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Cosmology with Fast Radio Bursts

GCCL GERMAN CENTRE FOR COSMOLOGICAL LENSING

ORIGINS Excellence Cluster

Robert Reischke & Steffen Hagstotz
with Robert Lilow

November 15 I 2022

Astroparticle Symposium

Fast Radio Bursts

- Mechanism unknown
- First discovered in archival data 2007
- Short (~ms), bright (~Jy) radio transients
- Frequencies 300 Mhz - 8 Ghz
- Extragalactic
- About 600 known events, soon several 1000s
- Some repeating?

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Proposed Mechanisms

A Living Theory Catalogue for Fast Radio Bursts

E. Platts[a,*], A. Weltman[a], A. Walters[b,c], S. P. Tendulkar[d], J.E.B. Gordin[a], S. Kandhai[a]

arXiv 1810.05836

www.frbtheorycat.org

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Neutron stars? Mergers? AGN?

Article | Published: 04 November 2020

A bright millisecond-duration radio burst from a Galactic magnetar

The CHIME/FRB Collaboration

Nature **587**, 54–58(2020) | Cite this article

A repeating fast radio burst source in a globular cluster

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Fast Radio Bursts from Extragalactic Light Sails

Manasvi Lingam, Abraham Loeb

We examine the possibility that Fast Radio Bursts (FRBs) originate from the activity of extragalactic civilizations. Our analysis shows that beams used for powering large light sails could yield parameters that are consistent with FRBs. The characteristic diameter of the beam emitter is estimated through a combination of energetic and engineering constraints, and both approaches intriguingly yield a similar result which is on the scale of a large rocky planet. Moreover, the optimal frequency for powering the light sail is shown to be similar to the detected FRB frequencies. These `coincidences' lend some credence to the possibility that FRBs might be artificial in origin. Other relevant quantities, such as the characteristic mass of the light sail, and the angular velocity of the beam, are also derived. By using the FRB occurrence rate, we infer upper bounds on the rate of FRBs from extragalactic civilizations in a typical galaxy. The possibility of detecting fainter signals is briefly discussed, and the wait time for an exceptionally bright FRB event in the Milky Way is estimated.

millisecond-duration radio burst from a Galactic magnetar

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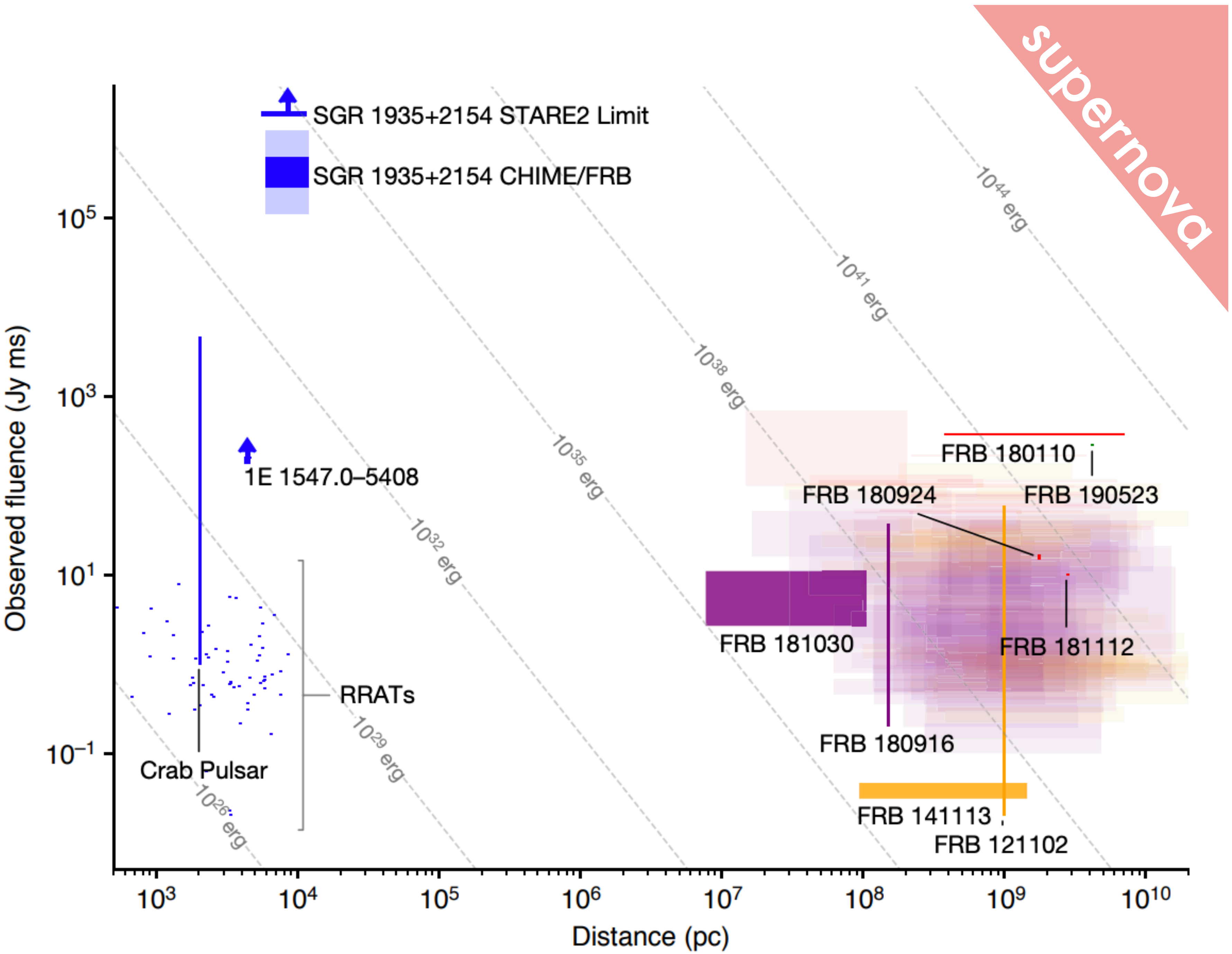
Energy



