A Test for Cosmological Models of Fast Radio Bursts

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A Test of Cosmological Models of Fast Radio Bursts

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ABSTRACT
Fast Radio Bursts (FRBs) are mysterious millisecond-duration transient radio bursts. The large dispersion measure (DM) of FRBs and especially the identification of the host galaxy of FRB 121102 at $z = 0.193$ firmly established the cosmological origin of FRBs. The physical origins and progenitors of FRBs, however, remain a puzzle and a highly debated topic. Proposed progenitor models range from young pulsars or magnetars that track star formation history of the universe, mergers of compact stars that have a delay with respect to star formation, and the events without significant cosmological evolution. In this paper, we test the cosmological origin of FRBs using the observational data and attempt to constrain the energy and redshift distributions of FRBs using Monte Carlo simulations. By confronting the model predictions with the observed peak flux, pulse width, and DM distributions, we discuss compatibility of three redshift-distribution models (no evolution, tracking star formation history, and compact star mergers) with the observational data. We find that with the limited data, all cosmological models can be made to be consistent with the data, with each model having different preferred values of the spectral index α and the energy-distribution index α_E. Future observations may pin down these parameters, and hence, provide better constraints on the redshift distribution models of FRBs.

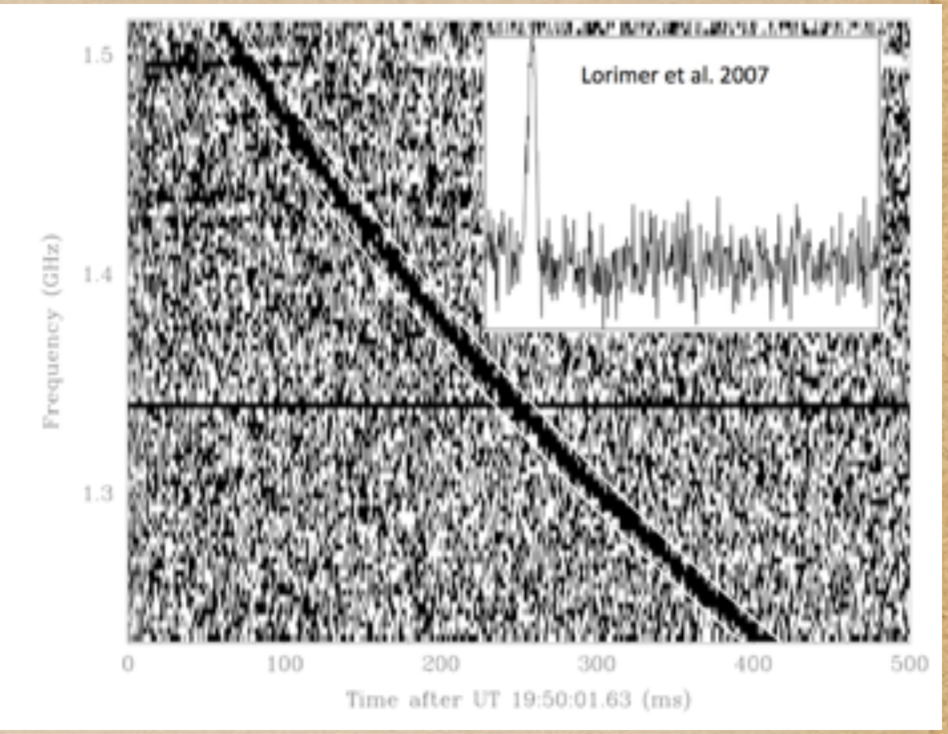
Key words: Fast Radio Bursts, Cosmological population.

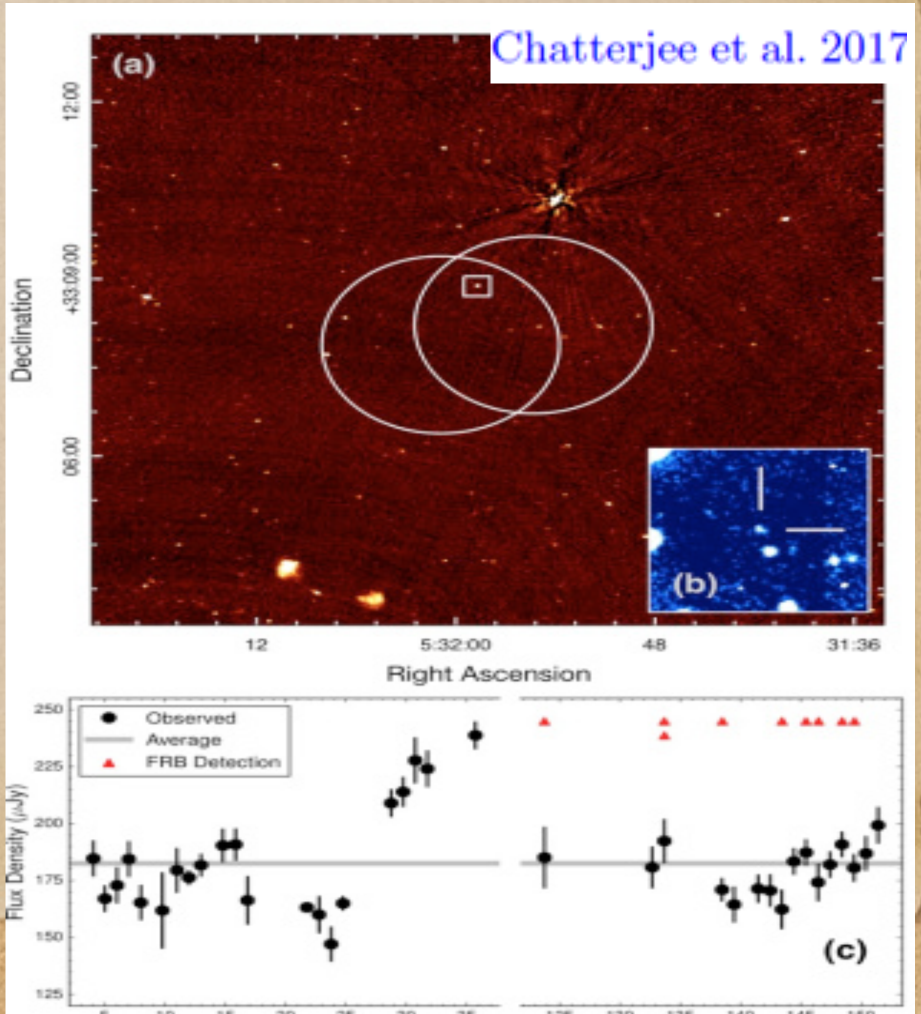
Outline

- FRB progenitors;
- Modeling FRB properties;
- Simulation and Results;
- Conclusions;

