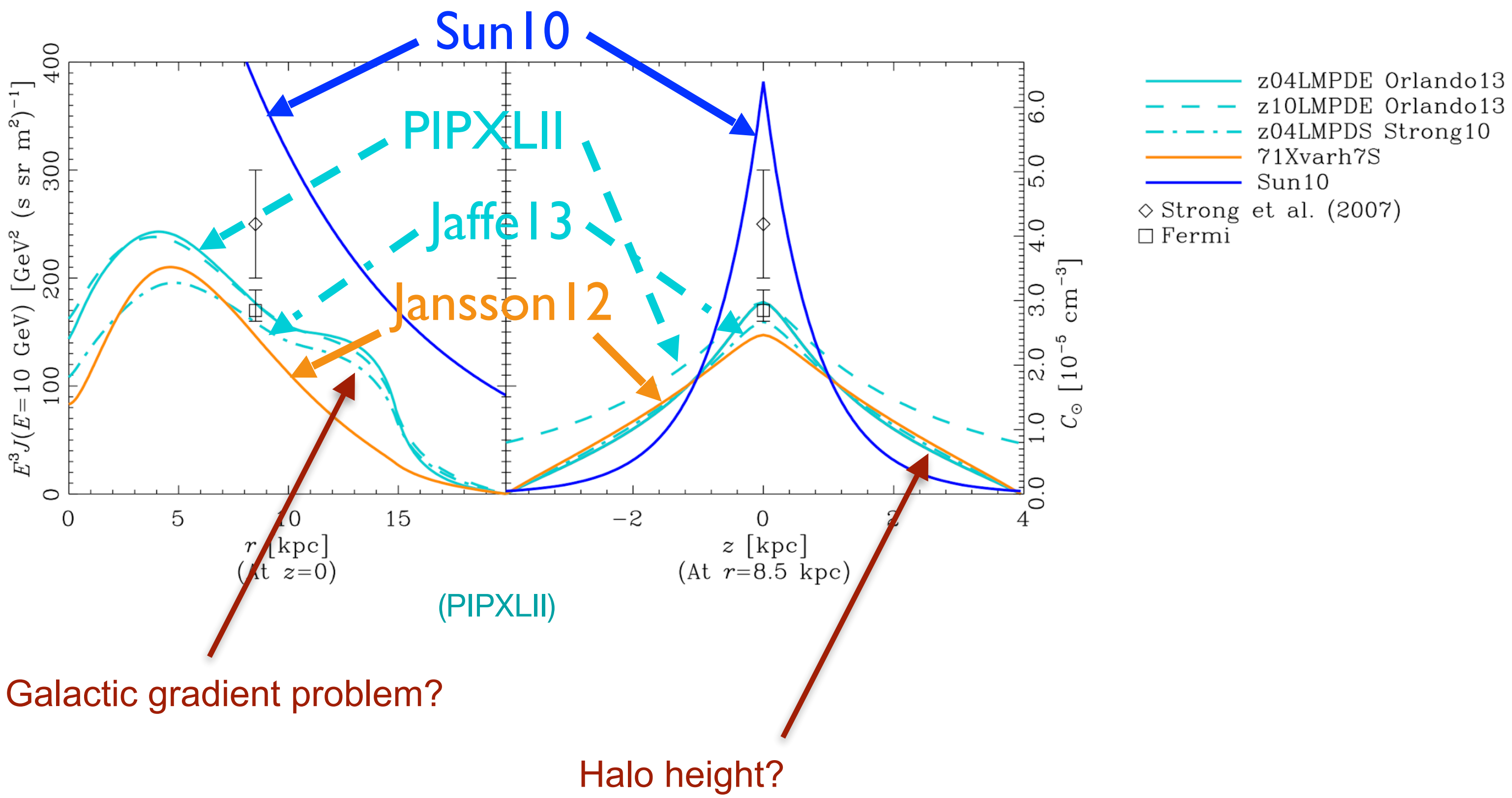


CR spatial distribution?



(PIPXLII)

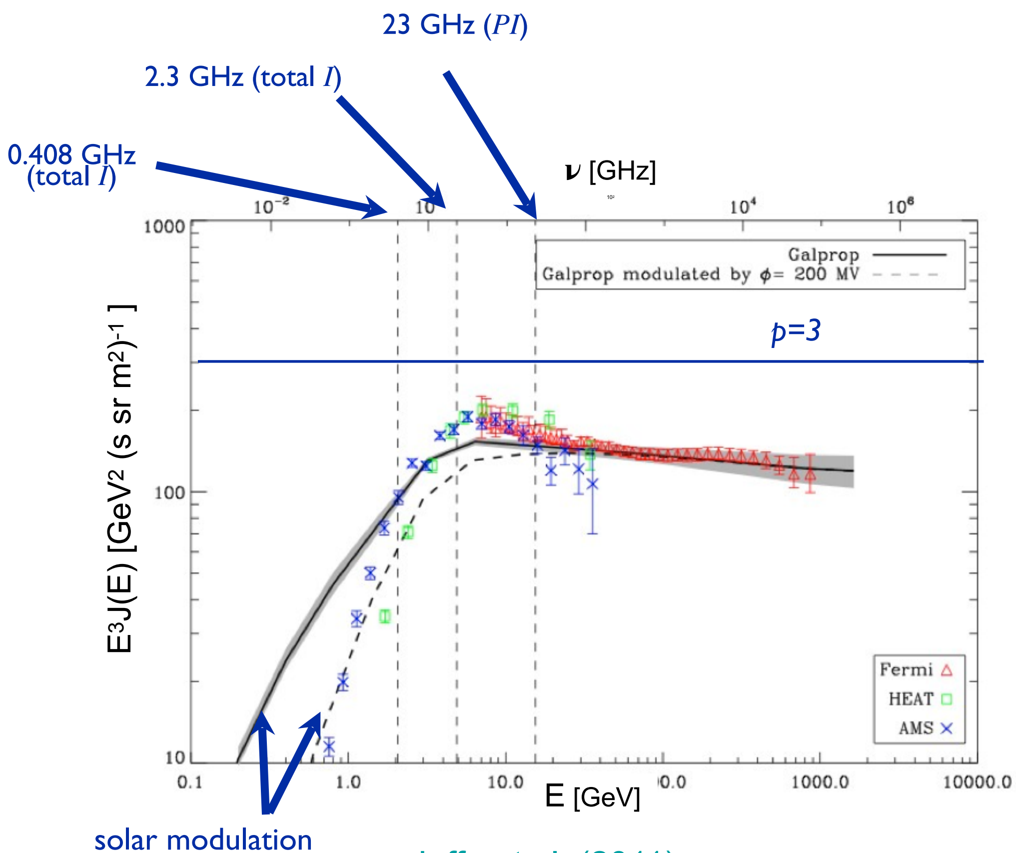
CR spatial distribution?



Galactic (low-energy) CR spectral distribution?

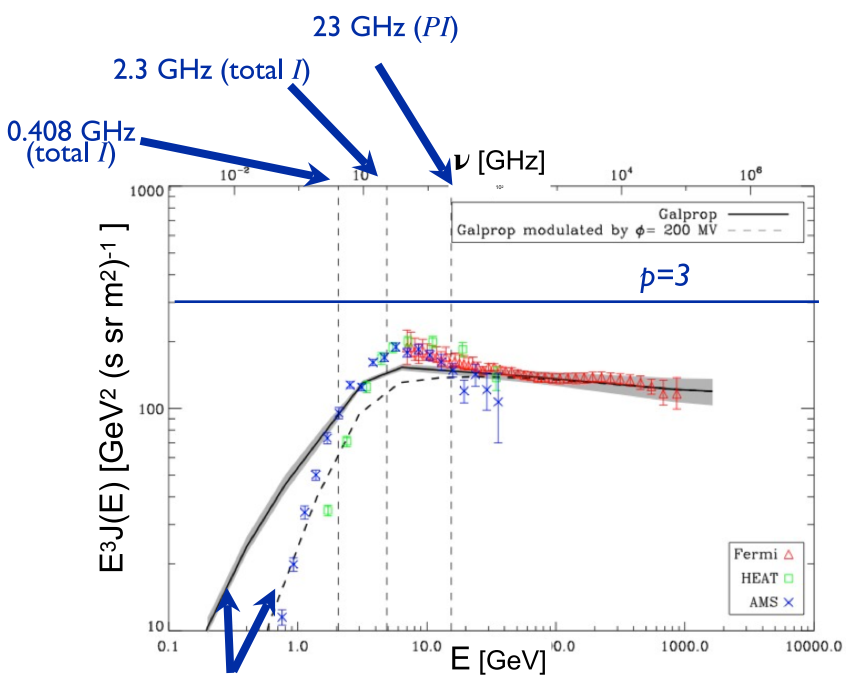
GMF <=> $N_{CRE}(\gamma) \propto \gamma^p$ where $p \propto f(\gamma) \propto f'(\nu)$

(each has the potential to constrain the other)



Jaffe et al. (2011)
(See also Strong, Orlando, & Jaffe 2011)

Galactic CR tracers: spectra



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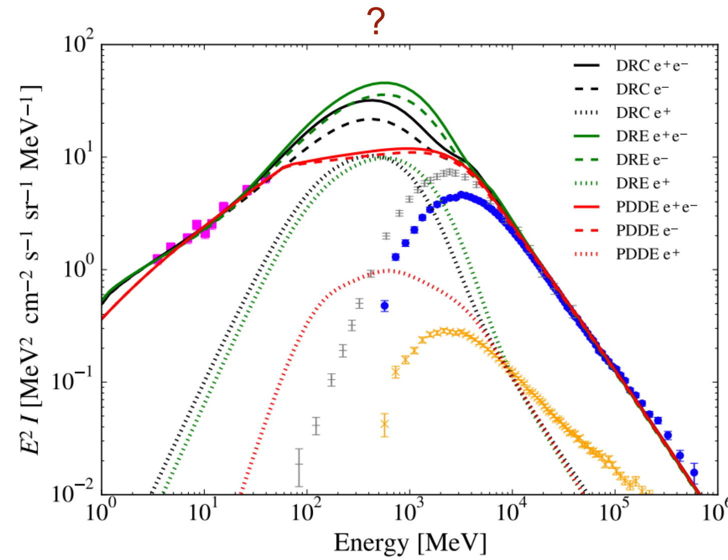
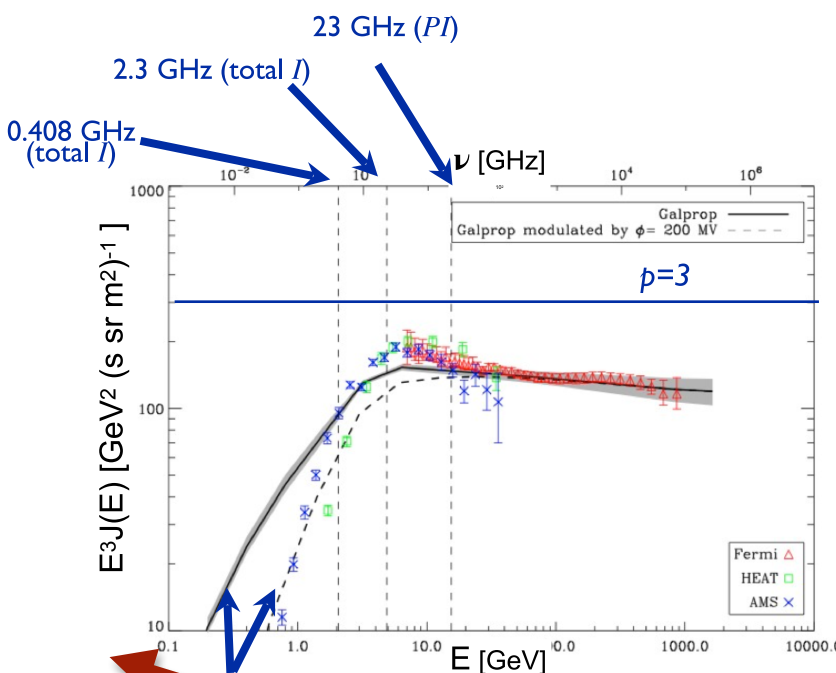


Figure 2. Propagated interstellar spectra of the three baseline models DRE (green line), DRC (black line), and PDDE (red line) for positrons (dotted lines), electrons only (dashed lines), and all-electrons (solid lines) compared with data: orange crosses: AMS-02 positrons (Aguilar et al. 2014); blue points: AMS-02 electrons (Aguilar et al. 2014); grey dashes: PAMELA electrons (Adriani et al. 2015); magenta squares: *Voyager 1* all-electrons (Cummings et al. 2016).

Orlando (2018)

Galactic CR tracers: spectra



Jaffe et al. (2011)

(See also Strong, Orlando, & Jaffe 2011)

?

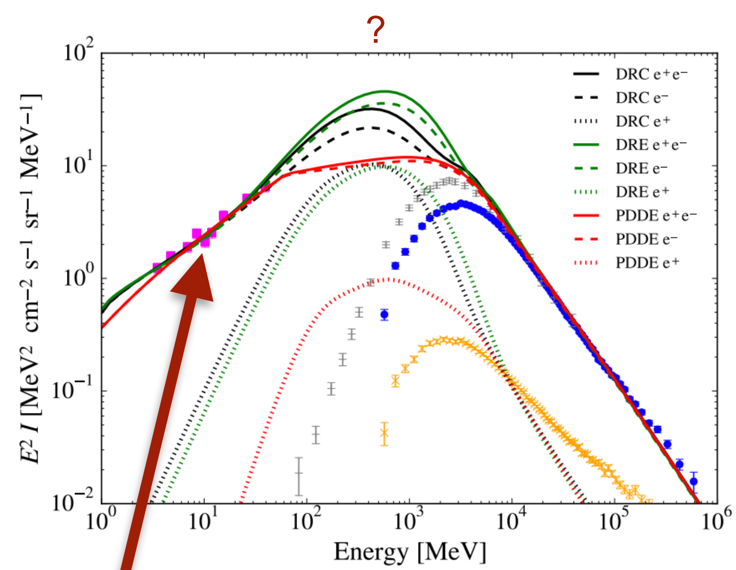


Figure 2. Propagated interstellar spectra of the three baseline models DRE (green line), DRC (black line), and PDDE (red line) for positrons (dotted lines), electrons only (dashed lines), and all-electrons (solid lines) compared with data: orange crosses: AMS-02 positrons (Aguilar et al. 2014); blue points: AMS-02 electrons (Aguilar et al. 2014); grey dashes: PAMELA electrons (Adriani et al. 2015); magenta squares: *Voyager 1* all-electrons (Cummings et al. 2016).

