Title: Constraining Primordial Magnetism

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Abstract: Primodial magnetic fields are a potentially interesting origin for cosmic magnetism. Such fields can leave an interesting signal not only in the CMB temperature and polarization, but in structure at low redshift, contributing to the matter power spectrum and SZ effect at small scales. I will talk about the reasons for considering primordial fields, their origin and evolution, and how their observational consequences constrain their nature.

Constraining Primordial Magnetism

Richard Shaw
with Antony Lewis

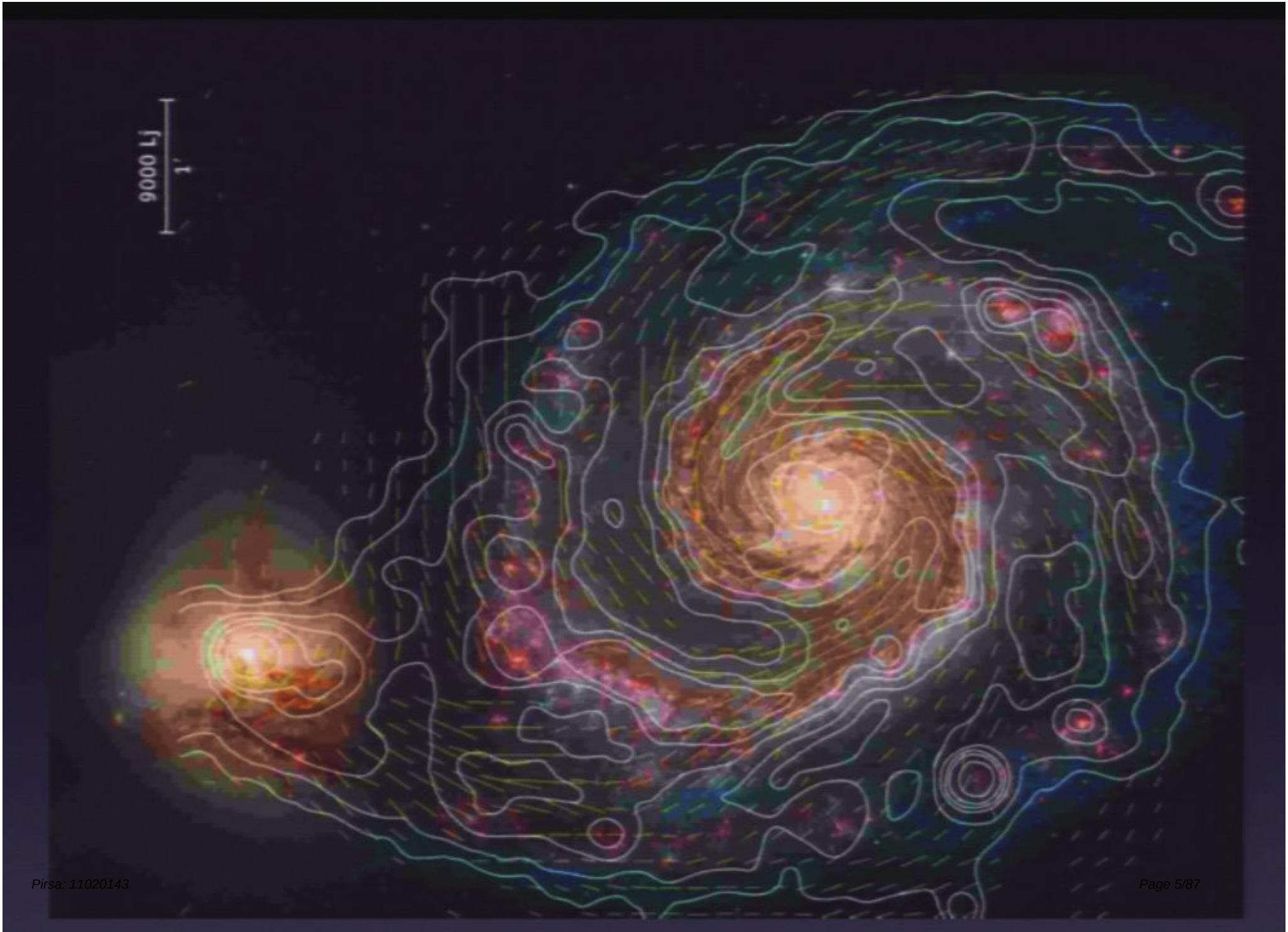
arXiv:0911.2714
arXiv:1006.4242

Magnetic Fields in the Universe

- Good review: Widrow 2002.
- Ubiquitous in gravitationally bound systems
  - Galaxies
  - Clusters
- Fields at the 1μG level (Earth ~ 1G)

Observations

- Synchrotron Emission
- Faraday Rotation
- Zeeman Splitting Measurements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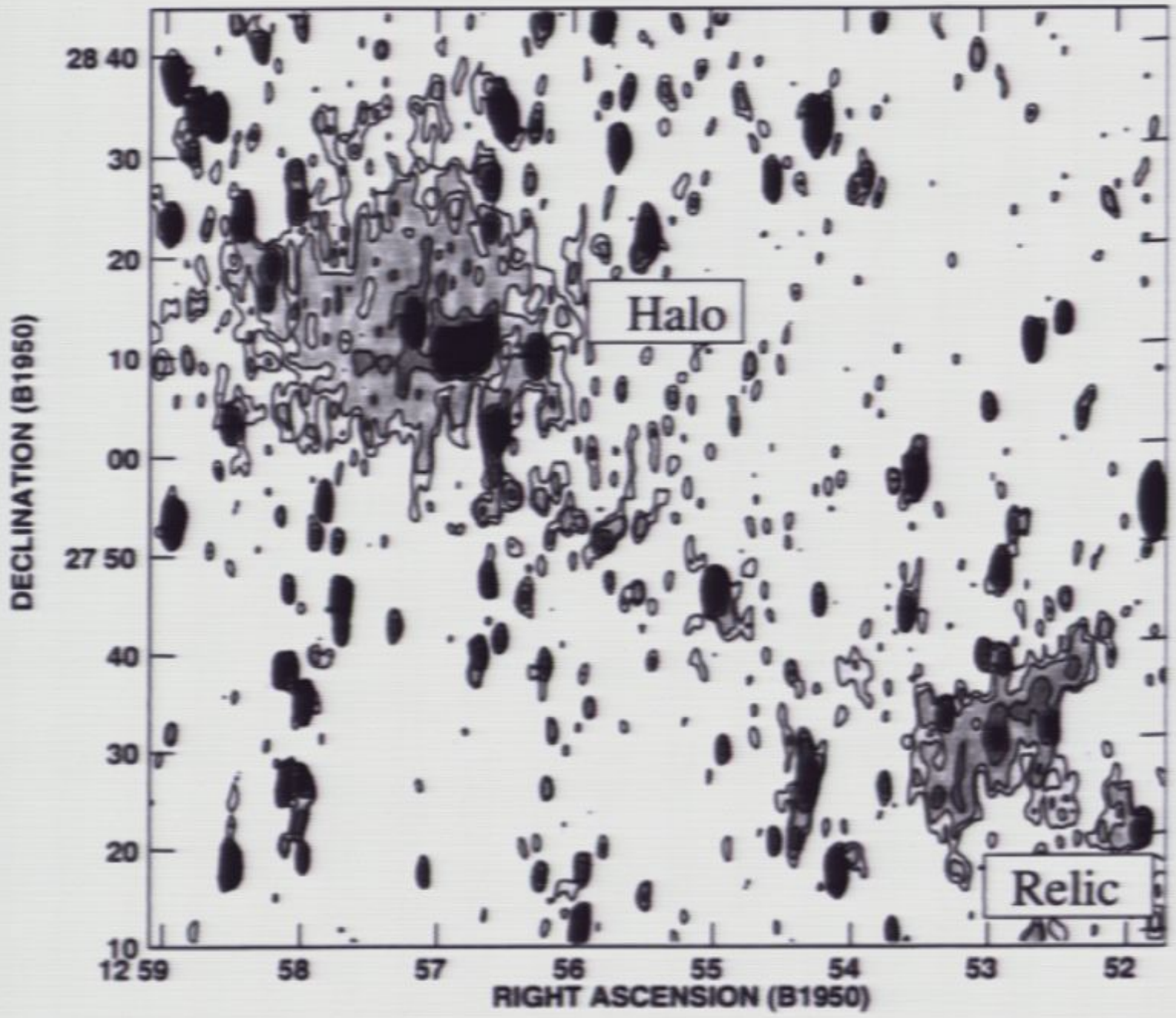
Galaxy Observations

- Hundreds of galaxies have magnetic field detections (1-10μG range)
- Observed in all types of galaxies
  - Spirals
  - Ellipticals
  - Dwarf Irregulars

Galaxy Observations

- Spirals exhibit coherence on scales comparable to their size
- Ellipticals much smaller coherence
- Galaxies observed with large fields at high-redshift: ~ 10μG at z ~ 0.7 (Bernet et al 2008; Wolfe et al 2008)


Halo
Relic
DECLINATION (B1950)
28 40
30
20
10
00
27 50
40
30
20
10
12 59
58
57
56
55
54
53
52
RIGHT ASCENSION (B1950)

Galaxy Clusters

- Clusters largest objects with confirmed magnetic fields
- Fields appear to be at the 0.1-3μG level

Intergalactic Fields

- Hints of fields on larger scales
- Radio emission suggests fields in superclusters of up to ~0.5 μG
- TeV Blazar observations suggest $B > 10^{-16}$ G in voids (Neronov et al 2010)

Origins

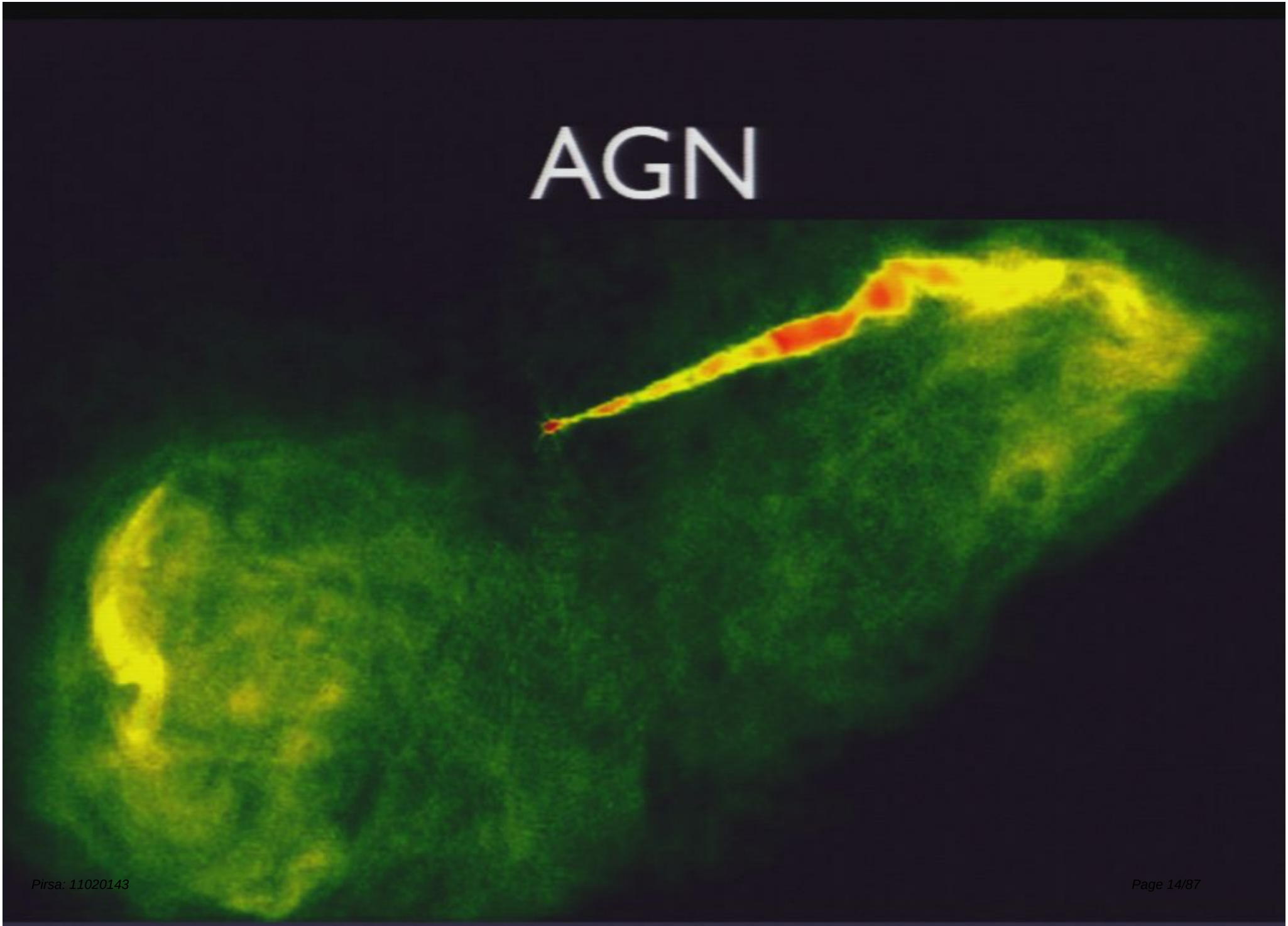
- Problem in astrophysics
- Difficult to produce fields within a galaxy, requires huge voltage to drive currents
- Usual method is to amplify seed fields produced by either
  - Pre-galactic Astrophysical process
  - Early Universe Mechanism

Adiabatic Amplification

- Need to amplify seed fields to today's observed levels
- Adiabatic growth of magnetic field in collapsing galaxy gives enhancement of around $\sim 10^3$–10^4 times
- Minimum field required $B \sim 10^{-10}\mathrm{G}$

Dynamo Amplification

- An effective dynamo can exponentially grow field, enhancement up $\sim 10^{14}$ times
- Minimum seed field: $B \sim 10^{-23}\mathrm{G}$
- Problems
  - Can dynamo survive back reaction?
  - Observations of high redshift galaxies
  - Mechanism in Ellipticals?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Supernova

Early Universe Origins

- Post inflationary mechanisms (causal)
- Generation at Electroweak or QCD phase transition
- Horizon problem, how do the small scale field propagate up to galactic scales?
  - Very strong small-scale fields to give weaker large scale fields
  - Inverse cascade from helical fields

Early Universe Origins

- Inflationary mechanisms (acausal)
- Can give scale invariant fields. Coherent fields in Galaxies, Clusters, Superclusters
- Also produce potential CMB signature
- Problem: naturally inflation produces tiny fields, $B \sim 10^{-100}\,\mathrm{G}$ needs a mechanism to break conformal symmetry. (Turner + Widrow 1988, Demozzi et al 2010)


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break co
Widrow

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Why look for Primordial Fields?

- Standard Inflation predicts tiny magnetic fields on large scales.
- Not observing large scale magnetic fields is a validation of this.
- Finding a signal of them suggests something interesting is going on.

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Primordial Magnetism

- Universe is a good conductor so field is frozen in
- Field $B^i(x^j,\tau) = B^i(x^j)/a(\tau)^2$ defining comoving field
- Contribute to energy-momentum tensor

$$T_0^0 = -\frac{1}{8\pi a^4} B^2(\mathbf{x}) \,,$$

$$T_j^i = \frac{1}{4\pi a^4}\left(\frac{1}{2}B^2(\mathbf{x})\delta_j^i - B^i(\mathbf{x})B_j(\mathbf{x})\right) \,.$$


$T_0^0 \equiv -$
$T_j^i = \frac{}{4\pi}$

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Primordial Magnetism

- Define a density and anistropic stress perturbation via

$$T^0_0 = -\rho_\gamma \Delta_B \ ,$$
$$T^i_j = p_\gamma \left(\Delta_B \delta^i_j + \Pi_B{}^i{}_j \right) \ ,$$

- Perturbations are constant in time
- As $\Delta_B \propto B^2(x^i)$, perturbation is manifestly non-gaussian

Early Evolution

- Imagine magnetic fields are produced at time τ_B prior to neutrino de-coupling τ_ν
- Photons, neutrinos, and baryons tightly bound. Zero anisotropic stress.
- Comoving curvature grows logarithmically

$$\zeta(\tau) = \zeta(\tau_B) - \frac{1}{3} R_\gamma \Pi_B \log\left(\tau/\tau_B\right)$$

- After τ_ν , decoupled neutrino stress grows. Total anisotropic stress quickly zero.

- Three types of perturbation generated
  - Passive: Adiabatic-like mode

$$\zeta(\tau) \propto \Pi_B \log\left(\tau_\nu/\tau_B\right)$$

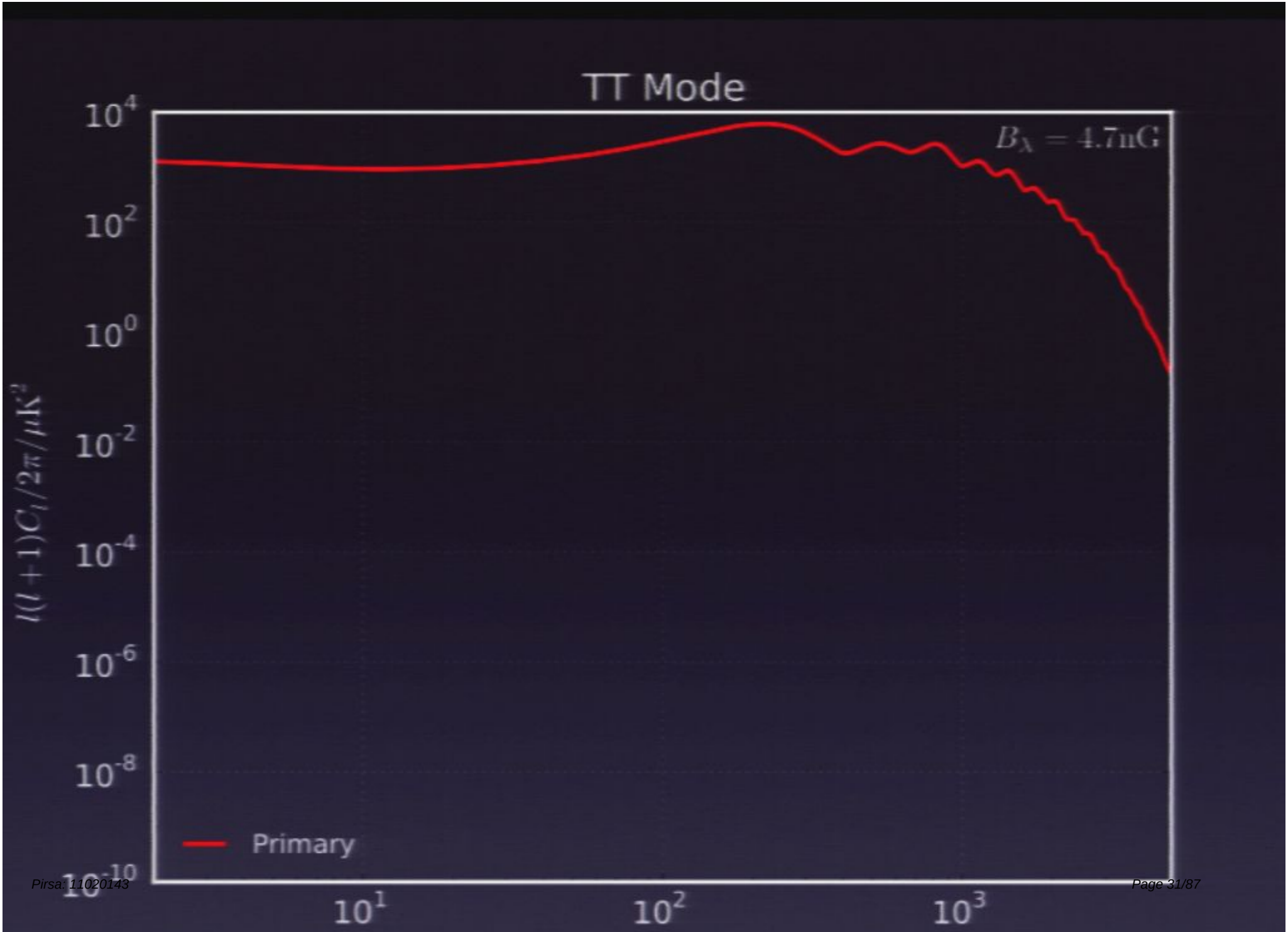
  - Compensated magnetic stress mode (non-zero anisotropic stresses) $\propto \Pi_B$
  - Compensated density mode (all non-zero density perturbation) $\propto \Delta_B$
- Similar for tensor (compensated and passive mode) and vector (compensated only)

