Cosmic Strings and the High Redshift Universe

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SIGRAV lecture, Feb. 16 2023

Work in collaboration with H. Jiao (in preparation), and with B. Cyr and H. Jiao, arXiv:2202.01799

Motivation I

Standard ΛCDM paradigm of cosmology is facing observational challenges from high redshift observations:

- Supermassive Black Holes at high redshifts.
- **Overabundance** of **early massive galaxies** (preliminary JWST results).

New observational windows to probe the high redshift universe are opening up.

- 21cm redshift surveys (e.g. HERA, SKA).
- **IR galaxy and quasar surveys** (e.g. ALMA, JWST).

Can cosmic strings help explain the observations and make interesting predictions for upcoming missions?

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Motivation II

- A large class of **Beyond the Standard Model** particle physics models have cosmic string solutions.
- If Nature is described by such a model, then a network of strings inevitably forms in the early universe and persists to the present time.
- Strings leave **signatures** in **any observational window.**

Searching for signatures of cosmic strings $\rightarrow$ **test of BSM particle physics models.**

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Outline

Plan

Cosmic Strings

T. Kibble, J. Phys. A **9**, 1387 (1976); Y. B. Zeldovich, Mon. Not. Roy. Astron. Soc. **192**, 663 (1980); A. Vilenkin, Phys. Rev. Lett. **46**, 1169 (1981).

- Cosmic string = linear topological defect in a quantum field theory.
- 1st analog: line defect in a crystal
- 2nd analog: vortex line in superfluid or superconductor
- Cosmic string = line of trapped energy density in a quantum field theory.
- Trapped energy density $\rightarrow$ gravitational effects on space-time $\rightarrow$ important in cosmology.

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Relevance to Particle Physics I

- Cosmic string solutions exist in many particle physics models beyond the “Standard Model".
- Cosmic strings are predicted to form at the end of inflation in many inflationary models.
- Cosmic strings may survive as cosmic superstrings in alternatives to inflation such as string gas cosmology.
- In models which admit cosmic strings, cosmic strings inevitably form in the early universe and persist to the present time.
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Relevance to Particle Physics II

- Cosmic strings are characterized by their tension μ which is associated with the energy scale η at which the strings form ($\mu \sim \eta^2$).
- Searching for the signatures of cosmic strings is a tool to probe physics beyond the Standard Model at energy ranges complementary to those probed by the LHC.
- Cosmic strings are constrained from cosmology: $G\mu \leq 1.3 \times 10^{-7}$ otherwise a conflict with the observed acoustic oscillations in the CMB angular power spectrum (Dvorkin, Hu and Wyman, 2011).
- Existing upper bound on the string tension rules out large classes of "Grand Unified" models.

Lowering the upper bound on the string tension by two orders of magnitude would rule out **all** grand unified models yielding cosmic string solutions.

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Relevance to Cosmology

Strings can produce many good things for cosmology:

- **Seeds for high redshift supermassive black holes** (S. Bramberger, R.B., P. Jreidini and J. Quintin, 2015; R.B., B. Cyr and H. Jiao, 2021).
- String-induced mechanism of baryogenesis (R.B., A-C. Davis and M. Hindmarsh, 1991).
- Explanation for the origin of primordial magnetic fields which are coherent on galactic scales (X.Zhang and R.B. (1999)).
- Origin of globular clusters (A. Barton, R.B. and L. Lin, 2015; R.B., L. Lin and S. Yamanouchi, 2015).
- Origin of fast radio bursts (R.B., B. Cyr and A. Iyer, 2017).
- Global 21-cm absorption signal (EDGES) (R. Thériault, J. Mirocha and R.B. 2021)

Preview

Important lessons from this talk:

- Cosmic strings $\rightarrow$ nonlinearities already at high redshifts.
- Signatures of cosmic strings more pronounced at high redshifts.
- Cosmic strings lead to perturbations which are non-Gaussian.
- Cosmic string loops $\rightarrow$ seeds for supermassive black holes.
- Cosmic string wakes predict specific geometrical patterns in position space.
- 21 cm surveys provide an ideal arena to look for cosmic strings (R.B., R. Danos, O. Hernandez and G. Holder, 2010).

Cosmic String Specifics

- Consider a particle physics model which has cosmic string solution.
- A network of string will form in the early universe and persist to the present time.
- Network consists of long string network (curvature radius $\sim H^{-1}$) and a distribution of string loops.
- Strings are characterized by mass per unit length μ.
- Note: μ is universal (unlike the current I for superconducting strings which varies from string to string, and may depend on time).
- Cosmic string scaling solution: statistical properties of the string network are independent of time if all length are scaled to the Hubble radius H^{-1}.

