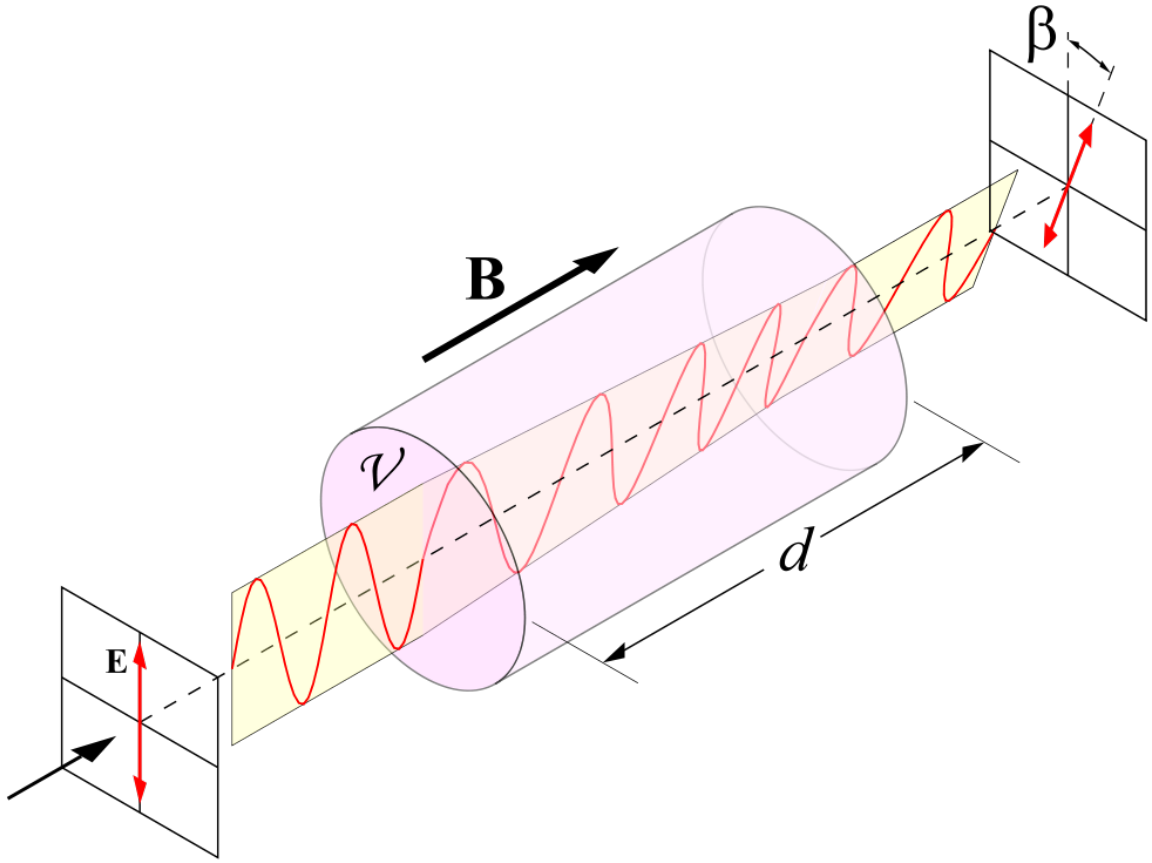
Faraday sky reconstruction & extragalactic magnetic field search

Niels Oppermann

in collaboration with:
V. Vacca, T.A. Enßlin, J. Jasche (MPA/LMU/TUM, Munich)
B.M. Gaensler (Dunlap, Toronto)
J. Stil, J.-A. Brown (UofC, Calgary)
H. Junklewitz, S.A. Mao, D. Schnitzeler (AIfA/MPIfR, Bonn)
E. Carretti (INAF, Cagliari)
and others

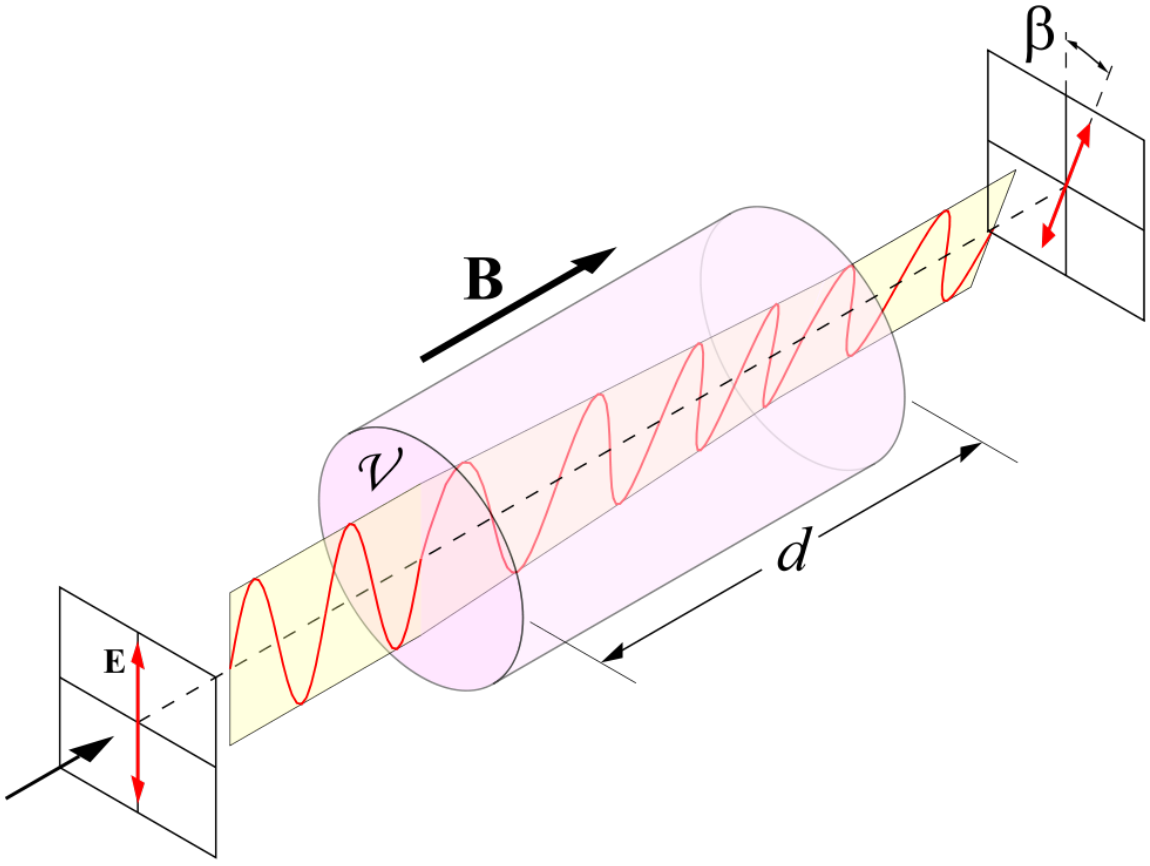
Faraday rotation



$$\mathrm{d}\beta \propto \lambda^2 n_\mathrm{e} B_r \,\mathrm{d}r$$

$$\Rightarrow \quad \beta \propto \lambda^2 \int_{r_\mathrm{source}}^{0} (1+z)^{-2}\; n_\mathrm{e} B_r \,\mathrm{d}r$$

Faraday rotation

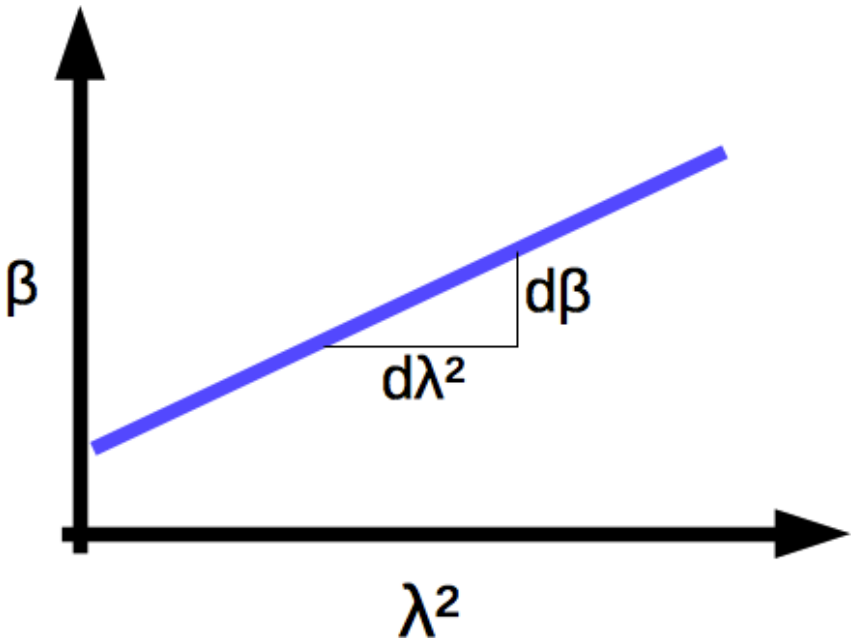


Faraday depth: $\phi \propto \int_{r_{\rm source}}^{0} (1+z)^{-2}\, n_{\rm e}\, B_r\, {\rm d}r$

$$\beta = \phi\lambda^2$$

Faraday rotation

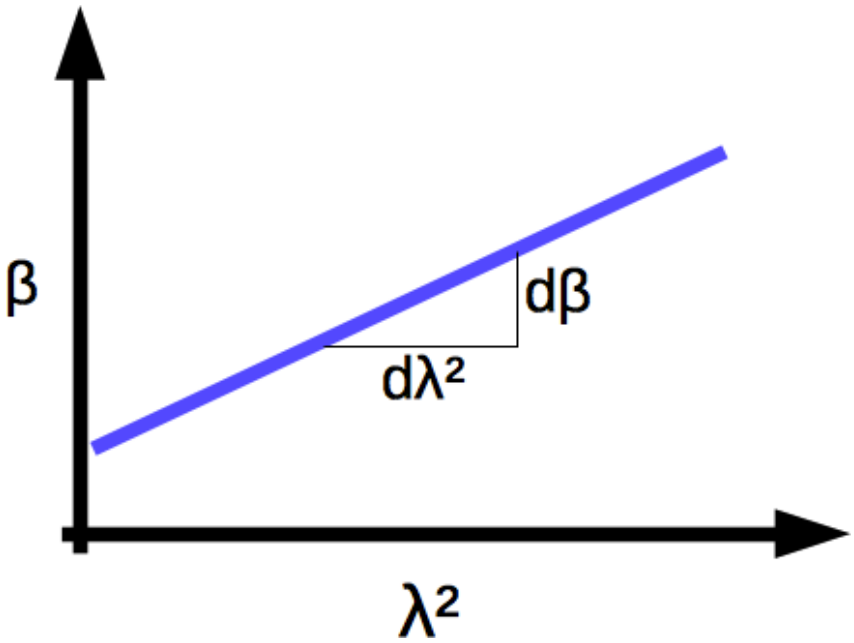
if *B*-fields in front of emission:



$$\phi = \mathrm{RM} = \frac{\mathrm{d}\beta}{\mathrm{d}\lambda^2}$$

Faraday rotation

if *B*-fields in front of emission:

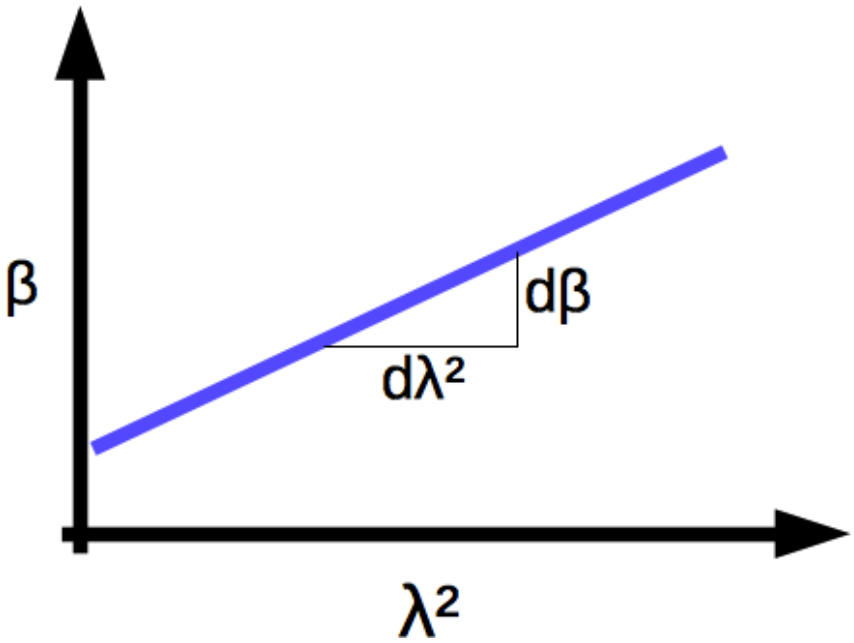


$$\phi = \mathrm{RM} = \frac{\mathrm{d}\beta}{\mathrm{d}\lambda^2}$$

if *B*-fields and emission mixed:

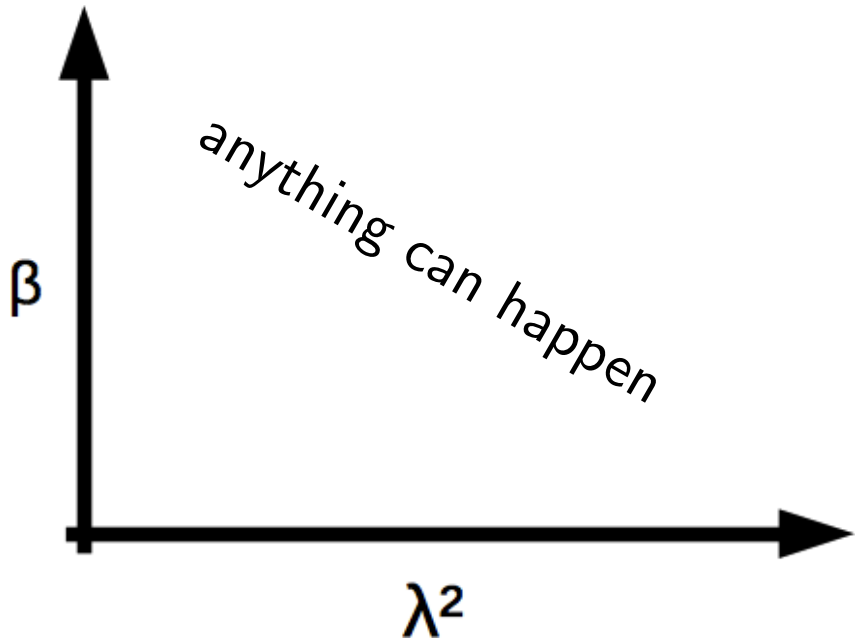
Faraday rotation

if *B*-fields in front of emission:



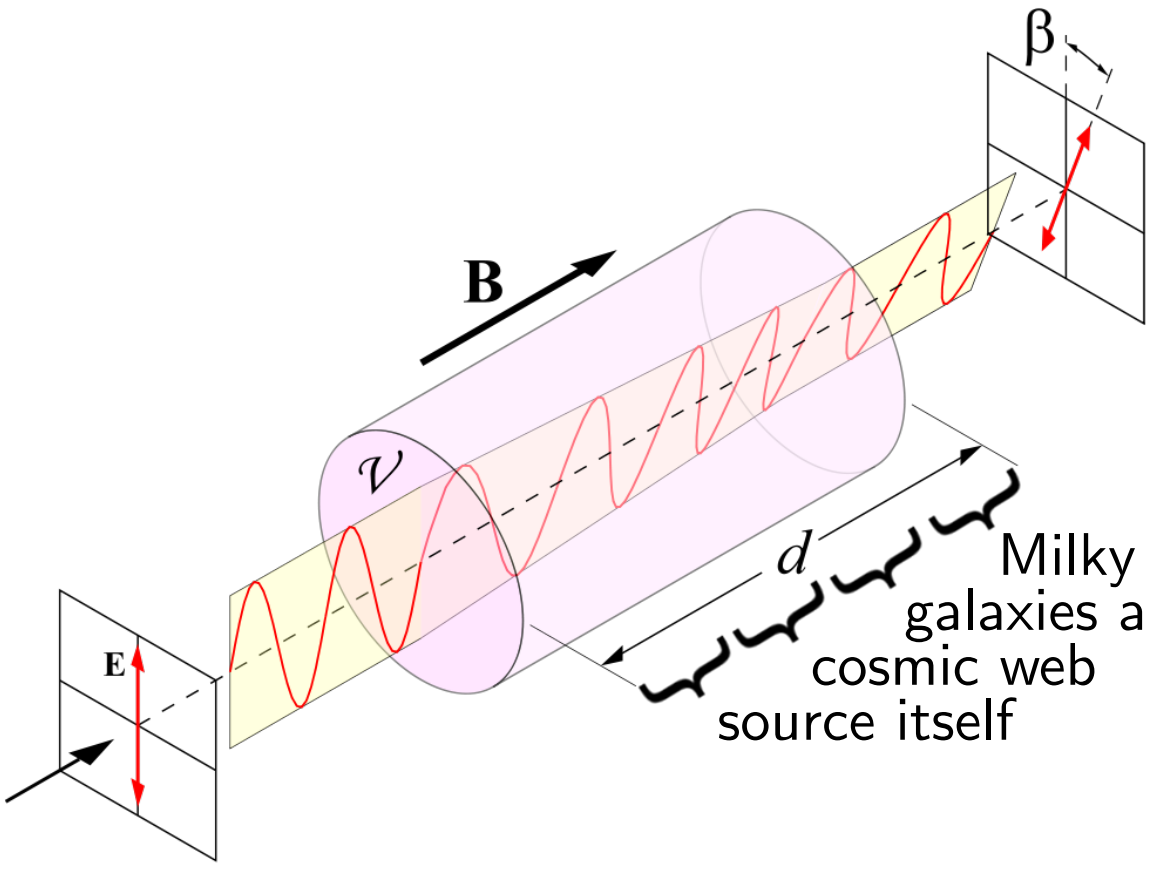
$$\phi = \mathrm{RM} = \frac{\mathrm{d}\beta}{\mathrm{d}\lambda^2}$$

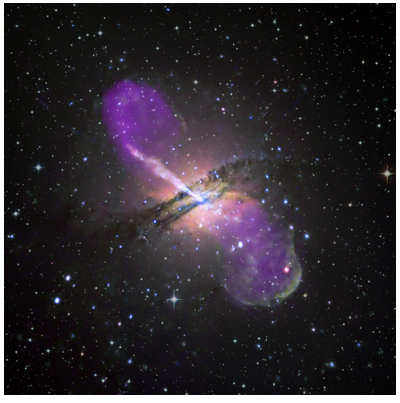
if *B*-fields and emission mixed:



Use $Q(\lambda)$, $U(\lambda)$, $I(\lambda)$, RM synthesis,...

Faraday rotation

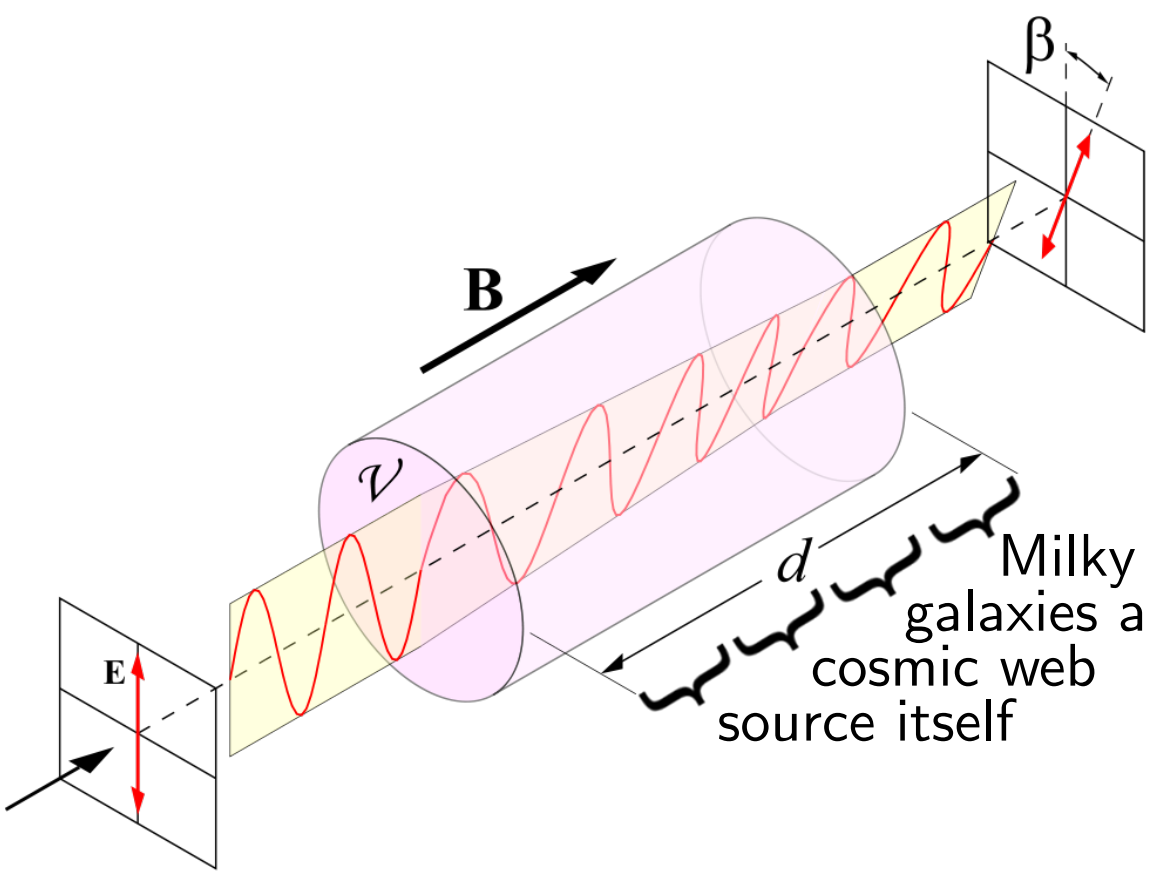


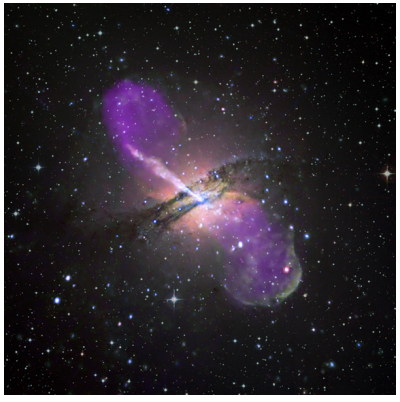


Faraday depth: $\phi \propto \int_{r_{\mathrm{source}}}^{0} (1+z)^{-2}\, n_{\mathrm{e}}\, B_r\, \mathrm{d}r$

