Signals of Cosmic Strings in the 21-cm Sky

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McGill University

Cosmology in the Alps 2024 (March 2024)

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.

Relevance to Particle Physics I

- Cosmic string solutions exist in many particle physics models beyond the “Standard Model".
- In models which admit cosmic strings, cosmic strings inevitably form in the early universe and persist to the present time.
- Seeing a cosmic string in the sky would provide a guide to particle physics beyond the Standard Model!

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 robust 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:

- 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)).
- **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, 2022).
- **Abundance of high redshift galaxies** detected in recent JWST observations (H. Jiao, R.B. and A. Refregier, 2023).

It is interesting to find evidence for the possible existence of cosmic strings.

Preview

Important lessons from this talk:

- Cosmic strings $\rightarrow$ nonlinearities already at high redshifts.
- Signatures of cosmic strings more pronounced at high redshifts.
- Cosmic string wakes lead to perturbations which are non-Gaussian with 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 Review

A. Vilenkin and E. Shellard, *Cosmic Strings and other Topological Defects* (Cambridge Univ. Press, Cambridge, 1994).

- Strings form after symmetry breaking phase transitions.
- Prototypical example: Complex scalar field ϕ with "Mexican hat" potential:

$$V(\phi) = \frac{\lambda}{4}\left(|\phi|^2 - \eta^2\right)^2$$

- Vacuum manifold $\mathcal{M}$: set up field values which minimize V.
- At high temperature: $\phi = 0$.
- At low temperature: $|\phi| = \eta$ - but phase uncorrelated on super-Hubble scales.
- $\rightarrow$ defect lines with $\phi = 0$ left behind.
- Existence of cosmic strings requires: $\Pi_1(\mathcal{M}) \neq 1$.

Formation of Strings

T. Kibble, Phys. Rept. **67**, 183 (1980).

- By causality, the values of ϕ in $\mathcal{M}$ cannot be correlated on scales larger than t.
- Hence, there is a probability $\mathcal{O}(1)$ that there is a string passing through a surface of side length t.
- Causality $\rightarrow$ network of cosmic strings persists at all times.

Sketch of the scaling solution:

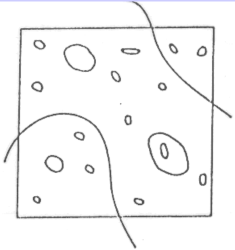

Figure 39. Sketch of the scaling solution for the cosmic string network. The box corresponds

Plan

Kaiser-Stebbins Effect

N. Kaiser and A. Stebbins, Nature **310**, 391 (1984).

- Space away from the string is locally flat (cosmic string exerts no gravitational pull).
- Space perpendicular to a string is conical with deficit angle $\alpha = 8\pi G\mu$
- Photons passing by the string undergo a relative Doppler shift

$$\frac{\delta T}{T} = 8\pi\gamma(v)vG\mu\,,$$

- $\rightarrow$ network of line discontinuities in CMB anisotropy maps.

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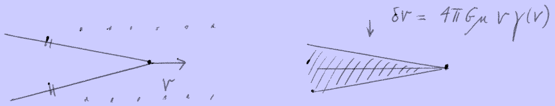
Cosmic String Wake

J. Silk and A. Vilenkin, Phys. Rev. Lett. **53**, 1700 (1984).

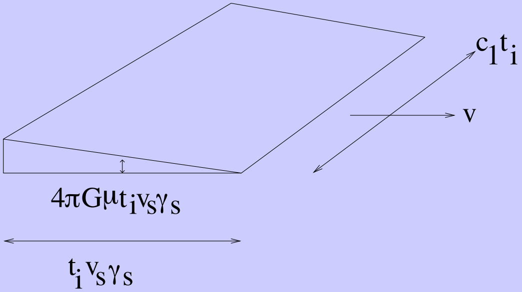
Consider a cosmic string moving through the primordial gas:

Wedge-shaped region of overdensity 2 builds up behind the moving string: wake.



Closer look at the wedge

- Consider a string at time t_i $[t_{rec} < t_i < t_0]$
- moving with velocity v_s
- with typical curvature radius $c_1 t_i$



