Theory of Interstellar Turbulence

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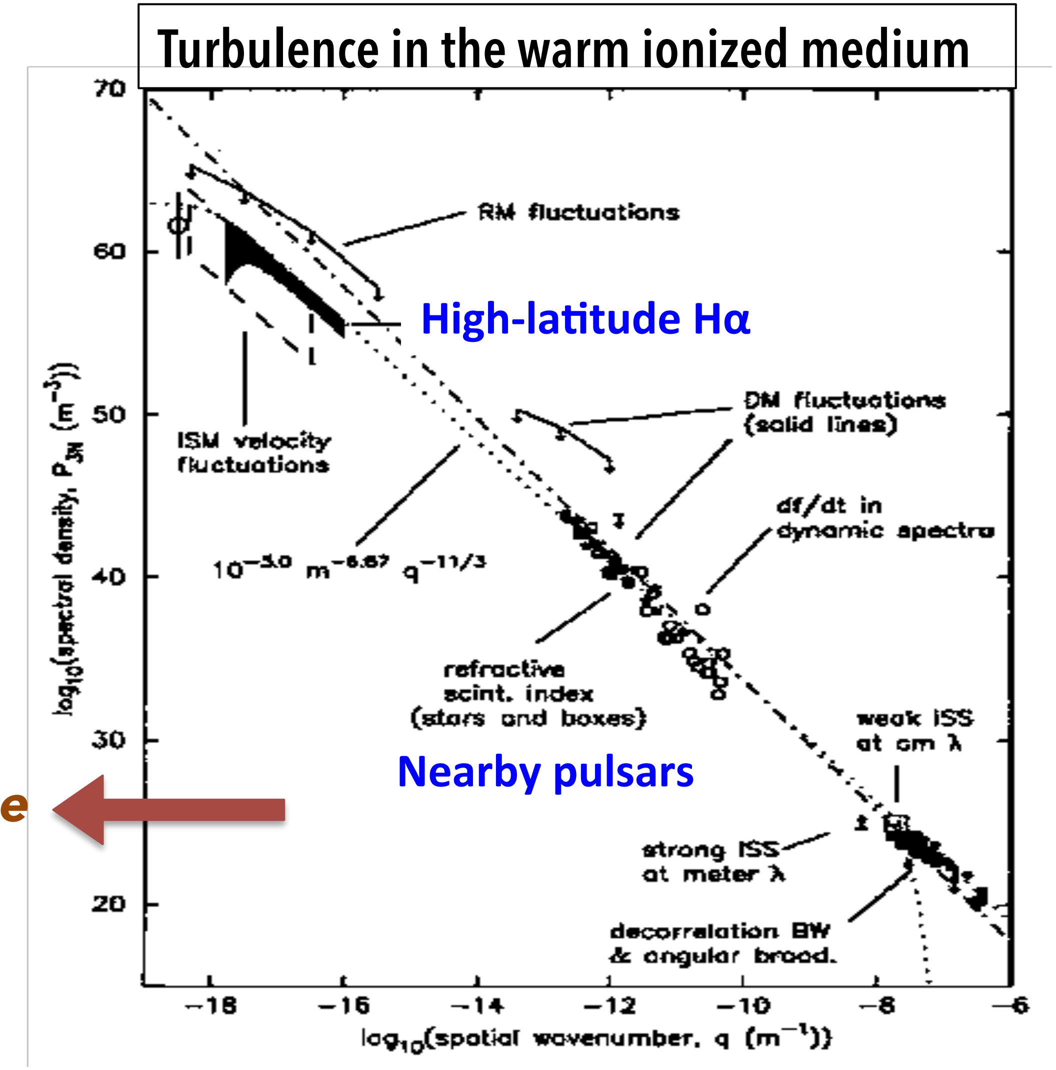
Length range of interstellar turbulence spans over 10 orders of magnitude

Andrey Kolmogorov (1903-1987)

Kolmogorov law of turbulence

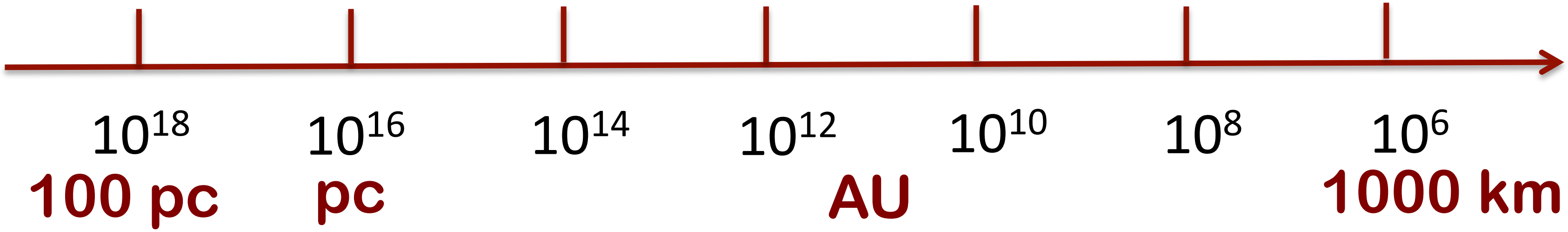


Turbulence in the warm ionized medium

Armstrong+ 95; Chepurnov & Lazarian 09

Very limited length range of simulated turbulence

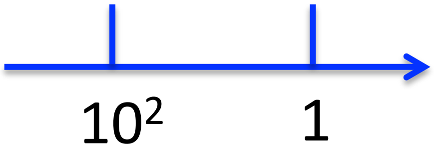
Turbulence length scales in the ISM [m]



