Universality of cosmic reionization: a data driven discovery

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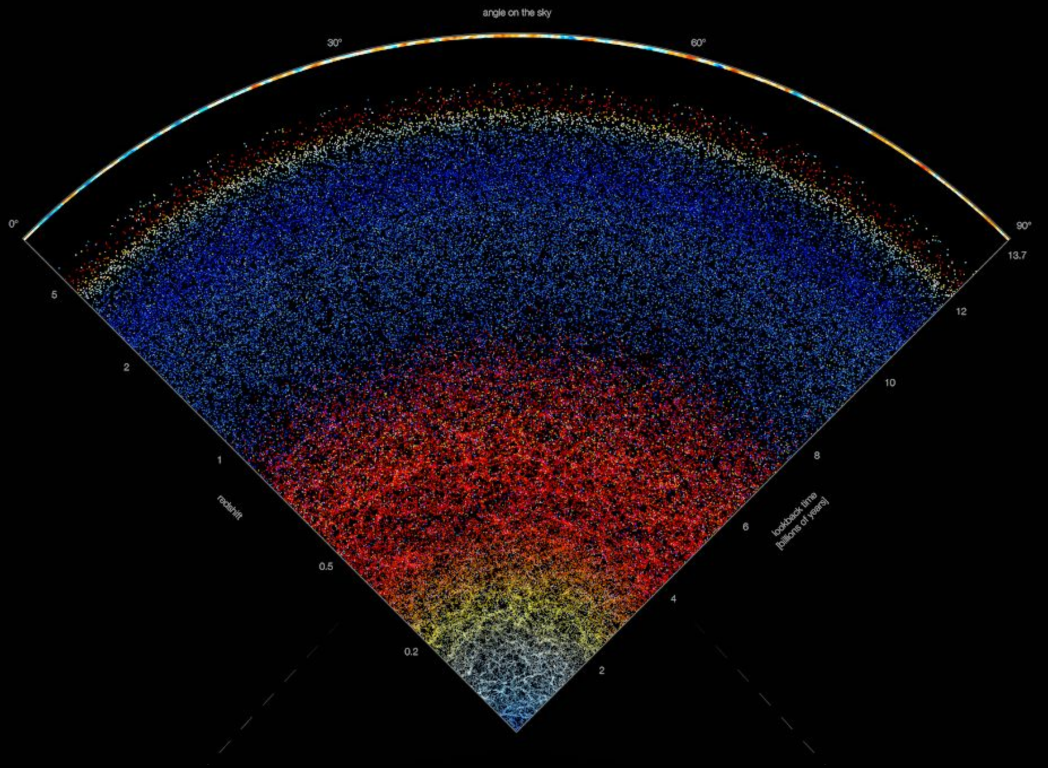
The 6th KMI International Symposium, Nagoya 2025-03-07

credit: Alvarez Kaehler Abel

Model

Data



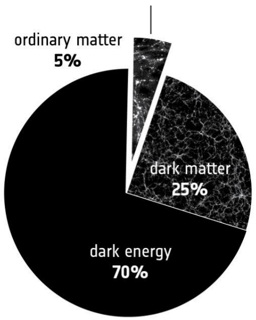
Inference

https://mapoftheuniverse.net/

ΛCDM explains cosmology using only 6 parameters

A_s, n_s:
power law amplitude and exponent

Ω_m, Ω_b:

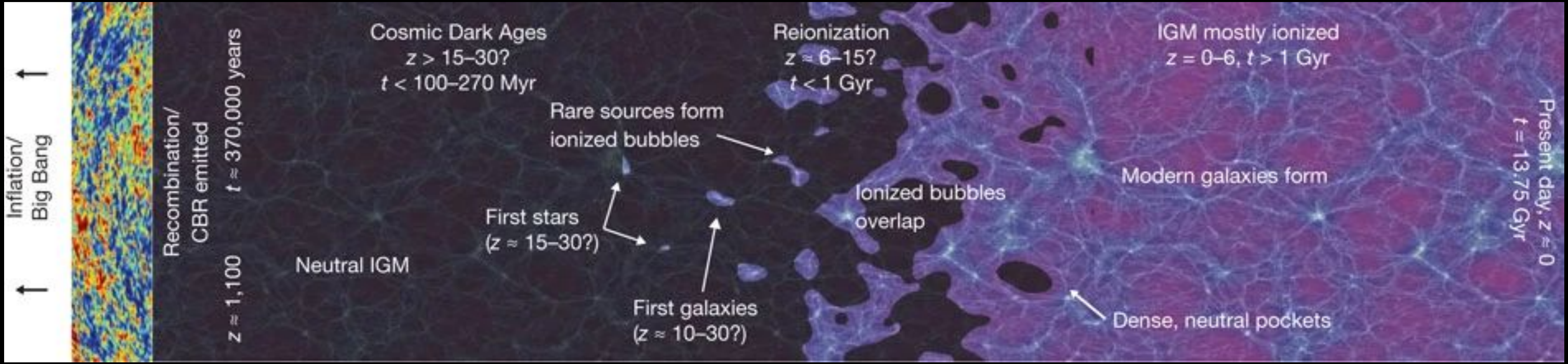


h: Hubble expansion rate

τ: optical depth to reionization

smells different?

