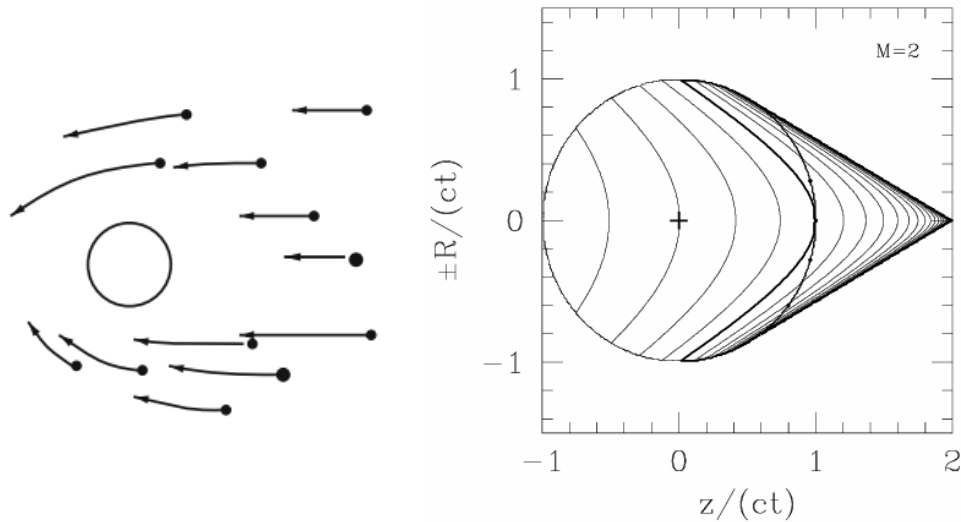


DYNAMICAL HEATING FROM DARK COMPACT OBJECTS AND AXION MINIHALOS



Φαινó 2026
The 2026 Phenomenology Symposium

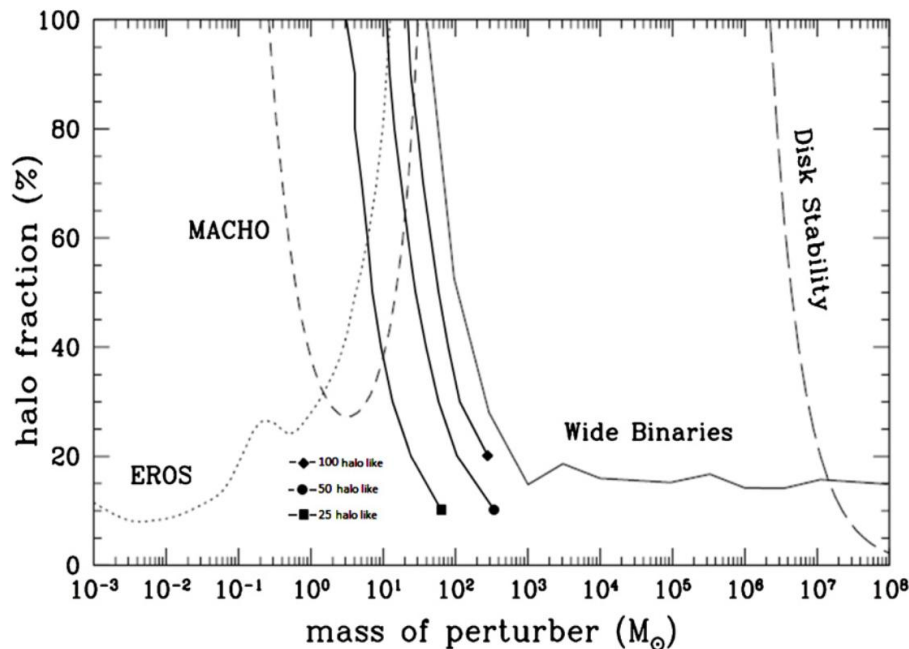
Badal Bhalla

Based on work with Aurora Ireland,
Hongwan Liu, Huangyu Xiao, Tao Xu.



MASSIVE ASTROPHYSICAL COMPACT HALO OBJECTS (MACHOS)

When dark matter was first discovered, the most obvious explanation was that the missing mass might consist of compact objects that emit very little light but are otherwise similar to known astrophysical objects such as planets, brown dwarfs, white dwarfs, neutron stars, or black holes.