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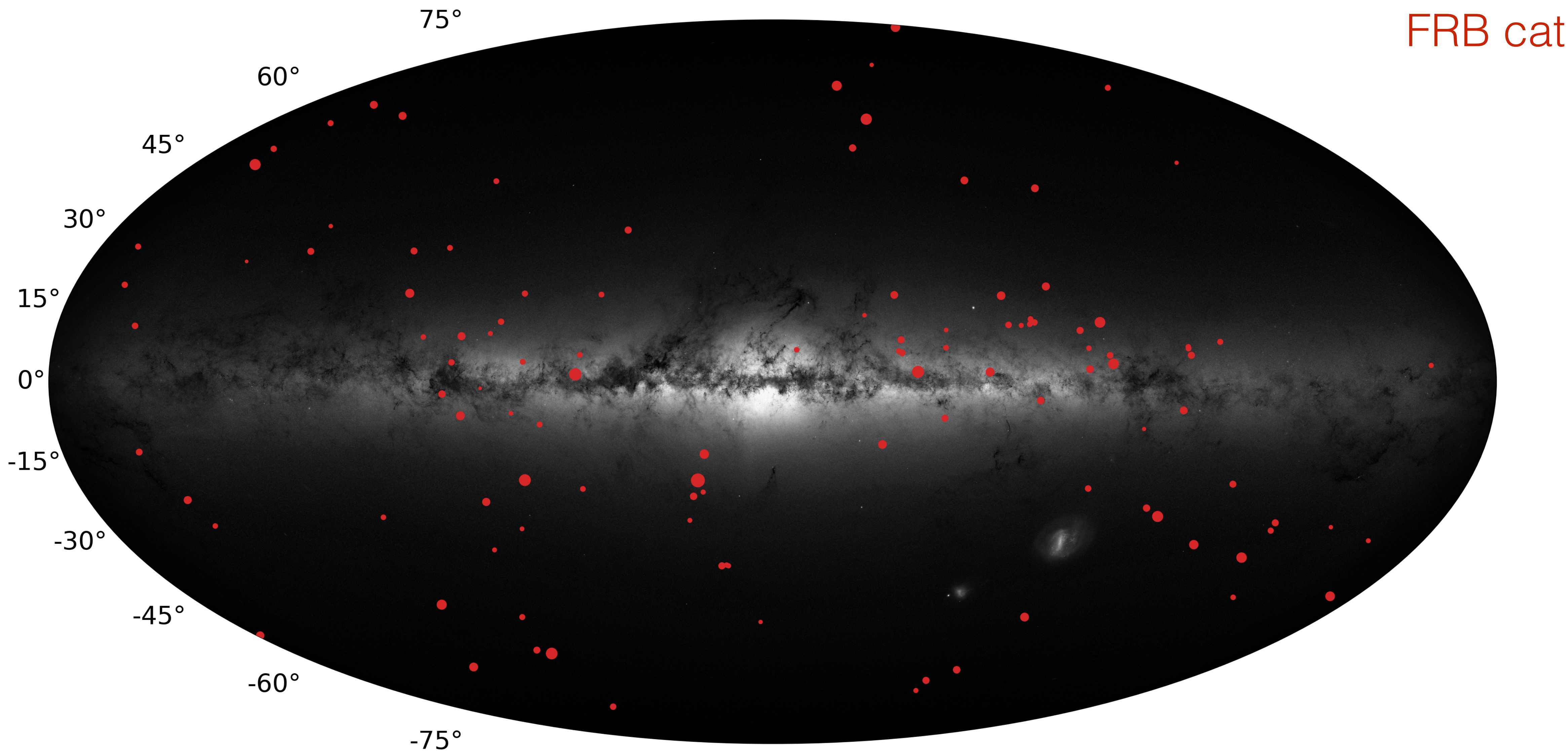
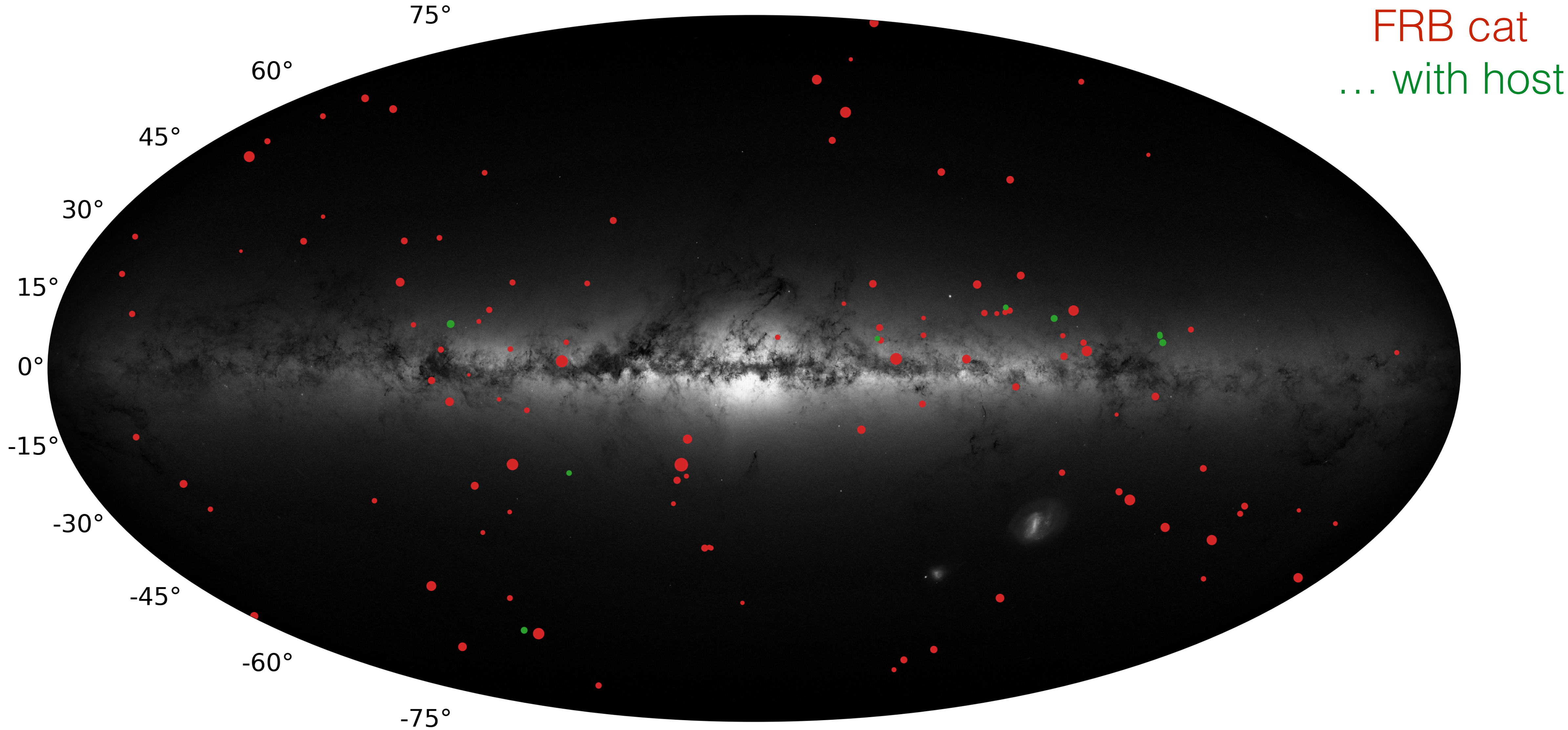
CHIME/FRB collaboration, Nature 587, 54-58(2020)

Known FRBs



Events uncorrelated with the Milky Way

Known FRBs



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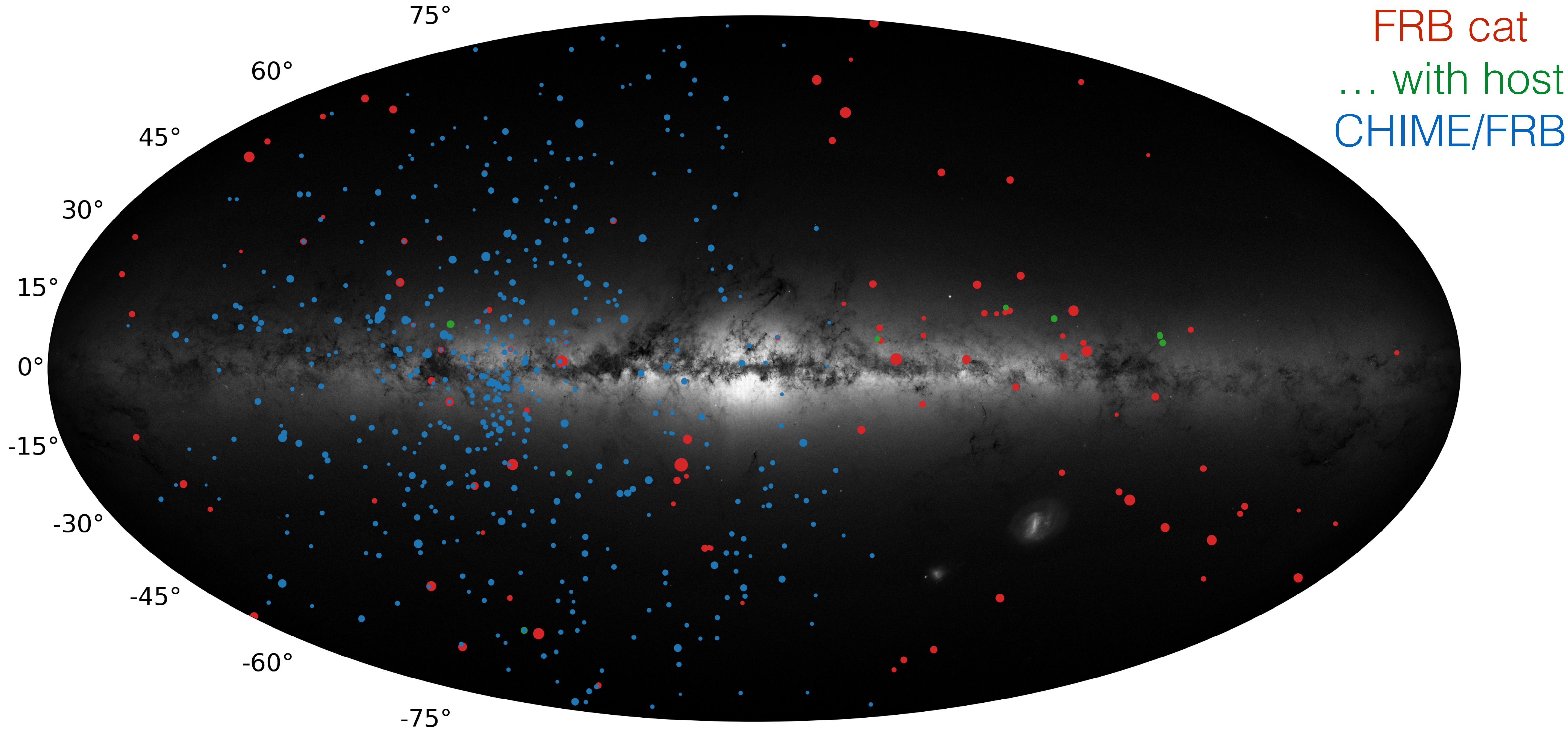