Cosmic Reionization

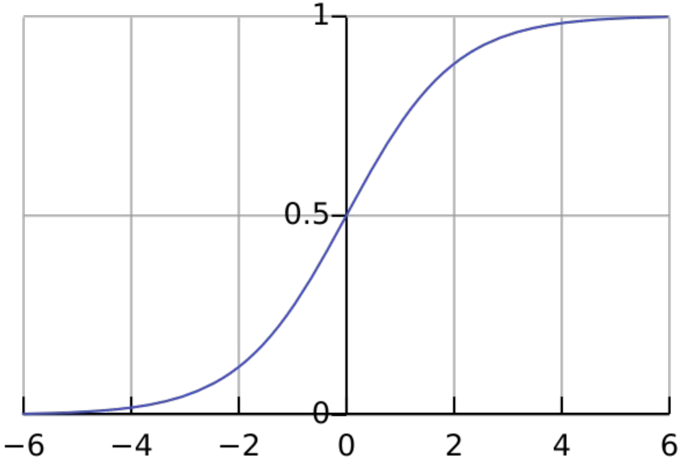


Multiscale, nonlinear physical processes, including hydrodynamics, radiative transfer, and galaxy formation

Uncertainties of Reionization: When did it happen? What sources caused it?

Importance: degenerate with scalar amplitude; sensitive to other types of DMs affecting reionization sources

Simple reionization history model with logistic ("tanh") function

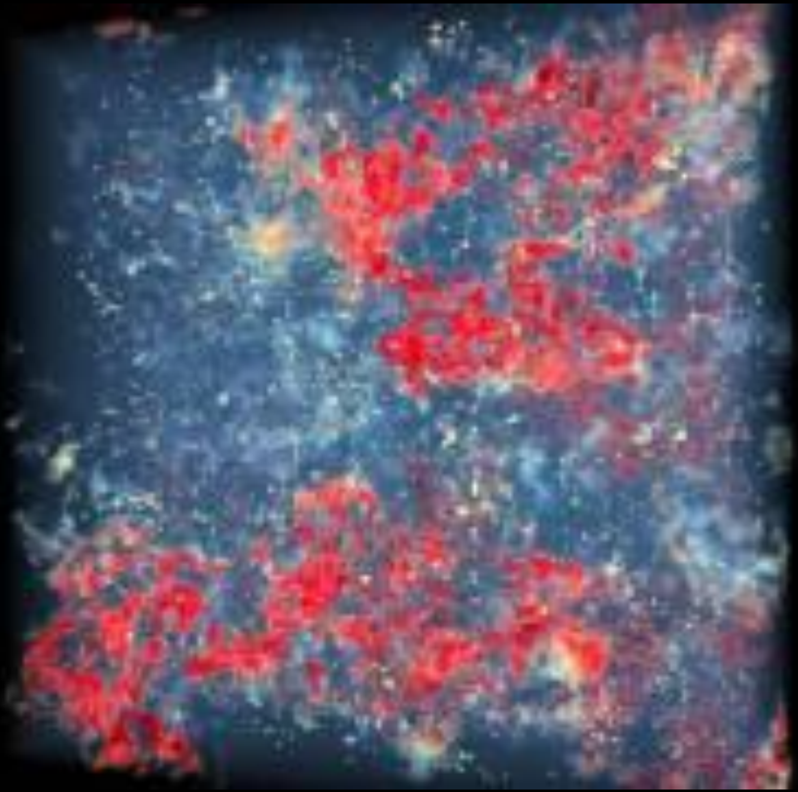


$$x_e = \frac{1 + n_{\mathrm{He}}/n_{\mathrm{H}}}{2}\left[1 + \tanh\left(\frac{y(z_{\mathrm{re}}) - y(z)}{\Delta y}\right)\right],$$

where $y(z) = (1+z)^{3/2}$, $\Delta y = \frac{3}{2}(1+z_{\mathrm{re}})^{1/2}\Delta z$, with $\Delta z = 0.5$.

