Turbulent Mixing in Galactic Disks

Chao-Chin Yang

Lund Observatory

Photo Credit: S. Brunier

Periodic Table of Elements

Atomic #
Symbol
Name
Atomic Mass

C Solid
Hg Liquid
H Gas
Rf Unknown

Metals: Alkali metals · Alkaline earth metals · Lanthanoids · Actinoids · Transition metals · Poor metals
Nonmetals: Other nonmetals · Noble gases

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	1 H Hydrogen 1.00794																	2 He Helium 4.002602
2	3 Li Lithium 6.941	4 Be Beryllium 9.012182											5 B Boron 10.811	6 C Carbon 12.0107	7 N Nitrogen 14.0067	8 O Oxygen 15.9994	9 F Fluorine 18.9984032	10 Ne Neon 20.1797
3	11 Na Sodium 22.98976928	12 Mg Magnesium 24.3050											13 Al Aluminium 26.9815386	14 Si Silicon 28.0855	15 P Phosphorus 30.973762	16 S Sulfur 32.065	17 Cl Chlorine 35.453	18 Ar Argon 39.948
4	19 K Potassium 39.0983	20 Ca Calcium 40.078	21 Sc Scandium 44.955912	22 Ti Titanium 47.867	23 V Vanadium 50.9415	24 Cr Chromium 51.9961	25 Mn Manganese 54.938045	26 Fe Iron 55.845	27 Co Cobalt 58.933195	28 Ni Nickel 58.6934	29 Cu Copper 63.546	30 Zn Zinc 65.38	31 Ga Gallium 69.723	32 Ge Germanium 72.64	33 As Arsenic 74.92160	34 Se Selenium 78.96	35 Br Bromine 79.904	36 Kr Krypton 83.798
5	37 Rb Rubidium 85.4678	38 Sr Strontium 87.62	39 Y Yttrium 88.90585	40 Zr Zirconium 91.224	41 Nb Niobium 92.90638	42 Mo Molybdenum 95.96	43 Tc Technetium (97.9072)	44 Ru Ruthenium 101.07	45 Rh Rhodium 102.90550	46 Pd Palladium 106.42	47 Ag Silver 107.8682	48 Cd Cadmium 112.411	49 In Indium 114.818	50 Sn Tin 118.710	51 Sb Antimony 121.760	52 Te Tellurium 127.60	53 I Iodine 126.90447	54 Xe Xenon 131.293
6	55 Cs Caesium 132.9054519	56 Ba Barium 137.327	57–71	72 Hf Hafnium 178.49	73 Ta Tantalum 180.94788	74 W Tungsten 183.84	75 Re Rhenium 186.207	76 Os Osmium 190.23	77 Ir Iridium 192.217	78 Pt Platinum 195.084	79 Au Gold 196.966569	80 Hg Mercury 200.59	81 Tl Thallium 204.3833	82 Pb Lead 207.2	83 Bi Bismuth 208.98040	84 Po Polonium (208.9824)	85 At Astatine (209.9871)	86 Rn Radon (222.0176)
7	87 Fr Francium (223)	88 Ra Radium (226)	89–103	104 Rf Rutherfordium (261)	105 Db Dubnium (262)	106 Sg Seaborgium (266)	107 Bh Bohrium (264)	108 Hs Hassium (277)	109 Mt Meitnerium (268)	110 Ds Darmstadtium (271)	111 Rg Roentgenium (272)	112 Uub Ununbium (285)	113 Uut Ununtrium (284)	114 Uuq Ununquadium (289)	115 Uup Ununpentium (288)	116 Uuh Ununhexium (292)	117 Uus Ununseptium	118 Uuo Ununoctium (294)

For elements with no stable isotopes, the mass number of the isotope with the longest half-life is in parentheses.

57 La Lanthanum 138.90547	58 Ce Cerium 140.116	59 Pr Praseodymium 140.90765	60 Nd Neodymium 144.242	61 Pm Promethium (145)	62 Sm Samarium 150.36	63 Eu Europium 151.964	64 Gd Gadolinium 157.25	65 Tb Terbium 158.92535	66 Dy Dysprosium 162.500	67 Ho Holmium 164.93032	68 Er Erbium 167.259	69 Tm Thulium 168.93421	70 Yb Ytterbium 173.054	71 Lu Lutetium 174.9668
89 Ac Actinium (227)	90 Th Thorium 232.03806	91 Pa Protactinium 231.03588	92 U Uranium 238.02891	93 Np Neptunium (237)	94 Pu Plutonium (244)	95 Am Americium (243)	96 Cm Curium (247)	97 Bk Berkelium (247)	98 Cf Californium (251)	99 Es Einsteinium (252)	100 Fm Fermium (257)	101 Md Mendelevium (258)	102 No Nobelium (259)	103 Lr Lawrencium (262)

Ptable.com

Periodic Table for Astronomers

H

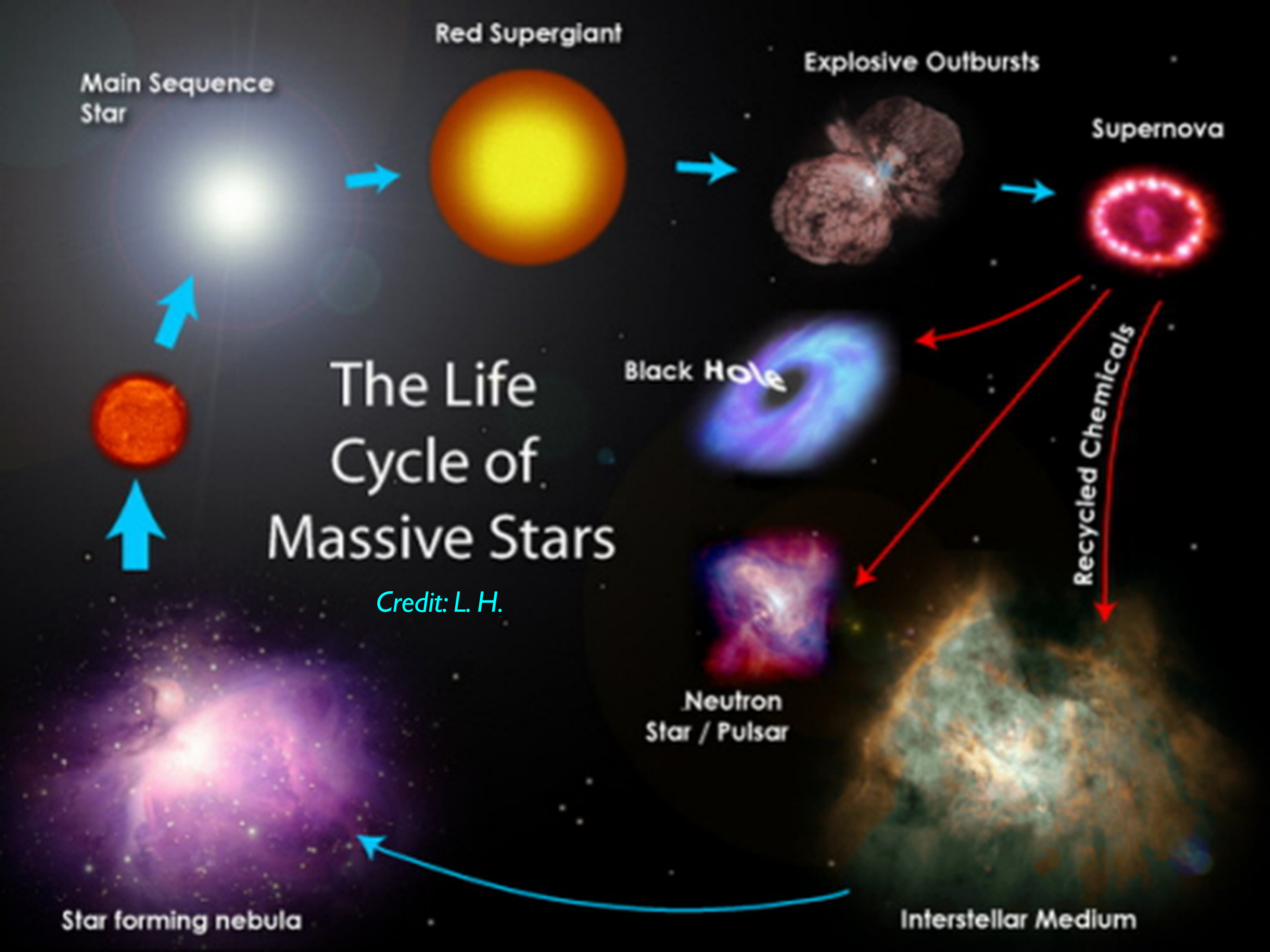
~70%

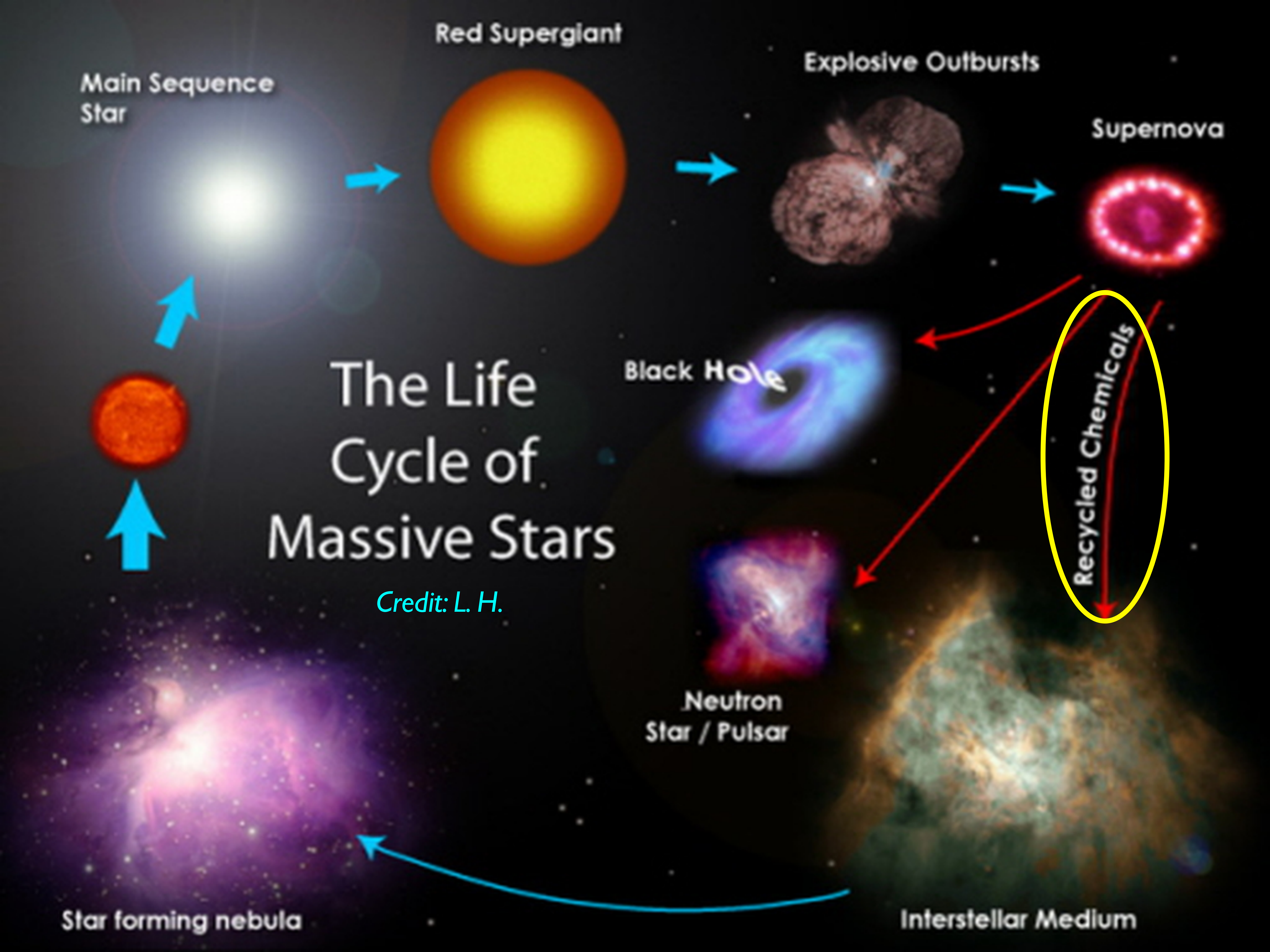
He

~28%

"Metals"

~2%


Main Sequence Star
Red Supergiant
Explosive Outbursts
Supernova
Black Hole
The Life Cycle of Massive Stars
Credit: L. H.
Recycled Chemicals
Neutron Star / Pulsar
Star forming nebula
Interstellar Medium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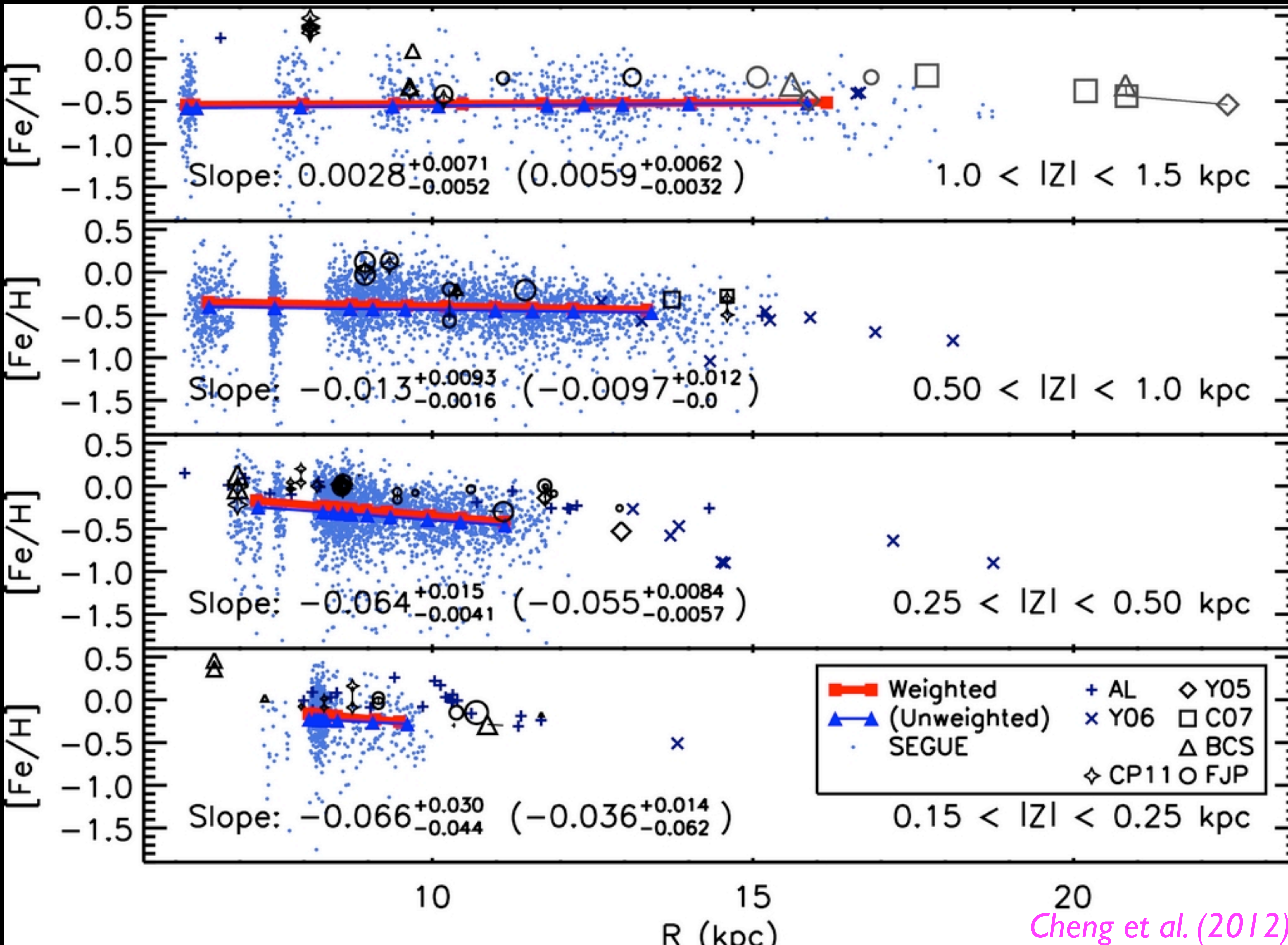
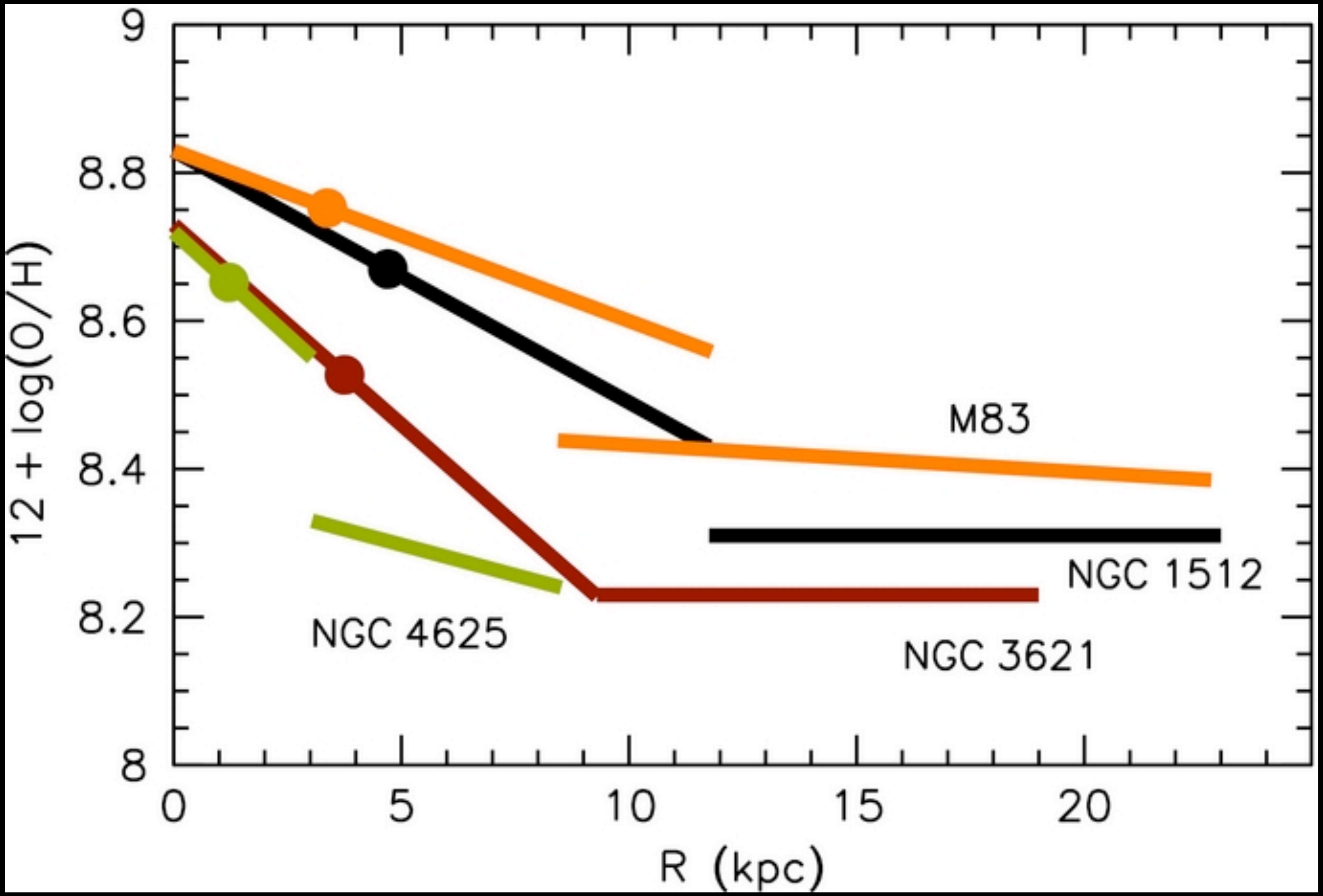
Radial Metallicity Gradient

The Milky Way



Cheng et al. (2012)

