# The physics of the early universe from CMB and large scale structure


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# Road map of my talk

- Alternatives to inflation: what sources primordial perturbations?

  G.Geshnizjani, W.Kinney, A.M, Phys.Rev. D82 (2010) 083506
  G.Geshnizjani, W.Kinney, A.M, JCAP 1202 (2012) 015
  G.Geshnizjani, W.Kinney, A.M, JCAP 1111 (2011) 049

- Constraining cosmology from CMB
  - Constraints on mixed inflaton/curvaton perturbations

    W. Kinney, A.M., B. Powell, A. Riotto, Phys.Rev. D86 (2012) 023527

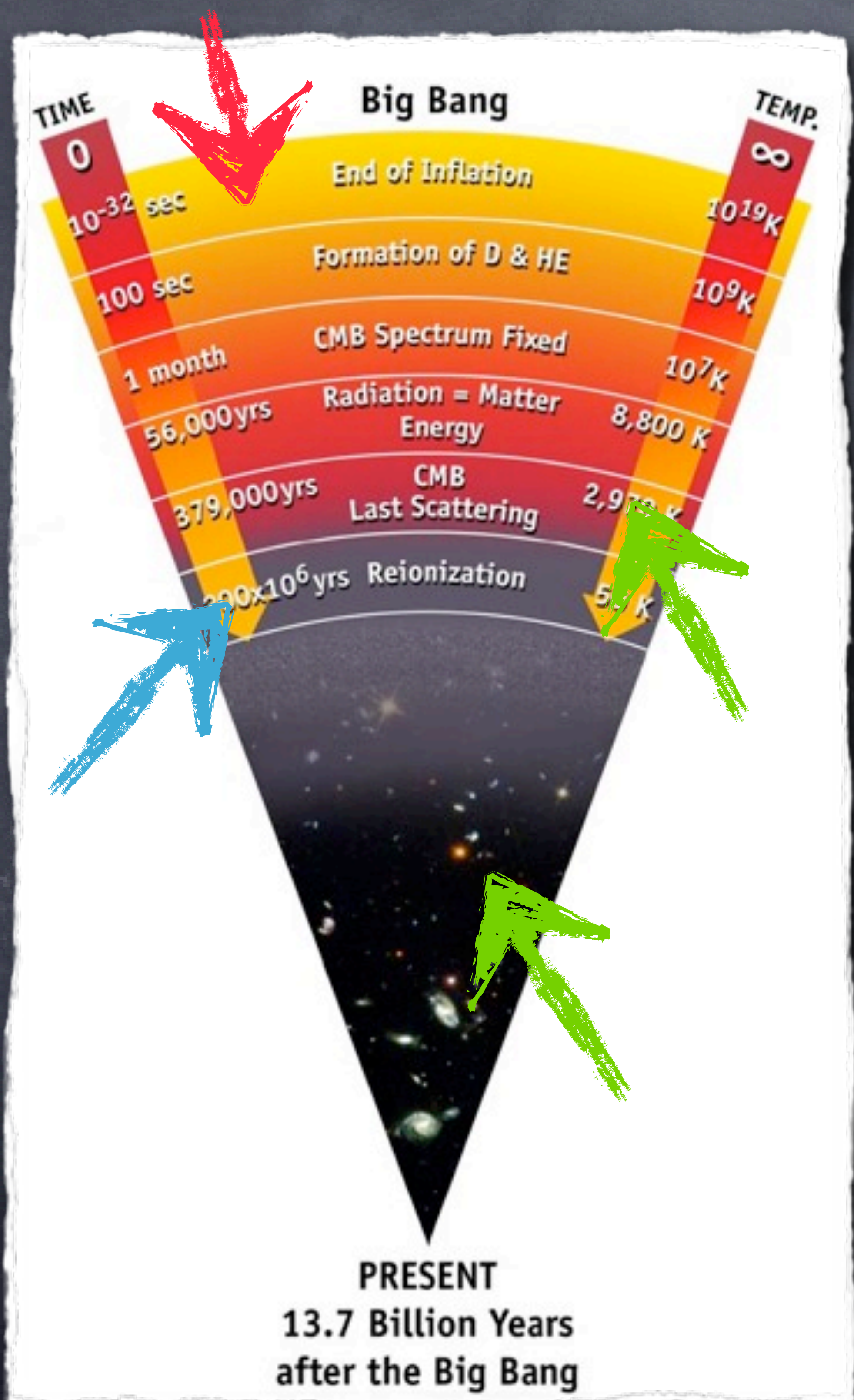
  - Impact of reionization history on CMB parameter estimation

    with Nick Gnedin & William Kinney, arXive: 1210.?

- Probing primordial NG with DM halo profile

  with Scott Dodelson & Antonio Riotto, arXive: 1210.?

# Timeline of the universe



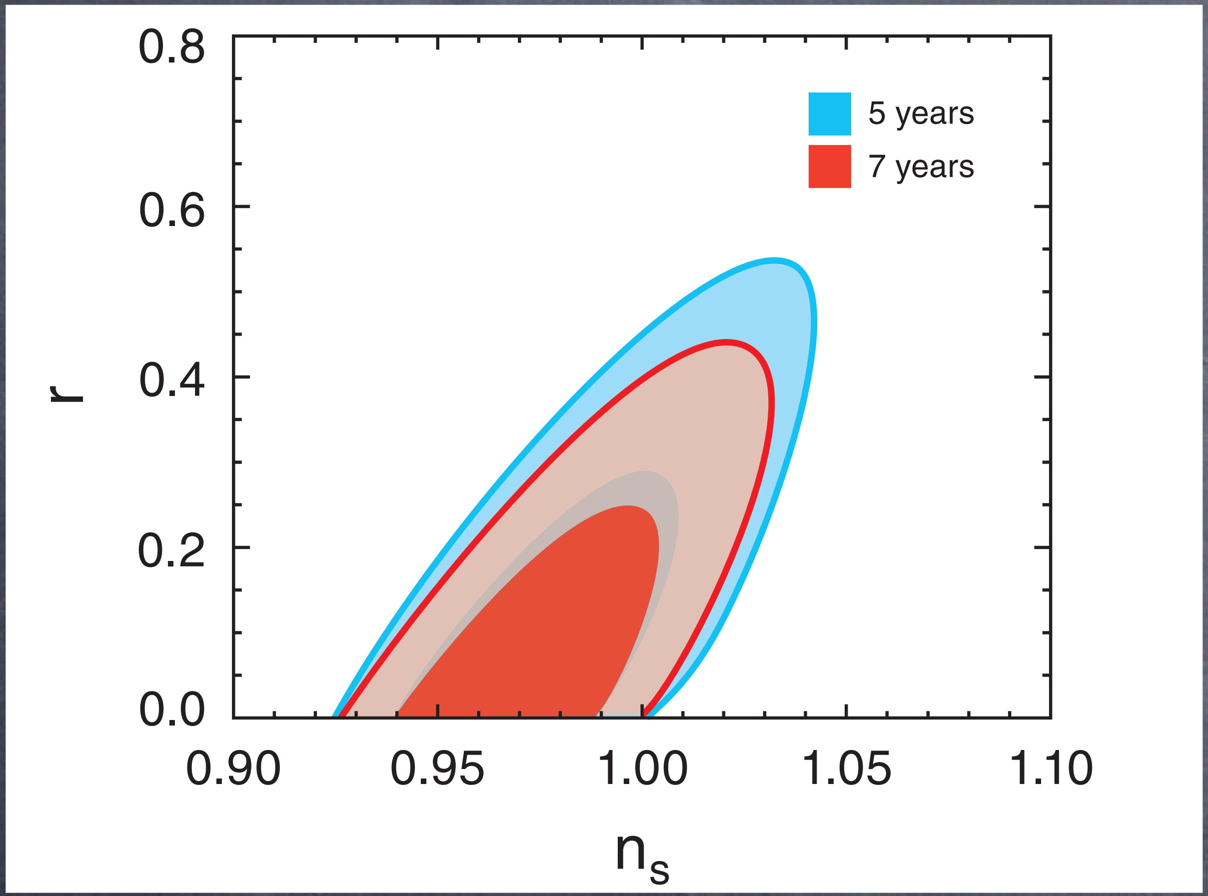

- Inflation
- Matter-radiation equality: DM inhomogenities start to collapse
- Recombination ( $z \simeq 1100$ ):
  $p^+ + e^- \to H$
  Universe becomes transparent to CMB photons (free streaming)
- Reionization ( $z \simeq 10$ ) : radiation from the first stars and quasars reionize the universe and of the photons re-scatter $\simeq 10\%$
- Structure continues to grow