Sketch of the Scaling Solution

Sketch of the scaling solution:

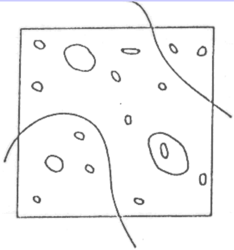

Figure 39. Sketch of the scaling solution for the cosmic string network. The box corresponds to one Hubble volume at arbitrary time t.

One Scale Cosmic String Model

- Loops formed at time t with initial radius $R_i(t) = \alpha t$ ($\alpha \sim 0.1$)
- Mean length of a loop of radius R: $l = \beta R$ ($\beta \sim 10$).
- String loops oscillate and **emit gravitational waves** and decay.
- Gravitational wave cutoff $R_c(t) = \gamma \beta^{-1} G\mu t$ ($\gamma \sim 10^2$).

Cosmic String Constraints

- Cosmic strings are constrained from cosmology: $G\mu \leq 1.3 \times 10^{-7}$ otherwise a conflict with the observed acoustic oscillations in the CMB angular power spectrum (Dvorkin, Hu and Wyman, 2011).
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Cosmic string scaling solution

- At any time t there will be a network of “infinite" strings with curvature radius $\sim t$, ~ 1 per Hubble volume.
- At any time t there will be a distribution of string loops with radii R

$$
\begin{aligned}
n(R,t) &= NR^{-2}t^{-2} \quad \alpha t_{eq} < R \\
n(R,t) &= NR^{-5/2}t_{eq}^{1/2}t^{-2} \quad \gamma G\mu t < R < \alpha t_{eq}
\end{aligned}
$$

- $R_c = \gamma G\mu t$: gravitational radiation cutoff. Loops with $R < R_c$ negligible.

Superconducting Strings

E. Witten, Nucl. Phys. B249, 557 (1985)

- In many models, cosmic strings can carry currents $\rightarrow$ superconducting cosmic strings.
- Bosonic and Fermionic superconductivity.
- In Grand Unified Models cosmic string superconductivity is generic.
- In superconducting string models there is an additional parameter characterizing the string network, the **current** I.
- "Maximal" current I_c: for $I > I_c$ electromagnetic radiation dominates $\rightarrow$ cutoff R_c on loop distribution changes..

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- String loops oscillate and **emit gravitational waves** and decay.
- Gravitational wave cutoff $R_c(t) = \gamma \beta^{-1} G\mu t$ ($\gamma \sim 10^2$).
- Superconducting string loops also **emit electromagnetic radiation.**
- $I < I_c(\mu) \rightarrow$ gravitational radiation dominates.
- $I > I_c(\mu) \rightarrow$ EM radiation dominates.
- $I_c = \gamma \kappa^{-1} (G\mu)^{3/2} m_{pl}$
- For $I > I_c$ the cutoff radius is $R_c(t) = \kappa \beta^{-1} \frac{I}{m_{pl}} (G\mu)^{-1/2} t$.

Plan

Supermassive black holes from superconducting cosmic strings

B. Cyr, H. Jiao and RB, arXiv:2202.01799, MNRAS, in press

- Loops of superconducting cosmic strings can seed direct collapse black hole formation at high redshifts.
- $\rightarrow$ explanation for the origin and abundance of observed high redshift super-massive black holes.

High Redshift Super-Massive Black Holes: Challenge for Standard ΛCDM Paradigm

- Black holes with masses $M > 10^9 M_{\odot}$ observed at redshifts $z > 6$.
- Accretion bounded by Eddington rate.
- $\rightarrow$ high mass nonlinear seeds required at early times.
- Standard ΛCDM model: probability of such nonlinear seeds exponentially suppressed.