Planck 2018 results. VI. Cosmological parameters

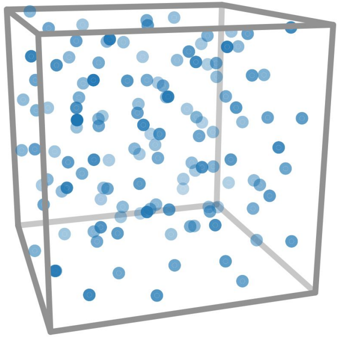
Cosmic Reionization



credit: Alvarez, Kaehler, & Abel

Simulate the Diversity of Reionization Histories

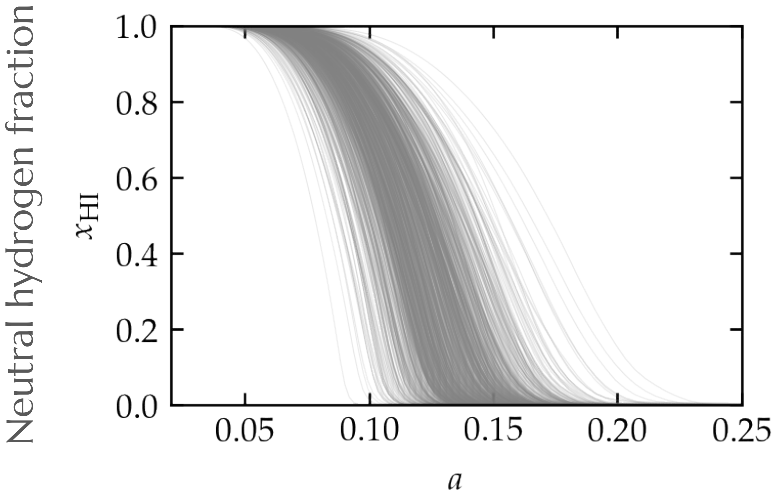
Sample parameters in 9D



$\sigma_8 \in (0.74, 0.90)$, $n_s \in (0.92, 1.00)$, $h \in (0.61, 0.73)$,
$\Omega_b \in (0.04, 0.06)$, $\Omega_m \in (0.24, 0.40)$, $\zeta_{UV} \in (20, 35)$.

Ionizing efficiency, capturing
dominating astrophysics
+3 more astrophys params

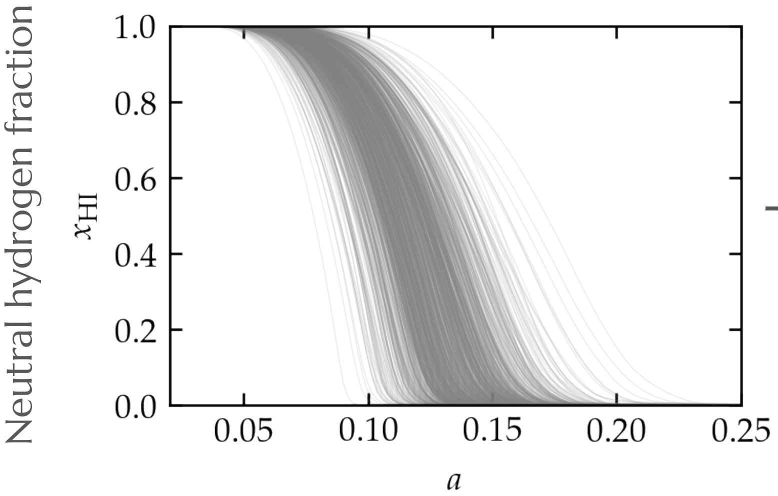
10^3 semi-numerical simulations (**21cmFAST**)



early time ← scale factor → late time

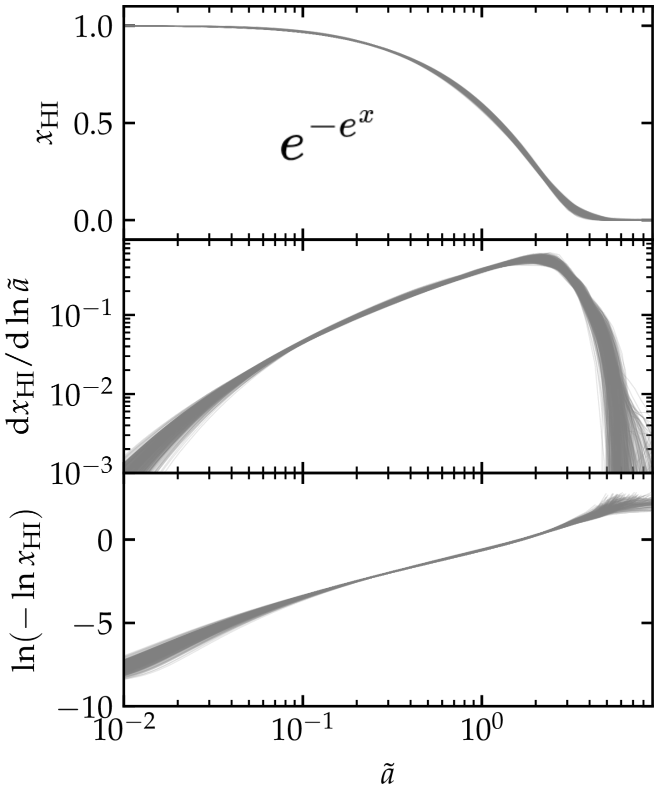
All of them share a common Universal Shape

