University of Houston Clear Lake

Numerical Analysis of the Biermann Battery Mechanism of Magnetogenesis for Relativistic MHD Turbulence

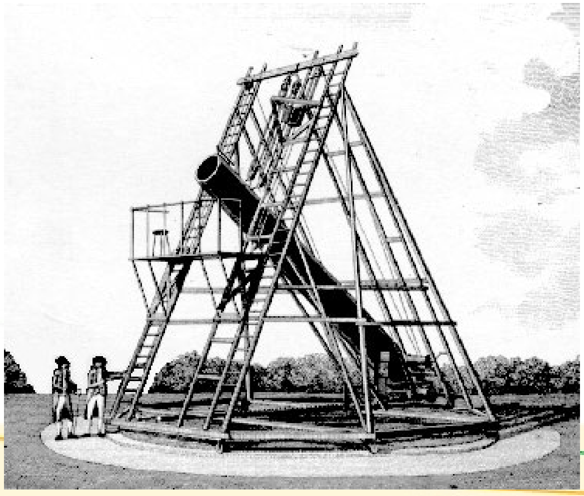
David Garrison
Professor of Physics, UHCL

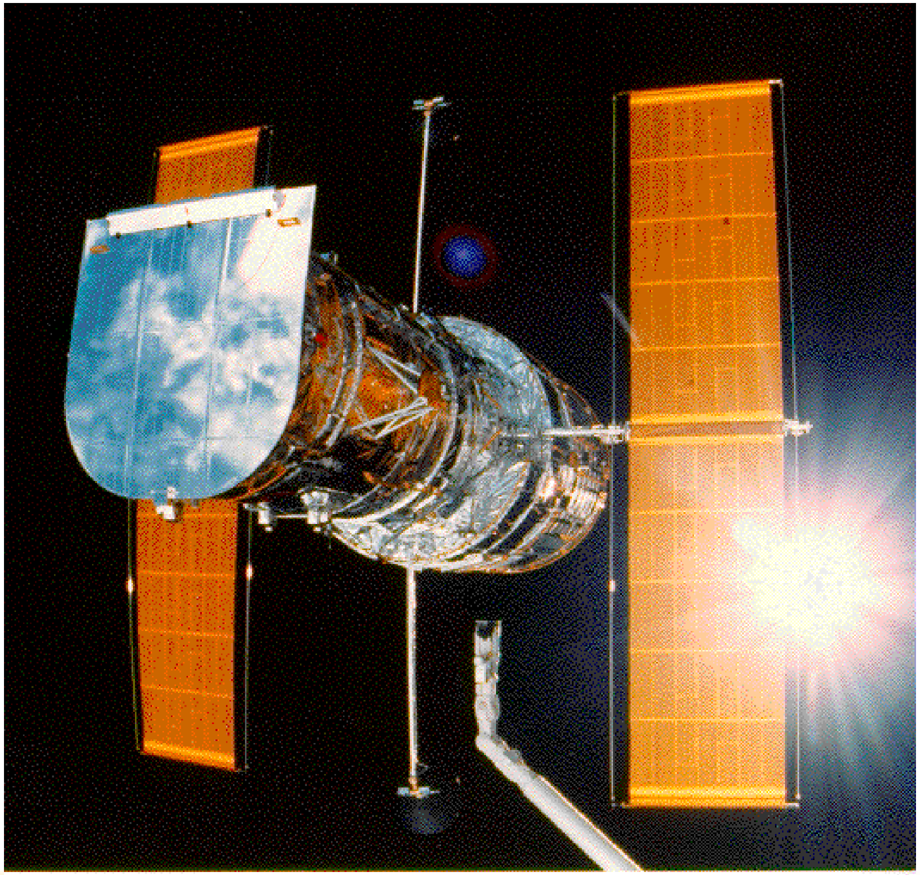
The Beginning

Where the Heck did all that come from?