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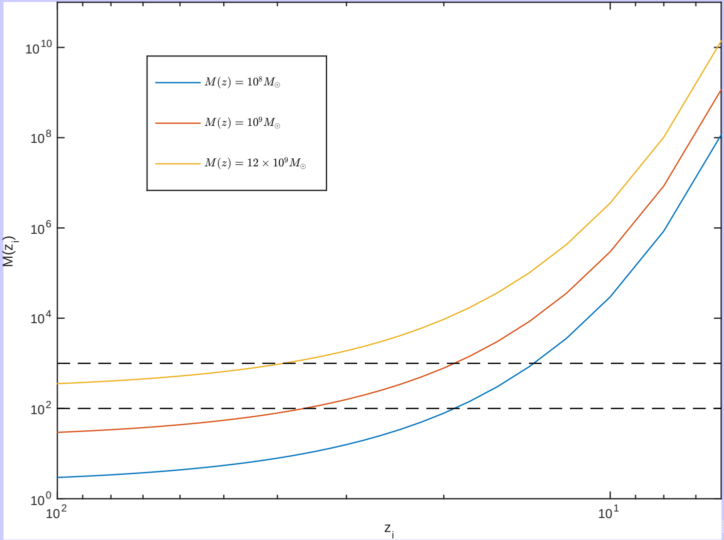
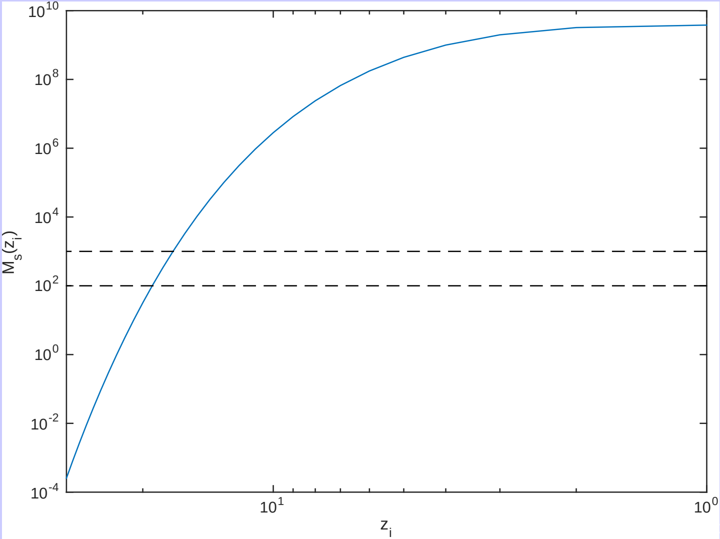
Required Seed Mass (Eddington Accretion)



Abundance of nonlinear overdensities in standard ΛCDM model



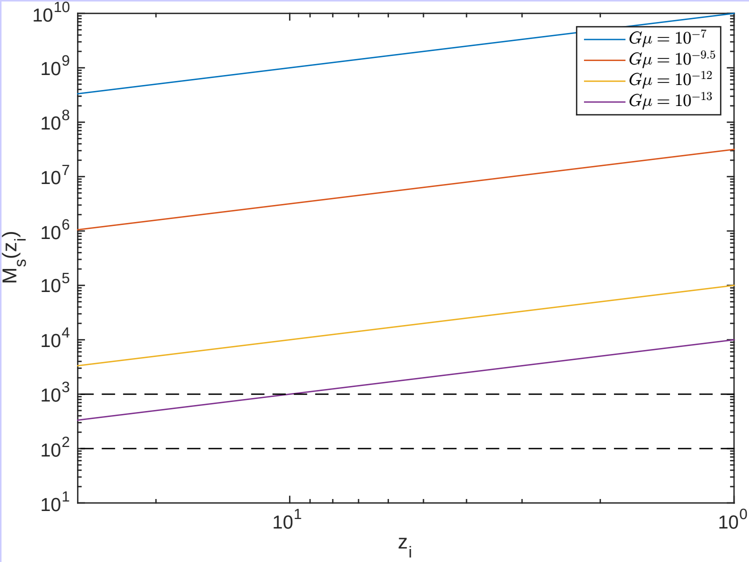
Cosmic Strings to the Rescue

T. Kibble, J. Phys. A **9**, 1387 (1976); Y. B. Zeldovich, Mon. Not. Roy. Astron. Soc. **192**, 663 (1980); A. Vilenkin, Phys. Rev. Lett. **46**, 1169 (1981).

- Assume: theory which describes our matter has cosmic string solutions.
- $\rightarrow$ scaling distribution of strings at all times.
- **Cosmic string loops $\rightarrow$ nonlinear perturbations at high redshifts.**
- $\rightarrow$ more massive seeds which have more time to grow.
- $\rightarrow$ solution of the supermassive black hole mystery.