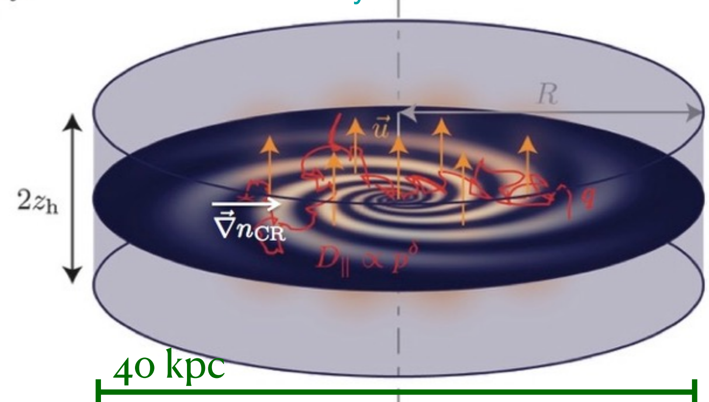
Orlando (2018)

Voyager!
(More later.)

CR transport

See many talks on CR propagation

Courtesy C. Evoli

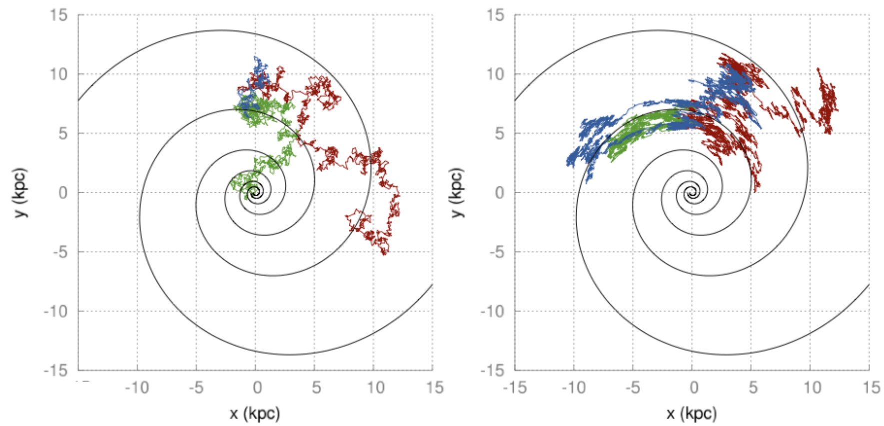


$$-\frac{\partial}{\partial z}\left(D_z \frac{\partial f_\alpha}{\partial z}\right) + u\frac{\partial f_\alpha}{\partial z} - \frac{du}{dz}\frac{p}{3}\frac{\partial f_\alpha}{\partial p} = q_{\mathrm{SN}} - \frac{1}{p^2}\frac{\partial}{\partial p}\left[p^2 \dot{p} f_\alpha\right] - \frac{f_\alpha}{\tau_\alpha^{\mathrm{in}}} + \sum_{\alpha'>\alpha} b_{\alpha'\alpha}\frac{f_{\alpha'}}{\tau_{\alpha'}^{\mathrm{in}}}$$

diffusion D — advection u — SN sources — energy losses — nuclear reactions

(negligible for our purposes?)

Effenberger et al.: Anisotropic diffusion of galactic cosmic ray protons



Effenberger et al. (2012)

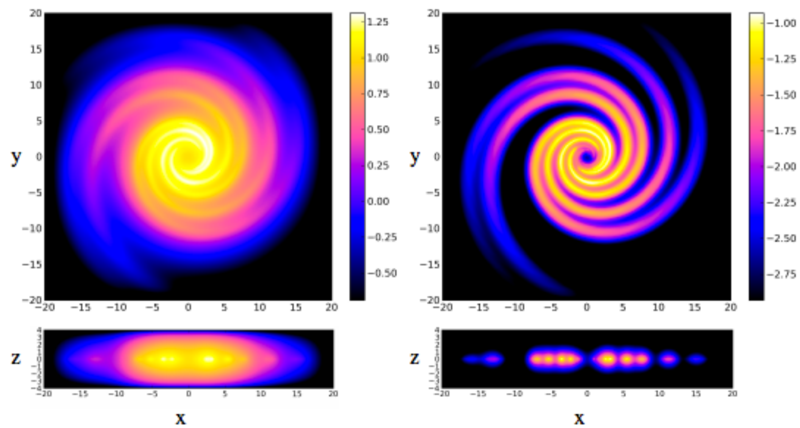


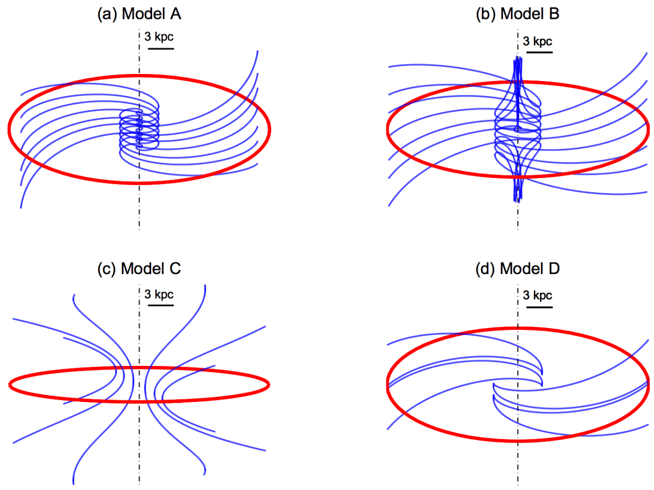
Figure 4

Werner et al. (2015)

A few of the problems with the state of the art

- **None is very connected to physics.**

  ➢ Ferrière and Terral (2014) and Shukurov et al. (2018) have made a good start:



Analytically derived x-shaped field models
Ferrière & Terral (2014)
(See also Terral & Ferrière 2017)

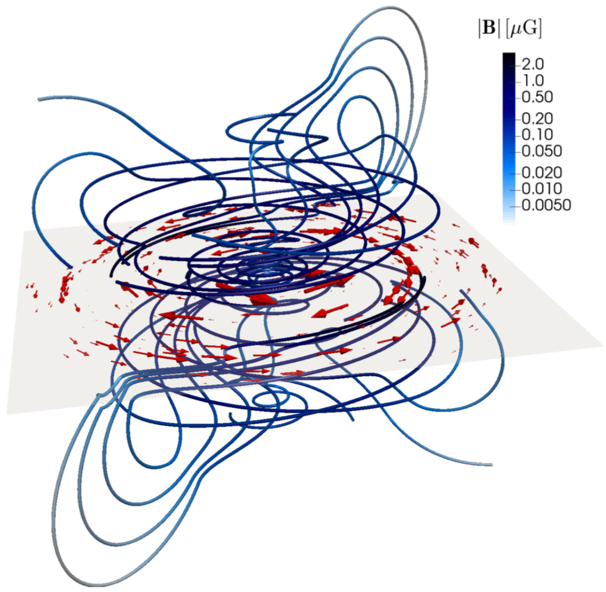


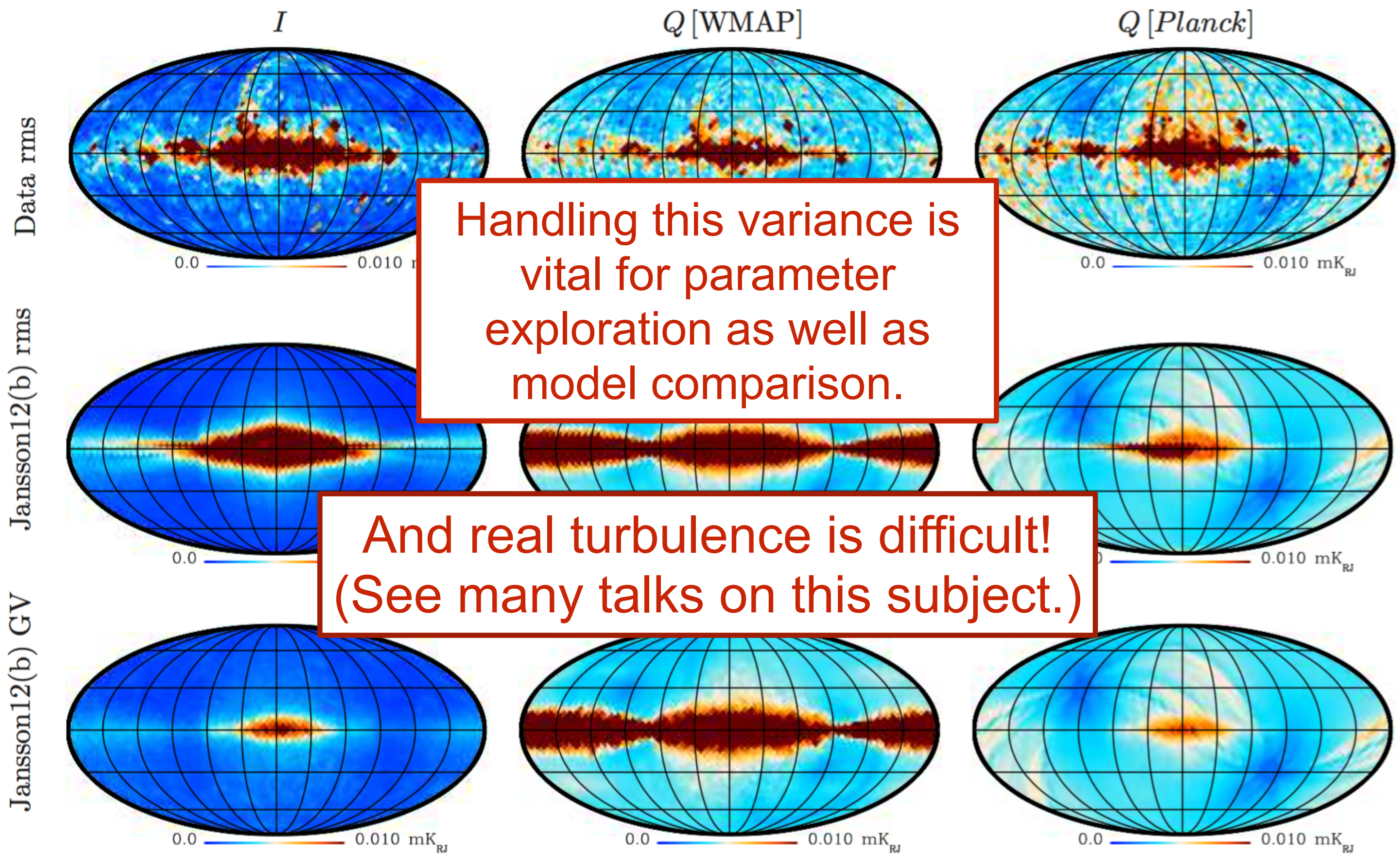
Figure 11. Three-dimensional rendering of a symmetric (quadrupolar) halo field solution combined with a quadrupolar disc field with two reversals at $s = 7\,\mathrm{kpc}$ and $12\,\mathrm{kpc}$. The domain is a $(17\,\mathrm{kpc})^3$ box. The field lines were seeded uniformly along a diagonal through the box. The arrows show the magnetic field at points randomly sampled within the slice of thickness $2.5\,\mathrm{kpc}$ around the galactic mid-plane (which is indicated by the semi-transparent surface) and are scaled according to the magnitude of the magnetic field.

Shukurov et al. (2018)

A few of the problems with the state of the art

- **And don't even ask about the treatment of the turbulence.**

Estimates of how much a random realization drawn from the same distribution (i.e., our best-fit model) would differ from what we observe in the Milky Way:



Handling this variance is vital for parameter exploration as well as model comparison.

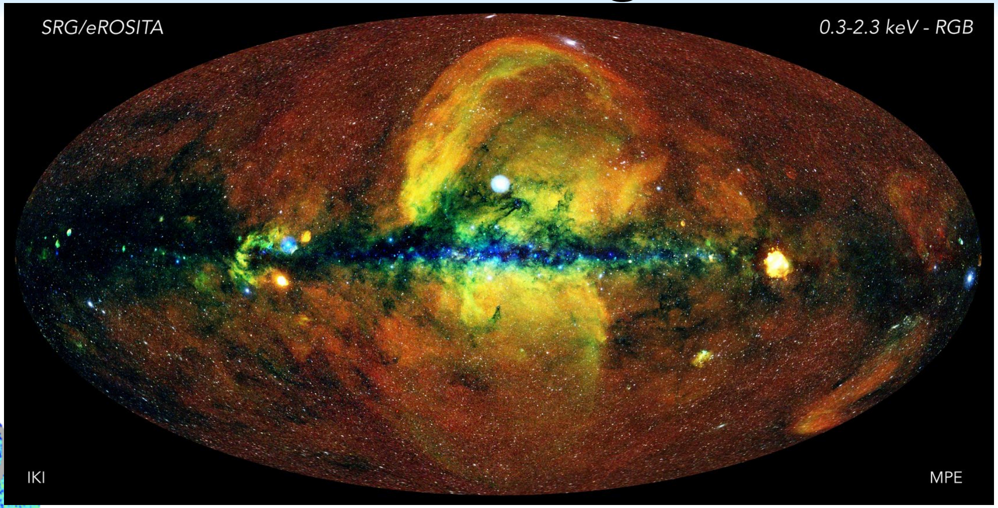
And real turbulence is difficult! (See many talks on this subject.)

(PIPXLII)

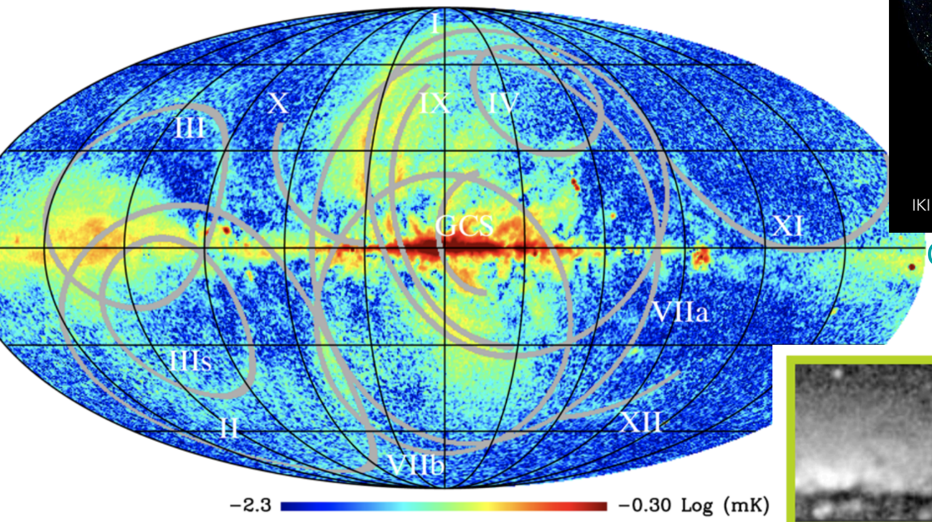
How do local features affect fitting?

