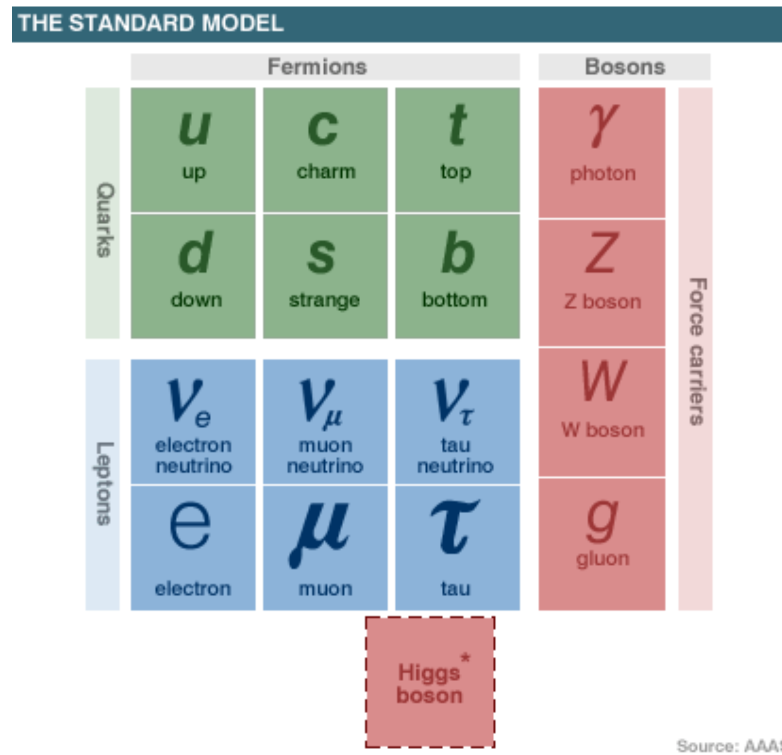
# Dark Matter Annihilation and Non-Gaussianity:
## Signals of New Physics Hidden by Messy Astrophysics

**Eric Baxter**
**The University of Chicago**

with Scott Dodelson, Peter Adshead, Adam Lidz, Brian Fields, Nachiketa Chakraborty

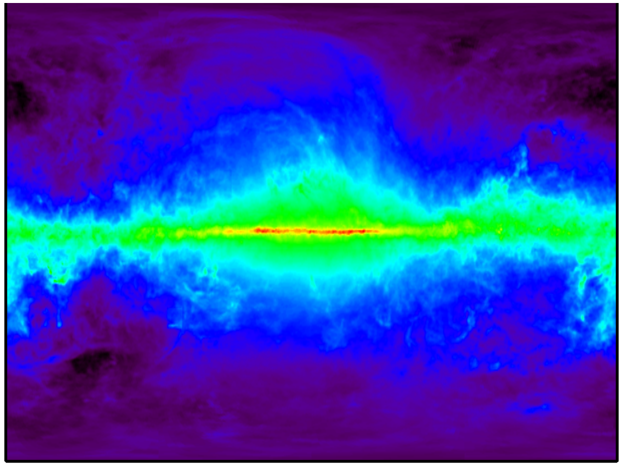
# Astrophysical Probes of Physics Beyond the Standard Model

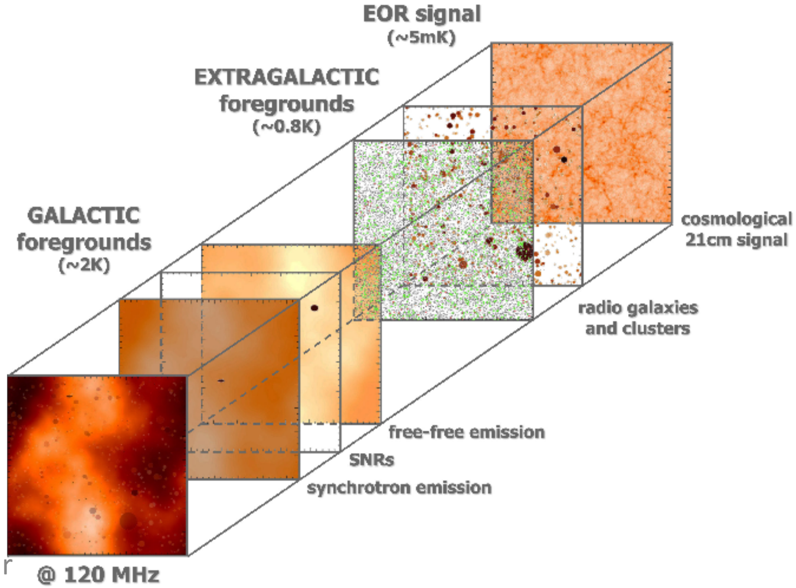
- Why are dark matter and non-Gaussianity attractive targets?
  - Dark Matter
    - Likely a new particle
    - We know it's there, and where to look for it
    - Hard to detect DM in lab
  - Non-Gaussianity
    - Can tell us about inflation
    - Inflation occurs at energy scale far beyond reach of colliders
    - Can constrain NG in interesting regimes with current/future observations



# Messy Astrophysics

- Astrophysical backgrounds interfere with our ability to measure signals of new physics
  - Dark Matter
    - Idea: measure gamma-rays produced by dark matter annihilations
    - Challenges:
      - Many astrophysical sources also produce gamma-rays
      - Modeling these astrophysical sources is difficult
  - Non-Gaussianity
    - Idea: measure NG with a redshifted 21 cm experiment
    - Challenges:
      - Many large astrophysical foregrounds
      - Uncertainties in physics of reionization



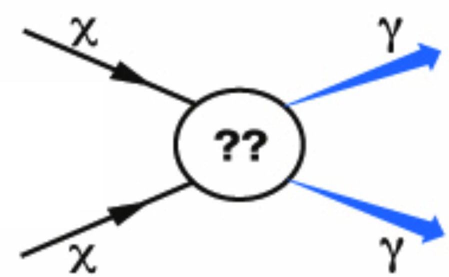


# Constraining Dark Matter Annihilation in Galactic Subhalos with Gamma-Ray Data

**Baxter**, Dodelson, Koushiappas, Strigari, 2010 (Phys. Rev. D, 82, arXiv: 1106.2399)
**Baxter**, Chakraborty, Dodelson, Fields, in prep.

