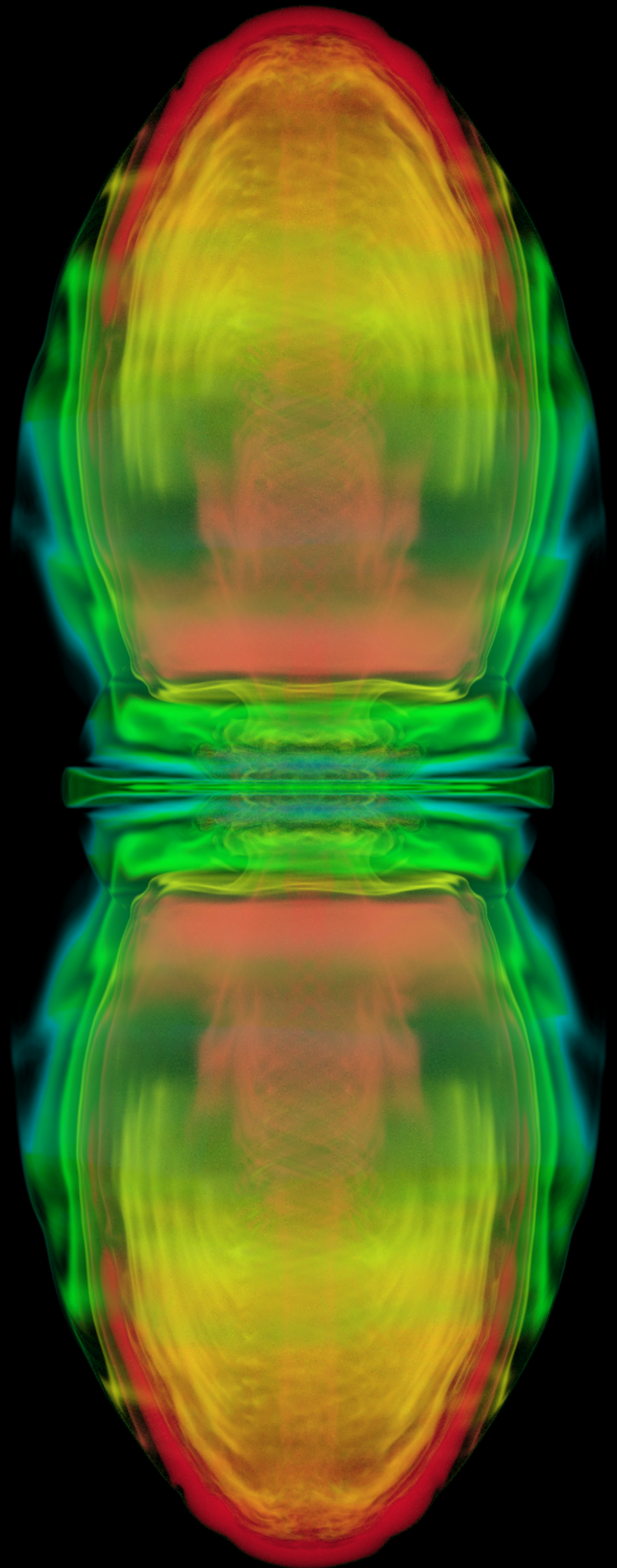
Magnetorotational Core-Collapse SNe as Sites of ***r*-process** Nucleosynthesis:

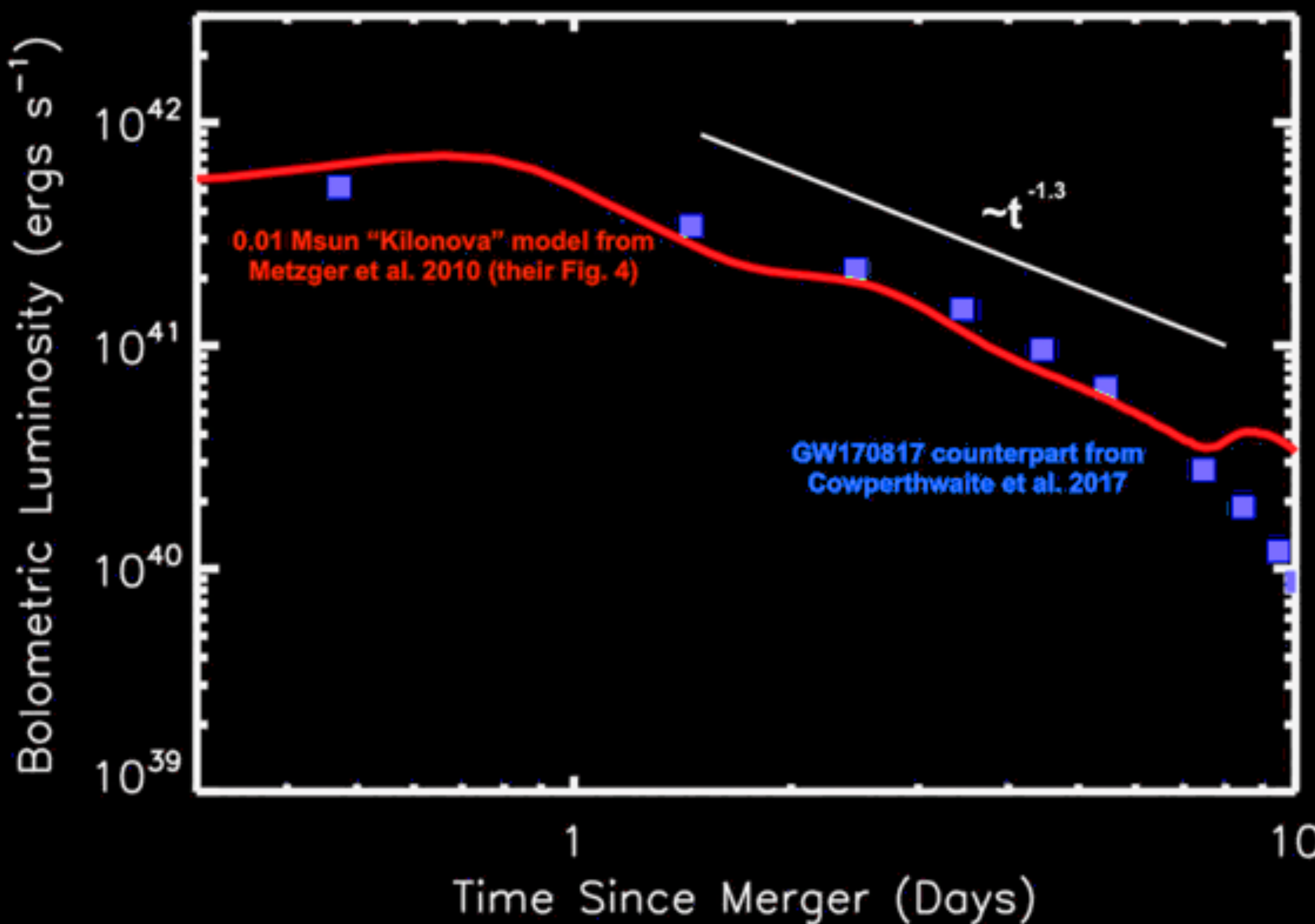
Neutrinos + Misalignments

Goni Halevi (Princeton)

MMGW2019 @ YITP



Astrophysical sites of *r*-process

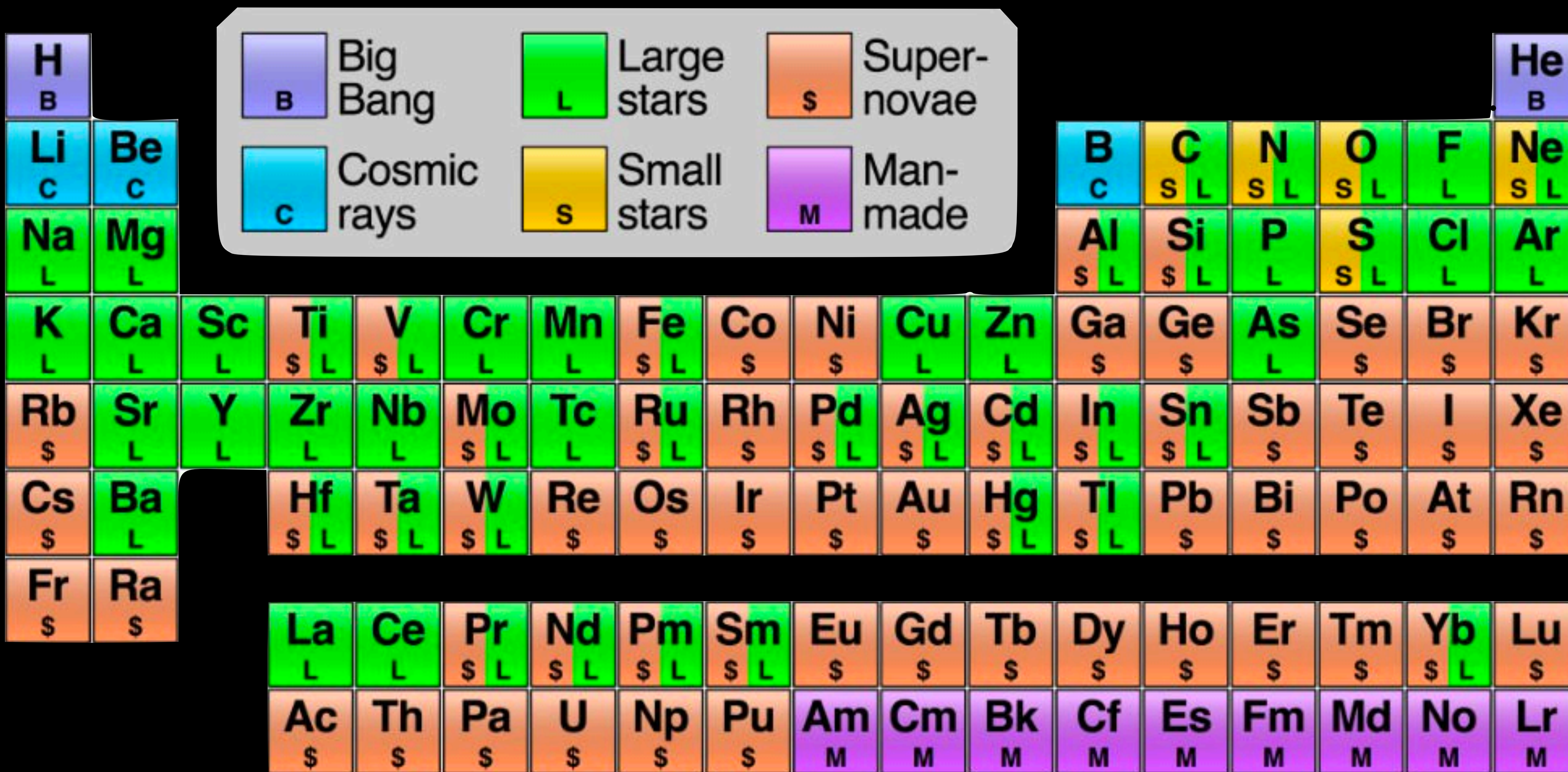


GW170817 EM counterpart confirms:

***r*-process elements produced in this event!**

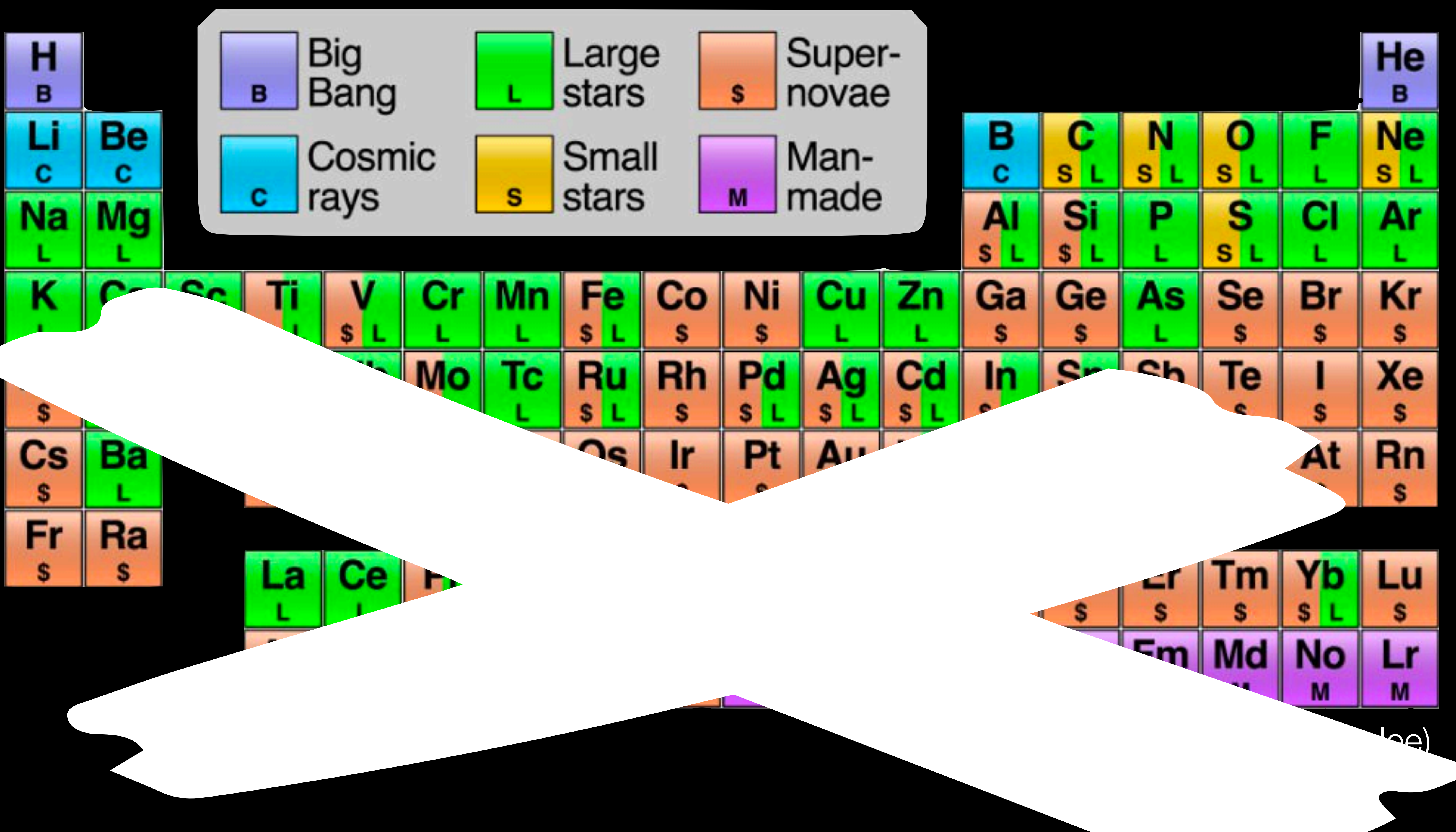
(Metzger 2019)

A paradigm shift

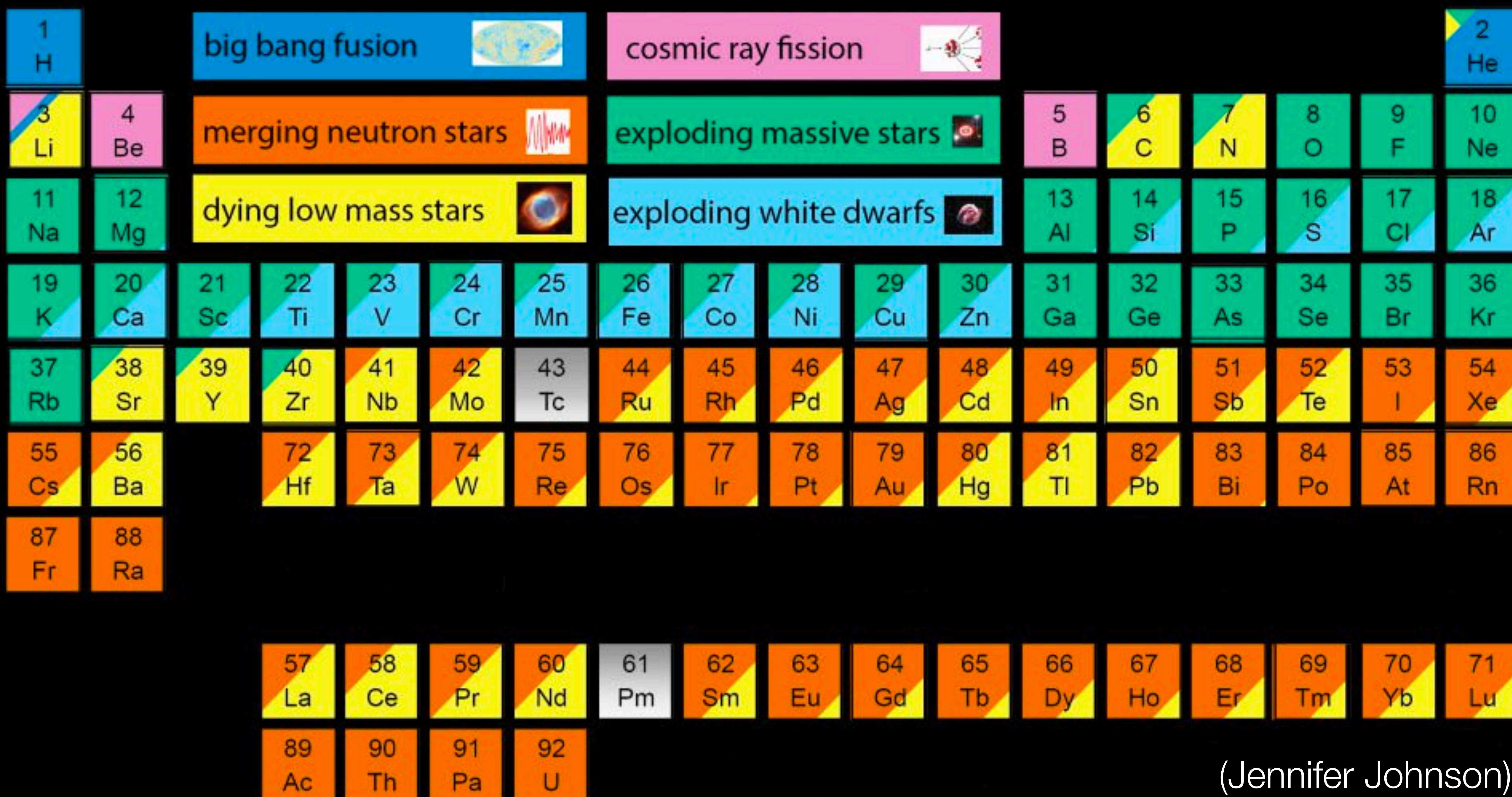


(wikipedia/Cmglee)

