WEIZMANN INSTITUTE OF SCIENCE

מכון ויצמן למדע

Analytic Description of Beta Decay Electron Thermalization in Kilonovae Ejecta

ULTRASAT collaboration workshop,

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Kilonovae Modeling Challenge

$\sim 10^6$ cm, $1 - 10^3$ ms

$M_{ej} \sim 10^{-2} M_{tot}$

$\sim 10^{15}$ cm, weeks

Merger	Ejecta	R-process	Radioactive Plasma	Radiative Transfer
Strong Gravity, Nuclear Matter	Mass	Nuclear masses	Radioactive Decays	Atomic physics
General Relativistic Hydrodynamics, viscosity	Velocity	beta, alpha decays, fission	Particle “thermalization"	Opacities
Weak Interactions (neutrinos)	Electron Fraction			Radiation Approx.
Magnetic Fields				non-LTE effects

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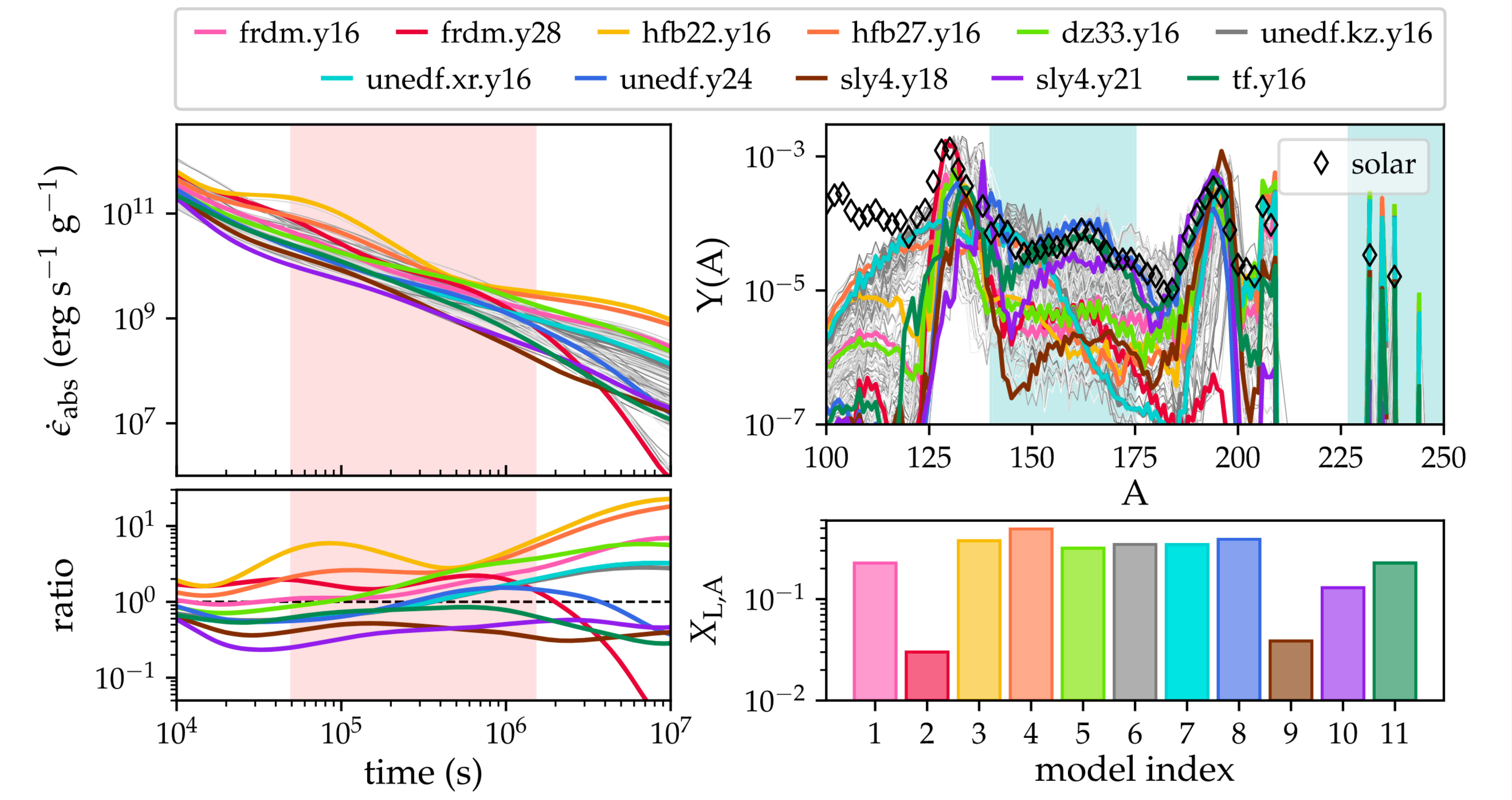

Barnes et al., 2020

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- Interpreting kilonovae observations requires understanding the **thermalization** of decay products (for $t \gtrsim 1 - 2$ days , γ-particles mostly escape, leaving e, α-particles as main heating source)

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Despite many complications and uncertainties -

To find a simple and robust analytic description for t_e - inefficient thermalization timescales - for a wide range of ejecta parameters

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  - $1 \leq s_0 \leq 10^2 [k_b/\text{baryon}]$, semi-linearly spaced. (from simulations, $s_{0,avg} \approx 20\ [k_b/\text{baryon}]$)
  - $0.05 \leq Y_e \leq 0.45$, linearly spaced.
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- Define and calculate t_e and t_α - **inefficient thermalization timescales**.
  - Using these, define interpolating functions for deposition.

Electron Energy Losses

- Time-dependent, mass-weighted composition: $\left(\frac{dE}{dX}\right)_{tot} = \sum_{iso} A_{iso} Y_{iso} \left(\frac{dE}{dX}\right)_{iso}$