# Probing Dark Matter with Gamma-Rays

- Self annihilation of dark matter particles can produce standard model particles, including gamma-rays
  - Possible in many popular dark matter models
- Might be possible to 'indirectly detect' dark matter by observing these gamma-rays
  - Fermi telescope has been in orbit for ~5 years
- Can hope to learn a lot about dark matter
  - Particle physics properties (e.g. mass, annihilation cross section, interactions, etc.)
  - Distribution in space



# Where should we look?

Astrophysics

$$\text{signal flux} \propto \left( \frac{N_\gamma \langle \sigma v \rangle}{M_\chi^2} \right) \int dl\, d\Omega \frac{\rho^2}{4\pi l^2}$$

Geometry

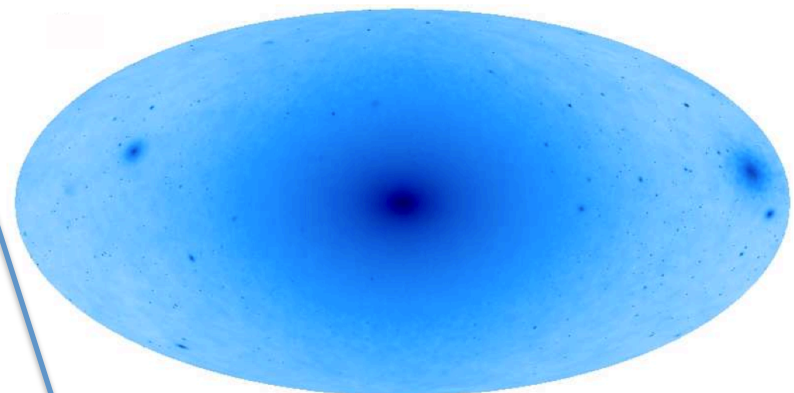
Particle physics

- Some possible targets:
  - Galaxy clusters (lots of dark matter, but distant)
  - Galactic center (lots of dark matter, close by, but astrophysics messy)
  - Individual dwarf galaxies (close by, lots of dark matter)

- **Diffuse Signal from Galactic Dark Matter Subhalos**
  - Will contribute to diffuse (no point sources detected) background
    - Might not be able to detect individual subhalo, but hope is to constrain *total* subhalo contribution
  - Clumpiness ➔ annihilation signal enhanced
  - Expected to dominate galactic annihilation signal beyond about 30 degrees from galactic center

# Galactic Dark Matter subhalos

- N-body simulations make predictions for subhalo properties
  - Smooth and subhalo components
  - $\frac{dN}{dM} \sim M^{-1.9}$ ➔ lots of small subhalos
    - Minimum subhalo mass depends on particle physics, but generally very small ($10^{-7}$ $M_{sun}$ not unreasonable)
  - Distribution of subhalos (very) roughly follows smooth dark matter
  - Internal density of subhalo (and thus annihilation luminosity) depends on properties of host halo, orbit of subhalo, and other factors
- We use results from Koushiappas et al. 2010
  - They use semi-analytic model (Zentner et al. 2007) to generate distributions of subhalo luminosities

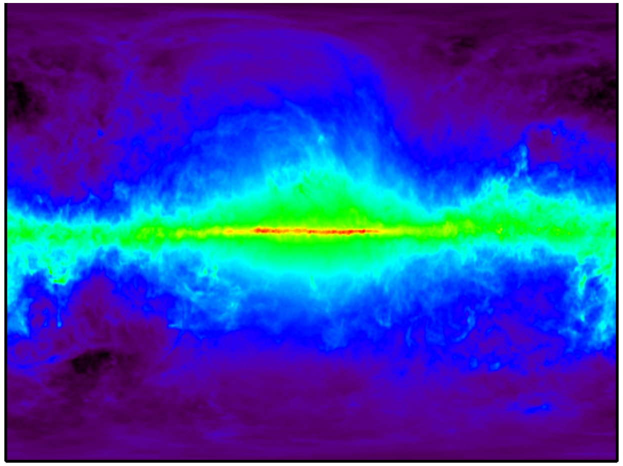


Via Lactea II simulation

- Mass function
- Mass-luminosity relation

# Astrophysical Backgrounds

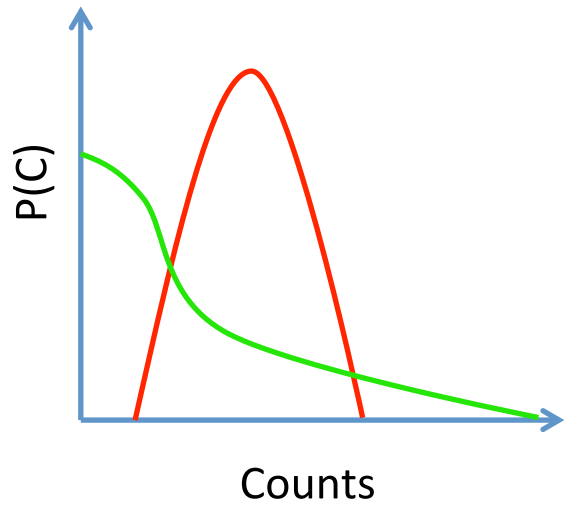
- There are several sources of diffuse (no point sources detected) gamma-rays
  - Galactic diffuse emission
  - Point sources below detection threshold
- Galactic diffuse emission
  - Cosmic rays interacting with galactic matter/photons
  - Modeling this background
    - Need to know gas + photon distribution + cosmic ray propagation
    - Models are good, but not perfect
  - It would be great if there were a way to separate diffuse galactic backgrounds from diffuse light produced by dark matter annihilation in subhalos…