# Scale-invariant perturbations: Is inflation the only way?

# What do we observe in CMB

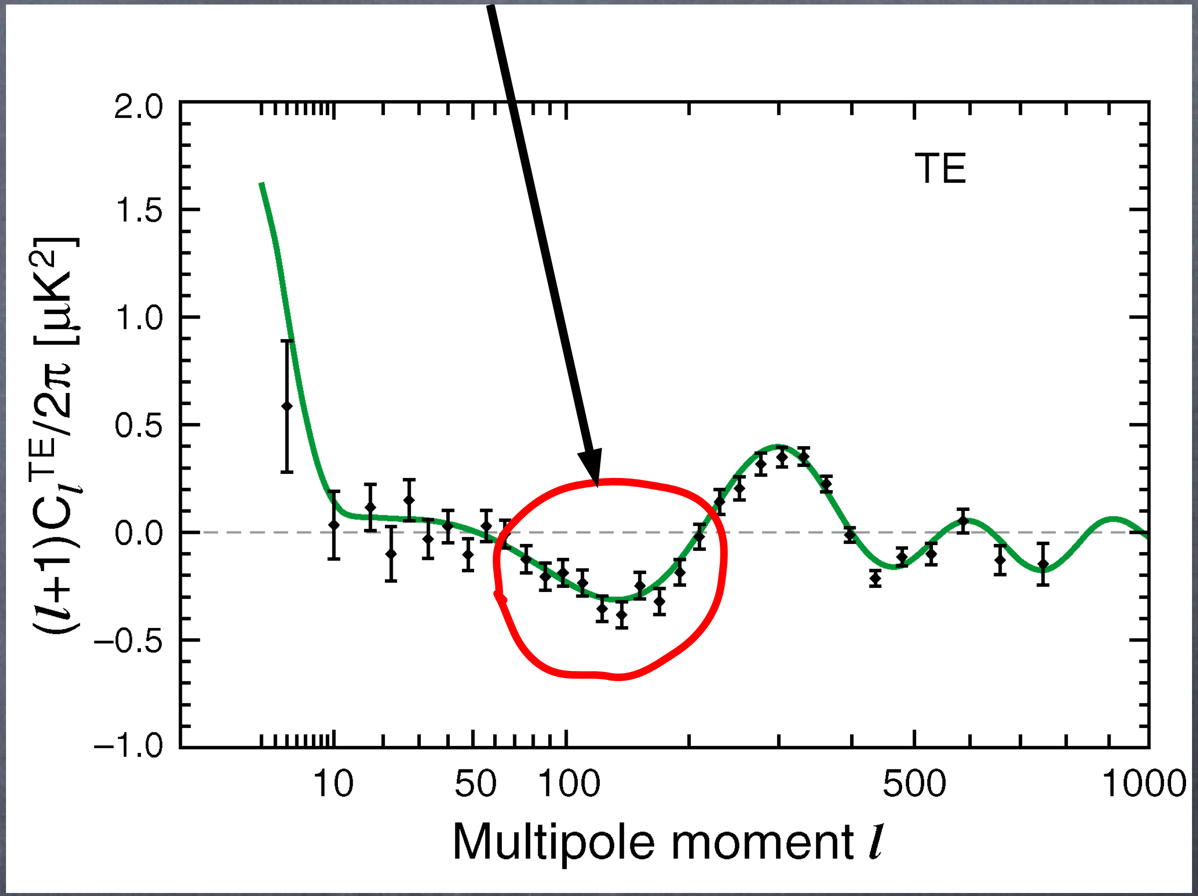
Scale-invariant perturbations

$$n_s = 0.963 \pm 0.014$$




Larson et.al., 2011, ApJS, **192**, 16

Super-Hubble correlated fluctuations at recombination




What general conclusions can be made about the physics of early universe?

# Result in short

- In an expanding universe, to obtain perturbations consistent with observation at least one of these three conditions must be satisfied:

  - Accelerated expansion, i.e. inflation ✓
  - Super-luminal speed of sound ?!
  - Super-Planckian energy density ✗

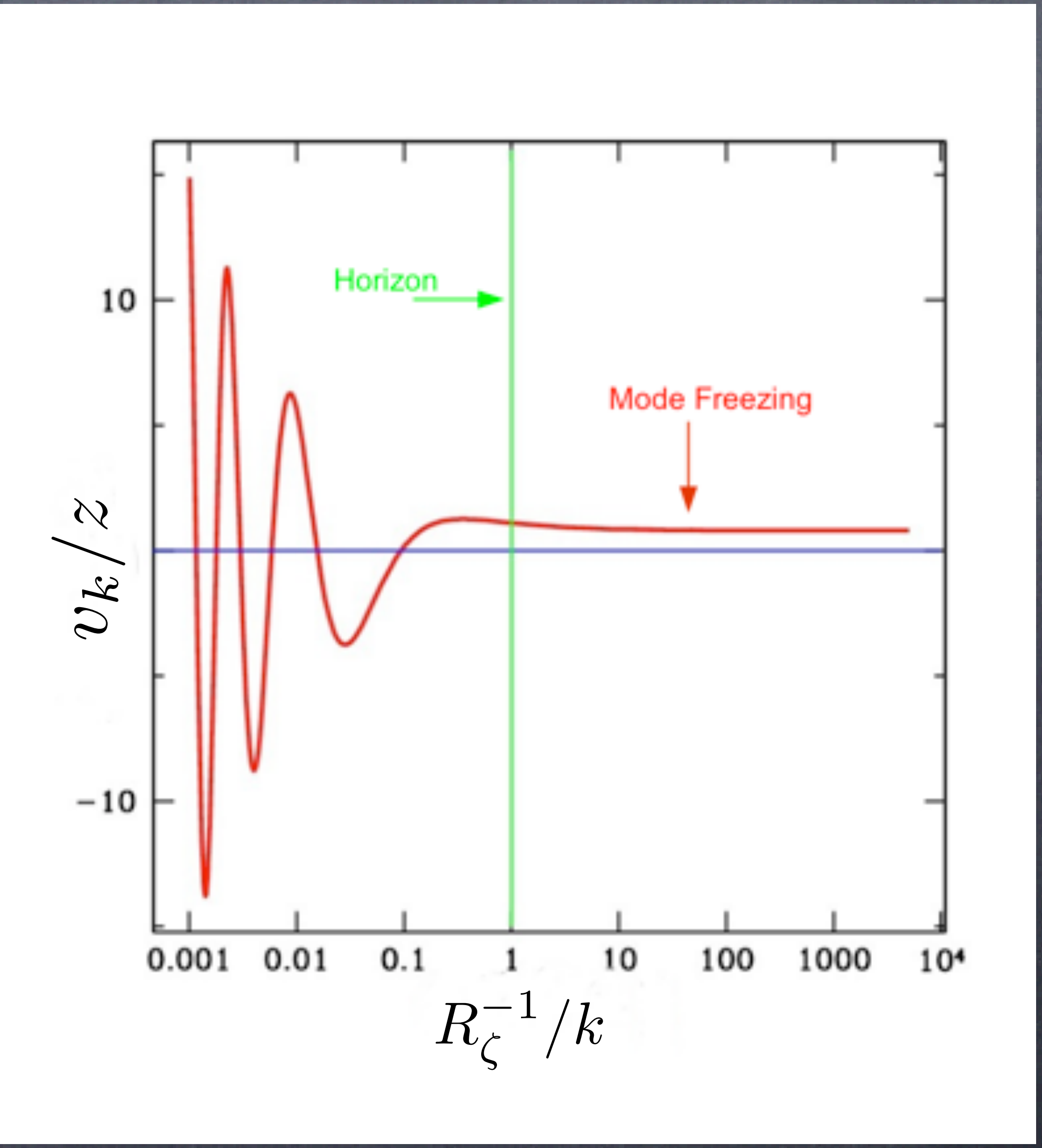
# Canonical Case:

- In terms of Mukhanov-Sasaki variables:

$$v \equiv z\zeta, \qquad z = a\sqrt{2\epsilon}$$

The mode equation in Fourier space given by:

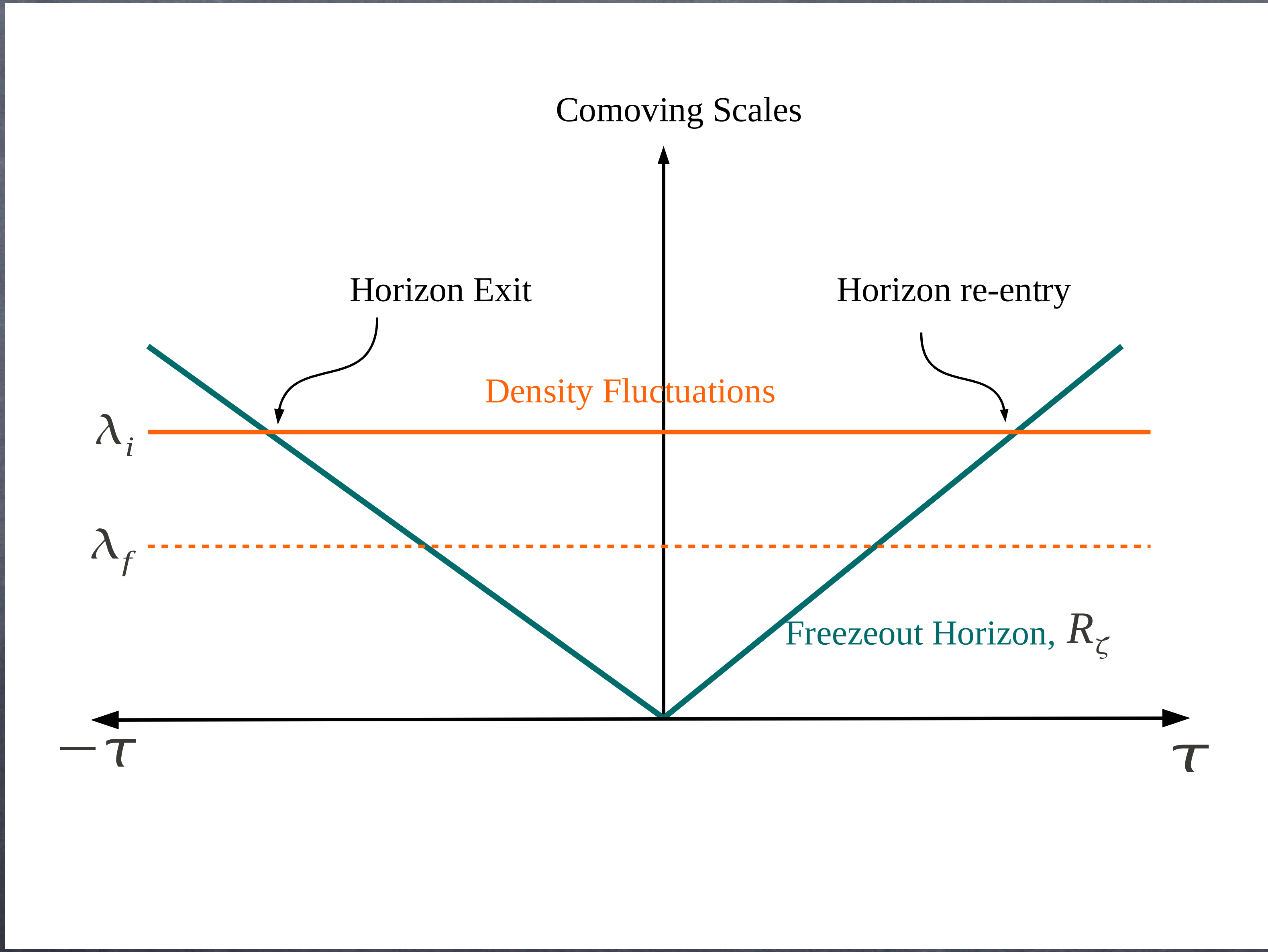
$$v_k'' + (k^2 - \frac{z''}{z})v_k = 0$$




- Scale-Invariance:

$$\frac{z''}{z} = \frac{2}{\tau^2} \equiv R_\zeta^{-2}$$

# Generation of perturbations



# Horizon Crossing and scales

- Assume decelerated expansion:

$$\epsilon > 1 \to \dot{R}_H > 0$$

- Horizon crossing :

$$\lambda_i(\tau_i) = R_\zeta(\tau_i) = |\tau_i|$$
$$\lambda_f = R_\zeta(\tau_f) = |\tau_f| > R_H(\tau_f)$$

- CMB + LSS: $\lambda_i > 1000\lambda_f$

$$\frac{\tau_f - \tau_i}{R_H(\tau_f)} > 1000$$

# Energy Density

- Continuity equation: $$\frac{\dot{\rho}}{\rho} = -2\epsilon H$$

$$ln\frac{\rho_i}{\rho_f} = 2\int_{t_i}^{t_f} \epsilon H dt = 2\int_{\tau_i}^{\tau_f} \epsilon R_H^{-1} d\tau$$

$$> 2R_H^{-1}(\tau_f)\int_{\tau_i}^{\tau_f} \epsilon d\tau \qquad (\dot{R}_H > 0)$$

$$> 2R_H^{-1}(\tau_f)(\tau_f - \tau_i) \qquad (\epsilon > 1)$$

# Super-Planckian energy density

- CMB + LSS $\quad \frac{\tau_f - \tau_i}{R_H(\tau_f)} > 1000$

- Continuity: $\quad ln\frac{\rho_i}{\rho_f} > 2\frac{\tau_f - \tau_i}{R_H(\tau_f)} > 2000$

$$\rho_i > 10^{868}\rho_f!$$

$$\rho_f \geq (100\ Mev)^4 \rightarrow \rho_i \gg M_p^4$$

# Non-Canonical Case

Quadratic action for curvature perturbations:

$$S_2 = \frac{M_{pl}^2}{2} \int dx^3 d\tau z^2 \left[ \left( \frac{d\zeta}{d\tau} \right) - c_s(\tau)^2 (\nabla\zeta)^2 \right]$$

Through a time transformation: $dy = c_s d\tau$

$$S_2 = \frac{M_{pl}^2}{2} \int dx^3 dy q^2 \left[ \left( \frac{d\zeta}{dy} \right) - (\nabla\zeta)^2 \right]$$

where:

$$z \equiv \frac{a\sqrt{2\epsilon}}{c_s} \qquad q \equiv \frac{a\sqrt{2\epsilon}}{\sqrt{c_s}}$$

Khoury and Piazza, JCAP 0907:026,2009

# Non-Canonical Case, contd.

- In terms of Mukhanov-Sasaki variables:

$$v \equiv q\zeta \qquad q = \frac{a\sqrt{2\epsilon}}{\sqrt{c_s}}$$

- The mode equation in Fourier space is given by:

$$v_k'' + (k^2 - \frac{q''}{q})v_k = 0$$

- Scale-invariance condition: $\frac{q''}{q} \propto \frac{2}{y^2}$

# Horizon Crossing and scales

- Assume decelerated expansion: $\epsilon > 1 \to \dot{R}_H > 0$
- Horizon crossing : $\lambda_i(\tau_i) = R_\zeta(\tau_i) = |\tau_i|$

$$\lambda_f = R_\zeta(\tau_f) = |\tau_f| > R_H(\tau_f)$$

$$y_f - y_i = \int_{\tau_i}^{\tau_f} c_s d\tau = \bar{c}_s(\tau_f - \tau_i)$$

- CMB + LSS: $\lambda_t > 1000\lambda_f$

$$\frac{\bar{c}_s(\tau_f - \tau_i)}{R_H(\tau_f)} > 1000$$

# Super-luminal speed of sound

- CMB + LSS $$\frac{\bar{c}_s(\tau_f - \tau_i)}{R_H(\tau_f)} > 1000$$

- Continuity: $$ln\frac{\rho_i}{\rho_f} > 2\frac{(\tau_f - \tau_i)}{R_H(\tau_f)} > \frac{2000}{\bar{c}_s}$$