10^{18} 10^{16} 10^{14} 10^{12} 10^{10} 10^{8} 10^{6}

100 pc **pc** **AU** **1000 km**

in high-resolution numerical simulations

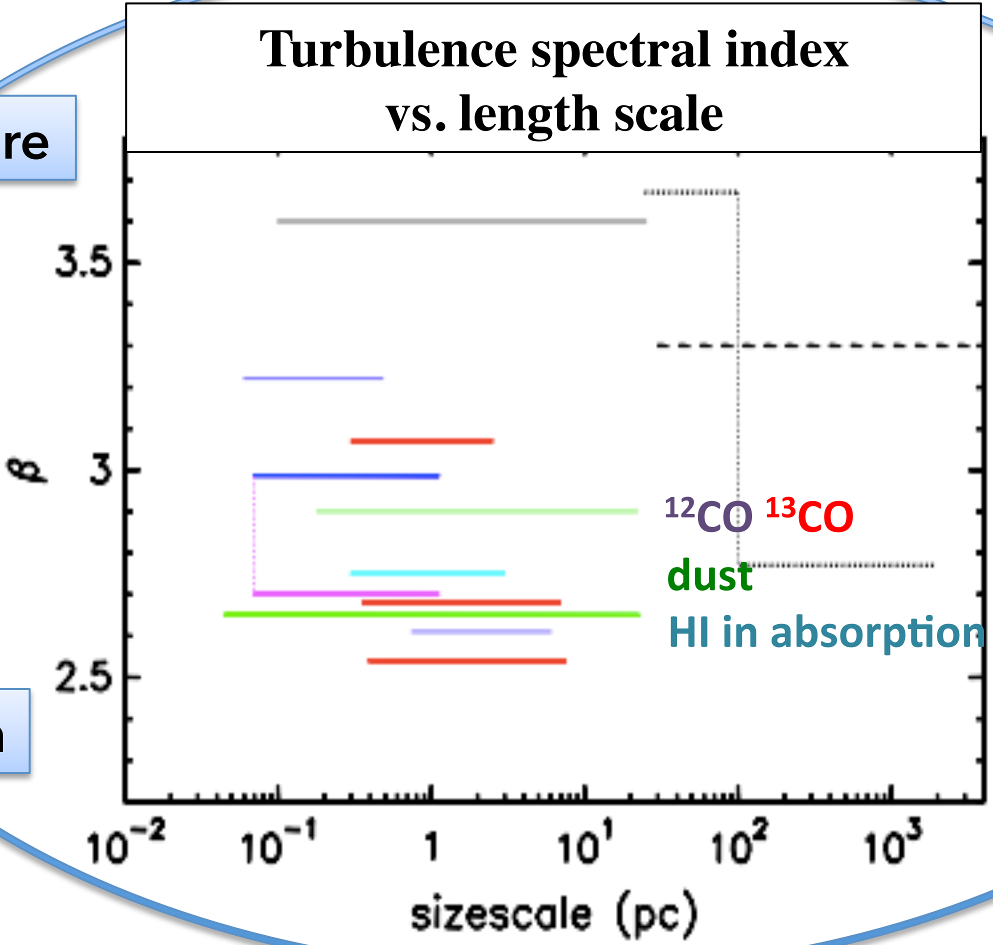


10^{2} 1

Turbulence has different properties in the multi-phase ISM

Temperature

Density



Turbulence spectral index vs. length scale

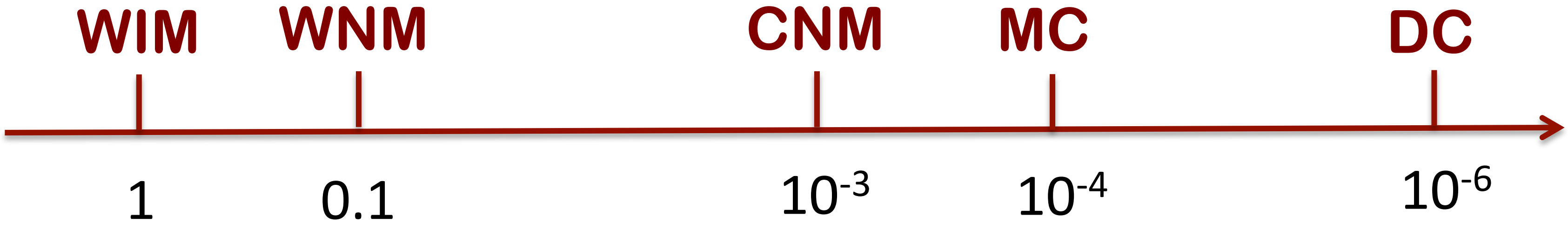
Magnetization

Ionization fraction

Lazarian 2009; Hennebelle & Falgarone 2012

Simulations of turbulence in the partially ionized ISM are very expensive

Ionization fraction **in the ISM**



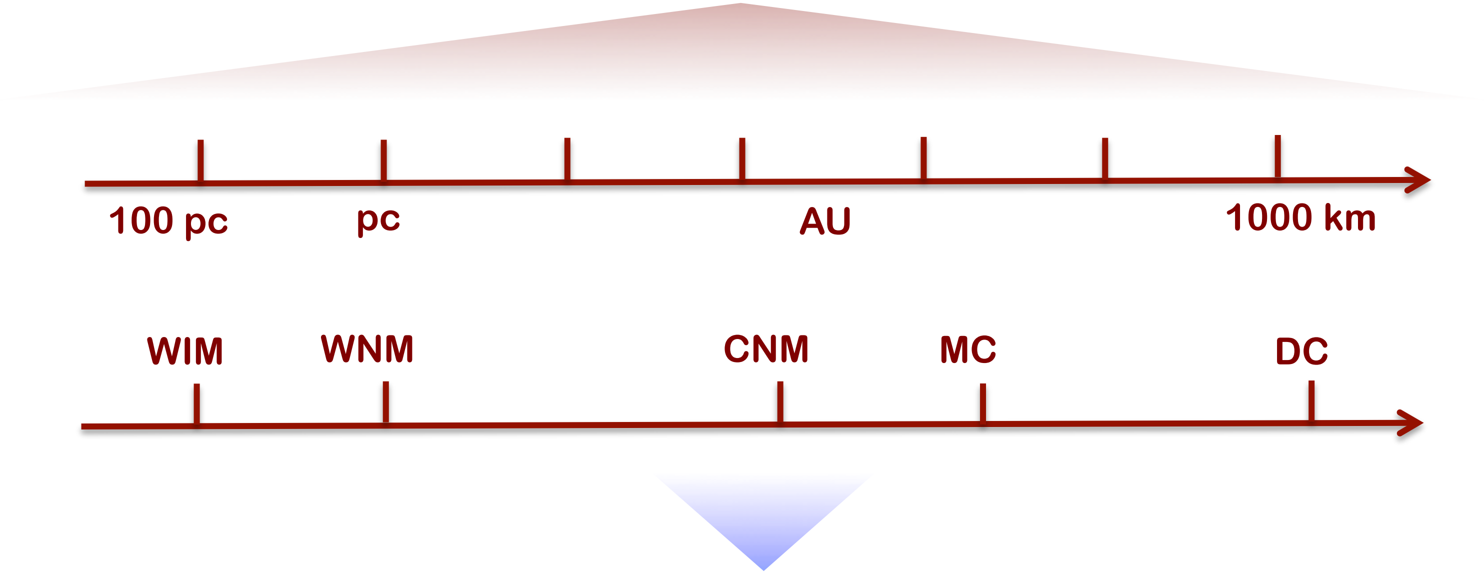
WIM	**WNM**	**CNM**	**MC**	**DC**
1	0.1	10^{-3}	10^{-4}	10^{-6}

two-fluid numerical simulations

**extremely time consuming*

Brute-force numerical studies of interstellar turbulence is beyond current computational resources.

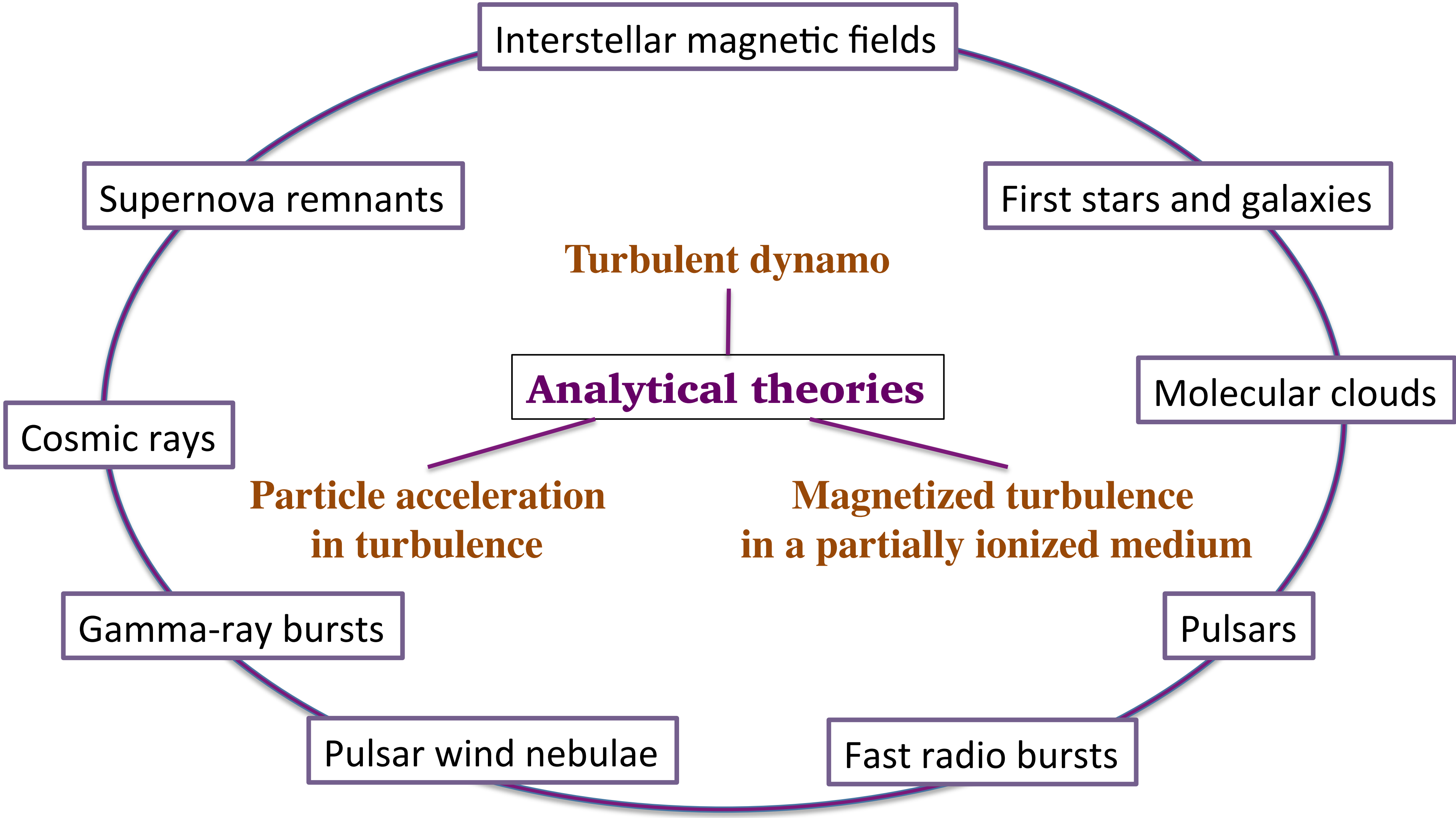
Analytical theories of interstellar turbulence are advantageous