Electron Losses

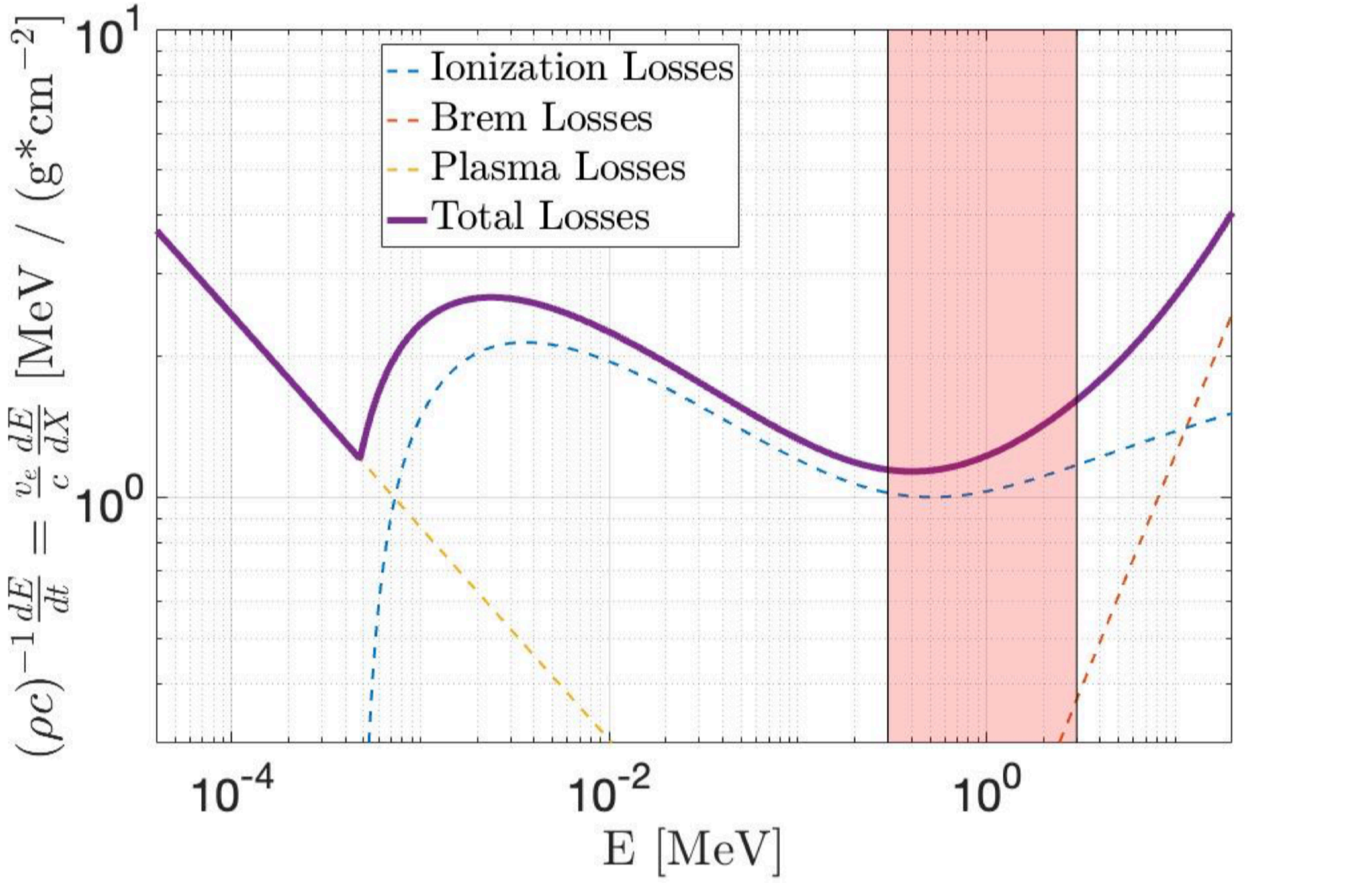

Figure 1: Energy loss rate of electrons propagating in a singly ionized $\chi_e = 1$ Xe plasma ($Z = 54$, $A = 131$). We take $\hbar\omega_p = 10^{-7}eV$. Shaded area shows typical average initial energies of β-decay electrons. For most relevant energies, ionization losses dominate.

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  - Where $t_l(E_i, t) = E_i \left(\frac{dE}{dt} \right)^{-1}$ is the energy loss timescale, and $\frac{dE}{dt} = \rho v \frac{dE}{dX}$.

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- Also calculated full, delayed energy deposition : $\dot{Q}_{dep}(t) = \int dE \frac{dE}{dt}(E, t) \times \frac{dN}{dE}(E, t)$
  - Where $\frac{dN}{dE}(E, t)$ is the electron distribution, dictated by: $\frac{\partial}{\partial t}\left(\frac{dN}{dE} \right) = - \nabla_E \left(\frac{dN}{dE} \right) + \dot{N}(E, t)$

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  - If $< E_\beta > \propto t^{-c}$ as often assumed, then $\frac{d\log(t_e)}{d\log(\rho t^3)} \geq 1/2$

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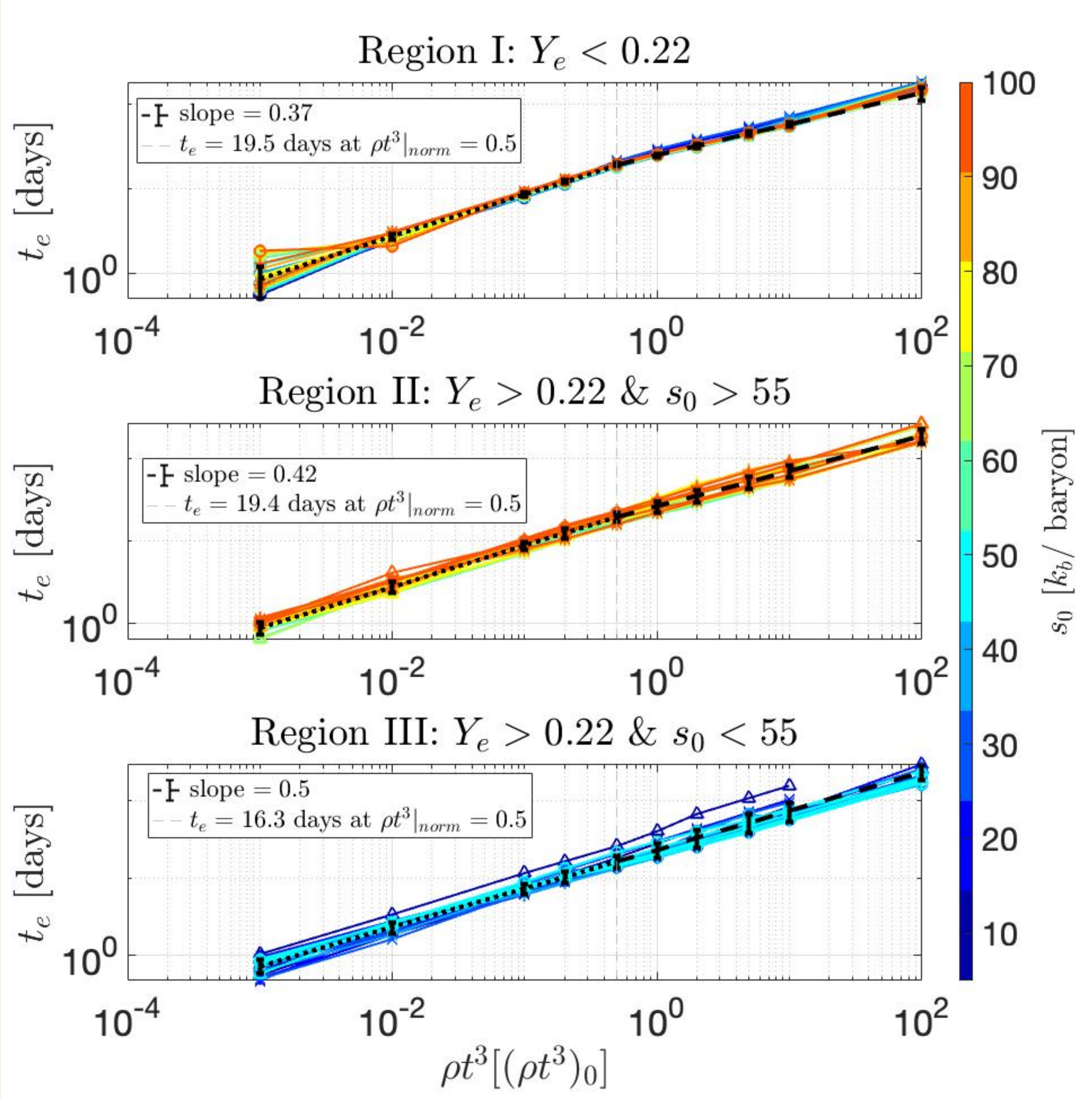