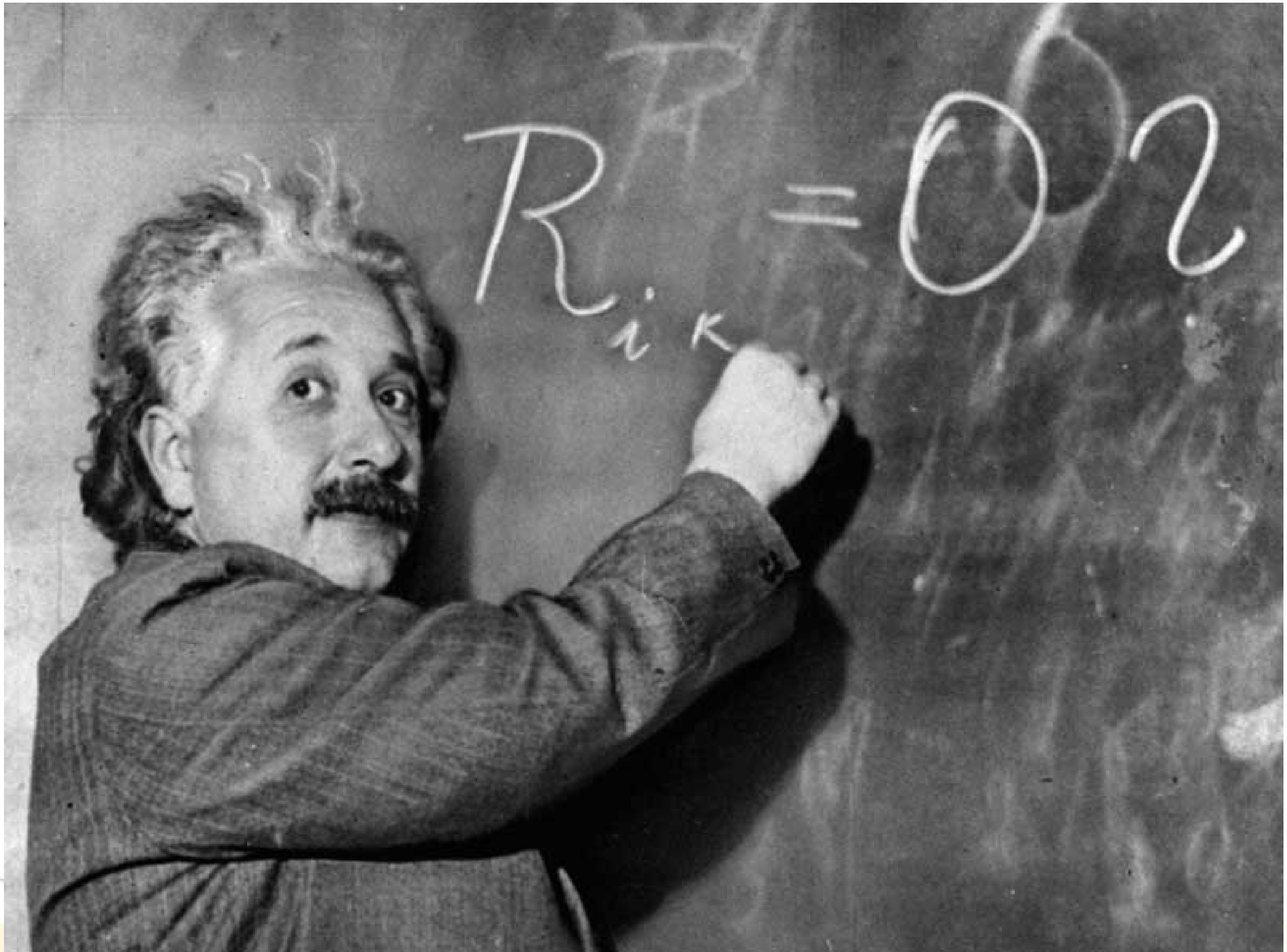
First Observatories

New Technologies



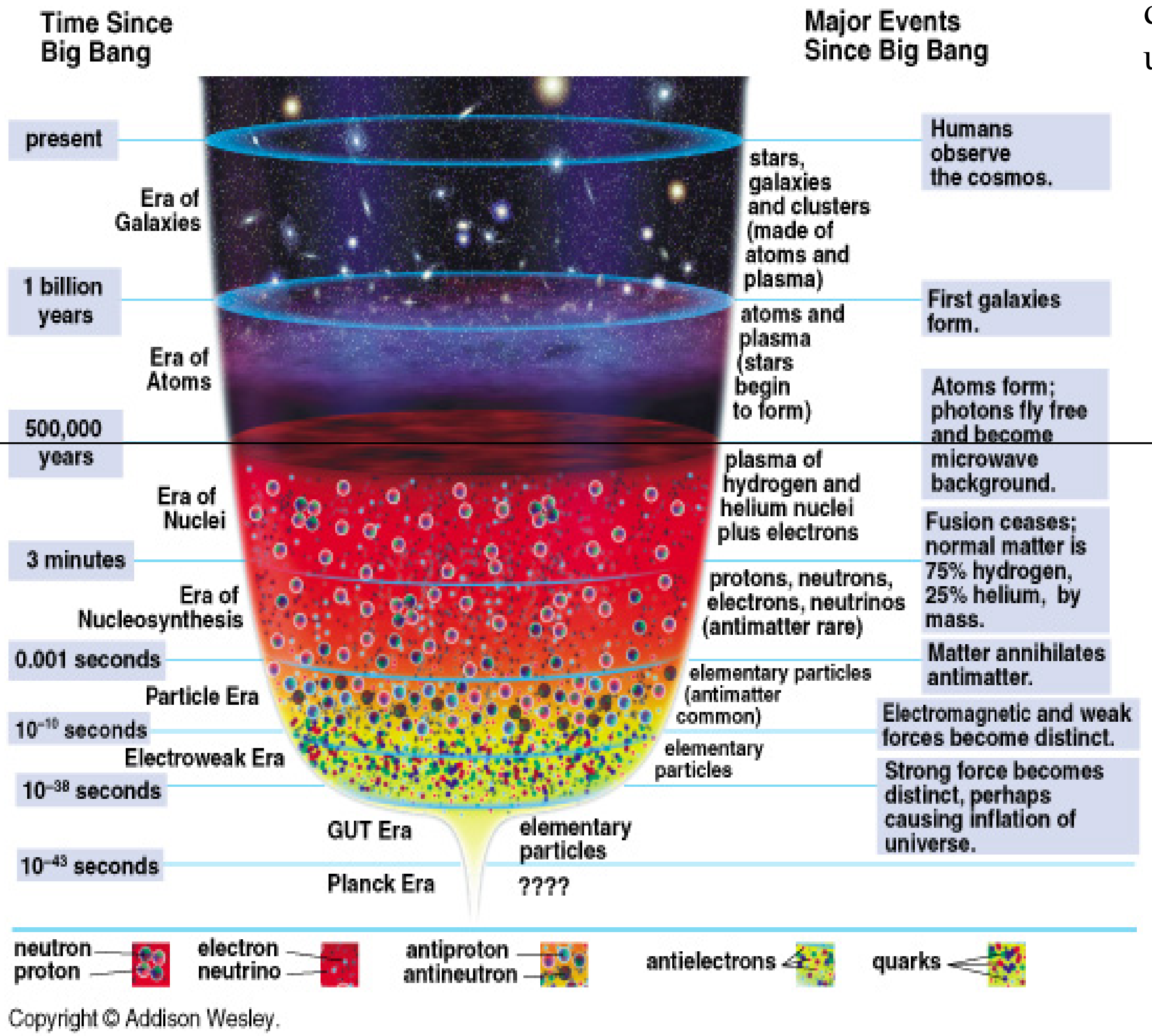


Putting it all together



Not Everyone Understands the Theory

History of the Universe



Copyright © Addison Wesley.

We have some idea, but don't know for sure how the universe is going to end yet.

The observable universe

We know what's going on base on our knowledge of elementary particle physics

We still don't know how physics works in this era yet.

Background

- Primordial Magnetic Fields (PMFs) are believed to have played a role in the dynamics of the evolution of the universe
- PMFs may have seeded large-scale magnetic fields on the Mpc scale
- PMFs can't be directly observed so nobody knows how large they were or when they formed
- After Magnetogenesis, they could have been amplified by dynamo and compression

Homogeneous MHD Turbulence

- Examine flow in a small 3-D cube (3-torus).
- Assume periodicity.
- *Homogeneous* means same statistics at different positions.
- Approximation that focuses on physics of turbulence.
- Periodic cube is a surrogate for a compact magneto-fluid.

GRMHD

- Essentially Navier-Stokes equations on curved space-time
- Dynamics depends on the curvature of space-time denoted with the 4-metric ($g_{\mu\nu}$), 3-metric (γ) and lapse (α)
- Fluid properties replaced by the stress-energy tensor ($T^{\mu\nu}$)
- 4D components such as 4-velocity (u^{ν}) are used

University of Houston Clear Lake

GRMHD Variables

- $\rho_* = \alpha\sqrt{\gamma}\rho_0 u^0$: Conserved Mass Density
- $S_i = \alpha\sqrt{\gamma}T_i^0$: Momentum Density
- $\tau = \alpha^2\sqrt{\gamma}T^{00} - \rho_*$: Energy Density
- $\tilde{B}^j = \sqrt{\gamma}B^j$: Magnetic Field
- $v^i = \frac{1}{u^0}\gamma^{ij}u_j - \beta^i$: 3-velocity
- $u^0 = \frac{1}{\alpha}\sqrt{1 + \gamma^{ij}u_i u_j}$
- $P = (\Gamma - 1)\rho_0\varepsilon$: Pressure