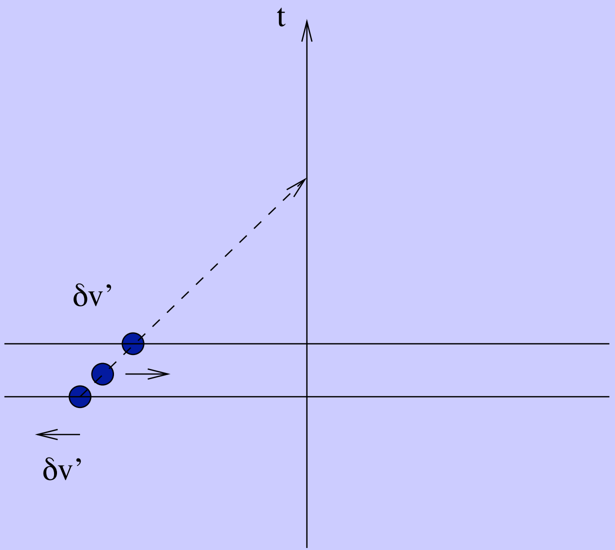
Gravitational accretion onto a wake

L. Perivolaropoulos, R.B. and A. Stebbins, Phys. Rev. D **41**, 1764 (1990).

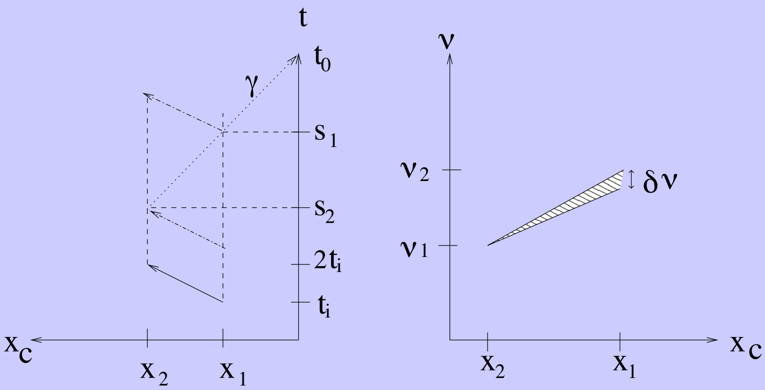
- Initial overdensity $\rightarrow$ gravitational accretion onto the wake.
- Accretion computed using the Zeldovich approximation.
- **Result**: comoving thickness $q_{nl}(t) \sim a(t)$.

Plan

21-cm Signal of a String Wake



Geometry of the signal



Brightness temperature

Cosmic Strings

R. Brandenberger

Brightness temperature:

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

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:

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

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

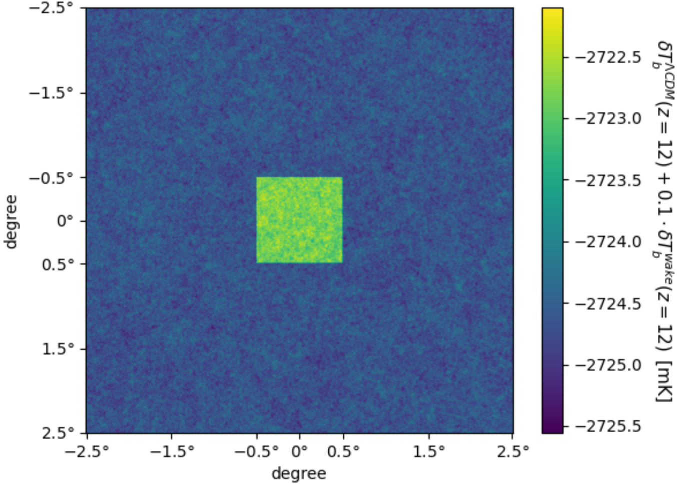
Relative brightness temperature:

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

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

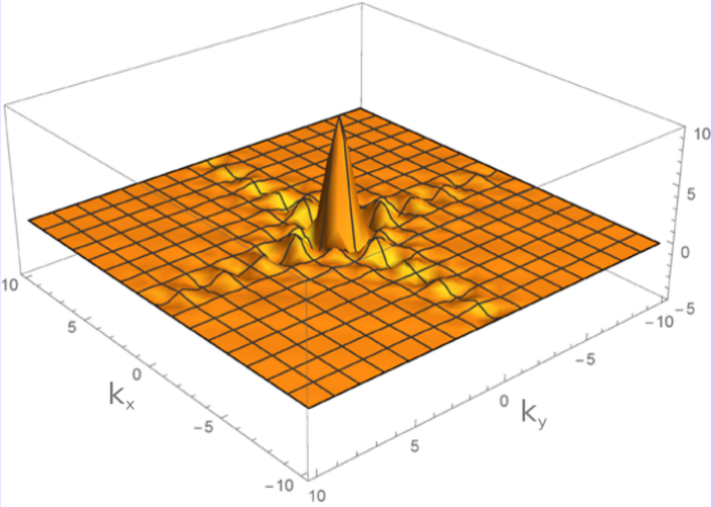
String Wake Signal + ΛCDM Fluctuations

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



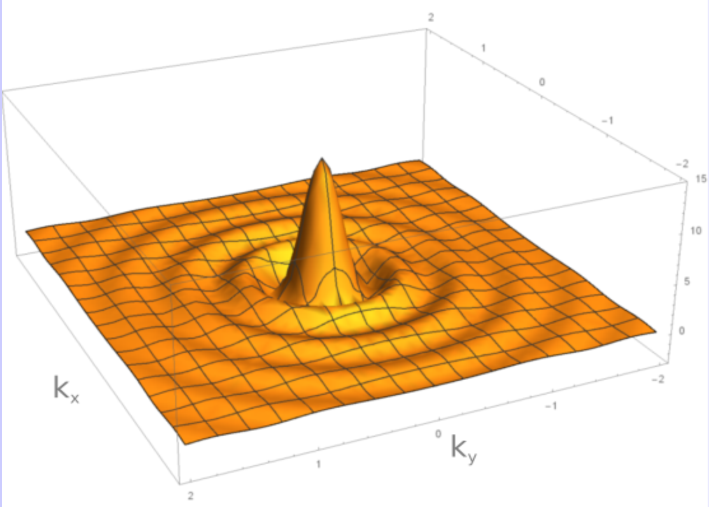
String Wake Signal in Fourier Space

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



Signal from a Spherical Overdensity in Fourier Space

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



Extracting the String Wake Signal from the Foregrounds

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

Noise Sources Considered:

- Galactic Synchrotron
- Point Sources
- Galactic Free-Free
- Extra-Galactic Free-Free

$$C_l(\nu_1, \nu_2) = \sum_i A_i \left(\frac{l_{ref}}{l}\right)^{\beta_i} \left(\frac{\nu_{ref}^2}{\nu_1 \nu_2}\right)^{\alpha_i} \exp\left(\frac{-\log^2(\nu_1/\nu_2)}{2\xi^2}\right)$$

Extracting the String Wake Signal from the Foregrounds

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

Noise Sources Considered:

- Galactic Synchrotron:
  $A = 1100[mK]^2, \ \beta = 3.3, \ \alpha = 2.8$
- Point Sources: $A = 57[mK]^2, \ \beta = 1.1, \ \alpha = 2.07$
- Galactic Free-Free: $A = 0.088[mK]^2, \ \beta = 3, \ \alpha = 2.15$
- Extra-Galactic Free-Free:
  $A = 0.014[mK]^2, \ \beta = 1, \ \alpha = 2.1$

$$C_l(\nu_1, \nu_2) = \sum_i A_i \left(\frac{l_{ref}}{l}\right)^{\beta_i} \left(\frac{\nu_{ref}^2}{\nu_1 \nu_2}\right)^{\alpha_i} \exp\left(\frac{-\log^2(\nu_1/\nu_2)}{2\xi^2}\right)$$

Extracting the String Wake Signal: Three Point Statistic

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

Assume string orientation such that the string signal lies in a single redshift bin.
Choose a statistic sensitive to the Fourier space ridges in the string signal.

$< T(\vec{k}_1) T(\vec{k}_2) T(\vec{k}_3) >$ with $\vec{k}_1 \approx -\vec{k}_2, \ |\vec{k}_1| \approx |\vec{k}_3|$ and $\vec{k}_1 \cdot \vec{k}_3 \approx 0$

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Extracting the String Wake Signal: Result

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

Result: Signal of a cosmic string with $G\mu = 10^{-7}$ is identifiable in a statistically significant way.

Plan

Conclusions

- Cosmic strings: connection between BSM and cosmological data.
- String signatures increase as η increases.
- Cosmic strings $\rightarrow$ non-Gaussianities with specific patterns in position space.
- String signals stick out more at higher redshifts.
- String wakes $\rightarrow$ distinctive signatures in high z 21-cm redshift surveys.

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Extracting the String Wake Signal from the Foregrounds and Instrumental Noise

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

Instrumental noise is modeled via a power spectrum following Alonso et al, 2017

$$P_T(l) = \frac{\lambda^2 T_{sys}^2 N_p}{A_e^2 \Delta\nu t_{tot} n(u = l/2\pi)}.$$

MWA specification.

Extracting the String Wake Signal: Signal Processing Techniques

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

- Wiener filtering
- Noise subtraction via modelling the redshift dependence of the noise pixel by pixel in the angular map.

