

Cosmic magnetism revealed through Faraday rotation

Niels Oppermann



CITA
ICAT

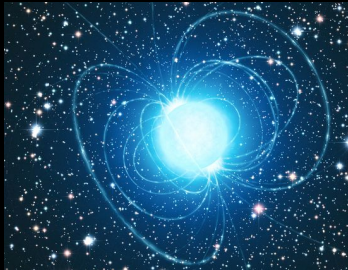
Canadian Institute for
Theoretical Astrophysics

L'institut Canadien
d'astrophysique théorique

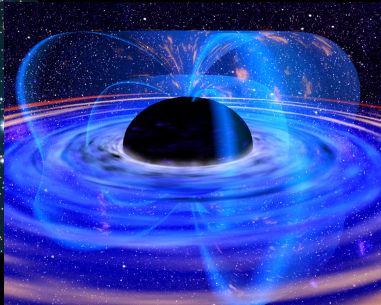
with: Valentina Vacca, Henrik Junklewitz, Torsten EnBlin
Bryan Gaensler, Dominic Schnitzeler, Jeroen Stil, Ann Mao, Jo-Anne Brown,

...

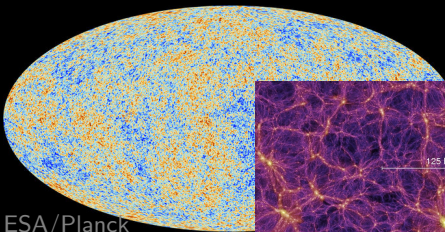
Bonn, 2015-07-20



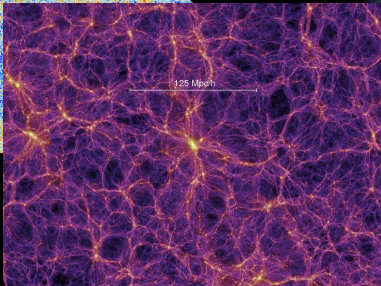
h+ magazine



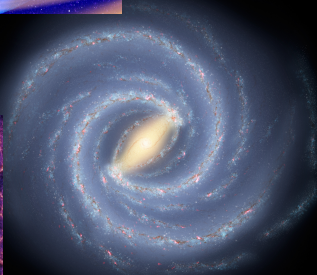
Dana Berry, NASA



ESA/Planck



MPA



NASA/JPL-Caltech



image credit: MPA

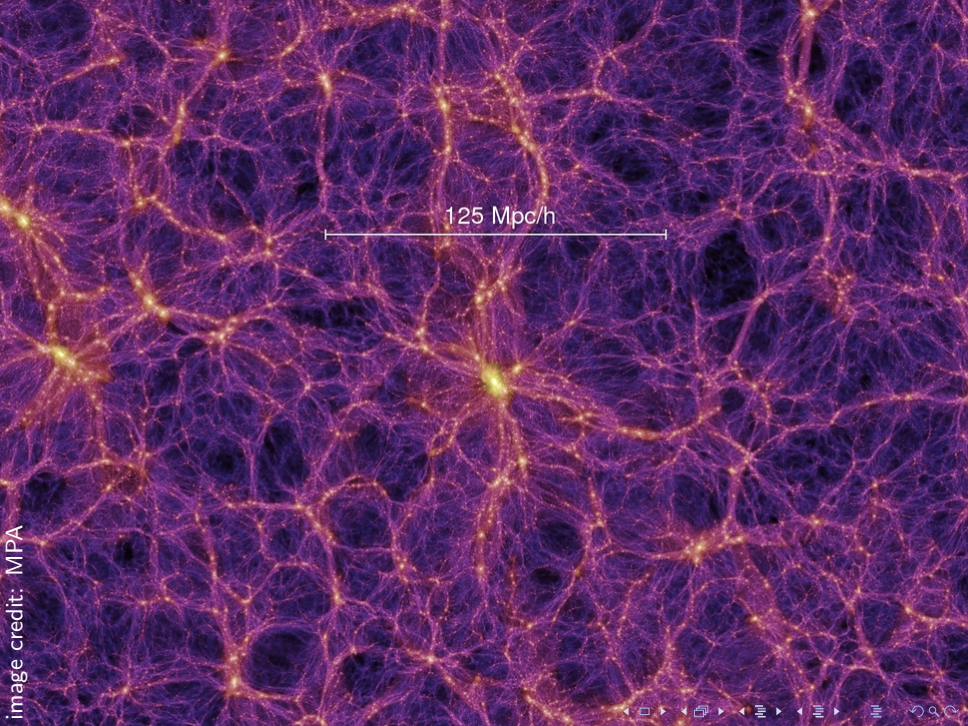
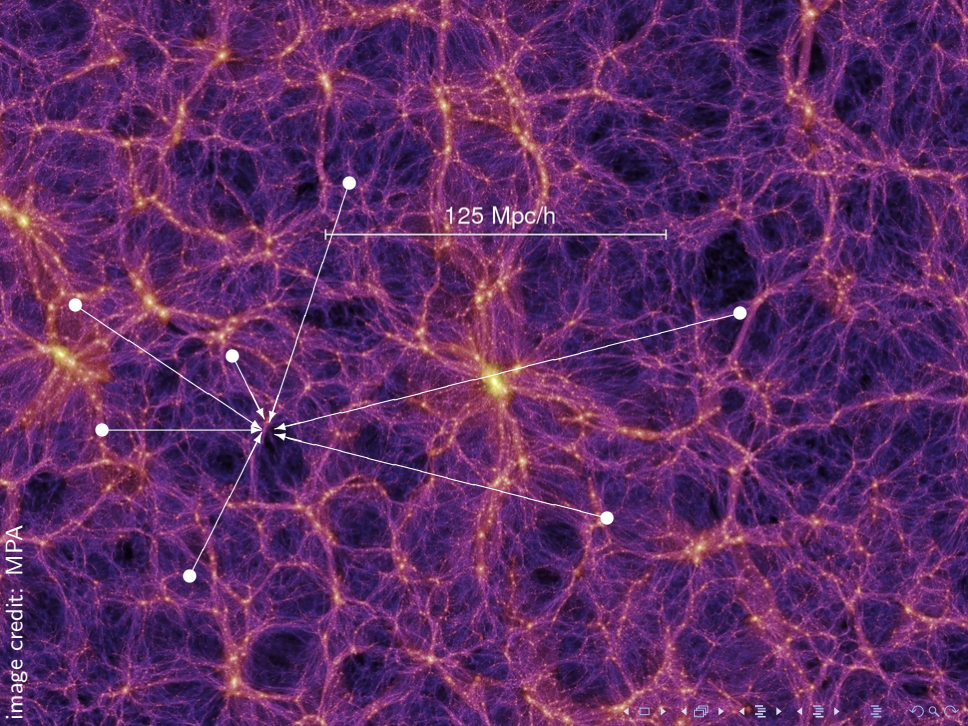
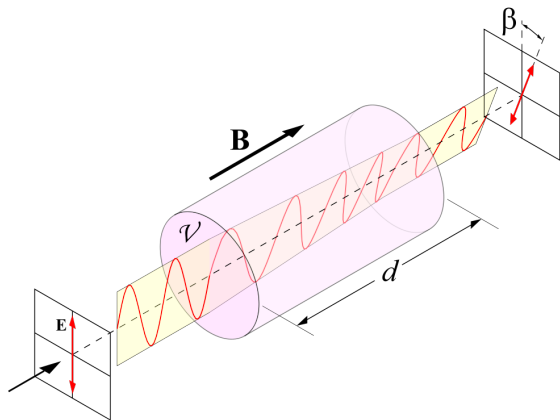