GRMHD Equations

1. $\partial_t \rho_* + \partial_j\left(\rho_* v^j\right) = 0$

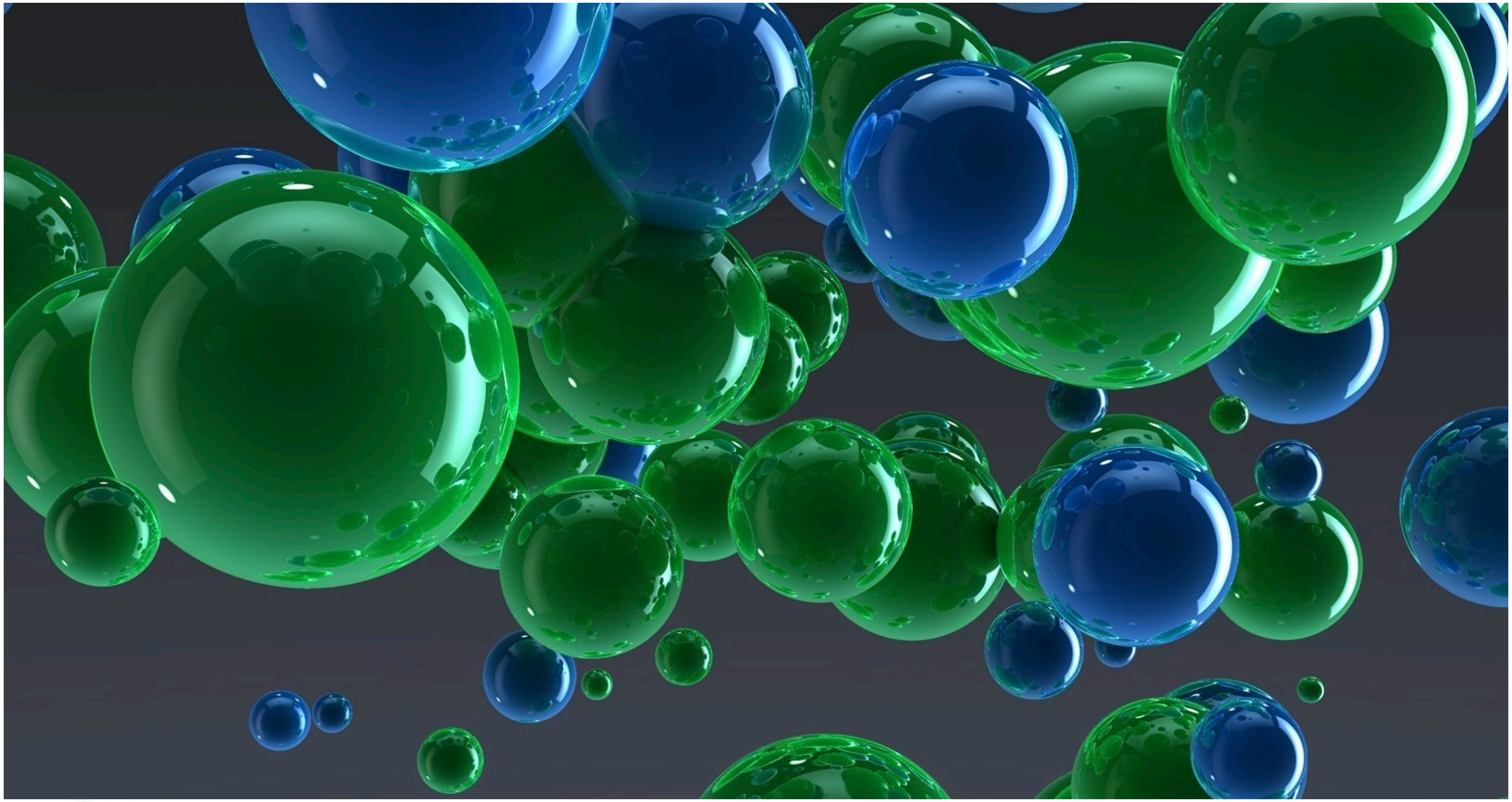
2. $\partial_t \tilde{\tau} + \partial_i\left(\alpha^2 \sqrt{\gamma} T^{0i} - \rho_* v^i\right) = s$

3. $\partial_t \tilde{S}_i + \partial_j\left(\alpha \sqrt{\gamma} T_i^{\ j}\right) = \frac{1}{2} \alpha \sqrt{\gamma} T^{\alpha\beta} g_{\alpha\beta,i}$

4. $\partial_t \tilde{B}^i + \partial_j\left(v^j \tilde{B}^i - v^i \tilde{B}^j\right) = 0$

Where: $s = -\alpha \sqrt{\gamma} T^{\mu\nu} \nabla_\nu n_\mu$

Vacuum Bubble Collisions



PMFs from Phase Transistions

- EW and QCD Phase Transitions studied
- Phase Transitions cause stirring with velocities comparable to the speed of sound in the fluid
- This results in a short-term intense turbulent GRMHD fluid
- Biermann Battery effects describe how a turbulent magnetofluid can generate magnetic fields from no initial magnetic field

Biermann Battery

- MHD equations require an initial B-field
- The Biermann Battery works because of differences between temperature and density gradients
- The modified B-field MHD equation becomes

$$\partial_t \tilde{B}^i = -\partial_j\left(v^j \tilde{B}^i - v^i \tilde{B}^j\right) + \frac{1}{q n_e \gamma} \nabla T_e \times \nabla n_e + \frac{T_e}{q n_e \gamma^2} \nabla n_e \times \nabla \gamma$$

Experiment

University of Houston Clear Lake

- Code developed in Cactus utilizing GRMHD equations
- All runs utilized 128^3 internal grid points on the UH UHPC Cluster
- Fourier Spectral Methods and ICN utilized
- Simulation domain ~1 Mpc adjusted for scale factor
- Initial temperature & density fluctuations ~ k
- Initial velocity fluctuations ~ k^3

