THE SEEDS OF A MAGNETIC UNIVERSE

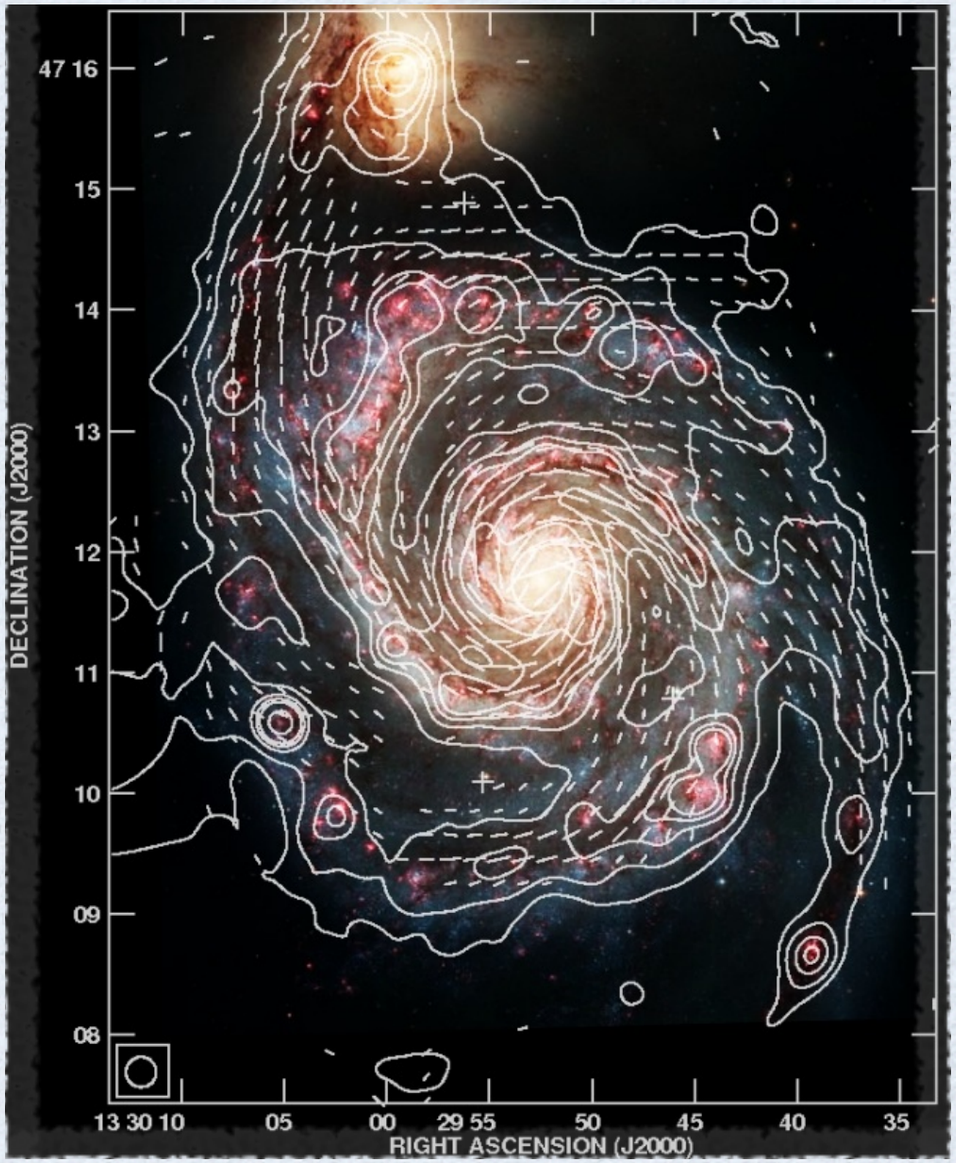
Smadar Naoz
Einstein Fellow,
Harvard Smithsonian Center for Astrophysics ITC

Naoz & Narayan 2013, PRL

The Universe is Magnetized
The need for a B seed

- Coherent magnetic fields in galaxies and clusters ~ 10^{-6} Gauss e.g., Widrow 2002

M51 B~30μG



Radio 6cm, Fletcher et al 2011

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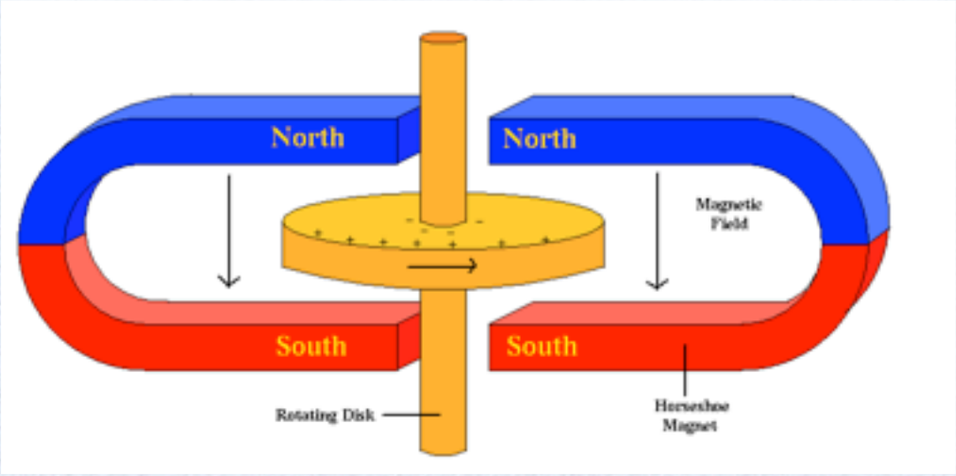
The dynamo mechanism?



e.g., Parker 1955; Ruzmaikin et al 1988; Kulsrud 1999; Brandenburg and Subramanian 2005; Kulsrud and Zweibel 2008

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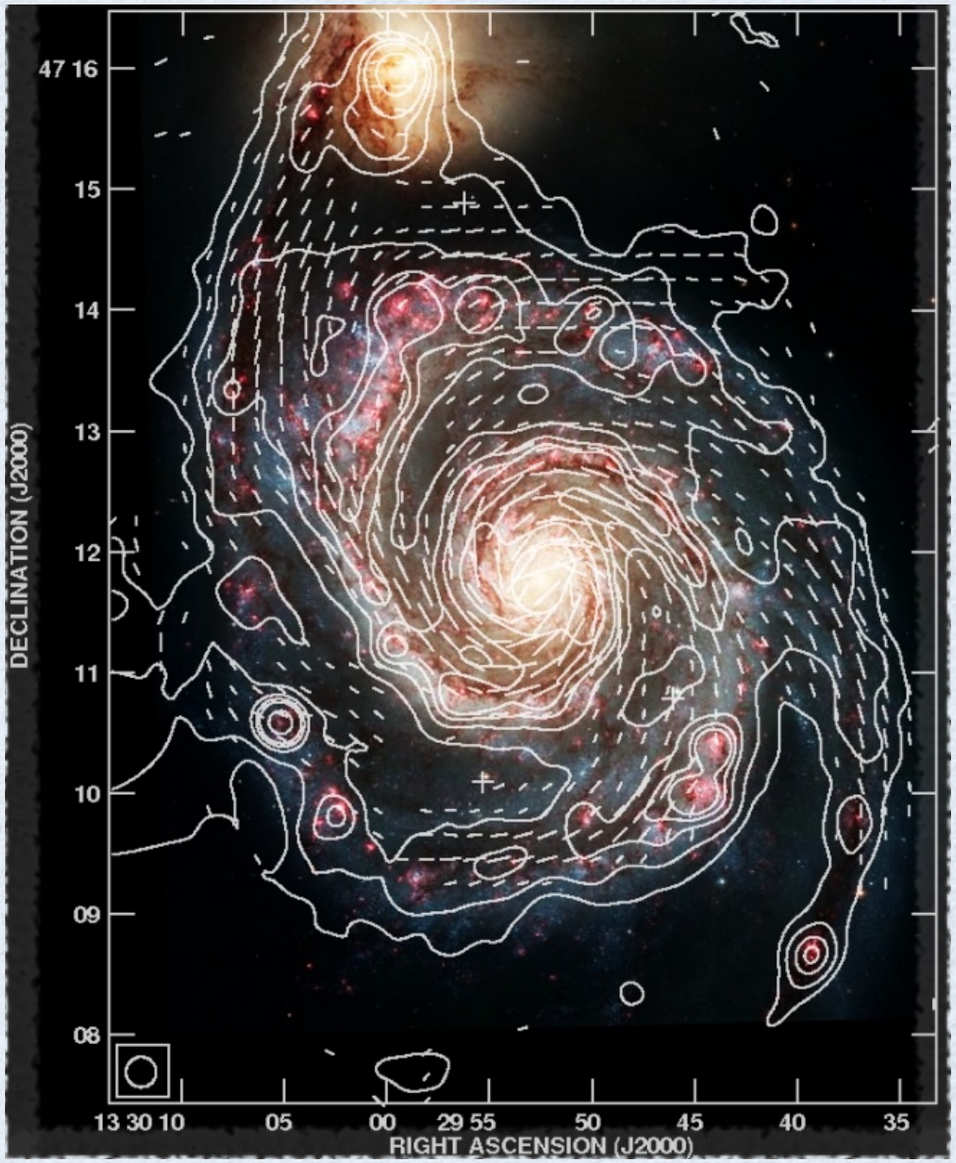

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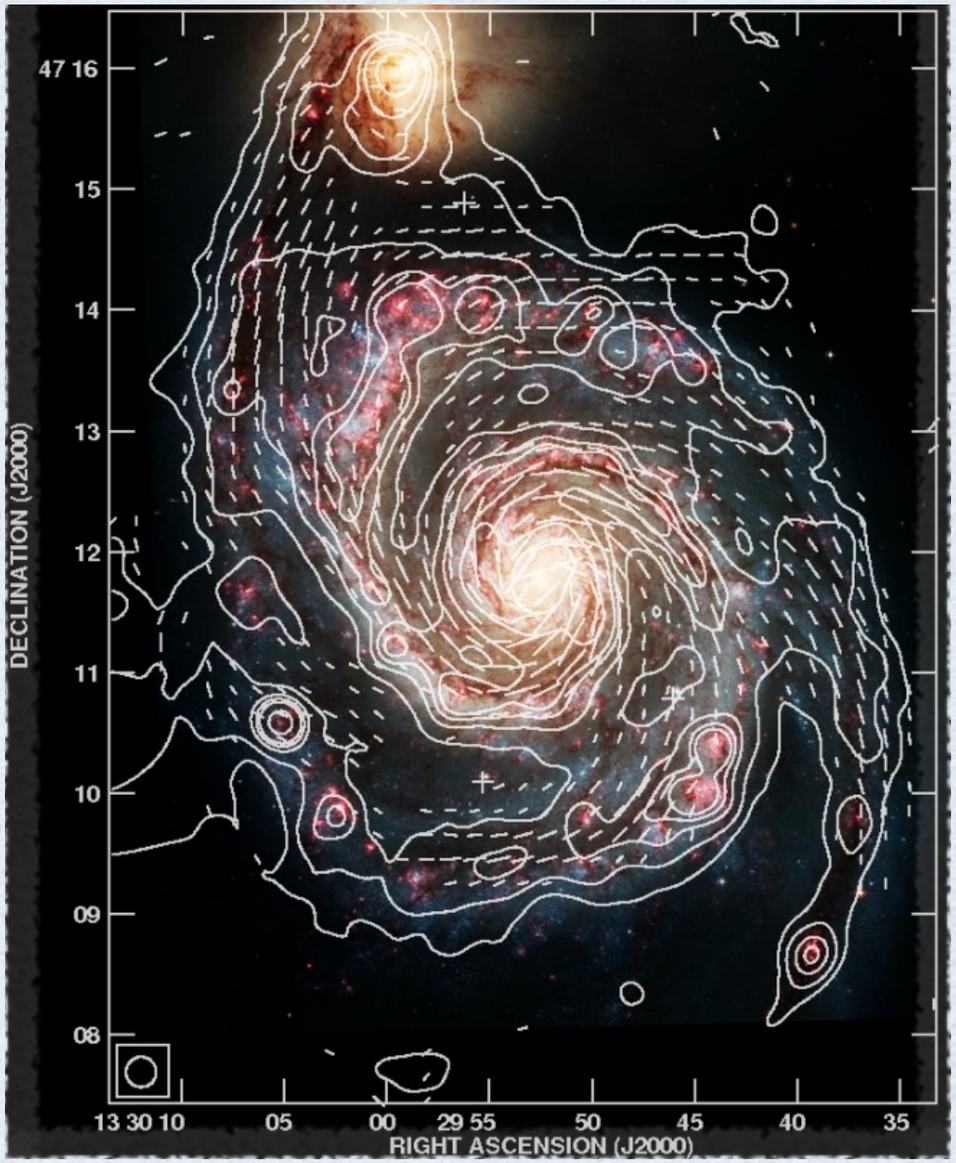

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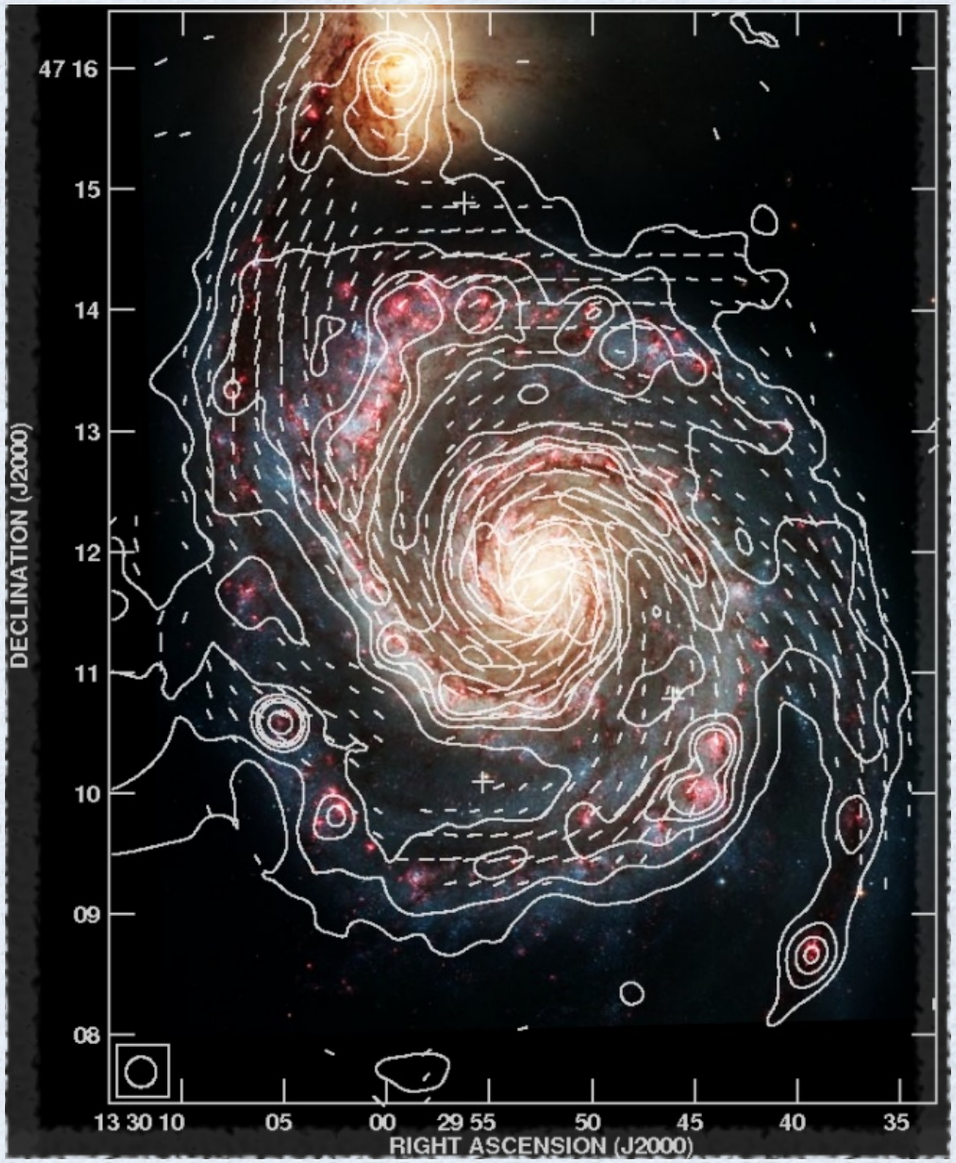

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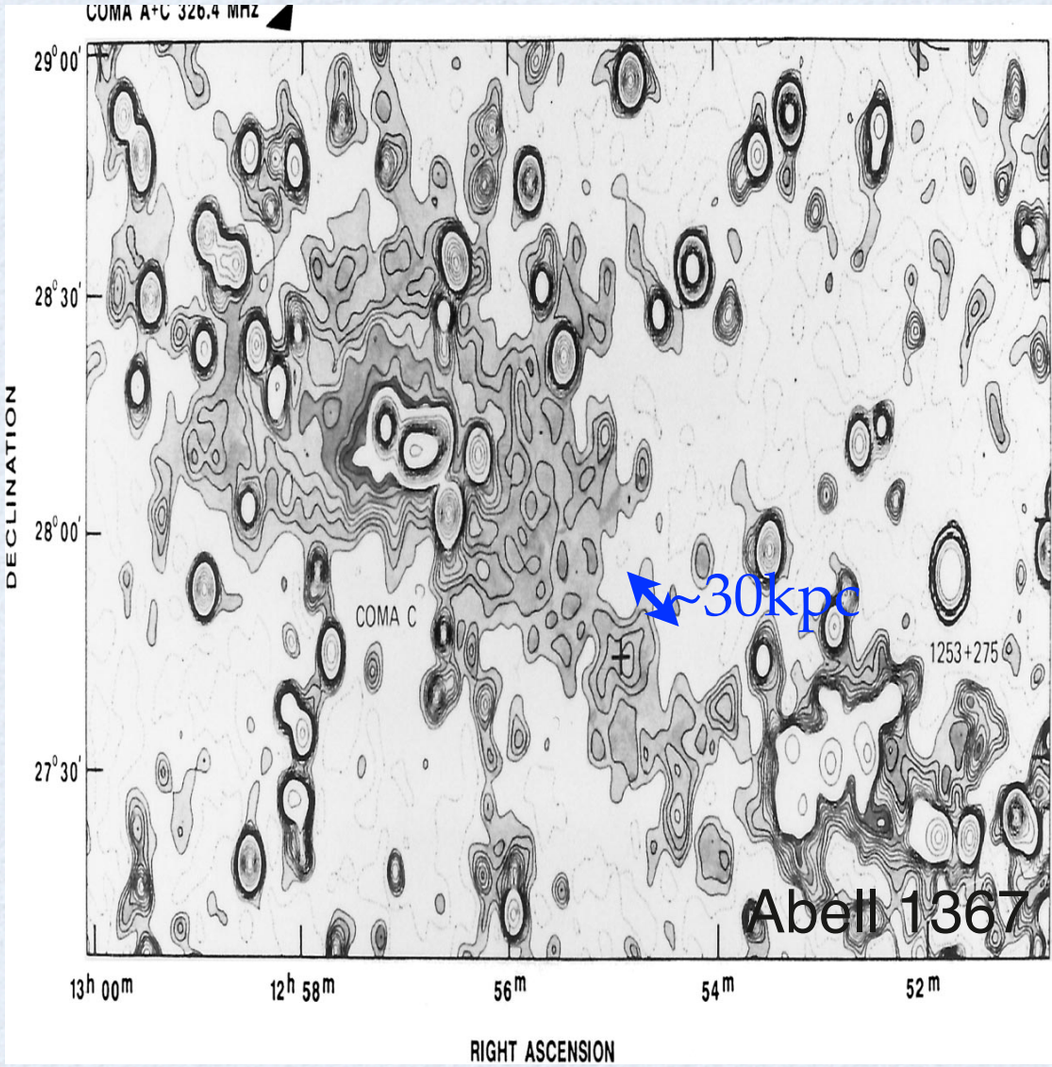

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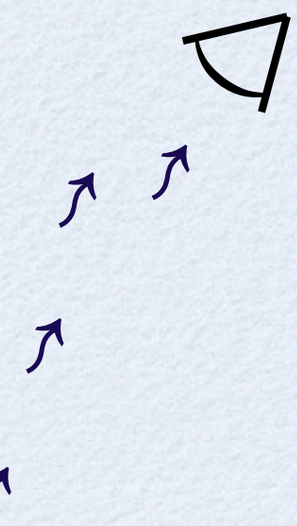

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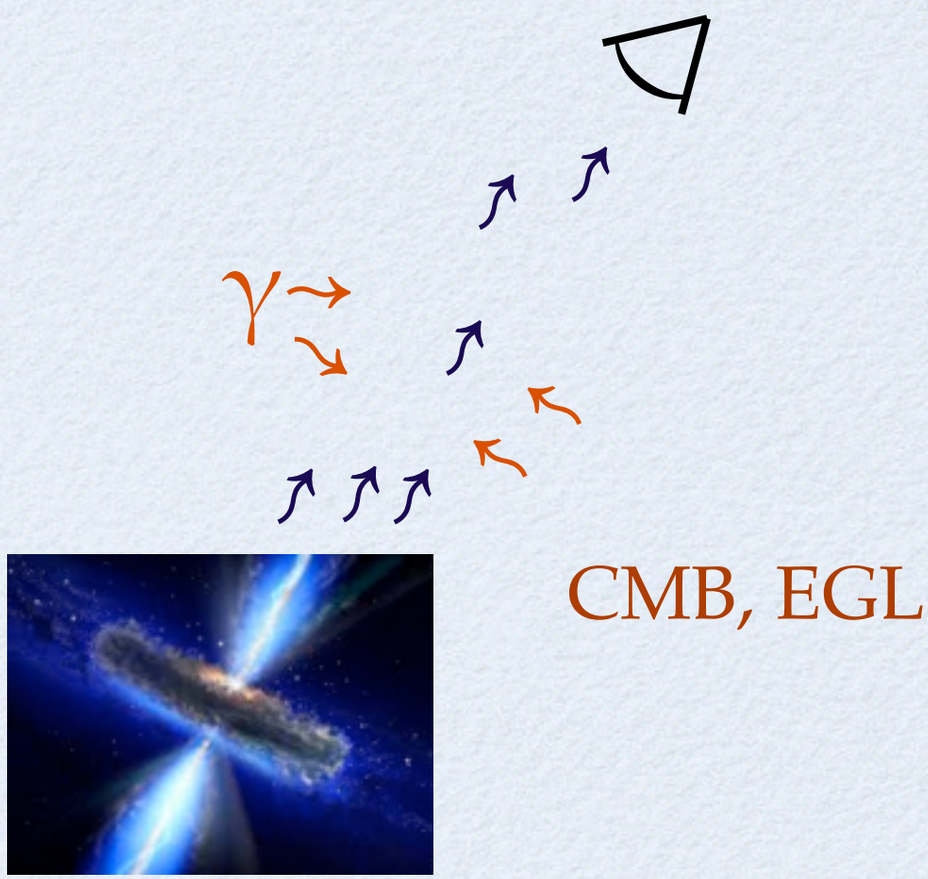

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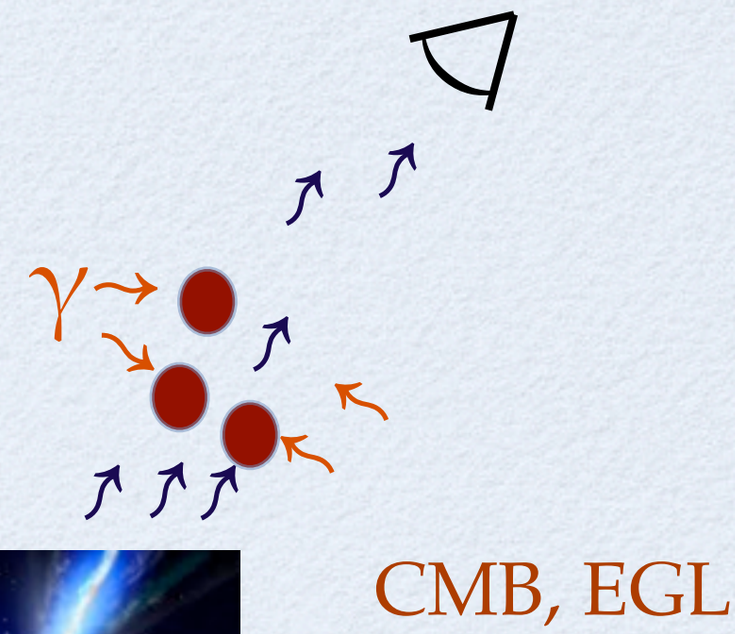

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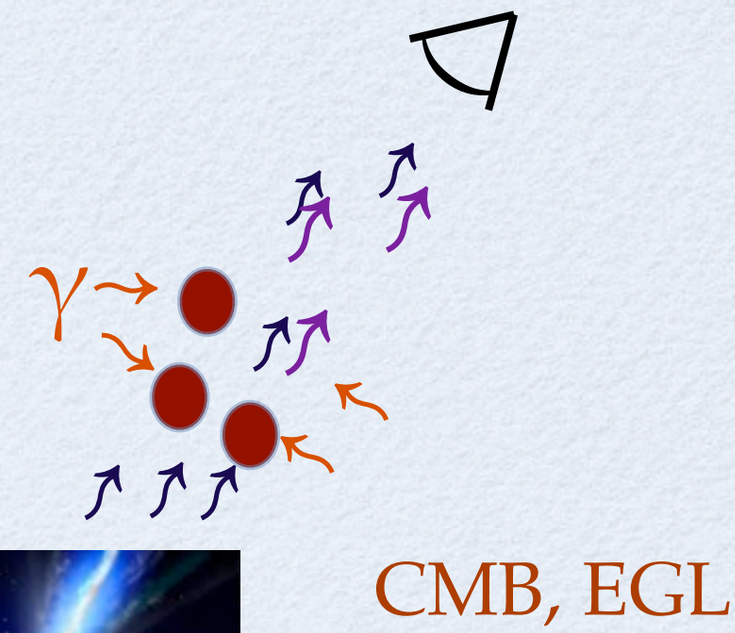

