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Radio signatures of star-forming galaxies across cosmic history

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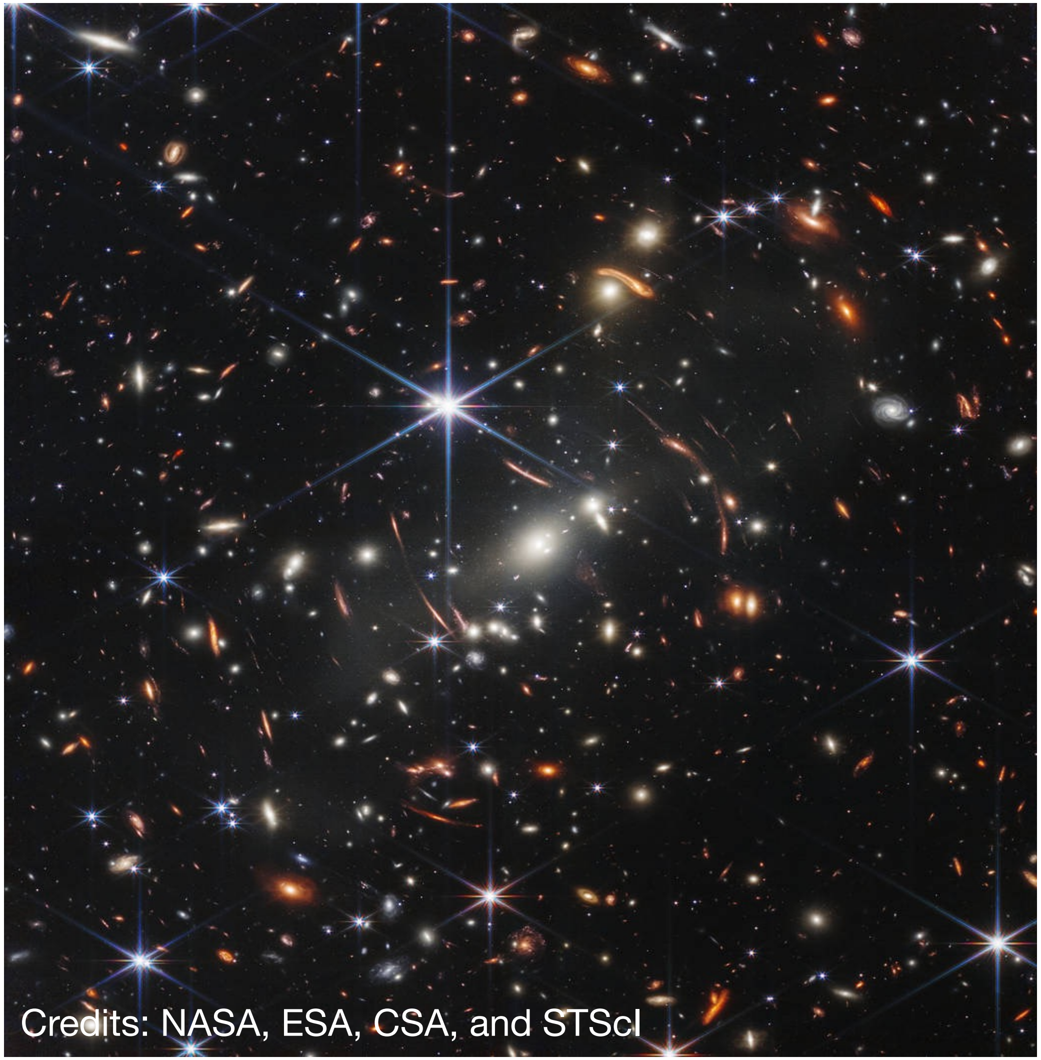
Galaxy evolution over cosmic times



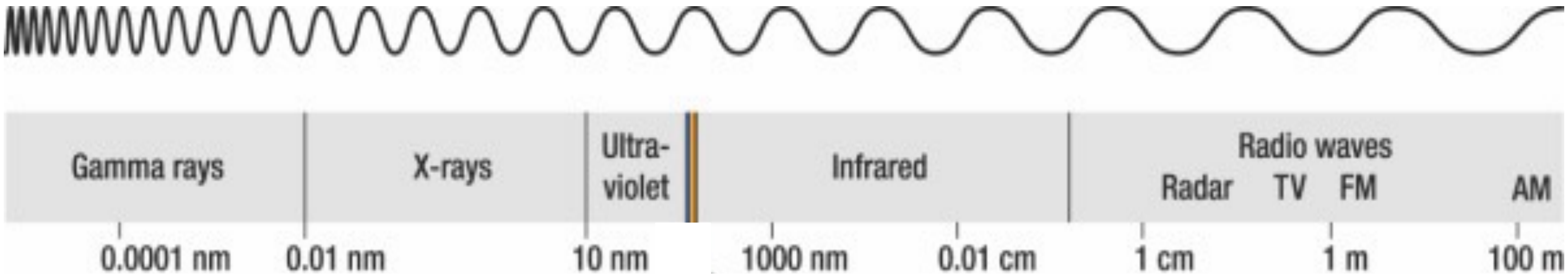
We are observing more and more galaxies of the young Universe, but their evolution is still unclear.

Star formation is a principal agent of galaxy evolution.

We need observational tracers of the star formation rate (SFR) that are reliable also in the early Universe.

Tracers of star formation

…exist across the entire electromagnetic spectrum Kennicutt & Evans (2012)



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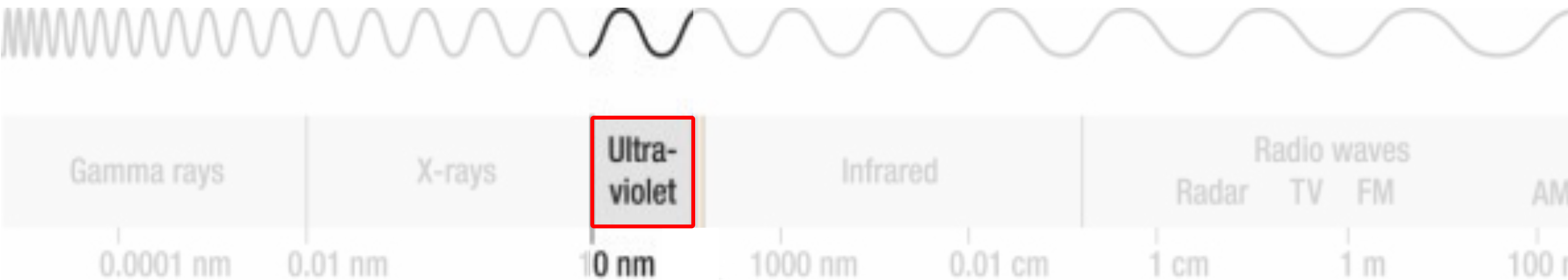
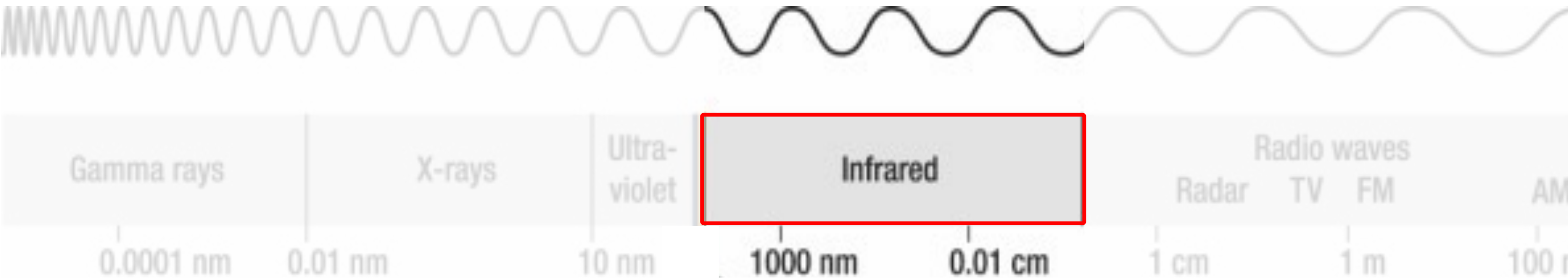


Based on photospheric emission of young stars:
Direct tracer of recent star formation

Madau et al. 1998
Hao et al. 2011
Murphy et al. 2011

Tracers of star formation

…exist across the entire electromagnetic spectrum Kennicutt & Evans (2012)



Based on dust:
UV emission of young stars is absorbed by interstellar dust and then re-emitted as thermal infrared light.

Kennicutt 1998
Hao et al. 2011;
Murphy et al. 2011

Tracers of star formation

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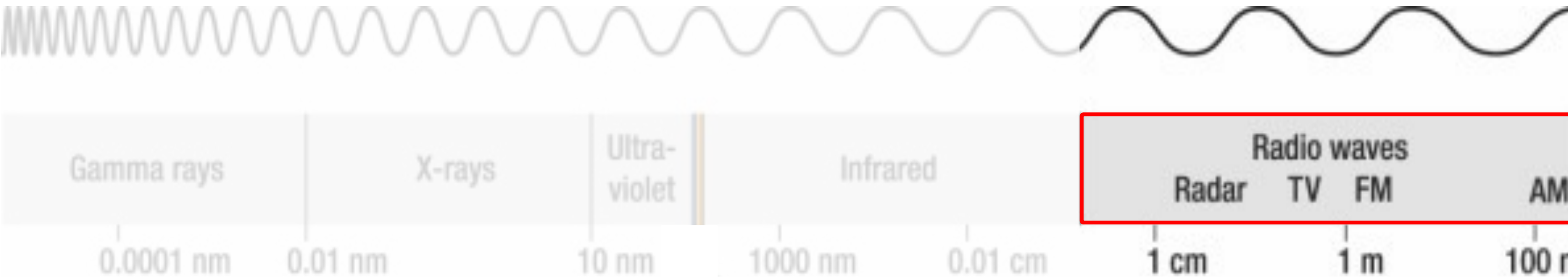

→ Can radio surveys be used as a tracer?

Condon 1992; Yun, Reddy & Condon 2001; Bell 2003

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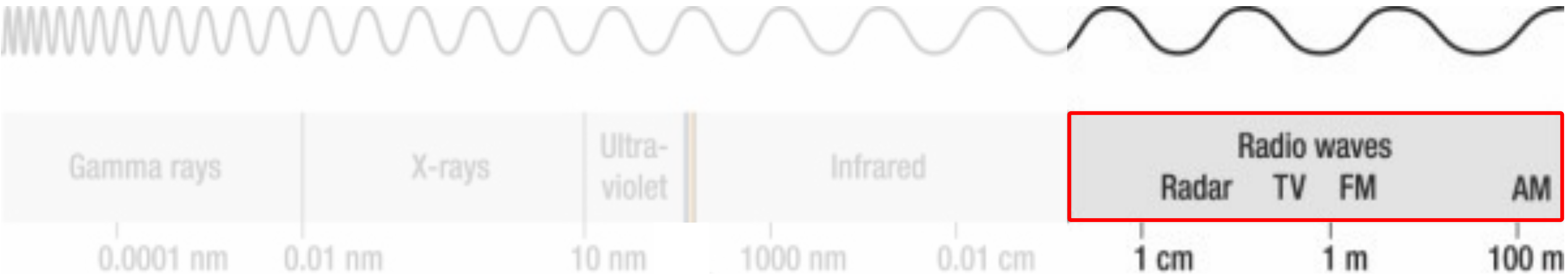
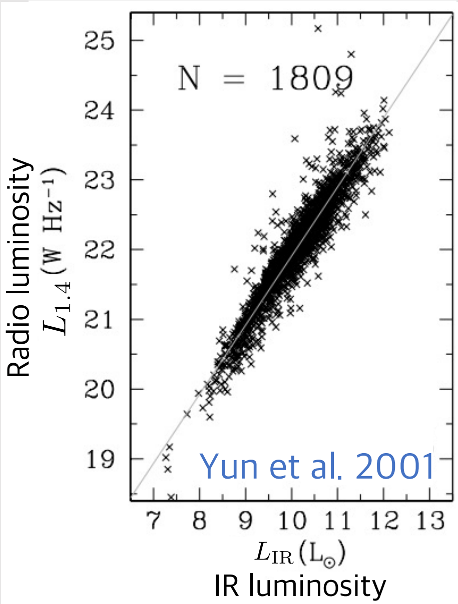


Based on the (locally) observed IR-radio correlation:



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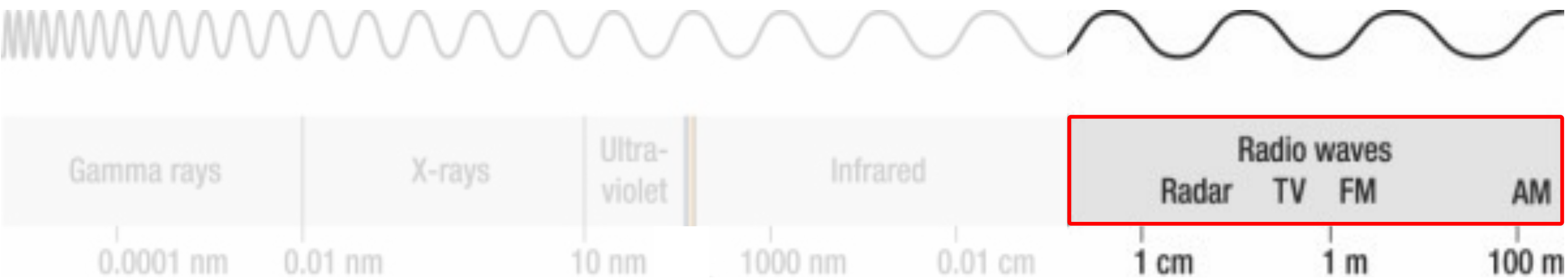

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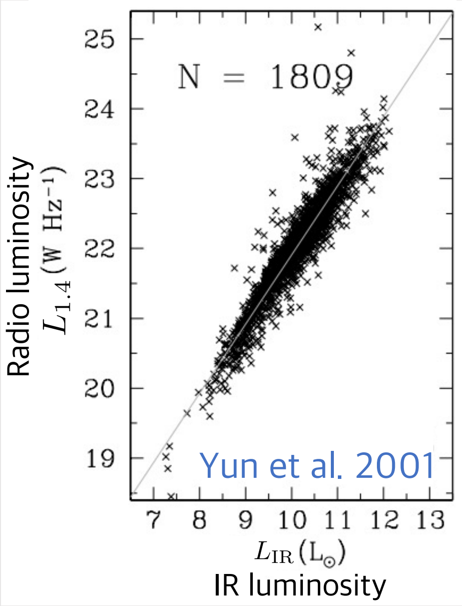

Definition of the IR-to-radio luminosity ratio:

$$q = \log_{10}\left(\frac{L_{\rm IR}}{3.75\times10^{12}\ \rm W}\right) - \log_{10}\left(\frac{L_{1.4}}{\rm W/Hz}\right)$$

[The mean of data shown on the left is $\overline{q} = 2.34 \pm 0.01$.]