A decade ago and after

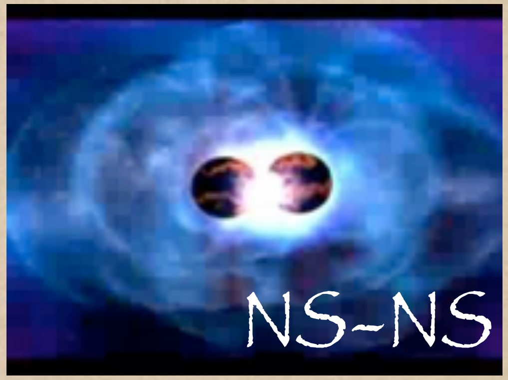
- A decade ago, we didn't know short duration radio bursts from cosmological distance could be observed;
- In the years since, we have detected 26 bursts;
- Have been scouring the cosmos, hoping to pinpoint their locations, to figure out their progenitor and host Galaxy;
- After a decade, we have finally found our quarry;
- Thanks to continuous effort and multi-wavelength observations that lead to precisely locate the radio nebula associated with the repeating FRB and a star-forming host galaxy at z=0.193;

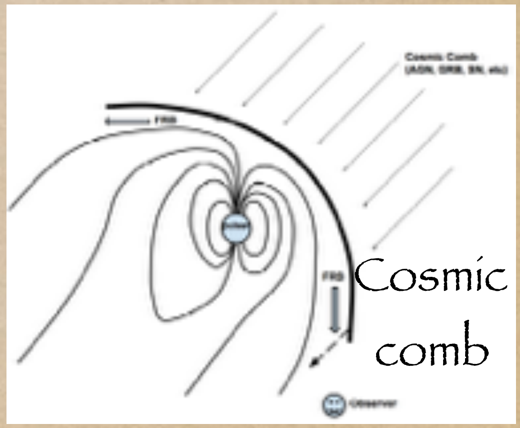




FRB progenitors

- FRB progenitor are yet to be identified and is highly debated topic;
- Except for one FRB, no other FRBs have been detected to repeat;
- Even though we are looking for one single type of progenitor may explain all the FRB, their might be multiple progenitors;