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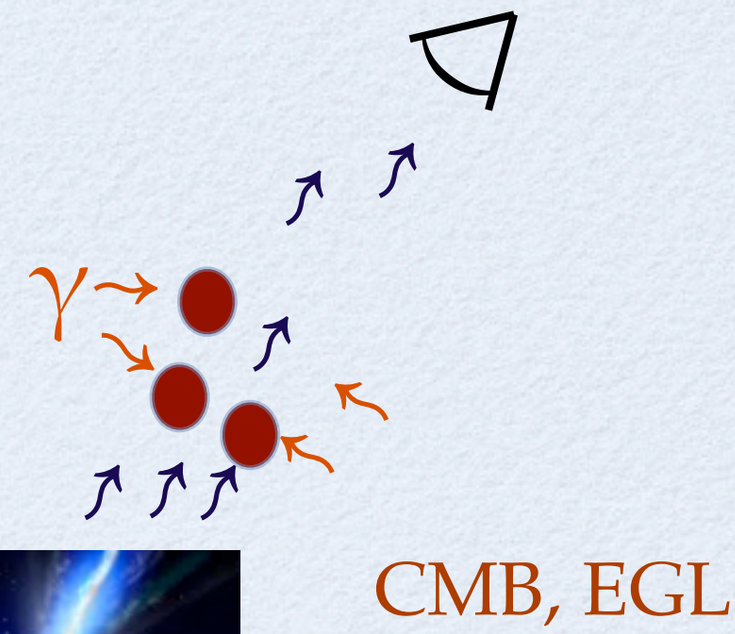

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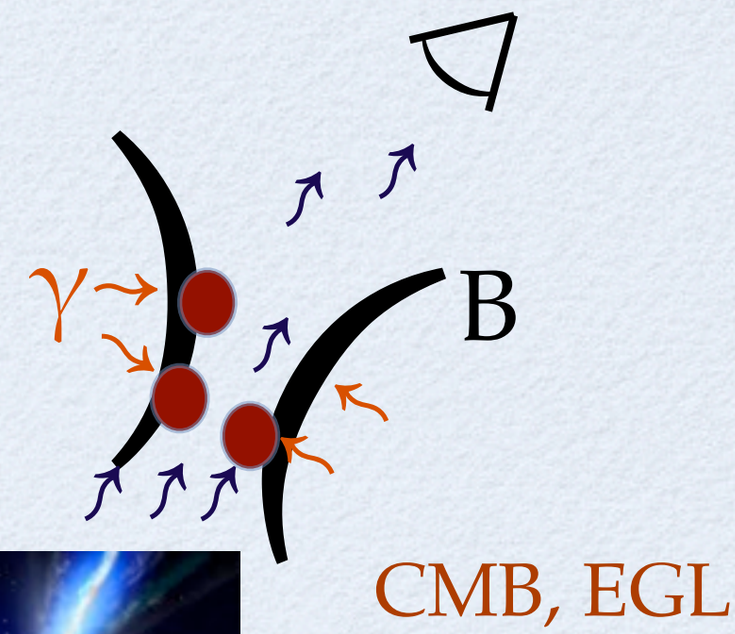

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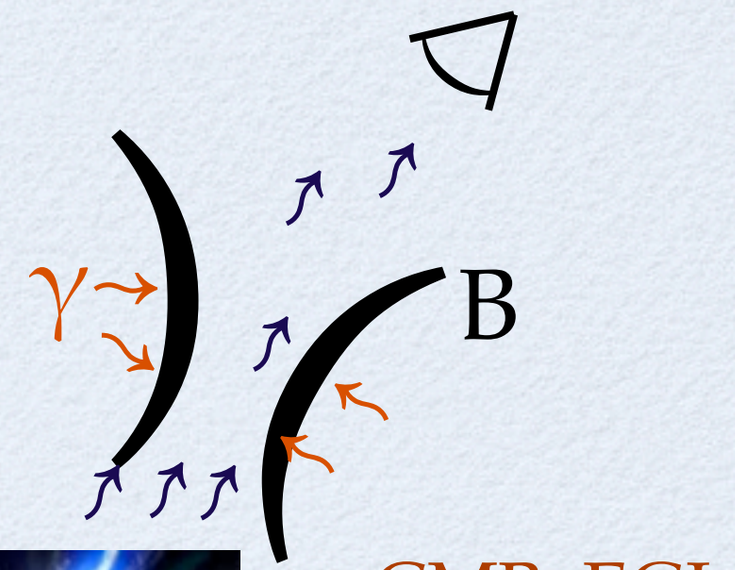

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Top down

Bottom up

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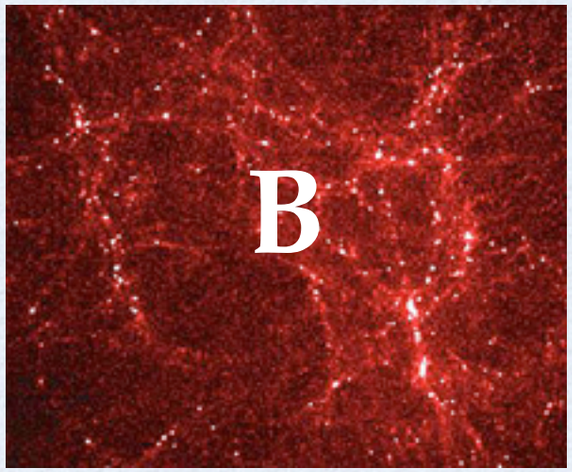

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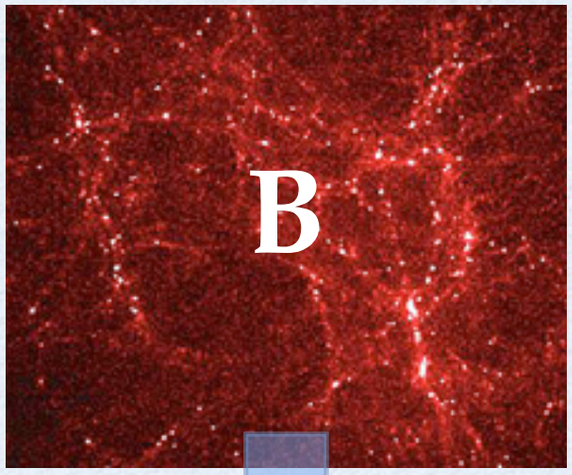

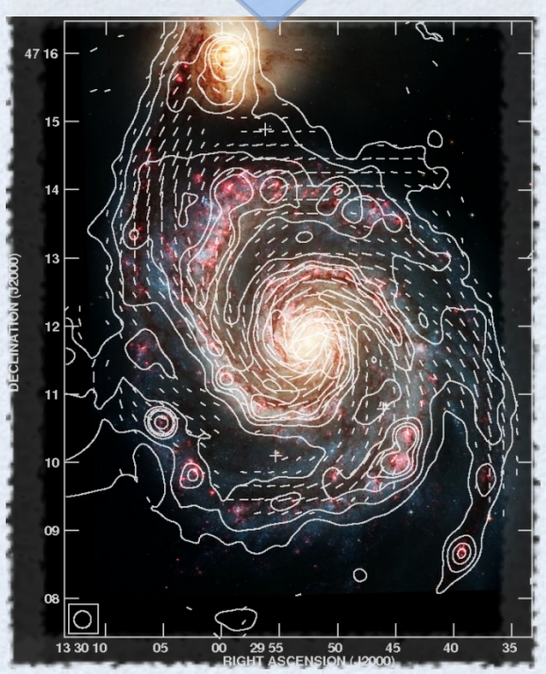

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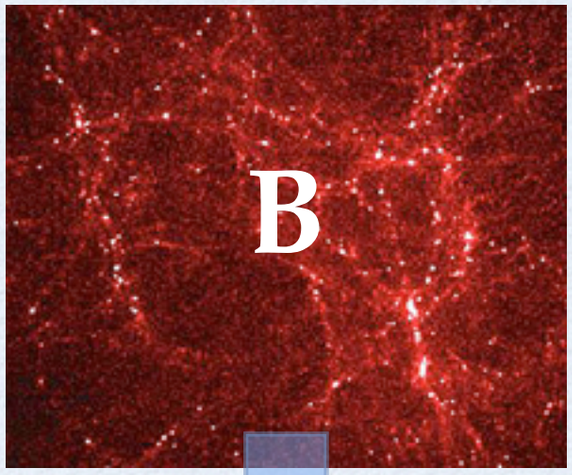

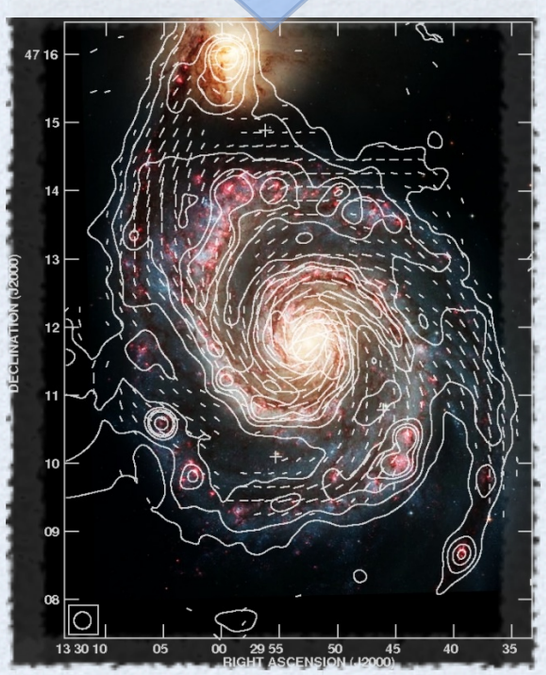

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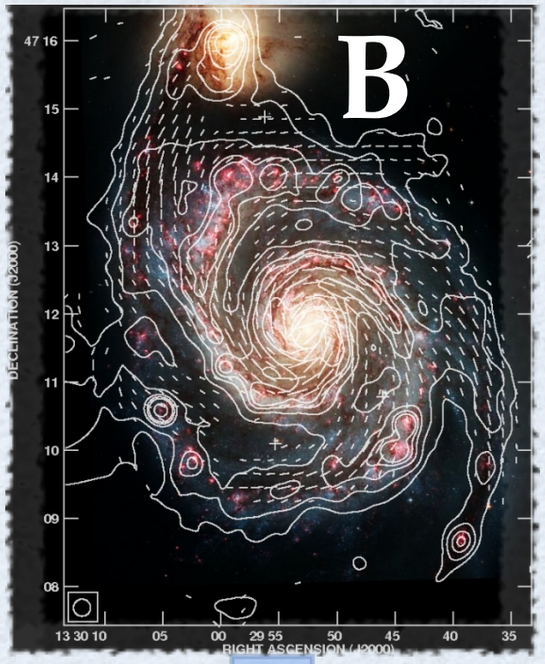

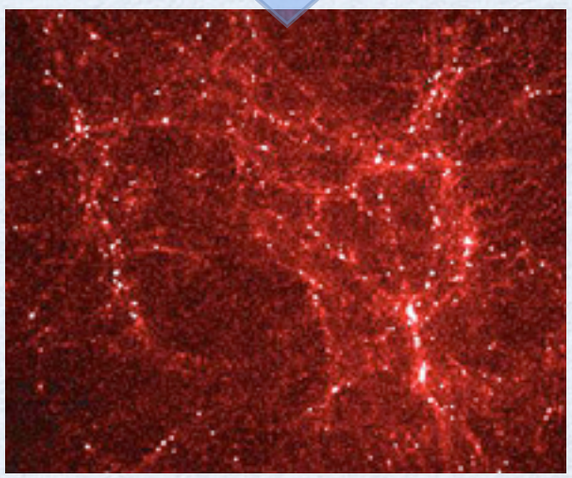

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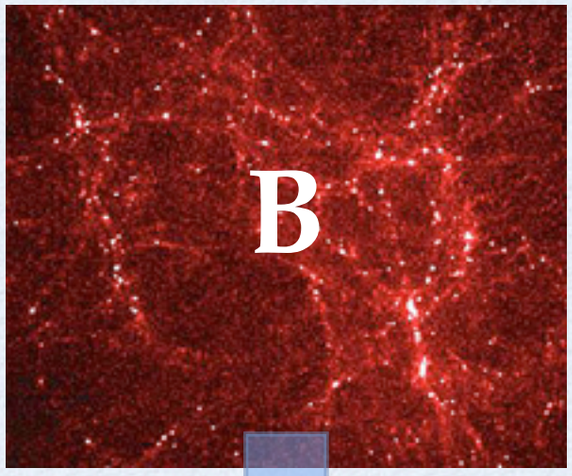

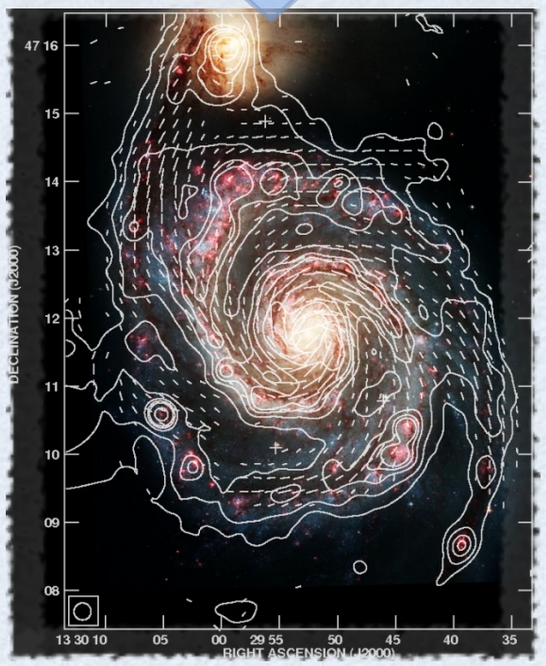

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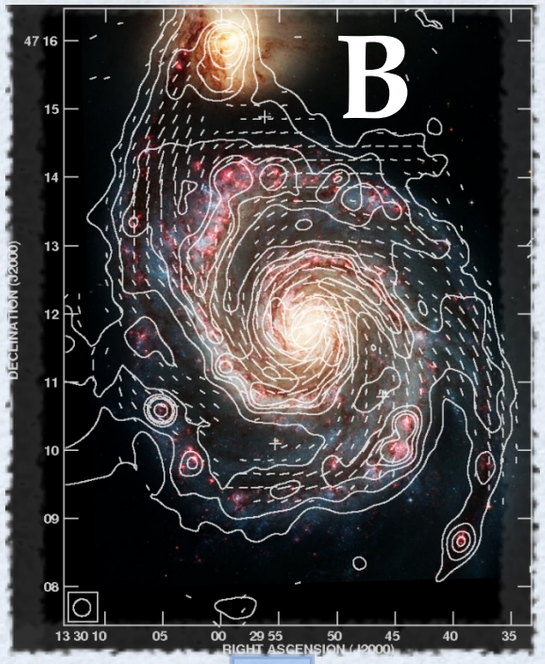

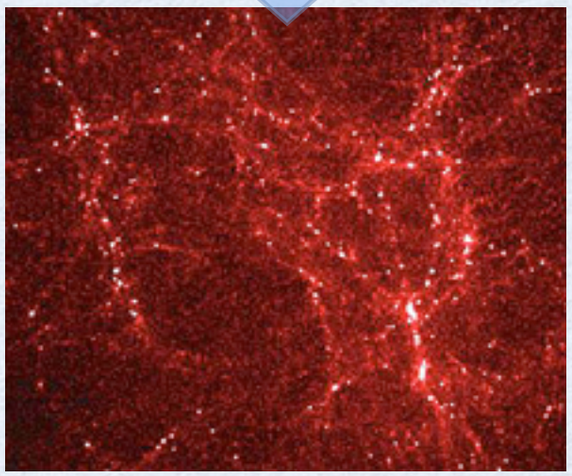

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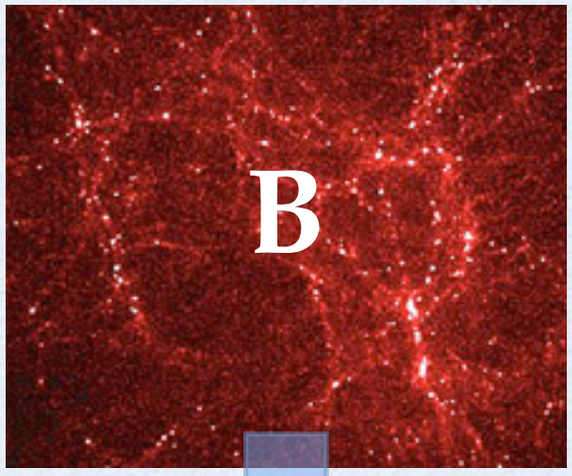

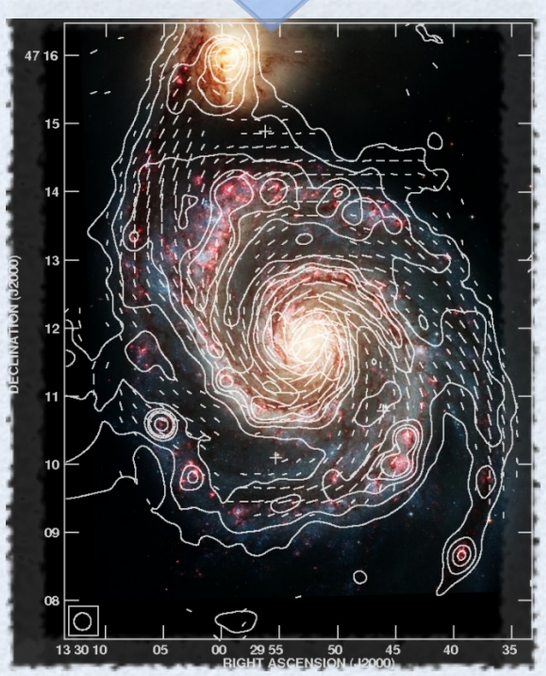

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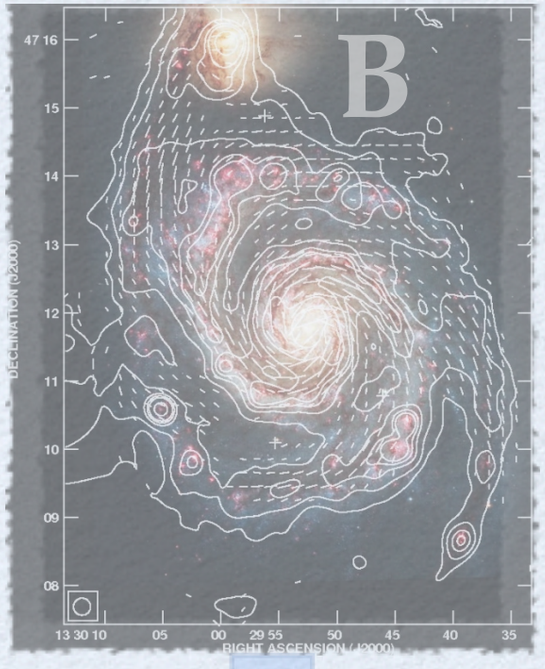

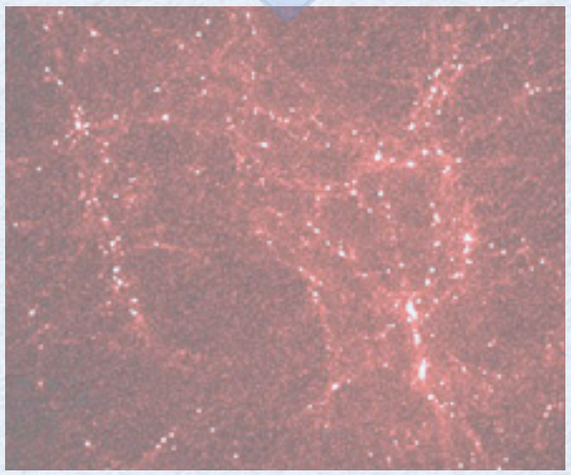

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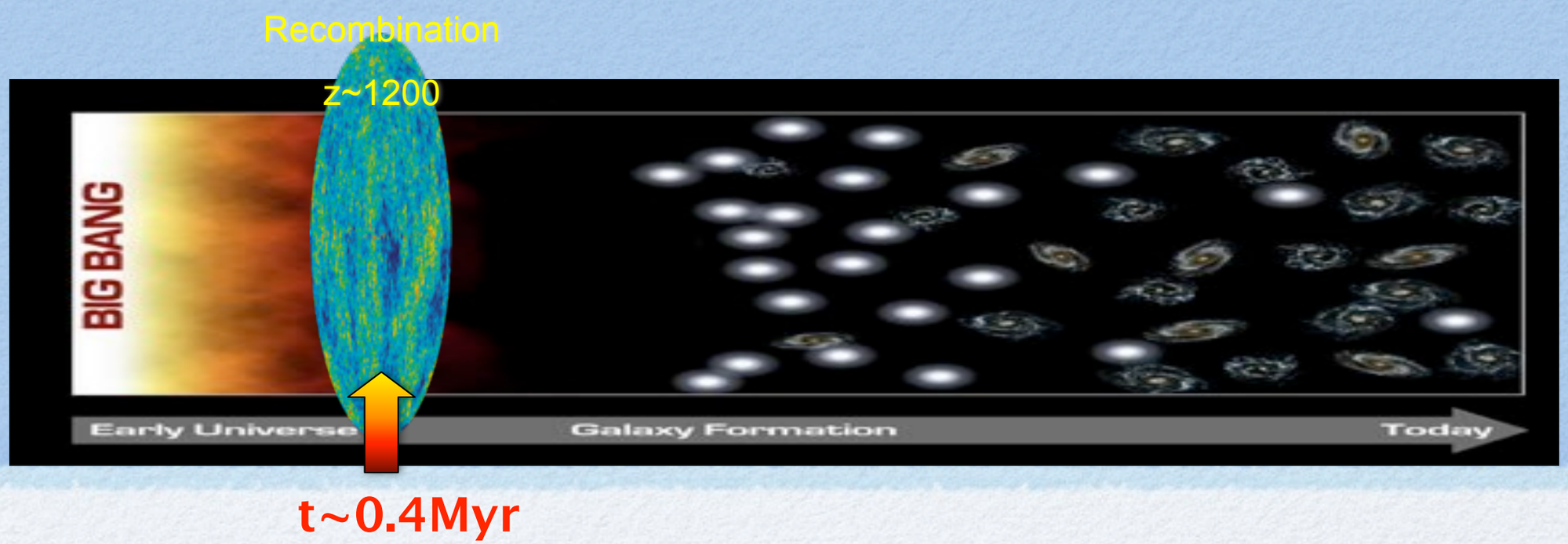

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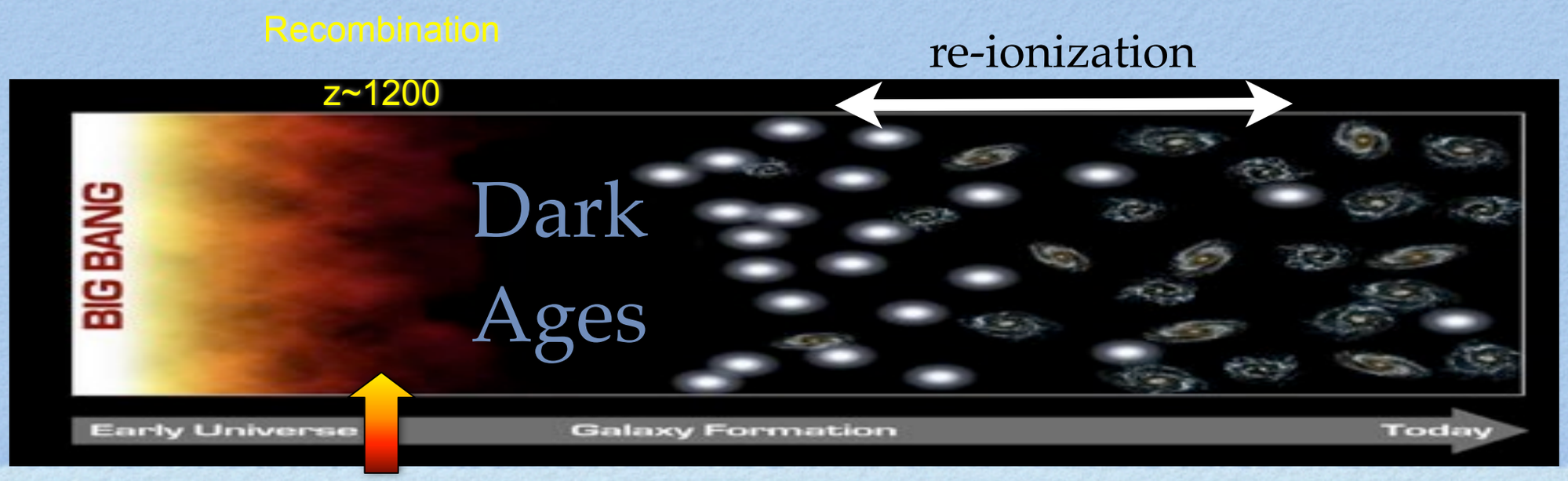