For: $$\rho_i \leq M_{pl}^4$$
$$\rho_f \leq (100 Mev)^4$$

$$\bar{c}_s > 10$$

# Result in short

- In an expanding universe, to obtain perturbations consistent with observation at least one of these three conditions must be satisfied:

  - Accelerated expansion, i.e. inflation
  - Super-luminal speed of sound
  - Super-Planckian energy density

# Impact of primordial non-Gaussianity on Dark Matter halo profile

# Outline II:

- Motivation
- Semi-analytical model
- Excursion set approach
    - Excursion set theory
    - Path-integral formulation
- Results

# Motivation:

- CMB: perturbations small and still unprocessed
- LSS: highly evolved perturbations, Fourier modes are coupled and interact
- Successful use of LSS for probing primordial NG: identify a feature that can be caused by primordial NG and not standard gravitational instability,

**Imprints on DM Halo Profile ?!**

# Ingredients:

- Semi-analytical model for halo profile
  Dalal et al. arXiv: 1010.2539

- NG correction to linear density field: path-integral formulation of excursion set theory
  Maggiore & Riotto ApJ 711, 907 ( 2010)
  Maggiore & Riotto ApJ 717, 515 (2010)
  Maggiore & Riotto ApJ 717, 526 (2010)

# Formation of DM halos

- Initial conditions are laid down by inflation
- Growth of perturbations under gravitational-instability
  - Linear growth: modes evolve independently

    $\delta_k \propto D(t)$ → cosmology dependent

  - Non-linear growth: modes couple
    - Turn around $\delta \sim 1$
    - DM = collisionless → Shell crossing
- Merger and accretion events

- Structure formation is a messy process
- N-body simulations show regularity in properties of halos:
    - density profile, abundance, clustering
- Can we explain this universality ?
- Dalal et al. : crude semi-analytical model to explain the main physical effects in formation of halos

# PNG and DM halo profile ?!

Halos form from the peaks of smoothed initial (Gaussian random) density field

properties of initial density peaks → properties of halos

- Dalal et al. :
  - Properties of initial peaks ← PNG
  - mapping from peaks to halos (collapse model)

# Origin of NFW halo profile

- Adiabatic contraction:

adiabatic invariant: $J_r \equiv \oint v_r dr \propto [r \times M(r)]^{1/2}$

Given its value before the collapse (turn around), predict its value at later times

@ turn around: $M_L \times r_{ta} \propto M_L^{4/3} / \bar{\delta}_{\rm lin}$

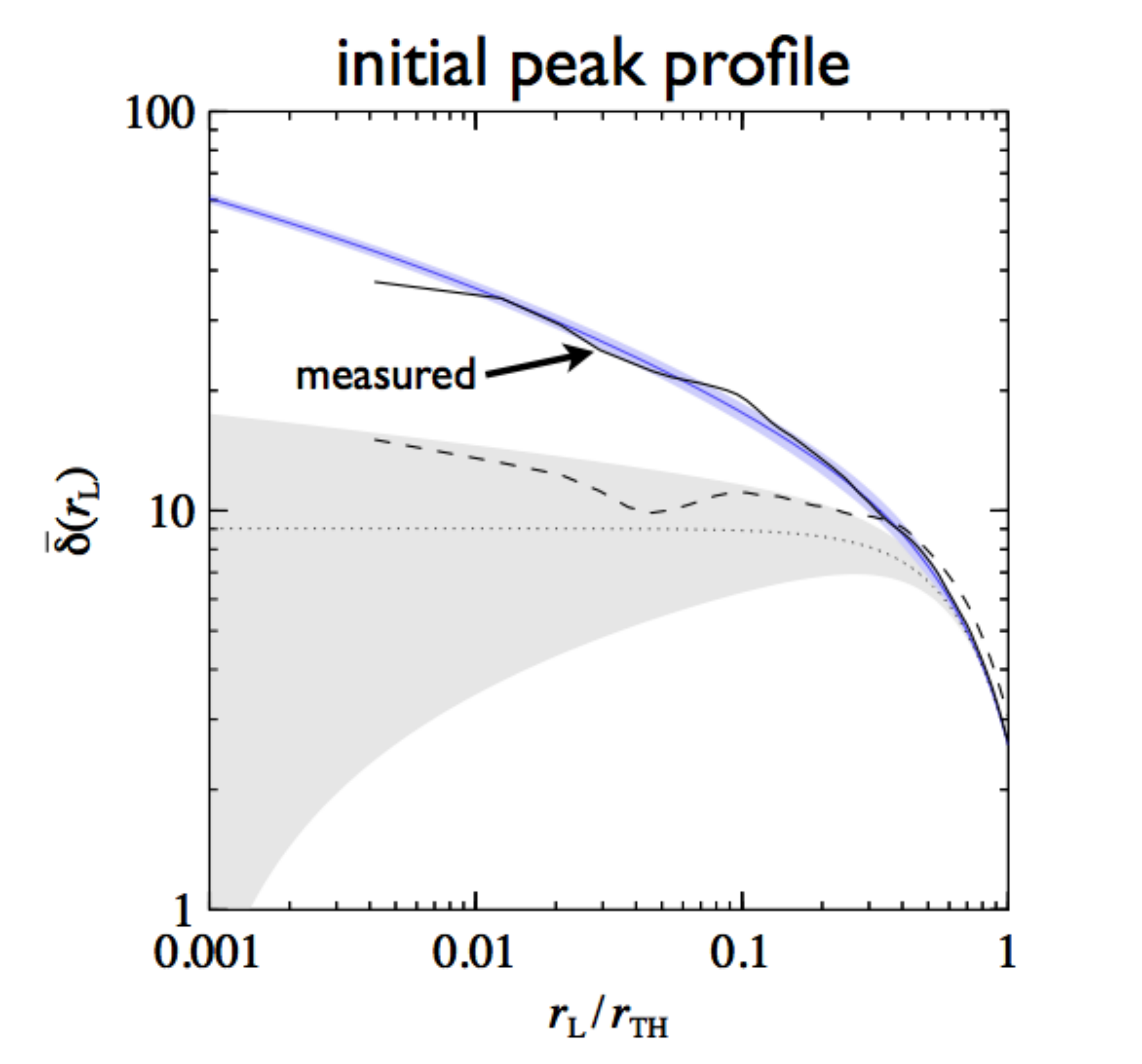
we can predict the halo profile given the initial peak profile

# Dynamical friction:

- Naive Gaussian statistics of the peaks (BBKS): $P(X|Y) = P(\bar{\delta}_{\rm lin}(r_L)|\delta_{\rm pk}, \delta'_{\rm pk})$
- The naive calculation ignores the **hierarchy of peaks within peaks** for CDM
- During the collapse, processes such as dynamical friction drag off-center sub-peaks to the center
- Simple model: densest material comes from the highest sub-peaks that collapse first → statistics of highest sub-peaks