A paradigm shift

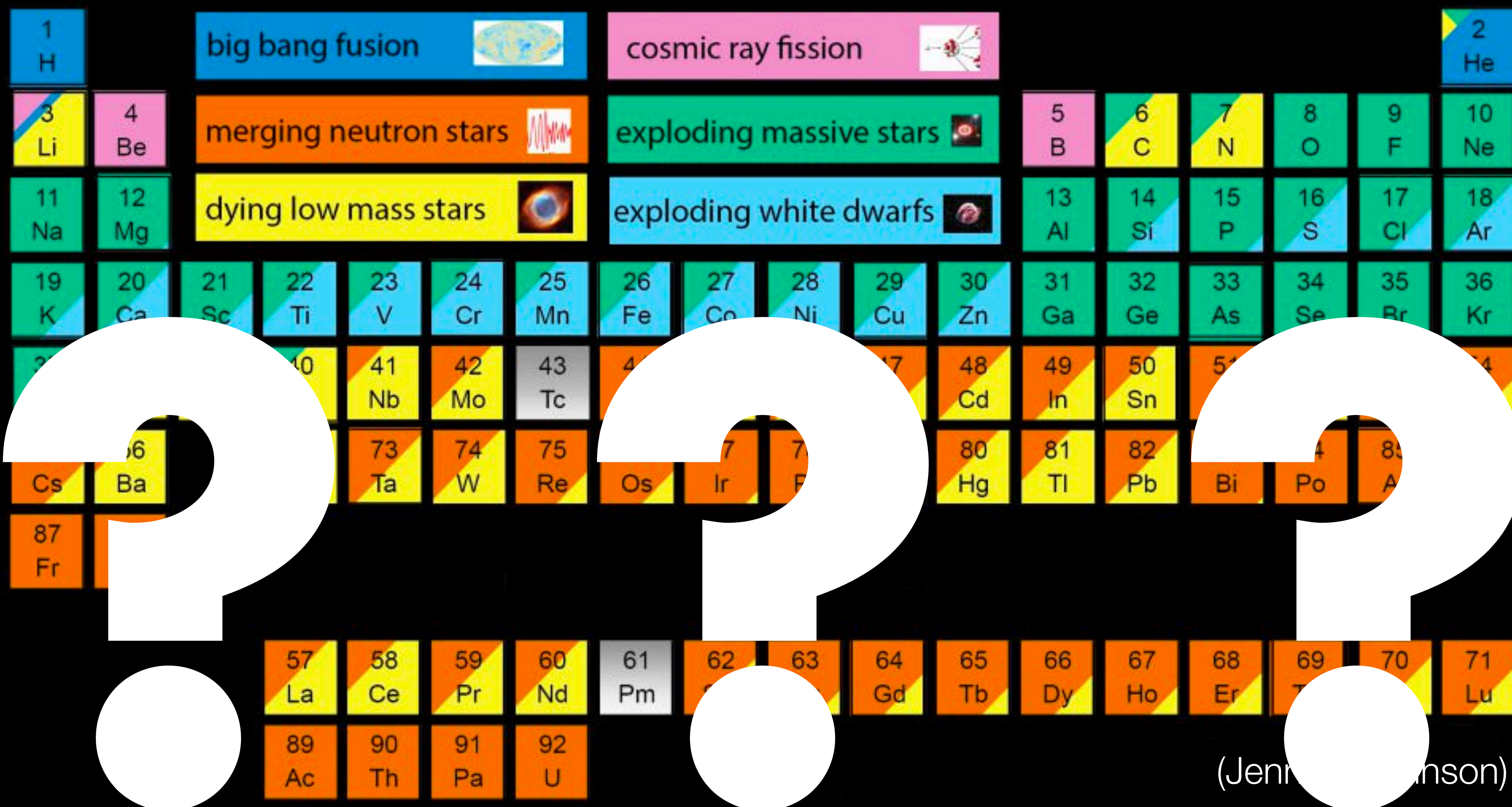


A paradigm shift

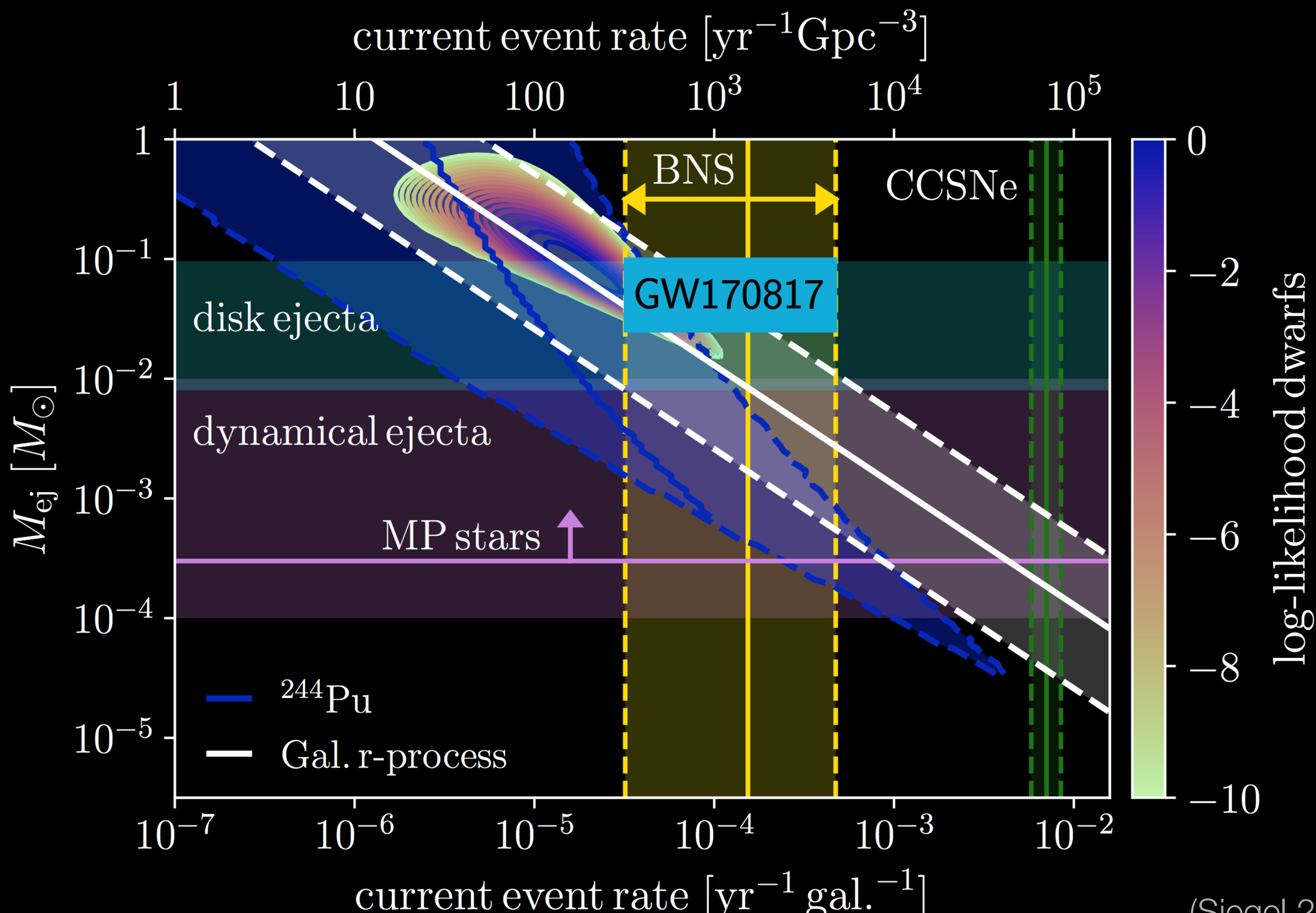


(Jennifer Johnson)

A paradigm shift

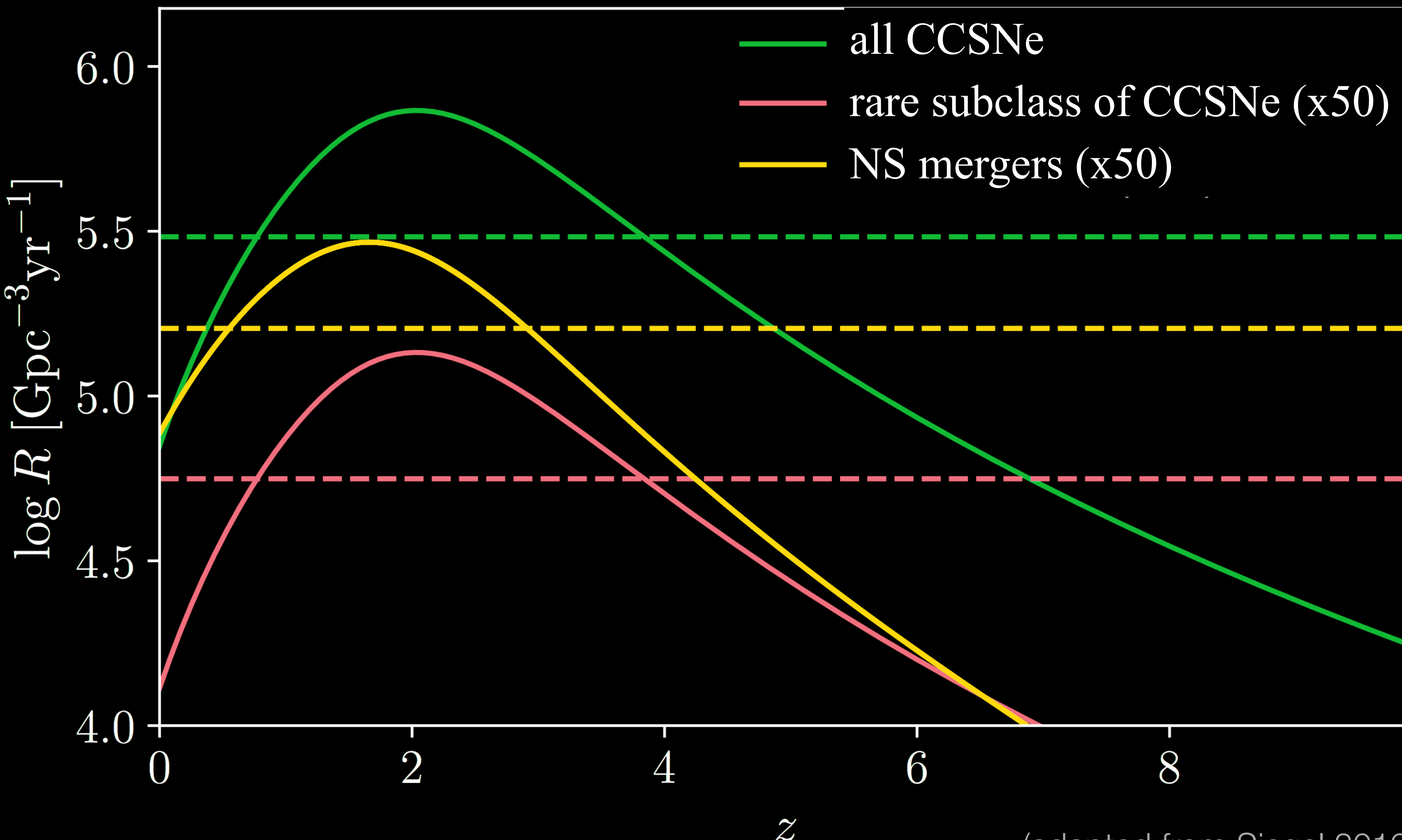


Astrophysical sites of *r*-process



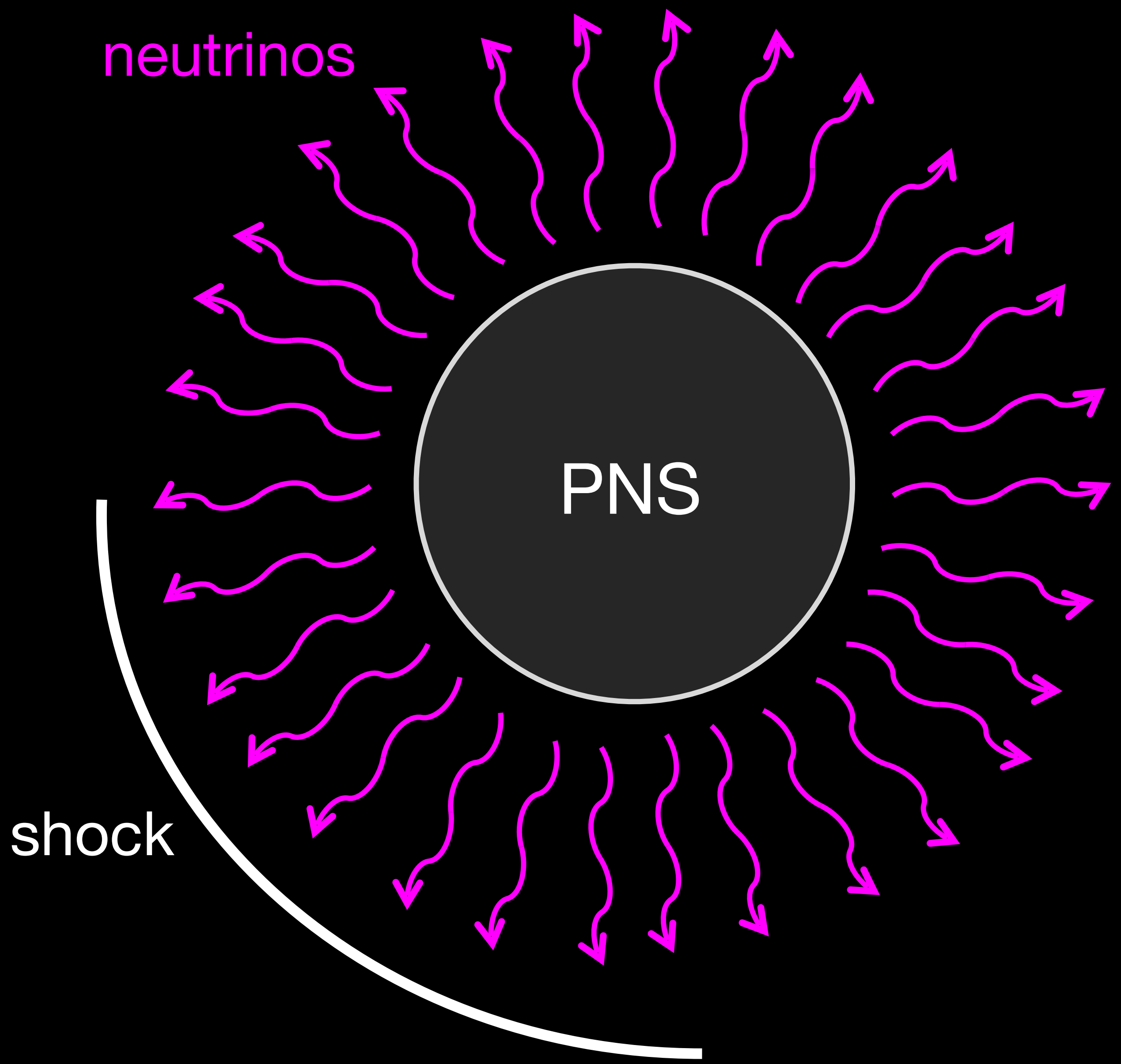
(Siegel 2019)

Astrophysical sites of *r*-process



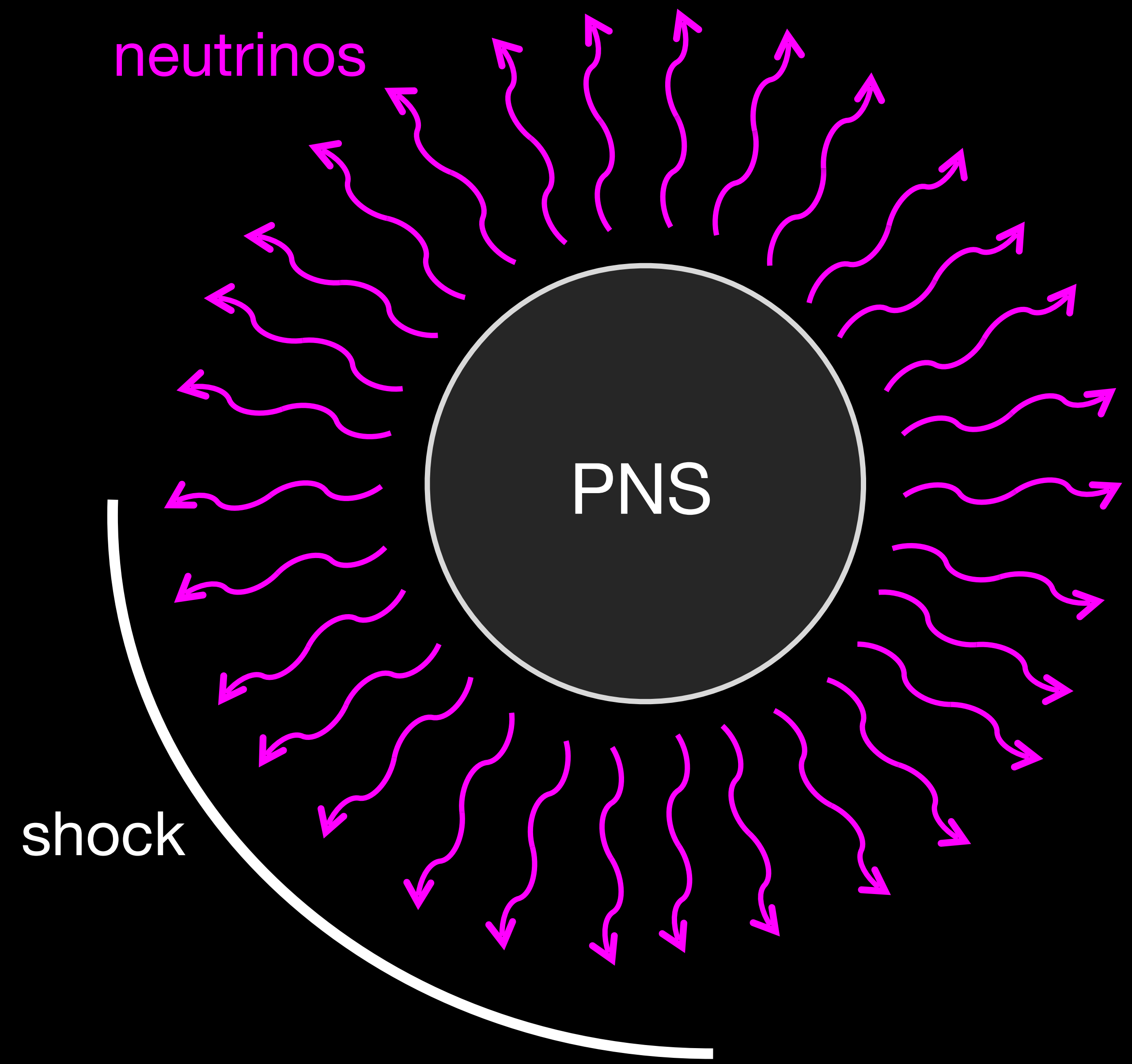
(adapted from Siegel 2019)