image credit: MPA



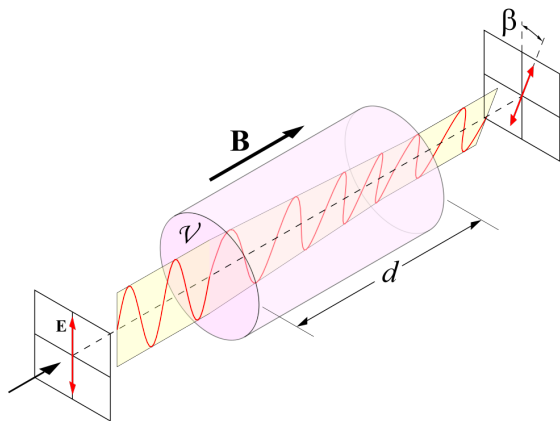
125 Mpc/h

Faraday rotation



$$d\beta \propto \lambda^2 n_e B_r dr$$
$$\Rightarrow \beta \propto \lambda^2 \int_{r_{\text{source}}}^0 (1+z)^{-2} n_e B_r dr$$

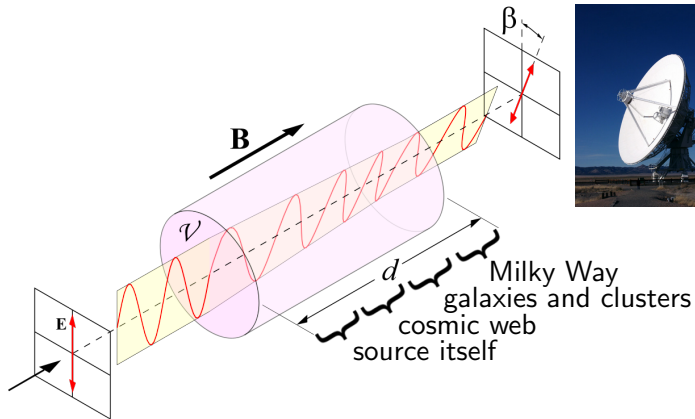
Faraday rotation

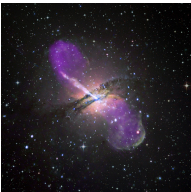


$$\text{Faraday depth: } \phi \propto \int_{r_{\text{source}}}^0 (1+z)^{-2} n_e B_r dr$$

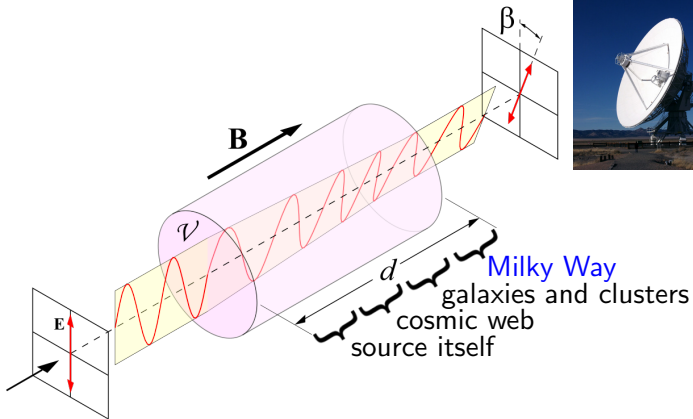
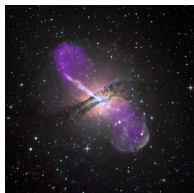
$$\beta = \phi \lambda^2$$

Faraday rotation




$$\text{Faraday depth: } \phi \propto \int_{r_{\text{source}}}^0 (1+z)^{-2} n_e B_r dr$$
$$\beta = \phi \lambda^2$$

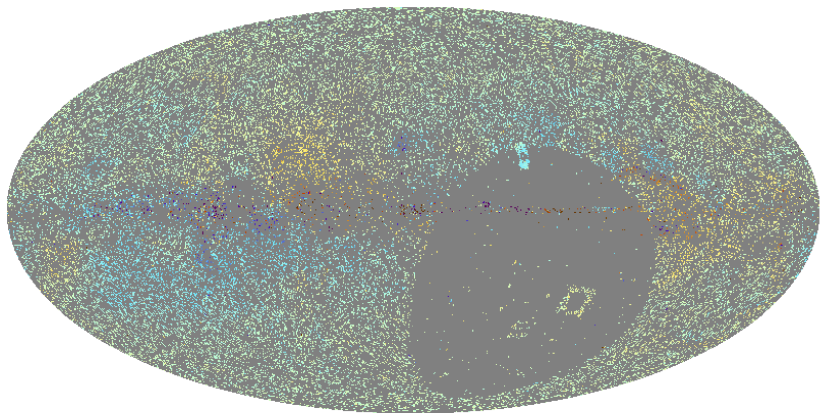
Extracting the Galactic contribution



Galactic Faraday depth:

$$\phi_{\text{MW}} \propto \int_{r_{\text{MilkyWay}}}^0 (1+z)^{-2} n_e B_r dr$$

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

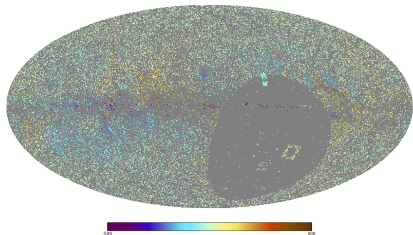


$\approx 40\,000$ data points

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

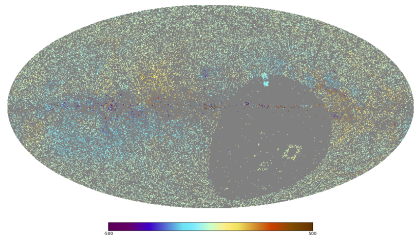
Challenges

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



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

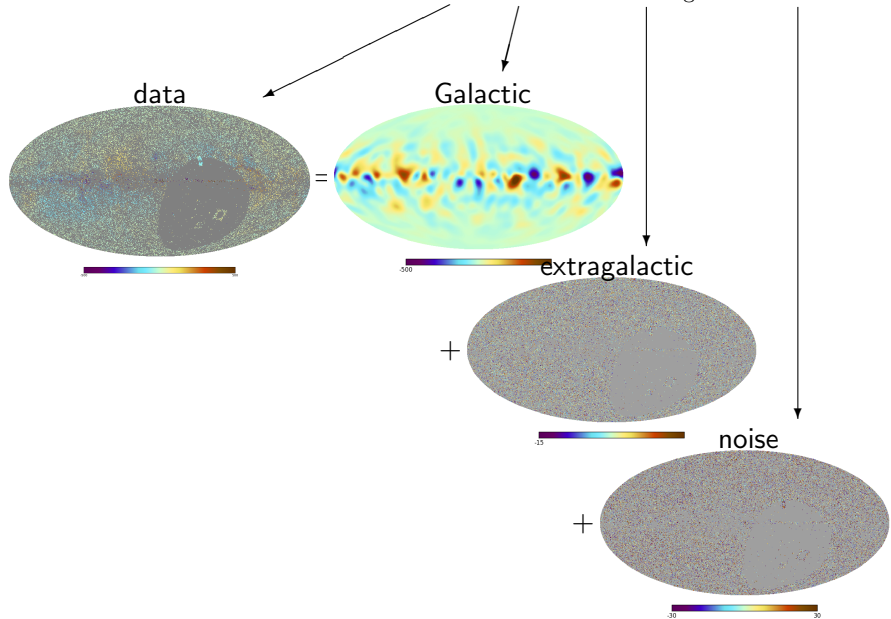
Challenges



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

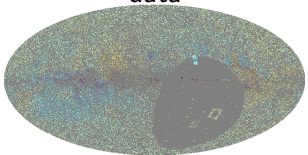
$$d = \phi_{\text{MW}} + \phi_{\text{extragalactic}} + n$$