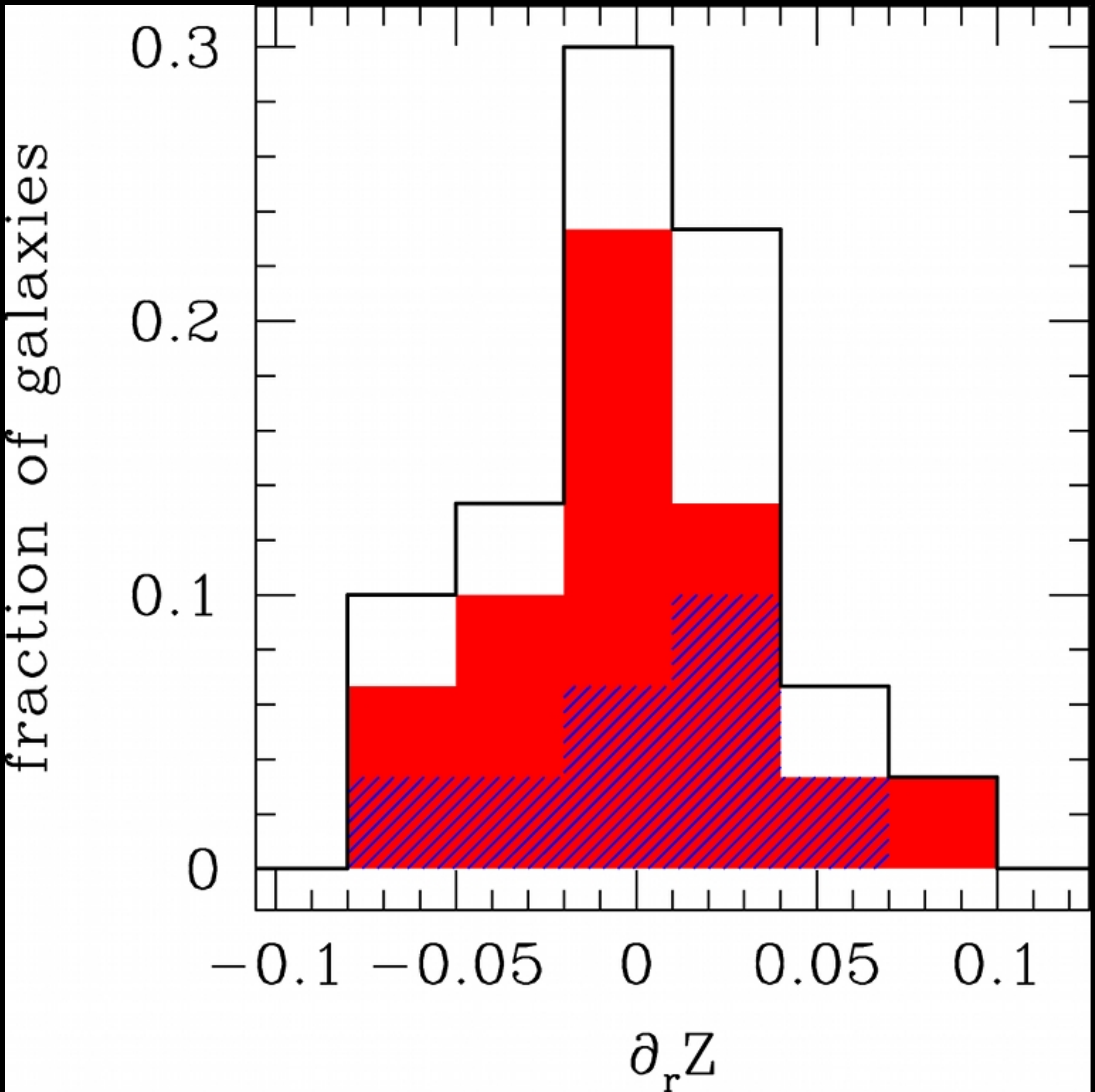
Radial Metallicity Gradient
Nearby Disk Galaxies



Bresolin, Kennicutt, & Ryan-Weber (2012)

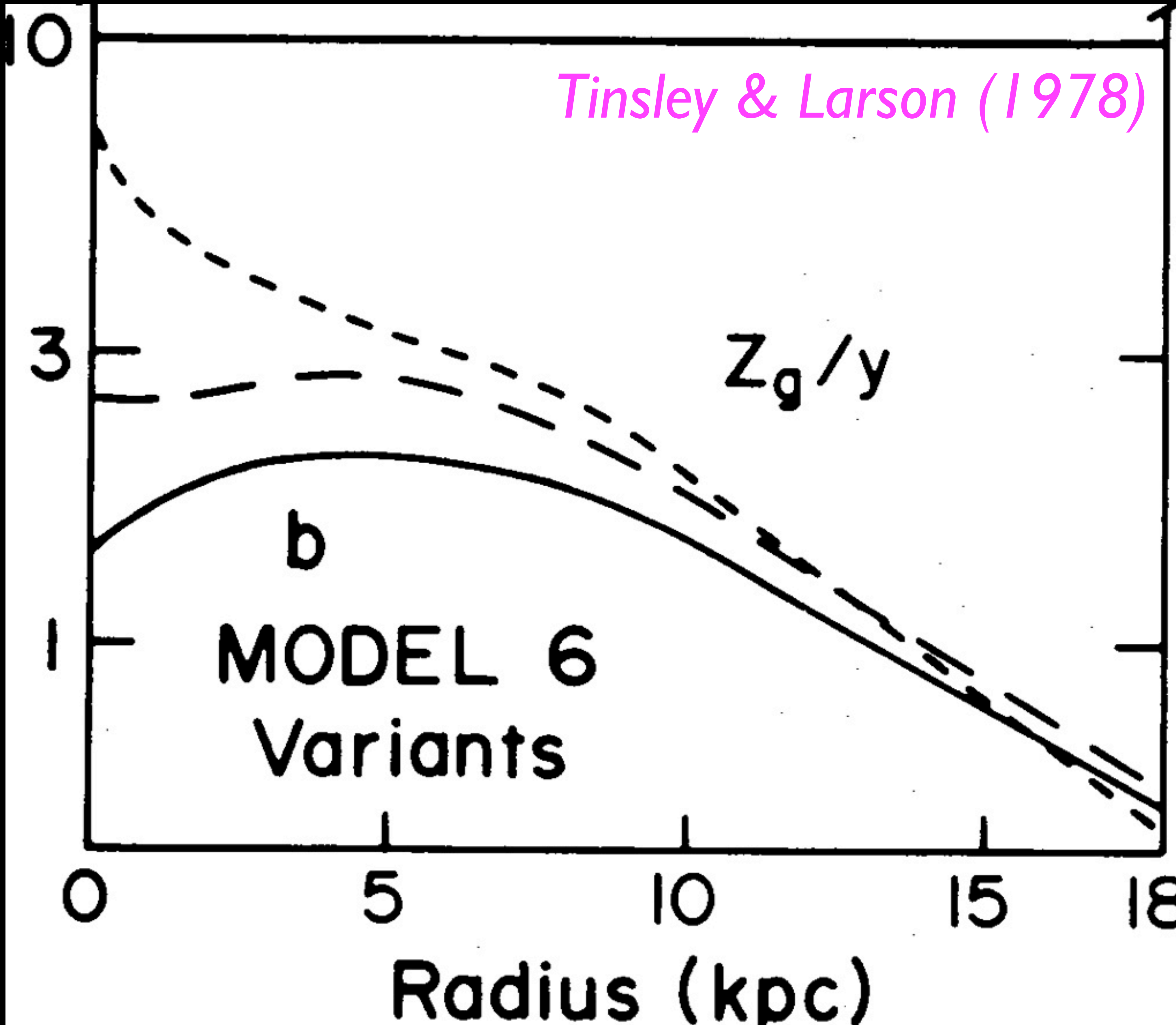
Radial Metallicity Gradient

26 MASSIV Galaxies at $z \sim 1.2$

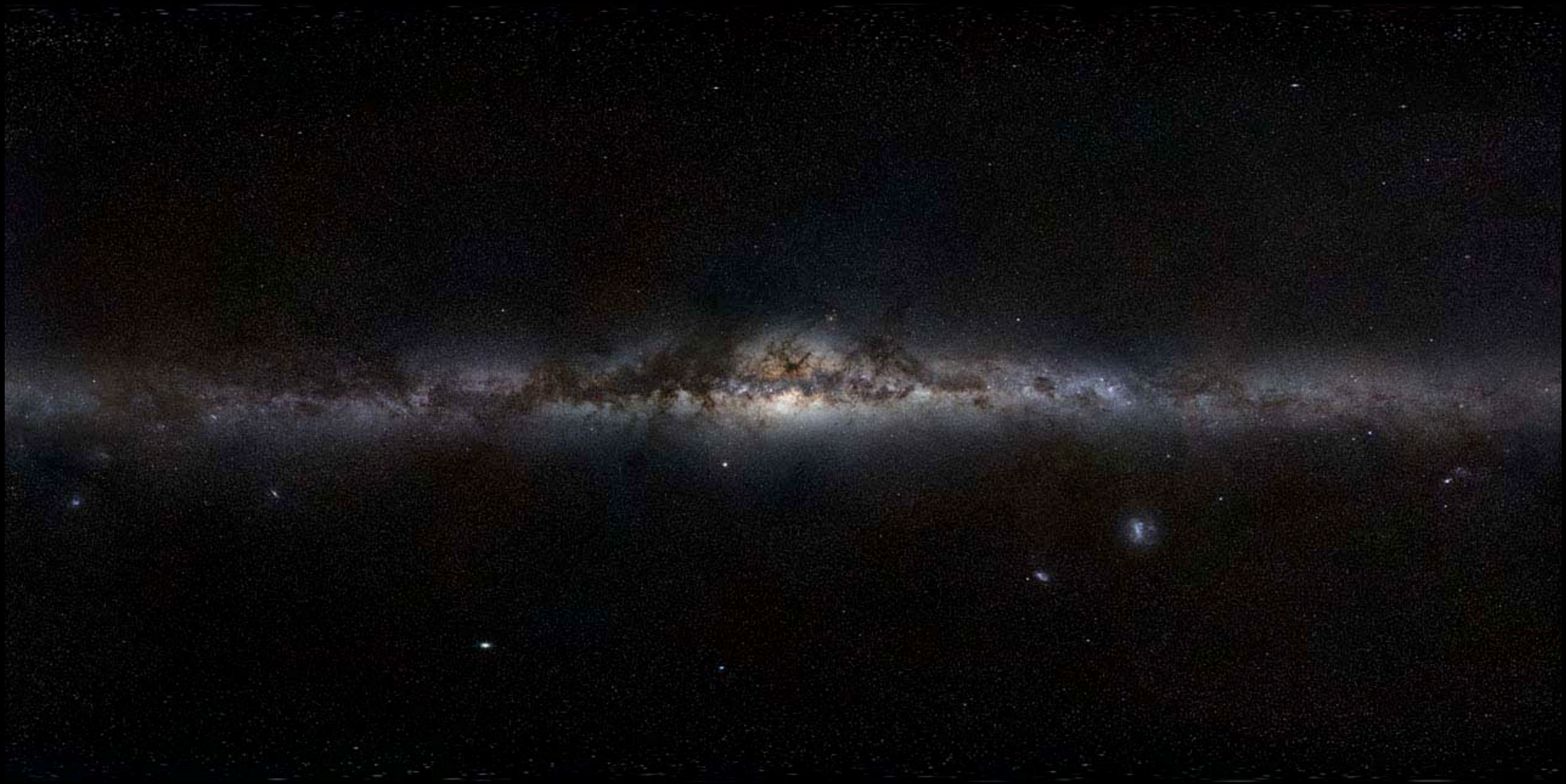


Queyrel et al. (2012)

Failure of Closed-system Models



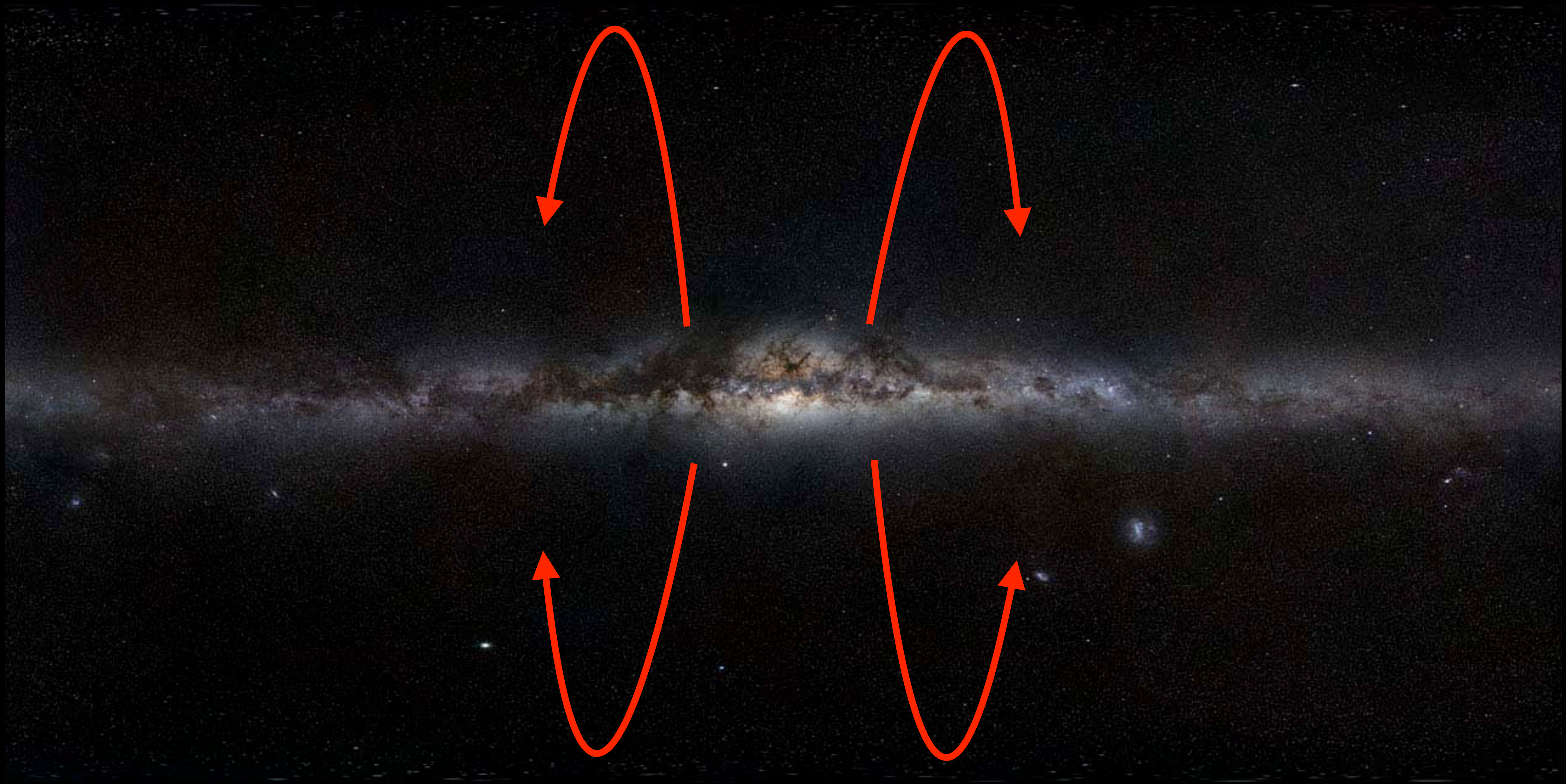
What flattens metallicity gradients?



Credit: S. Brunier

What flattens metallicity gradients?

Supernova-driven galactic fountains

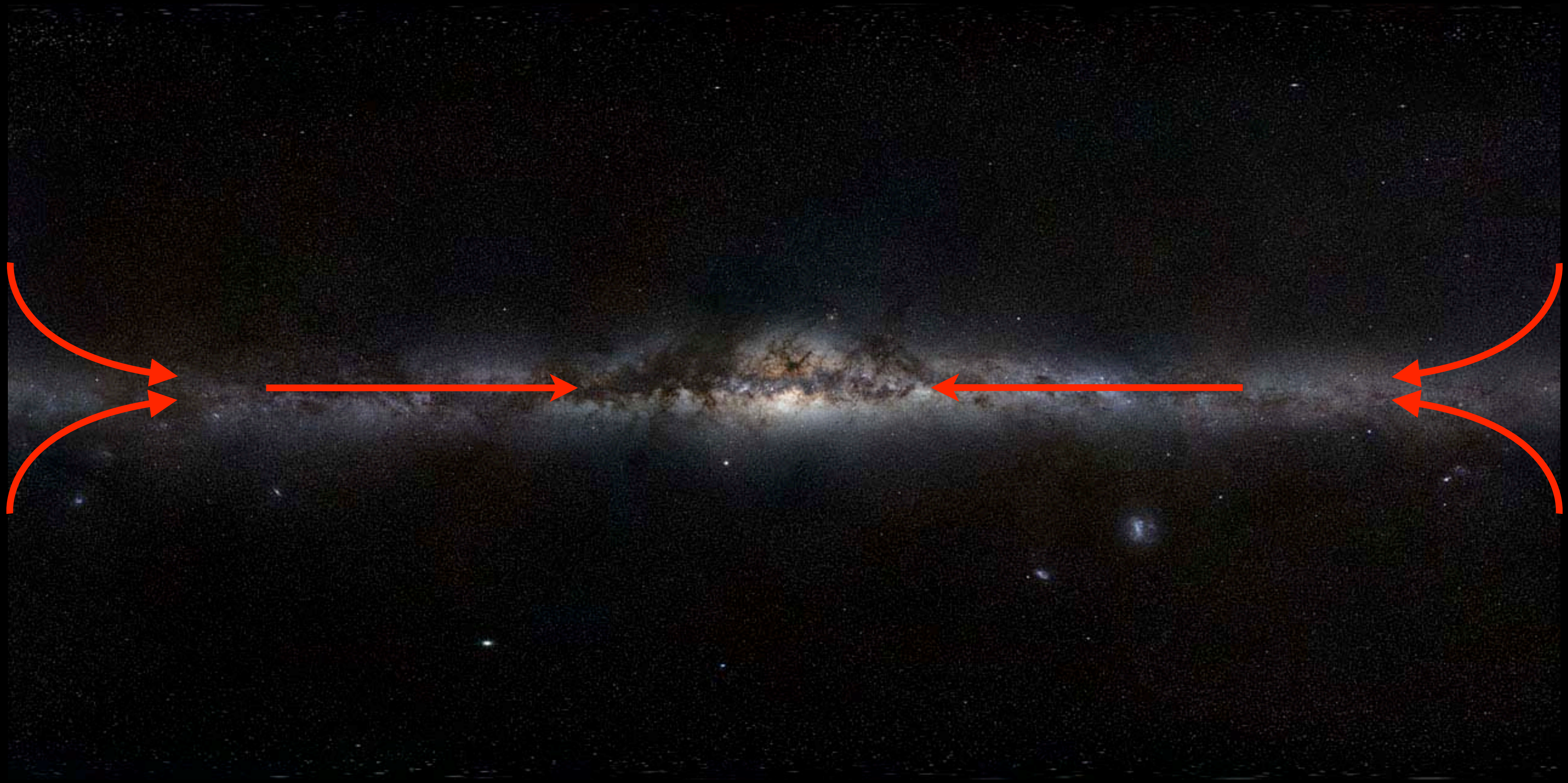


Credit: S. Brunier

e.g., Spitoni, Recchi, & Matteucci (2008); Spitoni et al. (2009)

What flattens metallicity gradients?

