Quasar scintillation as a probe of the ionized intergalactic medium

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Introduction

Example: optical scintillation through the atmosphere

Moon snapshots (framerate: $\sim 1\,\mathrm{s}^{-1}$)
Loiano (Bo) telescope (R. Poggiani courtesy)

Features

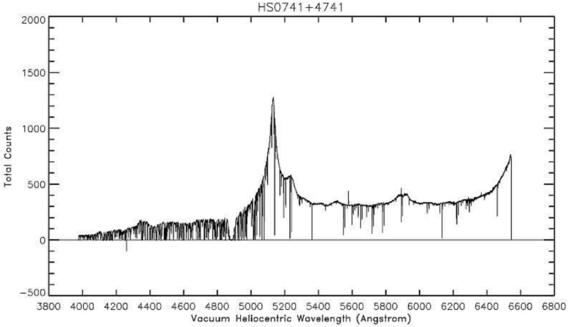
- Trace ionized turbulent gas
- Angular displacement (or deformation)
- Multiple images (extreme case)
- Modulation of intensity

Interstellar medium (ISM) scintillation

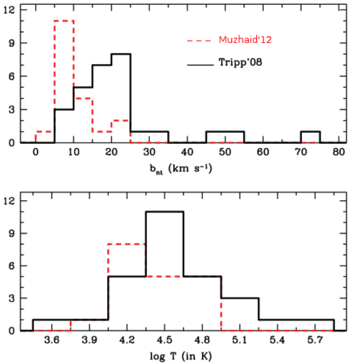
- pulsar through ISM e.g. Rickett (1981), Coles et. al (1987), Reynolds (1989)
- extragalactic sources through ISM e.g. Rickett et al. (2006) Macquart et al. (2007)
- extragalactic sources through extragalactic ISM e.g. Hall & Sciama (1979), Ferrara & Perna (2001)

Introduction

Intergalactic medium (IGM) signature in quasar spectra



e.g. Rauch (1998), Fan et al. (2006), Songaila (2006)



C IV and O VI observations

- Tripp et al. (2008)
  $z_{abs} \sim 0.5$
- Muzahid et al. (2012)
  $z_{abs} \sim 2$

Theoretical works
e.g. Evoli & Ferrara (2011), Iapichino (2013)

Intergalactic medium

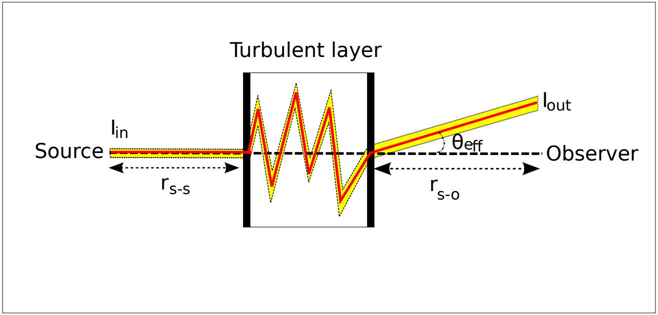
- ionized
- turbulent

Simulating intergalactic quasar scintillation Pallottini, Ferrara, Evoli (2013) (hereafter P13)

- Scintillation model
- IGM simulation
- Results

Scintillation model

Sketch of the Formalism 1/2



Optical equation

- $\left(\nabla^2 + \kappa^2\epsilon\right)\mathbf{E} = 0$
- where $\epsilon = \epsilon(\mathbf{x}, t)$

Ideal turbulent plasma

- $\epsilon = 1 - \left(\frac{\omega_p}{\omega}\right)^2$
- $\delta\epsilon = \delta n_e$

Scintillation model

Sketch of the formalism 2/2

Optical equation

- $\left(\nabla^2 + \kappa^2\epsilon\right)\mathbf{E} = 0$
- where $\epsilon = \epsilon(\mathbf{x}, t)$

Born/Rytov approximation

- $\mathbf{E} = \mathbf{A}\exp\left(i\kappa\Psi\right)$
- $\phi = \kappa\Psi = \kappa\int\sqrt{\epsilon}\,ds$

Ideal turbulent plasma

- $\epsilon = 1 - \left(\frac{\omega_p}{\omega}\right)^2$
- $\delta\epsilon = \delta n_e$

The phase structure function

- $D_\phi(\mathbf{r}_1 - \mathbf{r}_2) = \left\langle\left[\phi(\mathbf{r}_1) - \phi(\mathbf{r}_2)\right]^2\right\rangle$

