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Fast Radio Burst Dispersion Measures & Rotation Measures

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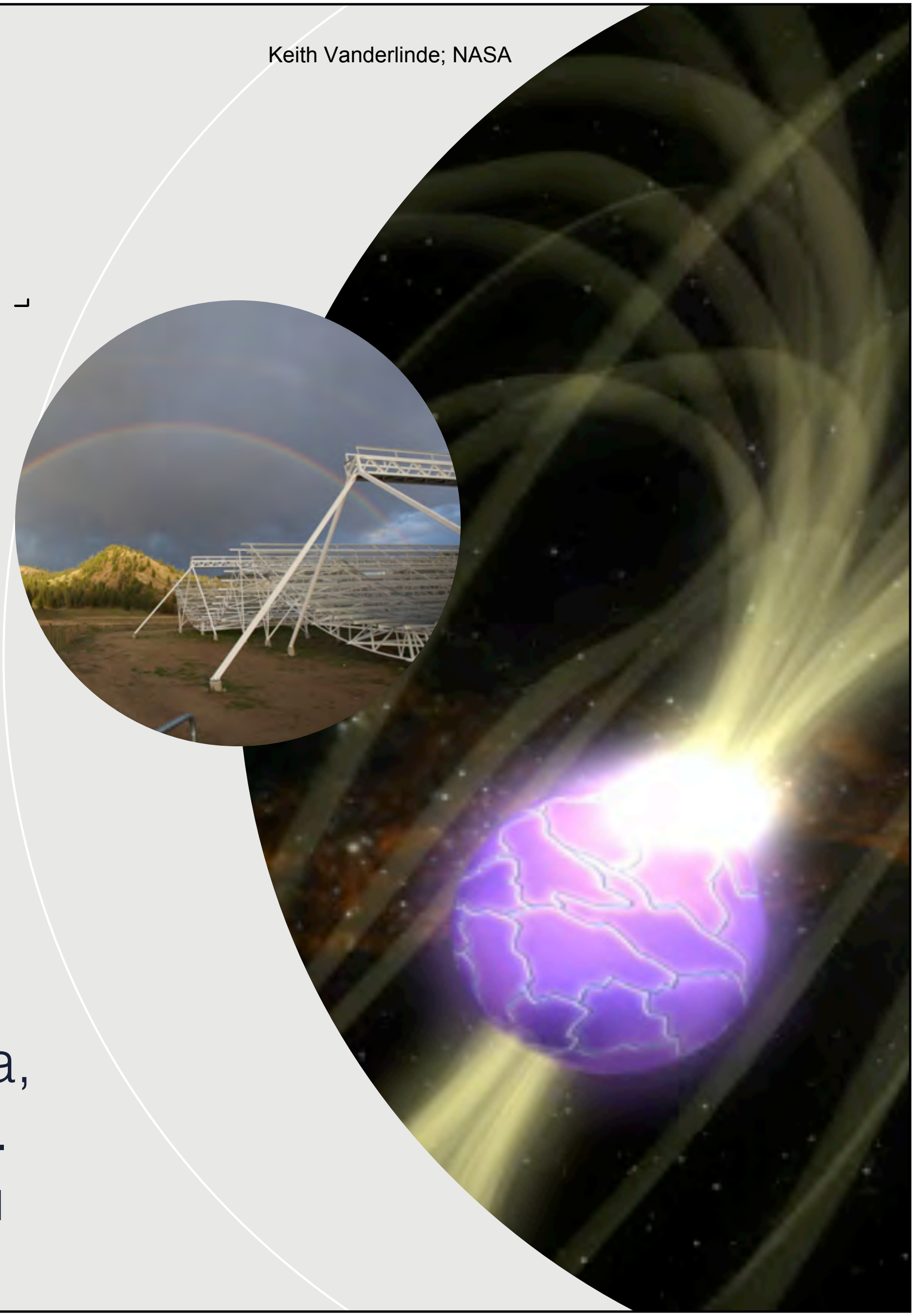

Keith Vanderlinde; NASA

Dispersion Measure and Rotation Measure

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$$\text{delay} = 0.41\ \text{seconds} \times \left(\frac{\text{DM}}{\text{pc cm}^{-3}}\right) \times \left(\frac{\nu}{100\ \text{MHz}}\right)^{-2}$$

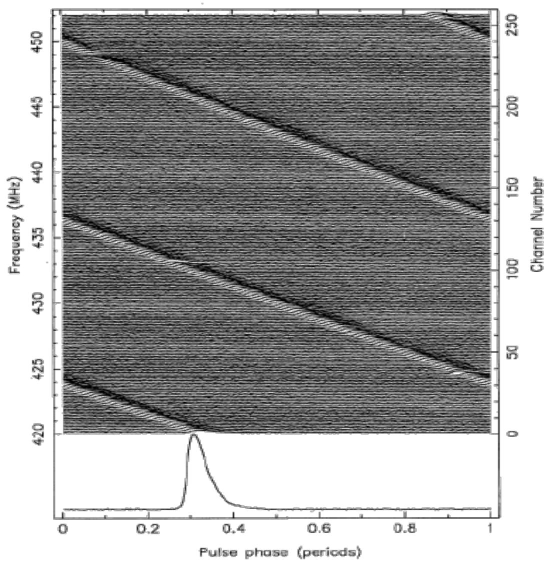
$$\Delta\Theta = \text{RM}\ \lambda^2$$

$$\text{DM} = \int_0^{L/\text{pc}} \left(\frac{n_e}{\text{cm}^{-3}}\right)\left(\frac{dl}{\text{pc}}\right)\ \text{pc cm}^{-3}$$

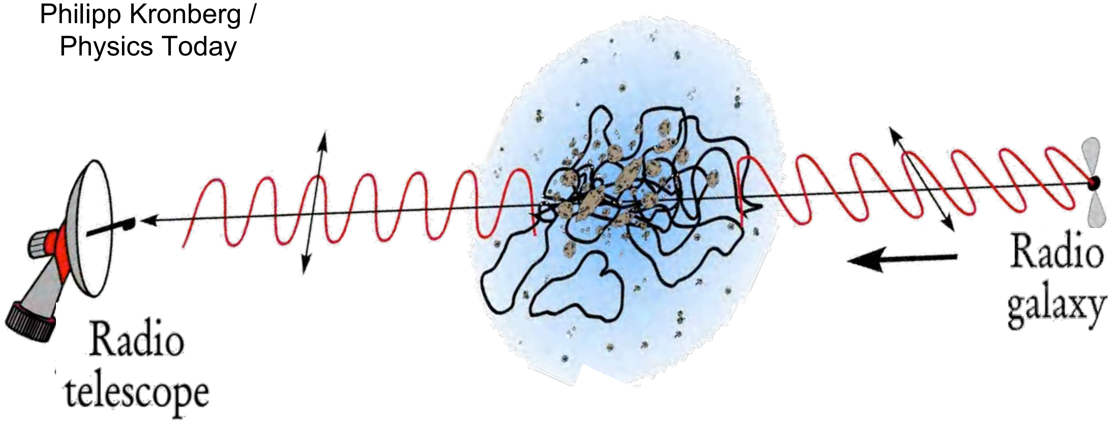
$$\text{RM} = 0.812 \int_{L/\text{pc}}^{0} \left(\frac{n_e}{\text{cm}^{-3}}\right)\left(\frac{B_{||}}{\mu\text{G}}\right)\left(\frac{dl}{\text{pc}}\right)\ \text{rad m}^{-2}$$

$$\langle B_{||} \rangle = 1.232 \frac{(\text{RM / rad m}^{-2})}{(\text{DM / pc cm}^{-3})}\ \mu\text{G}$$

Manchester et al. (1996)



Philipp Kronberg / Physics Today



Possible DM & RM Contributions

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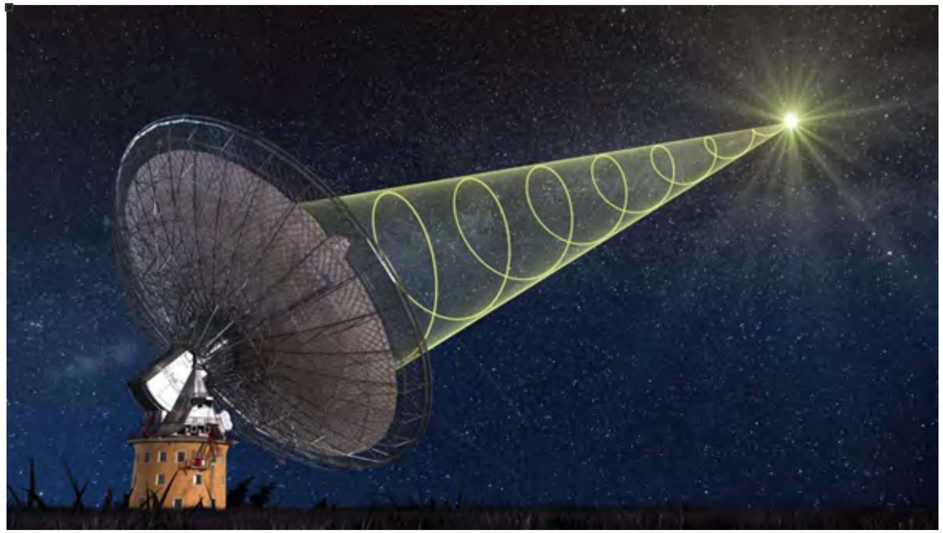
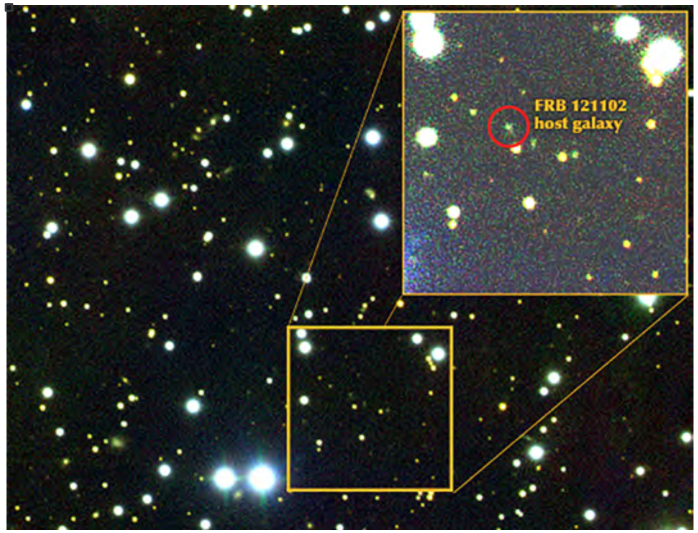
- Milky Way disk (Oppermann et al. 2015; Yao et al. 2016)
- Milky Way halo (Dolag, Gaensler et al. 2015)
- Host galaxy (Xu & Han 2015; Yang et al. 2016, 2017)
- Local environment (Connor+ 2016; Lyuitkov+ 2016; Piro 2016, 2017)
- Intergalactic medium (IGM) (McQuinn 2014; Dolag, Gaensler et al. 2015; Akahori, Ryu & Gaensler 2016)
- Cosmological expansion (Zhou et al. 2014; Gao et al. 2014)

