UNRAVELING NON-STANDARD PHYSICS THROUGH THE GLOBAL 21CM SIGNAL

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Understanding the Universe

Outline

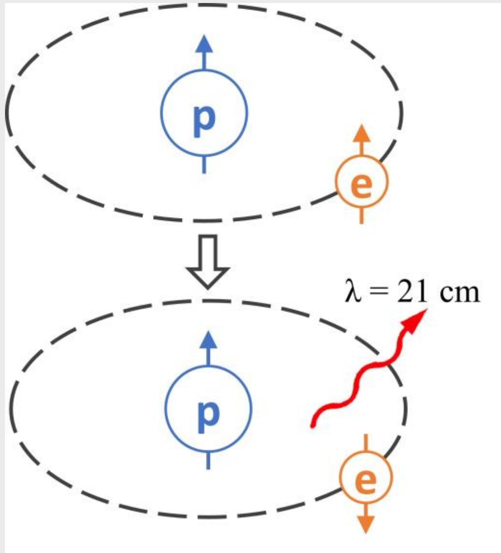
- **Introduction**
  - Physical principals
  - Simulating the Global 21cm Signal
  - Non-Standard Effects
  - Observations of Global 21cm Signal
- **Parameter Estimation Methods**
  - Levenberg-Marquardt
  - Markov Chain Monte-Carlo
- **Results**
  - Test Curve
  - EDGES data

Theoretical Background

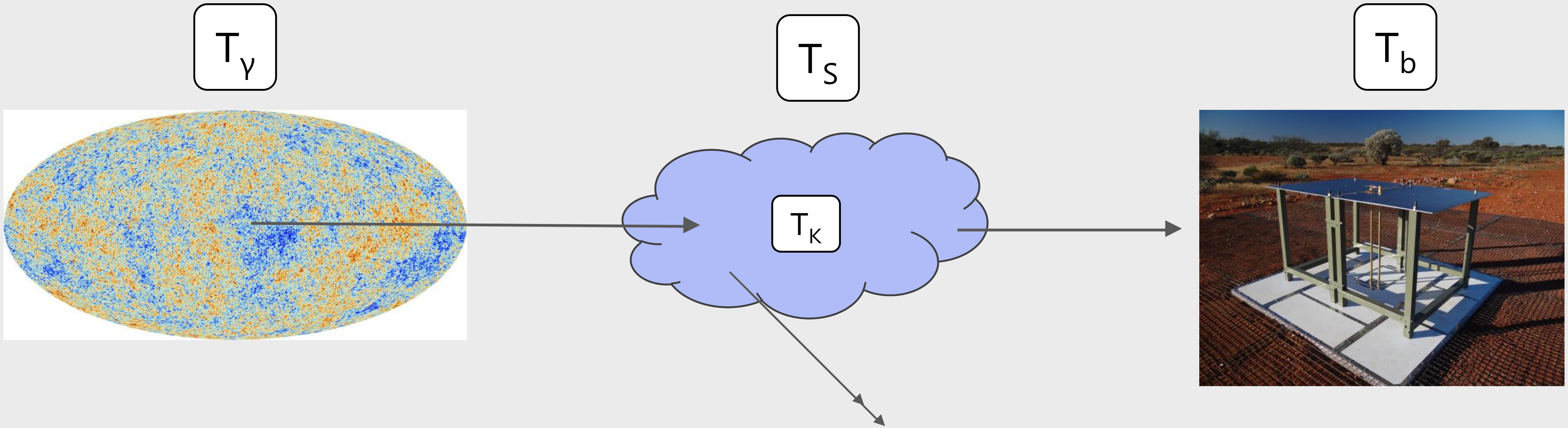
- $200<z<1100$ (Dark Ages): Universe composed of hydrogen (75%), helium, small traces of heavy elements, free electrons, residual photons (CMB)

- Neutral hydrogen: convenient tracer

- Spin-flip transition on 1S ground state (ν = 1420.4057 MHz, and λ=21.1cm)



Kit Grodias



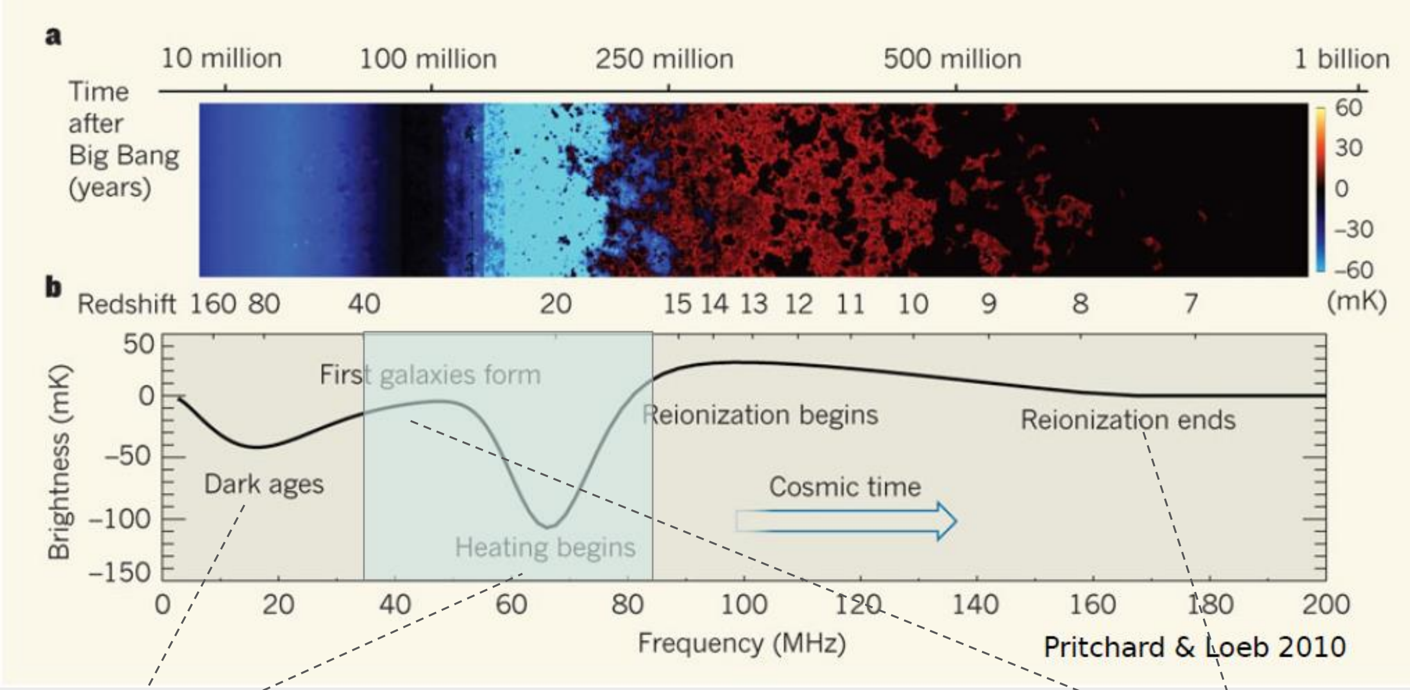
$$\frac{n_1}{n_0} = 3e^{-h\nu/kT_s}$$

$$T_S^{-1} = \frac{T_\gamma^{-1} + x_\alpha T_\alpha^{-1} + x_c T_K^{-1}}{1 + x_\alpha + x_c}$$

x_c : collisional coupling coefficient
x_α : Lyα coupling coefficient

Global 21cm Signal

- Average over the brightness temperature of the 21cm line
- Presents as an excess absorption or emission ($\delta T_b = T\gamma - T_S$)
- Coupling to Lyα background: Wouthuysen-Field effect/coupling



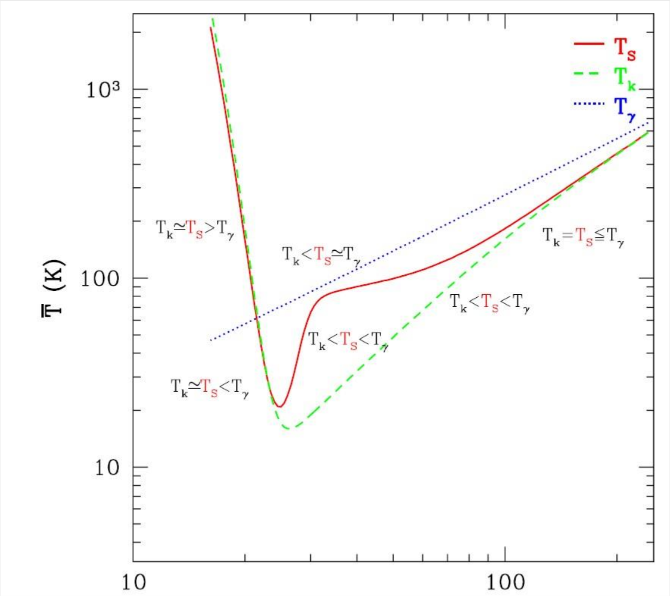
$T_S \rightarrow T_K$

$T_S \rightarrow T\gamma$

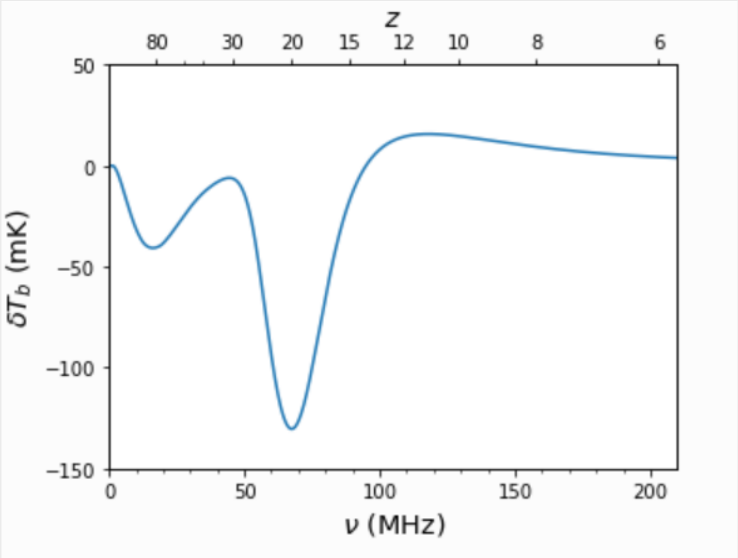
Simulating the Global 21cm Curve

$$\delta T_b \approx 27\,(1-\bar{x}_i)\left(\frac{\Omega_{b,0}h^2}{0.023}\right)\left(\frac{0.15}{\Omega_{m,0}h^2}\frac{1+z}{10}\right)^{1/2}\left(1-\frac{T_\gamma}{T_S}\right)$$