# The Photon Counts Probability Distribution Function, P(C)

- Toy example:
  - Source type 1 (rare and bright):
    - Assume there are either 0 or 1 sources in a pixel
    - Probability for single source to produce C photons is proportional to luminosity function (with some spatial integral)
    - ➔ P(C) follows luminosity function at high C
  - Source type 2 (common and dim):
    - Assume there are N >> 1 sources per pixel (on average)
    - Source can emit 1 photon with probability ε << 1, or 0 photons with probability (1-ε)
    - Probability for N sources to produce C photons is B(N, ε )
    - In limit that N is very large and ε very small, binomial approaches Poisson
    - ➔ P(C) follows Poisson distribution
- Galactic diffuse emission
  - Photons effectively produced by many sources along line of sight
  - Like source type 2
- Dark matter subhalos
  - Few subhalos along the line of sight will produce most photons in pixel
  - Like source type 1
- Idea of using P(C) to discriminate between subhalo annihilation signal and backgrounds proposed by Lee et al. 2009

P(C) = probability to observe C photons in a single pixel



# Calculating the PDF for Dark Matter Subhalos

- Want to convert mass function and mass luminosity relation ➔ prediction for P(C)
  - Use approach based on P(D) formalism (Scheuer 1957)
  - Basic problem:
    - Probability for one source to produce flux F = $P_1(F)$
    - Convolve this PDF with itself N times to get total P(F)
      - N is itself a Poisson random variable
    - Discretize P(F) to get P(C) assuming exposure E

- Mass function
- Mass-luminosity relation

$$P(F) = \mathcal{F}^{-1}\left[e^{\mu(\mathcal{F}[P_1(F)]-1)}\right]$$

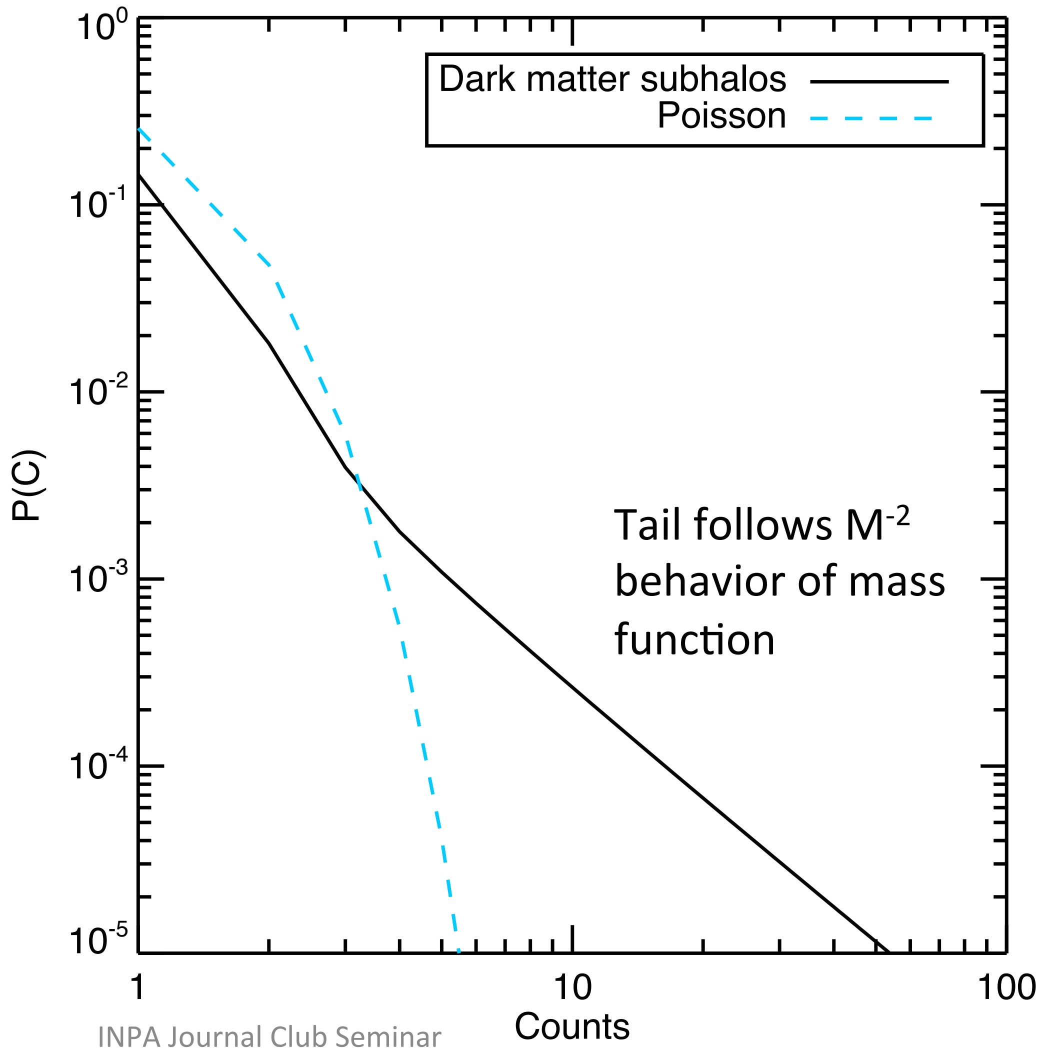
$$P(C) = \int dF \frac{\exp(-EF)(EF)^C}{C!} P(F)$$

- Allow P(C) to vary on the sky
  - Can account for non-isotropic subhalo emission
  - Non-uniform exposure of telescope

- One model parameter: $f_{\mathrm{WIMP}} = \frac{N_\gamma \langle \sigma v \rangle}{M_\chi^2}$