Swinburne Astronomy Productions





Gemini Observatory/AURA/NSF/NRC

DM & RM of Supernova Ejecta

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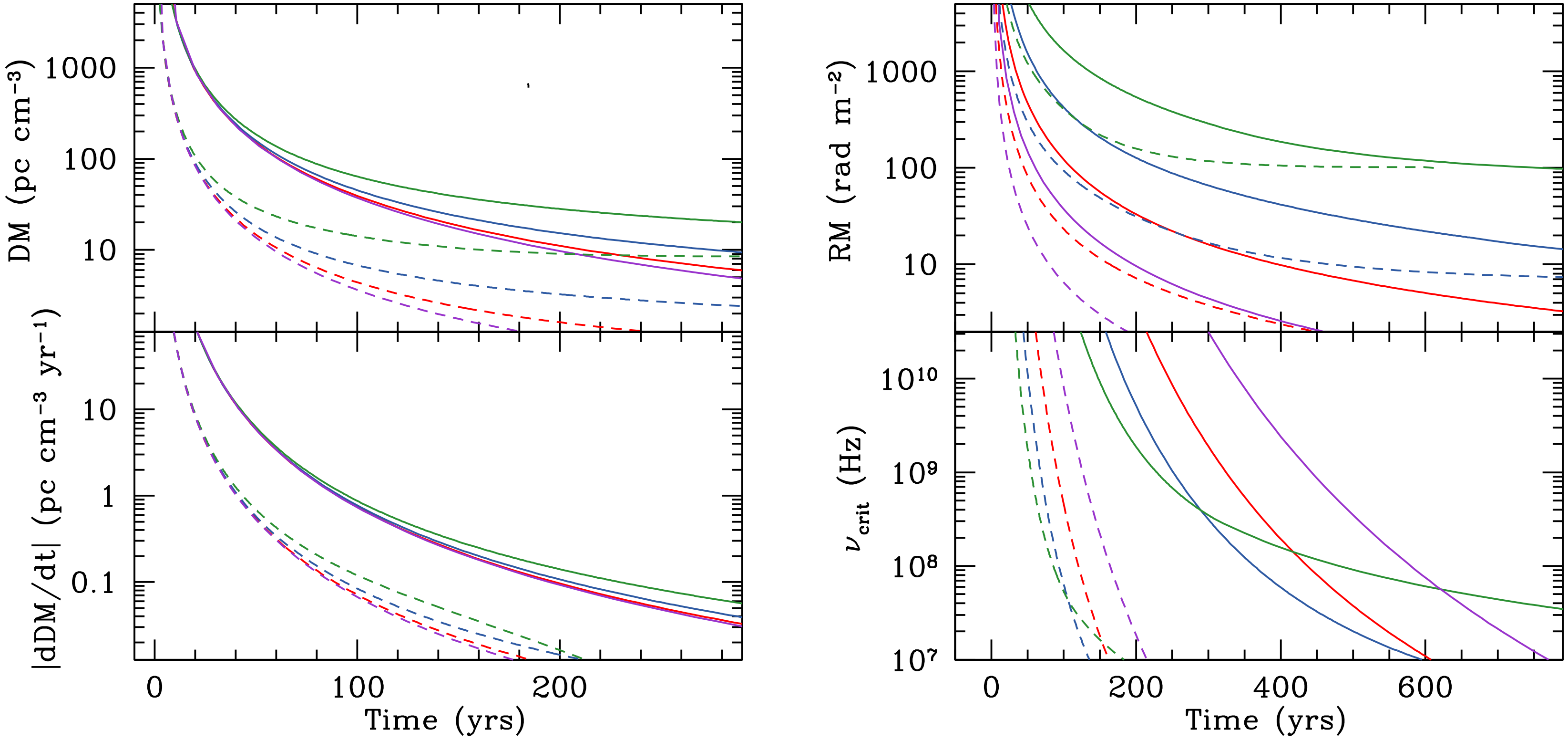

Piro (2016)

Stellar Winds

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“Bubble Nebula”, aka NGC 7635 (ESA/Hubble)

Progenitor Winds: SN 1987A

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ESA/Hubble

ESO / L. Calçada

Progenitor Winds: SN 1979C

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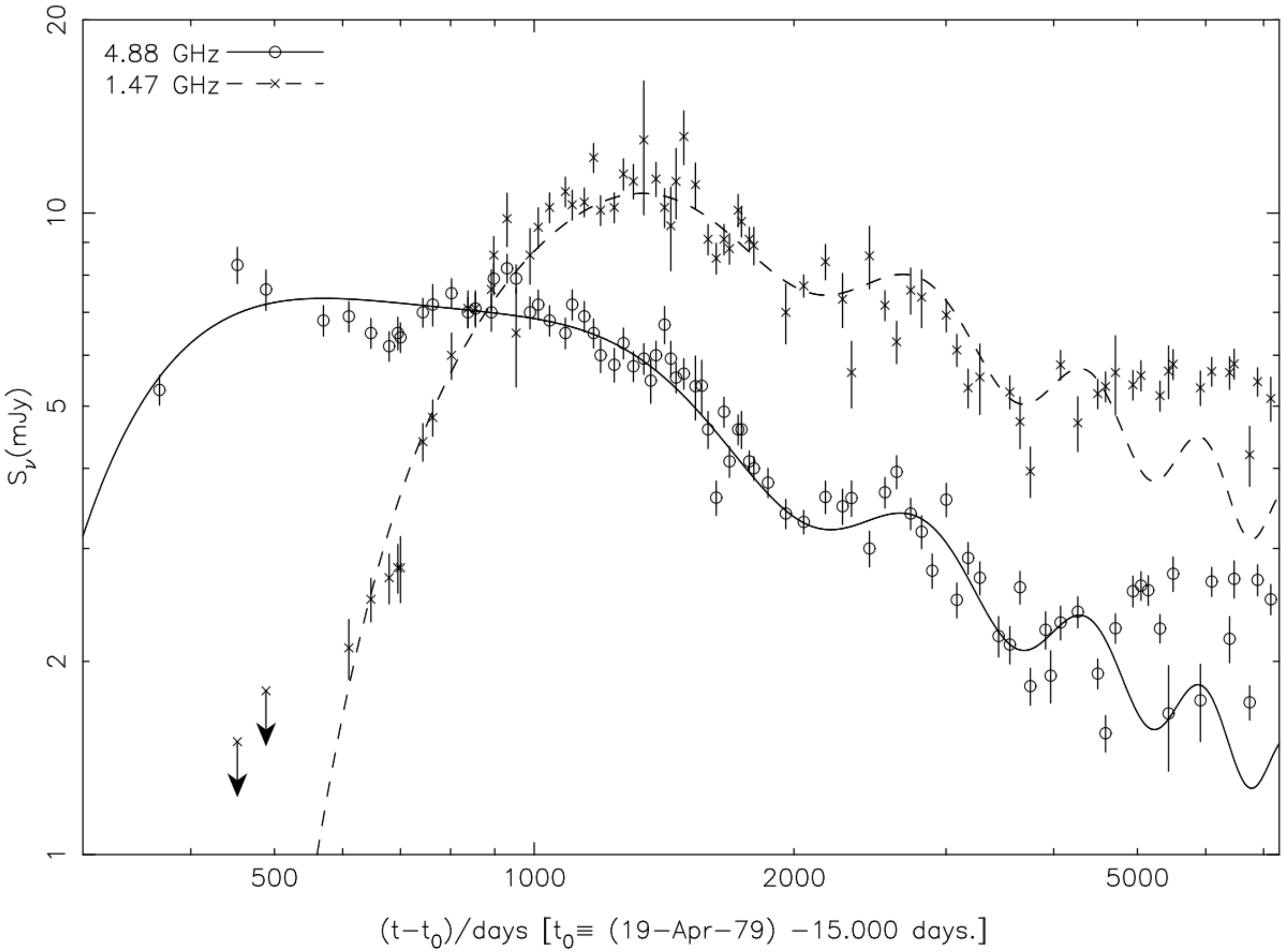

Montes et al. (2000)

Progenitor Winds: 1E 1048.1-5937

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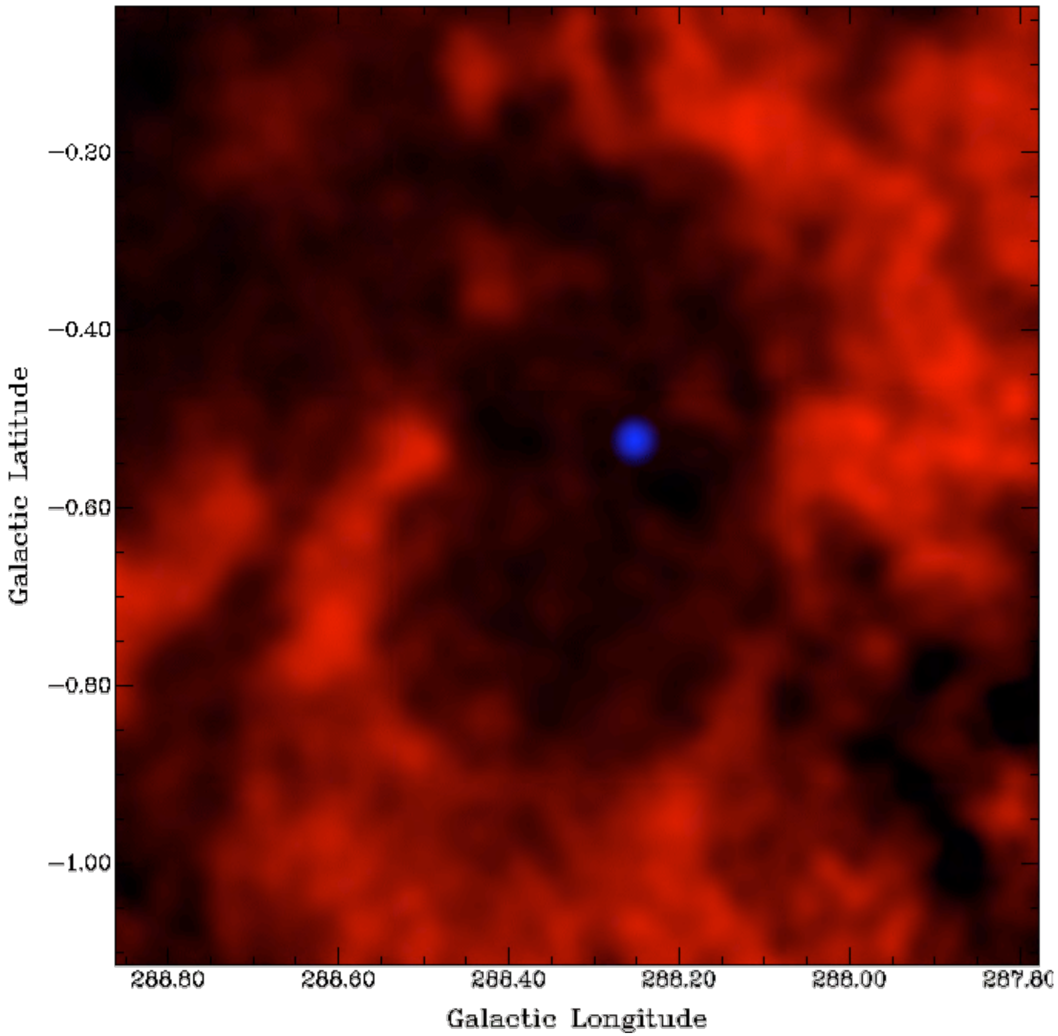