Core-collapse SNe

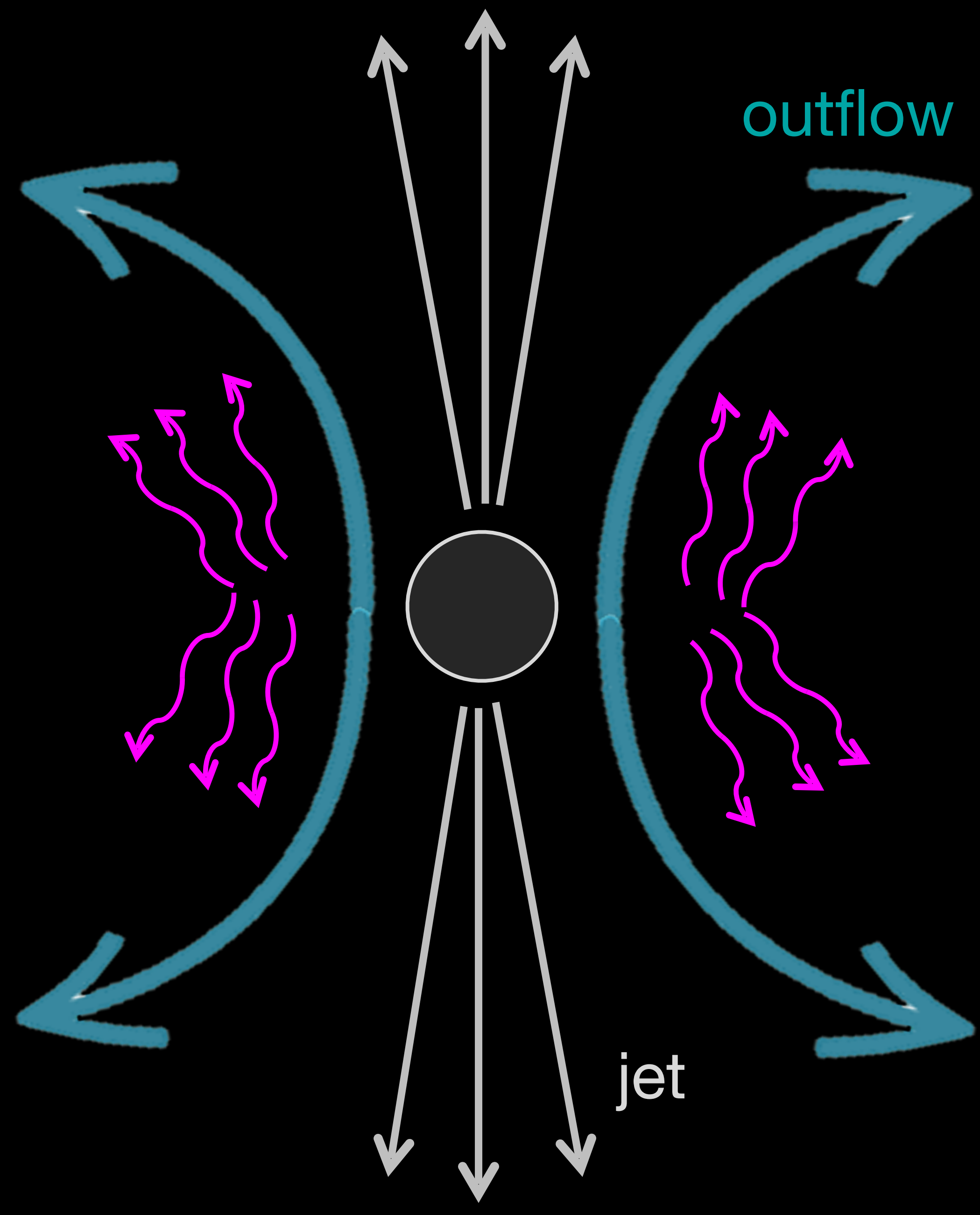


standard (neutrino-driven)

Core-collapse SNe



standard (neutrino-driven)

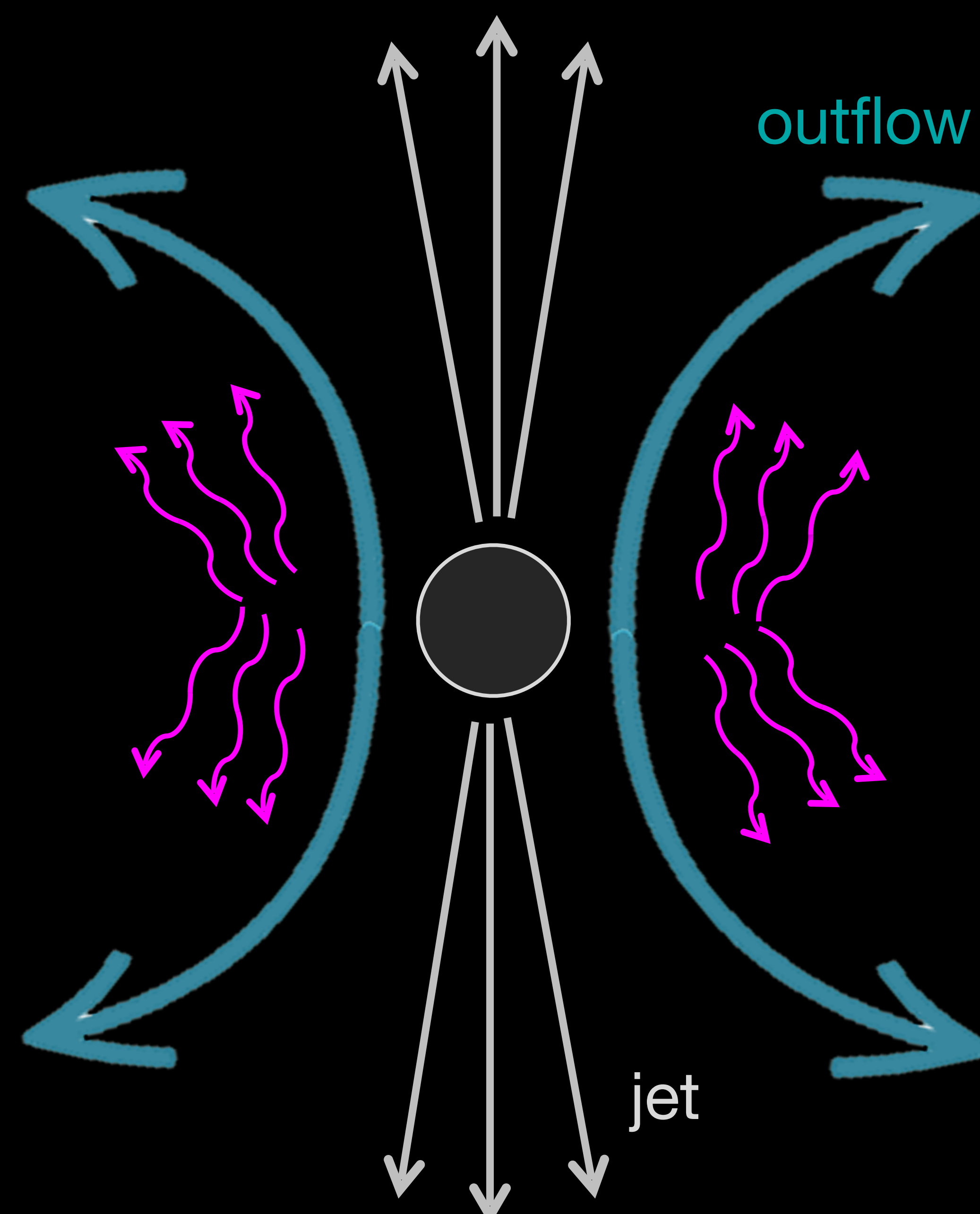


magneto-rotational or
“MHD” (jet-driven)
rare (<~1% of all CCSNe)

Core-collapse SNe

Physically motivated as engines driving **hyperenergetic** SNe of stripped-envelope progenitors

(type Ic-bl SNe)



magneto-rotational or "MHD" (jet-driven)

rare (<~1% of all CCSNe)

Methods & set-up

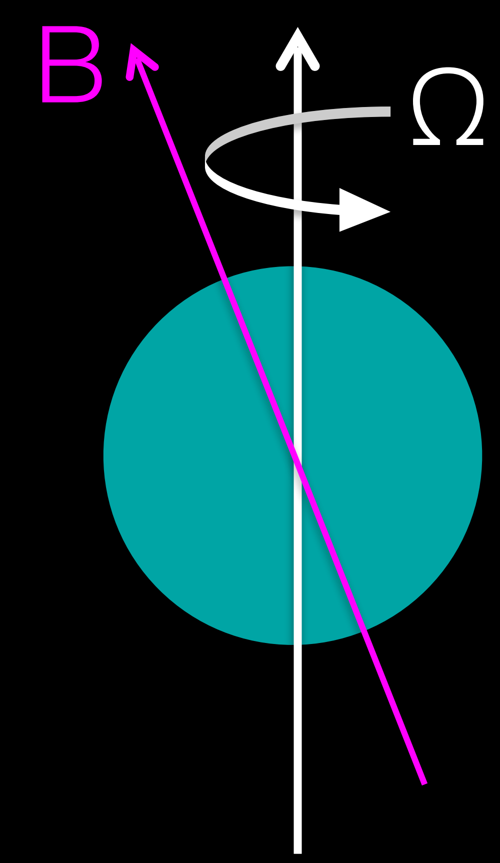
- Full dynamical-spacetime **3D GRMHD**
- Neutrino leakage scheme
- Progenitor: E25 (Heger+ 2000)
- Add strong modified dipole magnetic field
  - **$B = 10^{13}$ G** (progenitor core)
  - **$B \sim 10^{16}$ G** (PNS)
- Add rapid rotation
  - **1.18 ms** (PNS)
- **20,000** Lagrangian tracer particles

einstein toolkit

Models & parameters

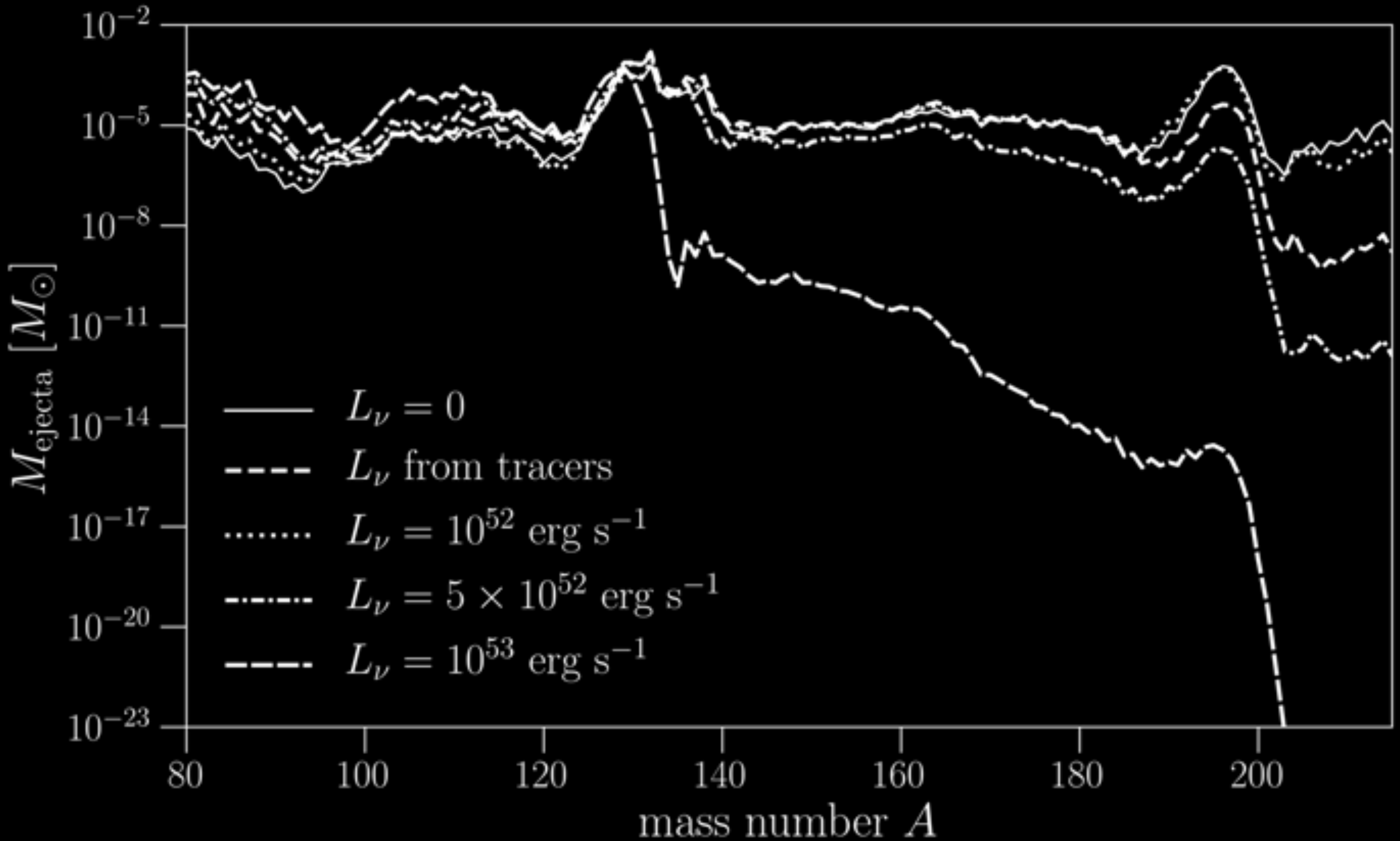
- Vary **neutrino luminosities** (L_ν) to account for approximate leakage scheme
  - Set in post-processing (with SkyNet)

- Explore **misaligned** magnetic fields
  - Parameterizes importance of **field configuration**
  - Fiducial aligned model, + 15, 30, and 45 deg. misalignments



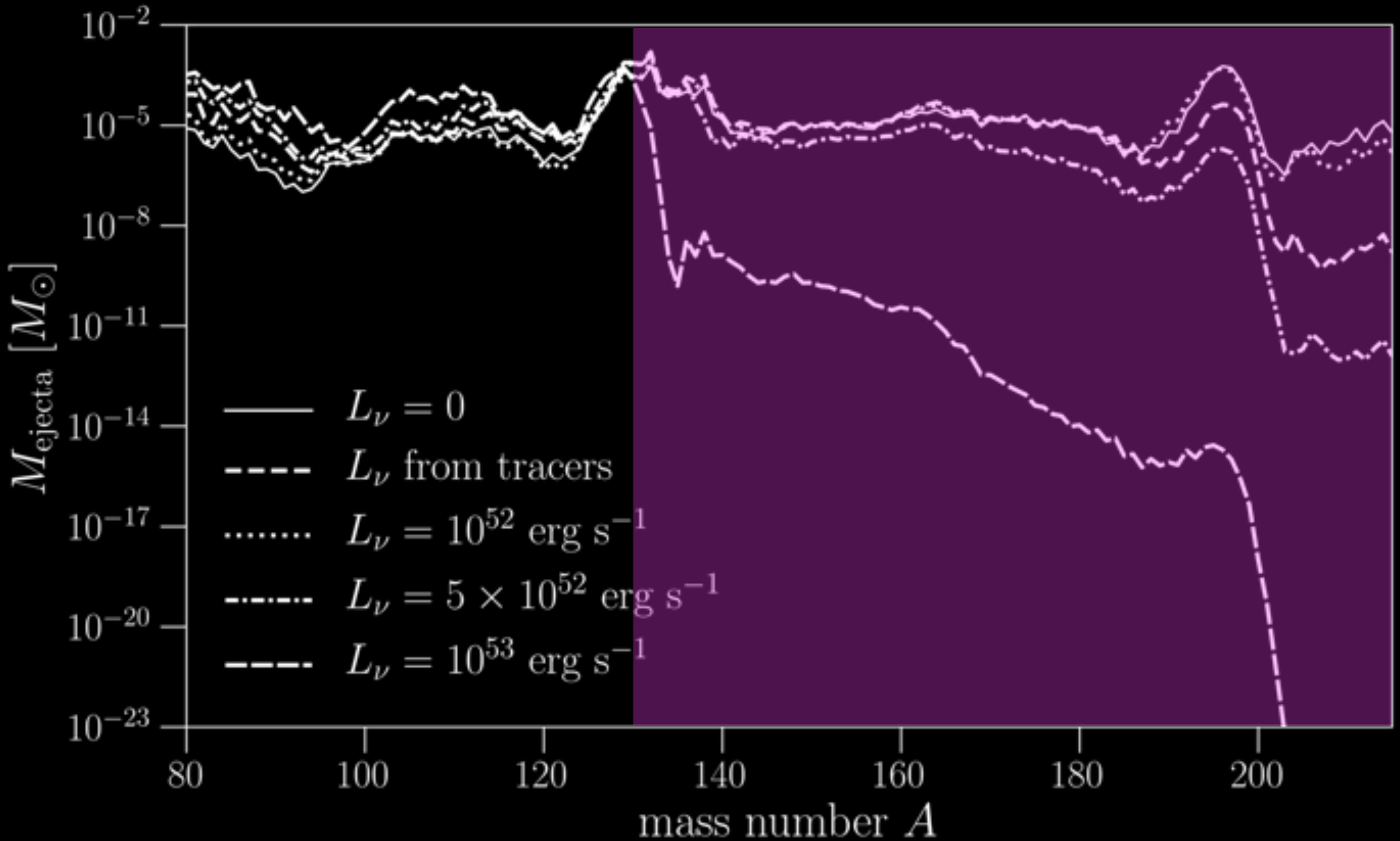
(GH&PM 2018)