Tracers of star formation

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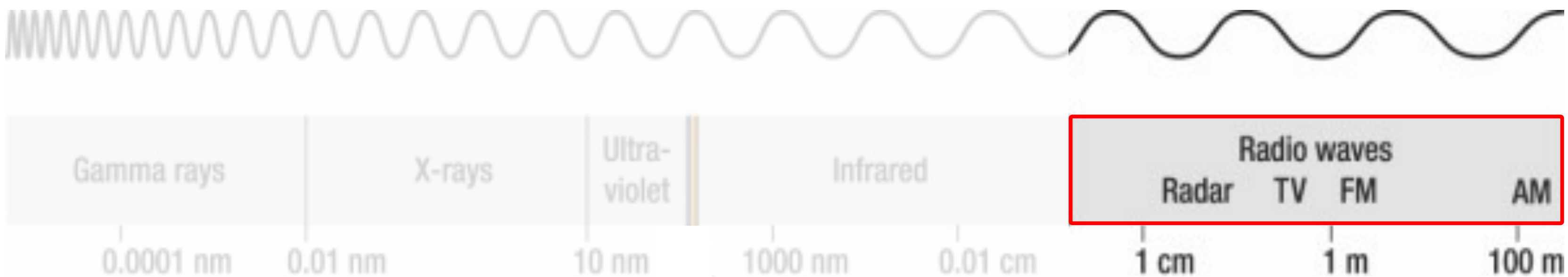

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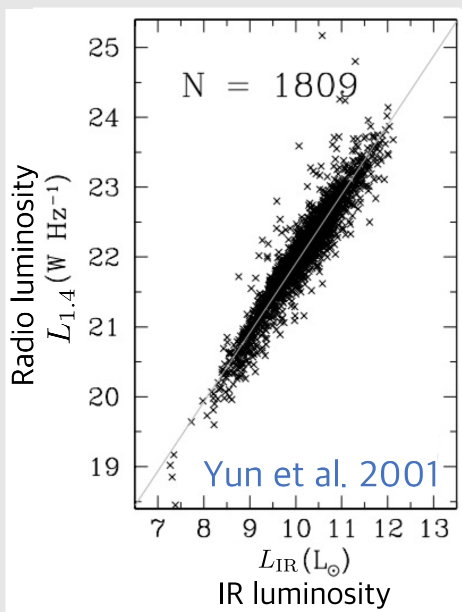

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Can this relation be used at high redshift?

Does the IR-radio correlation evolve?

$q = q(z)$?

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$$q = q(z)\ ?$$

No

Garrett 2002;
Appleton et al. 2004;
Jarvis et al. 2010;
Sargent et al. 2010;
Bourne et al. 2011;
Smith et al. 2014

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Smith et al. 2014

Yes,
it decreases

Seymour et al. 2009;
Ivison et al. 2010;
Michałowski et al. 2010a,b;
Ivison et al. 2010;
Basu et al. 2015;
Magnelli et al. 2015;
Delhaize et al. 2017;
Calistro-Rivera et al. 2017

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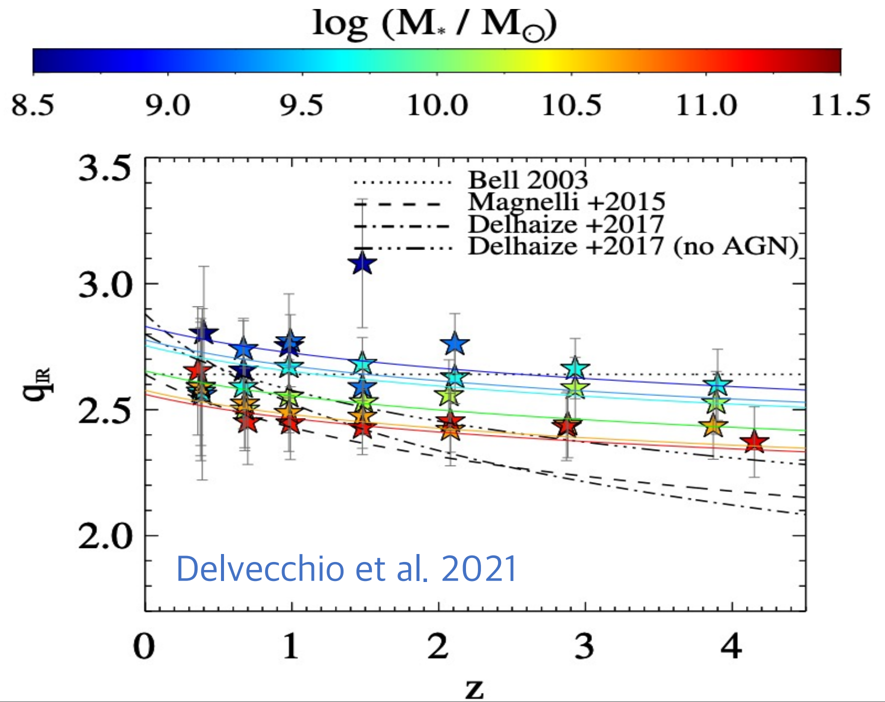
No, but it depends on stellar mass

Based on analysis of >400000 starforming galaxies in the COSMOS field.



Modelling the IR-radio correlation

In theoretical studies, different trends of q as a function of redshift have been discussed [e.g. Lacki, Thompson & Quataert 2010; Schleicher & Beck 2013; Schober, Schleicher & Klessen 2016].

Modelling the IR-radio correlation

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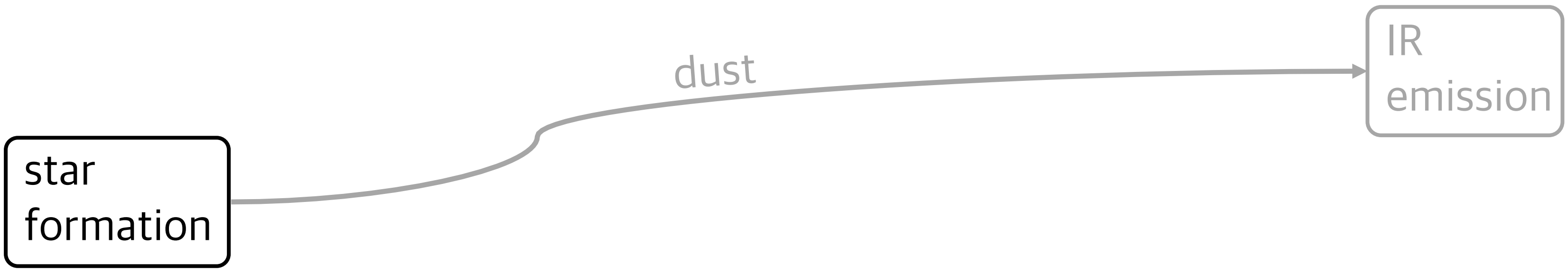
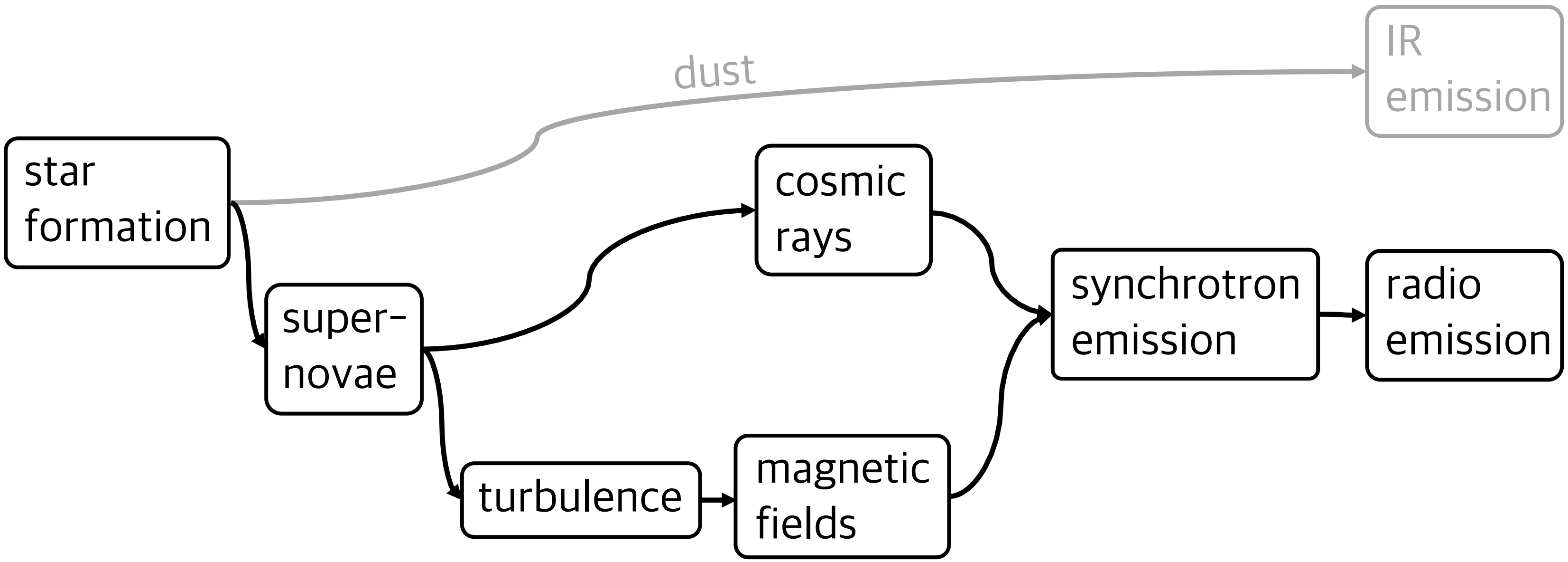
Our goal: Implementation of a dependence on stellar mass.

IR-radio correlation and the SFR



IR-radio correlation and the SFR



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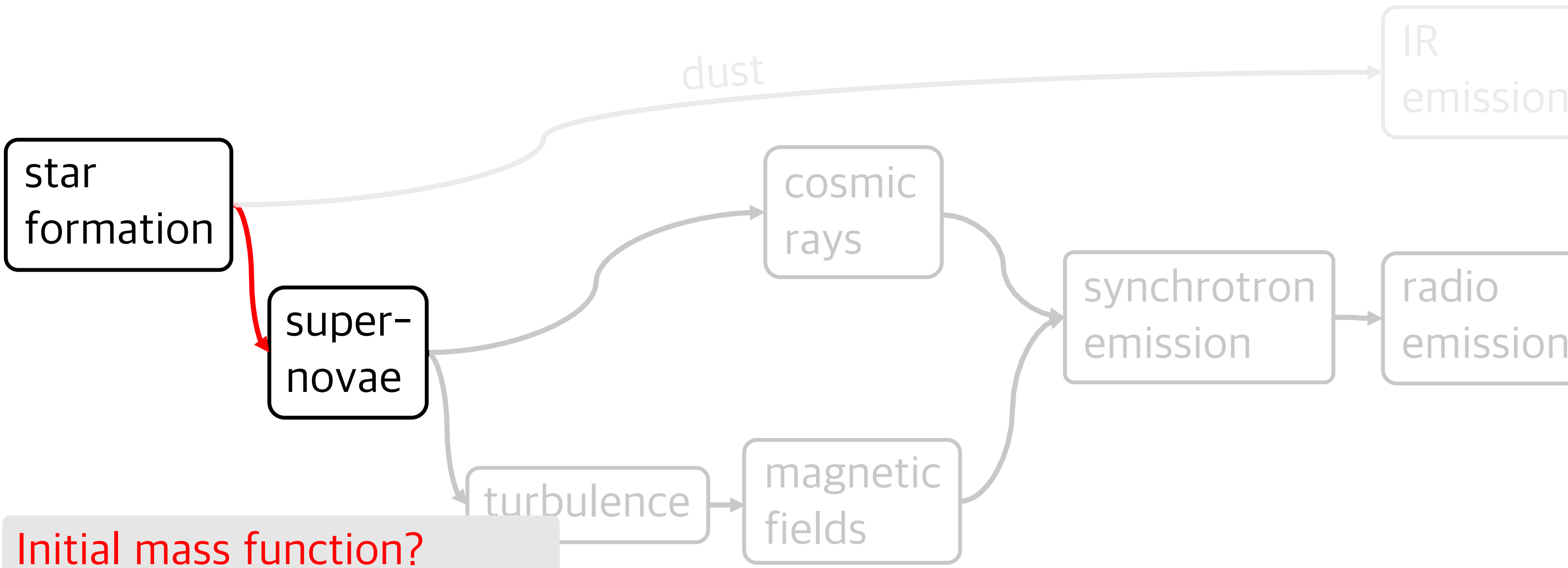
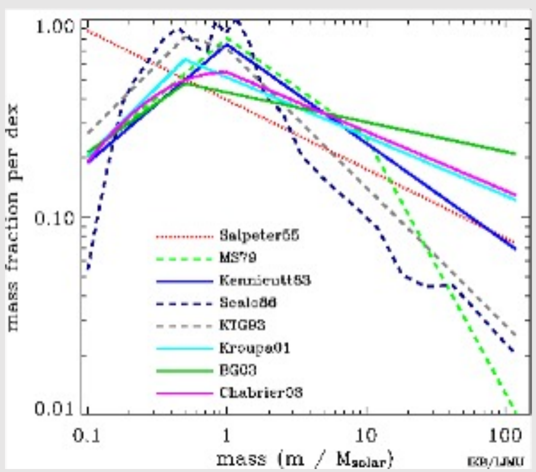
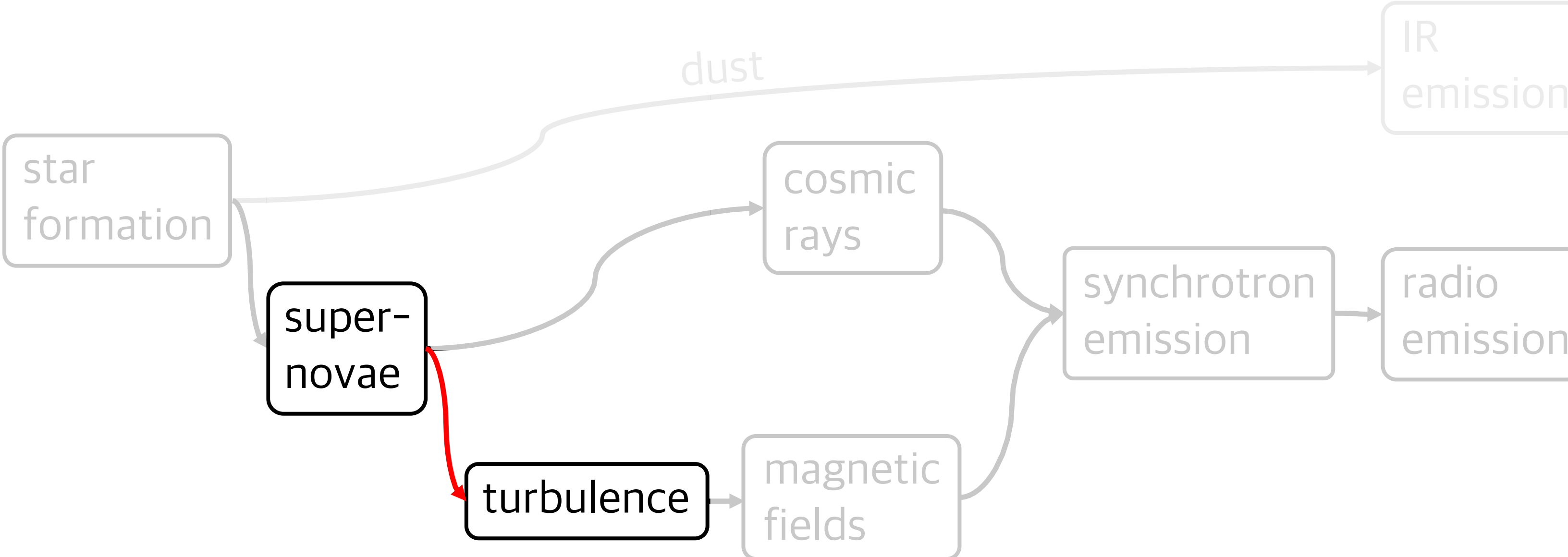


Initial mass function?