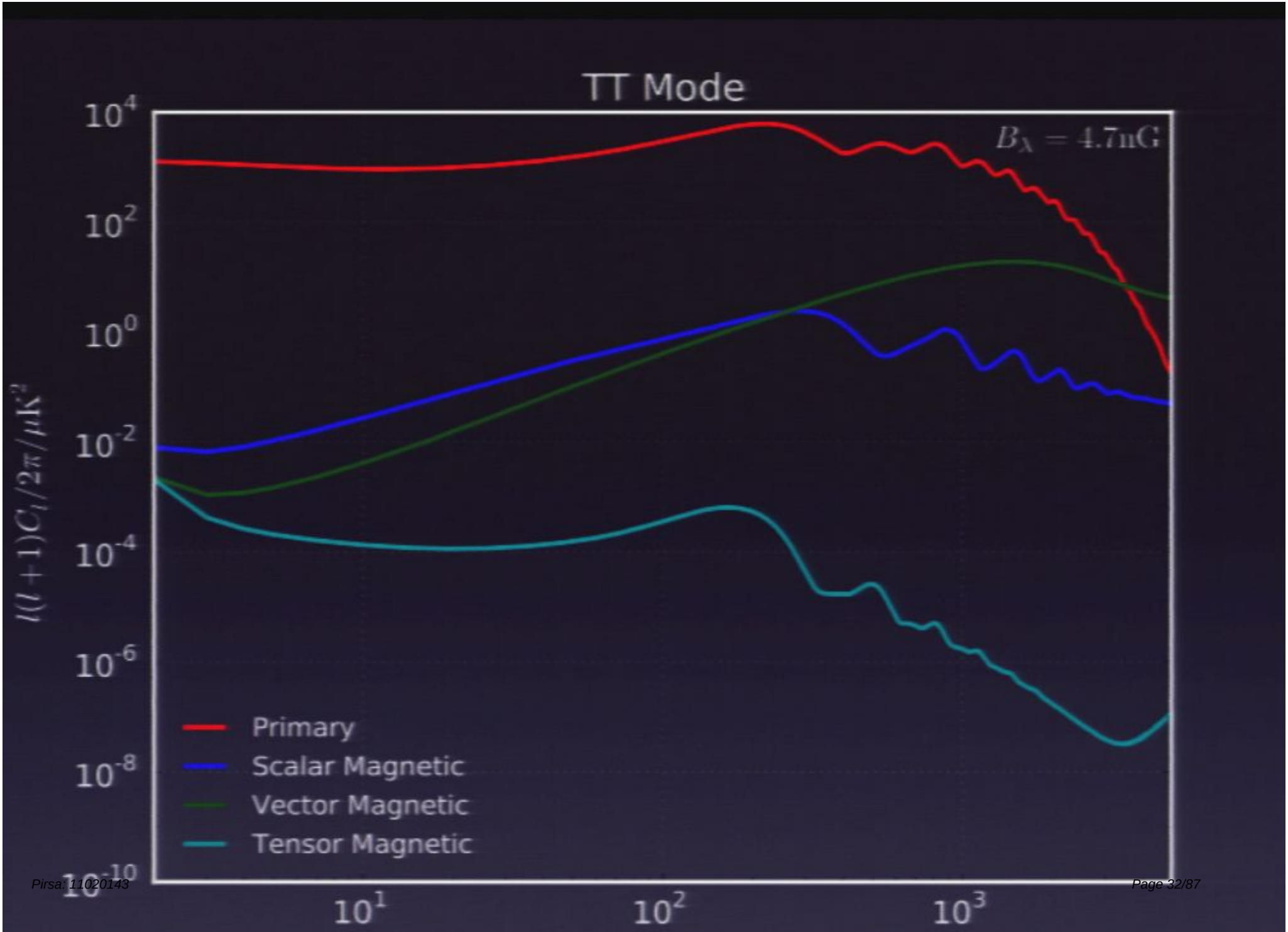
Statistics

- Magnetic field statistics gaussian with

$$\left\langle B_i(\mathbf{k}) B_j^*(\mathbf{k}') \right\rangle = (2\pi)^3 \delta(\mathbf{k} - \mathbf{k}') \frac{P_{ij}(\hat{k})}{2} P_B(k)$$

- Power spectrum $P_B(k) = Ak^{n_B}$
- Amplitude set by variance B_λ^2 at 1 Mpc
- We treat diffusion damping of magnetic field (Subramanian and Barrow 1997) and magnetic Jeans effect with evolving perturbations


TT Mode
$B_\lambda = 4.7\mathrm{nG}$
10^4
10^2
10^0
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
$l(l+1)C_l/2\pi/\mu\mathrm{K}^2$
Primary
10^1
10^2
10^3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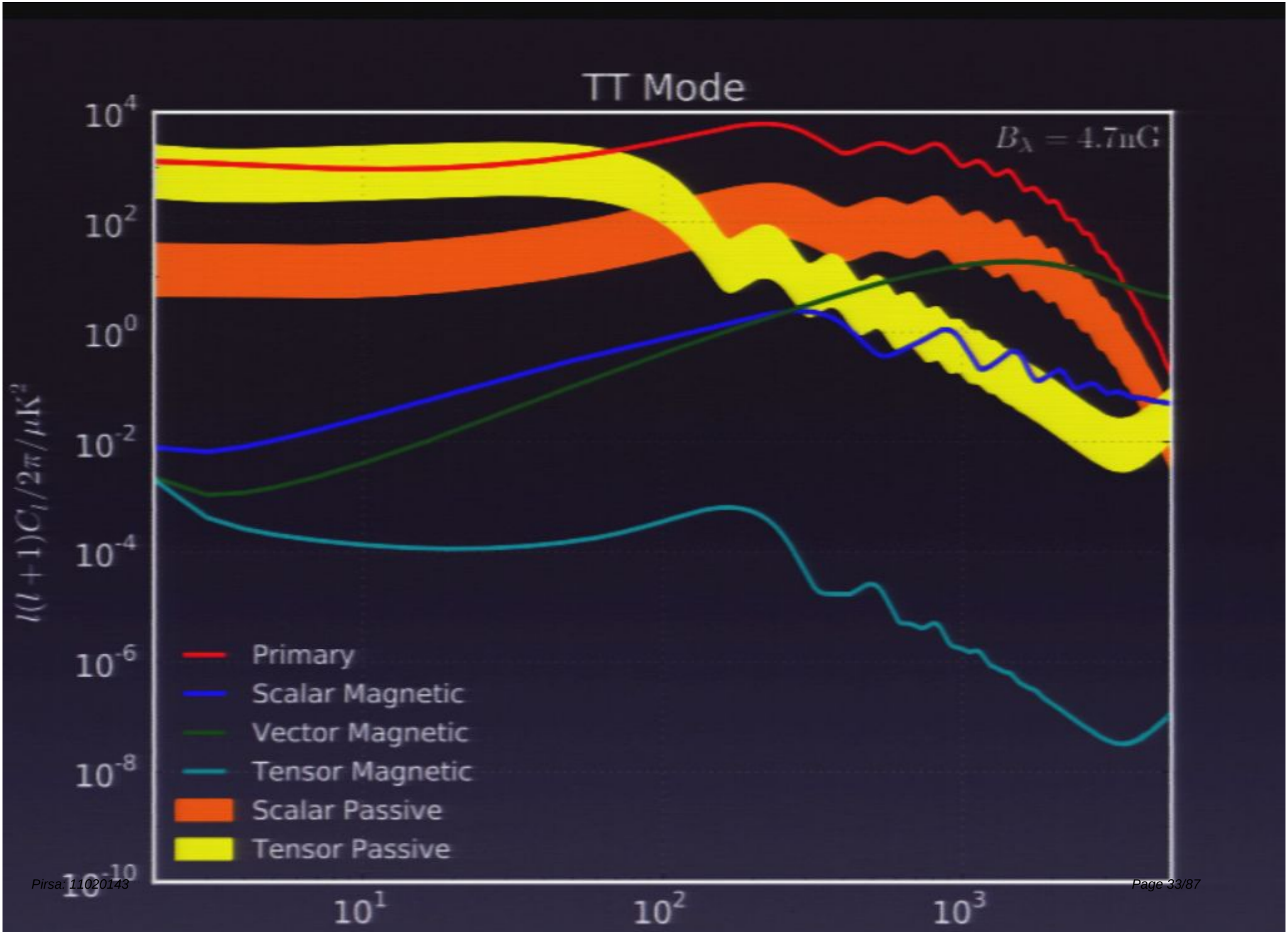
10^4
10^2
10^0
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
10^1
10^2
10^3
Primary
Scalar Magnetic
Vector Magnetic
Tensor Magnetic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10^4
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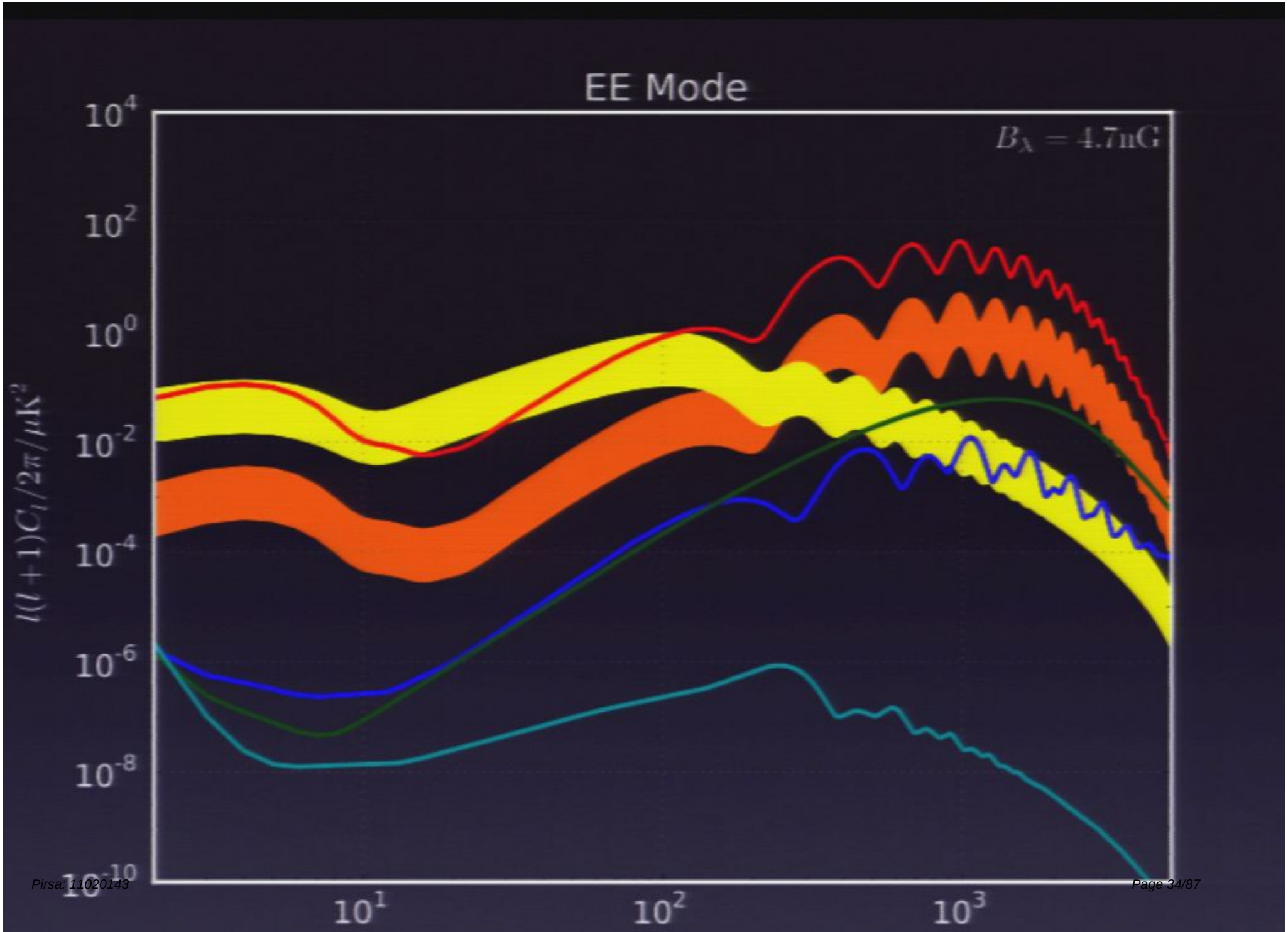
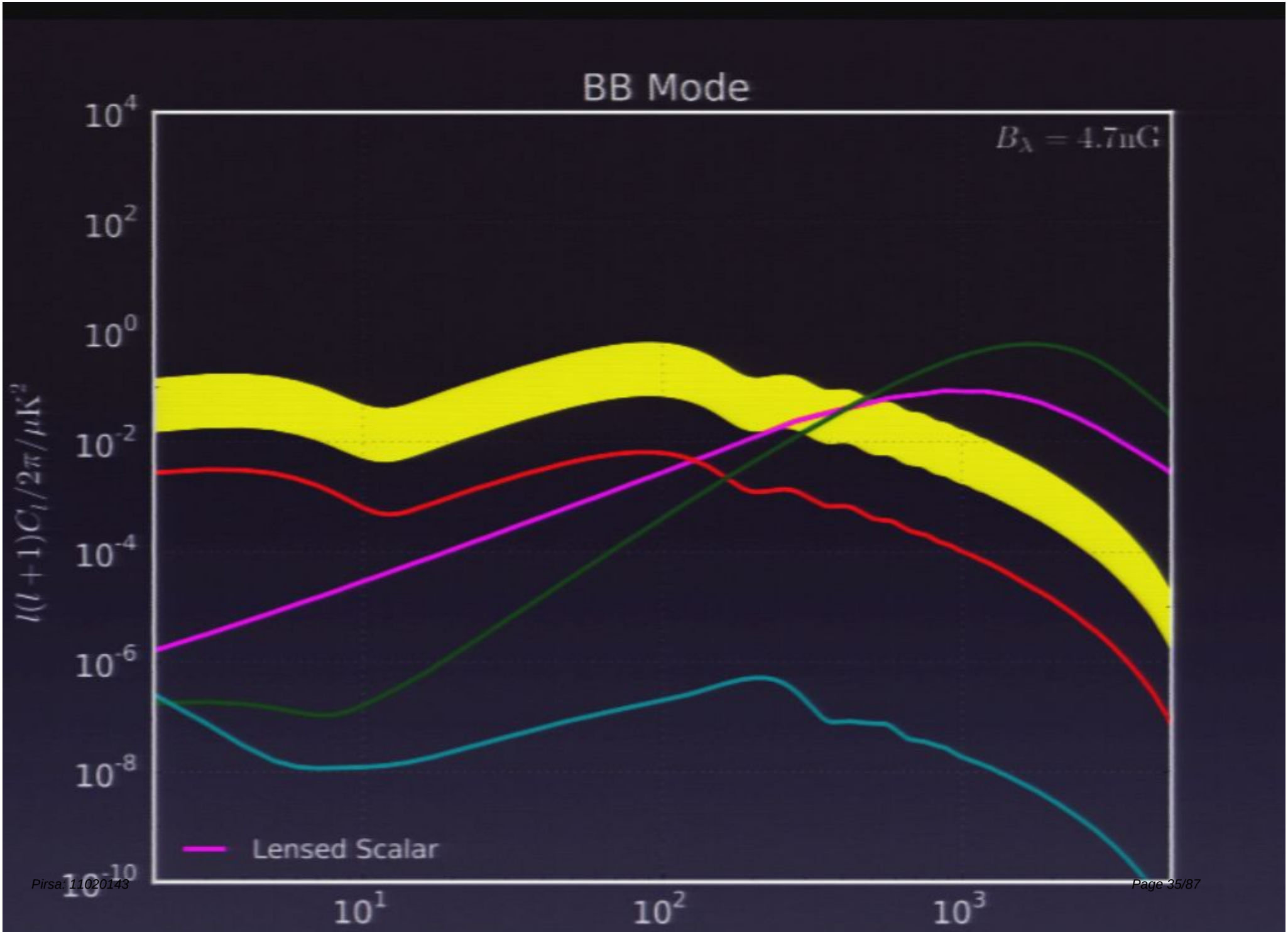
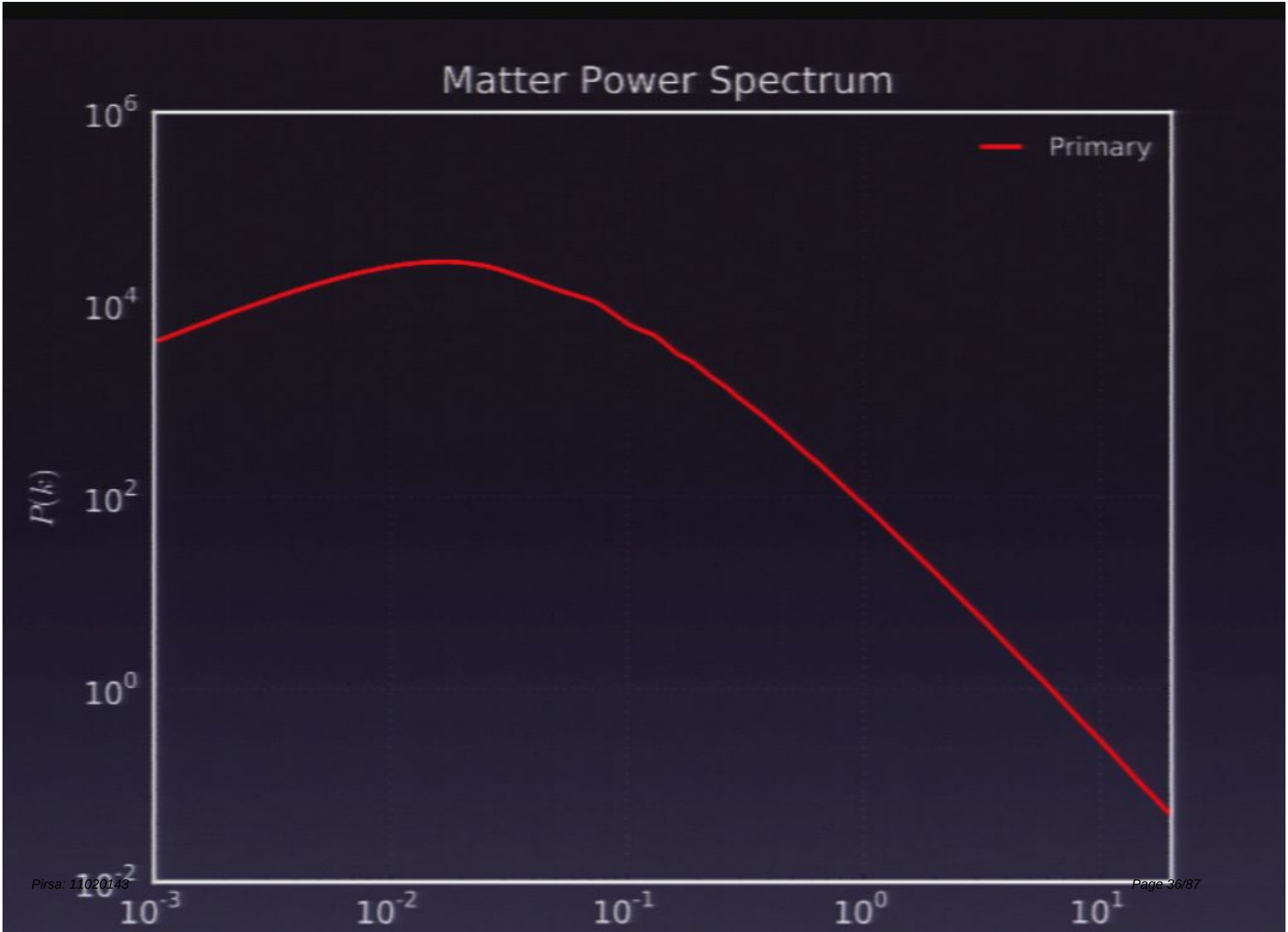
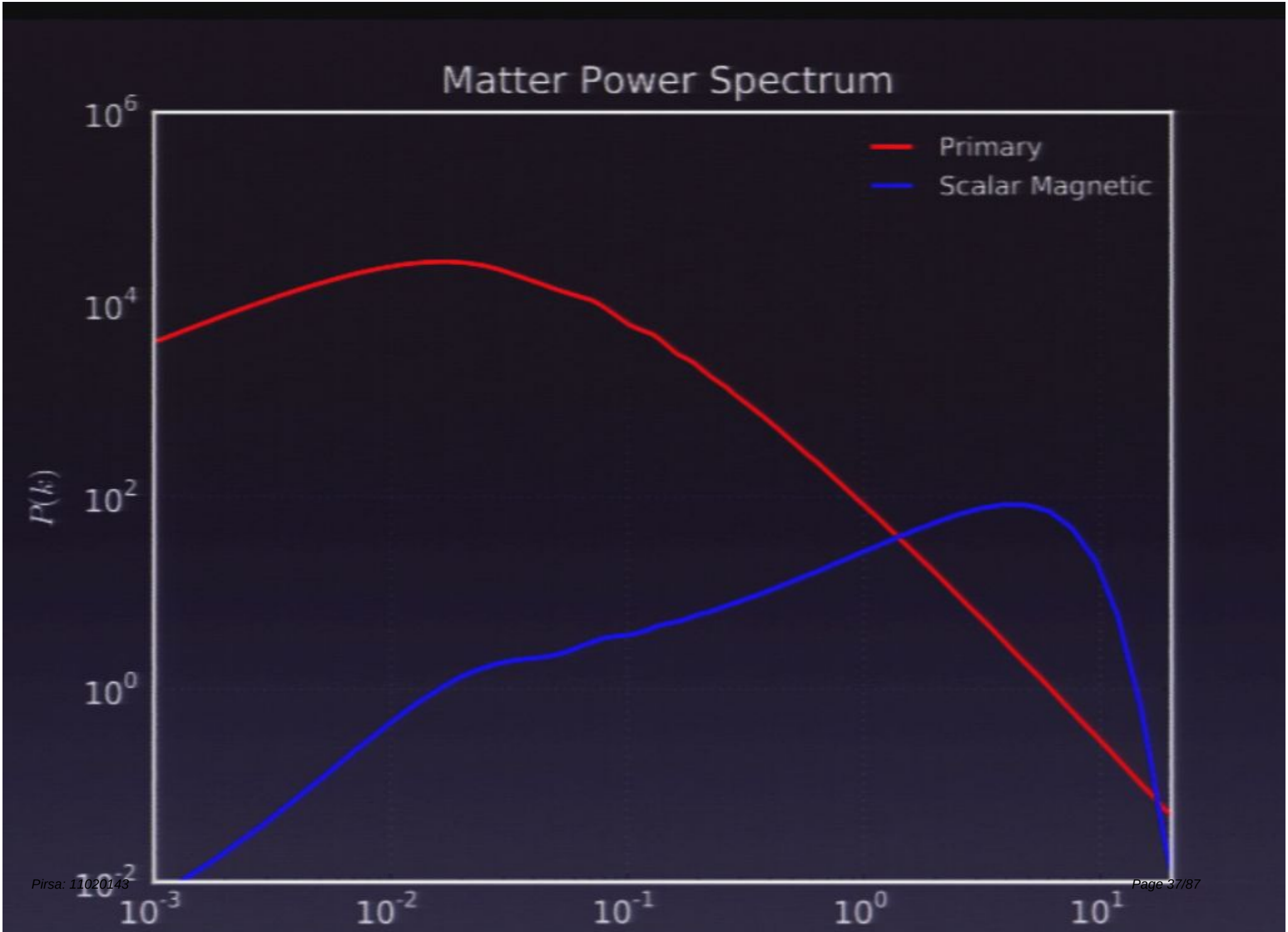
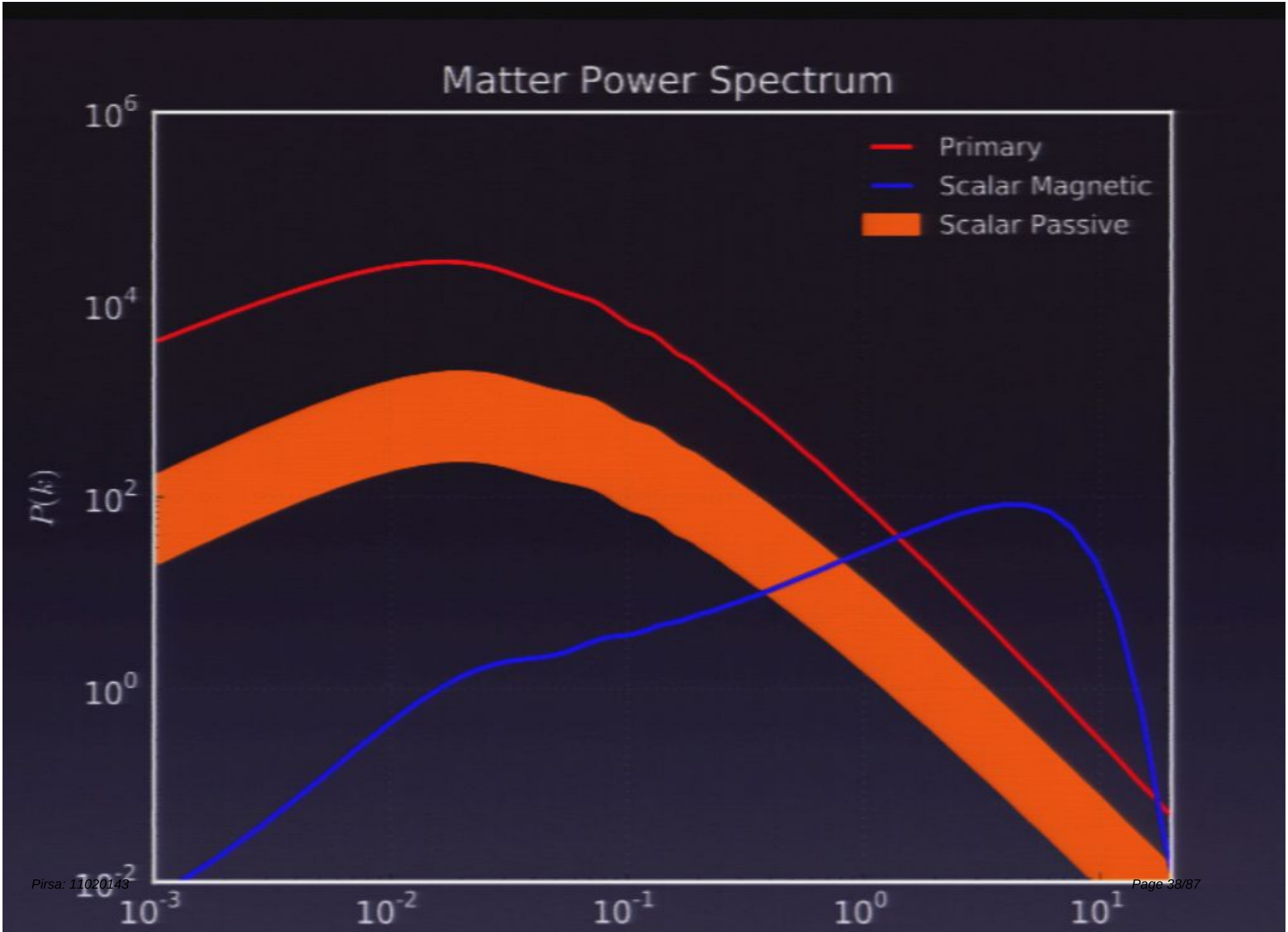
10^{-6}
10^{-8}
10^{-10}
10^1
10^2
10^3
Primary
Scalar Magnetic
Vector Magnetic
Tensor Magnetic
Scalar Passive
Tensor Passive