$$\beta = \phi\lambda^2$$

Faraday rotation

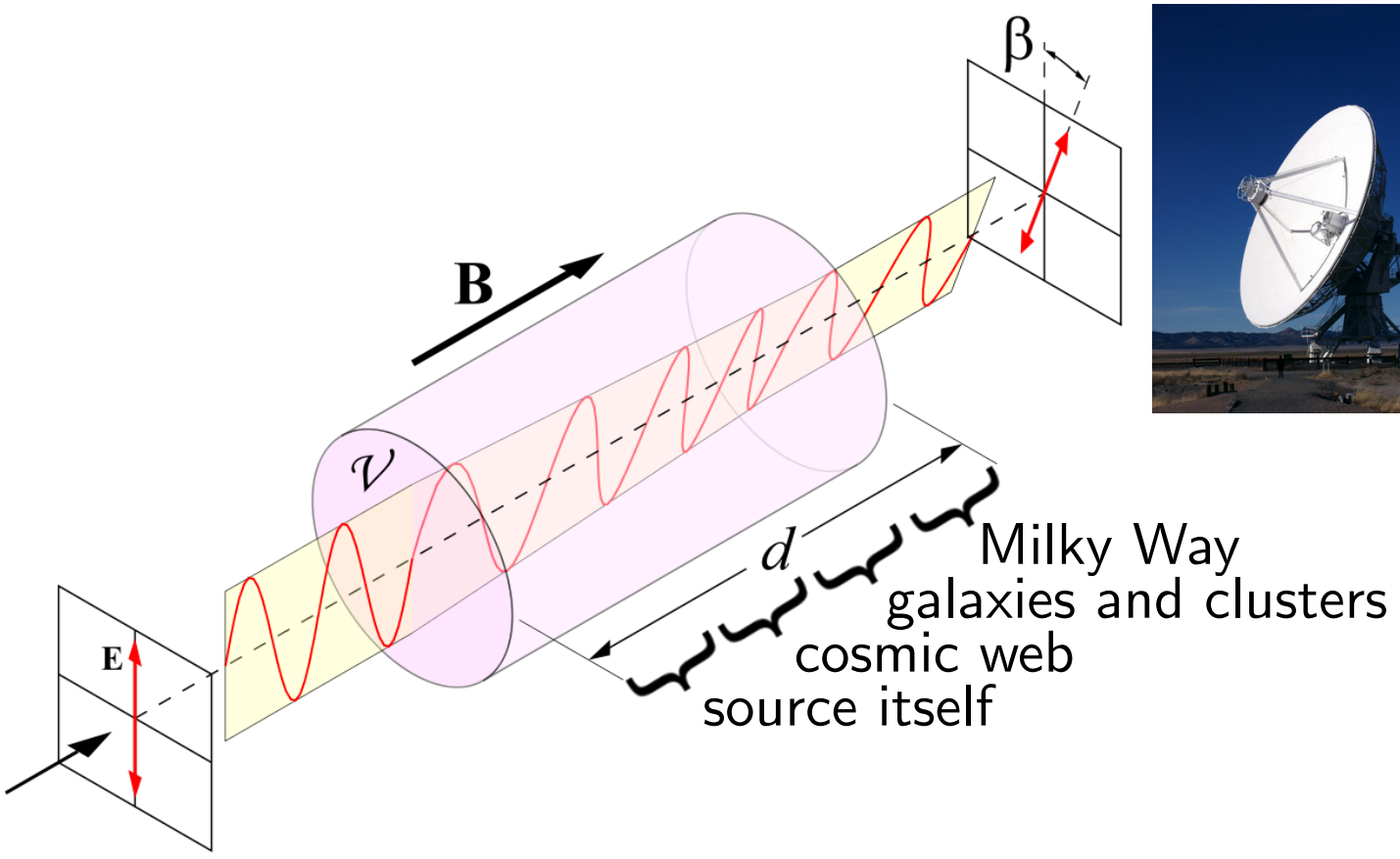


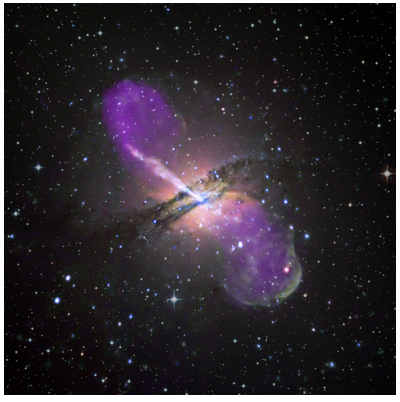


Faraday depth: $\phi \propto \int_{r_{\rm source}}^{0} (1+z)^{-2}\, n_{\rm e}\, B_r\, {\rm d}r$

$$\phi = \phi_{\rm MW} + \phi_{\rm other\ galaxies} + \phi_{\rm clusters} + \phi_{\rm filaments} + \phi_{\rm sheets} + \phi_{\rm voids} + \phi_{\rm source}$$

Faraday rotation

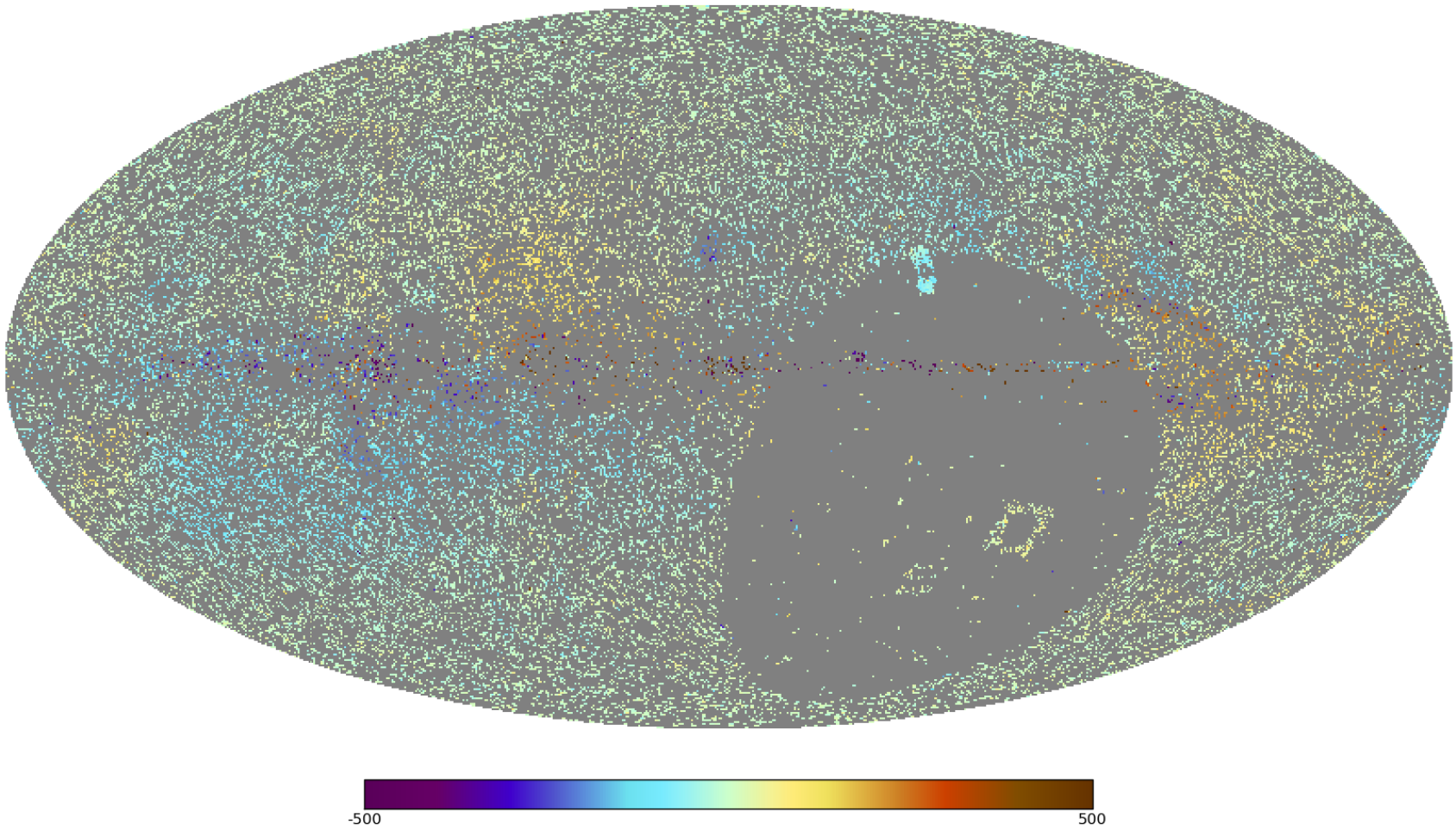




Faraday depth: $\phi \propto \int_{r_{\rm source}}^{0} (1+z)^{-2}\, n_{\rm e}\, B_r\, {\rm d}r$

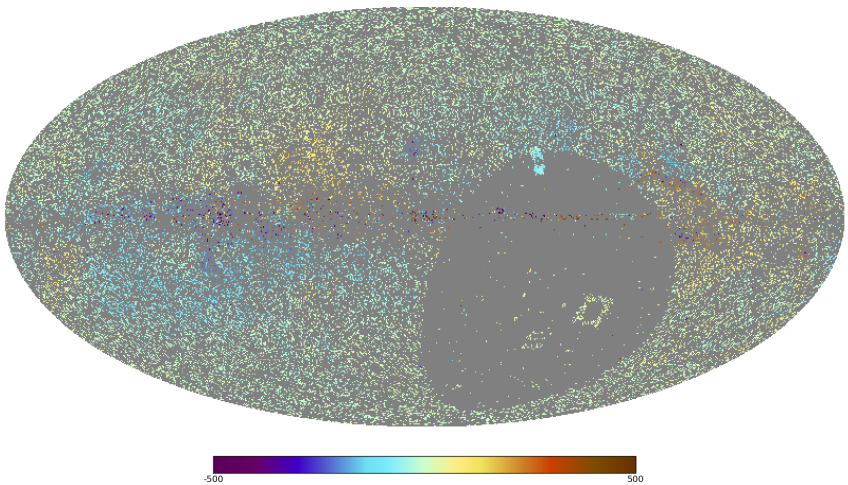
$$\phi = \phi_{\rm MW} + \phi_{\rm extragalactic}$$

$$d = \phi_{\mathrm{MW}} + \phi_{\mathrm{extragalactic}} + n$$



$\gtrsim$ 40 000 data points

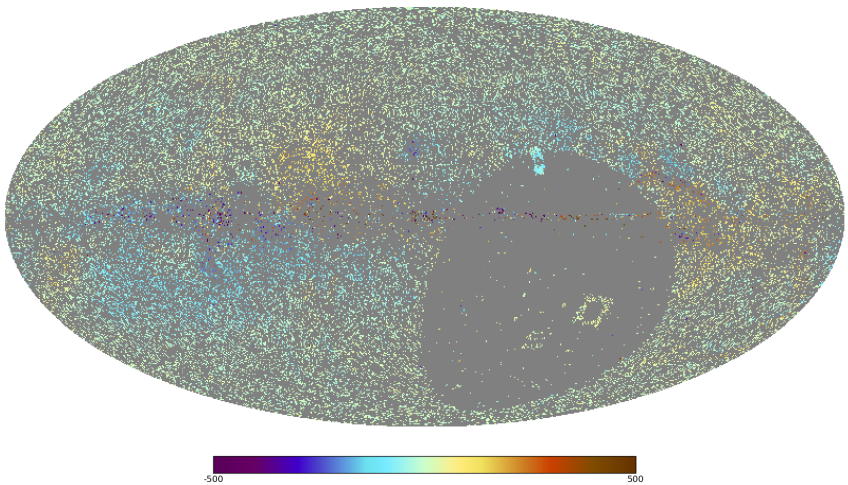
$$d = \phi_{\mathrm{MW}} + \phi_{\mathrm{extragalactic}} + n$$



Challenges

- Regions without data
- Galactic/extragalactic split unknown
- Uncertain uncertainties

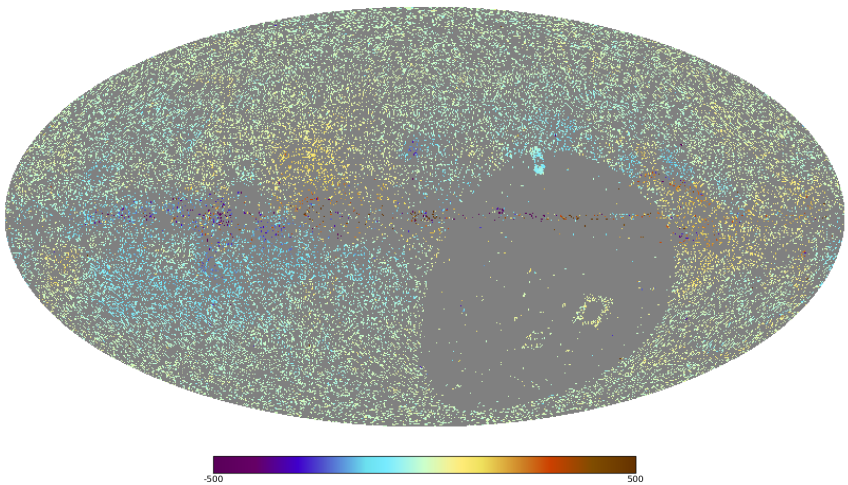
$$d = \phi_{\mathrm{MW}} + \phi_{\mathrm{extragalactic}} + n$$

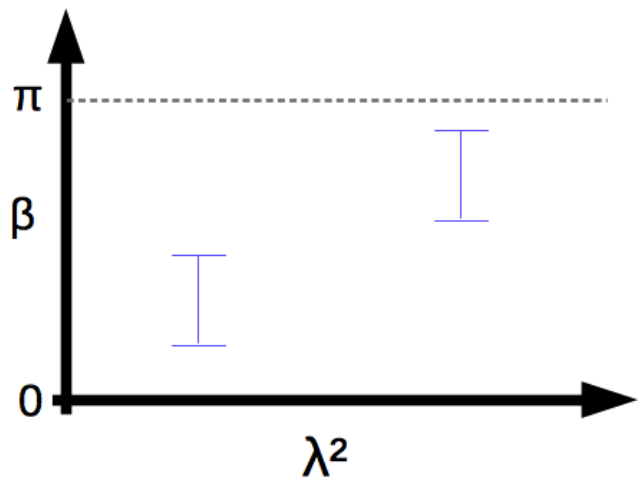


Challenges

- Regions without data
- Galactic/extragalactic split unknown
- Uncertain uncertainties
  - $n\,\pi$ ambiguity
  - multiple components along a LOS
  - ionosphere
  - ...