Testable: numerical simulations

Applications and predictions: a wide range of astrophysical problems

My thesis work



Interstellar magnetic fields

Supernova remnants

First stars and galaxies

Turbulent dynamo

Analytical theories

Molecular clouds

Cosmic rays

Particle acceleration
in turbulence

Magnetized turbulence
in a partially ionized medium

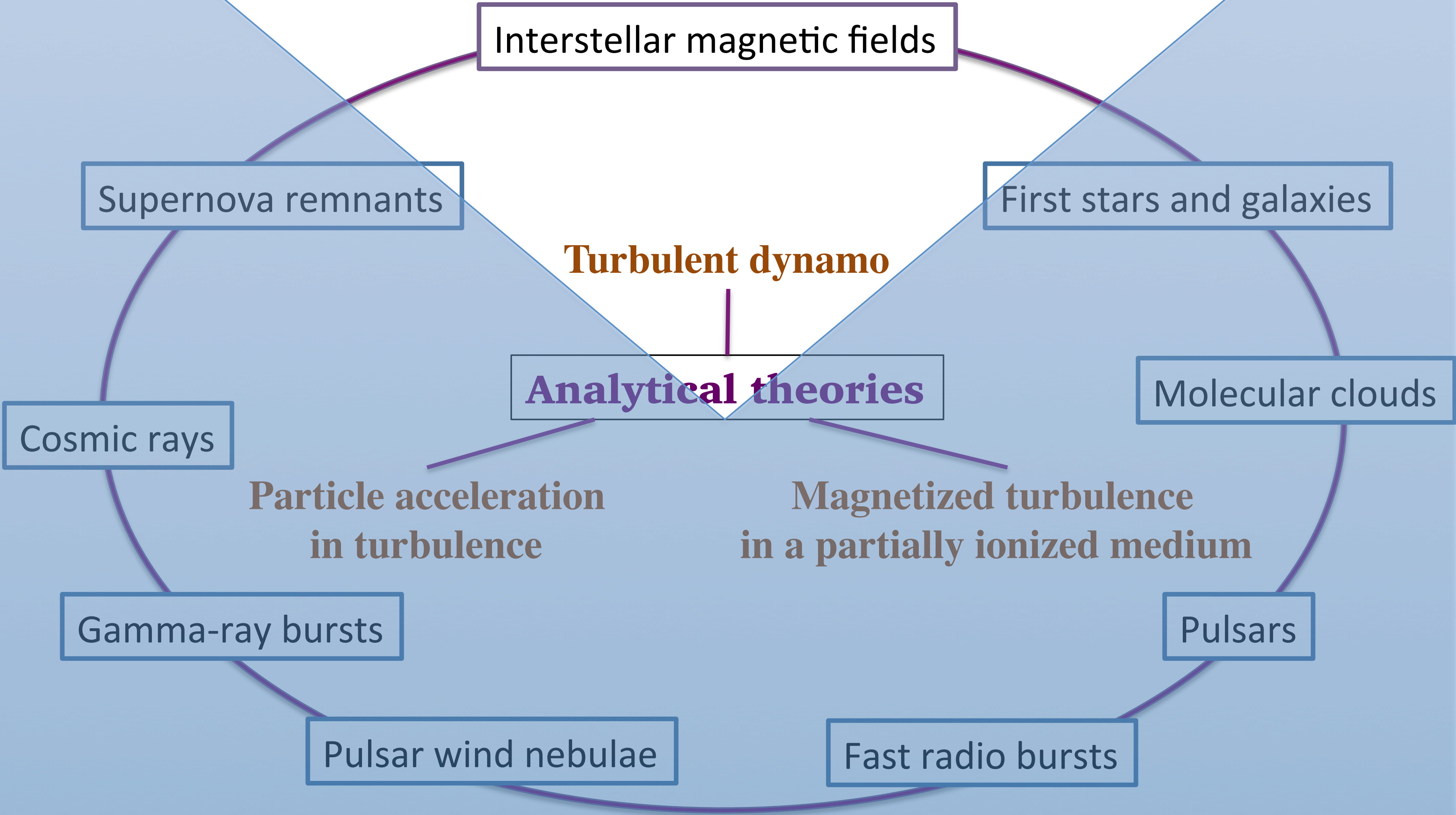
Gamma-ray bursts

Pulsars

Pulsar wind nebulae

Fast radio bursts

My thesis work



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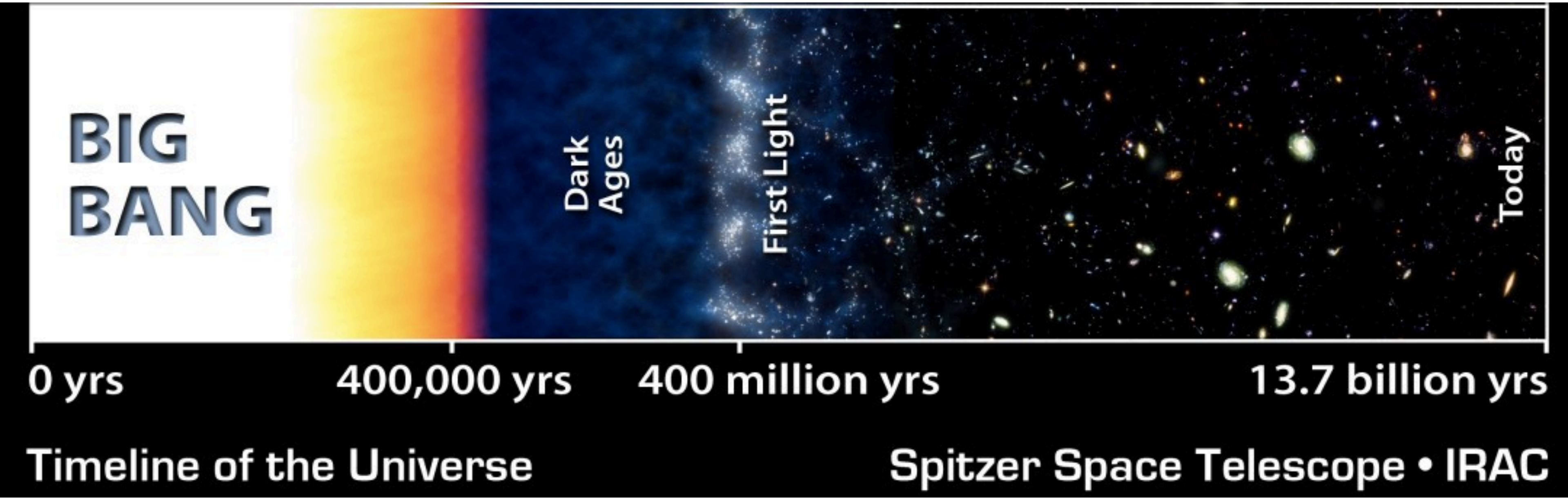
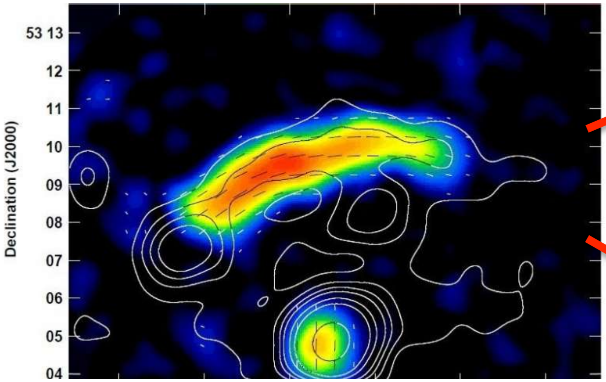
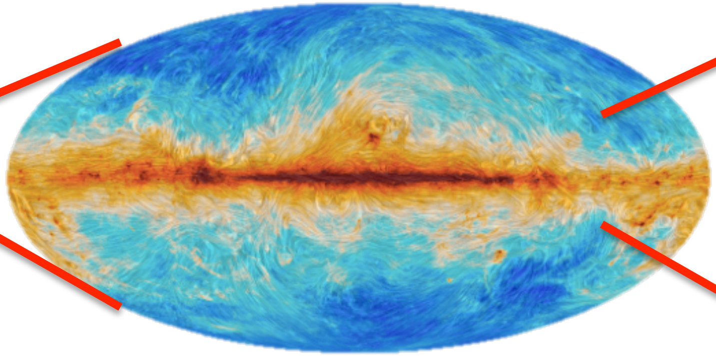
Cosmic magnetic fields are generated by dynamo

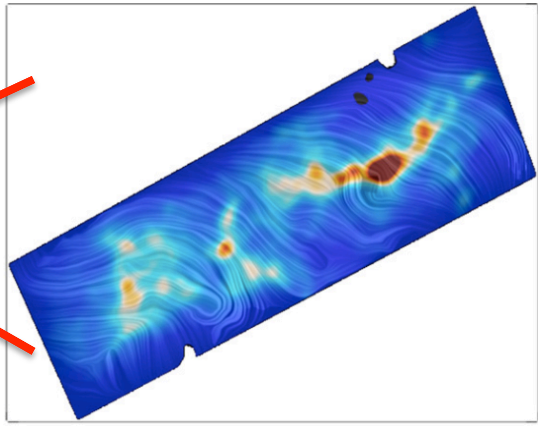




Kierdorf et al. 2017



Planck



Fissel et al. 2016

Turbulent dynamo amplifies magnetic fields

Turbulent motion

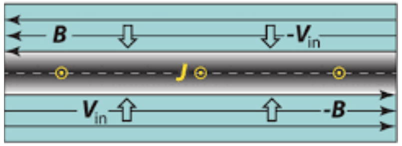
Magnetic field

Growth ⟷ Dissipation

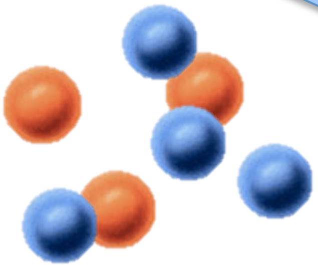
↓

Dynamo efficiency

Understanding of both plasma and turbulence physics is required for studying turbulent dynamo

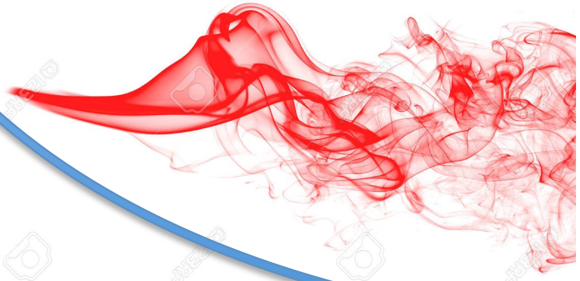


Resistive diffusion



Ambipolar diffusion

Turbulent diffusion



Turbulent reconnection

Kazantsev 1968; Goldreich & Sridhar 1995; Lazarian & Vishniac 99; **Xu+ 2015; 2016**

Disagreement between numerical experiments & earlier theories

Nonlinear turbulent dynamo

Numerical studies:

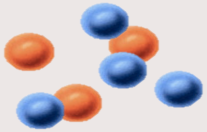
Inefficient dynamo

e.g.,
Cho & Vishniac 2000;
Cho et al. 2009;
Beresnyak 2012

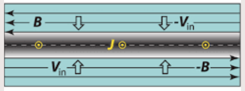
Analytical studies:

Efficient dynamo

e.g.,
Kulsrud & Anderson 1992;



Schekochihin et al. 2002;



MHD turbulence theories:
numerically tested

Goldreich & Sridhar 1995;
Lazarian & Vishniac 1999

New analytical theory of nonlinear turbulent dynamo

consistent with numerical results and provides predictions

Xu & Lazarian 2016, ApJ, 833, 215

- ***Magnetic energy:*** $$\mathcal{E} = \mathcal{E}_{\rm cr} + \frac{3}{38}\epsilon(t - t_{\rm cr}).$$
- ***Magnetic field length scale:*** $$k_p = \left[k_{\rm cr}^{-\frac{2}{3}} + \frac{3}{19}\epsilon^{\frac{1}{3}}(t - t_{\rm cr})\right]^{-\frac{3}{2}}$$
- ***Dynamo timescale:*** $$\tau_{nl} = \frac{19}{3}\left(\Gamma_{\rm tur,f}^{-1} - \Gamma_{\rm tur,i}^{-1}\right)$$

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consistent with numerical results

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Low efficiency: a *small* factor of turbulent energy transfer rate