Loops and spurs: most are local. All?

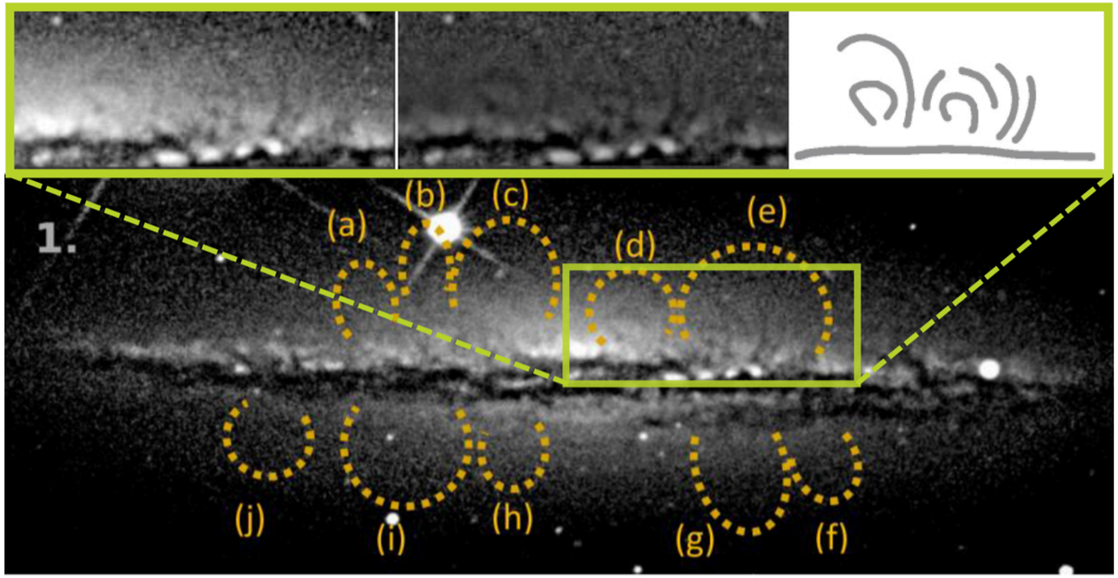
And how do they impact global GMF fits?



Credit: Jeremy Sanders, Hermann Brunner and the eSASS team (MPE); Eugene Churazov, Marat Gilfanov (on behalf of IKI)



WMAP data in Vidal et al. (2015)



NGC 4217, CHANG-ES XXI., Stein et al. (2020)

A few of the problems with the state of the art

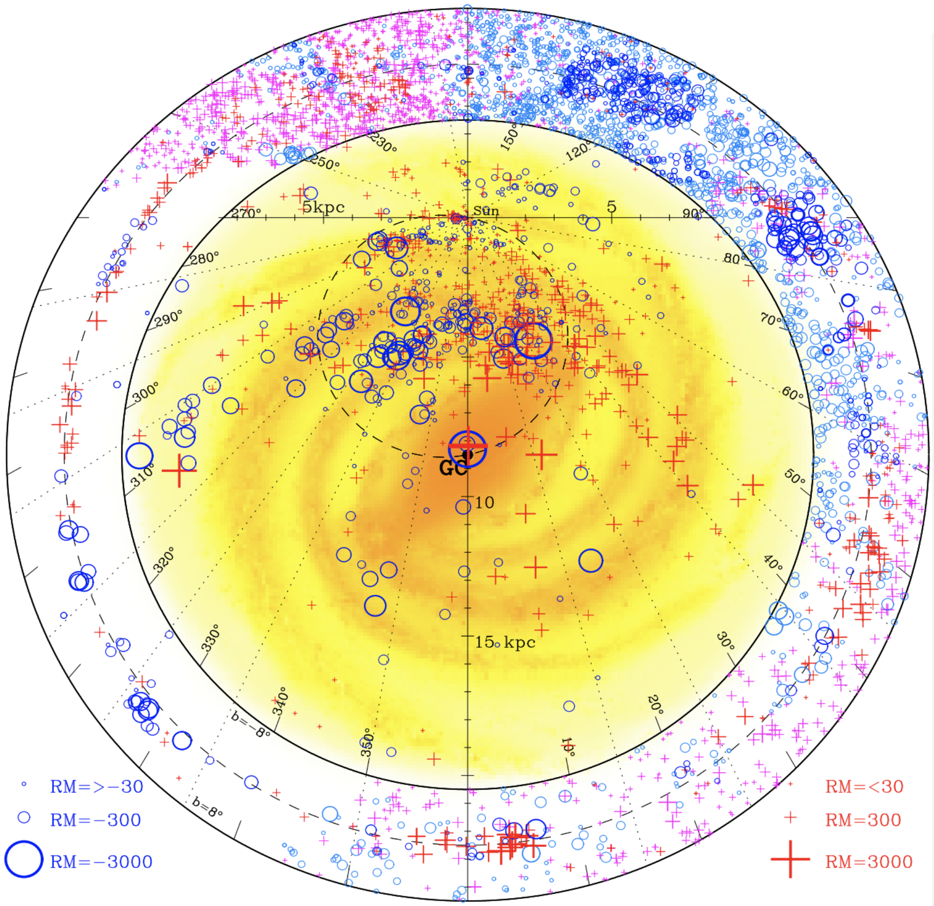
- Very different models all roughly match the same(ish) observables.
- None is very connected to physics.
- A Bayesian model comparison has not been done.
- And don't even ask about the treatment of the turbulence.

Planck Planck Intermediate Results XLII (2016, PIPXLII) showed why all previous fits (including mine) are wrong.

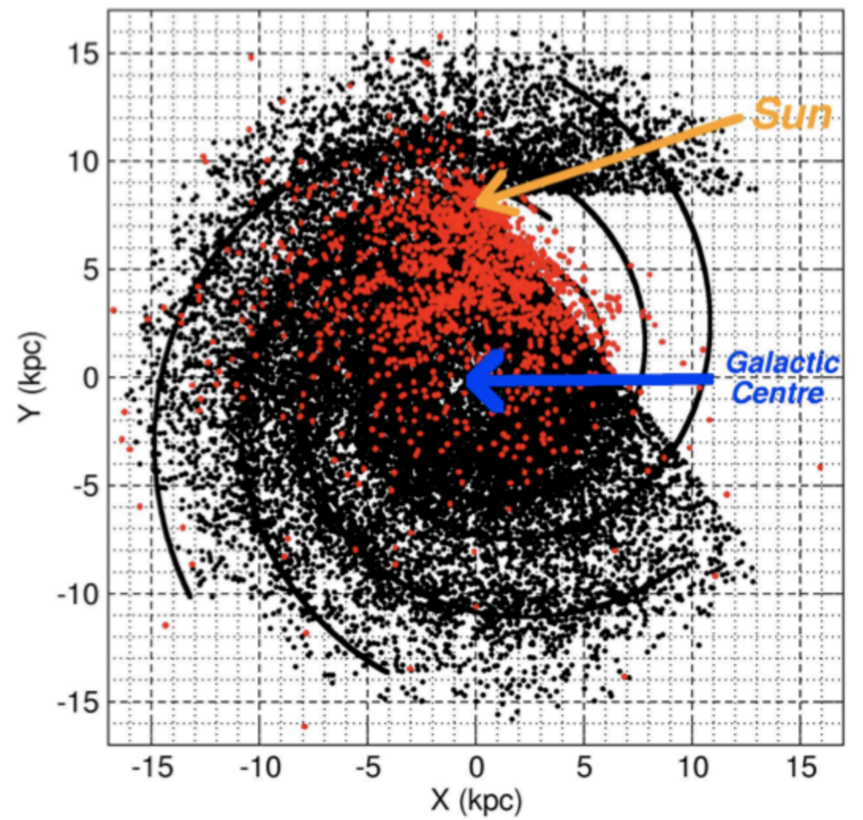
Enough with the problems.
How about some new tools!

- New ways of using traditional observables.
- New observables/tracers.
- New theoretical work.
- New numerical work.
- New collaborations.

3D Faraday rotation measures (RMs)

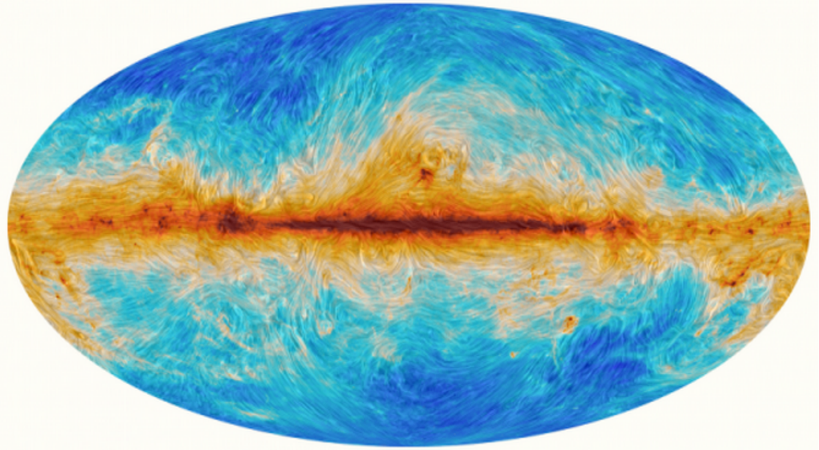


Galactic pulsars and extragalactic radio sources and their RMs. (Han et al. 2017)

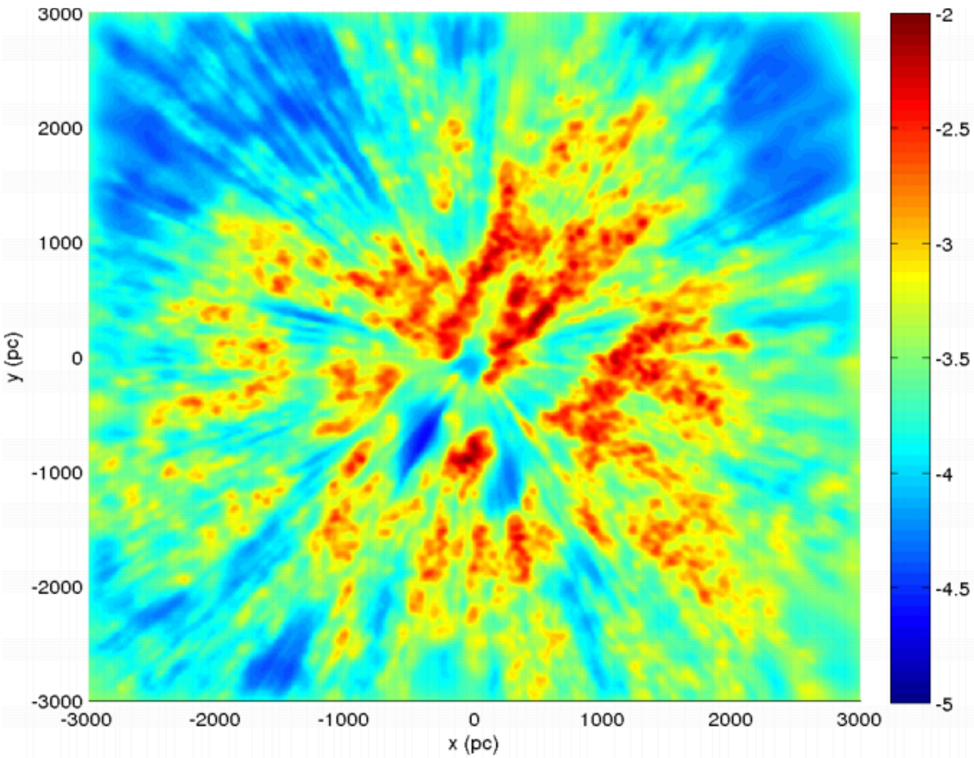


Simulated Galactic pulsar population discovered in a SKA survey of the entire sky. The ~20,000 pulsars are shown together with the spiral arms structure. The Galactic Centre is located at the origin while the Sun is at (0.0,8.5) kpc.