Abundance of nonlinear overdensities due to cosmic strings

S. Bramberger, R.B., P. Jreidnin and J. Quintin, arXiv:1503.02317



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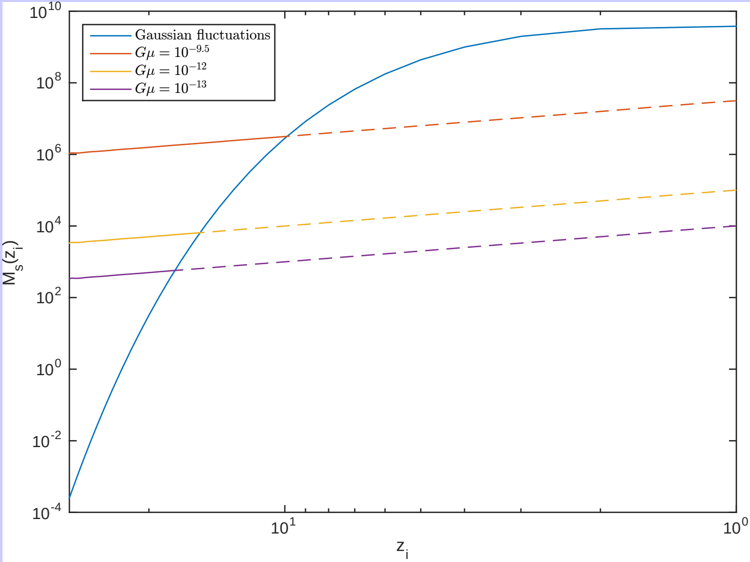

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- Accretion bounded by Eddington rate.
- $\rightarrow$ high mass nonlinear seeds required at early times.
- Standard ΛCDM model: probability of such nonlinear seeds exponentially suppressed.
- Additional challenge: How to get the contracting matter to fall inside its Schwarzschild radius?

New Challenge

- Nonlinear seeds of sufficient mass is a necessary but not a sufficient criterion for black hole formation.
- The mass needs to collapse to within its Schwarzschild radius.
- In general a collapsing cloud will fragment $\rightarrow$ no black hole formation.
- Presence of Lyman-Werner radiation can prevent the fragmentation.
- Superconducting cosmic strings produce Lyman-Werner radiation.
- Superconducting cosmic string loops $\rightarrow$ direct collapse black hole formation.

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- **Primordial black holes**: Hubble scale nonlinearities form a black hole because the Schwarzschild radius equals the radius of the overdensity.
- ΛCDM model of cosmology $\rightarrow$ nonlinearities form at late times and on scales much smaller than the Hubble radius. $\rightarrow$ Schwarzschild radius is parametrically smaller than the radius of the overdensity..
- Insufficient to have nonlinear fluctuations: Need to demonstrate that the mass collapses to inside the Schwazschild radius.
- In general, a collapsing gas cloud will fragment, form stars and never lead to a super-massive black hole (only stellar mass black holes).

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Direct Collapse Black Hole Criteria

To allow a gas cloud to collapse into a super-massive black hole the following criteria must be satisfied:

- **Sufficient mass condition**: $M_b > 10^5 M_\odot$ to form a super-massive black hole.
- **Atomic cooling threshold condition**: Collapse without fragmentation $\rightarrow T_{vir} > 10^4 K$.
- **No heavy metal condition**: presence of heavy metals woud allow cooling $\rightarrow$ fragmentation.
- **No molecular hydrogen**: would lead to cooling and fragmentation $\rightarrow$ requires presence of a Lyman-Werner background of $J > J_c \sim 10^{-44} \mathrm{GeV}^3$.

Realizing the Direct Collapse Black Hole Criteria I

B. Cyr, H. Jiao and RB, arXiv:2202.01799, MNRAS

Sufficient mass condition at redshift $z < z_{rec}$:

$$M_b(z) = \frac{\Omega_b(z)}{\Omega_M(z)} \beta \mu R \frac{1 + z_{eq}}{1 + z} > 10^5 M_\odot$$

$$\rightarrow R_c < R < \alpha t_{eq}$$

There is a range of loop radii for which the condition is satisfied.

Atomic cooling condition:

Spherical collapse $\rightarrow$ kinetic energy at collapse $\rightarrow$ converted to virial temperature.
Result: atomic cooling condition satisfied whenever the mass condition is met.

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Realizing the Direct Collapse Black Hole Criteria II

Lyman-Werner condition

Electromagnetic radiation from the superconducting cosmic string:

$$\frac{dP}{d\omega} = \kappa I^2 R^{1/3} \omega^{-2/3}$$

Assumption: radiation remains confined in overdense region. $\rightarrow$ can compute the density of photons with $10\mathrm{eV} < E < 13\mathrm{eV}$

$\rightarrow$ there is a range of currents $I < I_c$ for which the condition is satisfied.

