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

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Overview

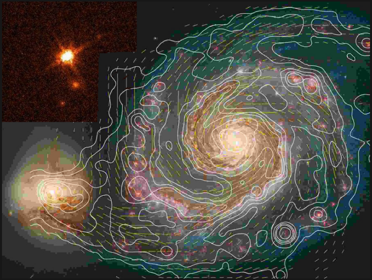
Magnetic Fields in the Universe
Fast Radio Bursts
PreFRBLE
Source
Galaxies
Intergalactic Magnetic Fields

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

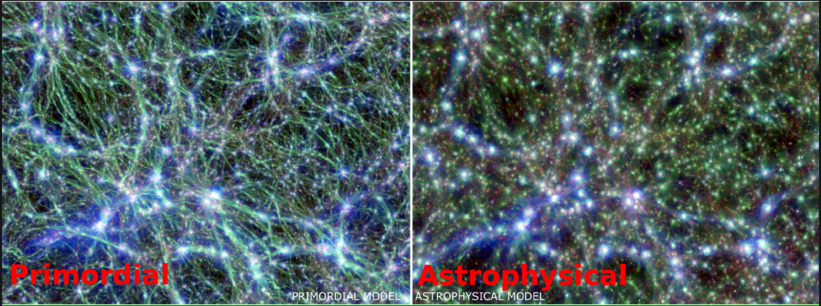
e. g. *Beck+ 2016, Feretti+ 2012, Brown+ 2017*

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

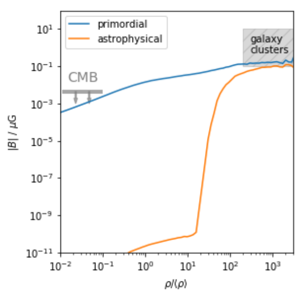
$B_0 \lesssim 1\ \mathrm{nG}$ (CMB)
Planck 2015

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

Vazza et al. 2018



Extra-Galactic Magnetic Fields



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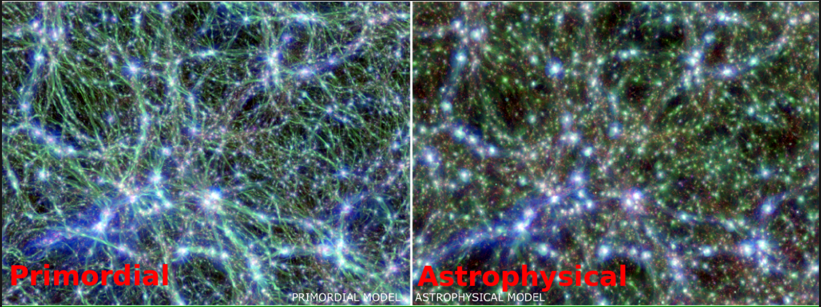


Motivation

Intergalactic Magnetic Fields:

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

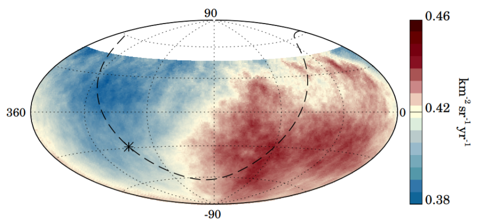
Ultra High Energy Cosmic Rays

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

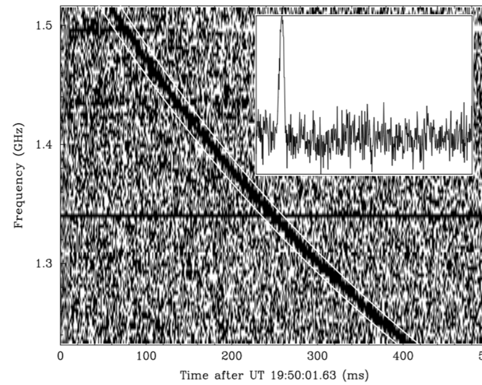
- heavy nuclei required to recreate observed anisotropy
- didn't find fitting source model
  (see Eichmann ICRC2019, Rachen & Eichmann in Prep.)
- no info on IGMF without known sources ...