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

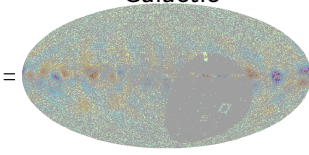


$$d = \phi_{\text{MW}} + \phi_{\text{extragalactic}} + n$$

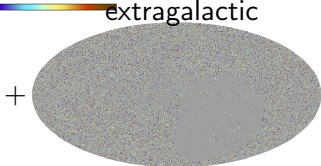
data



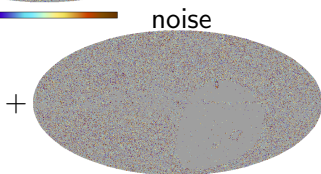
Galactic

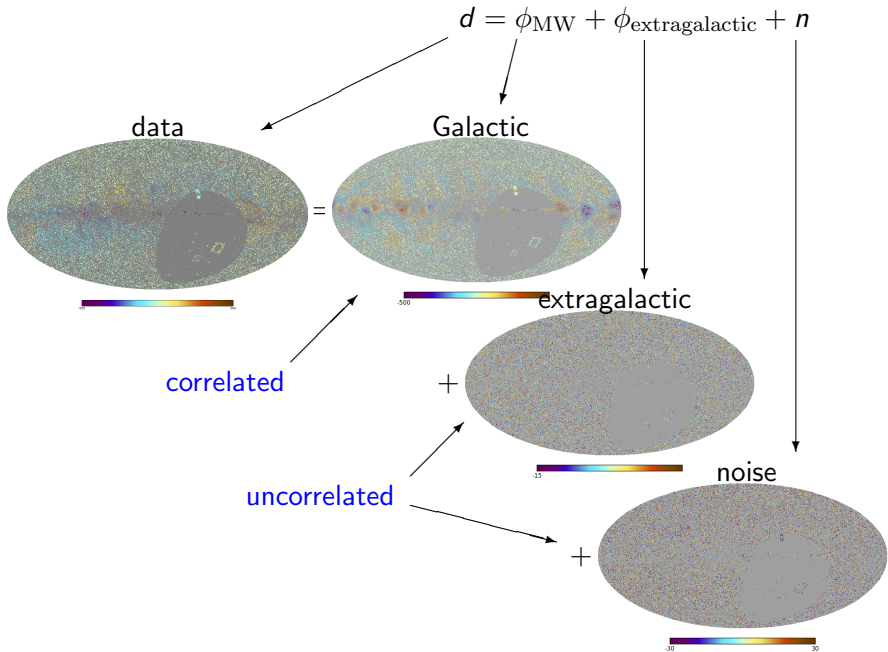


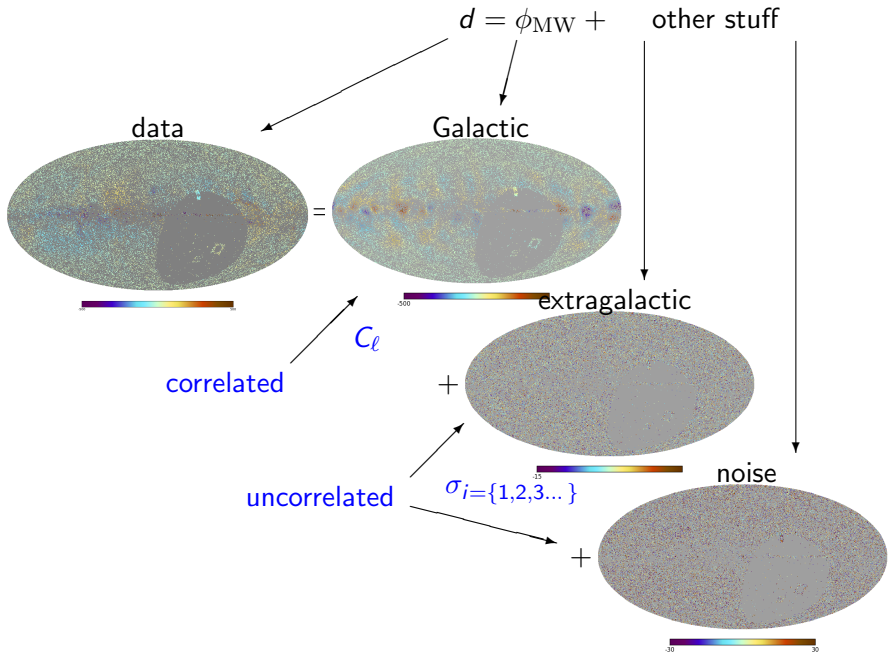
extragalactic



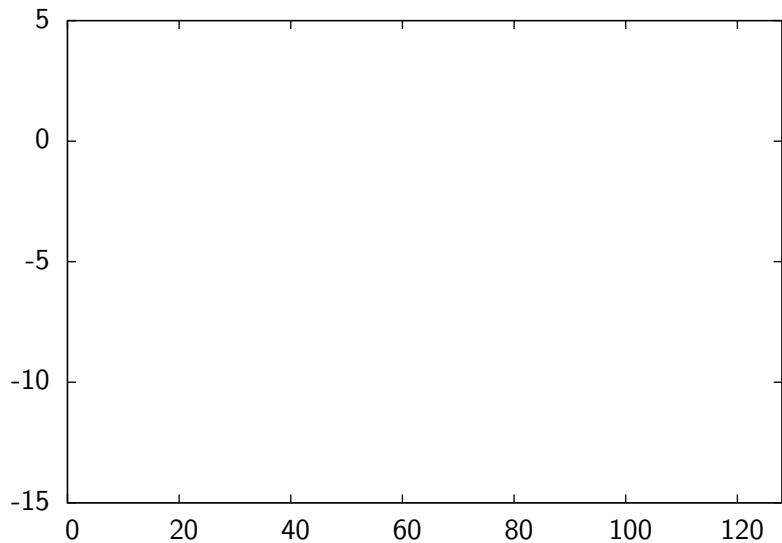
noise



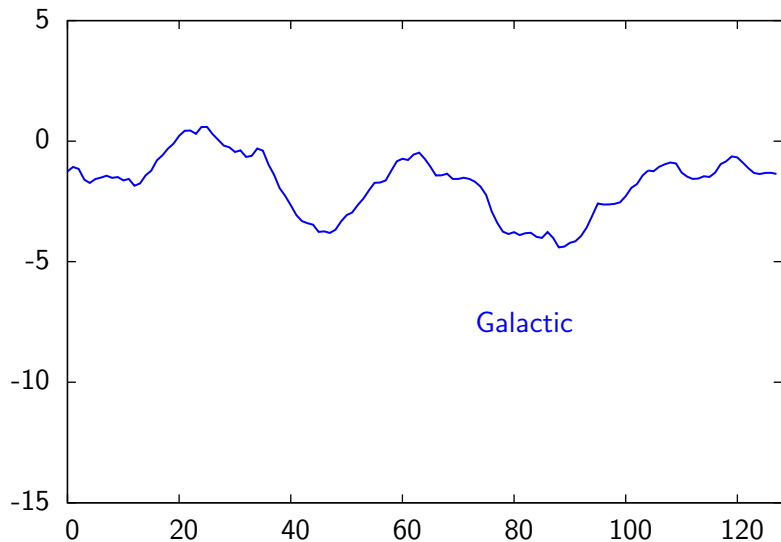