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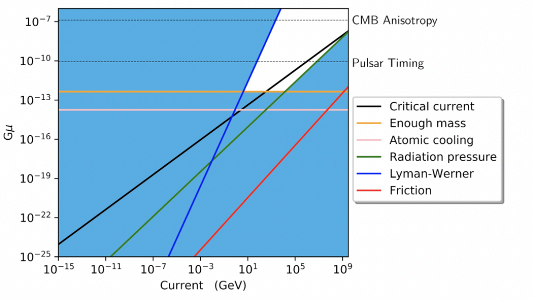
Parameter Space Region

B. Cyr, H. Jiao and RB, arXiv:2202.01799, MNRAS



Lessons

There is a range of the cosmic string parameter space for which the direct collapse black hole criteria can be satisfied.

- For $G\mu \sim 10^{-10}$ the mean separation of loops forming SMBH will be $d_g \sim 10^{2/3}\mathrm{Mpc}$
- $\rightarrow$ reasonable number density of SMBH (M. Volonteri).

Intermediate Mass Black Holes from Cosmic String Loops?

RB, B. Cyr, and H. Jiao, arXiv:2103.14057

- Consider $G\mu$ chosen to get the correct abundance of SMBH.
- $dn/dM \sim M^{-2}$ for $M_c < M < M_{SMBH}$ $\rightarrow$ abundance of seeds which *might* lead to BH formation.
- $M_c \sim M_\odot$
- $\rightarrow$ seeds in the *mass gap region* present in great abundance.

Plan

Preliminary JWST Data

H. Atek et al, arXiv:2207.12338; S. Finkelstein et al, arXiv:2207.12474; ...

- JWST has discovered an unexpectedly large number of high mass high redshift galaxies.
- Caveat: JWST has so far determined the redshift only photometrically.
- Standard ΛCDM model is unable to explain the data (see e.g. M. Biagetti, G. Franciolini and A. Riotto, arXiv:2210.04812).
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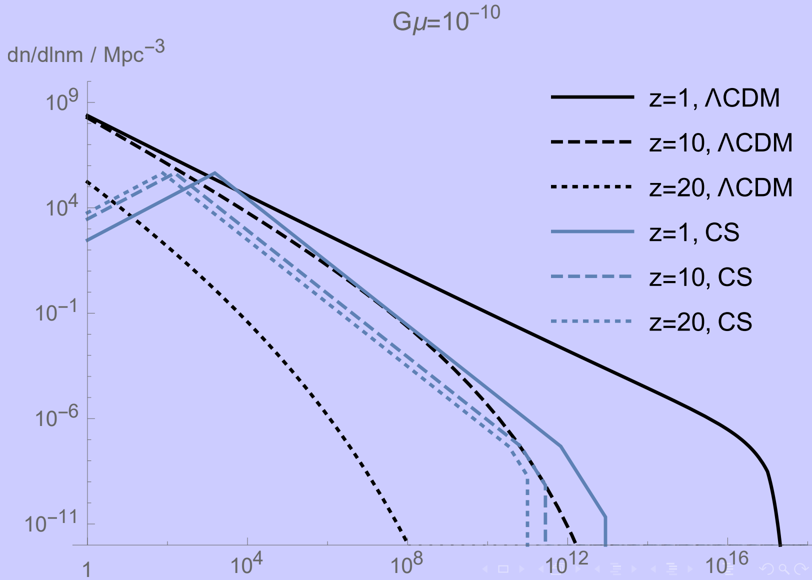
Cosmic String-Induced Halo Mass Function

H. Jiao, R.B. and A. Refregier, in progress



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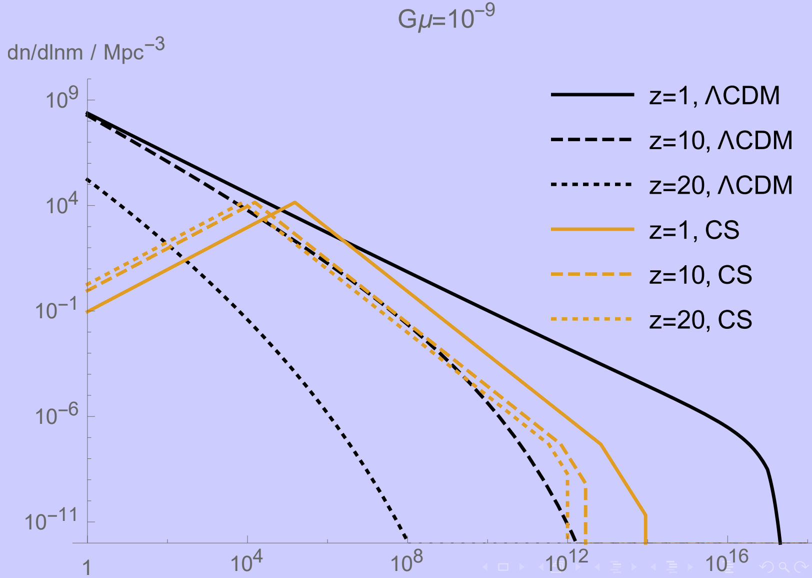