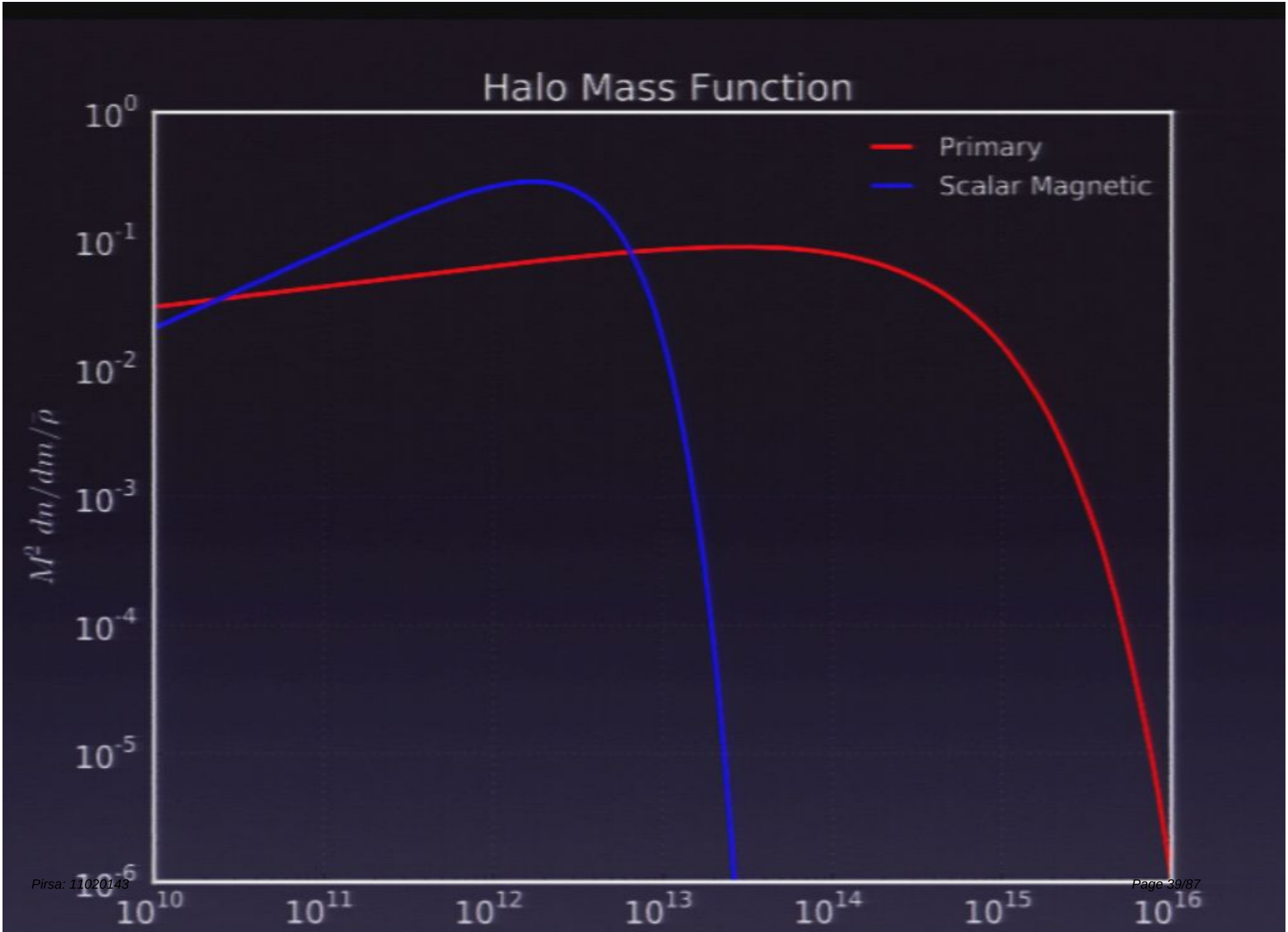

EE Mode
$B_\lambda = 4.7\mathrm{nG}$
10^4
10^2
10^0
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
$l(l+1)C_l/2\pi/\mu\mathrm{K}^2$
10^1
10^2
10^3


BB Mode
$B_\lambda = 4.7\mathrm{nG}$
$l(l+1)C_l/2\pi/\mu\mathrm{K}^2$
10^4
10^2
10^0
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
10^1
10^2
10^3
Lensed Scalar

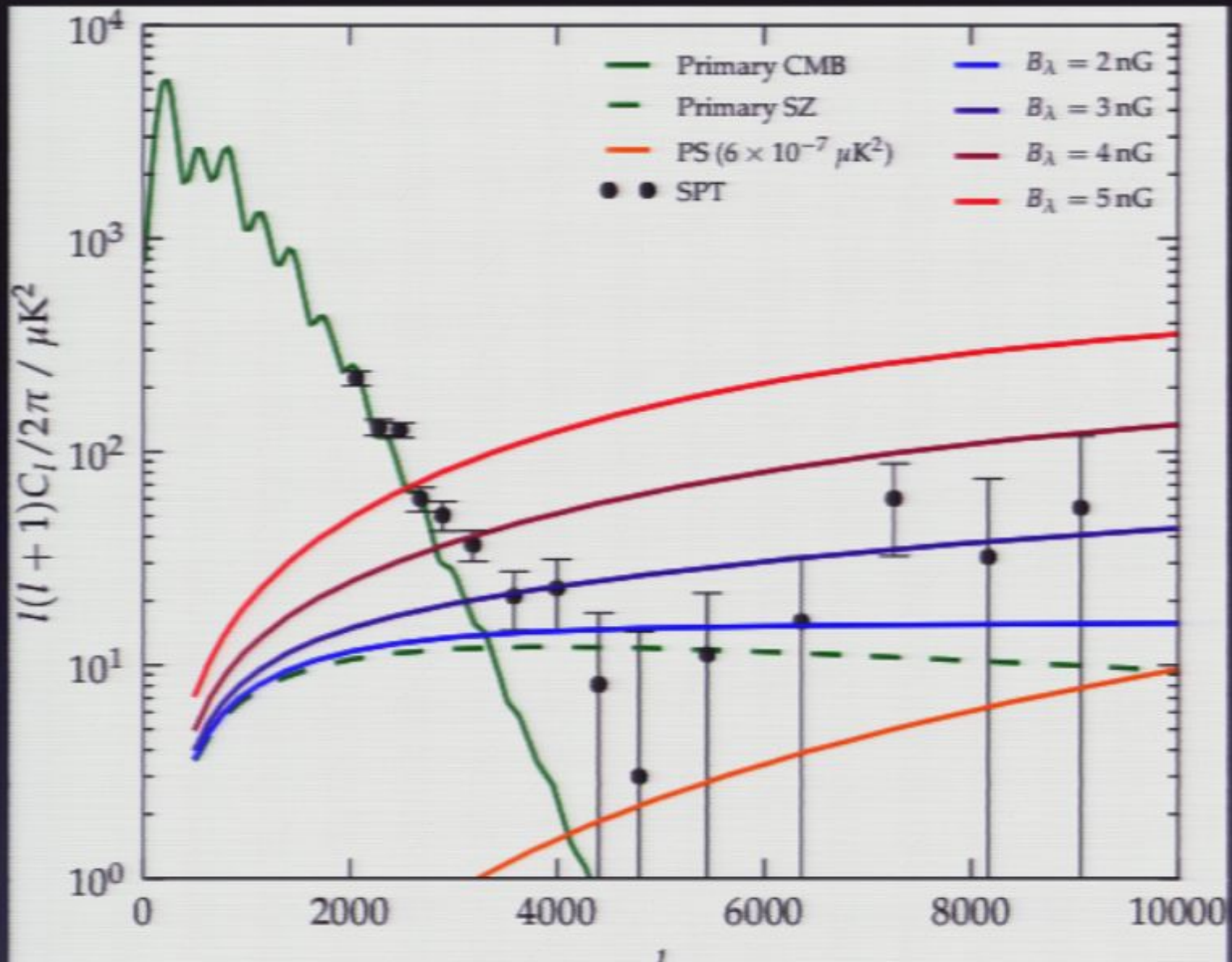

Matter Power Spectrum
Primary
$P(k)$
10^{6}
10^{4}
10^{2}
10^{0}
10^{-2}
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}


Matter Power Spectrum
Primary
Scalar Magnetic
$P(k)$
10^{6}
10^{4}
10^{2}
10^{0}
10^{-2}
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}


Matter Power Spectrum
Primary
Scalar Magnetic
Scalar Passive
$P(k)$
10^6
10^4
10^2
10^0
10^{-2}
10^{-3}
10^{-2}
10^{-1}
10^0
10^1


Halo Mass Function
Primary
Scalar Magnetic
$M^2\, dn/dm/\rho$
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{10}
10^{11}
10^{12}
10^{13}
10^{14}
10^{15}
10^{16}

Sunyaev Zel'dovich Effect from Magnetic Fields



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  - Small scale Matter power (scalar compensated), including contributions to SZ and Lyman Alpha

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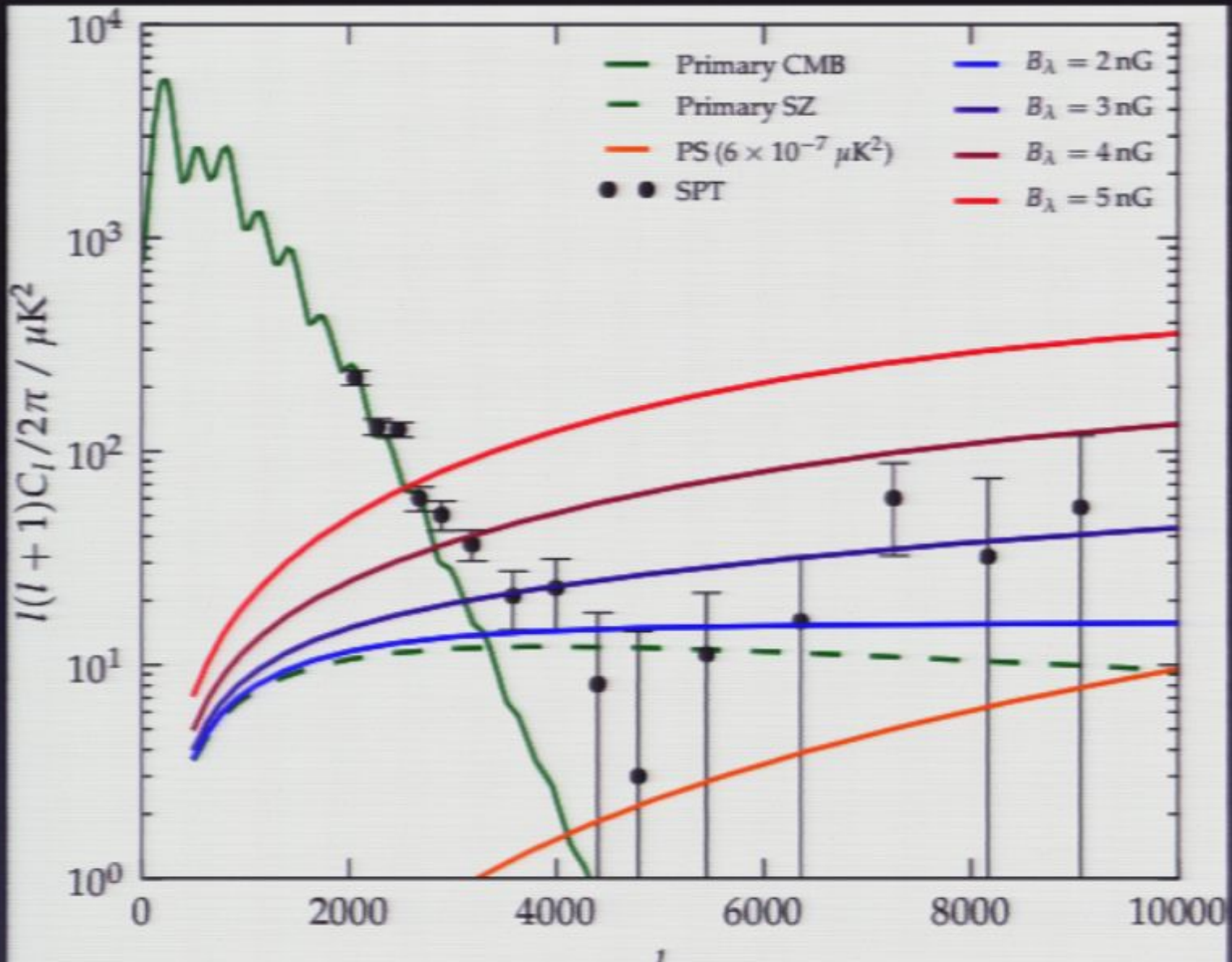