ATCA (21cm H I) + *Chandra* (Gaensler et al. 2005)

Supernova Remnants

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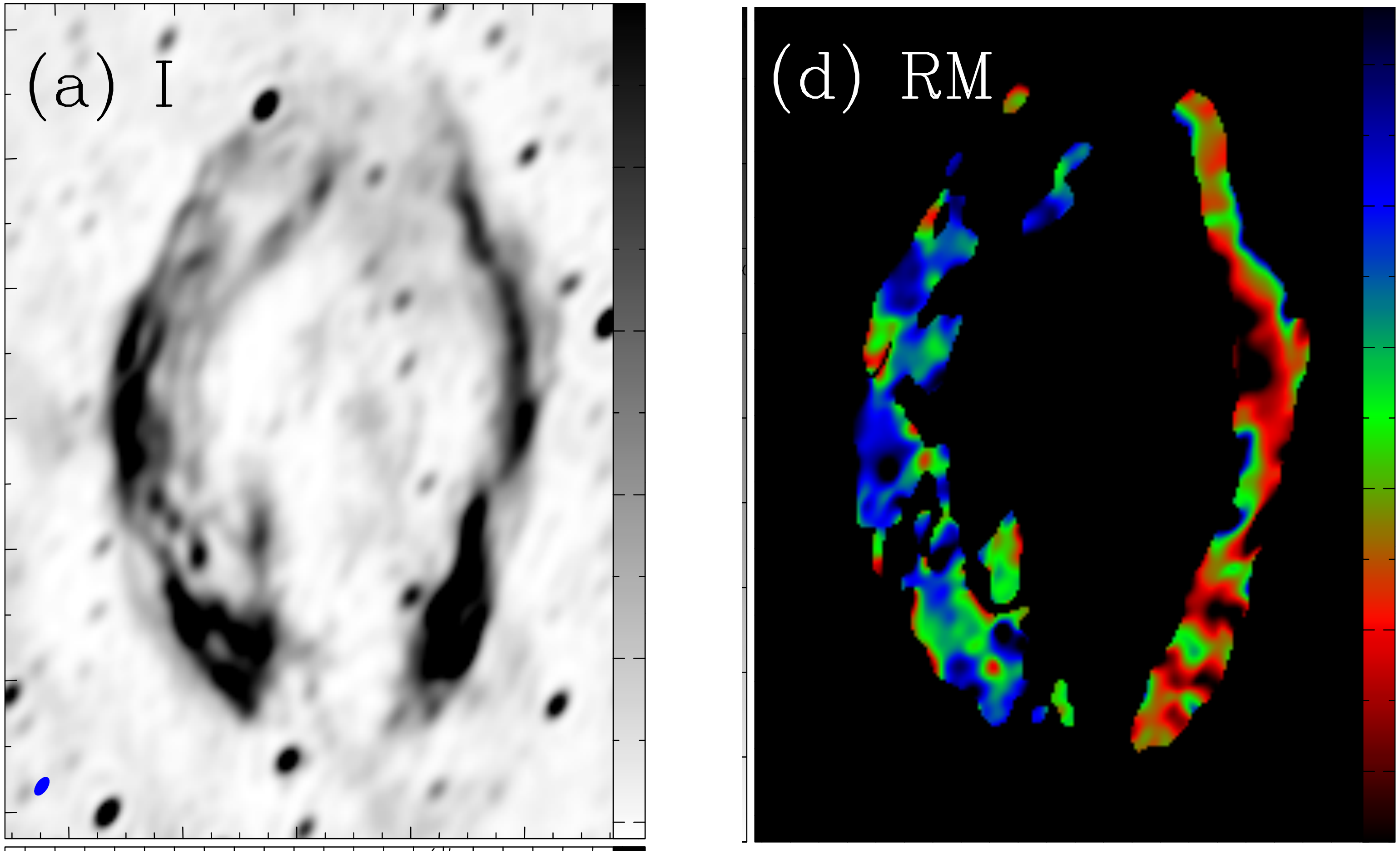

SNR G296.5+10.0 (Harvey-Smth, Gaensler et al. 2010)

Stellar Wind Structure

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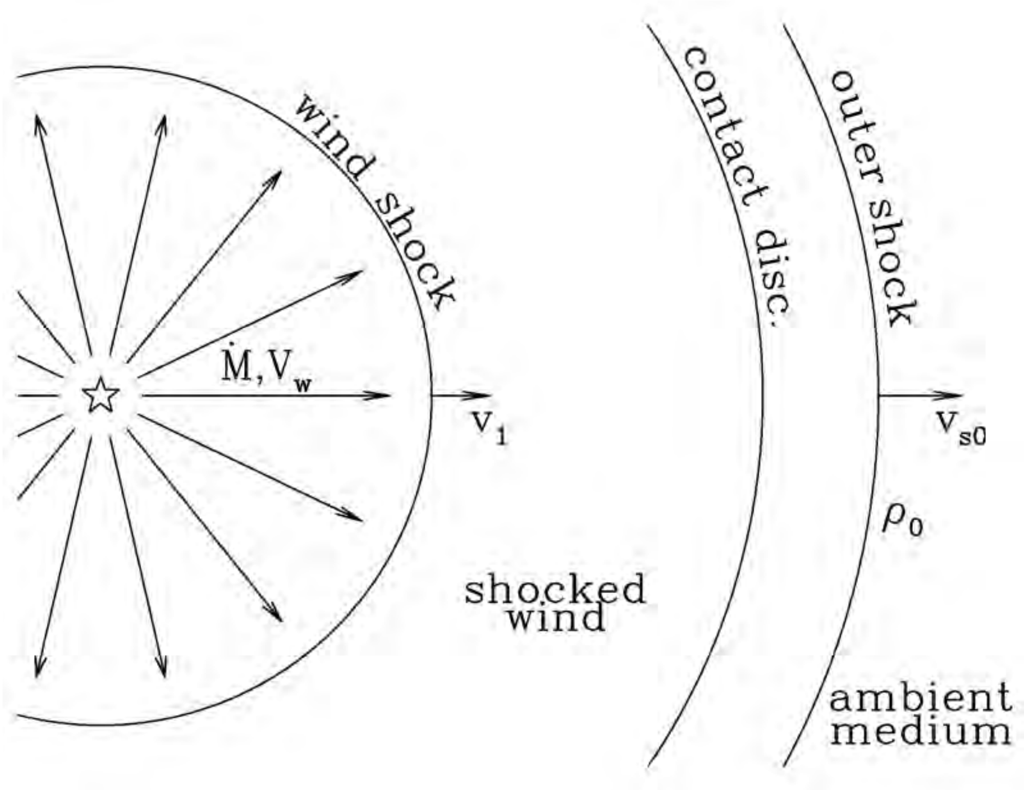

Unshocked wind:

$$n(r) = \frac{\dot{M}}{4\pi r^2 V_\infty m_H}$$

Draine (2010)

Stellar Wind Structure

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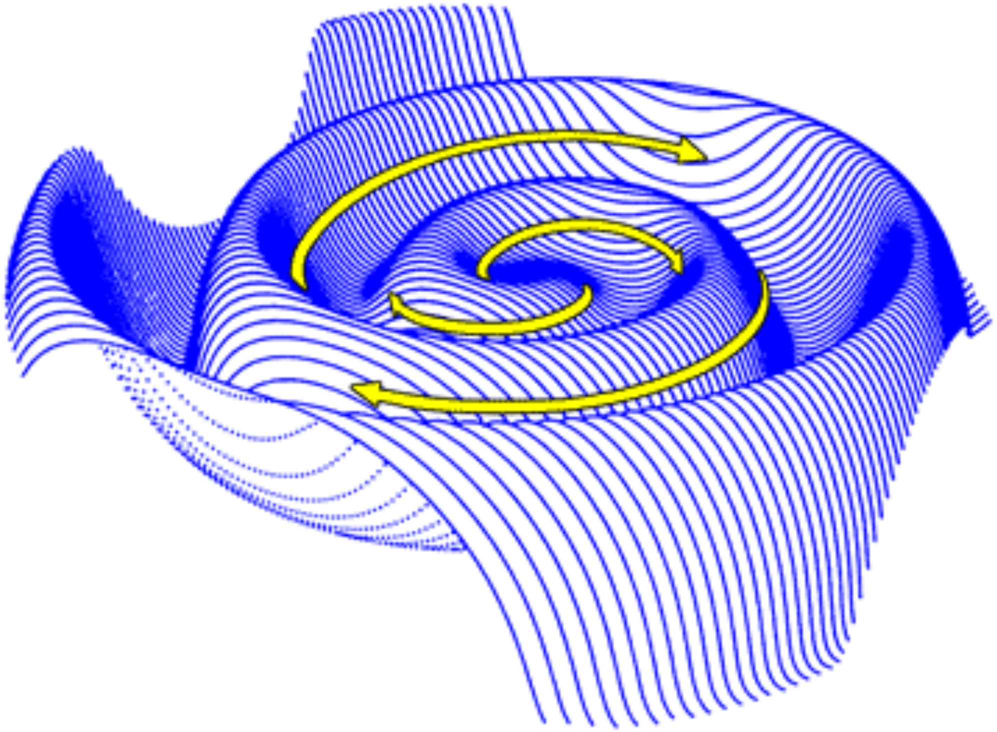

Unshocked wind:

$$B(r) \sim B_*\left(\frac{R_*}{r}\right)\left(\frac{V_{rot}}{V_\infty}\right)$$

J. Jokipii, University of Arizona

Swept Up RM and DM (I)

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- Shocked ejecta (Piro 2016):

$$\mathrm{DM}_{\mathrm{SNR}}(t) = \frac{3 f_{ion} M_{ej}}{4\pi V_{SNR}^2 m_H} t^{-2} \qquad \mathrm{RM}_{\mathrm{SNR}}(t) = 0.81 \left(4\pi \epsilon_B \rho V_{rev}^2\right)^{1/2} \frac{3 f_{ion} M_{ej}}{4\pi V_{SNR}^2 m_H} t^{-2}$$

- Uniform ambient medium (un-ionised) :

$$\mathrm{DM}_{\mathrm{SNR}}(t) = \frac{n_0 V_{SNR}}{3} t \qquad \mathrm{RM}_{\mathrm{SNR}}(t) = \frac{0.14}{\alpha} n_0 B_0 \left(\frac{R}{\Delta R}\right) V_{SNR}\, t$$

$$\alpha = \frac{\Delta R}{R} \approx \frac{1}{12}$$

- Stellar wind:

$$\mathrm{DM}_{\mathrm{SNR}}(t) = \left(\frac{\alpha+2}{\alpha+1}\right) \frac{\dot{M}}{4\pi V_\infty V_{SNR} m_H} t^{-1}$$

$$\mathrm{RM}_{\mathrm{SNR}}(t) = 0.81 \left[\frac{1}{\alpha} + \frac{1}{(1+\alpha)^2}\right] \left(\frac{V_{rot}}{V_\infty}\right) \frac{B_* R_* \dot{M}}{4\pi V_\infty V_{SNR}^2 m_H} t^{-2}$$

Piro (2016); Piro & Gaensler, in preparation

Swept Up RM and DM (II)