- Fully hydrodynamic simulations → semi–numerical
- faster and more efficient
- Simulators: 21cmFast, Accelerated Reionization Era Simulations (ARES)
- Emulator: 21cmGEM, Radial Basis Function Interpolation (RBFI)



A. Mesinger et al, 2011



ARES documentation

Non-Standard Effects

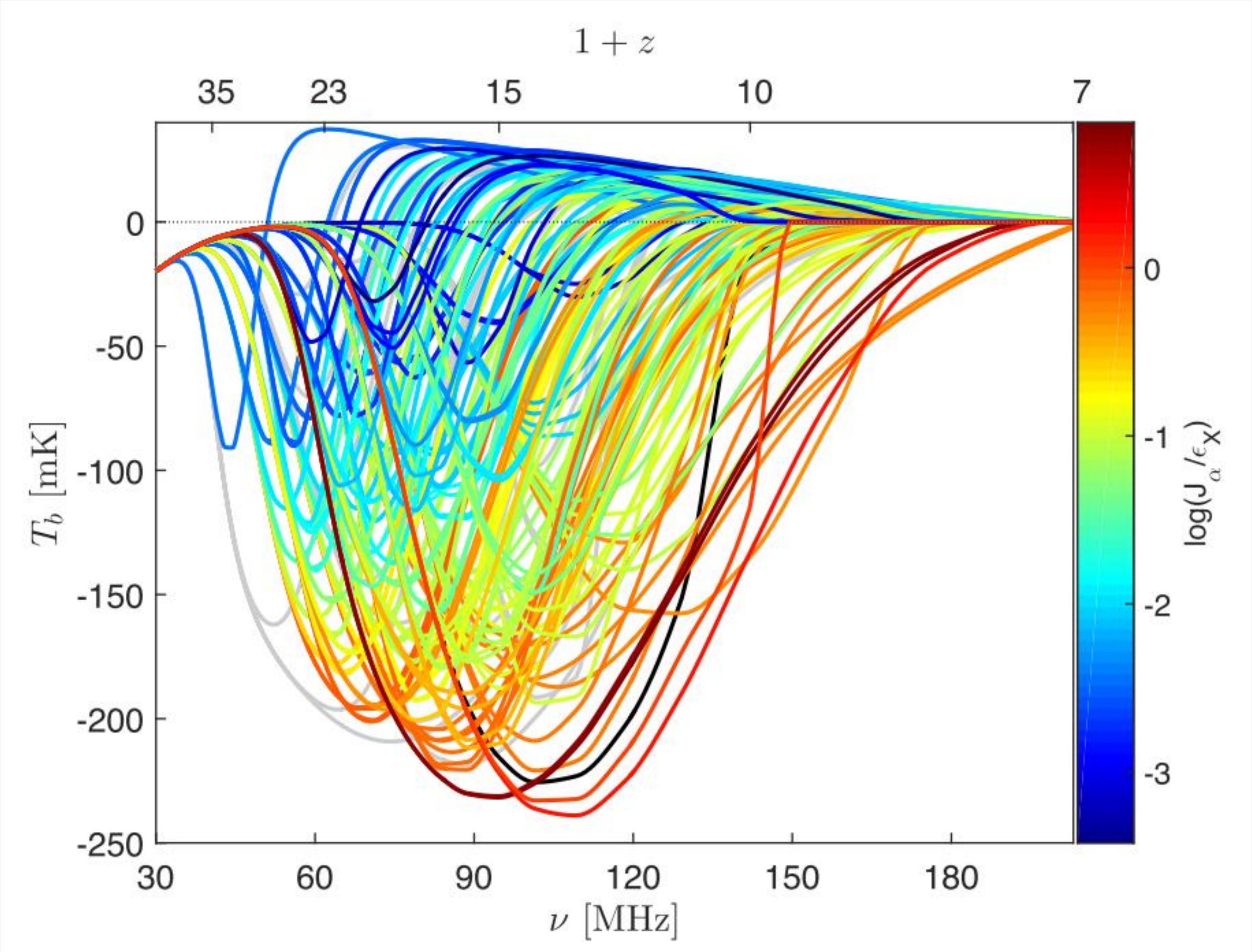
(So you wanna see the non-standard physics? 😈)

- Exotic Heating Mechanisms

- How is the signal affected, assuming different non-standard scenarios?

- Which non-standard effects demonstrate their signature in the global 21cm signal?

- Dark matter models, certain particle interaction, cosmic string wakes

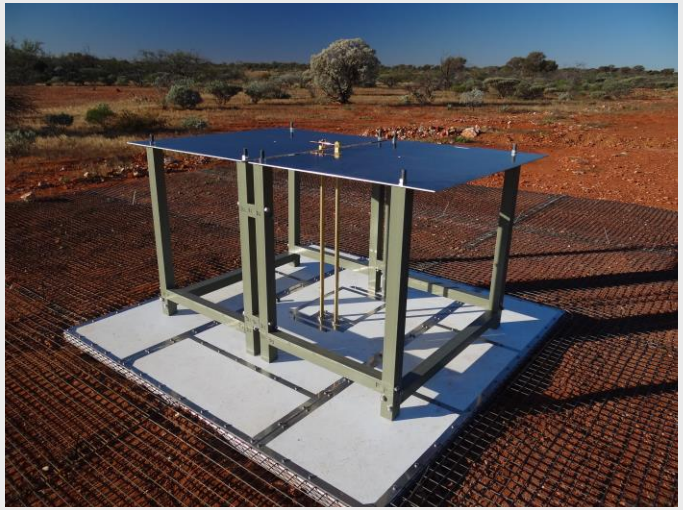


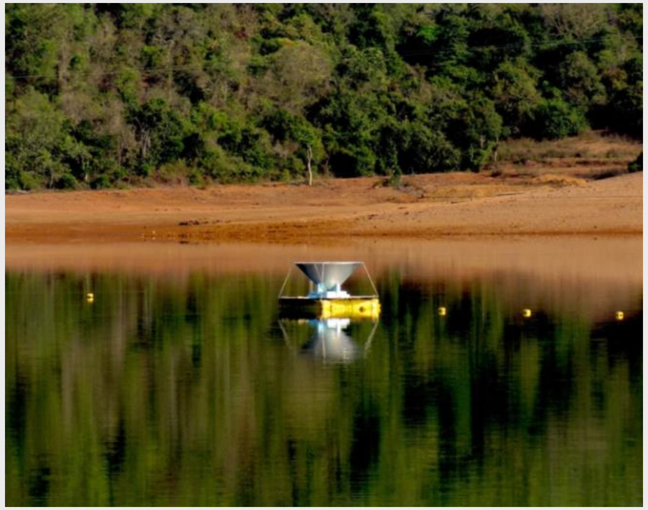
Cohen et al, 2017

The 21-cm global signal as a function of redshift for 193 different astrophysical models

Observations of Global 21cm Signal

- **EDGES (Experiment to Detect the Global EoR Signature)**
- **SARAS (Small Array for Research in Astrophysics of the South)**
- PRIZM (Probing Radio Intensity at high-Z from Marion)
- REACH (Radio Experiment for the Analysis of Cosmic Hydrogen)
- BIGHORNS (Broadband Instrument for Global HydrOgen ReioNisation Signal)