Events uncorrelated with the Milky Way

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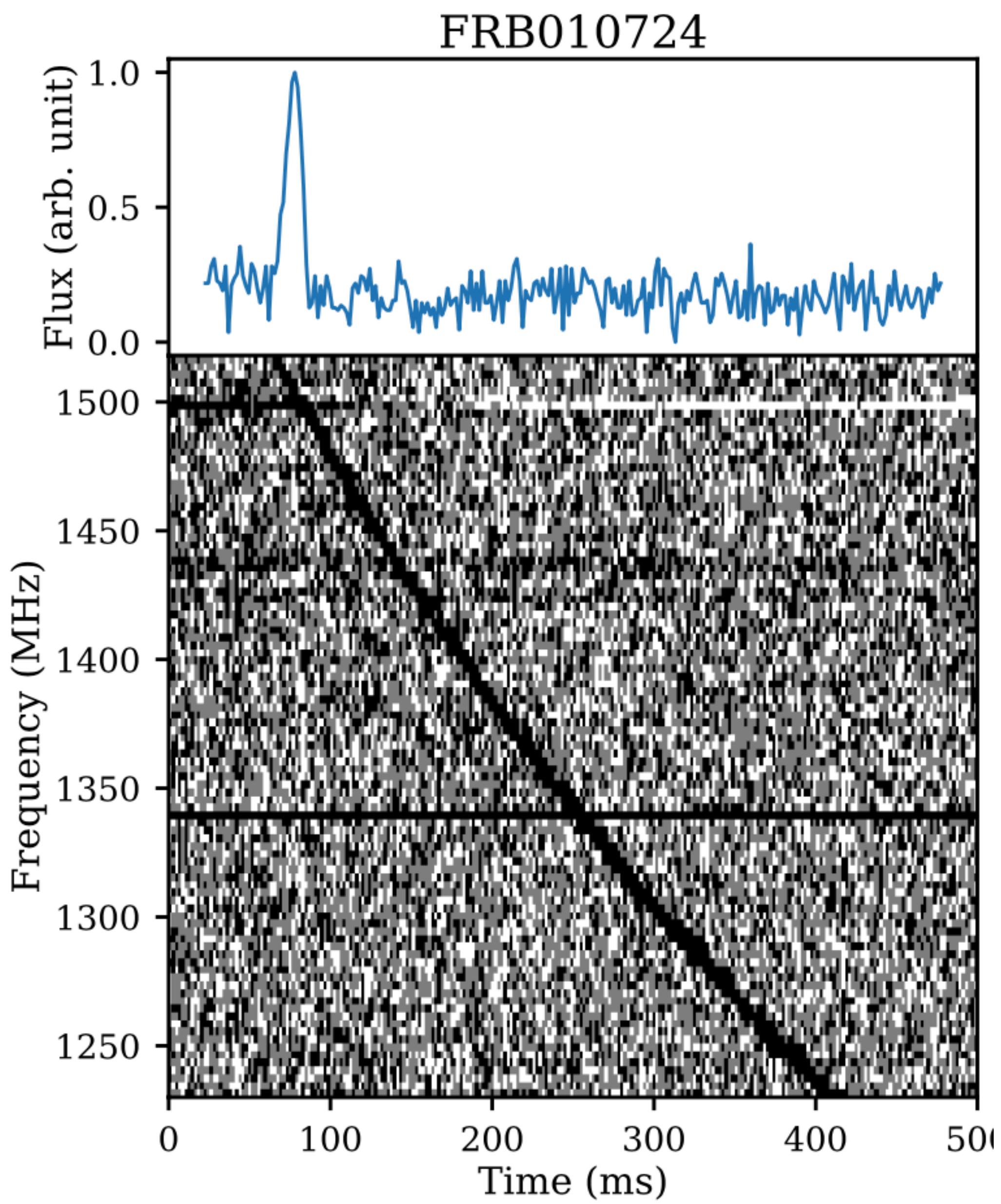
Dispersion measure



Lorimer et al 2007
Cordes & Chatterjee 2019

- Radio signals undergo dispersion
- Pulse delay $\Delta t \sim \nu^{-2}$
- Depends on integrated electrons along LoS

$$\mathrm{DM} = \int \frac{n_e}{1+z} \mathrm{d}l$$

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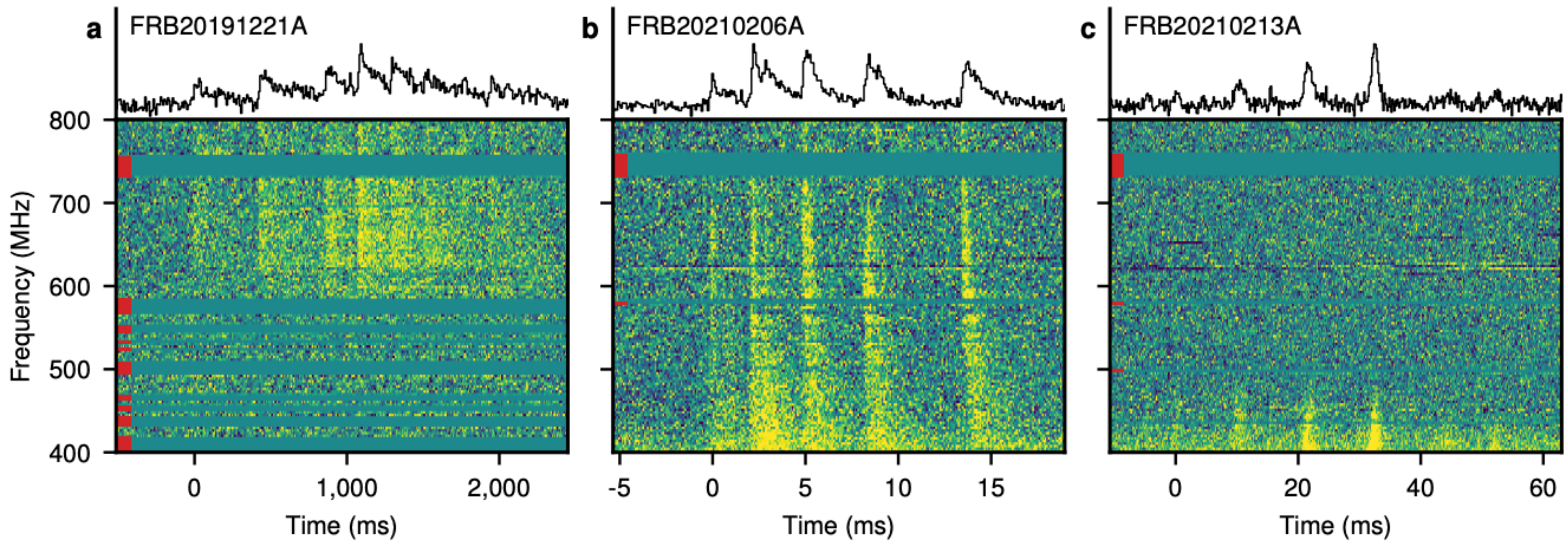
Pulse structure



Puls substructure at the ms level -> source not bigger than O(100) km

Dispersion measure

$$\mathrm{DM}_{\mathrm{tot}}(z) = \mathrm{DM}_{\mathrm{MW}} + \mathrm{DM}_{\mathrm{LSS}}(z) + \mathrm{DM}_{\mathrm{host}}(z)$$

LSS

Milky Way models
Can be checked with Pulsars
Quite accurate!