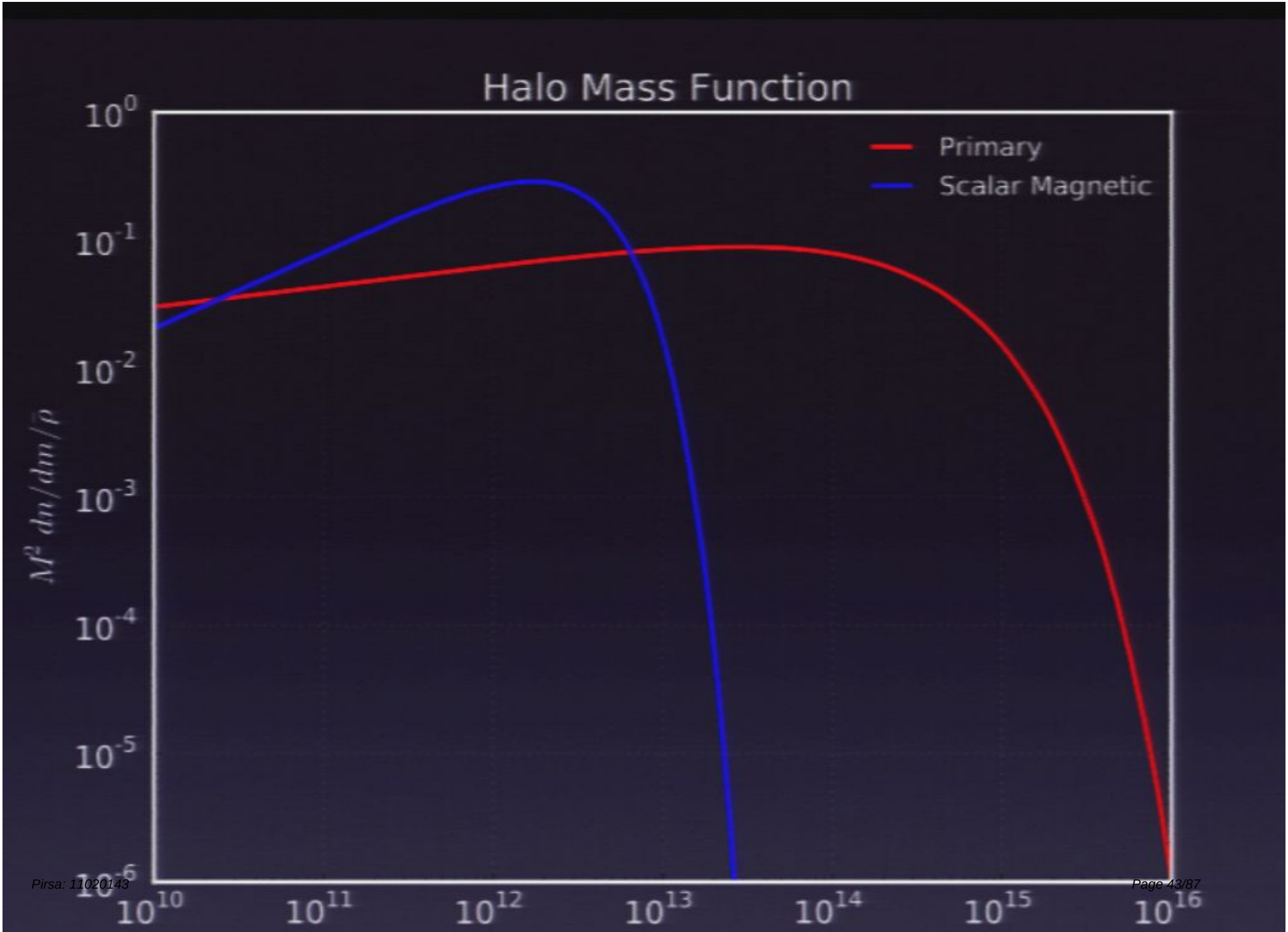
Halo Mass Function
Primary
Scalar Magnetic
$M^2\, dn/dm/\bar{\rho}$
10^0
10^{-1}
10^{-2}
10^{-3}
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10^{-6}
10^{10}
10^{11}
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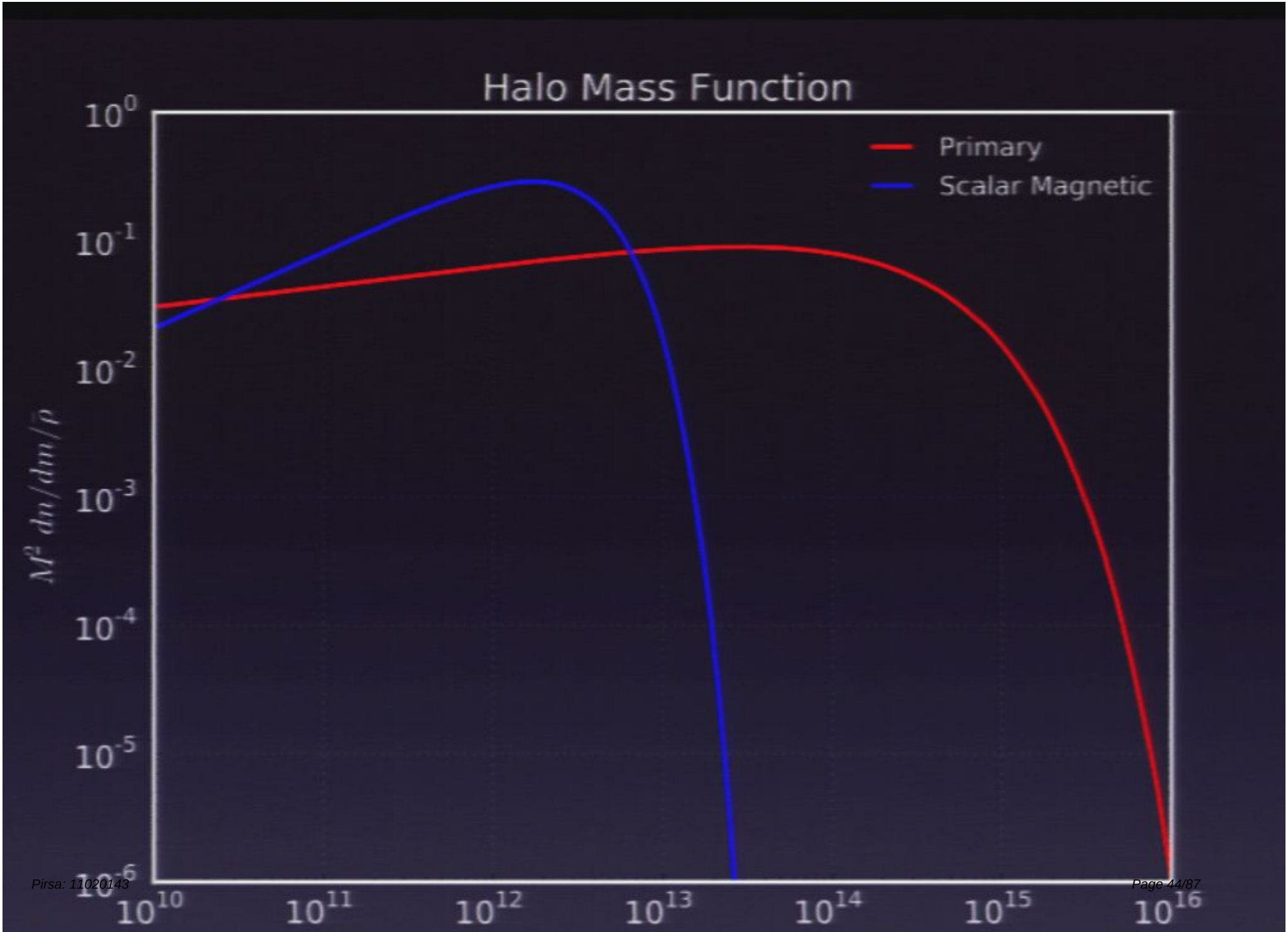
10^{16}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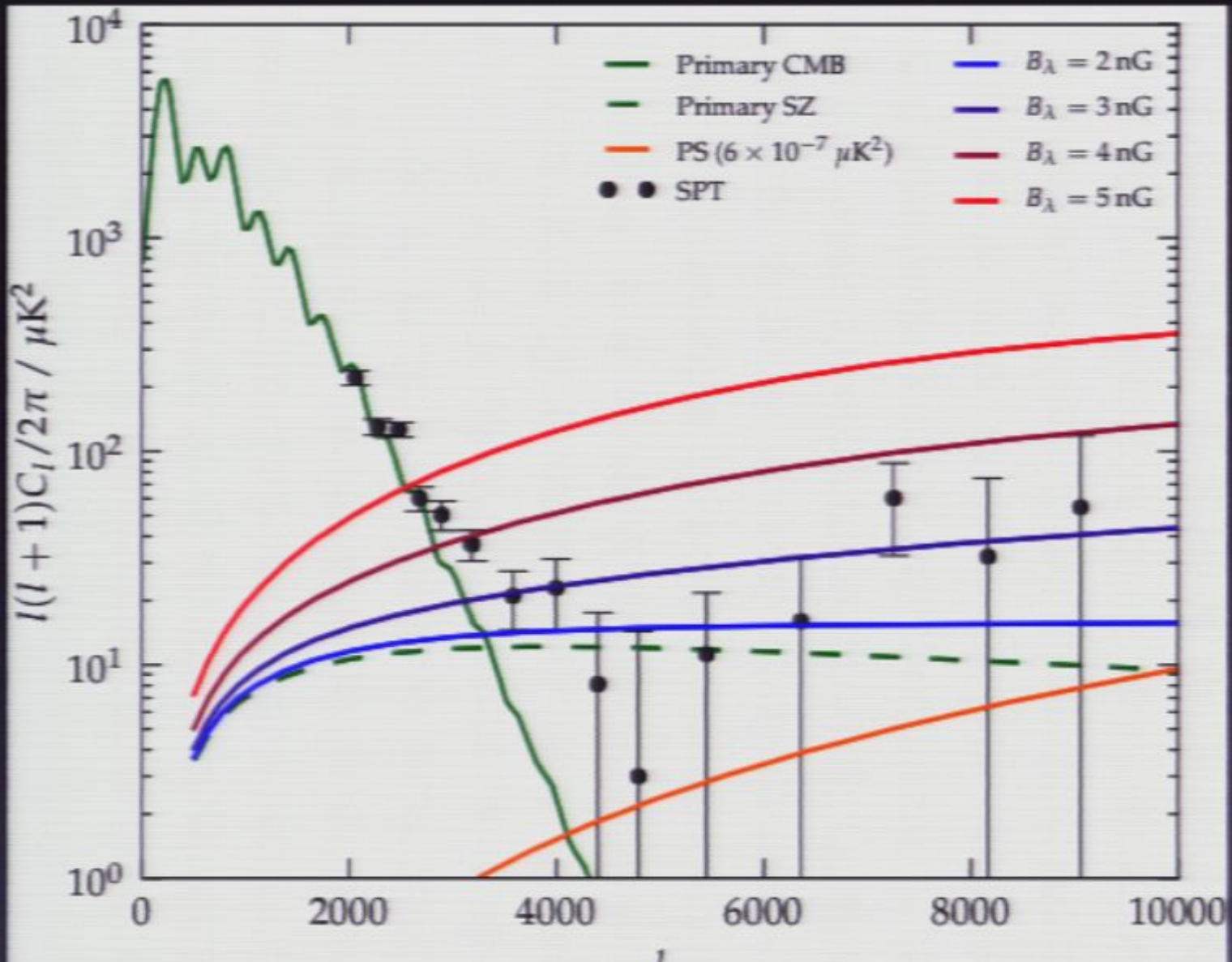
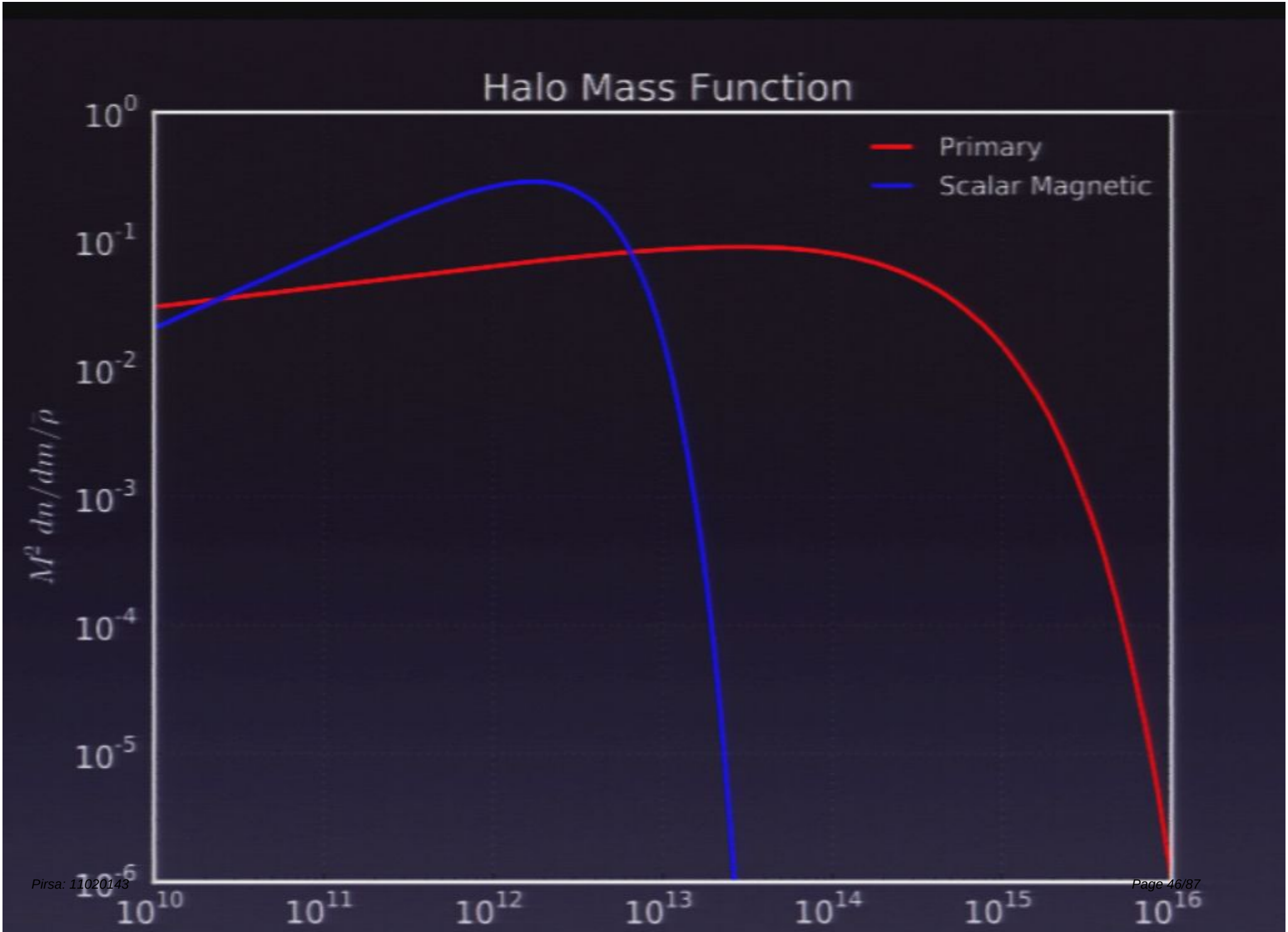
Sunyaev Zel'dovich Effect from Magnetic Fields

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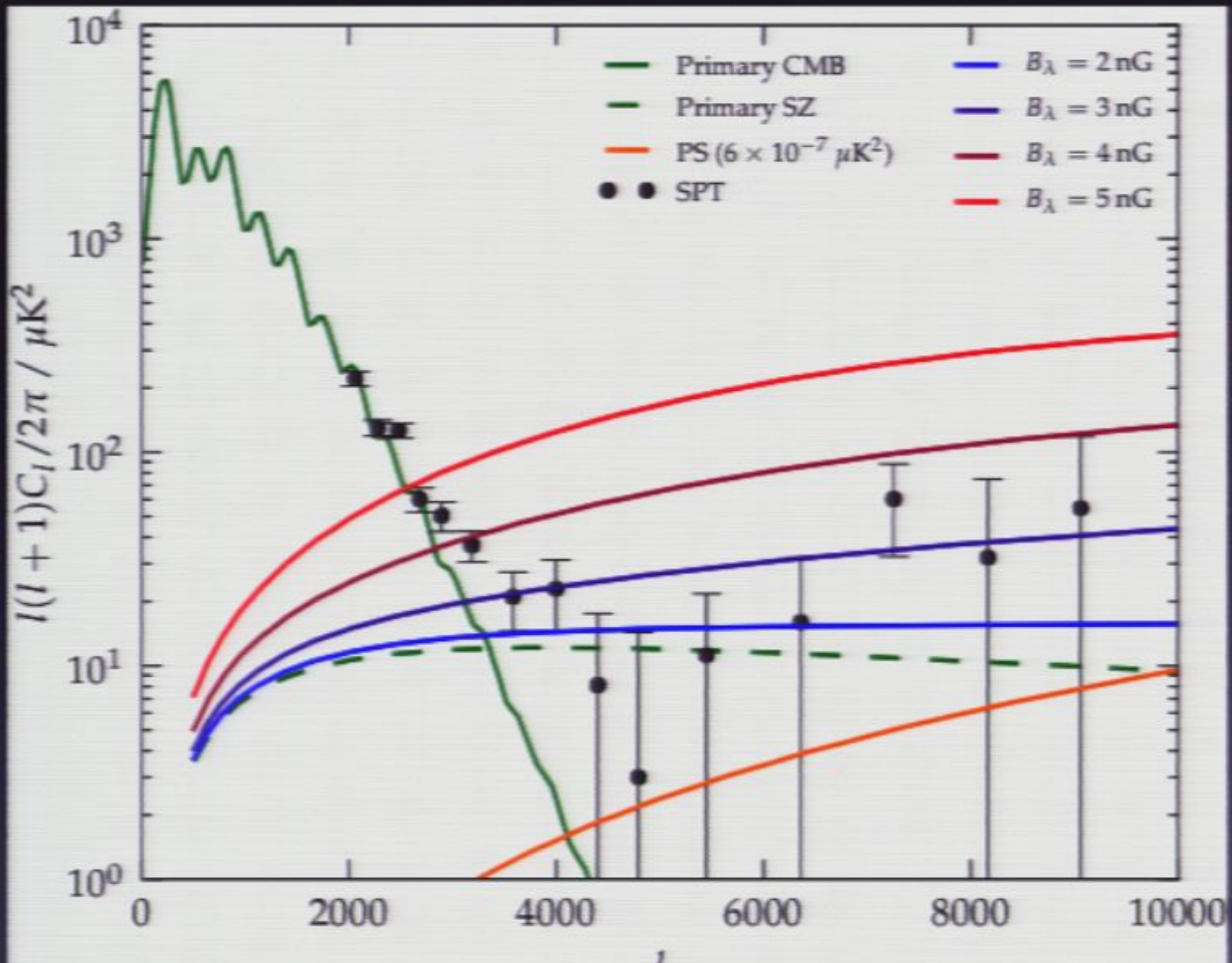