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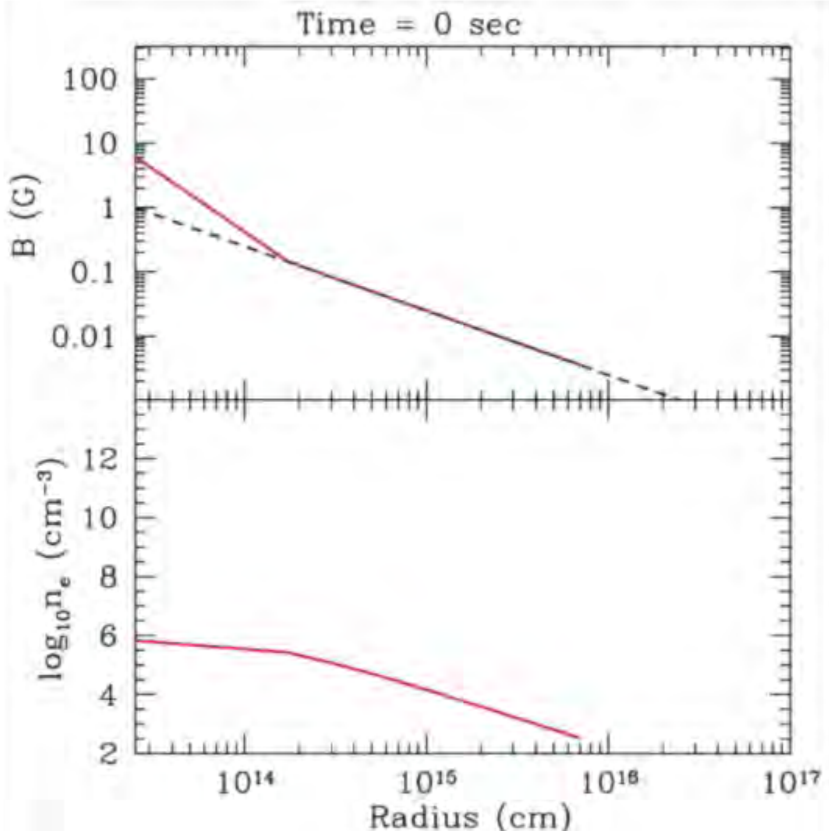

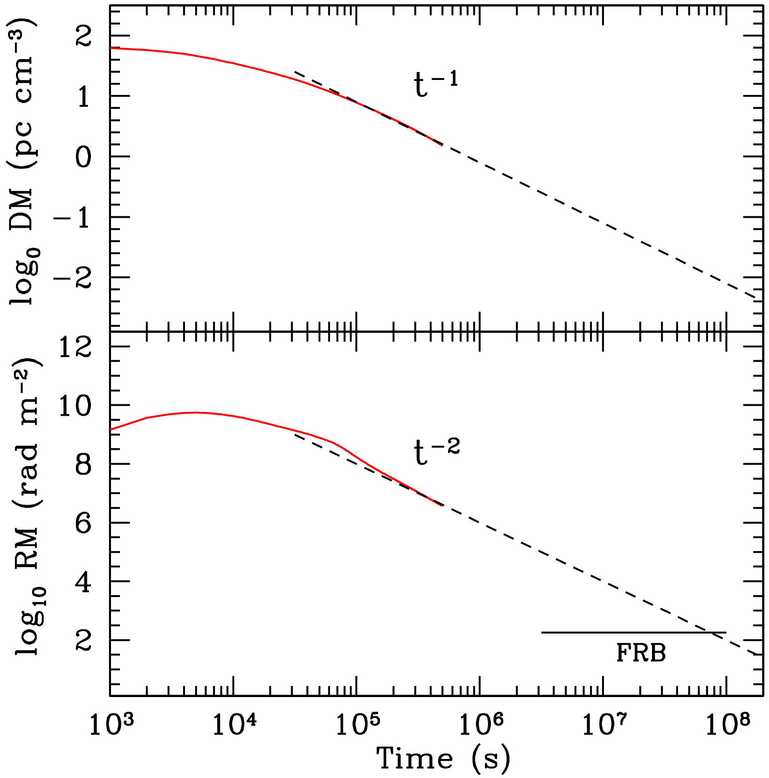

Piro & Gaensler, in preparation

Swept Up RM and DM (III)

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- Uniform ambient medium : negligible
- Shocked SNR ejecta: (Piro 2016; Piro & Burke-Spolaor 2017)

$$\mathrm{DM_{SNR}}(t) \sim 100 \left(\frac{M_{ej}}{\mathrm{M_\odot}}\right)\left(\frac{f_{ion}}{0.1}\right)\left(\frac{V_{SNR}}{10^4\,\mathrm{km/s}}\right)^{-2}\left(\frac{t}{10\,\mathrm{yr}}\right)^{-2} \mathrm{pc\,cm^{-3}}$$

$$\mathrm{RM_{SNR}}(t) \sim 400 \left(\frac{M_{ej}}{\mathrm{M_\odot}}\right)\left(\frac{f_{ion}}{0.1}\right)\left(\frac{V_{SNR}}{10^4\,\mathrm{km/s}}\right)^{-1}\left(\frac{t}{10\,\mathrm{yr}}\right)^{-2} \mathrm{rad\,m^{-2}}$$

- Stellar wind (normalised by parameters for a red supergiant):

$$\mathrm{DM_{SNR}}(t) \sim 10 \left(\frac{\dot{M}}{10^{-5}\,\mathrm{M_\odot\,yr^{-1}}}\right)\left(\frac{V_\infty}{30\,\mathrm{km/s}}\right)^{-1}\left(\frac{V_{SNR}}{10^4\,\mathrm{km/s}}\right)^{-1}\left(\frac{t}{10\,\mathrm{yr}}\right)^{-1} \mathrm{pc\,cm^{-3}}$$

$$\mathrm{RM_{SNR}}(t) \sim 3\times10^4 \left(\frac{B_*}{500\,\mathrm{G}}\right)\left(\frac{R_*}{300\,\mathrm{R_\odot}}\right)\left(\frac{\dot{M}}{10^{-5}\,\mathrm{M_\odot\,yr^{-1}}}\right)\left(\frac{V_{rot}/V_\infty}{0.1}\right)\left(\frac{V_\infty}{30\,\mathrm{km/s}}\right)^{-1}\left(\frac{V_{SNR}}{10^4\,\mathrm{km/s}}\right)^{-2}\left(\frac{t}{10\,\mathrm{yr}}\right)^{-2} \mathrm{rad\,m^{-2}}$$

- Evolution of DM & RM for repeating FRBs: overall + detailed diagnostic?

Piro & Gaensler, in preparation

Magneticum Pathfinder Simulation

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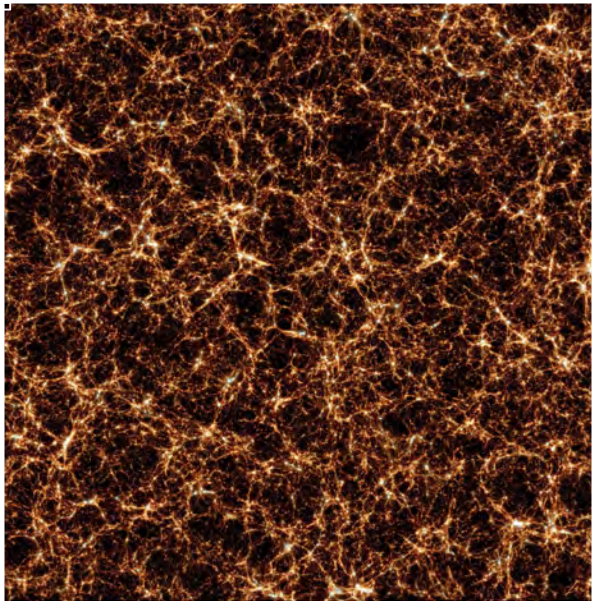
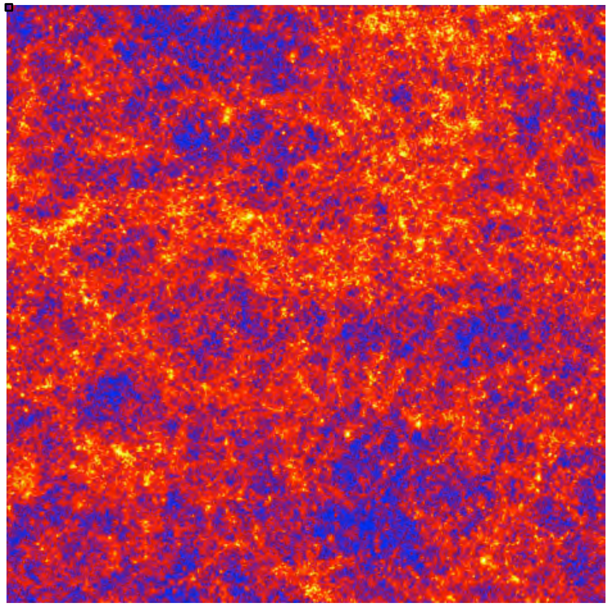
- Very large cosmological simulation ($896h^{-3}$ Mpc^3) (Dolag et al. 2014)
  - cosmic web and halos (but not disks)
  - supernova heating, winds, ionisation, AGN growth, chemical evolution
  - medium-resolution simulation for overall volume
  - high-resolution simulation for galaxies & halos

Dolag, Gaensler, Beck and Beck (2014)



T (colour) and *n* (intensity) at $z = 0$



DM out to $z = 2$

Klaus Dolag

DM Distribution: Random

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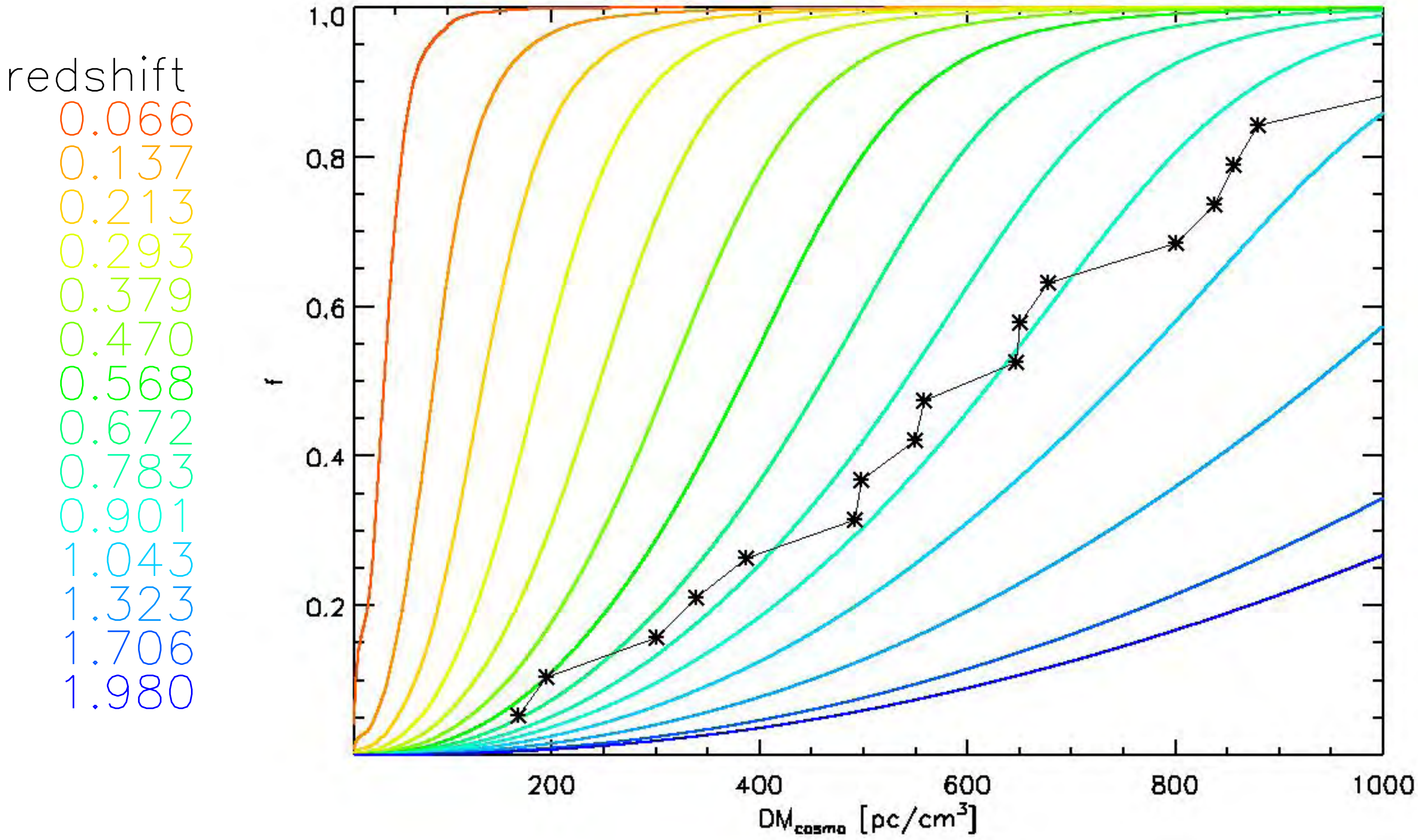