The end of the MACHO era- revisited
Monroy-Rodríguez, Allen, APJ 2014



DARK COMPACT OBJECTS

Dark compact objects are predicted by various Beyond the Standard Model (BSM) theories and may constitute all or part of Dark Matter.

1. **Primordial Black Holes (PBHs)** **Collapse of overdense regions in the early universe.**
Carr et al. arXiv:1607.06077
2. **Axion Stars** **Gravitationally bound states of axions.**
Kolb et al. arXiv: hep-ph/9303313
3. **Q-Balls** **Stable, long-lived solitons**
Kusenko et al. arXiv: hep-ph/9712212
4. **Quark Nuggets** **Dense clumps of quark matter (up, down and strange quarks)**
Bai et al. arXiv:1810.04360
5. **Mirror Stars** **Astronomical objects composed of mirror matter**
Mohapatra et al., arXiv: astro-ph/9902085



PROBES OF DARK COMPACT OBJECTS

1. **Gravitational Lensing**

A massive object causes light passing nearby to bend, shifting, distorting, magnifying, or even duplicating the image of the background source.

2. **Dynamical Probes**

Heavy compact objects can significantly alter or even destroy the state of astrophysical entities like binary stars, globular clusters, or dwarf galaxies.

3. **Accretion**

Dark compact objects, such as primordial black holes (PBHs), can accrete matter, which begins to radiate, giving black holes (BHs) a large luminosity.

4. **Gravitational Waves**

Mergers of dark compact objects are loud gravitational wave sources.

Carr et al. 2306.03903, 2006.02838

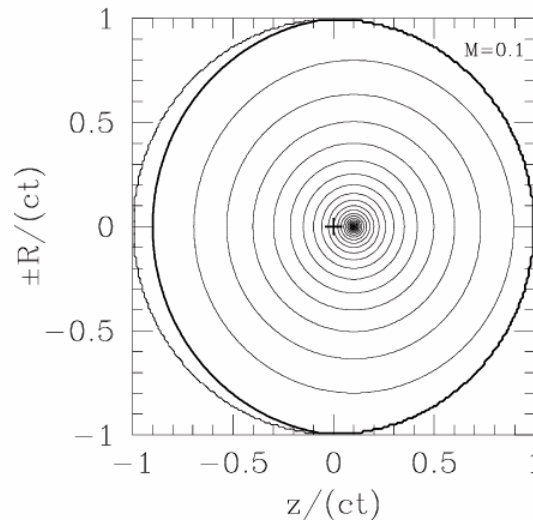
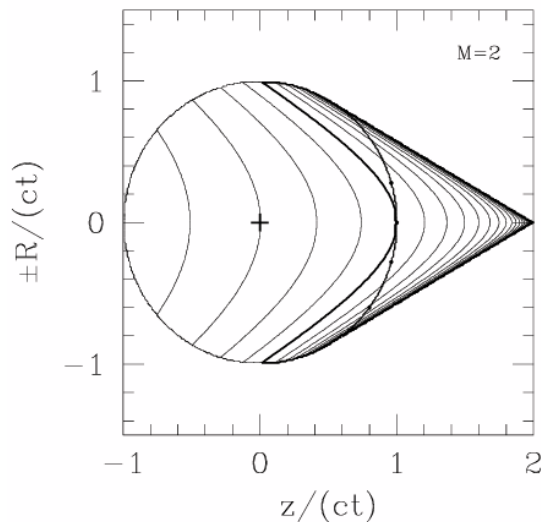


DYNAMICAL FRICTION

Dynamical friction (DF) refers to the deceleration experienced by a massive object moving through a background medium of lighter particles.

$$F_{\text{DF}}(M, v_{\text{rel}}) = \frac{4\pi G^2 M^2 \rho_{\text{B}}}{v_{\text{rel}}^2} \mathcal{I}(M, \Lambda)$$

$$\mathcal{I}(M, \Lambda) \approx \begin{cases} M^3/3, & M \ll 1, \\ \ln \Lambda, & M \gg 1. \end{cases} \quad \ln \Lambda \equiv \ln \left(\frac{b_{\text{max}}}{b_{\text{min}}} \right)$$