$$d = \phi_{\mathrm{MW}} + \phi_{\mathrm{extragalactic}} + n$$

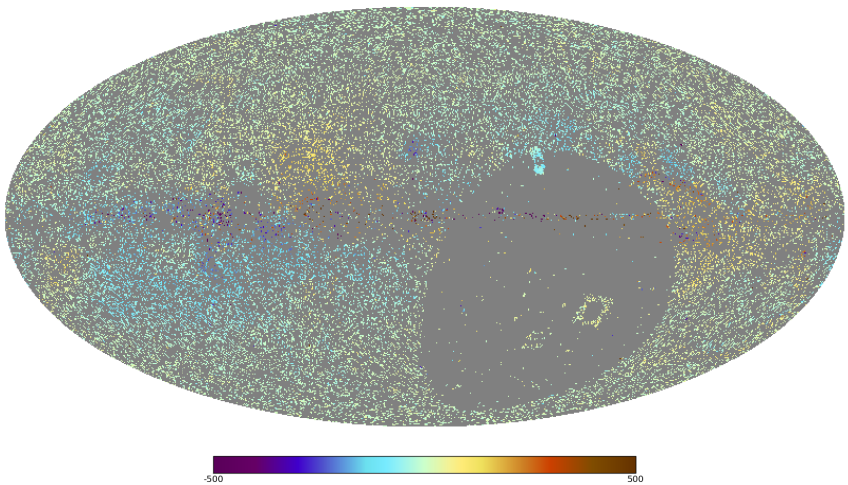


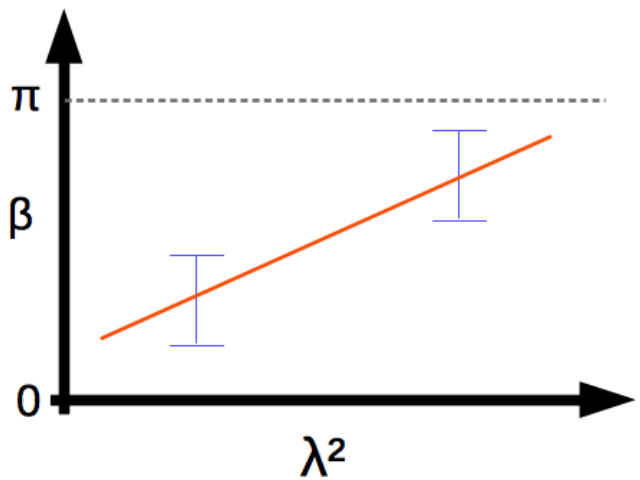


Challenges

- Regions without data
- Galactic/extragalactic split unknown
- Uncertain uncertainties
  - $n\,\pi$ ambiguity
  - multiple components along a LOS
  - ionosphere
  - ...

$$d = \phi_{\mathrm{MW}} + \phi_{\mathrm{extragalactic}} + n$$

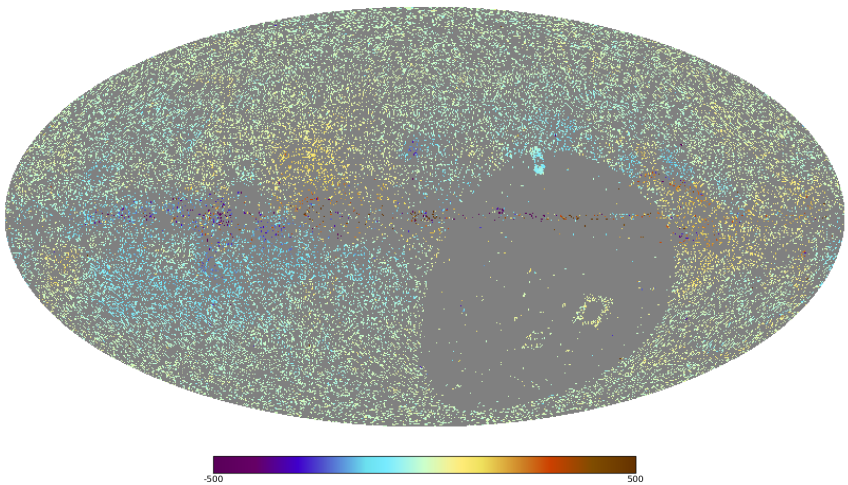


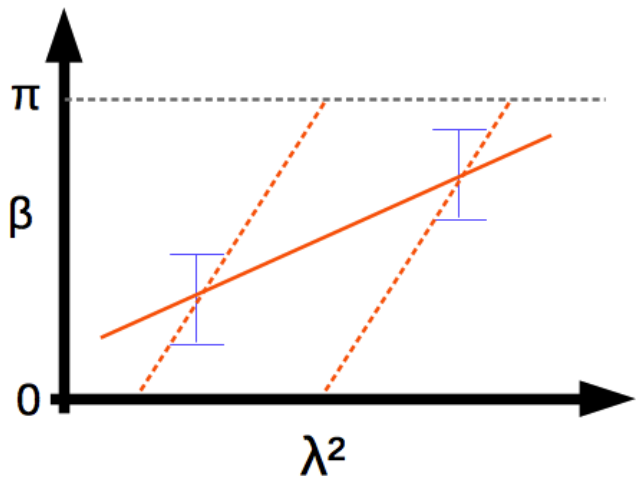


Challenges

- Regions without data
- Galactic/extragalactic split unknown
- Uncertain uncertainties
  - $n\,\pi$ ambiguity
  - multiple components along a LOS
  - ionosphere
  - ...

$$d = \phi_{\mathrm{MW}} + \phi_{\mathrm{extragalactic}} + n$$

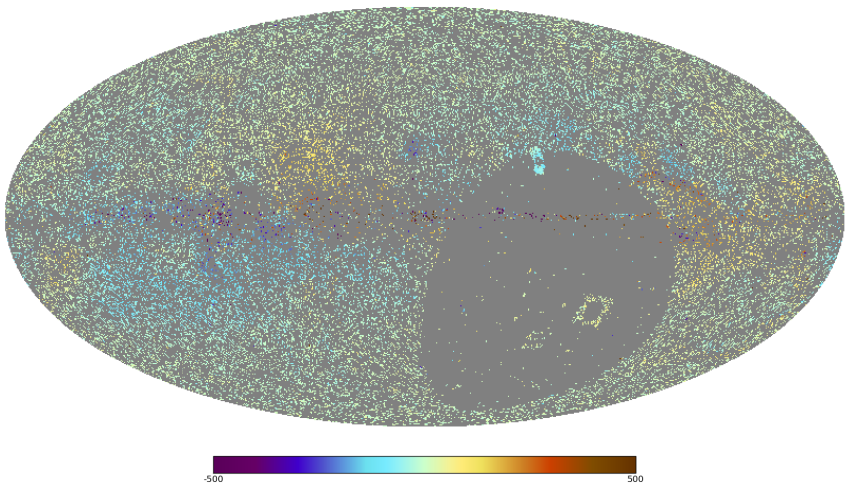


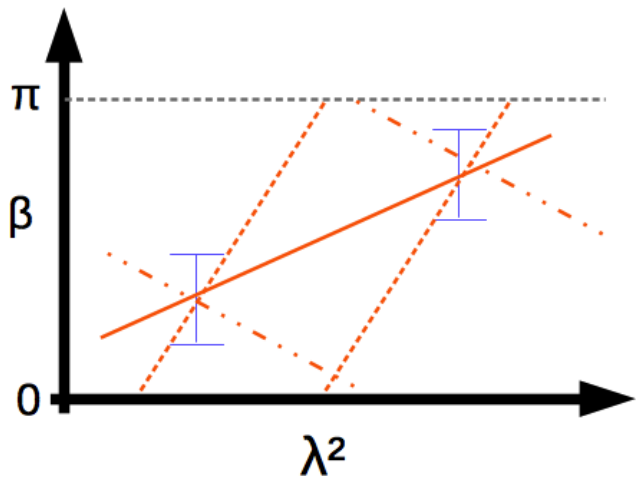


Challenges

- Regions without data
- Galactic/extragalactic split unknown
- Uncertain uncertainties
  - $n\,\pi$ ambiguity
  - multiple components along a LOS
  - ionosphere
  - ...

$$d = \phi_{\mathrm{MW}} + \phi_{\mathrm{extragalactic}} + n$$

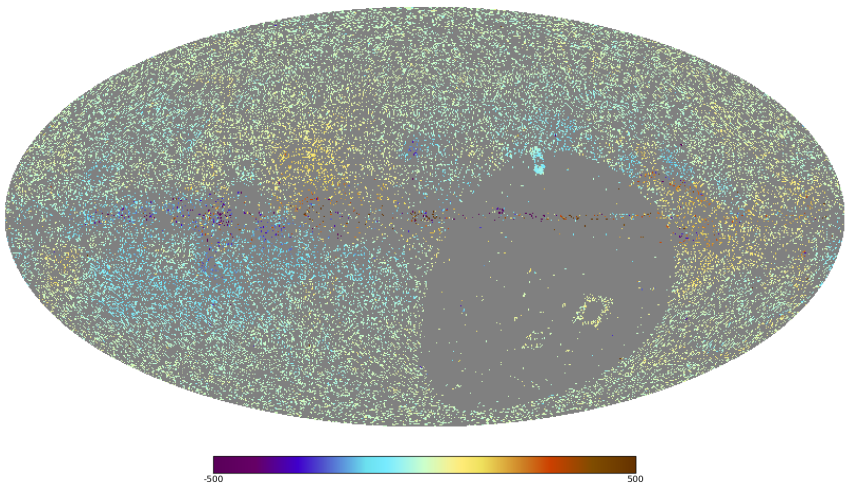


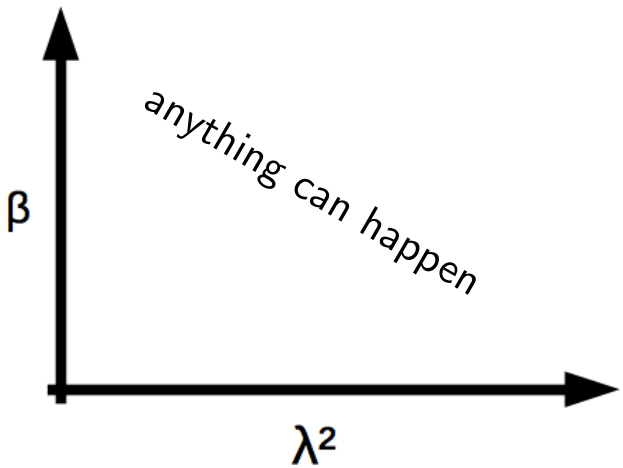


Challenges

- Regions without data
- Galactic/extragalactic split unknown
- Uncertain uncertainties
  - $n\,\pi$ ambiguity
  - multiple components along a LOS
  - ionosphere
  - ...

$$d = \phi_{\mathrm{MW}} + \phi_{\mathrm{extragalactic}} + n$$

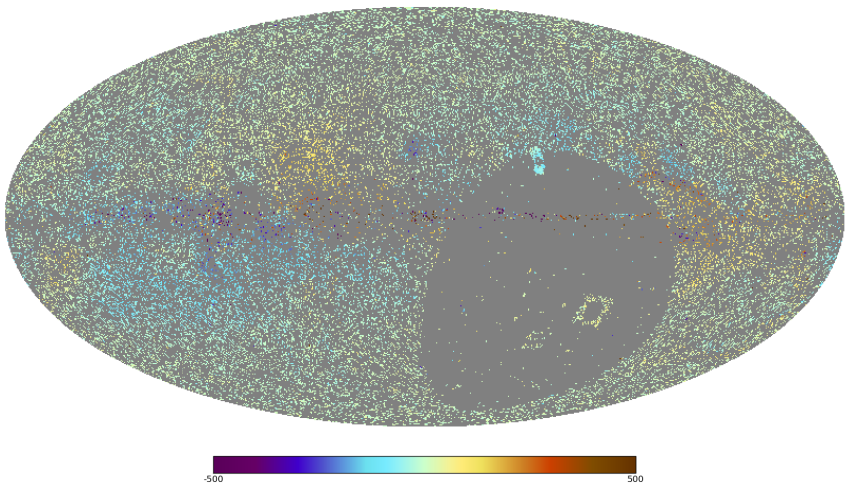




Challenges

- Regions without data
- Galactic/extragalactic split unknown
- Uncertain uncertainties
  - $n\,\pi$ ambiguity
  - multiple components along a LOS
  - ionosphere
  - ...

$$d = \phi_{\mathrm{MW}} + \phi_{\mathrm{extragalactic}} + n$$



Challenges

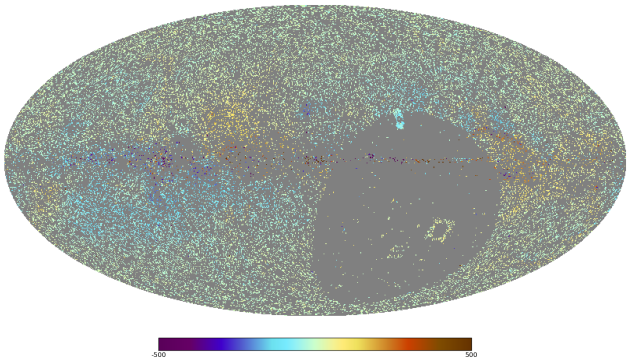
- Regions without data
- Galactic/extragalactic split unknown
- Uncertain uncertainties
  - $n\,\pi$ ambiguity
  - multiple components along a LOS
  - ionosphere
  - ...