- Broken power-law description:

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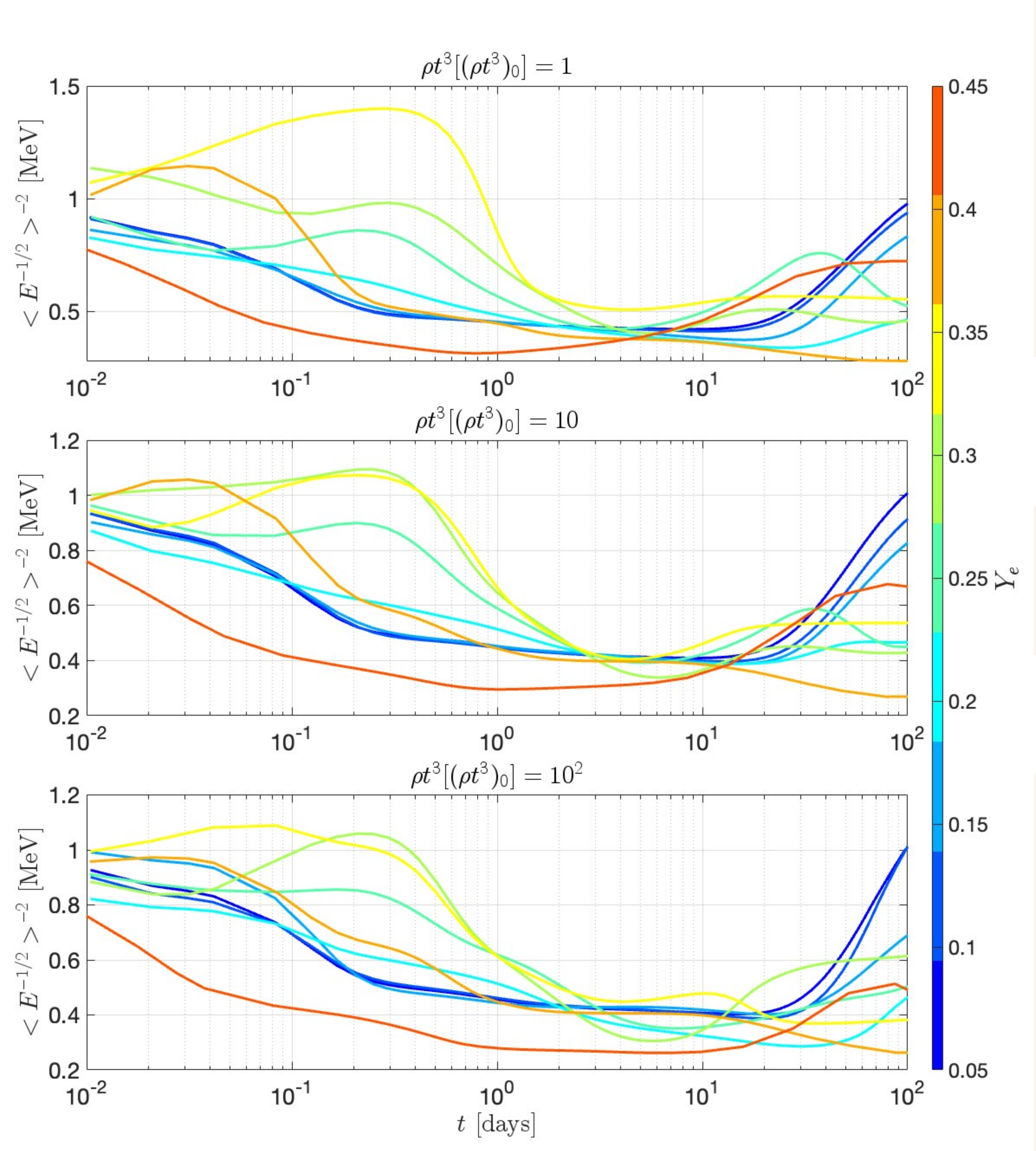
- Analytic estimate accurate to $\sim$ 20%, at worst

	Ejecta Parameters		**Fitted Parameters**		
	Y_e	s_0 [k_b/baryon]	a_1	a_2	$t_{e,0}$ [days]
Region I	< 0.22	$\forall s_0$	0.5	0.37	19.5
Region II	> 0.22	> 55	0.5	0.42	19.4
Region III	> 0.22	< 55	0.5	0.5	16.3