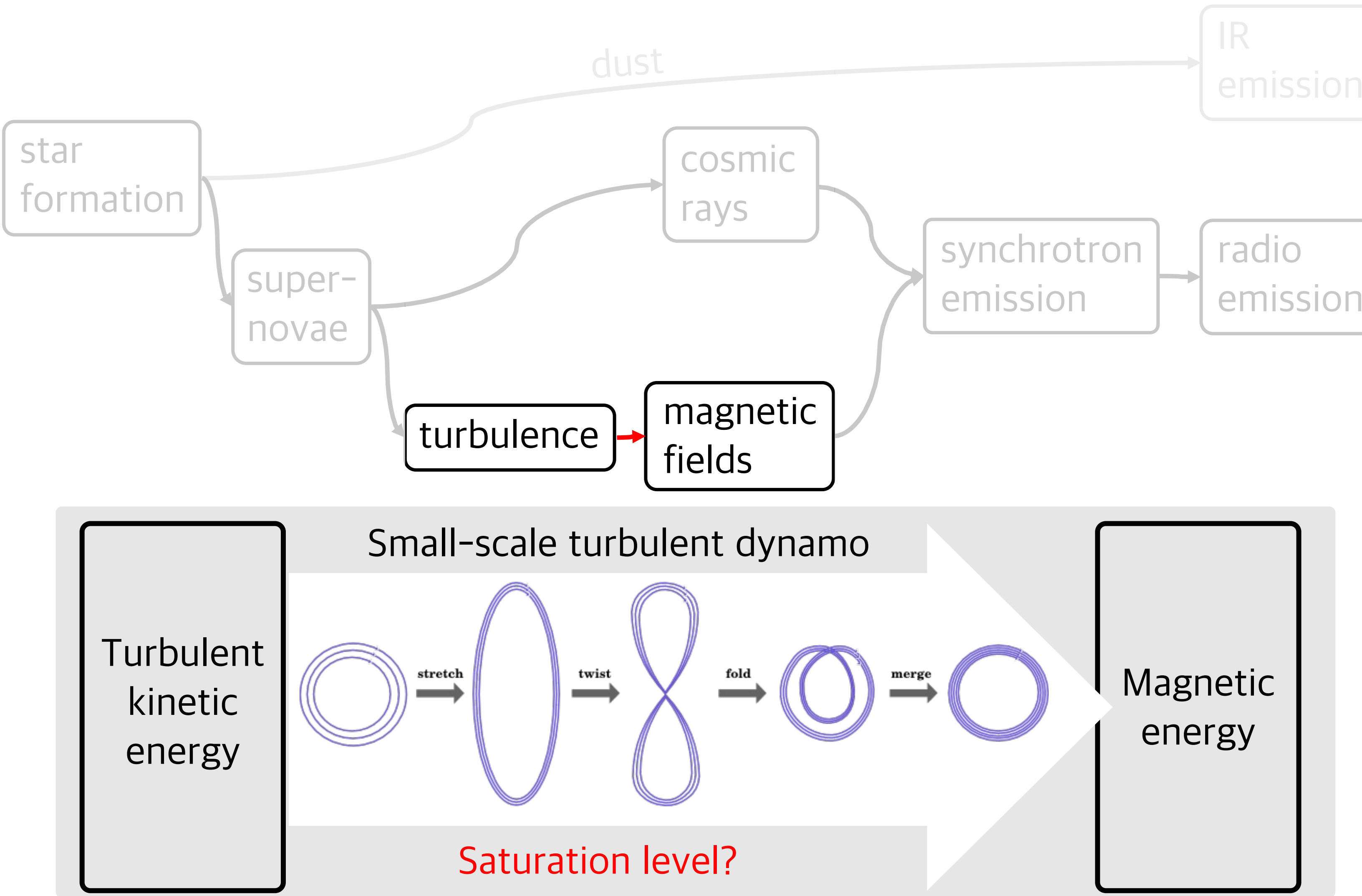


IR-radio correlation and the SFR



Efficiency?
Additional sources for driving?

IR-radio correlation and the SFR



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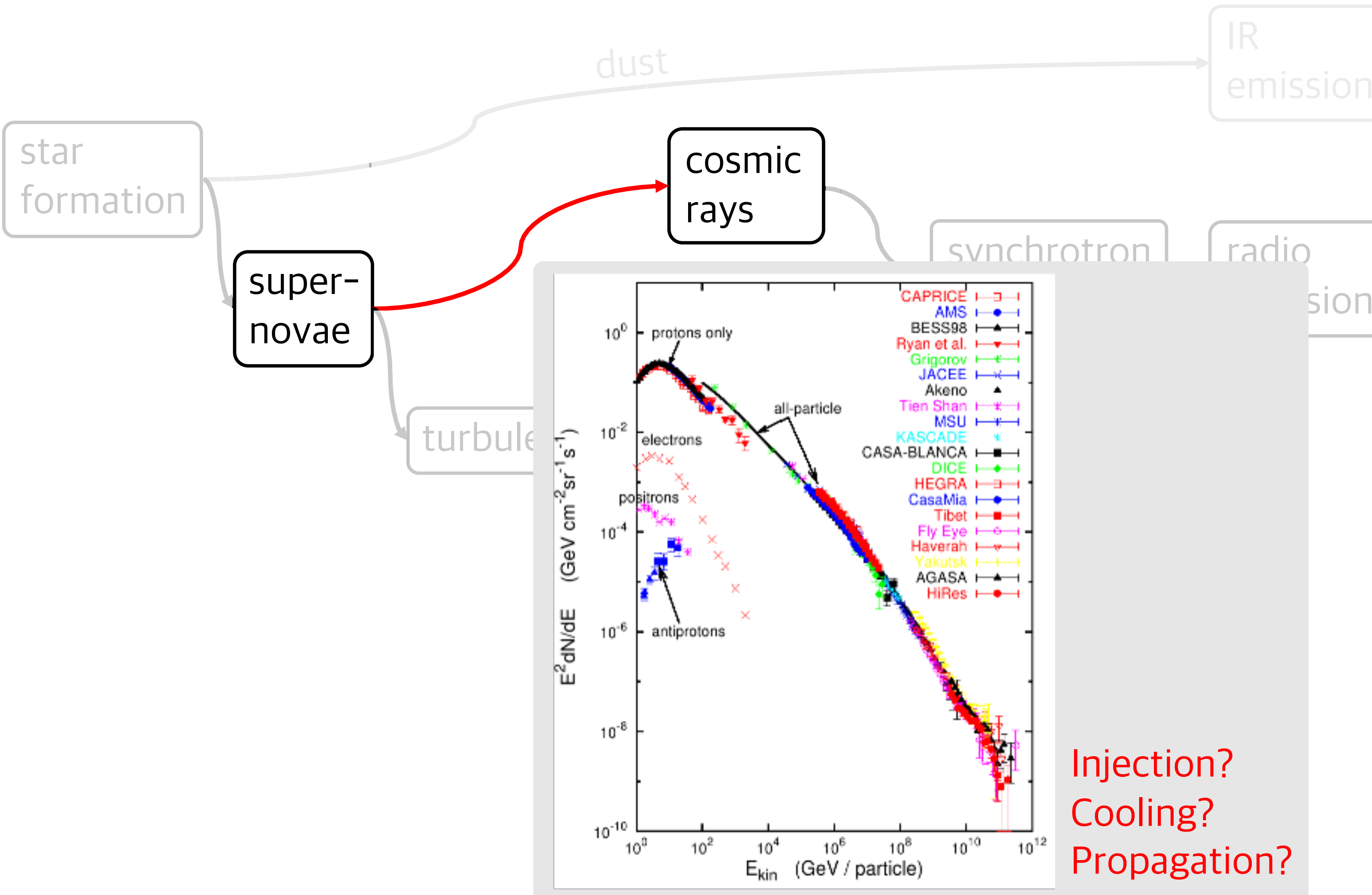

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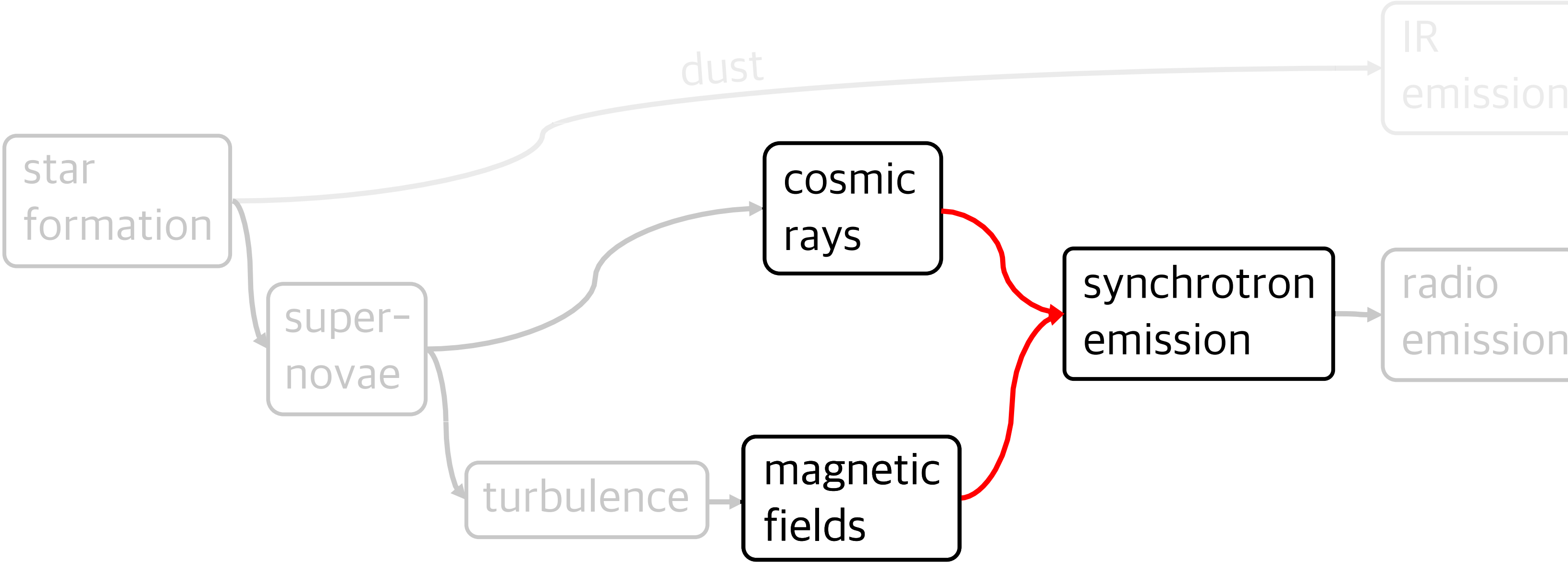