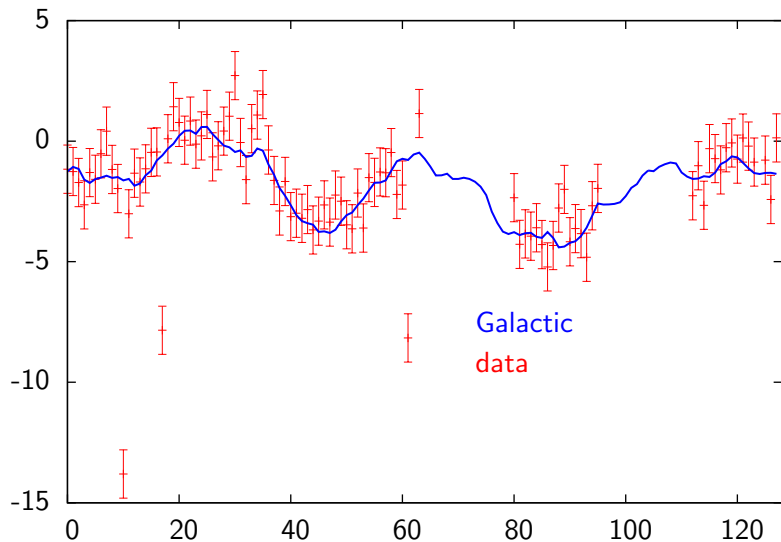
1D example



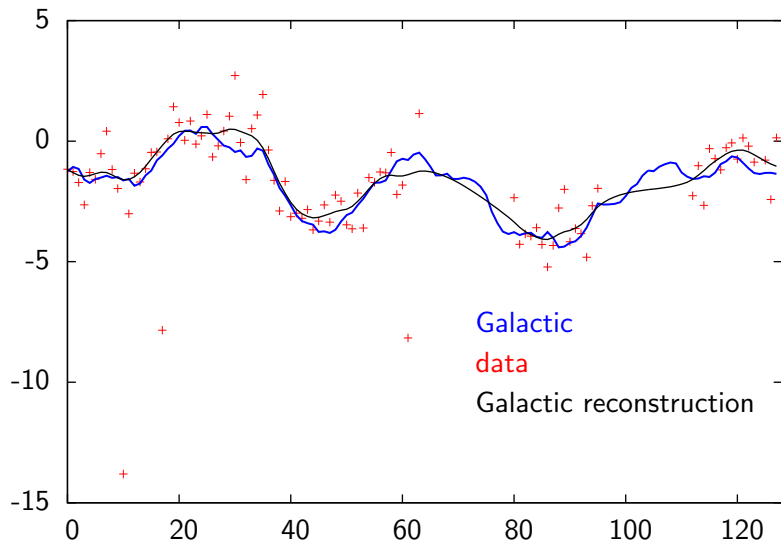
1D example



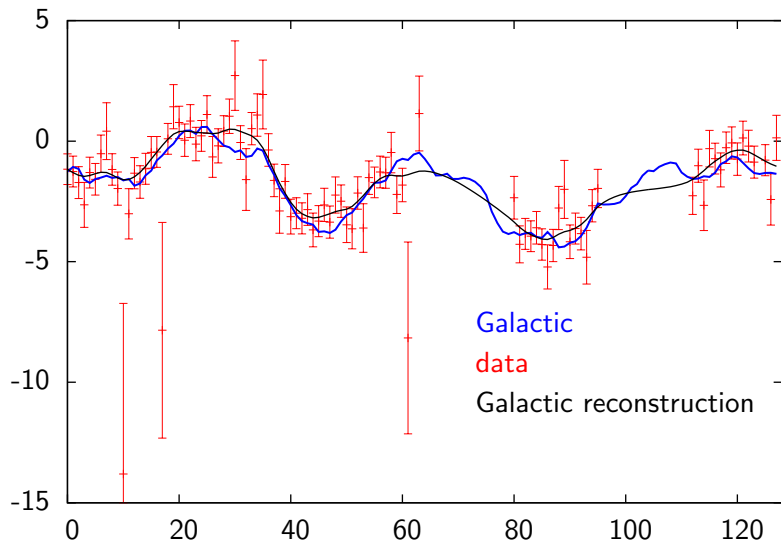
1D example



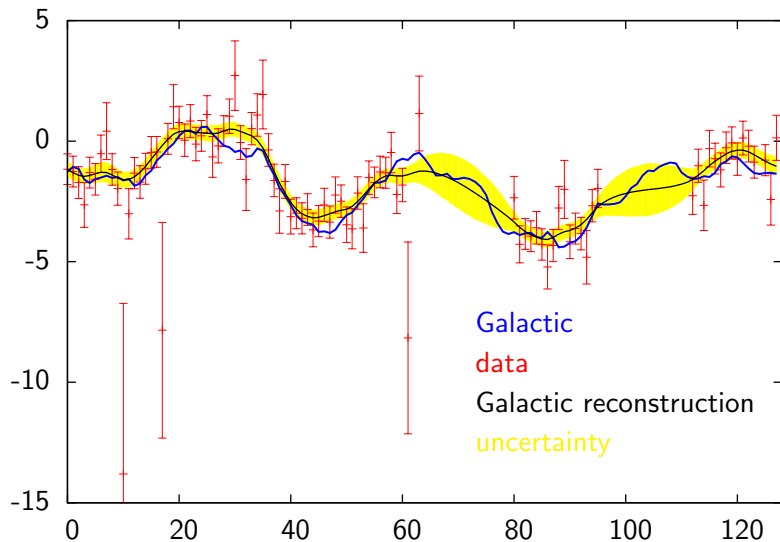
1D example



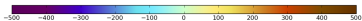
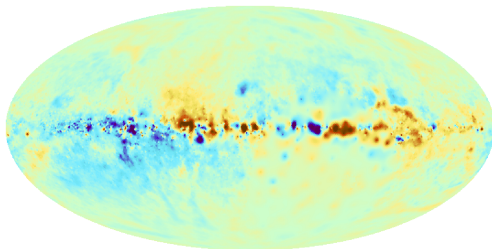
1D example



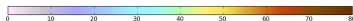
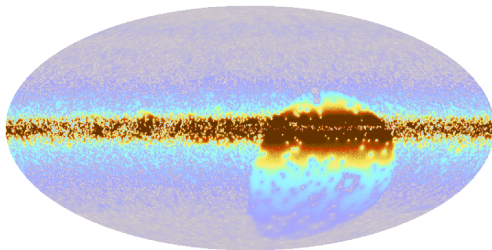
1D example