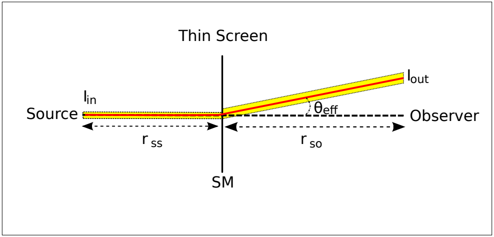
with isotropic turbulence $r = |\mathbf{r}_1 - \mathbf{r}_2|$

- $I(r) = \langle\mathbf{E}^*\mathbf{E}\rangle = E_0^2\exp\left(-\frac{D_\phi(r)}{2}\right)$
- $D_\phi(\theta_d\lambda) = 1$
- $m_r = \sqrt{\langle[I(r)^2 - \langle I(r)\rangle^2]/\langle I(r)\rangle^2\rangle}$

e.g. Wheelon (2001,2003)

Scintillation model

Thin screen model for interstellar scintillation



Turbulence assumption

- $\mathrm{SM} = \int n_e^2 \mathrm{d}s$
- $P(k) = k^{-11/3}$

Refractive Scintillation

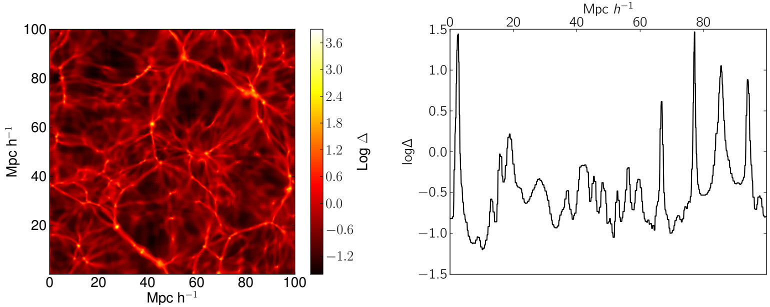
- Geometry: Fresnel angle θ_F
- Refraction condition $\theta_s < \theta_d$

$$\theta_{\mathrm{eff}} = \sqrt{\theta_s^2 + (0.71\,\theta_d)^2 + (0.85\,\theta_F)^2}$$

e.g. Lee (1977), Coles (1987), Rickett (1990), Goodman (1997), Ferrara & Perna (2001)

Scintillation model

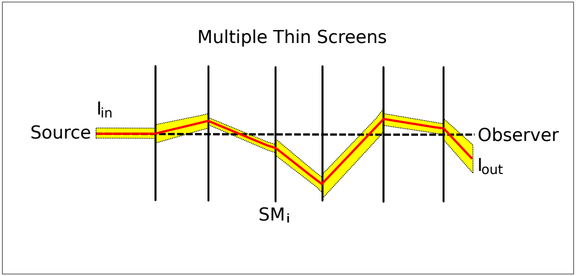
Taking a look at the intergalactic medium



- example of a wavepath through a $z = 0$ density map (P13)
- Thin screen model is not valid for the IGM!

Scintillation model

Multiple this screens model for intergalactic scintillation

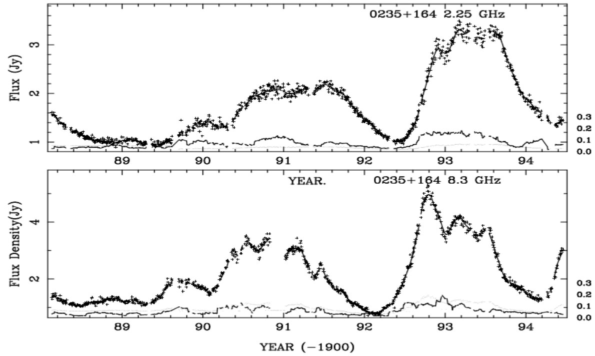


Model (P13):

- step 0: setting the screens (SM_i)
- step 1: calculate θ^i_{eff} and m^i_r for each screen
- step 2: calculate θ_{N} and m_N via effective interaction (MC)

Scintillation model

Validation: scintillation in the ISM using multiple thin screens 1/2

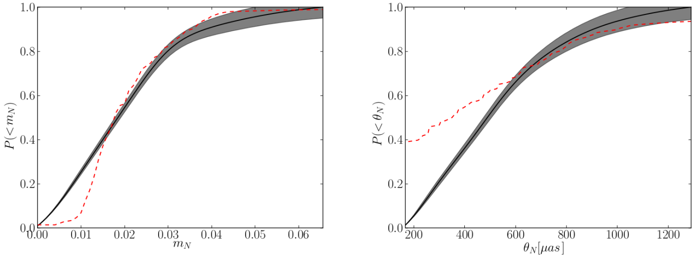


Rickett et al. (2006)