Plan

Supermassive black holes from superconducting cosmic strings

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

- 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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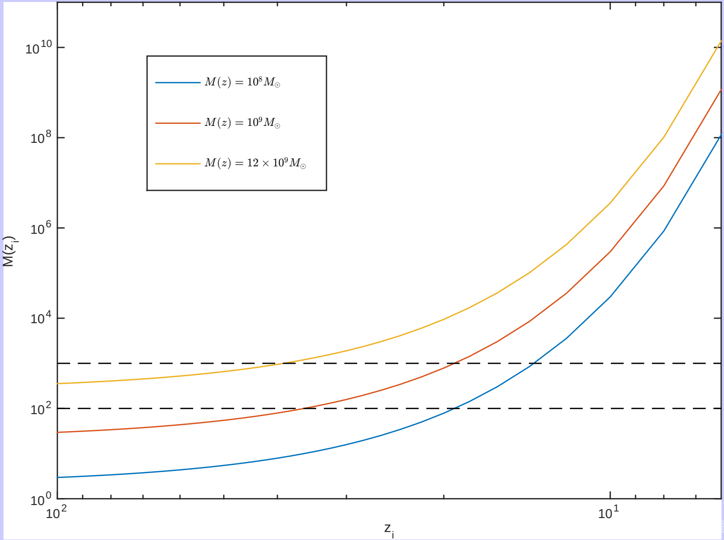
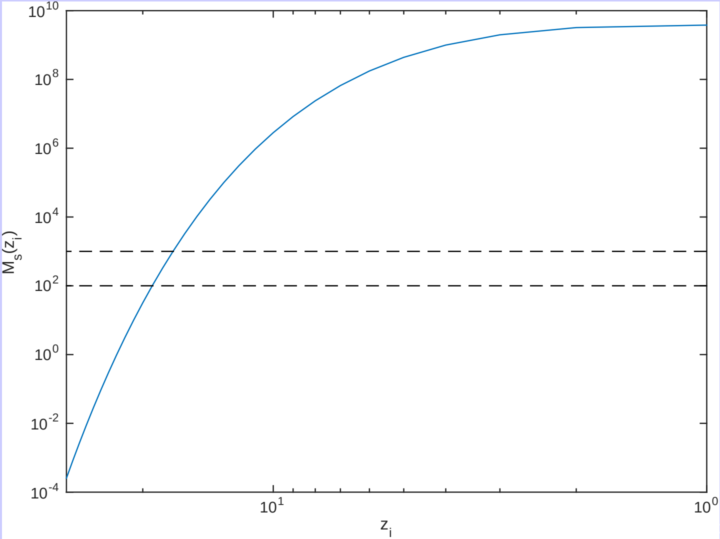
Required Seed Mass (Eddington Accretion)



Abundance of nonlinear overdensities in standard ΛCDM model



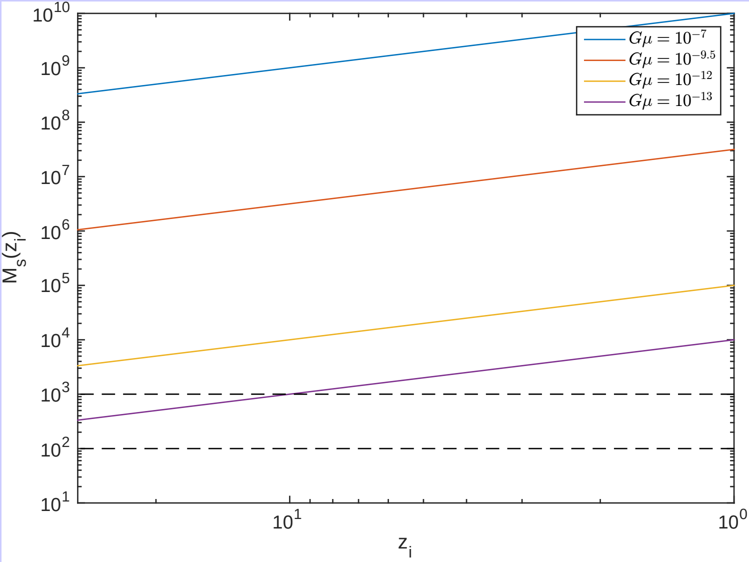
Cosmic Strings to the Rescue

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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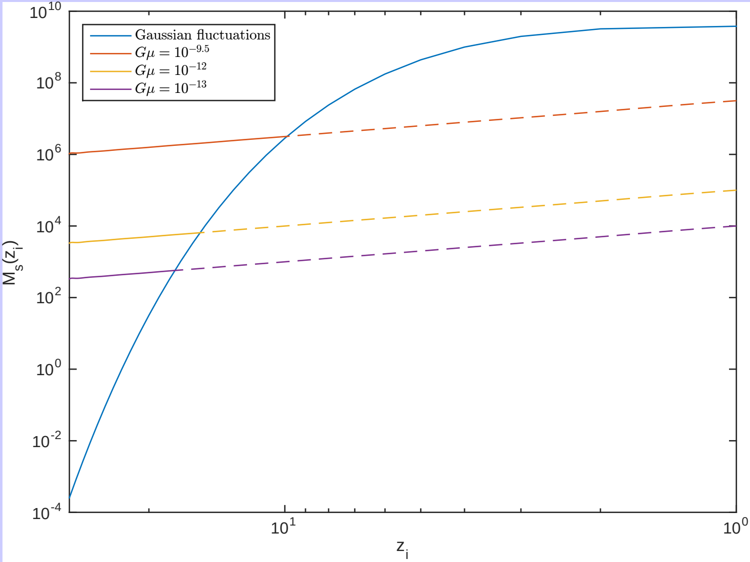