Radial inflows within the disk

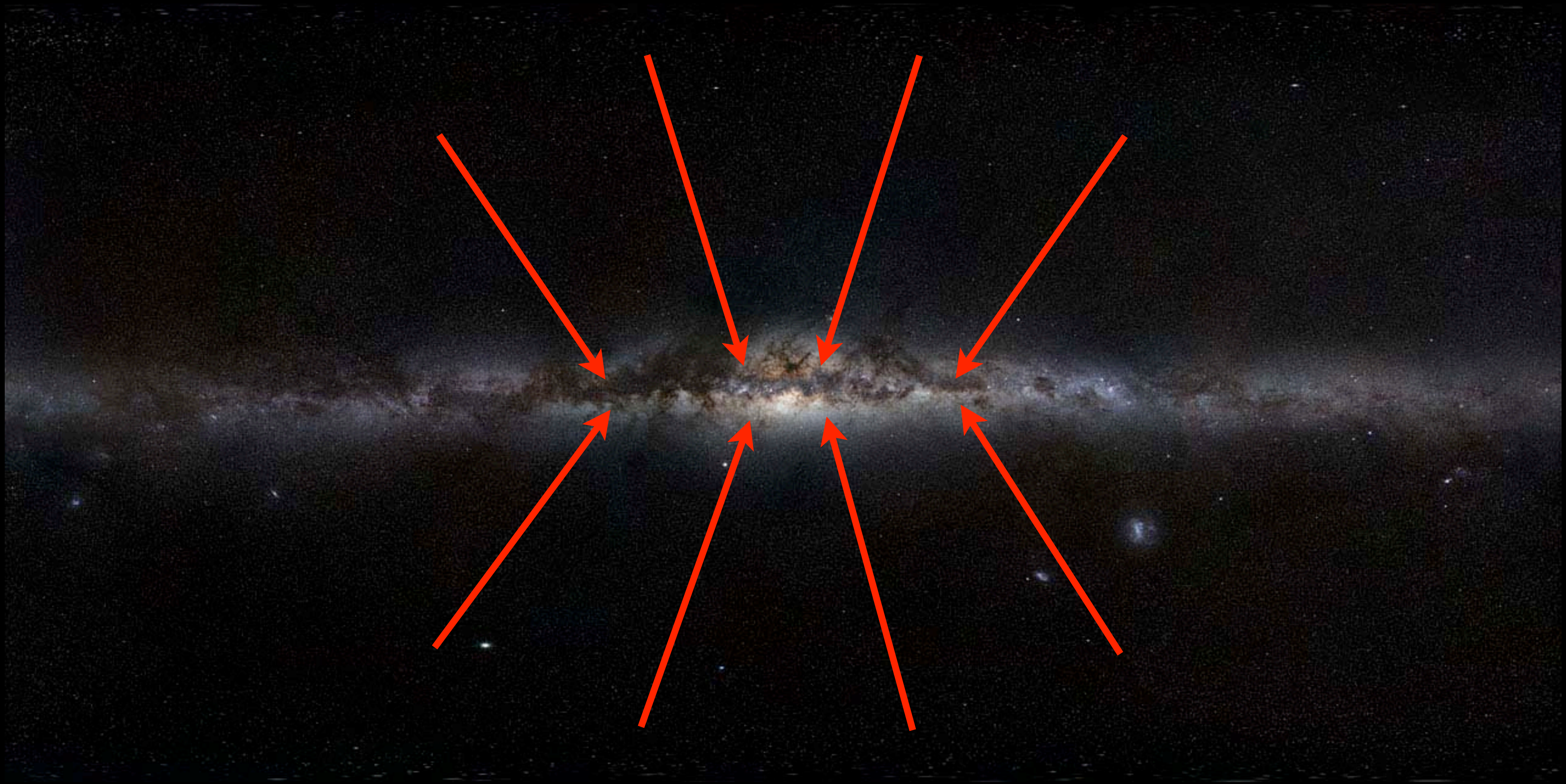


Credit: S. Brunier

Mayor & Vigroux (1981); Lacey & Fall (1985); Pitts & Tayler (1989)
Götz & Köppen (1992); Portinari & Chiosi (2000)
Spitoni & Matteucci (2011); Bilitewski & Schönrich (2012)

What flattens metallicity gradients?

Accretion/infall from halo/circumgalactic medium

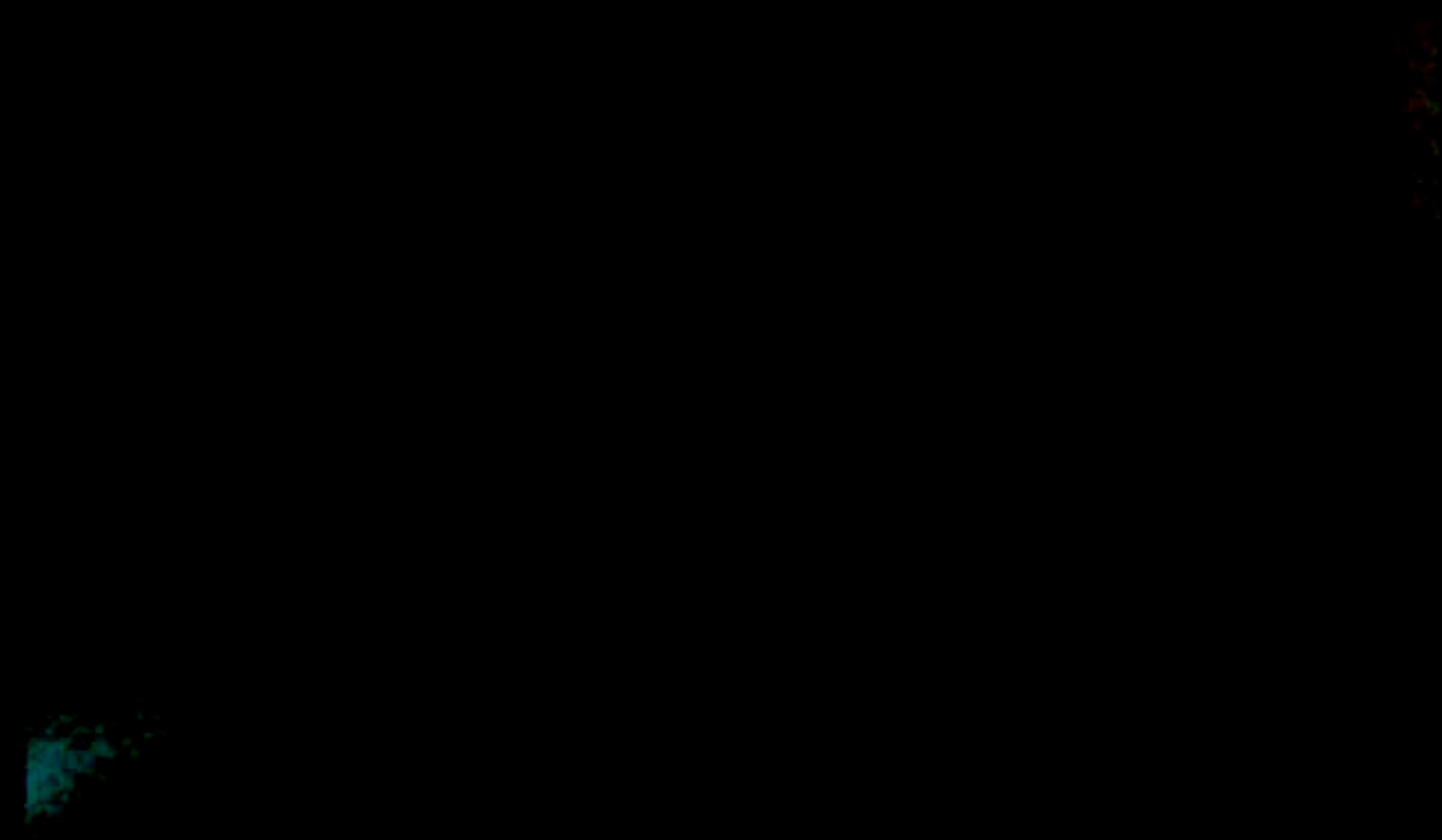


Credit: S. Brunier

Tinsley & Larson (1978); Chiosi (1980); Matteucci & François (1989)
Chiappini et al. (1997, 2001); Prantzos & Boissier (2000)

What flattens metallicity gradients?

Merger/interaction history

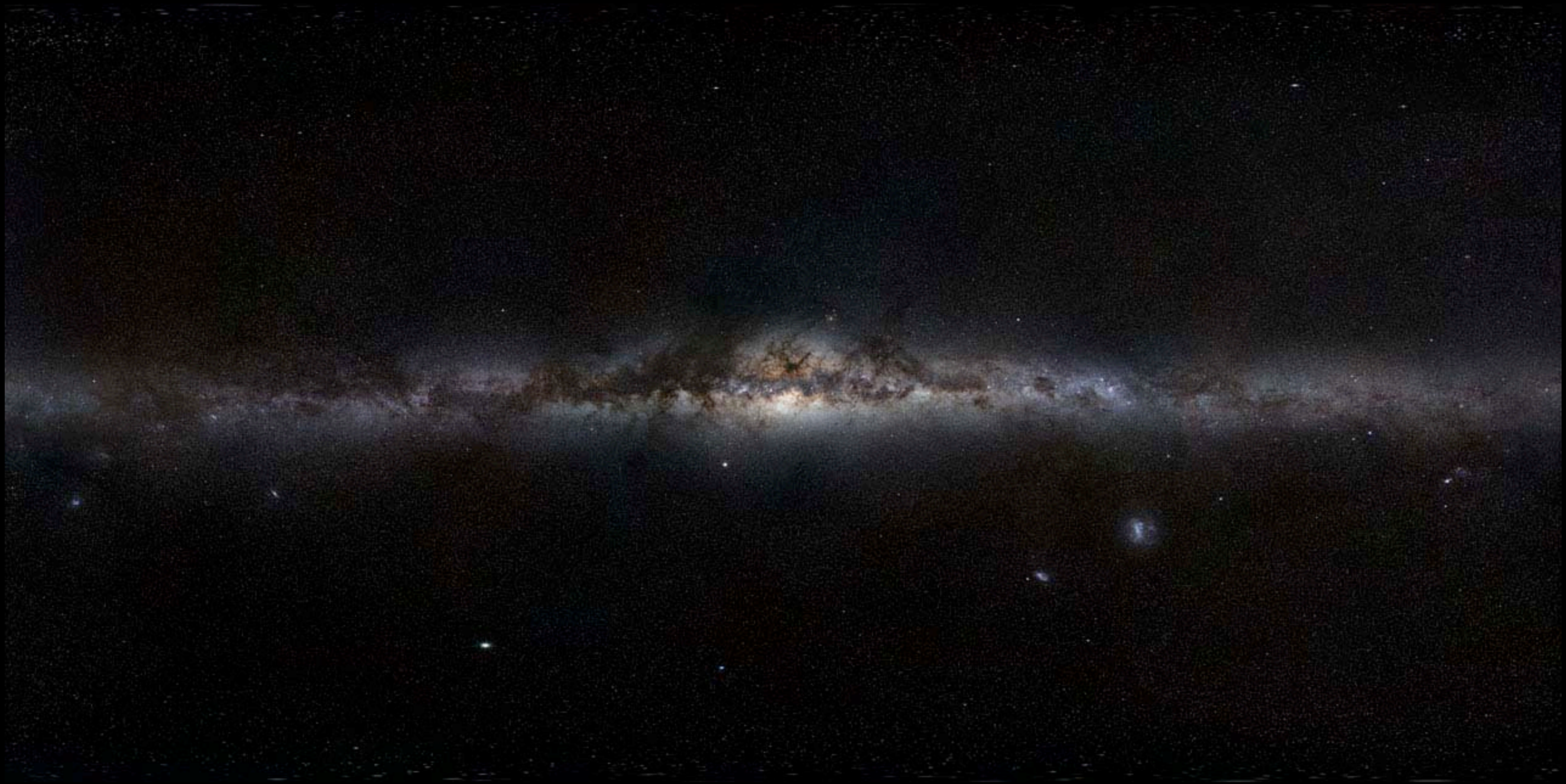


Credit: J. E. Barnes

Perez et al. (2006, 2011); Kewley et al. (2010); Rupke, Kewley, & Barnes (2010); Rupke, Kewley, & Chien (2010); Torrey et al., in prep.

What flattens metallicity gradients?

Stellar radial migration

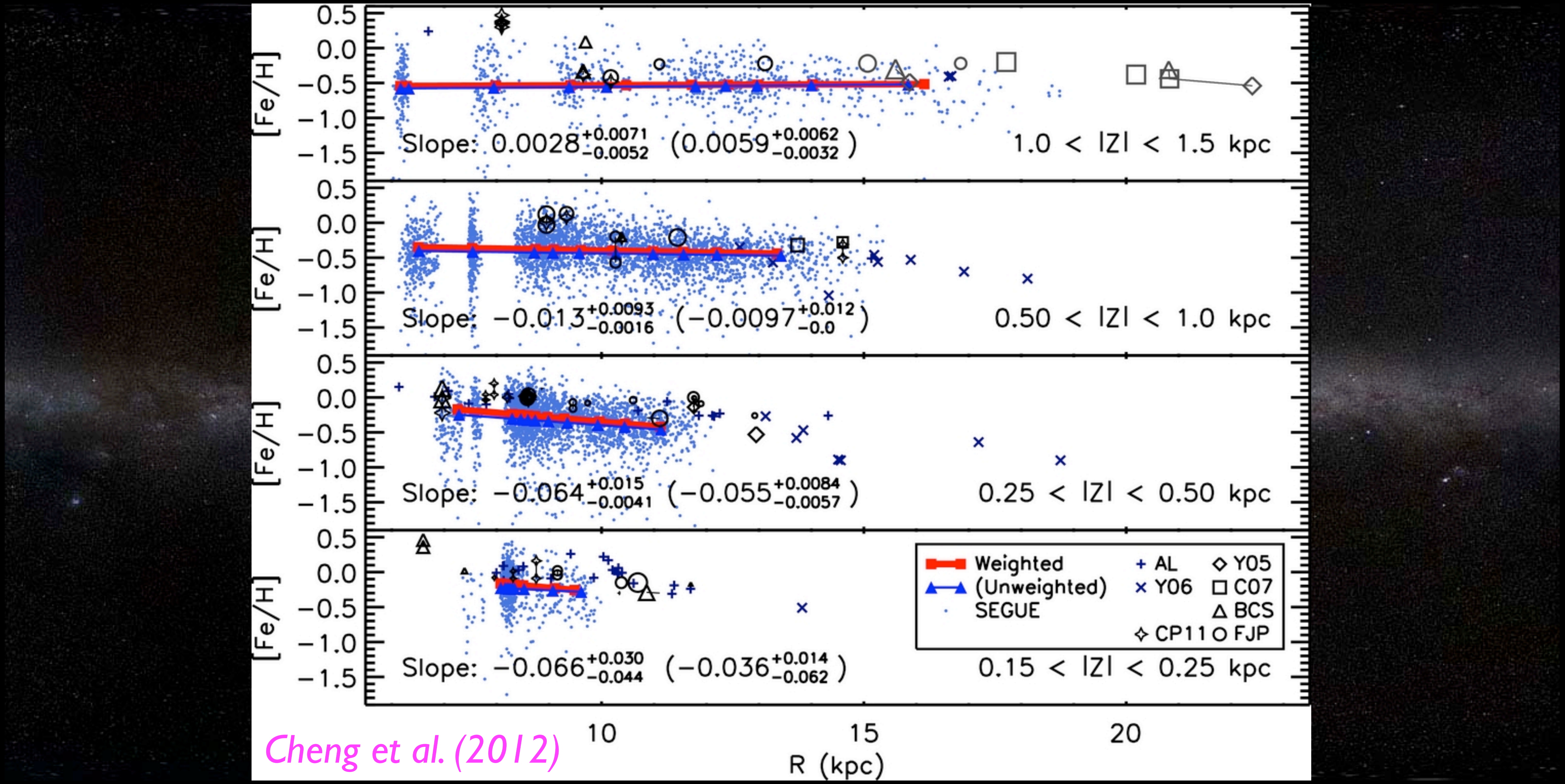


Credit: S. Brunier

Roškar et al. (2008a,b); Schönrich & Binney (2009)

What flattens metallicity gradients?

Stellar radial migration



Roškar et al. (2008a,b); Schönrich & Binney (2009)

Turbulent Diffusion (?)

- Shakura & Sunyaev (1973) α-prescription
  - Kinematic viscosity: $\nu = \alpha c_s H, \;\; 0 < \alpha < 1$
- Diffusion timescale: $\tau \sim L^2 / \nu$
  - Typical galactic disks: $c_s \sim 7$ km/s, $H \sim 200$ pc
  - $\tau \sim (10 \text{ Gyr}) (\alpha / 10^{-2})^{-1}$ for $L \sim 10$ kpc

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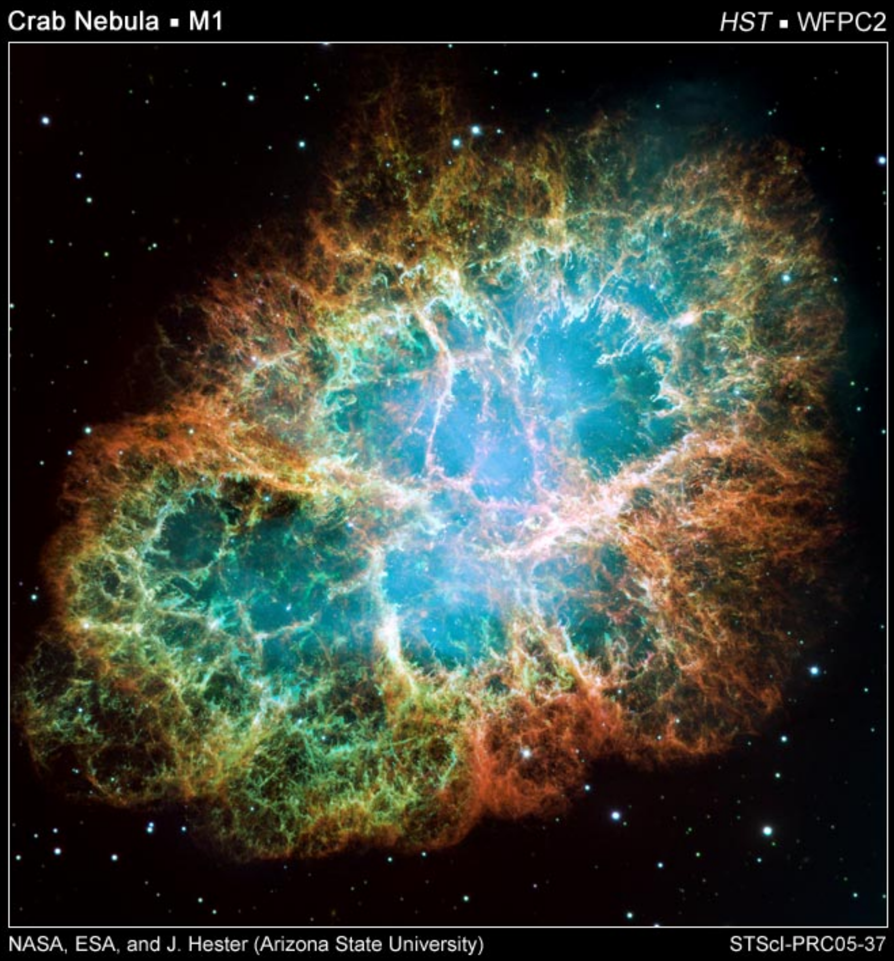
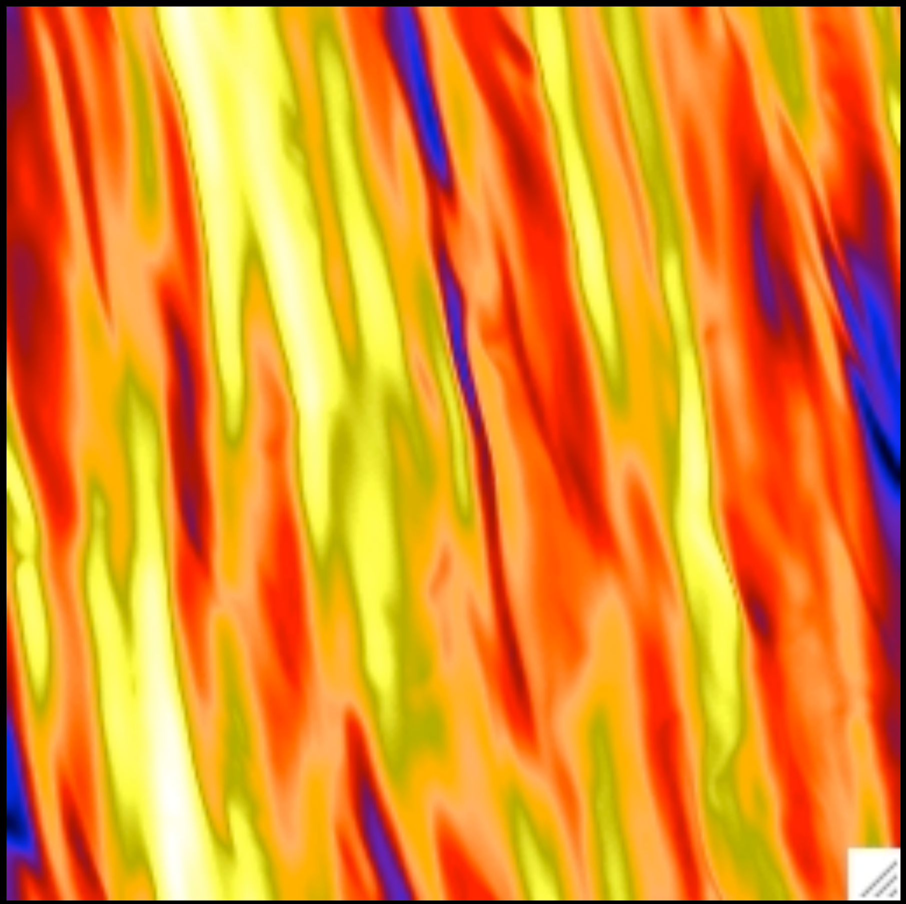
- *Is that so?*