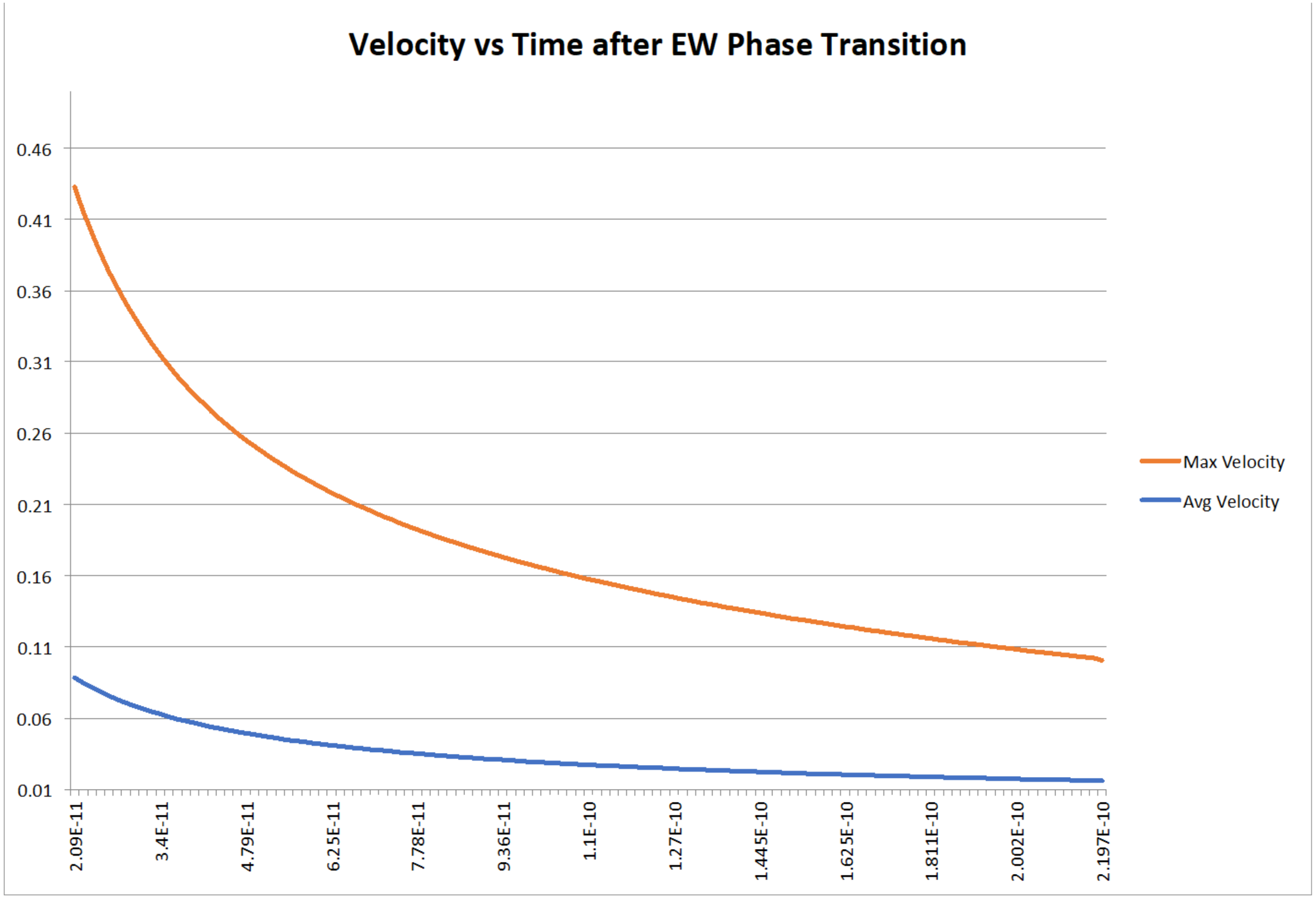
Initial Conditions (EW)

- Energy = 246 GeV
- Temperature = 2.85 x 10^{15} K
- Thermal Degrees of Freedom = 106.75
- Scale Factor = 9.58 x 10^{-16}
- Initial Time = 2.09 x 10^{-11} s
- Mass Density = 2.90 x 10^{31} kg/m^3
- Maximum Velocity = 0.55 c

Initial Conditions (QCD)