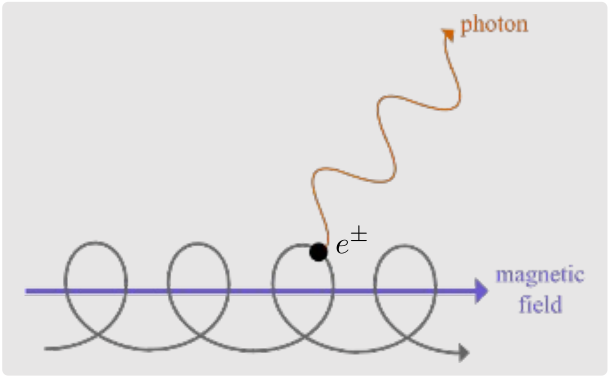

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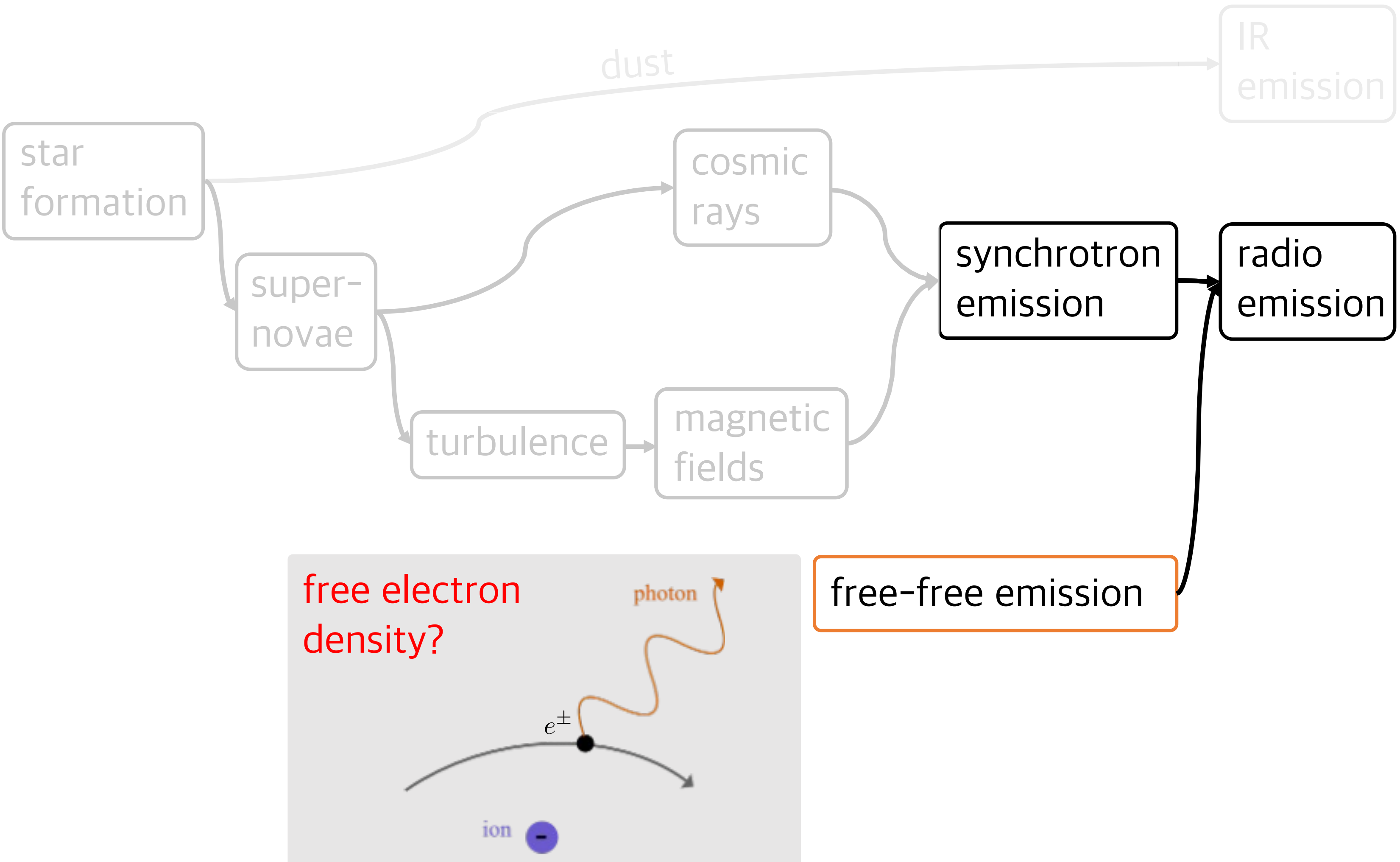

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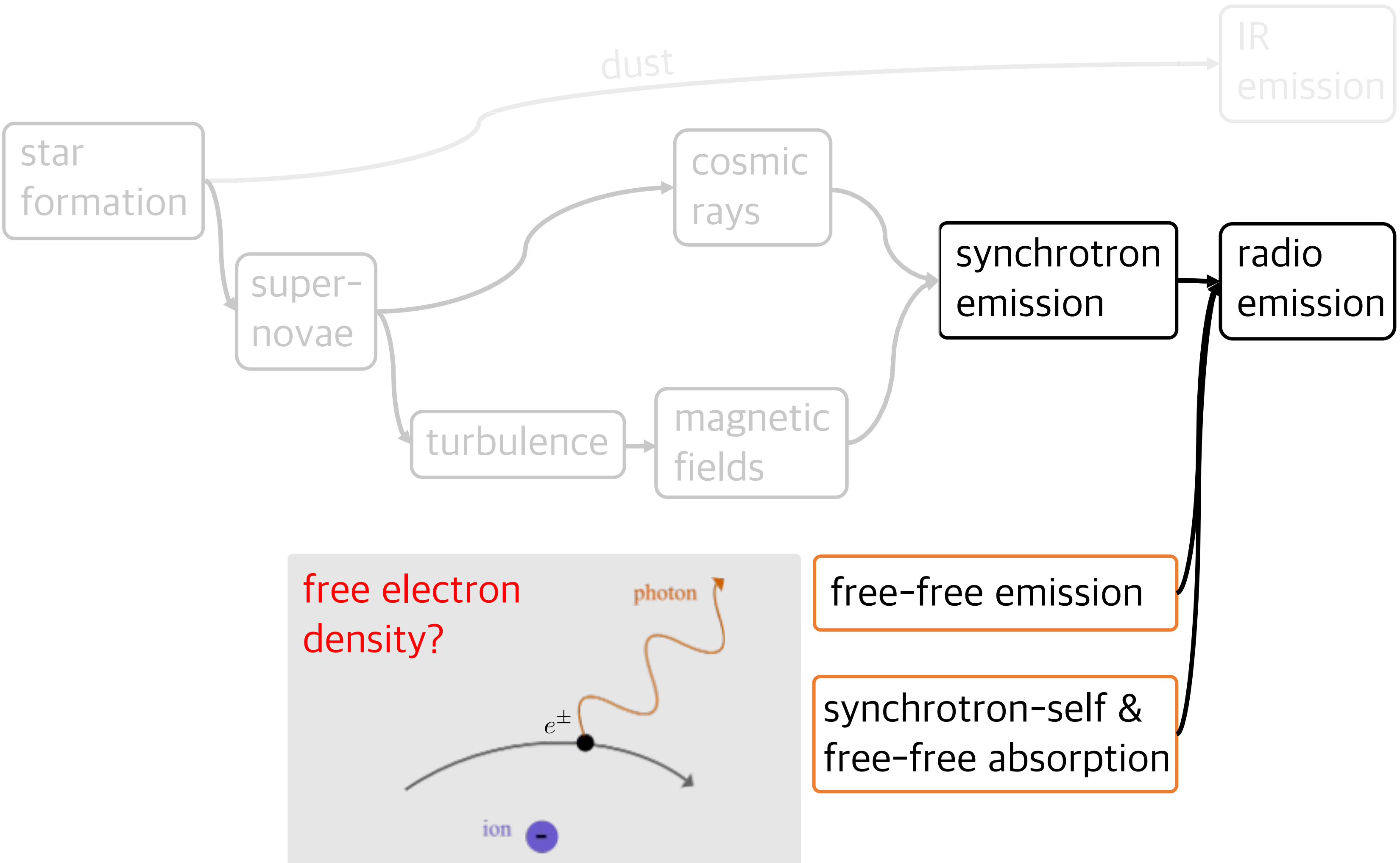

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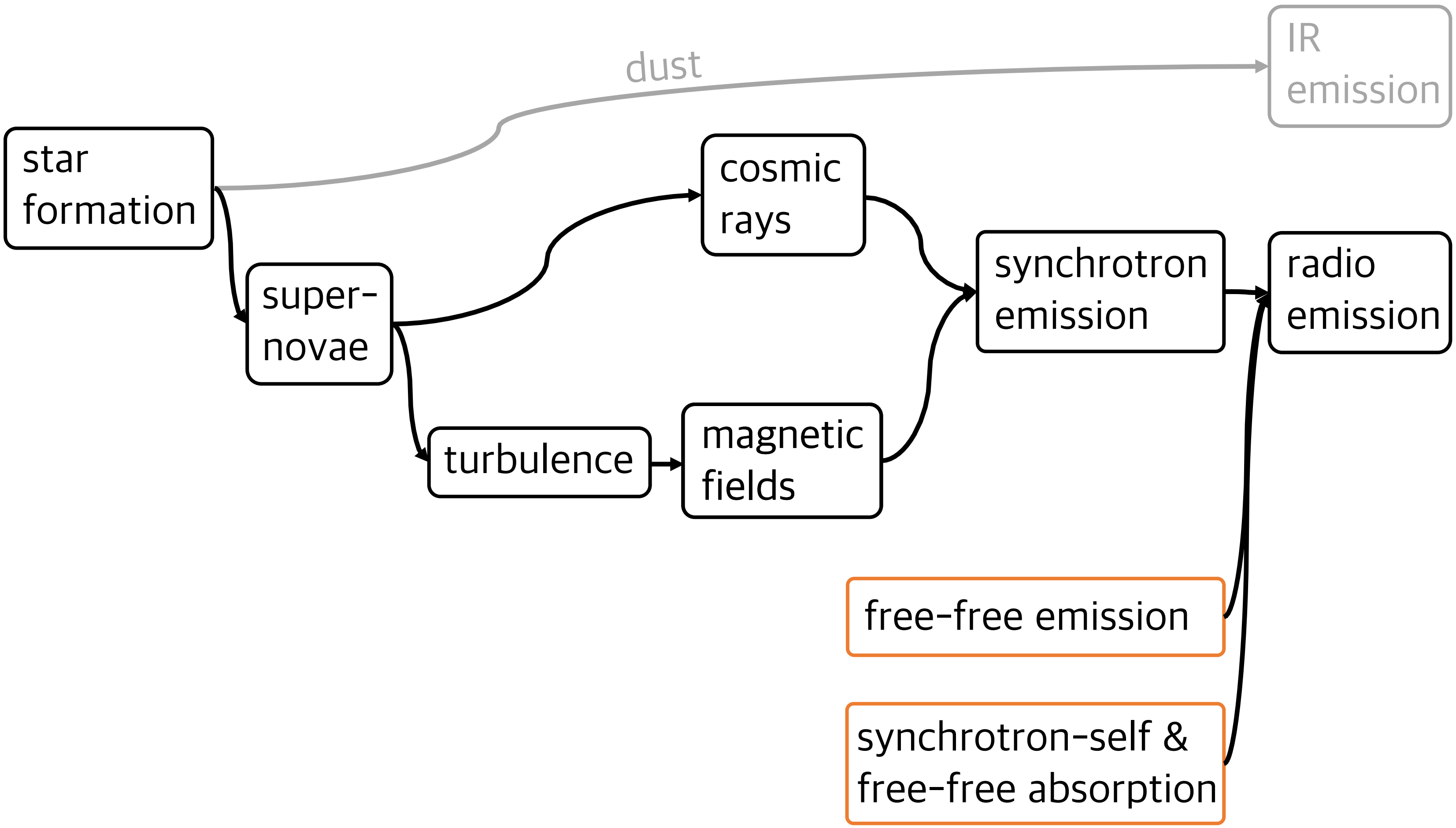

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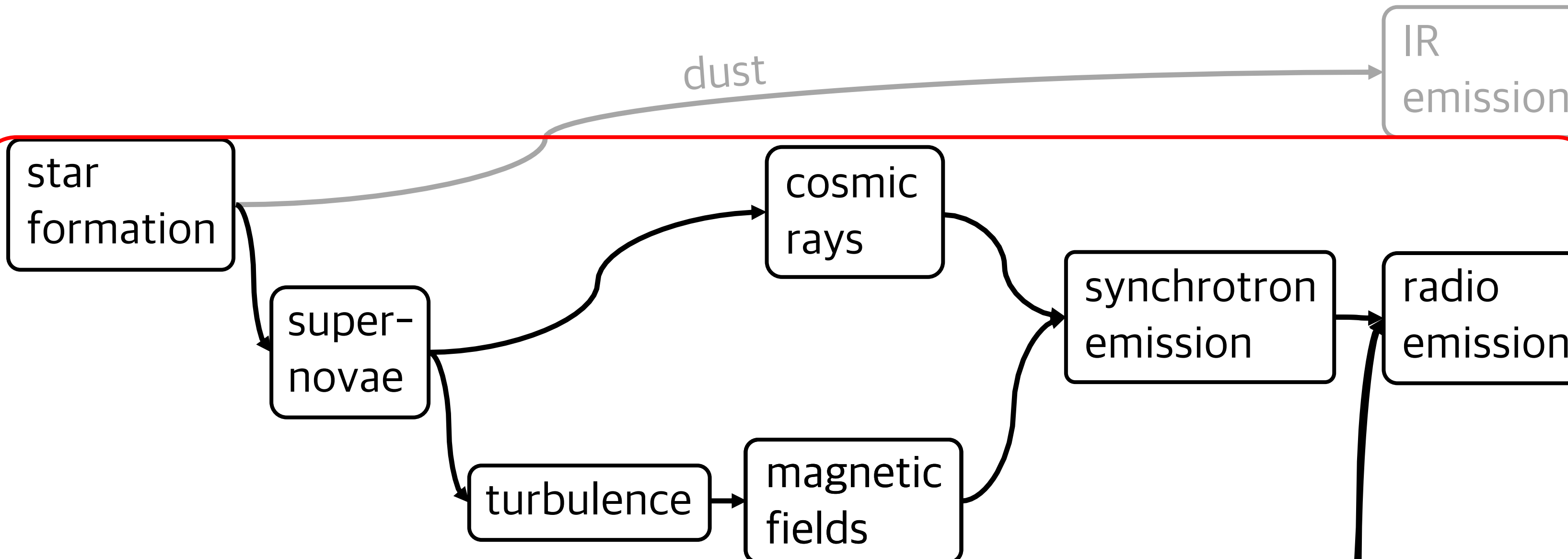
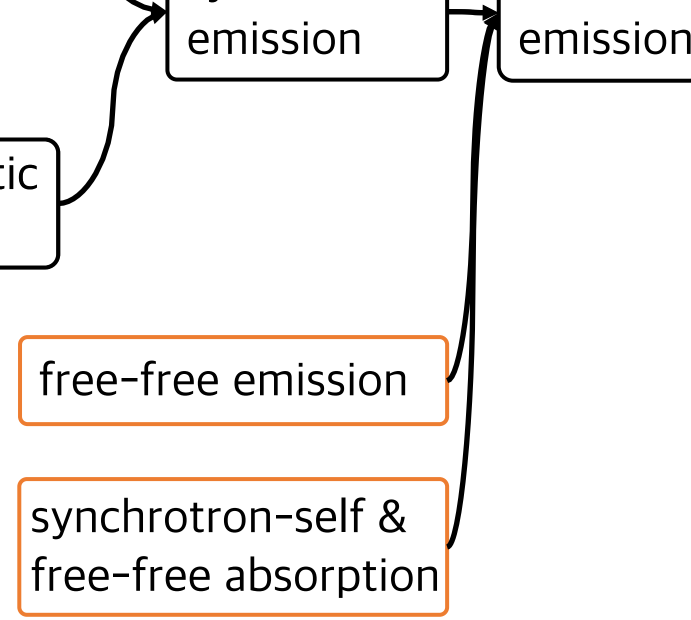


Input as a function of stellar mass $M_\star$:

- Star formation rate [Schreiber et al. 2015]
- Gas density [Sargent et al. 2014]
- Radius and scale height [Jiménez-Andrade et al. 2021; Thompson et al. 2005]