Numerical measurements: e.g., Cho & Vishniac 00; Cho+ 09; Beresnyak 12

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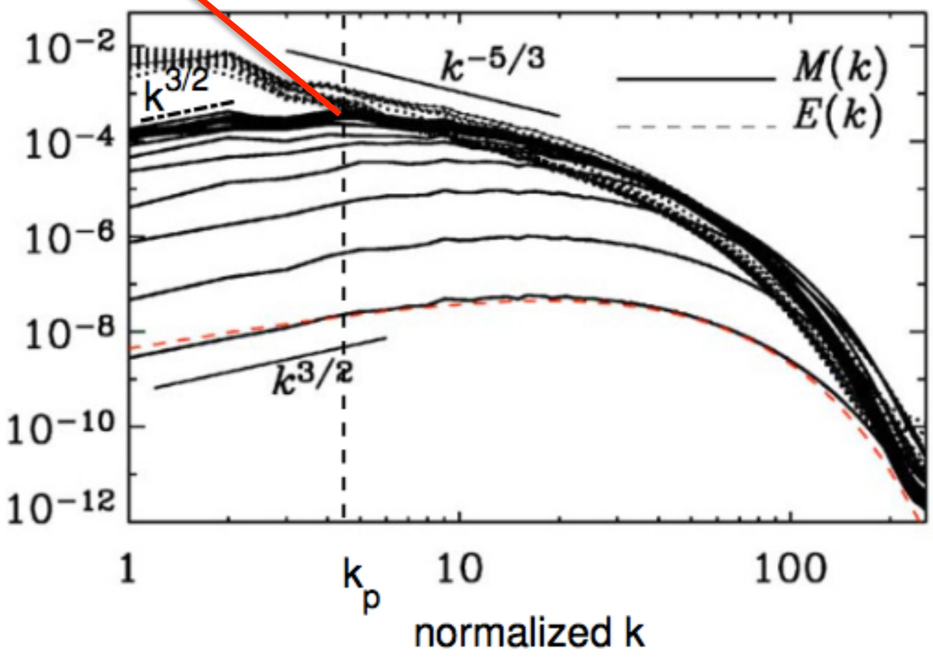
Numerical measurements:

Brandenburg & Subramanian 05



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beyond numerical simulations

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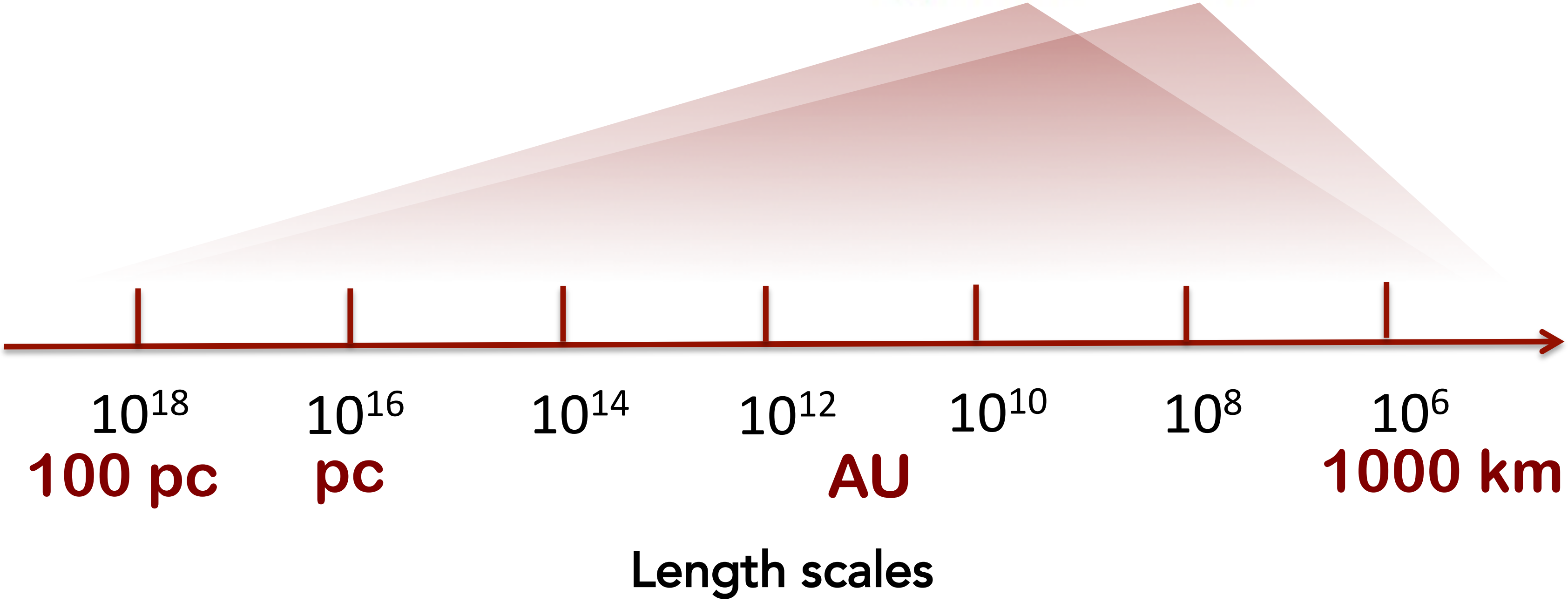
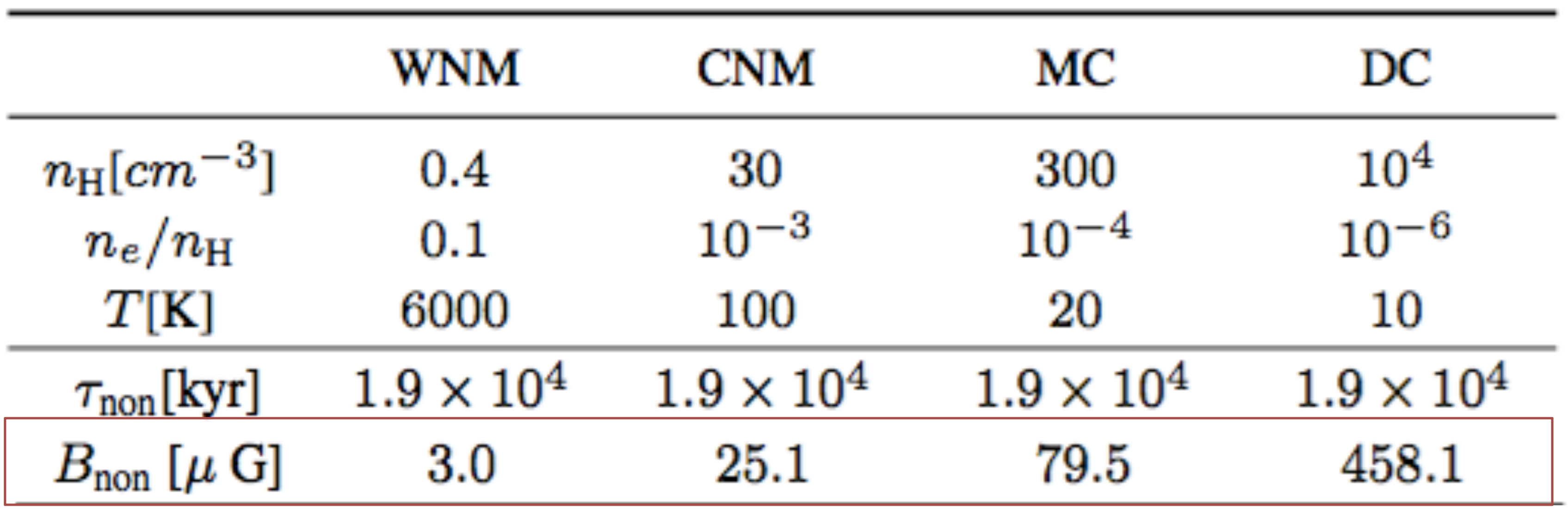


Interstellar magnetic fields generated by turbulent dynamo agree with observed field strengths

Turbulence driven by supernova explosions $L = 30\,\mathrm{pc},\ V_L = 10\,\mathrm{km\,s}^{-1}$



	WNM	CNM	MC	DC
$n_{\mathrm{H}}[cm^{-3}]$	0.4	30	300	10^4
n_e/n_{H}	0.1	10^{-3}	10^{-4}	10^{-6}
$T[\mathrm{K}]$	6000	100	20	10
$\tau_{\mathrm{non}}[\mathrm{kyr}]$	1.9×10^4	1.9×10^4	1.9×10^4	1.9×10^4
$B_{\mathrm{non}}\ [\mu\,\mathrm{G}]$	3.0	25.1	79.5	458.1

Xu & Lazarian 2016

Interstellar magnetic fields generated by turbulent dynamo explain observed field strengths

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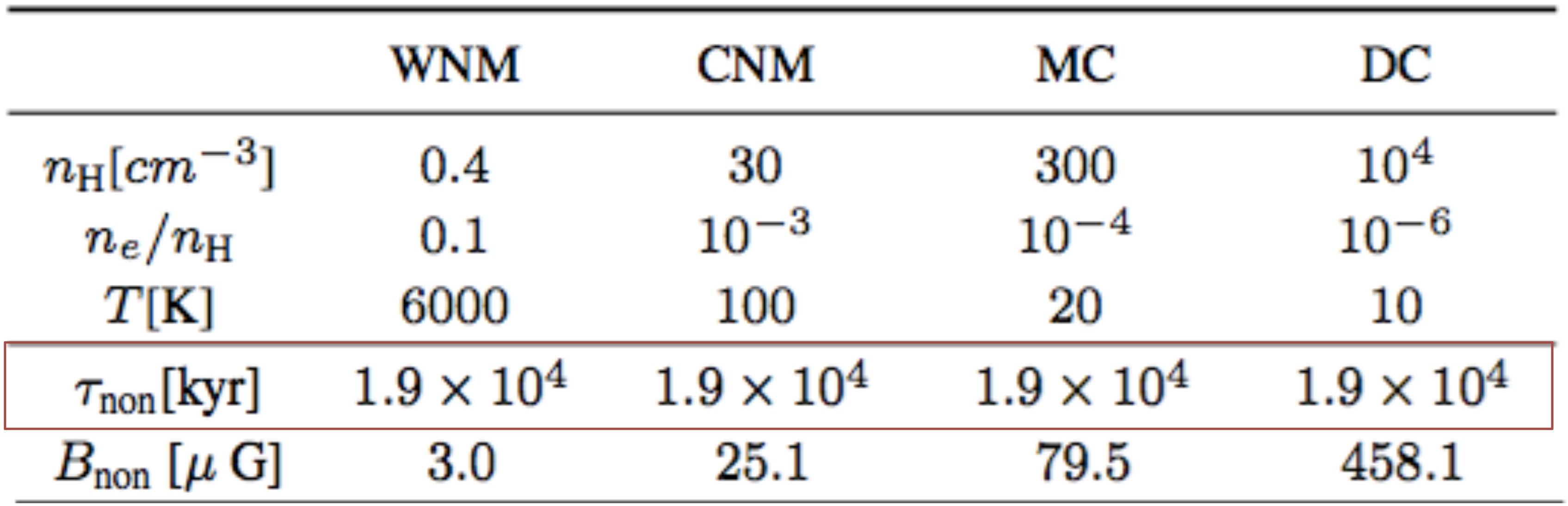