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- Black holes with masses $M > 10^9 M_\odot$ observed at redshifts $z > 6$.
- Accretion bounded by Eddington rate.
- $\rightarrow$ high mass nonlinear seeds required at early times.
- Standard ΛCDM model: probability of such nonlinear seeds exponentially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

- **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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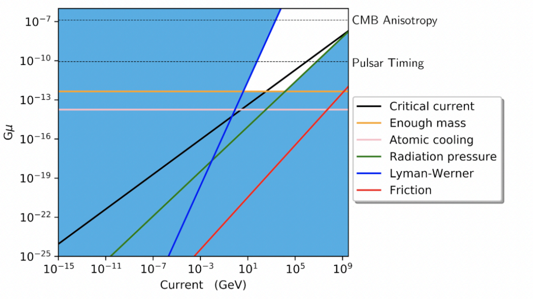
Parameter Space Region

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).

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).
- **Question:** Can cosmic string provide an explanation for the data?

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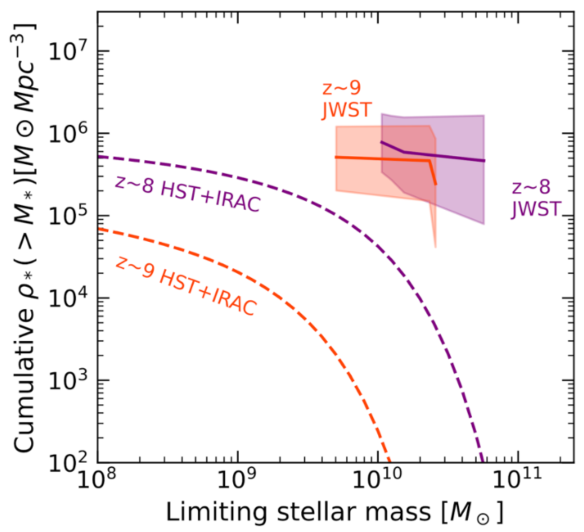
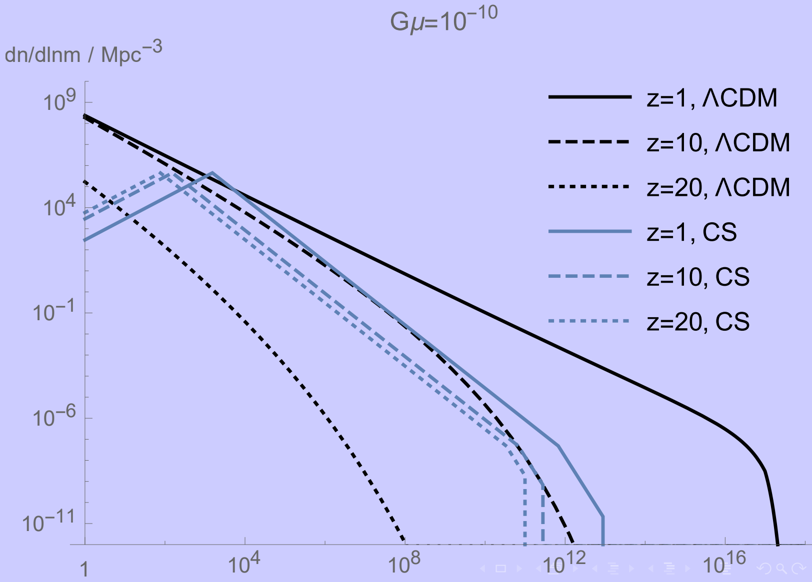
JWST Data