$$d = \phi_{\mathrm{MW}} + \phi_{\mathrm{extragalactic}} + \phi_{\mathrm{ionosphere}}(t) + n$$

$$d = \phi_{\mathrm{MW}} + \phi_{\mathrm{extragalactic}} + n$$

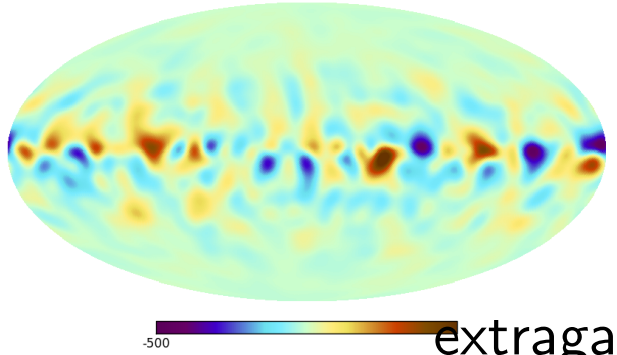
$$d = \phi_{\mathrm{MW}} + \phi_{\mathrm{extragalactic}} + n$$

data



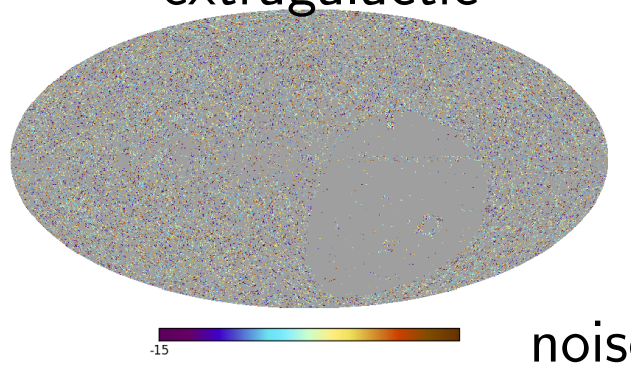
=

Galactic



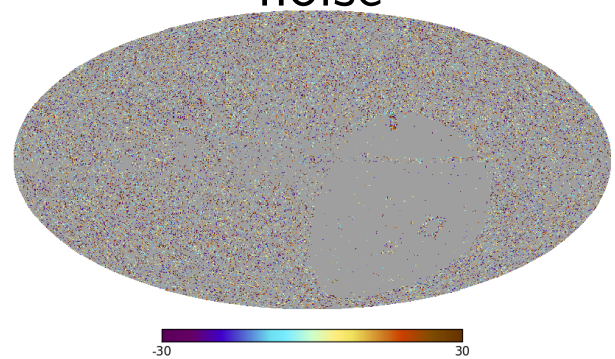
+

extragalactic



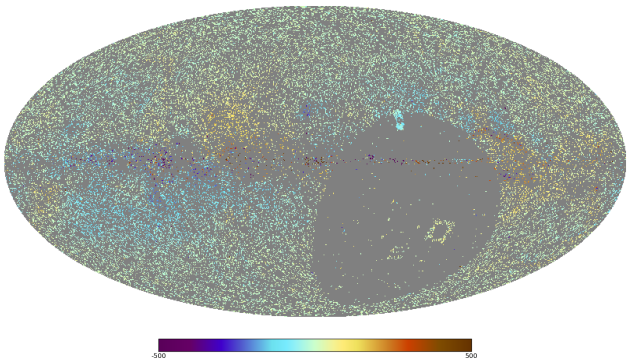
+

noise



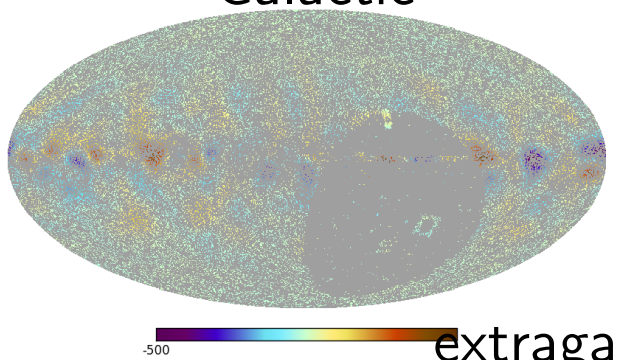
$$d = \phi_{\mathrm{MW}} + \phi_{\mathrm{extragalactic}} + n$$

data



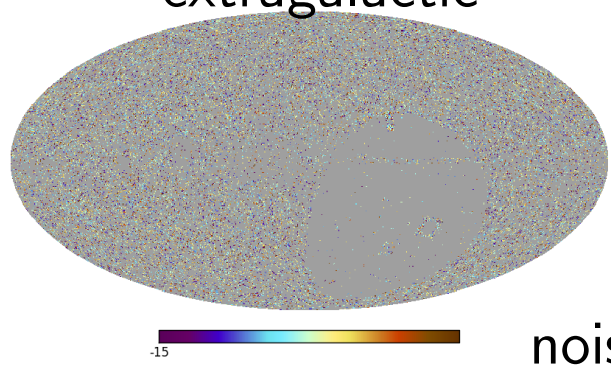
=

Galactic



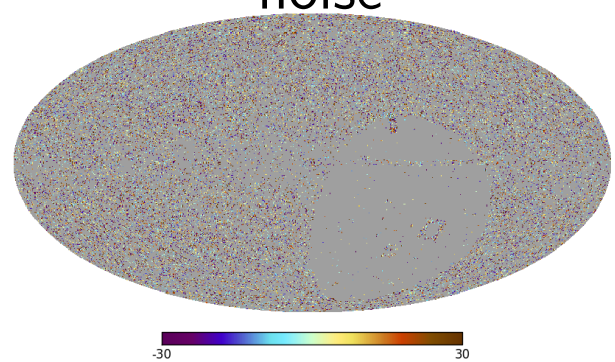
+

extragalactic



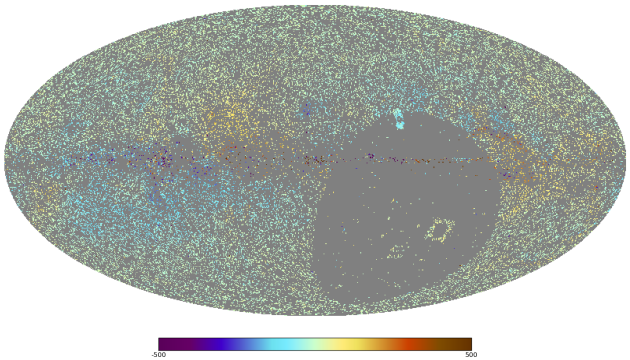
+

noise



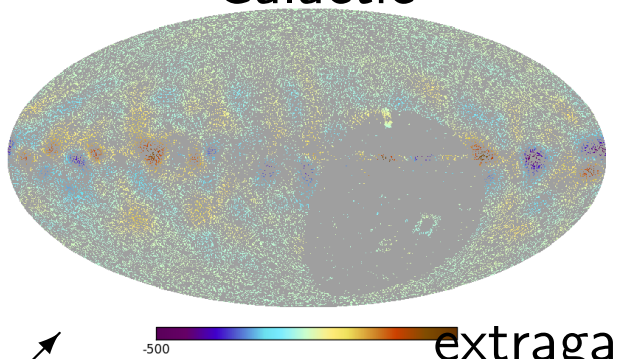
$$d = \phi_{\mathrm{MW}} + \phi_{\mathrm{extragalactic}} + n$$