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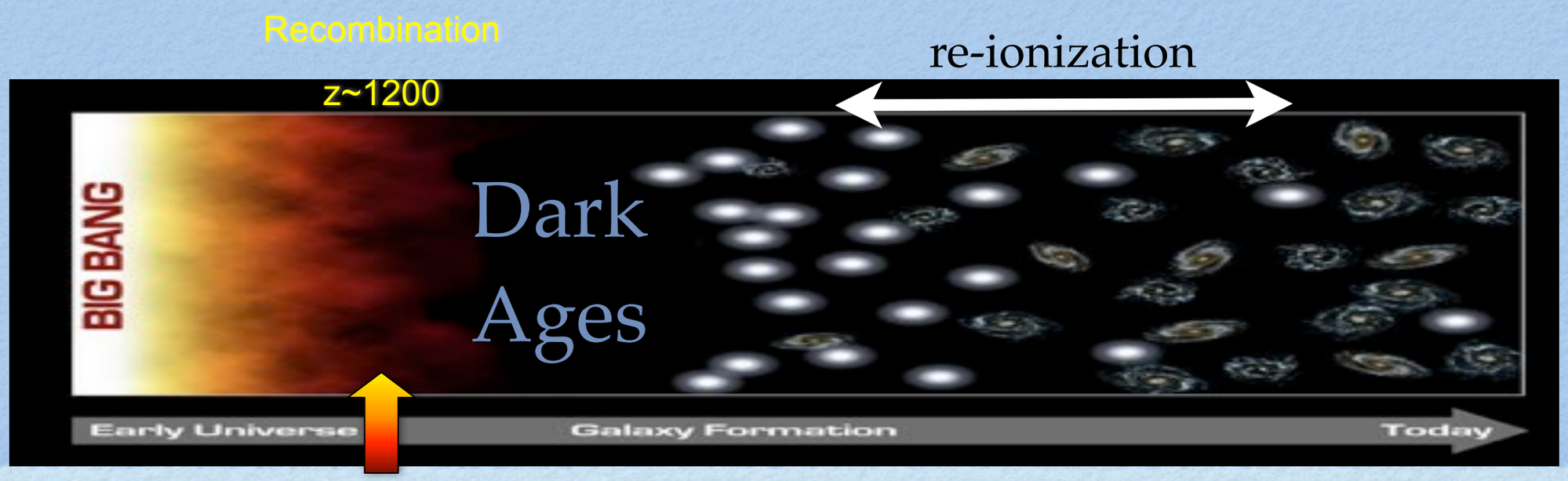

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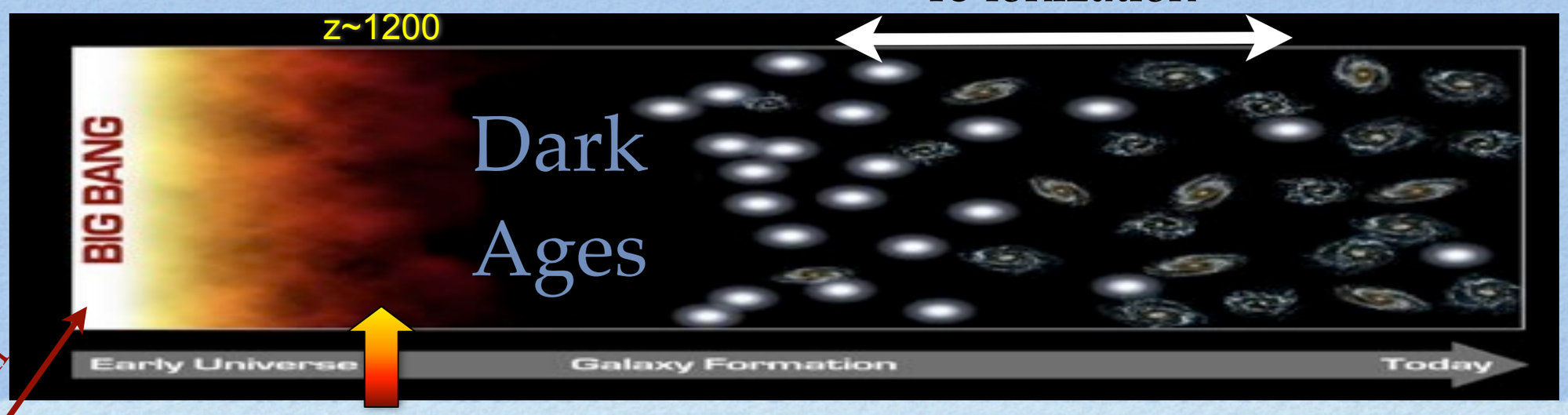

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e.g., Turner and Widrow 1988,
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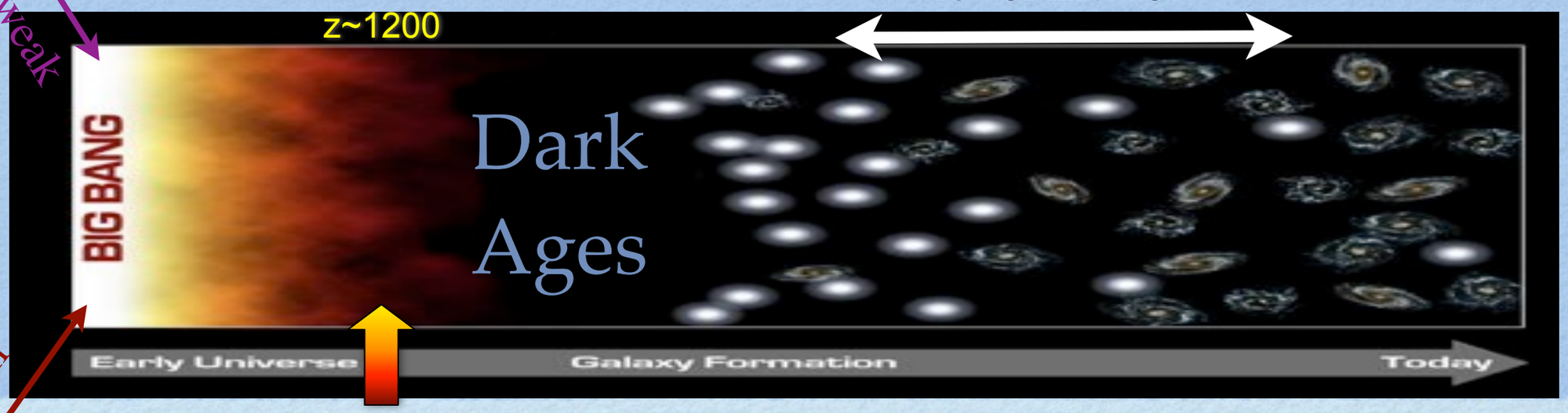
e.g., Durrer & Neronov 2013

electroweak + QCD



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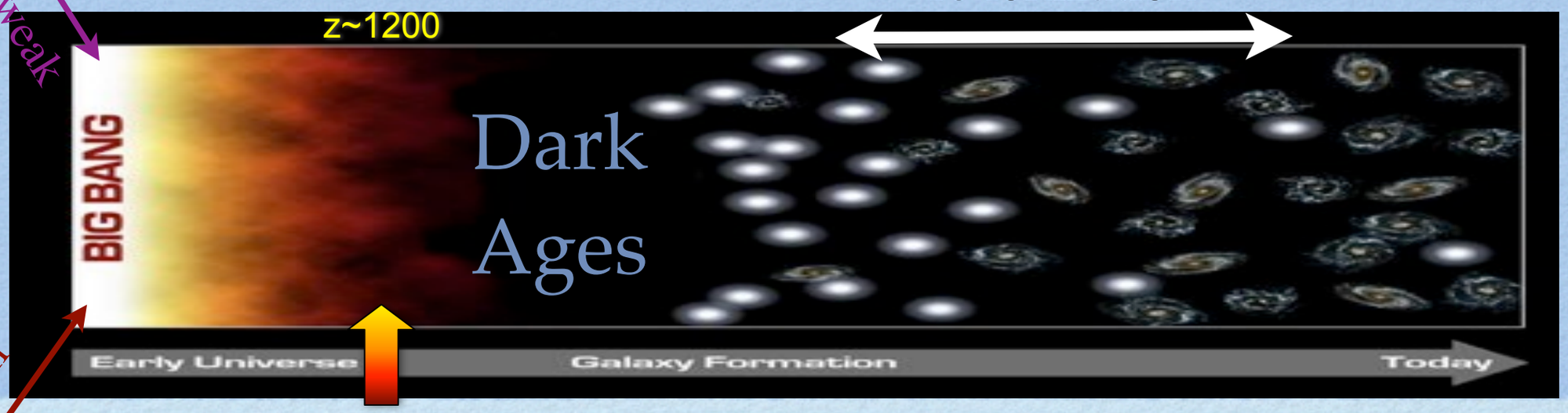

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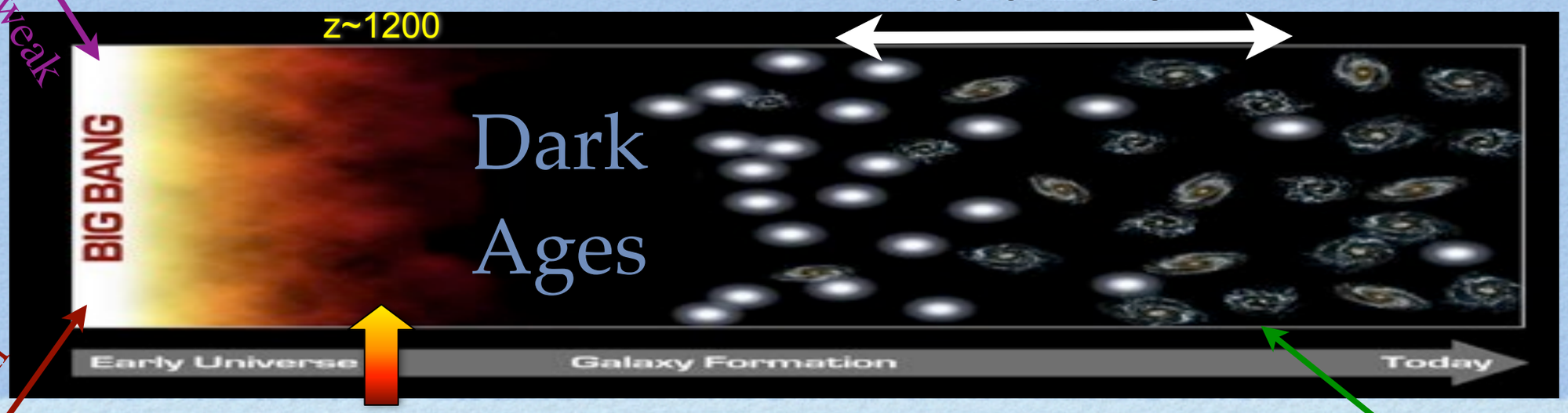

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during the collapse no see needed

e.g., Kronberg 1994, Subramanian et al 1994, Kulsrud et al 1997, Gnedin et al 2000

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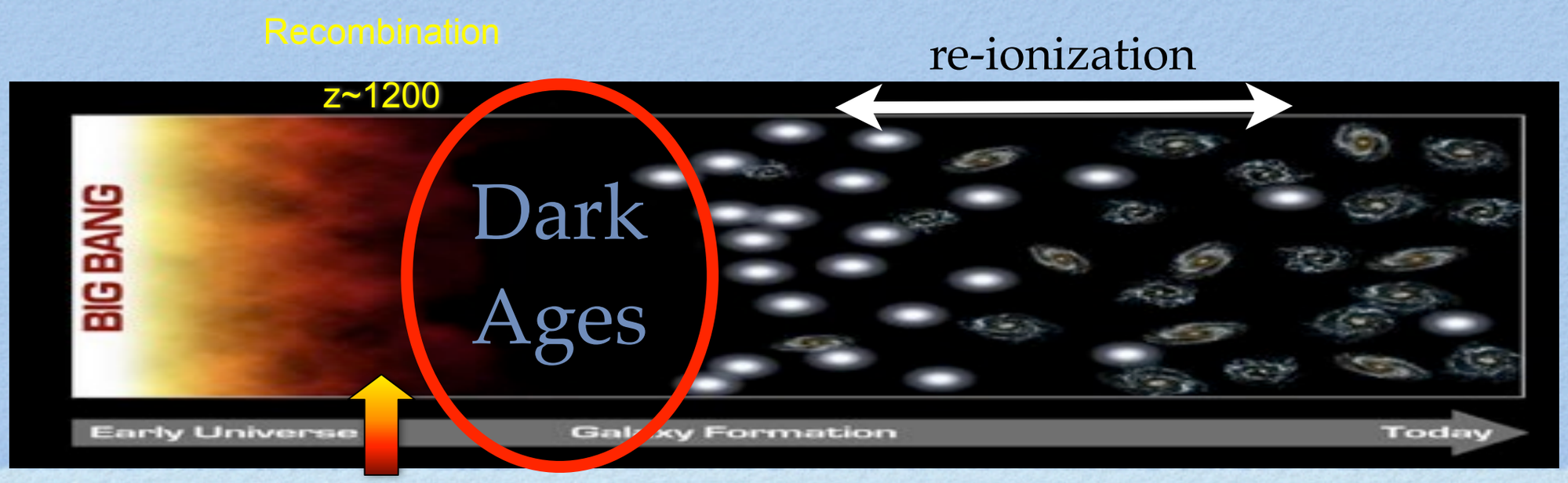

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Generate magnetic field from zero B

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Generate magnetic field from zero B through vortex like motion:

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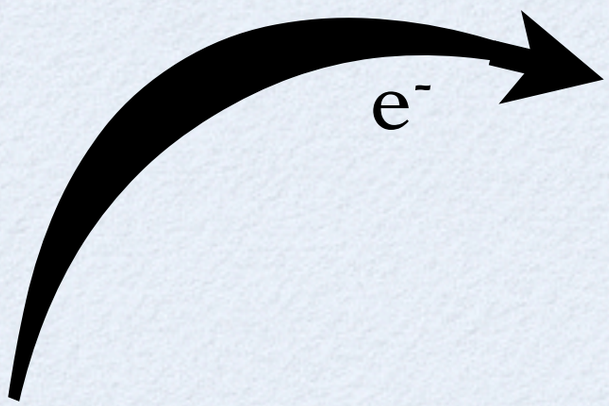

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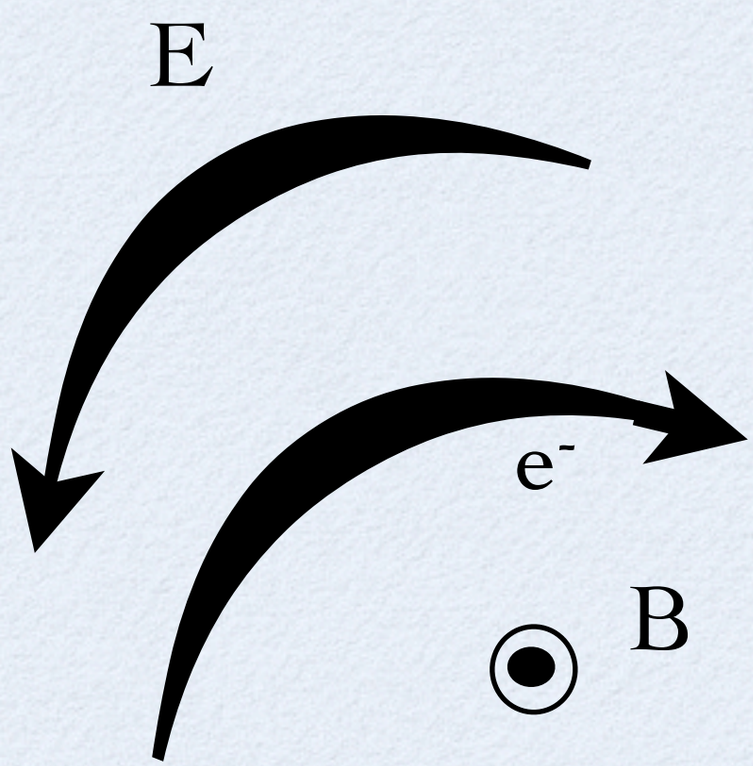

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Generate magnetic field from zero B through vortex like motion Q: How do we generate vorticity?

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A: Biermann 1950: $\nabla n \times \nabla P \neq 0$

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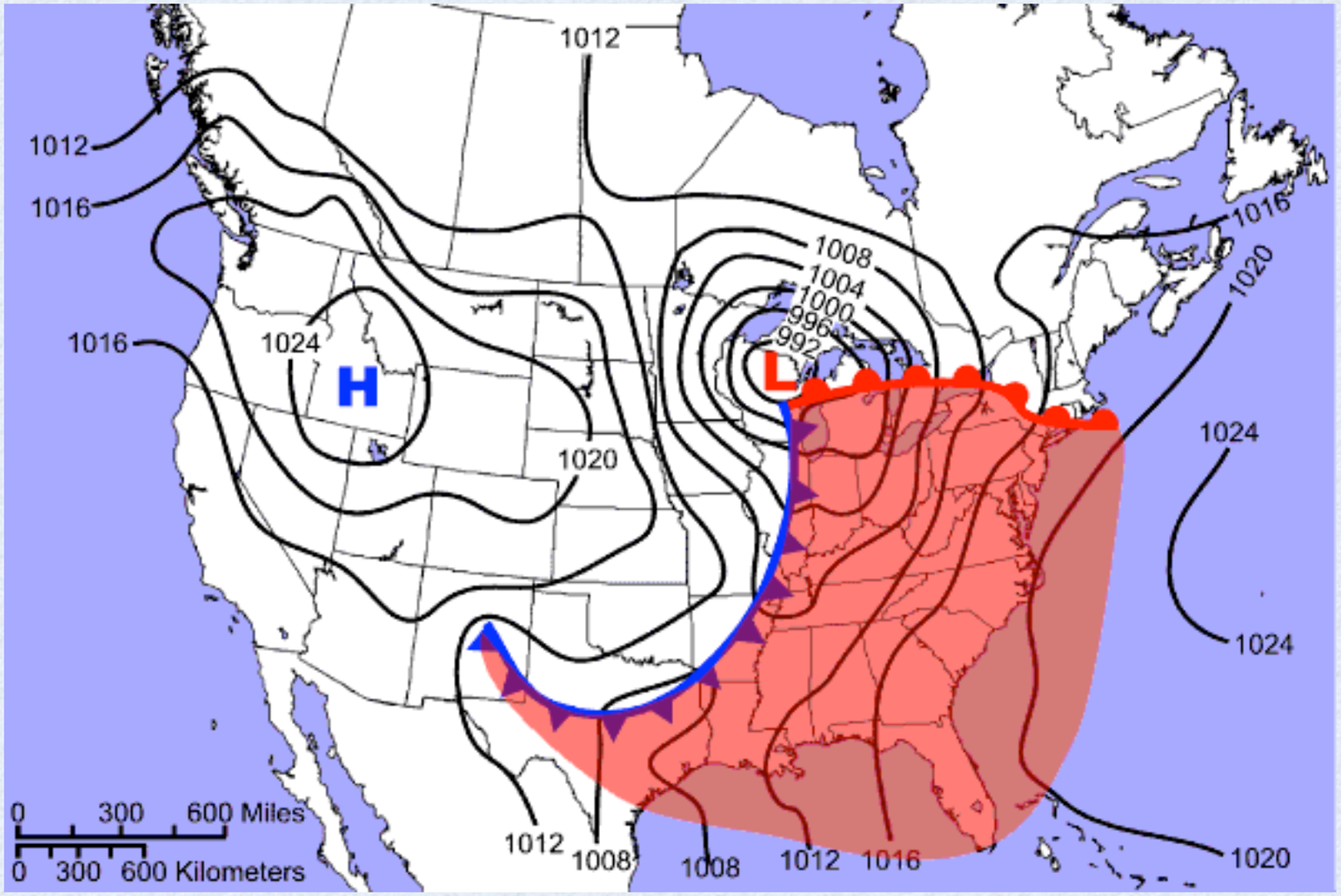

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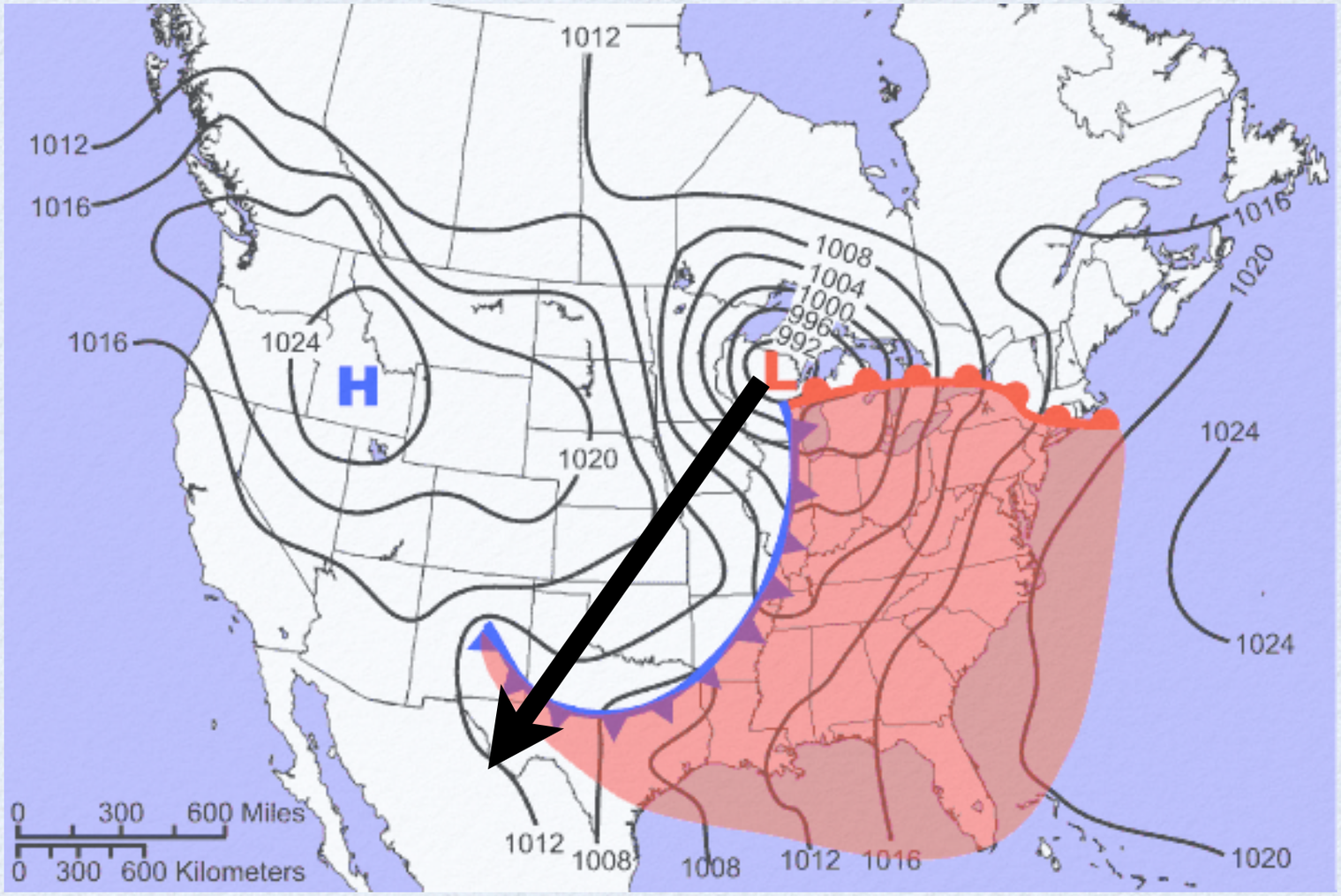

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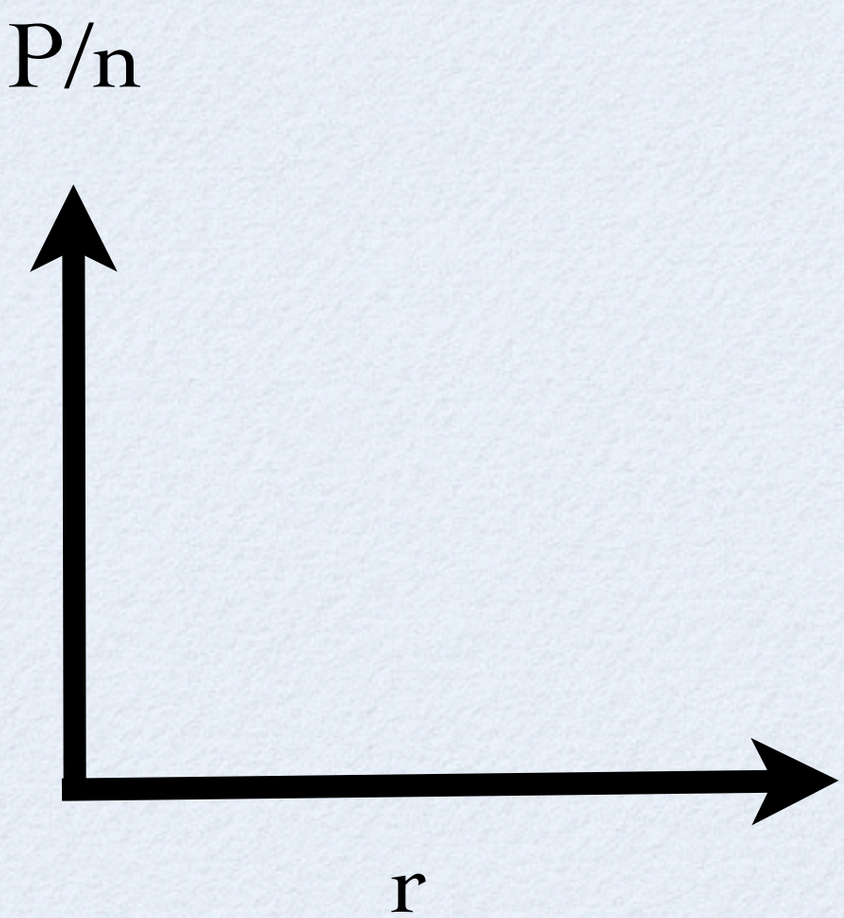