Electron Characteristic Energy Release



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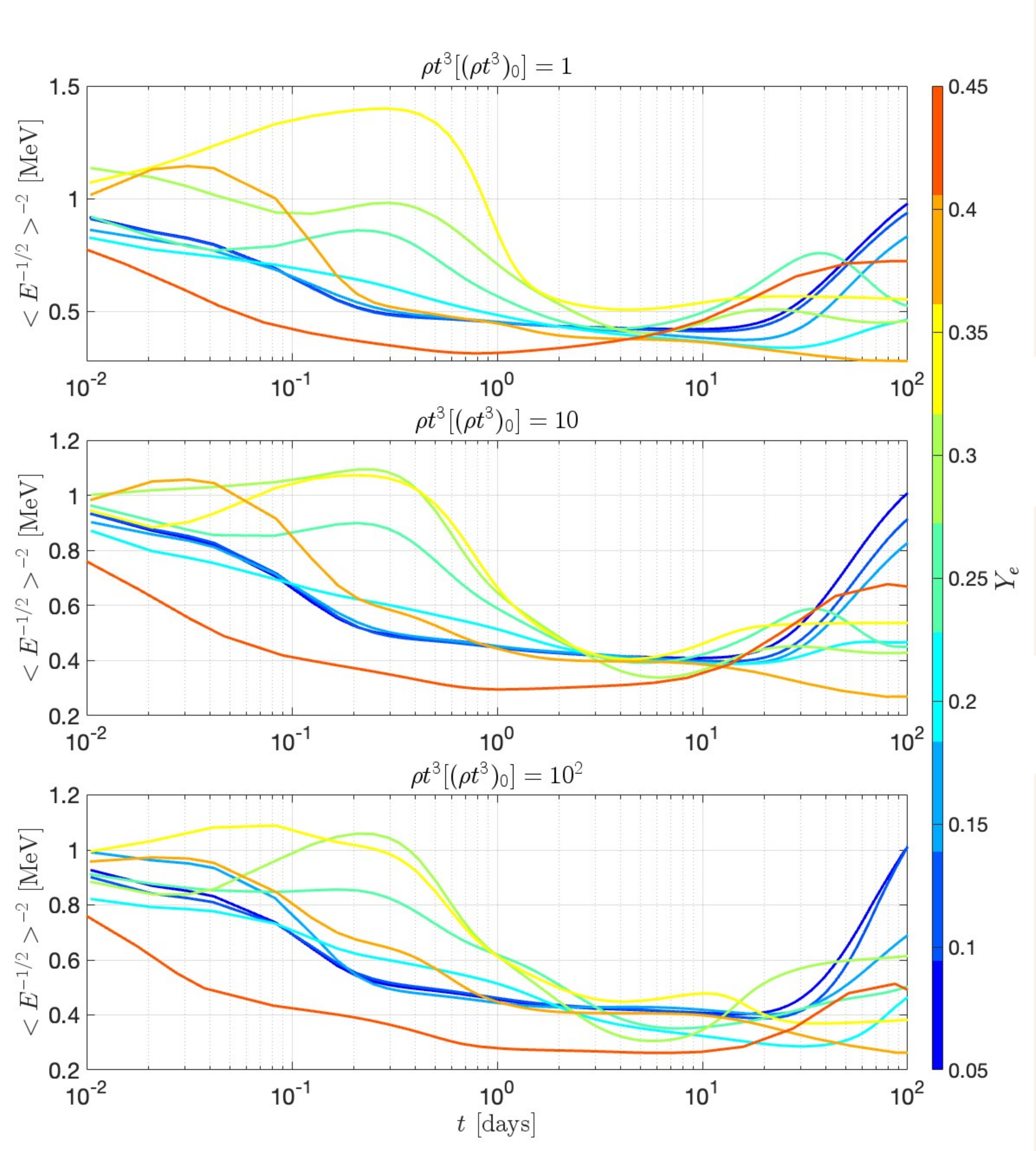

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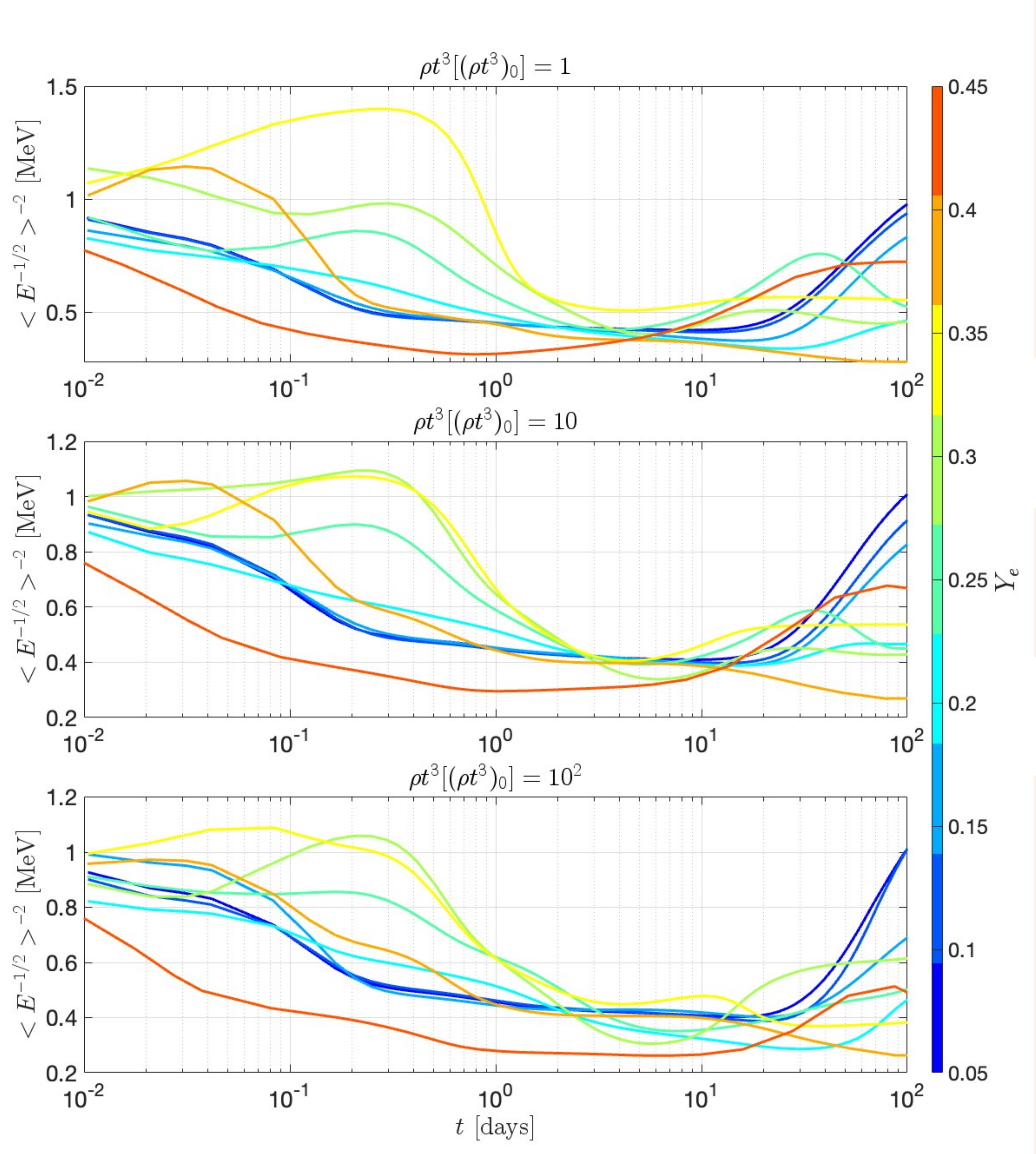