data



=

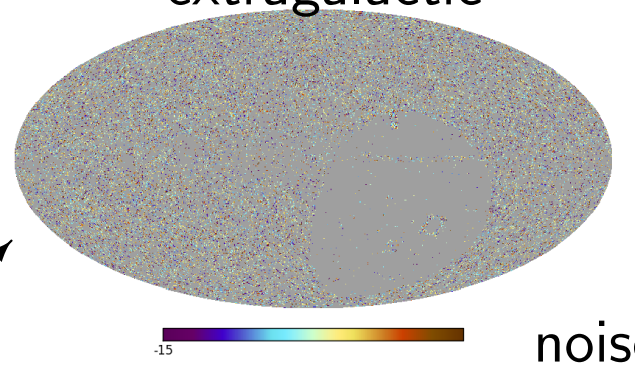
Galactic



correlated

+

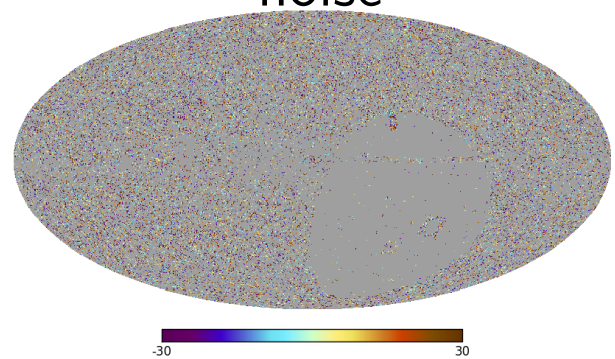
extragalactic

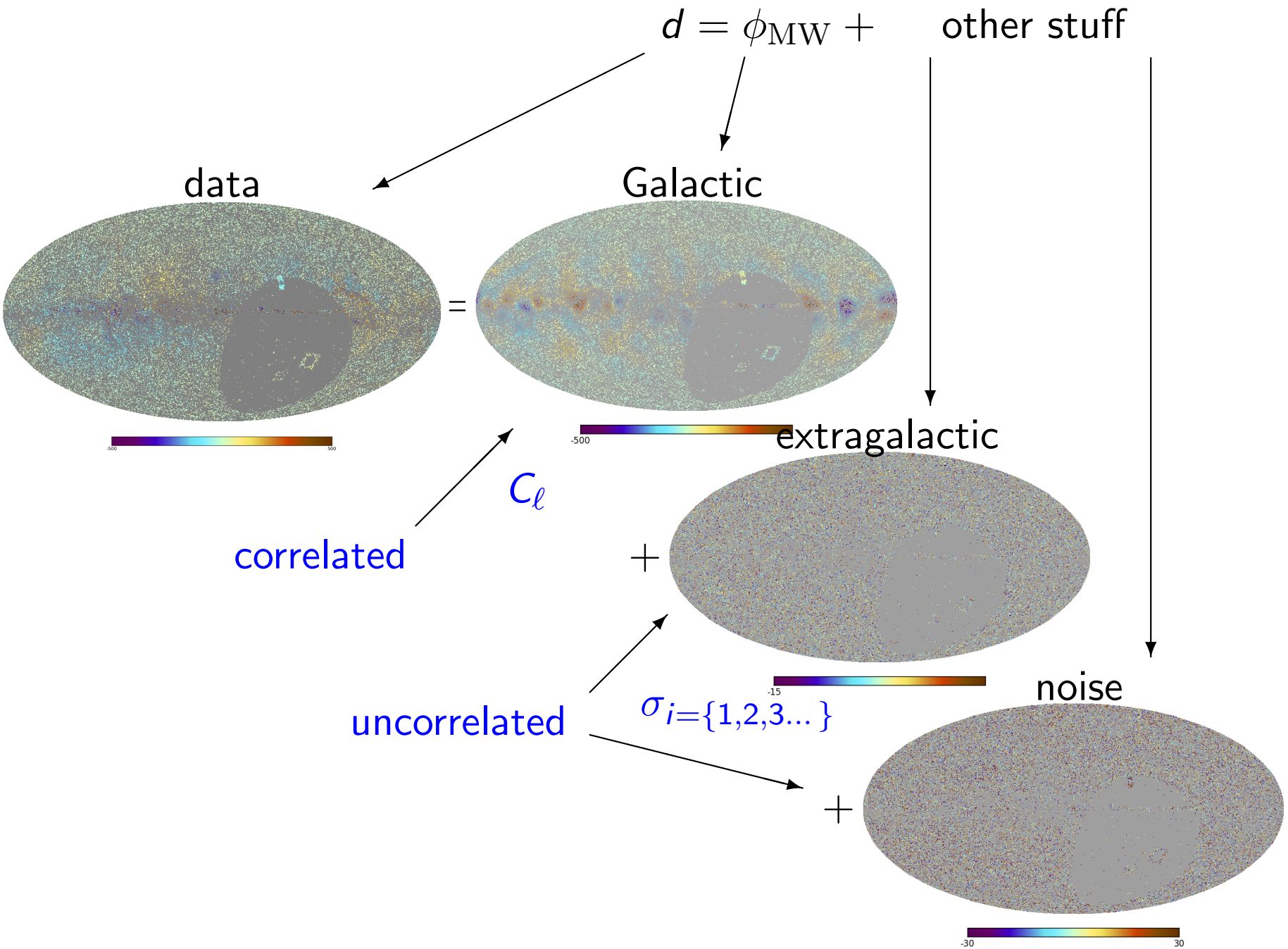


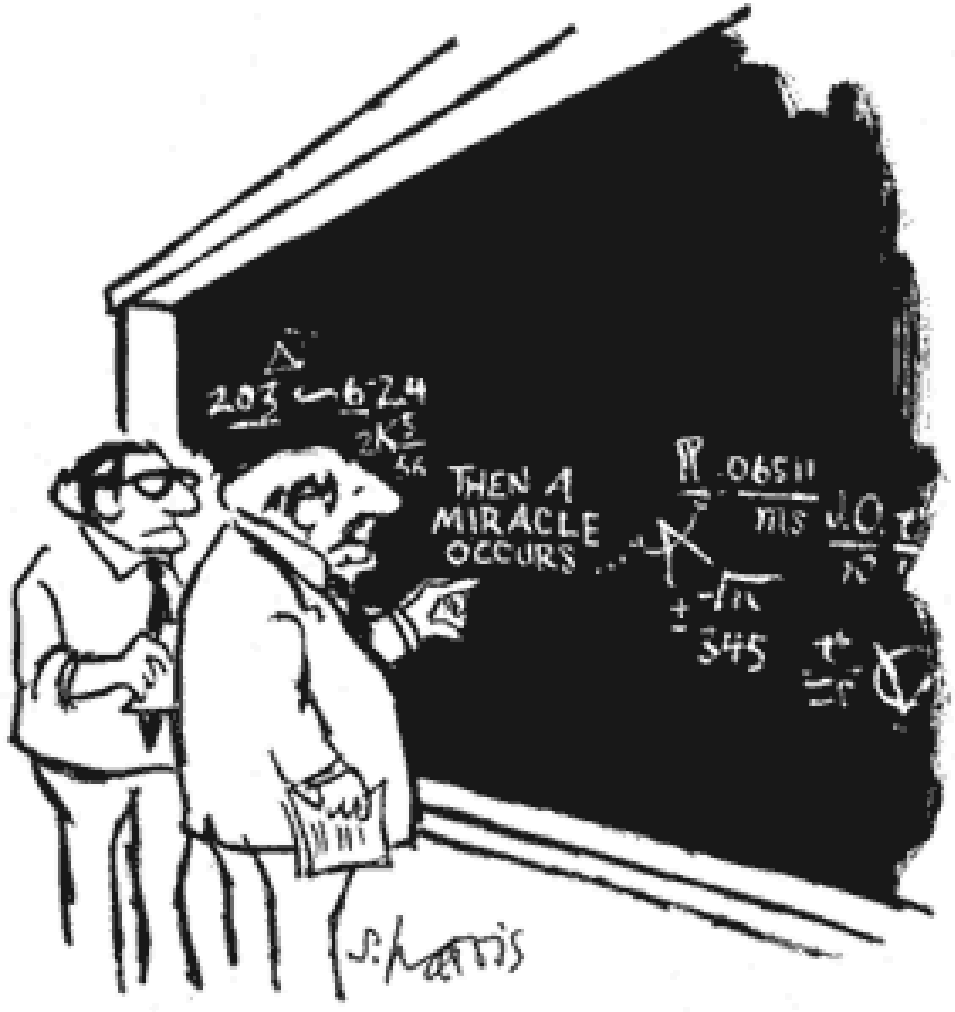
uncorrelated

+

noise

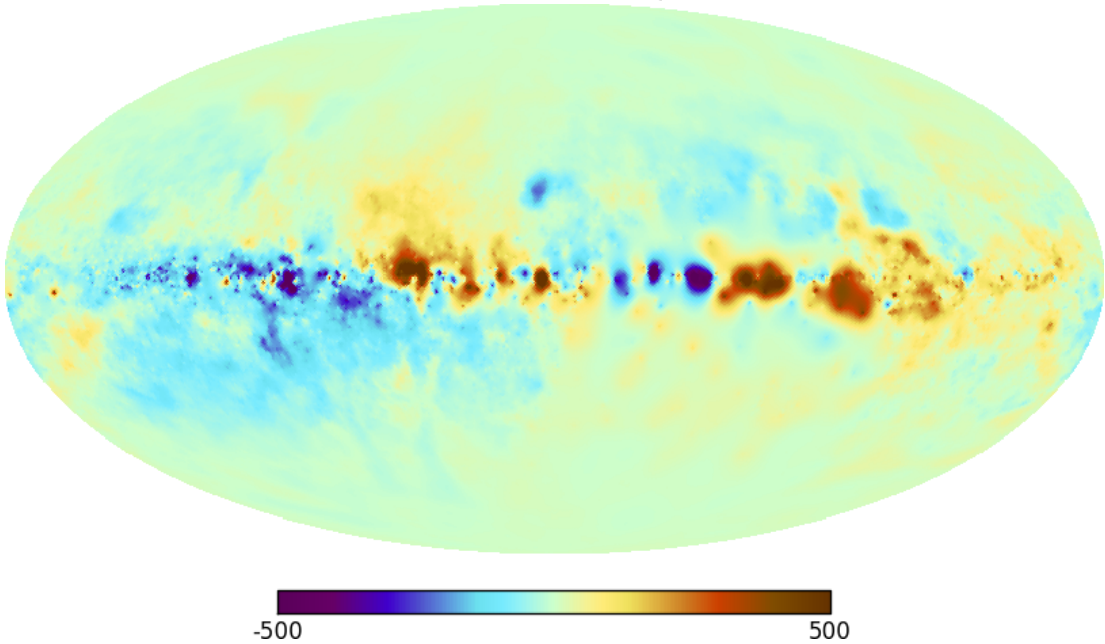



$d = \phi_{\rm MW} +$
other stuff
data
Galactic
=
-500
extragalactic
C_ℓ
correlated
+
-15
uncorrelated
$\sigma_{i=\{1,2,3...\}}$
noise
+
-30
30

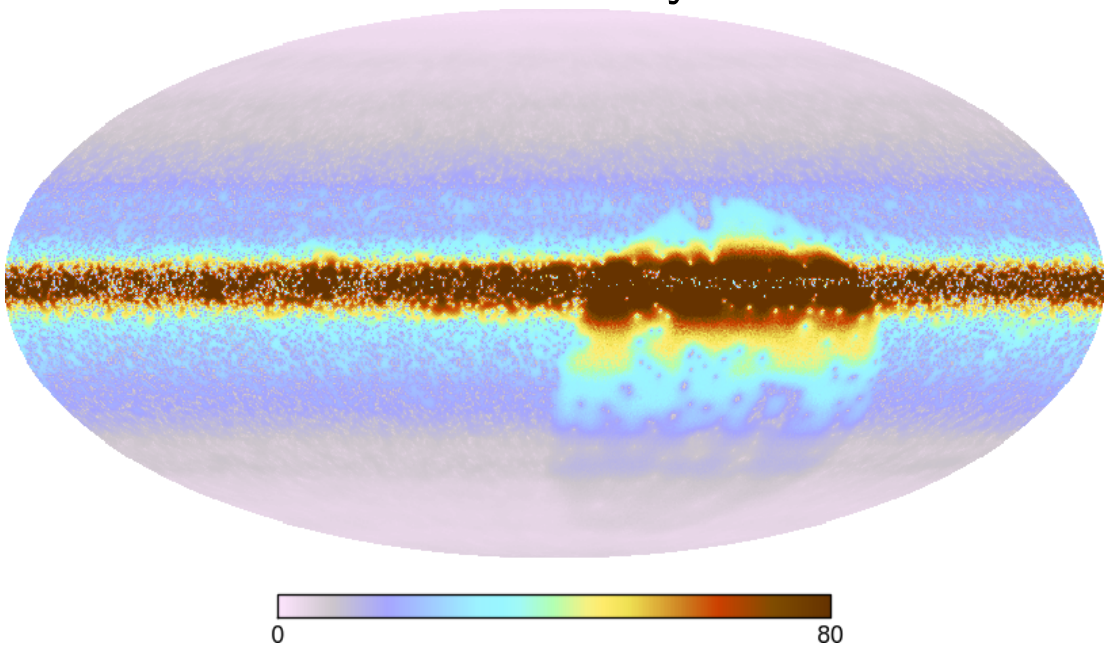


"I THINK YOU SHOULD BE MORE EXPLICIT HERE IN STEP TWO."

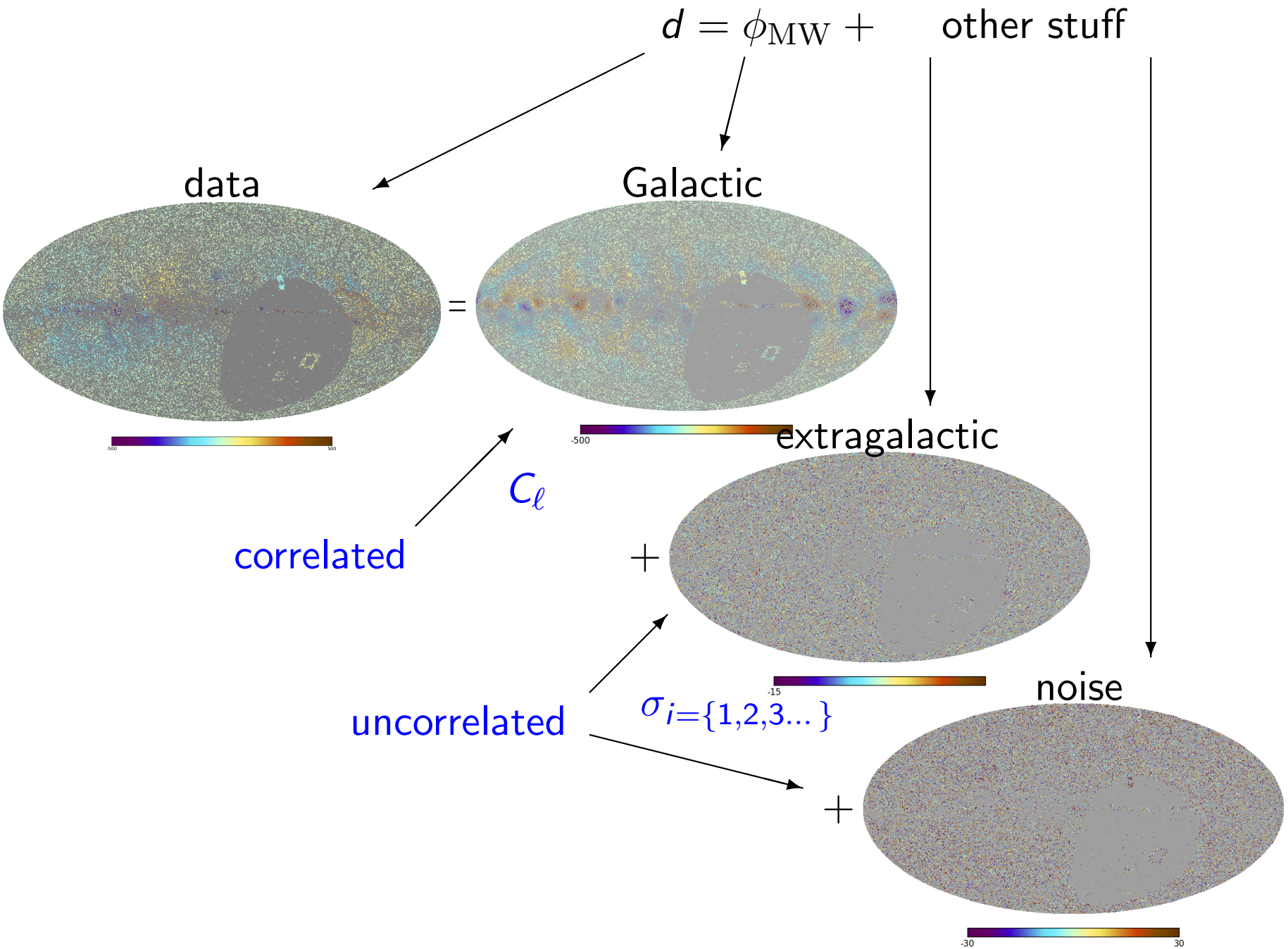
Galactic Faraday depth



uncertainty

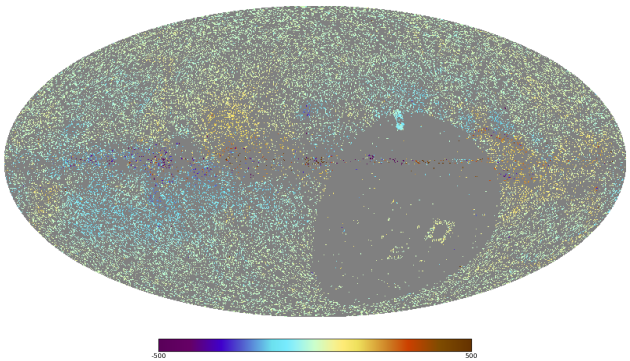


NO et al., A&A, 2012/2015; arXiv:1111.6186/ arXiv:1404.3701


$d = \phi_{\rm MW} +$
other stuff
data
Galactic
=
-500
extragalactic
C_ℓ
correlated
+
-15
uncorrelated
$\sigma_{i=\{1,2,3...\}}$
noise
+
-30
30