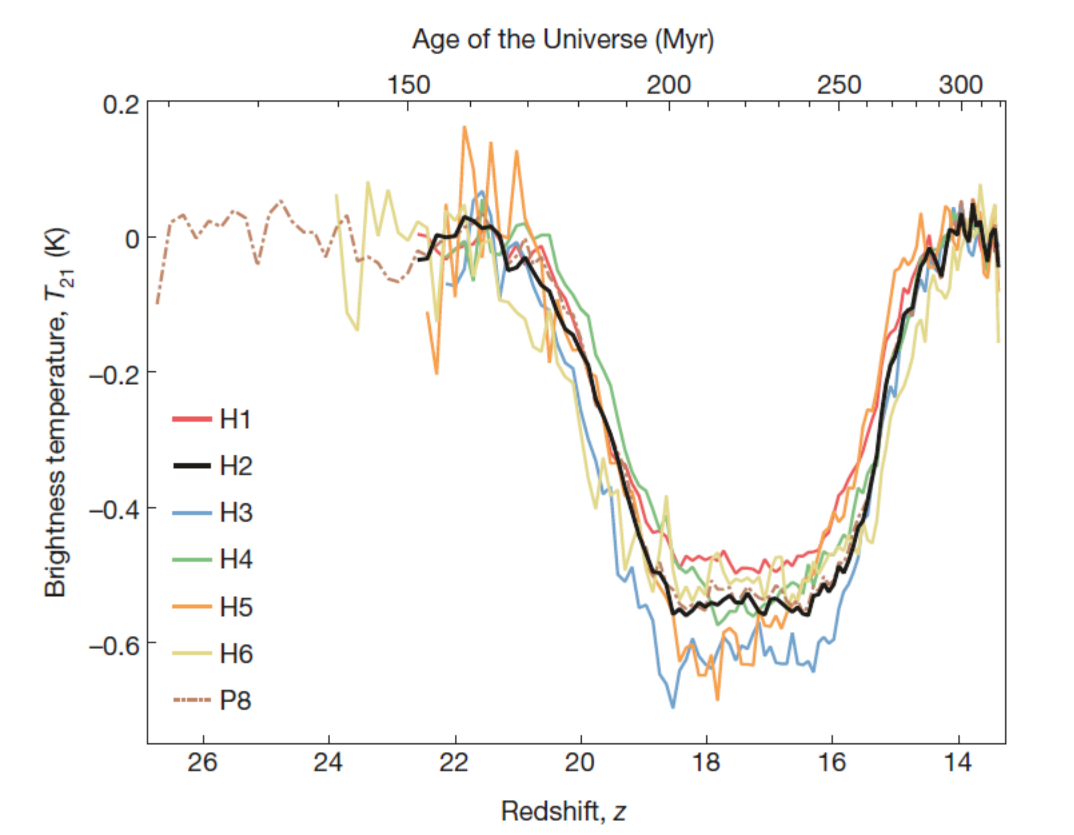
Judd D. Bowman et al, 2017

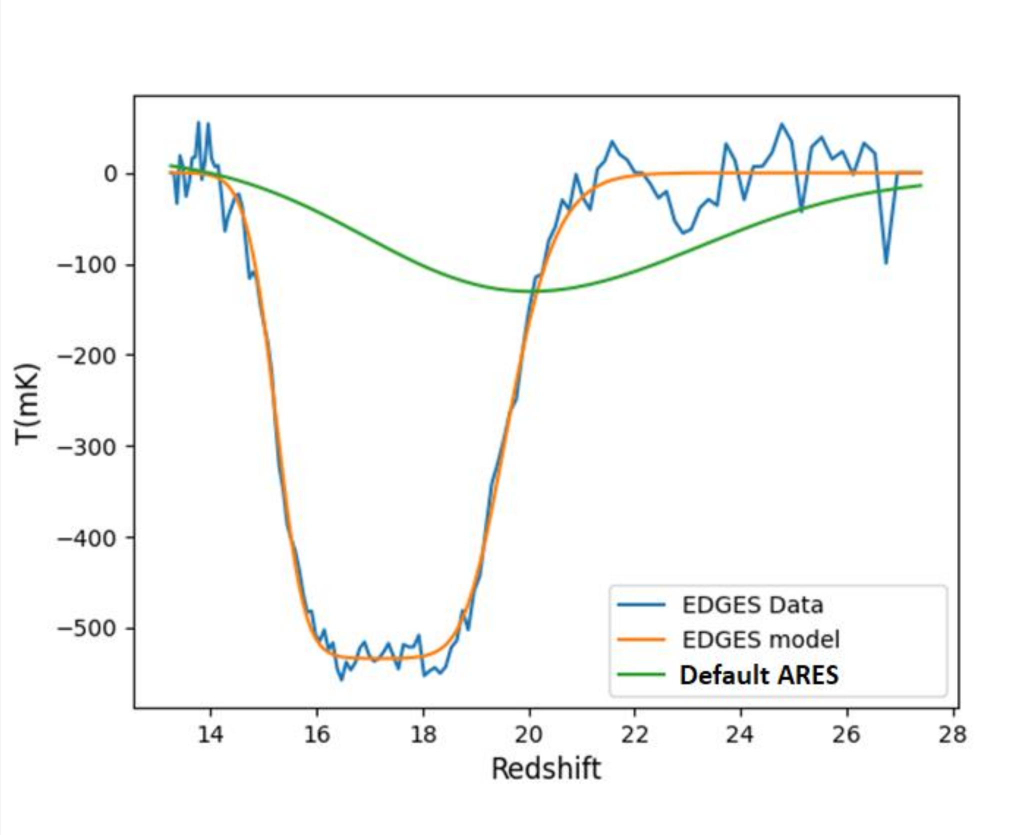
S. Singh et al, 2018

L. Philip et al, 2019

The EDGES Affair

- Data released in 2017
- Indicating that the gas temperature is cooler than what we expected
- In contrast with SARAS results





Judd D. Bowman et al, 2017

Parameter Estimation

Parameter Estimation

Key Astrophysical Parameters

1. ***f_X* :** High-redshift normalization factor in the relation between X-ray luminosity and star formation rate (SFR)

2. ***N_{ion}*:** Mean number of ionizing photons produced per baryon of star formation (= pop_rad_yield_2)

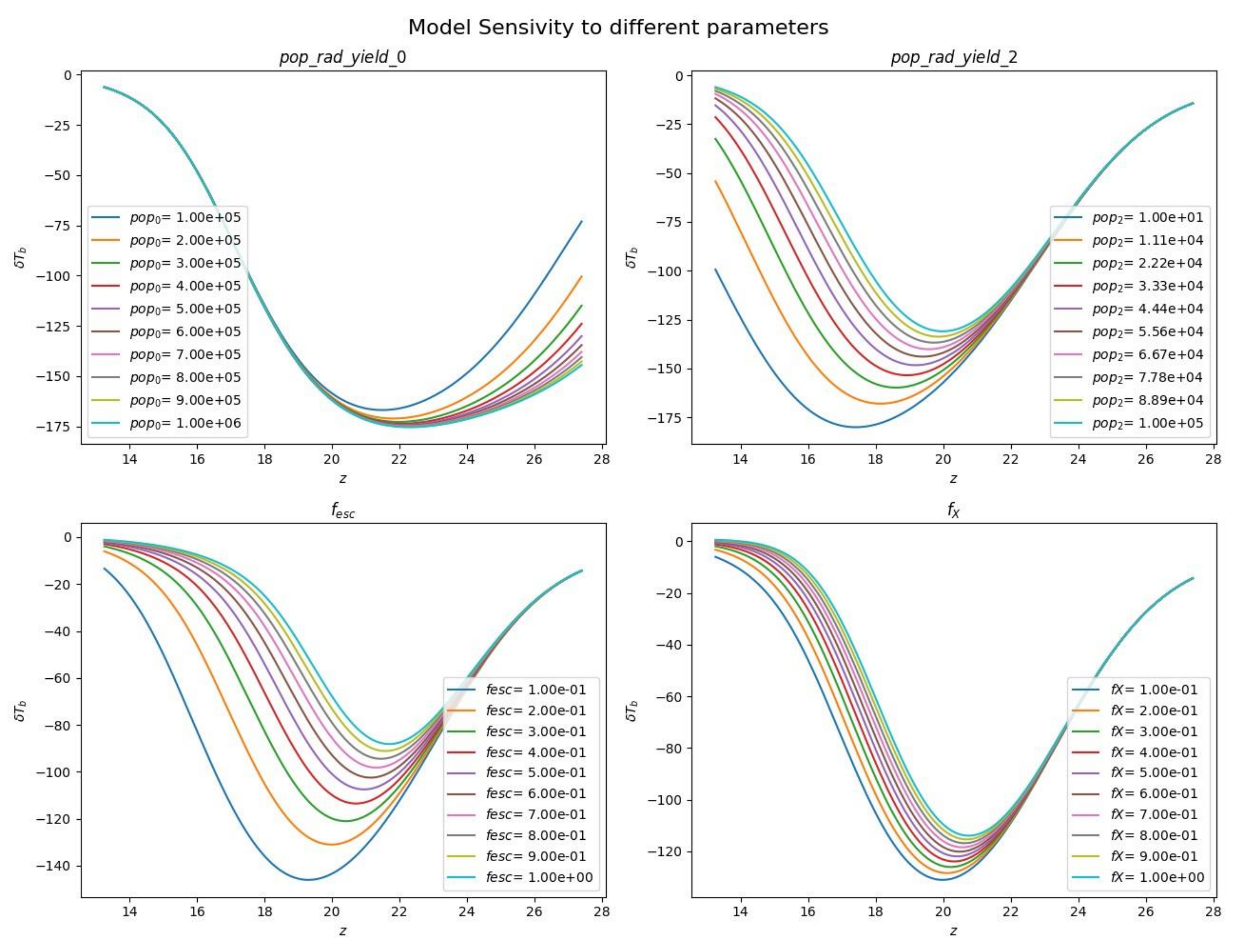
3. ***f_{esc}*** : Fraction of ionizing photons that escape their host galaxy into the IGM

4. ***N_{lw}*:** Number of photons emitted in the Lyman-Werner band (11.2 – 13.6eV) per baryon of star formation (= pop_rad_yield_0)