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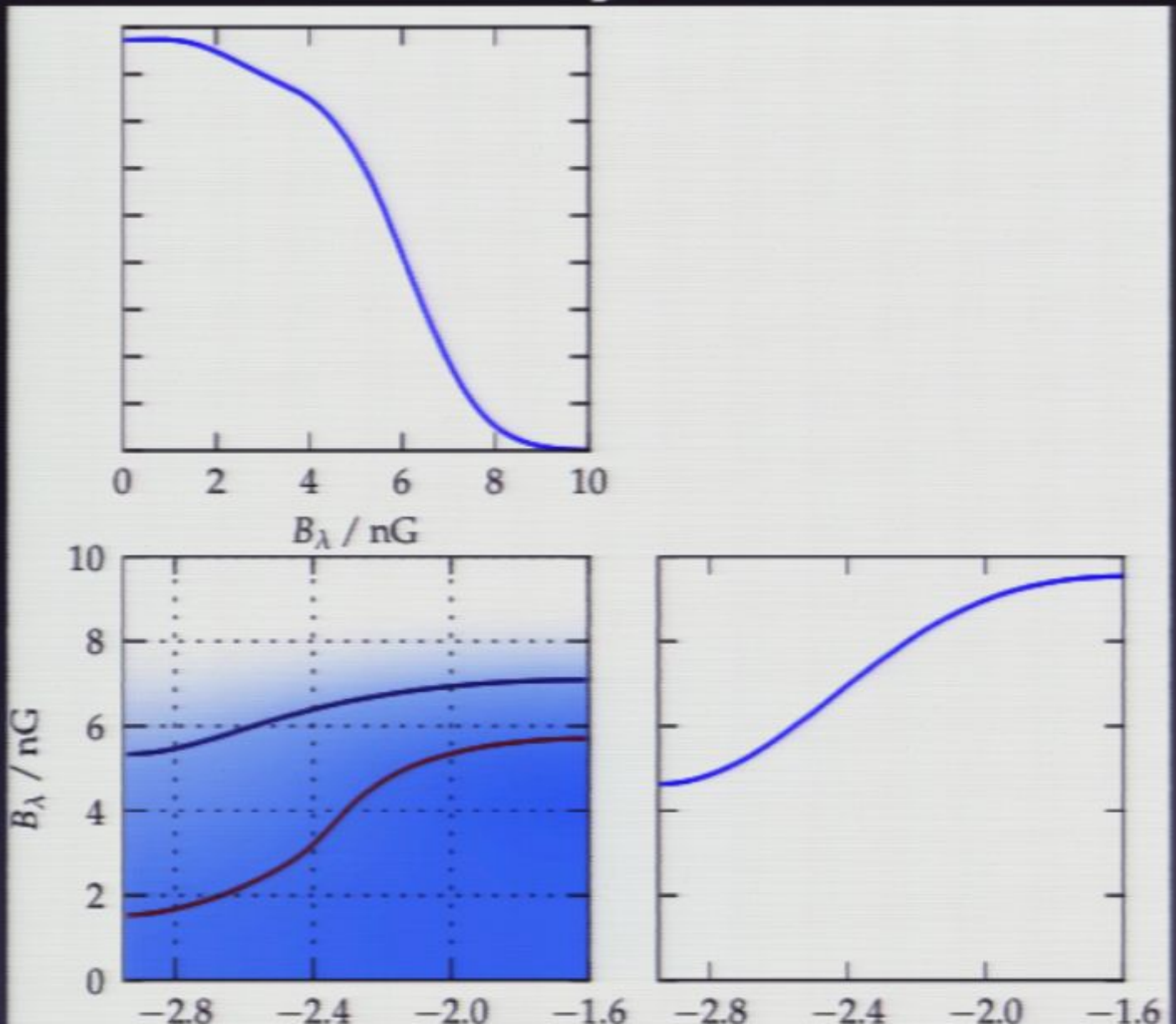
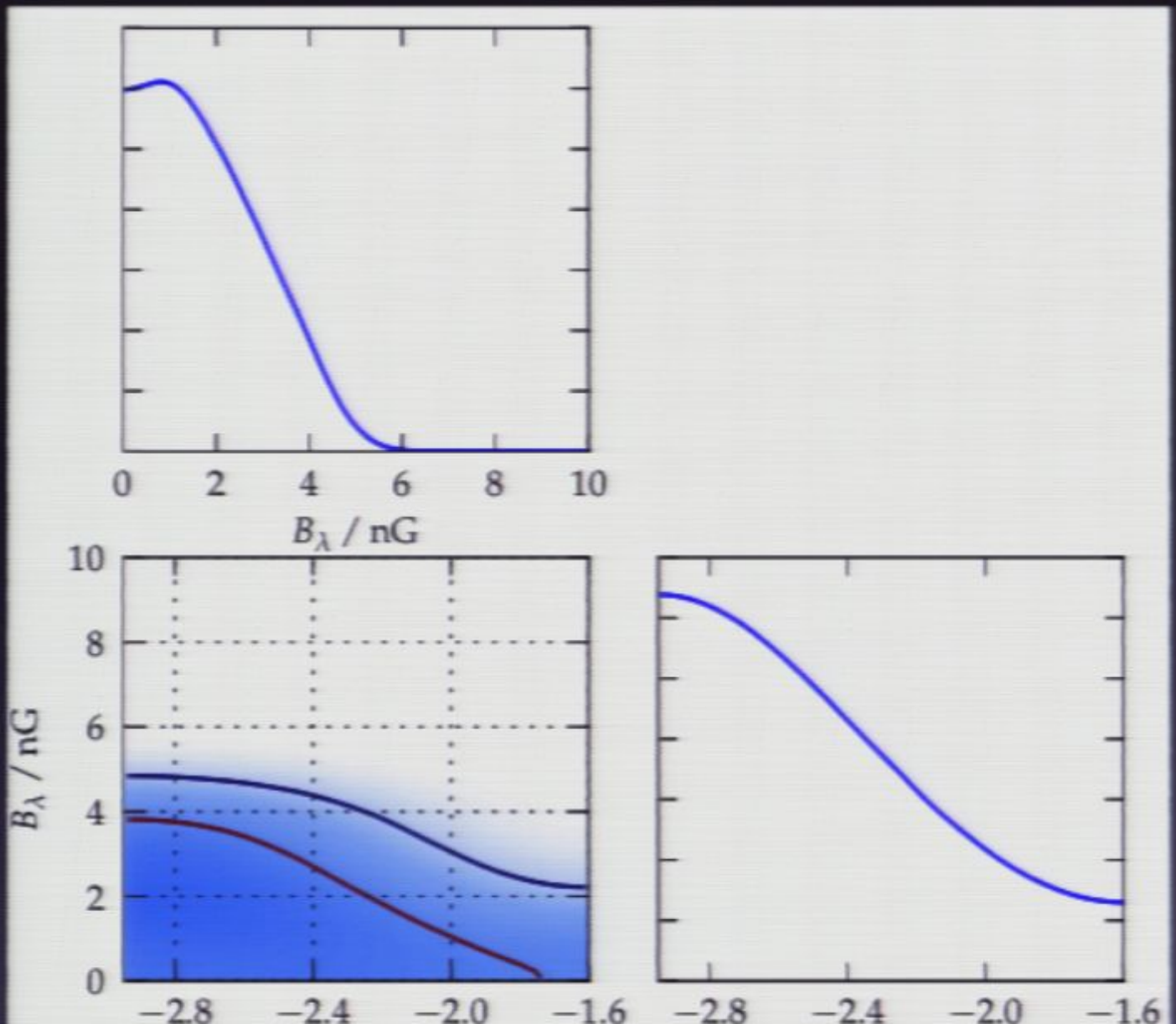
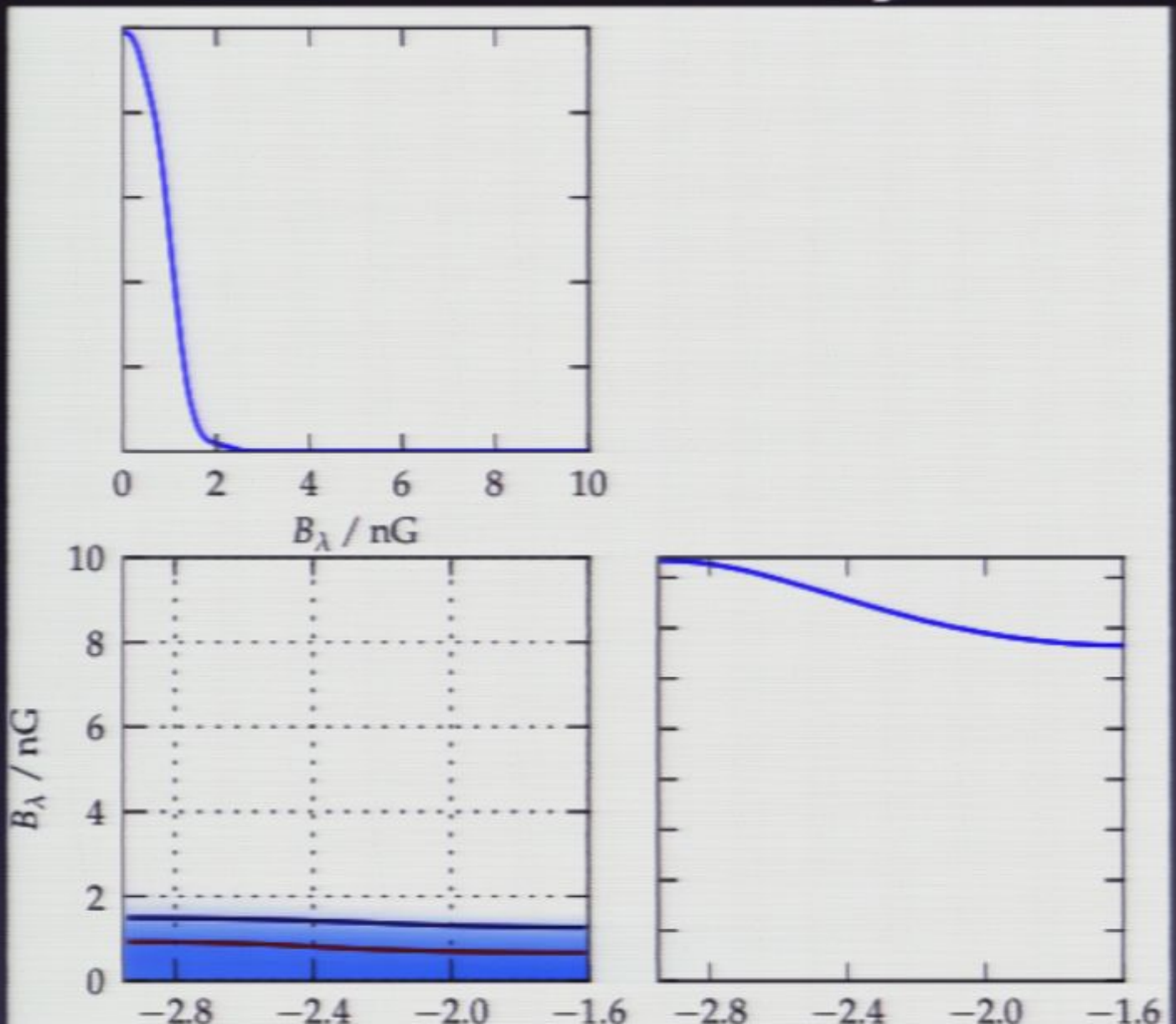
Primary CMB

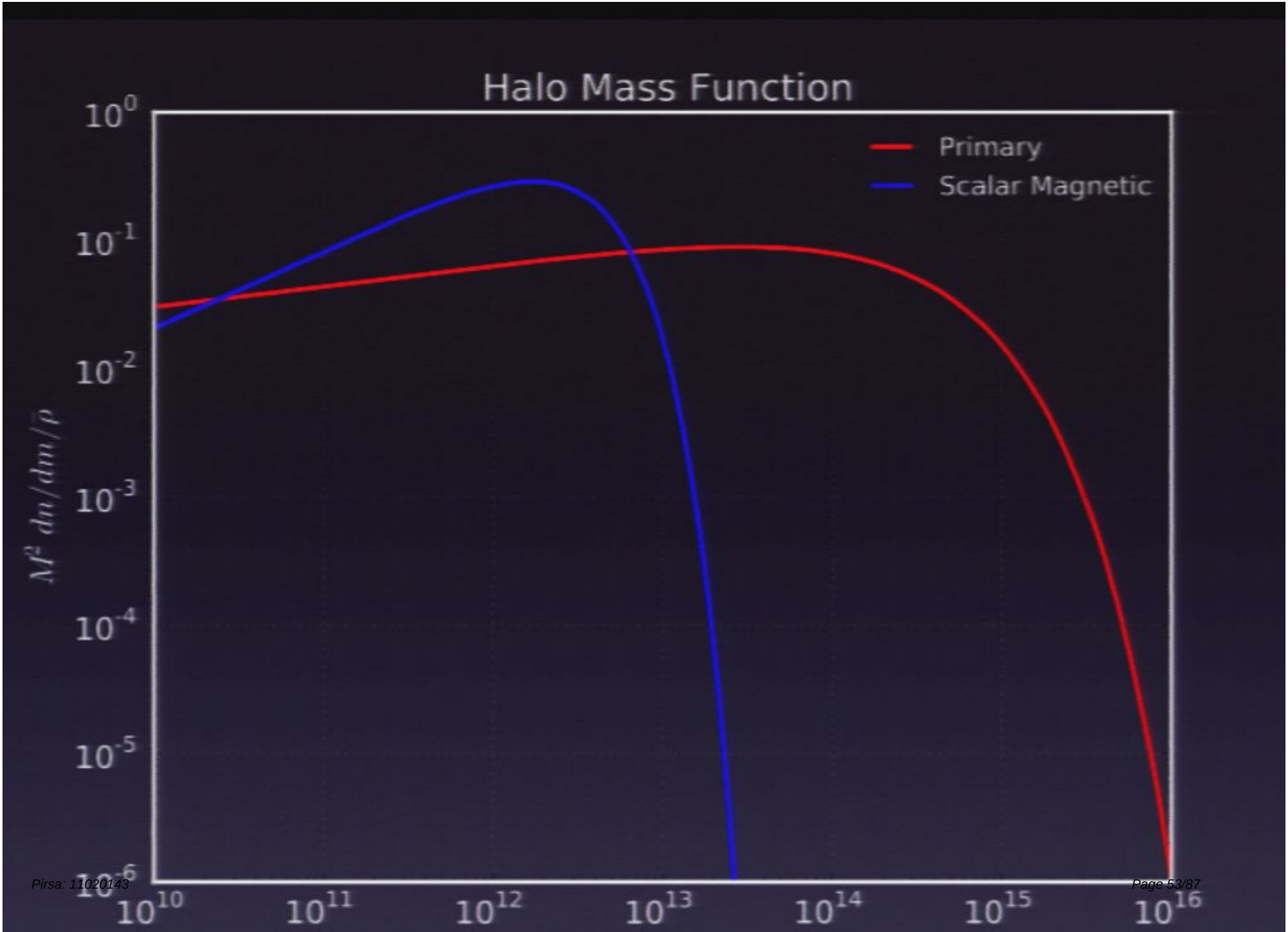


CMB+SZ



CMB+SZ+Lya

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Primary
Scalar Magnetic
$M^2\, dn/dm/\bar{\rho}$
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10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
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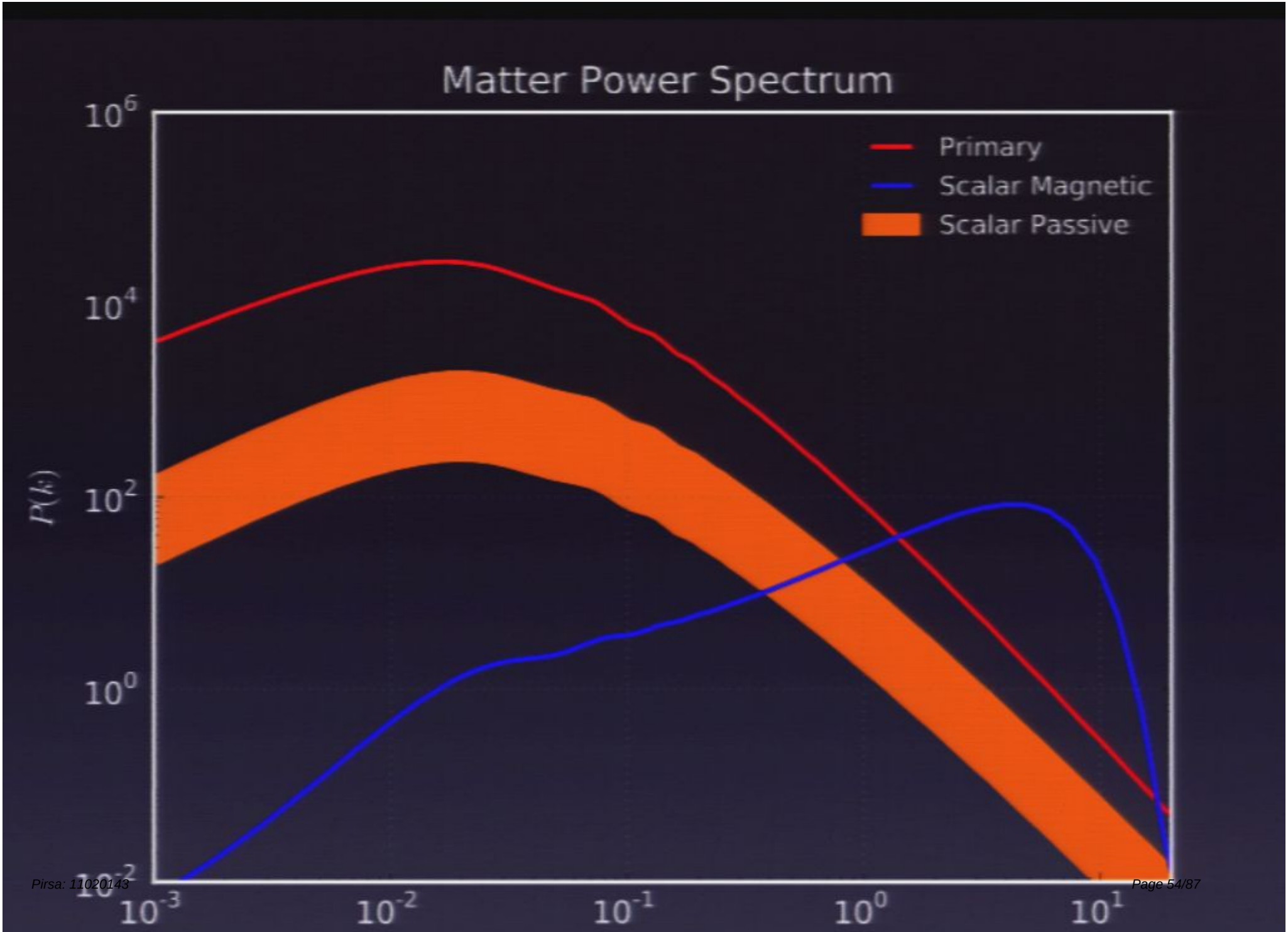
10^{14}
10^{15}
10^{16}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Primary
Scalar Magnetic
Scalar Passive
$P(k)$
10^6
10^4
10^2
10^0
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10^{-3}
10^{-2}
10^{-1}
10^0
10^1