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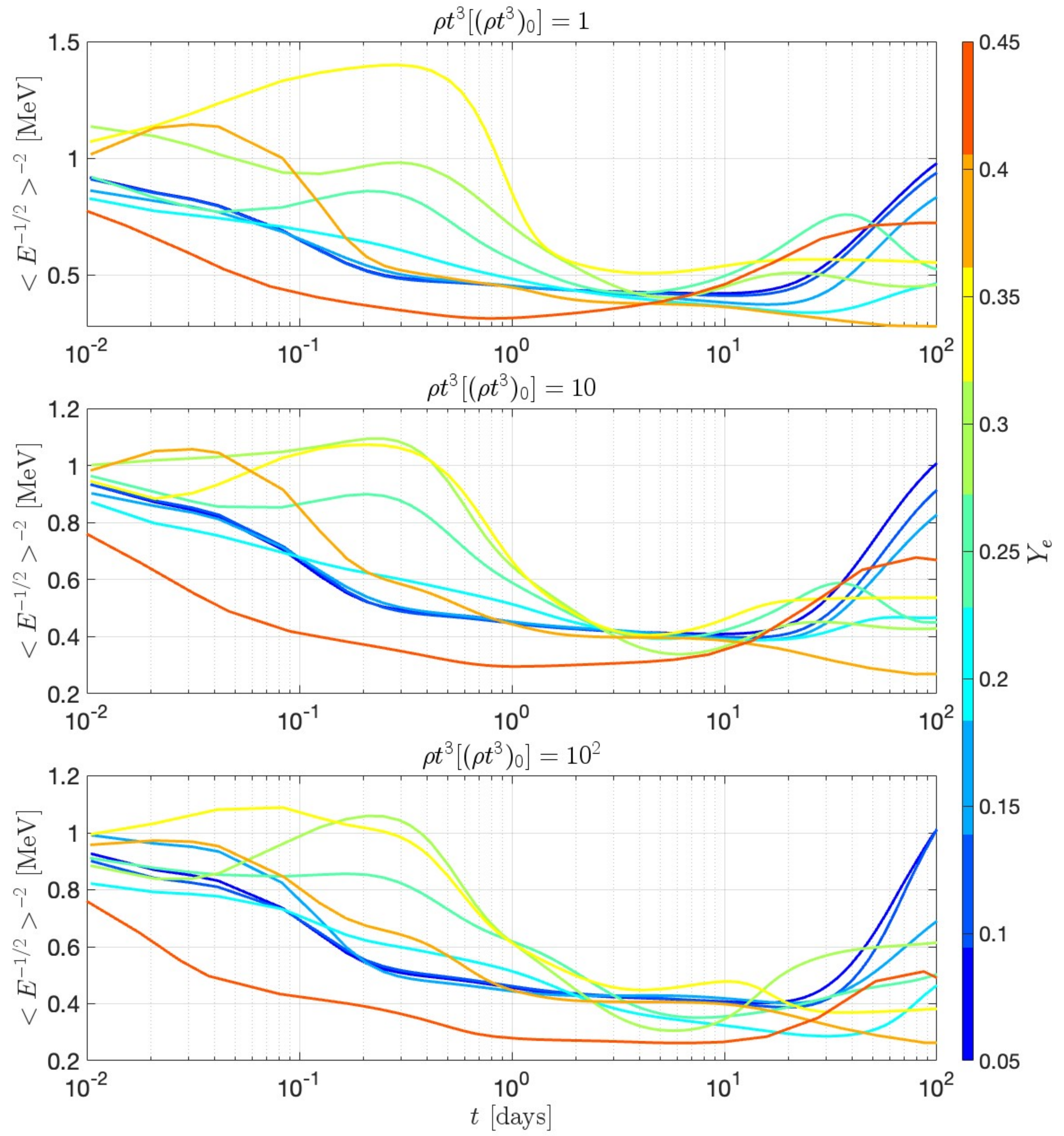

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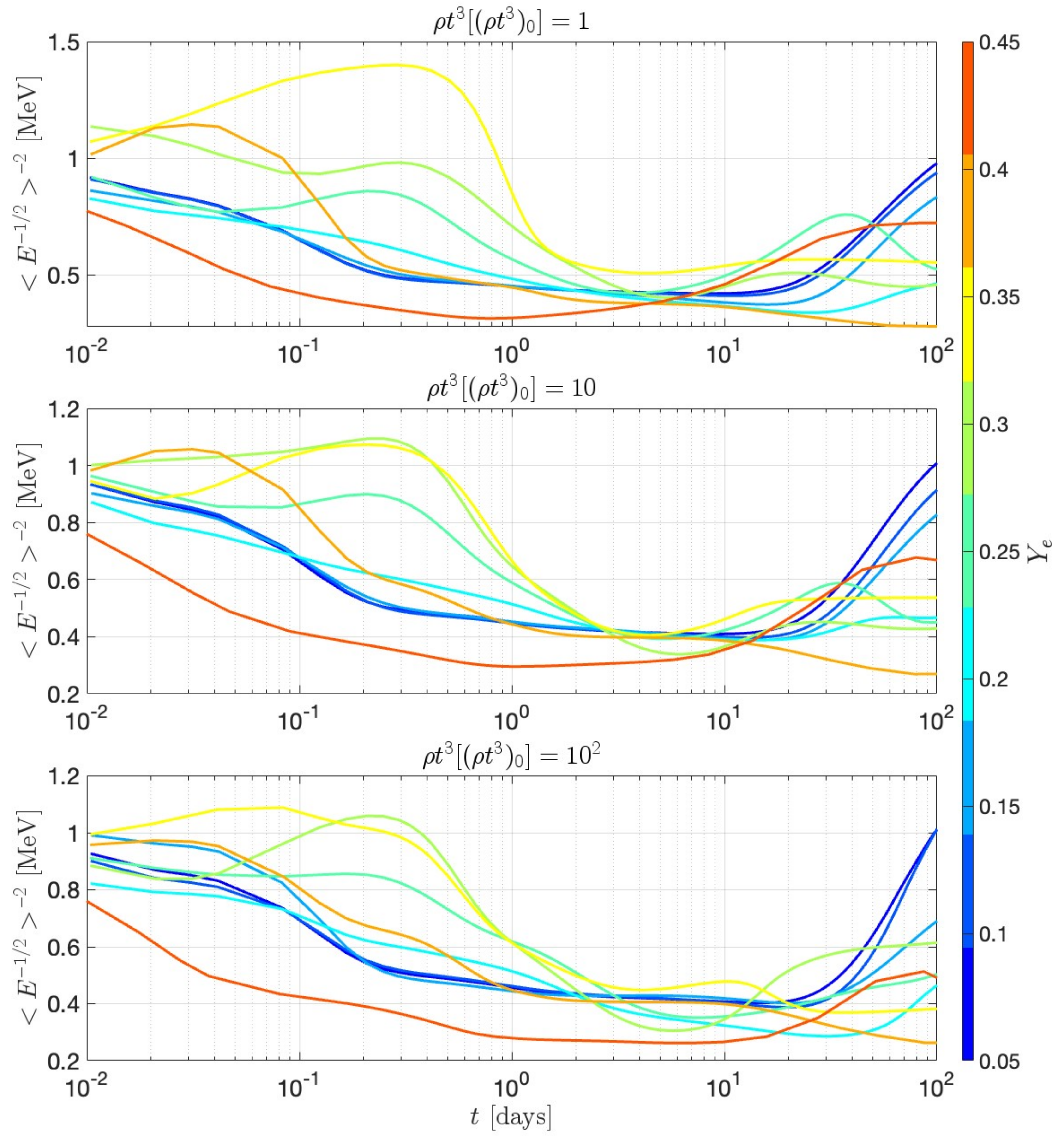