Gaia 3D dust mapping + *Planck* polarization + GPIPS

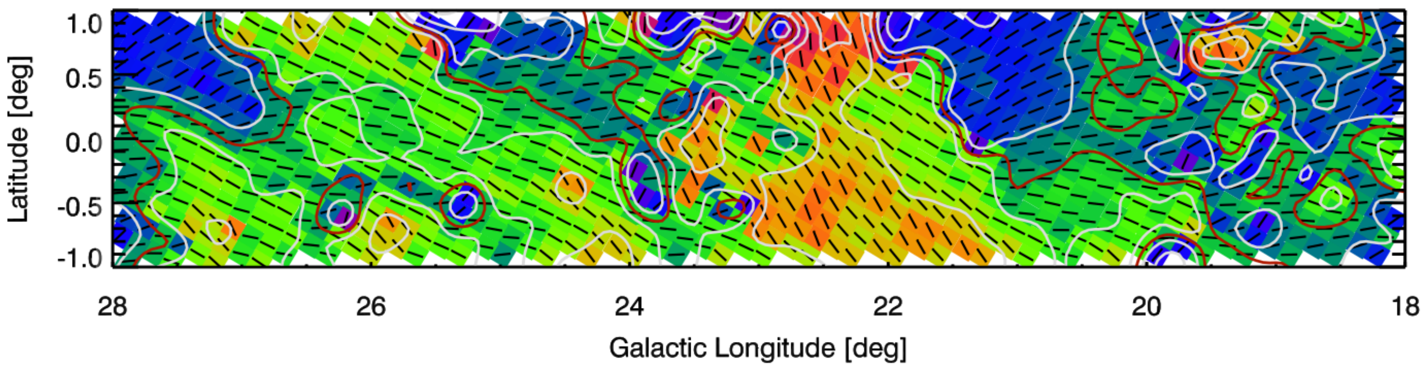


353 GHz polarized dust (ESA, Planck Collaboration)

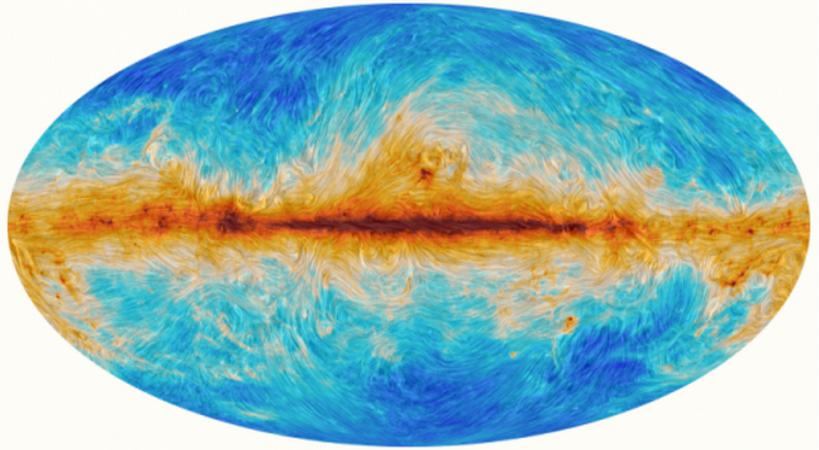


3D dust distribution from stellar extinctions with Gaia and 2MASS (Lallement et al. 2019)

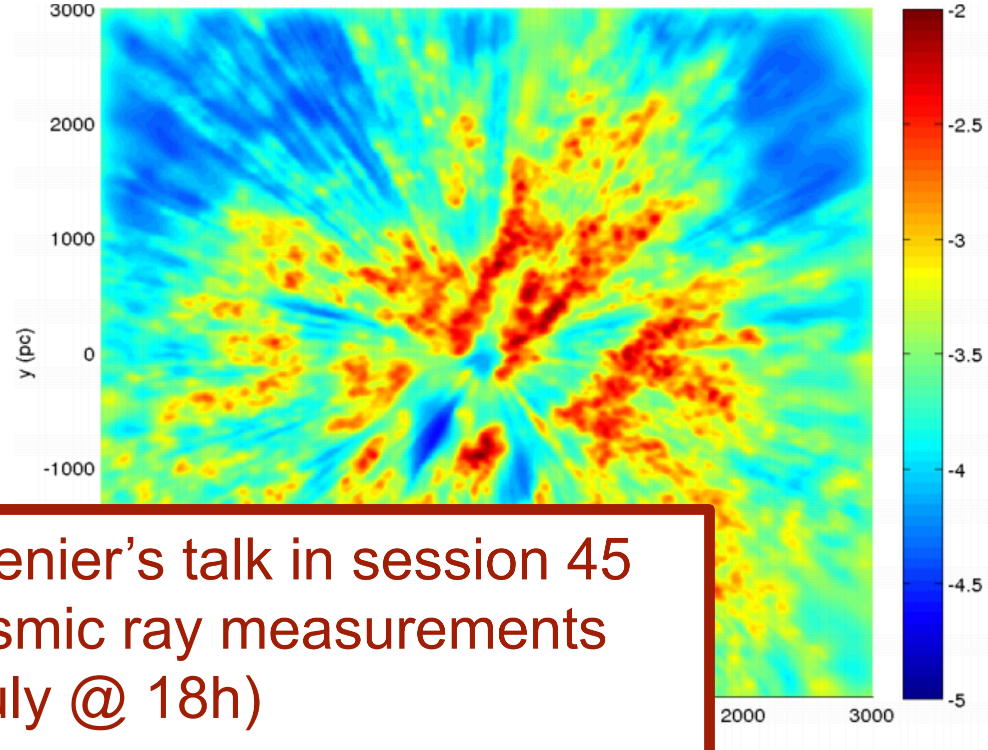
Starlight polarization from GPIPS (Clemens et al. 2020)



Gaia 3D dust mapping + *Planck* polarization + GPIPS



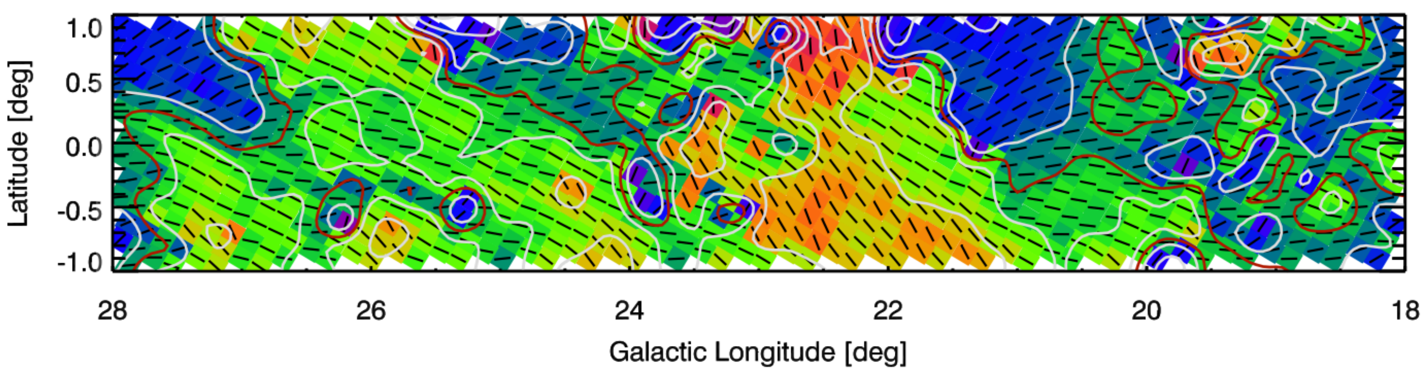
353 GHz polarized dust (ESA, Planck Collaboration)



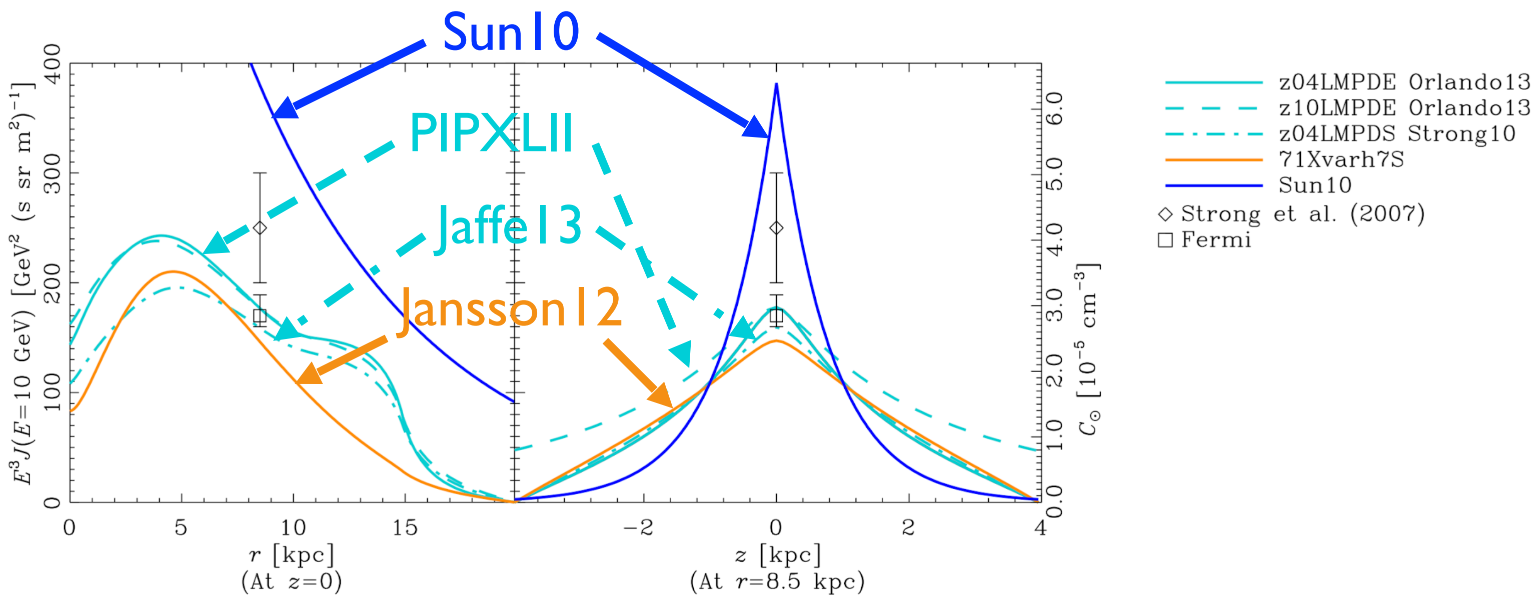
s with Gaia and 2MASS (Lallemont et al. 2019)

And see Isabelle Grenier's talk in session 45 about the 'local' cosmic ray measurements (19 July @ 18h)

Starlight polarization from GPIPS (Clemens et al. 2020)



CR vs B spatial distribution?



(PIPXLII)

CR vs B spatial distribution?

Faraday rotation constraints on large scale Halo model Thomas Fitoussi

Thomas Fitoussi's contribution 194, discussion session 01

or

Ralf-Jürgen Dettmar's contribution 1004, on B in halos

(or Stefano Gabici's contribution 1029, on Giant CR halos)

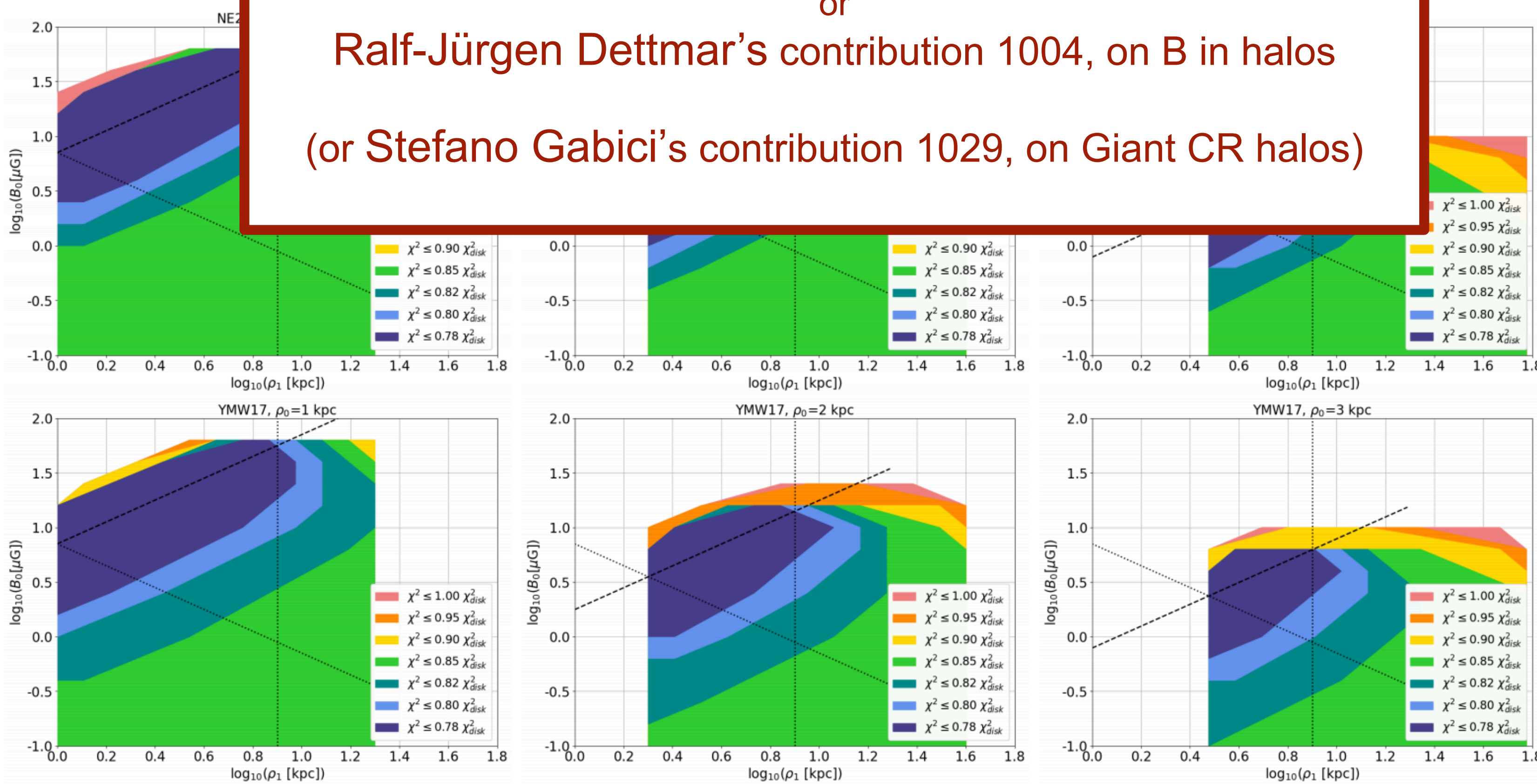
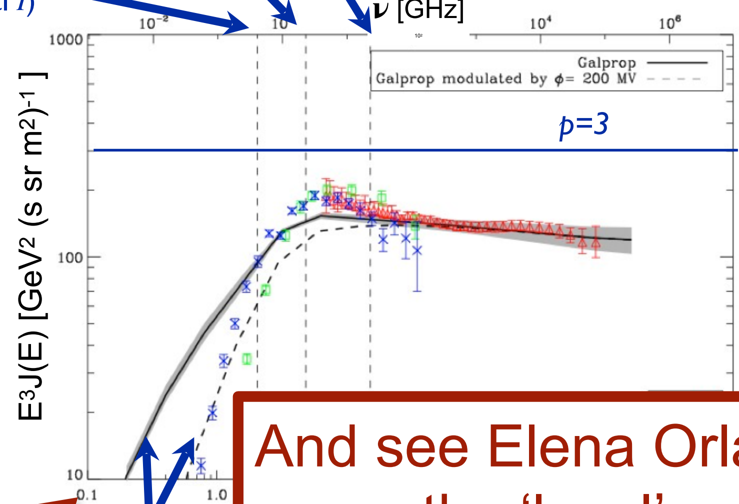


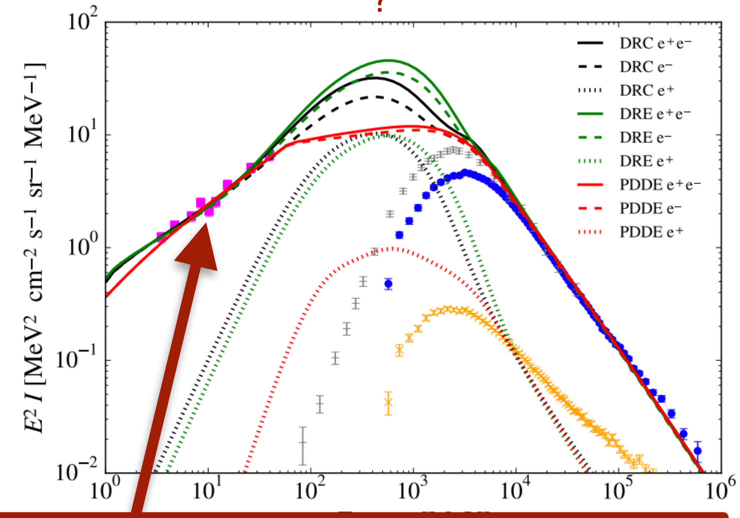
Figure 3: Parameters space of the halo field versus the reduced χ^2. Colored areas give the fluctuation of the χ^2 compare to the best fit with only the disk field.