Host halo models
Depends on galaxy types?
Location of FRBs?

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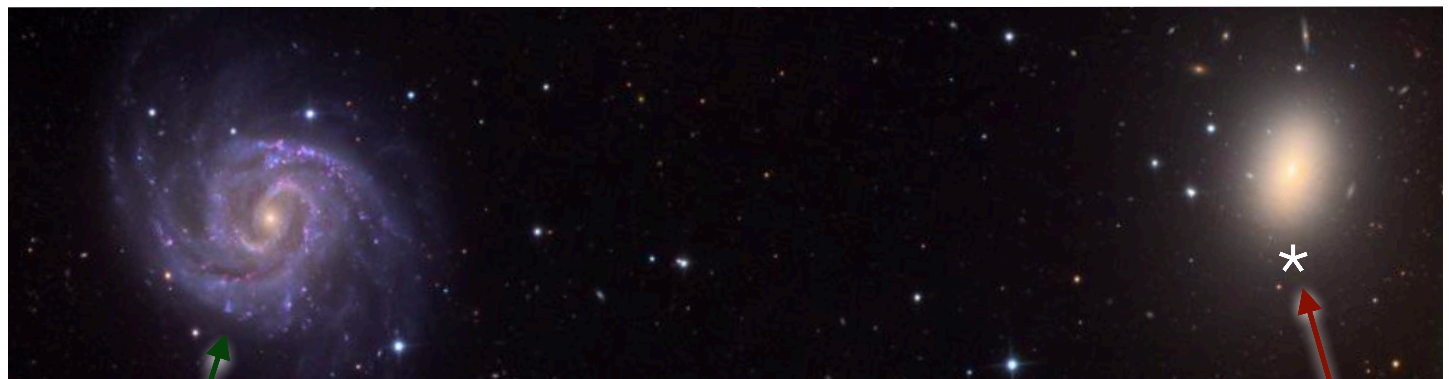

LSS

Milky Way models
Can be checked with Pulsars
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Host halo models
Depends on galaxy types?
Location of FRBs?

Redshift scaling:

const.

$$\propto \int^{z} \frac{1+z'}{E(z')} \mathrm{d}z'$$

$$\propto \frac{1}{1+z}$$

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Statistics can tell contributions apart

Dispersion measure

Dispersion measure has several contribution:

$$\mathrm{DM}_{\mathrm{tot}}(z) = \mathrm{DM}_{\mathrm{MW}} + \mathrm{DM}_{\mathrm{LSS}}(z) + \mathrm{DM}_{\mathrm{host}}(z)$$

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$$n_e \approx F(z)\frac{\rho_b}{m_p} = F(z)\frac{\bar{\rho}_b}{m_p}\left[1 + b_e\delta_m\right]$$

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Density field

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Ionisation history

Density field

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Baryon fraction

$$n_e \approx F(z) \frac{\rho_b}{m_p} = F(z) \frac{\bar{\rho}_b}{m_p} \left[1 + b_e \delta_m\right]$$

Distance measure

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Need redshifts

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FRB statistics

Redshifts in general not known: consider angular clustering

Correlate FRBs

$$C_\ell = \langle \delta_\ell^{\mathrm{FRB}} \, \delta_{\ell'}^{\mathrm{FRB}} \rangle$$

Sparse, noisy distances, shot-noise dominated

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Correlate dispersion measure

$$C_\ell = \langle \mathrm{DM}_\ell \, \mathrm{DM}_{\ell'} \rangle \sim \int \mathrm{d}\chi \Big[\ldots P_{ee}(k) \Big] + \frac{\sigma^2_{\mathrm{host}}}{\bar{n}}$$

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signal >> noise

Because ${\rm DM}_{\rm LSS}(z) \gg {\rm DM}_{\rm host}$

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weak lensing on steroids*

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$$C_\ell = \langle {\rm DM}_\ell\, {\rm DM}_{\ell'} \rangle \sim \int {\rm d}\chi \left[\ldots P_{ee}(k) \right] + \frac{\sigma^2_{\rm host}}{\bar{n}}$$

*(but still sparse)

signal >> noise

Because ${\rm DM}_{\rm LSS}(z) \gg {\rm DM}_{\rm host}$

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Equivalence principle

- If EP is broken, photons of different frequencies would pick up an additional (to ν^{-2} scaling) delay

$$\Delta t = \Delta t_{\mathrm{DM}} + \Delta t_{\mathrm{grav}}$$

- So far what has been assumed is the classical Shapiro delay expression

$$t_{\mathrm{grav}} = -\frac{1+\gamma}{c^3} \int_{\boldsymbol{r}_\mathrm{e}}^{\boldsymbol{r}_\mathrm{o}} \mathrm{d}\lambda \, U(\boldsymbol{r}(\lambda))$$

- Idea: assume to know a subset of potentials along line-of-sight

- Put upper limits on $\Delta\gamma$

Problems

- Adding structure increases the limit monotonically
- In a cosmological setting the standard expression diverges due to boundary conditions
- Should rather use

$$\Delta t_{\mathrm{grav}} = \frac{\Delta\gamma}{c^3} \int \mathrm{d}\chi a(\chi) \phi(\hat{\boldsymbol{x}}\chi)$$

- New problem: no longer upper bound since ϕ fluctuates

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Equivalence principle tests

- True observable: time delay between frequency arrival $\Delta t = \Delta t_{\rm DM} + \Delta t_{\rm grav}$