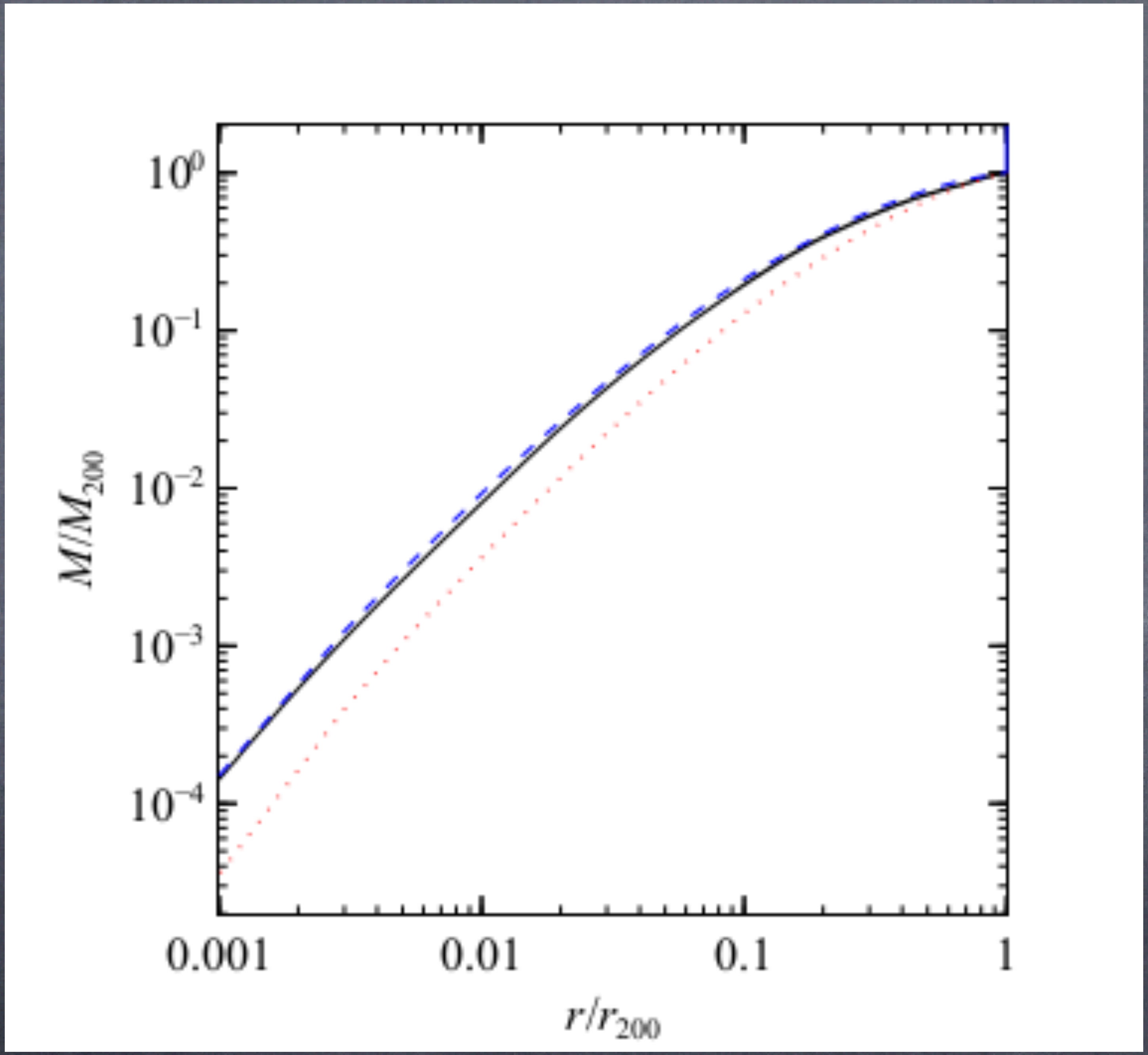
$$P_1(y) = \int_{-\infty}^{y} \frac{dP}{dx} \longrightarrow P_N(y) = P_1(y)^N$$

# Linear Density Field




Dalal et al. arXiv:1010.2539

# Mass Profile




Dalal et al. arXiv:1010.2539

# Origin of NFW halo profile

- Adiabatic contraction:

  adiabatic invariant: $J_r \equiv \oint v_r dr \propto [r \times M(r)]^{1/2}$

  Given its value before the collapse (turn around), predict its value at later times

  @ turn around: $M_L \times r_{ta} \propto M_L^{4/3} / \bar{\delta}_{\rm lin}$ → PNG

we can predict the halo profile given the initial peak profile

# Excursion set theory

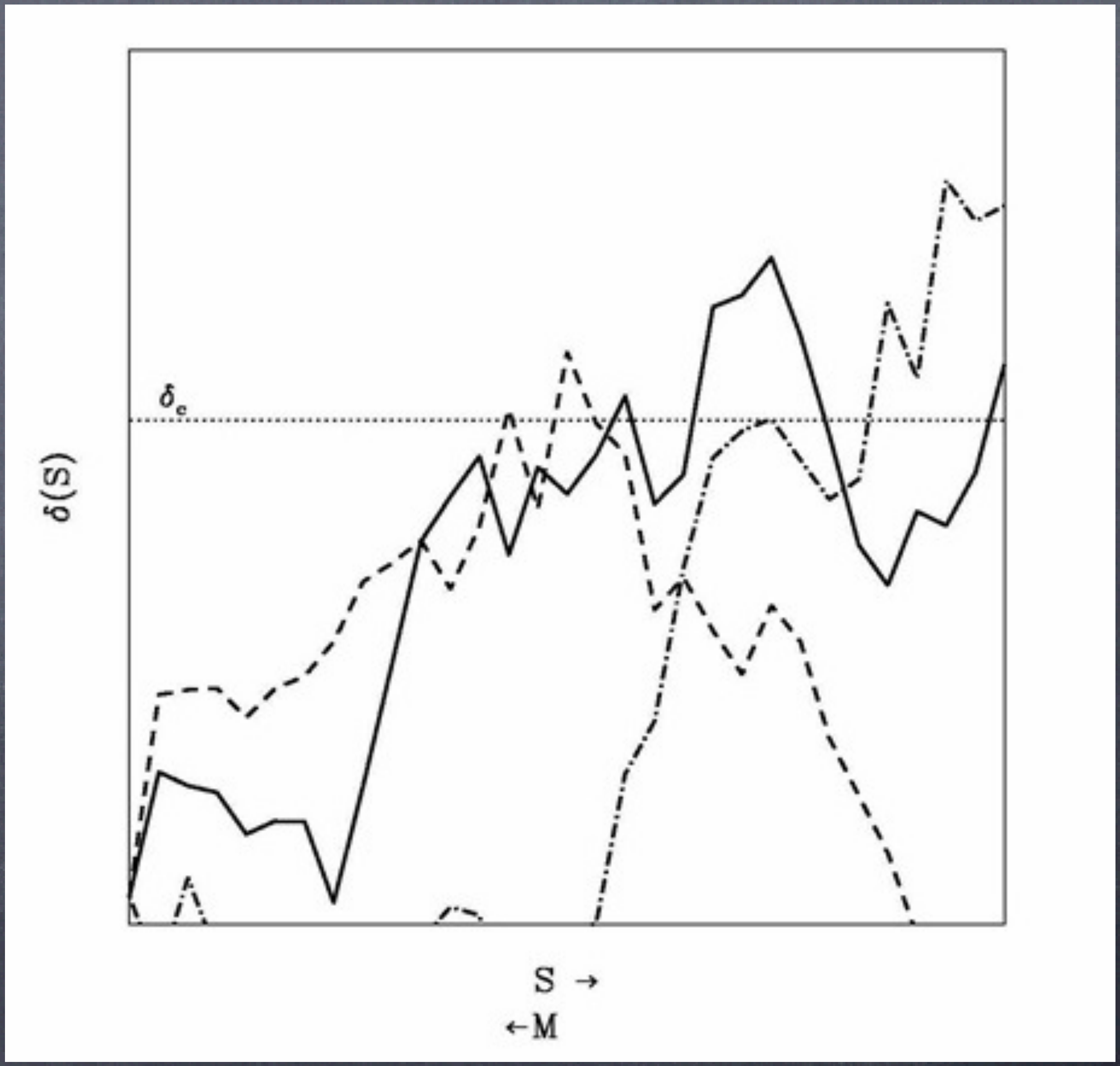
- Study the evolution of $\delta(R)$ as a function of $R$

Bond, Cole, Efstathiou and Kaiser (1991)
Peacock and Heavens (1990)