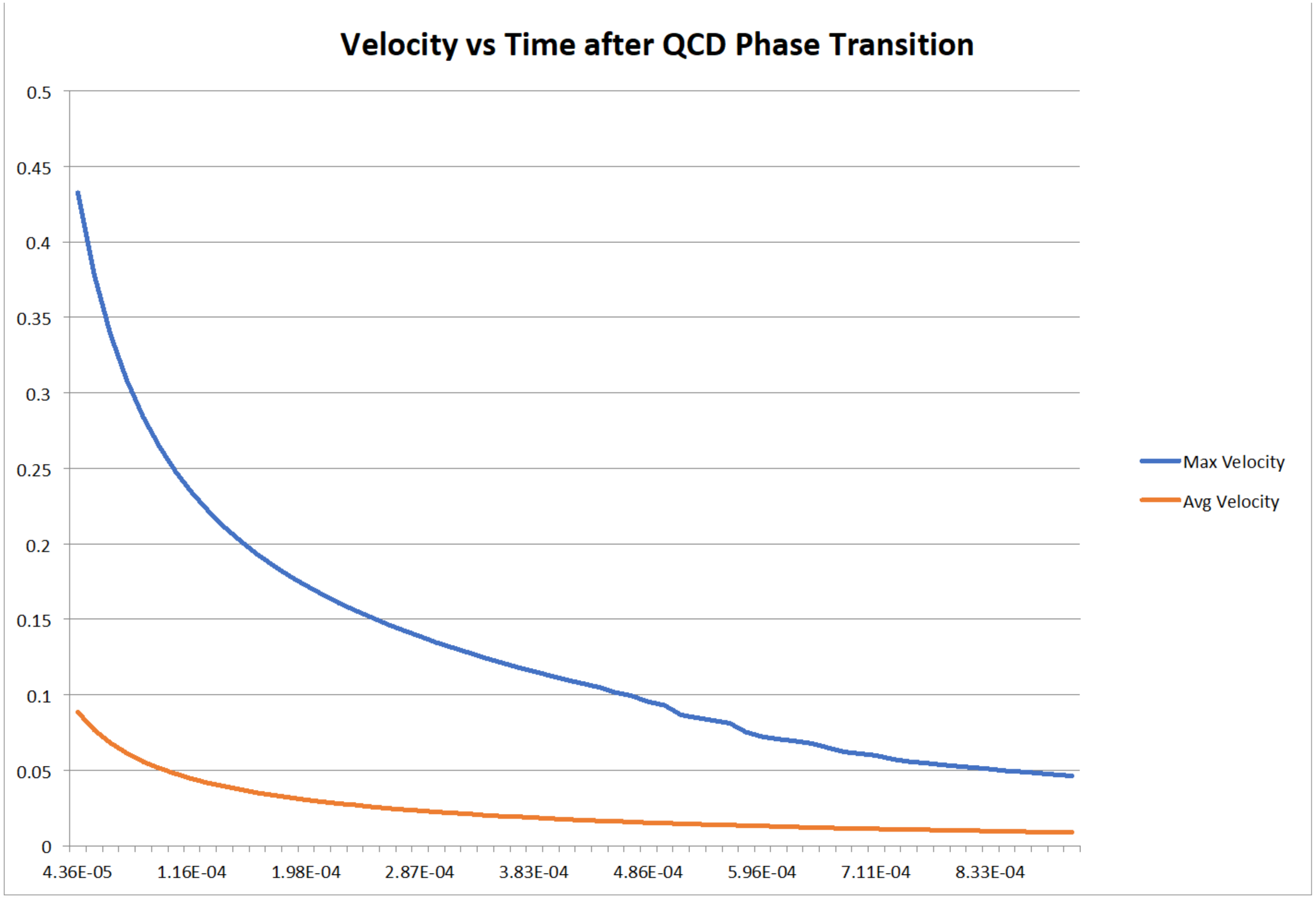
- Energy = 170 MeV
- Temperature = 1.97×10^{12} K
- Thermal Degrees of Freedom = 61.75
- Scale Factor = 1.38×10^{-12}
- Initial Time = 4.36×10^{-5} s
- Mass Density = 3.80×10^{18} kg/m^3
- Maximum Velocity = 0.55 c