- Shapiro delay

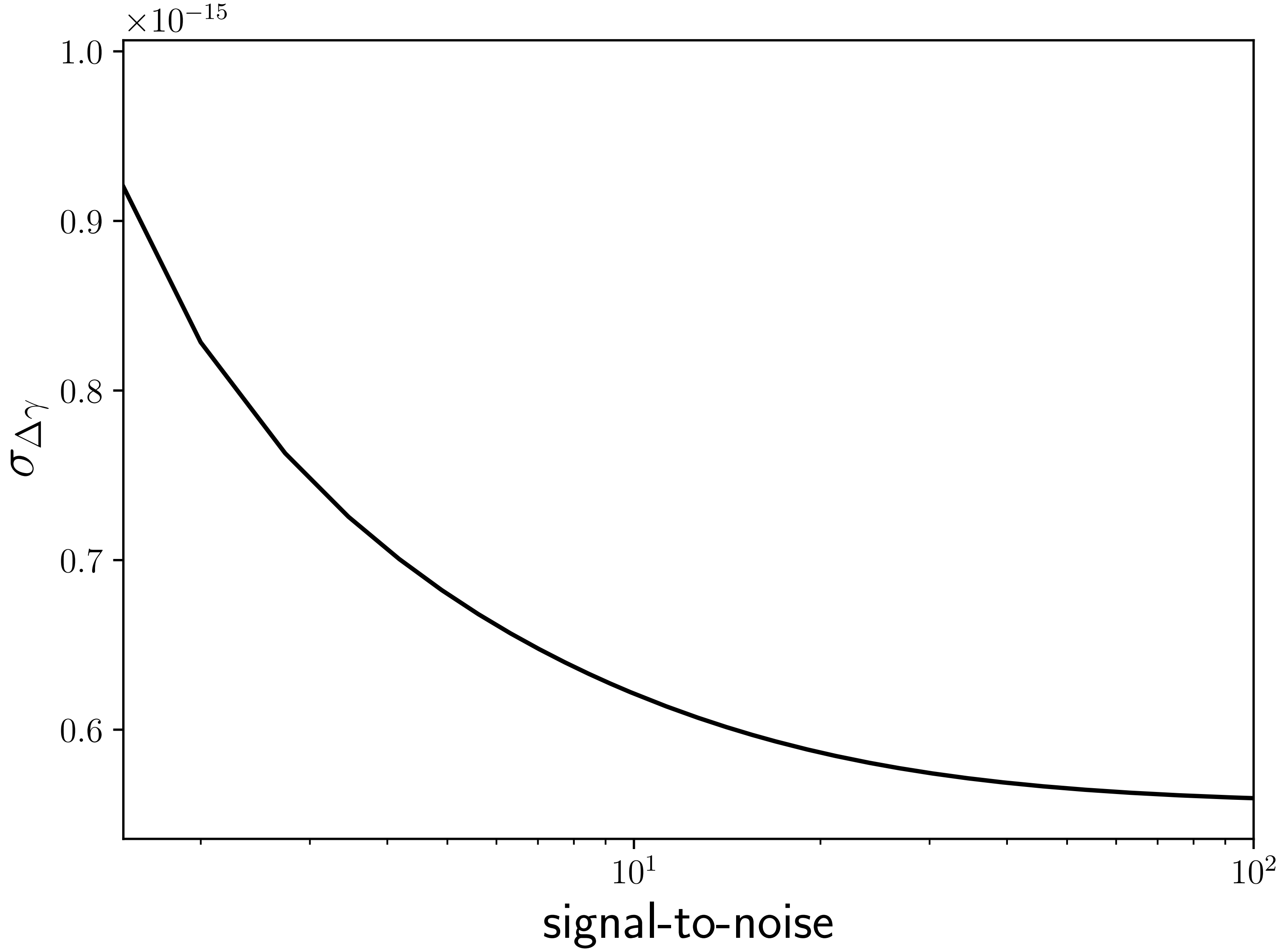
Possible frequency dependence

$$\Delta t_{\rm grav} = \frac{\Delta\gamma}{c^3}\int \mathrm{d}\chi a(\chi)\phi(\hat{\boldsymbol{x}}\chi)$$

- Can imprint additional correlations when interpreted as DM signal

Equivalence principle tests

Reischke, Hagstotz, Lilow, 2102.11554



- Events ~ms, line of sight ~Gpc
- Any $\Delta\gamma$ would completely dominate the correlation signal
- Any detection puts tight constraints on the EP

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Distance scales

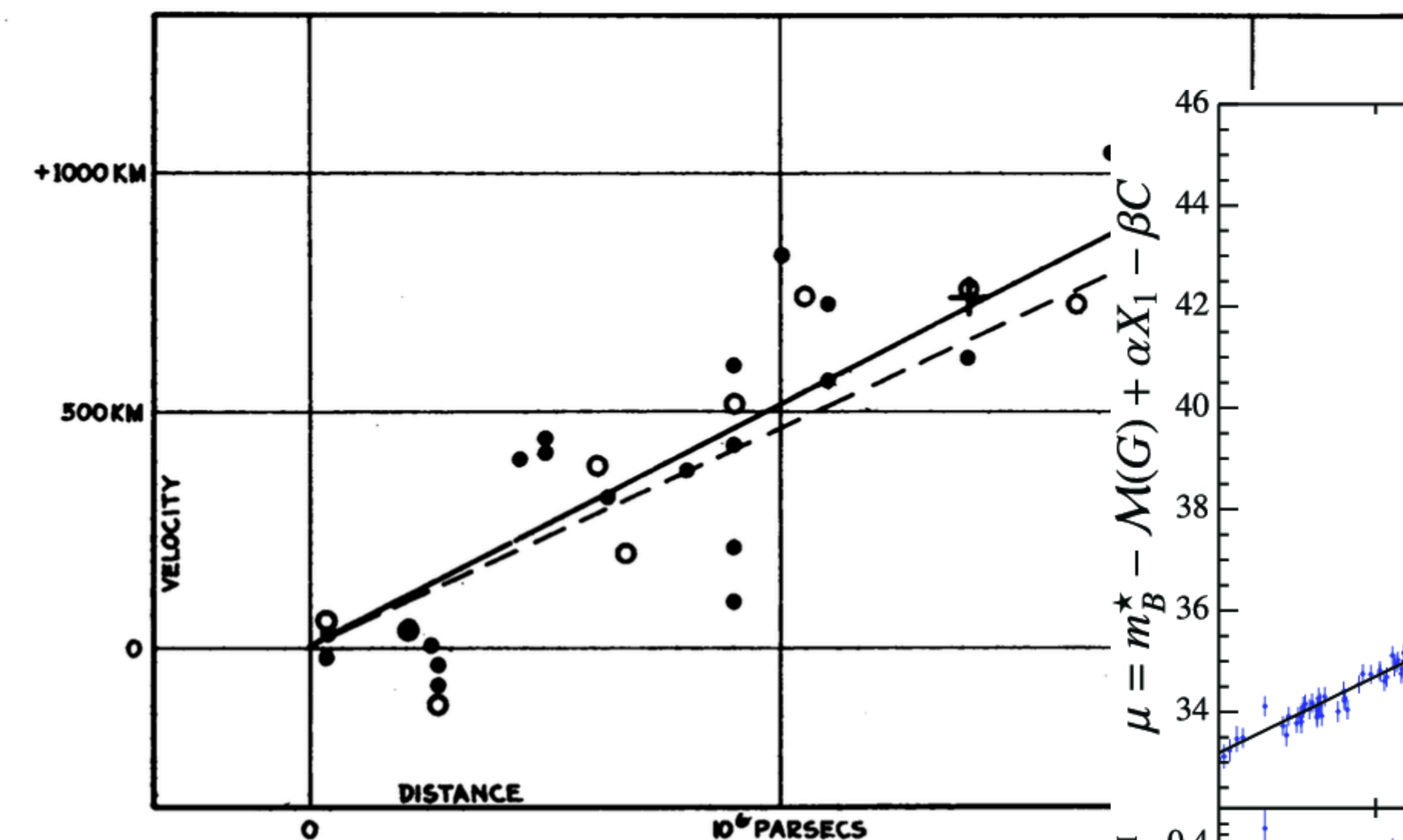
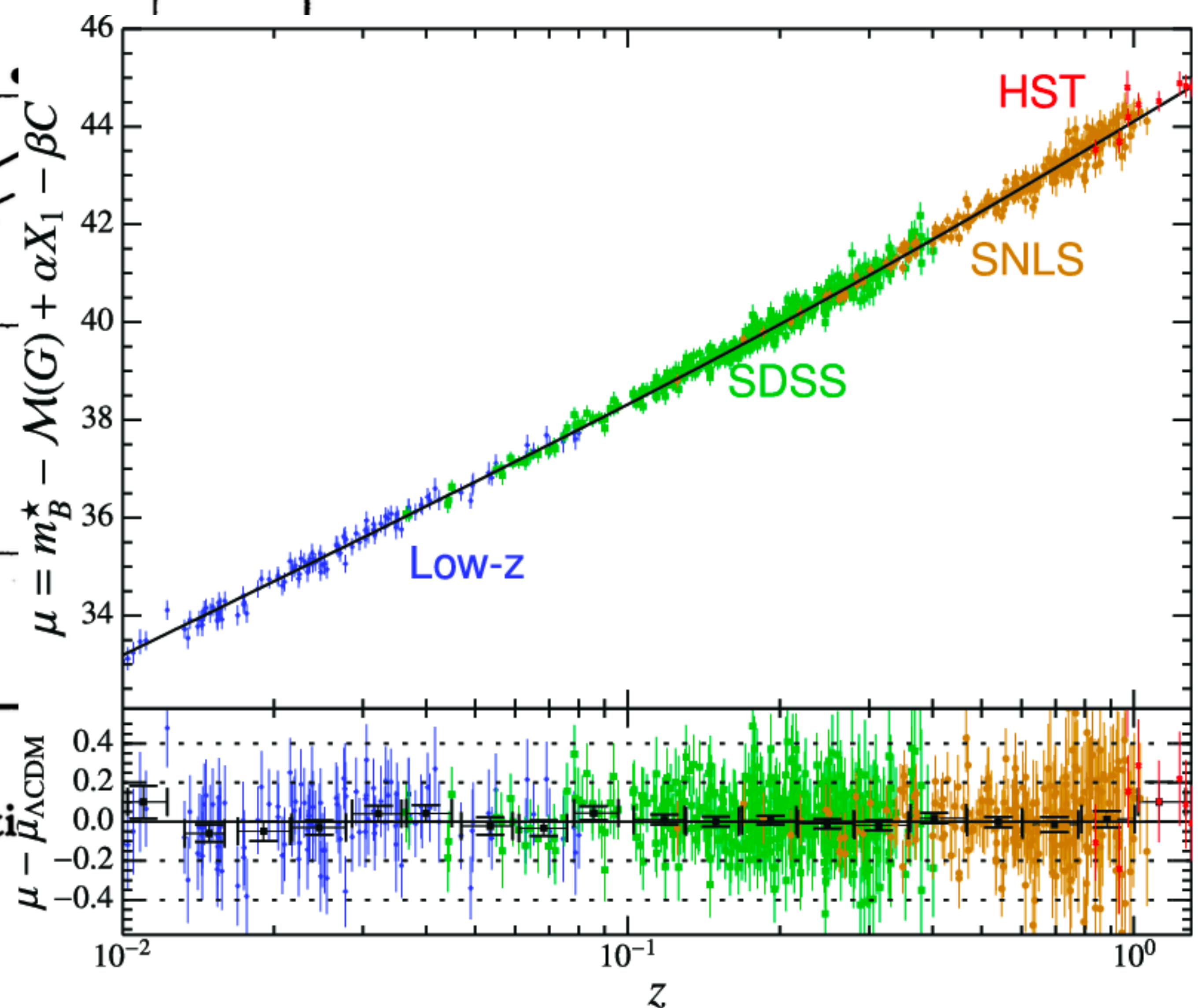