Outline

Fast Radio Bursts

Fast Radio Bursts

- bright ms bursts $\approx 10^{40}$ erg
- 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 $\propto B_\|$
- events collected in frbcat.org (Petroff+16)



First FRB by 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):

dispersion $v_\gamma \propto \nu^2$ $\Rightarrow$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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(Measurement Inference of Short Radio Bursts for Likelihood Estimates)

PreFRBLE

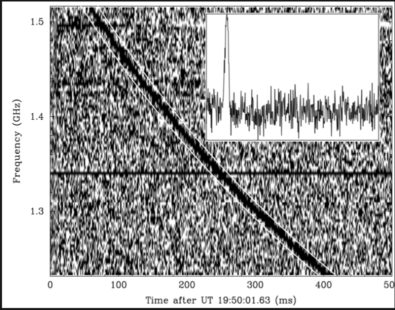
(Predict Fast Radio Bursts to obtain model Likelihood Estimates)

Fast Radio Bursts

- brilliant probes for traversed medium
- extragalactic origin
- measure of magnetic field
- $\Rightarrow$probe EGMFs?

- source unknown
  $N_{\mathrm{models}} \approx N_{\mathrm{FRBs}} \gtrsim 200$
  $\frac{\mathrm{d}}{\mathrm{d}t} N_{\mathrm{models}} \approx \frac{\mathrm{d}}{\mathrm{d}t} N_{\mathrm{FRBs}}$

  unless repeating (10 FRBs) or persistent companion (Spitler Burst, Chatterjee+17)
- hard to localize
- host galaxy unknown



First FRB by Lorimer+07

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

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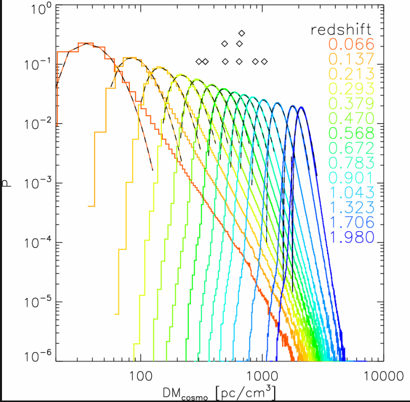
Redshift Estimate

Dolag+15



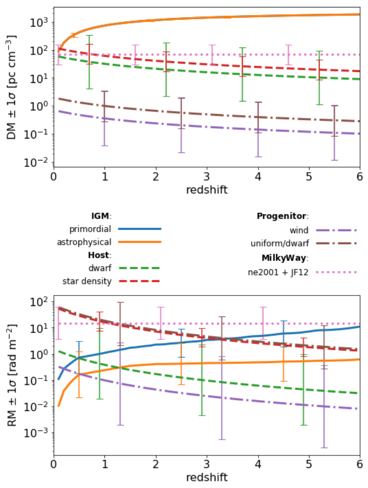
IGM dominates DM, small σ

$\Rightarrow$ **redshift(DM)**

only upper limits

(high DM from density peaks, local environment)

Hackstein+19



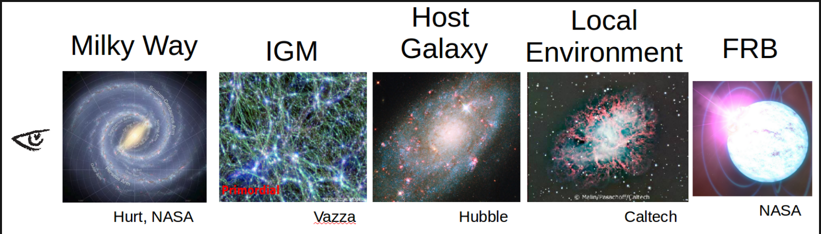
RM: all regions comparable

high model variation

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

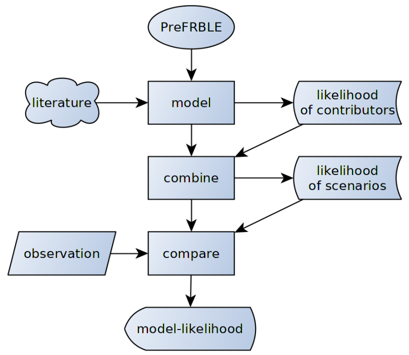
(soon) publicly available easy-to-use Python package
to interpret FRB observations