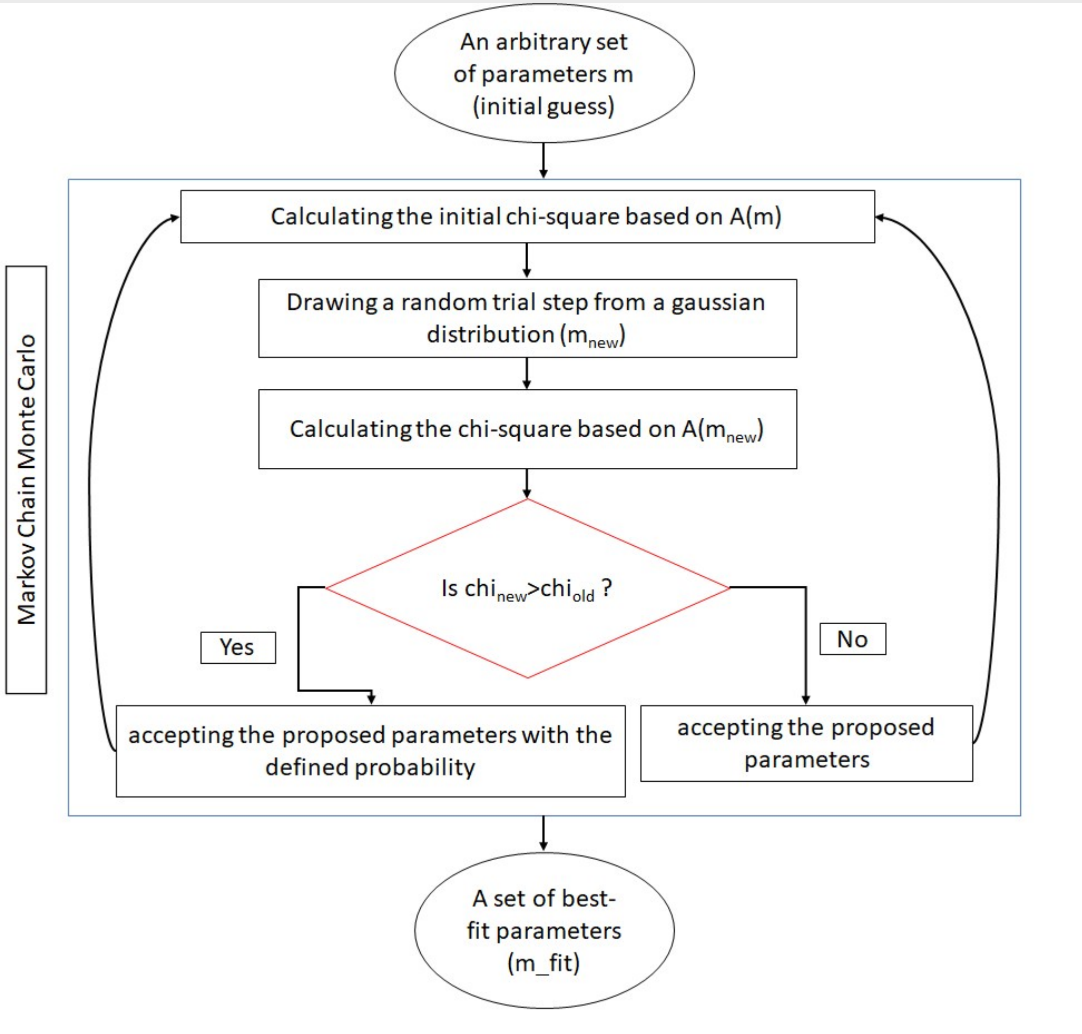
$$L_X = 3.4 \times 10^{40} f_X \left(\frac{SFR}{1\ M_\odot\ yr^{-1}} \right)\ erg\ s^{-1}$$

Ionizing fraction $$\bar{x}_i = \frac{\zeta f_{coll}}{1 + \bar{n}_{rec}}$$

Ionization efficiency $$\zeta = A_{He}\ f_*\ f_{esc}\ N_{ion}$$

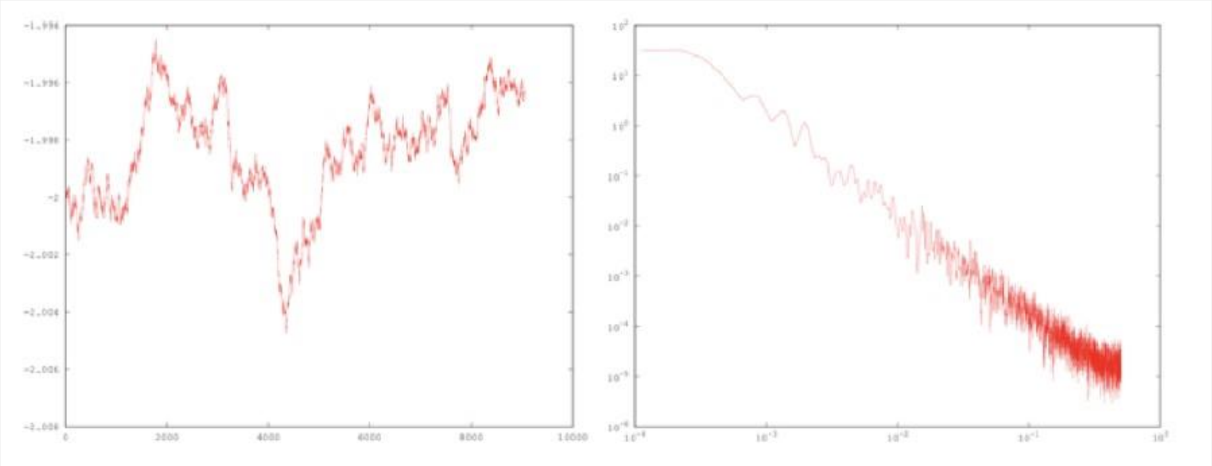

Model Sensivity to different parameters
pop_rad_yield_0
pop_rad_yield_2
f_{esc}
f_X
δT_b
z
pop_0= 1.00e+05
pop_0= 2.00e+05
pop_0= 3.00e+05
pop_0= 4.00e+05
pop_0= 5.00e+05
pop_0= 6.00e+05
pop_0= 7.00e+05
pop_0= 8.00e+05
pop_0= 9.00e+05
pop_0= 1.00e+06
pop_2= 1.00e+01
pop_2= 1.11e+04
pop_2= 2.22e+04
pop_2= 3.33e+04
pop_2= 4.44e+04
pop_2= 5.56e+04
pop_2= 6.67e+04
pop_2= 7.78e+04
pop_2= 8.89e+04
pop_2= 1.00e+05
$fesc$= 1.00e-01
$fesc$= 2.00e-01
$fesc$= 3.00e-01
$fesc$= 4.00e-01
$fesc$= 5.00e-01
$fesc$= 6.00e-01
$fesc$= 7.00e-01
$fesc$= 8.00e-01
$fesc$= 9.00e-01
$fesc$= 1.00e+00
fX= 1.00e-01
fX= 2.00e-01
fX= 3.00e-01
fX= 4.00e-01
fX= 5.00e-01
fX= 6.00e-01
fX= 7.00e-01
fX= 8.00e-01
fX= 9.00e-01
fX= 1.00e+00

Markov Chain Monte-Carlo (MCMC)