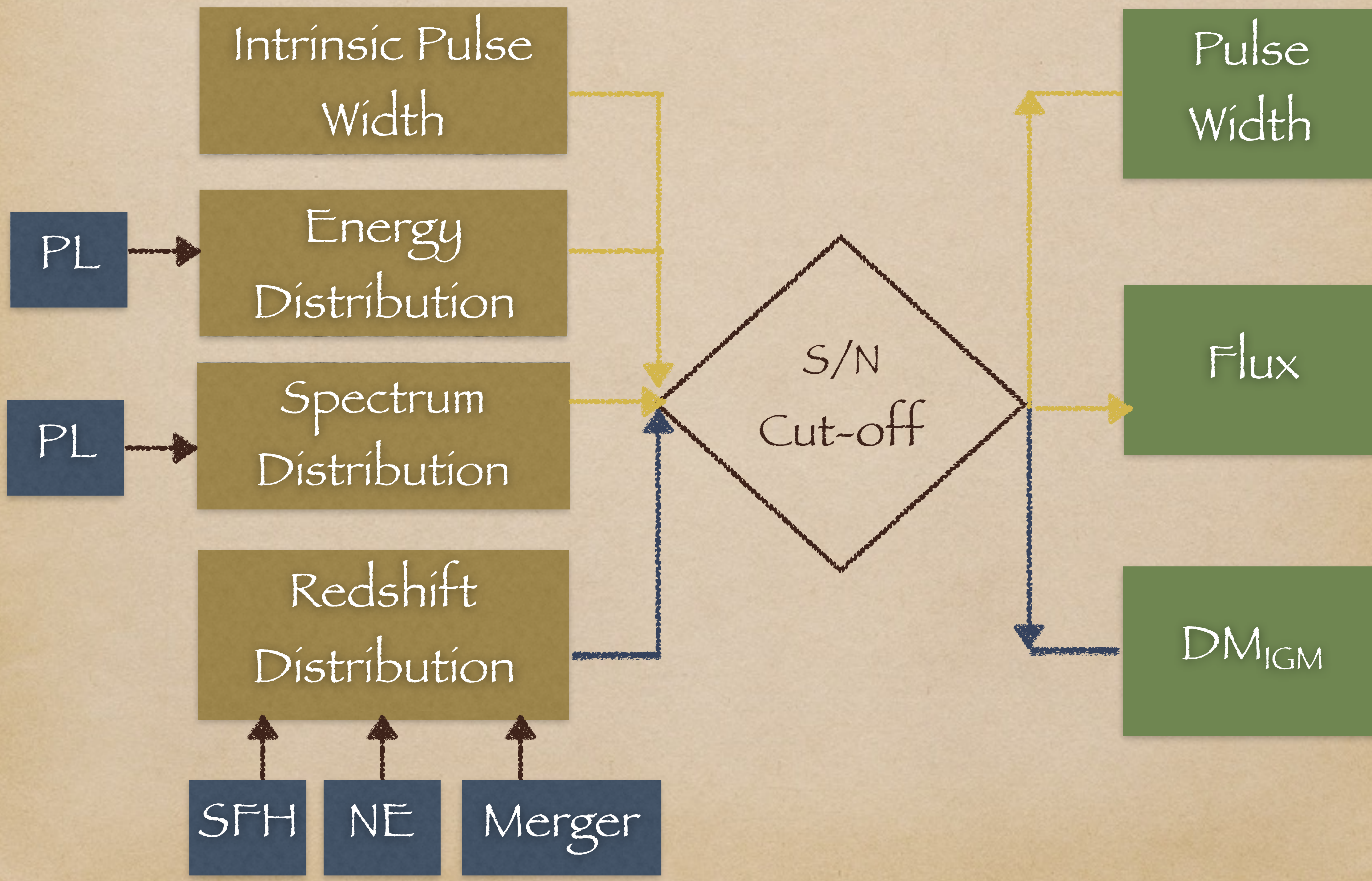
FRB progenitors and their evolution

In order to understand the progenitor system of the FRBs and their evolution, we need to constrain the distance, energy distribution and emission spectrum of FRBs- two ways

1. Radio telescopes should be able to localize the FRB with high angular resolution to get a better estimates on distance, energy distribution, emission spectrum and event rate;
2. Alternatively, one could consider ensemble properties of observed FRBs and compare them to simulated FRBs.

An Alternative Approach

Modeling the ensemble properties of FRBs



Modeling Redshift Distribution of FRBs

$$\frac{dN}{dz} \propto \dot{\rho}(z)\frac{dV}{dz} = \dot{\rho}_0 f(z)\frac{dV}{dz},$$

f(z) - evolutionary effect

- For some of the models, the FRB redshift distribution should closely track the star formation history.

$$f^{\mathrm{SFH}}(z) = \left[(1+z)^{3.4\eta} + \left(\frac{1+z}{5000}\right)^{-0.3\eta} + \left(\frac{1+z}{9}\right)^{-3.5\eta}\right]^{1/\eta}, \quad (28)$$

where $\eta = -10$. Yüksel et al. 2008

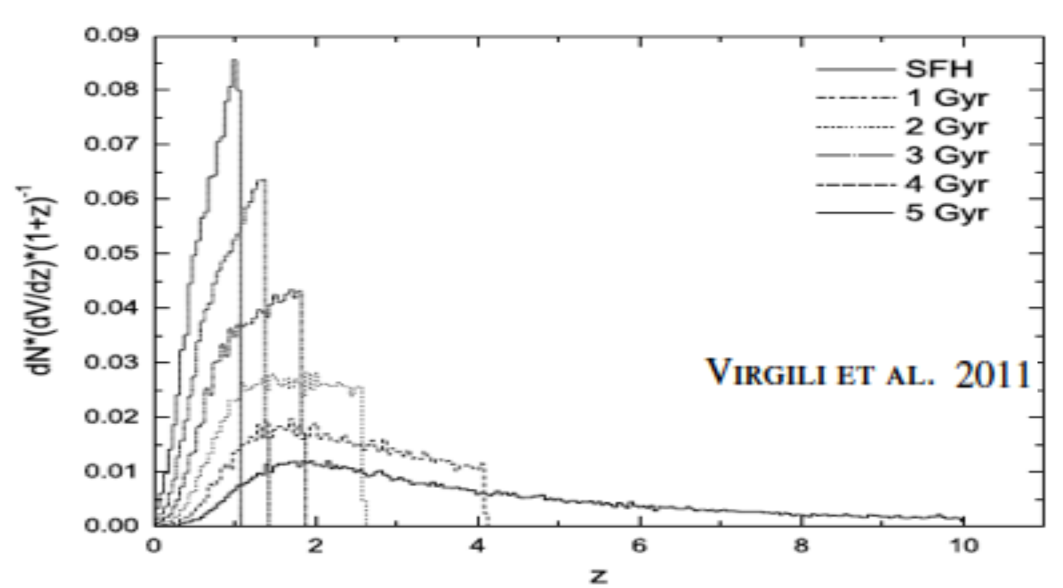
- For Double compact merger models, the redshift distribution models, the redshift distribution differ from the models that track the star formation - since there is delay in the star formation and merger

$$f^{\mathrm{G}}(z) = \left[(1+z)^{5.0\eta} + \left(\frac{1+z}{0.17}\right)^{0.87\eta} + \left(\frac{1+z}{4.12}\right)^{-8.0\eta} + \left(\frac{1+z}{4.05}\right)^{-20.5\eta}\right]^{1/\eta} \quad (29)$$

where $\eta = -2$. Sun et al. 2015

- Or in the simplest case, they are just uniformly distributed in space.

$$f(z) = \mathrm{constant}.$$



Virgili et al. 2011

Modeling observed DM

- For each FRB, the observed DM consist of three components;