github.com/shackste/PreFRBLE

PreFRBLE

Predict Fast Radio Bursts →model-Likelihood Estimates

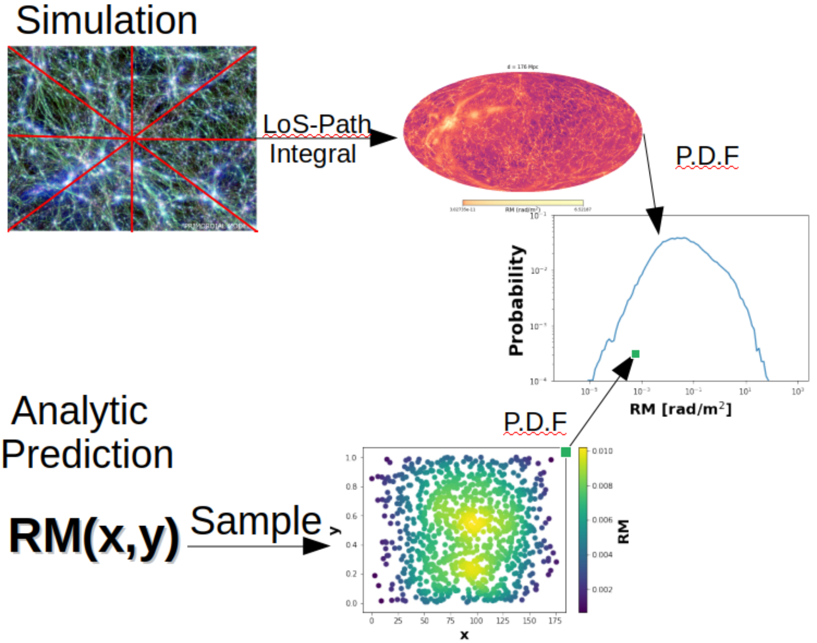
Hackstein et al. 2019, MNRAS



- models from 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 population $n_{\mathrm{FRB}}(z)$
- ...

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

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

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

(e. g. Jeffreys & Jeffreys 1961)

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

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

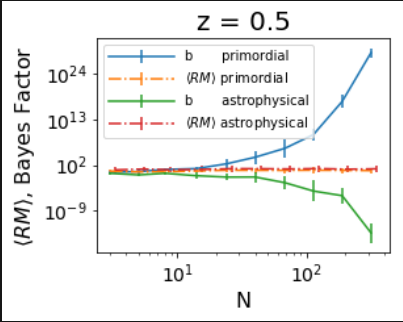
$\Rightarrow$redshift(DM)

Results

Hackstein et al. 2019, MNRAS

assume one model for host and source, mock sample of FRBs with DM & RM at redshift z=0.5 for extreme models of IGMF

<100 FRBs suffice to constrain IGMFs!



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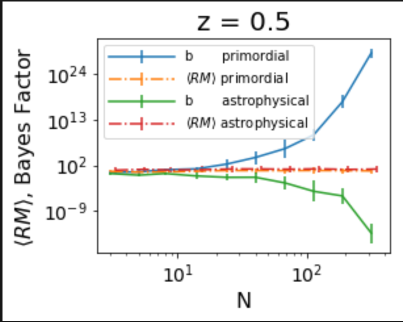
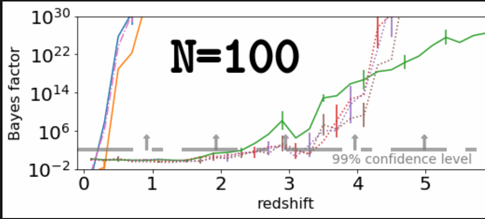


different host galaxy (dwarf & MW-like spiral) and source models might overshadow IGM