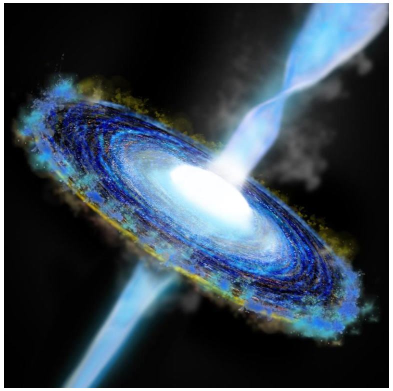
# P(C) for Dark Matter Subhalos

- Two curves produce same mean counts in a pixel
- Dark matter P(C) has non-Poisson tail
  ➔ Background discrimination

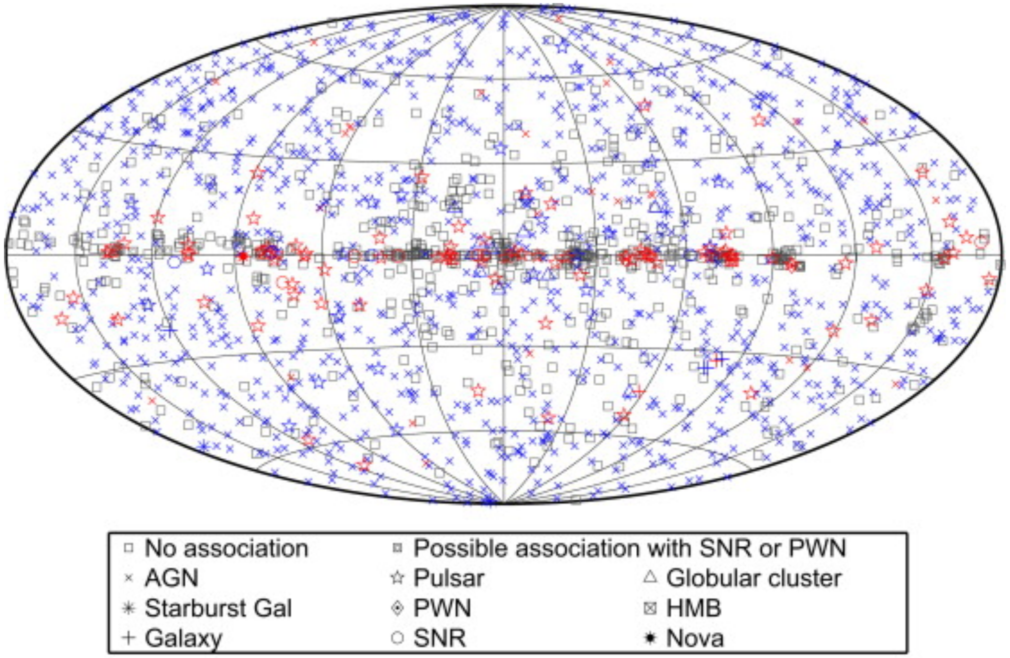


# Other Astrophysical Backgrounds

- Undetected point sources also contribute to diffuse gamma ray background
  - A point source population that is rare/bright may produce similar P(C) to dark matter
- Blazars
  - Galaxies that host active galactic nuclei
  - Possible large contribution to gamma-ray sky below point source detection threshold



- We model the Blazar P(C) using the same P(D) techniques
  - Fit for parameters of both Blazars and dark matter simultaneously
  - Turns out there isn't a lot of degeneracy



# A Maximum Likelihood Approach

- Total model P(C) for a pixel is convolution of dark matter + blazar + poisson

- Likelihood of observing the data given our model P(C) is

$$\mathcal{L} = \prod_{i=1}^{N_{pix}} P_i(C_i)$$

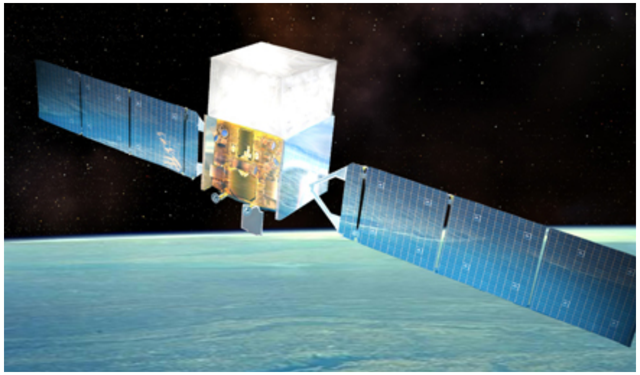
Data

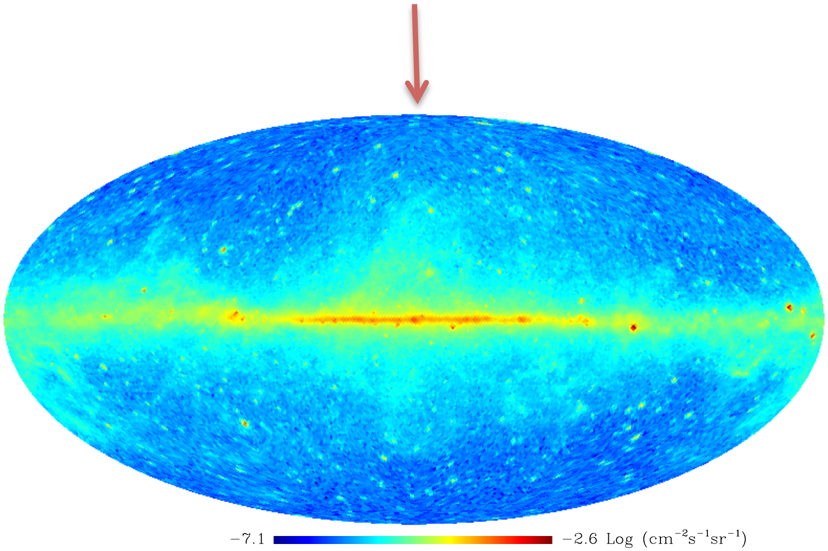
- Consider 5 different parameters
  - Dark matter: $f_{WIMP}$
  - Blazars: three parameters controlling behavior of luminosity function
  - Amplitude of Poisson component

# Data from Fermi

- The Large Area Telescope (LAT)
  - Gamma-rays can't be reflected or refracted → measure e+/e- upon pair conversion
  - Large field of view, broad energy range, good angular resolution, large collecting area and high quality event discrimination

    → great for indirect detection
  - Detects gamma-rays with approximately 20 MeV < E < 300 GeV
  - Has collected several years of data
  - Data are public!