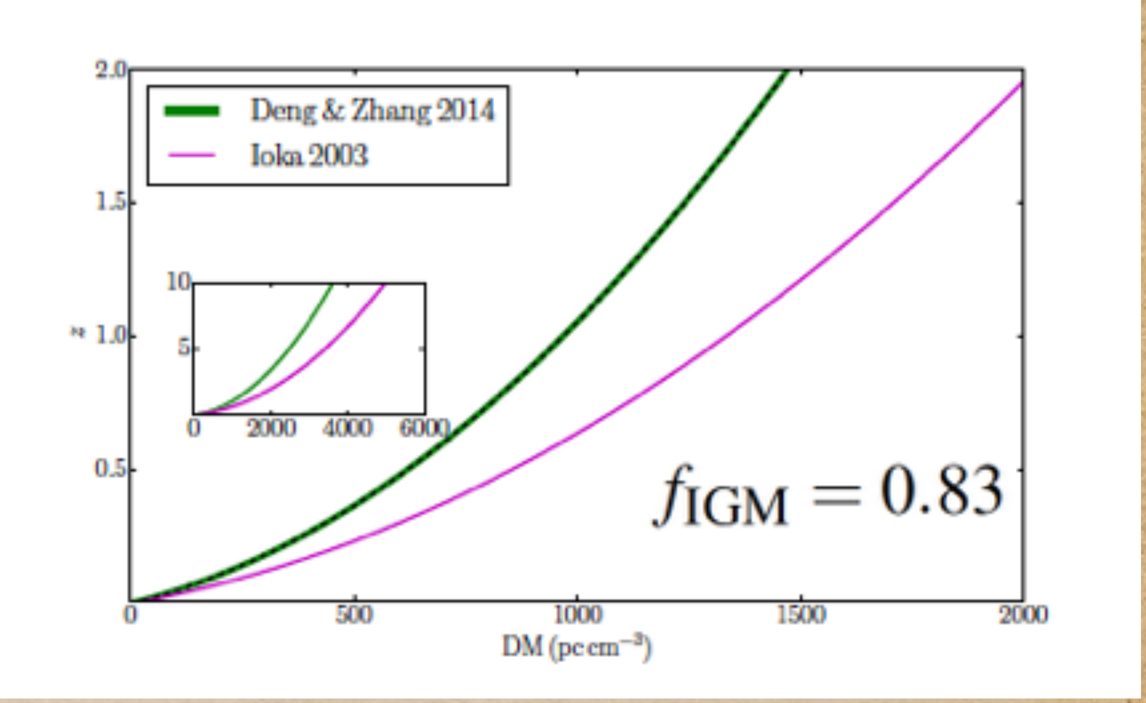
$$\mathrm{DM_{obs}} = \mathrm{DM_{MW}} + \mathrm{DM_{IGM}} + \mathrm{DM_{Host}},$$

- $\mathrm{DM_{obs}} >> \mathrm{DM_{MW}} + \mathrm{DM_{Host}}$ which implies $\mathrm{DM_{obs}}$ has a significant contribution from the free electron density in the IGM;

$$\mathrm{DM_{IGM}} = \mathrm{DM_{obs}} - (\mathrm{DM_{MW}} + \mathrm{DM_{Host}}).$$

- Averaging over all directions for a given 'z'

$$\langle \mathrm{DM_{IGM}}(z) \rangle = \frac{3 H_0 c \Omega_b}{8 \pi G m_p} \int_0^z \frac{(1+z) f_{\mathrm{IGM}} [(3/4) X_{e,H}(z) + (1/8) X_{e,He}(z)]}{[\Omega_m (1+z)^3 + \Omega_\Lambda (1+z)^3]^{1/2}},$$



correction factor = 0.73

$z \approx \mathrm{DM_{excess}}/875$

Deng & Zhang (2014).

Modeling the observed Pulse Width

- Observed Pulse Width are generally influenced by several factors

Signal Processing related effects

$$\tau_d^2 = \tau_{DM}^2 + \tau_{\delta DM}^2 + \tau_{\delta\nu}^2 + \tau_{samp}^2.$$

$\tau_{DM} = 8.3 \times 10^6 \, \Delta\nu \, \mathrm{DM} \, \nu^{-3}$ ms,

$\tau_{samp} \sim \mu s.$

$\tau_{\delta\nu} \sim (\Delta\nu)^{-1} = (\Delta\nu_{MHz})^{-1} \, (\mu s)$

$\tau_{\delta DM} = \tau_{DM}(\delta \mathrm{DM}/\mathrm{DM})$

Intrinsic Width

Scattering in IGM

$$\tau_{obs}^2 = \tau_{int}^2 + \tau_{MW}^2 + \tau_{IGM}^2 + \tau_{host}^2 + \tau_d^2.$$

Scattering in Milky Way at HighLat $< 10^{-6}$ s at 1 GHz

Scattering in ISM of host Galaxy

Cordes et al. (2016)

(Cordes & McLaughlin 2003)

Modeling scattering in the IGM

The scattering time scale in general is given by:

$$\tau_{\rm s} = \frac{D_{\rm eff}\lambda}{2\pi c k (1+z_{\rm L}) r_{\rm diff}^2},$$

$$r_{\rm diff} = \begin{cases} \left[\frac{\pi r_e^2 \lambda^2}{(1+z_L)^2} \mathrm{SM}\, l_0^{\beta-4} \left(\frac{\beta}{4}\right) \Gamma\left(\frac{-\beta}{2}\right)\right]^{-1/2}, & r_{\rm diff} < \ell_0, \\ \left[2^{2-\beta} \frac{\pi r_e^2 \lambda^2 \beta}{(1+z_L)^2} \mathrm{SM} \frac{\left(\frac{-\beta}{2}\right)}{\frac{-\beta}{2}}\right]^{1/(2-\beta)}, & r_{\rm diff} > \ell_0, \end{cases}$$

Diffraction scale of the scattering medium

Macquart & Koay 2013

$$\tau_{\rm scat} \sim \frac{r_{\rm e}^2 \lambda^4 D_{\rm eff} l_0^{\beta-4} L^{3-\beta}}{4\pi H_0} (\delta n_{\rm e})^2 \left(\frac{\beta}{4}\right) \Gamma\left(\frac{-\beta}{2}\right) \left(\frac{3-\beta}{2(2\pi)^{4-\beta}}\right) \mathrm{s} \int_0^z \frac{\left[\Omega_\Lambda + \Omega_{\rm m}(1+z_{\rm L})^3\right]^{-1/2}}{(1+z_{\rm L})^3} dz \tag{11}$$

We assume turbulence in IGM is close to Kolmogorov spectrum $\beta = 11/3$

$$\tau_{\rm scat} \sim 1.2 \times 10^{-5} \left(\frac{\lambda}{1\,\rm m}\right)^4 \left(\frac{D_{\rm eff}}{1\,\rm Gpc}\right) \left(\frac{\delta n_{\rm e}}{10^{-7}\,\rm cm^{-3}}\right)^2 \left(\frac{l_0}{1\,\rm AU}\right)^{-1/3} \left(\frac{L}{1\,\rm pc}\right)^{-2/3} \mathrm{s} \int_0^z \frac{\left[\Omega_\Lambda + \Omega_{\rm m}(1+z_{\rm L})^3\right]^{-1/2}}{(1+z_{\rm L})^3} \tag{12}$$

