PreFRBLE: Predict Fast Radio Bursts to Learn about Extragalactic magnetic fields

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Overview

Magnetic Fields in the Universe
Fast Radio Bursts
PreFRBLE
Galaxies
IGMFs

Outline

Magnetic Fields in the Universe

The Universe is magnetized!

Earth 0.5 G

Sun 1 G

Planets 10^{-2} - 10^{3} G

Stars 10 - 10^{4} G

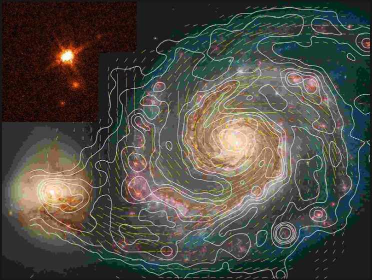
LHC 10^{5} G

Neutron Stars 10^{8} - 10^{12} G

Magnetars 10^{12} - 10^{14} G

Galaxies $\sim$ 5–15 μG

Galaxy Clusters $\sim$ μG



Extra-Galactic Magnetic Fields

well known:
LSS ($\approx$ 20% of volume)

galaxies $\sim 5 - 15\ \mu\mathrm{G}$

clusters $\sim \mu\mathrm{G}$

filaments $\lesssim 0.1\mu\mathrm{G}$

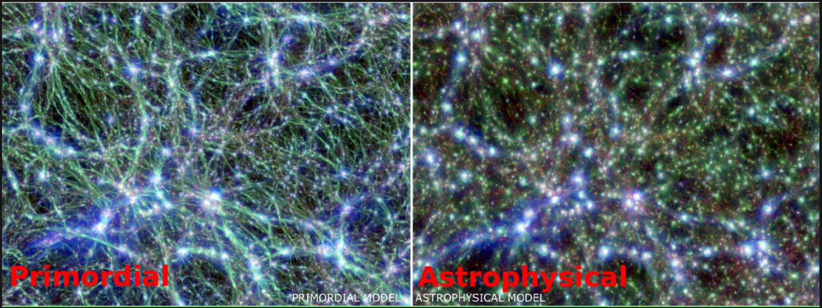
e. g. *Beck+ 2016, Feretti+ 2012, Brown+ 2017*

huge uncertainty:
Voids ($\approx$ 80% of volume)

$B_0 \lesssim 1\ \mathrm{nG}$ (CMB)
Planck 2015

$B_{\mathrm{void}} \gtrsim 10^{-7}\mathrm{nG}$ (Blazars)
Neronov & Vovk 2010

Vazza et al. 2018



Motivation

Intergalactic Magnetic Fields:

- how strong are they?
- what is their origin?

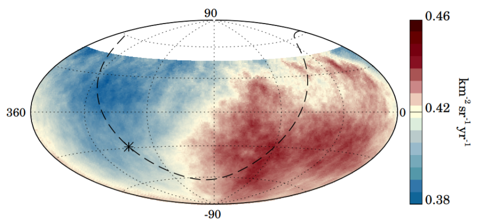
Ultra High Energy Cosmic Rays

fully ionized nuclei are deflected by magnetic fields

measure IGMFs with UHECRs?

Hackstein et al. 2016 & 2018

constrained IGMF models freely available at CRPropa.desy.de



PAO 2017

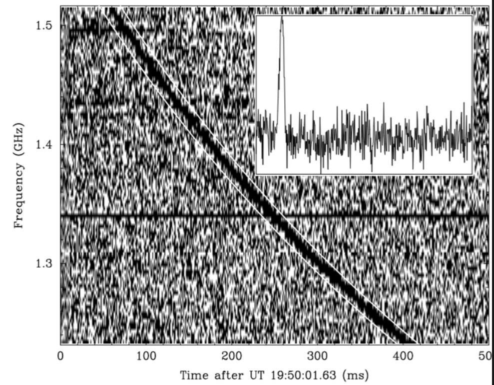
- heavy nuclei required to recreate anisotropy
- didn't find fitting source model
  (Eichmann ICRC2019, Rachen & Eichmann in Prep.)
- no info on IGMF without known sources . . .