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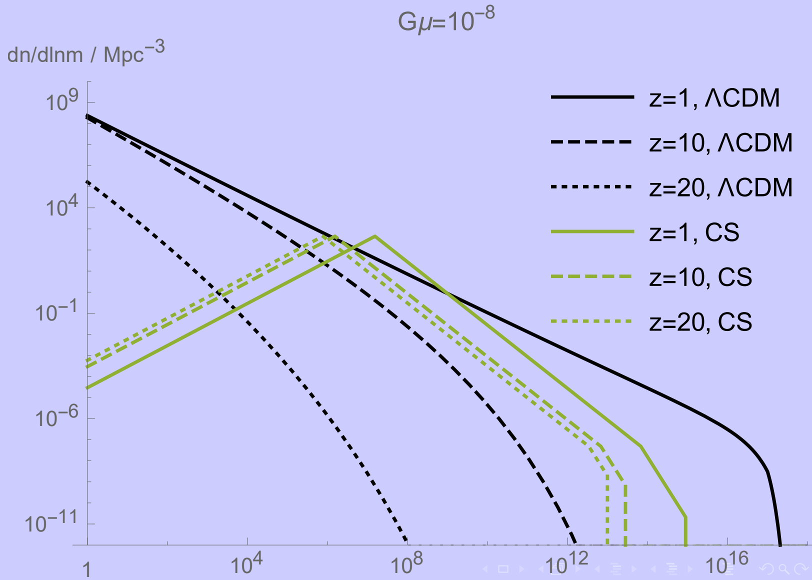
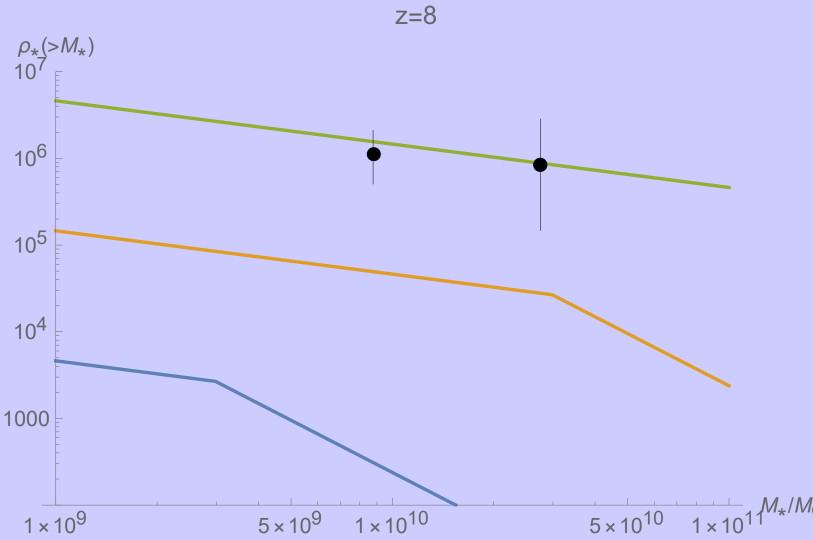