Ostriker..astro-ph/9810324



COULOMB LOGARITHM

The maximum impact parameter is $b_{max} = \mathcal{M}R_J$,
where R_J is the Jean's length given by

$$R_J = c_S \sqrt{\pi / G \rho_m}$$

For compact objects, we set b_{min} to
be the Bondi-Hoyle-Lyttleton radius

$$b_{min, M} = \frac{GM}{c_s^2 + v_{rel}^2}$$

For extended objects, we set this scale
to be the virial radius

$$b_{min, a} = 0.35 \mathcal{M}^{0.6} r_{vir}$$

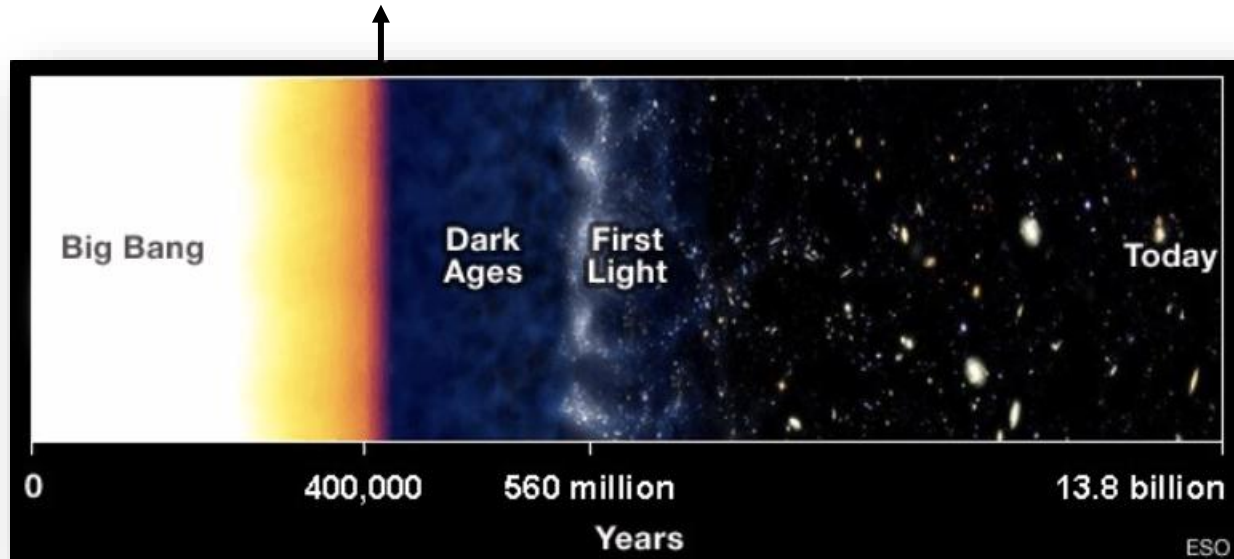


COSMIC DARK AGES

The hot Big Bang was an energetic, brilliantly luminous event. Today's Universe is alight with stars. But in between, the dark ages ruled.

- Big Think

The bulk relative velocity between baryons and DM at the time of recombination is 30 km/s

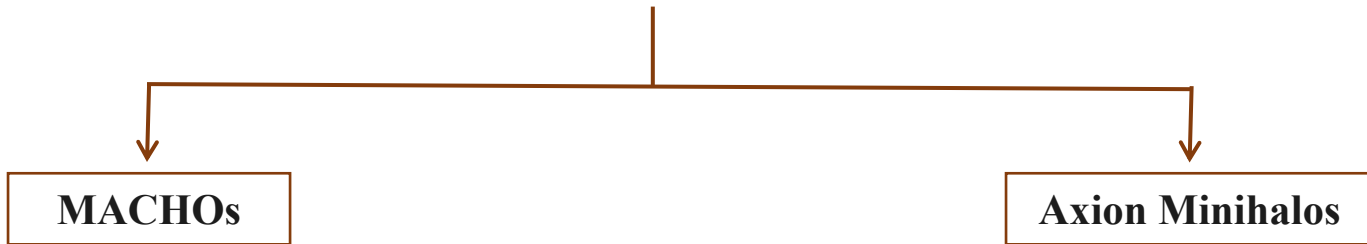


DYNAMICAL FRICTION DURING COSMIC DARK AGES

The DF heating rate per baryon is

$$\dot{Q}_{\text{DF}}(v_{\text{rel}}, z) = \frac{1}{n_{\text{B}}} \int dM \frac{\rho_{\text{DM}}}{M} \frac{df}{dM} v_{\text{rel}} F_{\text{DF}}$$