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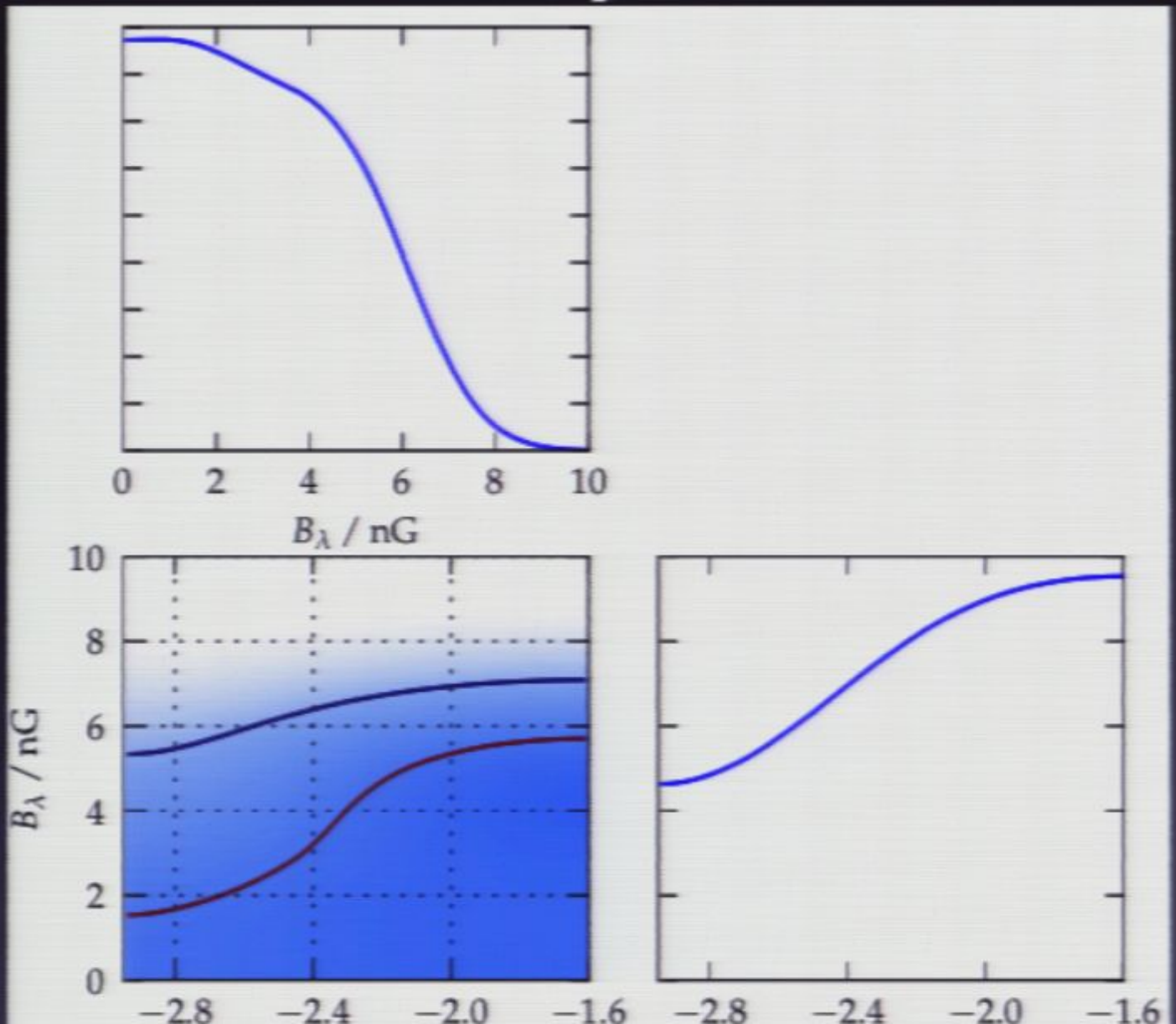
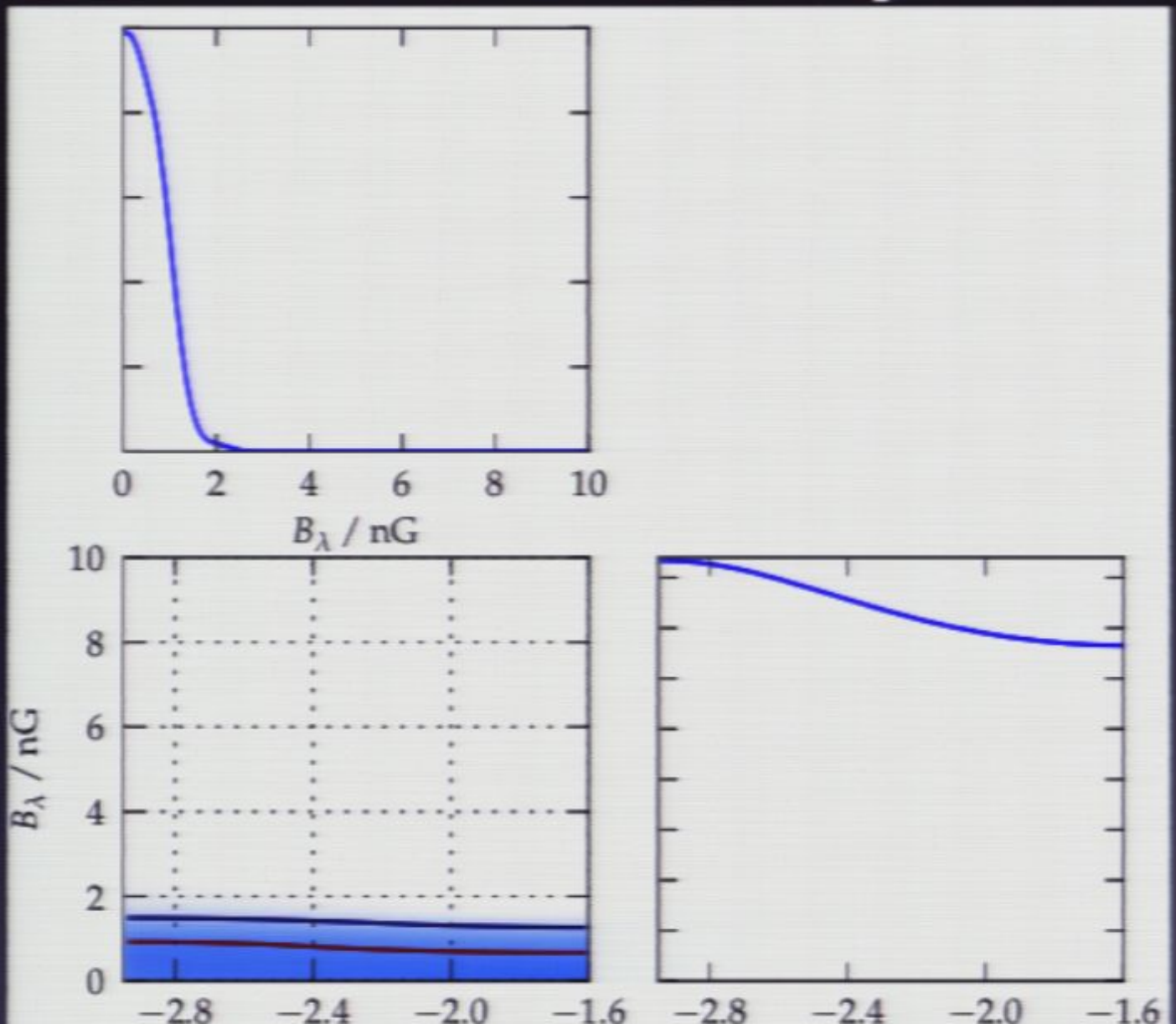


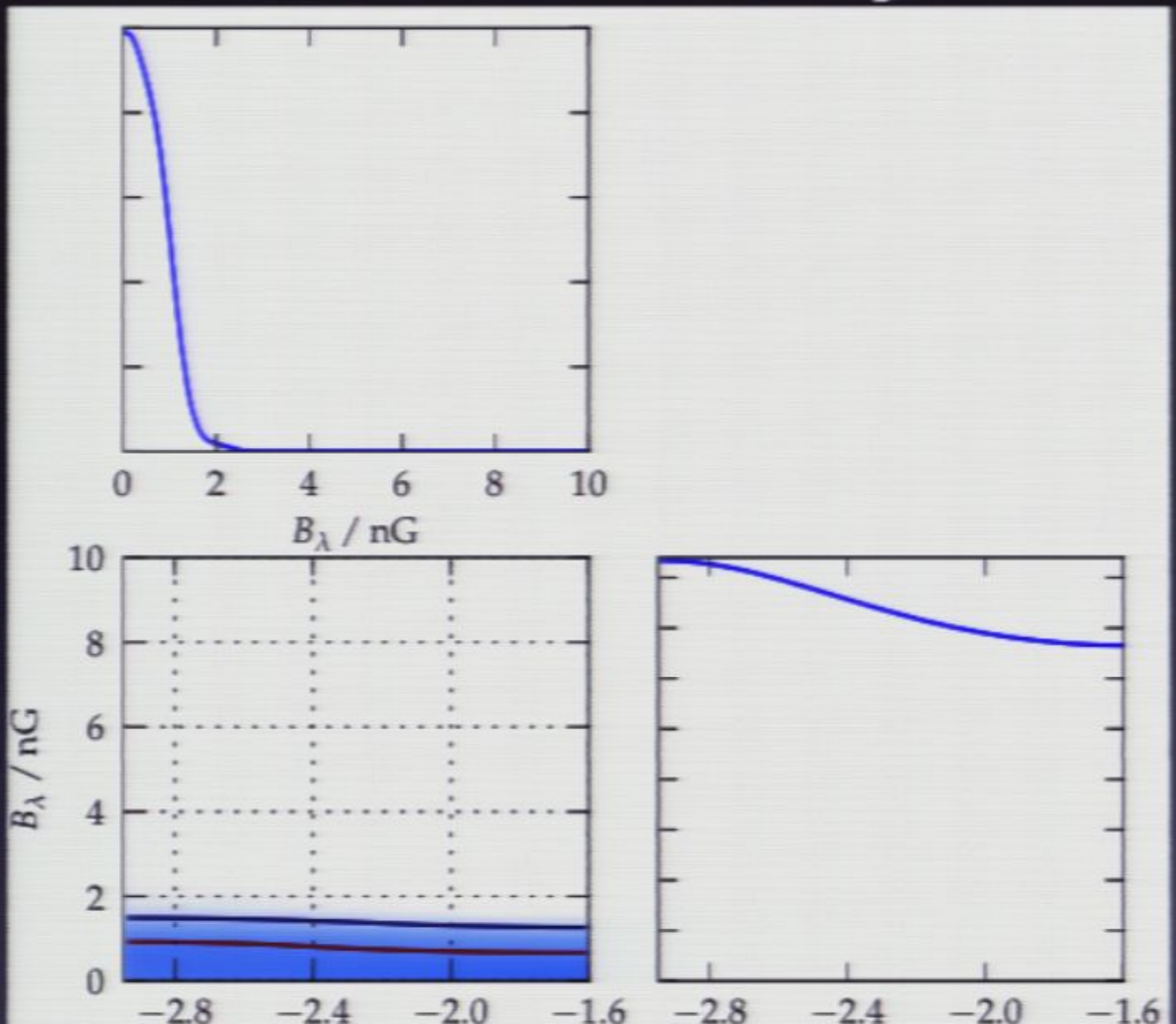
CMB+SZ+Lya



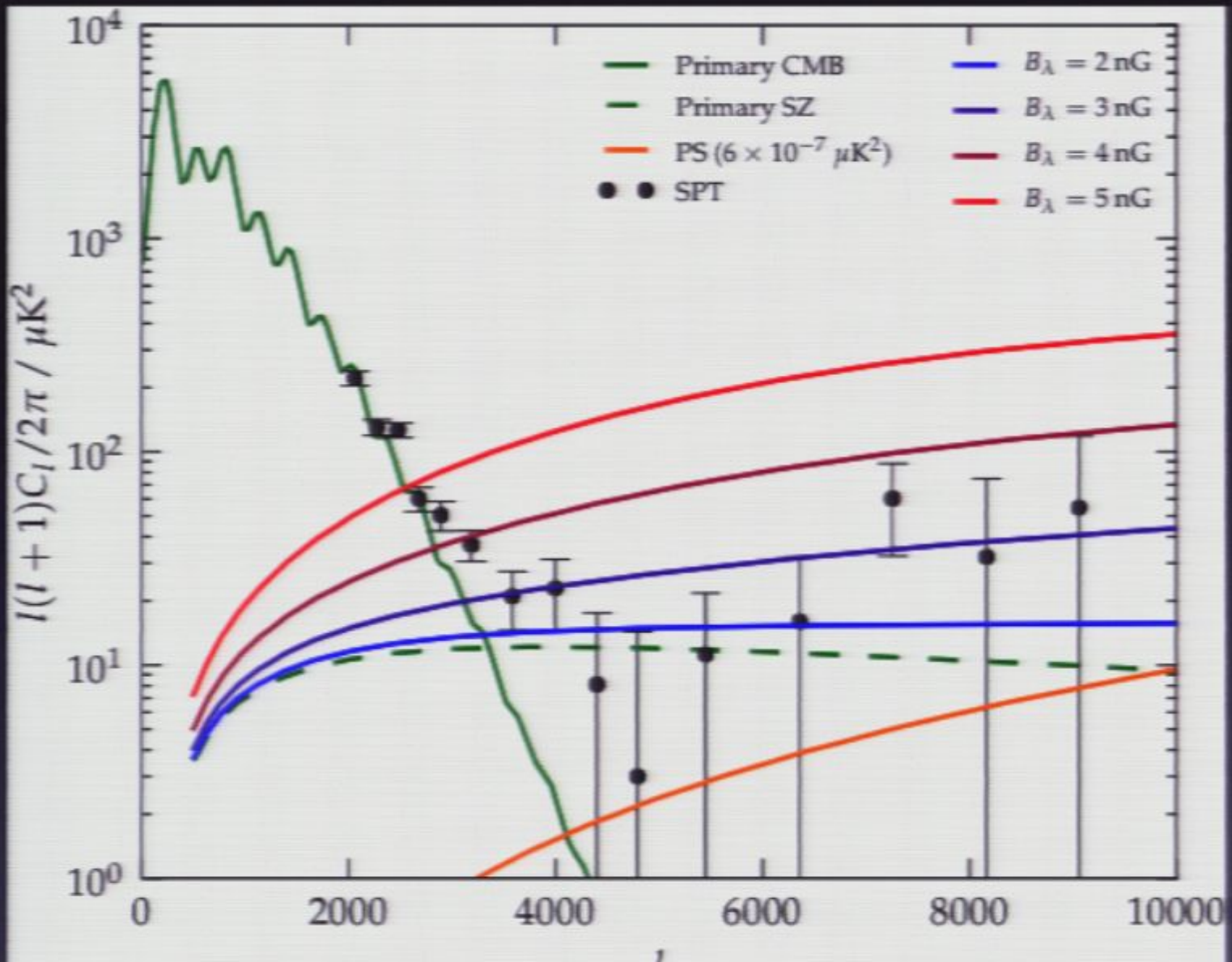
Nucleosynthesis Constraints

- Caprini and Durrer (2001) look at nucleosynthesis constraints on magnetic production of gravitational waves.
- For causal processes ($n_B > 2$) $B_\lambda < 10^{-27}\mathrm{G}$
- Nearly scale invariant fields are largely unconstrained

CMB+SZ+Lya



Sunyaev Zel'dovich Effect from Magnetic Fields



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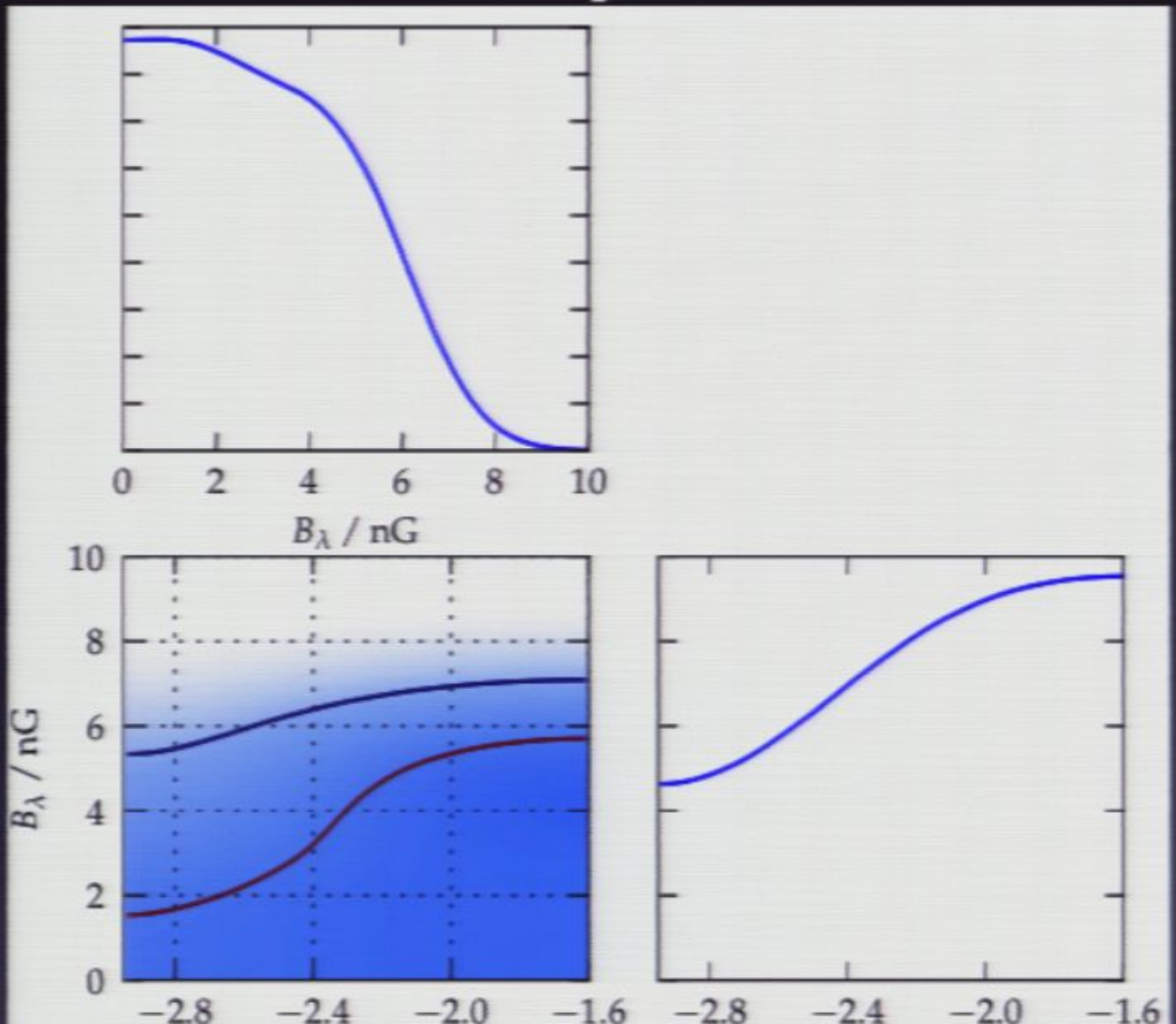

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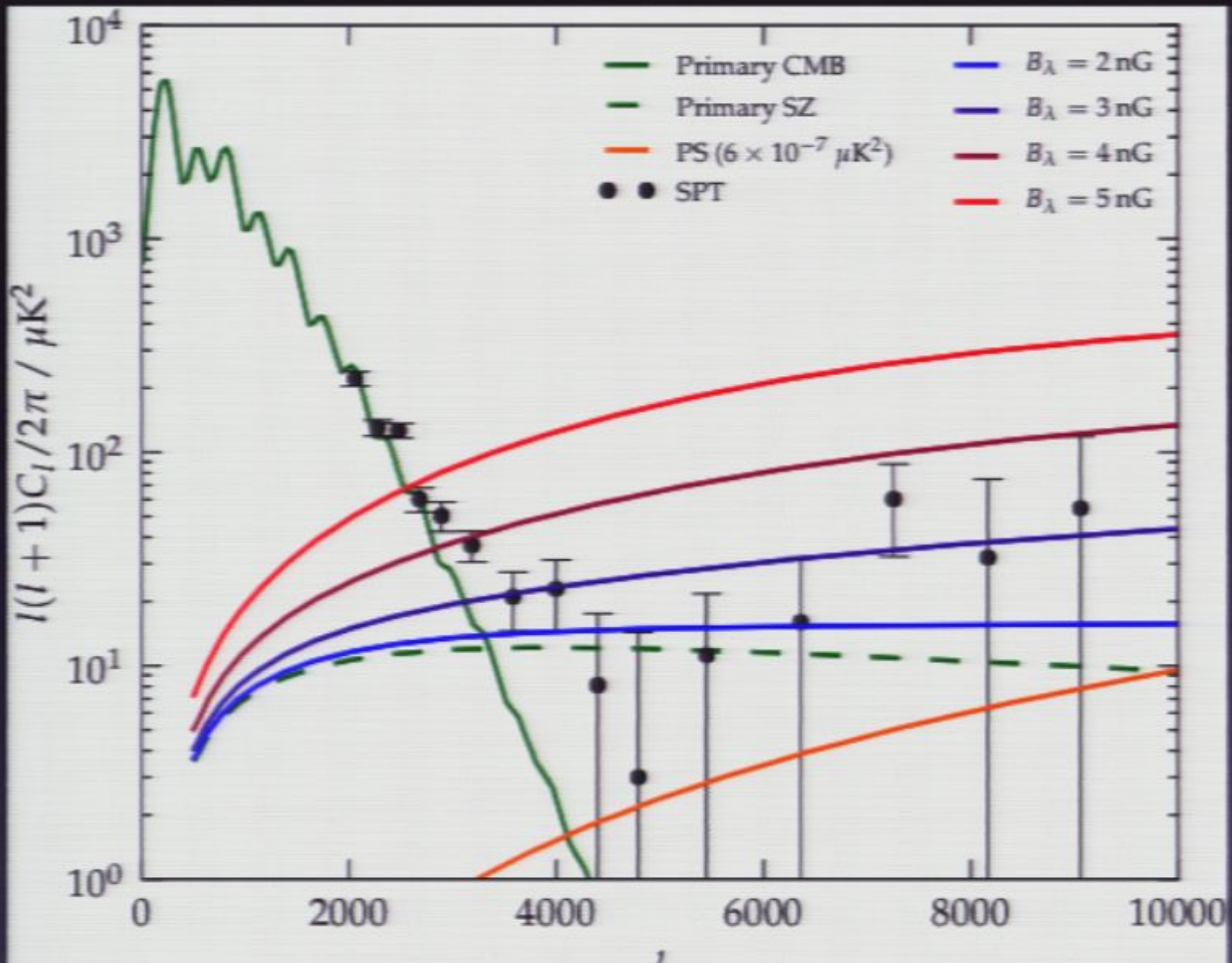
Sunyaev Zel'dovich Effect from Magnetic Fields