- 146 extra-galactic sources (Fiedler et al. 1987; Waltman et al. 1991; Lazio et al. 2001)
- $\nu_{obs} = 2\,,8$ Ghz

Scintillation model

Validation: scintillation in the ISM using multiple thin screens 2/2



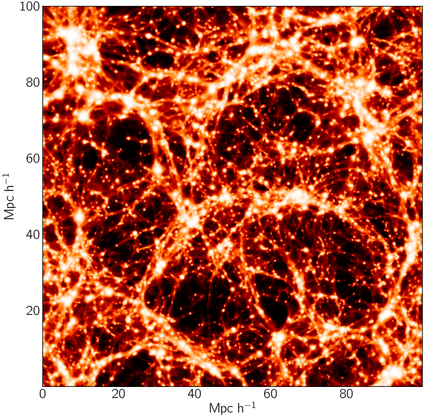
Comparison for $\nu_{obs} = 8$ Ghz (P13)

- analytical ISM model: Reynolds layer (e.g. Ferriere 2001)
- Rickett et al. (2006): $\delta m_N \sim 0.01$, $\delta\theta_N \sim 100\ \mu$as

Cosmological Simulation
Settings and overview

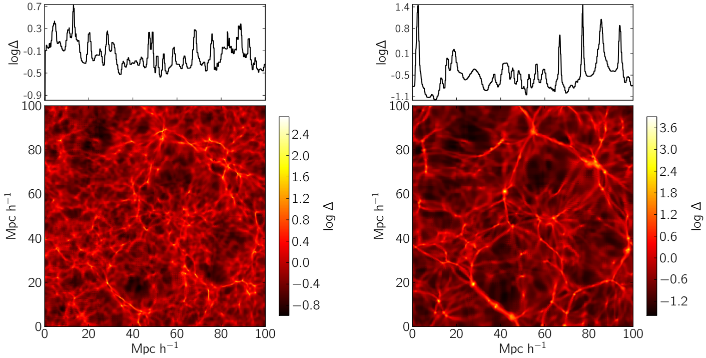
Setup

- WMAP7 cosmology (Larson et al. 2011)
- RAMSES AMR code (Teyssier 2002)
- UV ionizing background (Haardt & Madau 2012)
- 256^3 particle in 100 Mpc/h
- 6 refinement level: $0.36/h\,\mathrm{Mpc} - 6/h\,\mathrm{Kpc}$

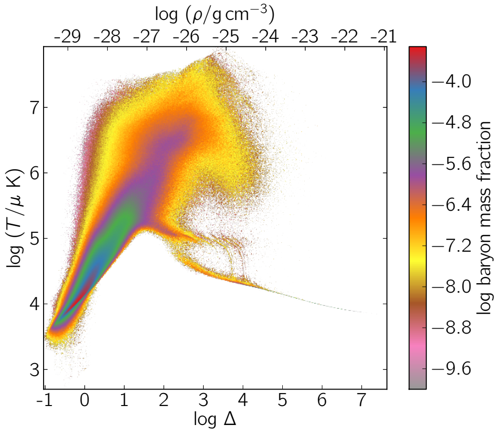


Cosmological Simulation

Simulating the IGM 1/3



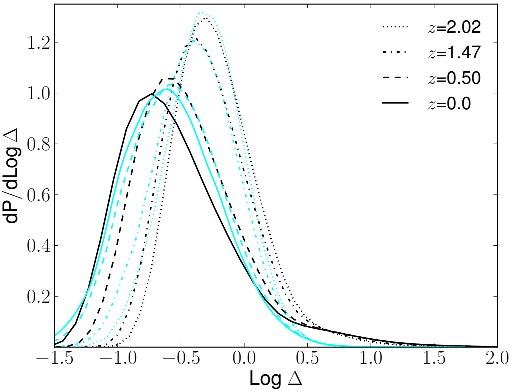
Spatial distribution evolution from $z = 3$ to $z = 0$



Baryonic equation of state at $z = 3$

cfr. Rasera & Teyssier (2006), Peeples et al. (2010)

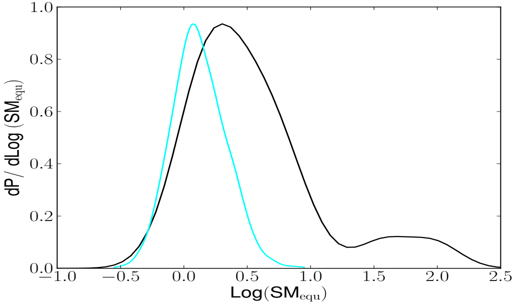
Cosmological Simulation
Simulating the IGM 3/3