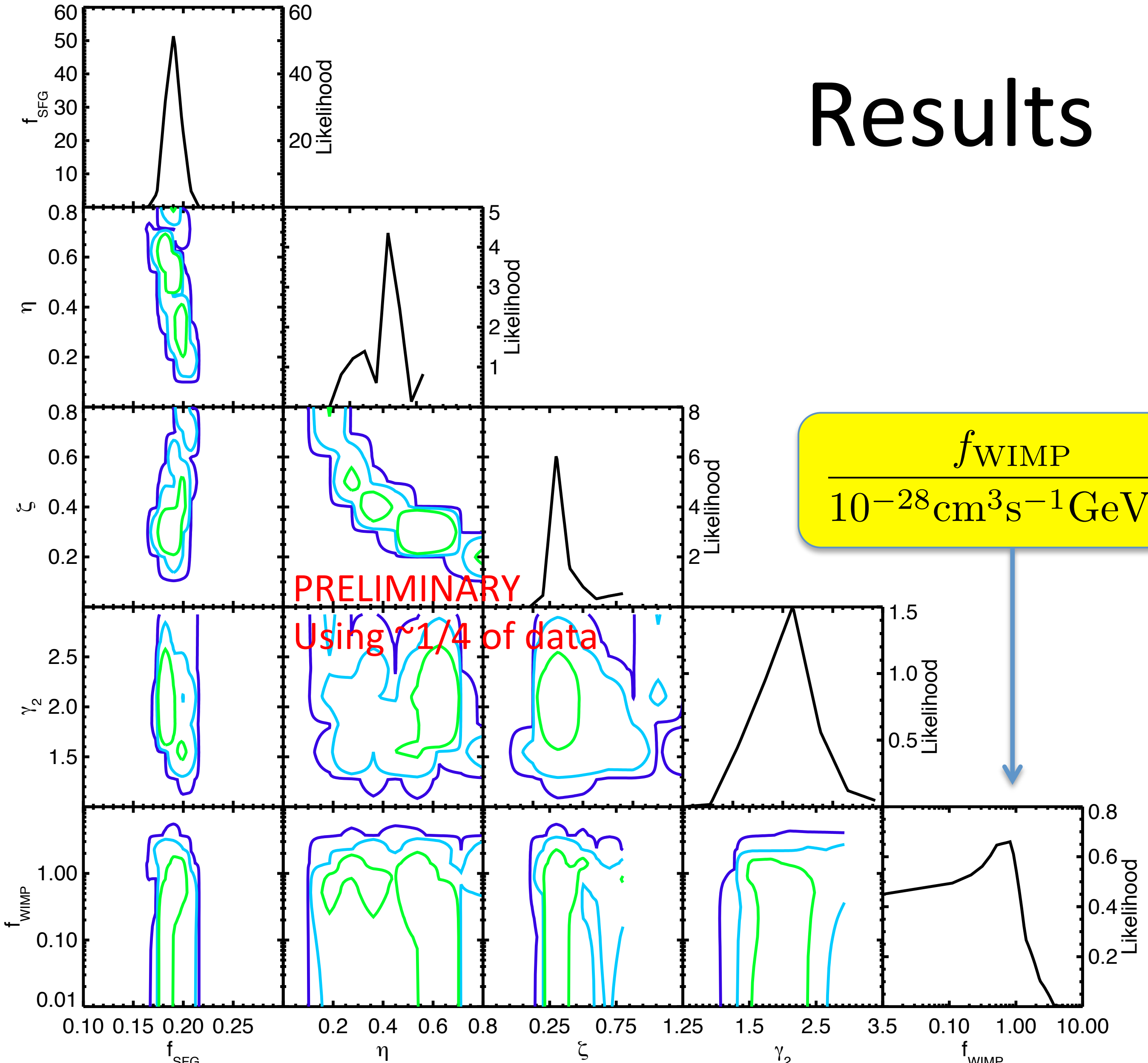


# Results

Poisson parameter

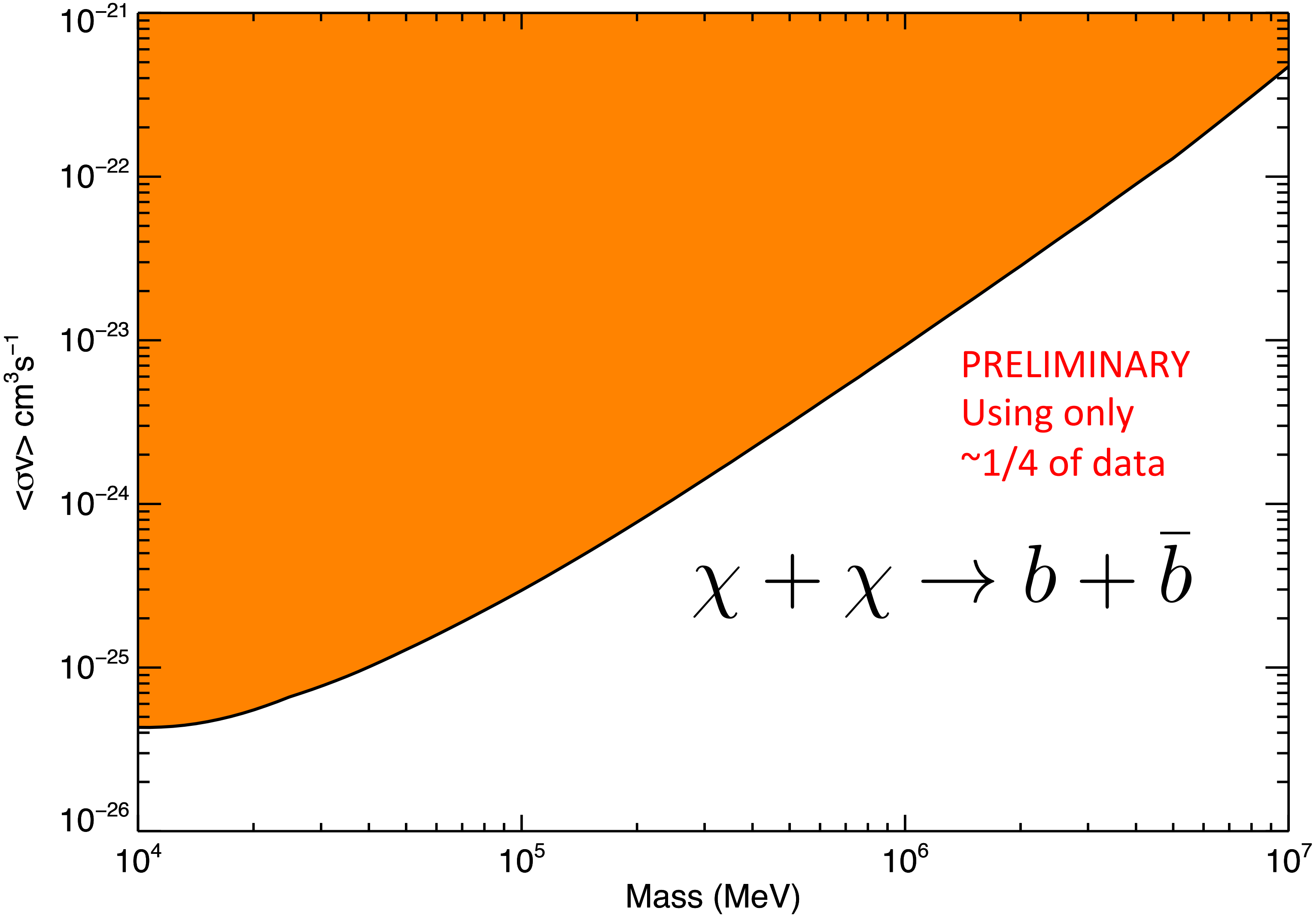
Blazar parameters

DM normalization




$$\frac{f_{\mathrm{WIMP}}}{10^{-28}\mathrm{cm}^3\mathrm{s}^{-1}\mathrm{GeV}^{-2}}$$

# Dark Matter Constraints



# Summary: Dark Matter Annihilation in Galactic Subhalos

1. Dark matter subhalos are promising targets for indirect detection

2. Photon counts PDF is a powerful tool
   – Performs background discrimination automatically

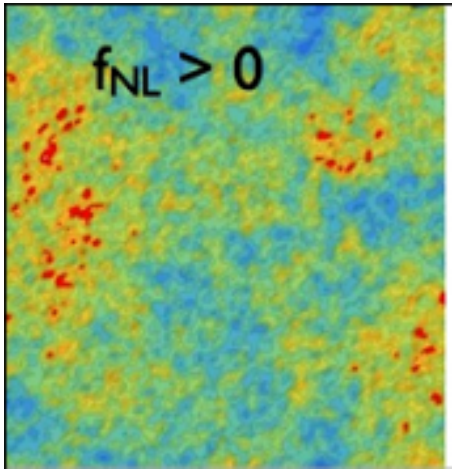
3. Early results are promising

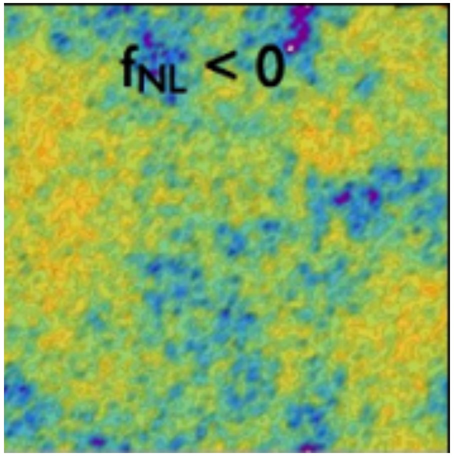