$At\ R = \infty, \delta(R) = 0$
Lowering $R, \delta(R)$ evolves stochastically

- Time: $S = \sigma^2(R)$
  At $R = \infty, S = 0$
  $R$ decreases, $S$ increases

- Probability of forming a halo mapped to first passage time problem



- Evolution of $\delta(S)$ is a stochastic process.
- For Gaussian density field smoothed with sharp k-space filter, $\delta(S)$ obeys Langevin equation with Dirac delta noise
- The corresponding distribution function, $\pi(\delta, S)$ is a solution to Folker-Planck equation:

$$\frac{\partial \pi}{\partial S} = \frac{1}{2}\frac{\partial^2 \pi}{\partial \delta^2} \xrightarrow{\text{BCs}} \begin{cases} \Pi(\delta, S)|_{\delta=\delta_c} = 0 \\ \Pi(\delta, S)|_{\delta\to\pm\infty} = 0 \end{cases}$$

- Probability of first crossing:

$$\mathcal{F} = -\frac{1}{2}\frac{\partial \Pi}{\partial \delta}\bigg|_{\delta=\delta_c}$$

# Path-integral formulation

- Compute the probability distribution of $\delta(S)$ in terms of its correlators $< \delta(S_1)\ \delta(S_2) >_c,\ < \delta(S_1)\ \delta(S_2)\ \delta(S_3) >_c,\ ...$

- Not solve PDE for $\pi(\delta, S)$

- Constructs it by summing over all trajectories that never exceeded the threshold, i.e path integral.

- Consider ensemble of trajectories all starting from $\delta(S_0 = 0) = 0$ and follow them for time S
- Discretize time interval $[0, S]$ into steps, $\Delta S = \epsilon$ so that $S_k = k\epsilon$
- A discretized trajectory is a set of values $\{\delta_1, \delta_2, ..., \delta_n\}$ where $\delta(S_i) = \delta_i$
- Find the probability of arriving at point $\delta_n$ at time $S_n$ through trajectories that have never exceeded some threshold,

$$\Pi_\epsilon(\delta_0;\delta_n;S_n) \equiv \int_{-\infty}^{\delta_c} \mathrm{d}\delta_1 ... \int_{-\infty}^{\delta_c} \mathrm{d}\delta_{n-1}$$

$$\times W(\delta_0;\delta_1;...\delta_{n-1};\delta_n;S_n)$$

where:

$$W \equiv < \delta_D(\delta(S_1)-\delta_1)...\delta_D(\delta(S_n)-\delta_n) >$$

Using integral representation of Dirac delta:

$$\delta_D(x) = \int_{-\infty}^{\infty} \frac{\mathrm{d}\lambda}{2\pi} e^{-i\lambda x}$$

We have:

$$W(\delta_0;\delta_1;...;\delta_n;S_n) = \int_{-\infty}^{\infty} \frac{\mathrm{d}\lambda_1}{2\pi} ... \frac{\mathrm{d}\lambda_n}{2\pi} e^{i\sum_{i=1}^{n}\lambda_i\delta_i}$$

$$\times < e^{-i\sum_{i=1}^{n}\lambda_i\delta(S_i)} >$$

- The expectation value $< e^{-i \sum_{i=1}^{n} \lambda_i \delta(S_i)} >$ can be written as:

$$= \exp \left[ \sum_{p=2}^{\infty} \frac{(-i)^p}{p!} \sum_{j_1,\ldots,j_p=1}^{n} \lambda_{j_1} \ldots \lambda_{j_p} < \delta(S_{j_1}) \ldots \delta(S_{j_p}) >_c \right]$$

connected p-point function

- For Gaussian case only $< \delta(S_i)\delta(S_j) >_c$
- For NG case higher order correlators should be included

# What we need?

Conditional probability: $P(\delta_n|\delta_0,\delta_1)$

$$P(\delta_n|\delta_0,\delta_1) = \frac{\Pi_{NG}(\delta_0;\delta_1;\delta_n)}{\Pi_{NG}(\delta_0;\delta_1)}$$

$$\Pi_{NG}(\delta_0;\delta_1;\delta_n) = \Pi_G(\delta_0;\delta_1;\delta_n) + \Delta\Pi_{NG}(\delta_0;\delta_1;\delta_n)$$

$$\Delta\Pi_{NG}(\delta_0;\delta_1;\delta_n) = \frac{(-1)^3}{6} \sum_{i,j,k=0}^{1} < \delta_i\delta_j\delta_k > \partial_i\partial_j\partial_k W_G(\delta_0;\delta_1;...\delta_n)$$

$$P_{NG}(\delta_n|\delta_0,\delta_1) = P_G(\delta_n|\delta_0,\delta_1) + \Delta P_{NG}(\delta_n|\delta_0,\delta_1)$$

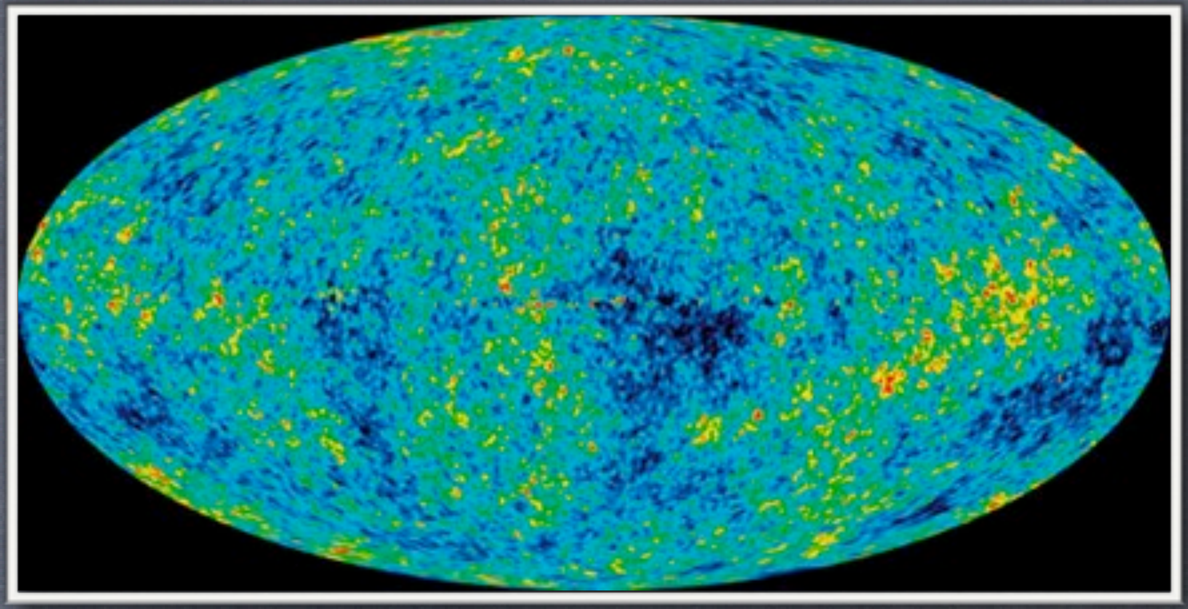
$$\Delta P_{NG}(\delta_n,\delta_0,\delta_1) = -\frac{1}{2}\sum_{i,j=0}^{1} < \delta_i\delta_j\delta_n > \partial_i\partial_j\partial_n P_G(\delta_n|\delta_0,\delta_1)$$
$$-\frac{1}{2}\sum_{i,j=0}^{1} < \delta_i\delta_n^2 > \partial_i\partial_n^2 P_G(\delta_n|\delta_0,\delta_1)$$
$$-\frac{1}{6}\sum_{i,j=0}^{1} < \delta_n^3 > \partial_n^3 P_G(\delta_n|\delta_0,\delta_1)$$