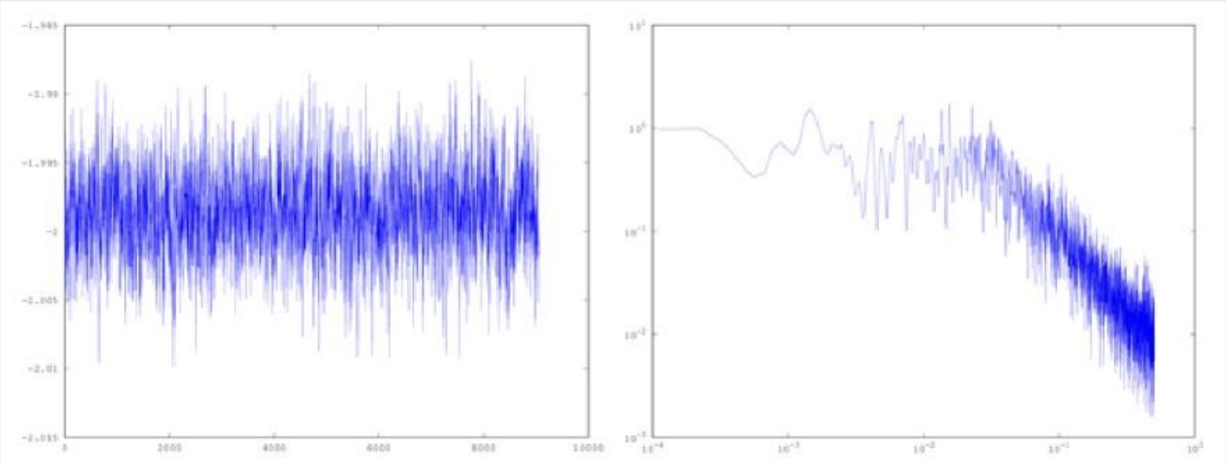


Convergence Test

MCMC chain *power spectrum*

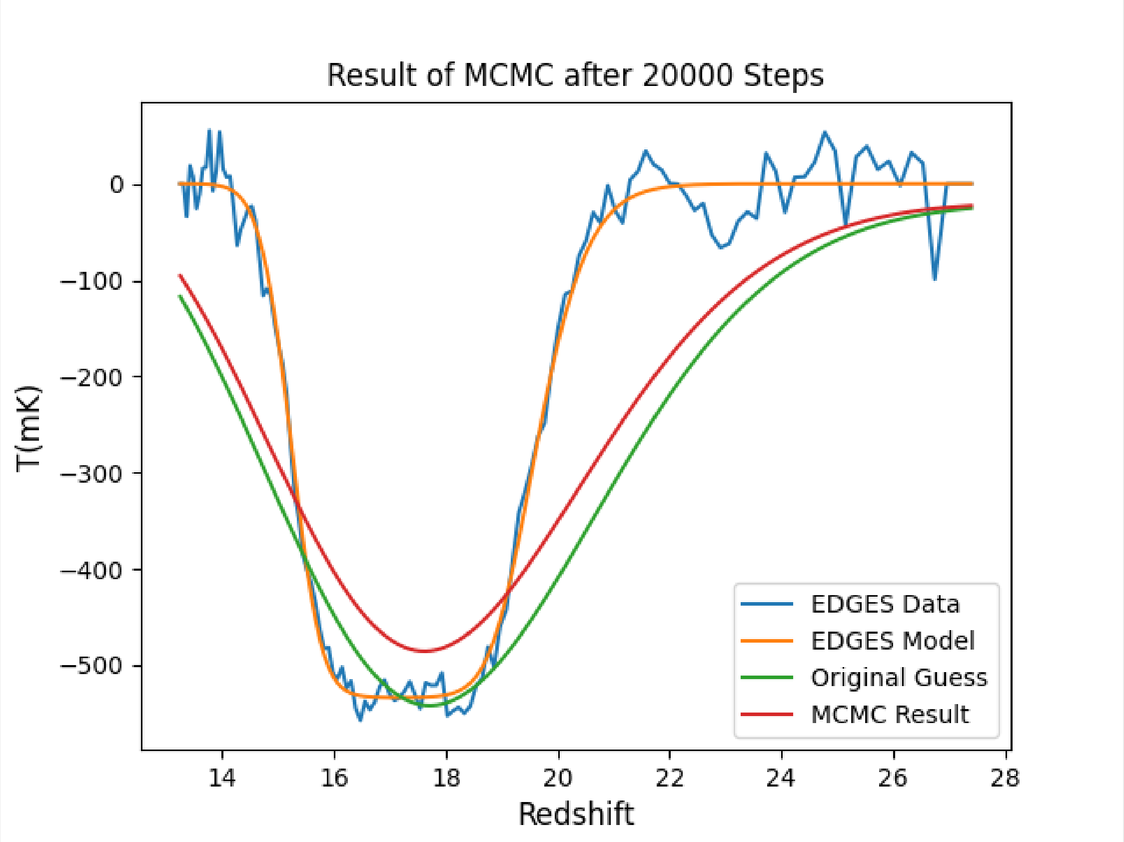


unconverged



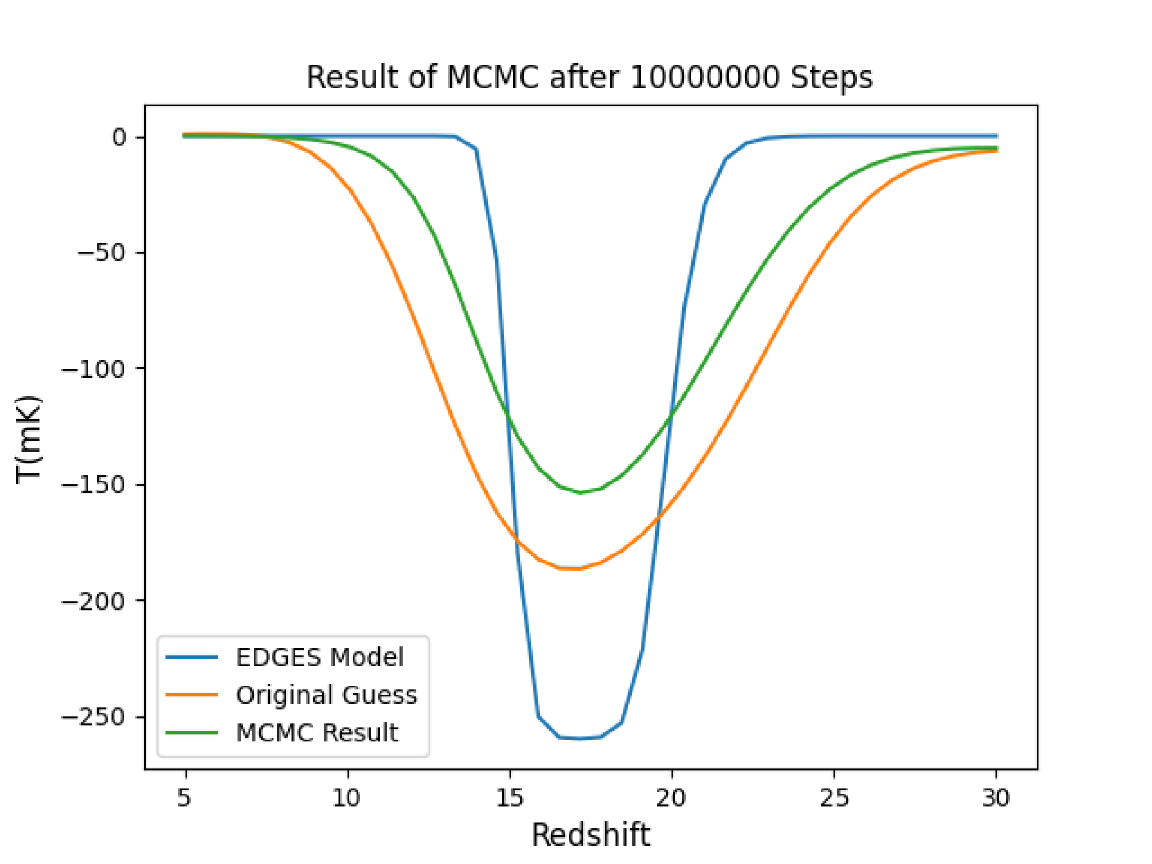
converged

MCMC with ARES



- A chain of 2E4 steps
- ~ 23 hours to produce this plot!
- Still not yet fully converged!
- Approximately 4 seconds for each ARES run

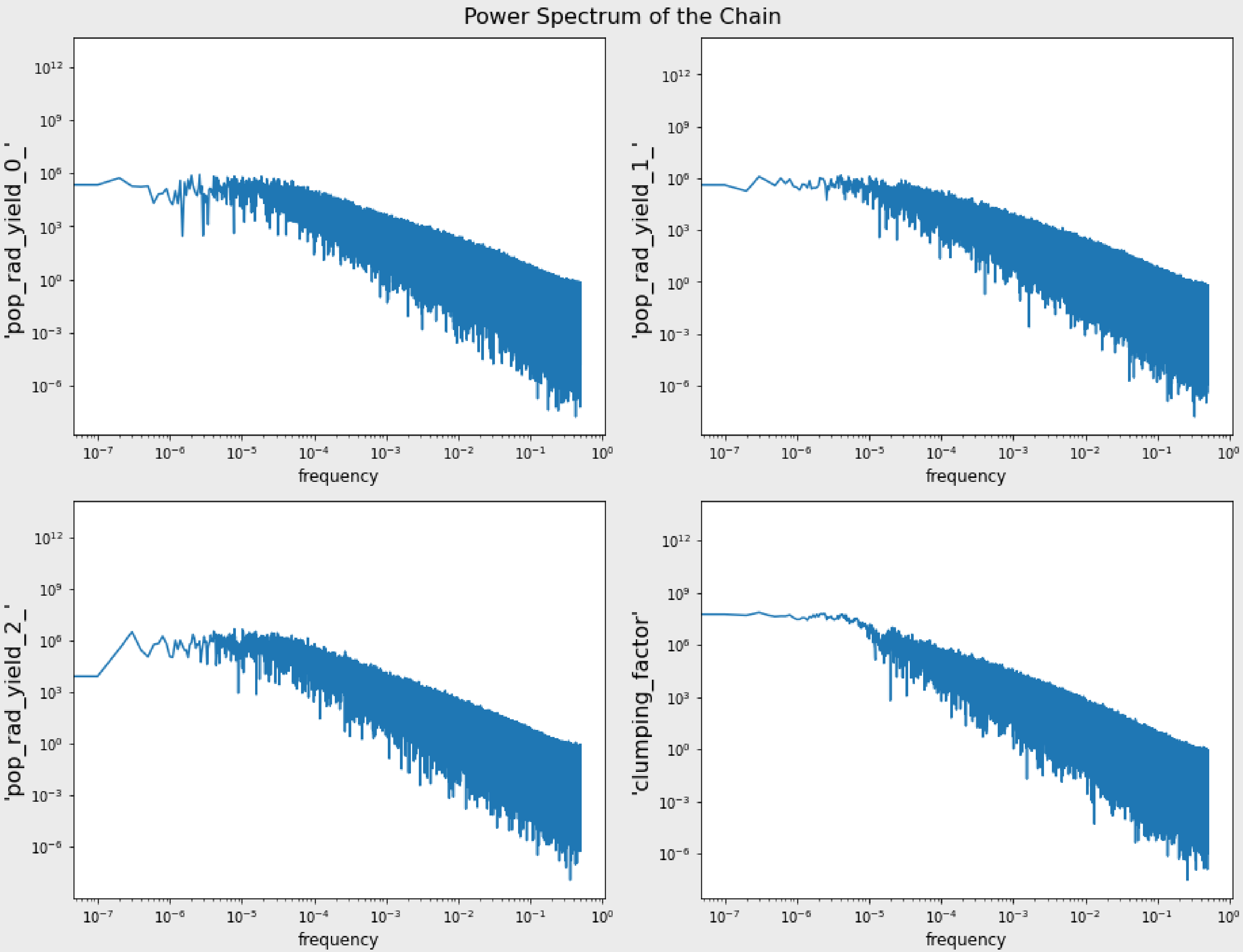
MCMC with RBFI
(Radial Basis Function Interpolation)