# Constraining Inflation by Measuring the Impact of Primordial Non-Gaussianity on the Ionization Field During Reionization

Adshead, **Baxter**, Dodelson, Lidz, 2012 (Phys. Rev. D 86, 063526, arXiv: 1206.3306)
Lidz, **Baxter**, Dodelson, Adshead, in prep.

# Inflation and Primordial Non-Gaussianity

- Non-Gaussianity as probe of inflation
  - Simplest inflationary model predicts initial fluctuations are drawn from Gaussian distribution
  - Detection of primordial non-Gaussianity
    - Multiple fields?
    - Derivative interactions?
    - Features in inflaton potential?
  - Many ways to constrain non-Gaussianity



# Scale Dependent Bias

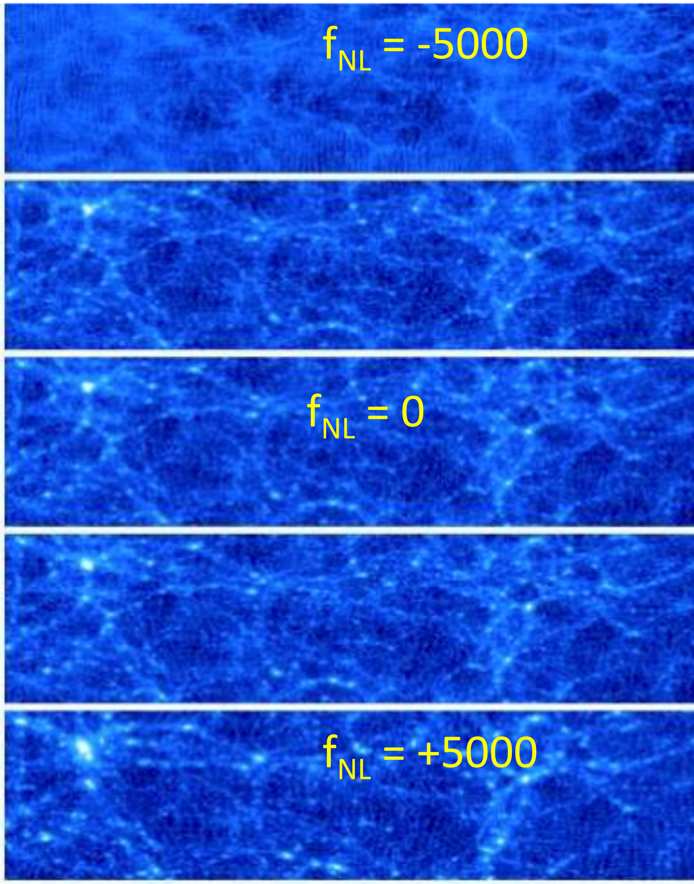
- Dalal et al. 2008 showed that primordial non-Gaussianity leads to scale dependence of the halo bias
  - Bias model:

$$\delta_{halo}(\vec{k}) = b(M)\delta_{matter}(\vec{k})$$

  - $f_{NL}$ type non-Gaussianity ➔ scale dependence of bias:

$$\Delta b_{NG}(M,k) \propto \frac{f_{NL}}{k^2}$$

- Constraints from large scale structure potentially more powerful than constraints from CMB
  - Measure bias, fit for $f_{NL}$

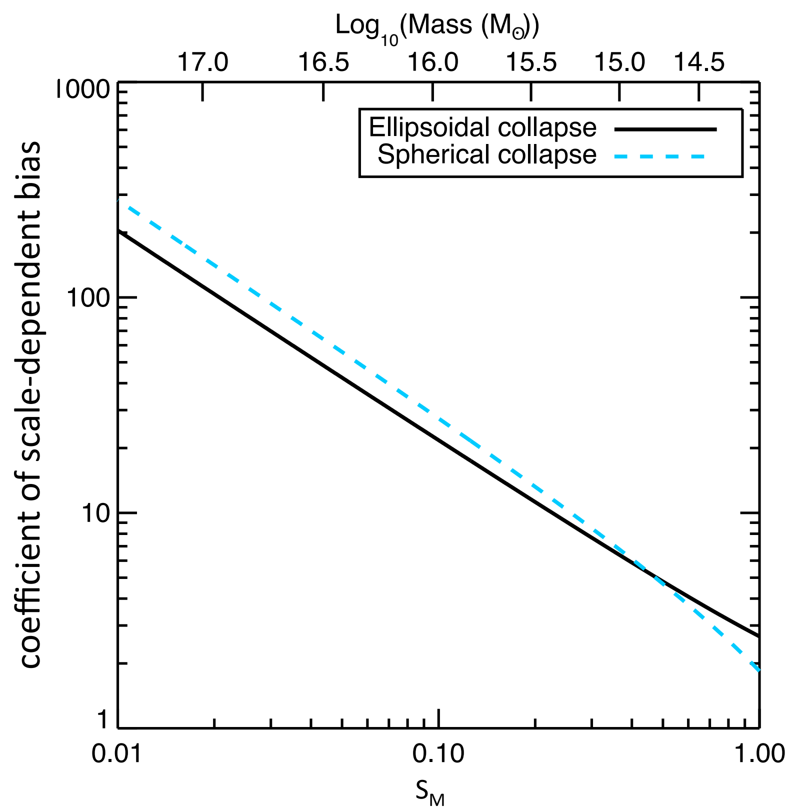


# Scale-Dependent Bias with Excursion Sets

- Can derive scale dependent bias using excursion set formalism (Adshead, Baxter, Dodelson, Lidz, 20120)
  - Standard approach doesn't work because of coupling between different scale modes ➔ used the Maggiore and Riotto (2010)
  - Showed that the $k^{-2}$ dependence is very general
  - Showed how different collapse models and different forms of NG ➔ different coefficient of scale-dependent bias

- Understanding variations in predictions for scale-dependent bias important
  - To place robust constraints on NG we need to understand how predictions change with different collapse models (i.e. messy astrophysics)
  - Important for large scale structure surveys like BOSS

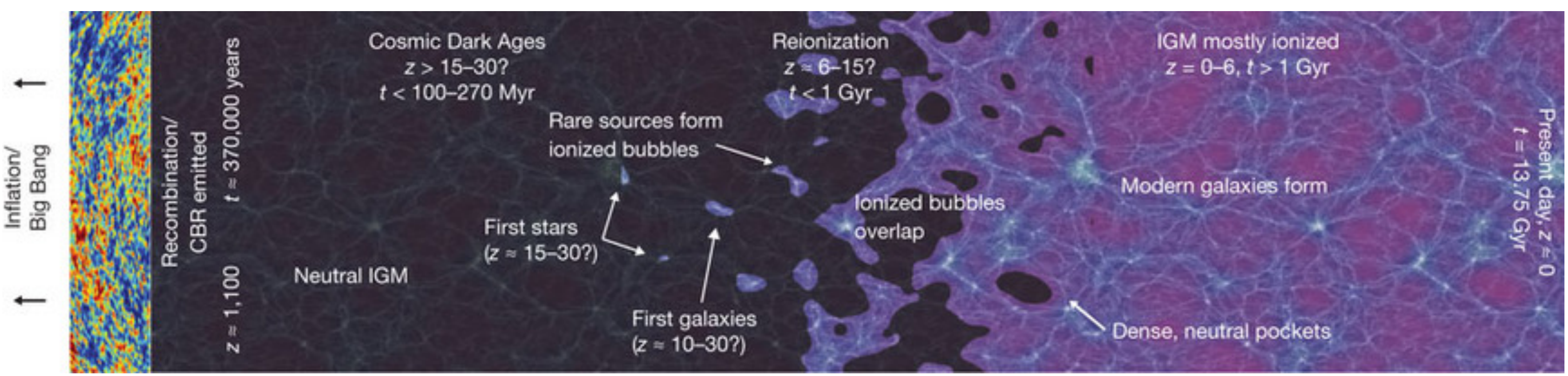
- Will allow us to understand effects of NG on reionization