df/dM is the fraction of DM (by mass) in perturbers of mass M



$$df/dM' = f_{\text{M}} \delta(M' - M)$$

$$M_{\text{h,c}} \approx 1.5 \times 10^{-11} M_{\odot} \left(\frac{m_a}{10^{-6} \text{ eV}} \right)^{-2} \left(\frac{f_a}{10^{11} \text{ GeV}} \right)^{-2} g_{*,\text{osc}}^{-1/2}$$

$$\frac{df}{dM_{\text{h}}}(z) = \int_{z_{\text{eq}}}^z dz' \frac{df_{\text{col}}^{\text{CDM}}}{dz'} \frac{df_{\text{h}}}{dM_{\text{h}}}(z') + [1 - f_{\text{col}}^{\text{CDM}}(z)] \frac{df_{\text{h}}}{dM_{\text{h}}}(z)$$



DYNAMICAL FRICTION DURING COSMIC DARK AGES

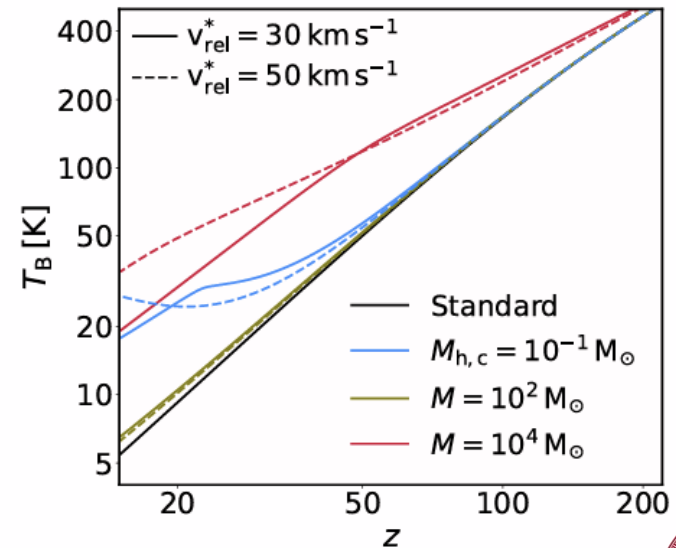
The DF heating rate per baryon is

$$\dot{Q}_{\text{DF}}(v_{\text{rel}}, z) = \frac{1}{n_{\text{B}}} \int dM \frac{\rho_{\text{DM}}}{M} \frac{df}{dM} v_{\text{rel}} F_{\text{DF}}$$

The resulting change in baryon temperature can be estimated by

$$\frac{dv_{\text{rel}}}{d \ln a} = -v_{\text{rel}} - \frac{F_{\text{DF}}}{MH},$$

$$\frac{dT_{\text{B}}}{d \ln a} = -2T_{\text{B}} + \frac{\Gamma_{\text{C}}}{H} (T_{\text{CMB}} - T_{\text{B}}) + \frac{2}{3} \frac{\dot{Q}_{\text{DF}}}{H}$$



21-CM SIGNAL FROM COSMIC DAWN

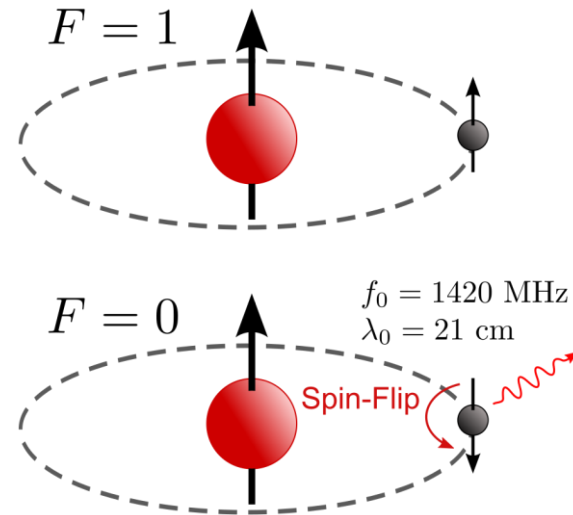
Neutral hydrogen in the ground state can emit 21-cm radiation through the hyperfine spin-flip transition.