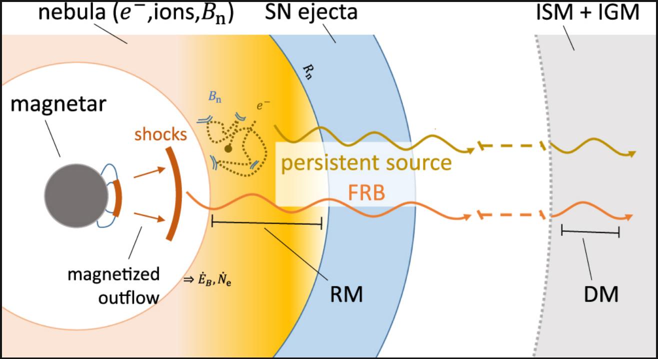


Outline

Source

Source models

isolated magnetar (young neutron star, $B = 10^{14} - 10^{16}$ G)
(Popov+10, Beloborodov'17, Murase+17, Metzger+19, Wadiasingh+19)



Margalit & Metzger'18

DM & RM from environment described by Piro & Gaensler '18

for more source models, visit frbtheorycat.org (Platts+19)

More source models?

So far only consider
FRBs from isolated magnetars

including more models,
e. g. mergers, collapses, AGN, axion stars
and source specific observables
$\Rightarrow$ 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!)

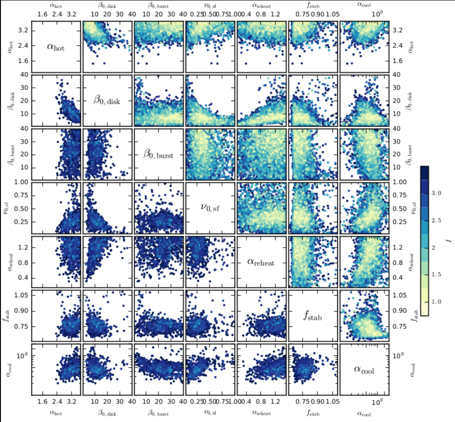
Outline

Galaxies

Host Galaxy

So far	consider single type of Host galaxy, allows to identify host of individual FRBs
Surveys	entail all possible types of galaxies!
Problem	vast parameter space

Host Galaxy



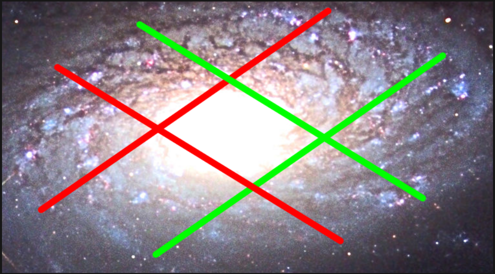
Rodrigues et al. 2016:

use GALFORM, constrain galaxy formation parameters with GSMF $\Phi(M|z)$, $\Rightarrow$samples of possible galaxy populations

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

Messier 63

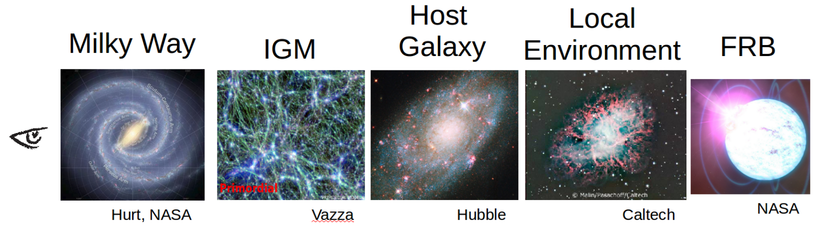


$$P(RM_{\mathrm{Host}}|z) = \int P(RM_{\mathrm{gal}}|\epsilon, z)\pi(\epsilon|z)\mathrm{d}\epsilon$$

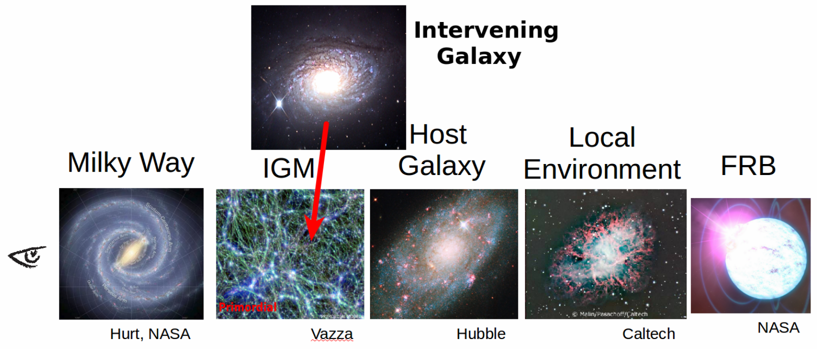
$\pi(\epsilon|z)$ from Rodrigues et al. 2016 $\equiv$ all galaxies may host FRBs,

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

Did we miss something?