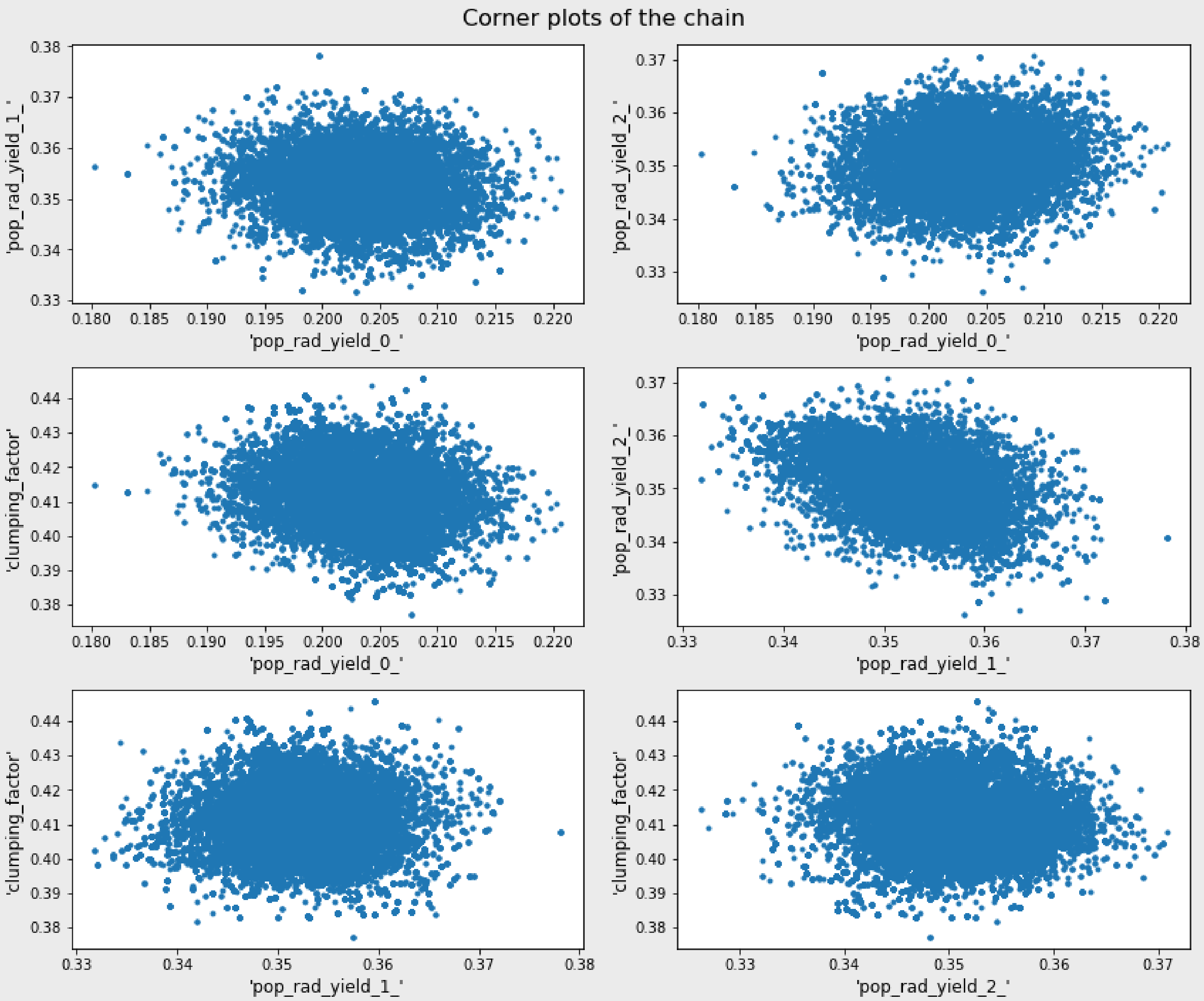
- A chain of 1E7 steps
- Runtime: ~ 22 hours
- fully converged!
- Half of the amplitude of the actual observed data

RBFI Credits: Hans Hopkins, Justin Cardona, Jared Tritt, Luc Bojorquez-Lopez

Convergence



Corner Plots



Levenberg – Marquardt (LM)

- An iterative damped-least squares method
- *Will give us a reasonable starting point*
- *More critical: The covariance matrix*
- *We will draw samples from this covariance matrix and feed these samples to the MCMC*

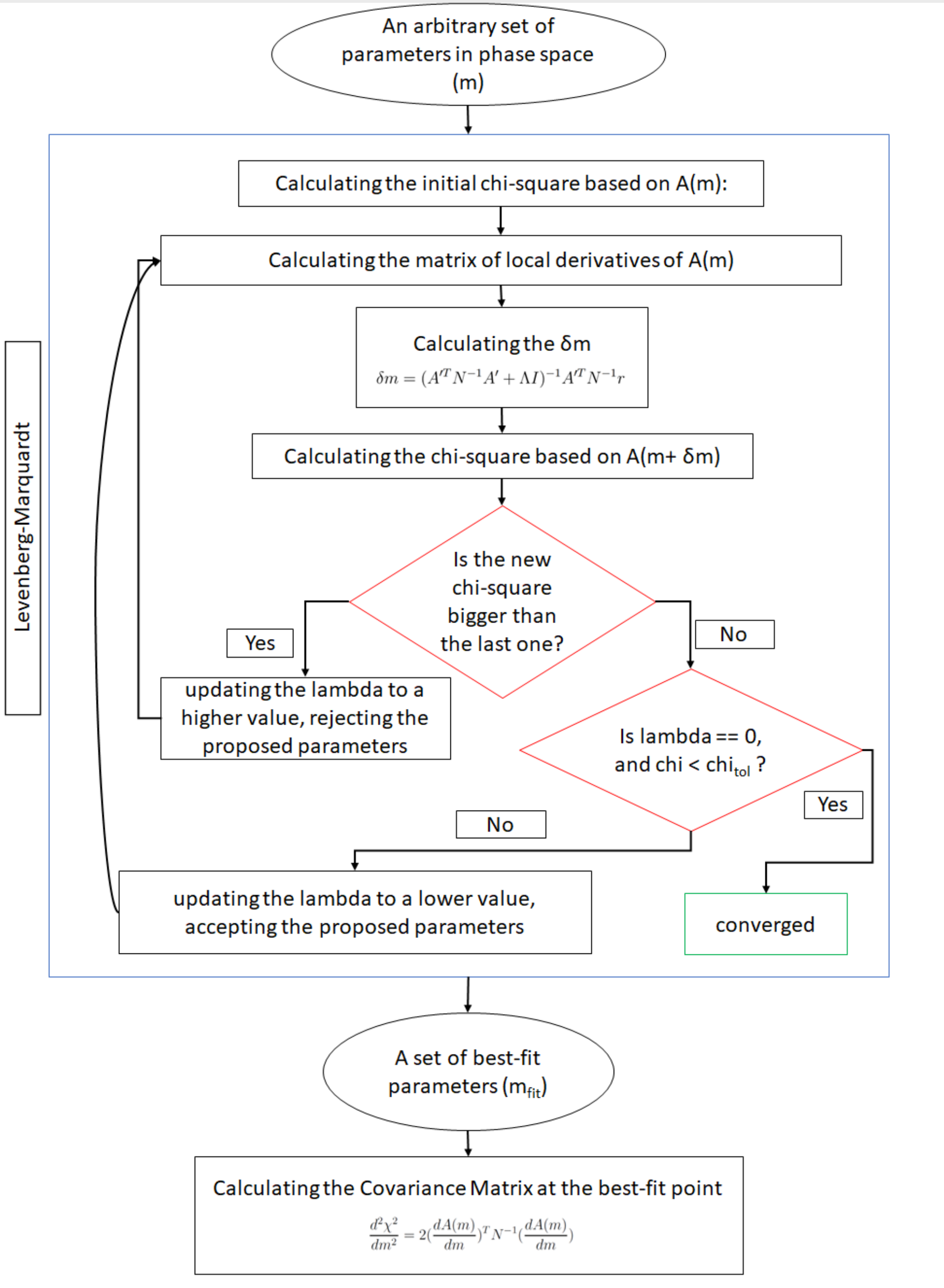
$$\chi^2 \equiv (d - A(m))^T N^{-1} (d - A(m))$$

$$\chi^2 (m + \delta m) = \chi^2 (m) + \left(\frac{d\chi^2}{dm}\right) \delta m$$