10^3 semi-numerical simulations (21cmFAST)



early time ← scale factor → late time

$$\tilde{a} \equiv (a/\alpha)^{\beta}$$



Symbolic Regression

Gompertz function

$$y = ke^{-e^{a-bx}}$$

Gompertz 1825

$$\frac{dy}{dx} = by\,(\log k - \log y)$$

Interesting, **many** application:

- evolution of population
- growth of tumors
- spread of diseases
- impact in financial market
- **New**: history of cosmic reionization

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Universal Shape & Symbolic Regression

$$x_{\mathrm{HI}}(\tilde{a}) = \mathrm{gomp}\big(P_5(\tilde{a})\big) \equiv \exp\big[-\exp\big(P_5(\tilde{a})\big)\big],$$
$$P_5(\tilde{a}) = \textstyle\sum_{m=0}^{5} c_m \ln^m \tilde{a},$$
$$\boldsymbol{c} = \{0, 1, 0.1130, 0.02600, 0.0005491, -0.00006518\},$$
$$\tilde{a}(a;\boldsymbol{\theta}) = \left[\frac{a}{\alpha(\boldsymbol{\theta})}\right]^{\beta(\boldsymbol{\theta})},$$

$$\ln\alpha(\boldsymbol{\theta}) = \left(\frac{\Omega_{\mathrm{b}}}{\Omega_{\mathrm{m}}}\right)^{h} + (0.04835 - \sigma_8)(n_{\mathrm{s}} + 0.3558\ln[0.1123\zeta_{\mathrm{UV}}]) - \Omega_{\mathrm{m}} - n_{\mathrm{s}},$$
$$\beta(\boldsymbol{\theta}) = \left(\frac{0.005660^{\Omega_{\mathrm{m}}}}{0.6015} - \ln[\zeta_{\mathrm{UV}} - (\Omega_{\mathrm{m}} + n_{\mathrm{s}}h)^{15.05}] + h\right)\ln\Omega_{\mathrm{b}} + \frac{h}{\sigma_8},$$

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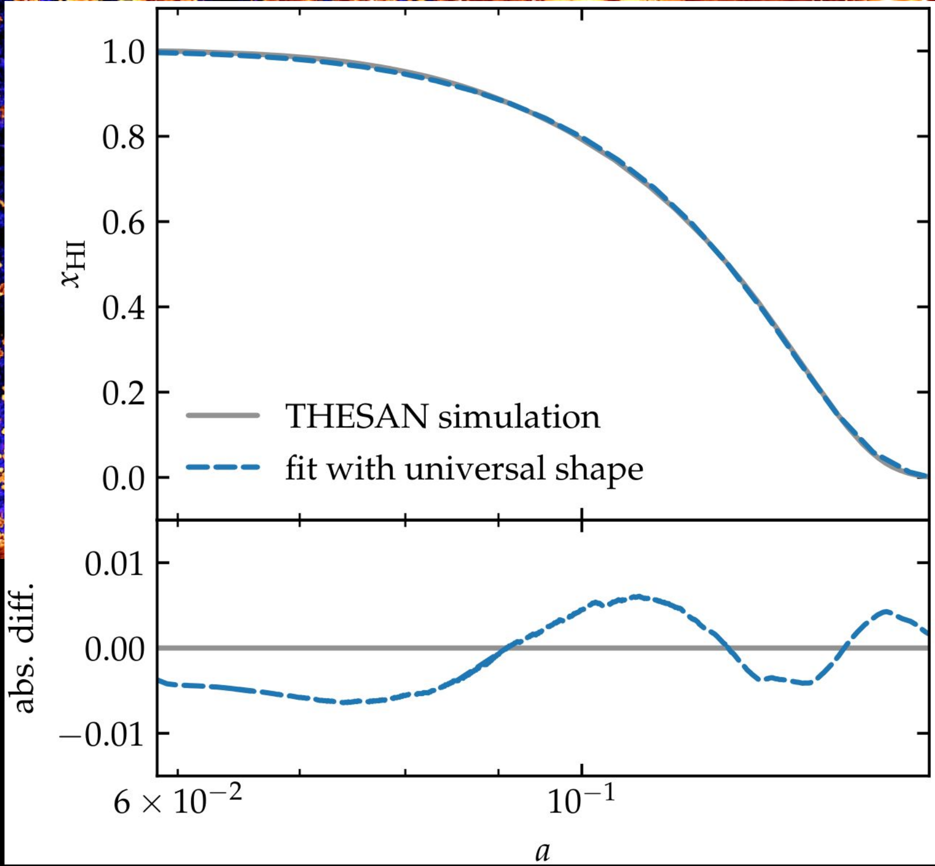
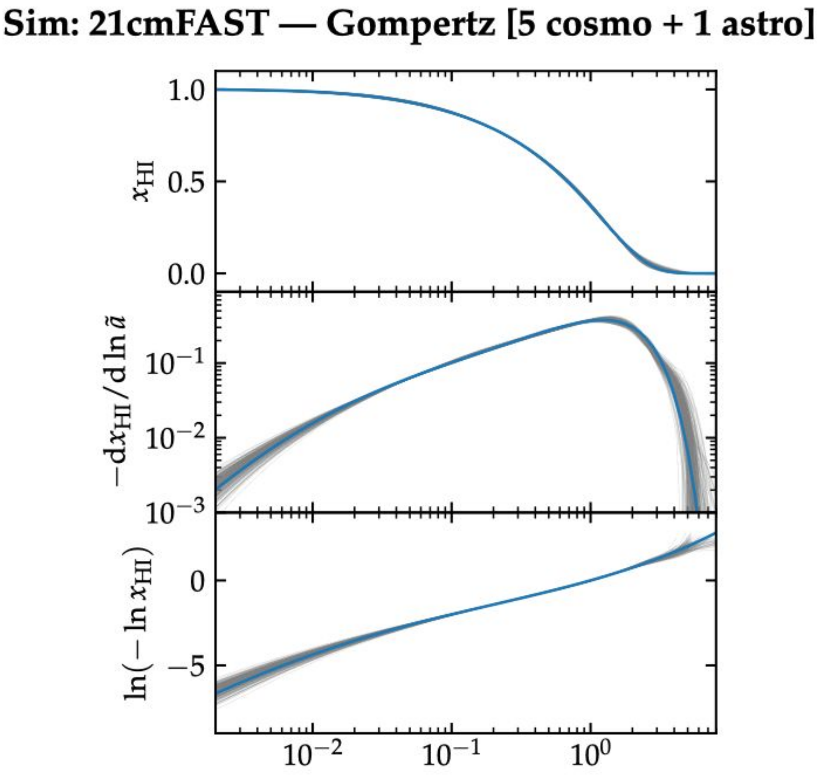
From 21cmFAST to