Effects of L_ν



(GH&PM 2018)

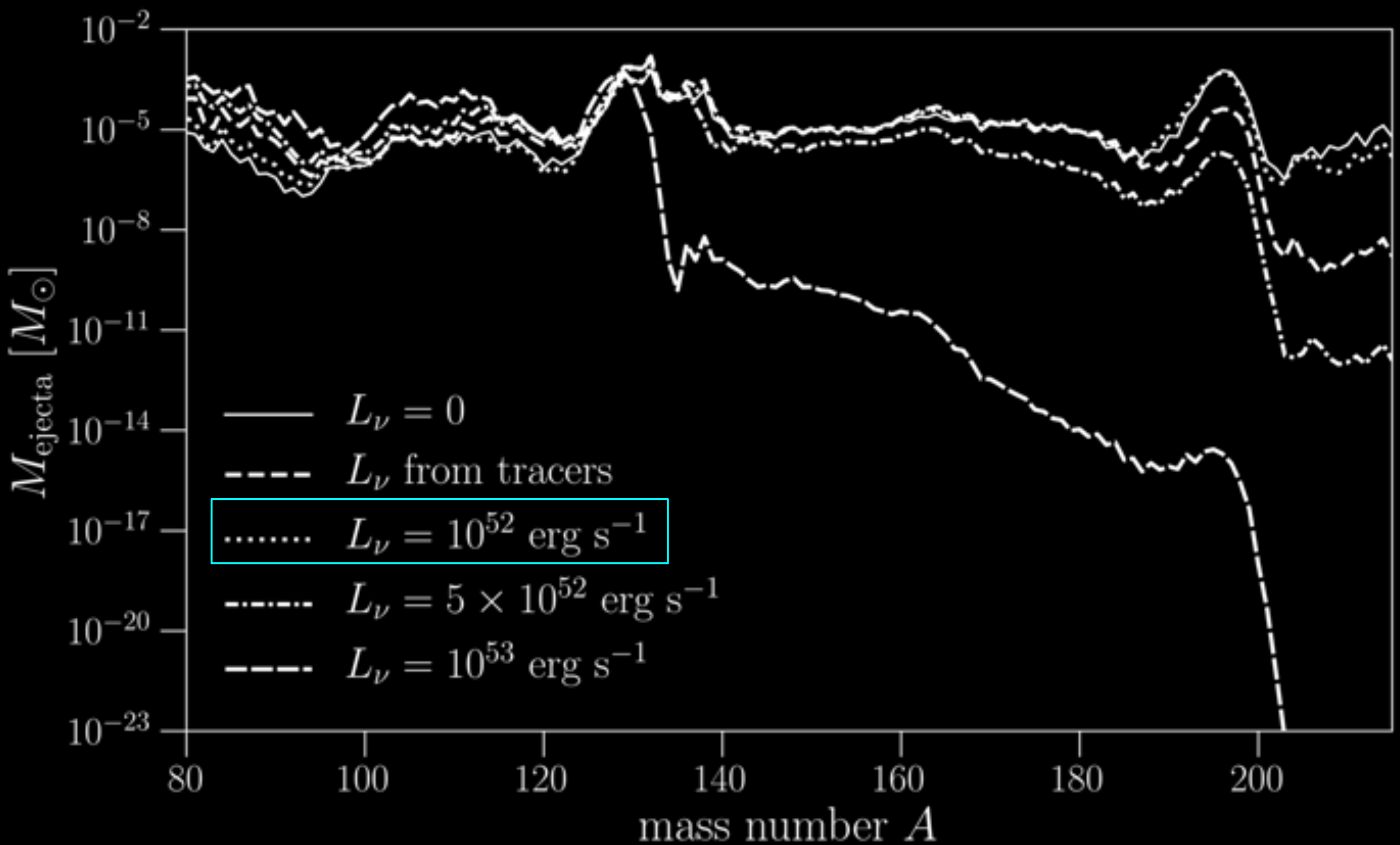
Effects of L_ν



- 2nd peak and beyond most affected

(GH&PM 2018)

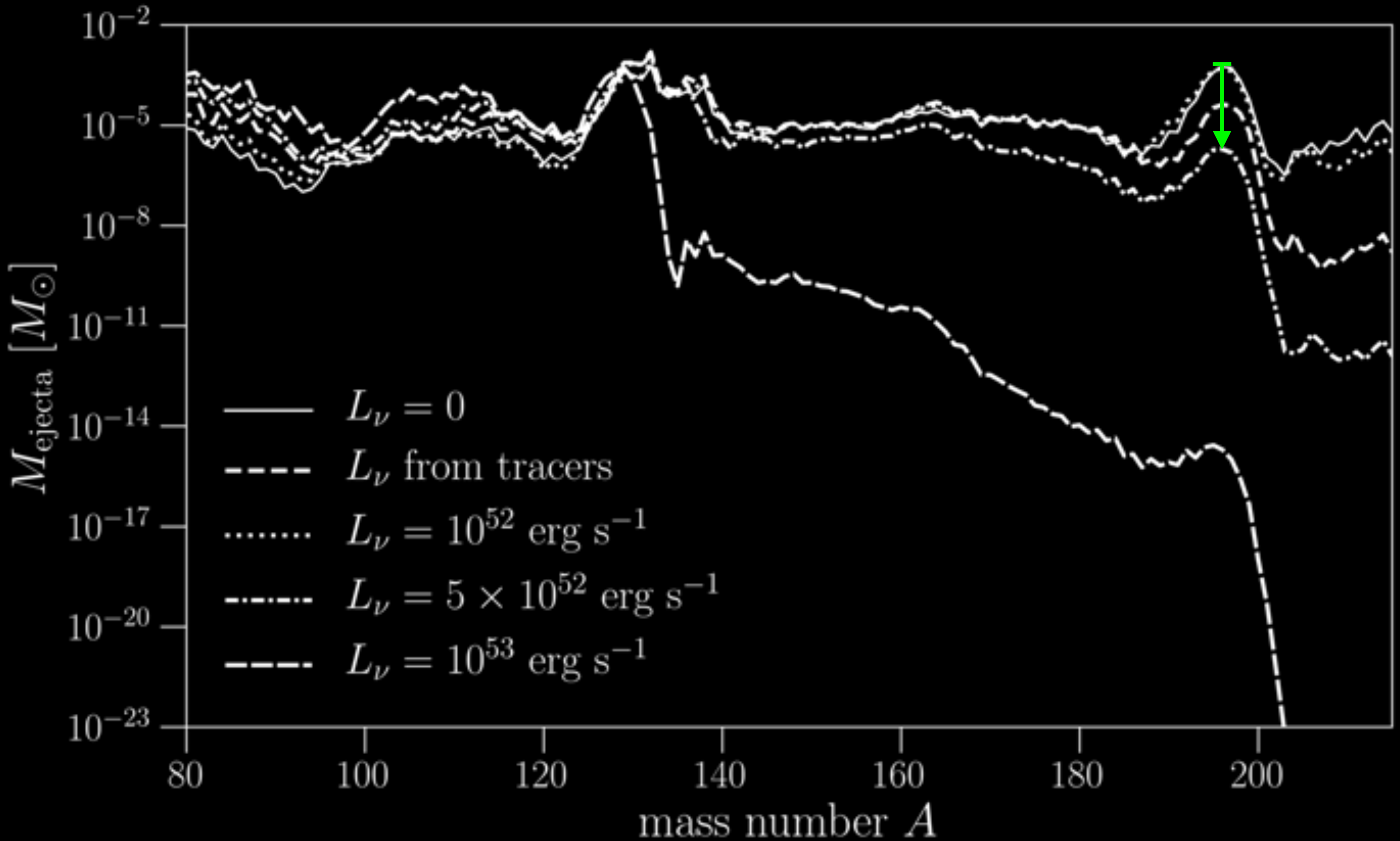
Effects of L_ν



- 2nd peak and beyond most affected
- Virtually no effect for $L_\nu \lesssim 10^{52}$ erg/s

(GH&PM 2018)

Effects of L_ν

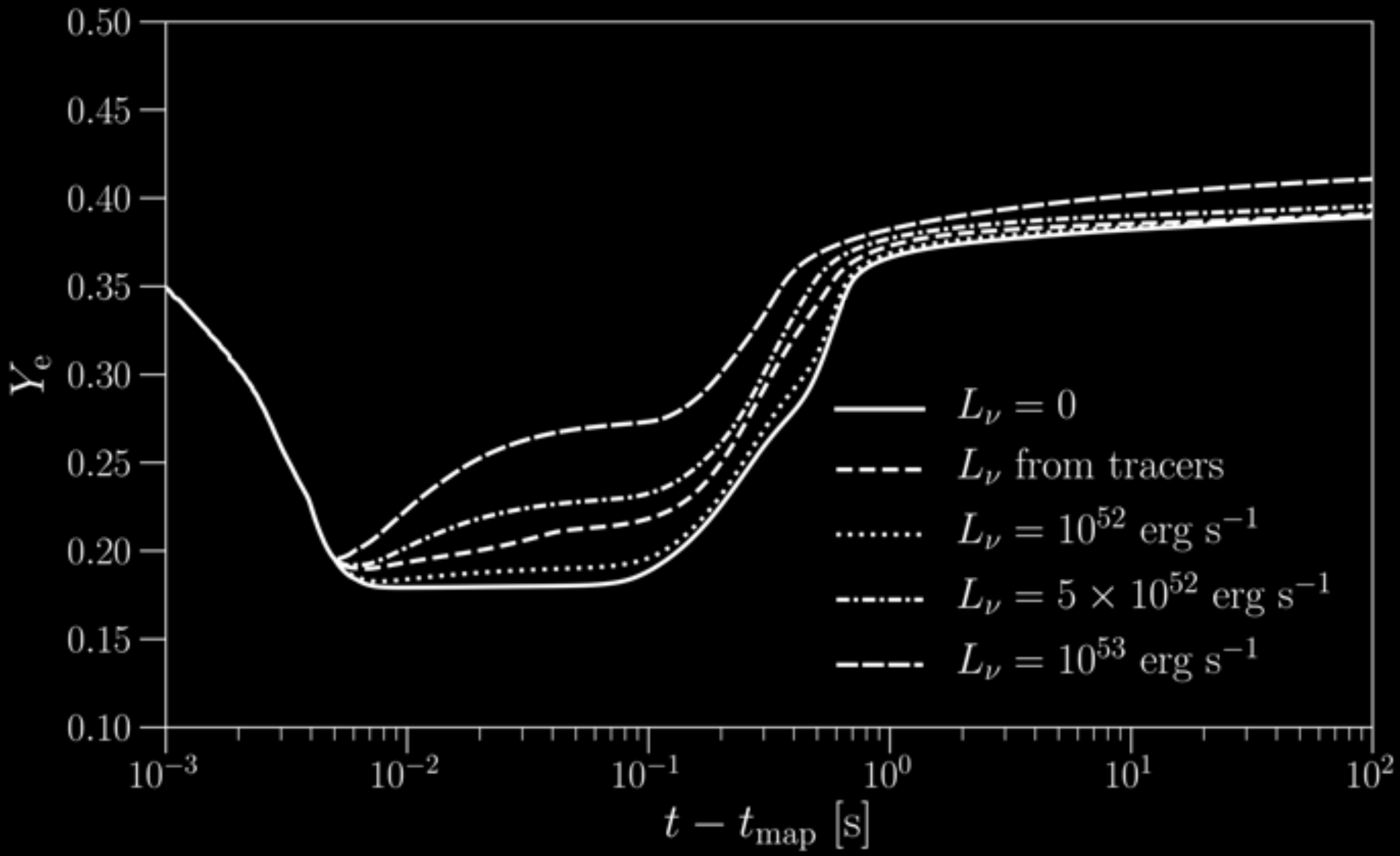


- 2nd peak and beyond most affected
- Virtually no effect for $L_\nu \lesssim 10^{52}$ erg/s

- 3rd peak: suppressed by ~10^3 for 10^{52} —> 5 x 10^{52} erg/s

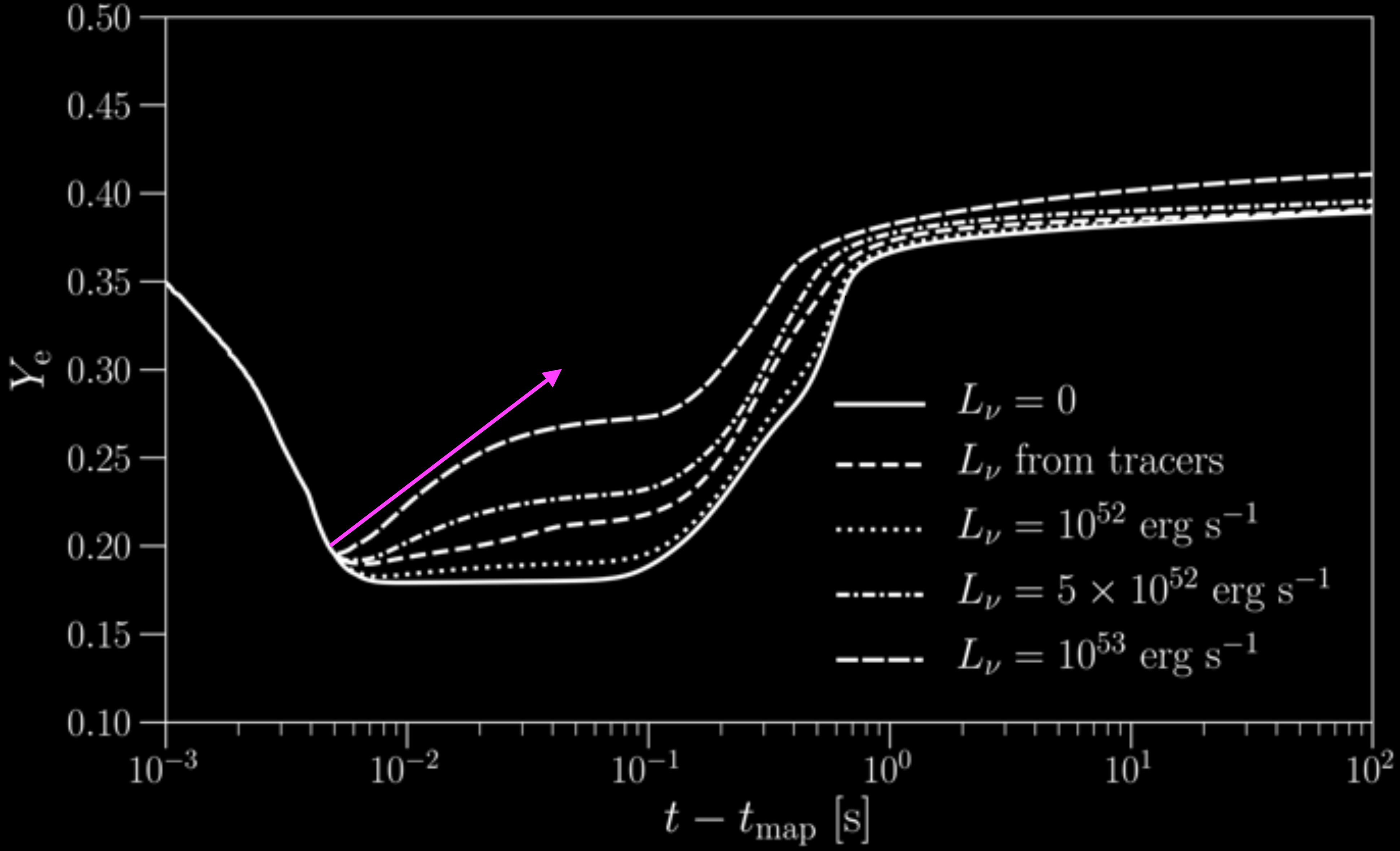
(GH&PM 2018)

Y_e evolution



(GH&PM 2018)