FIGURE 1
Velocity-Distance Relation among Extra-Galacti



Bahcall 2015

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FRB distance scale

Mean LSS dispersion:

$$< \mathrm{DM}_{\mathrm{LSS}} > (z) = \int \mathrm{d}l \frac{n_e}{1+z}$$

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$$= \frac{3\Omega_\mathrm{b} H_0}{8\pi G m_\mathrm{P}} \chi_\mathrm{e} f_\mathrm{IGM} \int^z \frac{1+z'}{E(z')} \mathrm{d}z'$$

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- Perfect degeneracy at the background level
- Combine with prior on baryon density $\Omega_\mathrm{b} h^2$ (from CMB or BBN)

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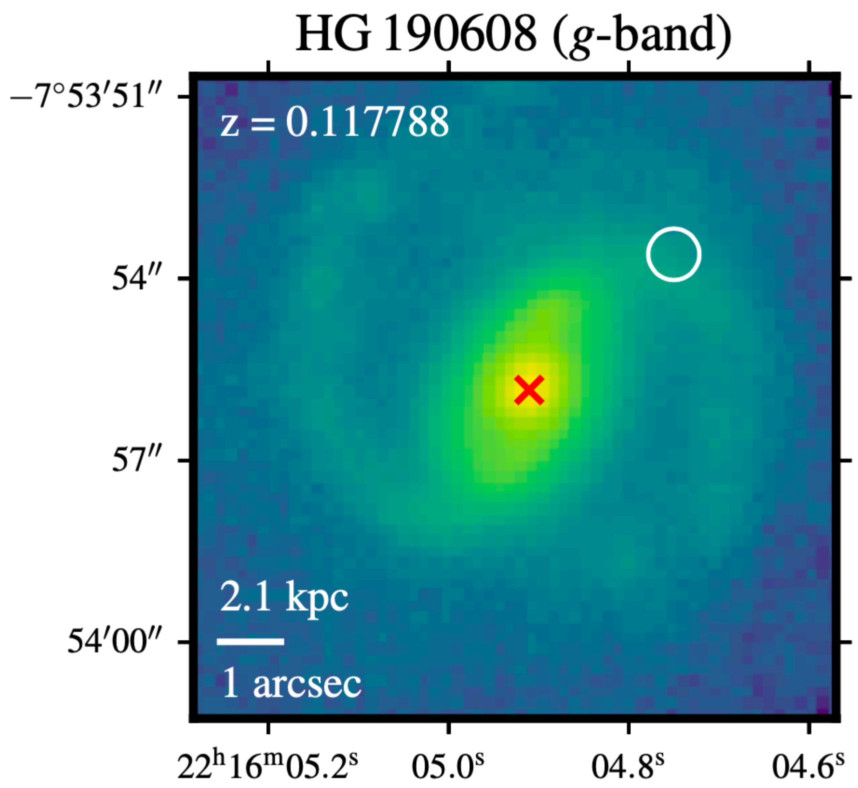
Host ID



VLT + ASKAP (Macquart et al 2020)

- Dedicated FRB searches from radio arrays
- Long baselines, excellent angular resolution
- Optical follow-up allows host ID and redshift

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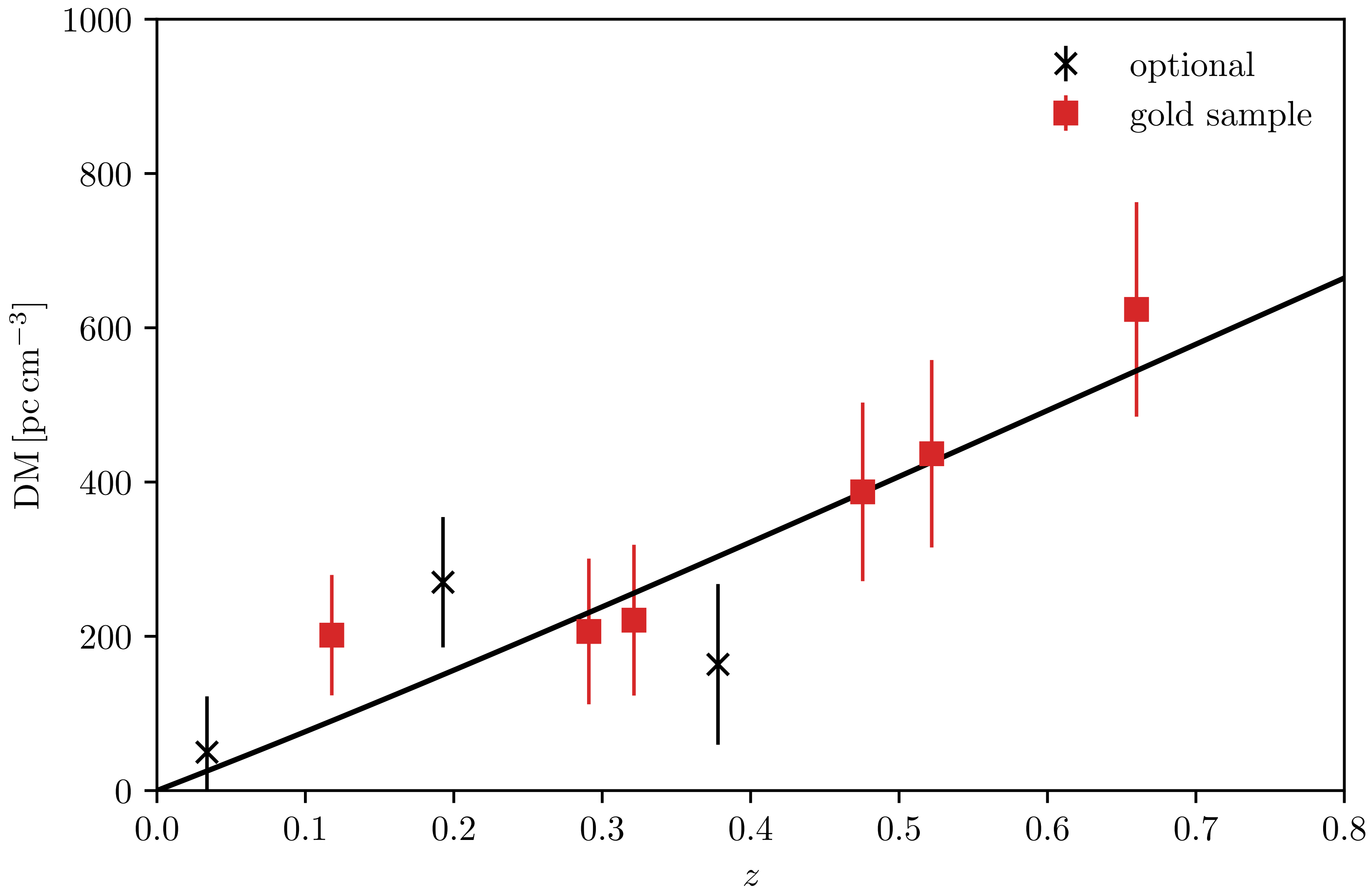
FRB distance scale



- Compile DM-z diagram similar to SNe Ia
- Absolute calibration via subtraction of host & MW DM
- Additional “gold sample” of high quality events