Constraints

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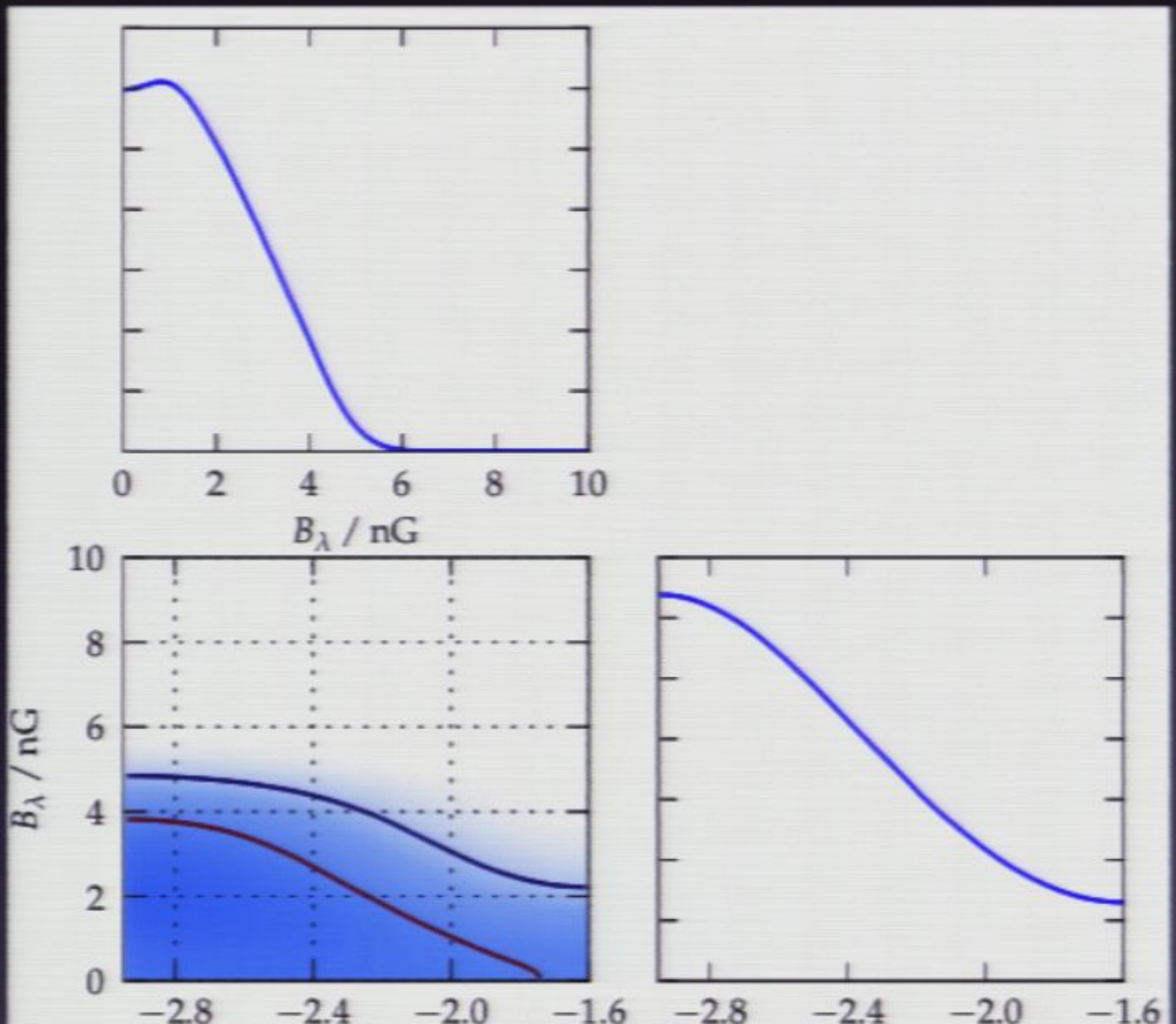
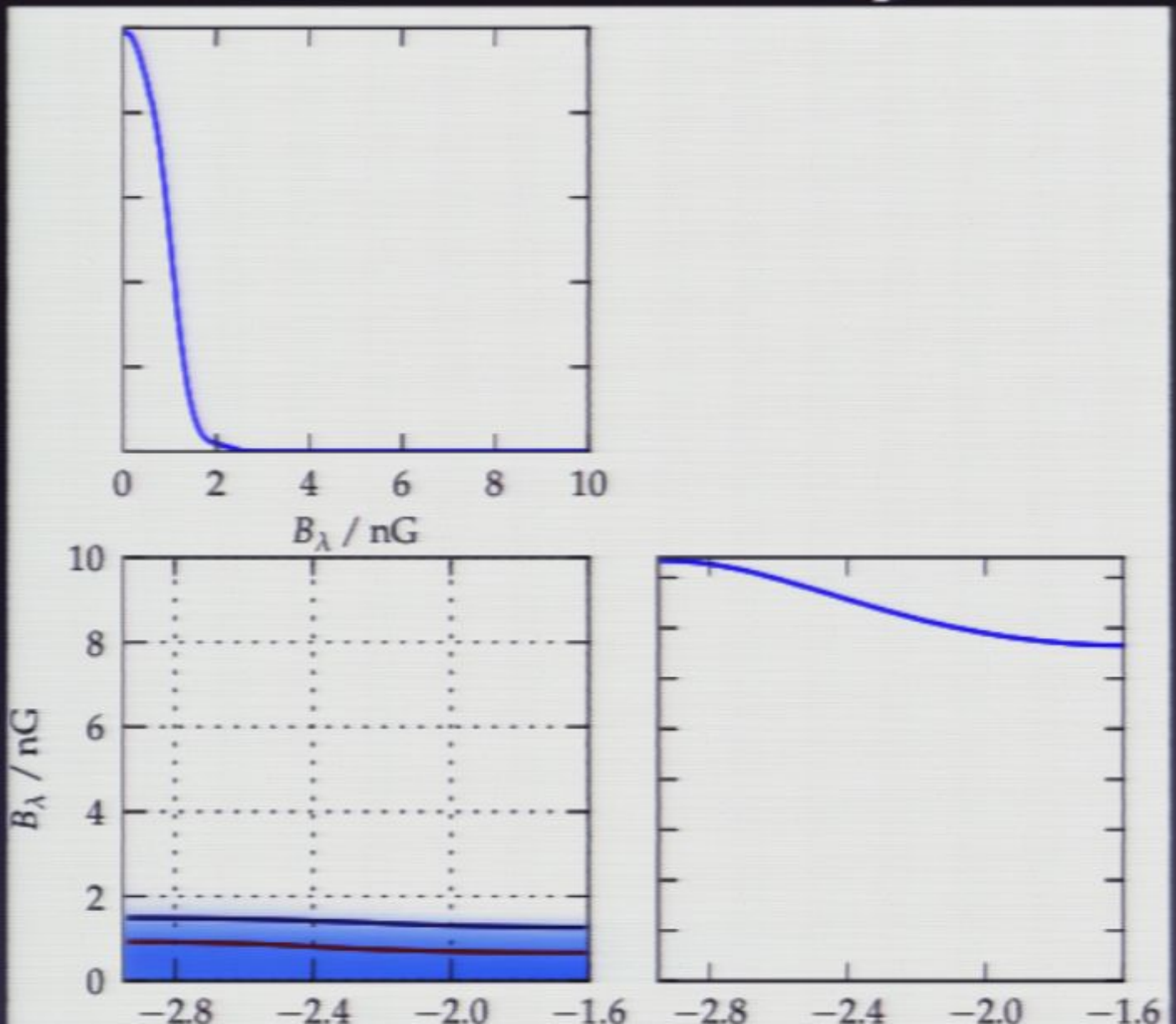
CMB+SZ



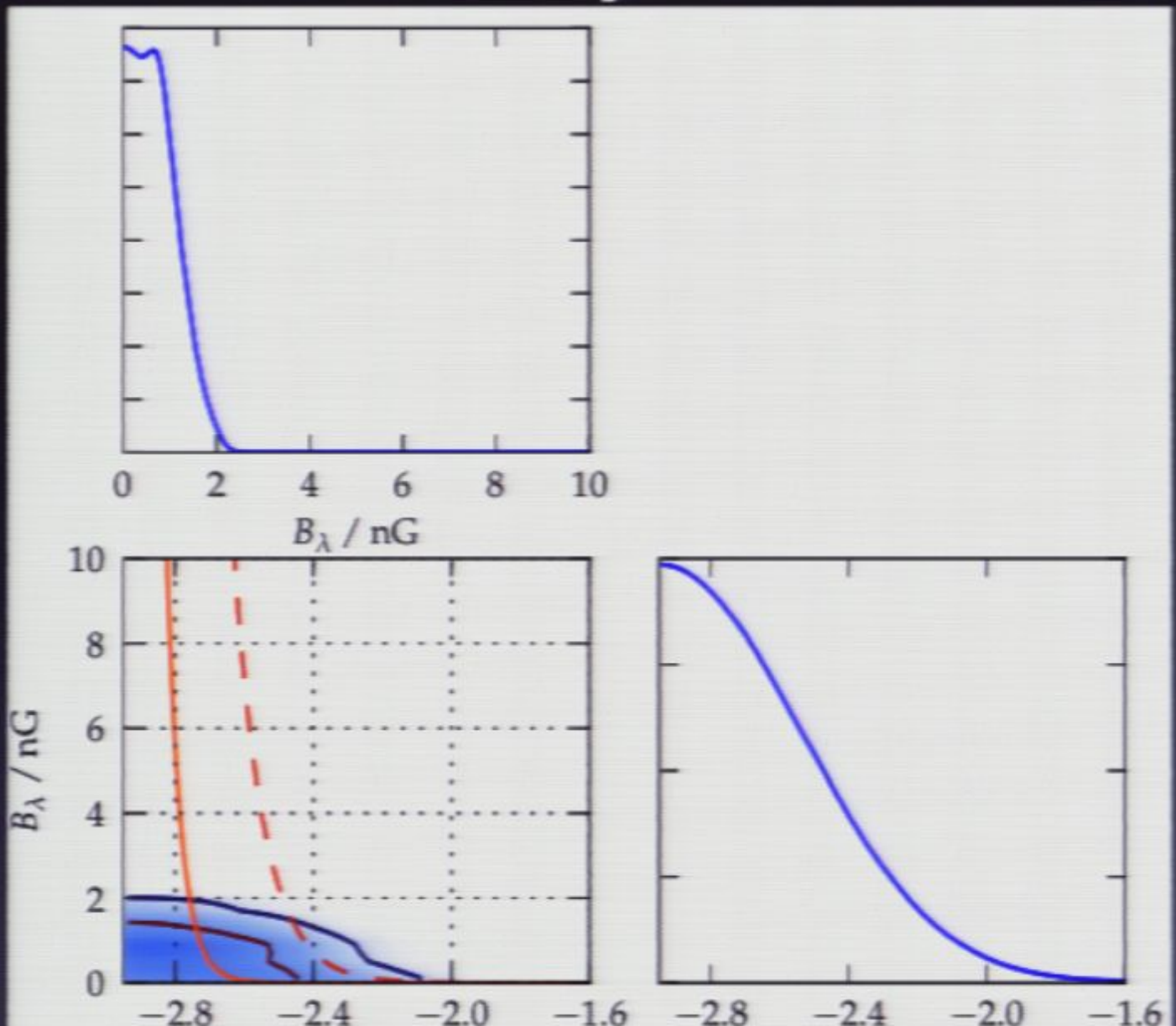
CMB+SZ+Lya



Nucleosynthesis Constraints

- Caprini and Durrer (2001) look at nucleosynthesis constraints on magnetic production of gravitational waves.
- For causal processes ($n_B > 2$) $B_\lambda < 10^{-27}\mathrm{G}$
- Nearly scale invariant fields are largely unconstrained

Nucleosynthesis



Conclusions

- Origin of cosmic magnetic fields is an unsolved problem.
- CMB on its own provides weak constraints on the magnetic fields
- Small scale matter power (SDSS, 2dF, Lya) dramatically improves this.

Future Constraints?

- Going to become difficult to dramatically improve constraints from CMB/ Matterpower spectrum type observations.
- Amplitudes $\propto B_{\lambda}^{4}$
- Big improvement in observations. Weak improvement in constraints

Conclusions

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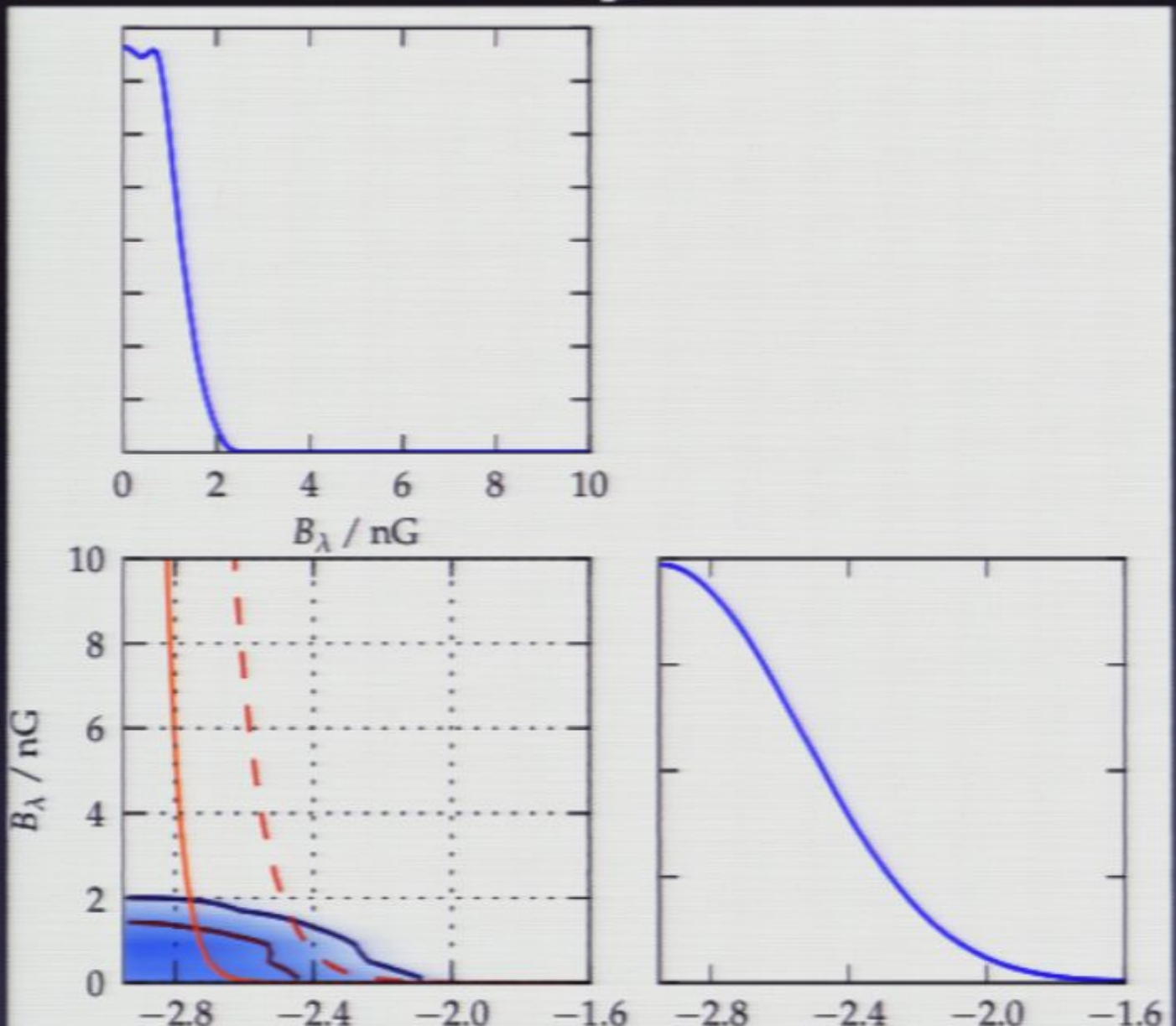
Nucleosynthesis



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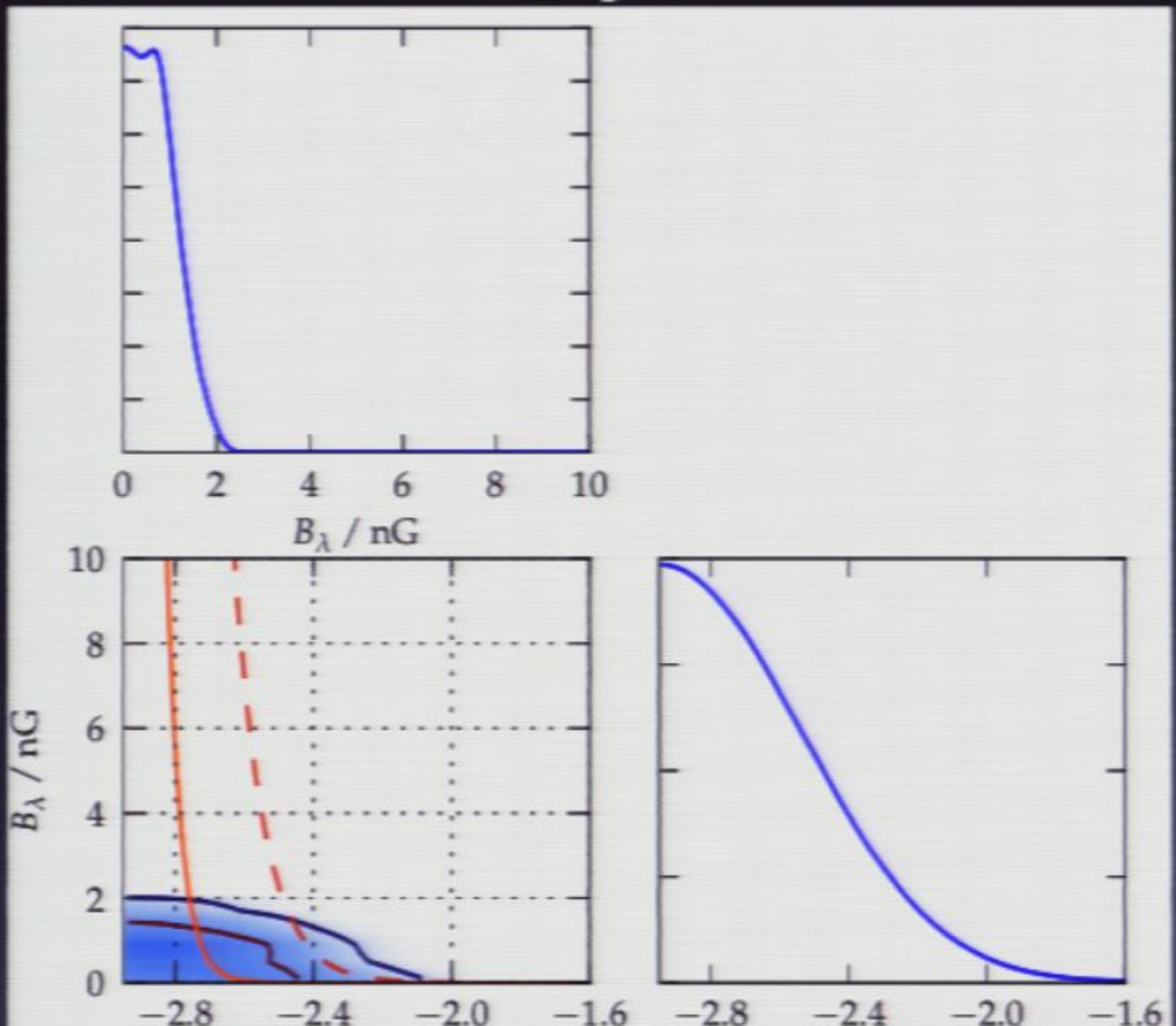