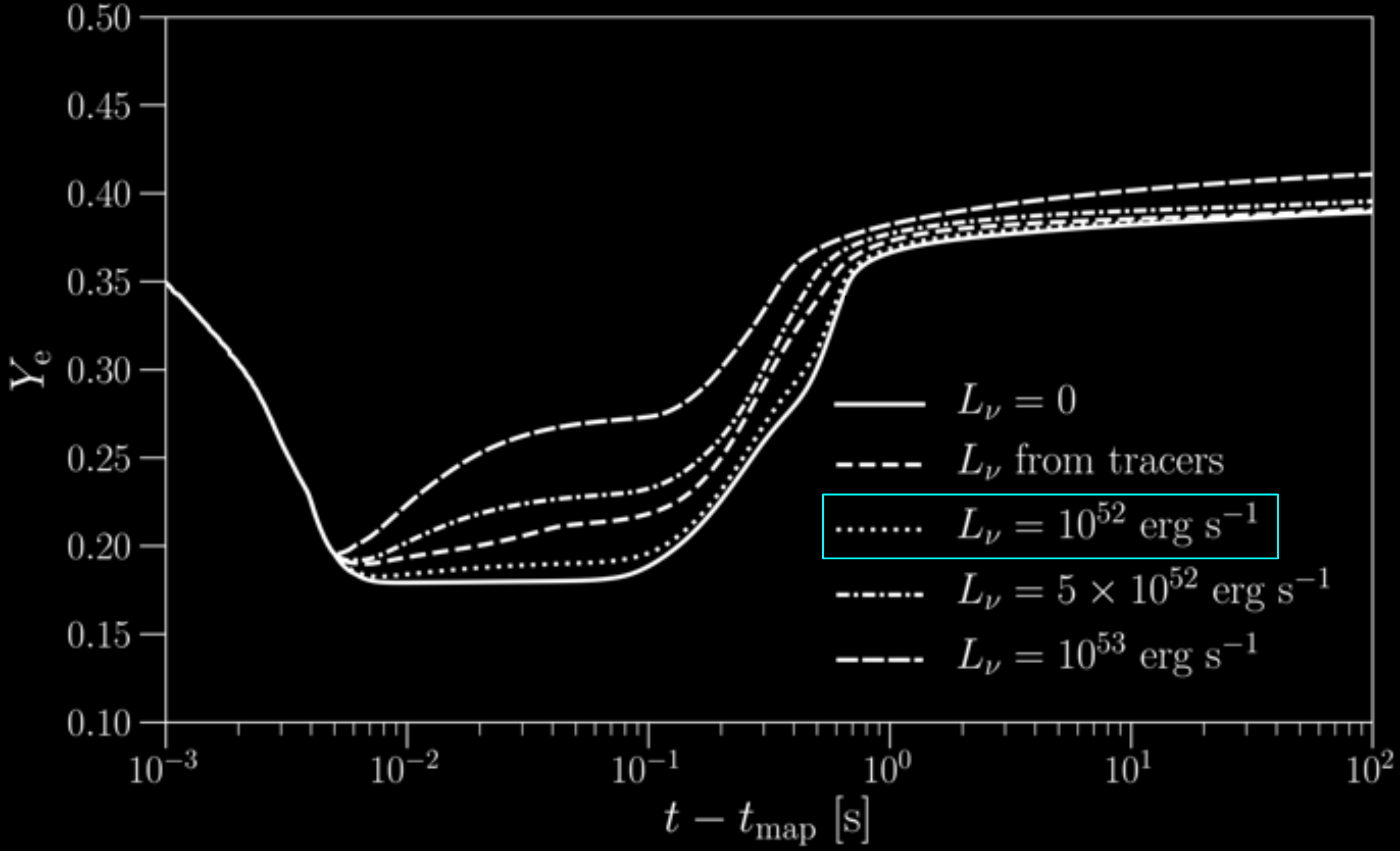
Y_e evolution



- Y_e rises steeply for higher L_ν

(GH&PM 2018)

Y_e evolution



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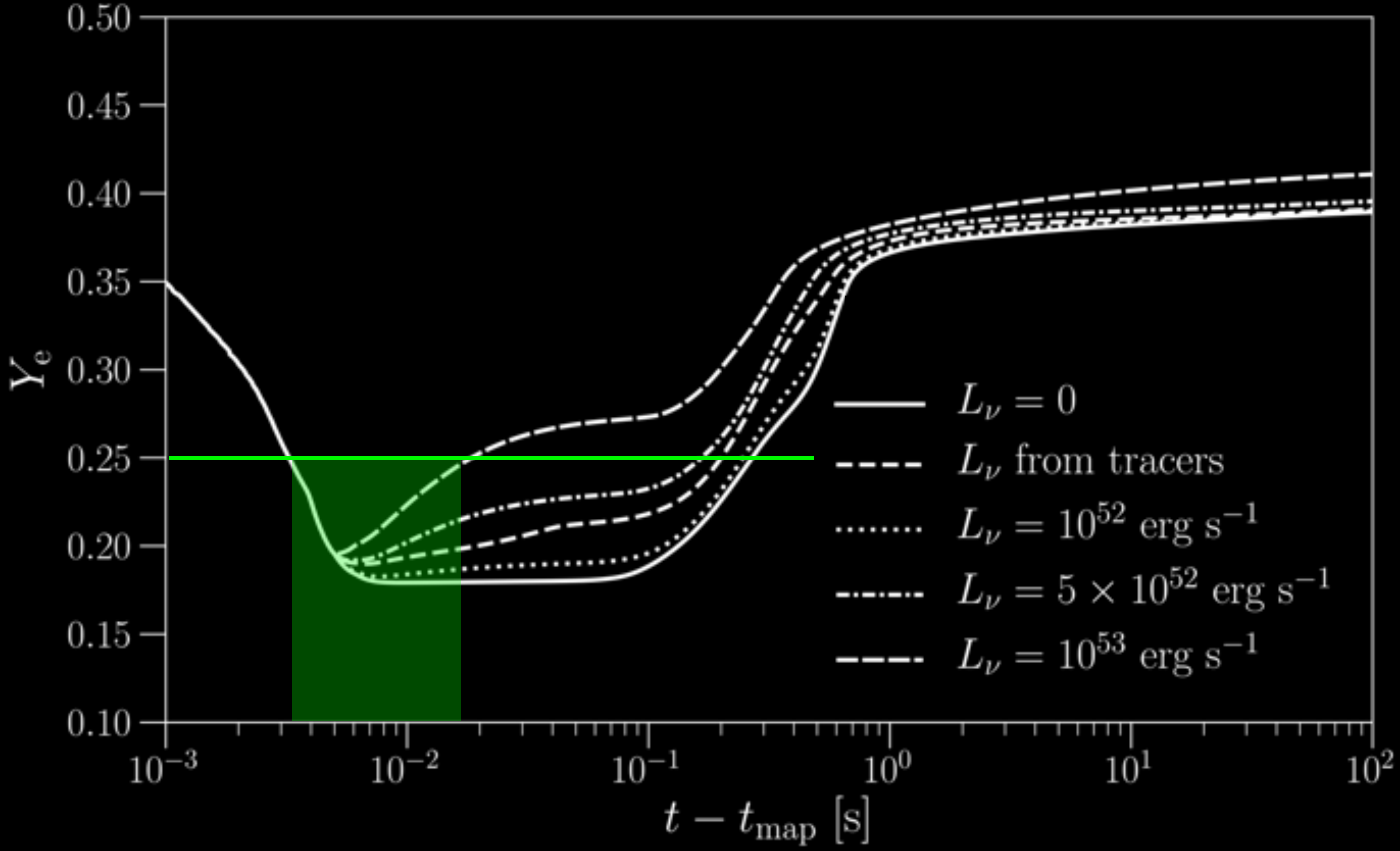
(GH&PM 2018)

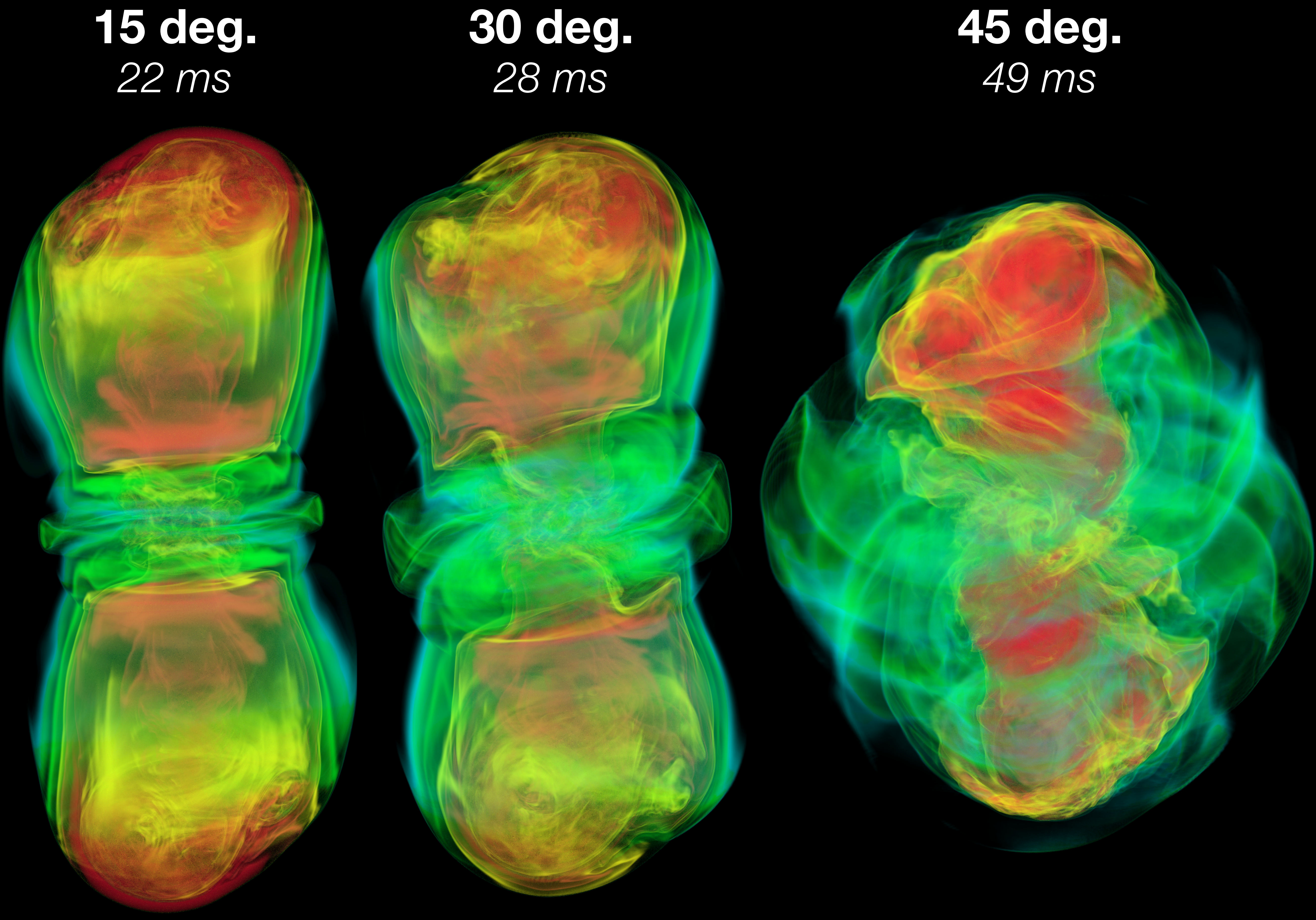
Y_e evolution



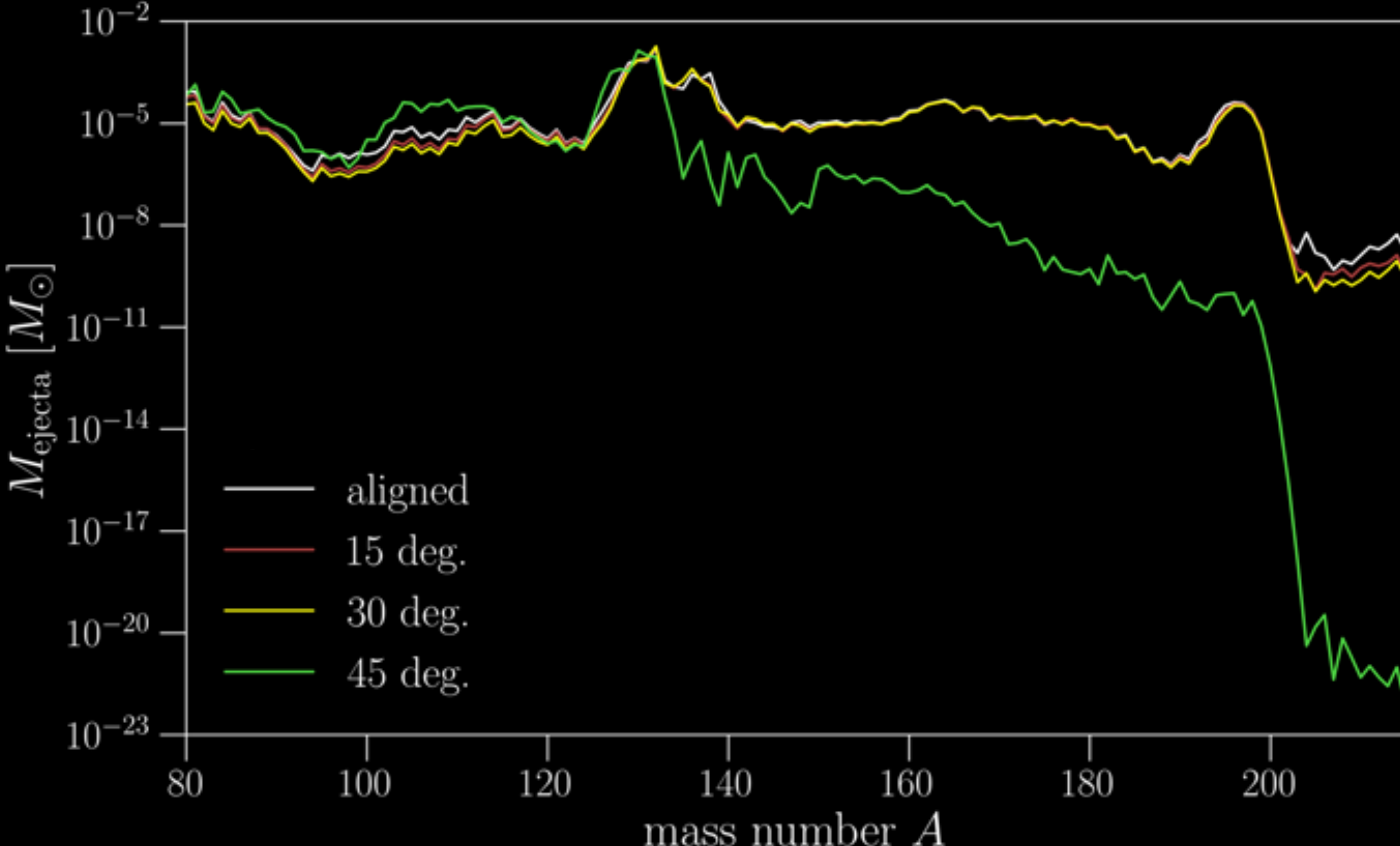
- Y_e rises steeply for higher L_ν
- Virtually no effect for $L_\nu \lesssim 10^{52}$ erg/s

- Material spends less time at low Y_e for higher L_ν

(GH&PM 2018)