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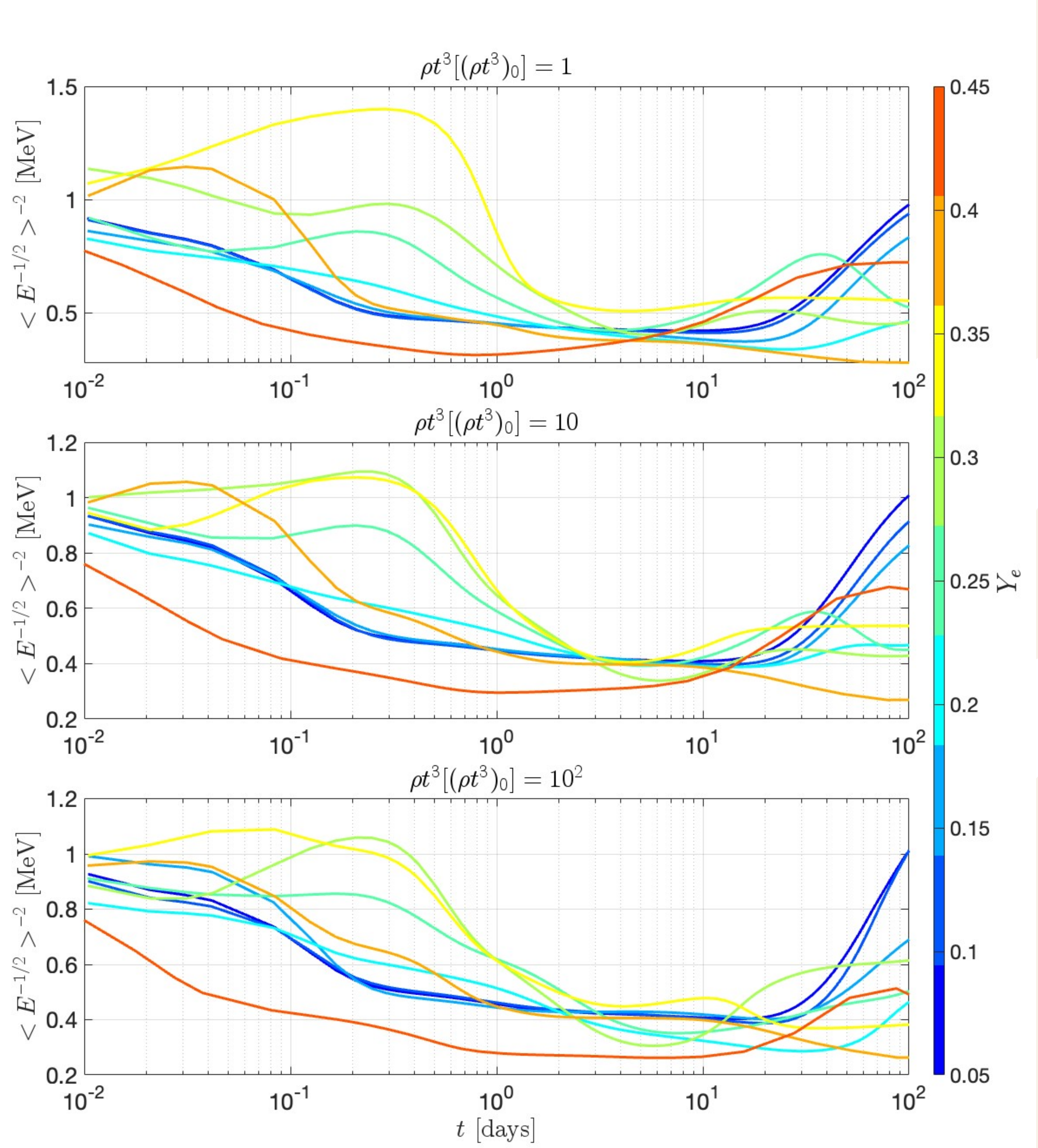

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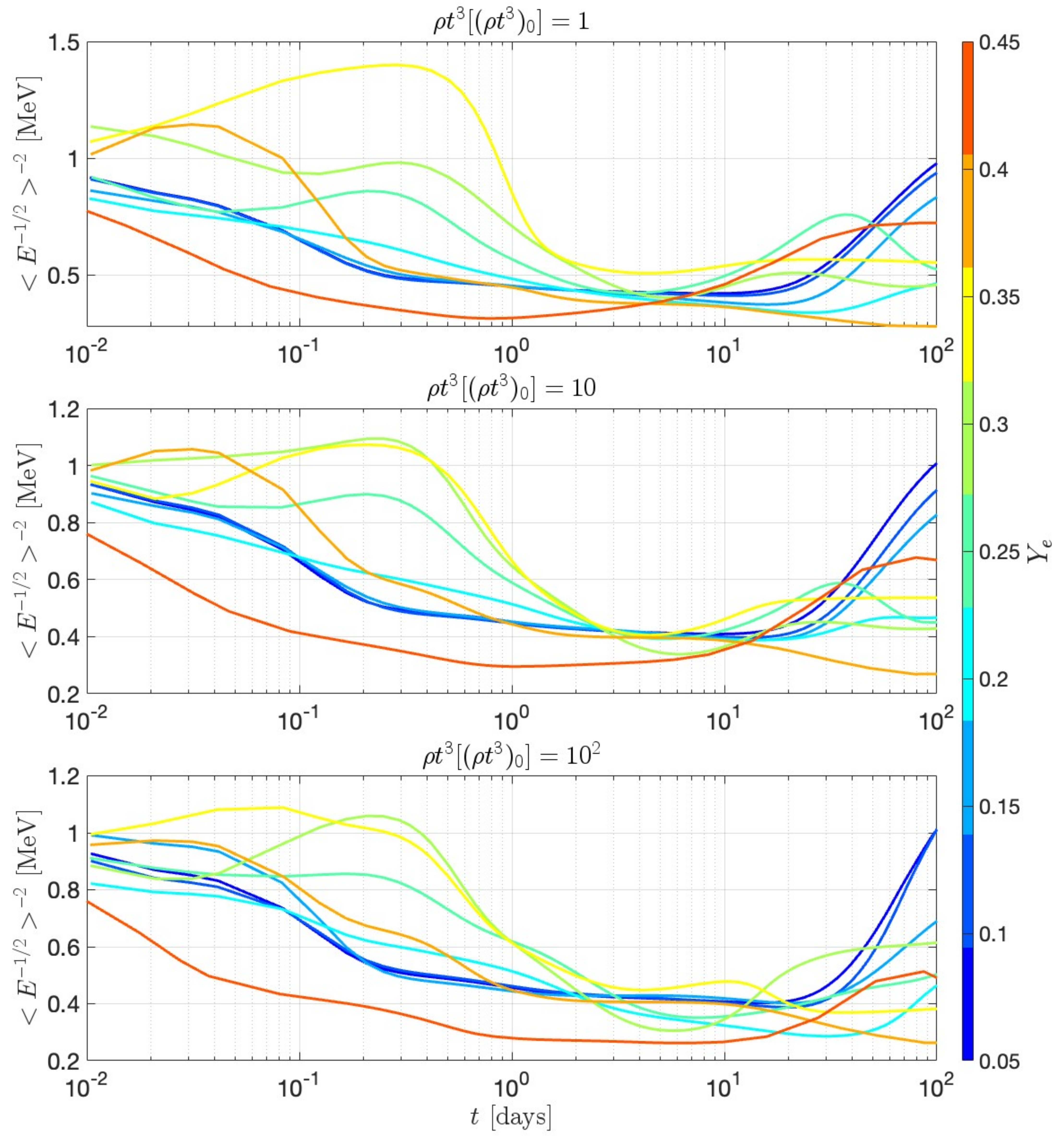
- Overall, 40 inverted chains with half-life $< 10^2 \times t_{1/2}$ of parent isotope