Outline

Fast Radio Bursts

Fast Radio Bursts

- bright ms bursts
- short frequency band ~ 1 GHz
- Very short duration
  $\Rightarrow$small source $\sim$ 10 km
  $\Rightarrow$**brilliant probes for traversed medium**
- dispersion consistent with plasma propagation
  $v_\gamma \propto \nu^2$
- $\mathrm{DM}_{\mathrm{FRBs}} > \mathrm{DM}_{\mathrm{MilkyWay}}$
  $\Rightarrow$**extragalactic**
- **linear polarized**
  $\Rightarrow$Faraday rotation $\propto B_\|$



Lorimer'07

$$DM = \int \frac{n_e}{1+z} dl$$

$$RM = \int B_\| \frac{n_e}{1+z} dl$$

Fast? Radio Bursts

Francesco de Gasperin, (jun. Prof at Sternwarte Hamburg):

$v_\gamma \propto \nu^2$ $\Rightarrow$compared to GRBs, FRBs are **slow**!!!

characteristic feature: FRBs are **short**!

They should be called **Short Radio Bursts (SRBs)**!

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MISRBLE

(Measurement Inference of Short Radio Bursts for Likelihood) Estimates

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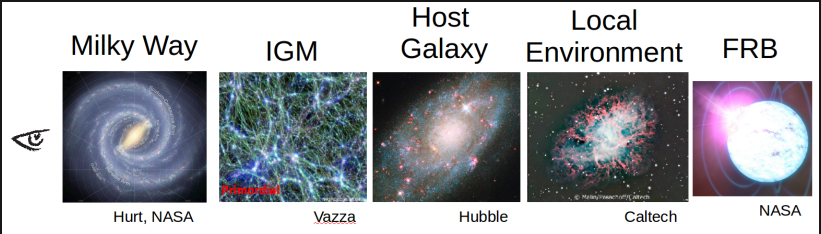
PreFRBLE

(Predict Fast Radio Bursts to obtain model Likelihood Estimates)

Key Question

Can Fast Radio Bursts tell us about Intergalactic Magnetic Fields?
(see also Akahori+ 2016, Vazza+ 2018)

- Consider **all regions** along line-of-sight
- Consider different possible **models**
- Compare **prediction & observation**