Galactic CR tracers: spectra



(See also S

?



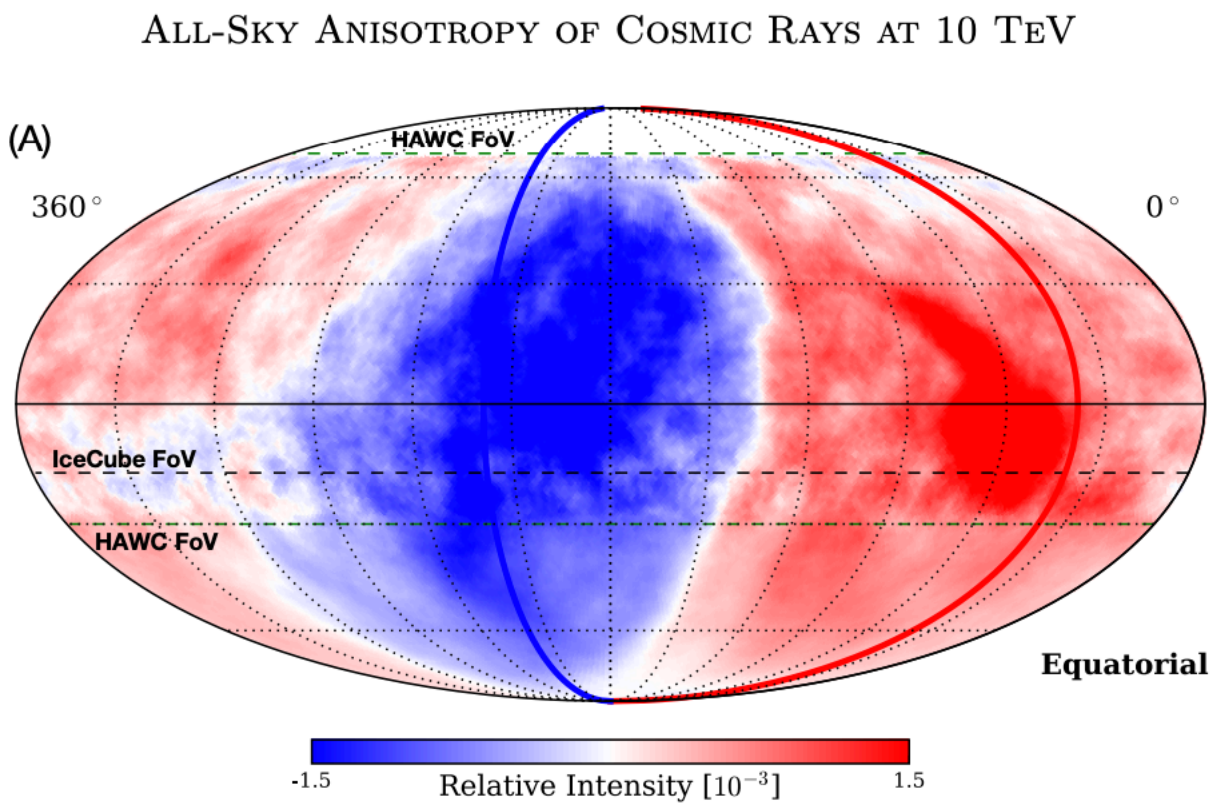
And see Elena Orlando's talk in session 45 about the 'local' cosmic ray measurements (19 July @ 18h)

aseline d line) nd all- AMS- ctrons driani et al. 2015); magenta squares: *Voyager 1* all-electrons (Cummings et al. 2016).

Voyager!

Orlando (2018)

Galactic CR tracers: arrival directions

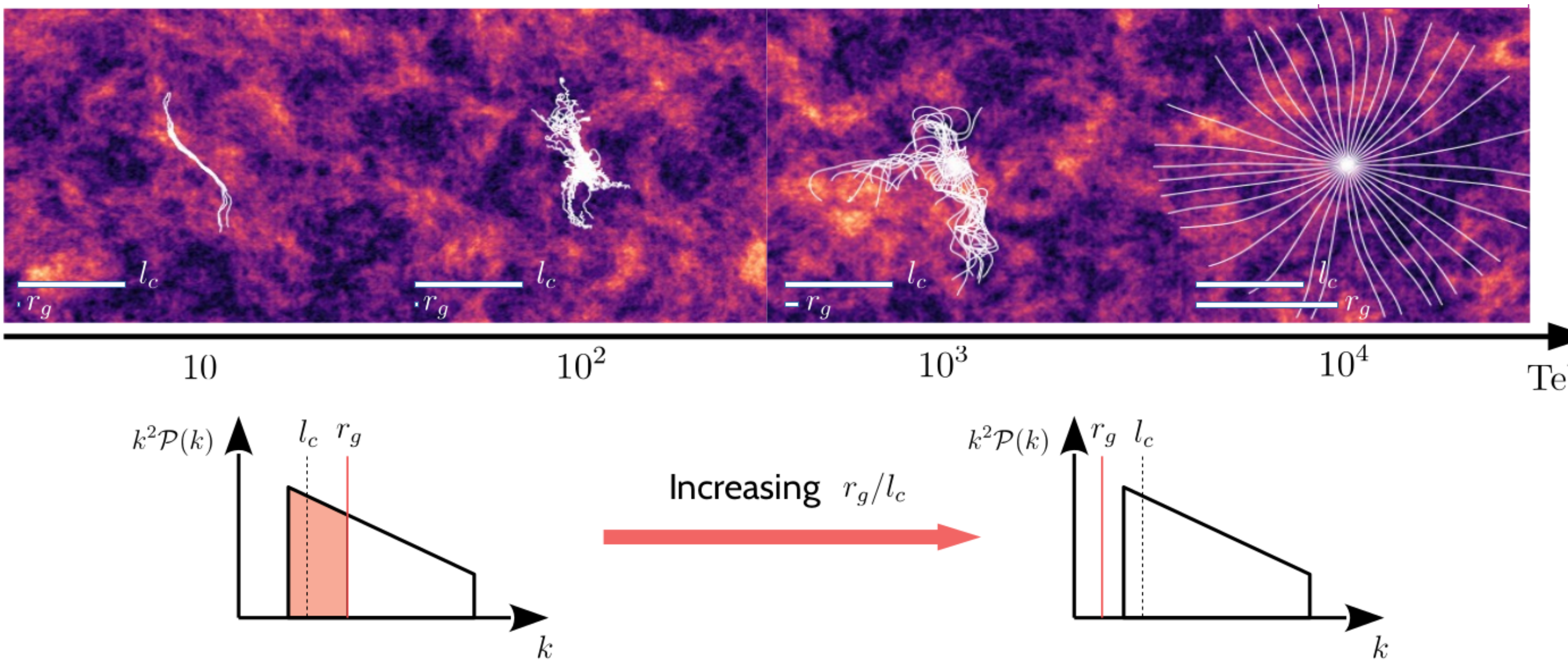


Galactic CR tracers: arrival directions

For more details, see:

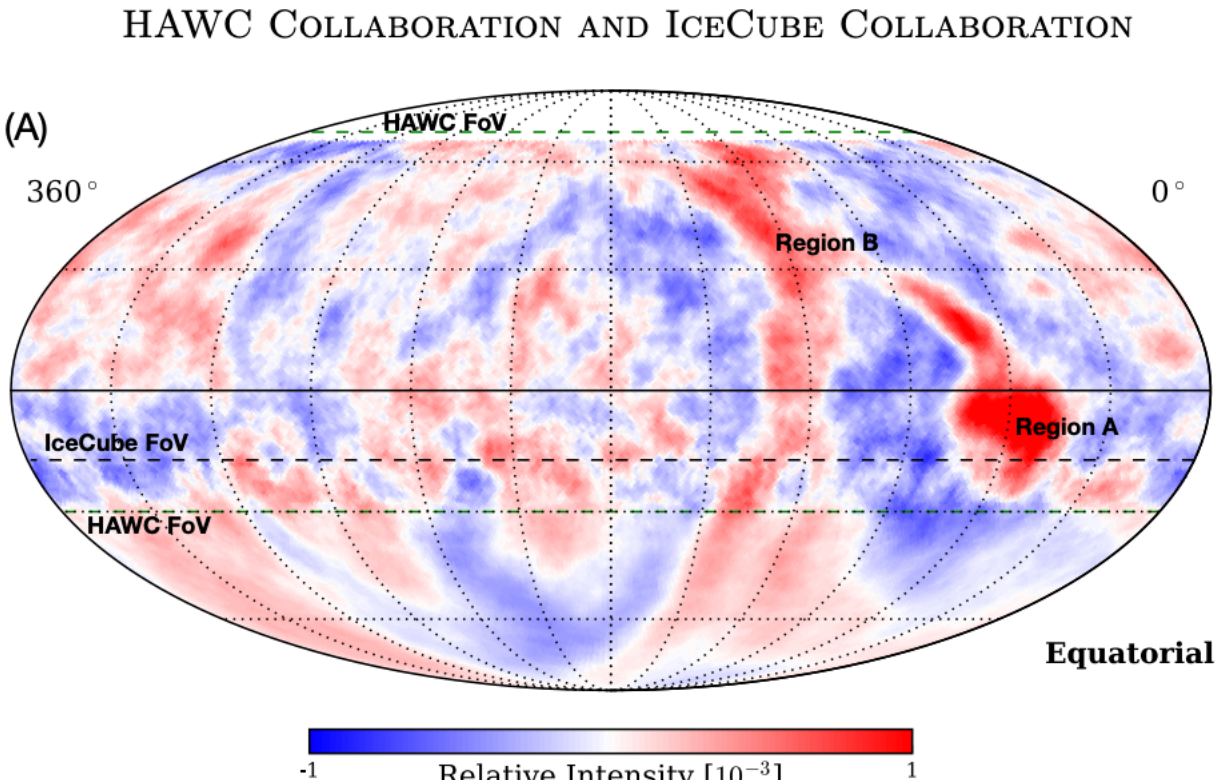
Yoann Génolini's contribution 532, discussion 06 (and 01)

on local turbulence and the dipole anisotropy



→ **At low energies particles stream along the local magnetic field**

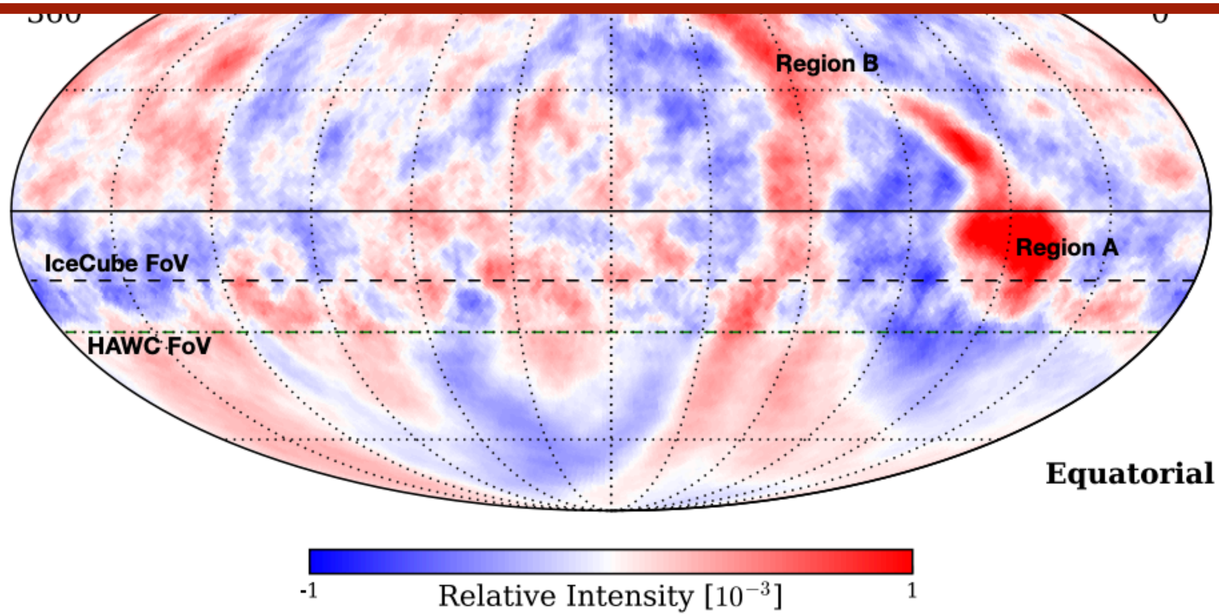
Galactic CR tracers: arrival directions



HAWC + IceCube 10 TeV cosmic rays
Abeysekara 2019 (ApJ 871, 1, 96, p15)

Galactic CR tracers: arrival directions

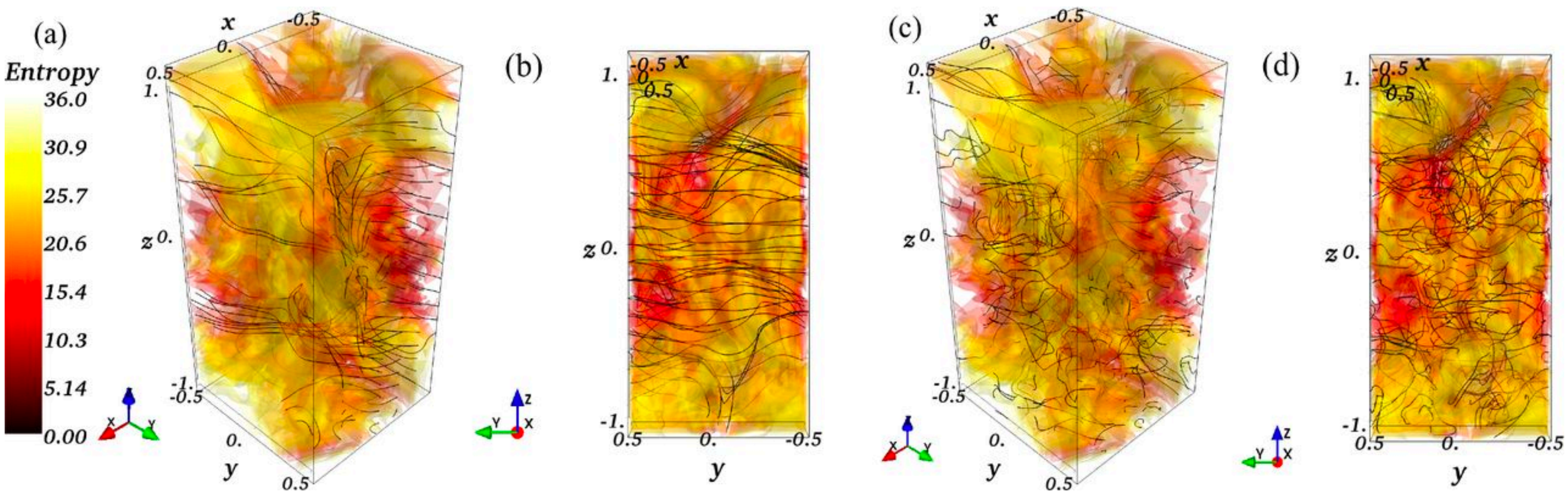
For more details, see:
Marco Kuhlen's contribution 118 discussion 06 (and 01)
on higher-order multipoles and small-scale turbulence and
Gwenael Giacinti's contribution 233 (ditto).