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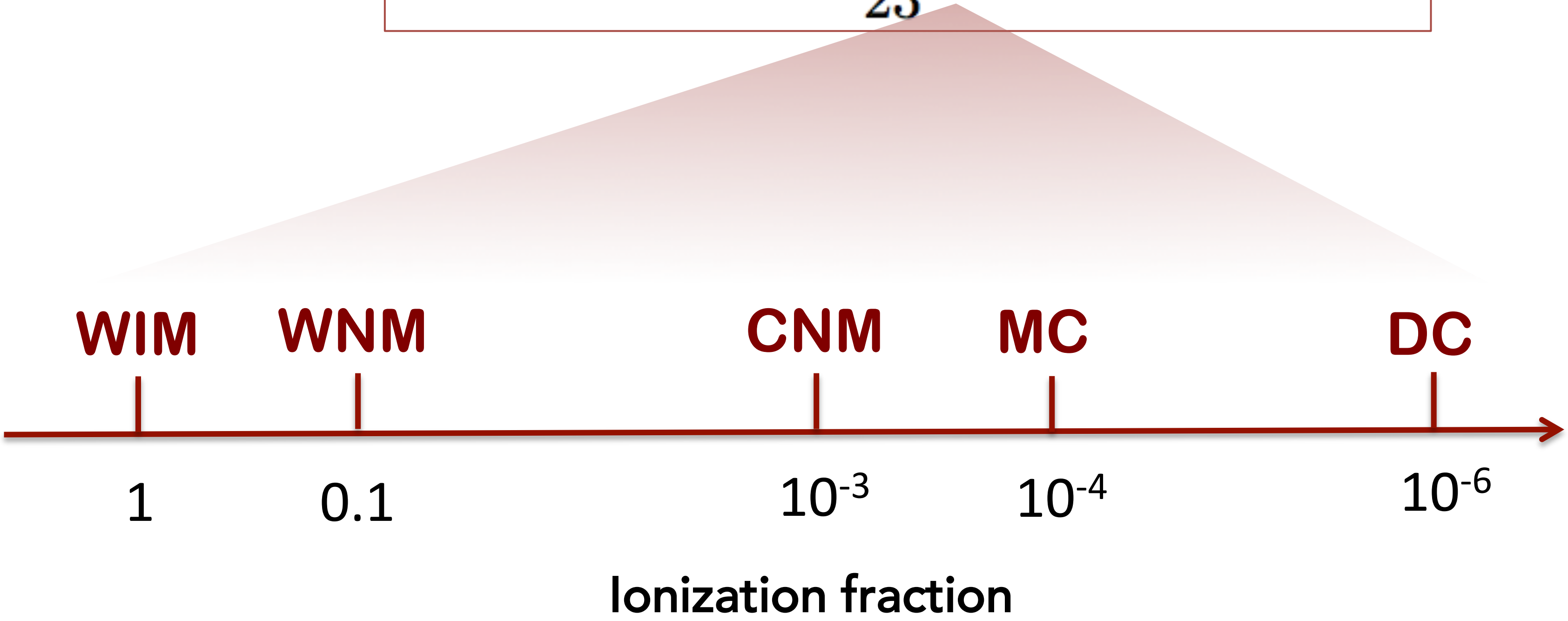
High-redshift galaxies have interstellar field strengths comparable to local galaxies.

Xu & Lazarian 2016

New analytical theory of turbulent dynamo in partially ionized ISM

Xu & Lazarian 2016, ApJ, 833, 215

Evolution law: $\boxed{\sqrt{\mathcal{E}_M} = \sqrt{\mathcal{E}_{M1}} + \frac{3}{23}\mathcal{C}^{-\frac{1}{2}} L^{-\frac{1}{2}} V_L^{\frac{3}{2}} (t - t_1),}$



WIM 1

WNM 0.1

CNM 10^{-3}

MC 10^{-4}

DC 10^{-6}

Ionization fraction

New analytical theory of turbulent dynamo in partially ionized ISM

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Numerical testing:

Two-fluid dynamo simulations

RIEMANN code see Balsara 2004

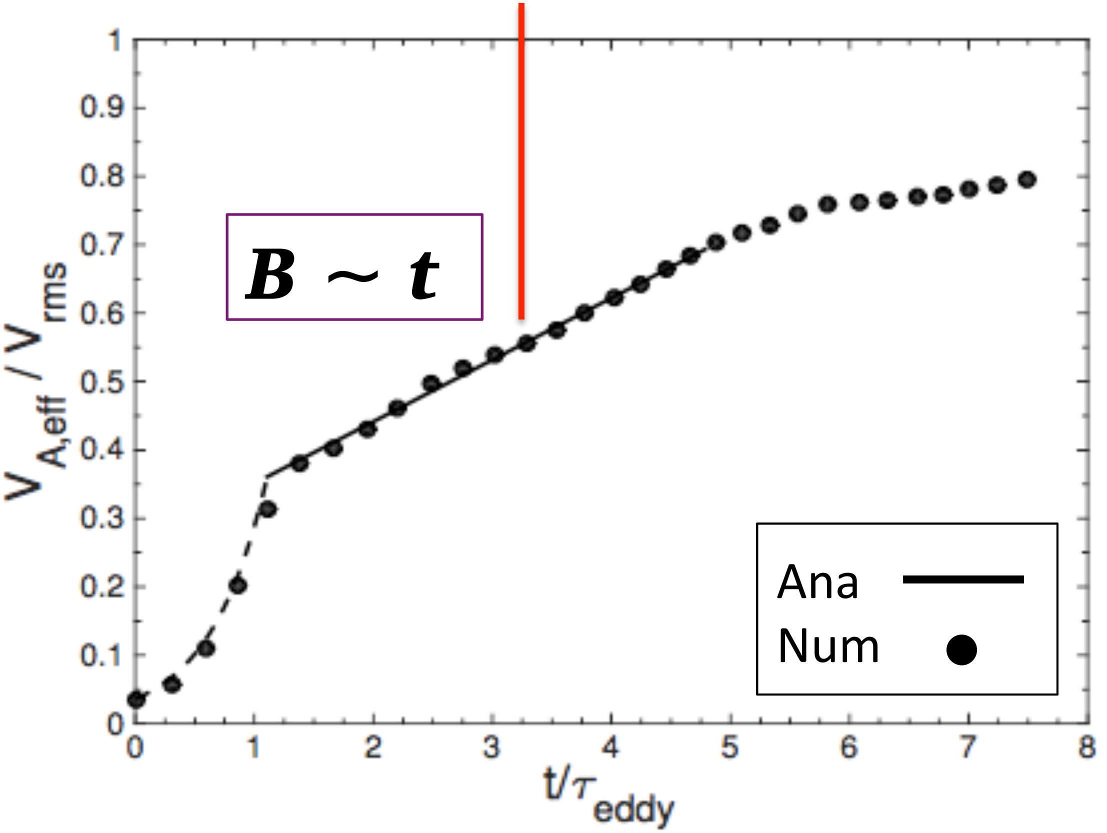
R	L	ρ_i/ρ_n	$V_{\rm rms}$	c_s	M_{A0}	$l_{\rm AD0}$
1024^3	$256-512$	1.26×10^{-3}	0.2	1	500	12.8