The ratio between the number densities of hydrogen atoms in the two hyperfine levels defines the “spin temperature.”

$$\frac{n_1}{n_0} = \frac{g_1}{g_0} e^{-E_{21}/T_s} \approx 3 \left(1 - \frac{E_{21}}{T_s} \right)$$

The spin temperature is determined by the interactions between the two-level system and CMB photons, other hydrogen atoms, and Lyman- α radiation.

$$T_s^{-1} = \frac{T_{CMB}^{-1} + x_\alpha T_\alpha^{-1} + x_G T_{GAS}^{-1}}{1 + x_\alpha + x_G}$$



x_G, x_α are the coupling coefficients due to atomic collisions and scattering of Ly α photons.



OBSERVATION OF THE 21-CM SIGNAL FROM COSMIC DAWN

The absorption or emission of 21-cm blackbody CMB photons via the hyperfine transition of neutral hydrogen atoms at redshift z leads to a spectral distortion of the CMB at wavelength $21\text{cm} \times (1 + z)$, typically reported as a differential brightness temperature.

$$T_{21}(z) = \frac{1}{1+z} [T_S(z) - T_{CMB}(z)](1 - e^{-\tau(z)})$$

$\tau(z)$ is the optical depth of photons

The large-scale fluctuations of the relative velocity imply that two regions with different initial relative velocities will exhibit different brightness temperatures. The sky-averaged brightness temperature is

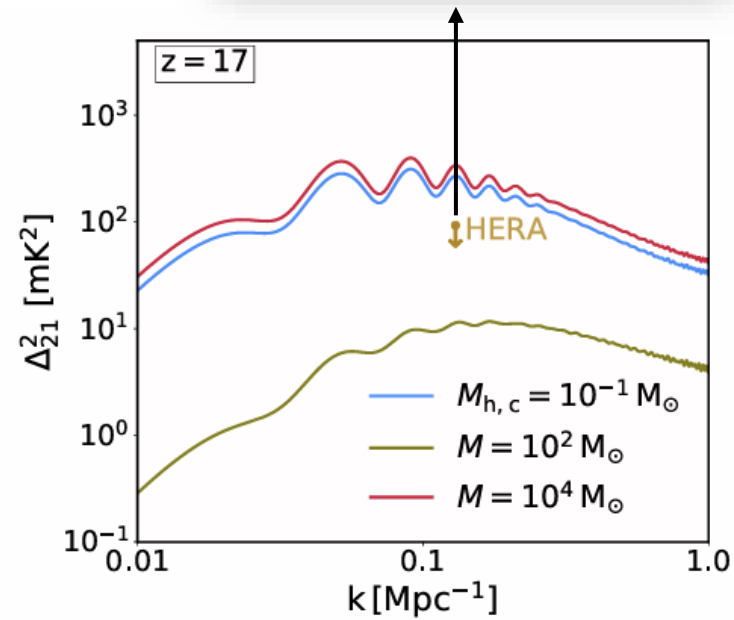
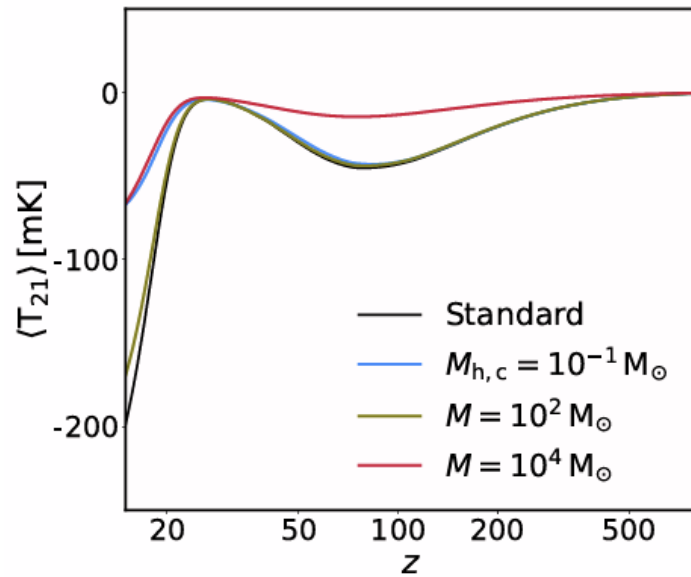
$$\langle T_{21} \rangle(z) = \int d^3 \vec{v}_{\text{rel}}^* f(\vec{v}_{\text{rel}}^*) T_{21}(v_{\text{rel}}^*, z)$$

$$\Delta_{21}^2(k, z) = \frac{2k^3}{\pi} \langle T_{21} \rangle^2(z) \int_0^\infty dr r^2 \xi(r) \frac{\sin(kr)}{kr}$$