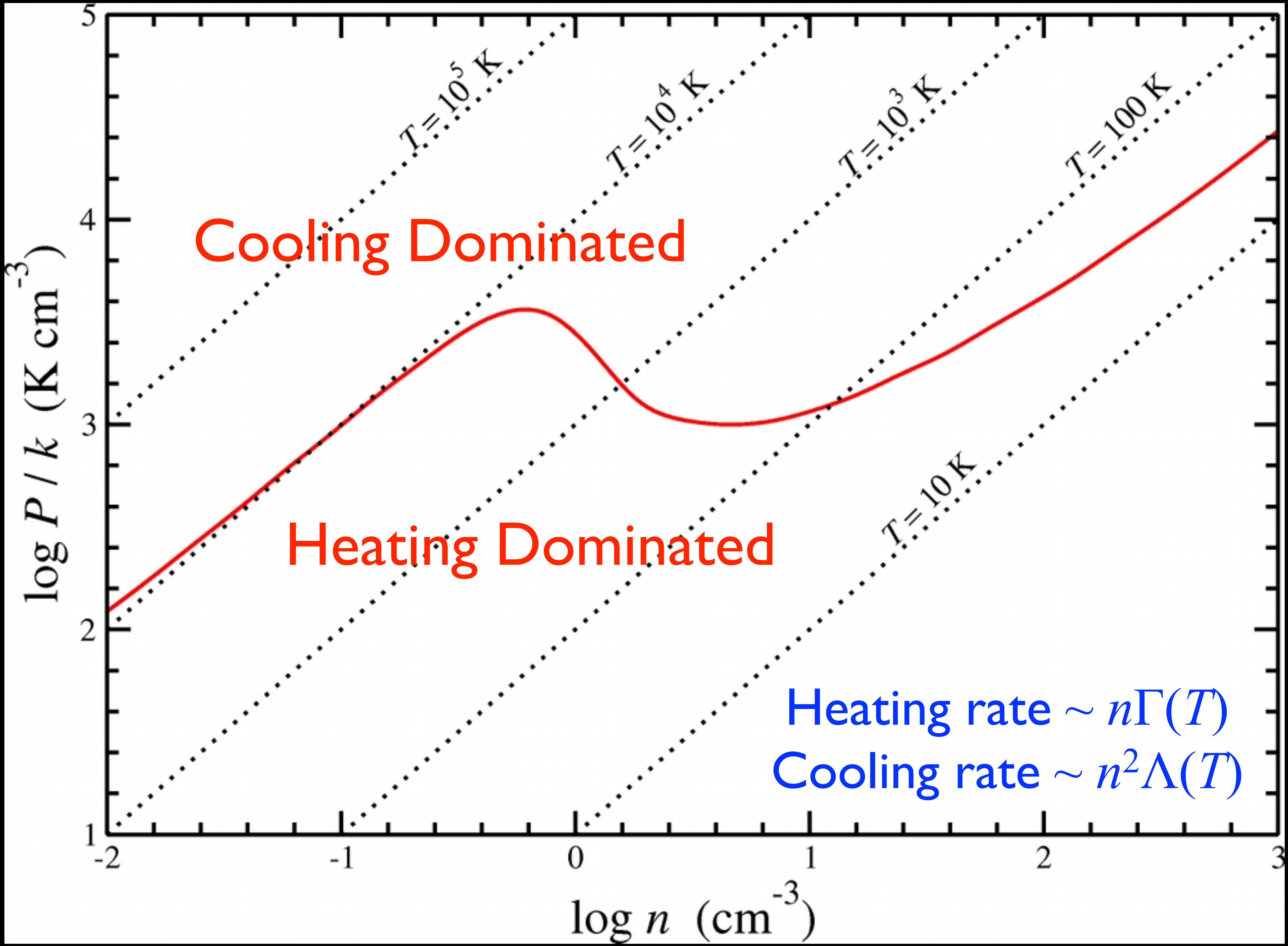
Driving Turbulence in the Interstellar Medium

- Supernova explosions
  - Rayleigh-Taylor instability
- Gravitational instability
- Magneto-rotational instability
- *Thermal instability*





Two-phase Model for the ISM



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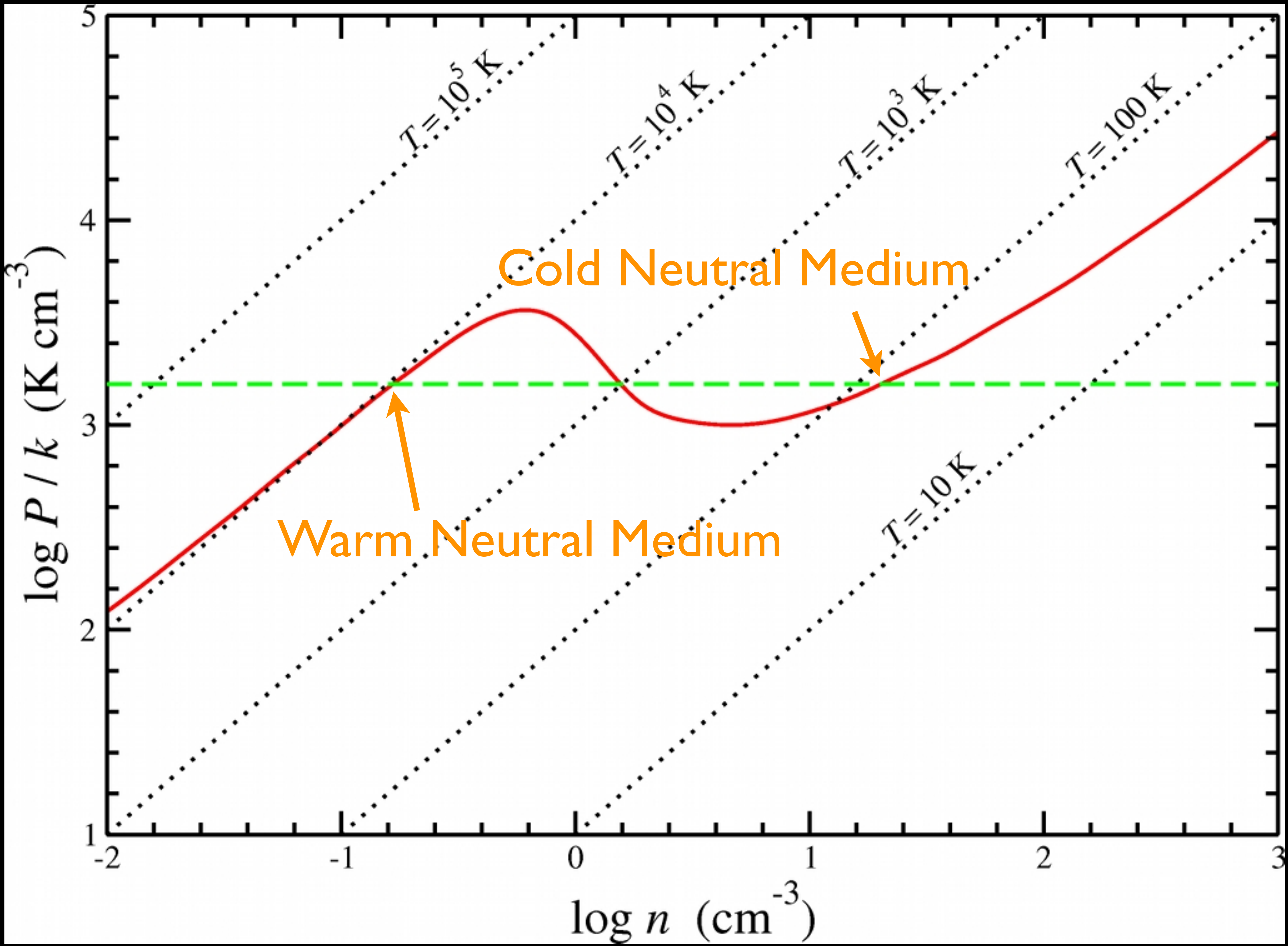

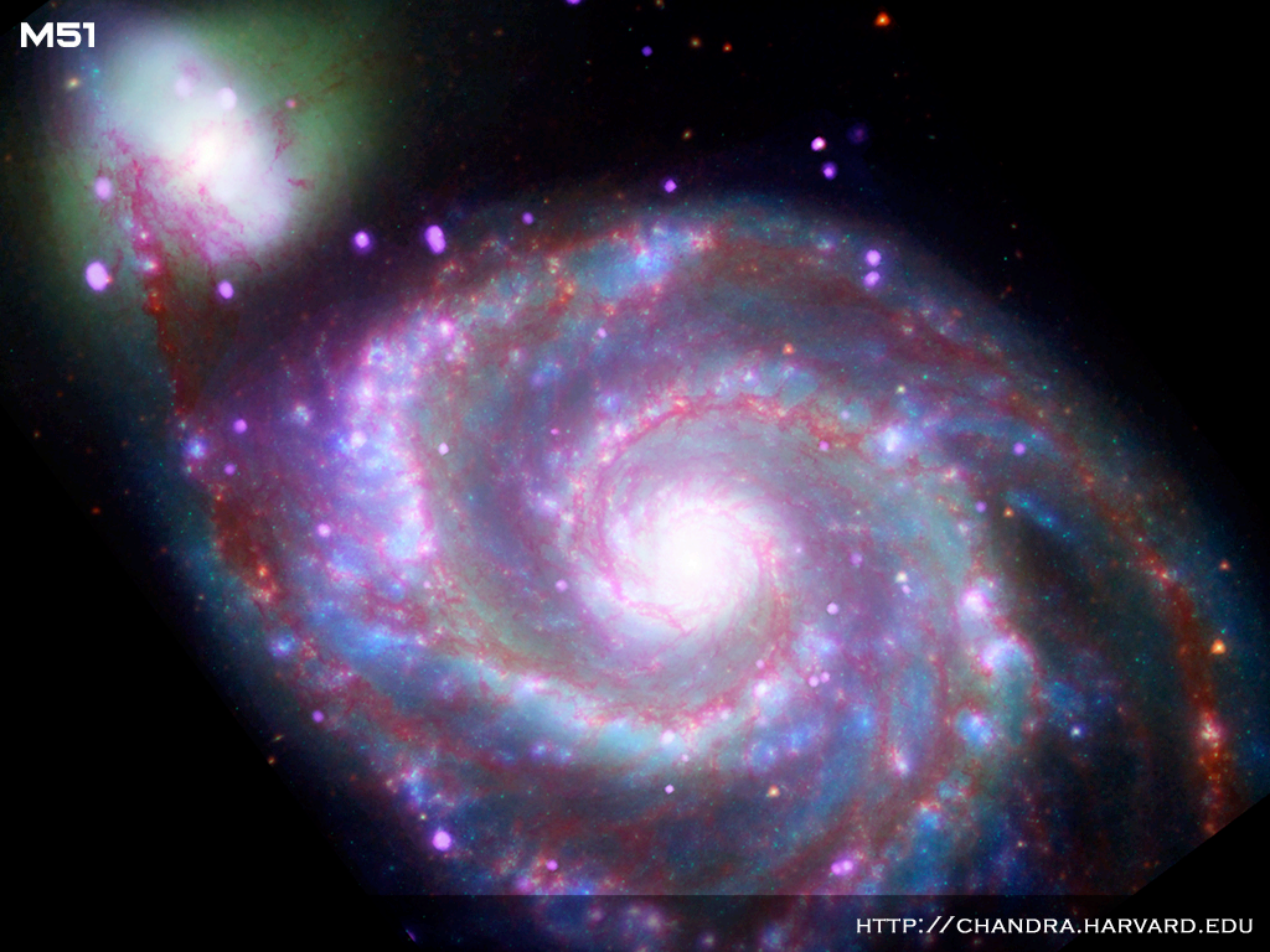
M51
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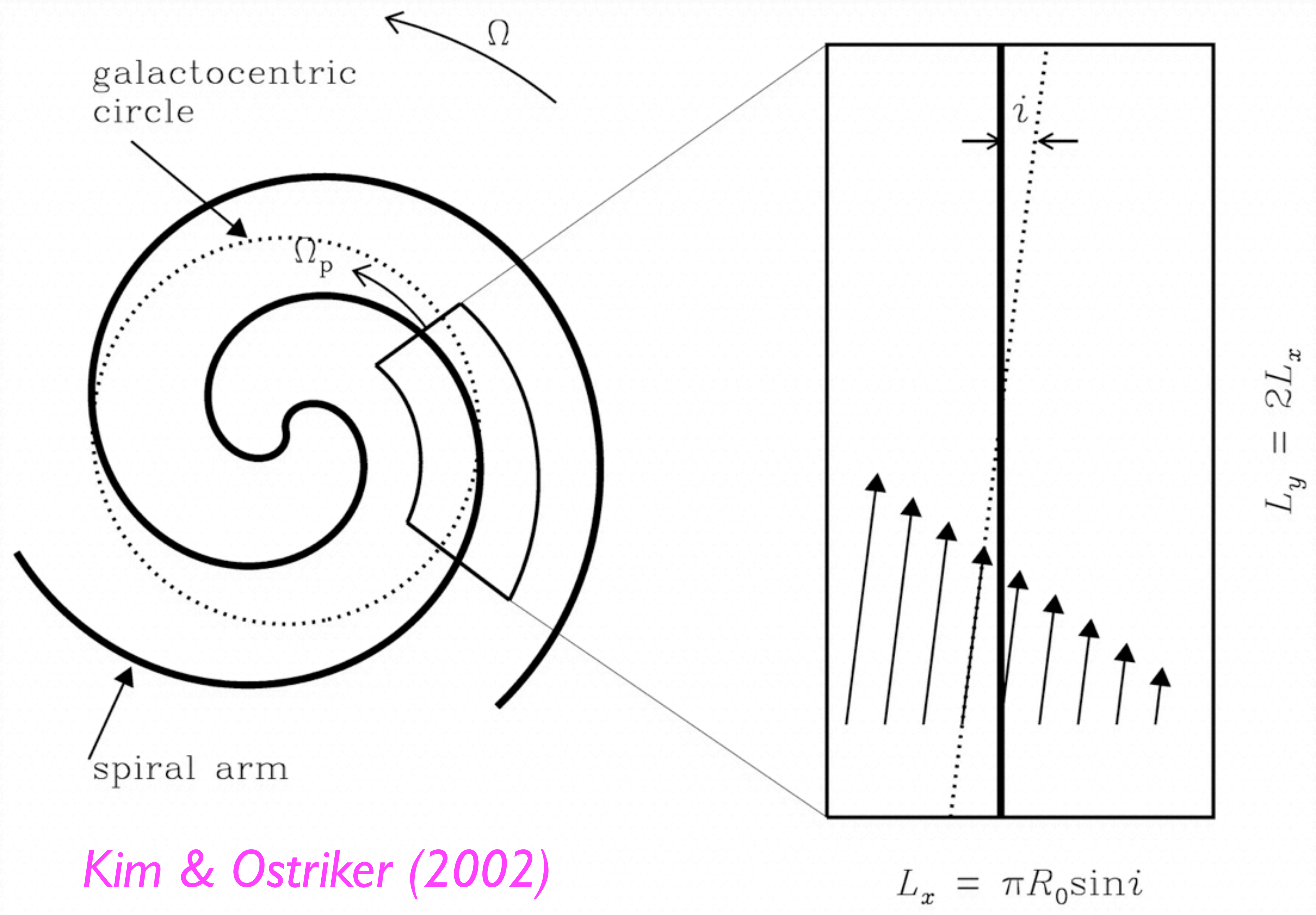
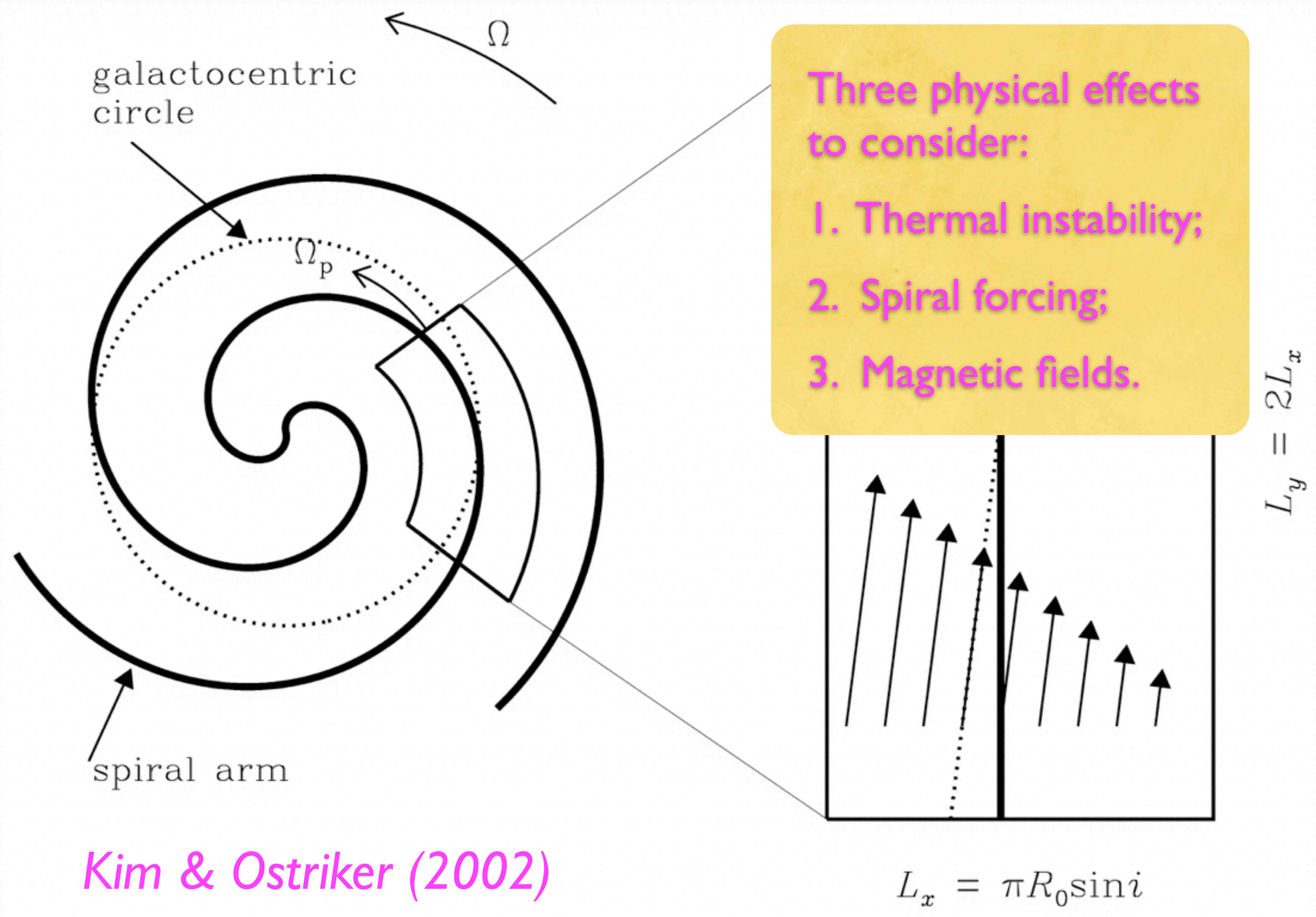
Local Shearing Sheet for a Thin Gas Disk



Kim & Ostriker (2002)

Local Shearing Sheet for a Thin Gas Disk



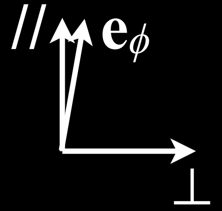
Three physical effects to consider:

1. Thermal instability;
2. Spiral forcing;
3. Magnetic fields.

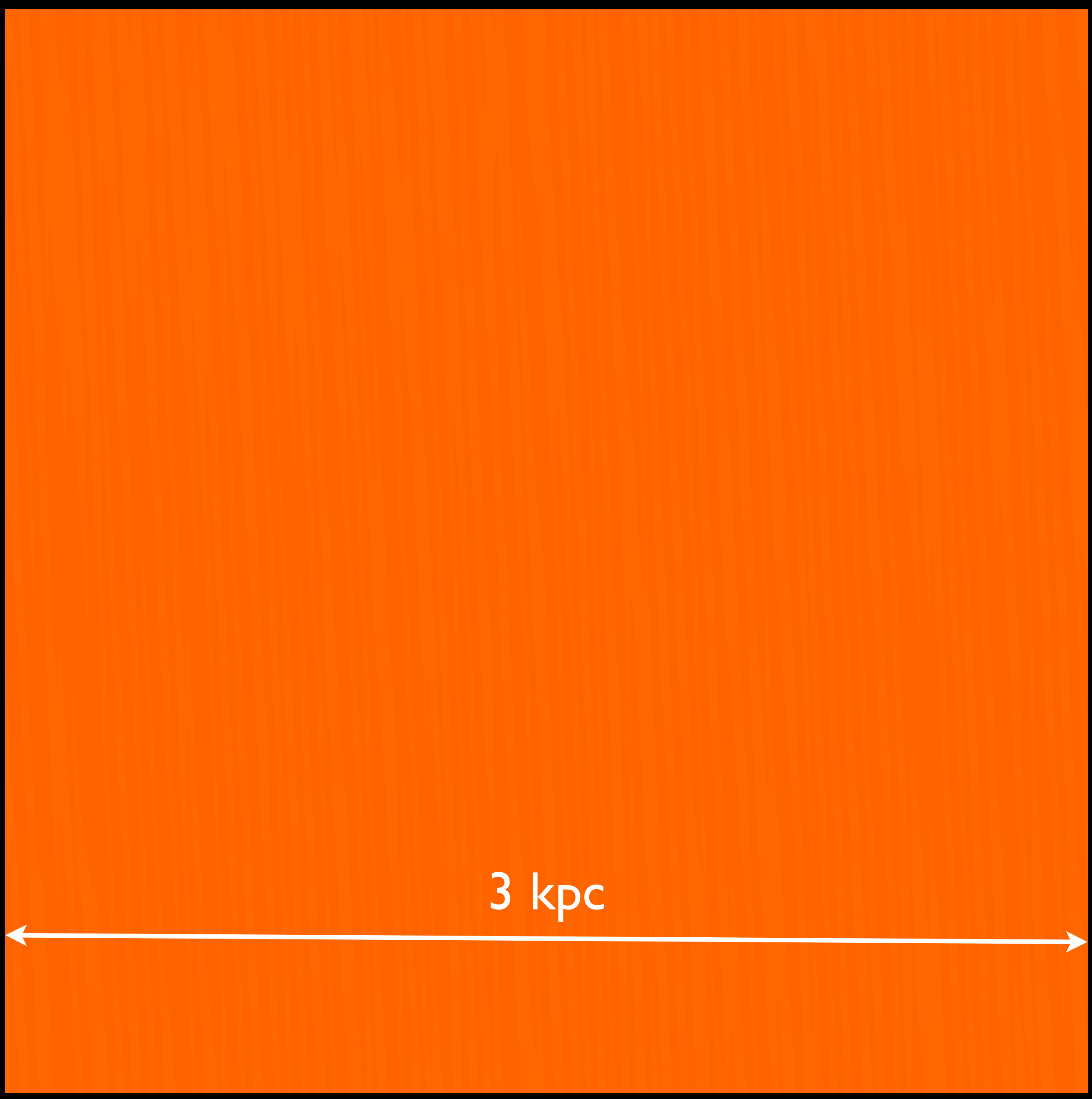
Kim & Ostriker (2002)

Turbulent Steady State

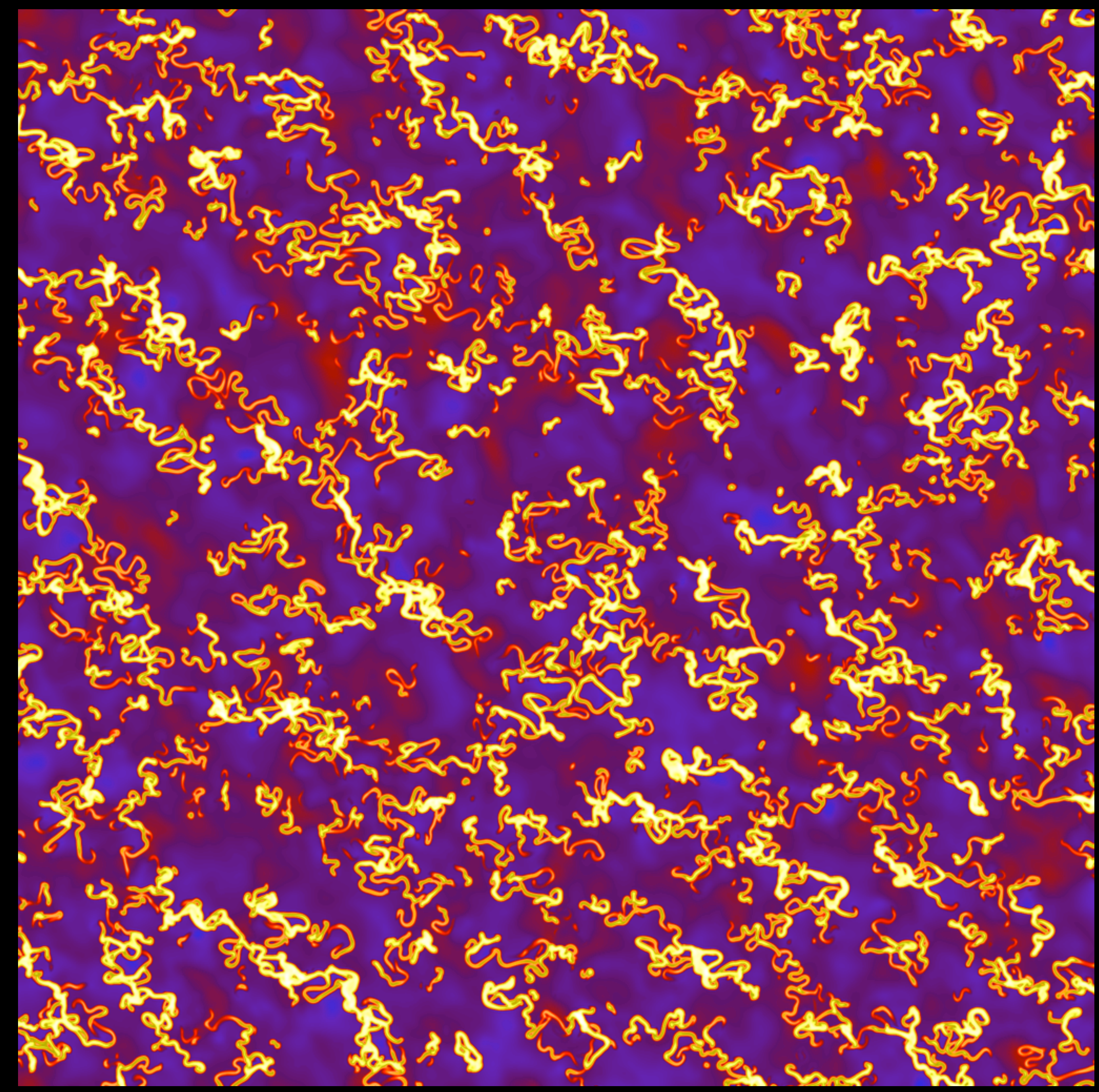
~~Spiral Forcing~~ ~~Magnetic Fields~~



Surface Density



Isothermal

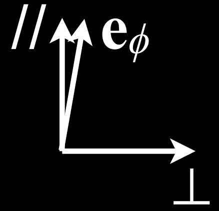


Thermally Unstable

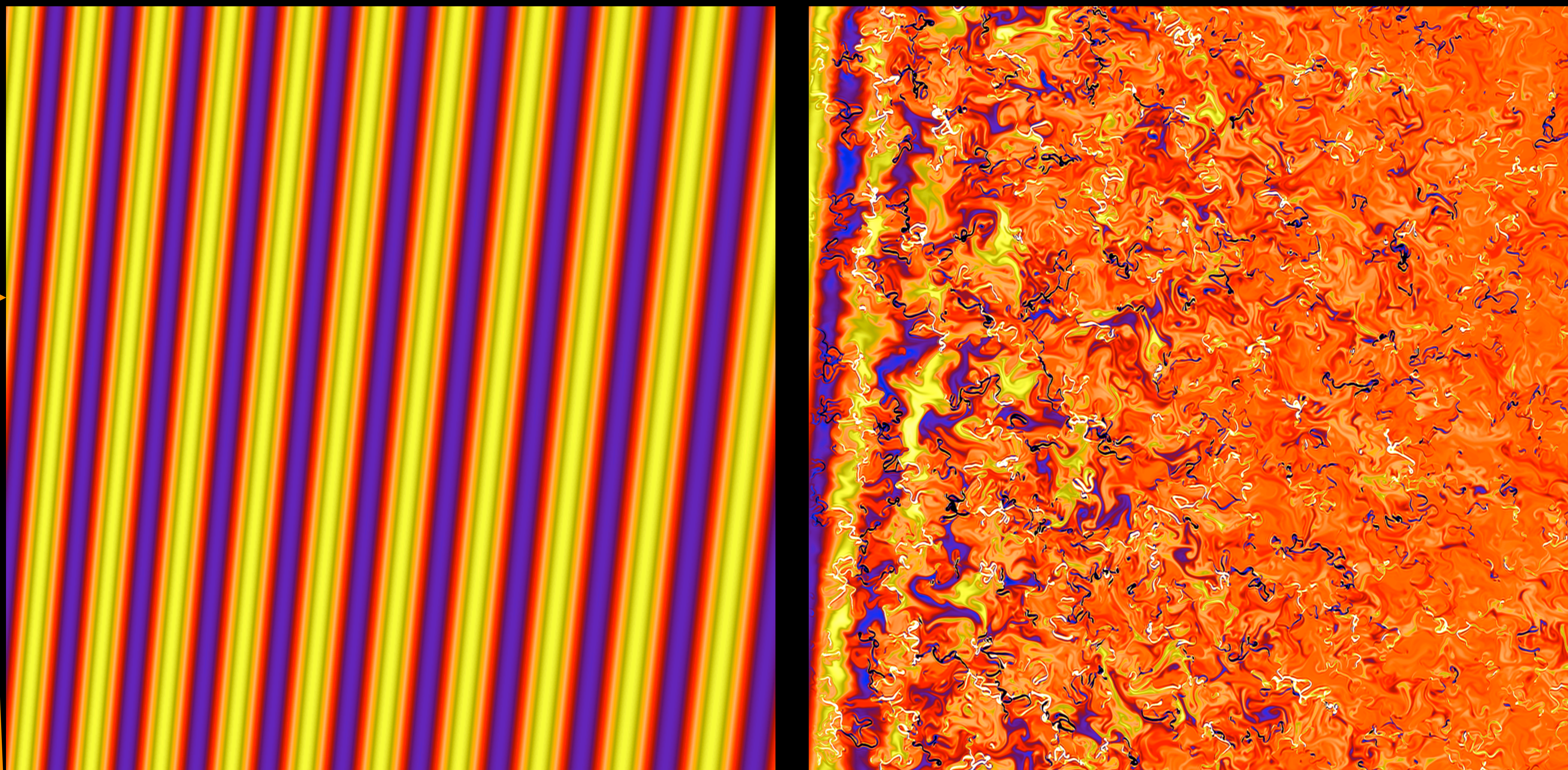
Yang & Krumholz (2012)

Turbulent Steady State

~~Spiral Forcing~~ ~~Magnetic Fields~~



Metal Tracer Field



Isothermal

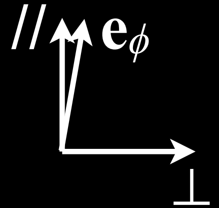
Thermally Unstable

Metal Injection Layer

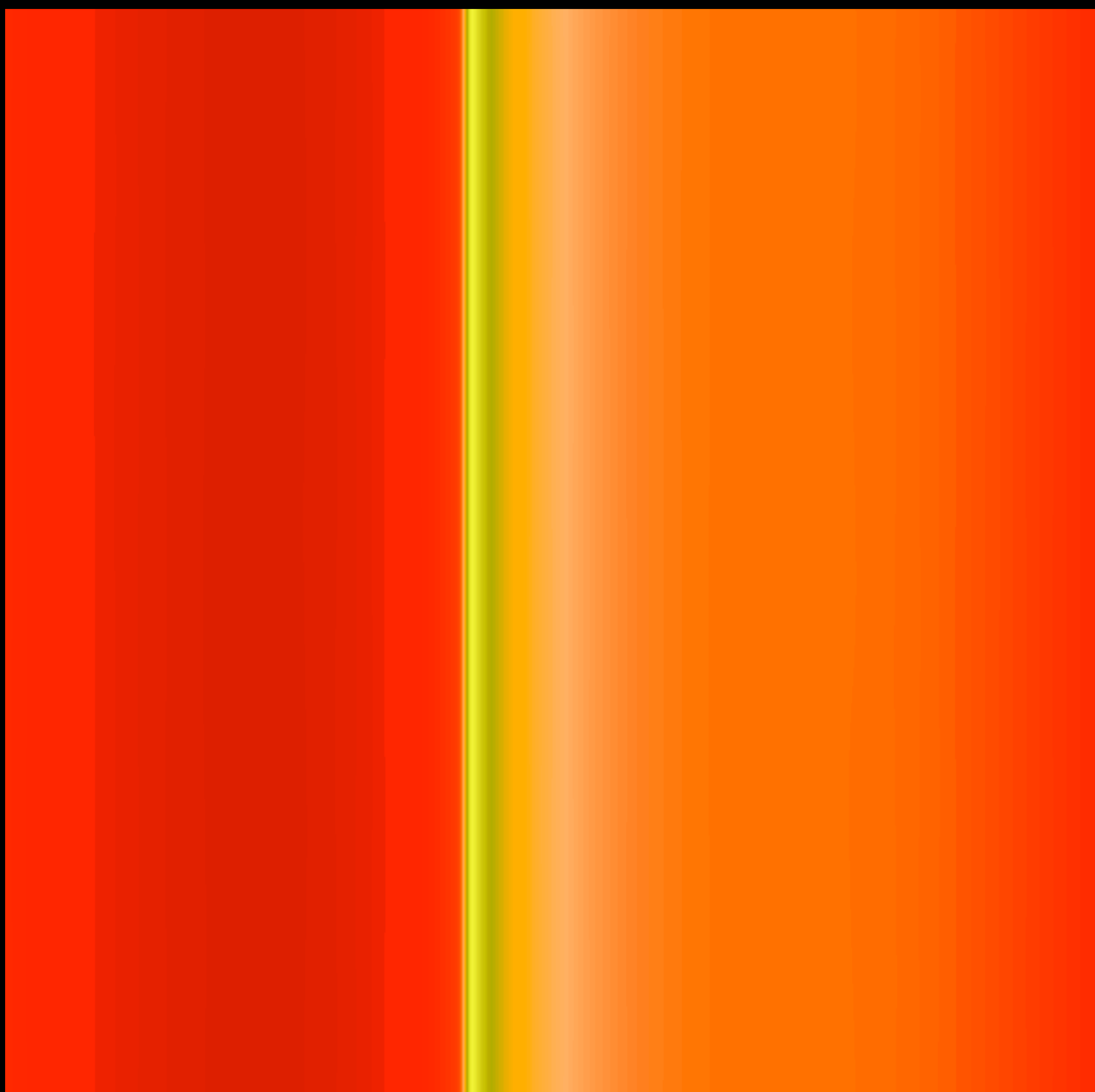
Yang & Krumholz (2012)

Turbulent Steady State

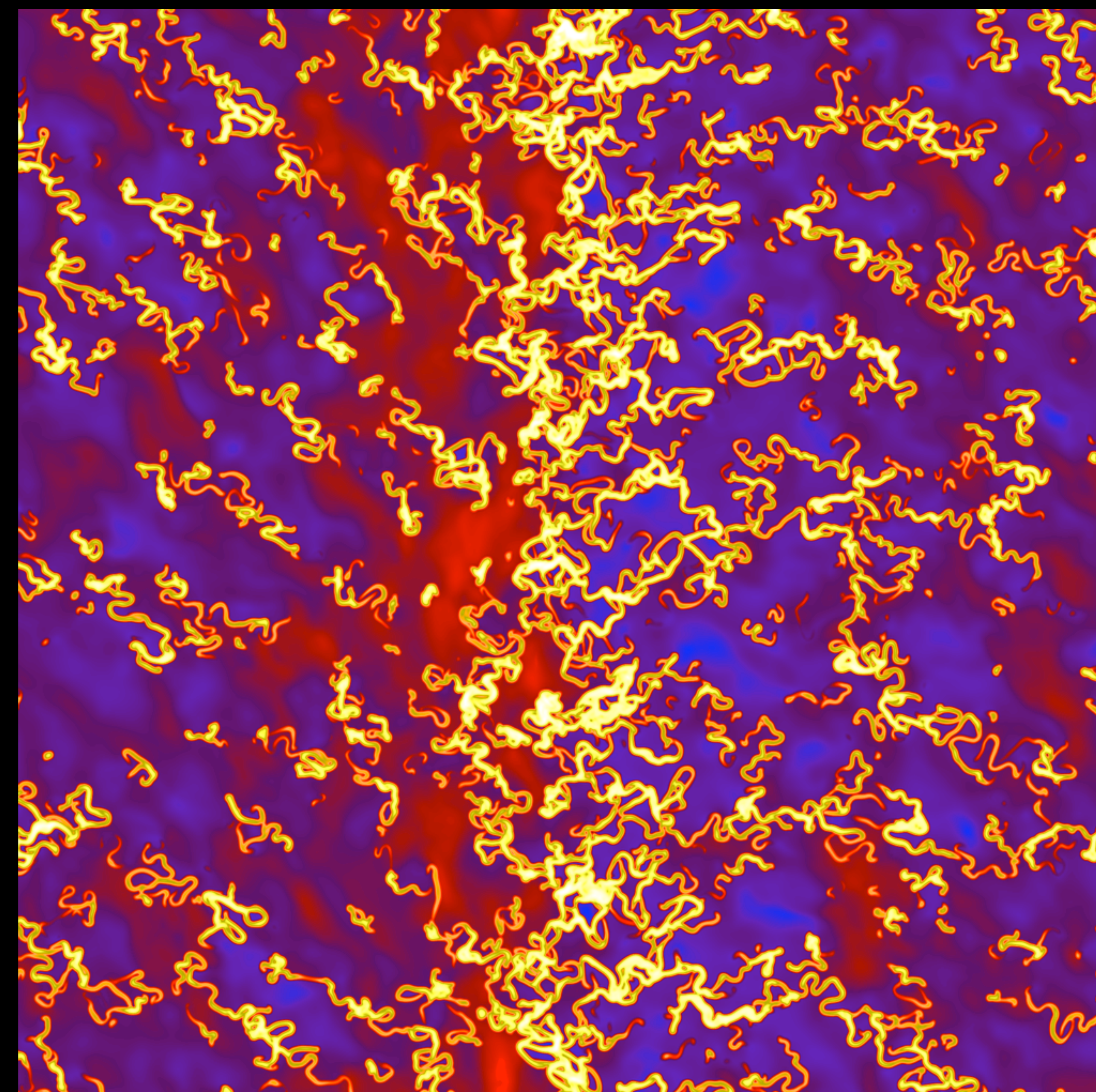
Spiral Forcing ~~Magnetic Fields~~



Surface Density



Isothermal



Thermally Unstable

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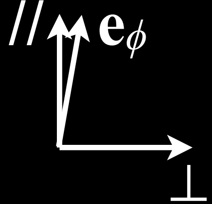
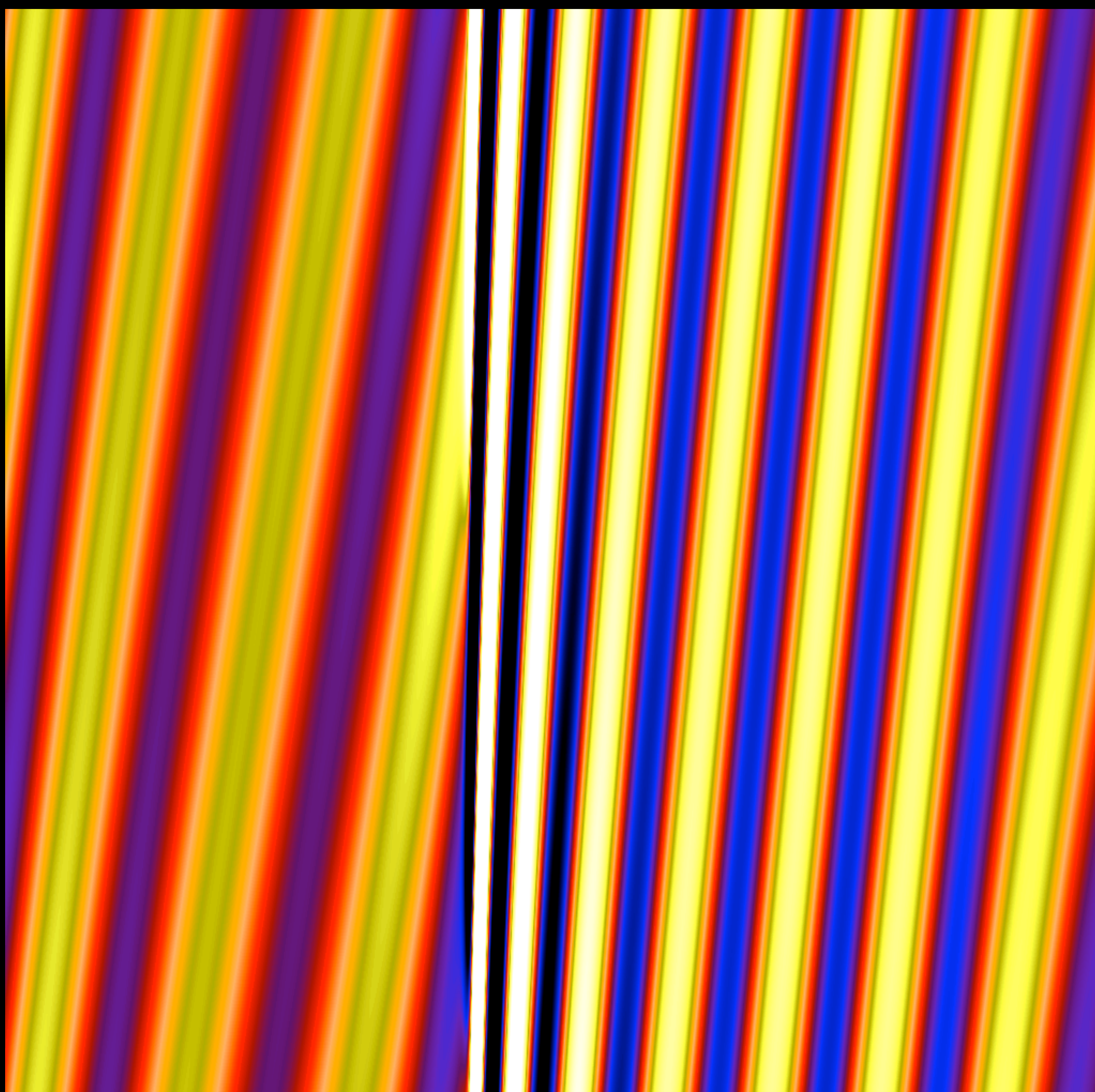
Turbulent Steady State