Dolag, Gaensler, et al., in preparation

DM Distribution: Traces Stars

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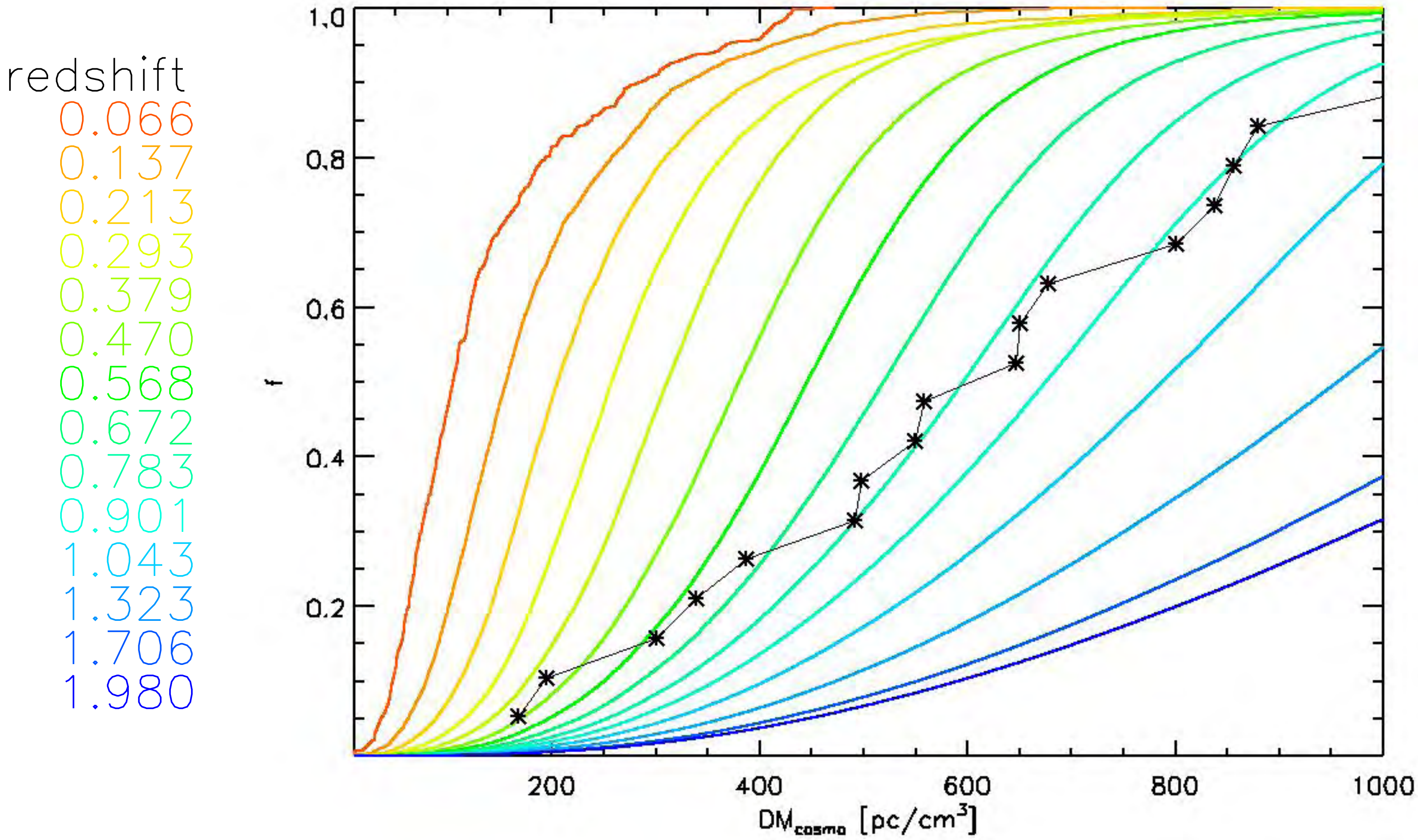

Dolag, Gaensler, et al., in preparation

DM Distribution: Stellar Populations

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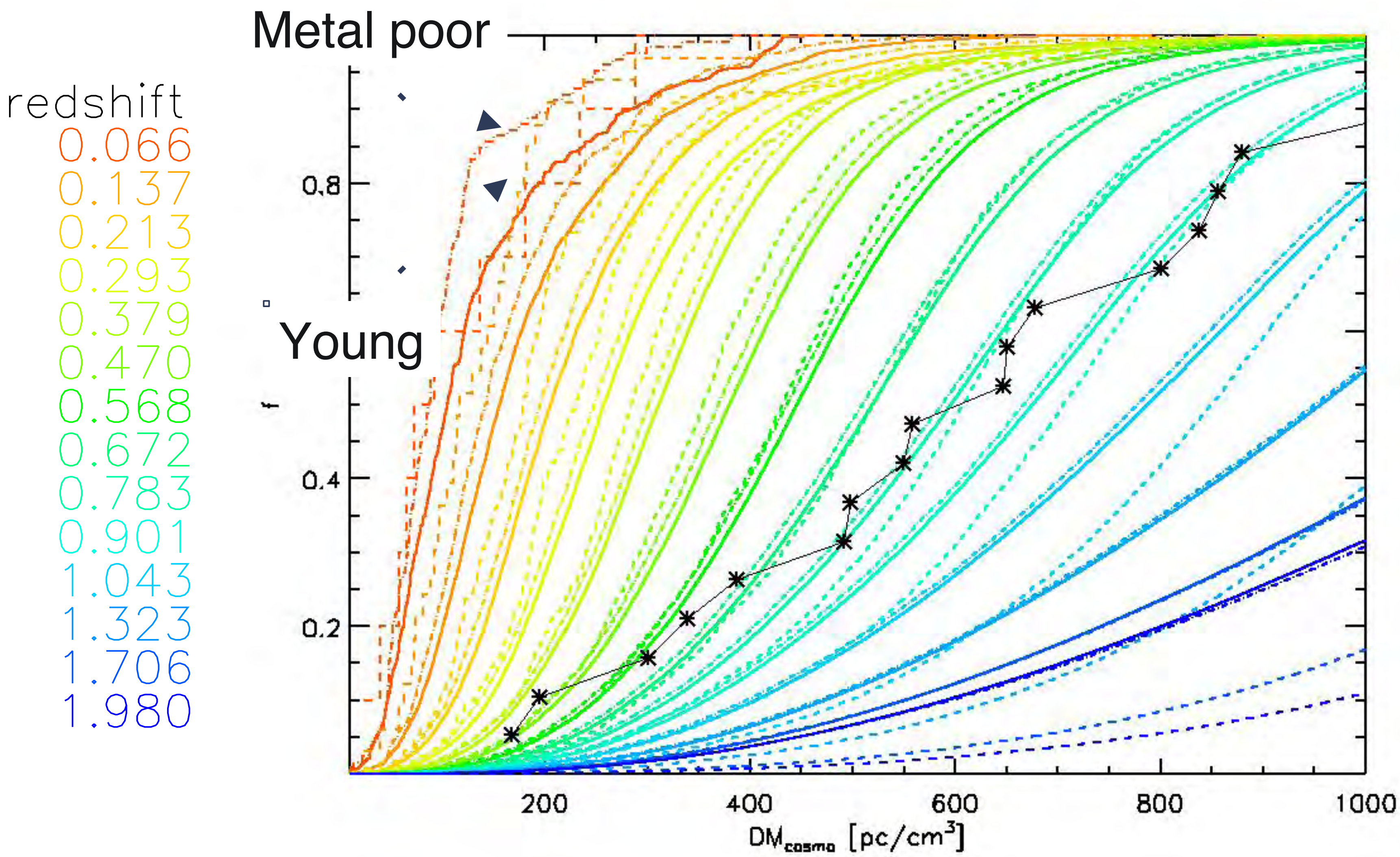

Dolag, Gaensler, et al., in preparation

Energy Distribution (I)