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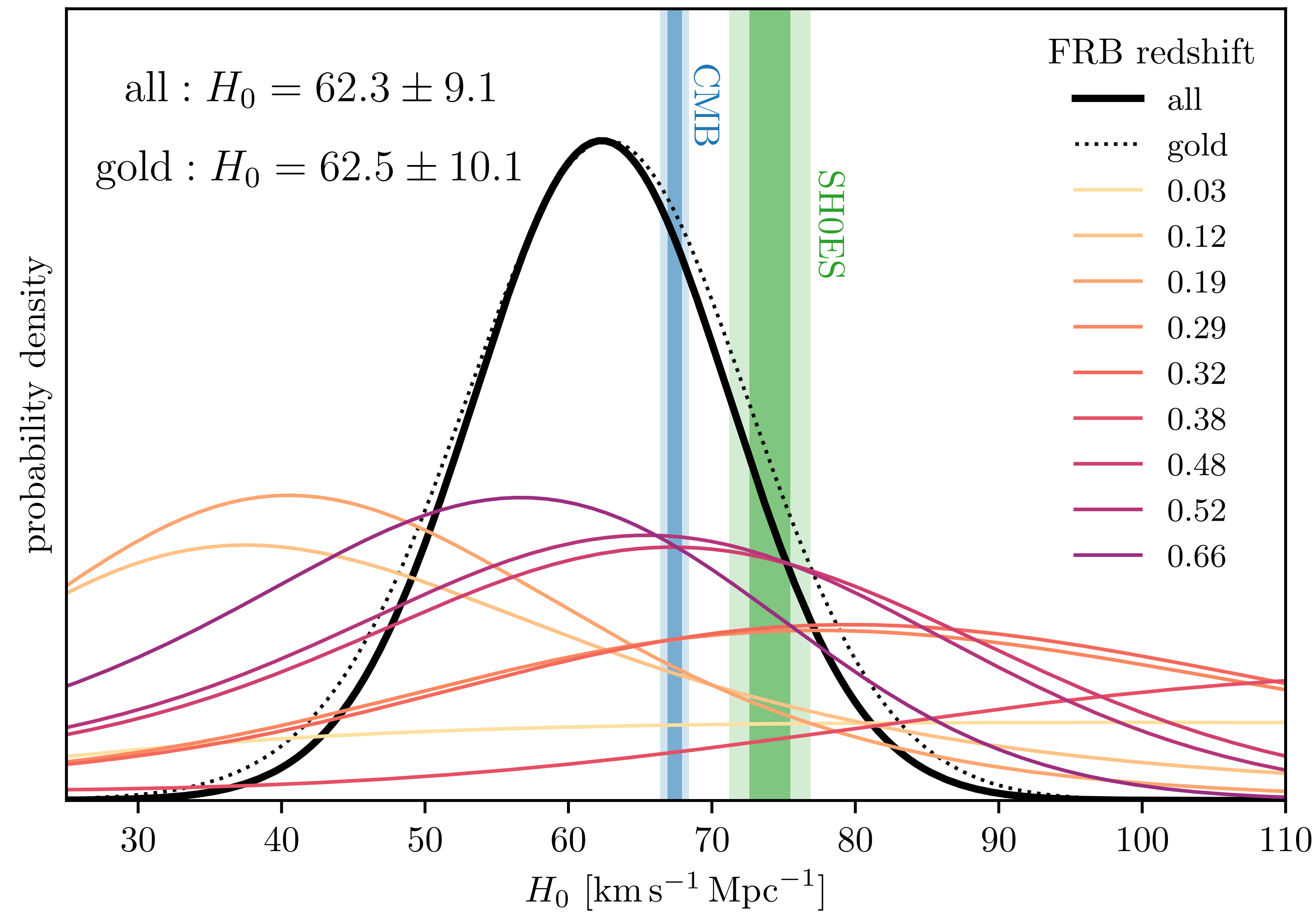
Hubble constant



Events at large z most important

Uncertainty in host DM dominates error

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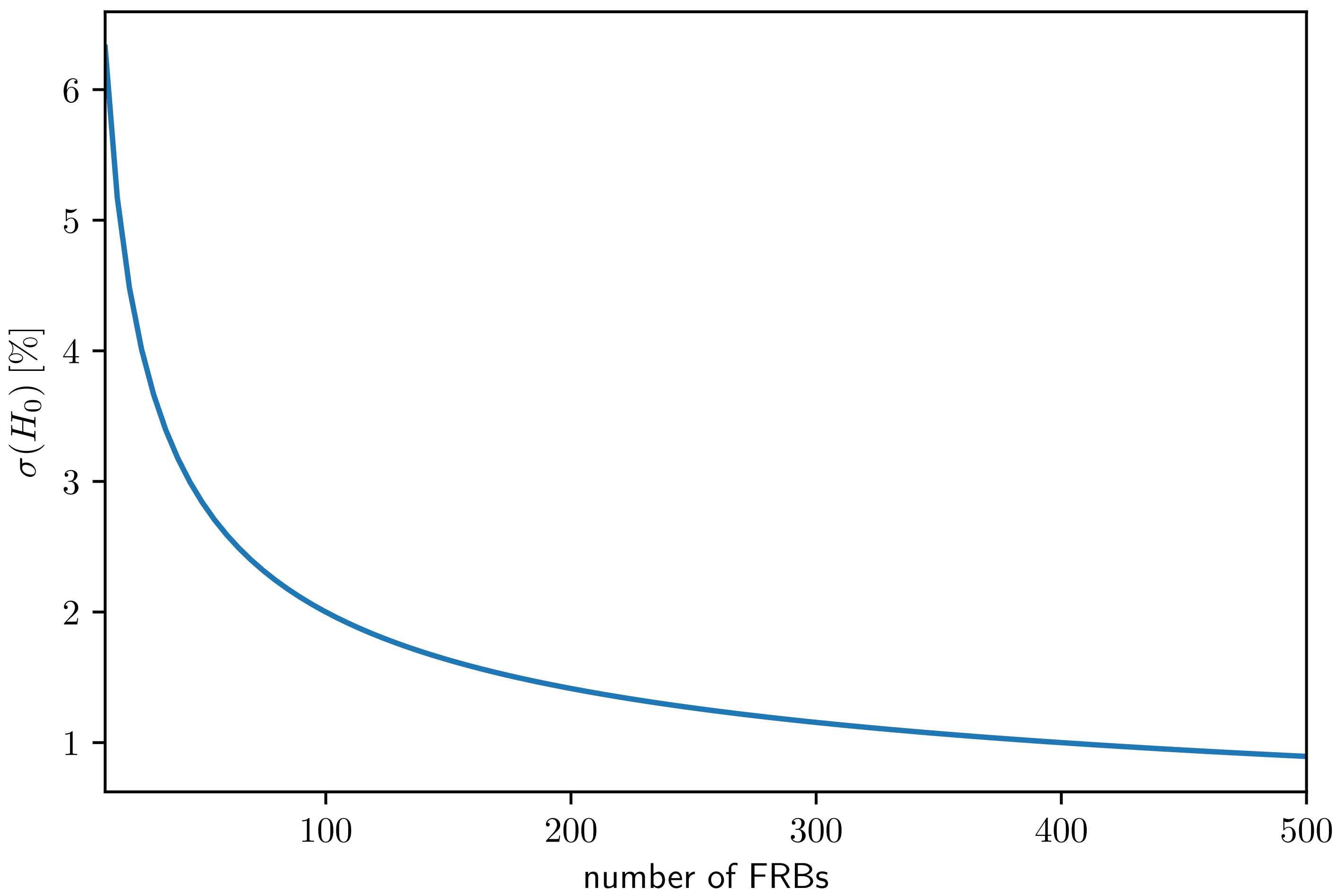
The Future

When can FRBs be competitive?



- A few hundred events with host ID get to ~1% precision

- Can we relax some assumptions with larger samples?

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Dispersion measure

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Quite accurate!

Host halo models
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Location of FRBs?