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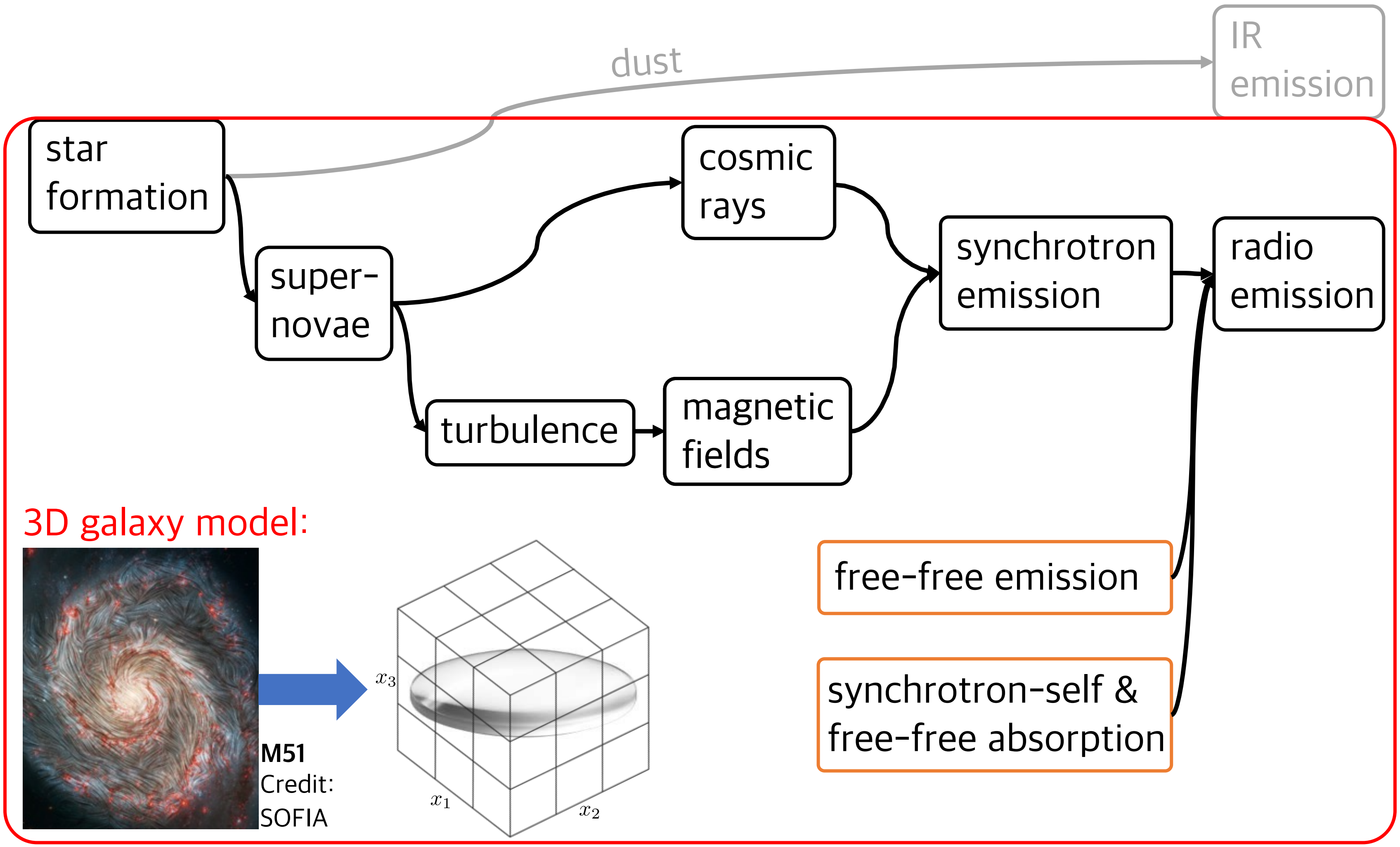
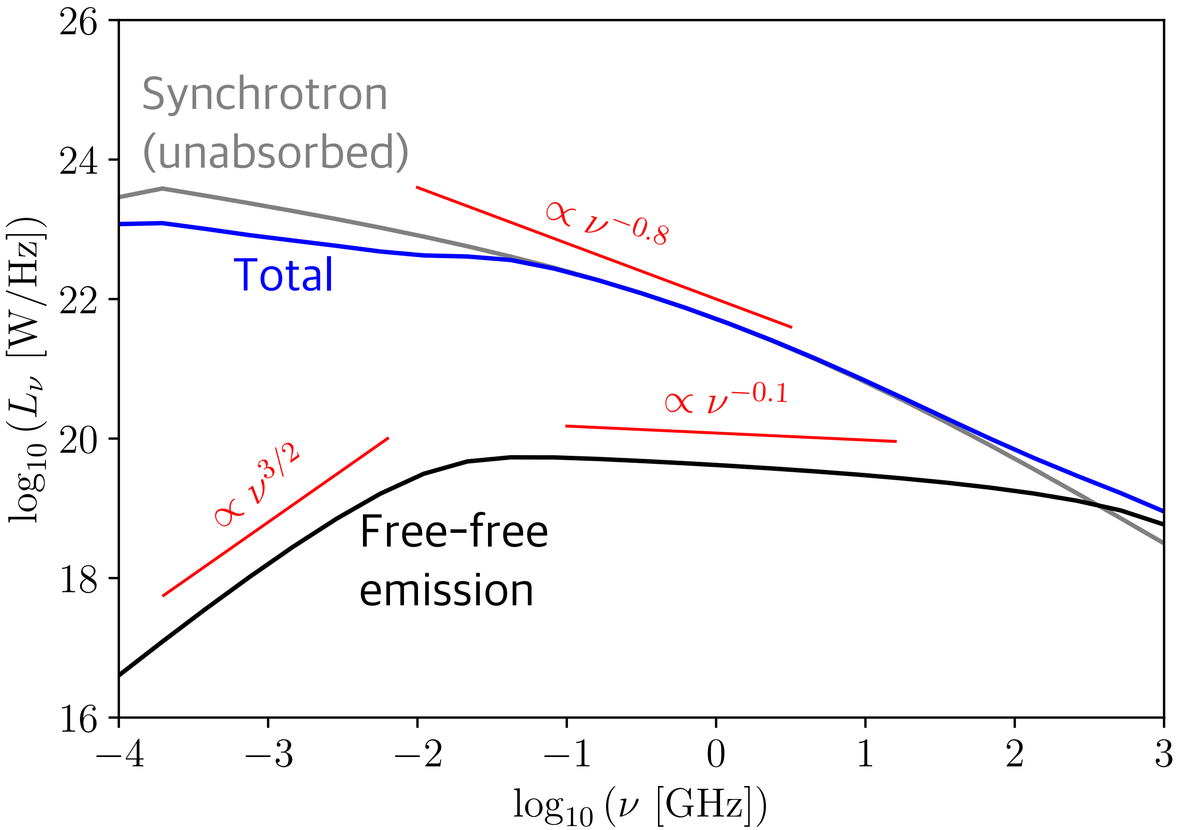


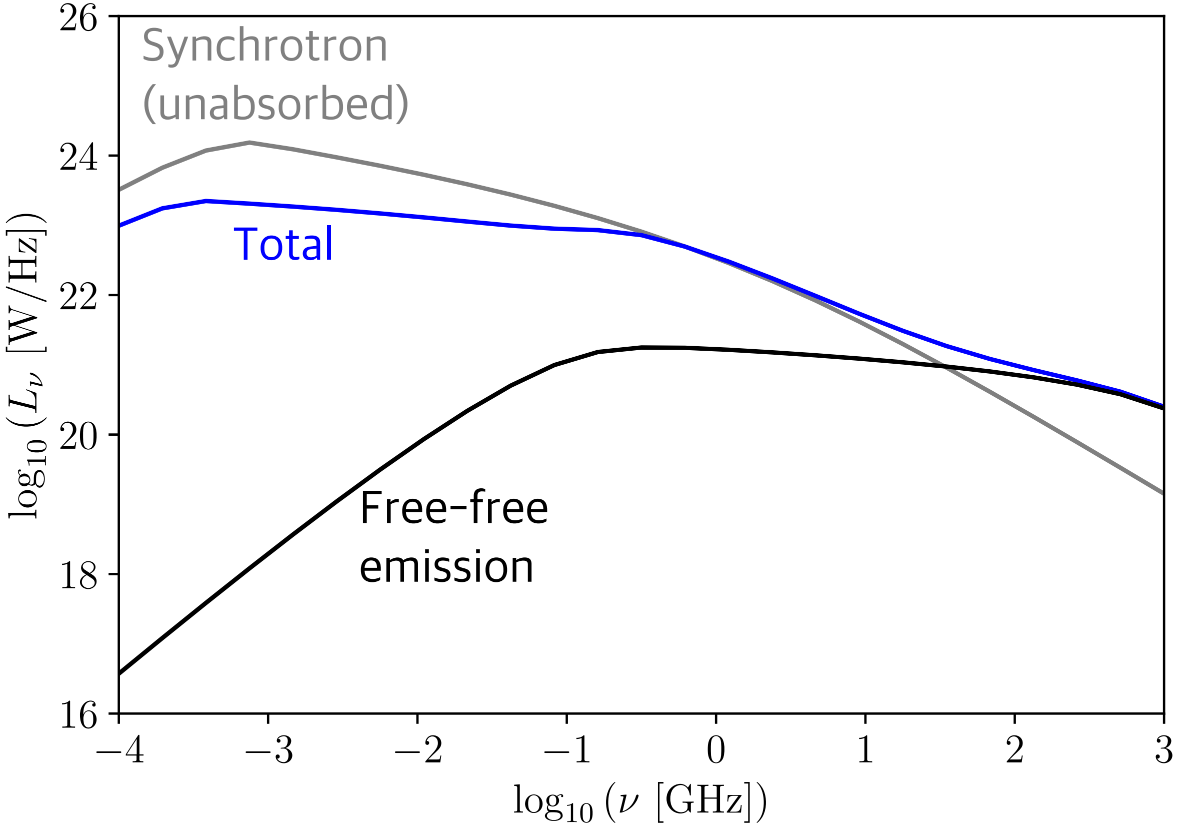
Resulting radio spectra



Example galaxy:

$$M_\star = 10^{10} \; M_\odot$$
$$z = 0$$

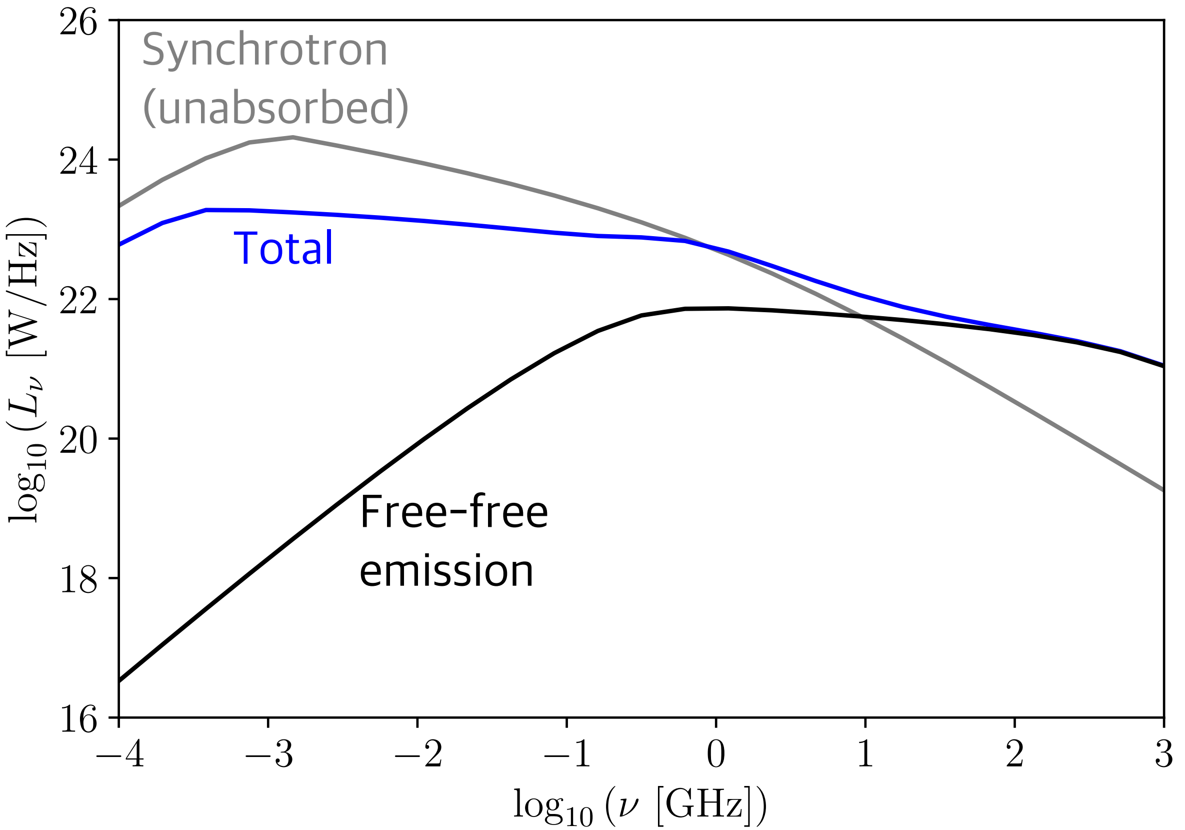
Resulting radio spectra



Example galaxy:

$$M_\star = 10^{10}\ M_\odot$$
$$z = 2$$

Resulting radio spectra

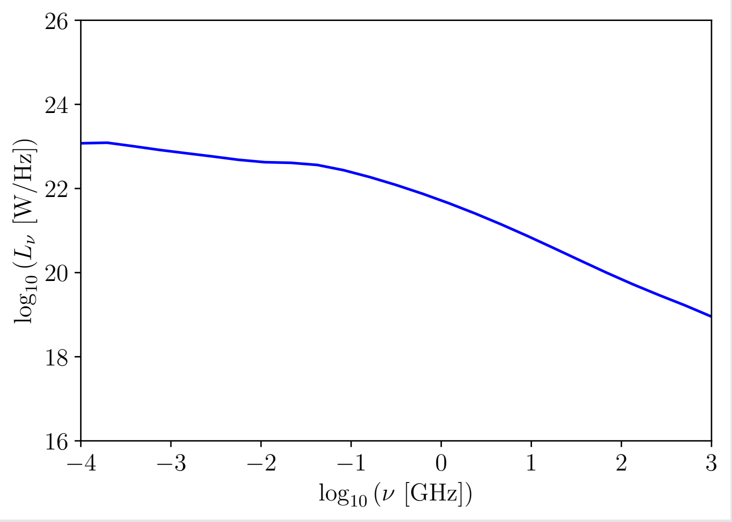


Example galaxy:

$$M_\star = 10^{10}\ M_\odot$$
$$z = 4$$

Resulting IR-radio correlation

Radio luminosity at 1.4 GHz:



Resulting IR-radio correlation

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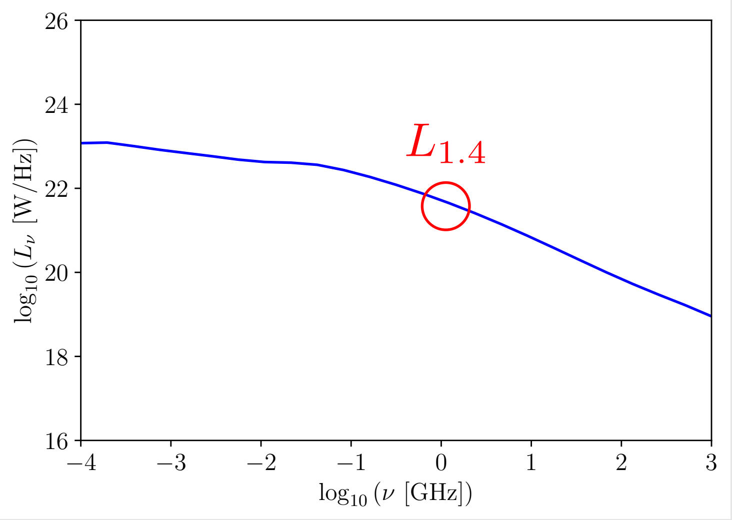

Resulting IR-radio correlation

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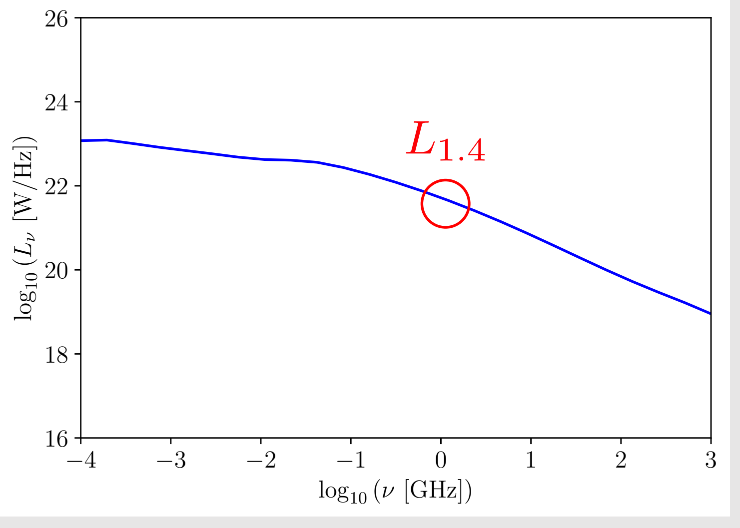

IR luminosity:

$$L_{\mathrm{IR}} = \frac{\dot{M}_\star}{K_{\mathrm{UV}}} \frac{10^{\mathrm{IRX}}}{1 + \frac{K_{\mathrm{IR}}}{K_{\mathrm{UV}}} 10^{\mathrm{IRX}}}$$

with

$$\mathrm{IRX} = \alpha \left(\log \left(\frac{M_\star}{M_\odot} \right) - 10.35 \right) + \mathrm{IRX}_0$$

$$K_{\mathrm{IR}} = 1.7 \times 10^{-10}\ M_\odot \mathrm{yr}^{-1} L_\odot^{-1}$$

$$K_{\mathrm{UV}} = 2.8 \times 10^{-10}\ M_\odot \mathrm{yr}^{-1} L_\odot^{-1}$$

$$\mathrm{IRX}_0 = 1.32$$

$$\alpha = 0.71$$

Bernhard et al. 2014

Resulting IR-radio correlation

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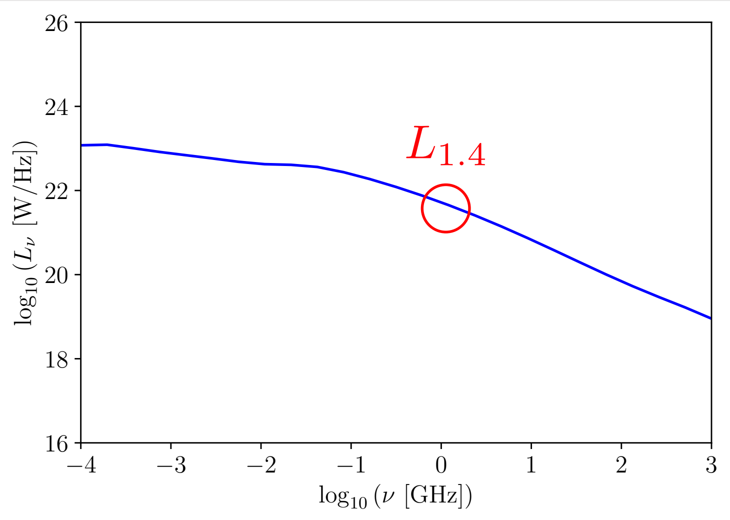

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Bernhard et al. 2014

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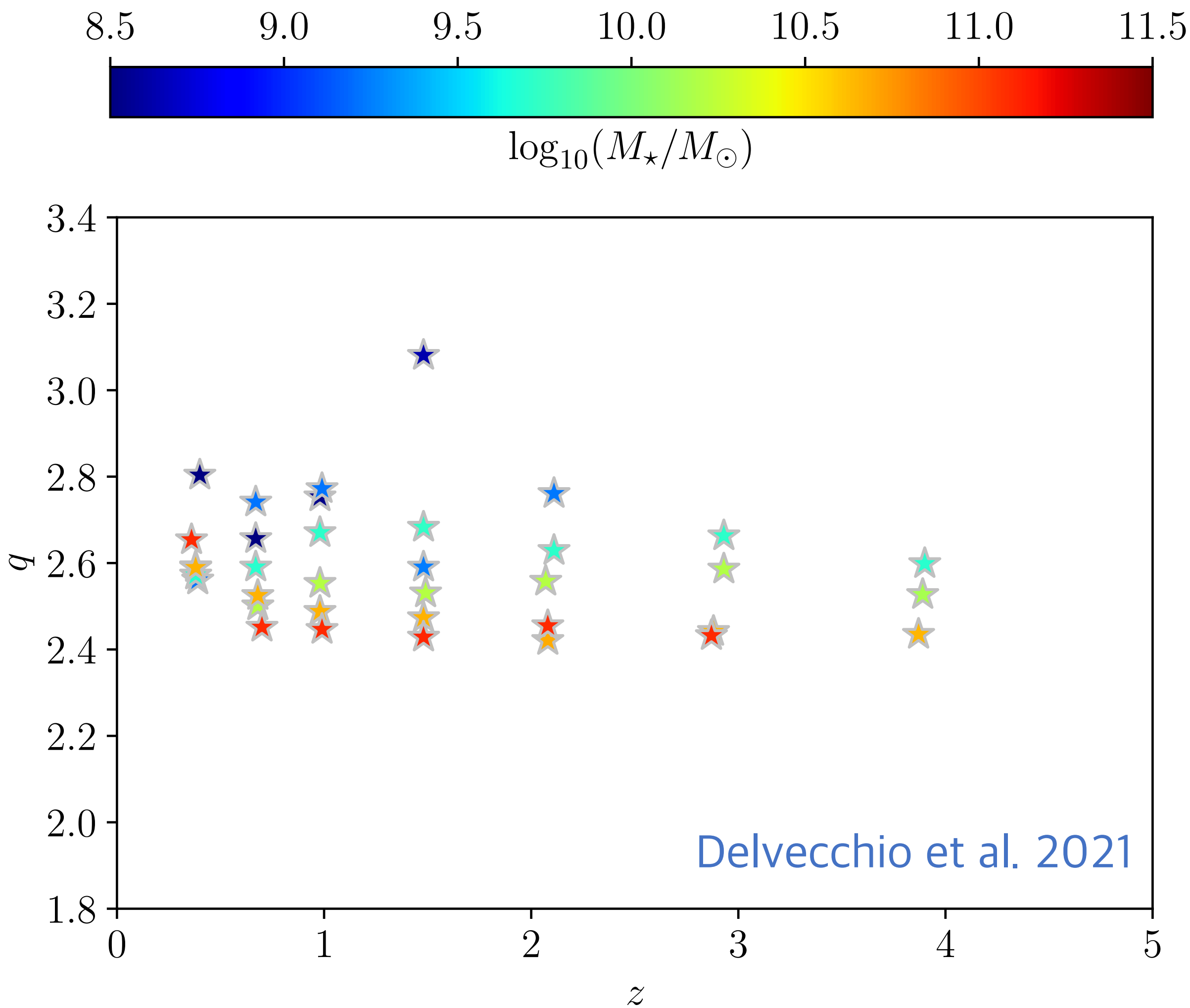
Resulting evolution of q



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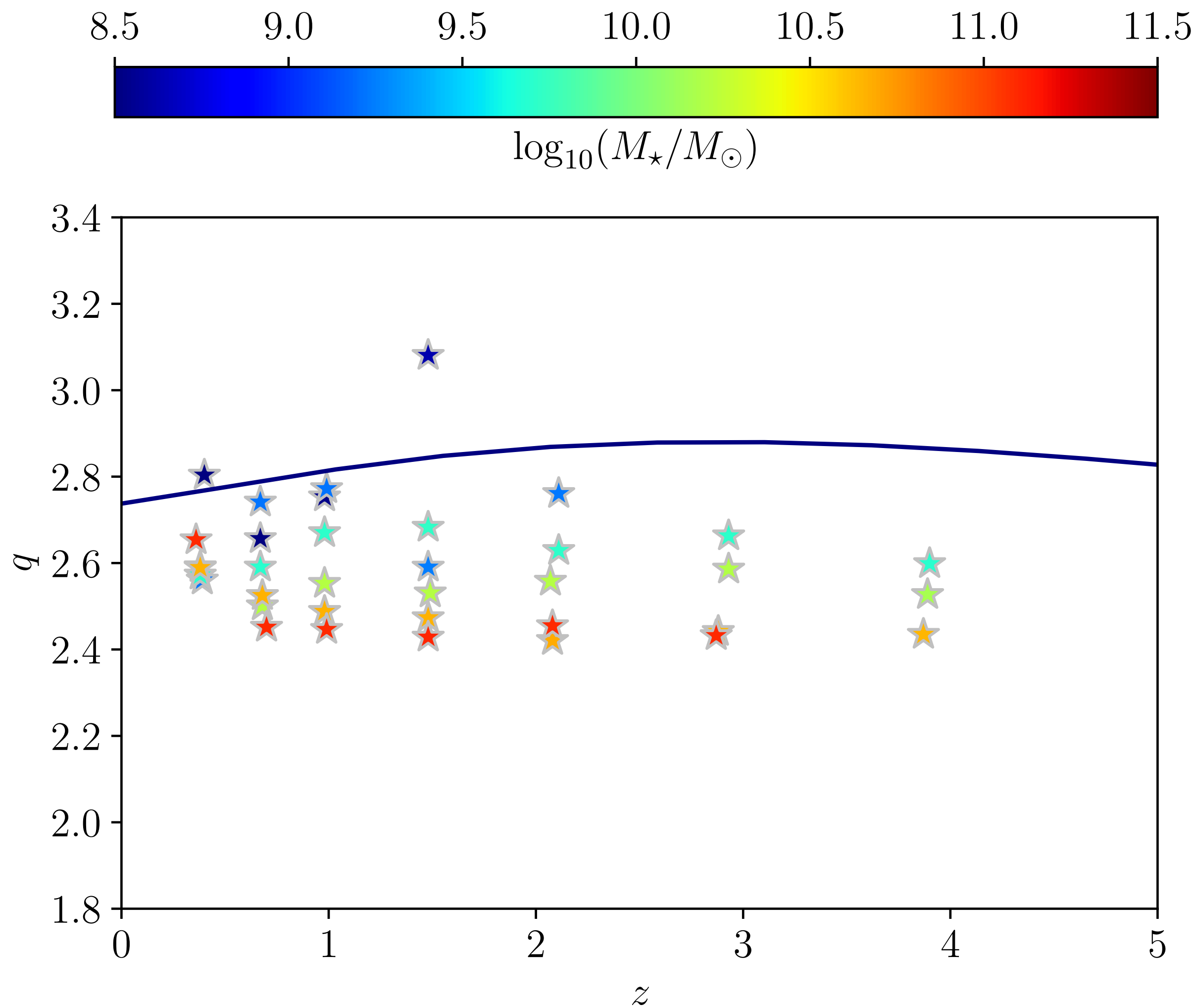