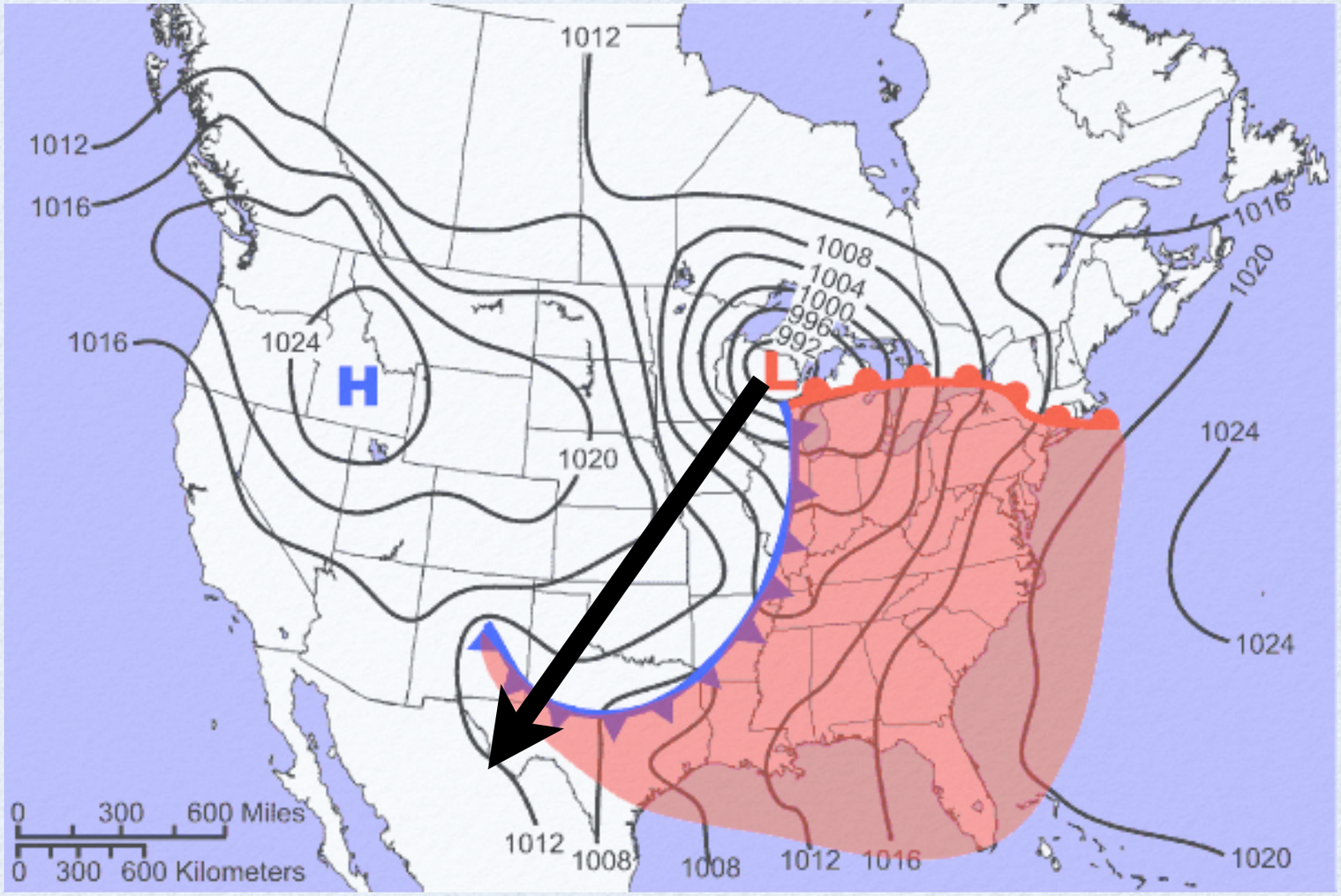

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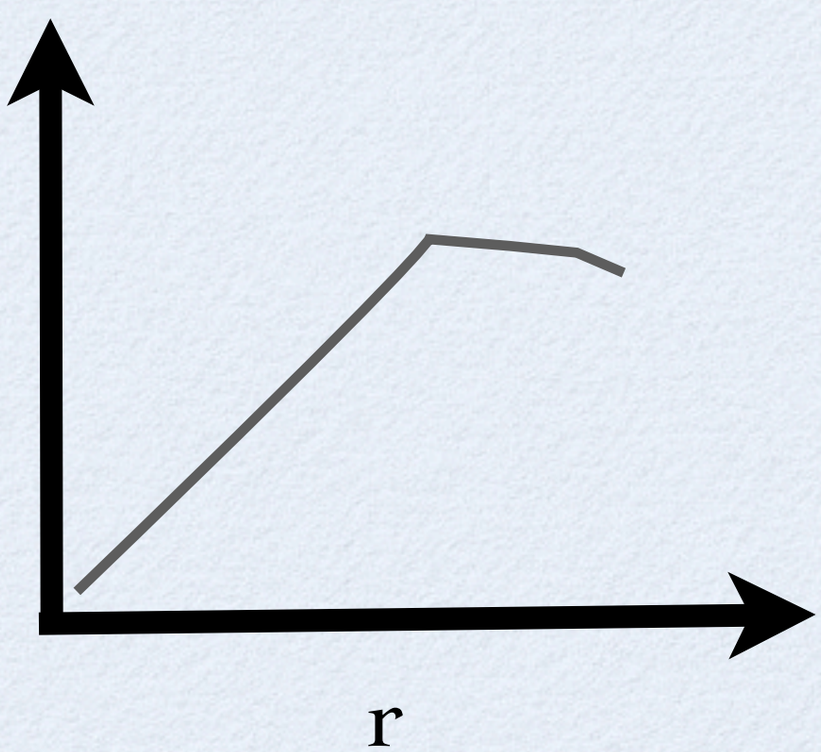
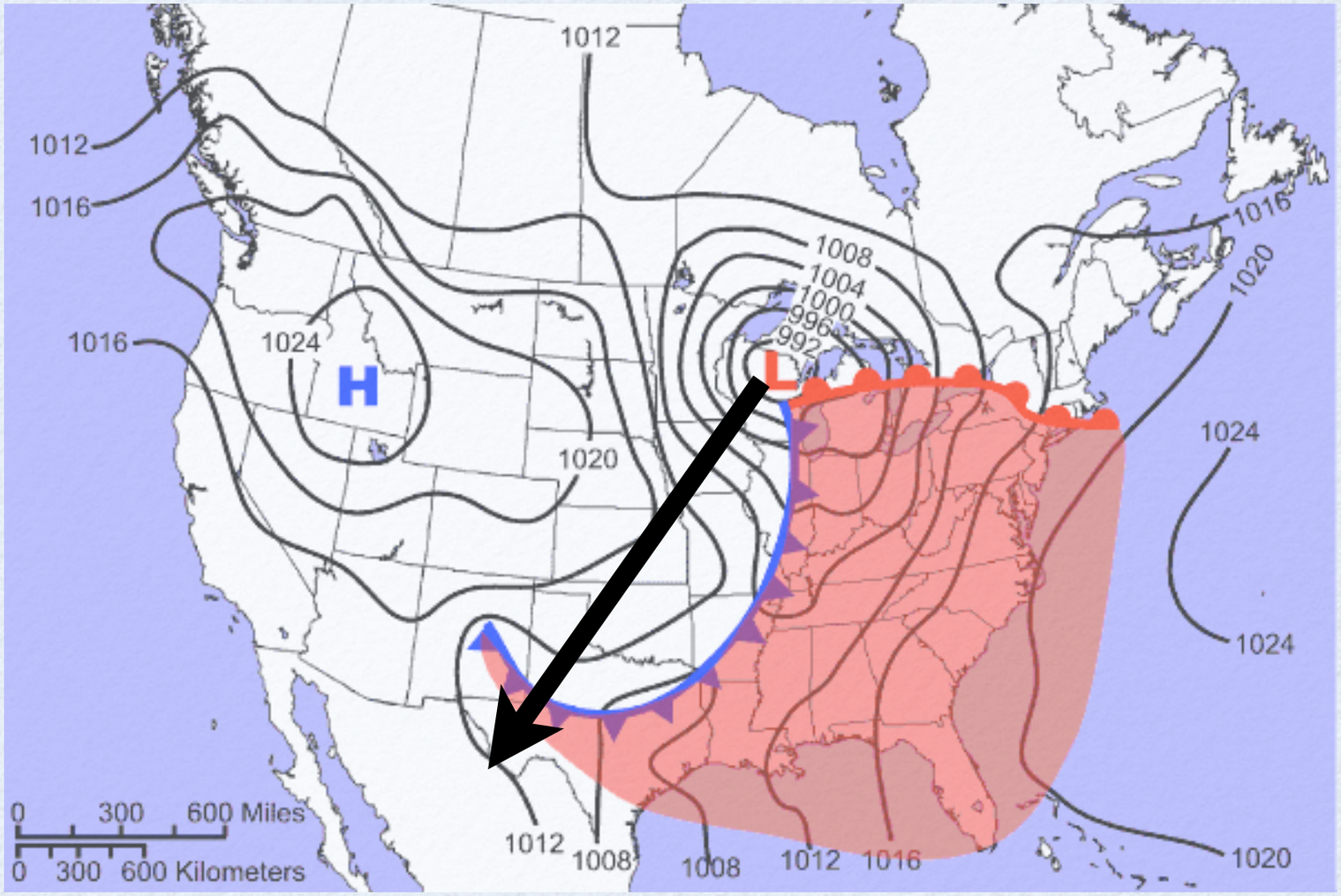
P/n (T/n)





GENERATING MAGNETIC FIELDS

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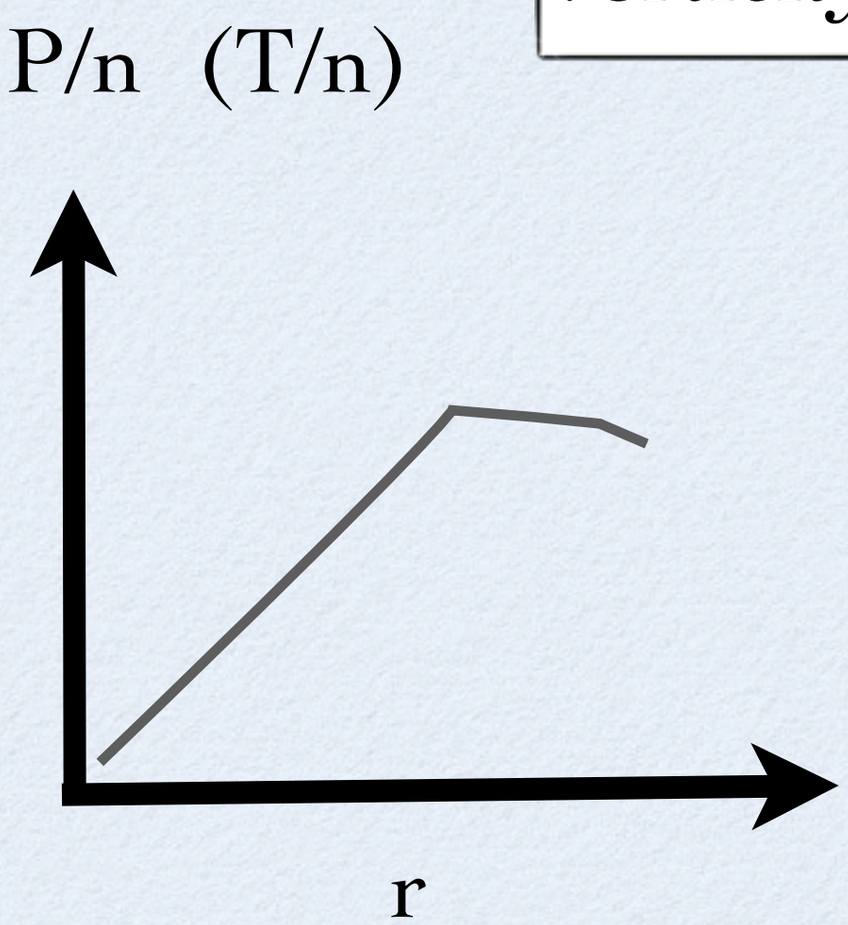

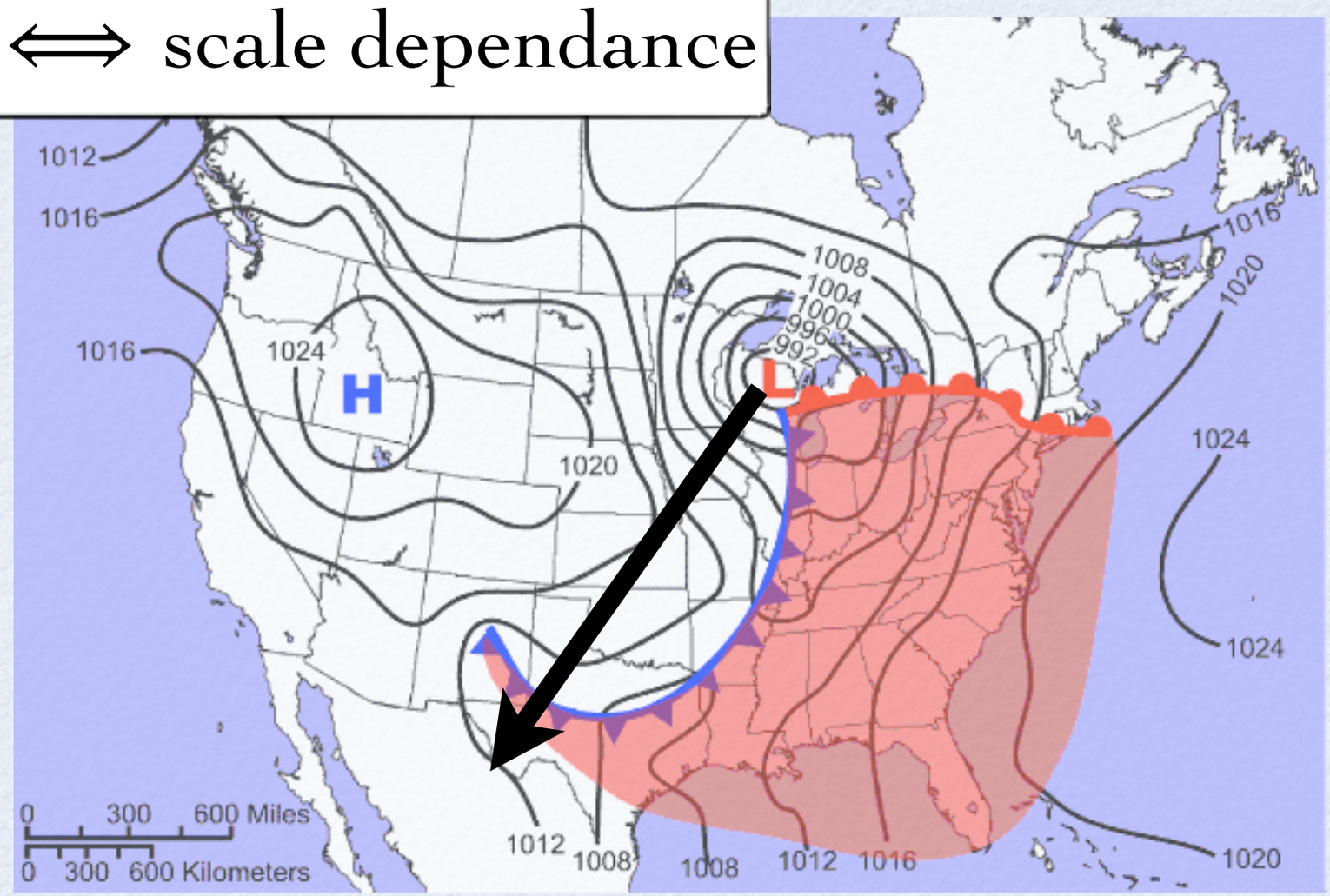

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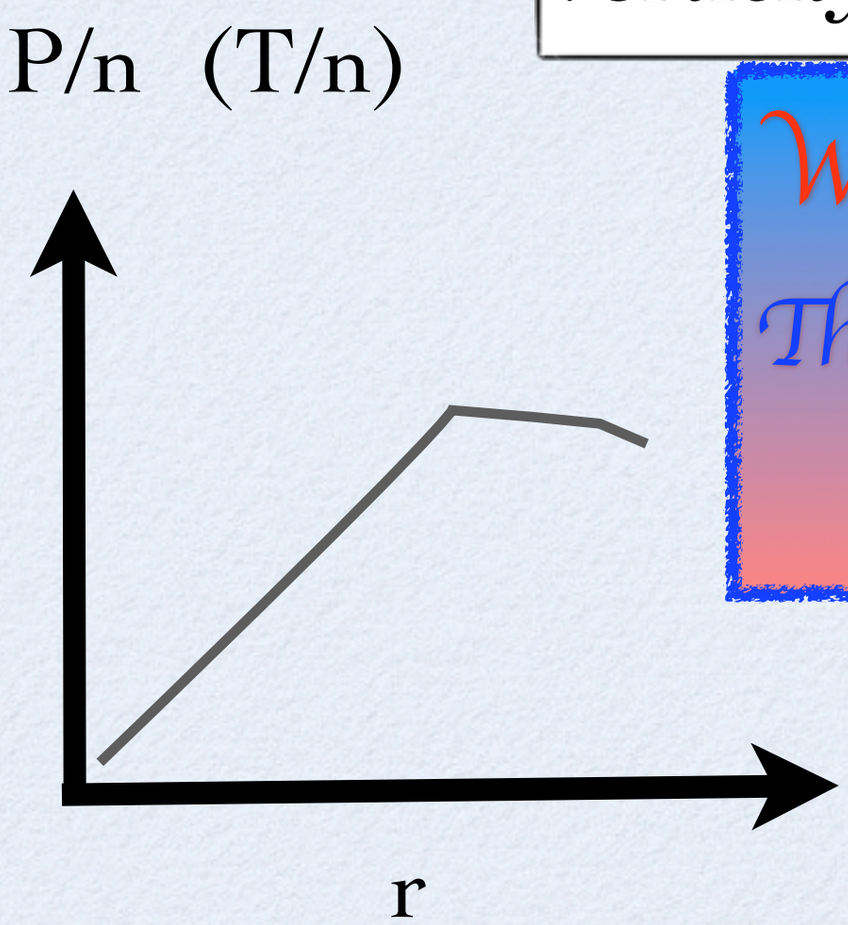

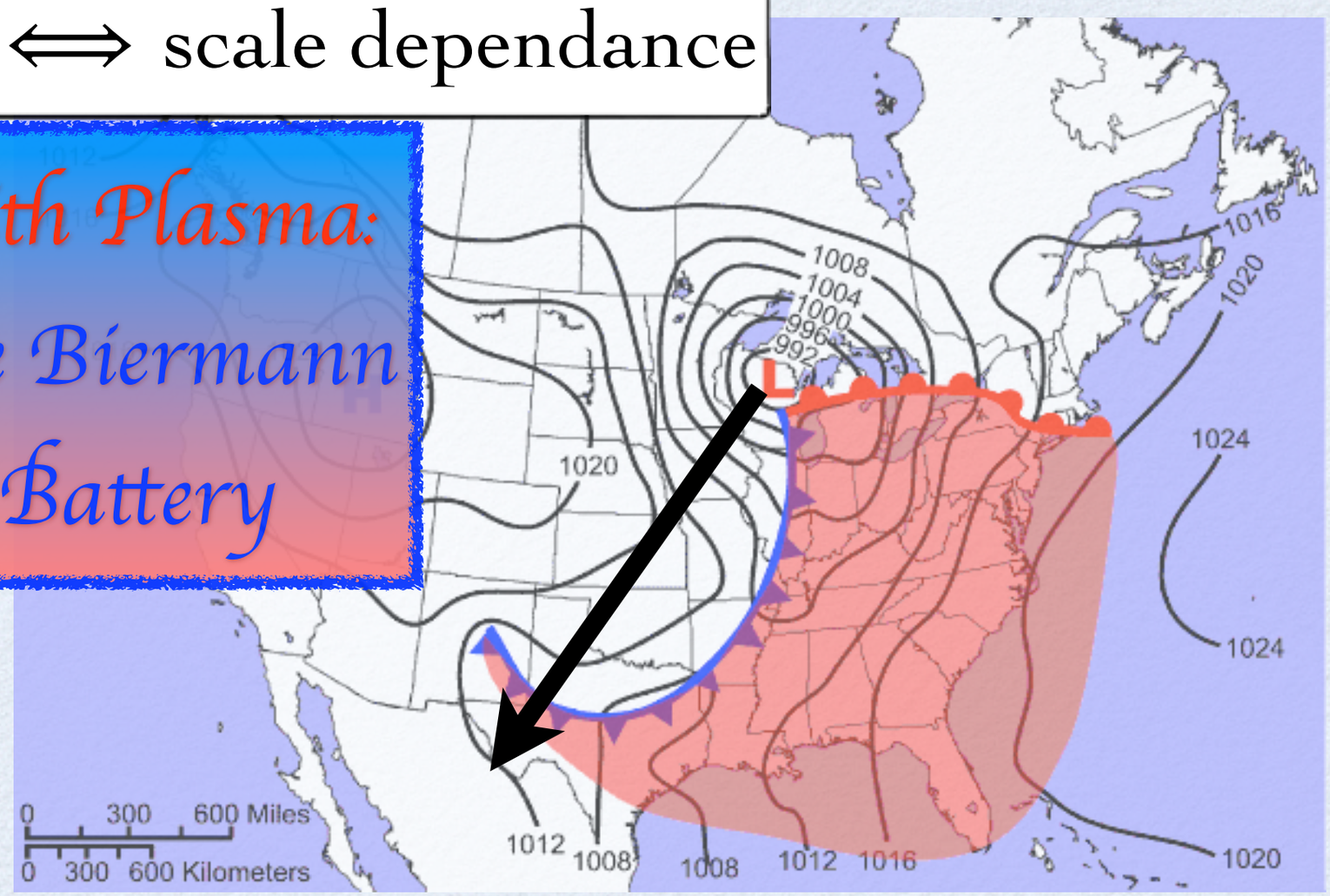

1. Where do we find vorticity in the dark ages?
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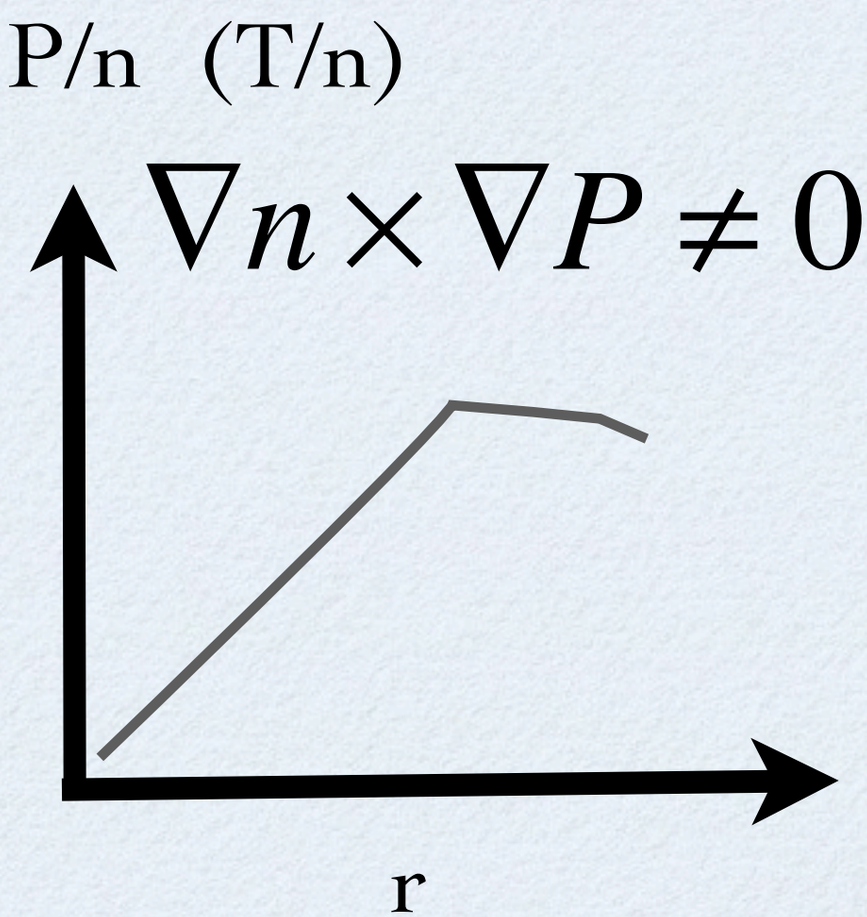