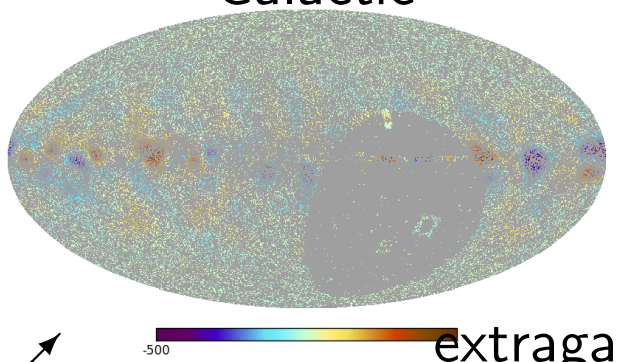
$$d = \phi_{\mathrm{MW}} + \phi_{\mathrm{extragalactic}} + n$$

data

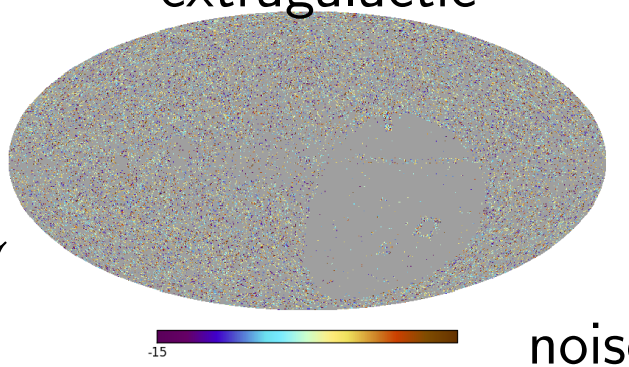


=

Galactic



extragalactic



correlated

C_ℓ

+

σ_{e}

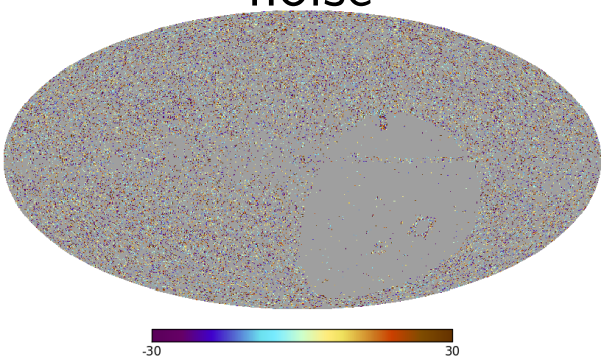
uncorrelated

degenerate

$\sigma_{i=\{1,2,3,\ldots\}}$

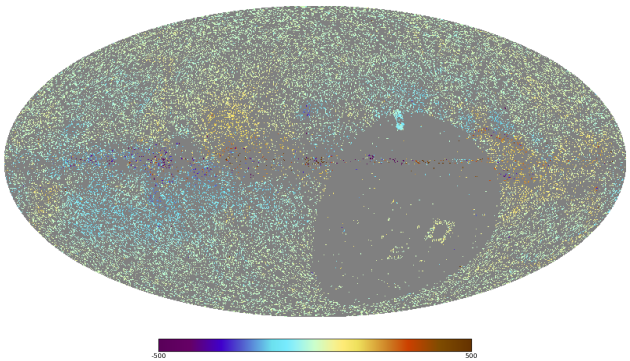
noise

+



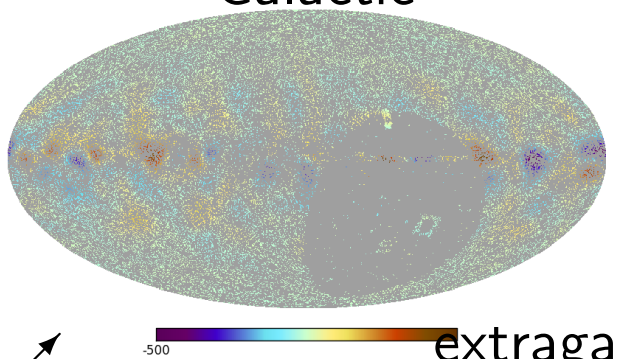
$$d = \phi_{\mathrm{MW}} + \phi_{\mathrm{extragalactic}} + n$$

data

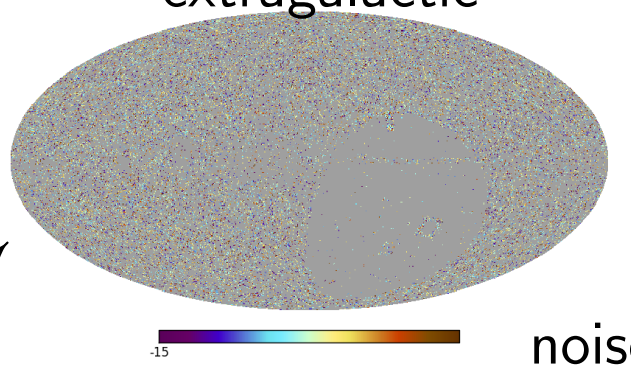


=

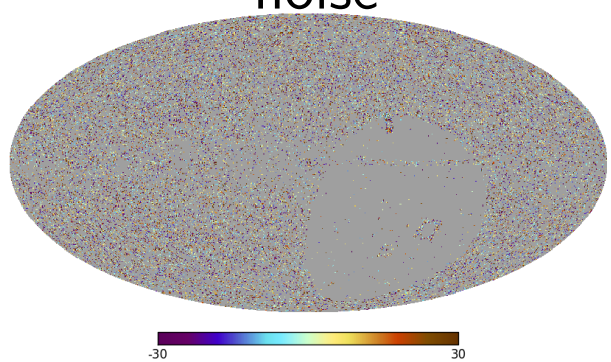
Galactic



extragalactic



noise



correlated

C_ℓ

uncorrelated

degenerate

σ_{e}

$\sigma_{i=\{1,2,3,\ldots\}}$

idea: find subset of data for which noise statistics are perfectly known

Results:

- $\sigma_{\mathrm{e}} \lesssim 7\,\mathrm{rad/m^2}$
- constraints on extragalactic contributions for individual sources very weak

NO et al., A&A, 2015; arXiv:1404.3701

What magnetic fields is this due to?

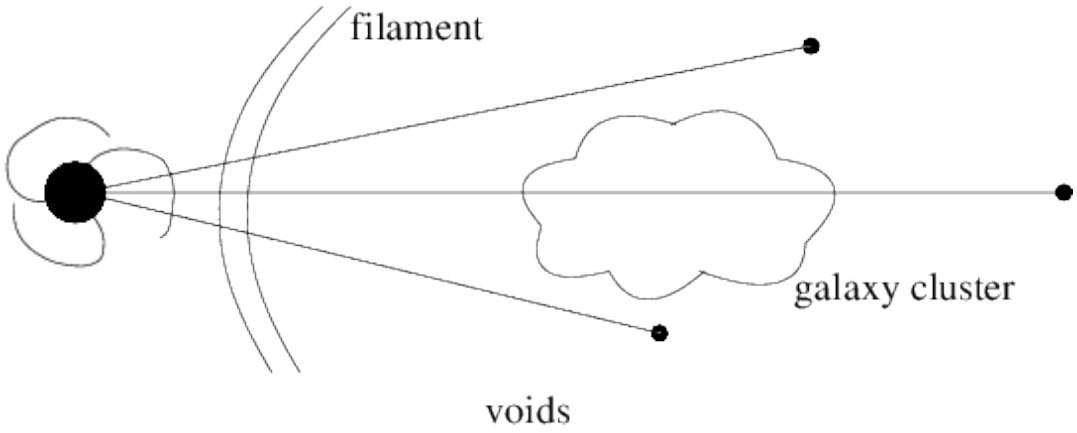
Results:

- $\sigma_{\rm e} \lesssim 7\,{\rm rad/m^2}$
- constraints on extragalactic contributions for individual sources very weak

NO et al., A&A, 2015; arXiv:1404.3701

Faraday Depth

slide courtesy of V. Vacca



$$d_i = \phi_{\mathrm{g},i} + \phi_{\mathrm{e},i} + n_i$$

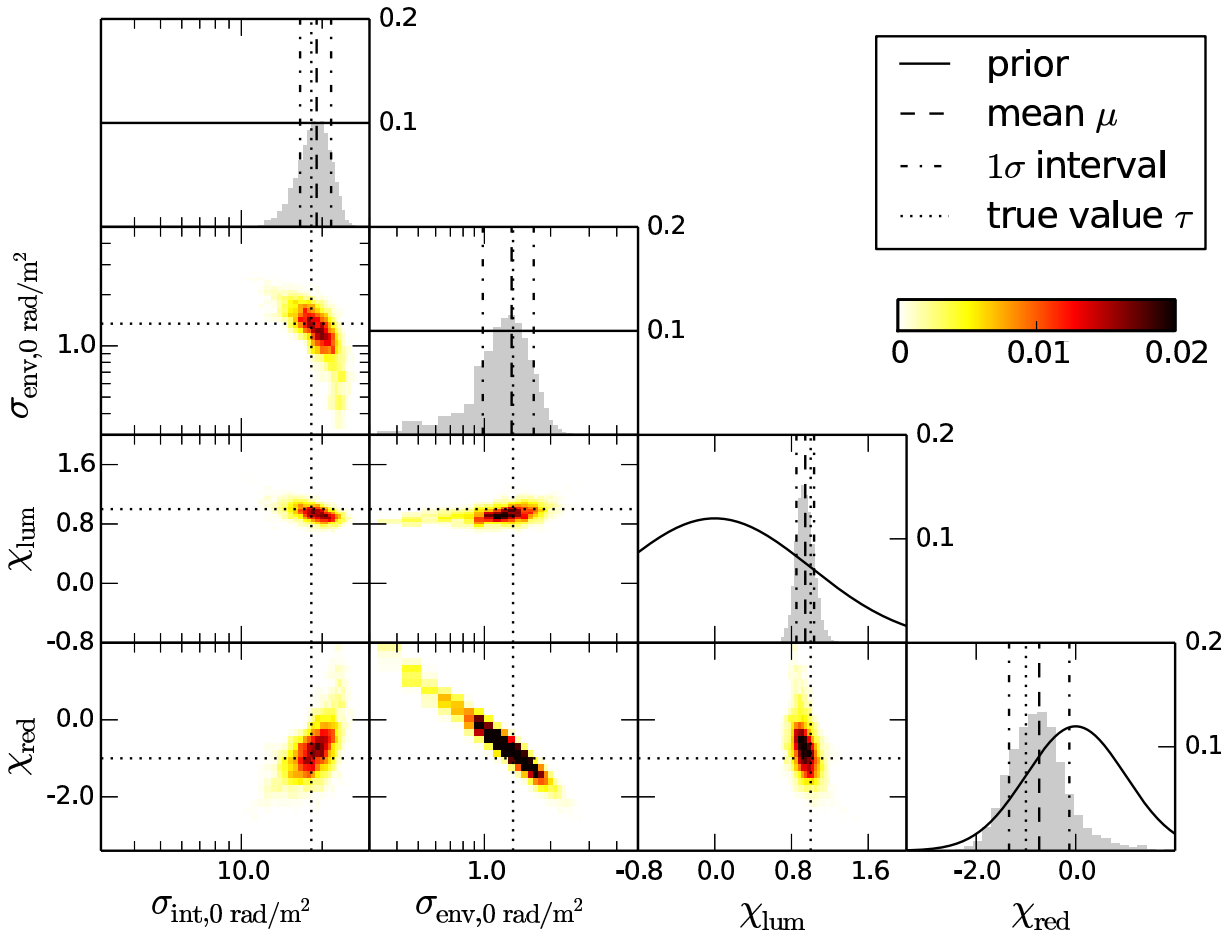
$$\langle \phi^2_{\mathrm{e},i} \rangle \approx \sigma^2_{\mathrm{int},i} + \sigma^2_{\mathrm{env},i}$$

$$\approx \left(\frac{L_i}{L_0} \right)^{\chi_{\mathrm{lum}}} \frac{\sigma^2_{\mathrm{int},0}}{(1+z_i)^4} + \frac{D(z_i, \chi_{\mathrm{red}})}{D_0} \sigma^2_{\mathrm{env},0}$$