Intervening Galaxies



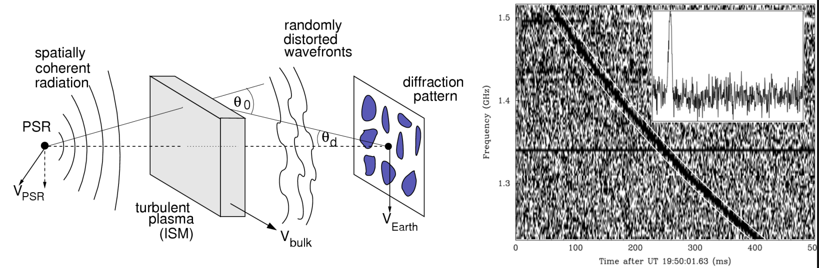
intervening galaxies $\mathrm{RM}_{\mathrm{inter}}$ likely to overshadow $\mathrm{RM}_{\mathrm{IGM}}$,

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**

Scattering

Lorimer & Kramer '04



interaction with plasma $\rightarrow$radio waves scatter off LoS
some waves scatter back on LoS

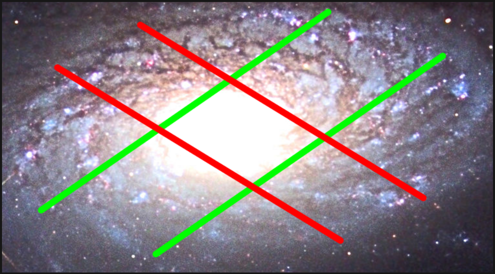
$\Rightarrow$angular broadening

$\Rightarrow$temporal broadening $\propto \lambda^\gamma,\ \gamma \geq 4$

depends on lense position, ideally half-way to source
$\Rightarrow$dominated by dense plasma in intervening galaxies

Model Intervening Galaxies

Messier 63



Number and redshift uncertain, do statistical modelling

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

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

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

account for intersection likelihood

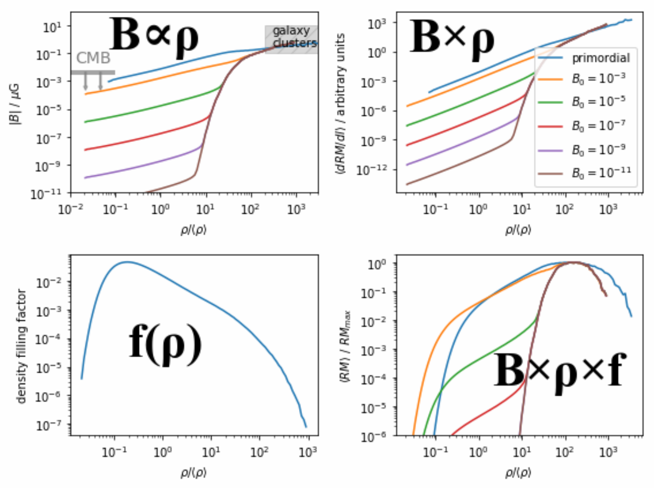
Outline

Intergalactic Magnetic Fields

Intergalactic Magnetic Fields: significant contribution

estimate $\langle \mathrm{d}RM \rangle(\rho)$

Hackstein et al. in prep.



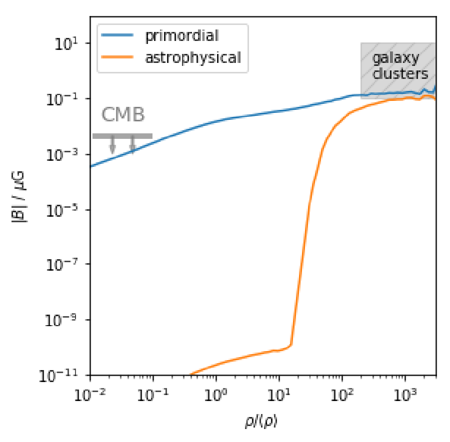
RM from overdensities < 1 are negligible