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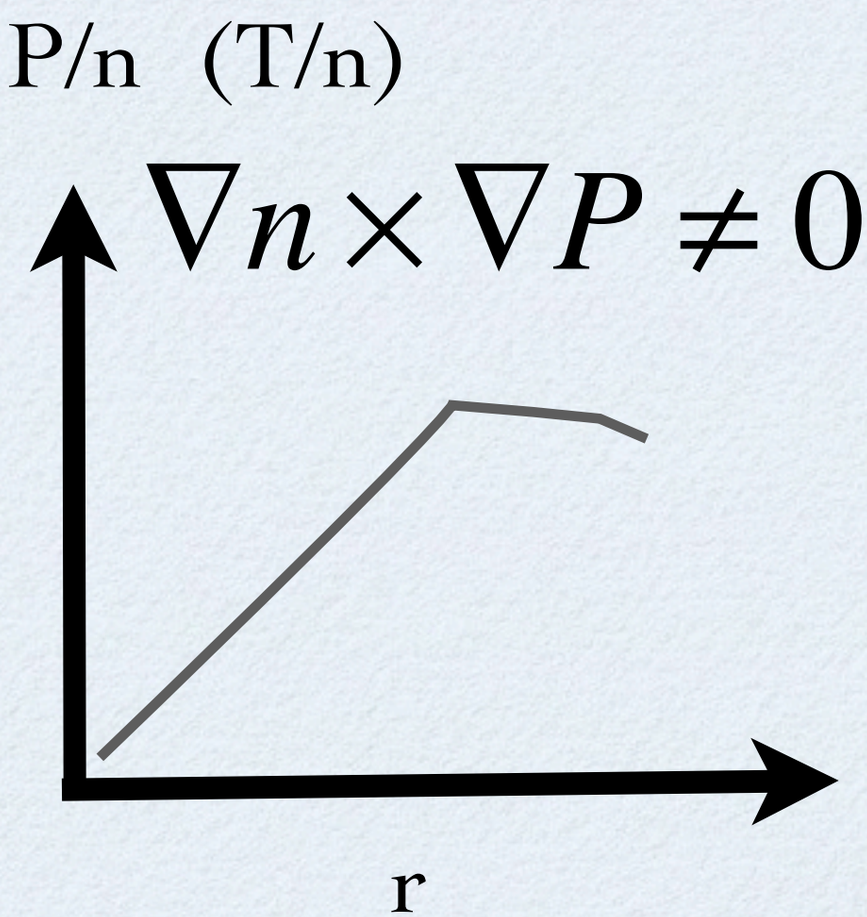

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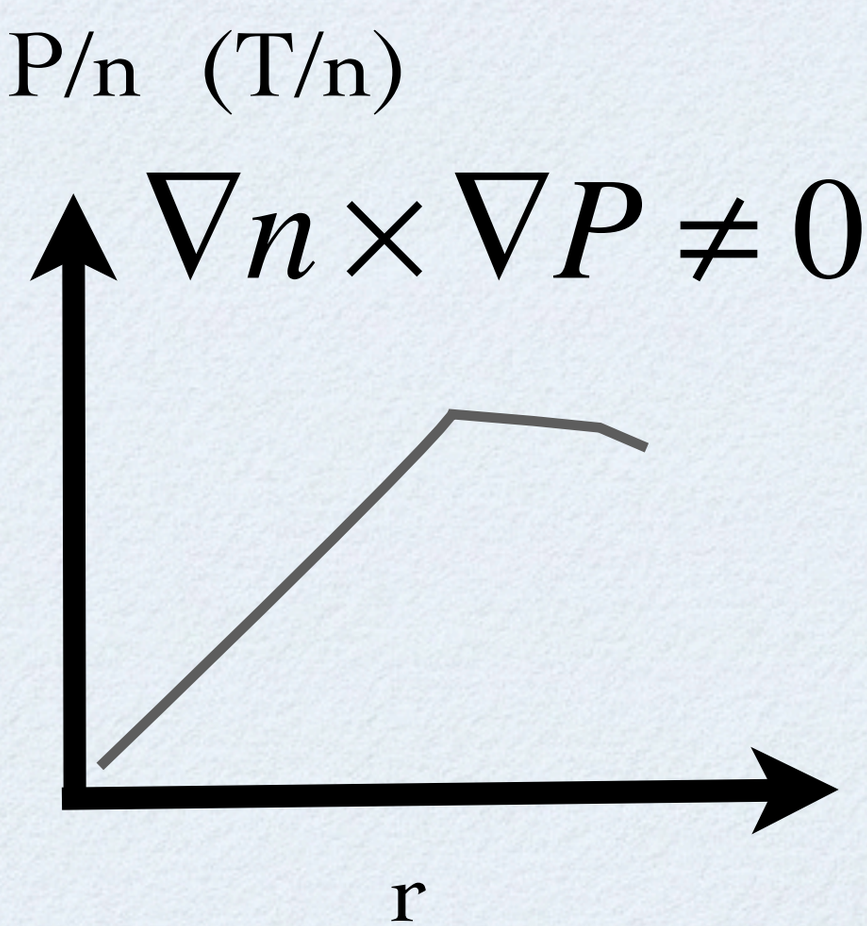

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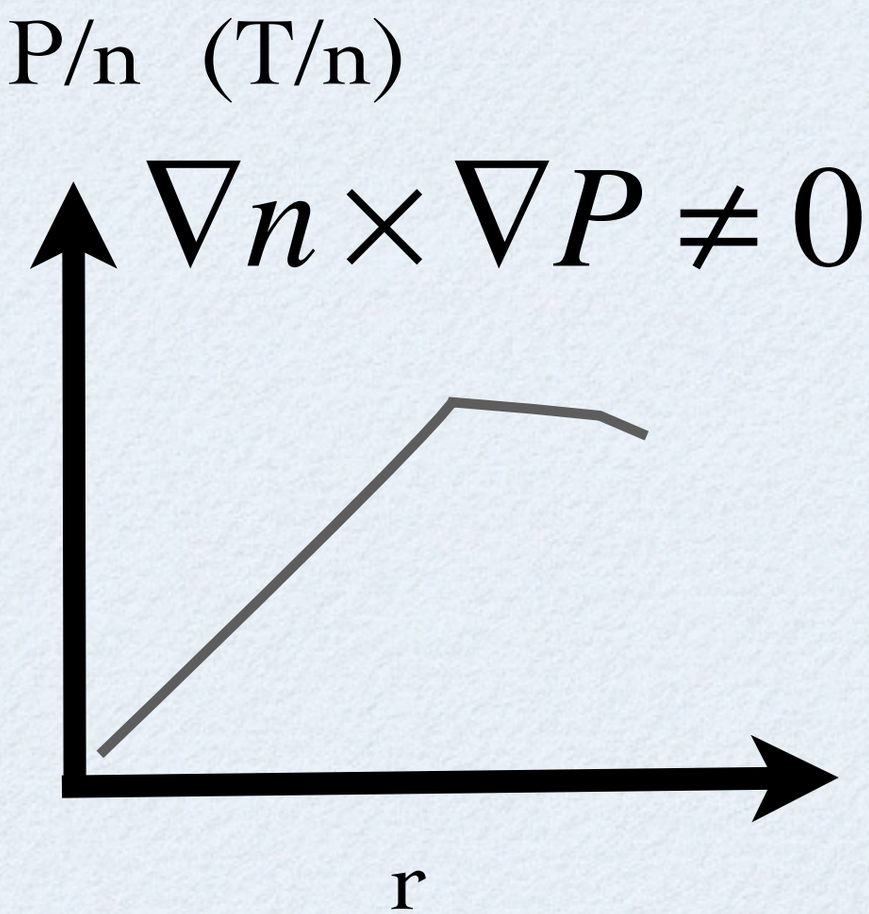

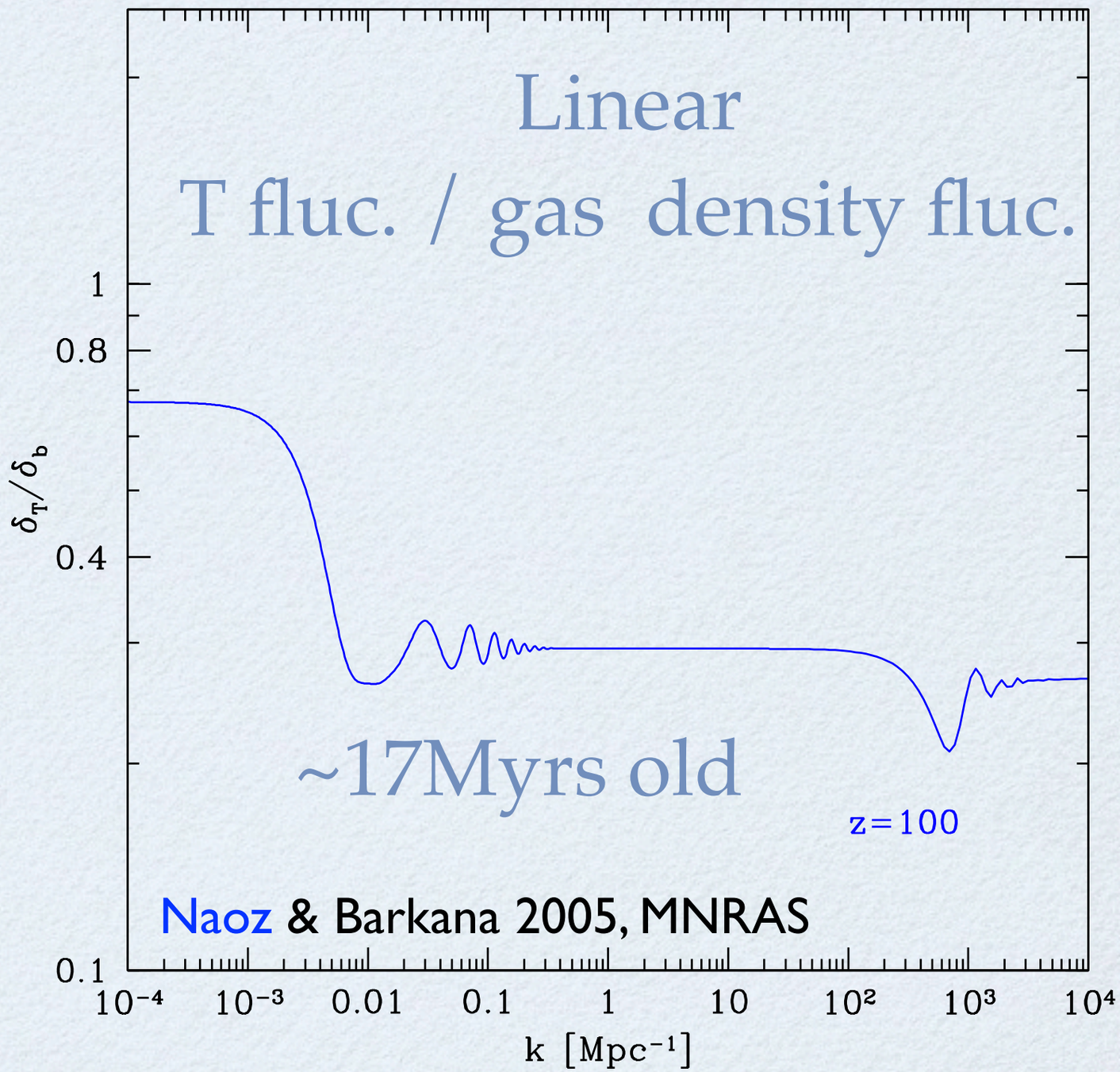

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Linear
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P/n (T/n) t~0.4Myr

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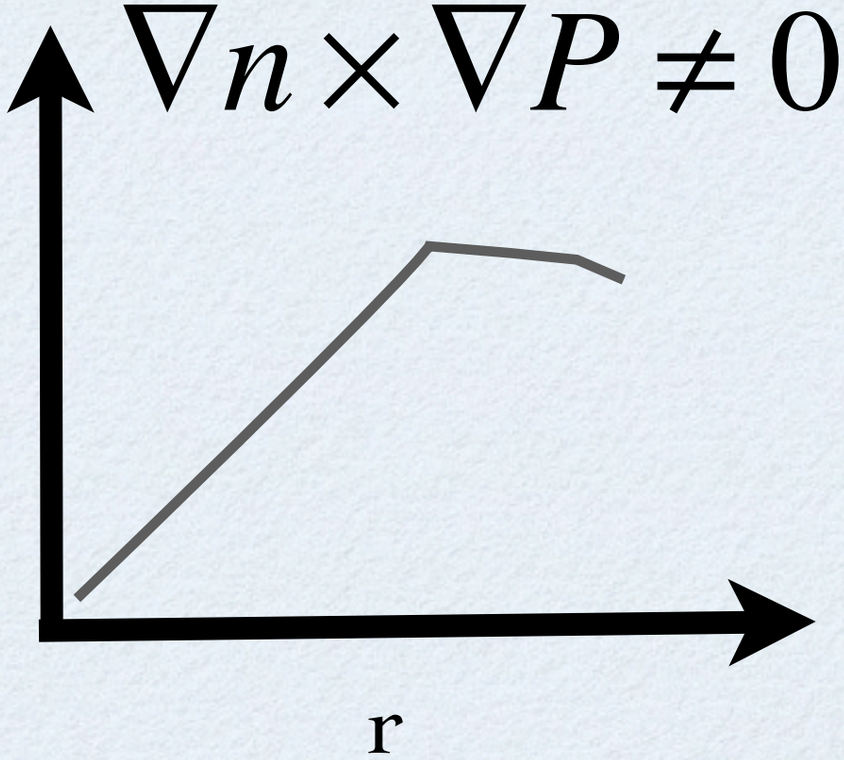

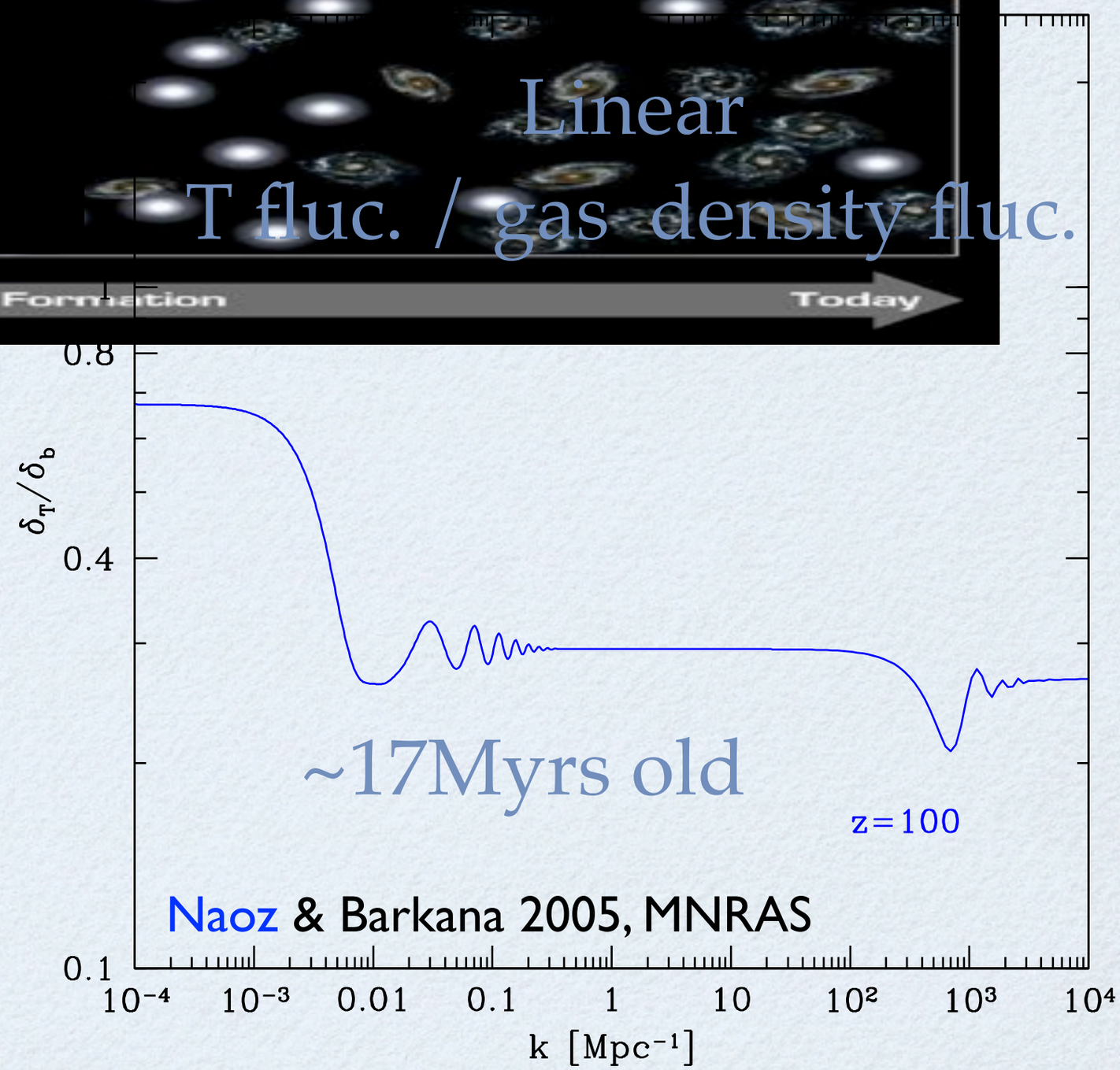

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Naoz & Barkana 2005, MNRAS

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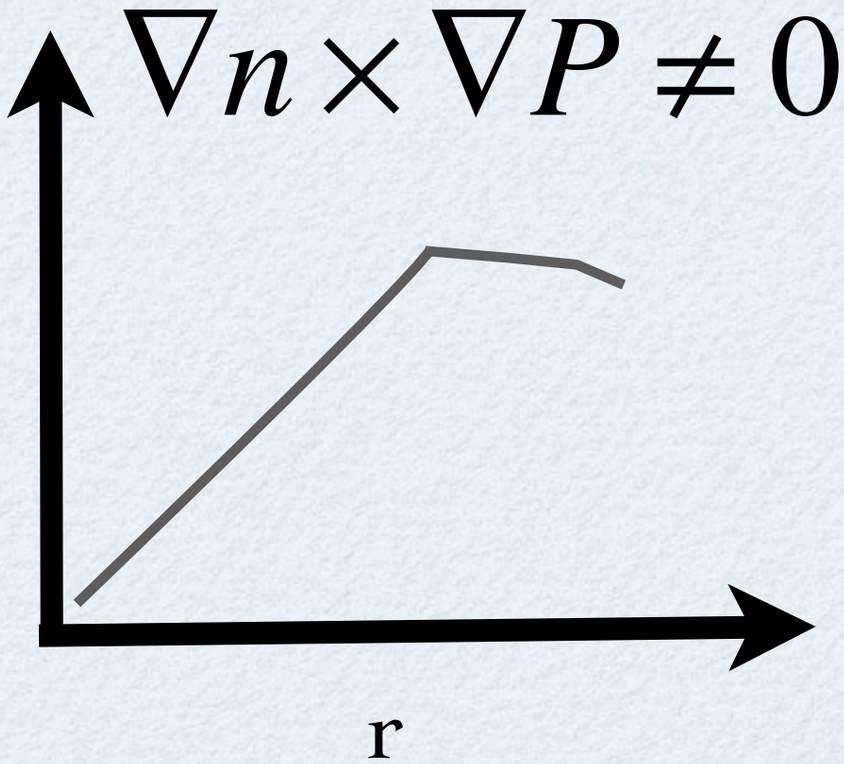

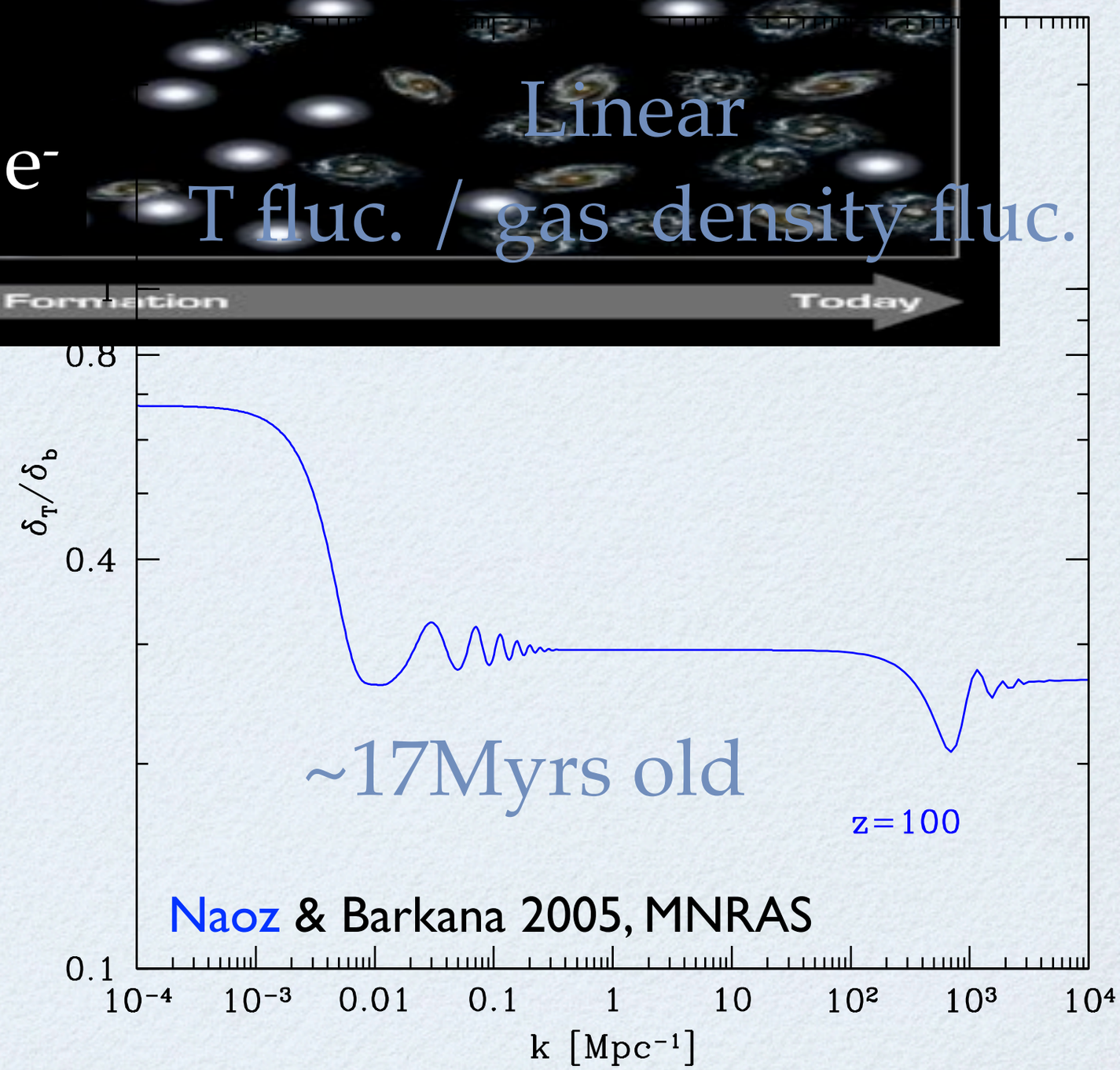

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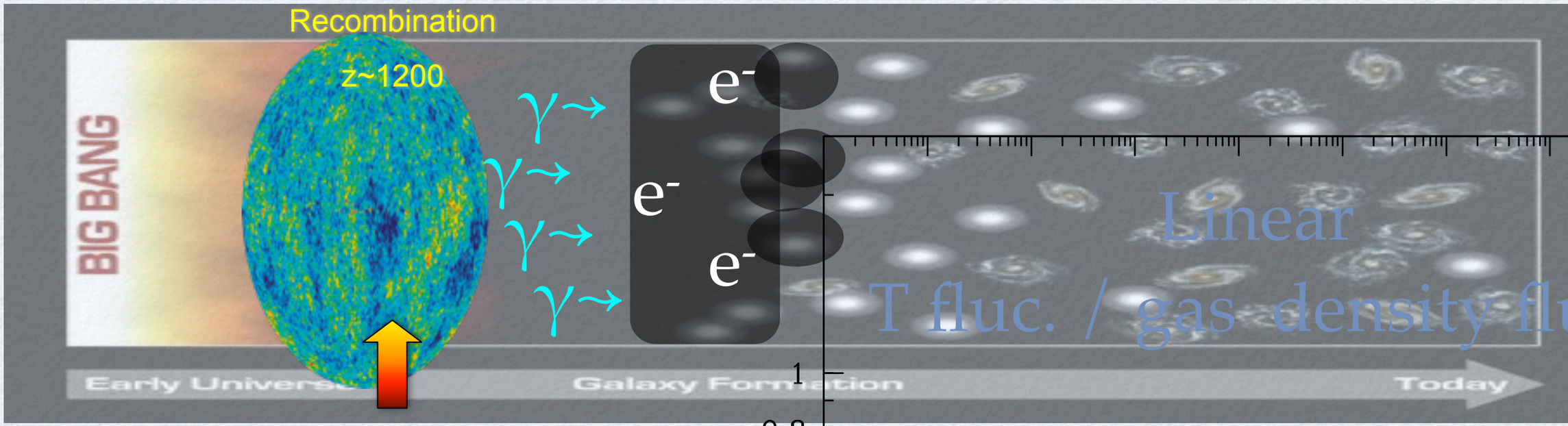

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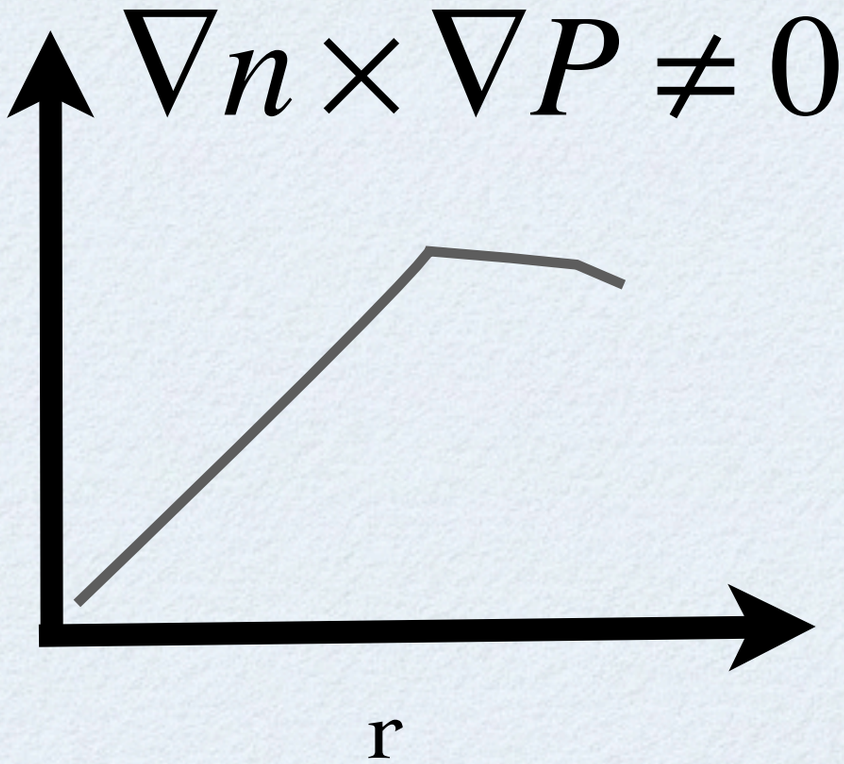