# Rionization history and CMB parameter estimation

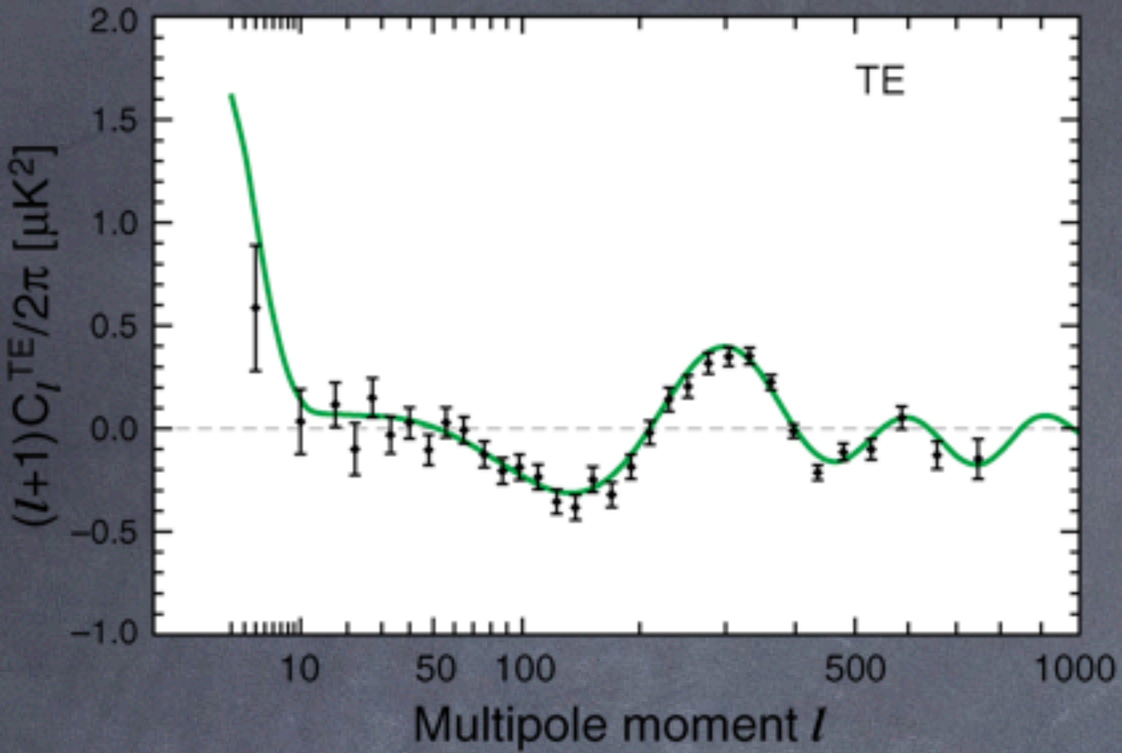
# Outline III:

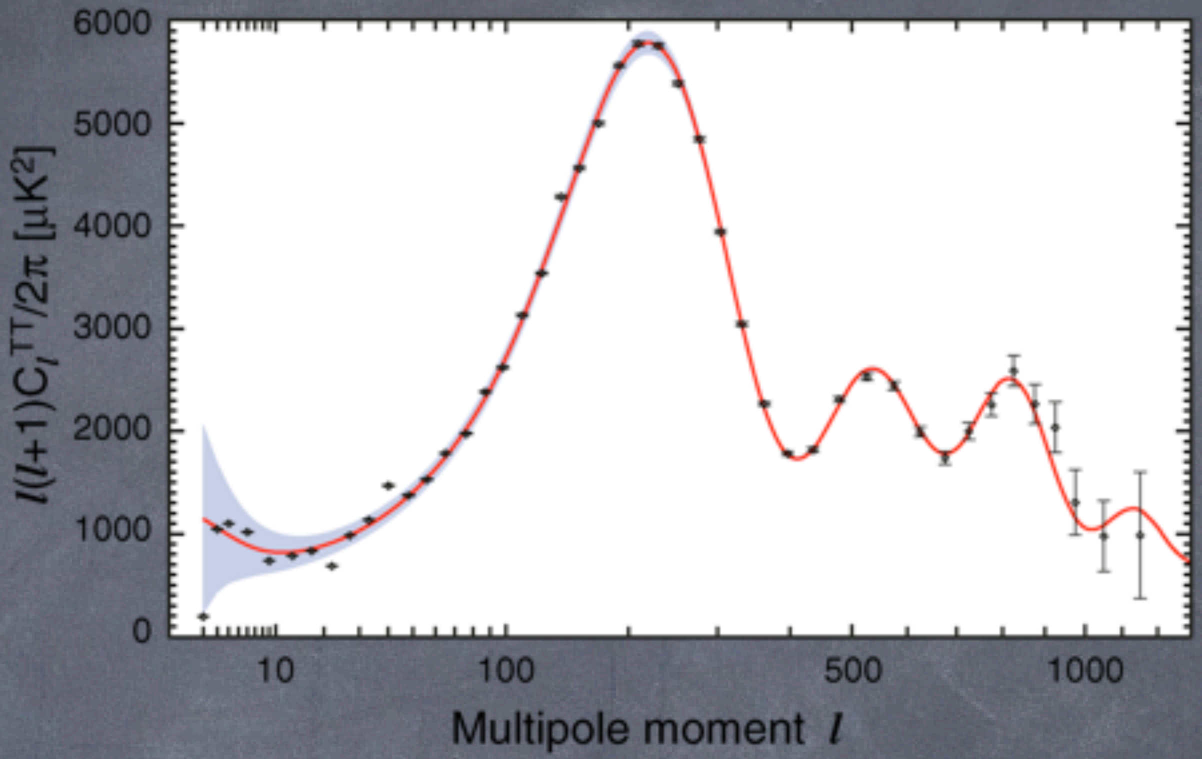
- Motivation: CMB and Reionization
- Basics of Reionization
- Constraints on reionization history from simulation
- MCMC Analysis
- Results

# Motivation



- CMB forms the foundation of precision cosmology
- CMB anisotropies are sourced by primordial perturbations produced by inflation
- Their growth is modified by the joint action of dark matter, baryonic matter and radiation

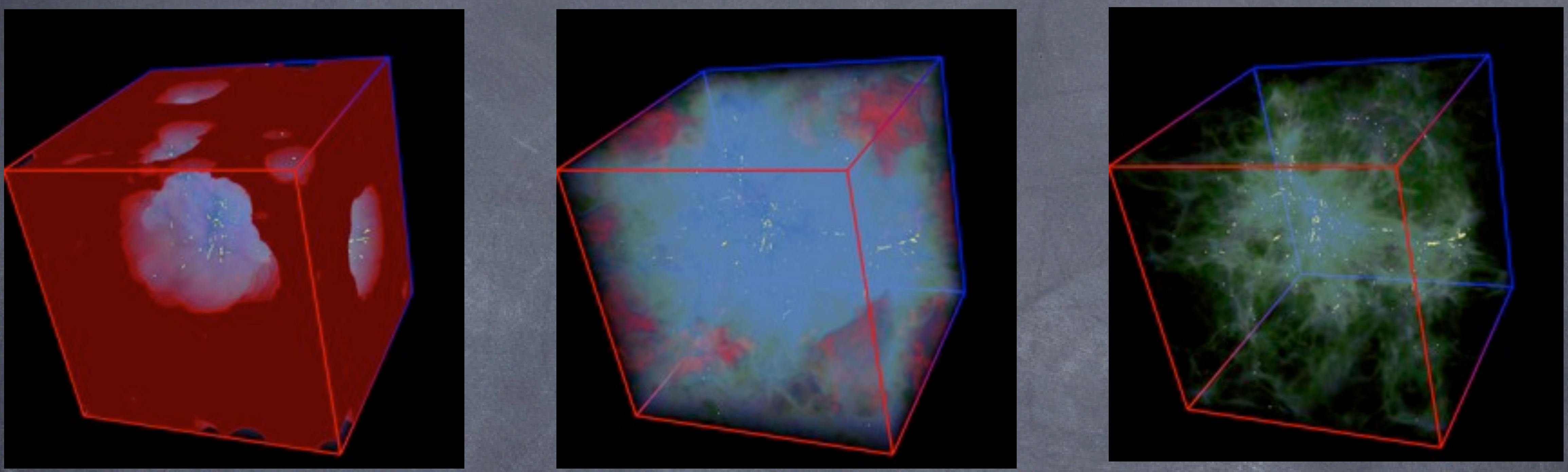



- Precise test of cosmological parameters
- Subject to cosmological foregrounds
- Ionization of intergalactic gas by UV and X-ray radiation (aka reionization) forms a screen in front of the CMB.
- Last major systematic effect.