Outline

PreFRBLE

PreFRBLE

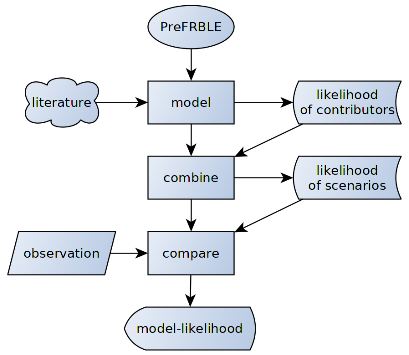
Predict Fast Radio Bursts

$\rightarrow$model-Likelihood Estimates

PreFRBLE

Predict Fast Radio Bursts →model-Likelihood Estimates

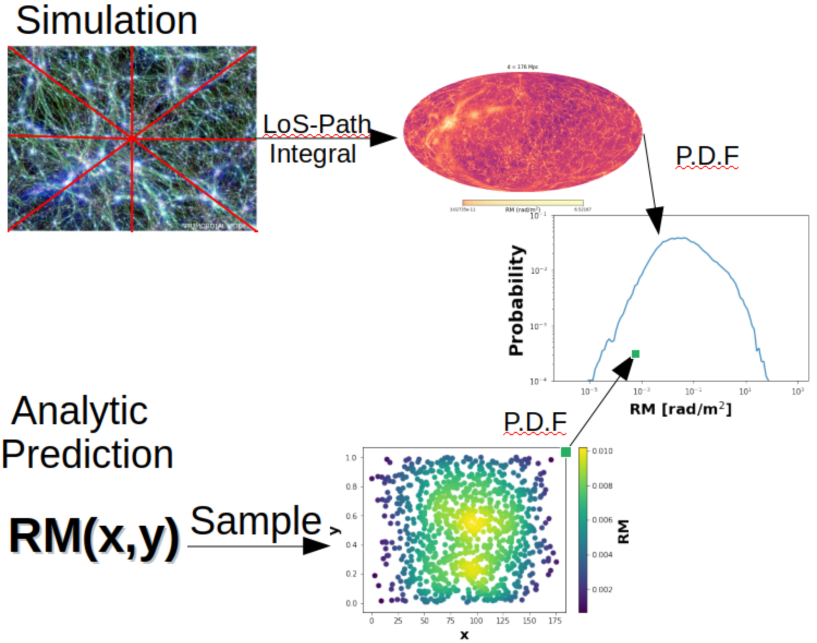
Hackstein et al. 2019, MNRAS



- models in literature →contribution of regions
- combine regions →realistic scenarios
- compare to observations →model likelihood

- **measure Intergalactic Magnetic Fields**
- find sources of FRBS
- find host galaxies of FRBs
- identify FRB populations
- ...

PreFRBLE: likelihood functions by Monte Carlo method



PreFRBLE: Bayesian inference

Full likelihood = convolution of contributions

$$P_{\mathrm{EG}} = P_{\mathrm{IGM}} * P_{\mathrm{Host}} * P_{\mathrm{Progenitor}}$$

Bayes factor (Model$_2$ $\xrightarrow{\text{corroboration}}$ Model$_1$)

$$\mathcal{B}(Model_1, Model_2|observation) = \frac{P(observation|Model_1)}{P(observation|Model_2)}$$

$\mathcal{B} > 100$ ($\equiv$ 99 % C. L.) is considered decisive

(e. g. Jeffreys & Jeffreys 1961)

Model Likelihood ($\equiv$ how likely is the measurement observed in model)

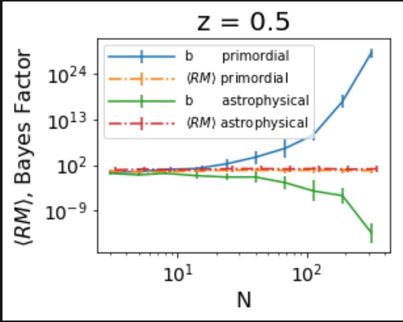
$$P(DM, RM, M) \propto \int P(RM|z_{\mathrm{FRB}}, M)\ \underbrace{P(DM|z_{\mathrm{FRB}}, M)\ \pi(z_{\mathrm{FRB}}, M)}_{\propto P(z_{\mathrm{FRB}}|DM,M)}\ \mathrm{d}z$$

$\Rightarrow$redshift(DM)

Results

Hackstein et al. 2019, MNRAS

- sample DM & RM expected for extreme IGMF models
- $\Rightarrow <$**100 FRBs suffice to constrain IGMFs!**



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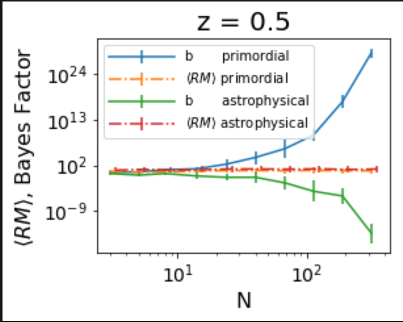

- sample DM & RM expected for extreme IGMF models
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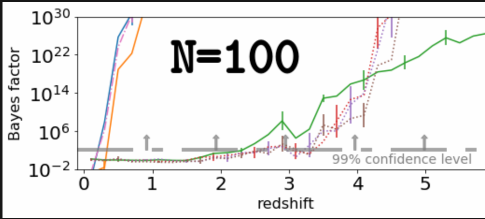


- However, host galaxy might overshadow IGM signal

Outline

Galaxies

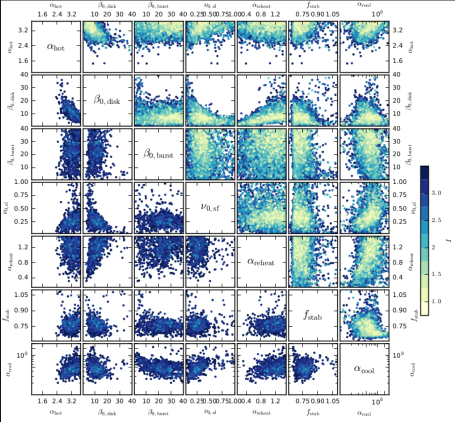
Host Galaxy

So far consider single type of Host galaxy,
allows to identify host of individual FRBs

Surveys consider all possible types of galaxies!