$\Rightarrow$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

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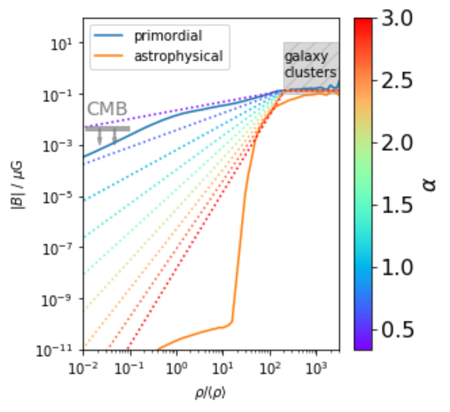

- only $1 - 10 \lesssim \rho/\langle\rho\rangle \lesssim 200$ provide significant RM of IGMFs
- assume $|B| \propto \rho^{\alpha} \rightarrow$ vary & constrain α

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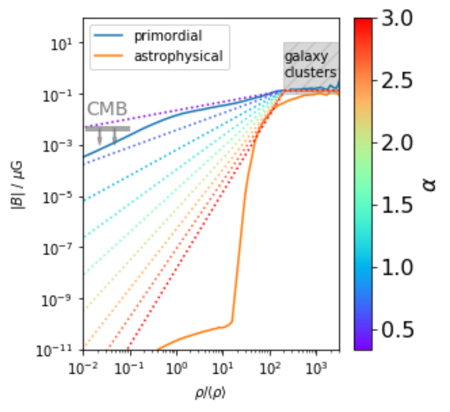

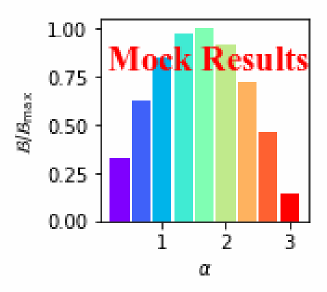

- only $1 - 10 \lesssim \rho/\langle\rho\rangle \lesssim 200$ provide significant RM of IGMFs
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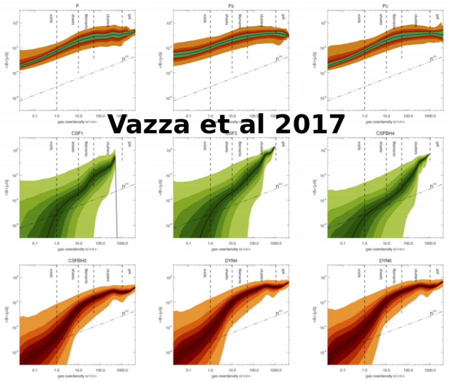
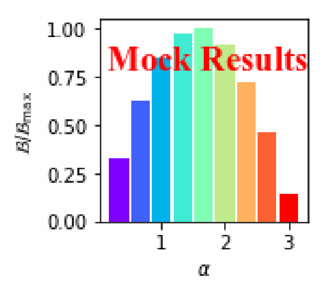
  $\Rightarrow$ general conclusions on formation of IGMFs

How to model the IGMF?

Hackstein et al. in prep





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  $\Rightarrow$ 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

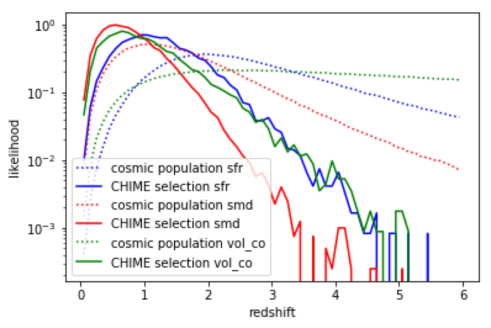
download this talk at
github.com/shackste/publications

More to come

- Since late 2018, CHIME operates, N_{FRB} grows fast.
  50 RM of FRBs, public by spring 2020
  $\Rightarrow$**First glimpse on IGMFs through FRBs early next year!!**
  soon many more interesting cosmological results
- 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
- **provide predictions taylored to individual telescope**
  assume cosmic population and consider selection effects to expected distribution of source redshifts
  $\Rightarrow$**identify population of FRBs**
- include more models to **find sources of FRBs**

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