EW Velocity

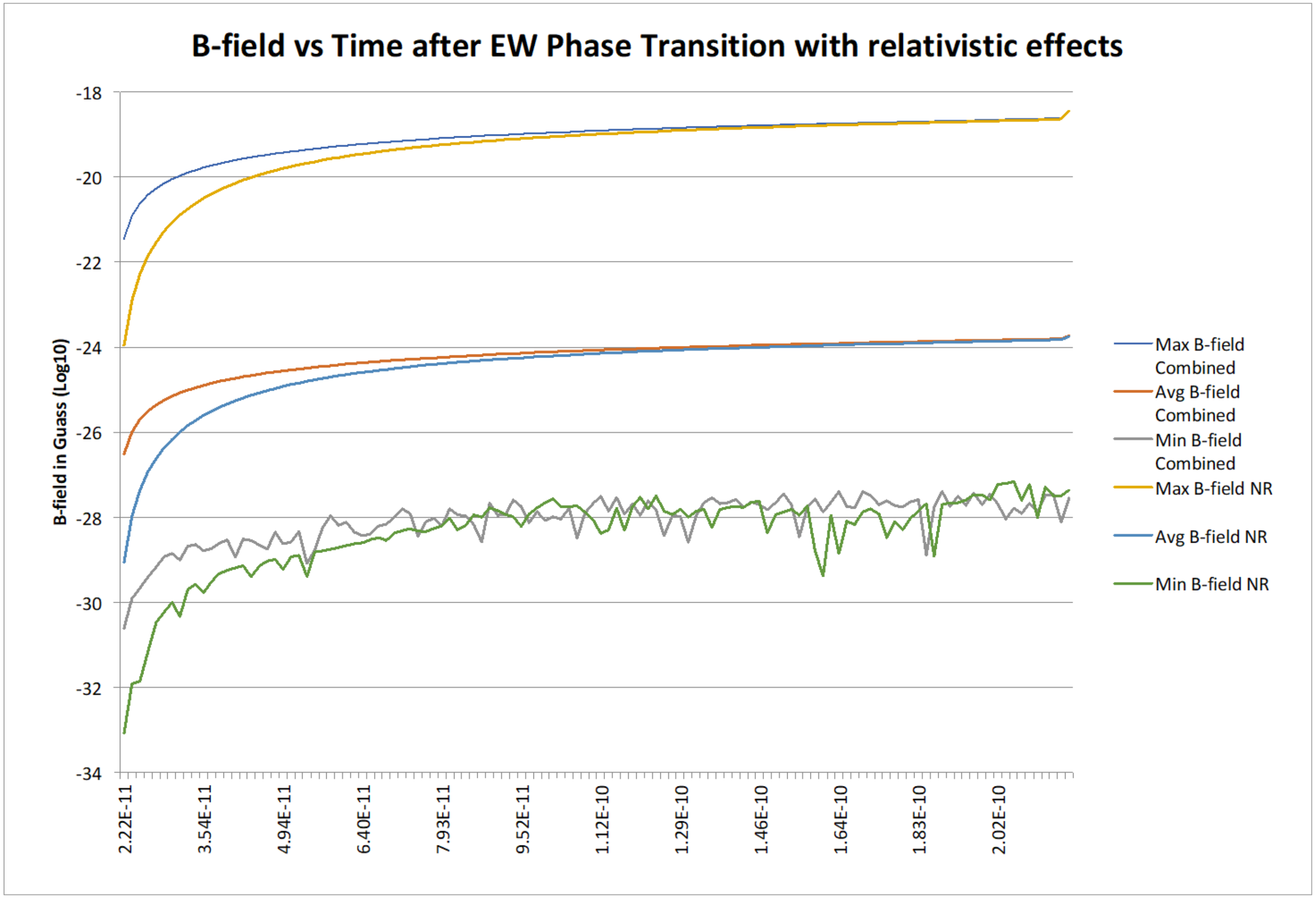


Velocity vs Time after EW Phase Transition
0.46
0.41
0.36
0.31
0.26
0.21
0.16
0.11
0.06
0.01
2.09E-11
3.4E-11
4.79E-11
6.25E-11
7.78E-11
9.36E-11
1.1E-10
1.27E-10
1.445E-10
1.625E-10
1.811E-10
2.002E-10
2.197E-10
Max Velocity
Avg Velocity