Problem vast parameter space

Host Galaxy

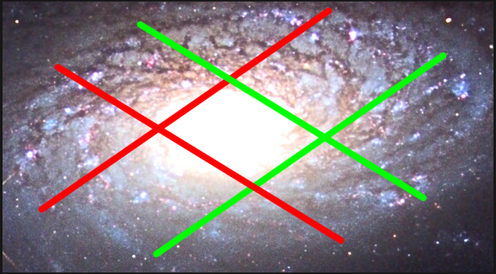


Rodrigues et al. 2016:

use GALFORM,
constrain galaxy
formation parameters
with GSMF $\Phi(M|z)$,
$\Rightarrow$**prior for galaxy properties** $\pi(\epsilon|z)$

Rodrigues et al. 2018: add magnetic fields
$\Rightarrow$numerous models of galaxies,
span plausible parameter space,
suitable to **model entirety of galaxies**

Model Host Galaxy

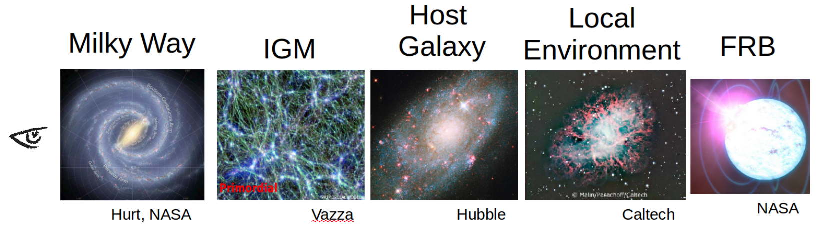


$$P(RM_{\mathrm{Host}}|z) = \int P(RM_{\mathrm{gal}}|\epsilon, z)\pi(\epsilon|z)\mathrm{d}\epsilon$$

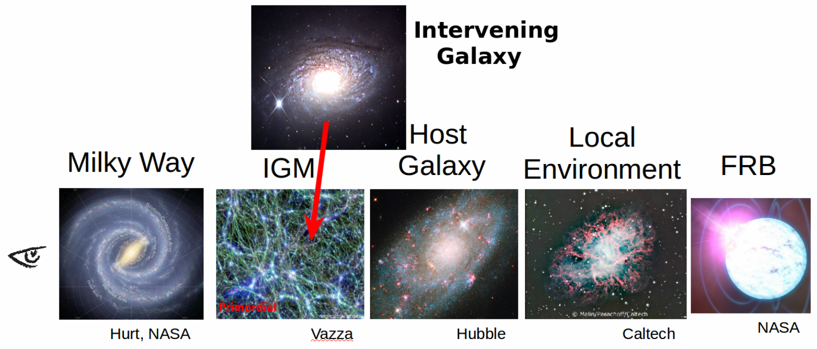
$\pi(\epsilon|z)$ from Rodrigues et al. 2016 $\equiv$ all galaxies may host FRBs,

Different choices of $\pi(\epsilon|z)$ (e. g. threshold on SFR) allow to **compare host scenarios**.

Did we miss something?