15 deg.
22 ms
30 deg.
28 ms
45 deg.
49 ms

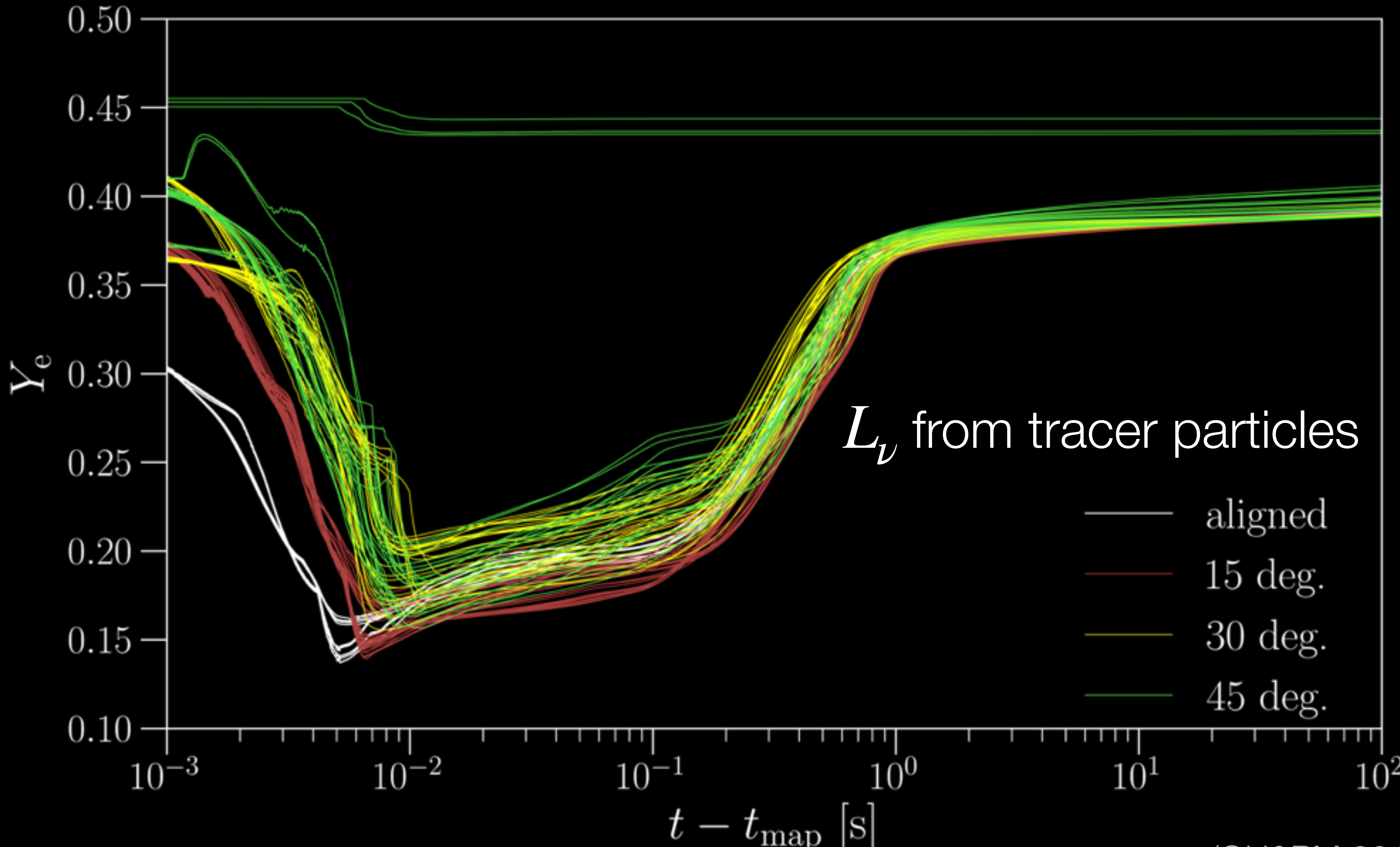
Effects of *B*-field misalignment



3rd peak production: robust for all but **45 deg.** case

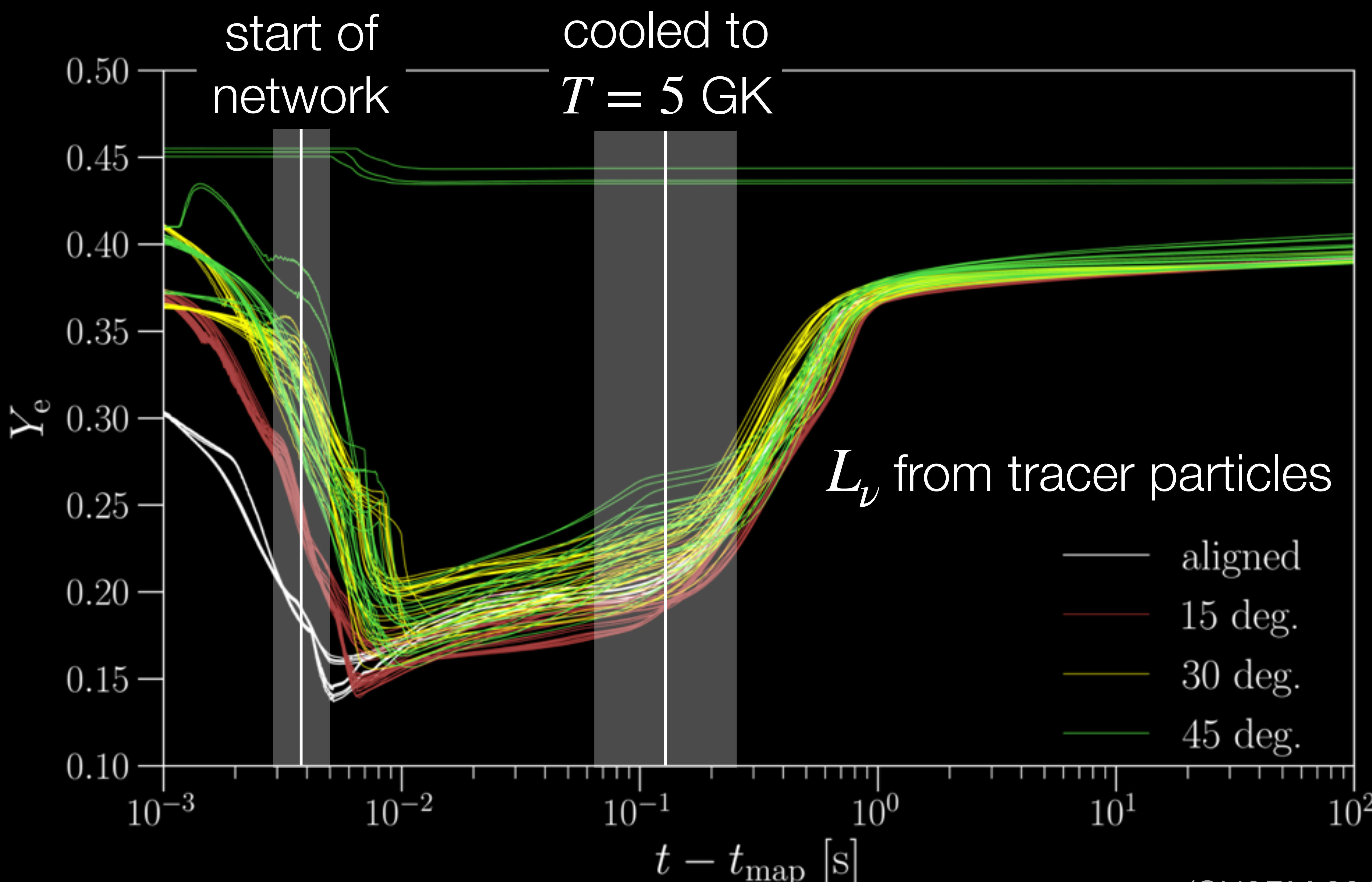
(GH&PM 2018)

Y_e evolution



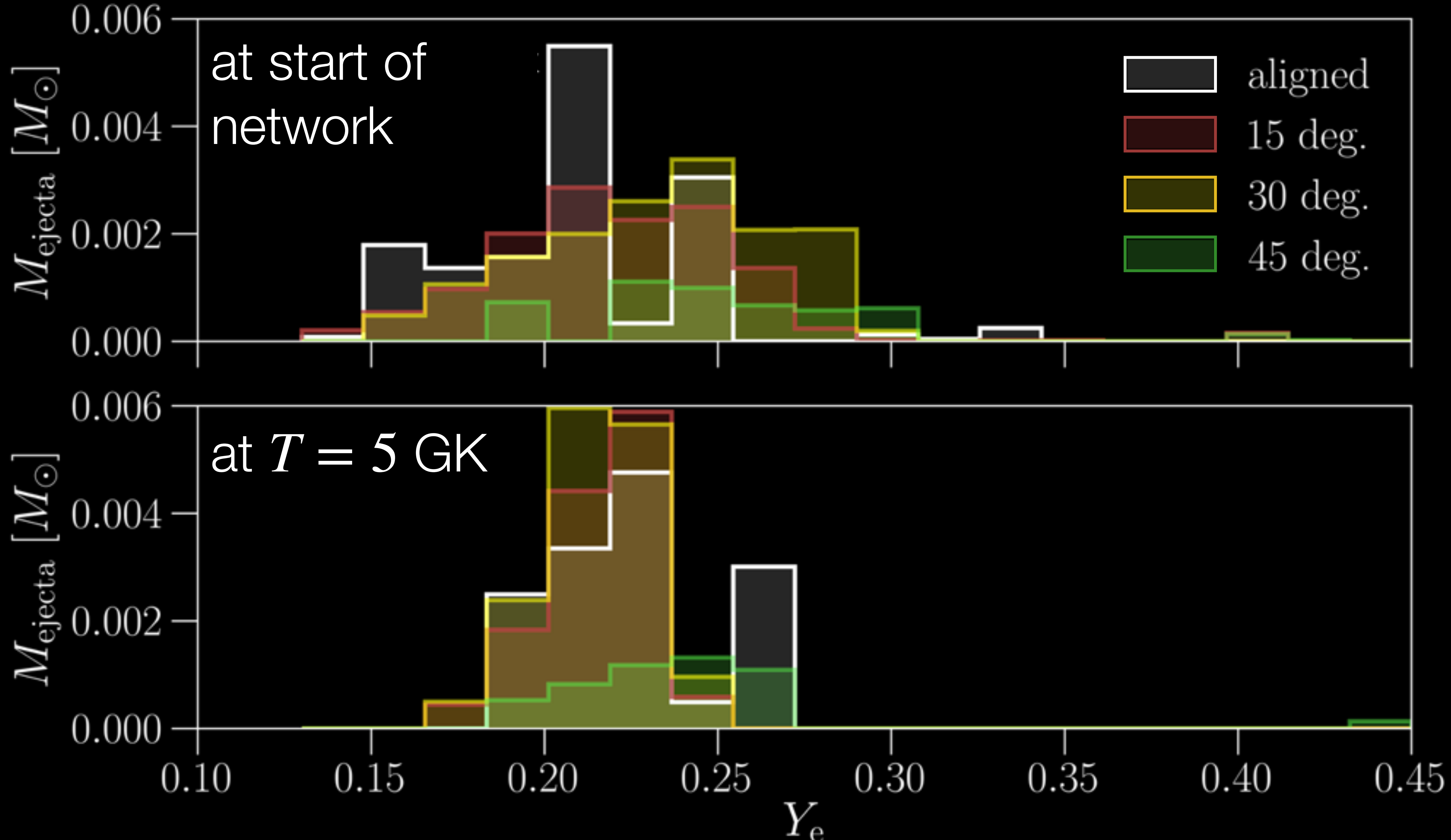
(GH&PM 2018)

Y_e evolution



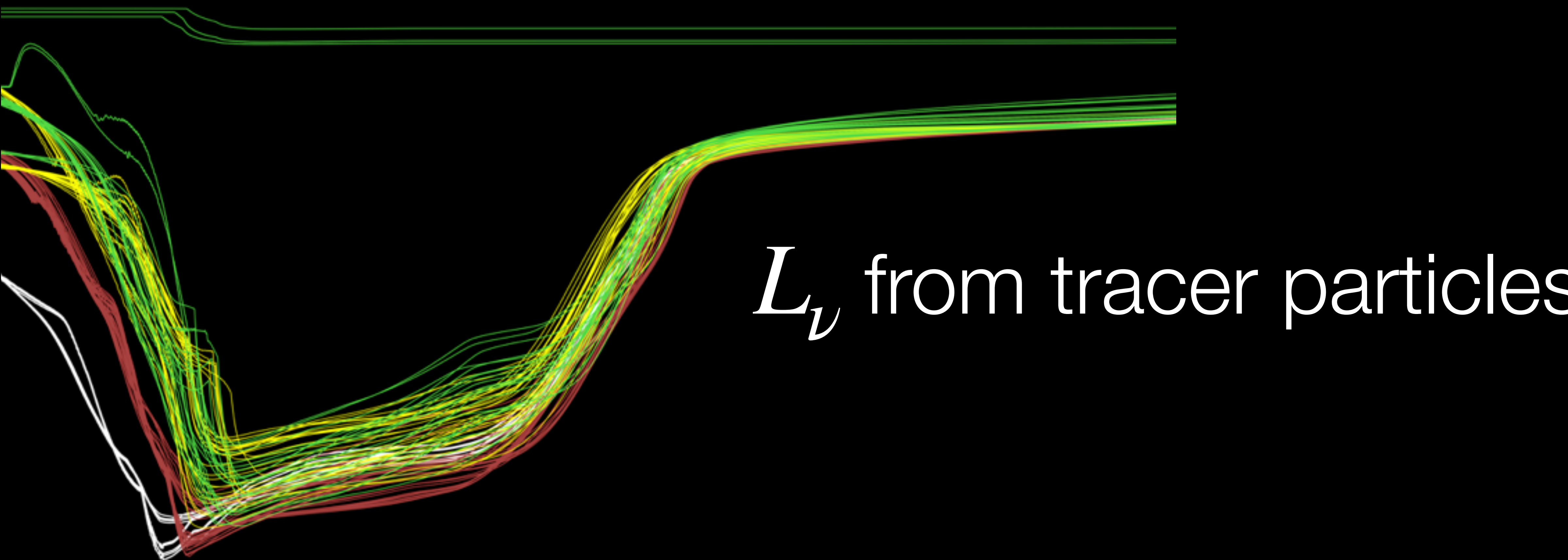
(GH&PM 2018)

Y_e distribution

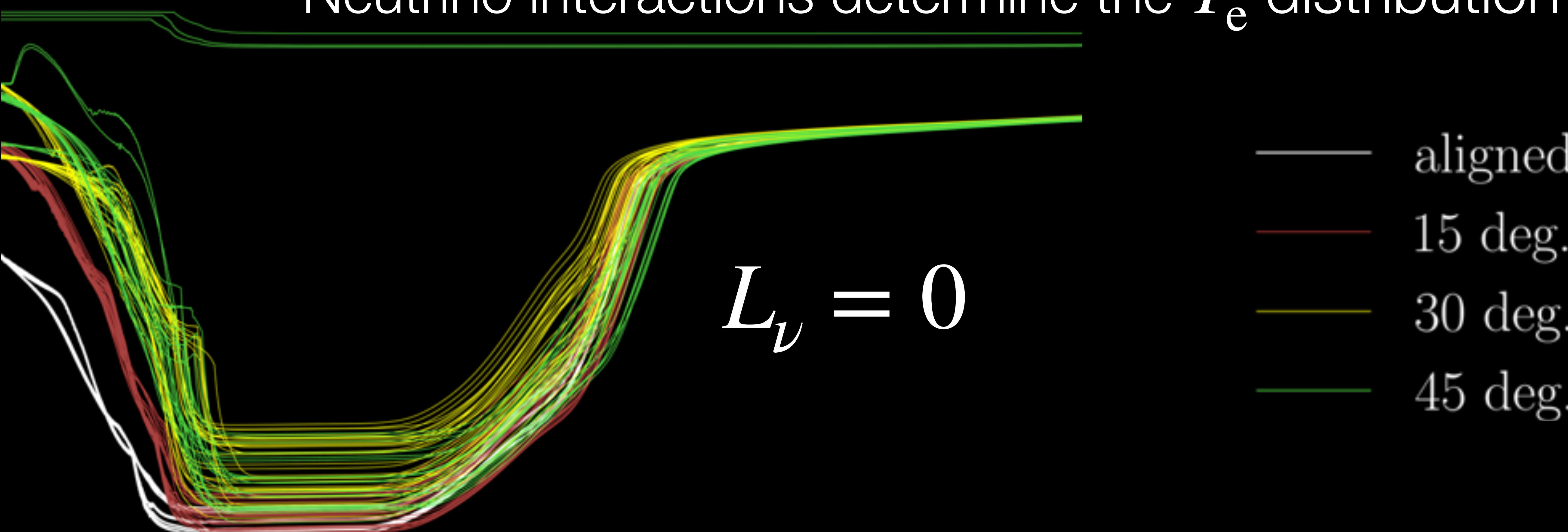


Y_e distribution determines the nucleosynthesis

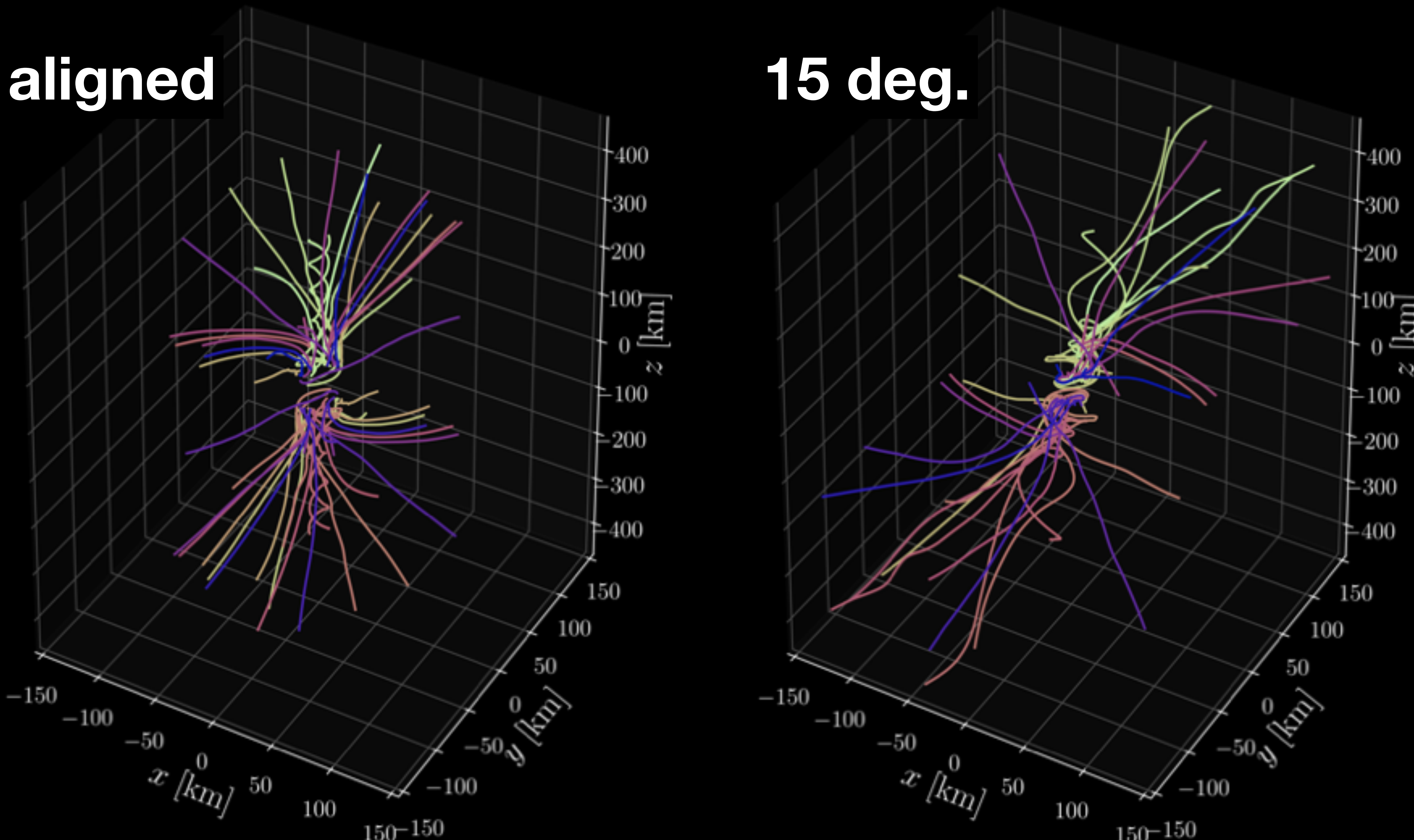
(GH&PM 2018)