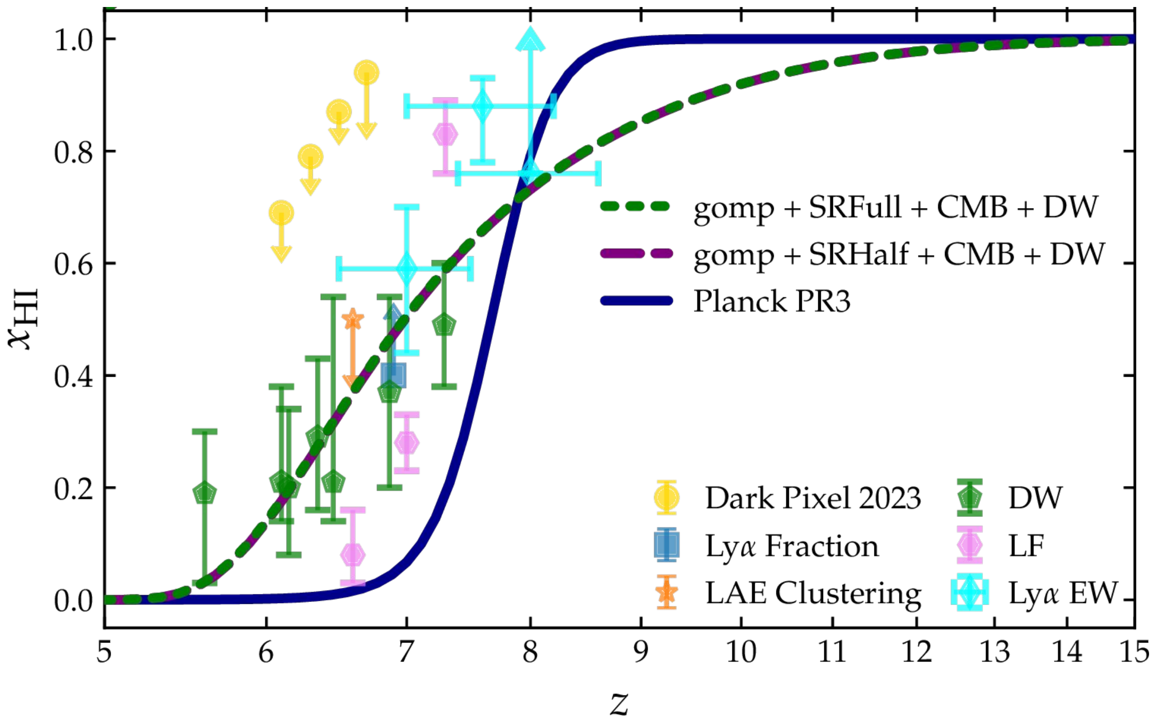
The state-of-the-art THESAN simulation also follows the same universal shape.