Redshift scaling:

const. $\quad \propto \int^{z} \frac{1+z'}{E(z')}\mathrm{d}z' \quad \propto \frac{1}{1+z}$

Statistics can tell contributions apart

GCCL
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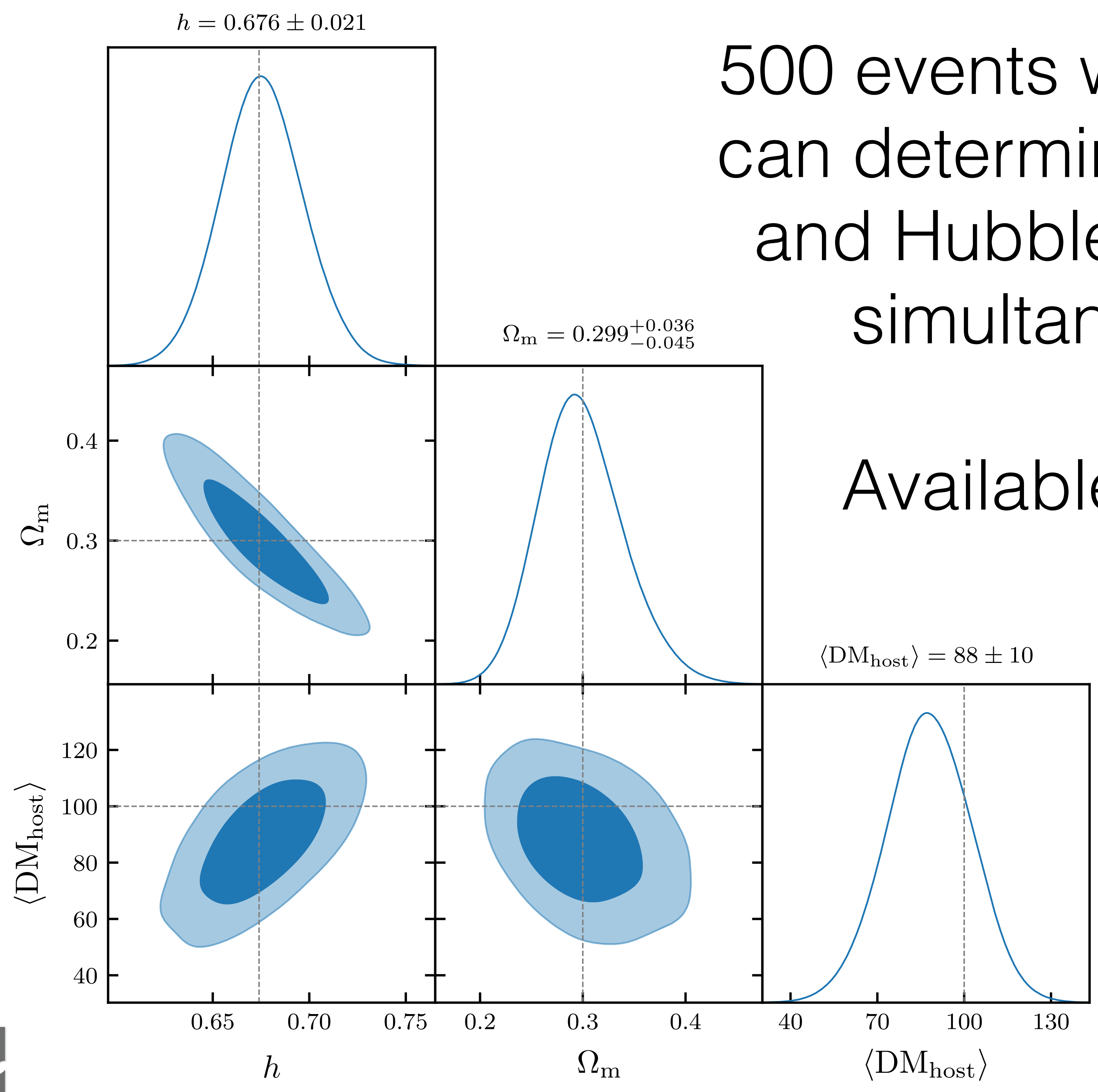
Forecast



500 events with host ID can determine host DM and Hubble constant simultaneously

Available soon!

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Summary

- Mechanism of the bursts unknown
- FRBs can provide independent* measurement of the Hubble constant $H_0 = 62.3 \pm 9.1$
- Currently limited by statistics, many more events are coming from CHIME/ASKAP/HIRAX
- FRBs can do many more things for cosmology!

  Primordial non-Gaussianity (Reischke, Hagstotz, Lilow 2020)

  Equivalence principle (Reischke, Hagstotz, Lilow 2021)

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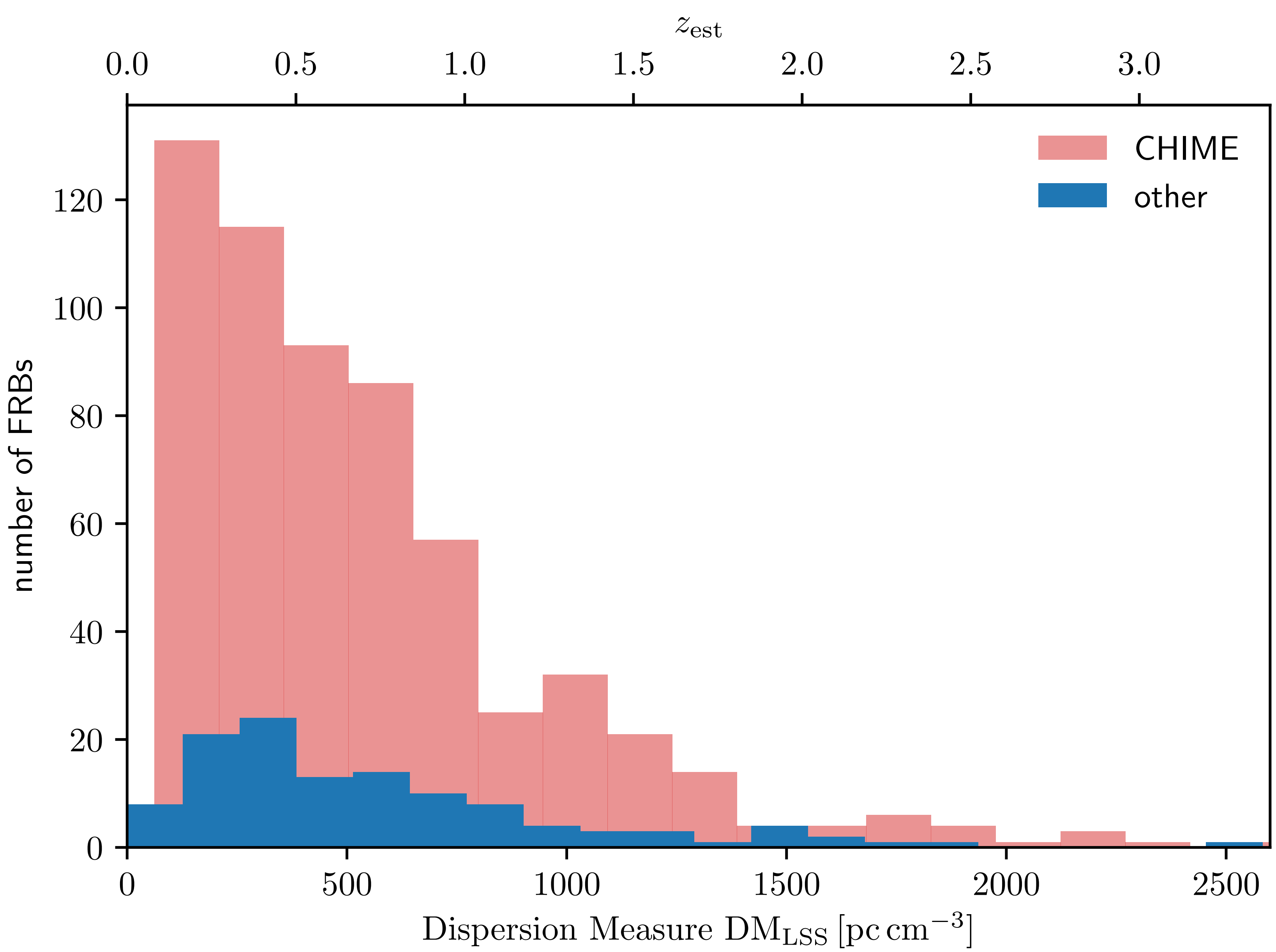
Backup

LUDWIG-
MAXIMILIANS-
UNIVERSITÄT
MÜNCHEN

Steffen Hagstotz

Known FRBs



- True FRB population not well known
- Detections up to z~2 possible
- Maybe beyond? Reionisation studies?

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