Intervening Galaxies



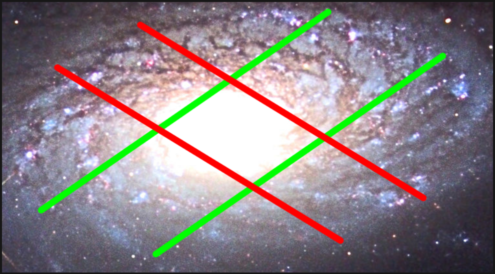
intervening galaxies $\mathrm{RM_{inter}}$ likely to overshadow $\mathrm{RM_{IGM}}$,

they dominate Scattering time $\tau \propto \int n_e^2 \, \mathrm{d}l$ (Macquart & Koay 2013)

$\Rightarrow$ use high τ to identify LoS with intervening galaxies

Model Intervening Galaxies

Messier 63



Number and redshift uncertain, do statistical modelling

$$N_{\mathrm{inter}}(z_{\mathrm{FRB}}) = \int \pi\ r_{\mathrm{gal}}^2\ n_{\mathrm{gal}}\ \mathrm{d}l = \int \pi(z_{\mathrm{inter}})\mathrm{d}z_{\mathrm{inter}}$$

$$P(RM_{\mathrm{inter}}|z_{\mathrm{FRB}}) = \int_0^{z_{\mathrm{FRB}}} P(RM_{\mathrm{inter}}|z_{\mathrm{inter}})\ \pi(z_{\mathrm{inter}})\ \mathrm{d}z_{\mathrm{inter}}$$

$$N_{\mathrm{inter}}(z_{\mathrm{FRB}}) = \int P(RM_{\mathrm{inter}}|z_{\mathrm{FRB}})\mathrm{d}RM_{\mathrm{inter}}$$

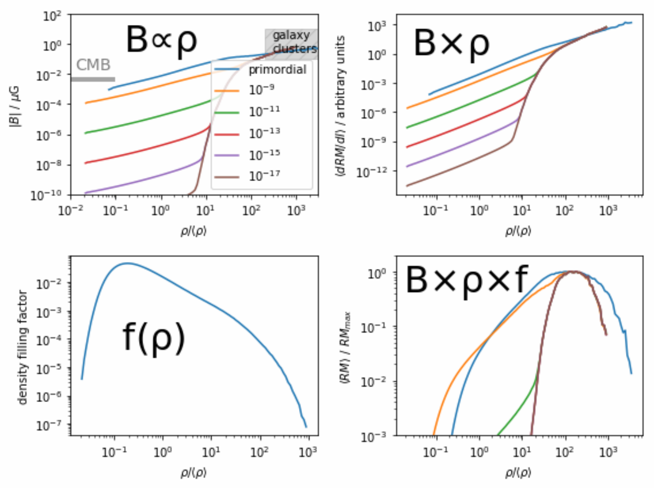
account for intersection likelihood

Outline

IGMFs

IGMFs: significant contribution

Hackstein et al. in prep.



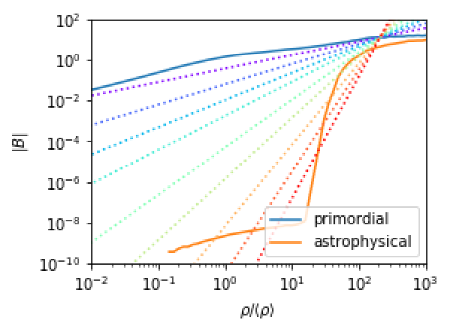
RM from overdensities < 1 are negligible

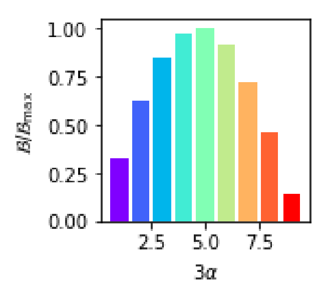
FRBs cannot measure IGMFs in voids

IGMFs: Constrain $|B| \sim rho$

How to model the IGMF?