Moreover, we checked on all state-of-the-art fully coupled reionization simulations, and on different DM models



Universal shape also **supported by data** of quasar damping wing



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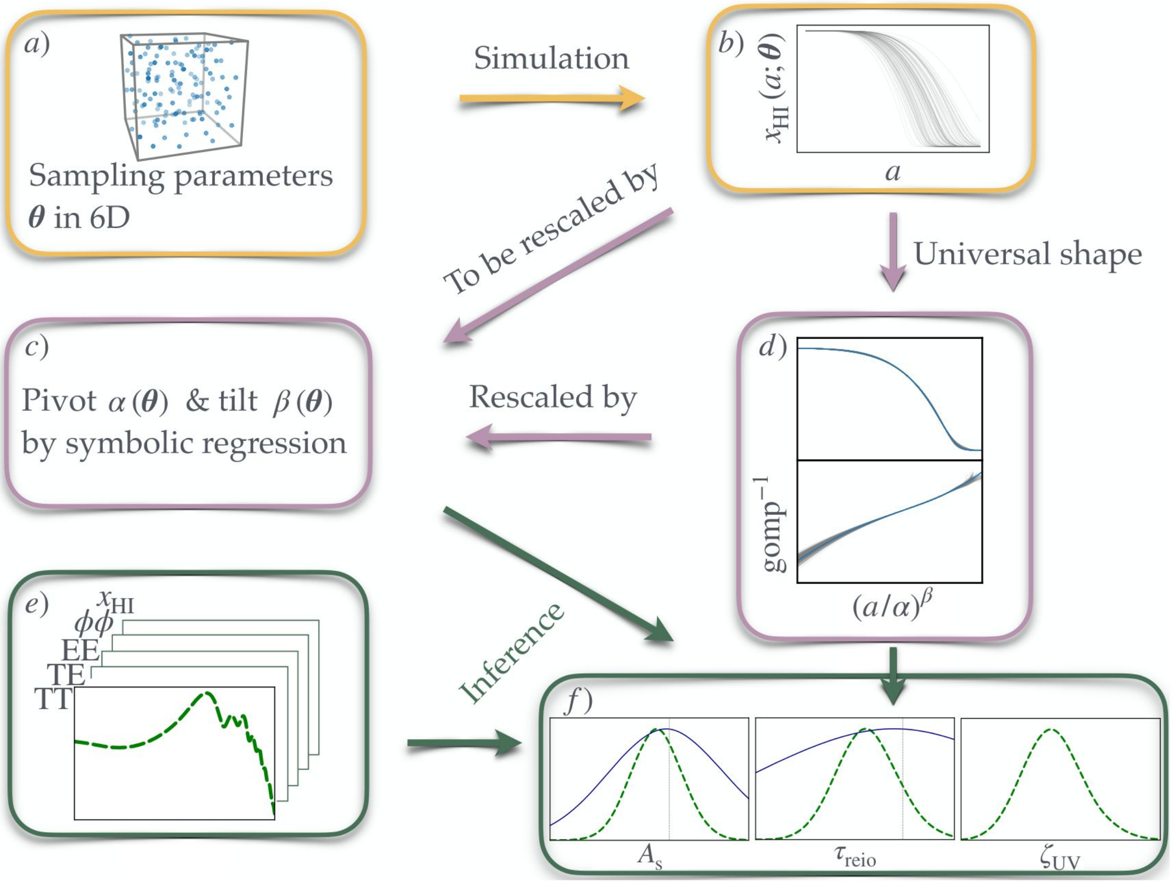
Strategy



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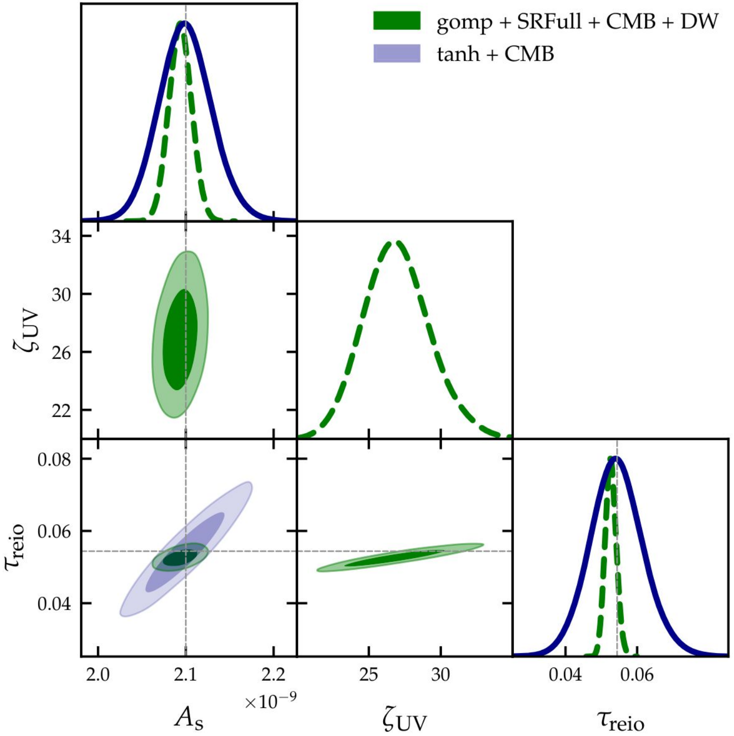
Reanalysis of Planck PR3 with additional quasar damping wing dat