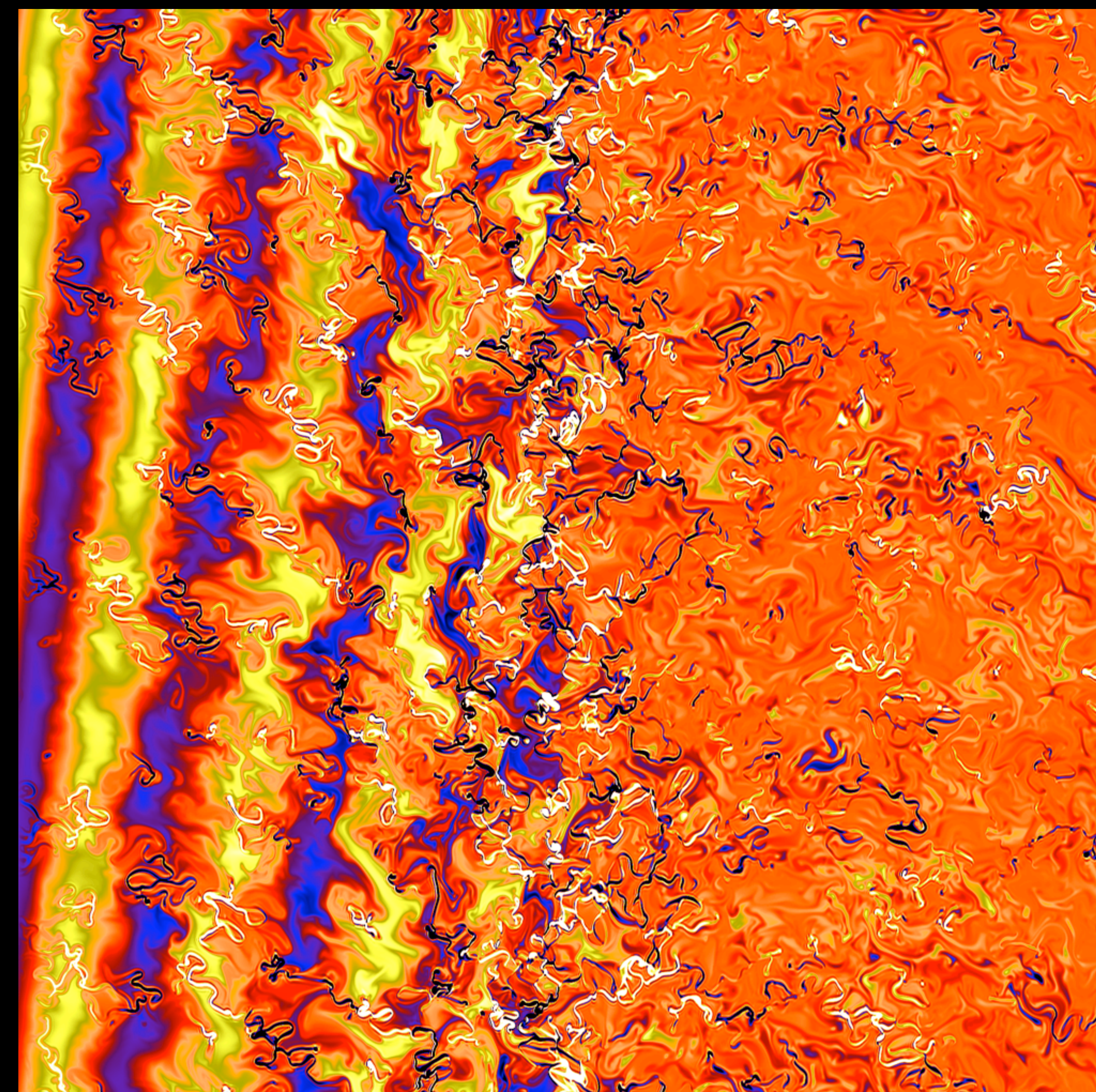
Spiral Forcing ~~Magnetic Fields~~



Metal Tracer Field



Isothermal

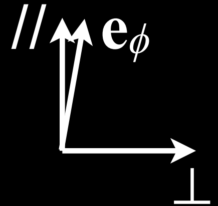


Thermally Unstable

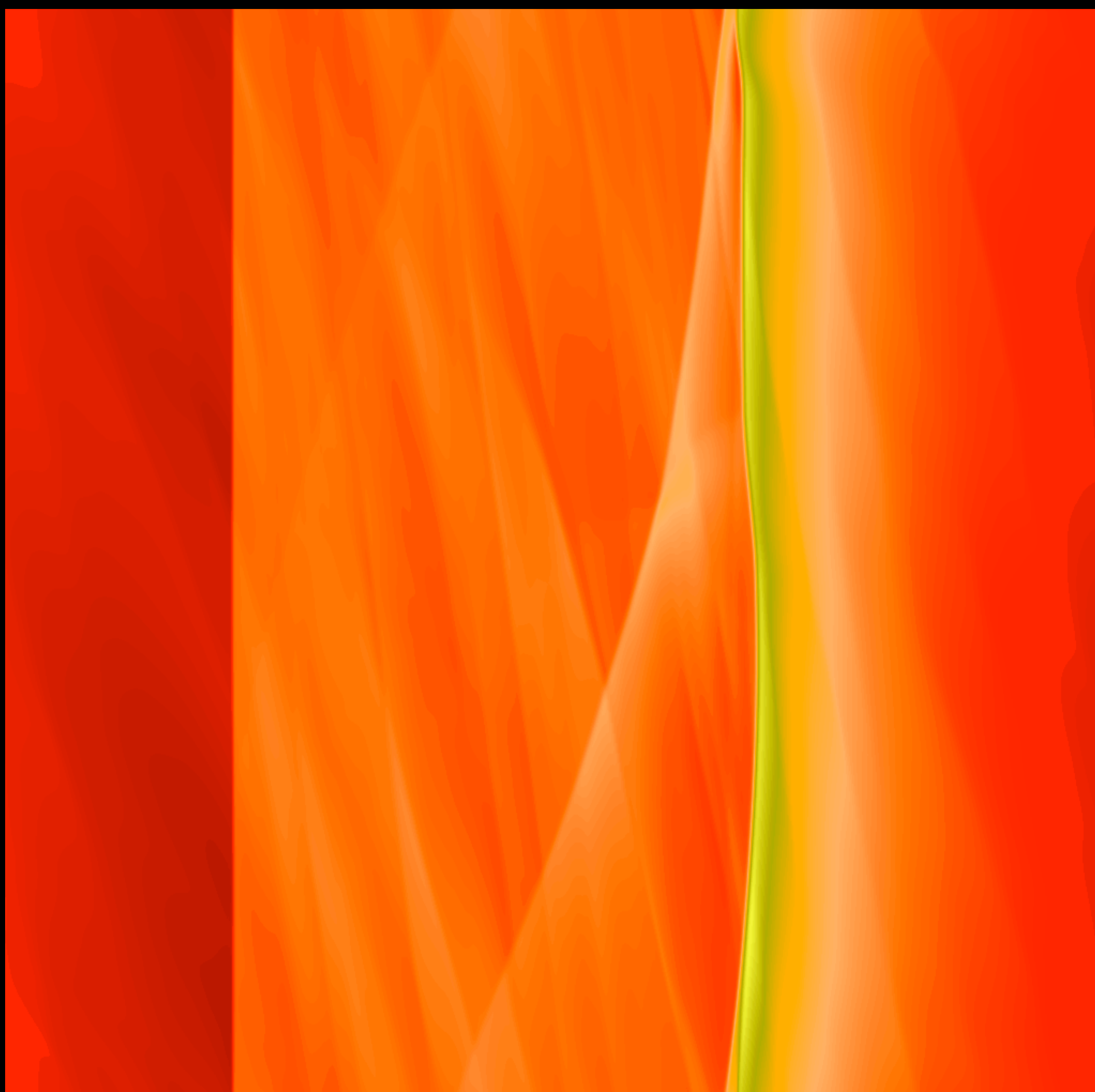
Yang & Krumholz (2012)

Turbulent Steady State

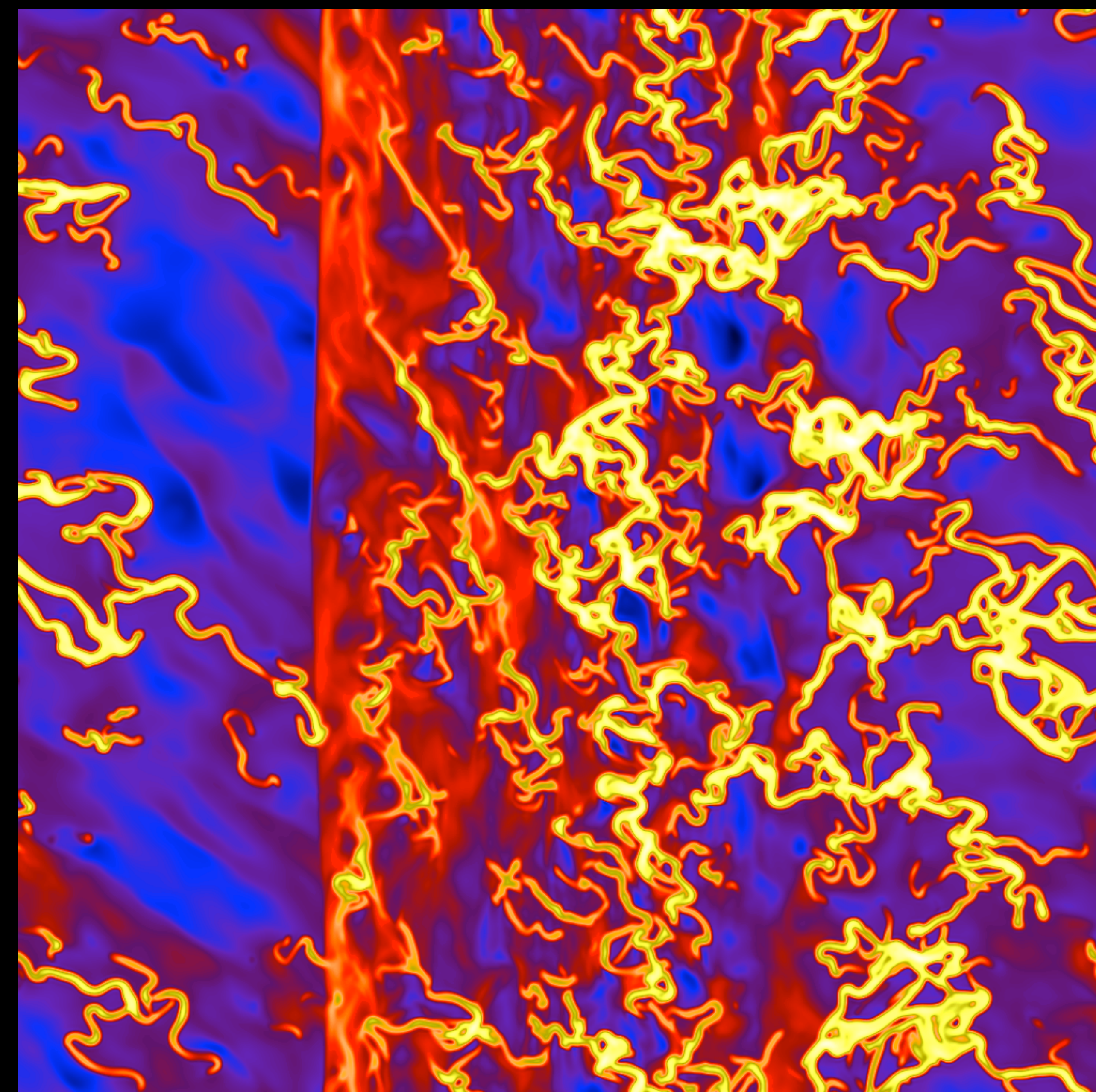
Spiral Forcing   Magnetic Fields



Surface Density



Isothermal



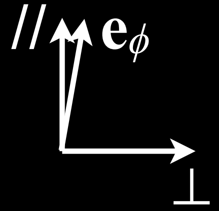
Thermally Unstable

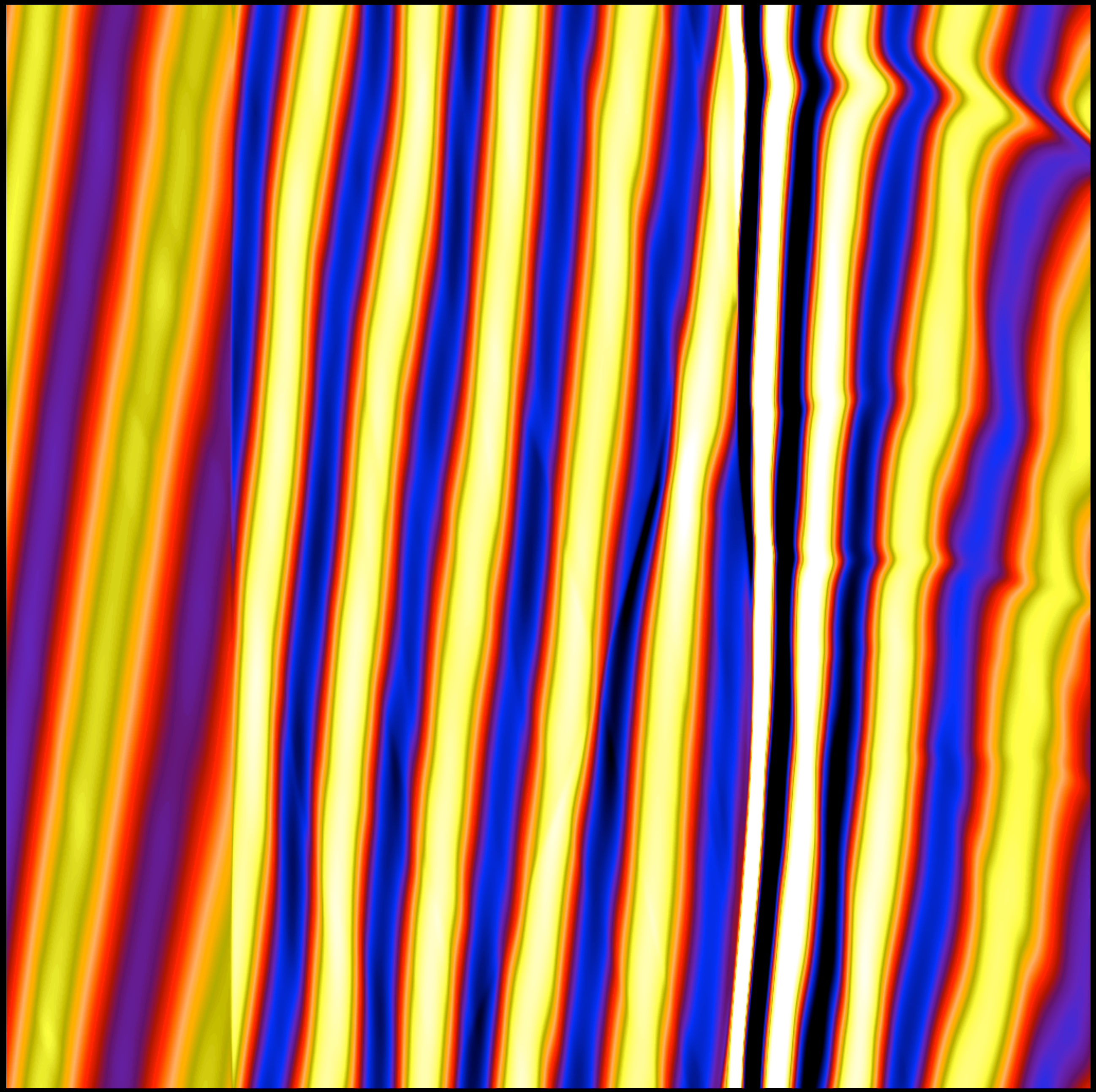
Yang & Krumholz (2012)