I. Labbe at al, arXiv:2207.12446



Cosmic String-Induced Halo and Stellar Mass Functions

H. Jiao, R.B. and A. Refregier, arXiv:2304.06429



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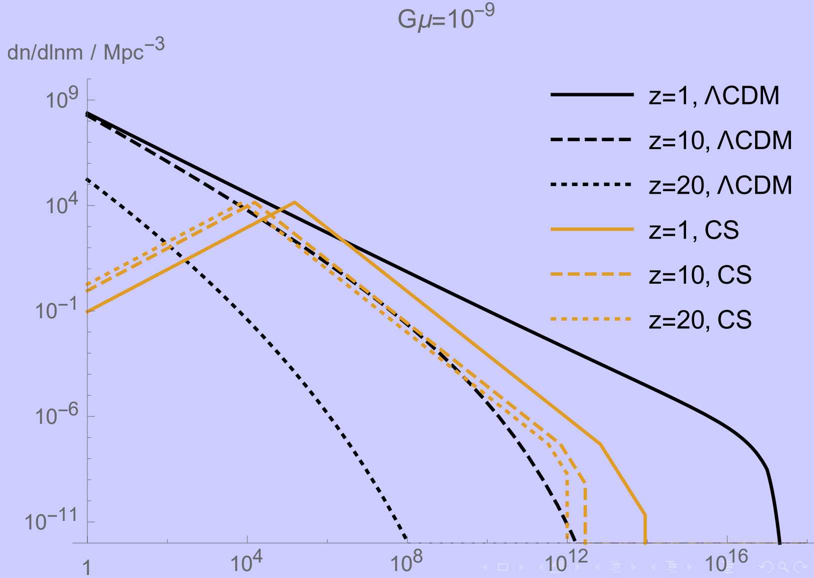
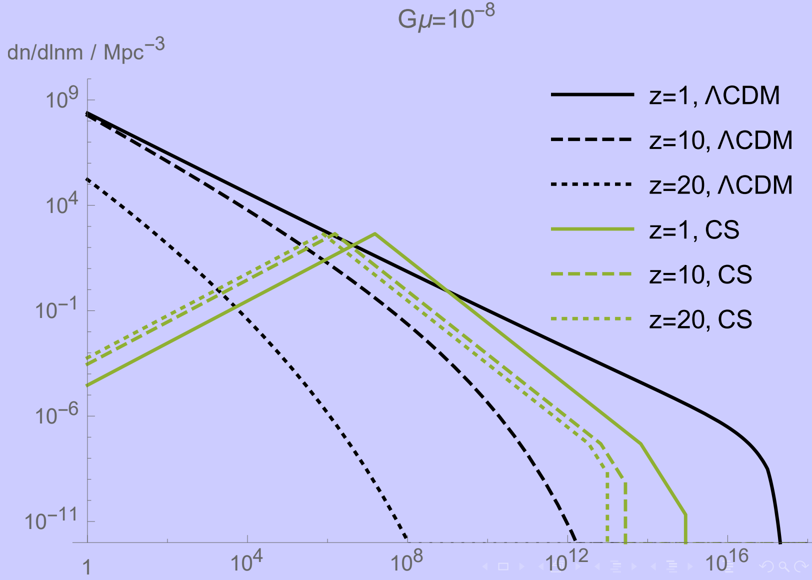