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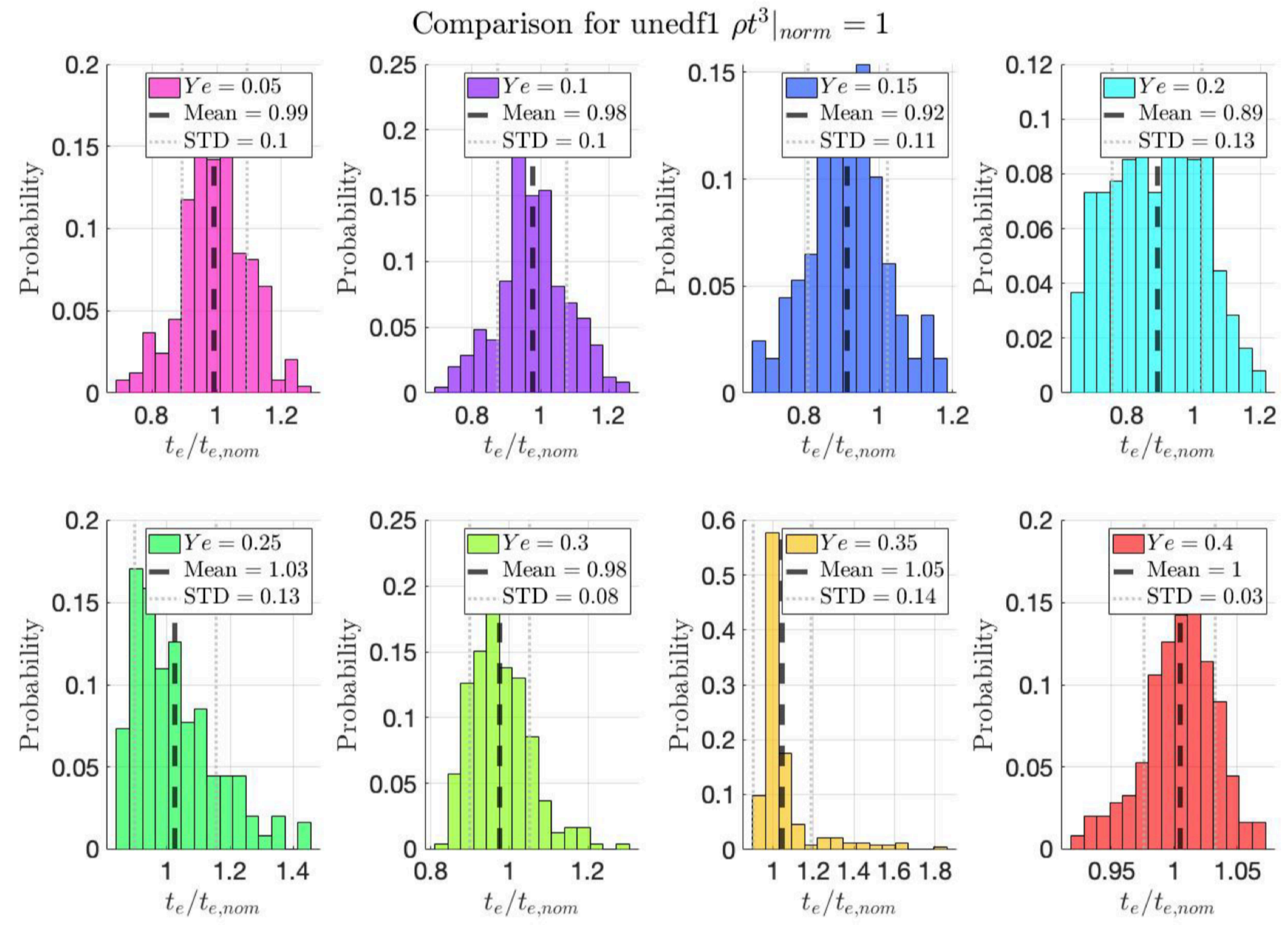

Figure 7: Histograms of $t_e/t_{e,nom}$, where t_e is calculated 500 times for runs with different randomized reaction rates file. $\frac{\rho t^3}{(\rho t^3)_0} = 1$ for all runs. Different panels show histograms for different values of Y_e. Mass model used is UNEDF1 [Kortelainen et al., 2012]. Mean is close to 1 for all. STD ≈ 0.1.

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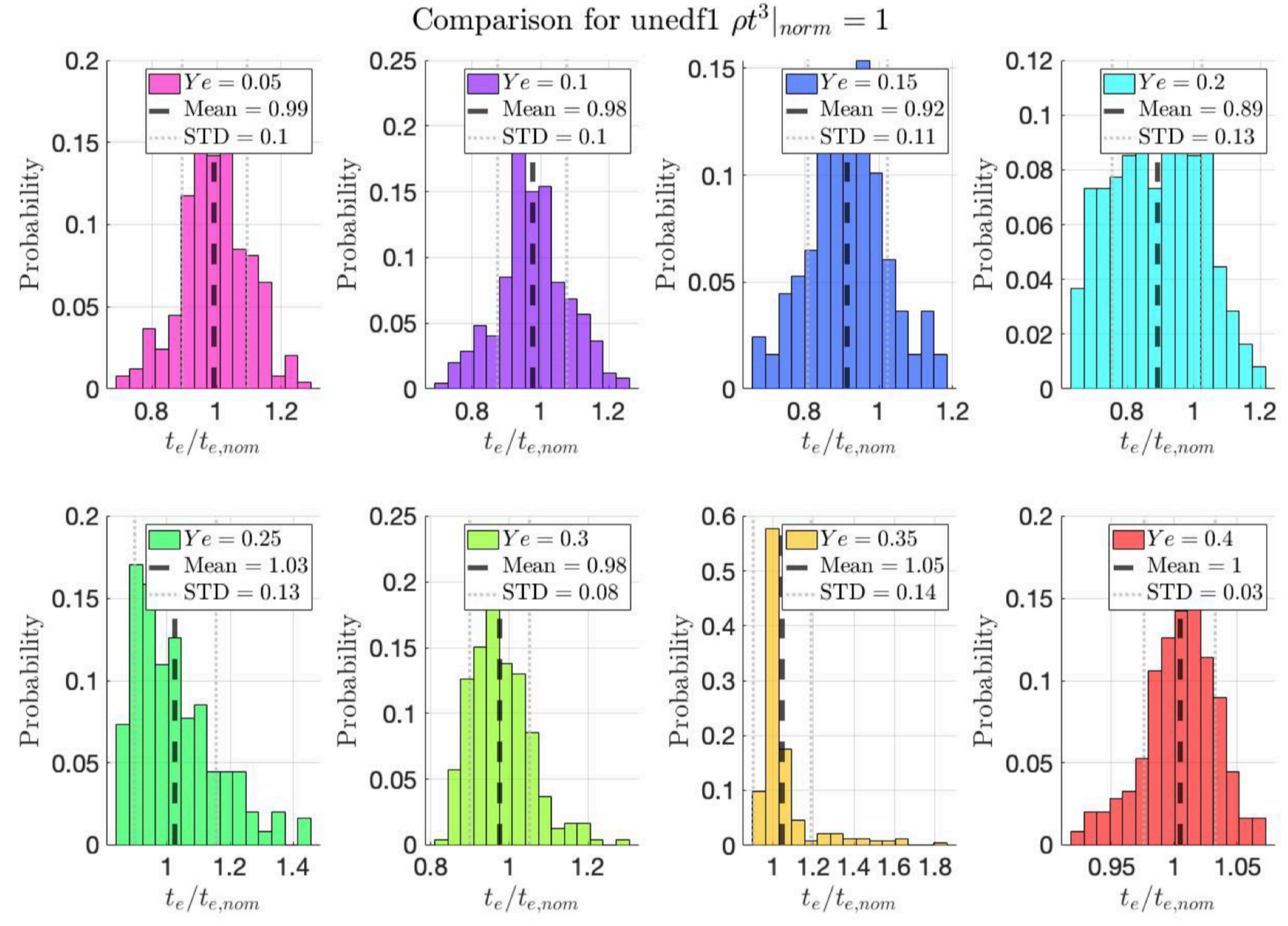