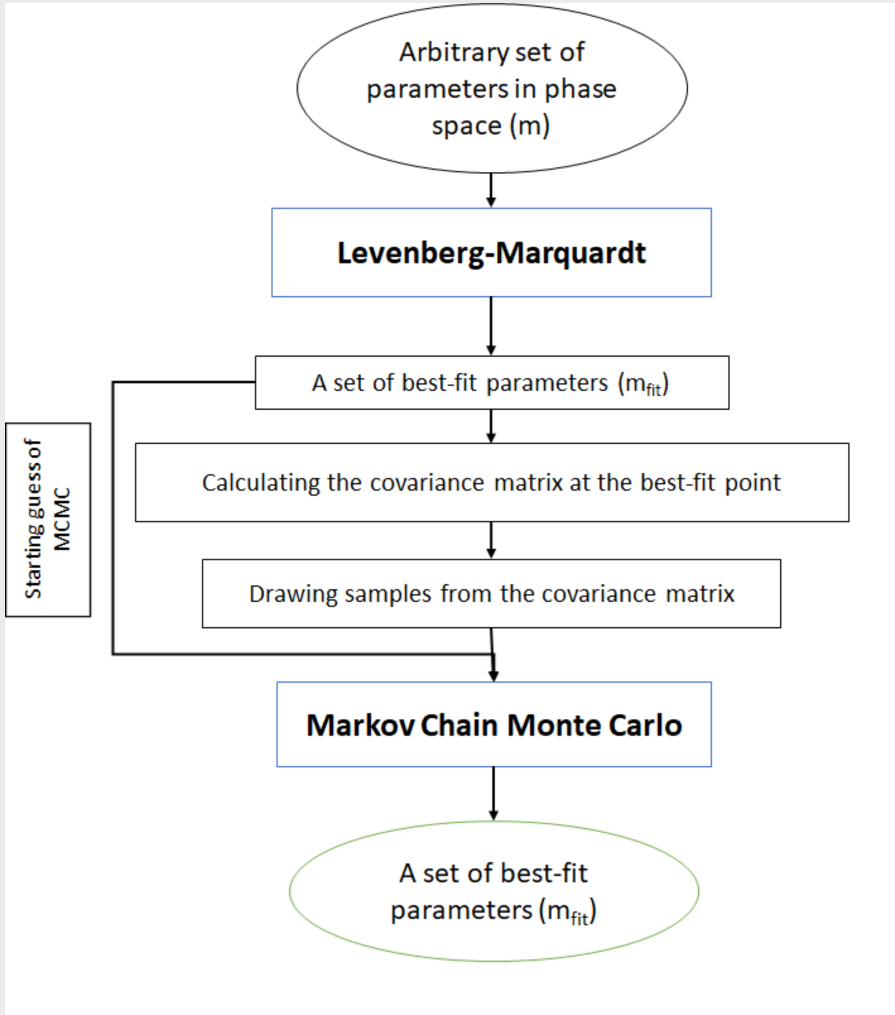
$$\delta m = \left(A'^T N^{-1} A' + \Lambda I\right)^{-1} A'^T N^{-1} r$$

Curvature matrix

$$\frac{d^2\chi^2}{dm^2} = 2 (A')^T N^{-1} A'$$

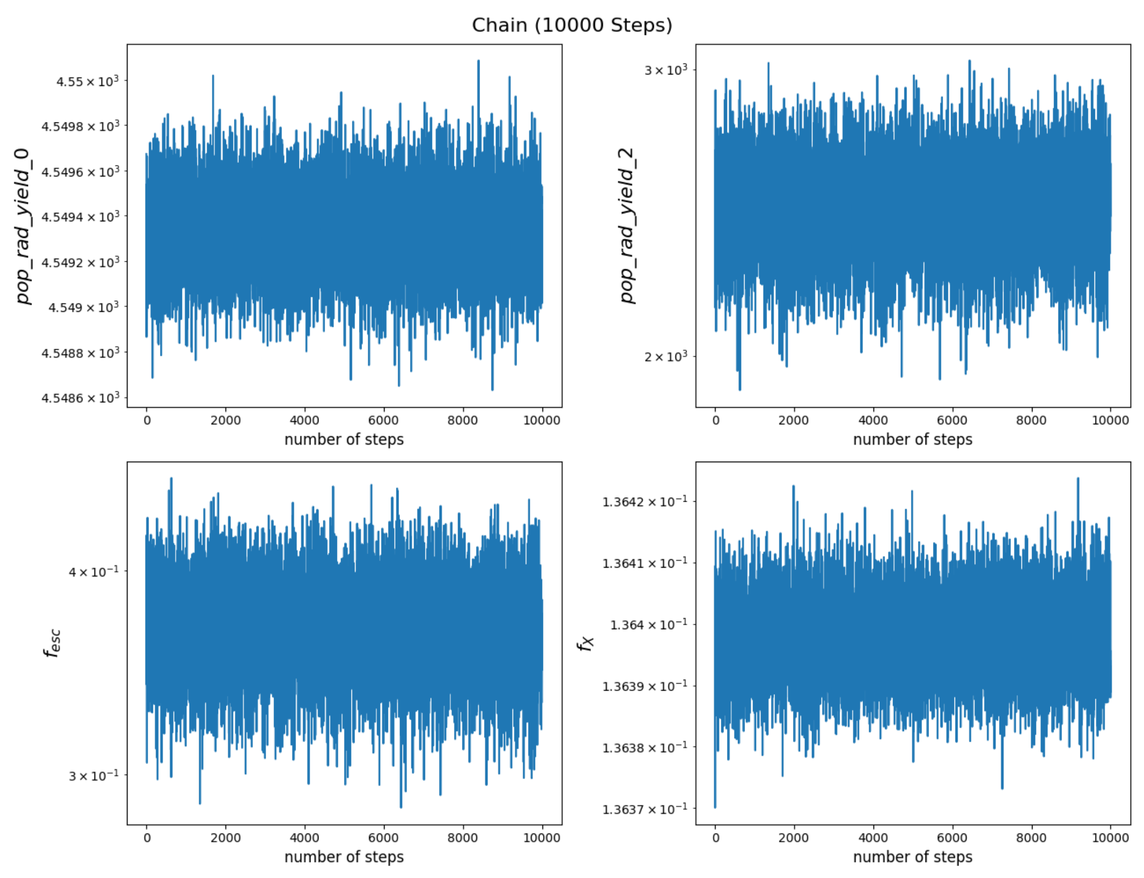

An arbitrary set of parameters in phase space (m)
Levenberg-Marquardt
Calculating the initial chi-square based on A(m):
Calculating the matrix of local derivatives of A(m)
Calculating the δm
$\delta m = (A'^T N^{-1} A' + \Lambda I)^{-1} A'^T N^{-1} r$
Calculating the chi-square based on A(m+ δm)
Is the new chi-square bigger than the last one?
Yes
No
updating the lambda to a higher value, rejecting the proposed parameters
Is lambda == 0, and chi < chi_{tol} ?
Yes
No
updating the lambda to a lower value, accepting the proposed parameters
converged
A set of best-fit parameters (m_{fit})
Calculating the Covariance Matrix at the best-fit point
$\frac{d^2\chi^2}{dm^2} = 2(\frac{dA(m)}{dm})^T N^{-1}(\frac{dA(m)}{dm})$