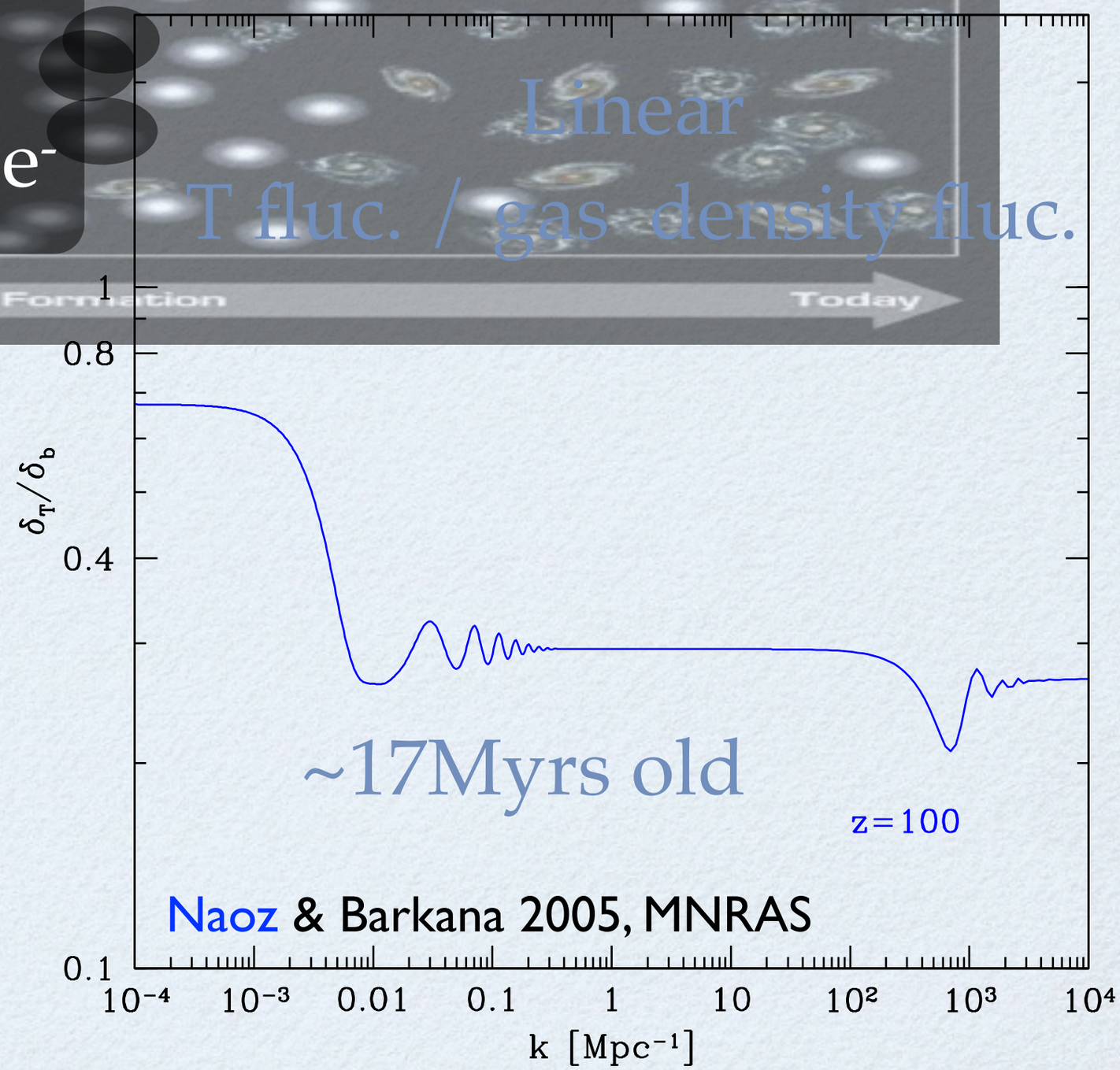

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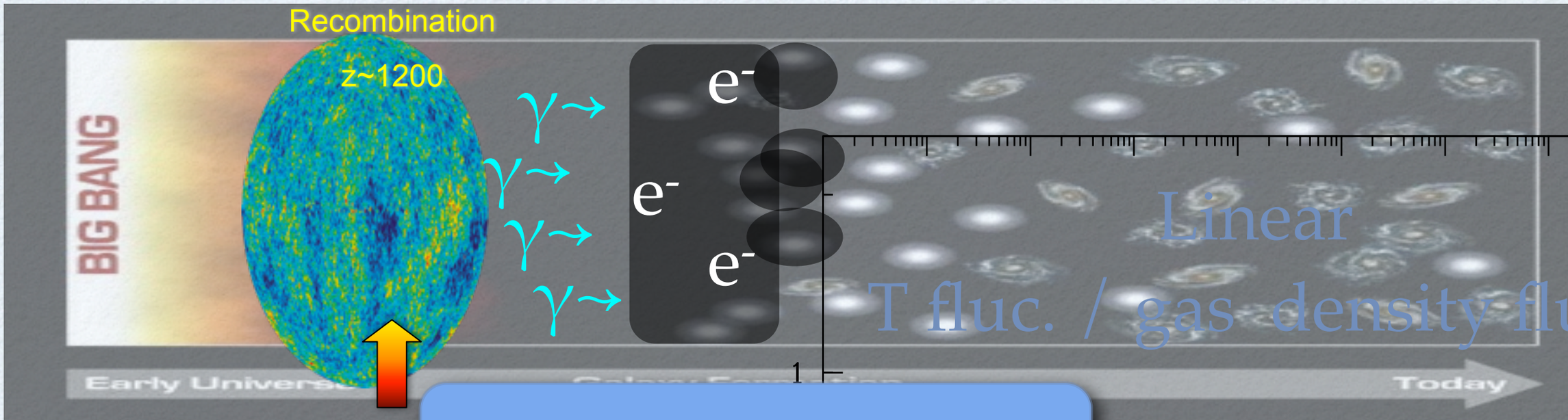
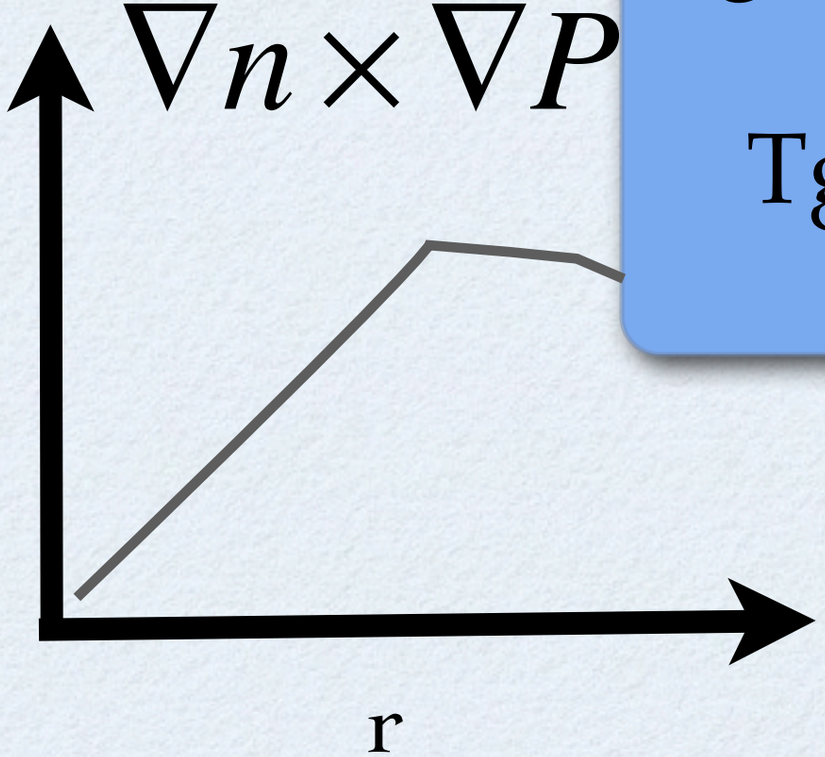


P/n (T/n) t~0.4

$\nabla n \times \nabla P$



$Tg \sim T\gamma \sim 1/a \quad z>150$

$Tg \sim 1/a^2 \quad z<150$

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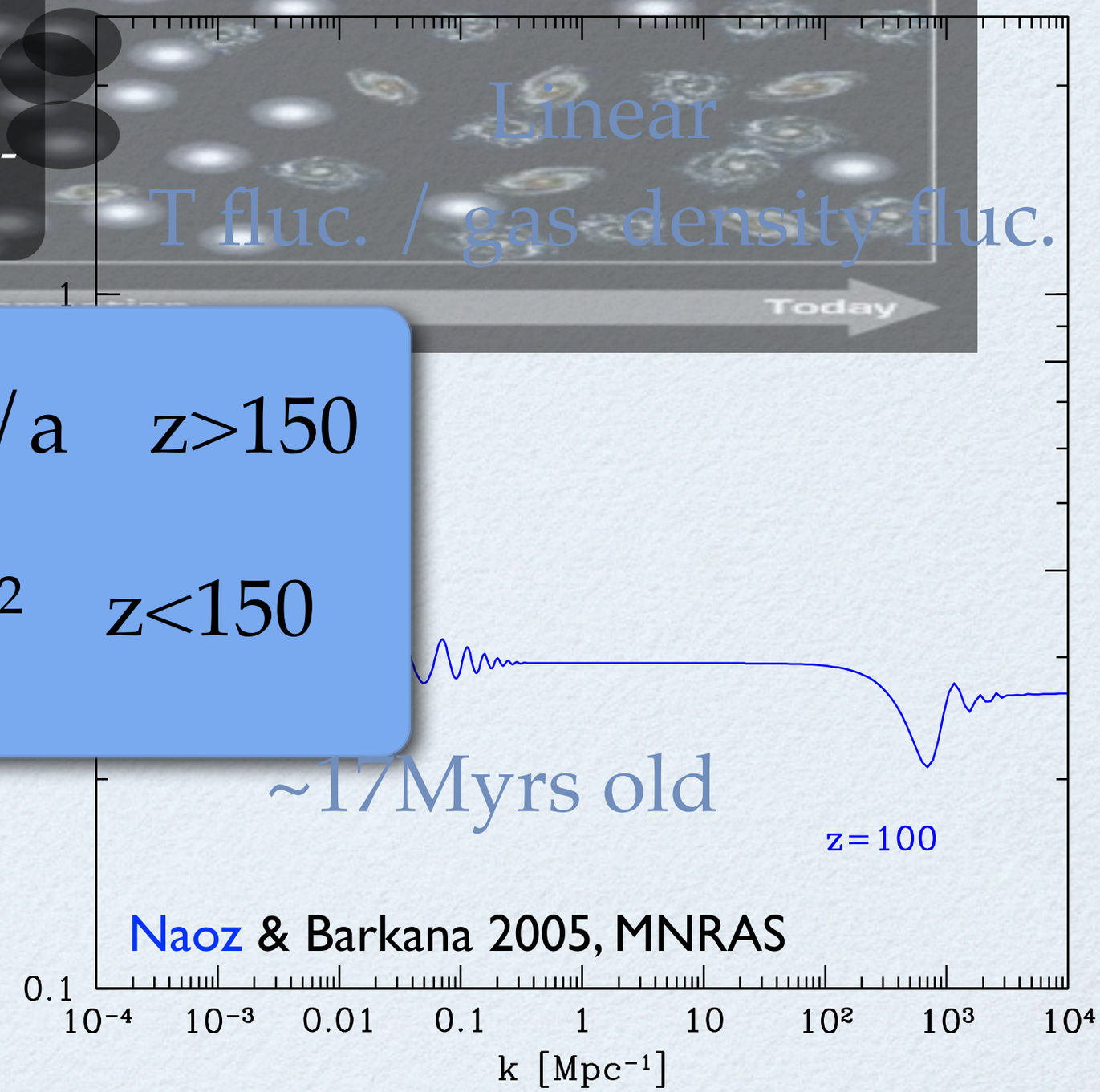

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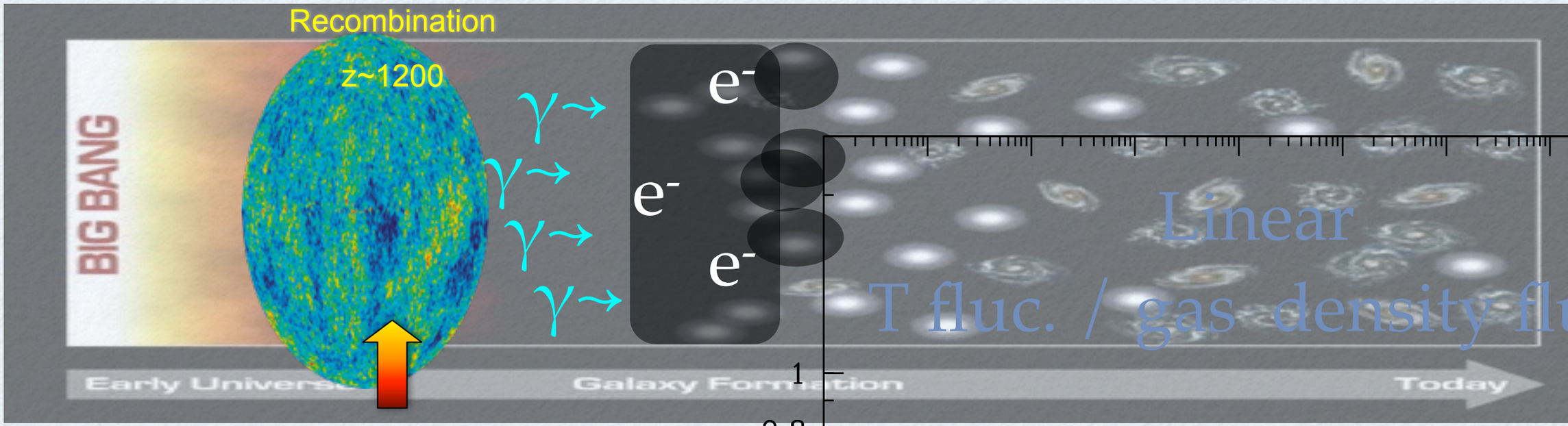

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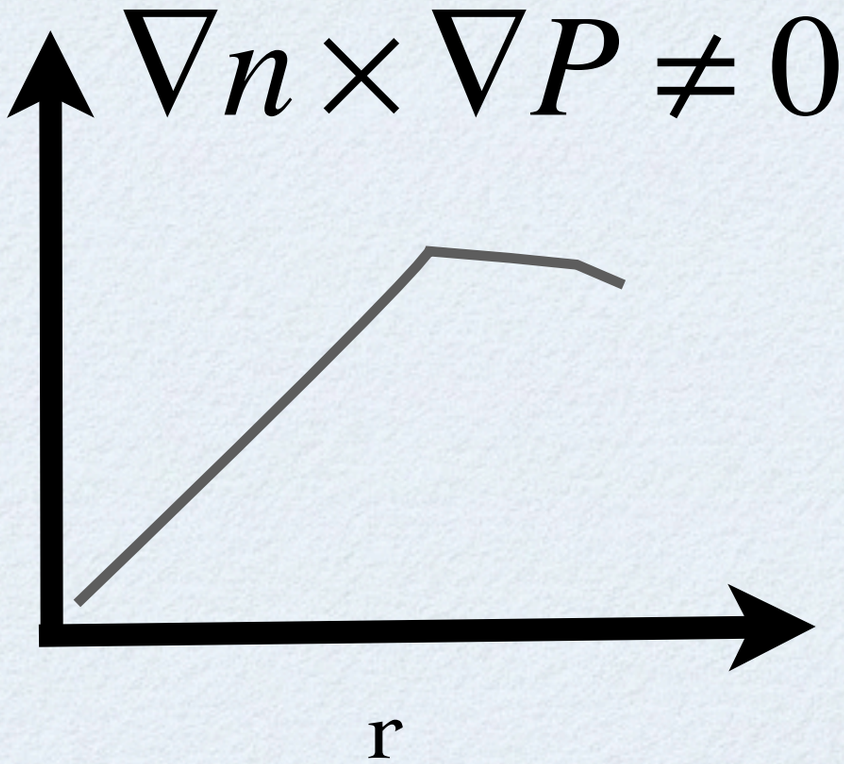

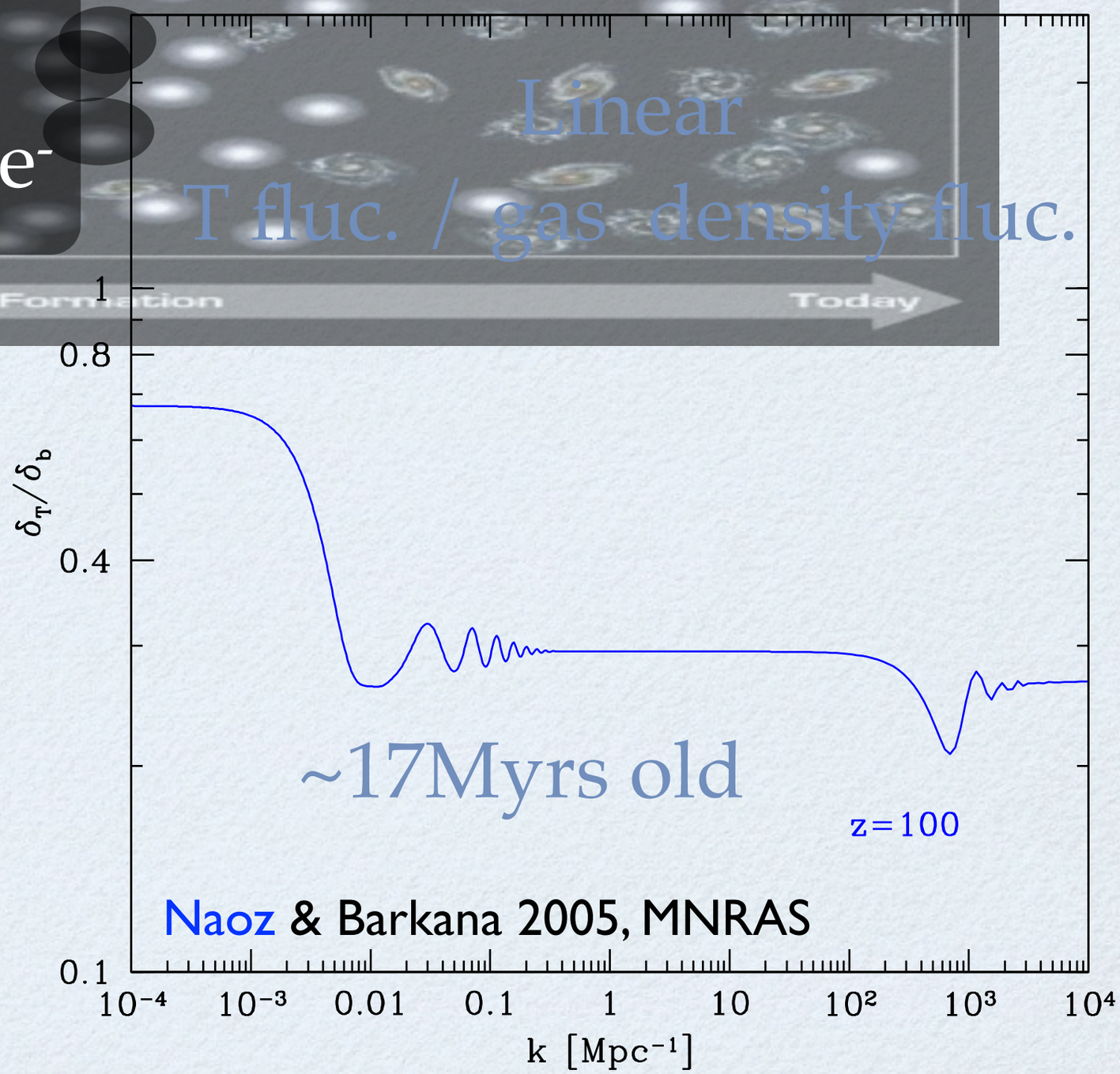

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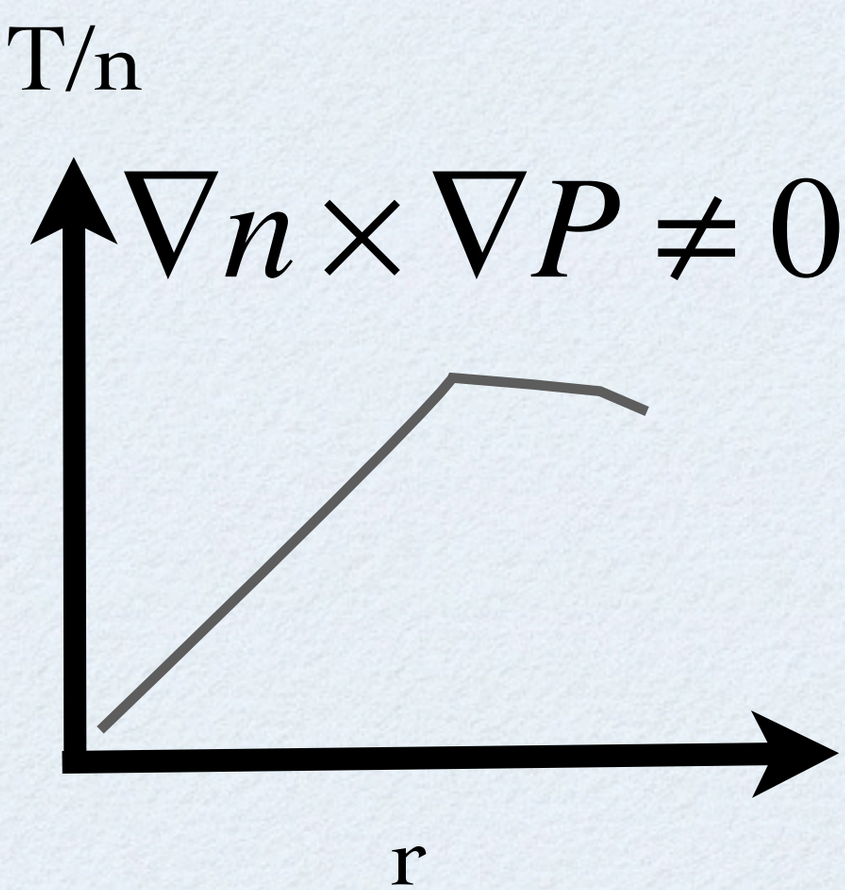
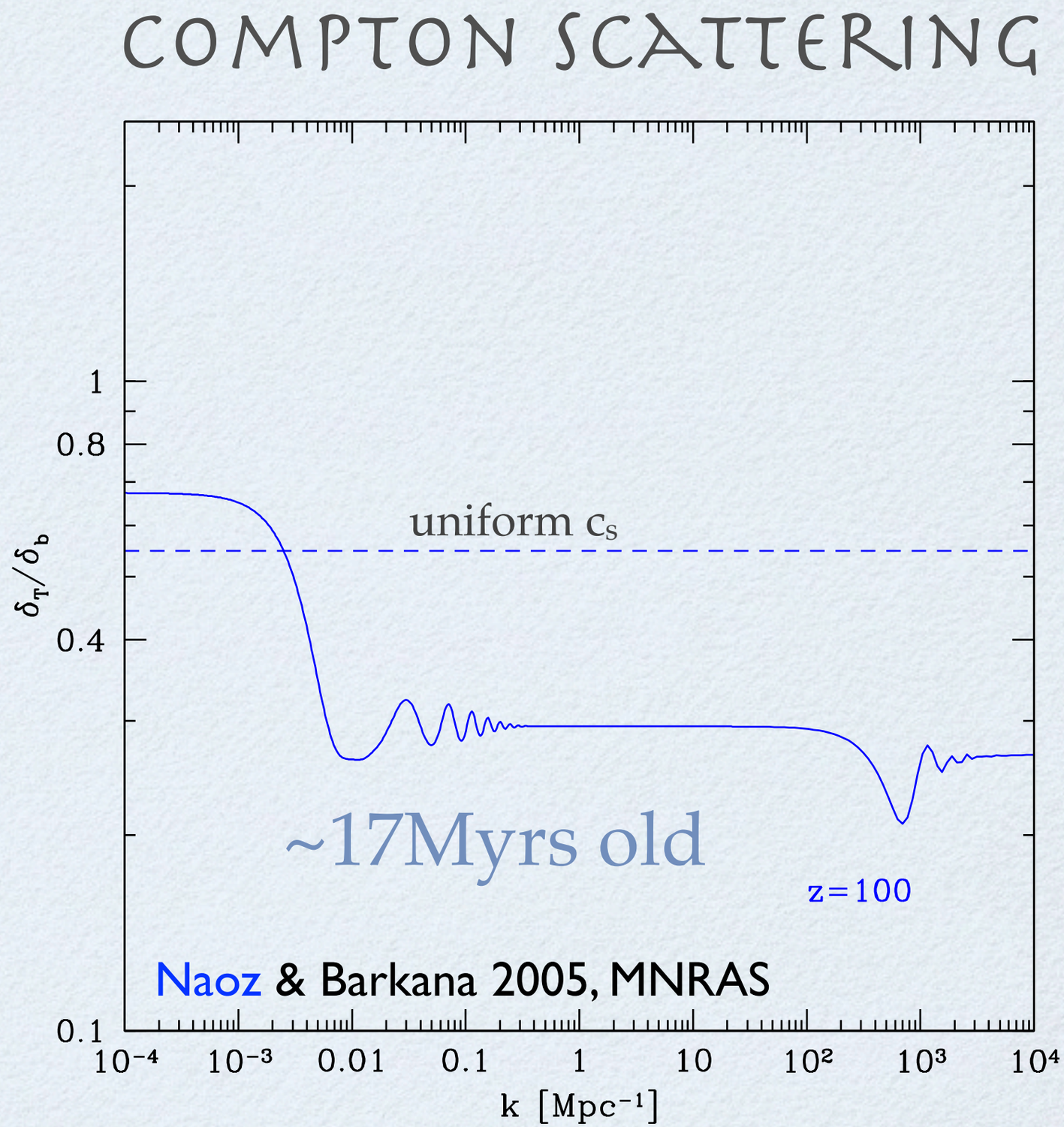
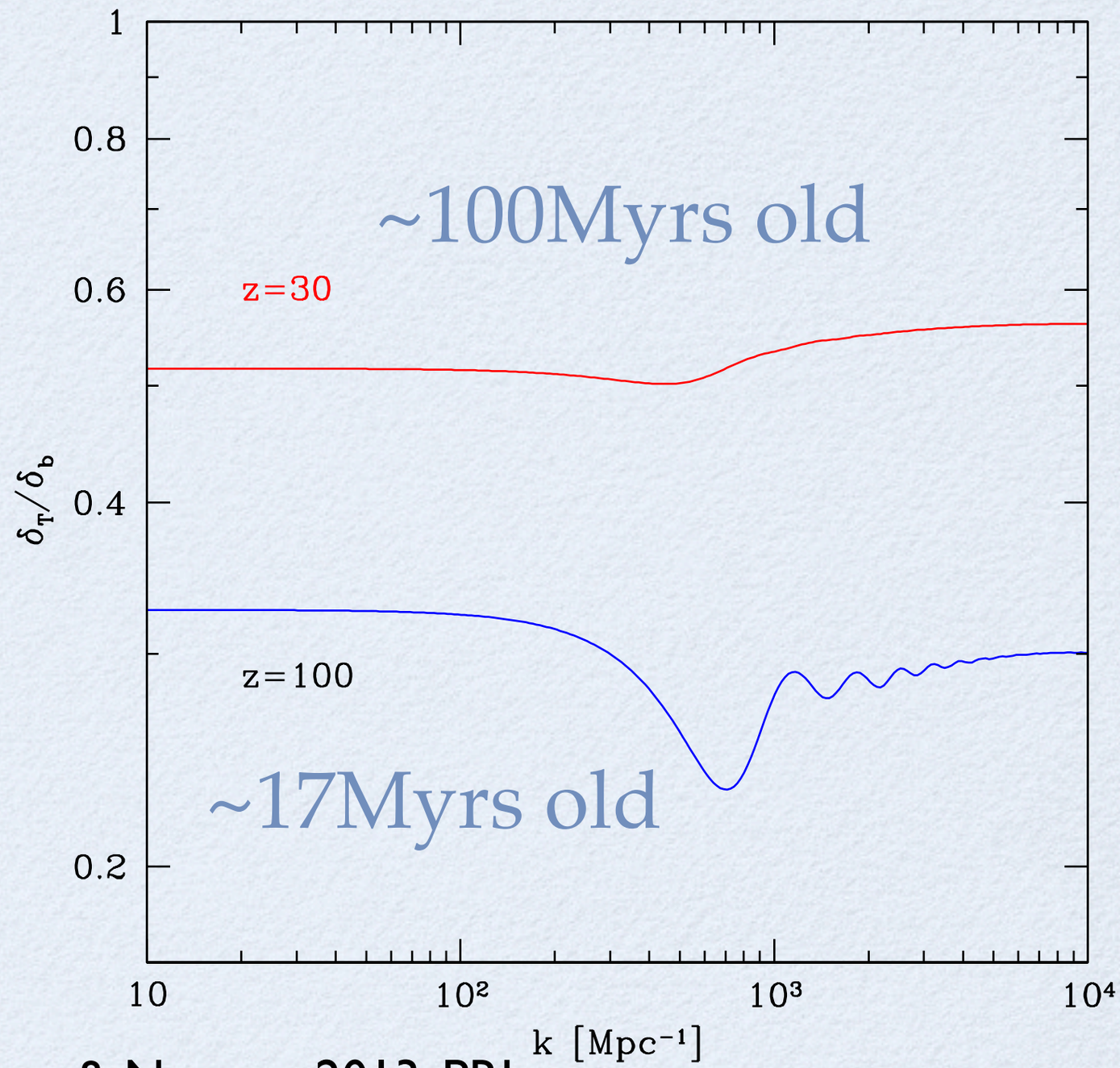