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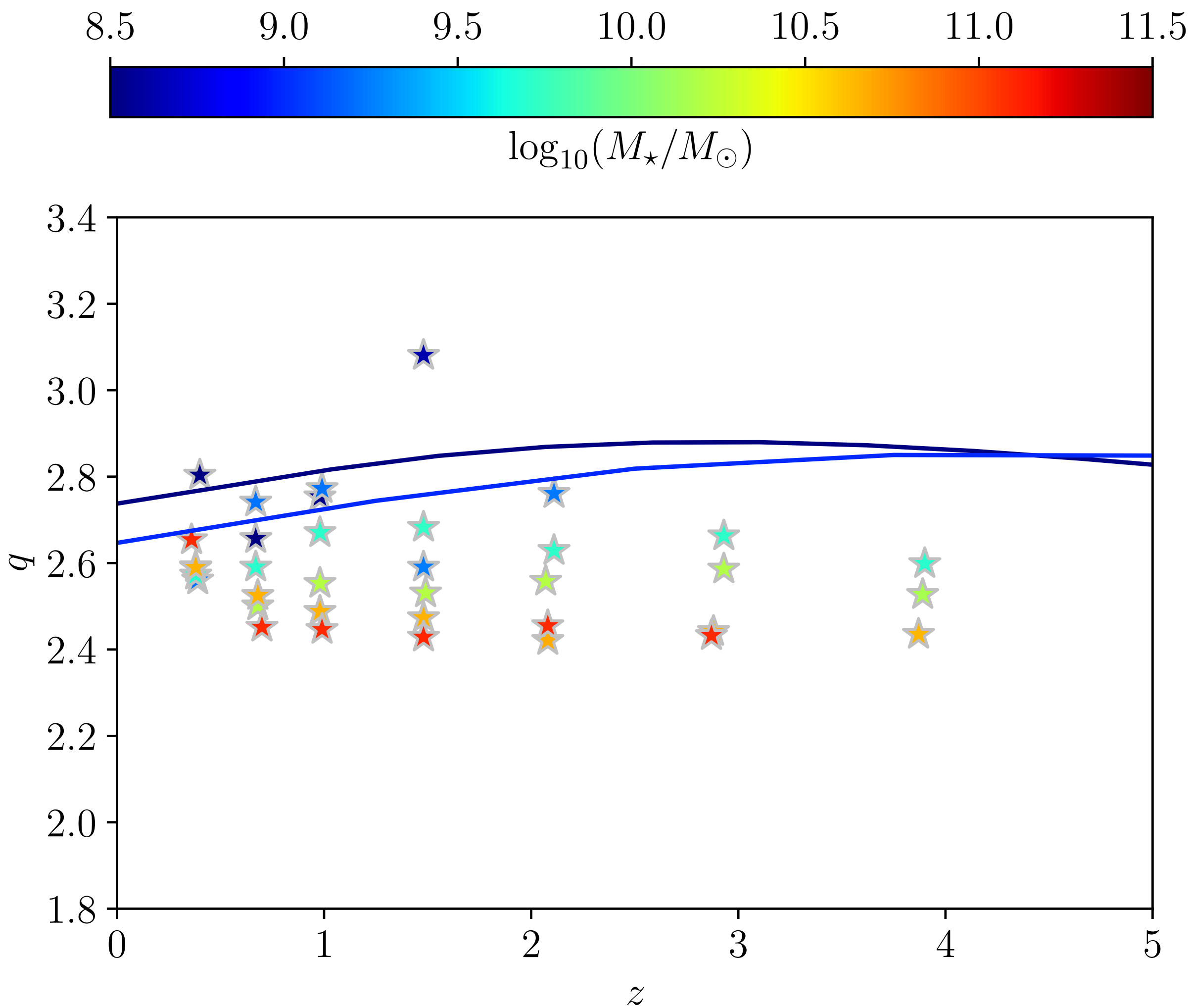

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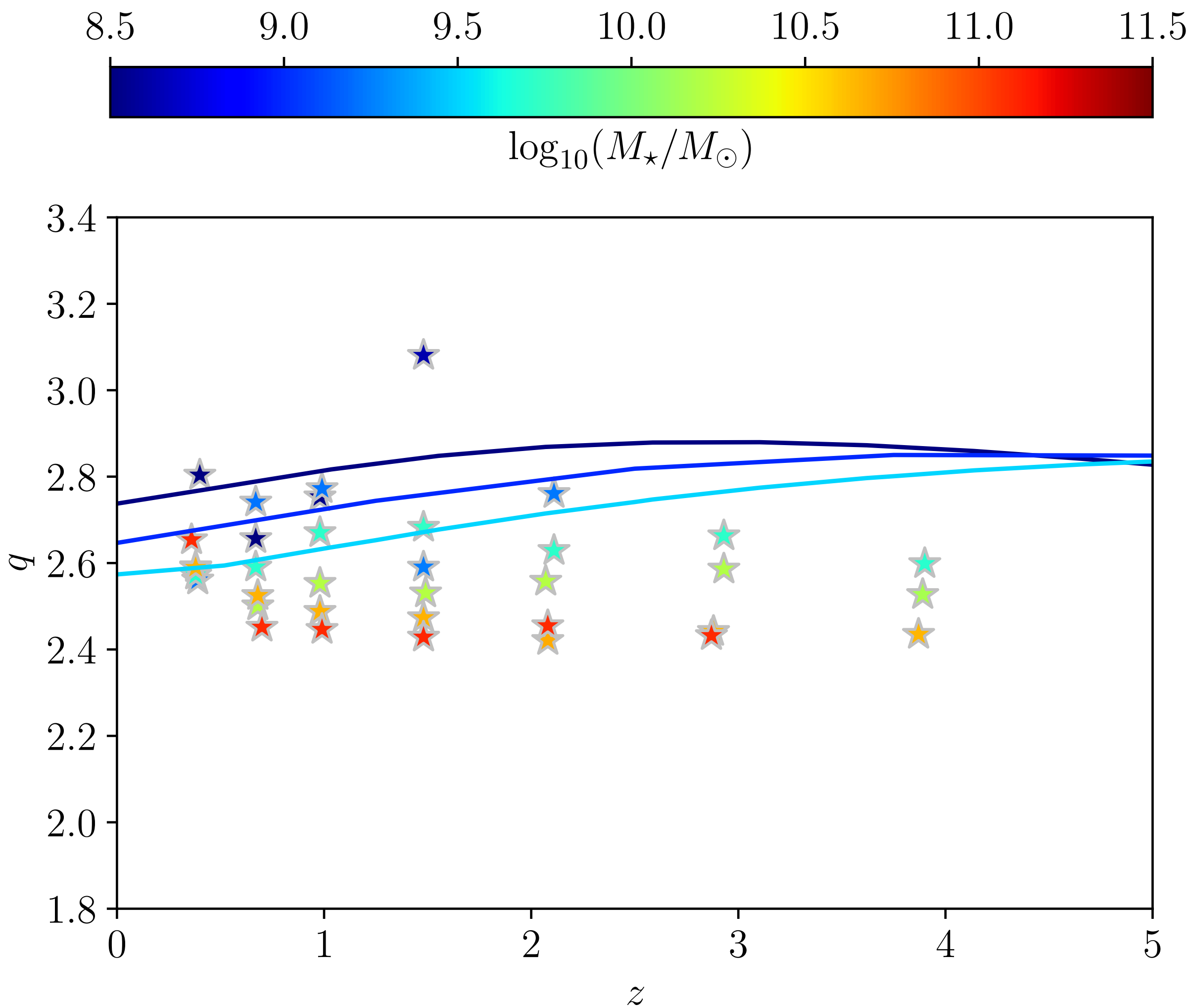

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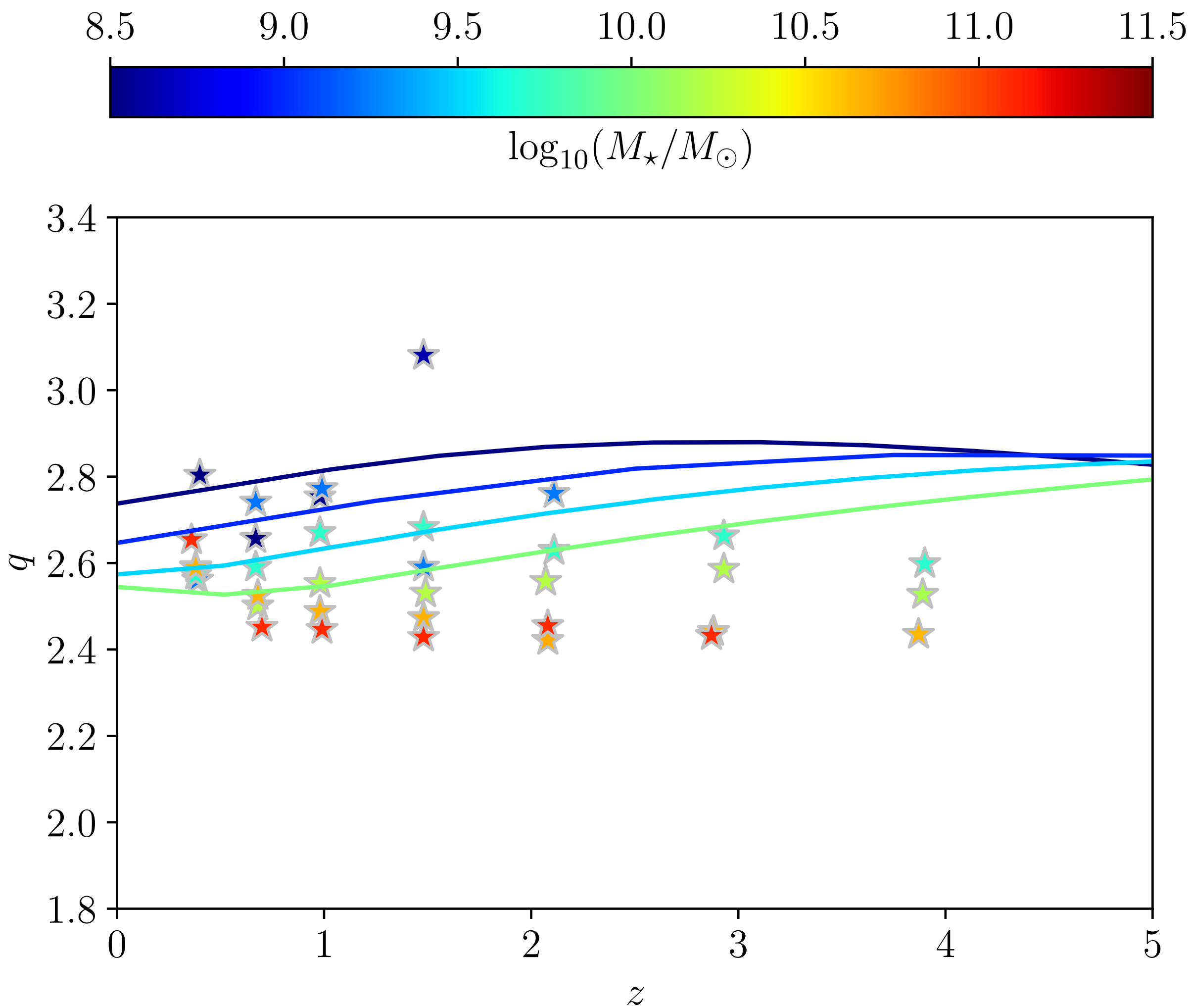

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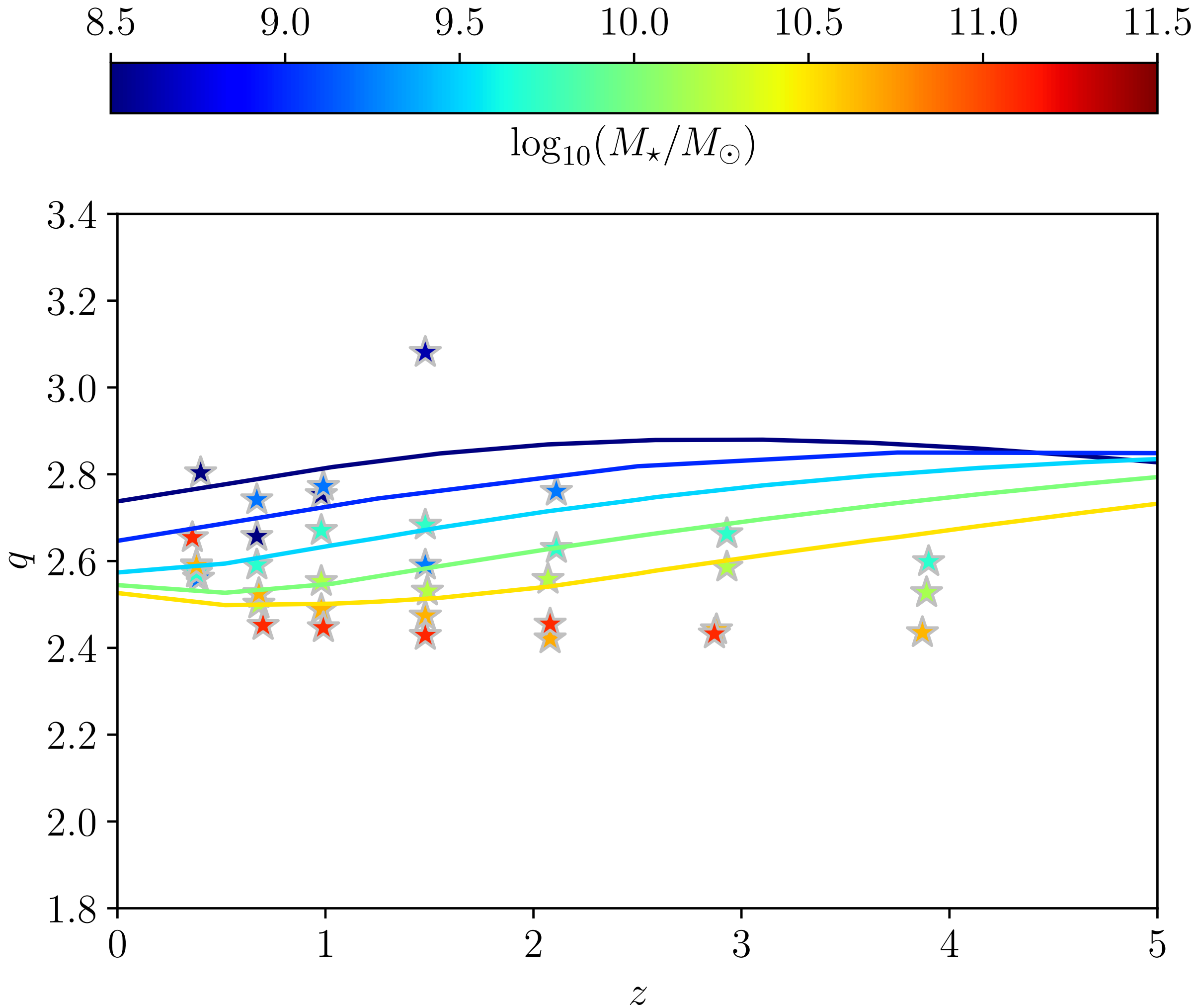