New analytical theory of turbulent dynamo in partially ionized ISM

confirmed by two-fluid numerical simulations

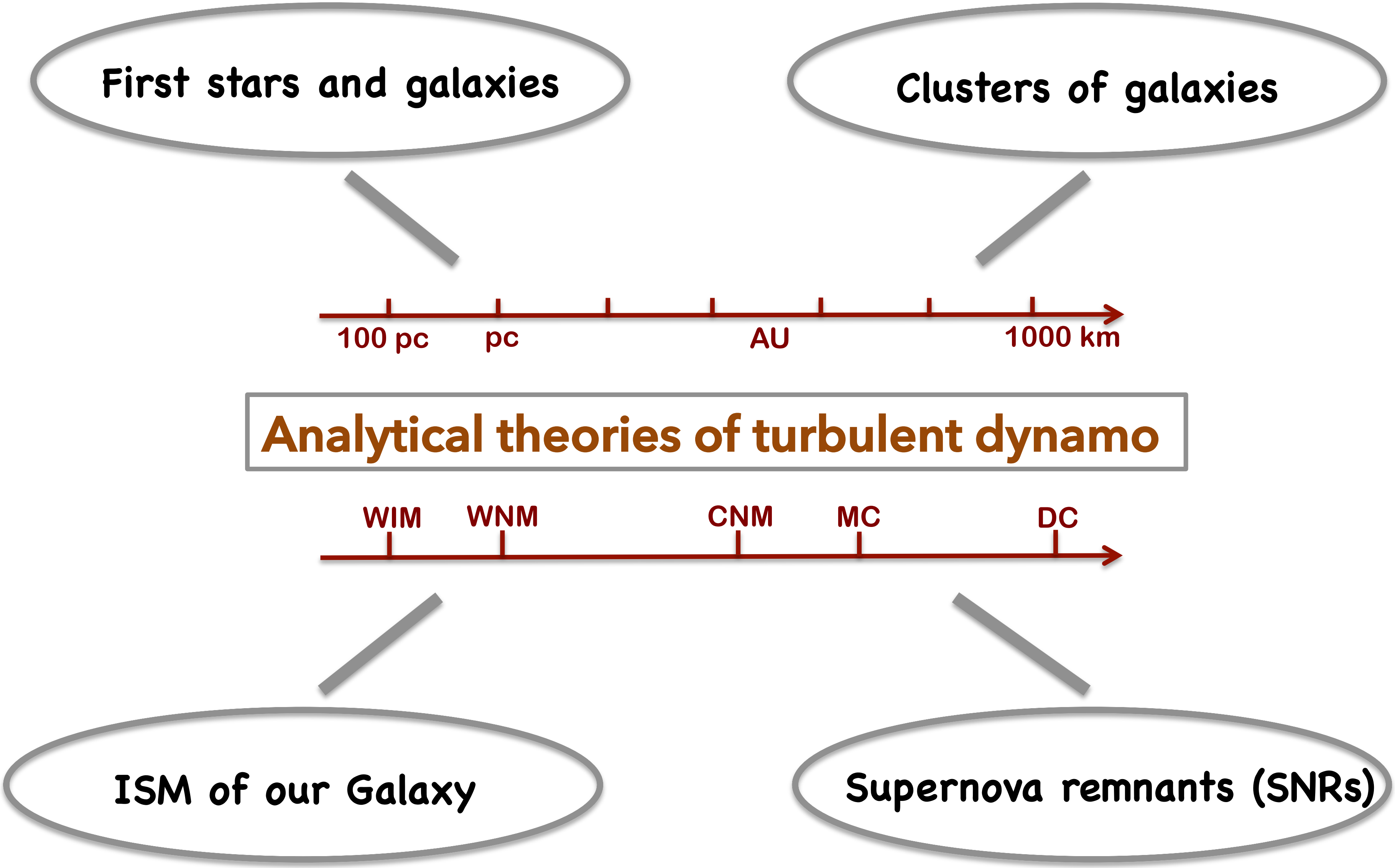
Evolution law:

$$\sqrt{\mathcal{E}_M} = \sqrt{\mathcal{E}_{M1}} + \frac{3}{23}\mathcal{C}^{-\frac{1}{2}} L^{-\frac{1}{2}} V_L^{\frac{3}{2}} (t - t_1),$$



$\boldsymbol{B \sim t}$

New turbulent dynamo theories have an extensive range of applications



First stars and galaxies

Clusters of galaxies

100 pc

pc

AU

1000 km

Analytical theories of turbulent dynamo

WIM

WNM

CNM

MC

DC

ISM of our Galaxy

Supernova remnants (SNRs)

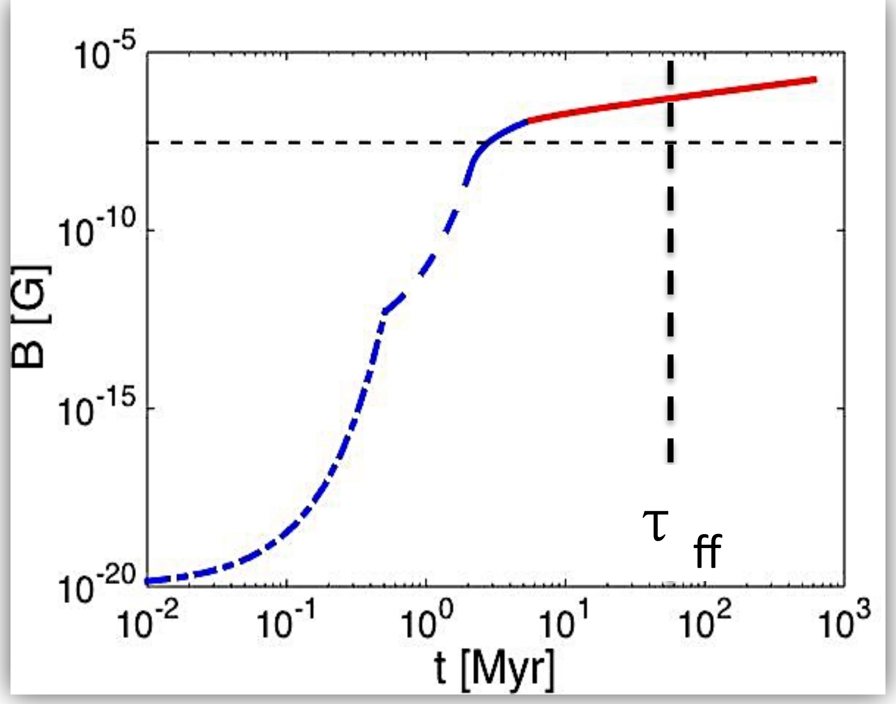
Example I: magnetic field evolution during the first star formation

Our new findings:

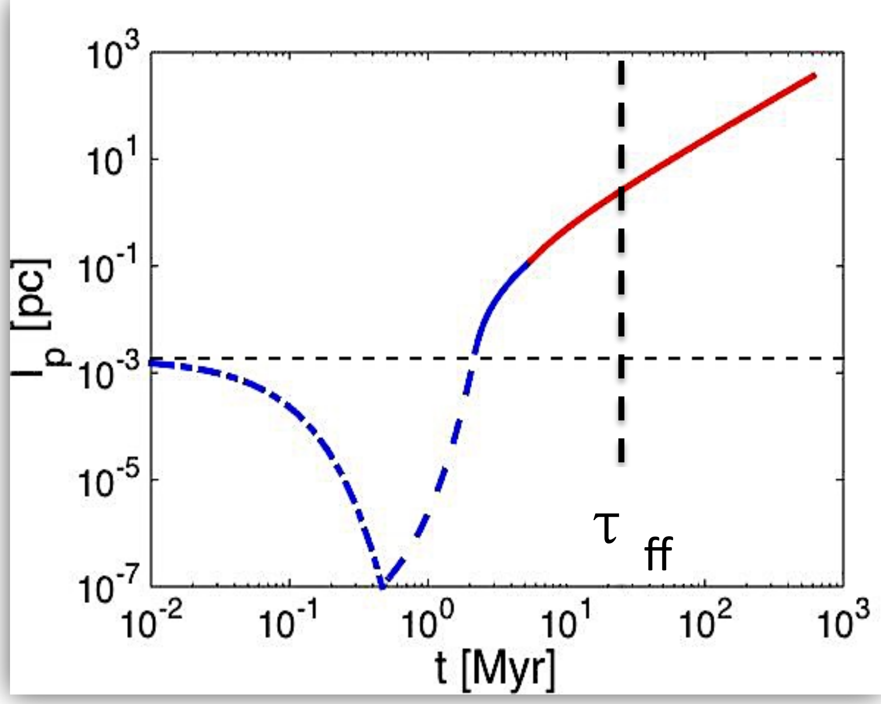
- **Dynamo has multi-evolutionary stages**
- **Dynamo timescale is longer than the free-fall timescale**

Our analytical prediction:

Xu & Lazarian 2016



Field strength vs. time

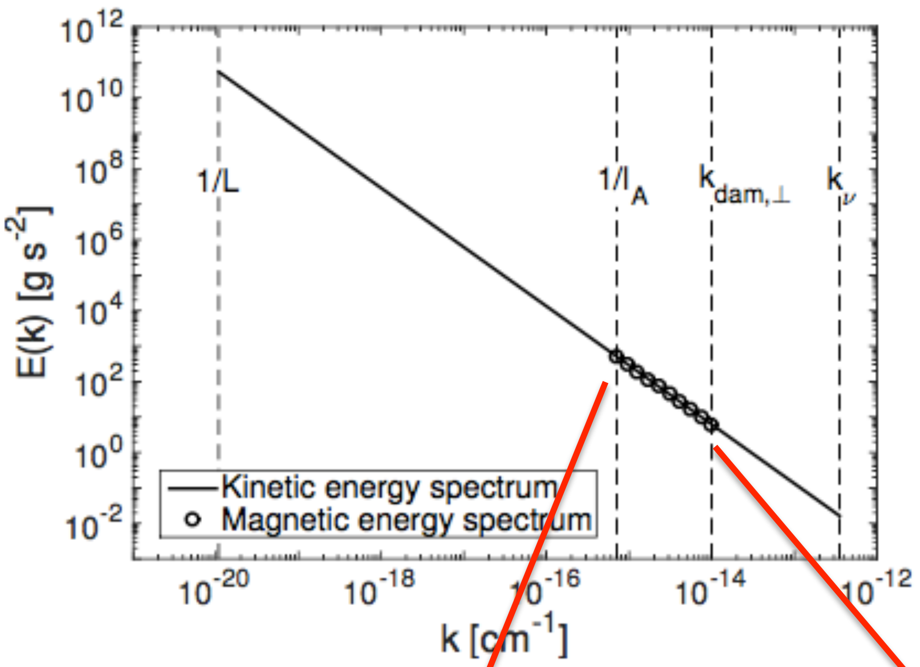


Filed length vs. time

Example II: magnetic field evolution in weakly magnetized molecular clouds

Our analytical prediction: **Xu** & Lazarian 2017

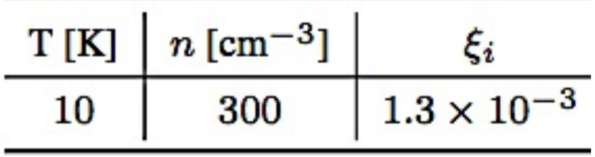
Evolving magnetic spectrum



Characteristic field strength and length

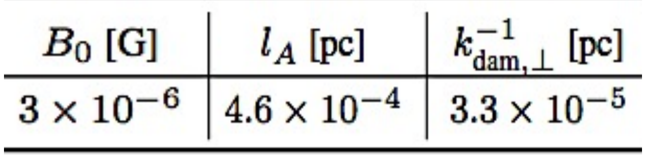
Dissipation scale

Physical conditions



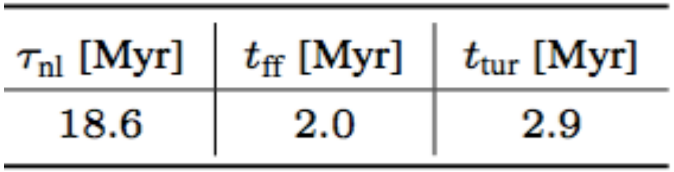
T [K]	n [cm^{-3}]	ξ_i
10	300	1.3×10^{-3}