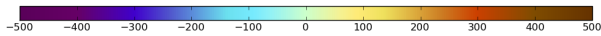
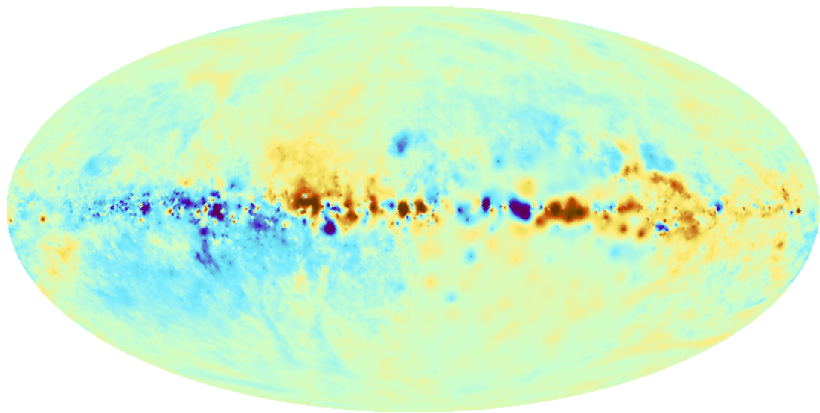
Galactic Faraday depth



uncertainty

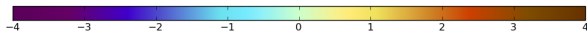
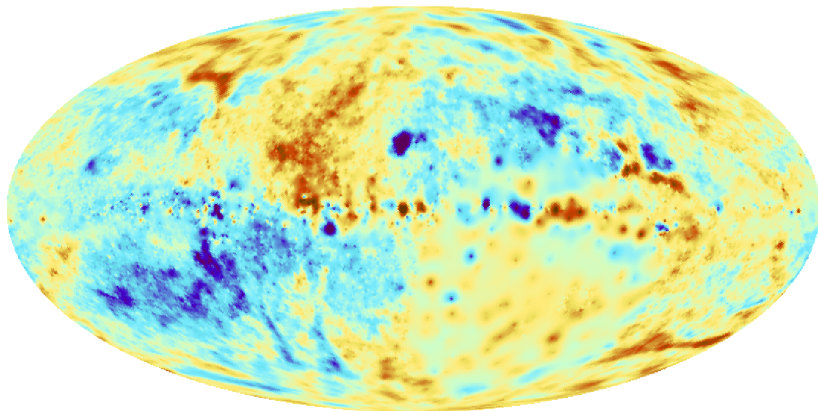


Galactic Faraday depth



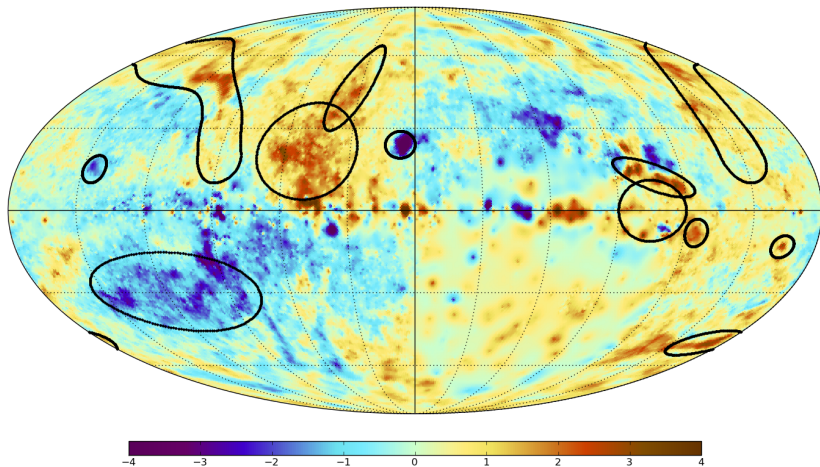
NO et al., A&A, 2012/2015; arXiv:1111.6186/1404.3701

rescaled Galactic Faraday depth



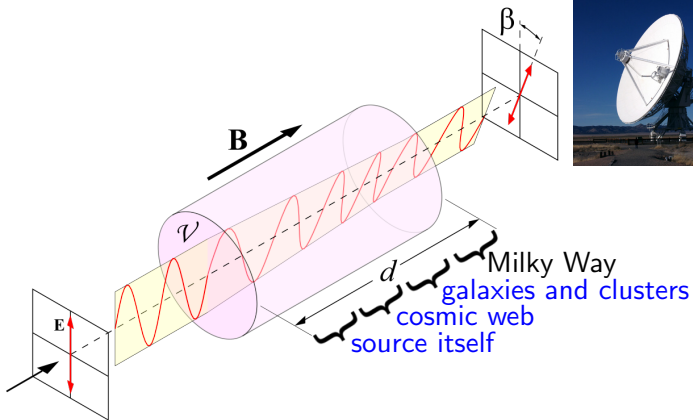
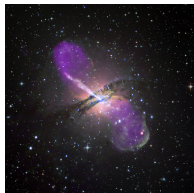
NO et al., A&A, 2012/2015; arXiv:1111.6186/1404.3701

rescaled Galactic Faraday depth



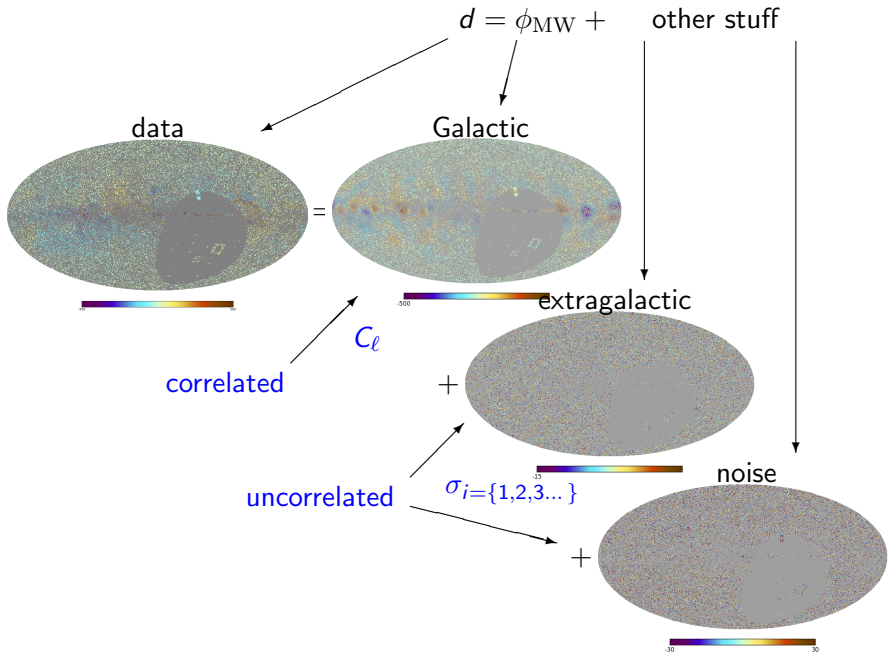
NO et al., A&A, 2012/2015; arXiv:1111.6186/1404.3701