HAWC + IceCube 10 TeV cosmic rays
Abeysekara 2019 (ApJ 871, 1, 96, p15)

Theoretical work: real magnetized turbulence?

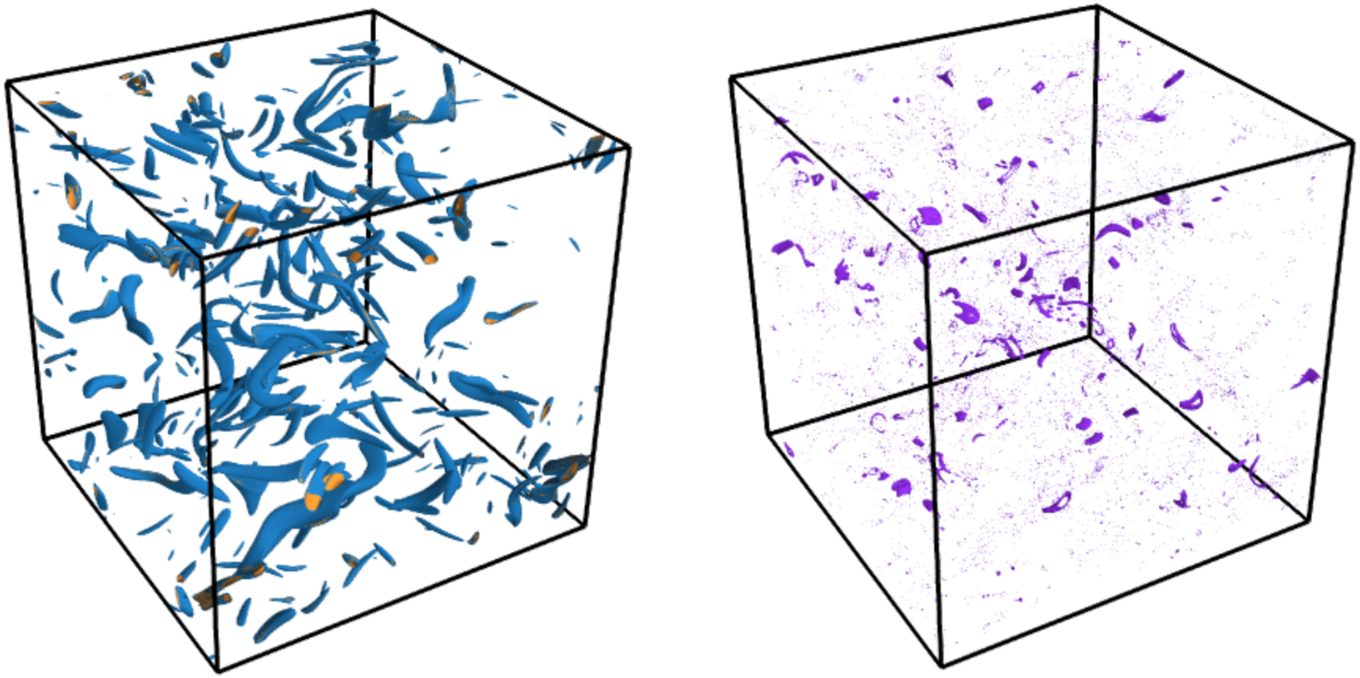
- Define "mean" versus "fluctuating" magnetic field
  - How to model both?



Field lines of "mean" field (a,b) or "fluctuating"/"random" (c,d) magnetic fields in MHD simulations of SNR-driven turbulence (Evirgen et al. 2017)

Theoretical work: real turbulence w/ CRs?

- CR propagation in a turbulent magnetic field
  - How does correlation affect large-scale modeling?

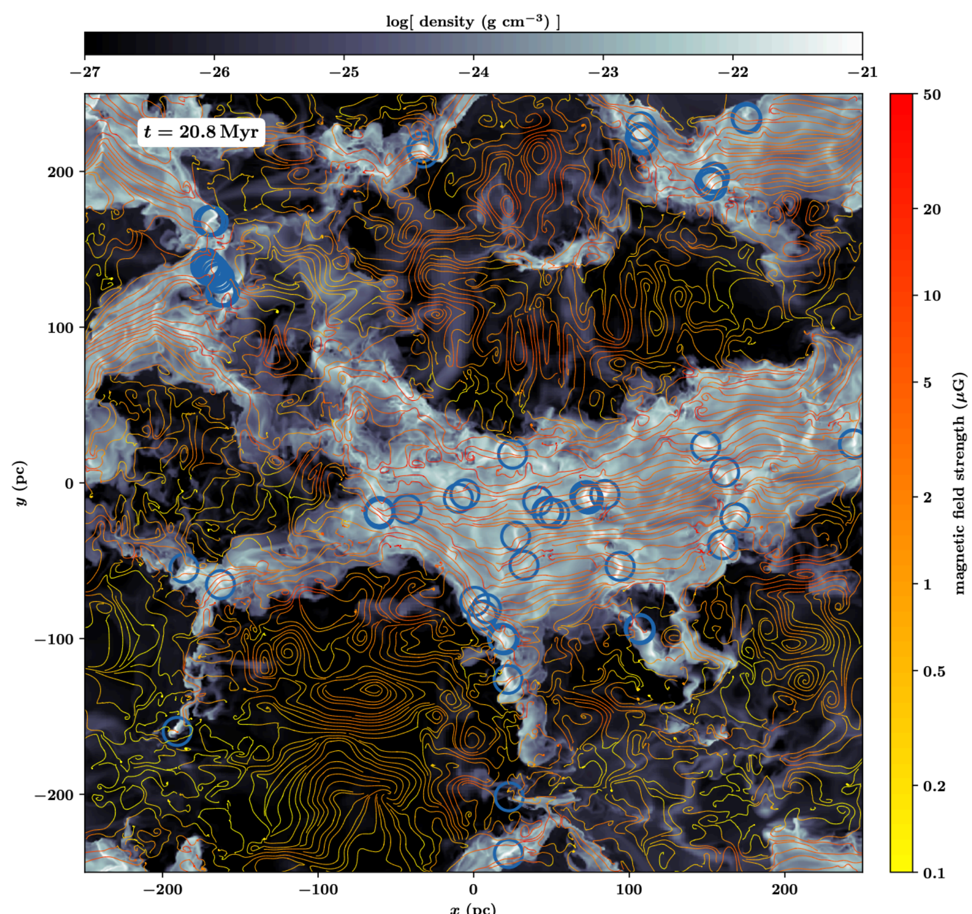


Isosurfaces of the strength of a random magnetic field *B (left)* and CR number density (*right*) produced by the fluctuation dynamo (Seta et al. 2018)

Theoretical work: real turbulence w/ CRs?

- CR propagation in a turbulent magnetic field
  - How does correlation affect large-scale modeling?

6 *Girichidis*



P. Girichidis (arXiv:2106.12596)

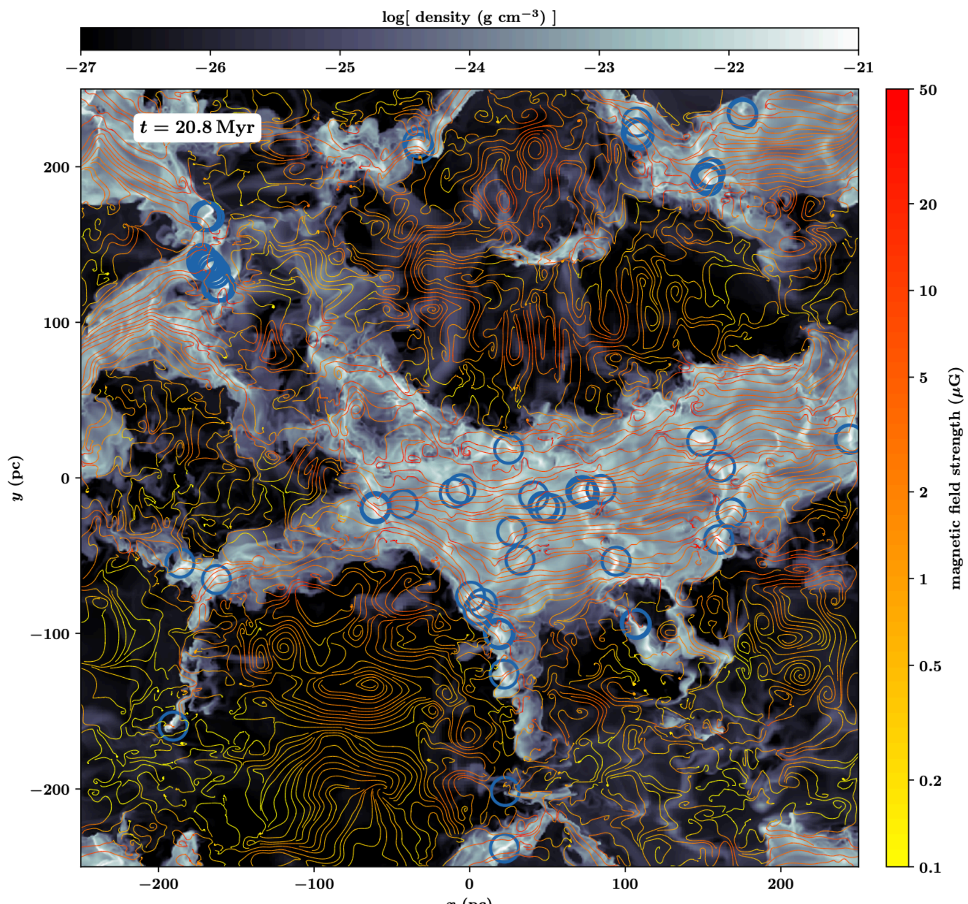
Figure 1. Cut through the centre of the box at $z = 0$ of simulation B3-0.25pc at $t = 20.8$Myr. The density is colour coded in gray-scale. The magnetic field lines are overplotted with the field strength indicated by the streamline colour. The blue circles indicate the identified clouds based on local minima of the gravitational potential.

Theoretical work: real turbulence w/ CRs?

- CR propagation in a turbulent magnetic field

How do we include anisotropy, clumpiness, correlations, etc. in large-scale field modeling? “Sub-grid modeling”?

6 *Girichidis*



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Theoretical work: real turbulence w/ CRs?

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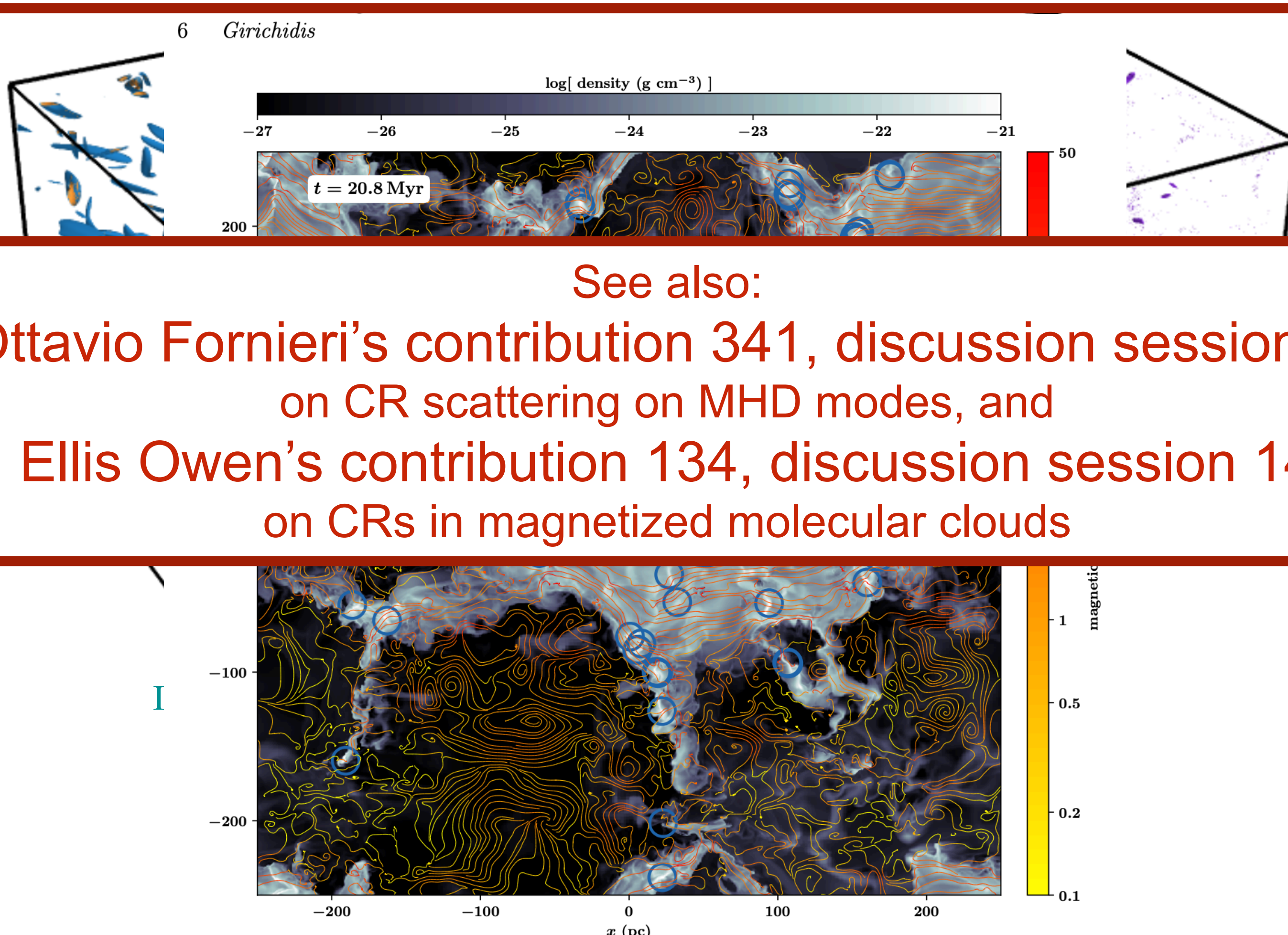
How do we include anisotropy, clumpiness, correlations, etc. in large-scale field modeling? "Sub-grid modeling"?