Neutrino interactions determine the Y_e distribution



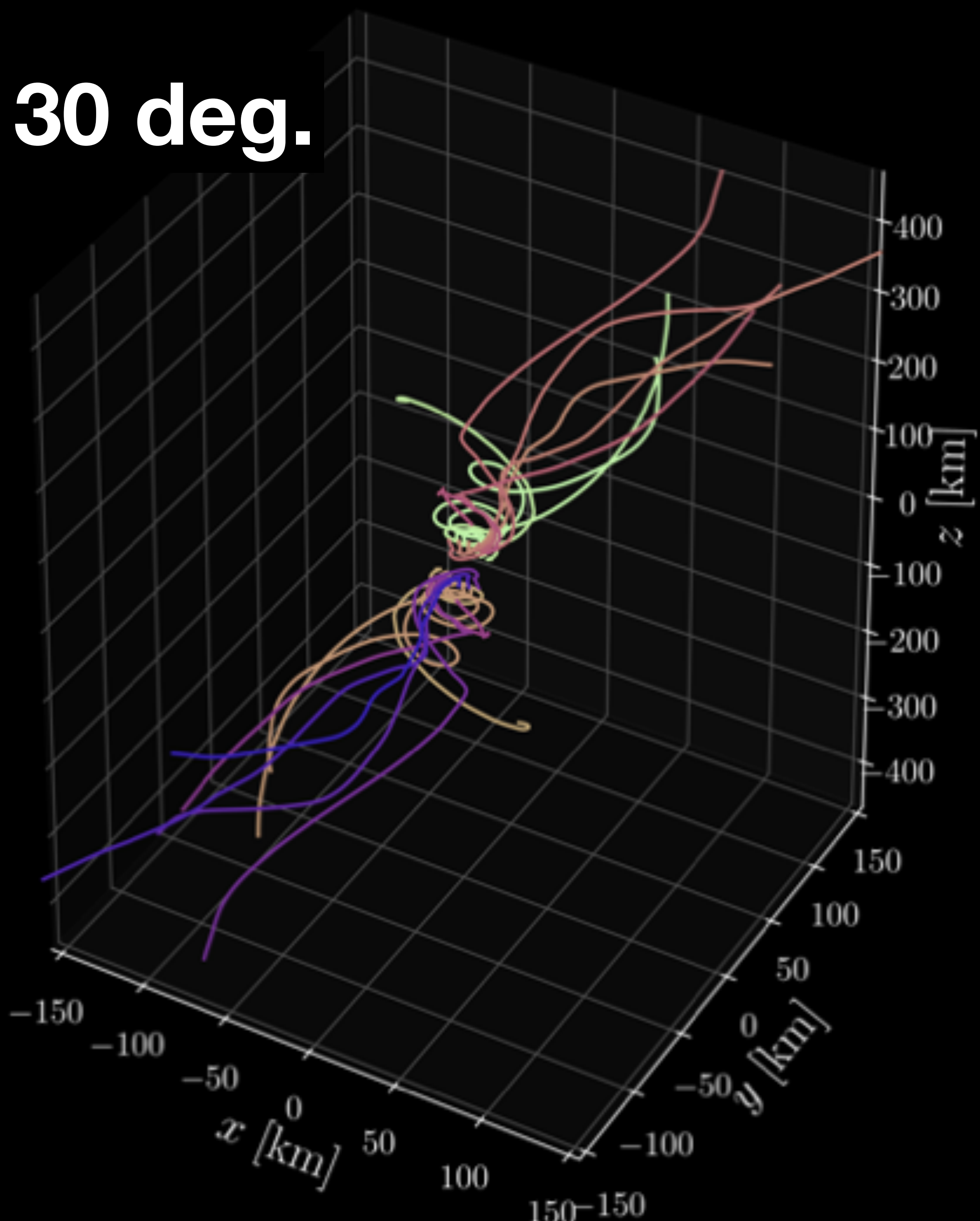
Tracer trajectories: 3D



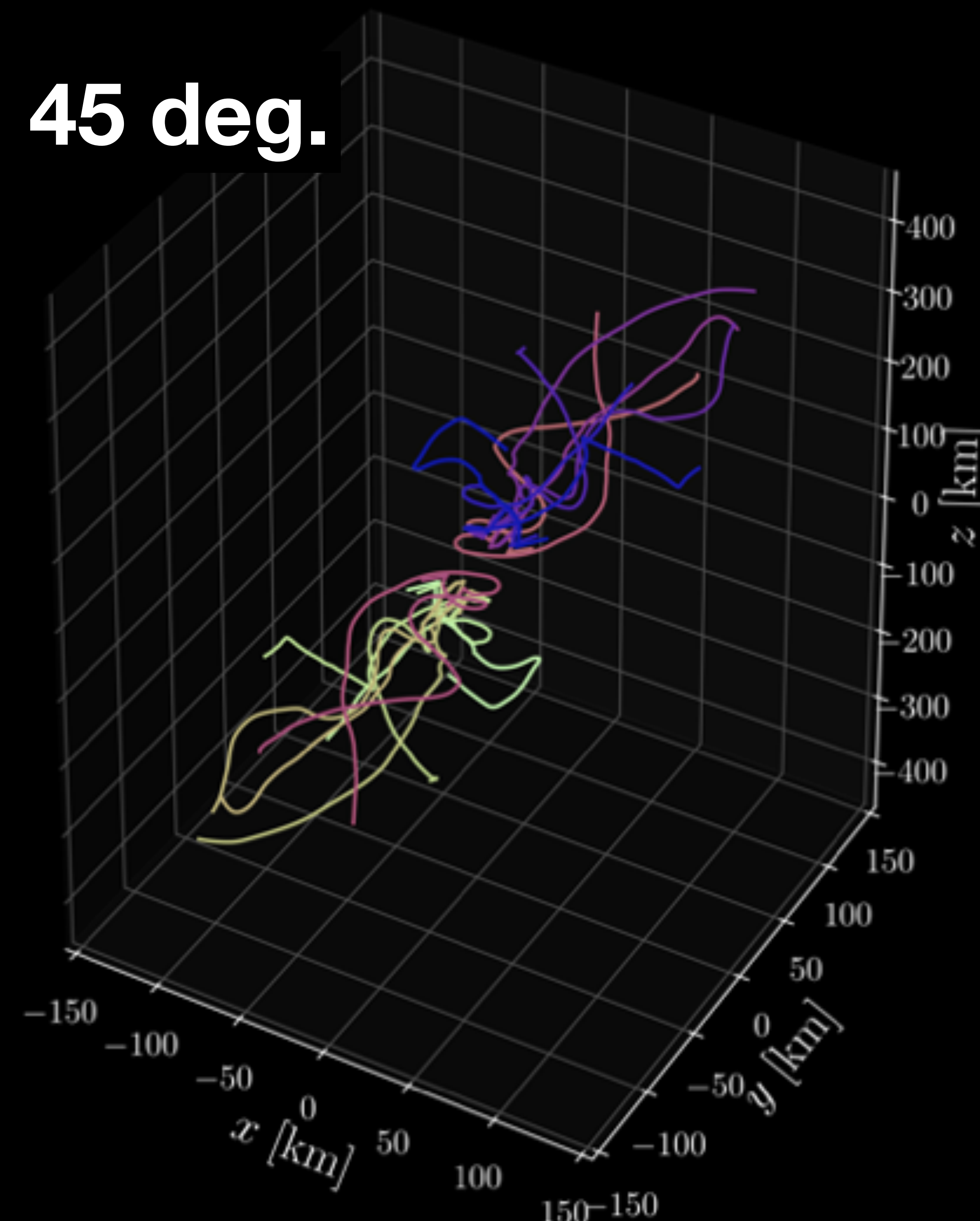
(GH&PM 2018)

Tracer trajectories: 3D

30 deg.

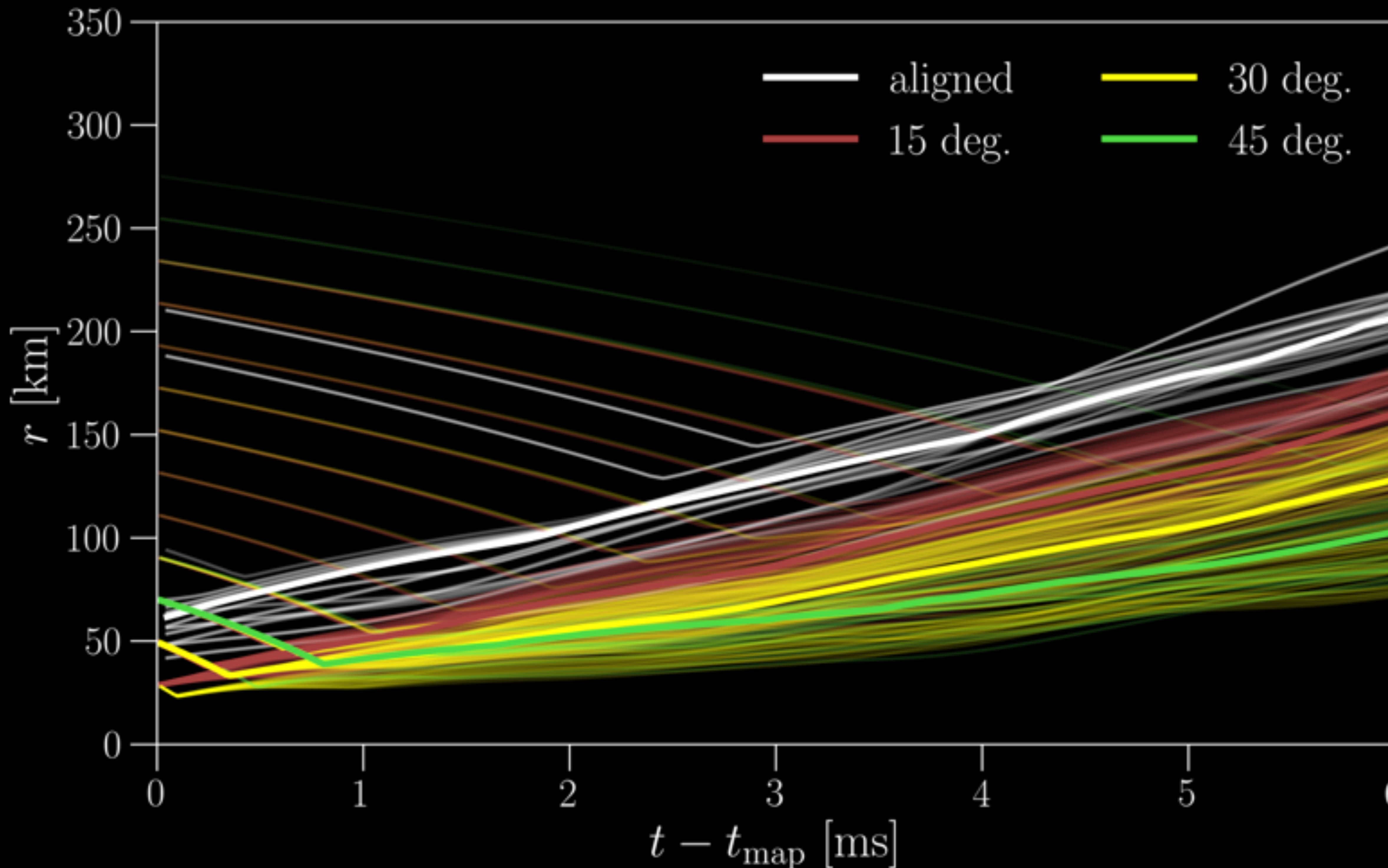


45 deg.



(GH&PM 2018)

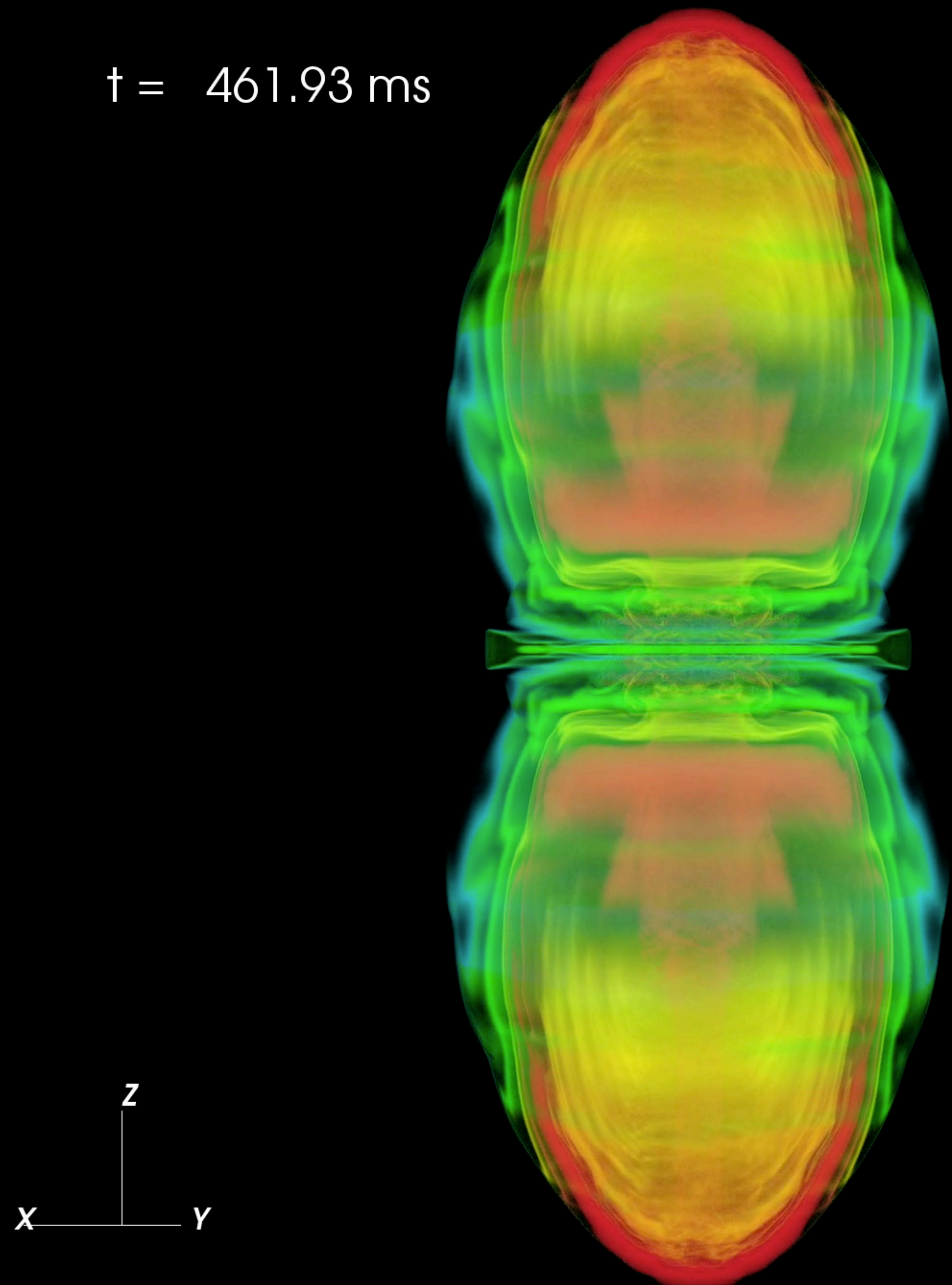
Tracer trajectories: 1D



Dynamics (dwelling time) determine the neutrino interactions

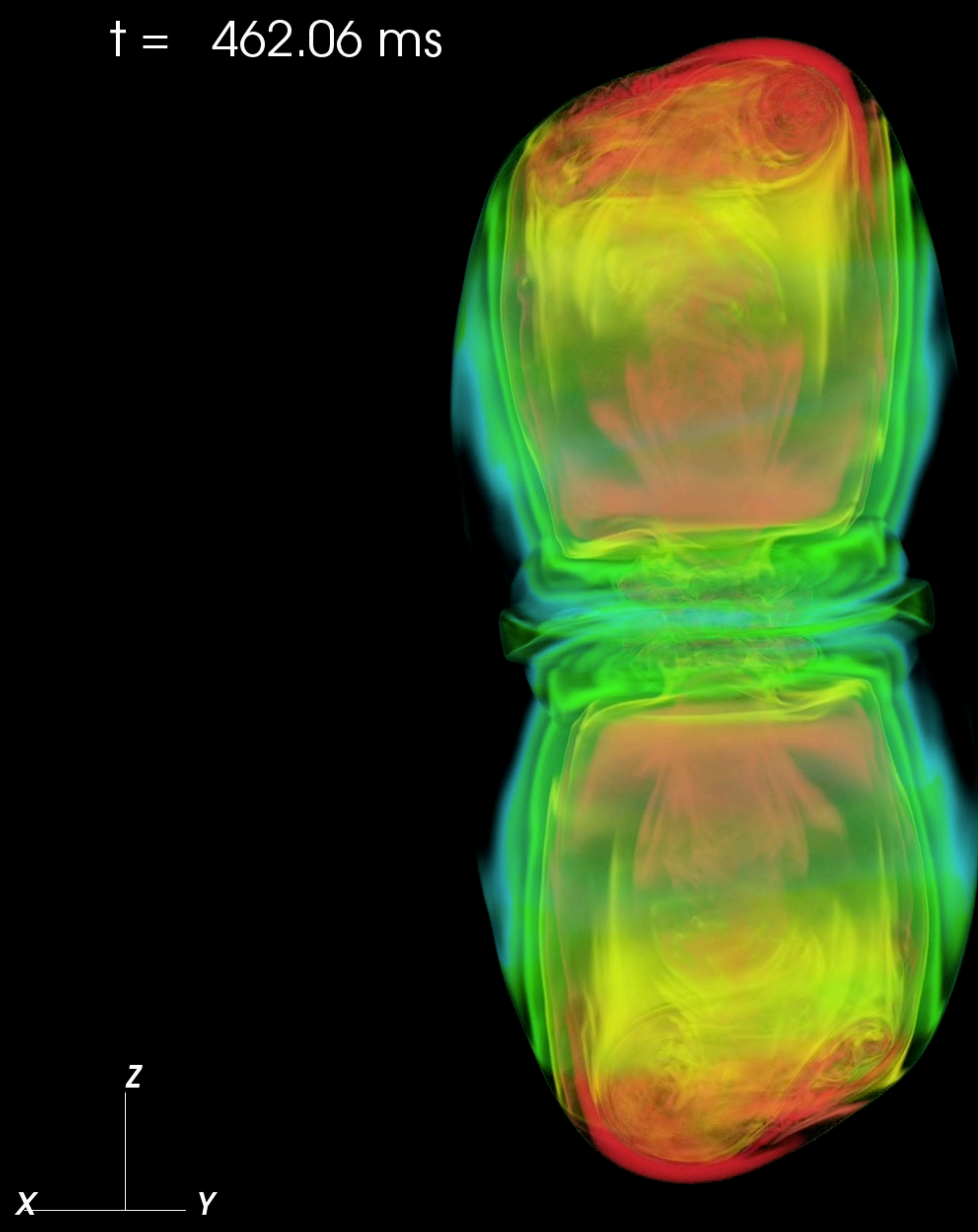
(GH&PM 2018)

aligned



(GH&PM 2018)