Vacca et al. (arXiv:1509.00747)

$$\left\langle \phi_{\mathrm{e},i}^2 \right\rangle \propto \left(\frac{L_i}{L_0} \right)^{\chi_{\mathrm{lum}}} \frac{\sigma_{\mathrm{int}}^2}{(1+z_i)^4} + \frac{D_i}{D_0} \sigma_{\mathrm{env}}^2$$

$$D_i = \int_0^{z_i} \frac{c}{H(z)} (1+z)^{4+\chi_{\mathrm{red}}} \, \mathrm{d}z$$

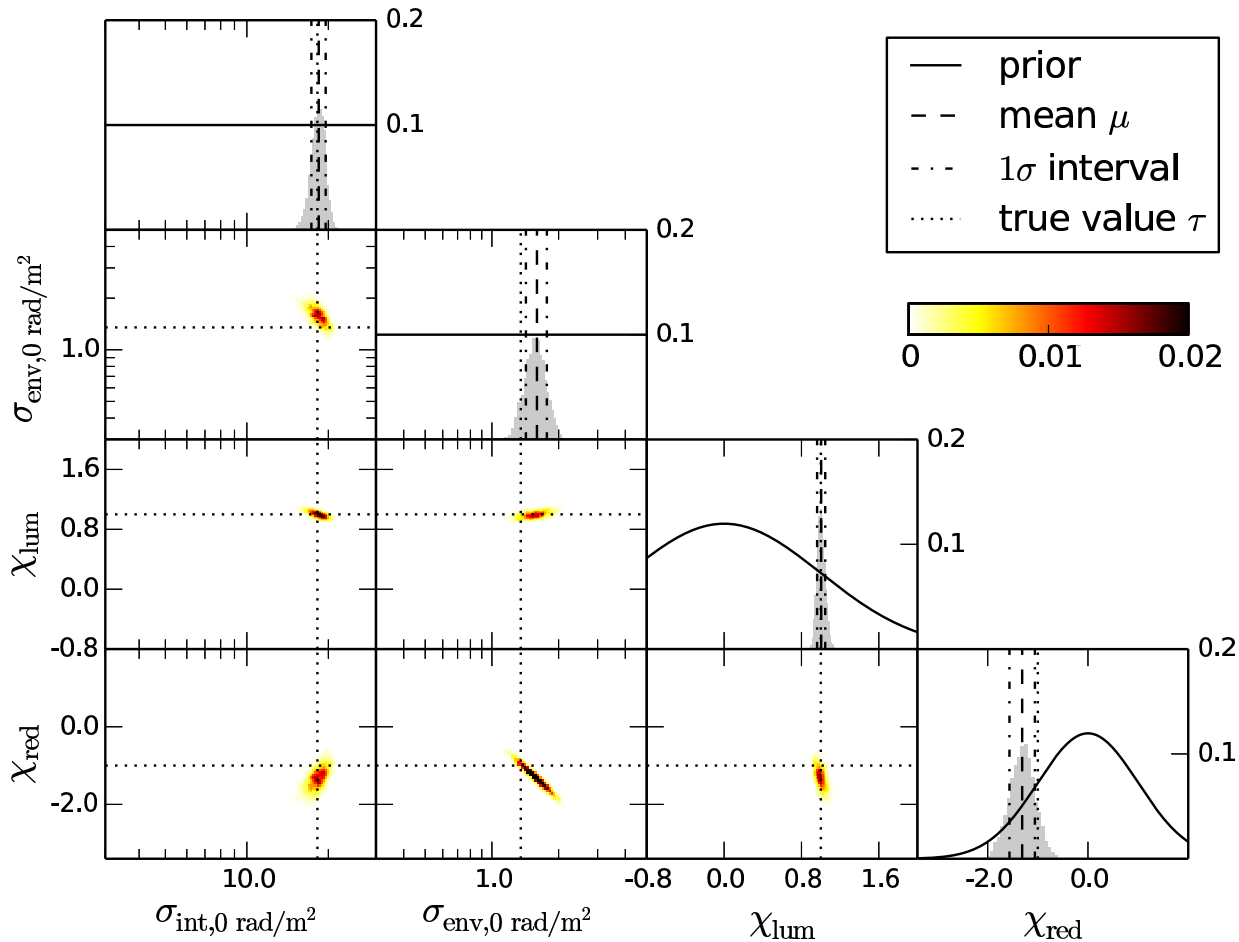


4003 lines of sight

V. Vacca, NO, et al.; arXiv:1509.00747

$$\left\langle \phi^2_{\mathrm{e},i} \right\rangle \propto \left(\frac{L_i}{L_0} \right)^{\chi_{\mathrm{lum}}} \frac{\sigma^2_{\mathrm{int}}}{(1+z_i)^4} + \frac{D_i}{D_0}\,\sigma^2_{\mathrm{env}}$$

$$D_i = \int_0^{z_i} \frac{c}{H(z)}\,(1+z)^{4+\chi_{\mathrm{red}}}\,\mathrm{d}z$$

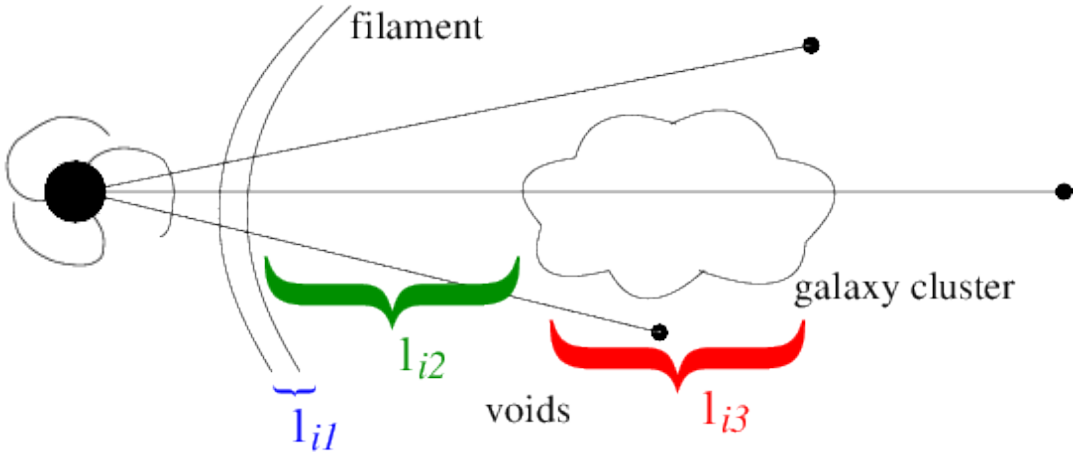


41632 lines of sight

V. Vacca, NO, et al.; arXiv:1509.00747

Further disentagling

slide courtesy of V. Vacca



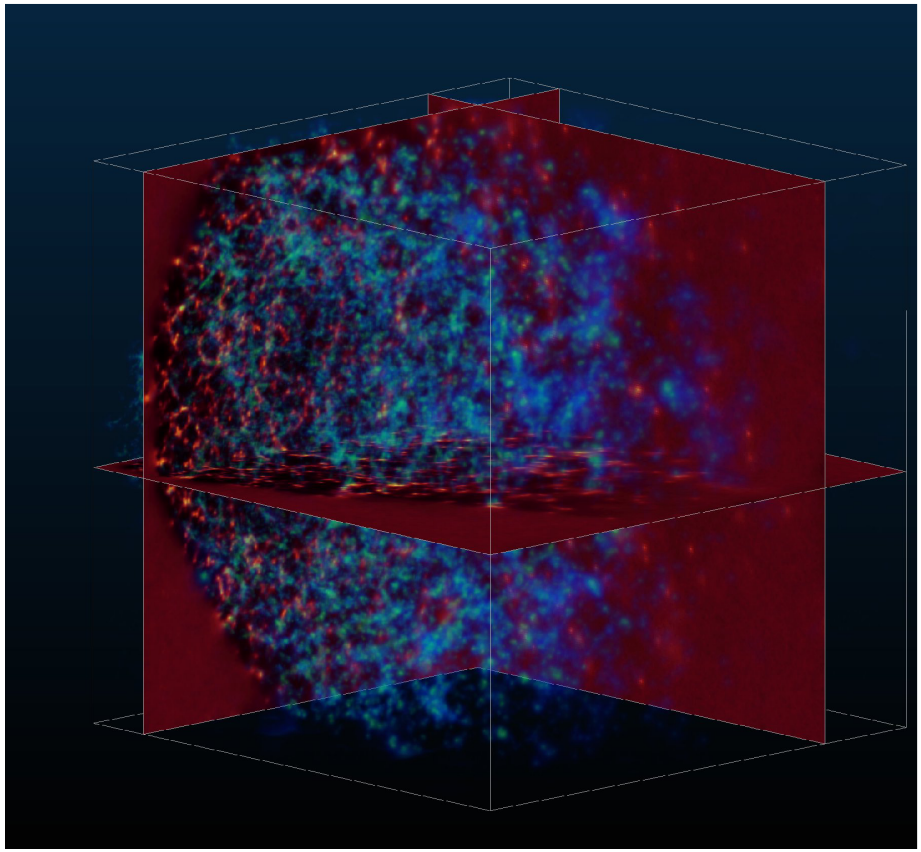
$$\langle \phi^2_{\mathrm{e},i} \rangle \approx \left[\left(\frac{L_i}{L_0} \right)^{\chi_{\mathrm{lum}}} \frac{\sigma^2_{\mathrm{int},0}}{(1+z_i)^4} + \sum_{j=1}^{N_{\mathrm{env}}} l_{ij} \sigma^2_j \right]$$

$$\approx \left[\left(\frac{L_i}{L_0} \right)^{\chi_{\mathrm{lum}}} \frac{\sigma^2_{\mathrm{int},0}}{(1+z_i)^4} + l_{i1}\sigma^2_1 + l_{i2}\sigma^2_2 + l_{i3}\sigma^2_3 + l_{i4}\sigma^2_4 + l_{i5}\sigma^2_5 \right]$$

Vacca et al. (arXiv:1509.00747)

Cosmic web reconstruction

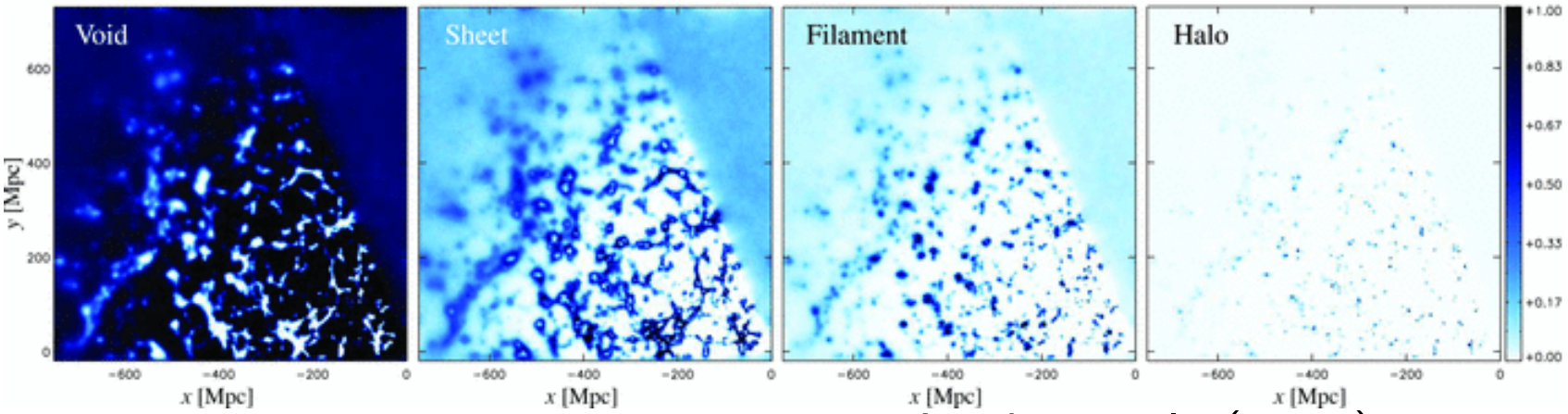
slide courtesy of V. Vacca



Jasche et al. (2010), see also Leclercq et al. (2015)

Cosmic web classification

slide courtesy of V. Vacca



Jasche et al. (2010)

$$\langle \phi^2_{\mathrm{e},i} \rangle \approx \left[\left(\frac{L_i}{L_0} \right)^{\chi_{\mathrm{lum}}} \frac{\sigma^2_{\mathrm{int},0}}{(1+z_i)^4} + \sum_{j=1}^{N_{\mathrm{env}}} l_{ij} \sigma^2_j \right]$$

Cosmic web structure, redshift catalog $\rightarrow$ length matrix l_{ij}

Summary

- Galactic contribution (correlated) can be separated from rest (uncorrelated)
- Rest can be separated statistically into extragalactic and noise
- Extragalactic contributions contain information on B-fields on cosmic scales
- Using parametric models and LSS information, this information can be extracted
- Uncertainties are large and need to be understood

Results available at
http://www.mpa-garching.mpg.de/ift/faraday/