Modeling scattering in the host ISM

- Xu & Zhang (2017) showed that a Kolmogorov spectrum is not adequate to produce a desired amount of scattering seen in the FRBs
- Hence, we need to introduce supersonic turbulence regions with $\beta < 3$ to account for the scattering tail of FRBs

$$\tau_{\rm Host} \sim \frac{r_e^2 \lambda^4 D_{\rm LS}^2 f \, \delta n_e^2 l_0^{-1}}{4\pi c} (1+z_L)^{-3} \left(\frac{\beta}{4}\right) \Gamma\left(\frac{-\beta}{2}\right) \left(\frac{3-\beta}{2(2\pi)^{4-\beta}}\right) \mathrm{s},$$

$\beta = 2.6$

$$\tau_{\rm Host} \sim \begin{cases} 2.5(1+z_L)^{-3} \left(\frac{\lambda}{1\,\mathrm{m}}\right)^4 \left(\frac{D_{\rm LS}}{1\,\mathrm{kpc}}\right)^2 \\ \left(\frac{\delta n_e}{10^{-1}\,\mathrm{cm}^{-3}}\right)^2 \left(\frac{f}{10^{-6}}\right) \left(\frac{l_0}{10^{-11}\mathrm{pc}}\right)^{-1} \mathrm{ms}. \end{cases}$$

Energy distribution

We assume the energy distribution of FRB follows a simple power law distribution. FRBs are not standard candles;

$$N(E) = N_0 \left(\frac{E}{E_0} \right)^{-\alpha_{\mathrm{E}}}$$

α_{E} is the energy index, which we vary from 0 to 3

The estimated energy for each FRB is calculated as

$$E_{\mathrm{FRB}} = \frac{4\pi\, BW\, D_{\mathrm{L}}^2\, F_{\mathrm{obs}} \times 10^{-26}}{(1+z)}\ erg$$

$E_{\mathrm{FRB}} \approx 10^{40\text{-}41}$ erg

Emission spectrum distribution

we assume intrinsic spectrum of FRB emission follows a power law distribution $S_\nu \propto \nu^{-\alpha}$

spectral index $-\alpha$ ranges from -5 to +5

The peak flux of an FRB as observed by the telescope

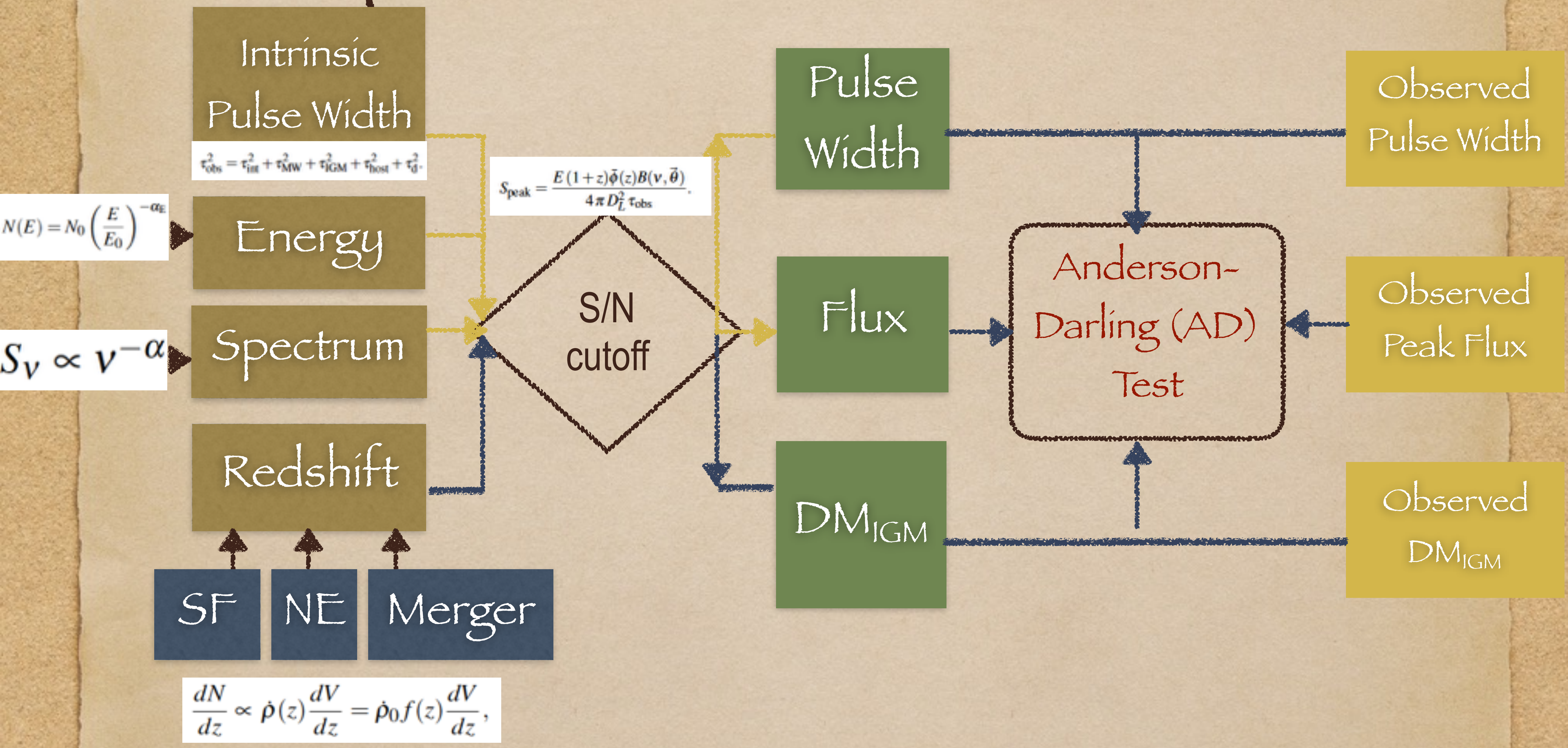
$$S_{\text{peak}} = \frac{E\,(1+z)\bar{\phi}(z)B(\nu,\vec{\theta})}{4\pi D_L^2\,\tau_{\text{obs}}}.$$

average emission line profile

$$\bar{\phi}(z) = \frac{1}{(1+z)(\nu_2-\nu_1)}\int_{\nu_1(1+z)}^{\nu_2(1+z)} \phi(\nu)d\nu,$$

Bera et al. 2016

Recap..