Cosmic String-Induced Stellar Mass Density



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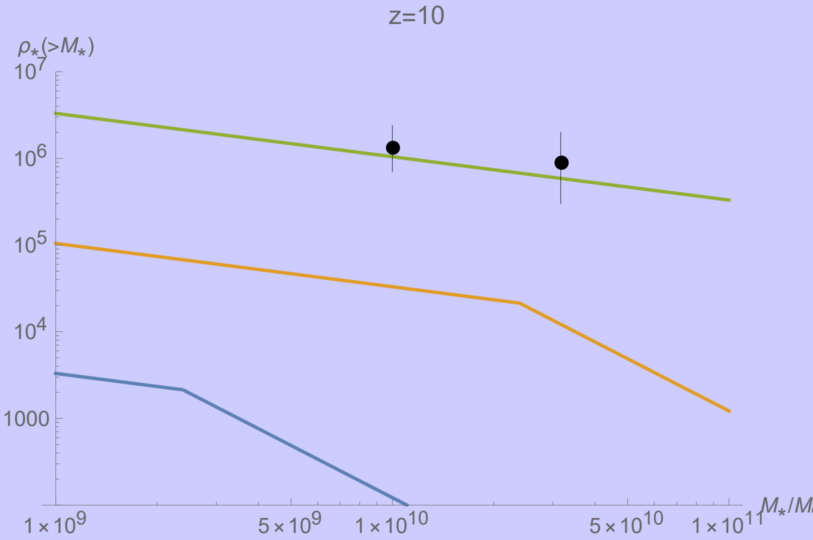

Lessons

- Cosmic string parameters $G\mu$ and N can be chosen to fit the current JWST data.
- Halo mass function is **not** exponentially suppressed.
- $\rightarrow$ specific predictions for the abundance of nonlinear structures at higher redshifts.
- $\rightarrow$ implications for **reionization**.

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Motivation

R.B., D. Danos, O. Hernandez and G. Holder, arXiv:1006.2514; O. Hernandez, Yi Wang, R.B. and J. Fong, arXiv:1104.3337.

- 21 cm surveys: new window to map the high redshift universe, in particular the “dark ages".
- Cosmic strings produce nonlinear structures at high redshifts.
- These nonlinear structures will leave imprints in 21 cm maps. (Khatri & Wandelt, arXiv:0801.4406, A. Berndsen, L. Pogosian & M. Wyman, arXiv:1003.2214)
- 21 cm surveys provide 3-d maps $\rightarrow$ potentially more data than the CMB.
- $\rightarrow$ 21 cm surveys is a promising window to search for cosmic strings.

The Effect

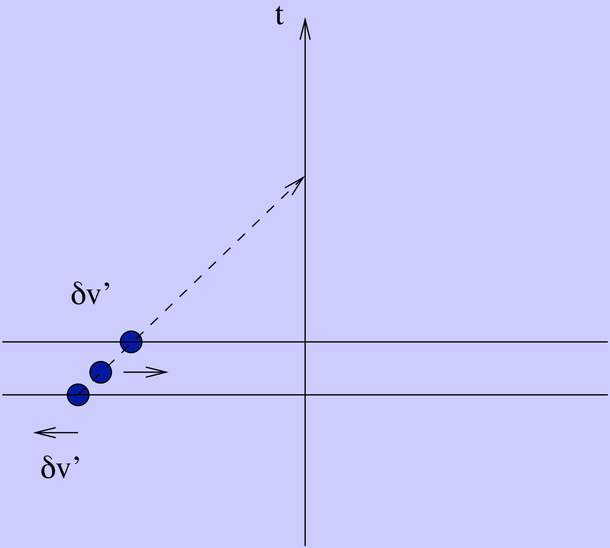
- $10^3 > z > 10$: baryonic matter dominated by neutral H.
- Neutral H has hydrogen hyperfine absorption/emission line.
- CMB radiation passing through a cold gas cloud will be partially absorbed by exciting a 21cm transition. A hot gas cloud will produce 21cm radiation by a de-excitation transition.
- 21cm redshift surveys map the density distribution of neutral H.
- 21cm surveys: method to probe baryonic matter distribution before the epoch of star formation (i.e. in the "dark ages").

The Effect (II)

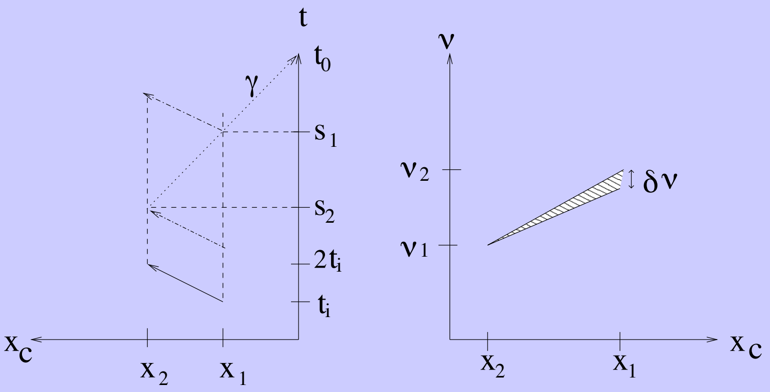
- String wake is a nonlinear overdensity in the baryon distribution with special geometry which emits/absorbs 21cm radiation.
- Whether signal is emission/absorption depends on the temperature of the gas cloud.
- At high redshifts the strings dominate the nonlinear structure and hence will dominate the 21cm redshift maps.