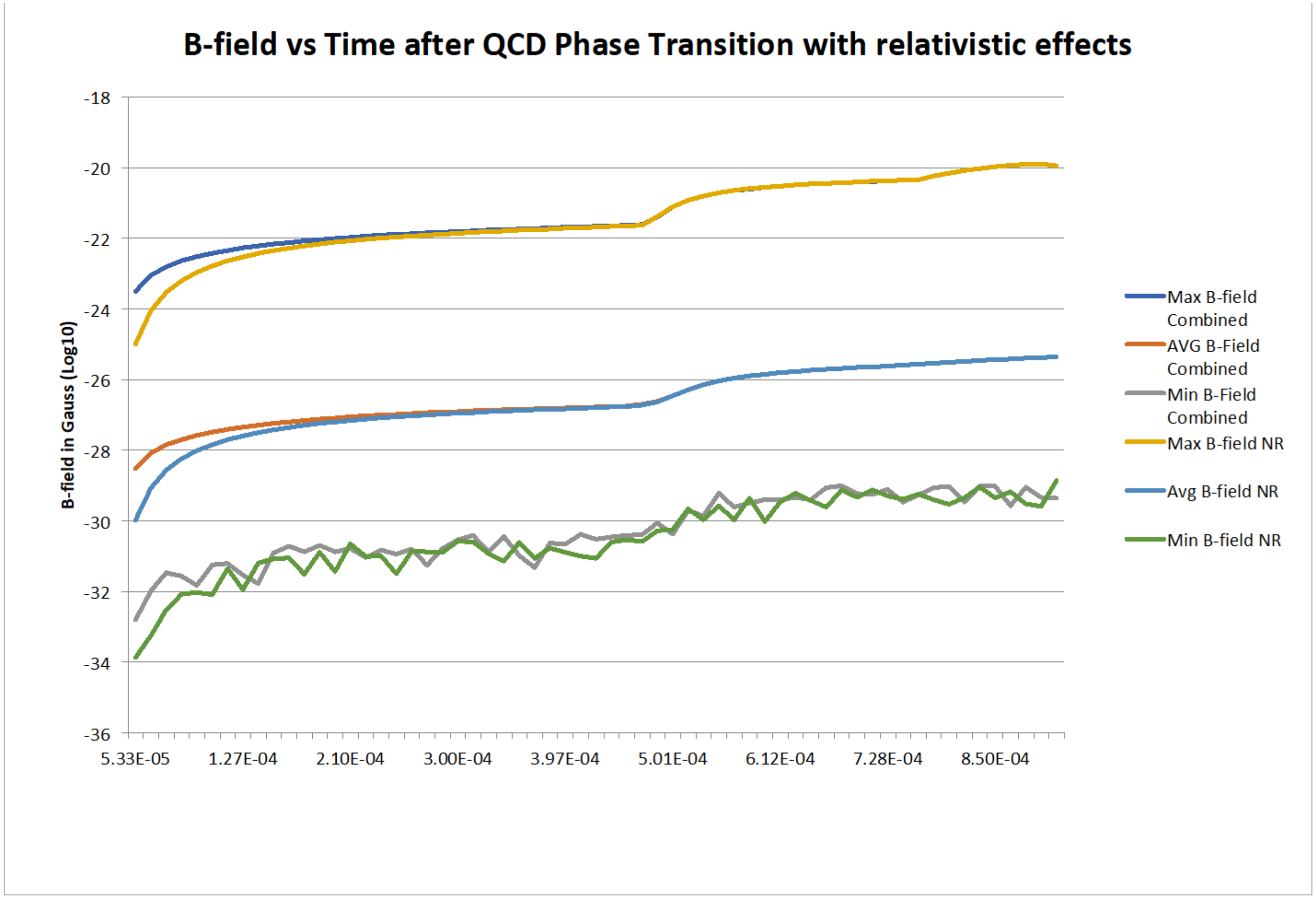
QCD Velocity



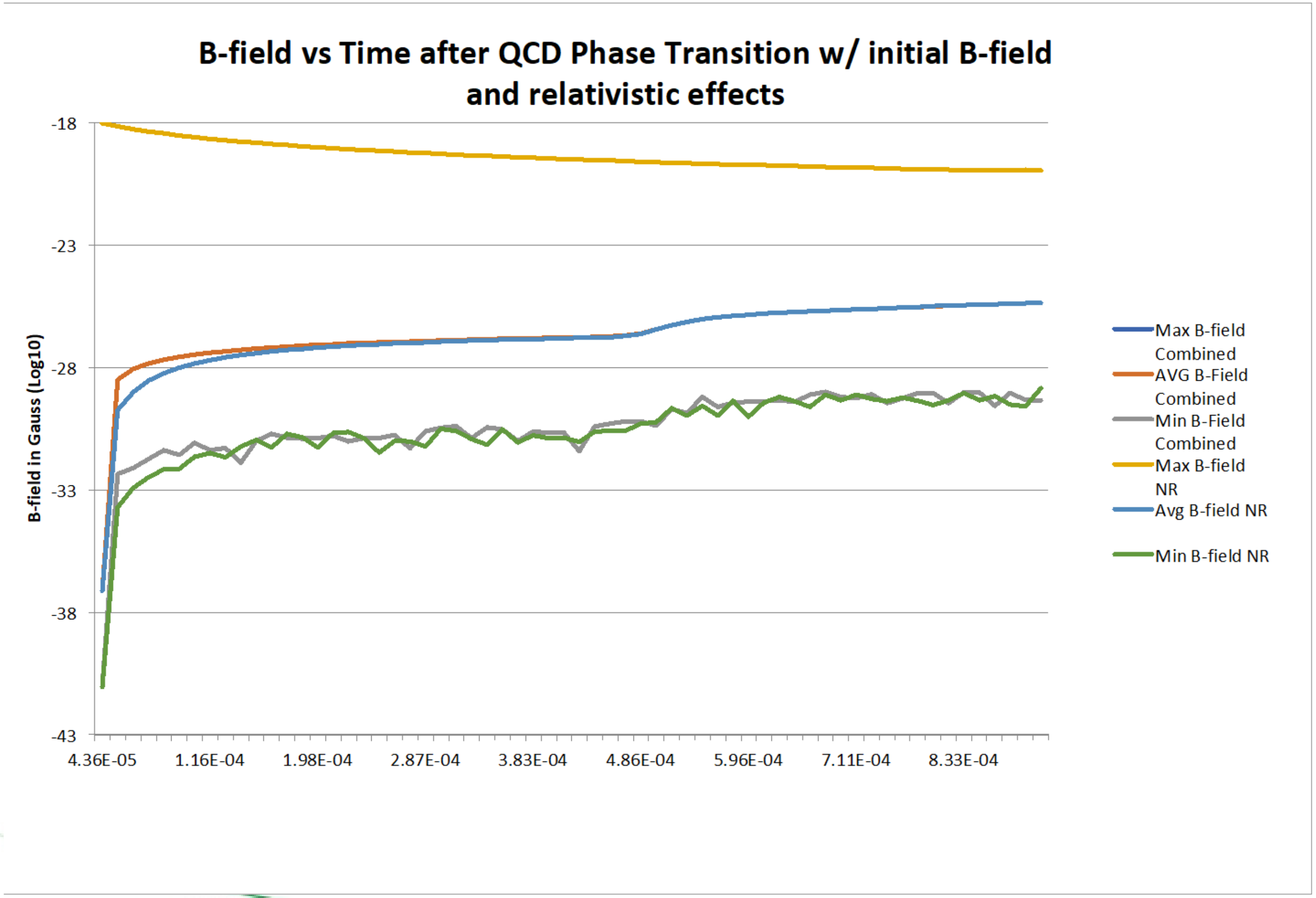
EW Phase Transition



QCD Phase Transition



QCD Phase Transition with initial B-field



Conclusion

- B-fields as large as 10^{-18} G may have been produced by the end of the EW phase transition
- These fields varied from 10^{-28} G to and average of 10^{-24} G over 1 Mpc
- The strongest B-fields may have been isolated to small areas
- More work is needed to understand how these fields may have evolved until the first stars and galaxies formed

University of Houston Clear Lake

Questions???