See also:

Ottavio Fornieri's contribution 341, discussion session 01

on CR scattering on MHD modes, and

Ellis Owen's contribution 134, discussion session 14

on CRs in magnetized molecular clouds

P. Girichidis (arXiv:2106.12596)

Figure 1. Cut through the centre of the box at $z = 0$ of simulation B3-0.25pc at $t = 20.8$ Myr. The density is colour coded in gray-scale. The magnetic field lines are overplotted with the field strength indicated by the streamline colour. The blue circles indicate the identified clouds based on local minima of the gravitational potential.

UHECRs

- Charged UHECRs deflected in B.
  - Need to know B to find sources.
  - *Or:*
- If you know the sources, you can infer B from the UHECRs.
  - Statistically?

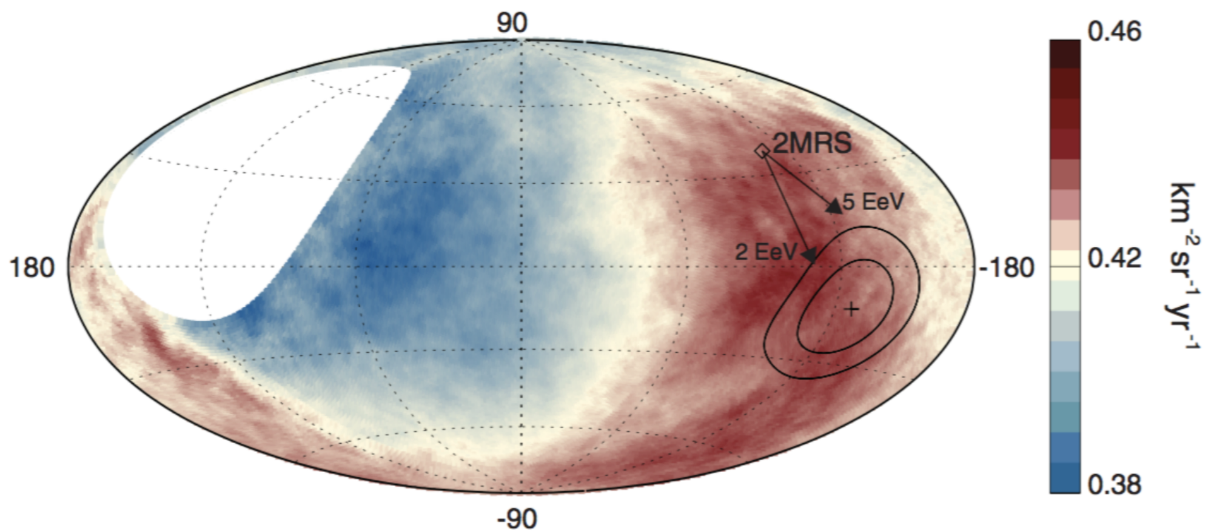


Figure 8. Sky map in galactic coordinates showing the cosmic ray flux as measured by the Pierre Auger Observatory for $E > 8$ EeV smoothed with a 45° top-hat function. The Galactic centre is at the origin. The cross indicates the measured dipole direction; the contours denote the 68% and 95% confidence level regions. The dipole in the 2MRS galaxy distribution is indicated. Arrows show the deflections expected for the JF12 GMF model on particles with $E/Z = 2$ or 5 EeV. Image credit: Pierre Auger Collaboration [149].

Pierre Auger Collaboration, 2017, *Science*, 357, 6357, p1266

UHECRs

- Charged UHECRs deflected in B.
  - Need to know B to find sources.
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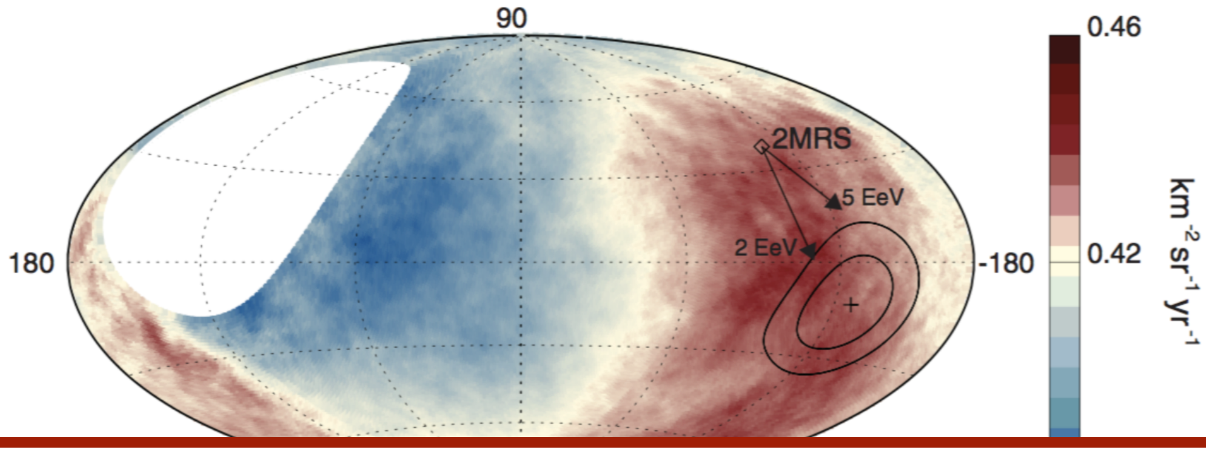


For more details, see:

Rafael Alves Batista's contribution 289, discussion 01, on CRpropa,

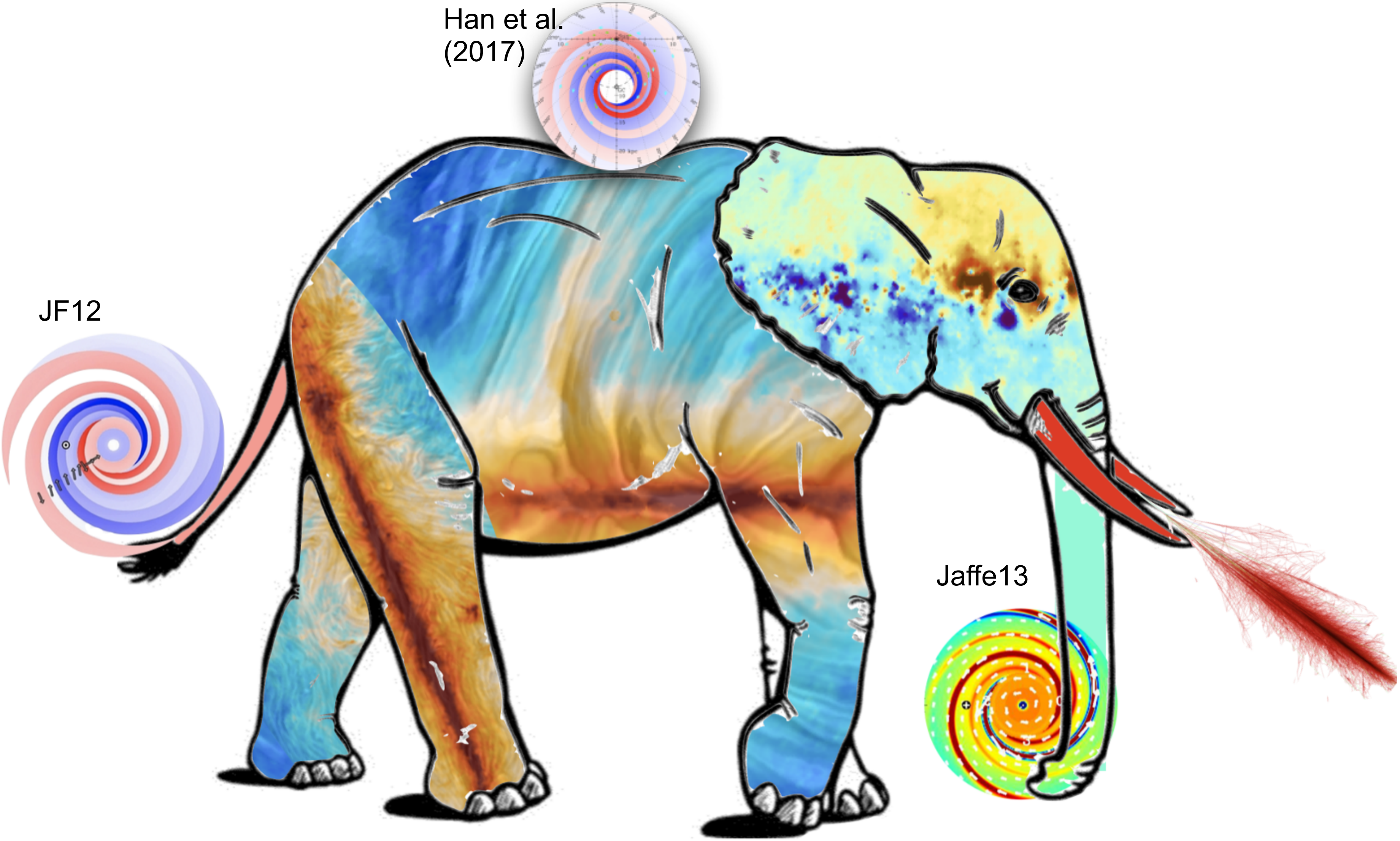
and

Arjen van Vliet's contribution 671, discussion 01, on correlations with neutrinos and extragalactic sources, and

Lots of talks about UHECR anisotropies, cross-correlations, etc., all of which relate to the magnetic field. 1470, 233, 902, 1230, 1415, …

Pierre Auger Collaboration, 2017, Science, 357, 6357, p1266

The proverbial elephant



Or maybe an elephant swallowing its tail: “If we knew the GMF, we could then use X to constrain Y. Likewise, if we knew Y, we could use X to constrain the GMF.”

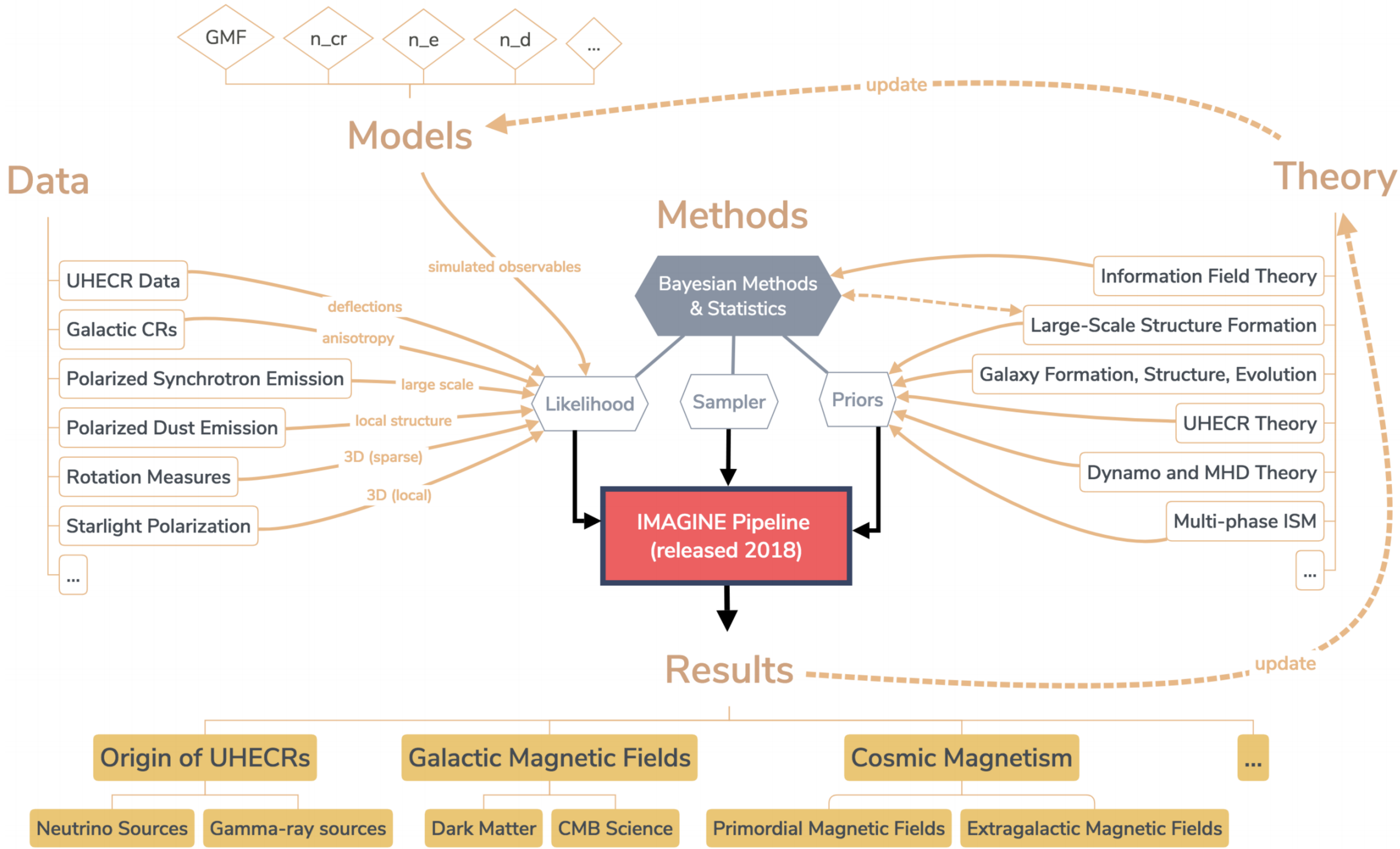
The proverbial elephant

At the risk of sounding new-age, this will have to be tackled holistically.