Cosmic Strings

R. Brandenberger



Geometry of the signal



Brightness temperature

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$$T_b(\nu) \; = \; T_S\left(1 - e^{-\tau_\nu}\right) + T_\gamma(\nu) e^{-\tau_\nu} \; ,$$

Spin temperature:

$$T_S \; = \; \frac{1 + x_c}{1 + x_c T_\gamma / T_K} T_\gamma \; .$$

T_K: gas temperature in the wake, x_c collision coefficient

Relative brightness temperature:

$$\delta T_b(\nu) \; = \; \frac{T_b(\nu) - T_\gamma(\nu)}{1 + z}$$

Application to Cosmic String Wakes

Thickness in redshift space:

$$\frac{\delta\nu}{\nu} = \frac{24\pi}{15} G\mu v_s \gamma_s \big(z_i + 1\big)^{1/2} \big(z(t) + 1\big)^{-1/2}$$
$$\simeq 3 \times 10^{-5} (G\mu)_6 (v_s \gamma_s) \,,$$

using $z_i + 1 = 10^3$ and $z + 1 = 30$ in the second line.

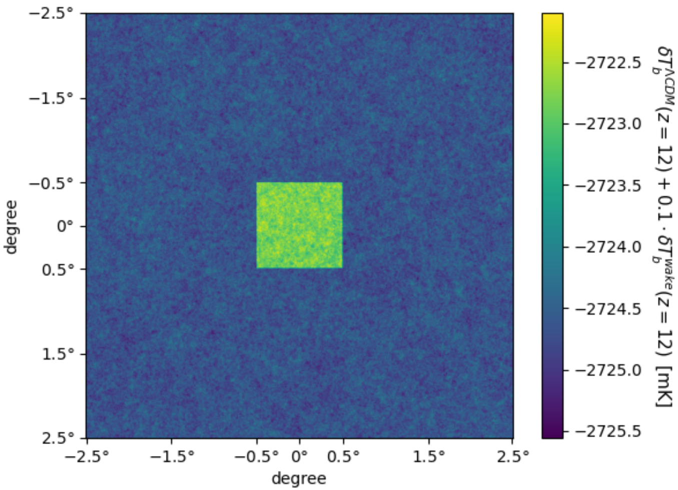
Relative brightness temperature:

$$\delta T_b(\nu) = [0.07 \text{ K}] \frac{x_c}{1 + x_c} \big(1 - \frac{T_\gamma}{T_K}\big) (1 + z)^{1/2}$$
$$\sim 200 mK \quad \text{for} \quad z + 1 = 30 \,.$$

Signal is emission if $T_K > T_\gamma$ and absorption otherwise.

String Wake Signal + ΛCDM Fluctuations

D. Maibach, RB, D. Crichton and A. Refregier, 2107.07289



Extracting the String Wake Signal from MWA Data (A Case Study)

D. Maibach, RB, D. Crichton and A. Refregier, 2107.07289

- The **specific non-Gaussian shape of the CS signal** allows the **extraction of the signal from astrophysical and instrumental noise**.
- Key features: large angular extent, small width in redshift direction.
- Q: Can the string signal be extracted from interferometric 21-cm redshift data?
- Case study: MWA
- Work in Fourier space: key signal: fringes at 90^o separation.
- Model galactic synchrotron, extragalactic point sources, galactic free-free and extra-galactic free-free signals as Gaussian processes with the amplitudes taken from the literature.
- Model instrumental noise based on MWA specifications.

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- Generate simulated data with and without a cosmic string wake for a $5^o \times 5^o$ patch of the sky.
- Consider a single MWA redshift bin at $z \sim 12$.
- Apply a particular three-point statistic sensitive to the cosmic string fringes.

Result: Cosmic string signal can be extracted down to the level of better than $G\mu = 10^{-7}$.

Plan

Conclusions

- For $G\mu \sim 10^{-10}$ loops of superconducting cosmic strings can seed the observed abundance of high redshift super-massive black holes.
- Specifically: direct collapse black hole criteria can be satisfied in a range of cosmic string parameter space.
- String loops $\rightarrow$ early galaxy formation.
- 21-cm sky is an idea arena to search for the signatures of cosmic strings.