Initial magnetic field



B_0 [G]	l_A [pc]	$k_{\text{dam},\perp}^{-1}$ [pc]
3×10^{-6}	4.6×10^{-4}	3.3×10^{-5}

Timescales



τ_{nl} [Myr]	t_{ff} [Myr]	t_{tur} [Myr]
18.6	2.0	2.9

Example III: magnetic field evolution in SNRs

Numerical measurements:
Inoue et al. 2009

— — —

Our analytical prediction:

Xu & Lazarian 2017

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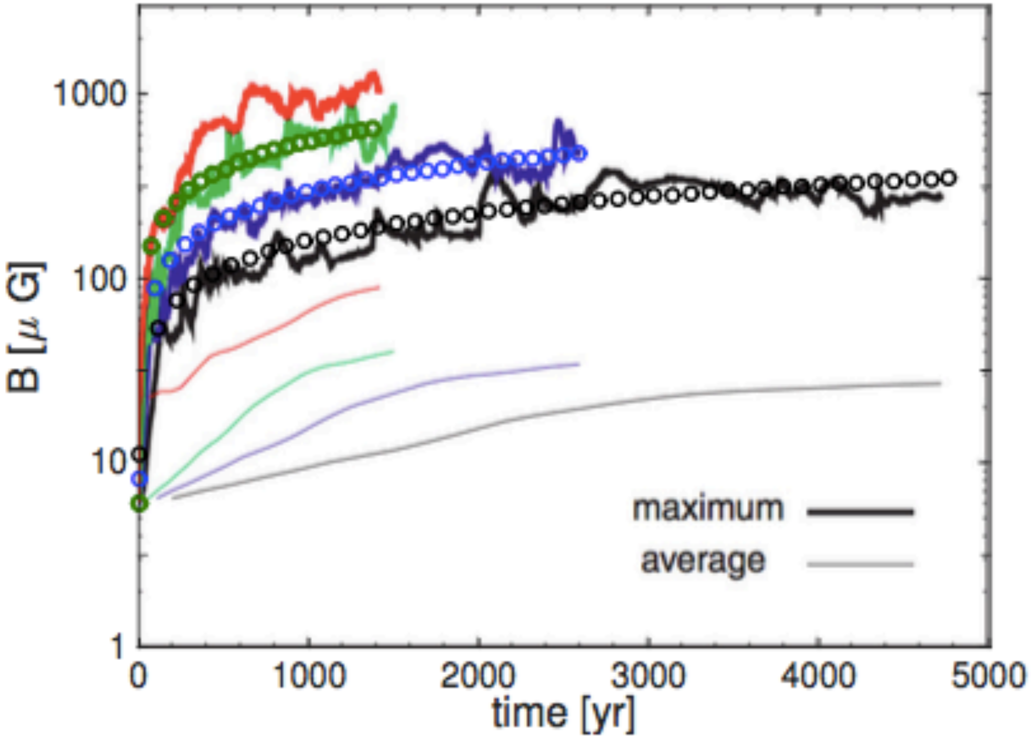
Field strength vs. time



● Dynamo generated magnetic field

Acceleration of Galactic cosmic rays up to the knee energy ~ 10^{15} eV

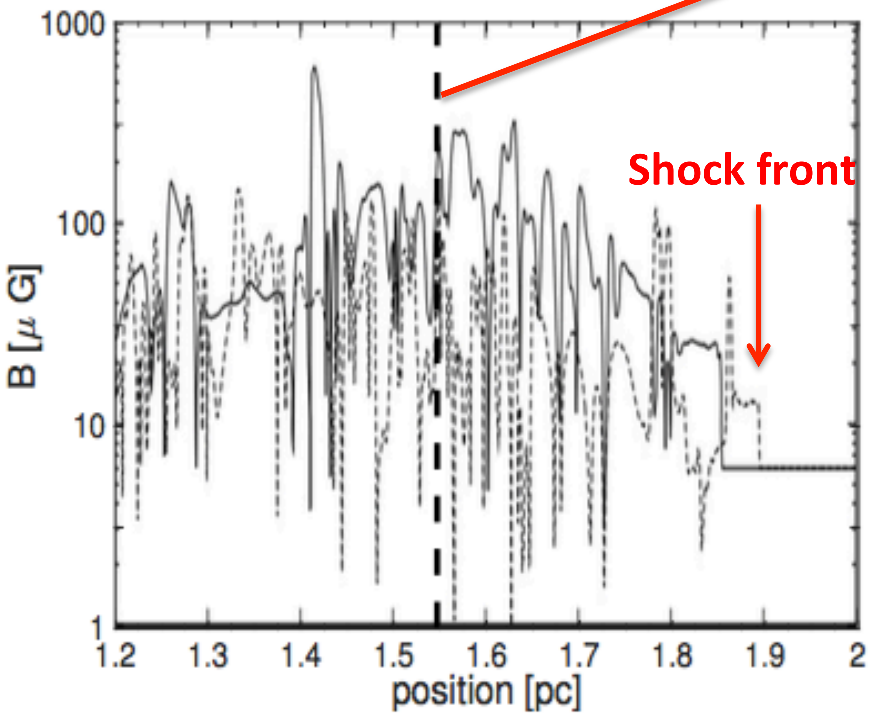
Example III: magnetic field evolution in SNRs

Numerical measurements:
Inoue et al. 2009

Our analytical prediction:

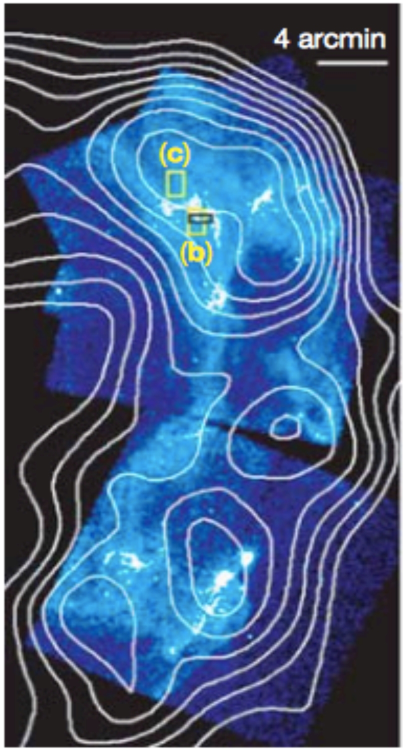
Xu & Lazarian 2017

Field strength vs. position



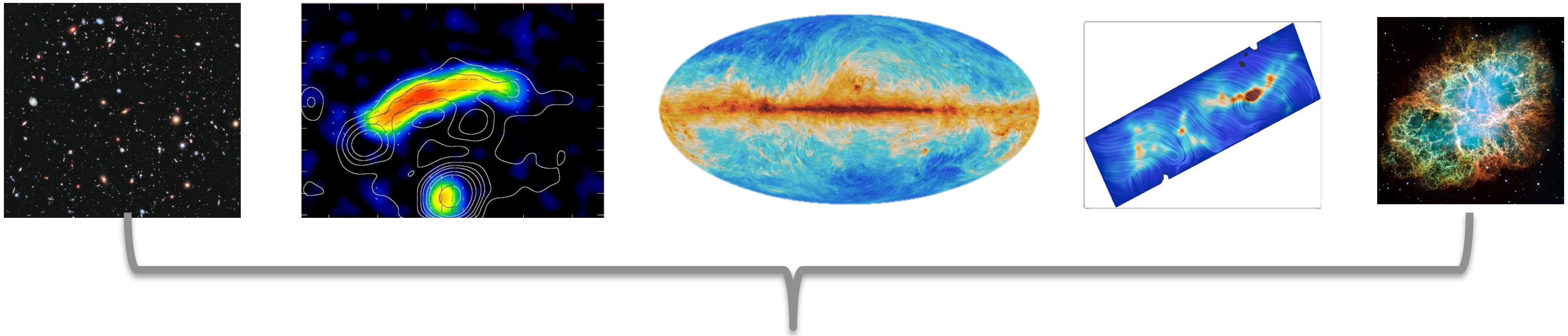
Shock front

● Low dynamo efficiency



Uchiyama+ 2007

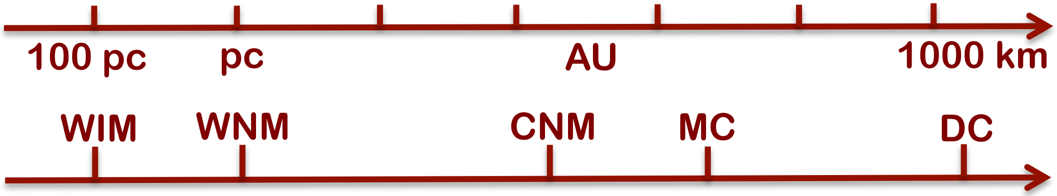
X-ray hot spots are located at **more than 0.1 pc behind the shock front.**