Hackstein et al. in prep





- only $1 - 10 \lesssim \rho/\langle\rho\rangle \lesssim 200$ provide significant RM of IGMFs
- assume $|B| \propto \rho^{\alpha} \rightarrow$ vary & constrain α
  $\Rightarrow$ general conclusions on formation of IGMFs

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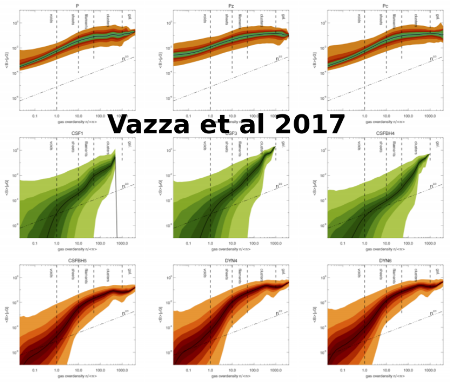

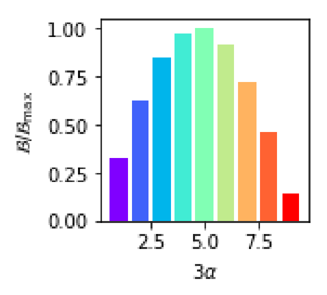

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- assume $|B| \propto \rho^{\alpha} \rightarrow$ vary & constrain α

  $\Rightarrow$ general conclusions on formation of IGMFs

Conclusions

- Fast Radio Bursts can tell us about IGMFs
  $1 - 10 \lesssim \rho/\langle\rho\rangle \lesssim 200$ (filaments, sheets)

- PreFRBLE: statistical tools (Bayesian) and careful consideration of all contributing regions along LoS
  $\Rightarrow$ evaluate prior assumptions and models

- PreFRBLE: way to connect theory & observations: (soon) open-source, easy-to-use python package for observers (interpret data) and theorists (test models).

soon available at
github.com/shackste/PreFRBLE

Progenitor?

FRBs from magnetars only
(Piro & Gaensler 2018)

including more models
$\Rightarrow$ identify source of FRBs

However, . . .
100s of models. . .
$\approx \frac{1}{2}$ *yr* before end of PhD . . .

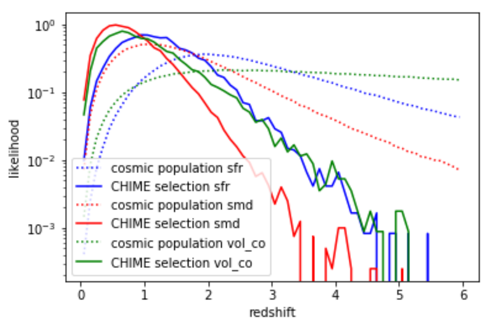
open-source is preferable,
PreFRBLE is open source!
provide your model!
let's find FRB sources together!
(or hire me to do that!)

More to come

- include more progenitor models to **find sources of FRBs**
- **provide predictions taylored to individual telescope**
  assume cosmic population and consider selection effects to expected distribution of source redshifts
  FRBpoppy, Gardenier et al. in subm.
- distinguish galactic & extragalactic RM using Wiener Filter
  Oppermann et al. 2015, Hutschenreuter et al. 2019
- remove RM of ionosphere, e. g. Jehle et al. 2008
- 50 RM of FRBs observed by CHIME, public by spring 2020
  $\Rightarrow$**First glimpse on IGMFs through FRBs early next year!!**

FRB population

FRBPOPPY, (Gardenier et al. in subm. 1910.08365)
assume cosmic population of FRBs (dotted)
consider telescope selection effects (solid)



$\Rightarrow$ prior on source redshift $\pi(z_{\mathrm{FRB}})$
$\rightarrow$ more reasonable & improved redshift estimates
$\rightarrow$ required to predict observations of individual telescope
$\rightarrow$ required to reasonably compute $\mathcal{B}$

Redshift estimate

$DM = \int n_e \, \mathrm{d}l$ dominated by IGM (e. g. Pol et al. 2019)

$\langle DM \rangle$ increases with redshift

$\tau \propto \int n_e^2 \, \mathrm{d}l$ dominated by overdensities (Macquardt & Koay 2013)

$\langle \tau \rangle$ decreases with redshift

Combine information of both, DM and τ

$$P(z_{\mathrm{FRB}}|DM, \tau) \propto P(DM|z_{\mathrm{FRB}}) \; P(\tau|z_{\mathrm{FRB}}) \; \pi(z_{\mathrm{FRB}})$$

provide improved redshift estimates with reasonable lower limits