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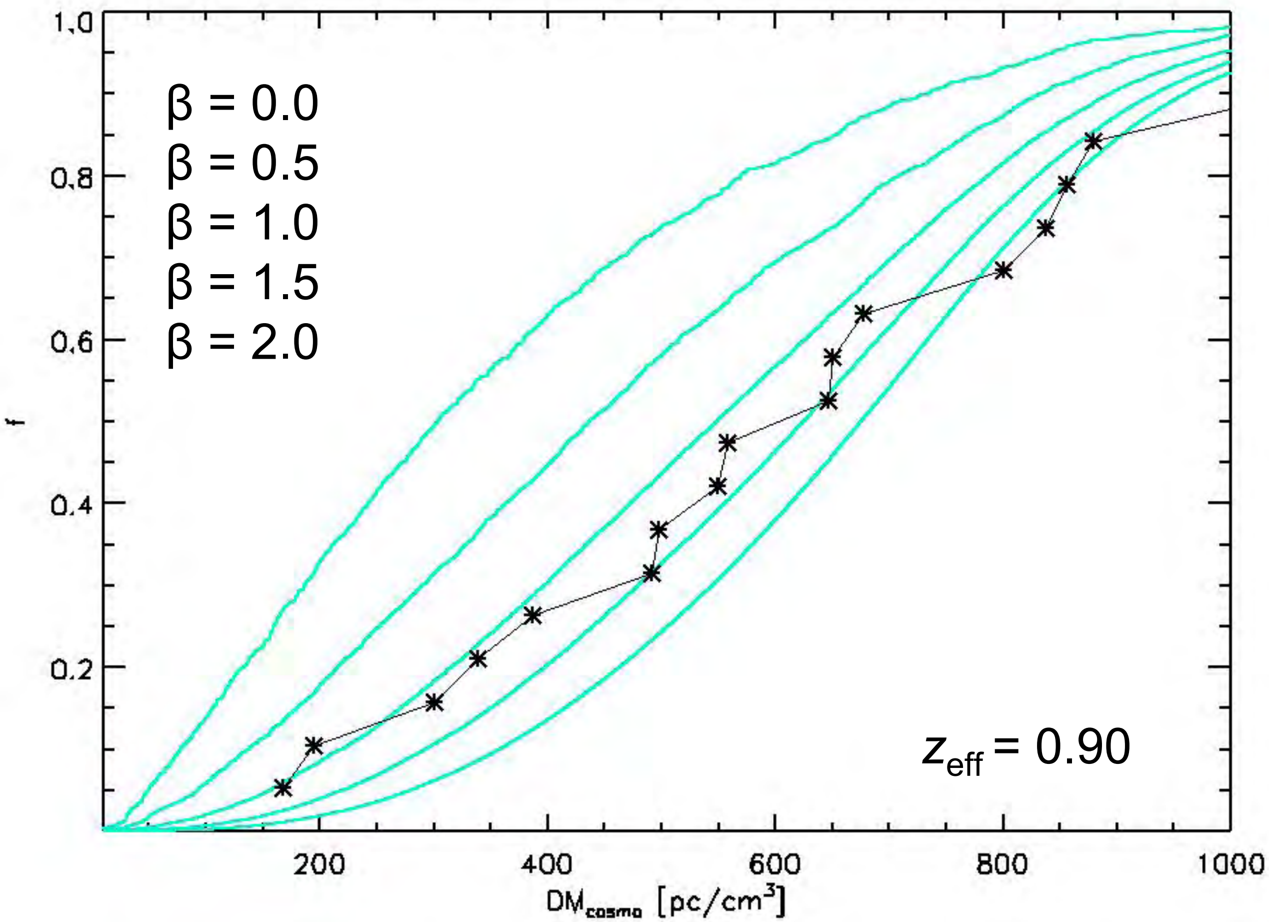
- p(E) ∝ $E^{-\beta}$, fluence > F_{detect}



Dolag, Gaensler, et al., in preparation

Energy Distribution (II)

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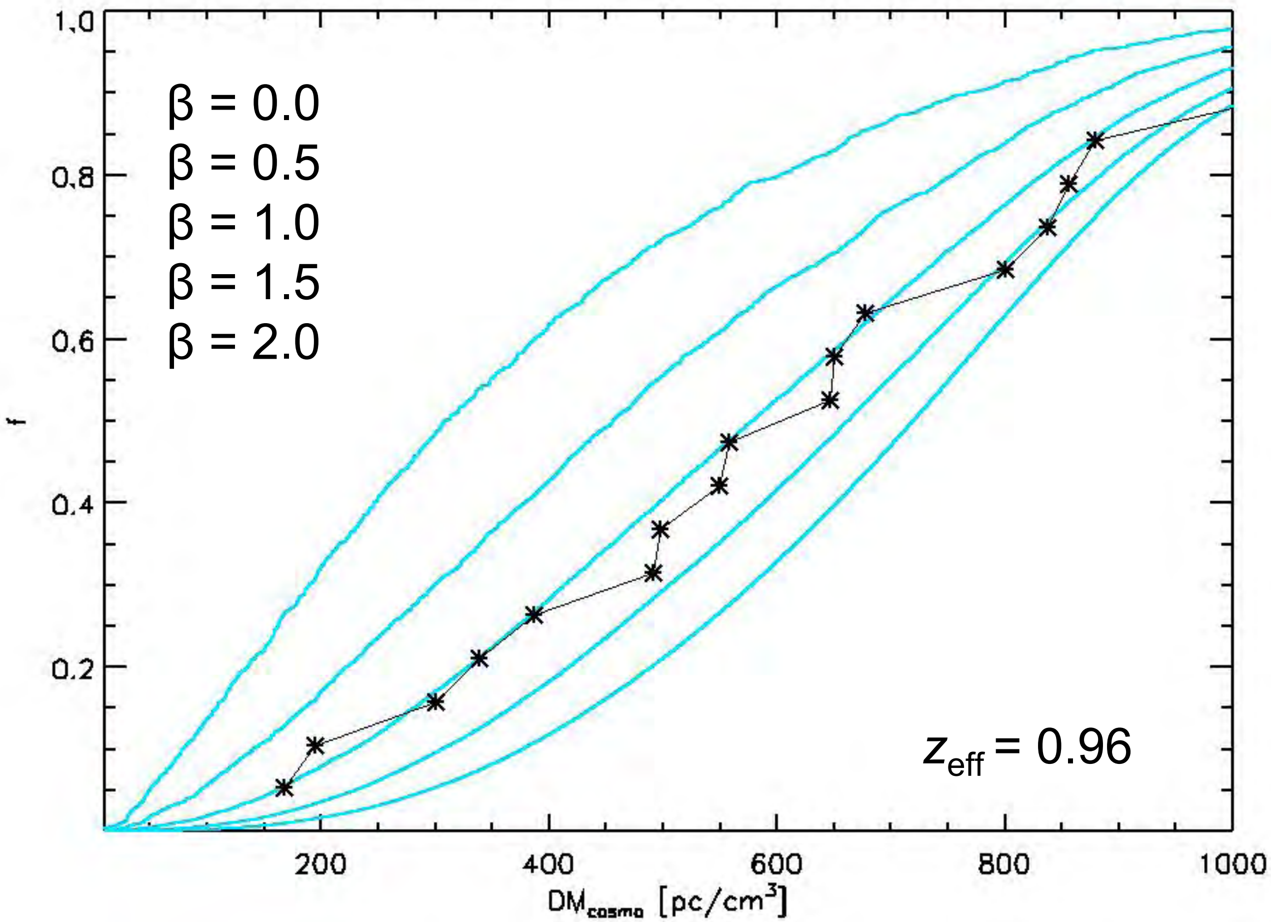
- p(E) ∝ $E^{-\beta}$, fluence > F_{detect}



Dolag, Gaensler, et al., in preparation

Energy Distribution (III)

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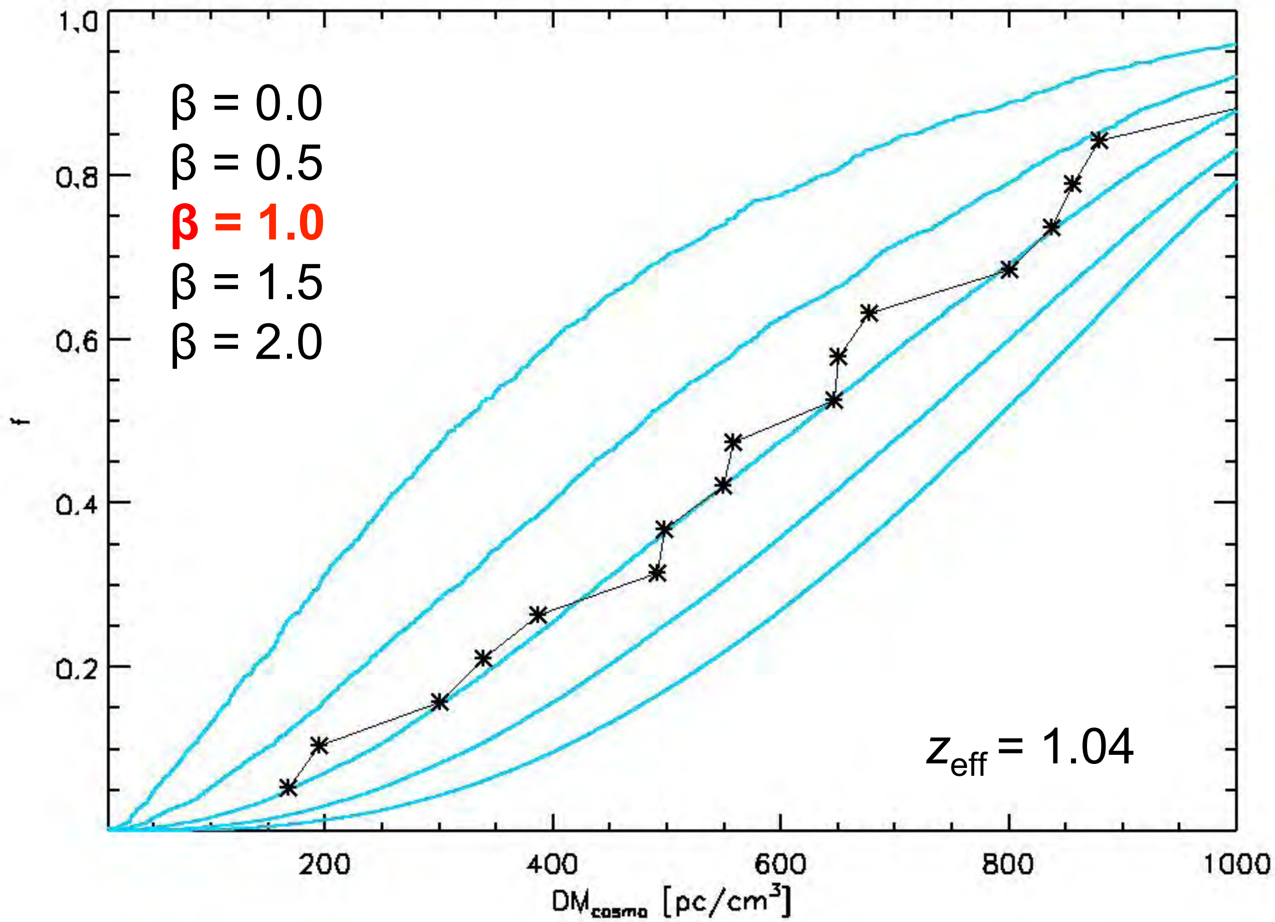
- p(E) ∝ $E^{-\beta}$, fluence > F_{detect}



Dolag, Gaensler, et al., in preparation

Energy Distribution (V)