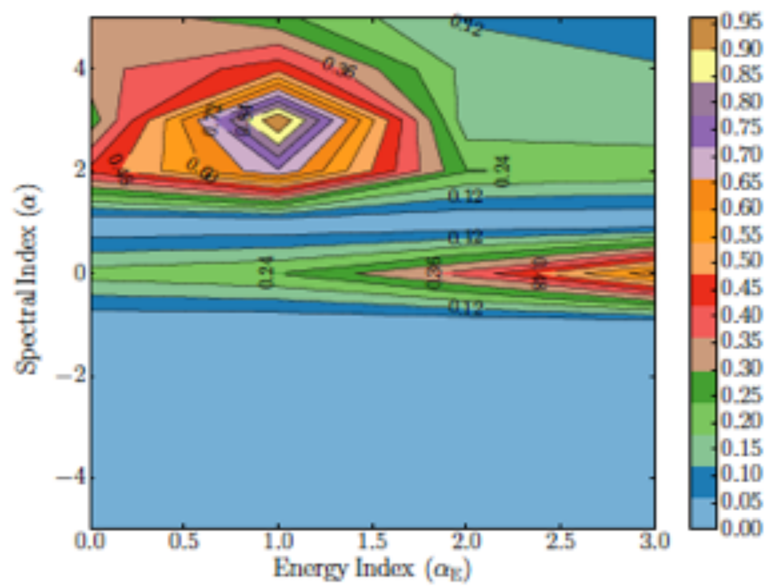
Intrinsic Pulse Width
$\tau_{obs}^2 = \tau_{int}^2 + \tau_{MW}^2 + \tau_{IGM}^2 + \tau_{host}^2 + \tau_d^2.$
$N(E) = N_0 \left(\frac{E}{E_0}\right)^{-\alpha_E}$
Energy
$S_\nu \propto \nu^{-\alpha}$
Spectrum
Redshift
SF
NE
Merger
$\frac{dN}{dz} \propto \dot{\rho}(z) \frac{dV}{dz} = \dot{\rho}_0 f(z) \frac{dV}{dz},$
$S_{peak} = \frac{E(1+z)\bar{\phi}(z)B(\nu,\vec{\theta})}{4\pi D_L^2 \tau_{obs}}.$
S/N cutoff
Pulse Width
Flux
DM_{IGM}
Anderson-Darling (AD) Test
Observed Pulse Width
Observed Peak Flux
Observed DM_{IGM}

Monte Carlo Simulation

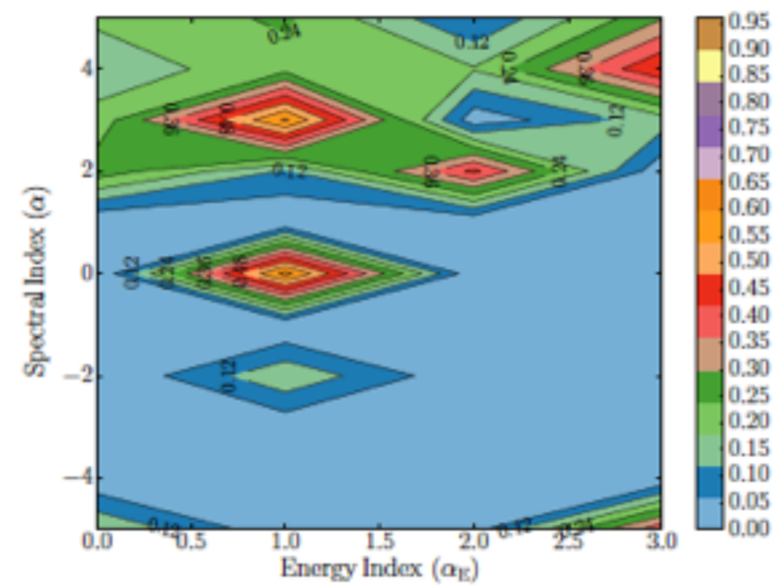
- We perform a series of MC simulations to confront the various Energy, spectrum and redshift distributions;

- $alpha_E$ - Energy distribution index and
  alpha - Spectral distribution index are free parameters in our simulations