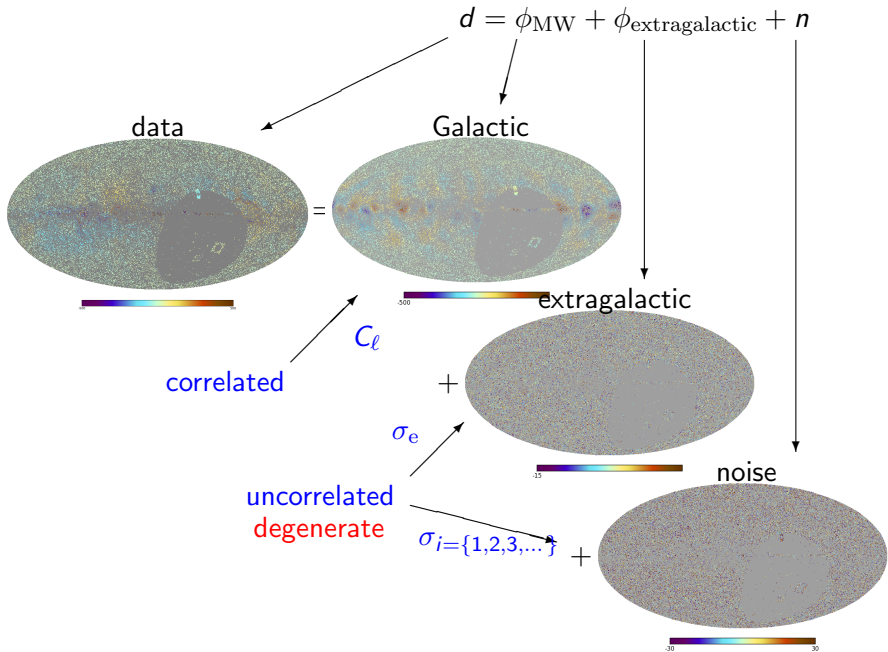
Extracting the extragalactic contribution

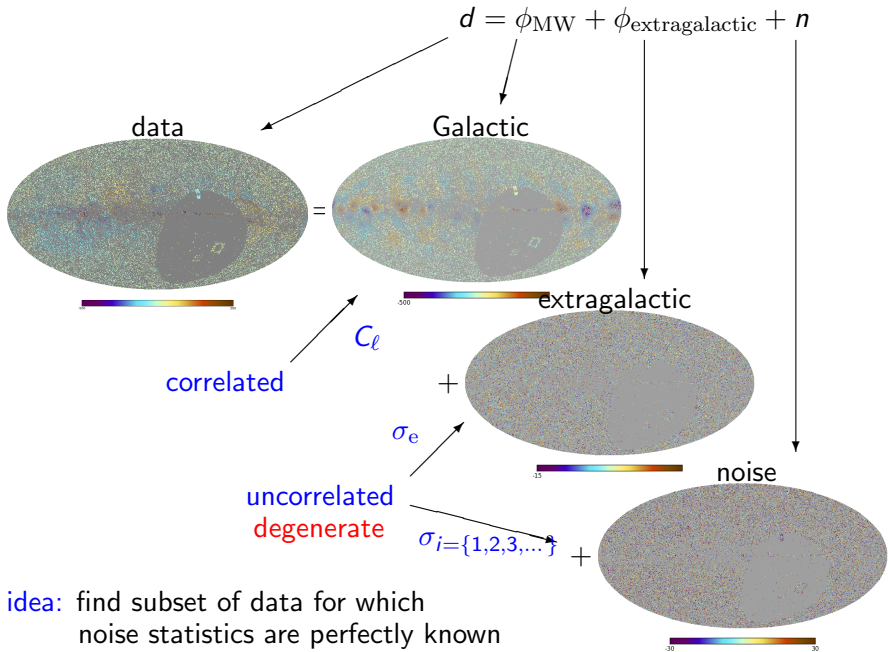


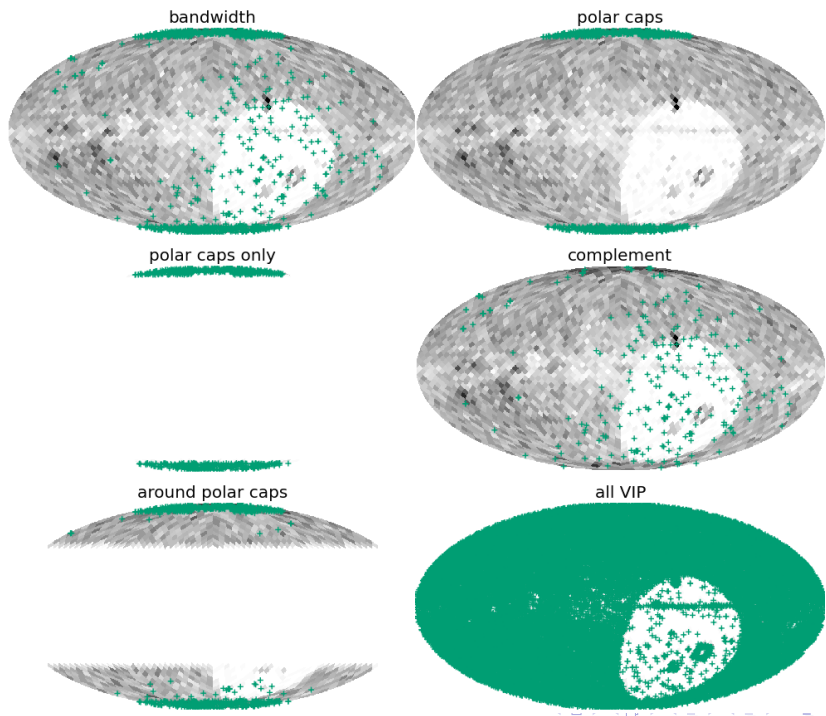
extragalactic Faraday depth:

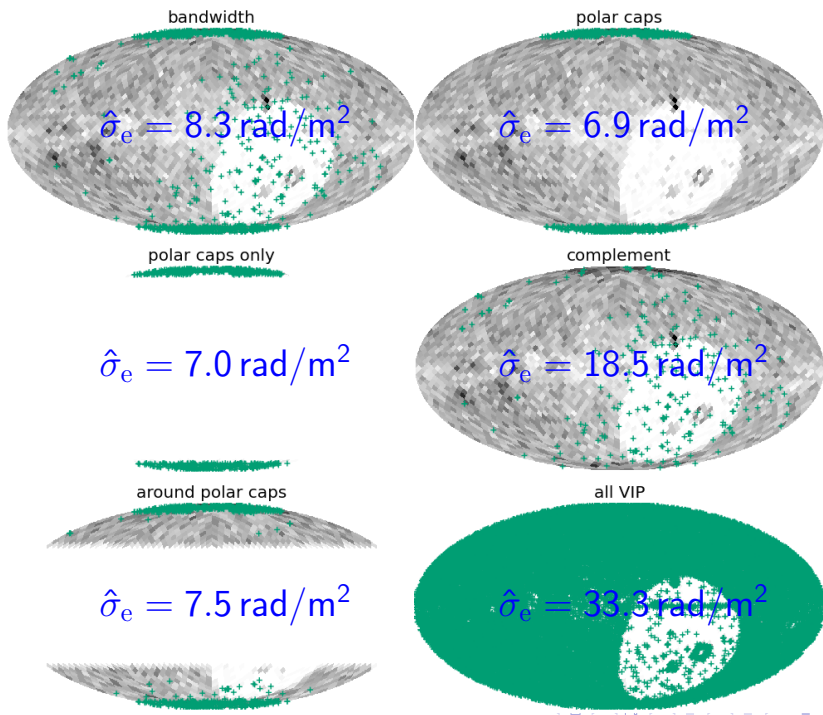
$$\phi_{\text{extragalactic}} \propto \int_{r_{\text{source}}}^{r_{\text{MilkyWay}}} (1+z)^{-2} n_e B_r dr$$