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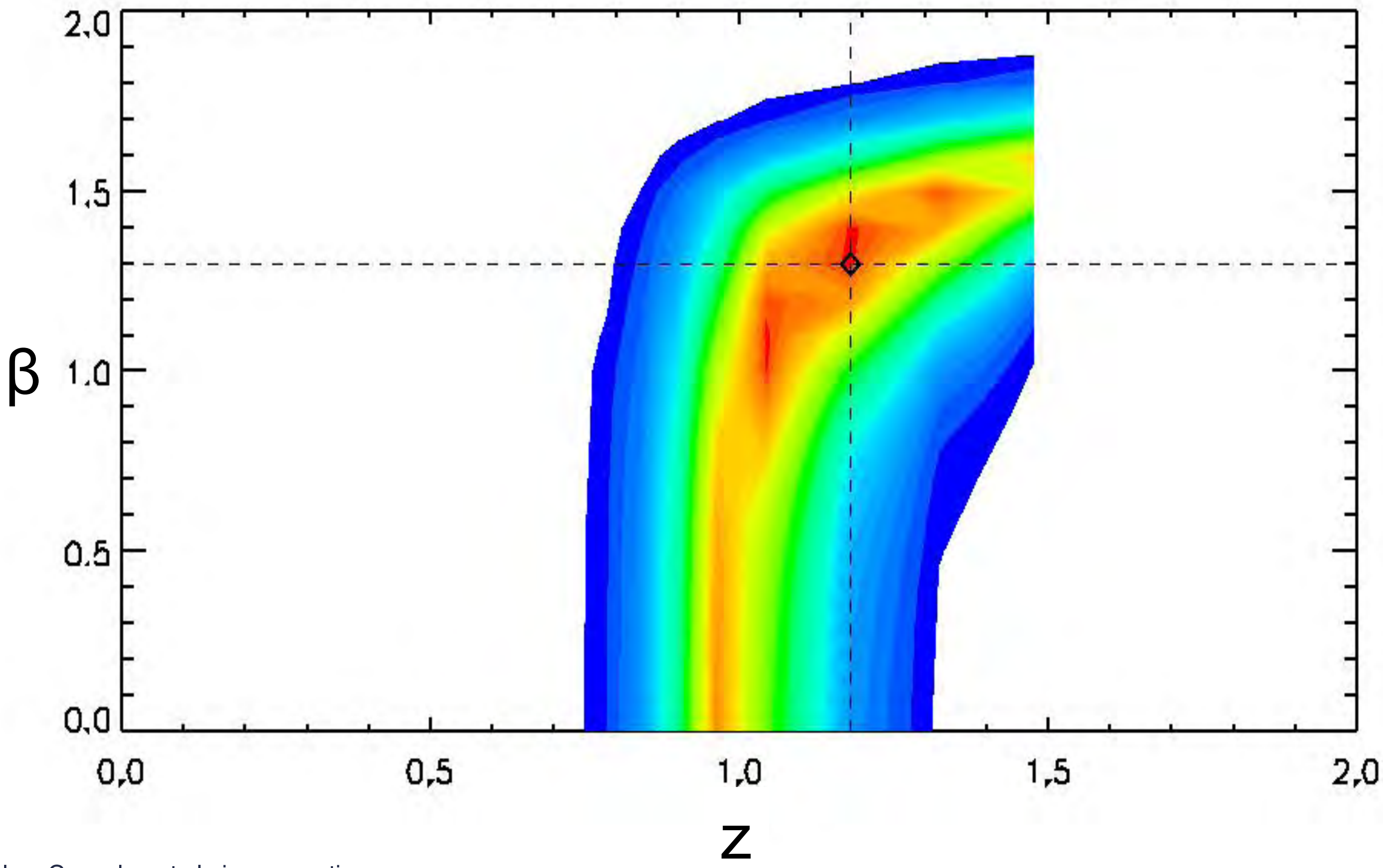
- p(E) ∝ $E^{-\beta}$, fluence > F_{detect}



Dolag, Gaensler, et al., in preparation

RM Contribution: Host Halo

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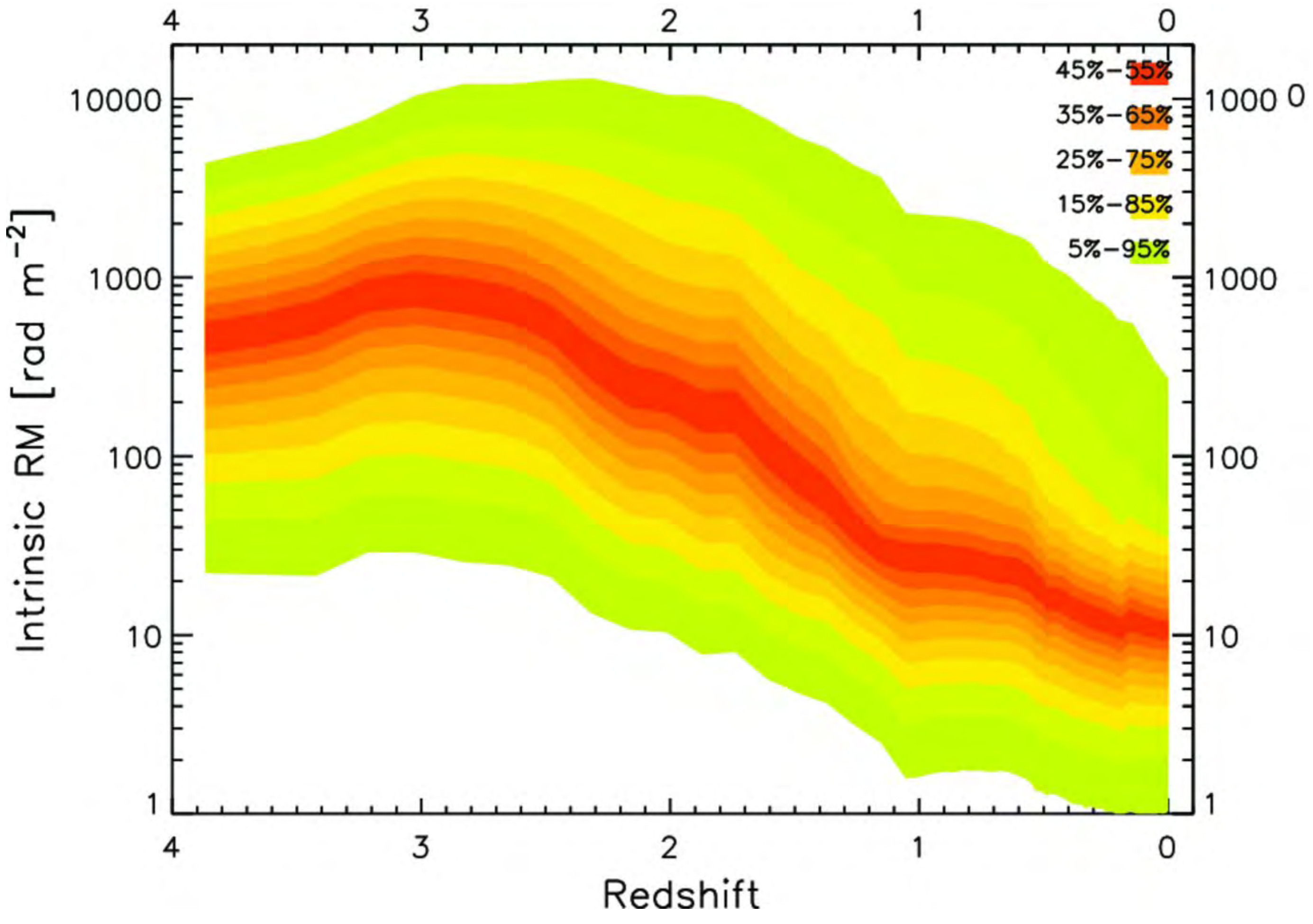

Beck et al. (2013)

RM vs DM (z = 1.74)

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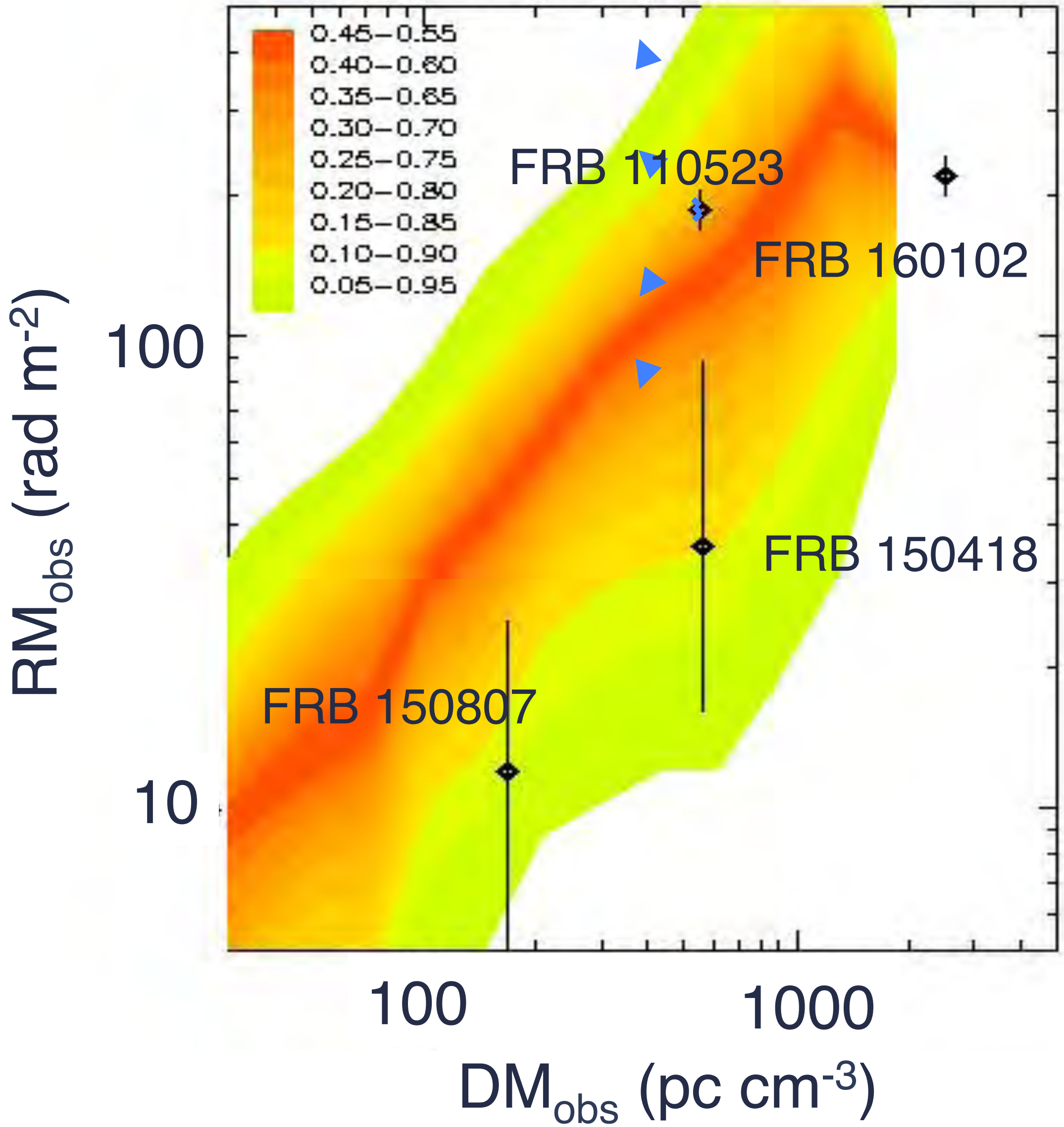

Disk contribution:

5 μG

HALO ONLY

Dolag, Gaensler et al.
(in preparation)

RM vs DM (z = 1.74)