# Reionization simulations

z = 8.1 z = 6.3 z = 5.5

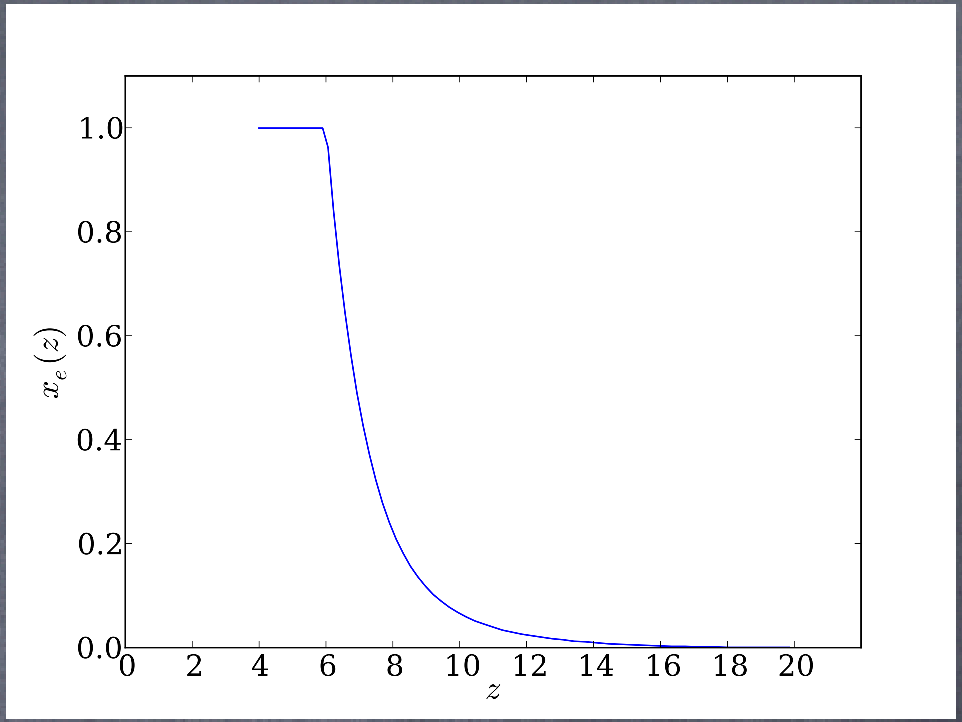


Gnedin et. al (2008)

- Formation of the first luminous objects
- Overlap of the ionized bubbles
- End of reionization

# Adapted reionization history

- Counting the number of ionizing photons per atom, $N_\gamma/a$
- Two sources:
  - Star forming galaxies
  - Quasars:




Volonteri & Gnedin
APJ. 703, 2113 (2009)

$$N_\gamma/a = N_{\gamma/a,*} + \frac{U_\gamma}{E_\gamma n_a} + f_{SI}(x)\,\frac{U_\gamma}{14.4\mathrm{eV}\, n_a}$$

quasars

Stellar population

Secondary ionization

# Two contributions:

- Contribution from quasars: estimated by studying the evolution of massive black holes within the quasar
- Contribution from galaxies: extrapolating the observed UV luminosity functions of high redshift galaxies (Bowens et al. 2007, 2008) + using an estimate of relative escape fraction of the ionizing radiation from Gnedin et al. (2007)

# MCMC Analysis:

- Dependance of estimated cosmological parameters on the assumed reionization history
  - Instantaneous reionization
  - Physically motivated reionization: VG
  - General reionization history parametrized in terms of principle components with respect to E-mode polarization

(Hu & Holder, Mortonson & Hu)

$$x_e(z) = x_e^{\rm fid} + \sum_i m_i S_i(z)$$

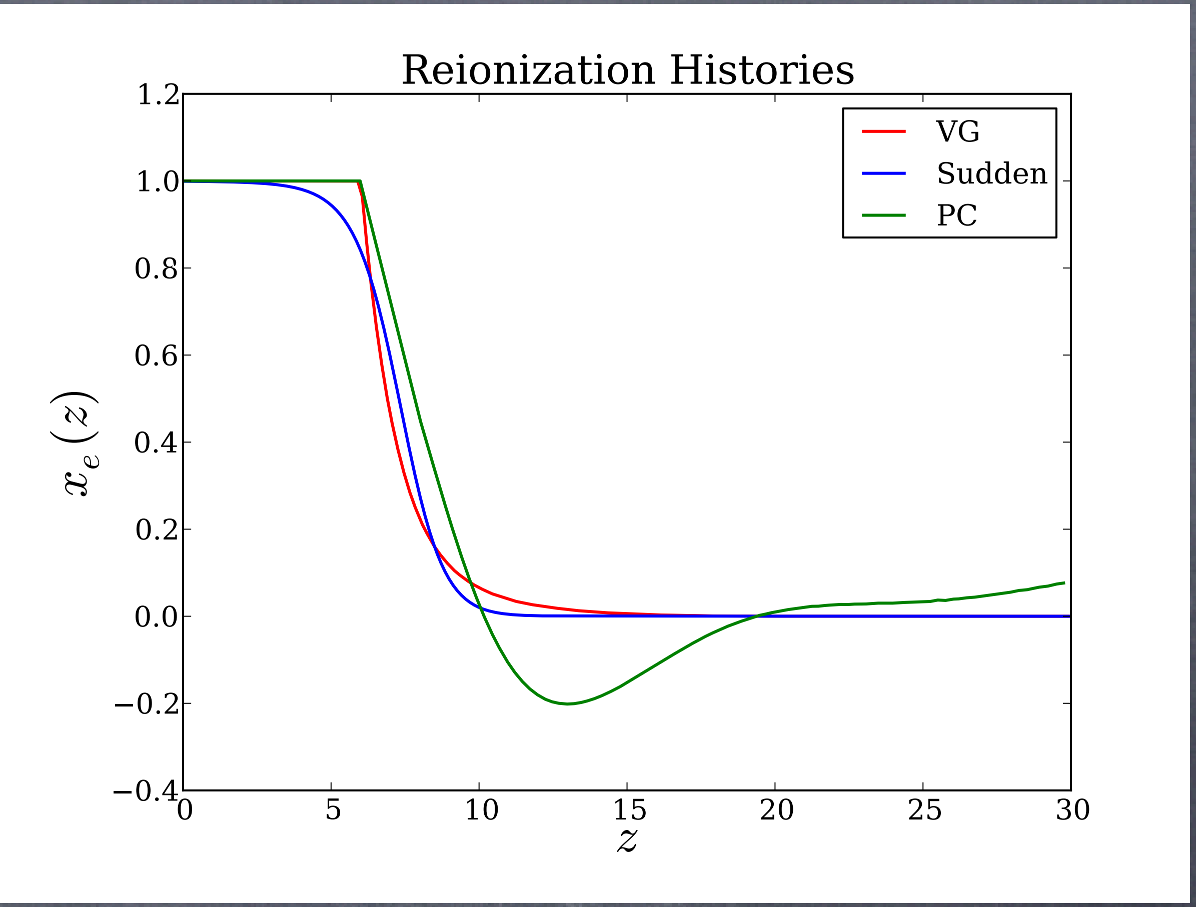
- Flat $\Lambda\mathrm{CDM}$
  - Base cosmological parameters
    $\Omega_b h^2, \Omega_c h^2, \theta_s, A_s, n_s$
  - Reionization :
    Sudden $\tau$
    VG: no free parameter
    PC parametrization $m_1, m_2, m_3, m_4, m_5$
- Data sets:
  - WMAP7 data set
  - Simulated Planck-precision data set

# Conclusions

- Cosmological parameters are mildly affected by the assumption of reionization

  WMAP: using PCs degrades the constraints on parameters.

  Planck: sudden reionization does as well as PC reionization.




- Using PCs does not offer an accurate reconstruction of ionization fraction.