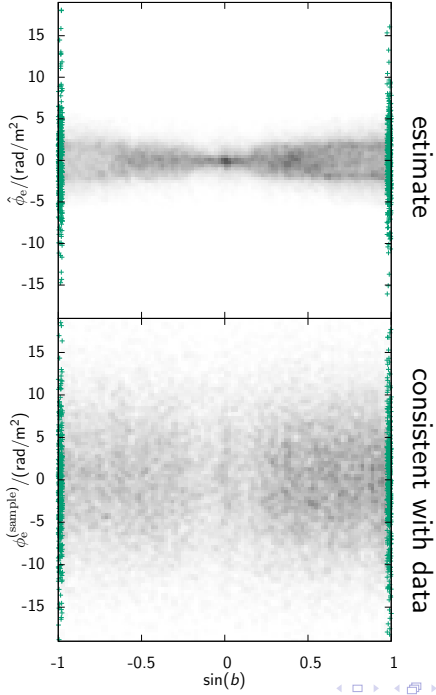




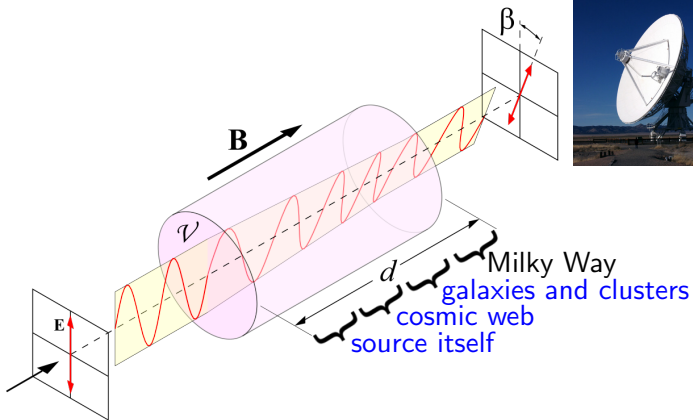
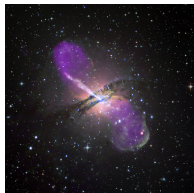






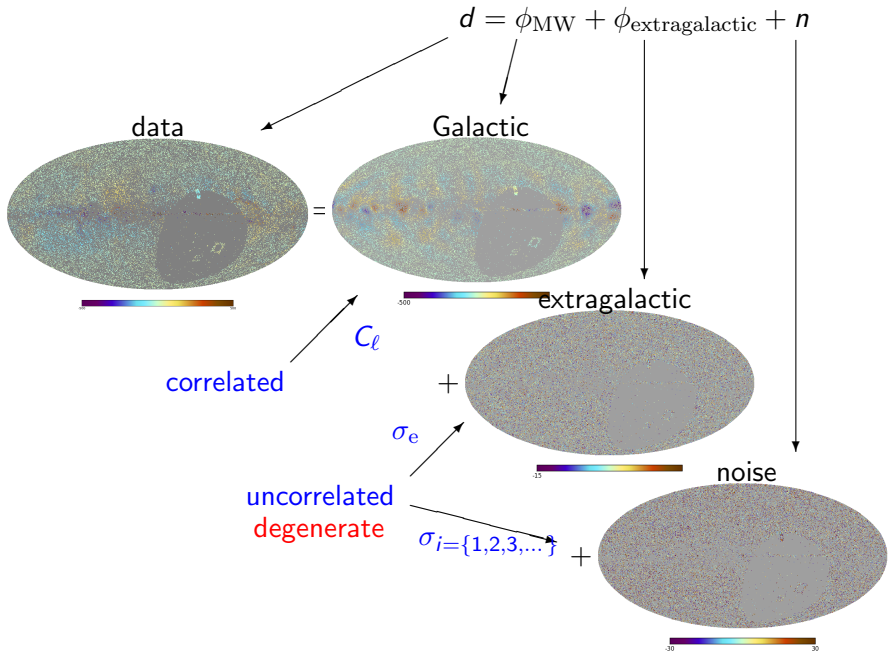


What is the extragalactic contribution?



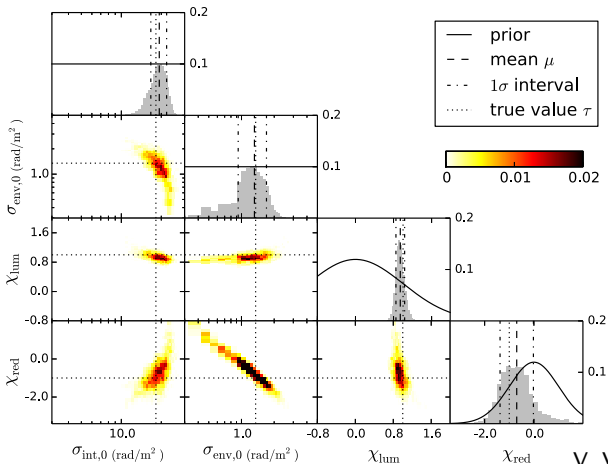
extragalactic Faraday depth:

$$\phi_{\text{extragalactic}} \propto \int_{r_{\text{source}}}^{r_{\text{MilkyWay}}} (1+z)^{-2} n_e B_r dr$$



$$\sigma_{e,i}^2 \propto \left(\frac{L}{L_0} \right)^{\chi_{\text{lum}}} \frac{\sigma_{\text{int}}^2}{(1+z_i)^4} + \frac{D_i}{D_0} \sigma_{\text{env}}^2$$

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

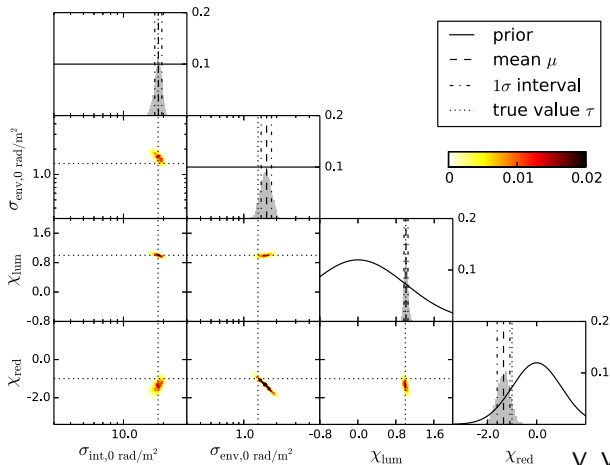


4003 lines of sight

$$\sigma_{e,i}^2 \propto \left(\frac{L}{L_0} \right)^{\chi_{\text{lum}}} \frac{\sigma_{\text{int}}^2}{(1+z_i)^4} + \frac{D_i}{D_0} \sigma_{\text{env}}^2$$