New nonlinear turbulent dynamo theory

New turbulent dynamo theory in partially ionized ISM

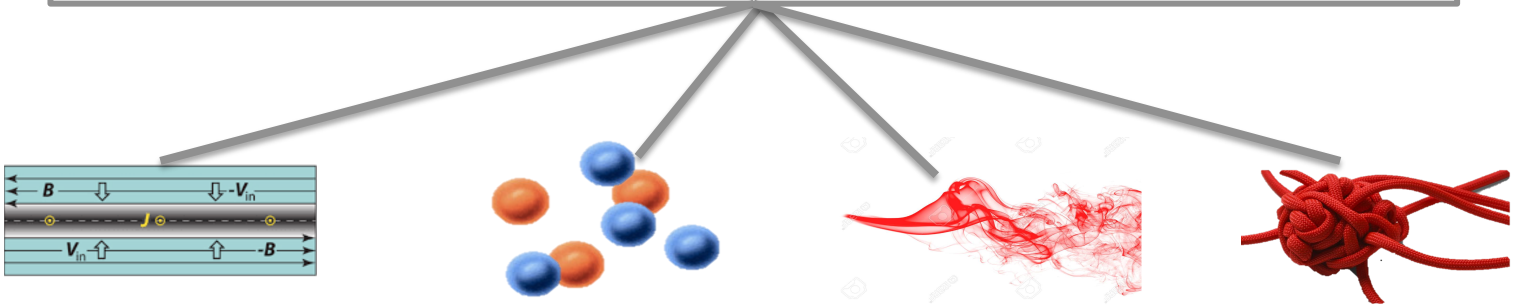
consistent with numerical simulations



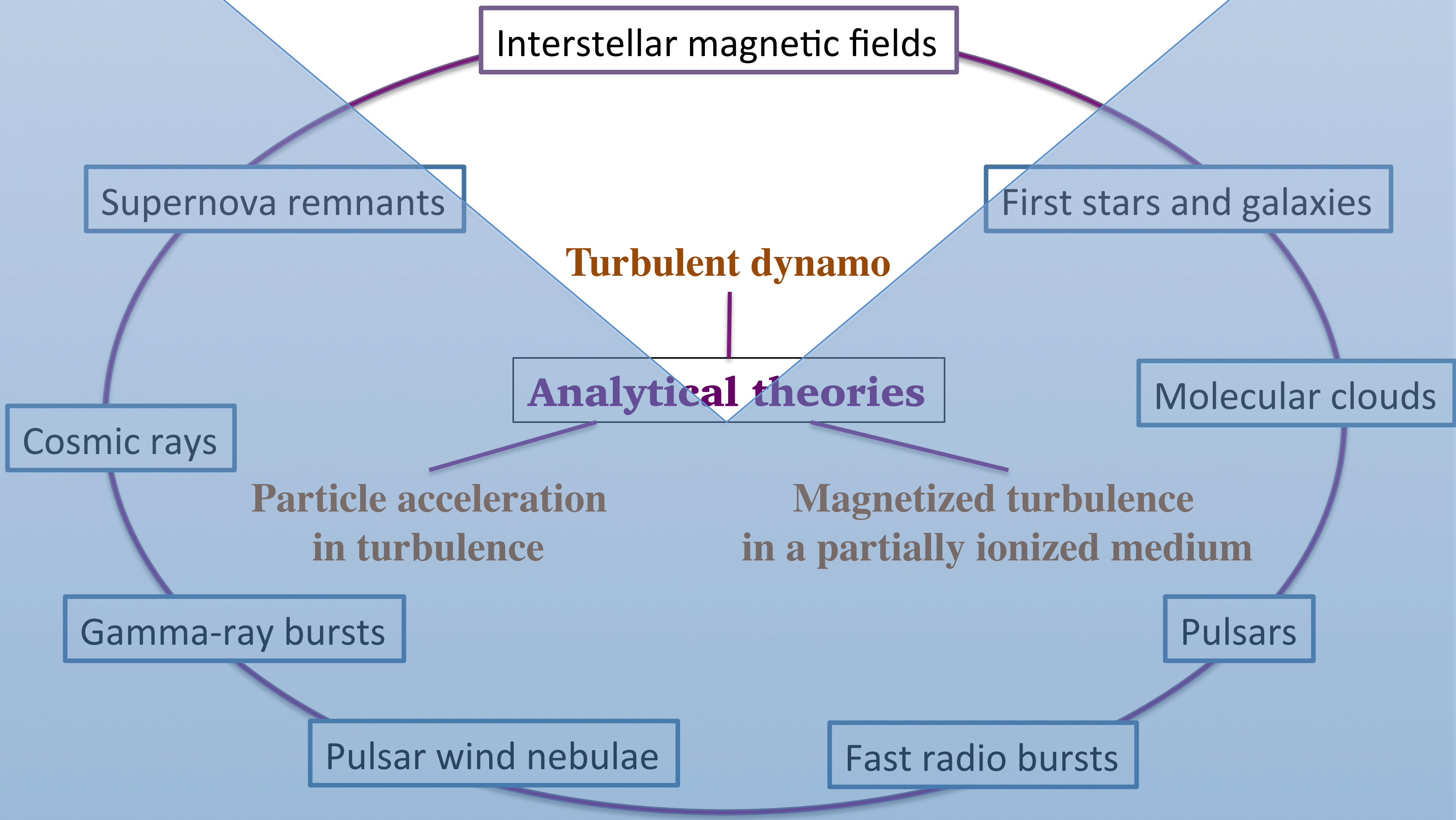
100 pc pc AU 1000 km

WIM WNM CNM MC DC

Analytical theories of turbulent dynamo



My thesis work



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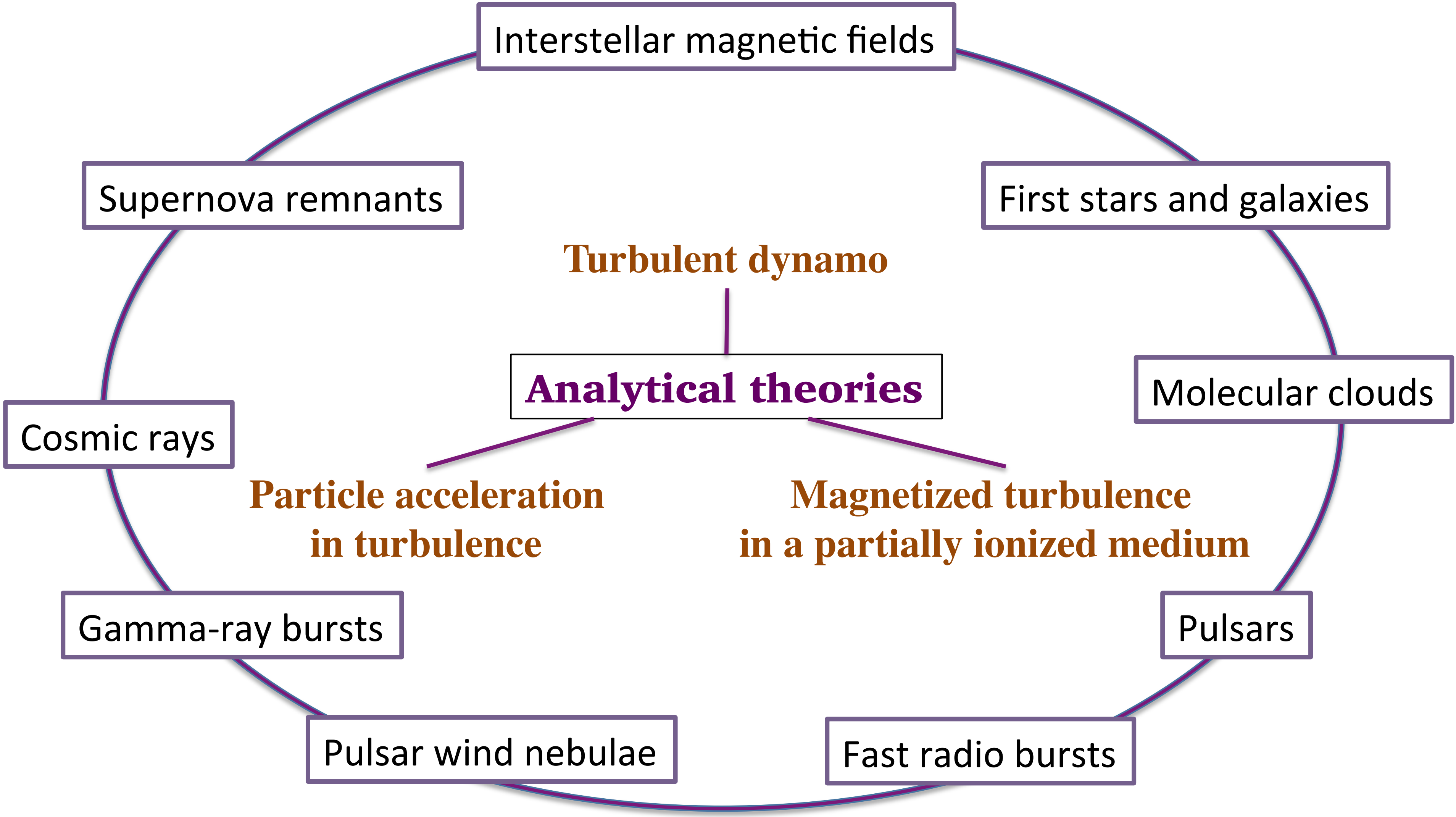

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My thesis work

1. **Xu S.**, Lazarian A., 2016, ApJ, 833, 215
2. **Xu S.** & Lazarian A. 2017, ApJ, 850, 126
3. **Xu S.** & Lazarian A. 2017, New Journal of Physics, 19, 5005
4. **Xu S.** & Zhang B. 2016, ApJ, 832, 199
5. **Xu S.** & Zhang B. 2017, ApJ, 835, 2
6. **Xu S.** & Zhang B. 2016, ApJ, 824, 113
7. **Xu S.**, Lazarian A. & Yan H. 2015, ApJ, 810, 44
8. **Xu S.**, Yan H. & Lazarian A. 2016, ApJ, 826, 166
9. **Xu S.** & Yan H. 2013, ApJ, 779, 140
10. **Xu S.** & Zhang B. 2017, ApJL, 846, 28
11. **Xu S.,** Zhang H. & Liu X. 2013, Research in Astronomy and Astrophysics, 13, 313
12. **Xu S.** & Li Z. 2014, Research in Astronomy and Astrophysics, 14, 411
13. López-Barquero, V., **Xu, S.**, Desiati, P., Lazarian, A., Pogorelov, N.V. & Yan, H. 2017, ApJ, 842, 54
14. López-Barquero, V., Farber, R., **Xu, S.**, Desiati, P. & Lazarian, A. 2016, ApJ, 830, 19