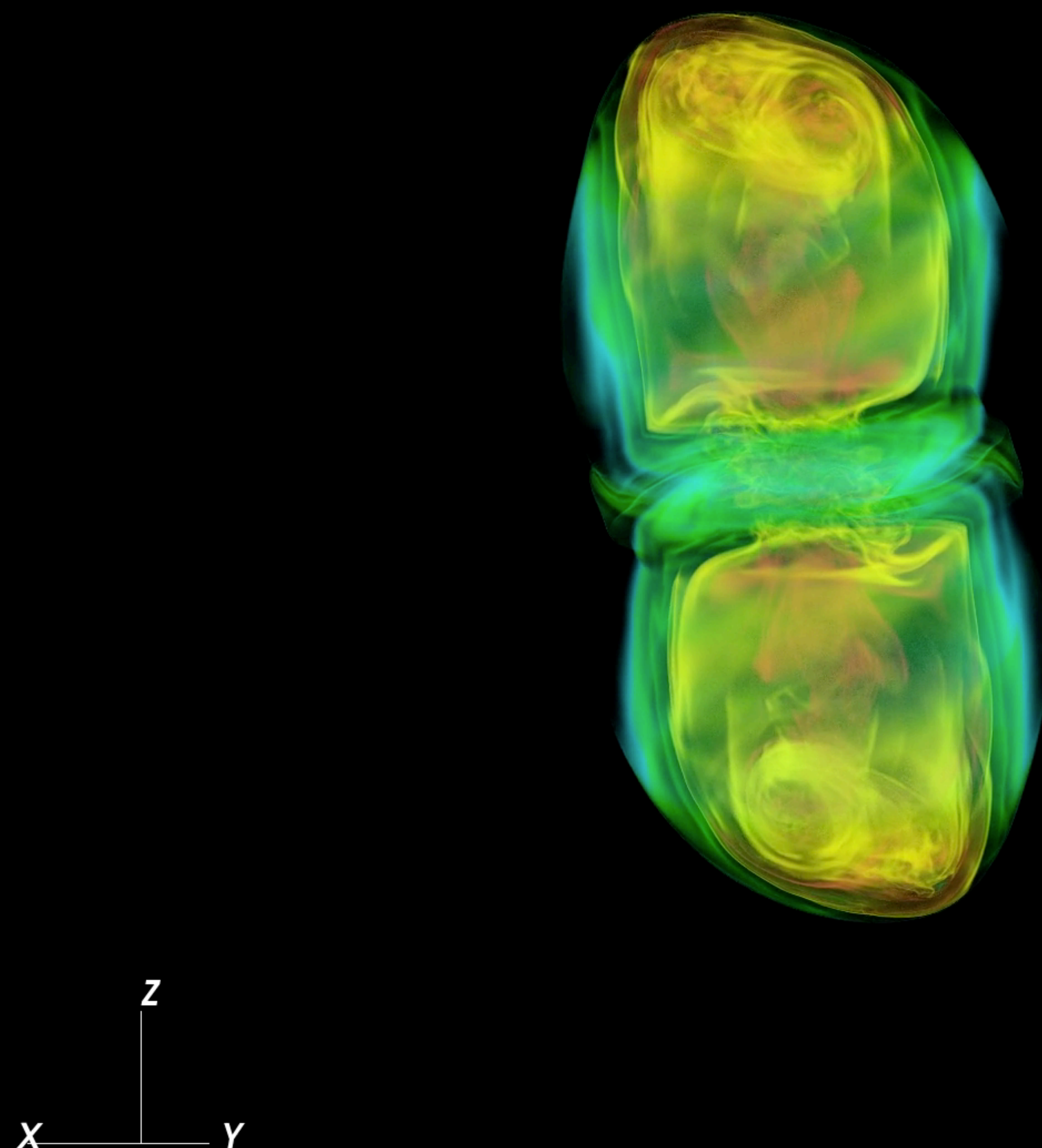
15 deg.



(GH&PM 2018)

t = 459.54 ms

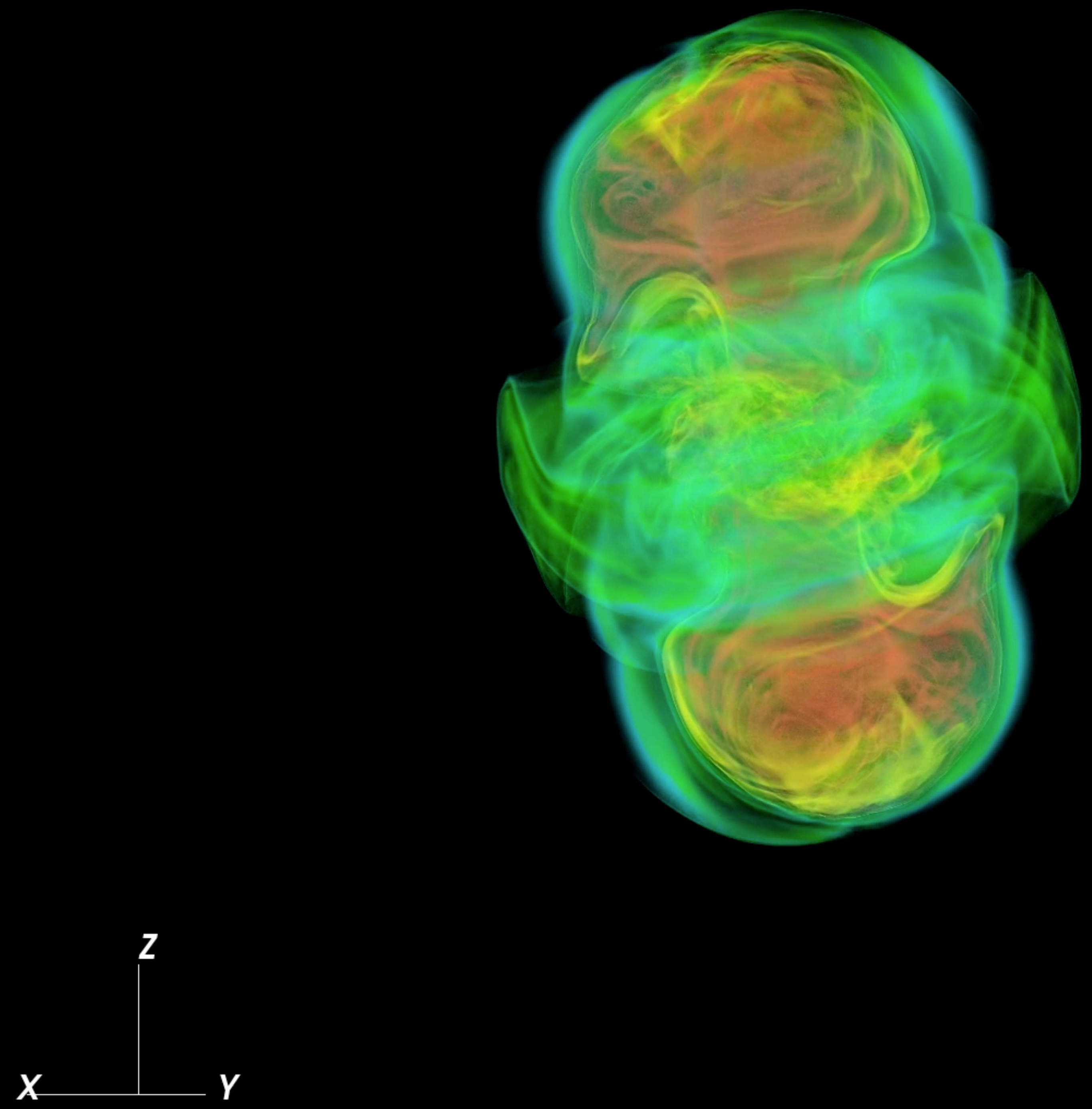
30 deg.



(GH&PM 2018)

t =   466.98 ms

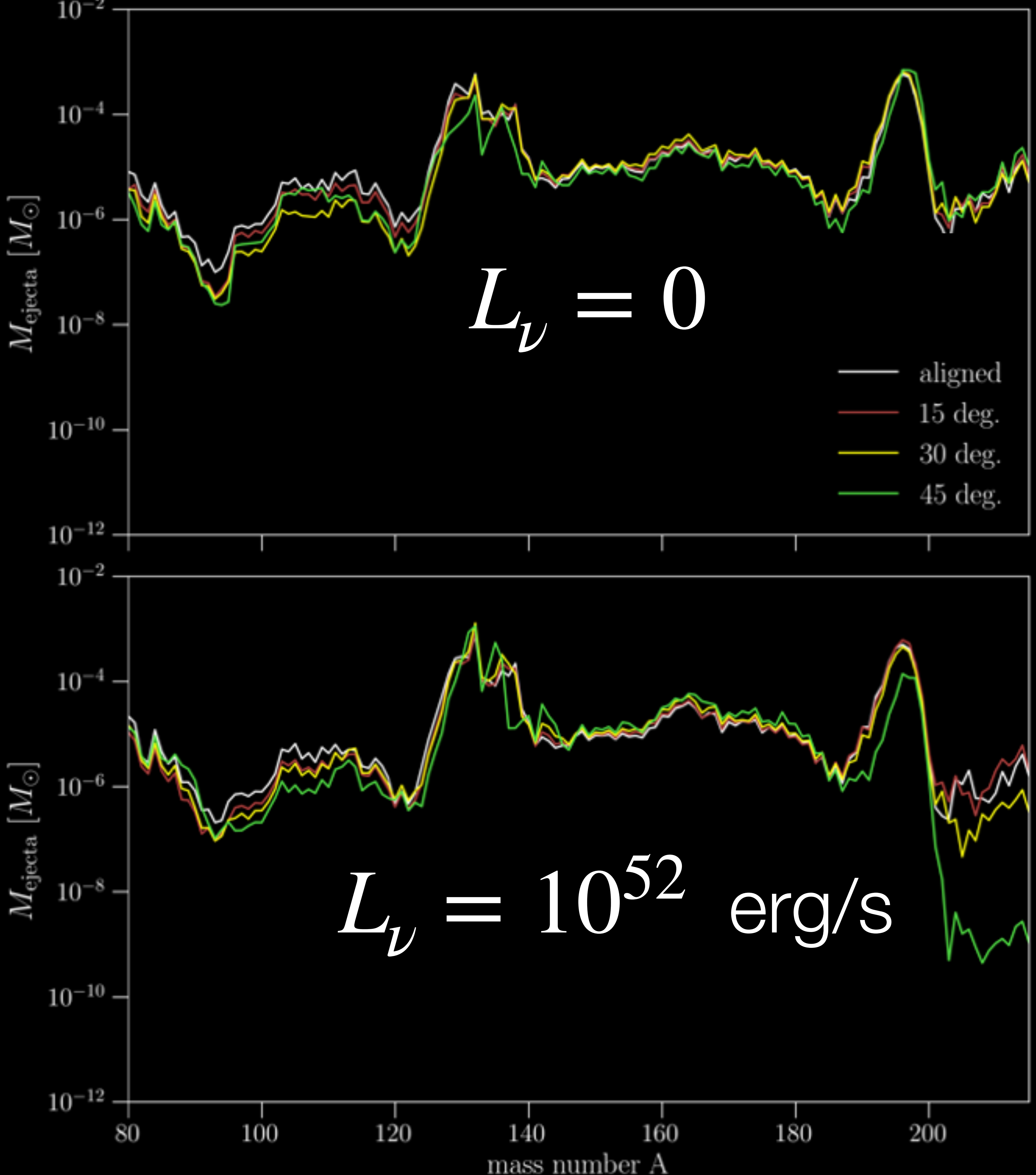
45 deg.



(GH&PM 2018)

Summary & conclusions

- $L_\nu \gtrsim 5 \times 10^{52}$ erg/s —> only weak ***r*-process** production
- **Uncertainty** in L_ν —> uncertainty in 3rd peak abundances
- **Robust *r*-process** for misalignments up to 30 deg.
- 45 deg. misalignment —> a very **different explosion**
- **Neutrino interactions** drive differences in MR CCSNe nucleosynthesis abundance patterns
- For sufficiently **strong B-fields**, the configuration is **unimportant**
- *r*-process nucleosynthesis remains an interesting astrophysical problem



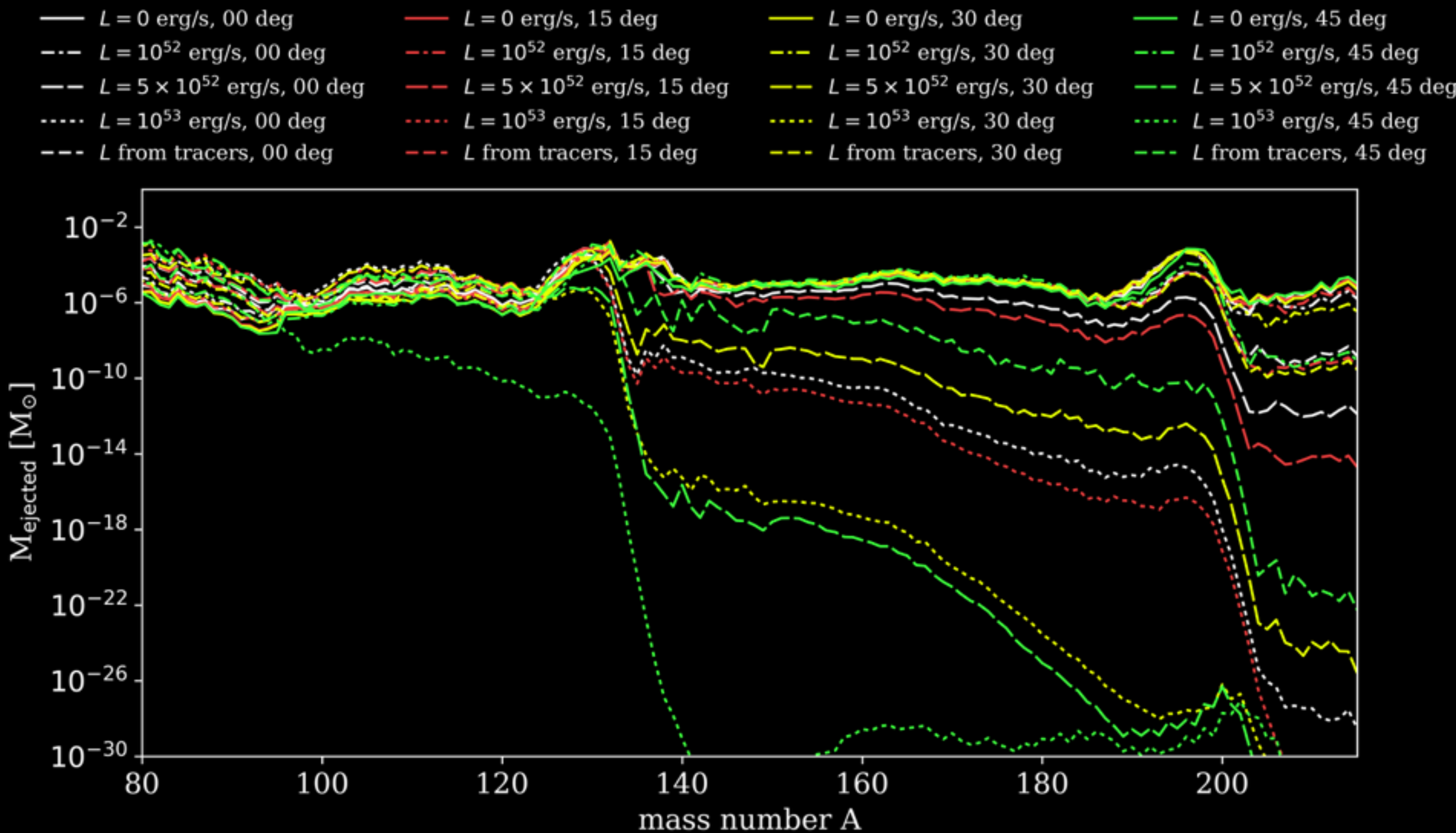
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
10^{-12}
$M_{\rm ejecta}\ [M_\odot]$
$L_\nu = 0$
aligned
15 deg.
30 deg.
45 deg.
$L_\nu = 10^{52}$ erg/s
80
100
120
140
160
180
200
mass number A

(GH&PM 2018)

Ejecta Masses

model		0 deg.	15 deg.	30 deg.	45 deg.
$\mathbf{M}_{\mathrm{ej,tot}}$ $[10^{-2} M_\odot]$		1.41	1.32	1.55	0.51
$\mathbf{M}_{\mathrm{ej,r}}$ $[10^{-2} M_\odot]$	$L_\nu = 0$	1.29	1.29	1.53	0.49
	$L_\nu = 10^{52}$	1.24	1.26	1.49	0.47
	L_ν from sim.	1.11	1.19	1.43	0.37
	$L_\nu = 5 \times 10^{52}$	0.81	0.73	0.48	0.03
	$L_\nu = 10^{53}$	0.32	0.18	0.06	6×10^{-5}

(GH&PM 2018)



$L = 0$ erg/s, 00 deg
$L = 10^{52}$ erg/s, 00 deg
$L = 5 \times 10^{52}$ erg/s, 00 deg
$L = 10^{53}$ erg/s, 00 deg
L from tracers, 00 deg
$L = 0$ erg/s, 15 deg
$L = 10^{52}$ erg/s, 15 deg
$L = 5 \times 10^{52}$ erg/s, 15 deg
$L = 10^{53}$ erg/s, 15 deg
L from tracers, 15 deg
$L = 0$ erg/s, 30 deg
$L = 10^{52}$ erg/s, 30 deg
$L = 5 \times 10^{52}$ erg/s, 30 deg
$L = 10^{53}$ erg/s, 30 deg
L from tracers, 30 deg
$L = 0$ erg/s, 45 deg
$L = 10^{52}$ erg/s, 45 deg
$L = 5 \times 10^{52}$ erg/s, 45 deg
$L = 10^{53}$ erg/s, 45 deg
L from tracers, 45 deg
10^{-2}
10^{-6}
10^{-10}
10^{-14}
10^{-18}
10^{-22}
10^{-26}
10^{-30}
$M_{ejected}$ [$M_\odot$]
80
100
120
140
160
180
200
mass number A

(GH&PM 2018)

Post-processing: SkyNet