Cosmic String-Induced Halo and Stellar Mass Functions

H. Jiao, R.B. and A. Refregier, arXiv:2304.06429



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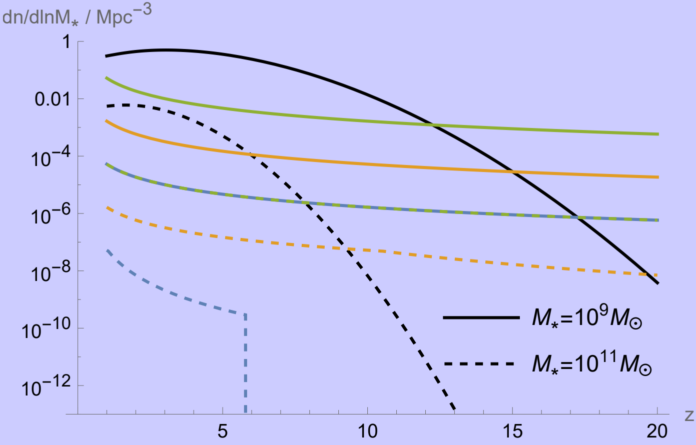
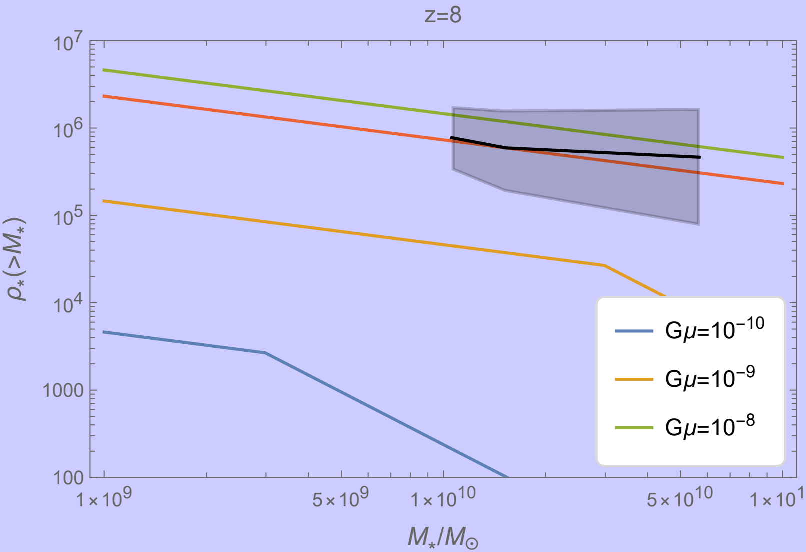
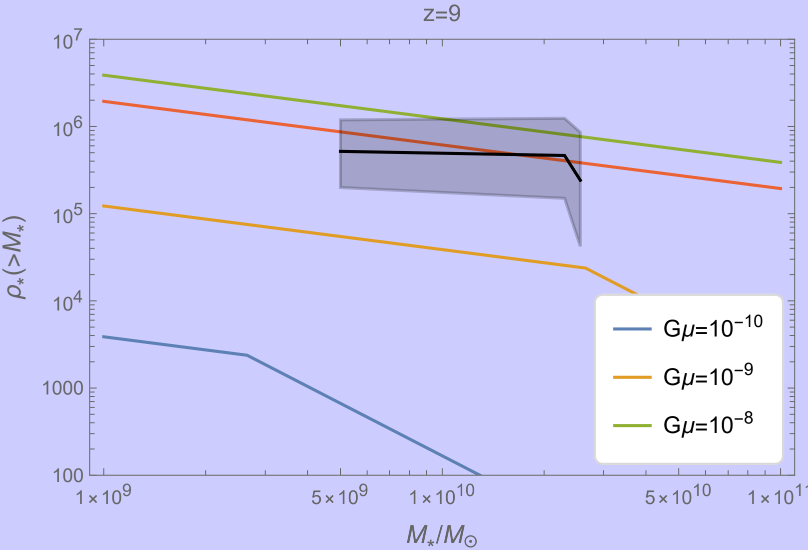


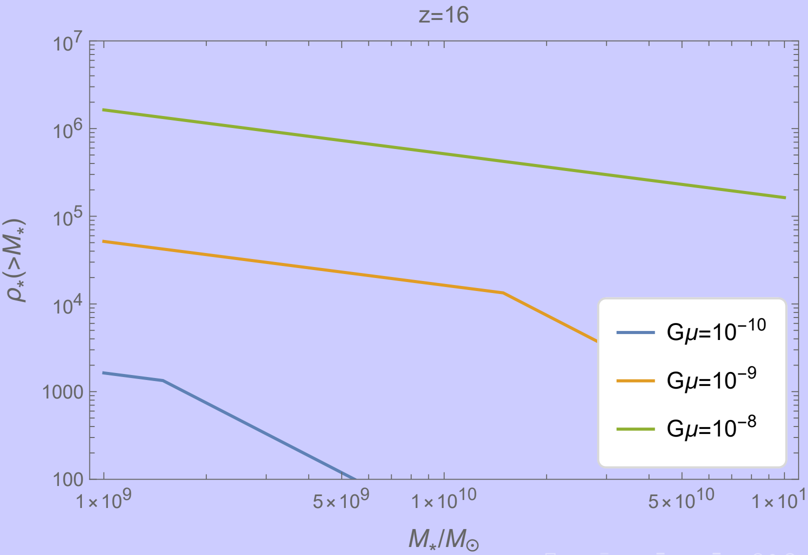
Comparison with data ($z = 8$)



Comparison with data ($z = 9$)



Prediction for $z = 16$



Lessons

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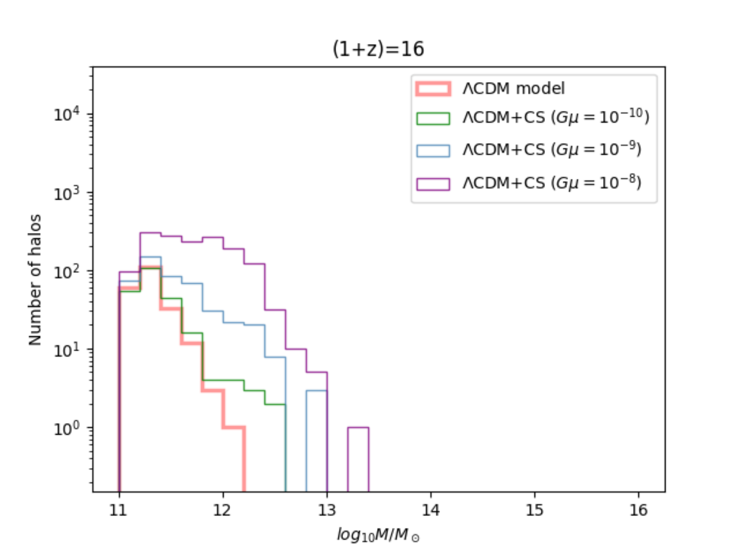
N-Body Simul. of LCDM + Cosmic String Loops (H. Jiao, RB, A. Refregier, arXiv:2402.06235)