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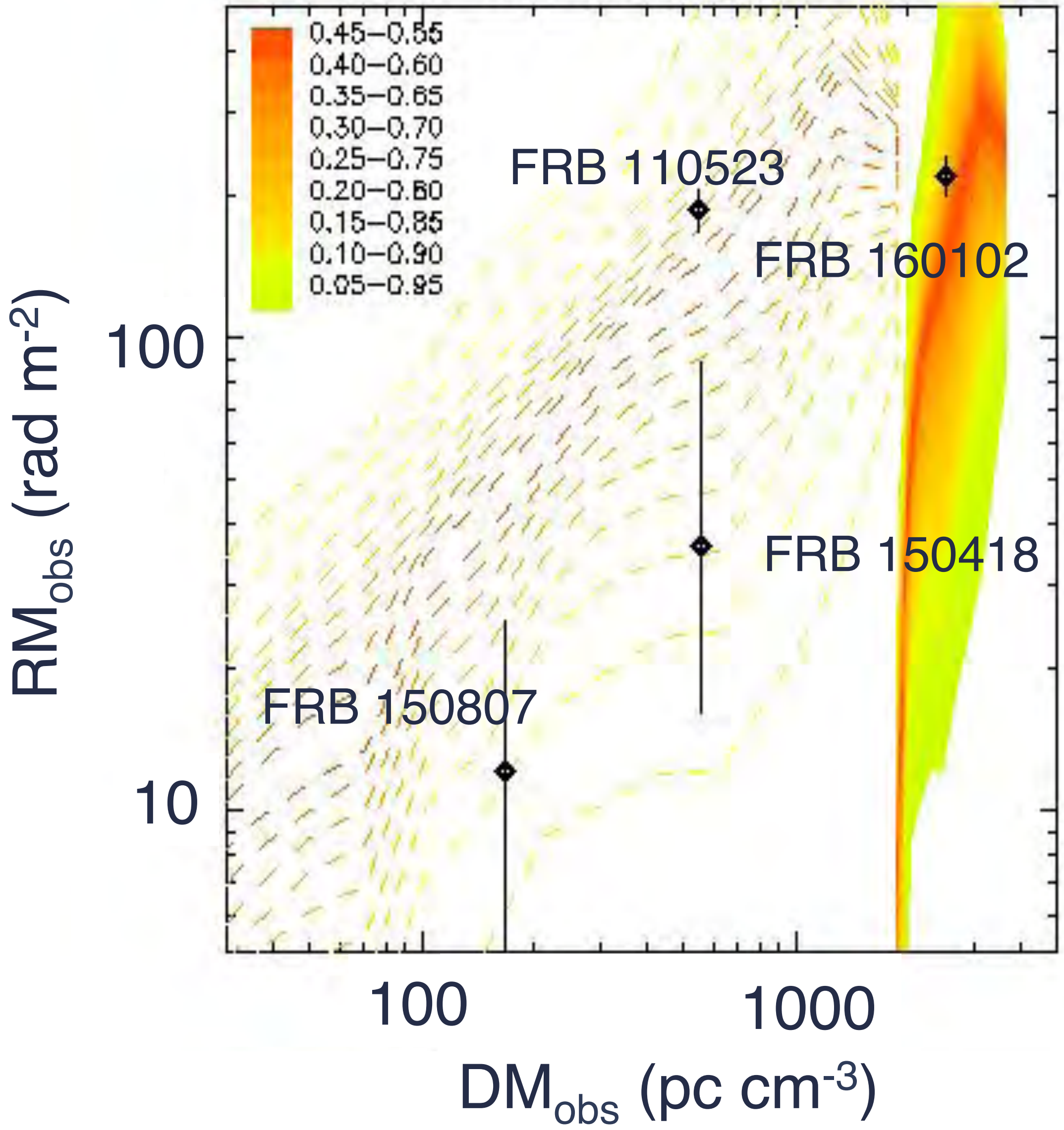

HALO
+
IGM

Dolag, Gaensler et al.
(in preparation)

RM vs DM vs Redshift

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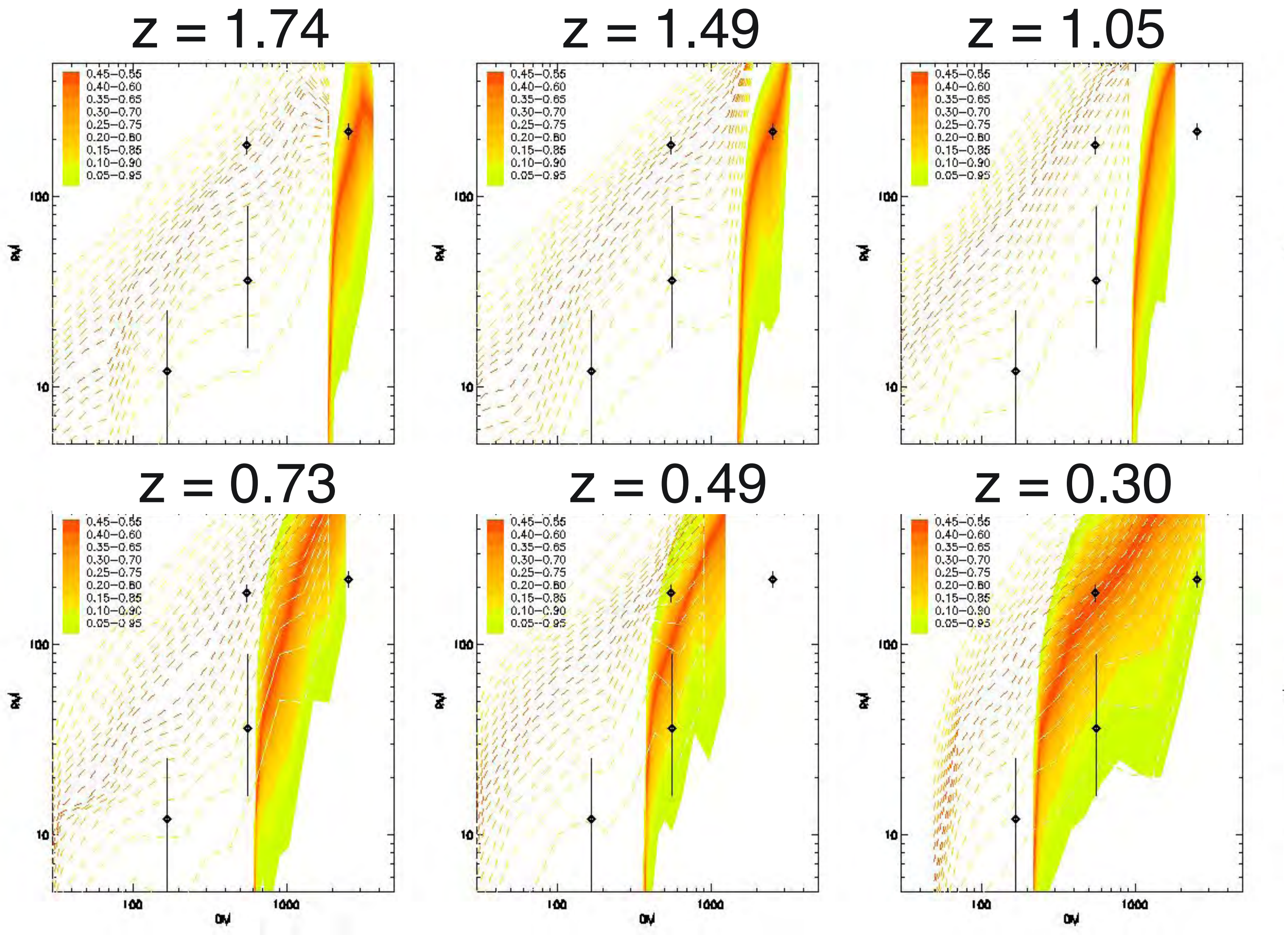

Dolag, Gaensler et al.
(in preparation)

Faraday Rotation of the IGM

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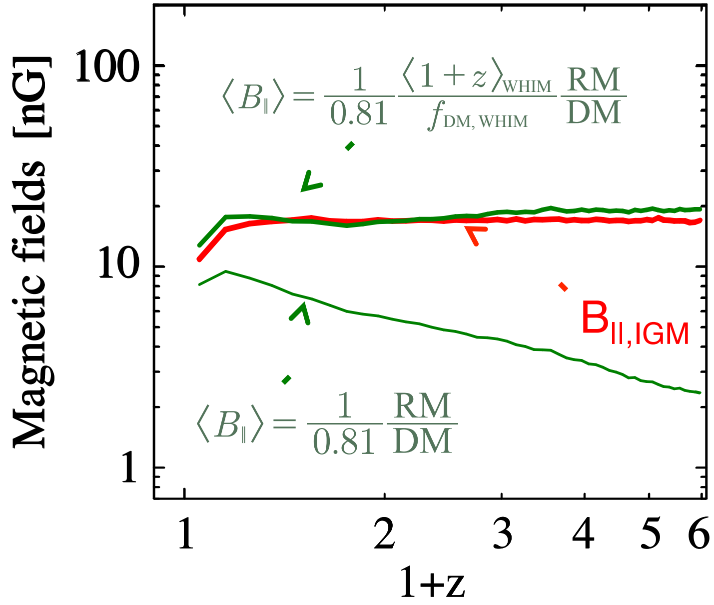
- B_{IGM} is discriminant between competing models of cosmic magnetism

$$\langle B_\parallel \rangle = \frac{1}{0.81} \frac{\mathrm{RM}}{\mathrm{DM}}$$

- Three issues for RM of IGM RM :
  - Main DM source depends on z (WHIM at low z ; voids at high z)
  - Main source of RM: hot cluster gas
  - DM and RM have different redshift dependencies



- Modified equation: (Akahori, Ryu & Gaensler 2016)

$$\langle B_\parallel \rangle = \frac{1}{0.81} \frac{\langle 1+z \rangle_{\mathrm{WHIM}}}{f_{\mathrm{DM,\,WHIM}}} \frac{\mathrm{RM}}{\mathrm{DM}}$$

Akahori, Ryu & BMG (2016)

Summary & Future Work

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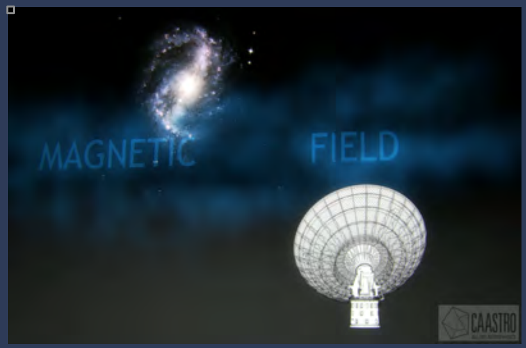
- DM and RM from progenitor wind could be significant, should evolve with time
  - to do: full simulations, realistic wind models
- Joint statistics of DM and RM will become increasingly important probe
  - to do: properly incorporate host contribution, simulate fluence distributions
- FRB DMs may be sensitive to cosmology beyond flat ΛCDM
  - to do: sophisticated modelling of host galaxies and uncertainties
  - full joint constraints from FRBs with CMB, SNe, BAOs, IM, WL, RSD

CAASTRO



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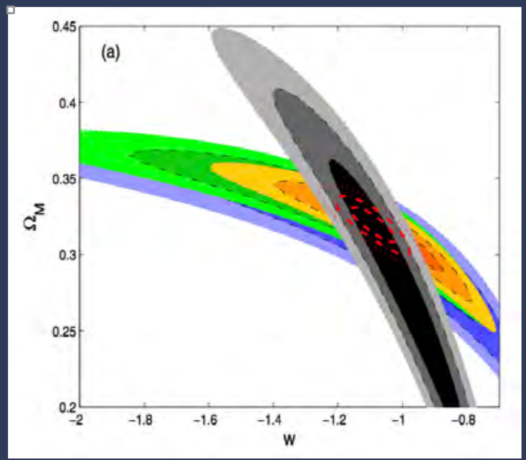

Gao et al. (2014)

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