δ_T/δ_T scale dependance

Compton scattering

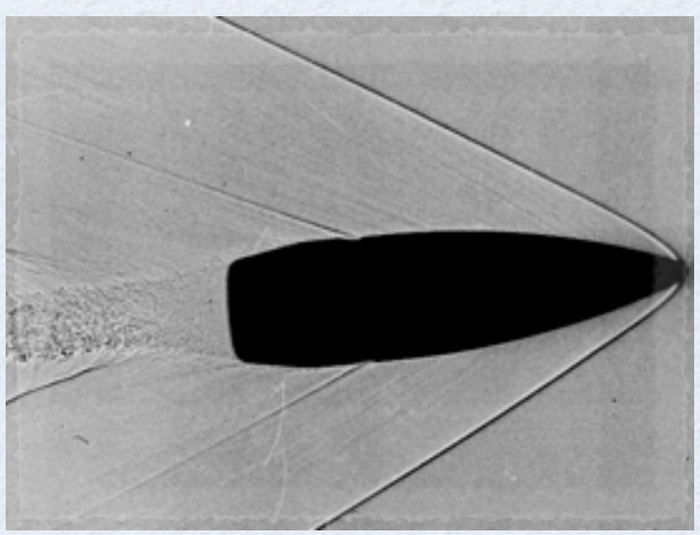


Naoz & Narayan 2013, PRL

δ_T/δ_T scale dependance

+ the stream velocity

Tseliakhovich & Hirata 2010



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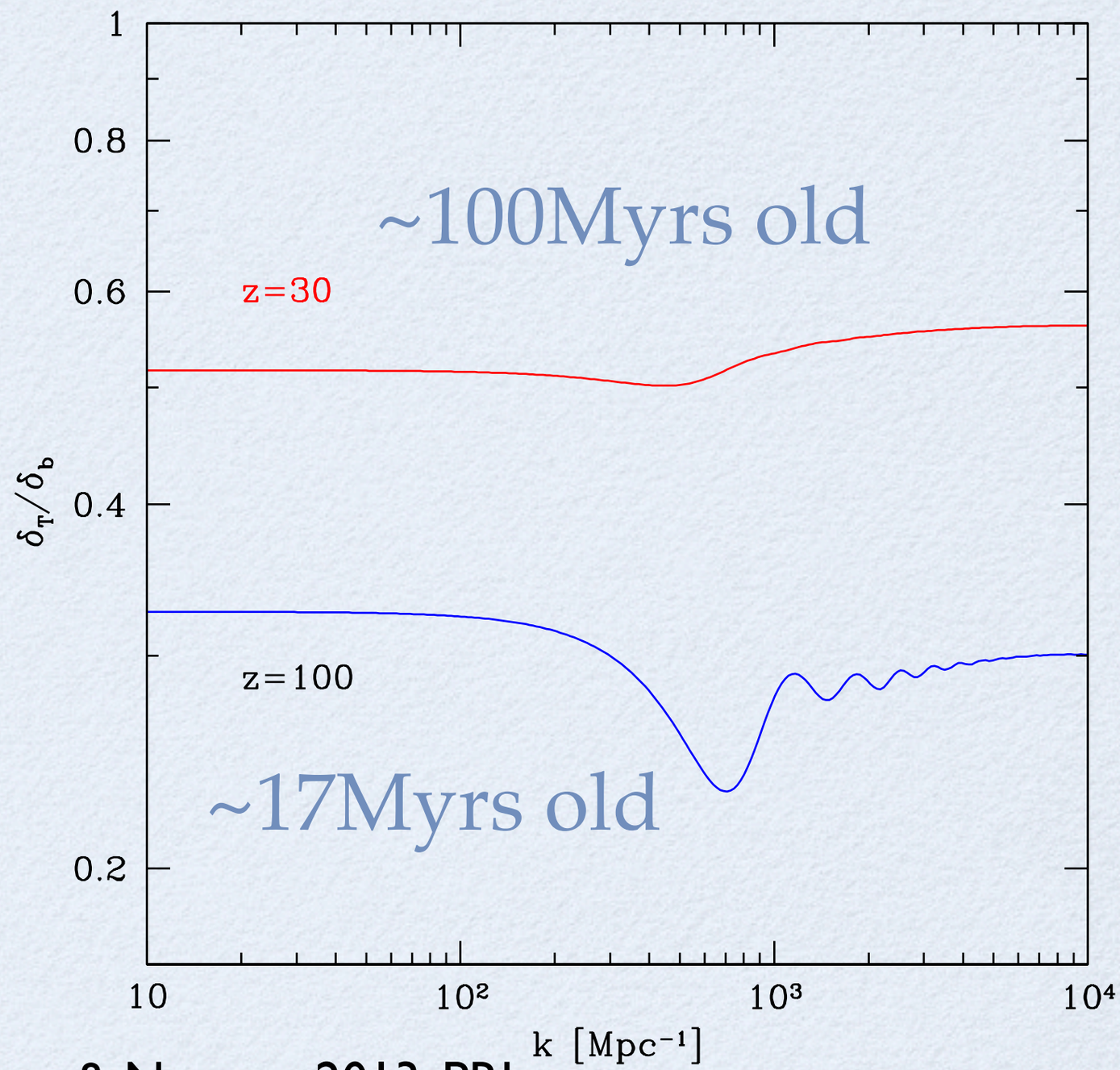

Naoz & Narayan 2013, PRL

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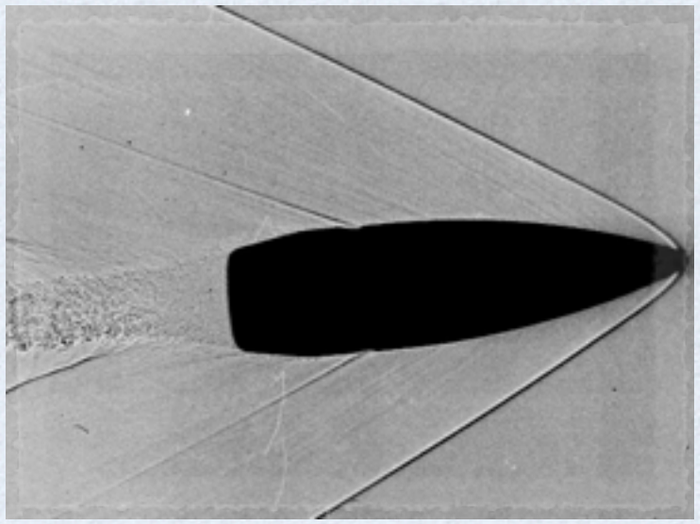
- $|v_b - v_{dm}| \approx 30$ km/sec at Recombination time =Mach 5
- scales as 1/a



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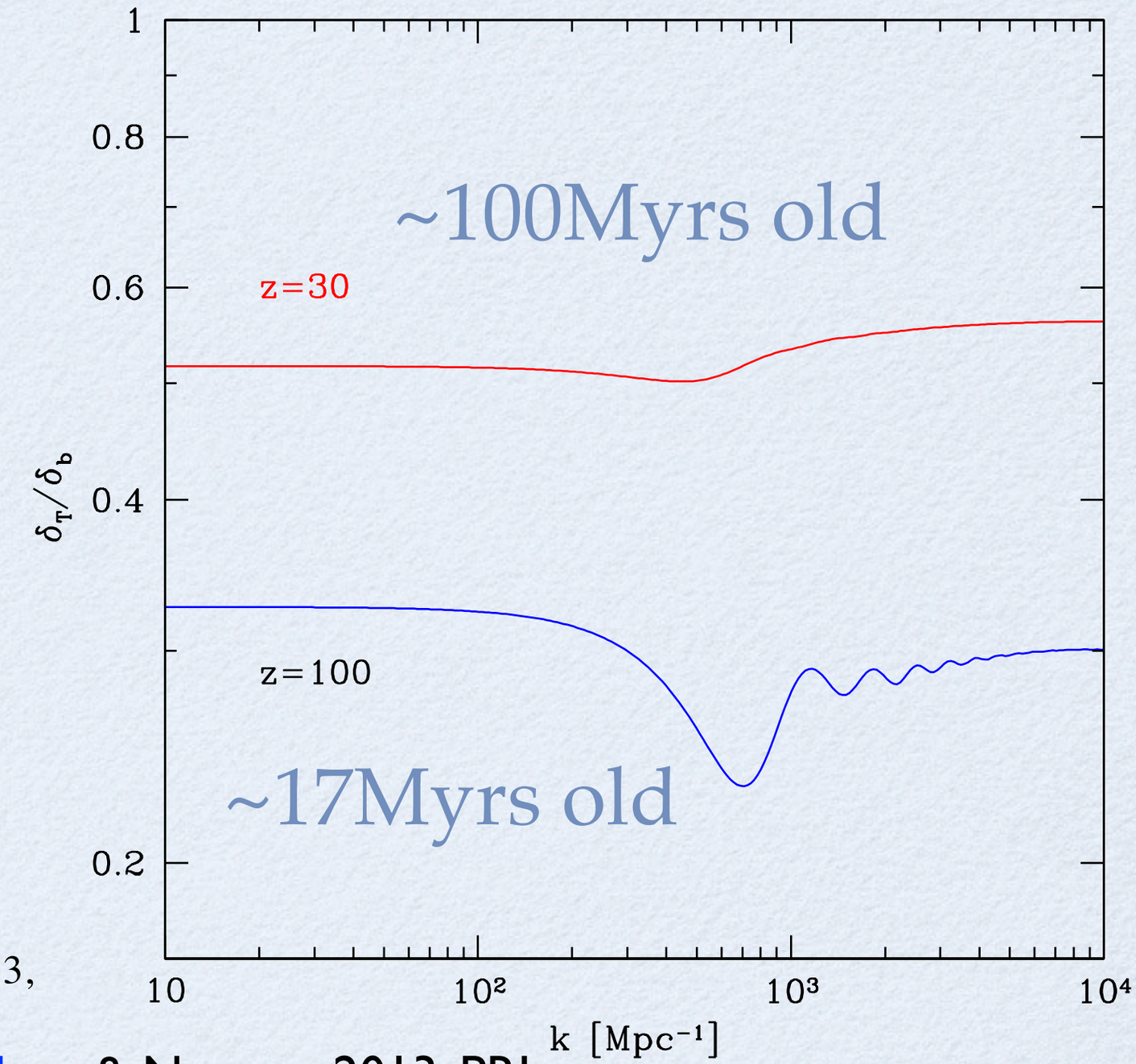

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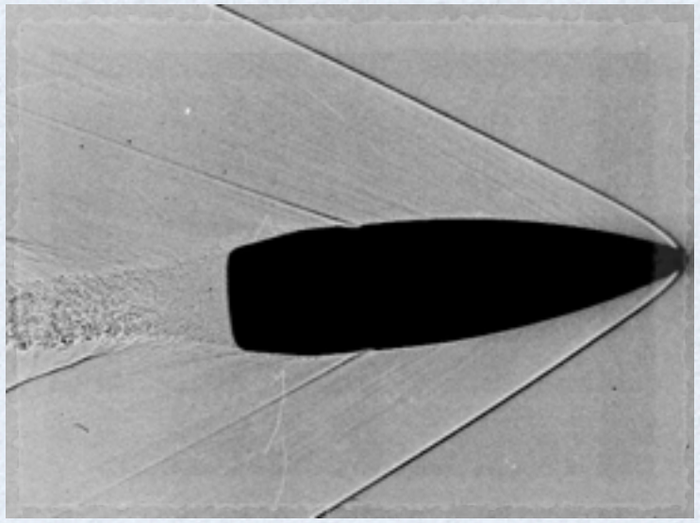

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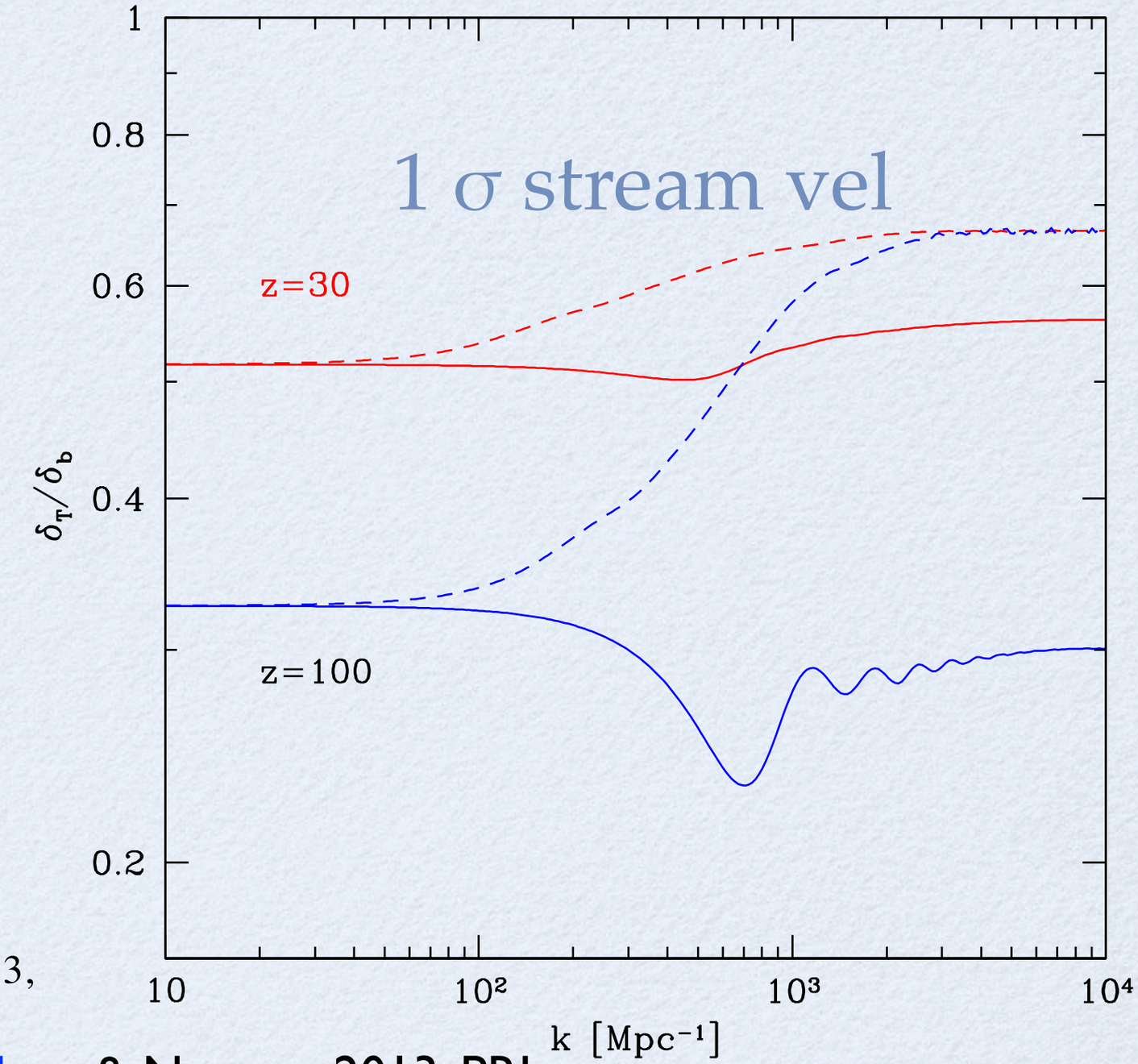
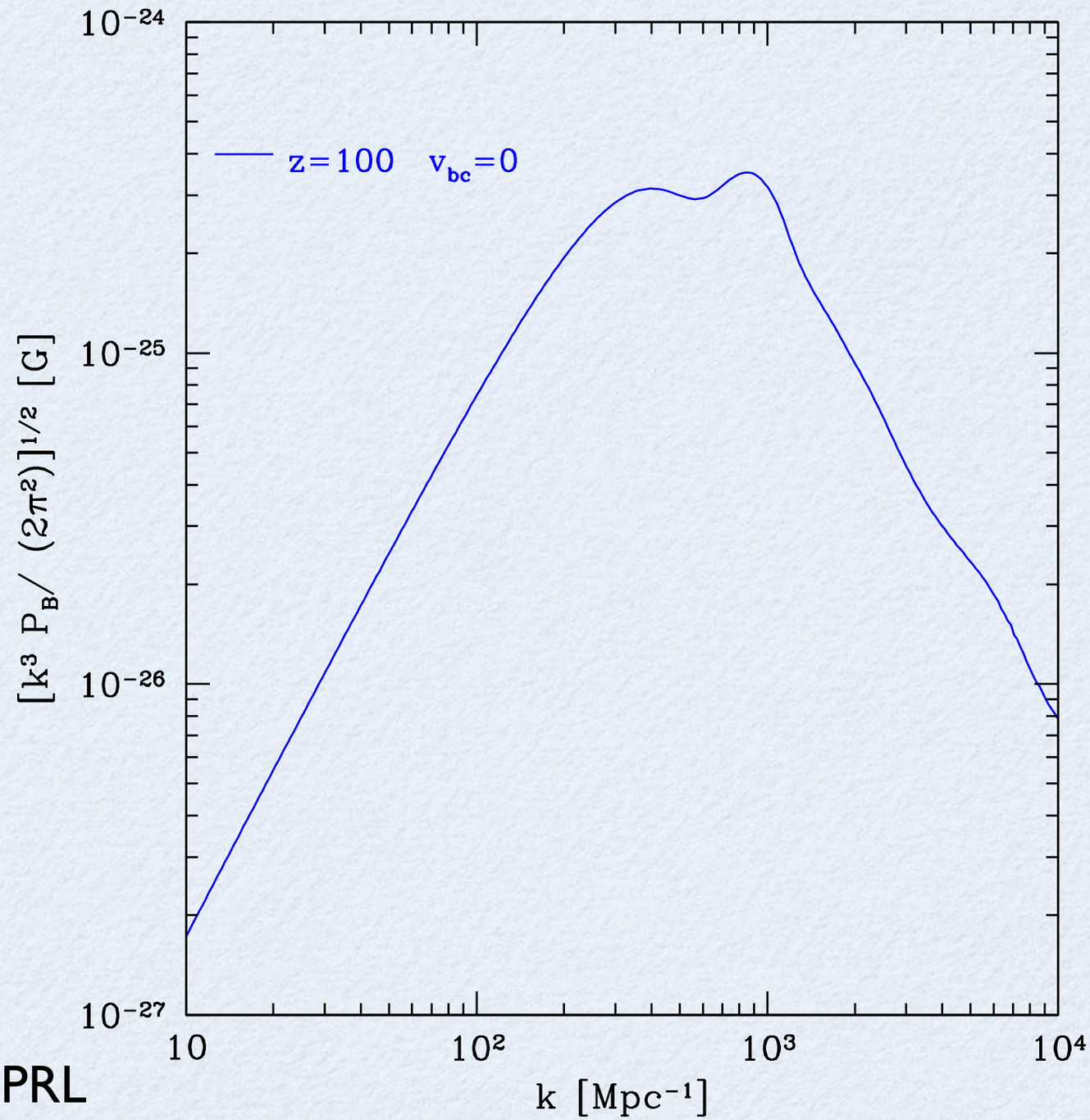