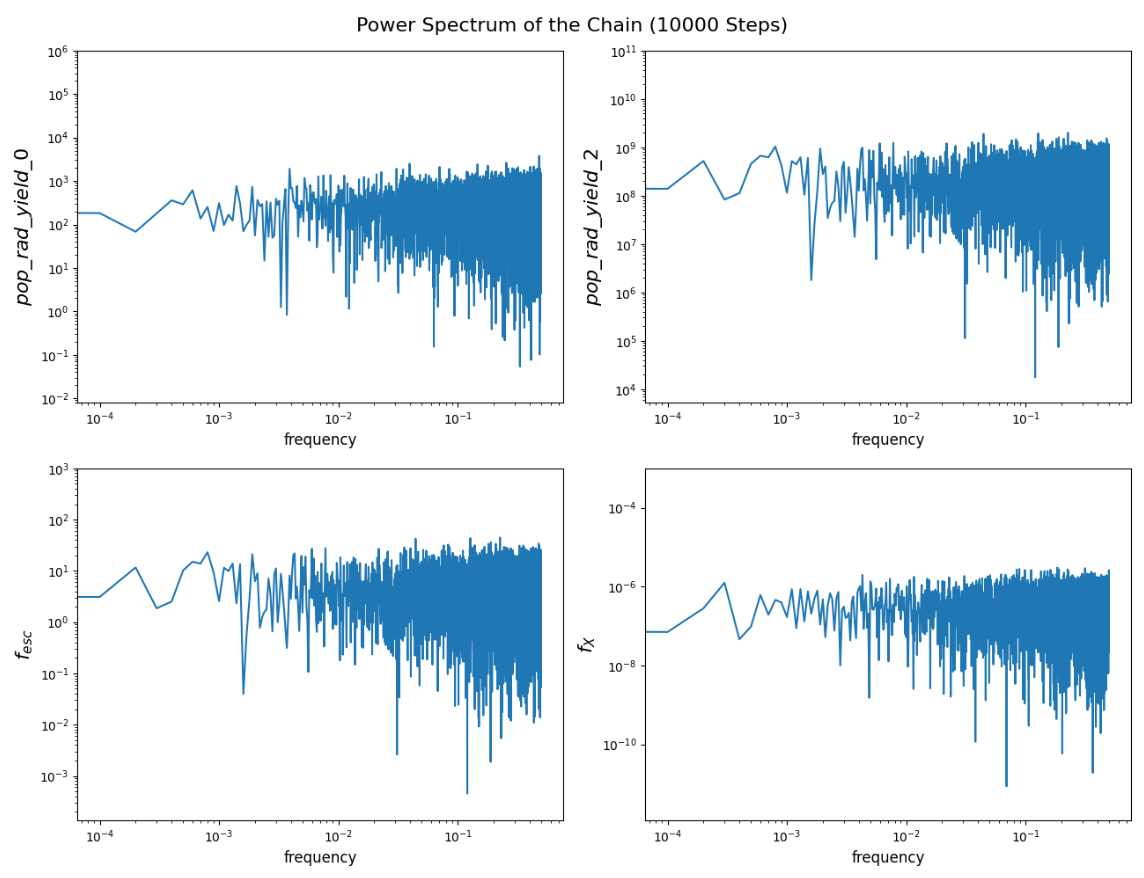
Combination of MCMC and LM

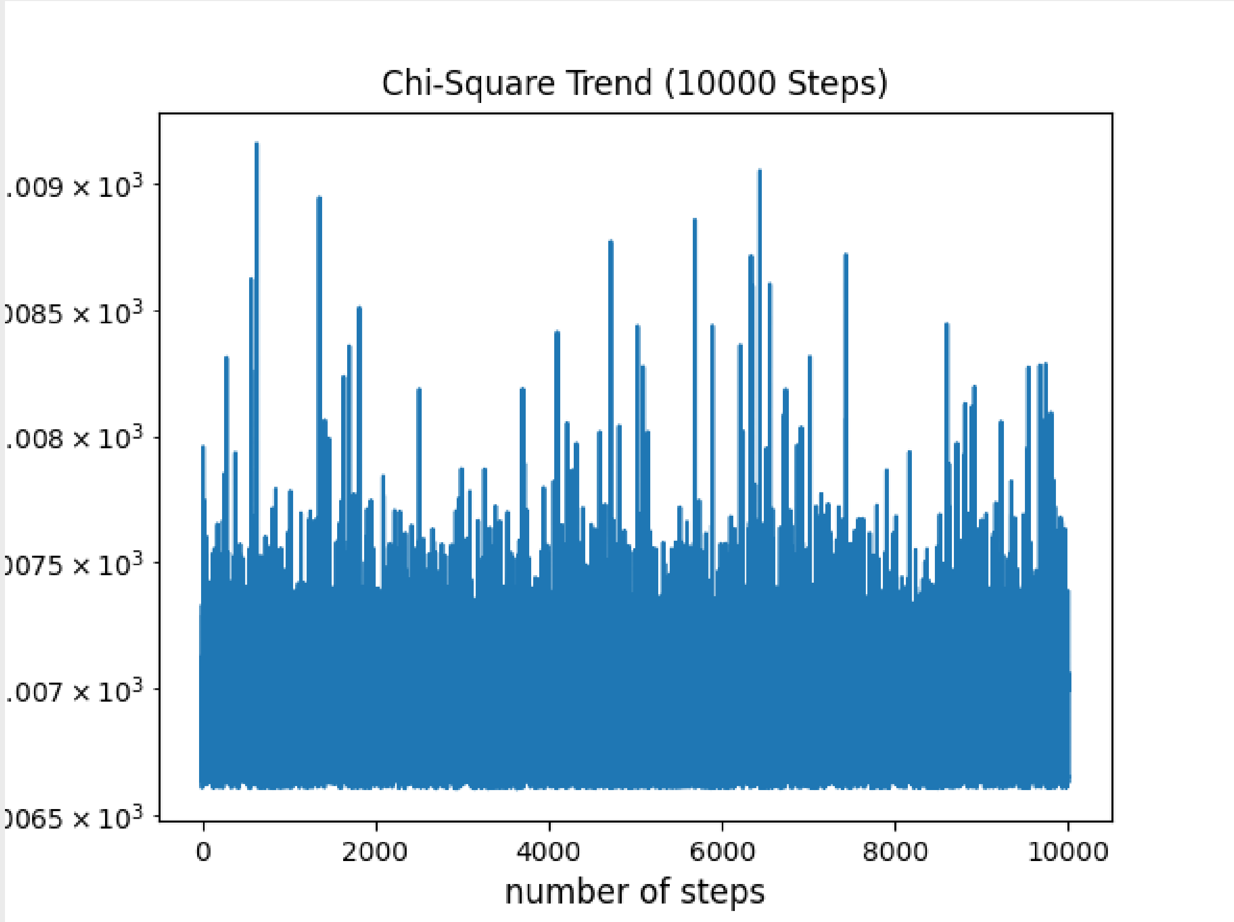


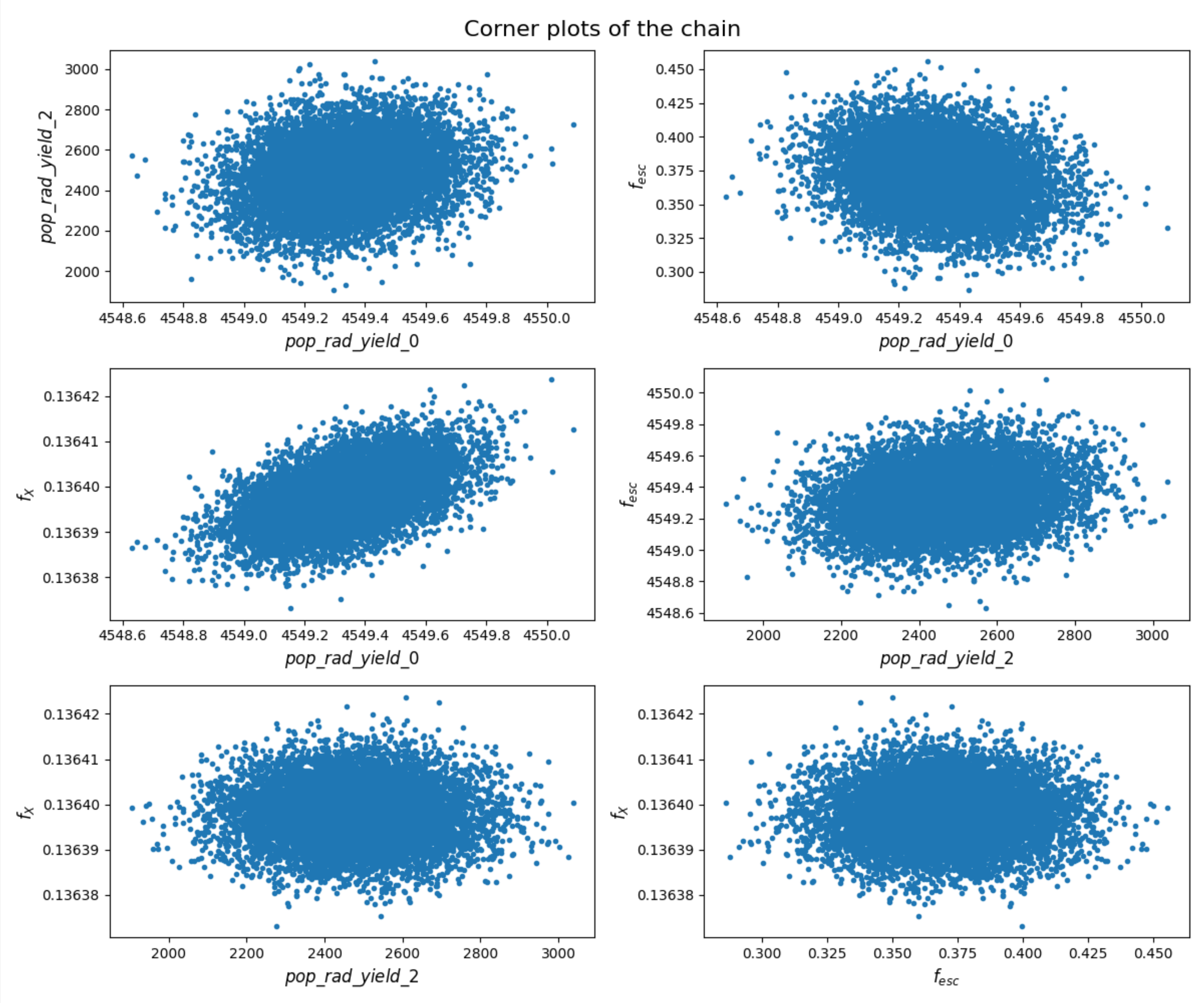
Results of Fit to EDGES data

Parameter / Value	*pop_rad_yield_0_*	*pop_rad_yield_2_*	f_{esc}	f_X
Fitted values	9.999×10^3	9.994×10^2	1.000×10^{-1}	1.000×10^{-1}
Error-bar of fit	3.541×10^{-2}	3.861×10^0	3.578×10^{-4}	3.392×10^{-6}


Chain (10000 Steps)
pop_rad_yield_0
pop_rad_yield_2
f_{esc}
f_X
number of steps


Power Spectrum of the Chain (10000 Steps)
pop_rad_yield_0
pop_rad_yield_2
f_{esc}
f_X
frequency


Chi-Square Trend (10000 Steps)
.009 × 10^3
)085 × 10^3
.008 × 10^3
)075 × 10^3
.007 × 10^3
)065 × 10^3
0
2000
4000
6000
8000
10000
number of steps



Corner plots of the chain
pop_rad_yield_2
3000
2800
2600
2400
2200
2000
4548.6
4548.8
4549.0
4549.2
4549.4
4549.6
4549.8
4550.0
pop_rad_yield_0
f_{esc}
0.450
0.425
0.400
0.375
0.350
0.325
0.300
pop_rad_yield_0
f_X
0.13642
0.13641
0.13640
0.13639
0.13638
pop_rad_yield_0
f_{esc}
4550.0
4549.8
4549.6
4549.4
4549.2
4549.0
4548.8
4548.6
2000
2200
2400
2600
2800
3000
pop_rad_yield_2
f_X
pop_rad_yield_2
f_X
0.300
0.325
0.350
0.375
0.400
0.425
0.450
f_{esc}

Future Perspective

- Publishing our method as a Python package for parameters estimation of the global 21cm signal
- Analyze the data from upcoming experiments
- Updating ARES to include the desired non-standard effects
- Investigate the difference in the behavior of specific astrophysical parameters in the presence of non-standard physics


Thank You for Your Attention