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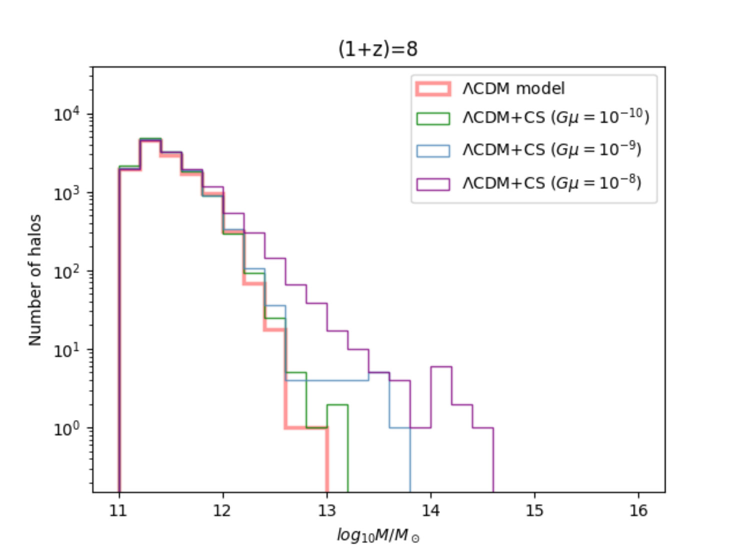

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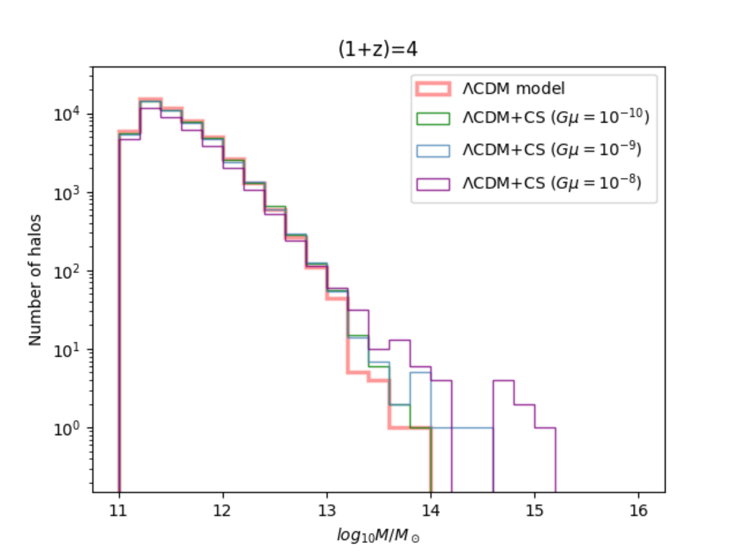

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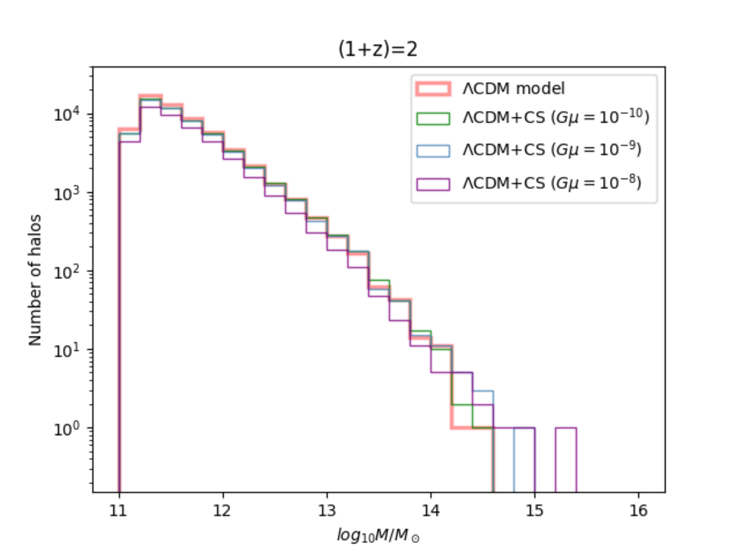

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