Or maybe an elephant swallowing its tail: “If we knew the GMF, we could then use X to constrain Y. Likewise, if we knew Y, we could use X to constrain the GMF.”

IMAGINE overview

White Paper: Boulanger et al. (2018) https://arxiv.org/abs/1805.02496
Demonstration paper: Steininger et al. (2018), https://arxiv.org/abs/1801.04341)



IMAGINE overview

White Paper: Boulanger et al. (2018) https://arxiv.org/abs/1805.02496
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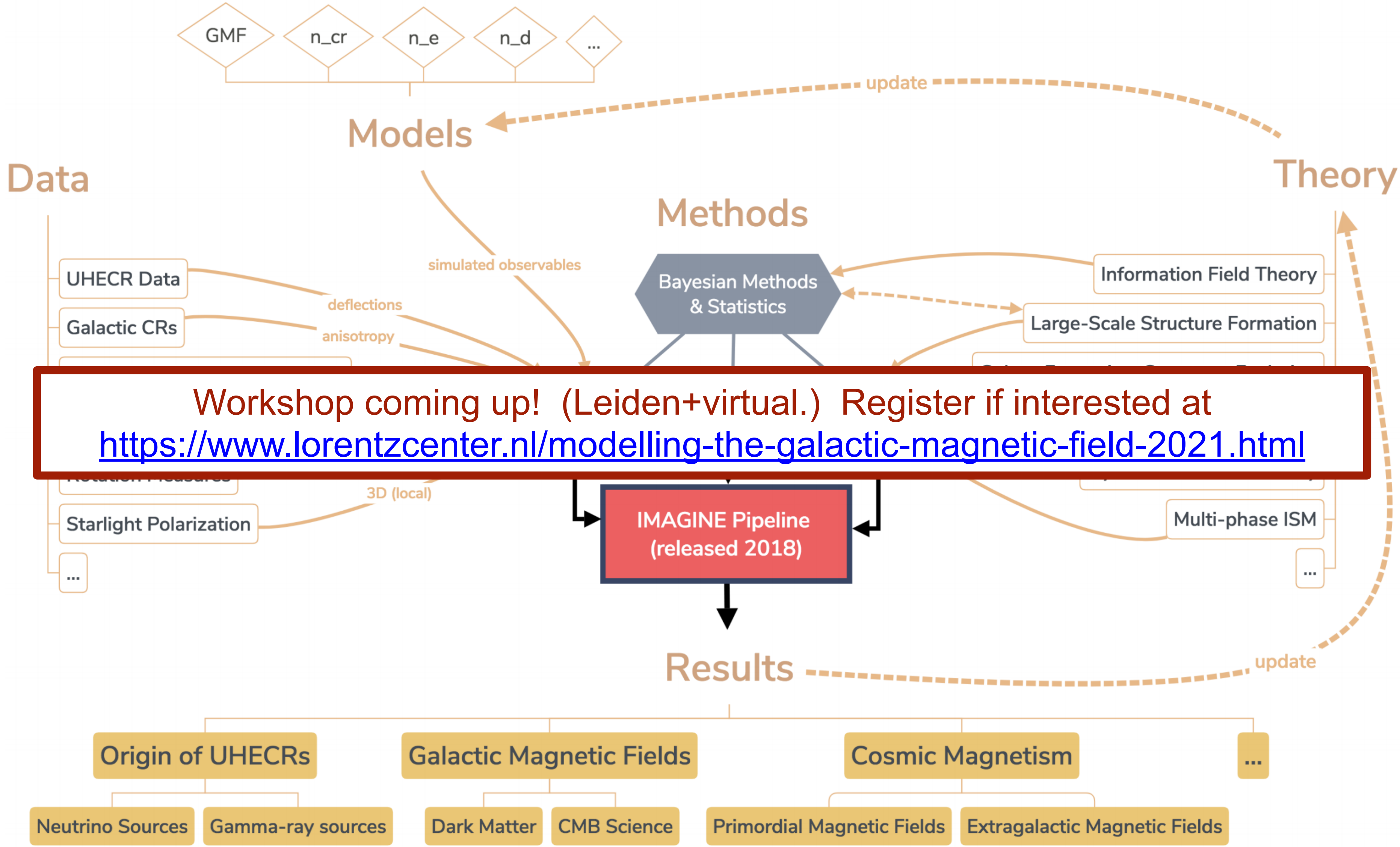
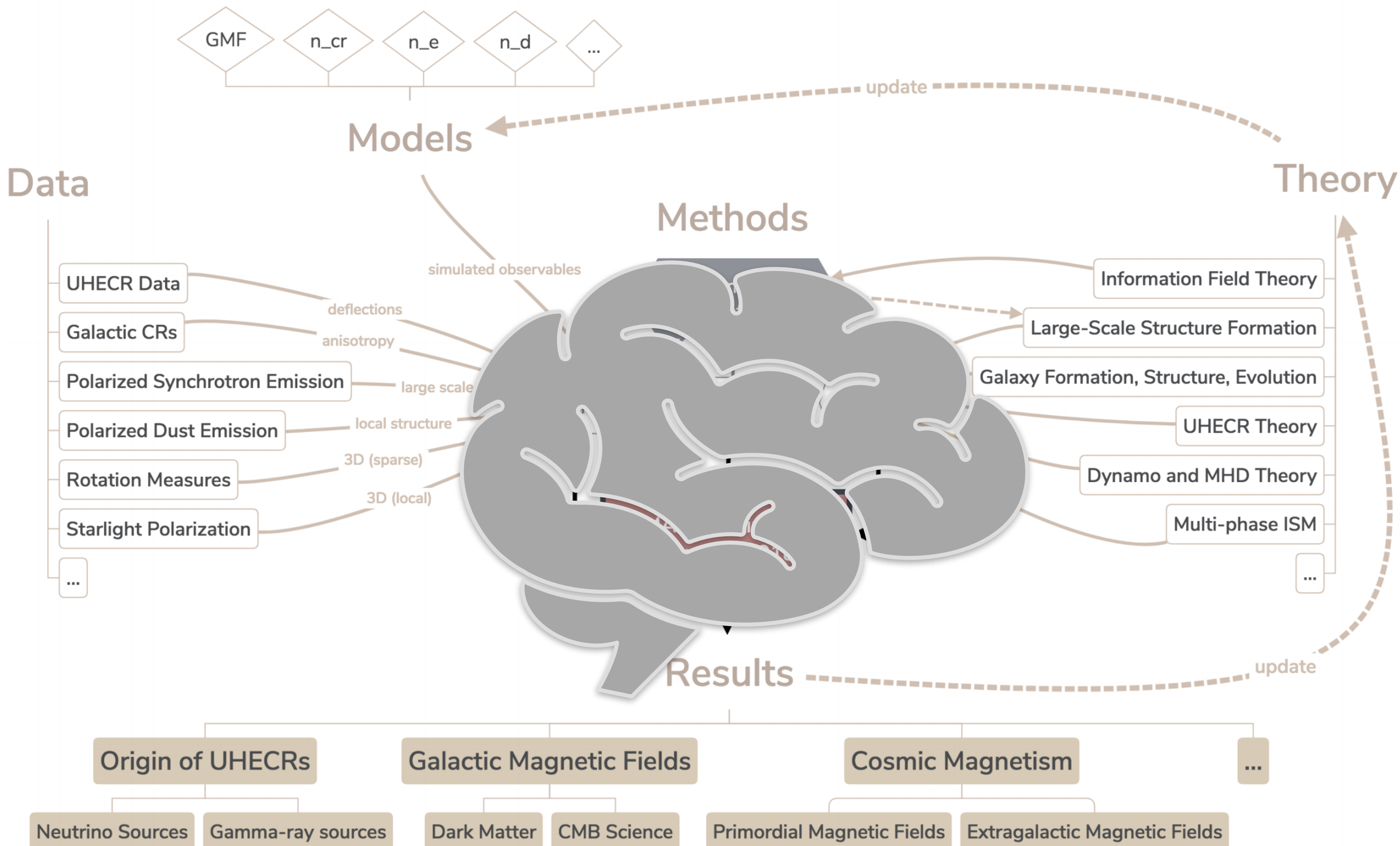


Workshop coming up! (Leiden+virtual.) Register if interested at
https://www.lorentzcenter.nl/modelling-the-galactic-magnetic-field-2021.html

ICRC connections



ICRC connections

Arjen Rene van Vliet: Extragalactic magnetic fields and directional correlations of ultra-high-energy cosmic rays with local galaxies and neutrinos

Stefano Gabici: Giant cosmic ray halos around M31 and the Milky Way (**19th @ 6pm**)

Alex Kääpä: Transition from Galactic to extragalactic cosmic rays. **PLENARY HIGHLIGHT @ 16h**

Rafael Alves Batista: CRPropa 3.2: A framework for high-energy astroparticle propagation

Ryo Higuchi: UHECR deflections in the GMF with CRPropa3 code (**15th @ 12pm**)

Marco Kuhlen: Cosmic Ray Small-Scale Anisotropies in Slab Turbulence (**15th @ 12pm**)

Yutaka Ohira: Magnetic field generation by the first cosmic rays

Ralf-Jürgen Dettmar: Magnetic field structure in halos of star-forming disk galaxies

Yoann Génolini: Local turbulence and the dipole anisotropy of galactic cosmic rays **(15th @ 12pm)**

Elena Orlando: Interstellar cosmic-ray spectra (1) just outside the heliosphere and (2) in the local medium: are they the same? **19th @ 18h**

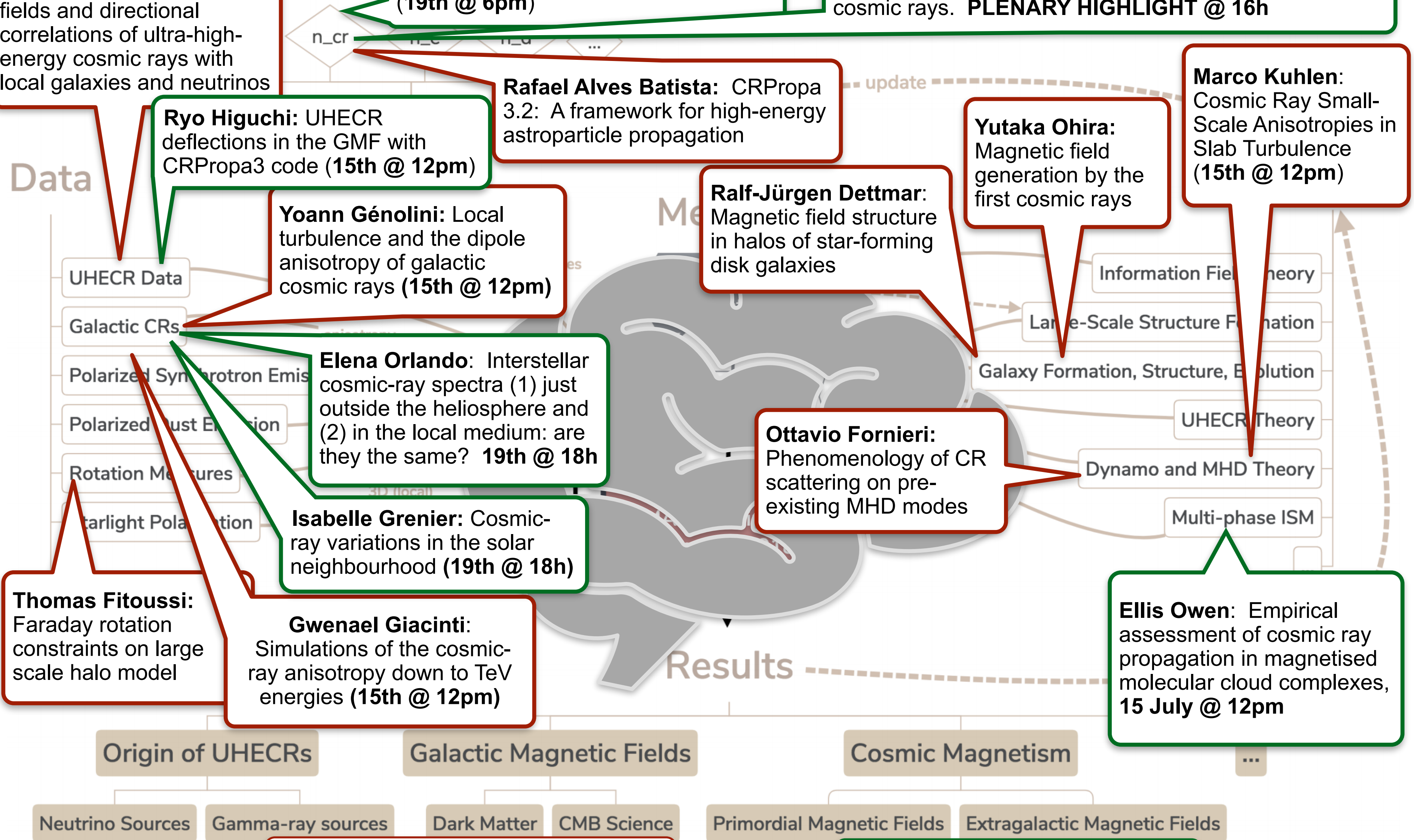
Ottavio Fornieri: Phenomenology of CR scattering on pre-existing MHD modes

Isabelle Grenier: Cosmic-ray variations in the solar neighbourhood **(19th @ 18h)**

Thomas Fitoussi: Faraday rotation constraints on large scale halo model

Gwenael Giacinti: Simulations of the cosmic-ray anisotropy down to TeV energies **(15th @ 12pm)**

Ellis Owen: Empirical assessment of cosmic ray propagation in magnetised molecular cloud complexes, **15 July @ 12pm**



Discussion Session 01 yesterday.

And many more in other sessions!