- Tighten A_s and τ constraints by 2.3x and 5x, respectively
- First "detection" of the ionizing efficiency parameter ζ_{UV}
- τ is now a derived parameter, so "**five parameters are all you need in ΛCDM**".



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Why the Universality?

$$y = ke^{-e^{a-bx}}$$

Gompertz 1825

$$\frac{dy}{dx} = by\,(\log k - \log y).$$

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Not easy to come up with a simple dynamics to explain much universality.

A Barebone Simulation of Ionizing Bubbles

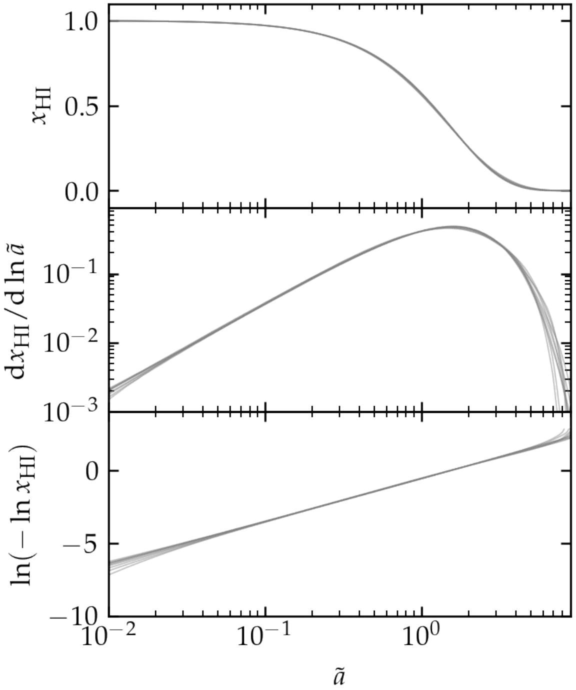
Minimalistic assumptions:

- UV photon bubbles grow and instantly ionize within spheres
- Bubbles grow during matter dominated era
- Bubbles emerge at a power-law rate in a, the scale factor

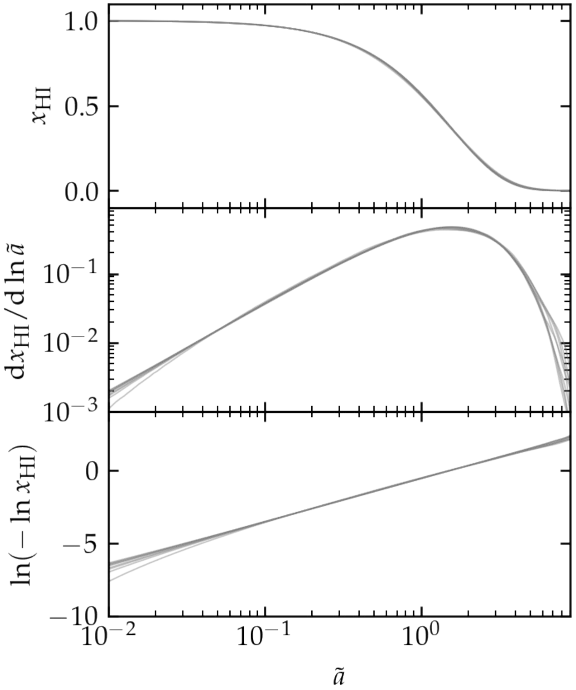
$$fa^b$$

- f and b controls how many bubbles, which we vary by 100x
- b controls the time dependence, which we vary by 4x
- spatial distribution of bubbles can be random, or follow large-scale structure of the Universe