Lognormal model e.g. Gnedin (2000), Choudhury et al. (2001)

Scintillation in the IGM

Strength of the scintillation: scattering measure



normalization: $\mathrm{SM}_{-3.5} = \int (n_e/0.02\,\mathrm{cm}^{-3})^2 ds/\mathrm{kpc}$

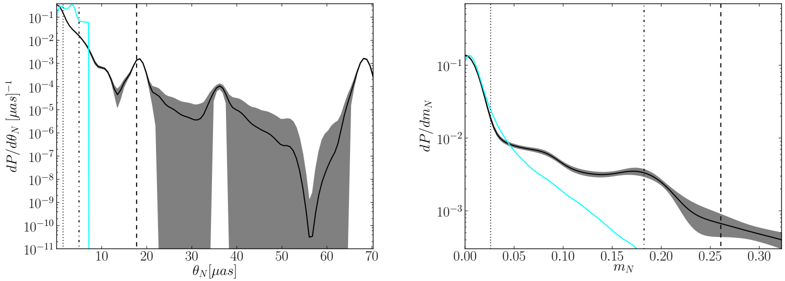
- Equivalent scattering measure $\langle \mathrm{SM}_{\mathrm{equ}} \rangle$ for a source at $z = 2$

FRW	$\simeq 0.1$	
LNM	$\simeq 1.3$	$\sigma \simeq 1.1$
SIM	$\simeq 3.9$	$\sigma \simeq 8.6$

FRW calculated using $\Delta = 1$

Scintillation in the IGM

Results: angular displacement and modulation



Source at $z = 2$, $\nu_s = 5\,\mathrm{GHz}$

displacement $\langle\theta_N\rangle/\mu\mathrm{as}$

SIM	$\simeq$ 1.9	$\sigma \simeq$ 5.7
LNM	$\simeq$ 2.1	$\sigma \simeq$ 1.7

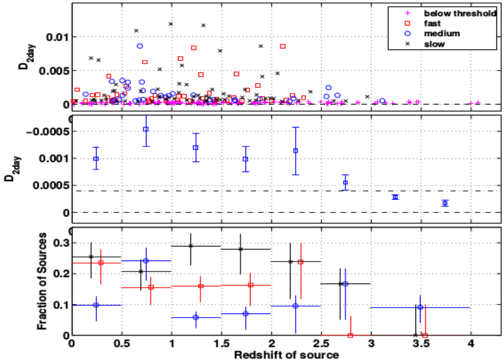
modulation $\langle m_N\rangle$

SIM	$\simeq$ 0.04	$\sigma \simeq$ 0.06
LNM	$\simeq$ 0.02	$\sigma \simeq$ 0.02

cfr. Rickett et al. (2007)

Scintillation in the IGM

Comparison with MASIV observation 1/2

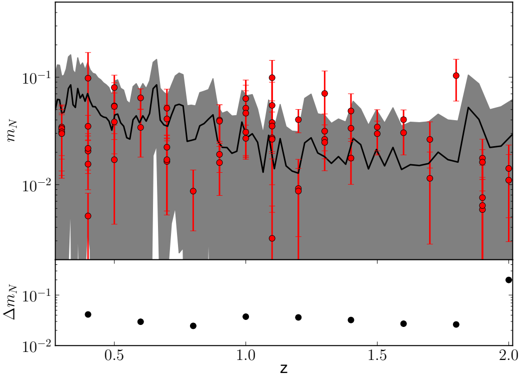


Micro Arcsecond Scintillation Induced Variability (MASIV)

- Lovell et al. (2008)
- 482 quasars $0 \leq z \leq 4$
- monitored at $\nu_{\rm obs} = 5\,\mathrm{GHz}$ for 4 observation epochs

Scintillation in the IGM

Comparison with MASIV 2/2



Comparing MASIV with IGM scintillation

- Koay et al. (2012) MASIV subsample
- $\nu_{\rm obs} = 8.4$ GHz ($\nu_s = 10.92 - 25.2$ GHz)

New scintillation model for ISM and IGM

- importance of correct density field description ($\mathrm{SM}_{\mathrm{SIM}} \simeq 40\mathrm{SM}_{\mathrm{FRW}}$)
- high m_N, $\theta_N \rightarrow$ highly non-linear structure
- the IGM scintillation can be dominant/comparable to ISM scintillation
- IGM scintillation model within $\simeq 4\%$ of Koay et al. (2012) observations