Turbulent Steady State

Spiral Forcing   Magnetic Fields

Metal Tracer Field





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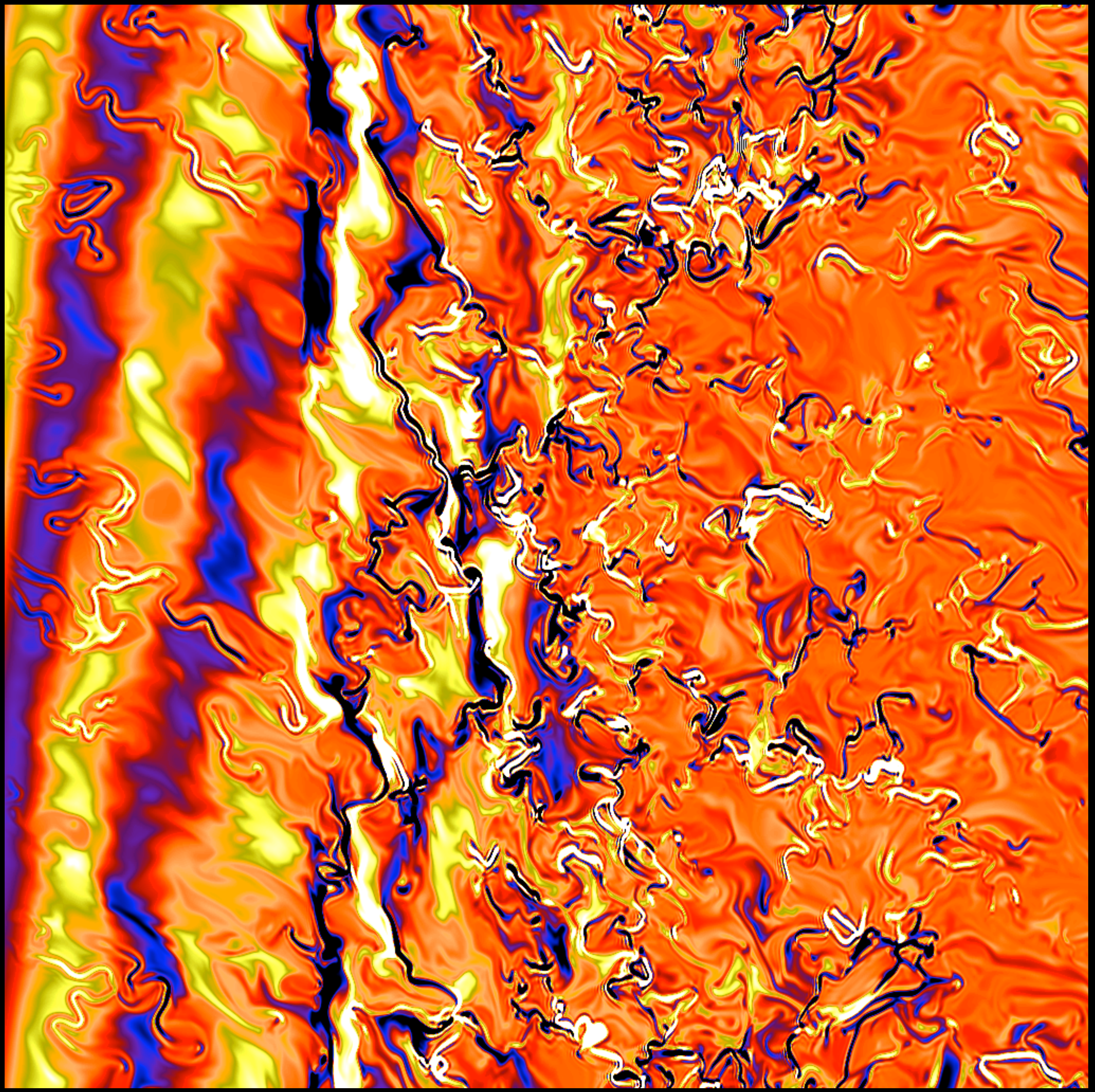
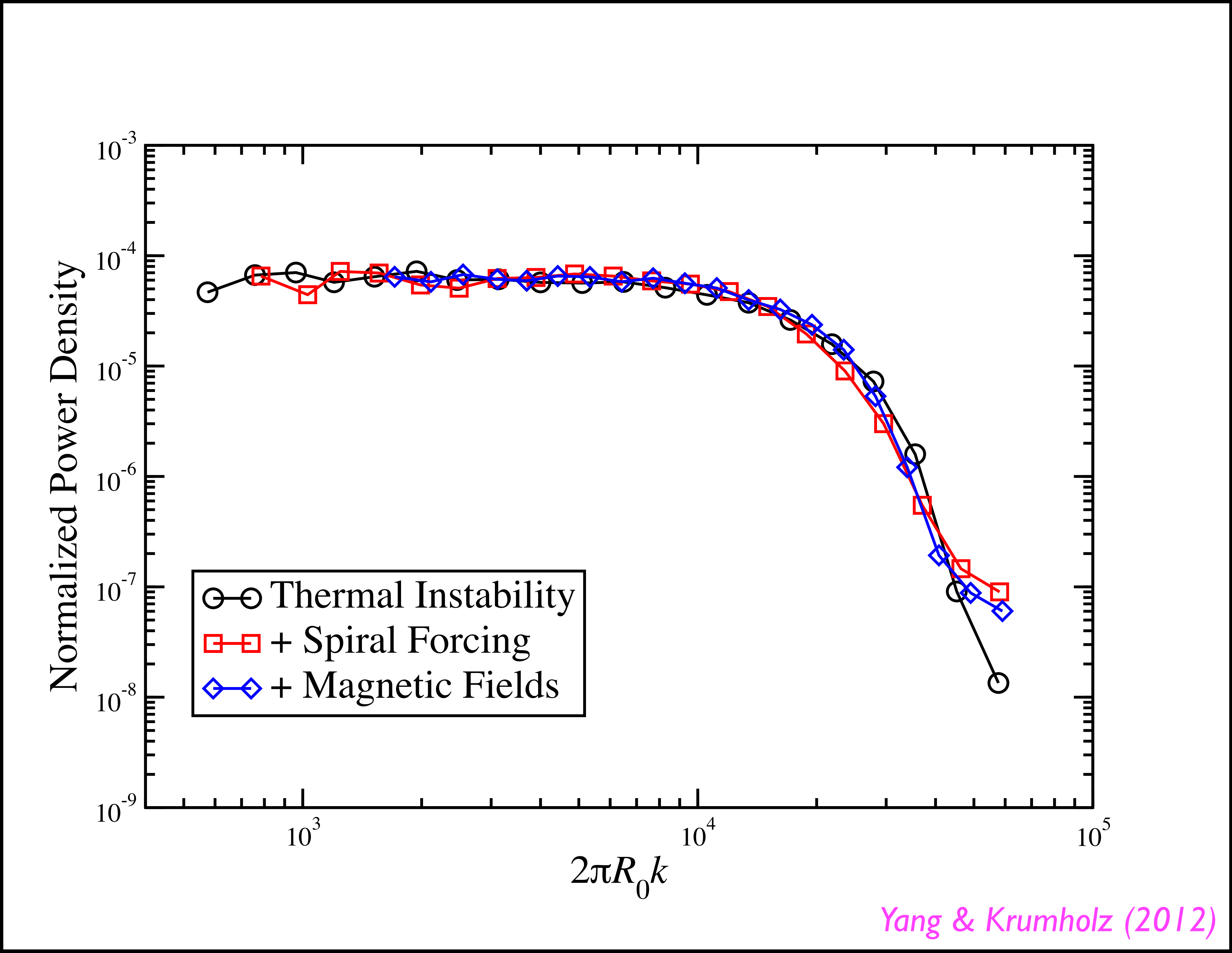


Thermally Unstable

Yang & Krumholz (2012)

Power Spectrum of Mixed Metals



Following the Flow

Metal Tracer Field

Power in k_y

Space

Time

// $\mathbf{e}_\phi$

$\perp$

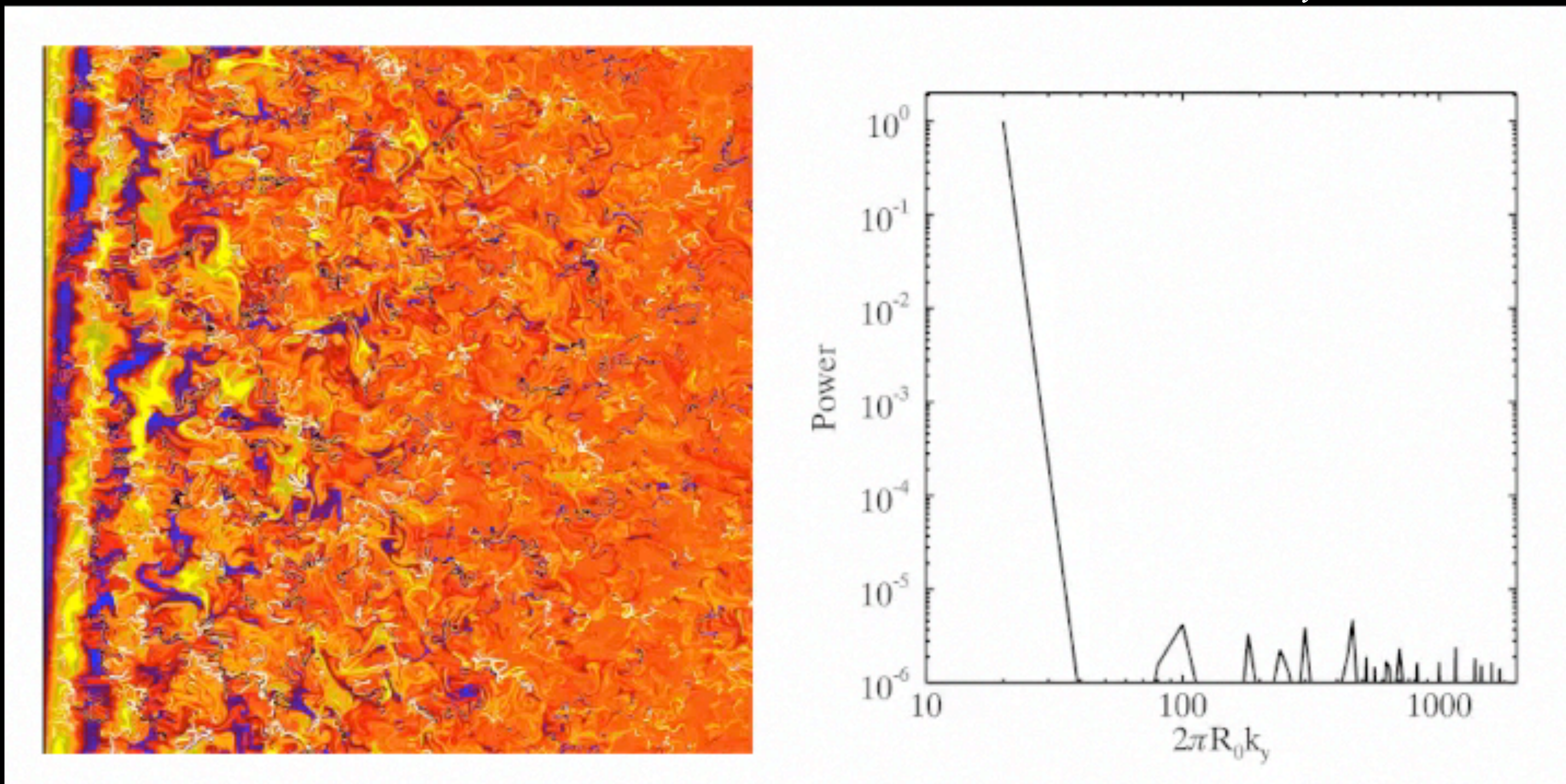
Yang & Krumholz (2012)

Following the Flow

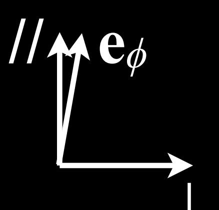
Metal Tracer Field

Power in k_y

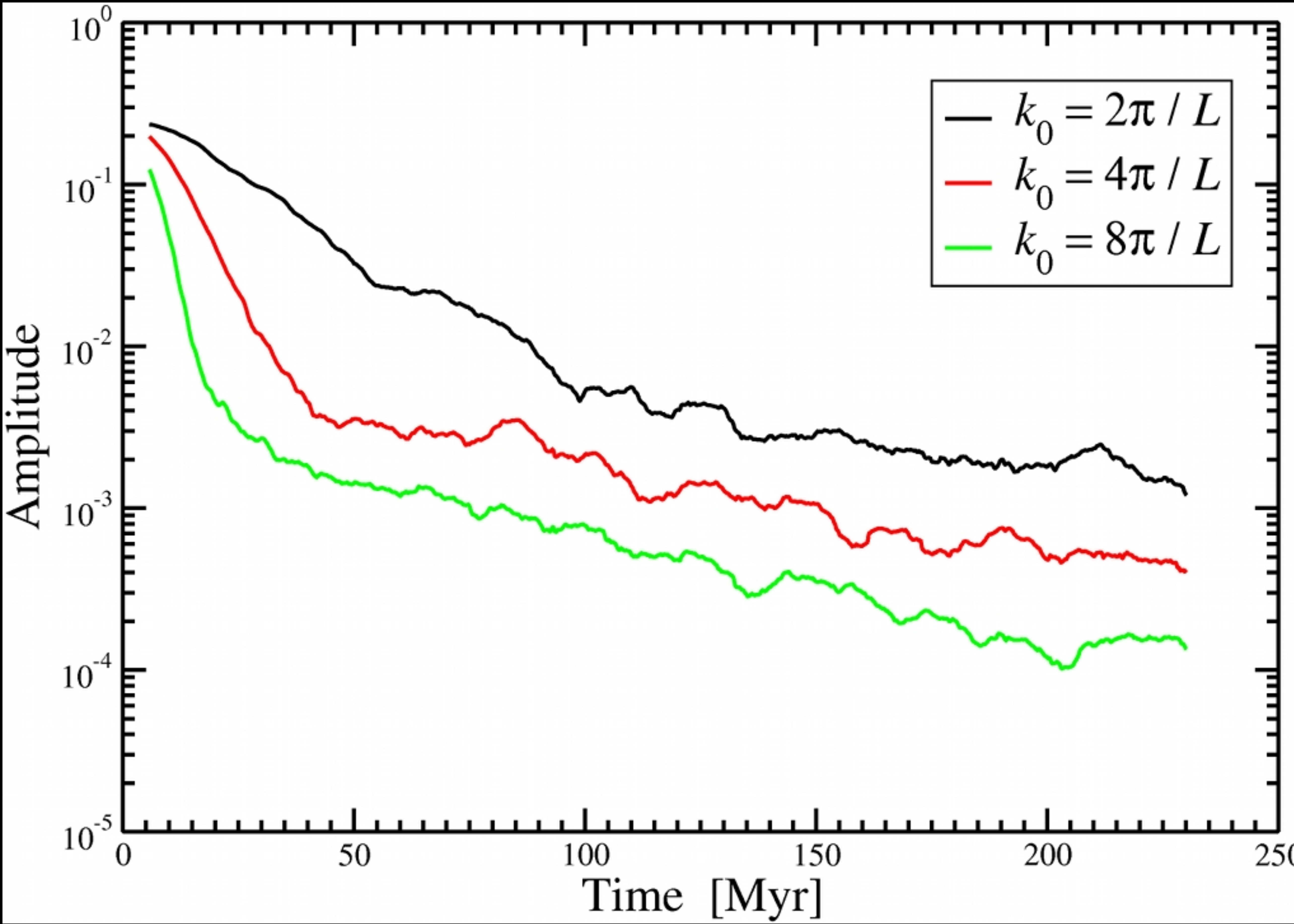
Space



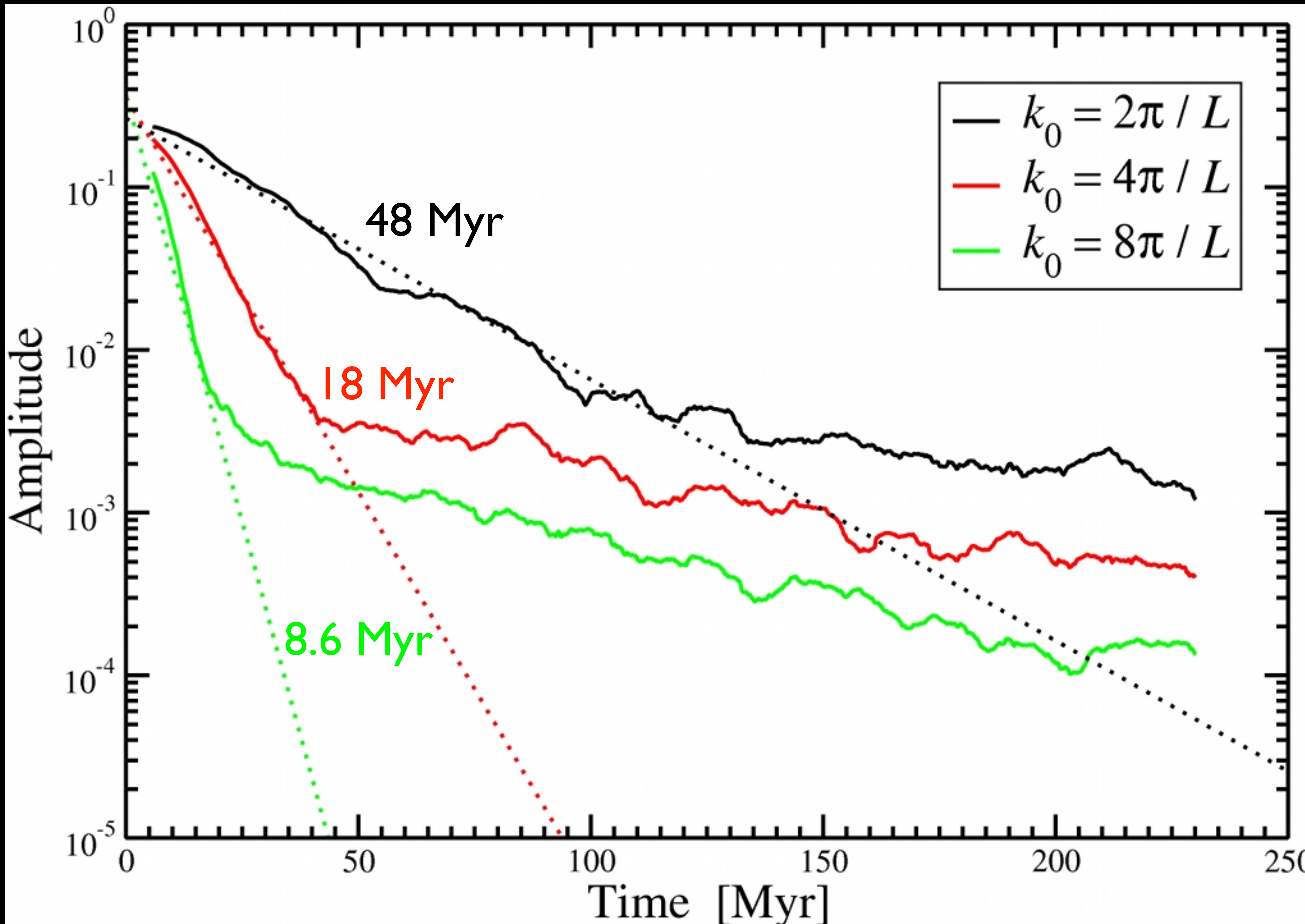
Time



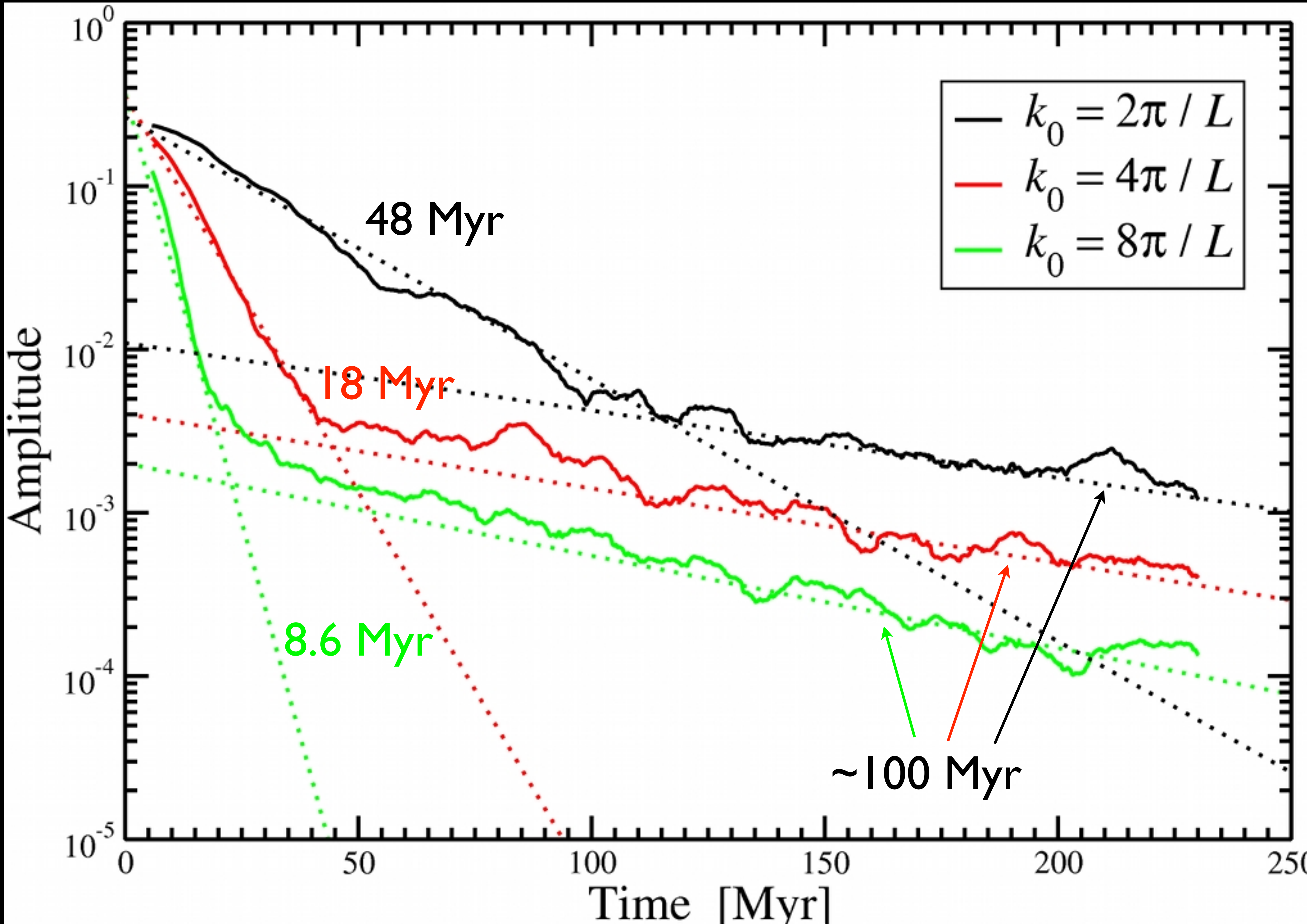
Yang & Krumholz (2012)



Yang & Krumholz (2012)



Yang & Krumholz (2012)



Yang & Krumholz (2012)

Table 3

Properties of the Mixing Process for Different Metal Tracers in Model T

		First Stage		Second Stage	
$\lambda_{\rm inj}$ (kpc)	$\bar{t}_0$ (Myr)	τ_D (Myr)	D ($\rm kpc^2\ Gyr^{-1}$)	τ_D (Gyr)	D ($\rm kpc^2\ Gyr^{-1}$)
3.1	100	48	5.2	0.20	1.2
1.6	41	18	3.5	0.16	0.38
0.78	22	8.6	1.8	0.13	0.12
0.39	12	4.0	0.96	0.11	0.037

Notes. $\lambda_{\rm inj}$ is the wavelength of the metal distribution injected from the left boundary. $\bar{t}_0$ denotes the approximate advection time when the mixing process transitions from the first stage to the second. τ_D and D respectively represent the decay time constant of the injected distribution and the corresponding diffusion coefficient at each stage.