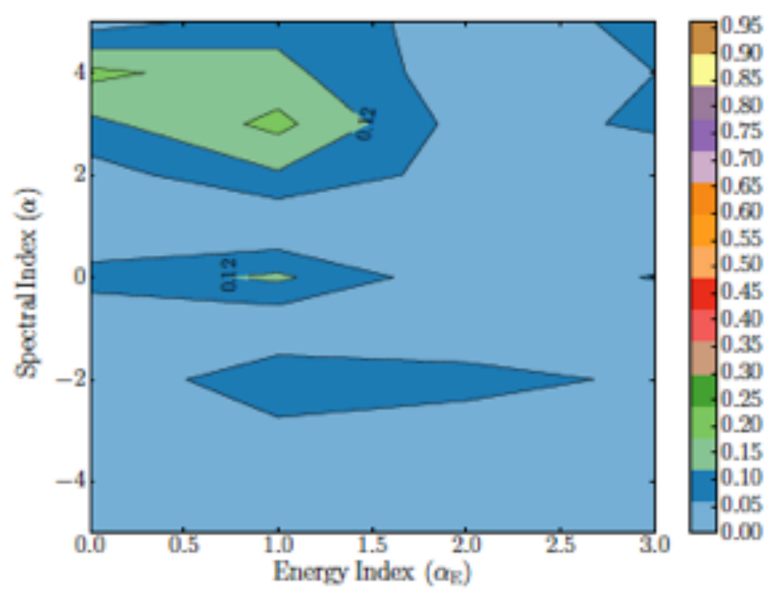
Results - SFH Model



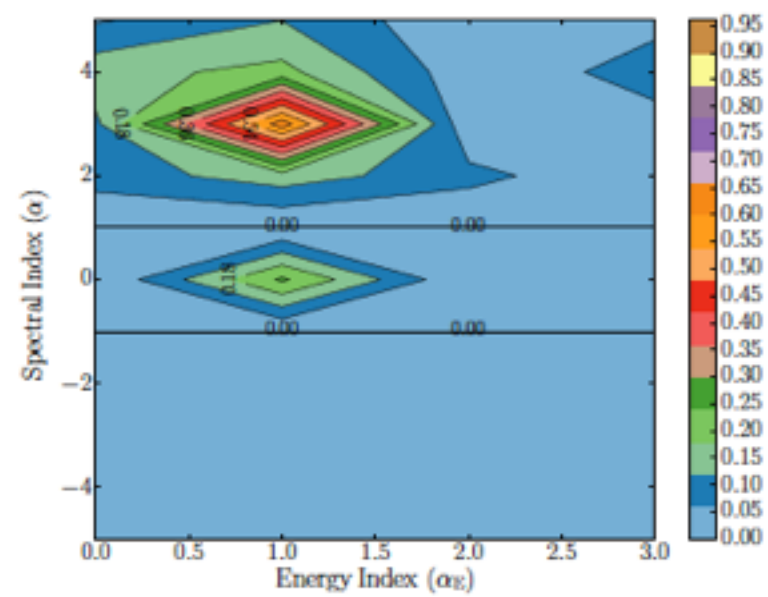
(a) $P_{AD,DM_{excess}}$ (SFH)



(b) $P_{AD,S_{peak}}$ (SFH)

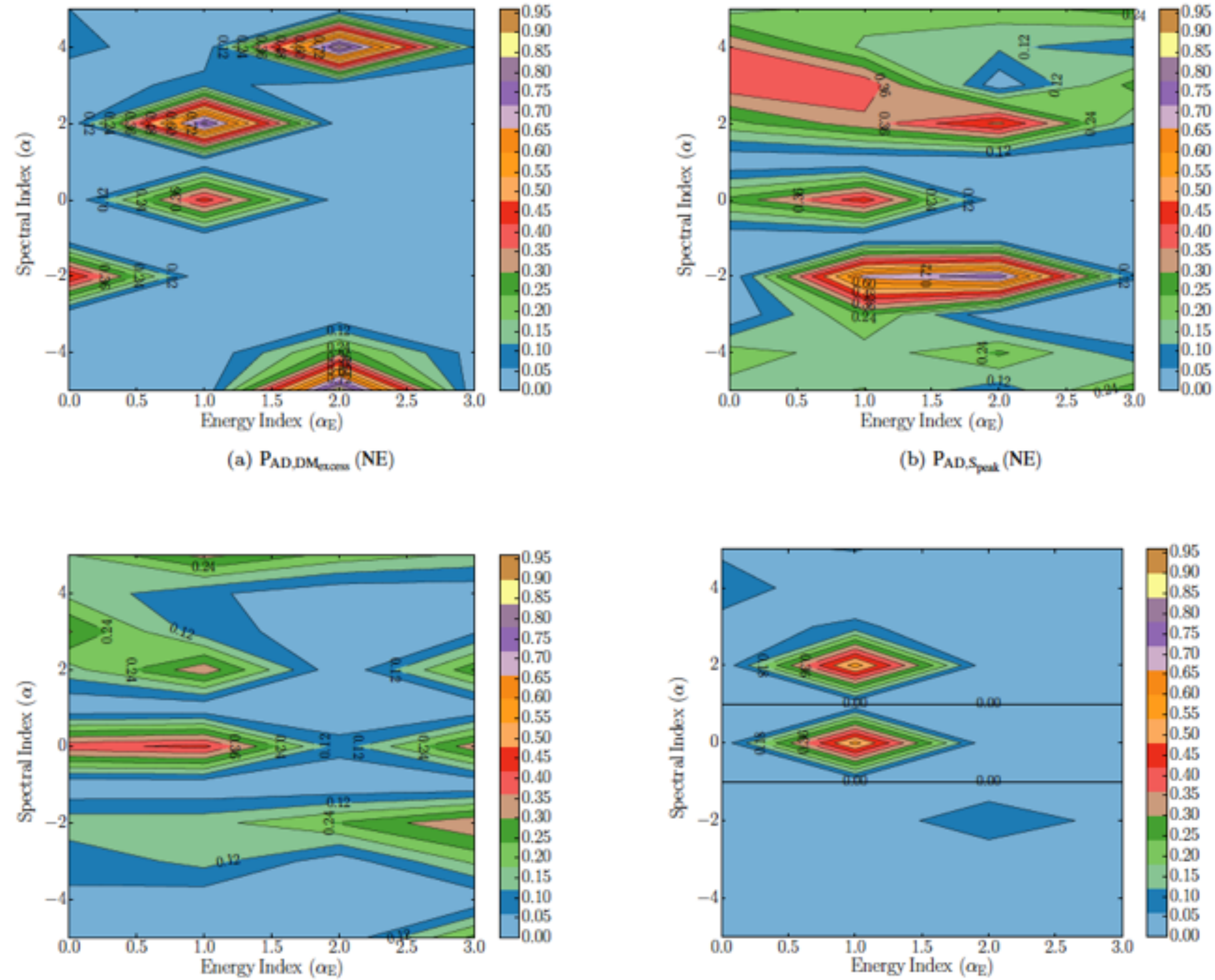


(c) $P_{AD,\tau_{obs}}$ (SFH)