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

41632 lines of sight



Summary

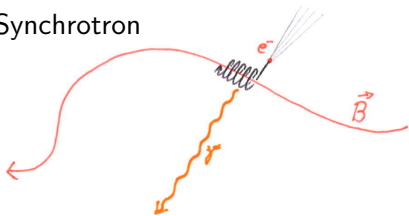
- ▶ Galactic contribution (correlated) can be separated from rest (uncorrelated)
- ▶ Rest can be separated statistically into extragalactic and noise
- ▶ Uncertainties are large and should not be ignored

All results at

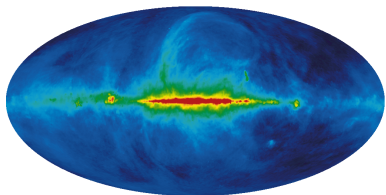
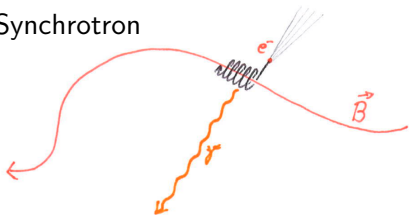
<http://www.mpa-garching.mpg.de/ift/faraday/>

BACKUP

Synchrotron

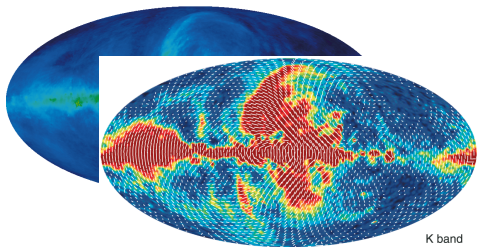
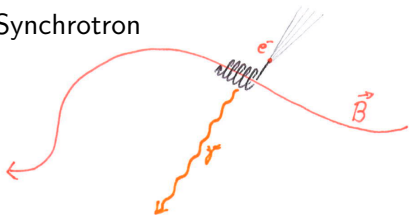


Synchrotron



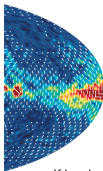
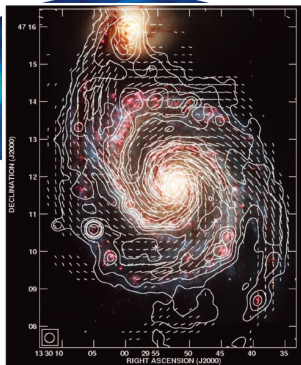
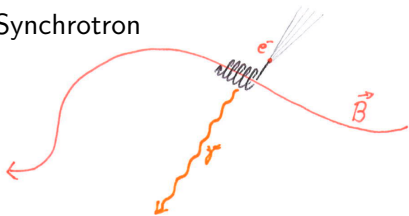
Haslam et al. 1981

Synchrotron



Hinshaw et al. 2009

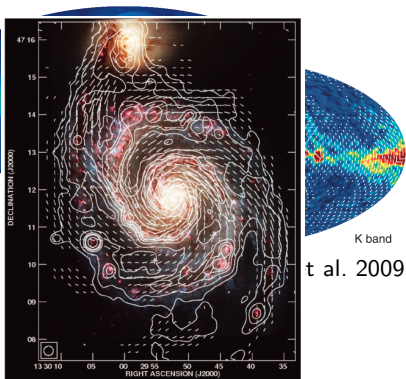
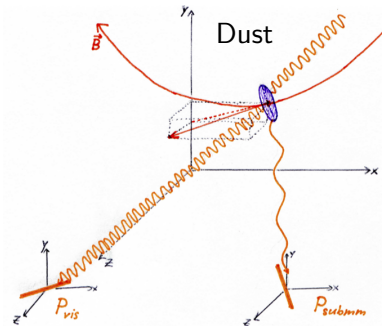
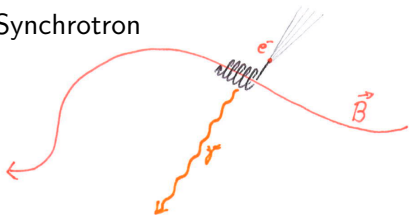
Synchrotron



K band
t al. 2009

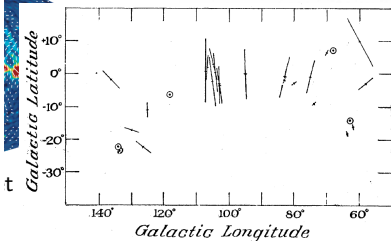
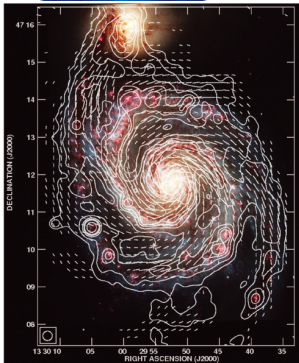
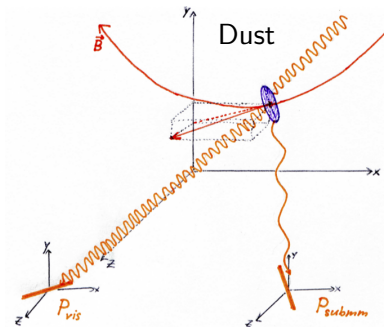
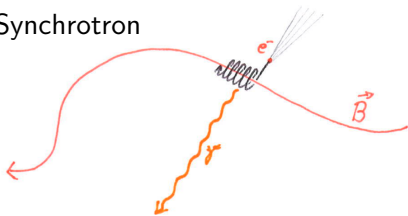
Fletcher et al. 2011

Synchrotron



Fletcher et al. 2011

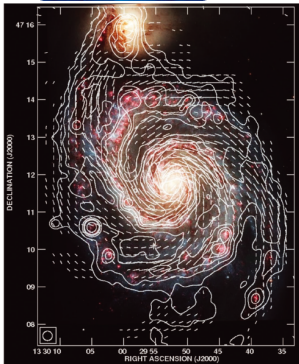
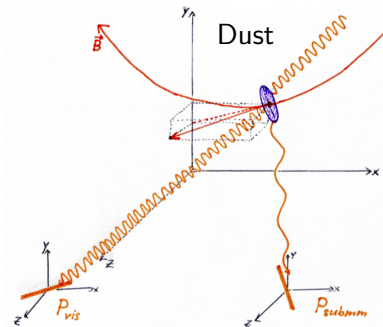
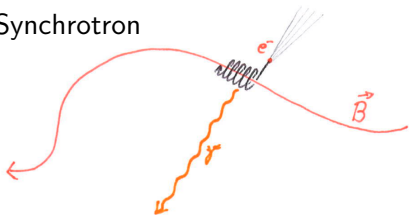
Synchrotron



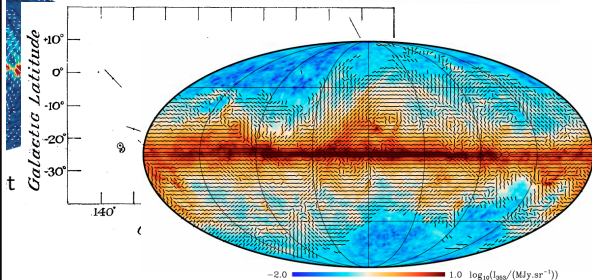
Hall 1949

Fletcher et al. 2011

Synchrotron



Fletcher et al. 2011



Planck Collaboration Int. XIX (2014)