OBSERVATION OF THE 21-CM SIGNAL FROM COSMIC DAWN

Forecasted Sensitivity by
HERA collaboration



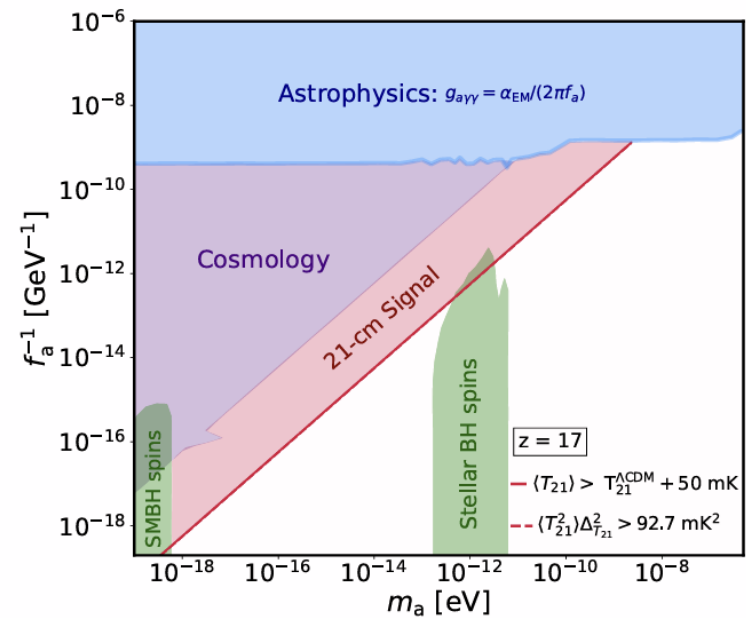
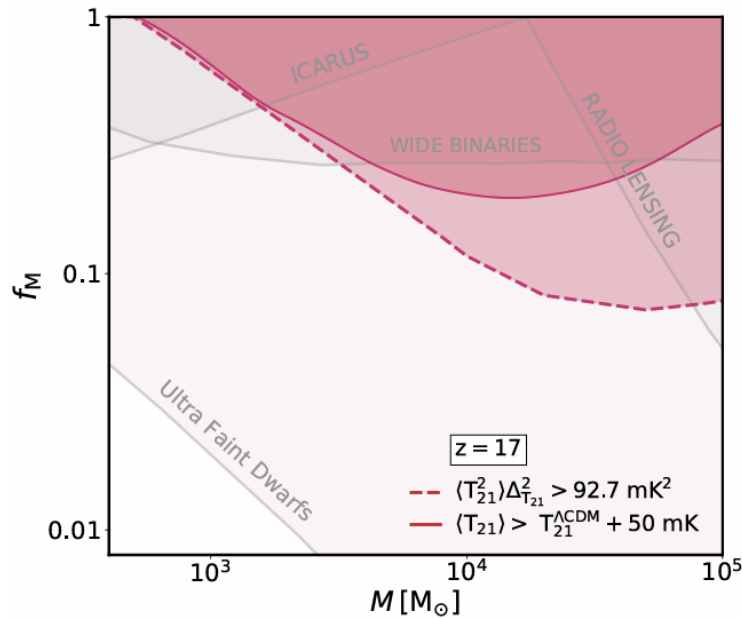
HERA Collaboration arXiv:2210.04912



FORECASTED SENSITIVITY OF THE 21-CM SIGNAL TO DARK OBJECTS

$$\langle T_{21} \rangle > \langle T_{21}^{LCDM} \rangle + 50 \text{ mK}$$

$$\Delta_{21}^2 > 92.7 \text{ mK}^2 \text{ for } k = 0.13 \text{ Mpc}^{-1} \text{ at } z = 17$$



SUMMARY

Dark compact objects or axion minihaloes are well motivated by physics beyond the Standard Model. They can explain all or a fraction of Dark Matter.

Future 21-cm observations provide a unique opportunity to explore Dark Compact Objects and Minihalos. Both the global 21-cm signal and its power spectrum can probe MACHO and axion parameter spaces.



THANK YOU !

“Dynamical Heating from Dark Compact Objects and Axion Mini-halos: Implications for the 21 cm Signal” BB, Aurora Ireland, Hongwan Liu, Huangyu Xiao, and Tao Xu. arXiv: 2512.00169