Naoz & Narayan 2013, PRL

Magnetic fields

Spatially varying c_s inducing vorticity



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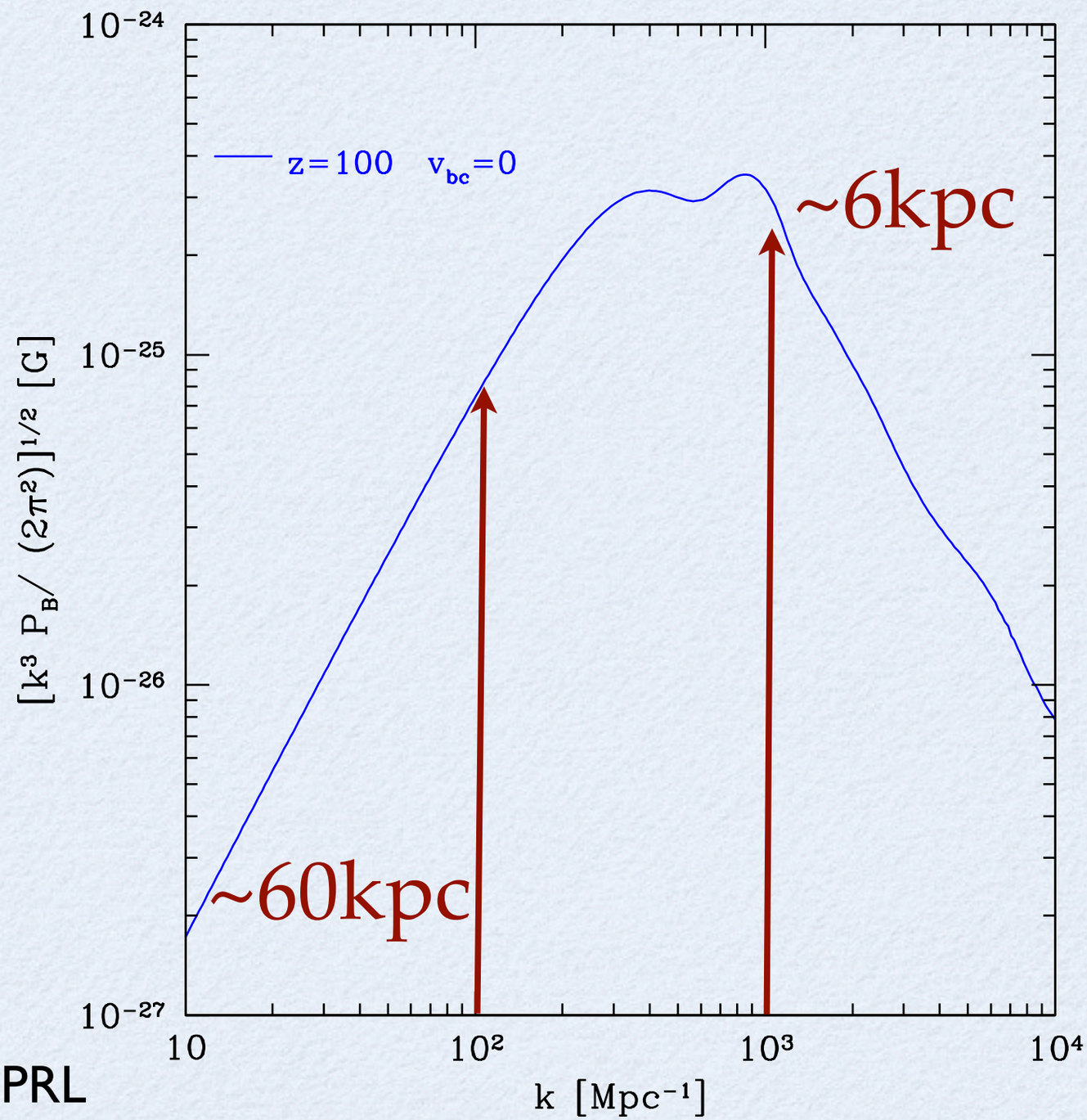

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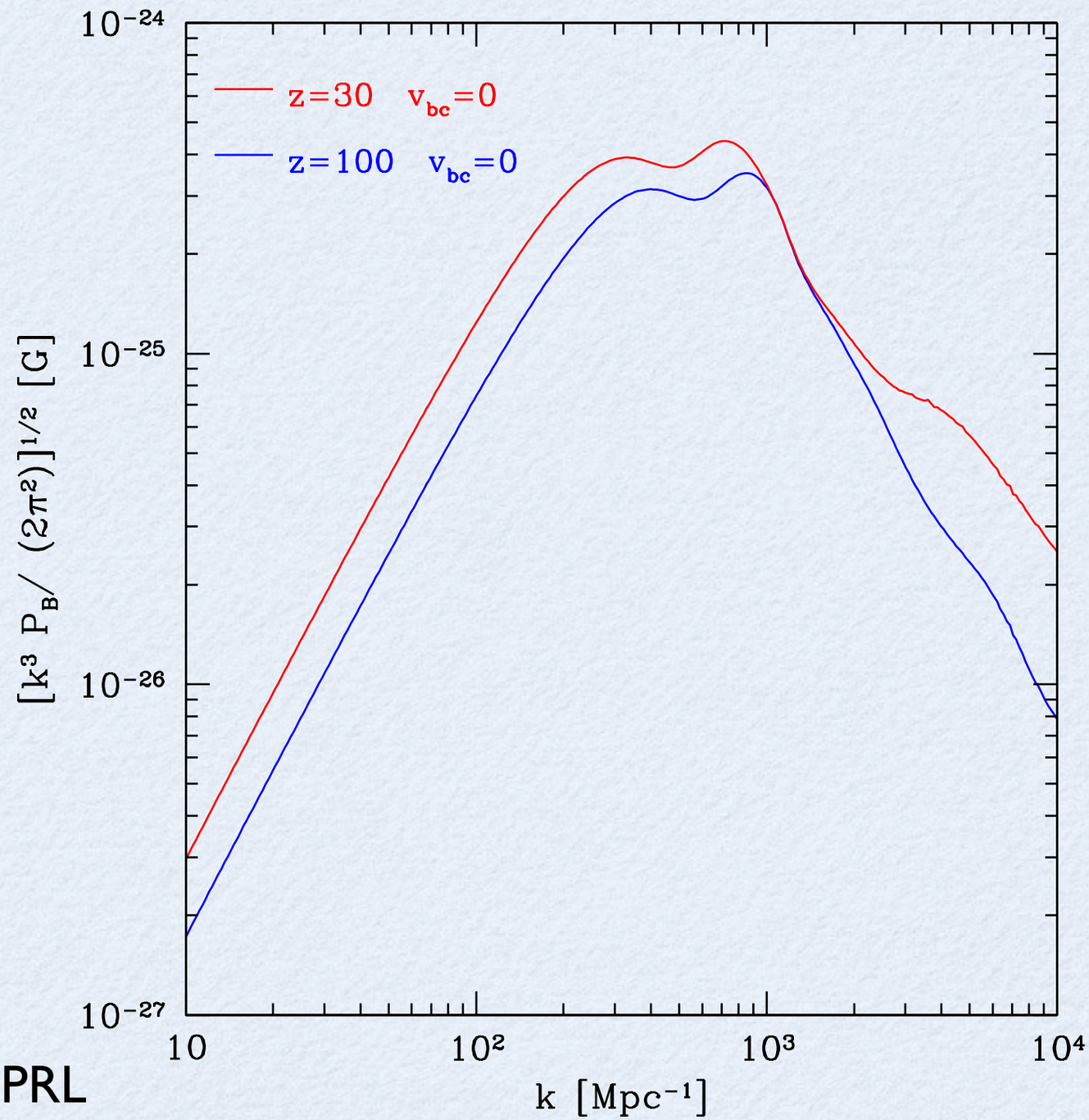

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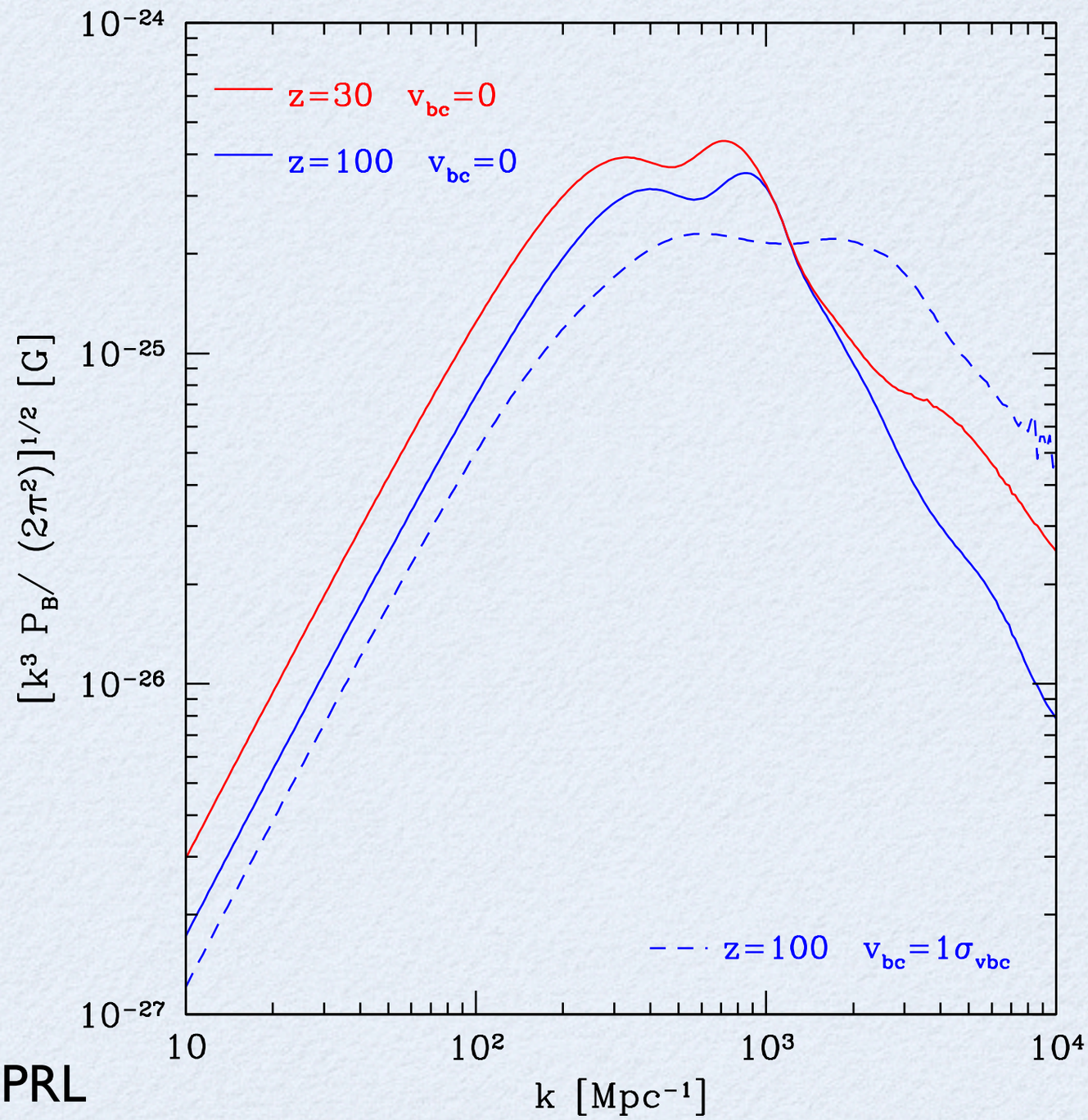

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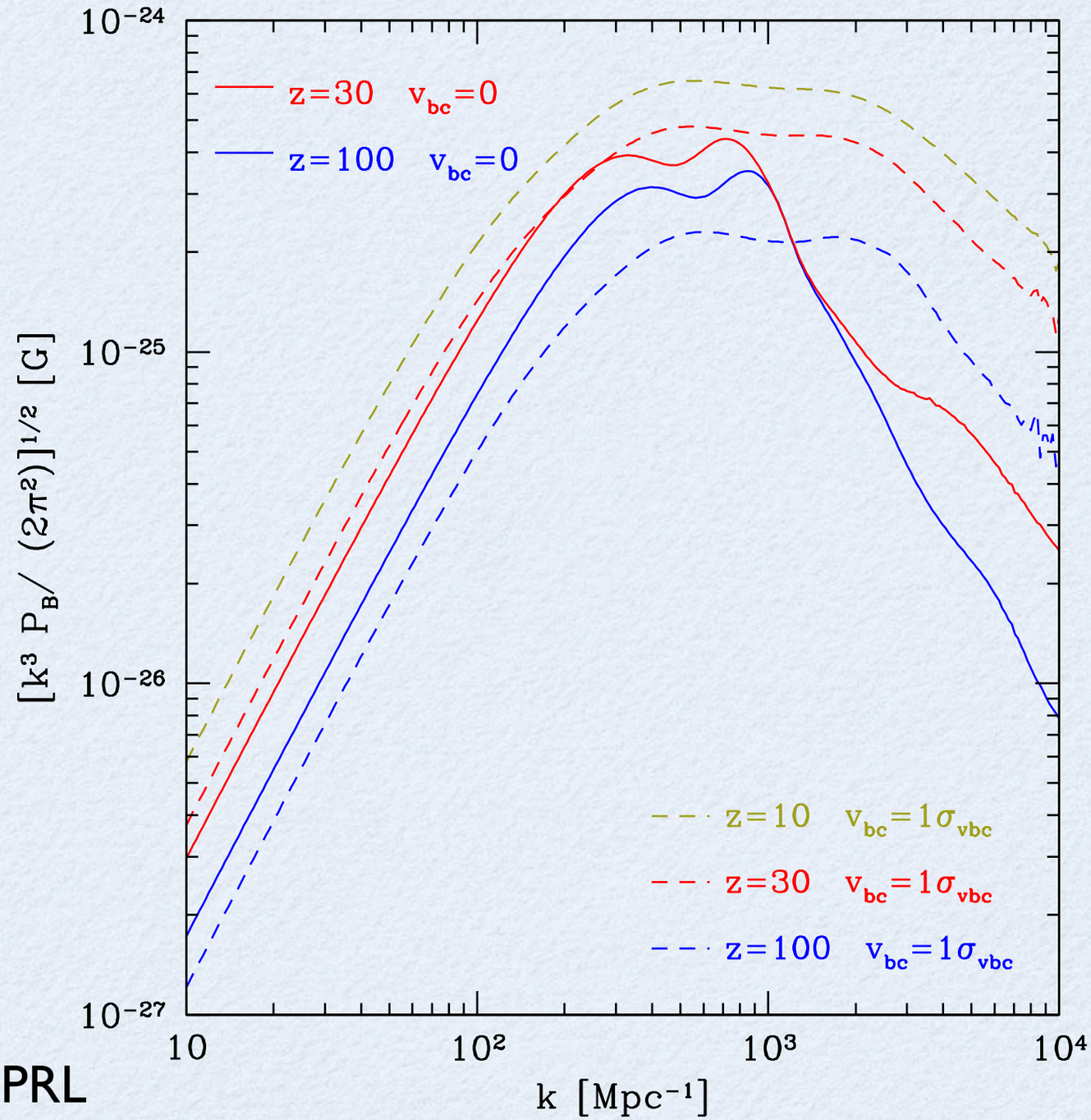

Naoz & Narayan 2013, PRL

The Effects of Reionization

$$\dot{B} \sim \bar{T} \nabla \delta_e \times \nabla \delta_T$$

- $T \rightarrow 10^4$ K
- $\delta_e \rightarrow$ Larger in $10\text{-}10^2$
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Pre-reionization $10^{-25}\text{-}10^{-24}$ G ↑ $B \rightarrow 10^{-18}$ G present day

PRESENT DAY FIELD

PRESENT DAY FIELD

e.g., Durrer & Neronov 2013

electroweak + QCD

re-ionization

inflation

e.g., Turner and Widrow 1988, Subramanian 2010

10^{-49}-10^{-23} G

recombination

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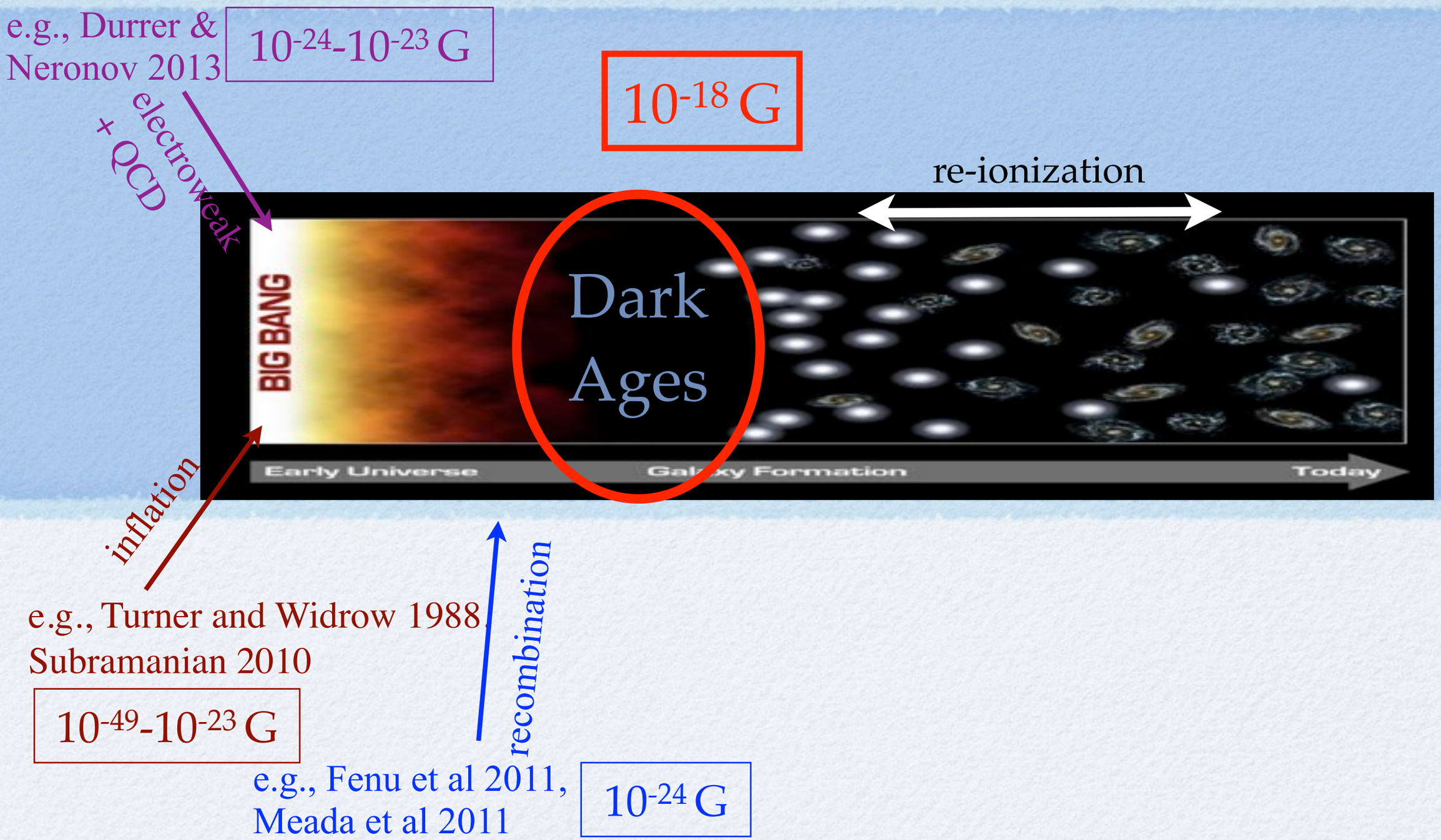
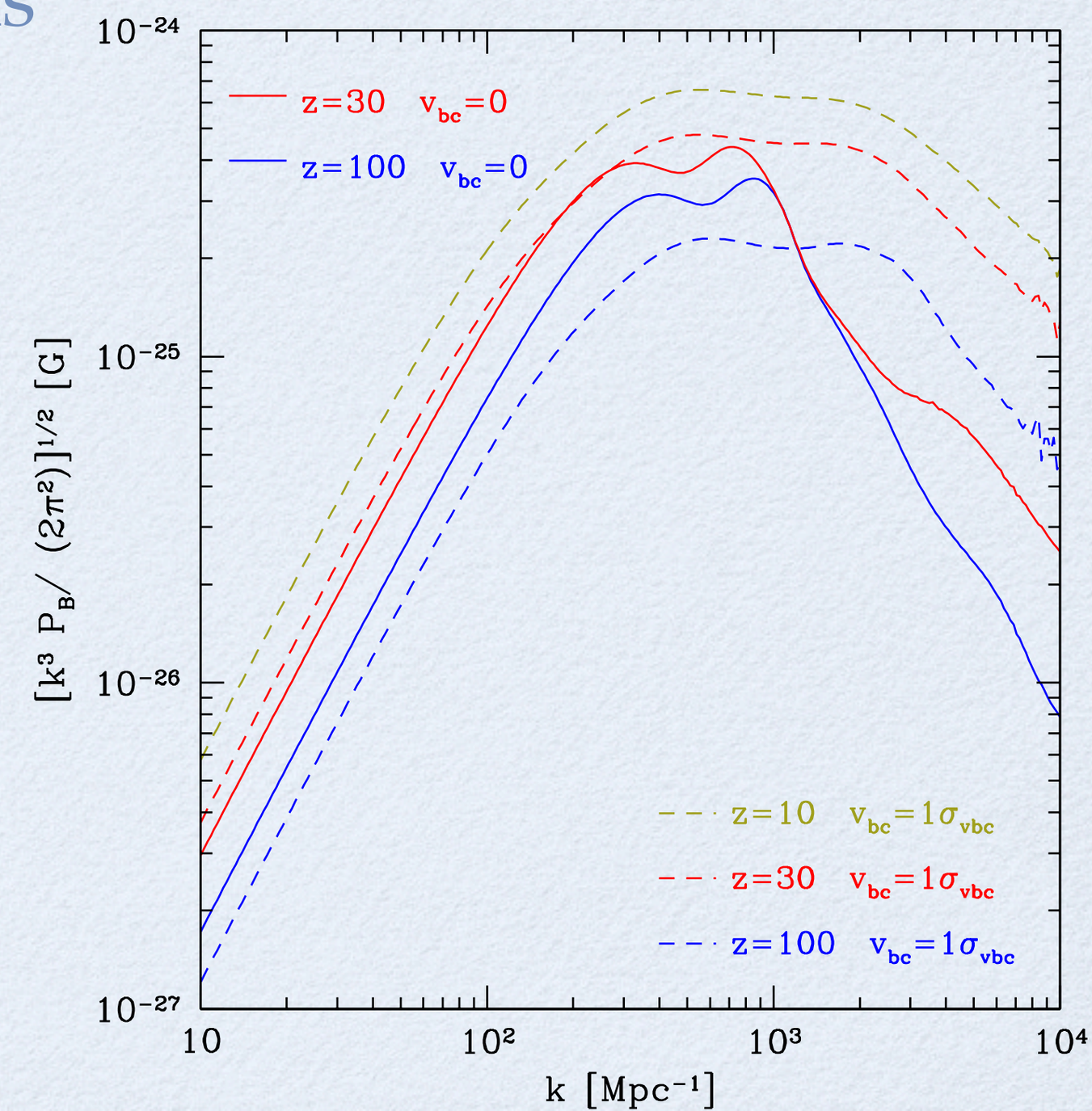


PRIMORDIAL MAGNETIC FIELDS

Compton scattering on the residual free electrons

Vortex like motion

Magnetic fields



Naoz & Narayan 2013, PRL

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Compton scattering on the residual free electrons

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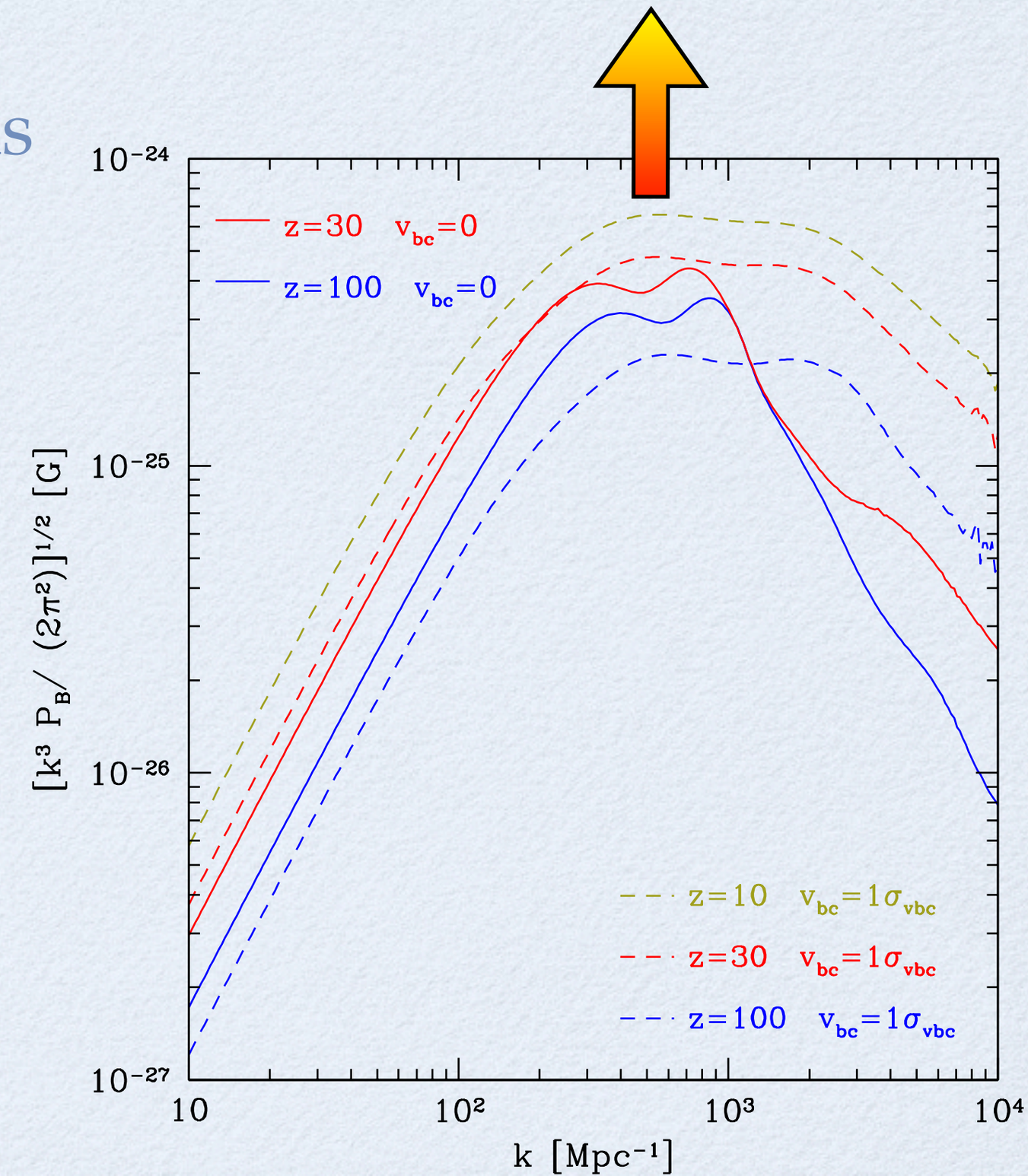
Magnetic fields

Reionization: T→10^4 k increase in the magnetic field



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