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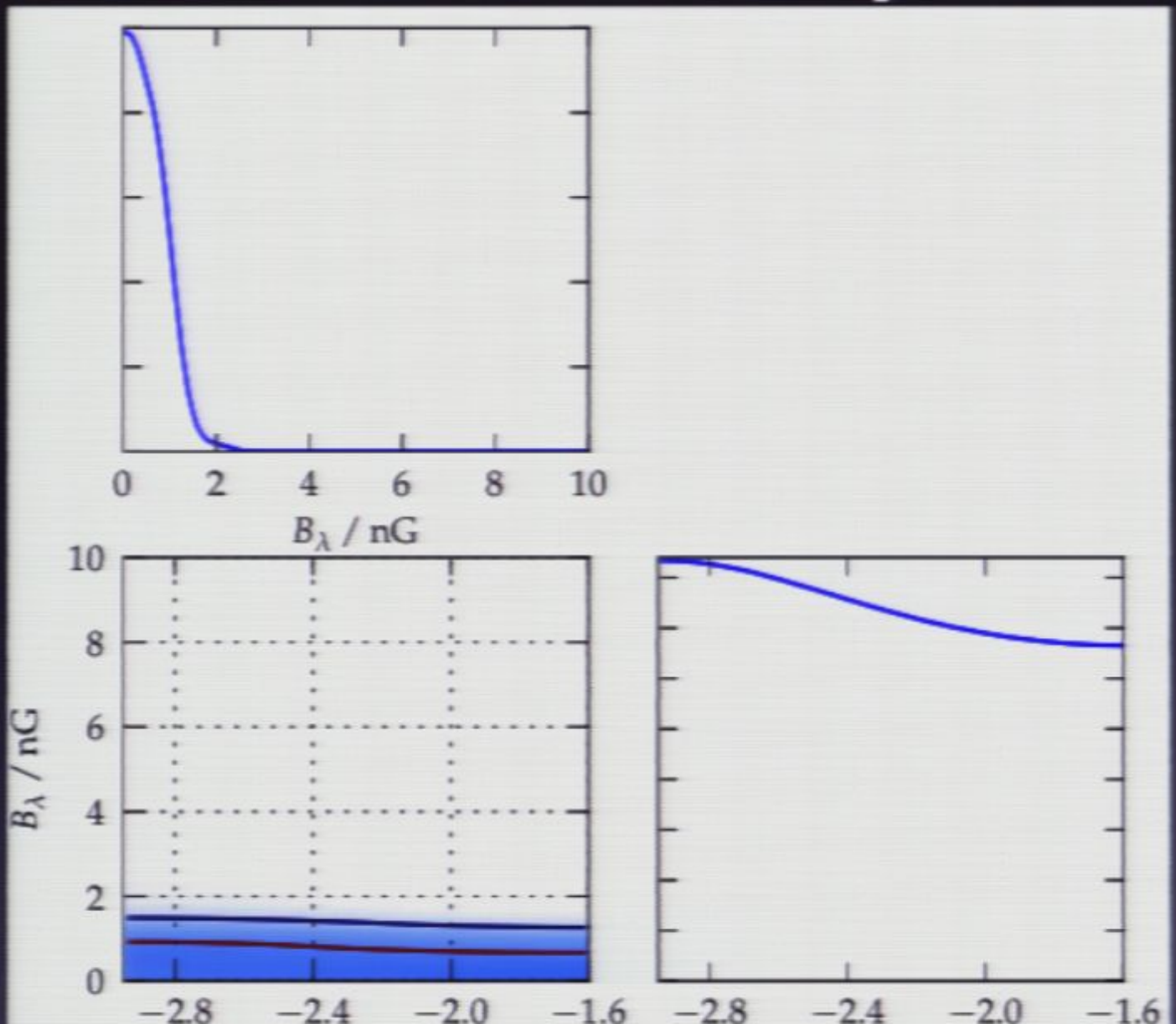
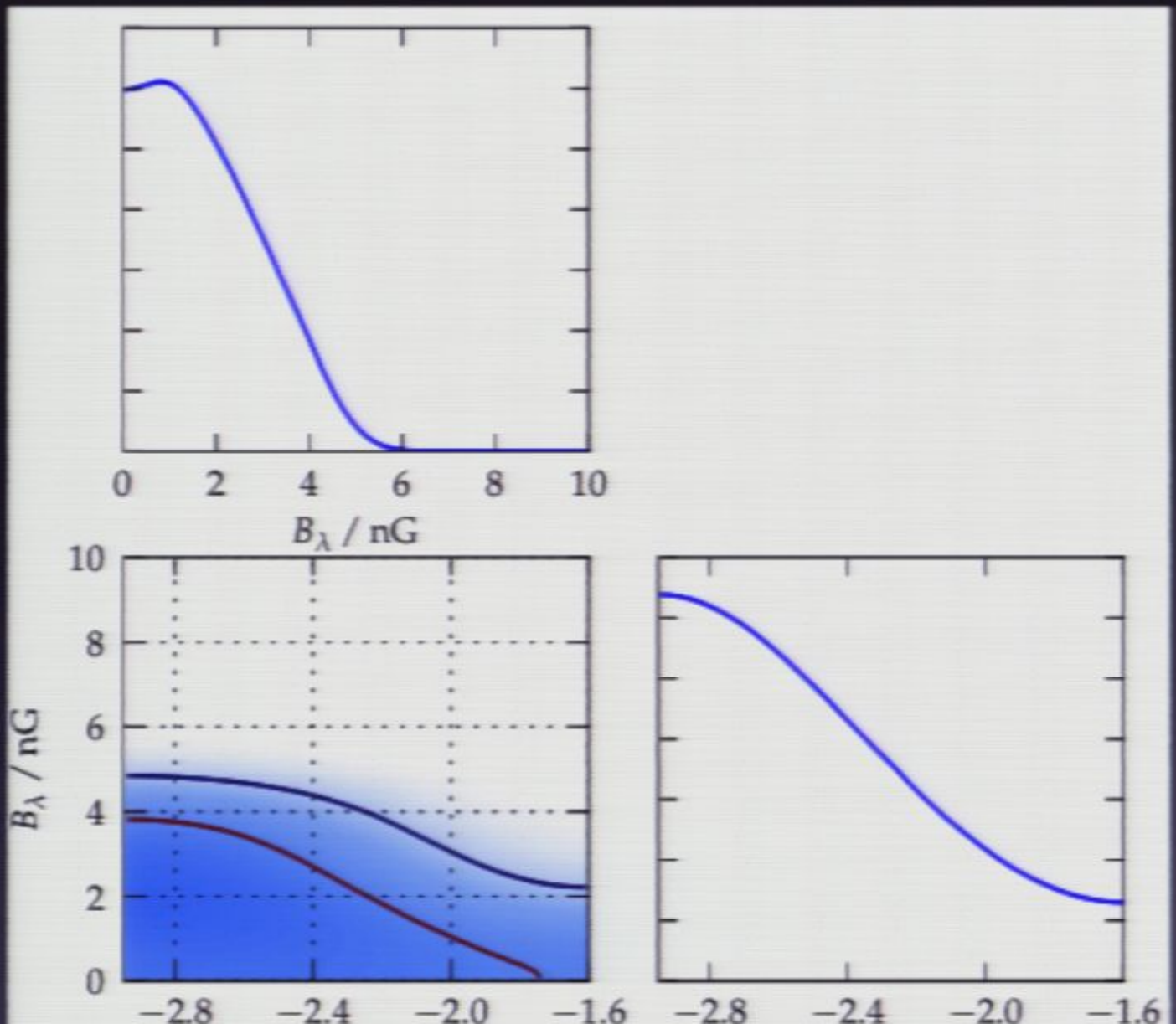


CMB+SZ



Constraints

- For proper constraints need to sample full parameter space of 6 standard params, plus
  - Magnetic amplitude: B_λ
  - Magnetic spectral index: n_B
  - Field production time: $\log_{10}(\tau_\nu/\tau_B)$
- Datasets: CMB (*WMAP, ACBAR, QUaD*), Lyman alpha (*SDSS*), SZ (*SPT*)
- CMB only, and CMB with SDSS has been done (Yamazaki et al., Paoletti et al.)

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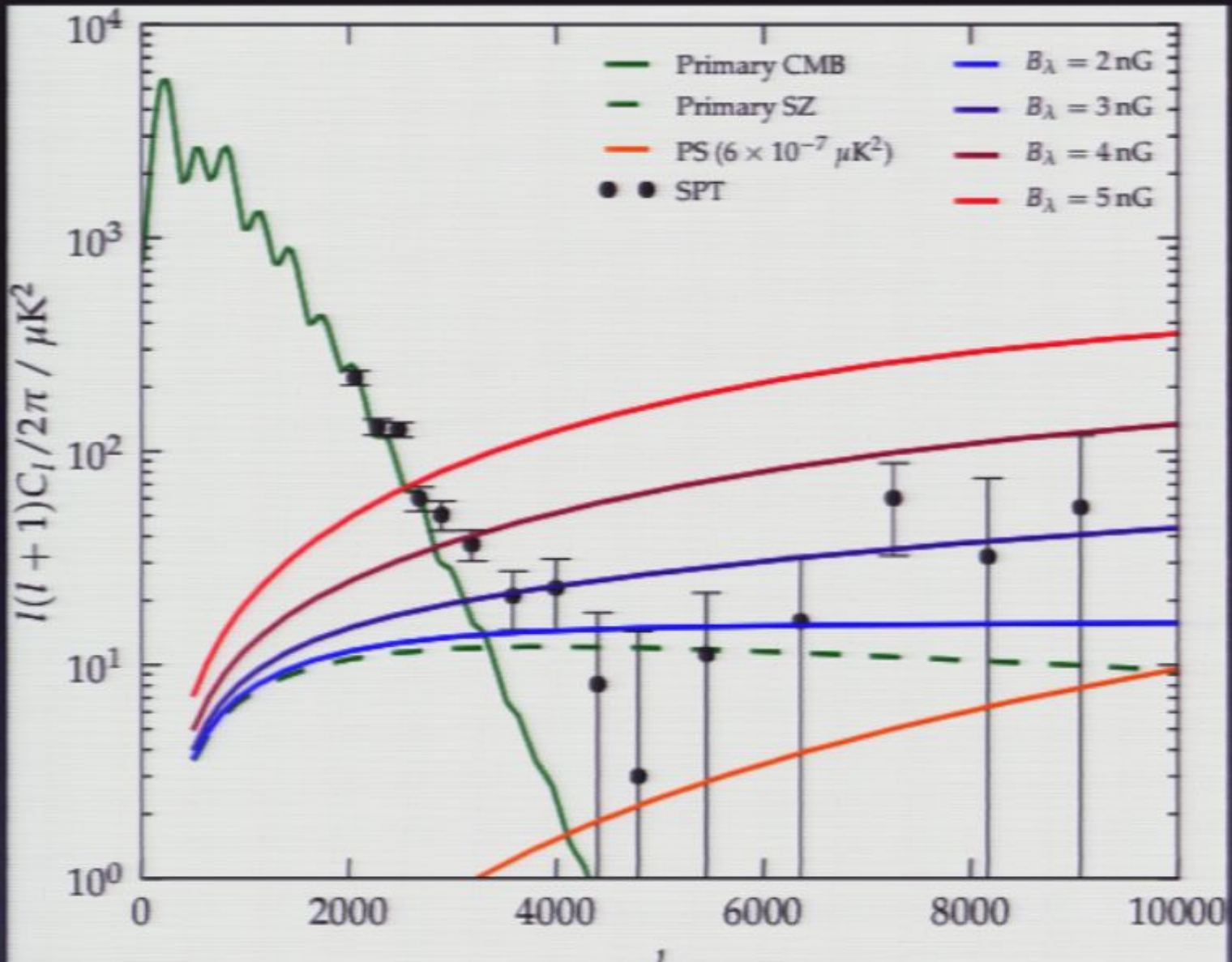

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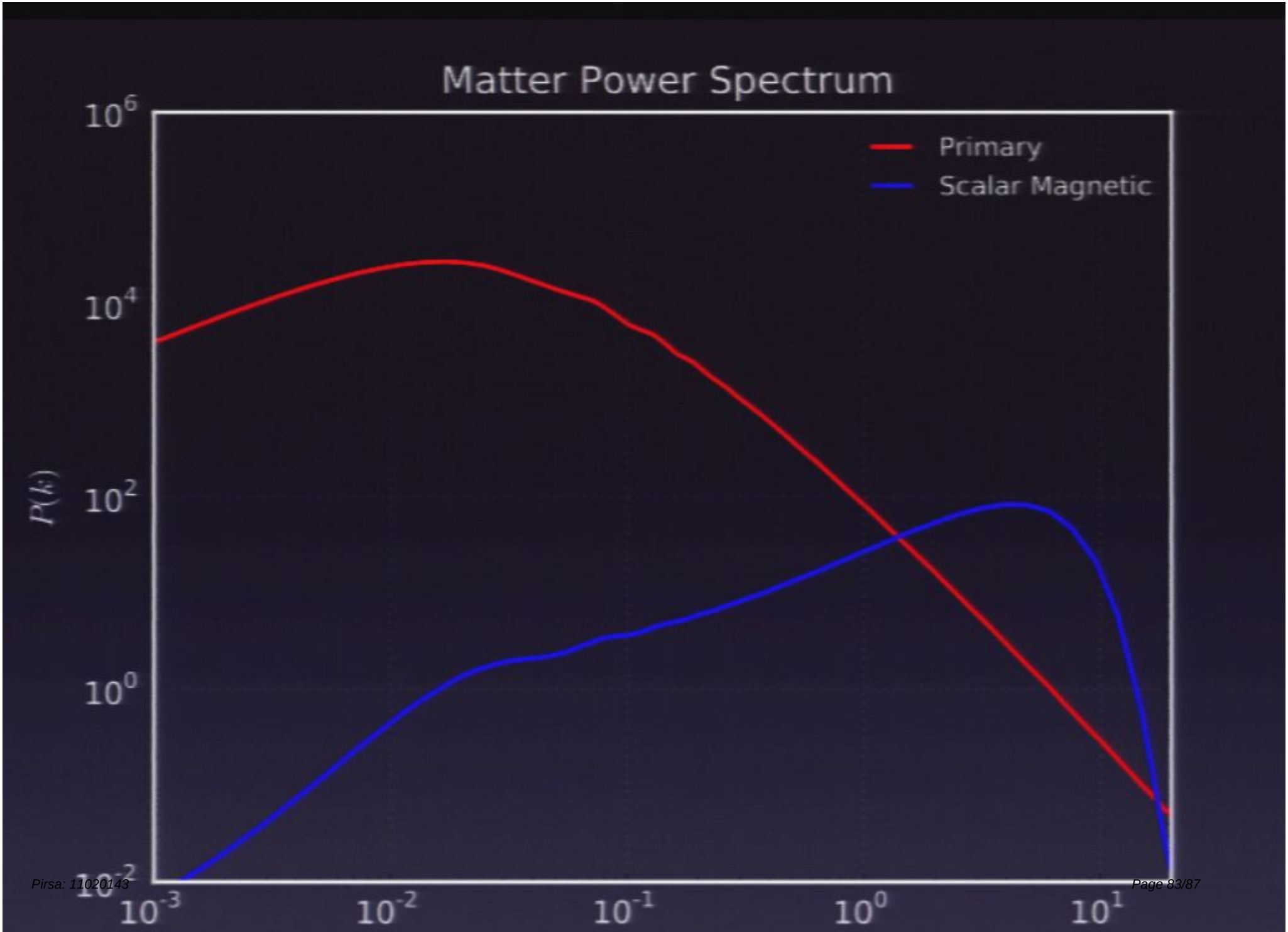
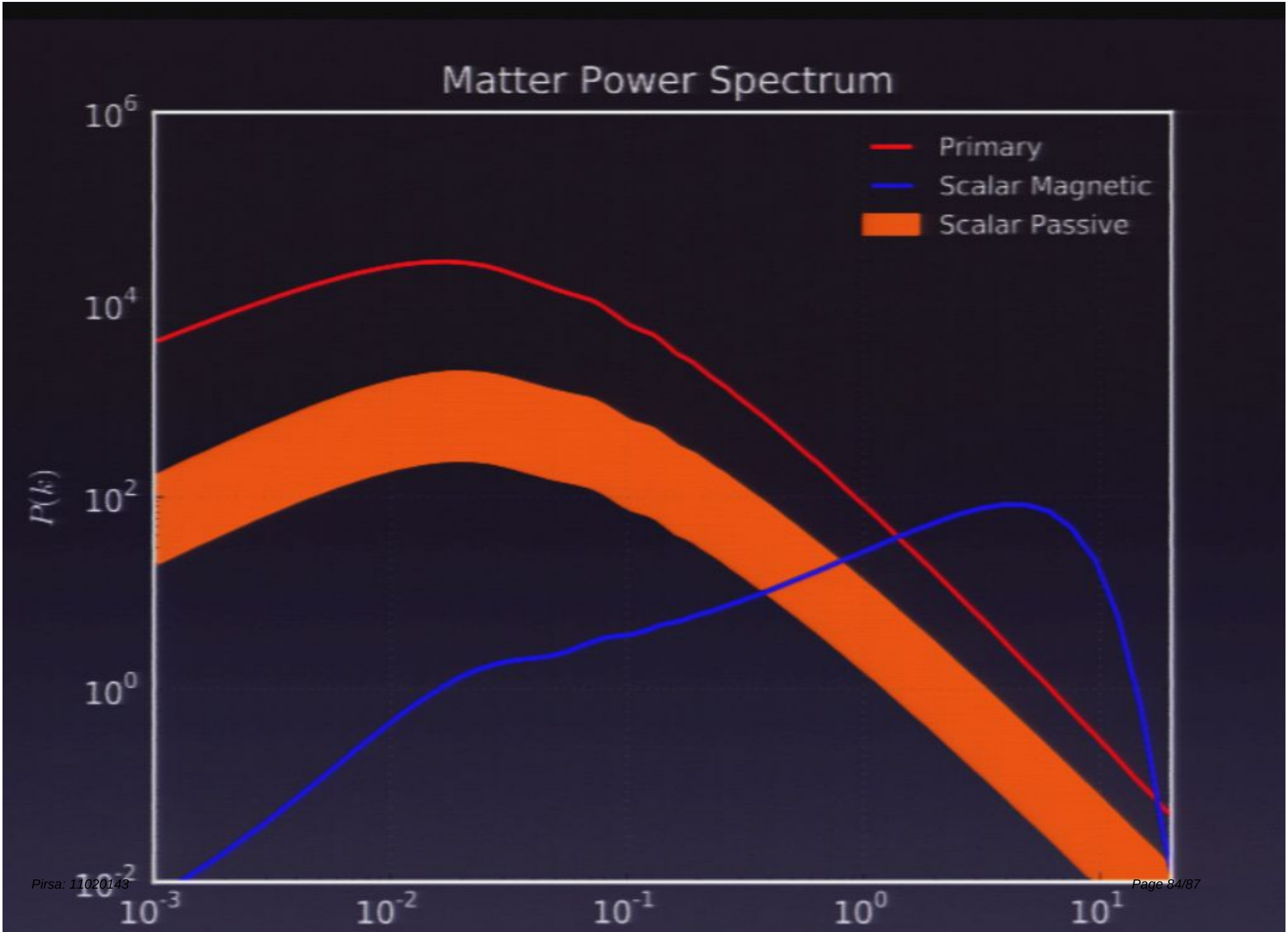

Matter Power Spectrum
Primary
Scalar Magnetic
$P(k)$
10^{6}
10^{4}
10^{2}
10^{0}
10^{-2}
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}


Matter Power Spectrum
Primary
Scalar Magnetic
Scalar Passive
$P(k)$
10^6
10^4
10^2
10^0
10^{-2}
10^{-3}
10^{-2}
10^{-1}
10^0
10^1


No Signal
VGA-1


No Signal
VGA-1


No Signal
VGA-1