# Non-Gaussianity and Reionization

- Universe experiences phase transition at z≈6-15
  - Goes from being neutral ➔ ionized
  - Expect ionizing sources to form in regions of high density
    - Ionization field should roughly trace matter overdensities

    ➔Maybe non-Gaussianity has some effect on ionization field



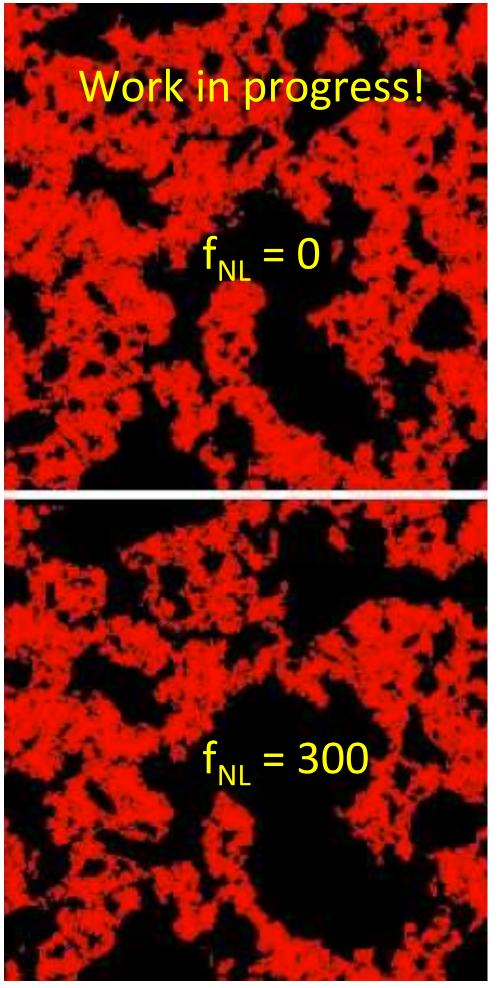

Ionized Neutral Reionization Ionized

# Effects of NG on Reionization

- Can model reionization using excursion sets (Furlanetto et al. 2004)

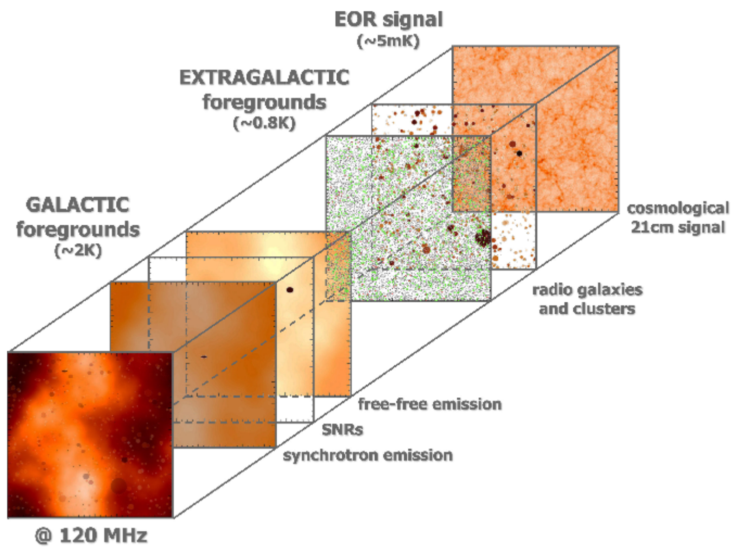
- Can solve excursion set problem in different ways:
  - Analytically using machinery of Maggiore and Riotto
  - Semi-analytically with Monte Carlo realizations of ionization field

- Results:
  - Positive $f_{NL}$ speeds reionization
  - Changes bubble size distribution
  - **Scale-dependent bias**
    - NG ➔ scale dependent bias of ionization field with same $1/k^2$ dependence



# Redshifted 21 cm Observations

- Redshifted 21 cm line can be used to measure ionization field during reionization
  - Spin-flip line of neutral hydrogen
  - Redshifted to roughly 100-250 Mhz




- Large astrophysical foregrounds
  - Extragalactic point sources, galactic synchrotron, galactic free-free
  - Expected to be roughly 4 orders of magnitude larger than cosmological signal

# Constraining non-Gaussianity with Redshifted 21 cm Measurements

- How well can we constrain non-Gaussianity with a redshifted 21 cm experiment?

- Foreground removal
  - Possible to remove them as they are smooth in frequency space (along line of sight)
  - However, foreground subtraction ➔ loss of large scale modes
  - Large scale modes contain most info about NG

# 21 cm Non-Gaussianity Fisher Projections

- Generate projections for constraint on $f_{NL}$ using Fisher matrix
- Survey assumptions
  - 10 degrees x 10 degrees
  - 100-200 Mhz ($z \approx 6$-13)
  - Divided into 13x13x13 pixels
- Calculate pixel-pixel covariance matrix
  - ➔ Calculate Fisher matrix
  - ➔ Invert to get parameter covariance matrix
- Foreground subtraction
  - Assume foregrounds captured by cubic polynomial with free coefficients

$$b_{\mathrm{total}}(k) = b_G + \frac{A f_{\mathrm{NL}}}{k^2}$$

# Summary: NG + Reionization

- Scale-dependent bias is a powerful probe of non-Gaussianity
  - Galaxy surveys
  - 21 cm experiments

- Important to understand dependence of scale-dependent bias on details of structure formation (both halos and bubbles)
  - Necessary for placing robust constraints on NG
  - This understanding can be obtained with excursion set formalism

- 21 cm experiments can place interesting constraints on non-Gaussianity in spite of foregrounds

# Summary

- Two exciting places to look for signals of physics beyond the standard model:
  - Gamma-rays from dark matter annihilation in galactic subhalos
  - Effects of non-Gaussianity on ionization field during reionization
- Astrophysical foregrounds/backgrounds are large, but manageable