$D \sim \alpha c_s H?$ $\qquad c_s H \simeq 0.7\ \rm kpc^2\ Gyr^{-1}$

Yang & Krumholz (2012)

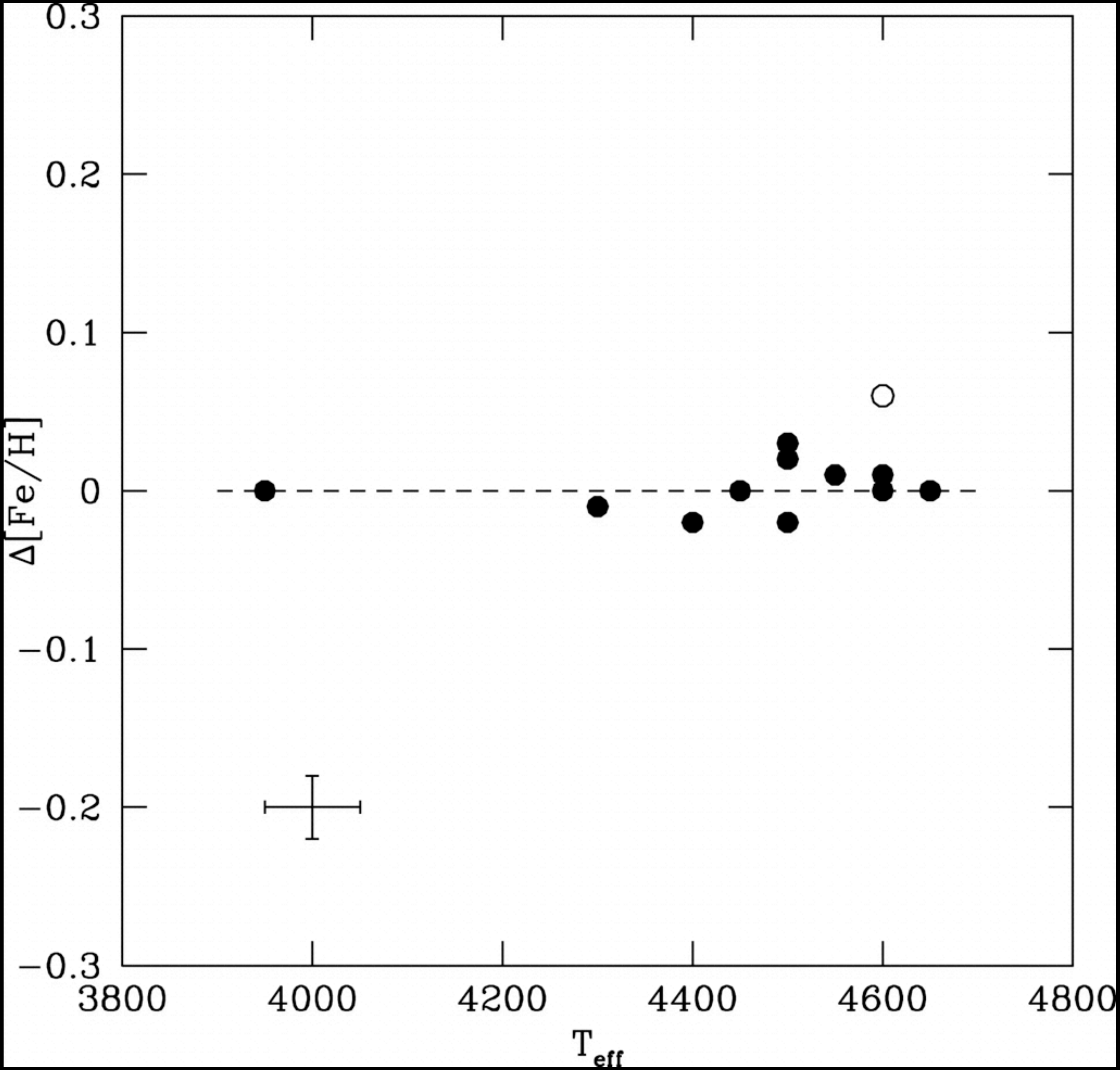
Conclusions

Turbulent mixing of metals...

- is efficient (timescale < orbital time).
- is not the same as the viscous stress of the gas.
- is important in setting metallicity gradients.

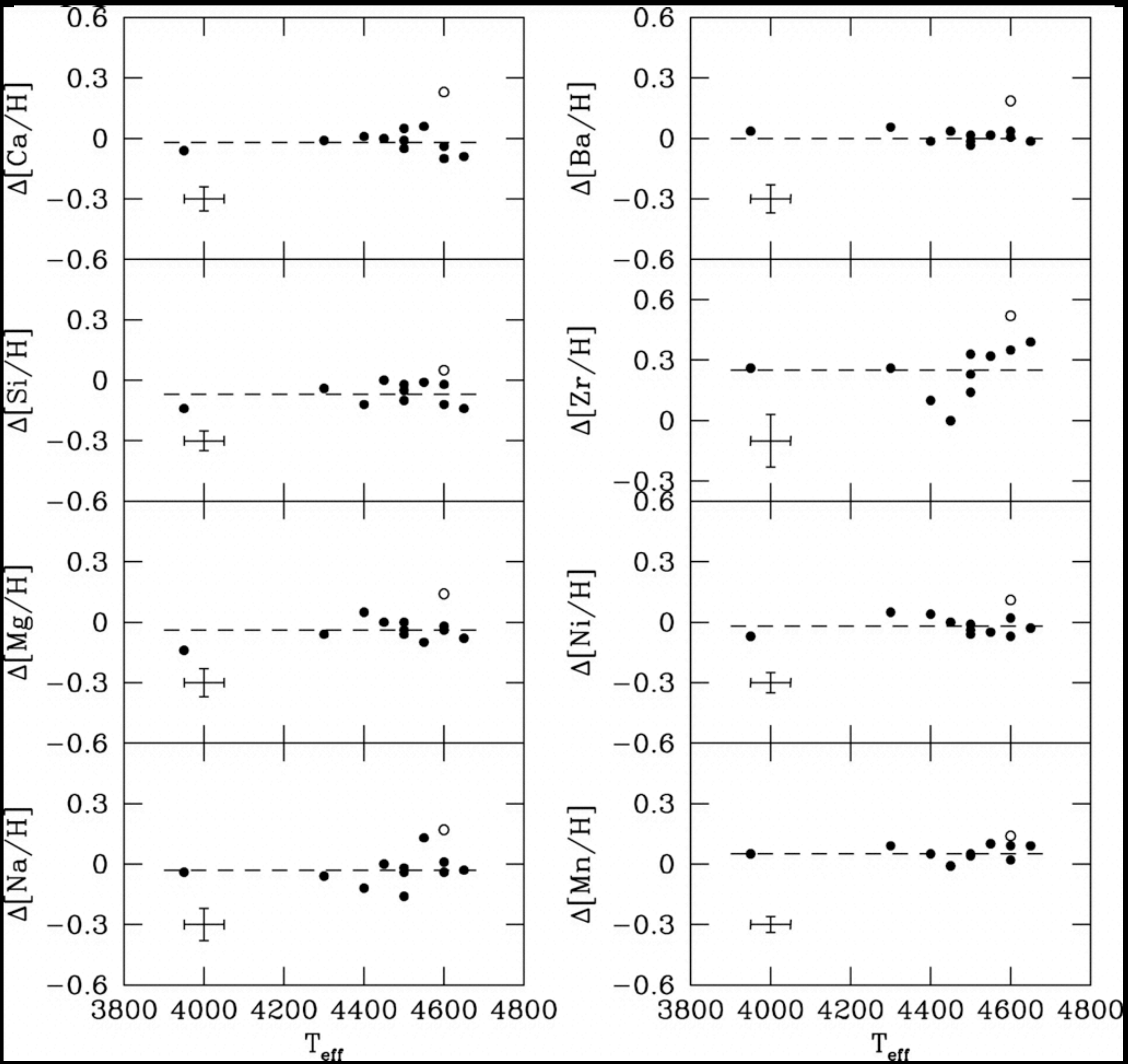
Where do we go from here?

Chemical Homogeneites in Old Open Clusters



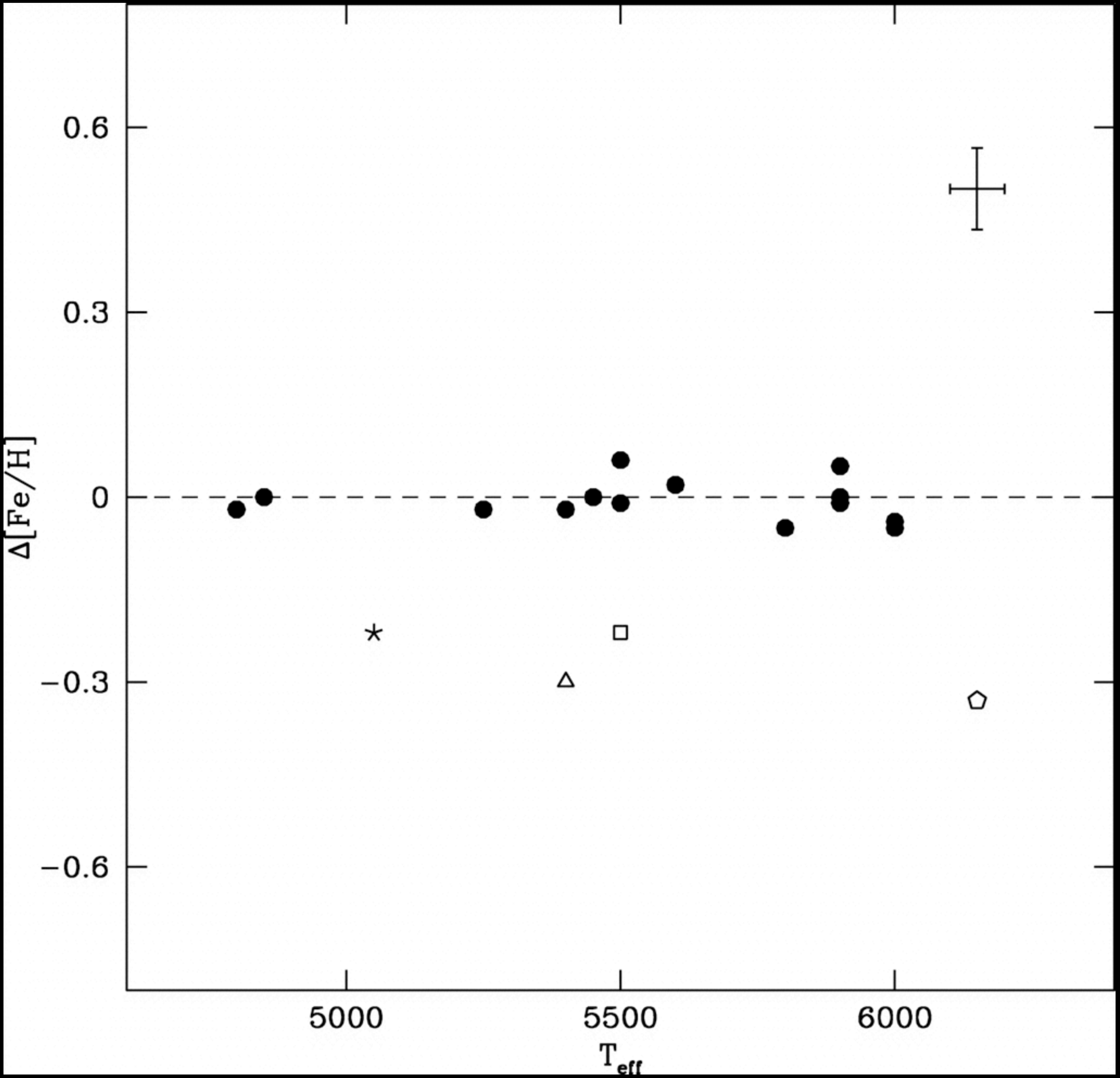
Cr 261, *de Silva et al. 2007b*

Chemical Homogeneites in Old Open Clusters



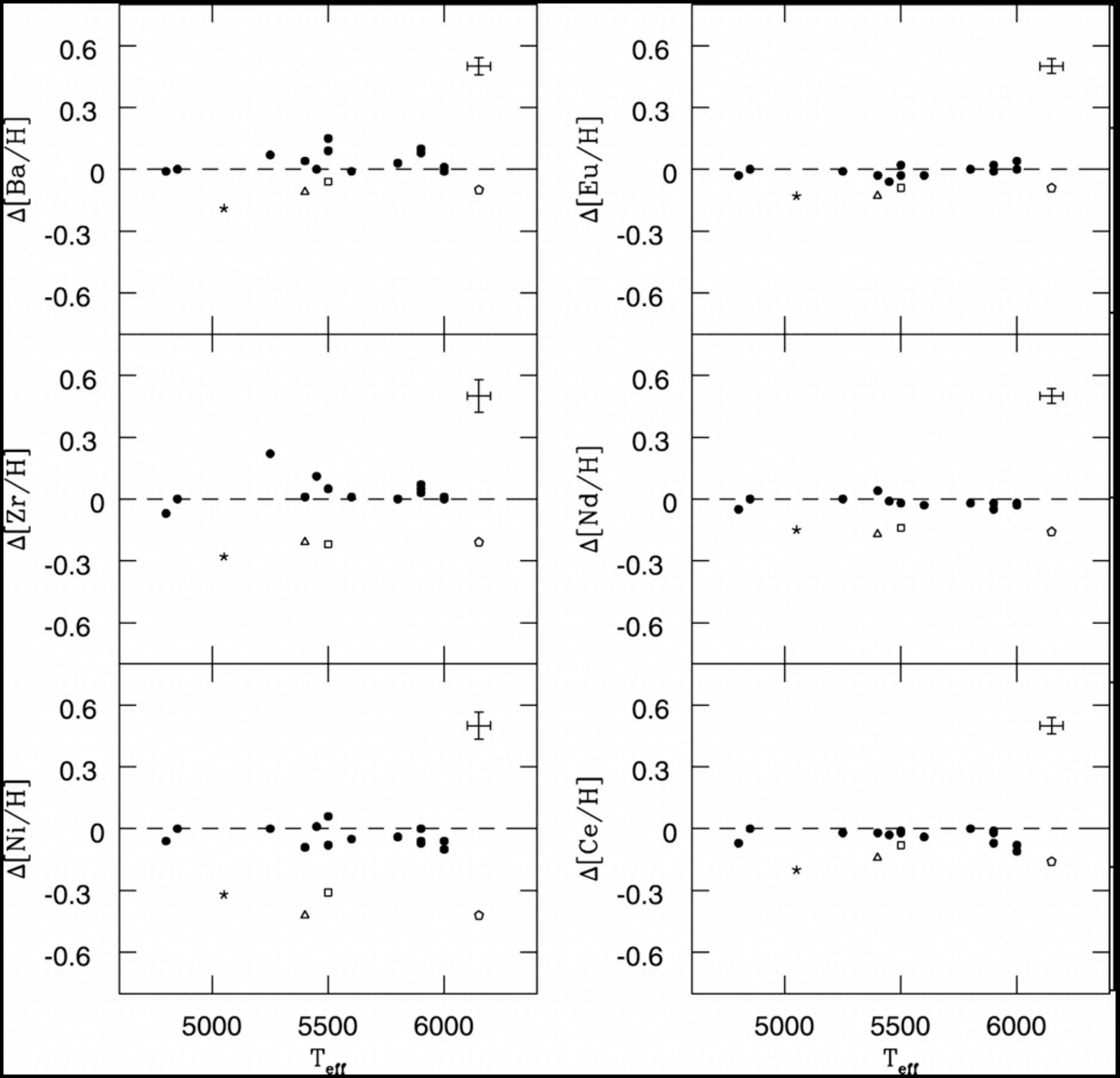
Cr 261, *de Silva et al. 2007b*

Chemical Homogeneites in Moving Groups



HR 1614, *de Silva et al. 2007a*

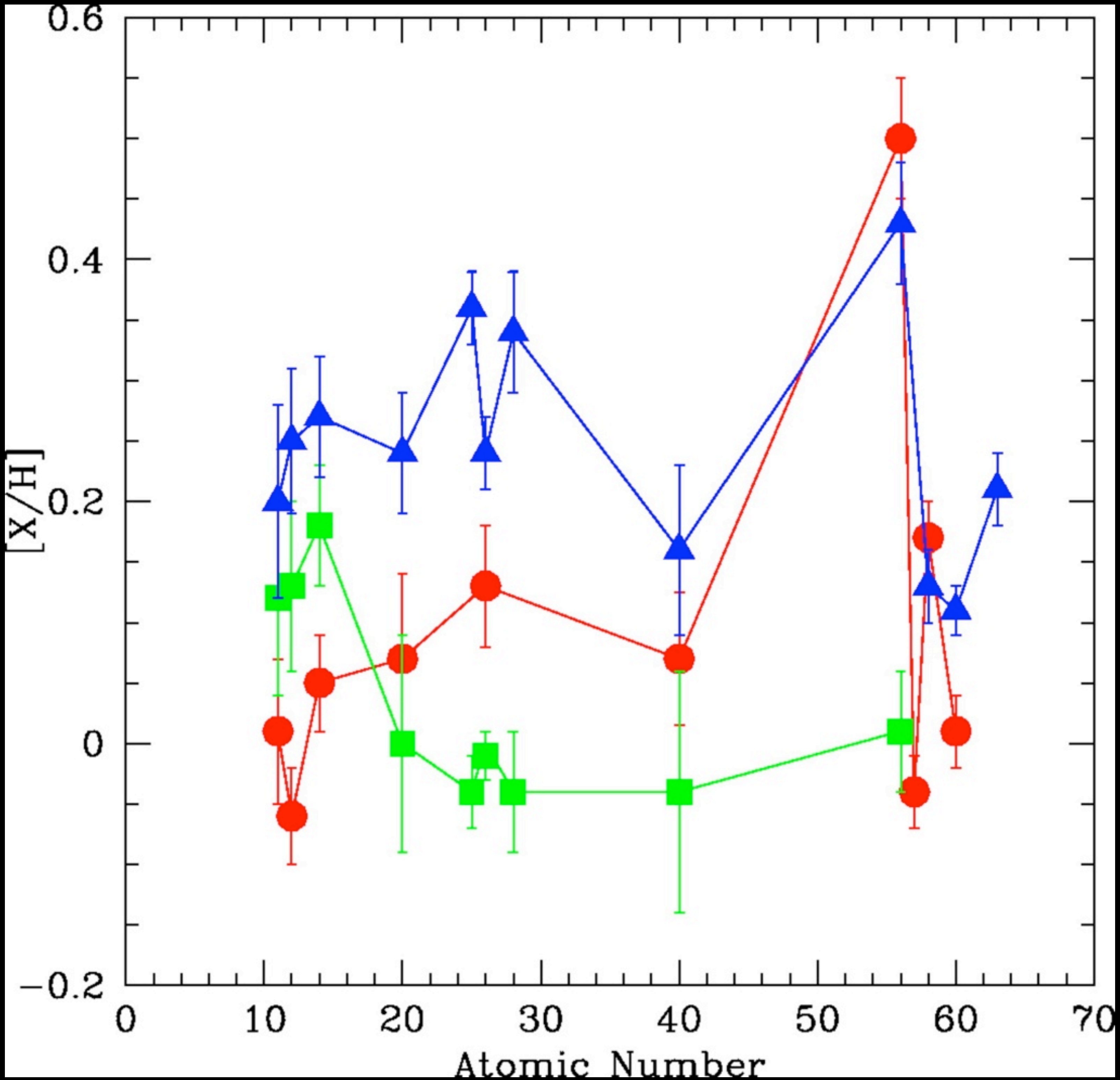
Chemical Homogeneites in Moving Groups



HR 1614, *de Silva et al. 2007a*

Chemical Tagging Technique

(Freeman & Bland-Hawthorn 2002)



de Silva et al. 2007b

Stay tuned...