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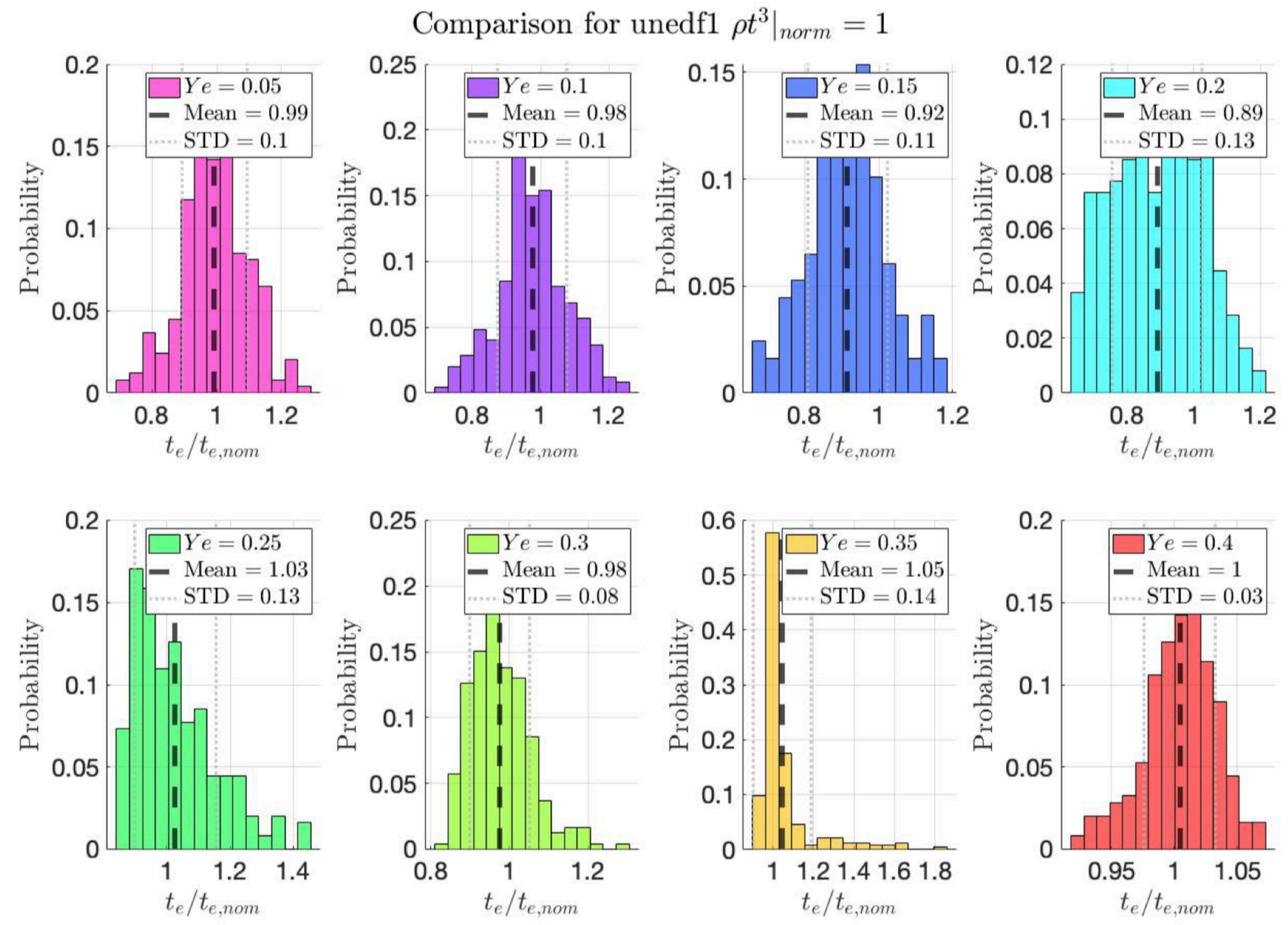
- **t_e remains robust**



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  - $a_1 = 0.5, a_\alpha \approx 0.37,\ (0.42),\ [0.5]$
  - for $Y_e < 0.22, \forall s_0$; $(Y_e > 0.22, \frac{s_0}{k_b/\text{baryon}} > 55)$; $[Y_e < 0.22, \frac{s_0}{k_b/\text{baryon}} < 55]$

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  - $a_1 = 0.5, a_\alpha \approx 0.37,\ (0.42),\ [0.5]$
  - for $Y_e < 0.22, \forall s_0$; $\left(Y_e > 0.22, \frac{s_0}{k_b/\text{baryon}} > 55\right)$; $\left[Y_e < 0.22, \frac{s_0}{k_b/\text{baryon}} < 55\right]$
- $< E^{-1/2} >^{-2}$ **does not** steadily decline over time - “inverted decay-chains”

Key Takeaways

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- Interpolating Function for Thermalization (not discussed) - easy implementation in kilonovae calculations.
- Formula for $t_{e,\alpha}$ can be used to further constrain $\frac{M}{v^3}$ of ejecta based on kilonovae measurements, similar to Ia SNe.

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Thank you.