(d) $P_{AD,DM} \times P_{AD,S_{peak}} \times P_{AD,\tau_{obs}}$

No-Evolution Model



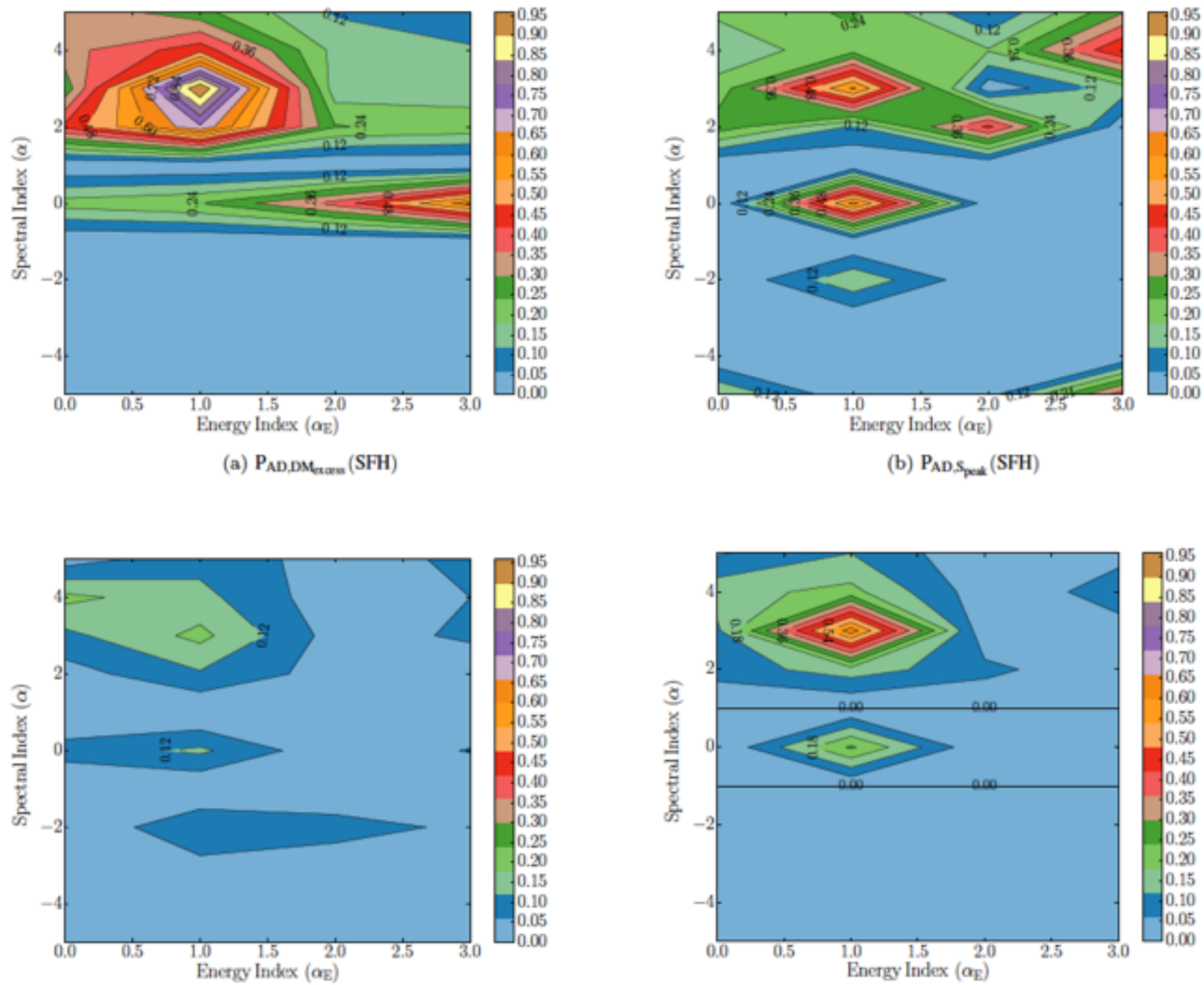
(a) $P_{AD,DM_{excess}}$ (NE)

(b) $P_{AD,S_{peak}}$ (NE)

(c) $P_{AD,\tau_{obs}}$ (NE)

(d) $P_{AD,DM} \times P_{AD,S_{peak}} \times P_{AD,\tau_{obs}}$ (NE)

Merger Model



(a) $P_{AD,DM_{excess}}$ (SFH)

(b) $P_{AD,S_{peak}}$ (SFH)

(c) $P_{AD,\tau_{obs}}$ (SFH)

(d) $P_{AD,DM} \times P_{AD,S_{peak}} \times P_{AD,\tau_{obs}}$

Results

Models	Parameters (α_E, α)	$AD_{DM_{excess}}$ T_{stat}, P – value	$AD_{S_{peak}}$ T_{stat}, P – value	$AD_{\tau_{obs}}$ T_{stat}, P – value	$AD_{DM_{excess} \times S_{peak} \times \tau_{obs}}$ P_t
No evolution	(1.0, 2.0)	0.764 0.799	1.079 0.3368	1.004 0.3407	0.57
	(1.0, 0.0)	0.951 0.448	0.373 0.453	0.953 0.4365	0.56
Star formation history	(1.0, 3.0)	-0.0620 0.96	0.750 0.611	1.477 0.1970	0.63
	(1.0, 0.0)	1.302 0.2418	0.735 0.622	1.800 0.1314	0.24
Merger (Gaussian)	(3.0, -2.0)	0.981, 0.4890	-0.024, 0.9345	0.781 0.5185	0.82
	(1.0, 3.0)	-0.514, 0.821	0.682, 0.458	1.898 0.090	0.34

Conclusions

- The observed DM, Flux and pulse widths are generally consistent with the cosmological models (see also Caleb et al. (2016));
- All the three redshift models can be made to verify the observational constraints;
- Each redshift distribution have different preferred values of (alpha_E, alpha) pair.
- If we could observational constraints the energy distribution index and spectral index would be useful to differentiate between the models and potentially identify the progenitor.

Thank you…