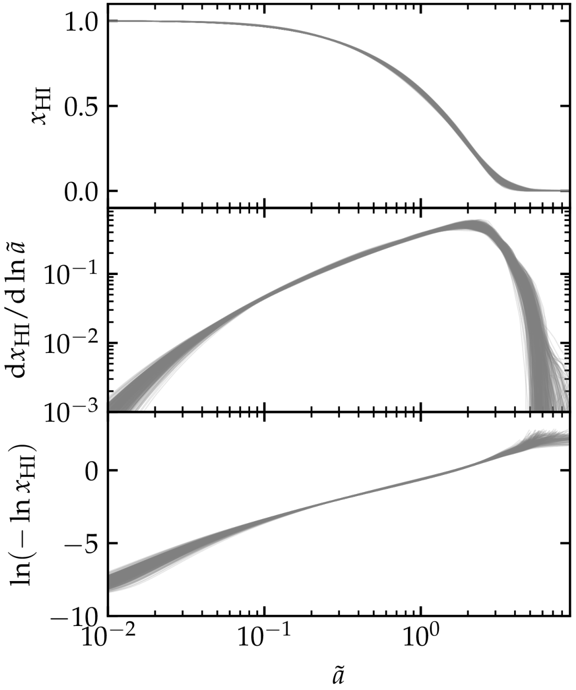
The Barebone Simulation captures the Universal Shape!



Poissonian bubbles



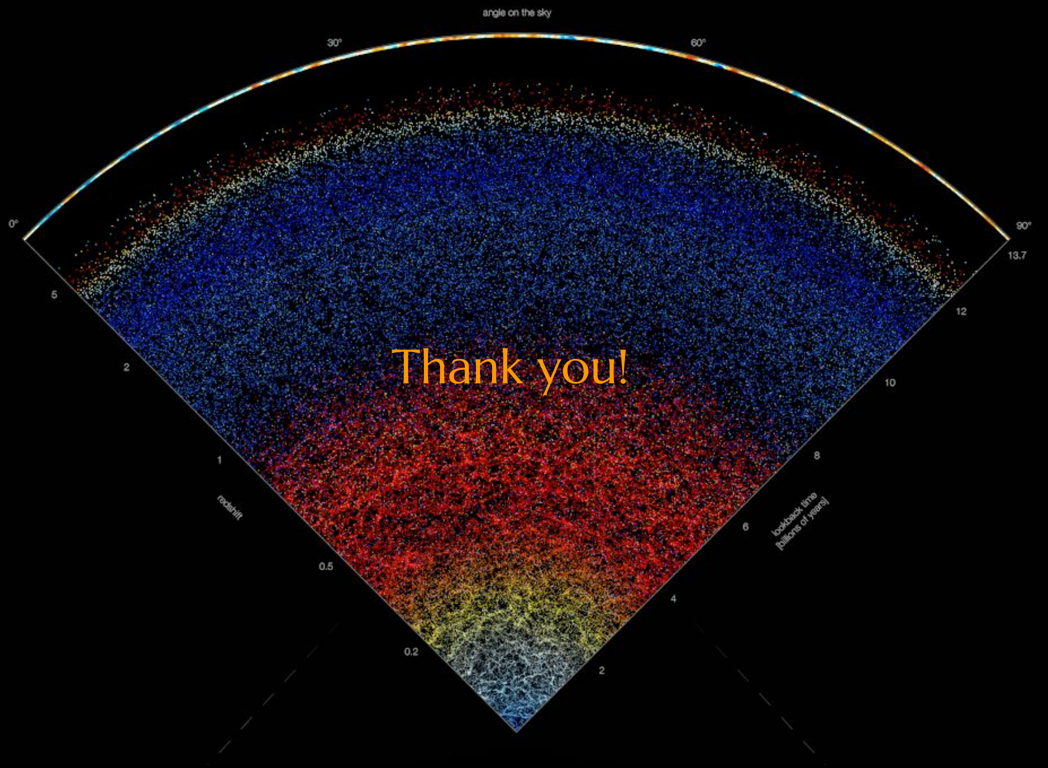
LSS bubbles



21cmFAST sims.

Model

Data



Thank you!

Inference

Non-Unique SR Expressions

Using all simulations

$$\ln \alpha(\boldsymbol{\theta}) = \left(\frac{\Omega_b}{\Omega_m}\right)^h + (0.04835 - \sigma_8)(n_s + 0.3558 \ln[0.1123\zeta_{UV}]) - \Omega_m - n_s,$$

$$\beta(\boldsymbol{\theta}) = \left(\frac{0.005660^{\Omega_m}}{0.6015} - \ln[\zeta_{UV} - (\Omega_m + n_s h)^{15.05}] + h\right) \ln \Omega_b + \frac{h}{\sigma_8},$$

Using ½ of simulations

$$\ln \alpha(\boldsymbol{\theta}) = \left(\frac{\Omega_b}{\Omega_m}\right)^{\Omega_m} - \ln^{0.5271}\left(h\left(\zeta_{UV} + \Omega_b^{-0.4982}\right)^{\sigma_8}\right) - n_s^{1.834},$$

$$\beta(\boldsymbol{\theta}) = \left(\frac{\zeta_{UV} - \Omega_m^{-1.583}}{\Omega_b h}\right)^{0.3163},$$

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