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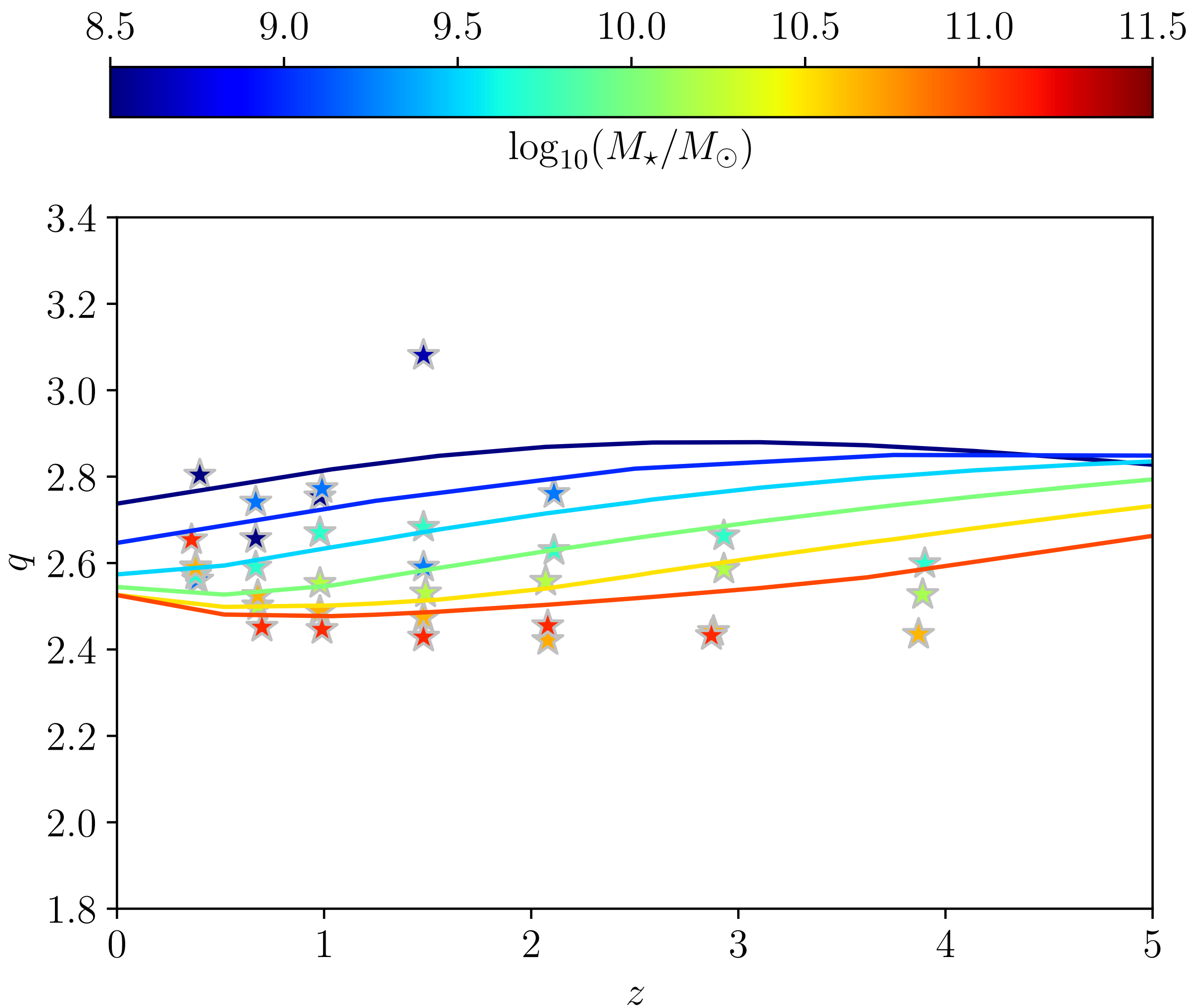

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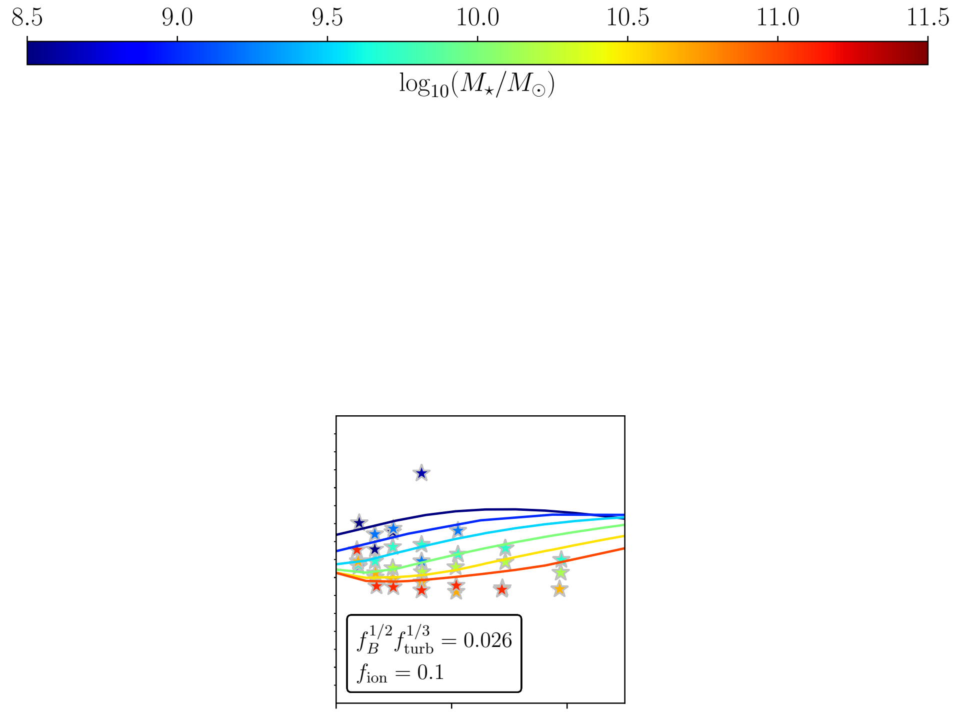
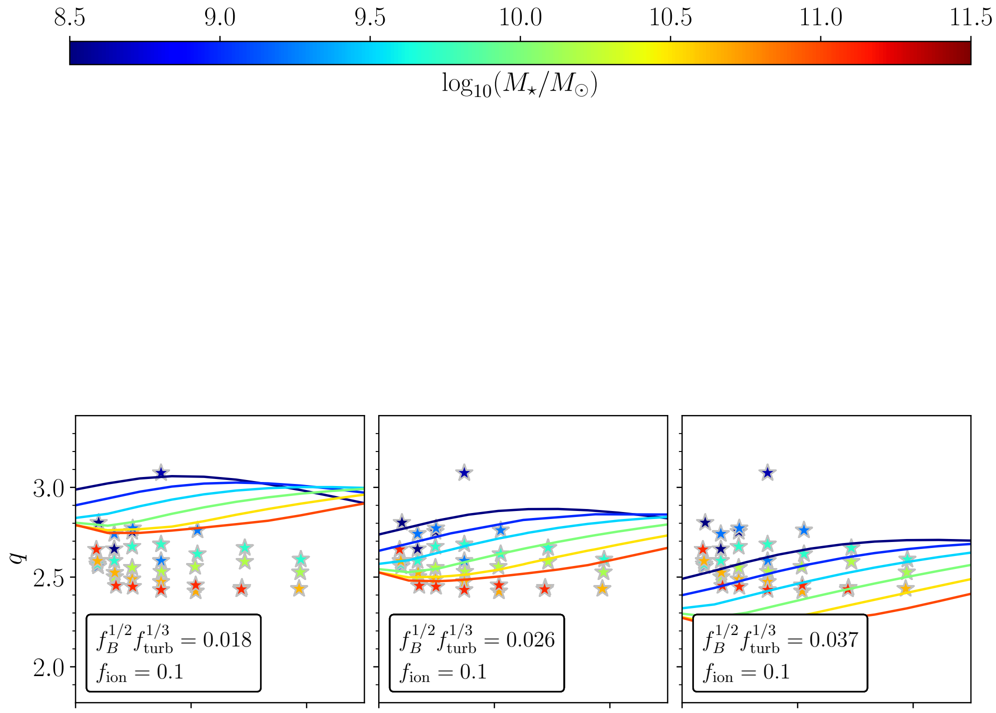
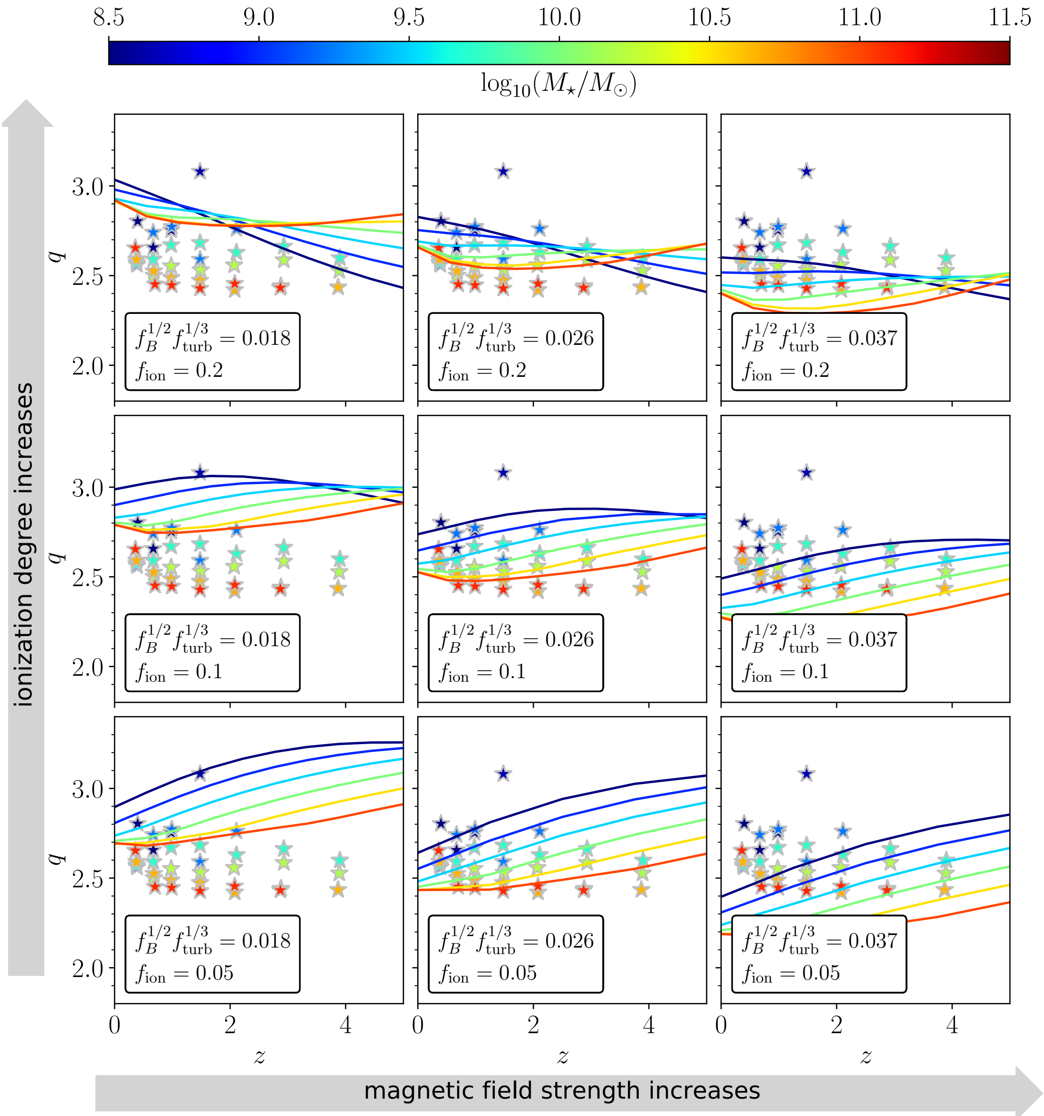


Resulting evolution of q

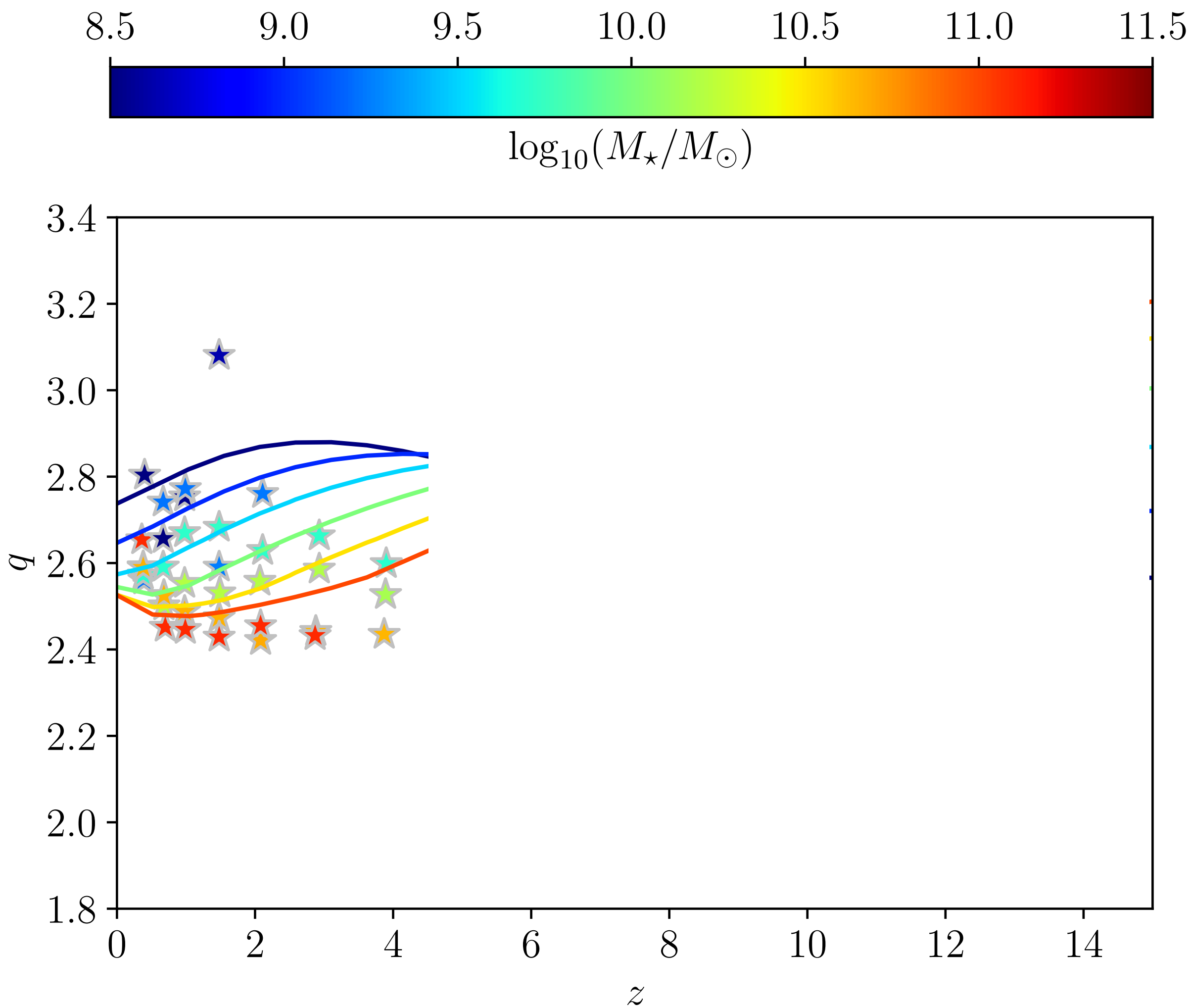


magnetic field strength increases

Resulting evolution of q



Resulting evolution of q



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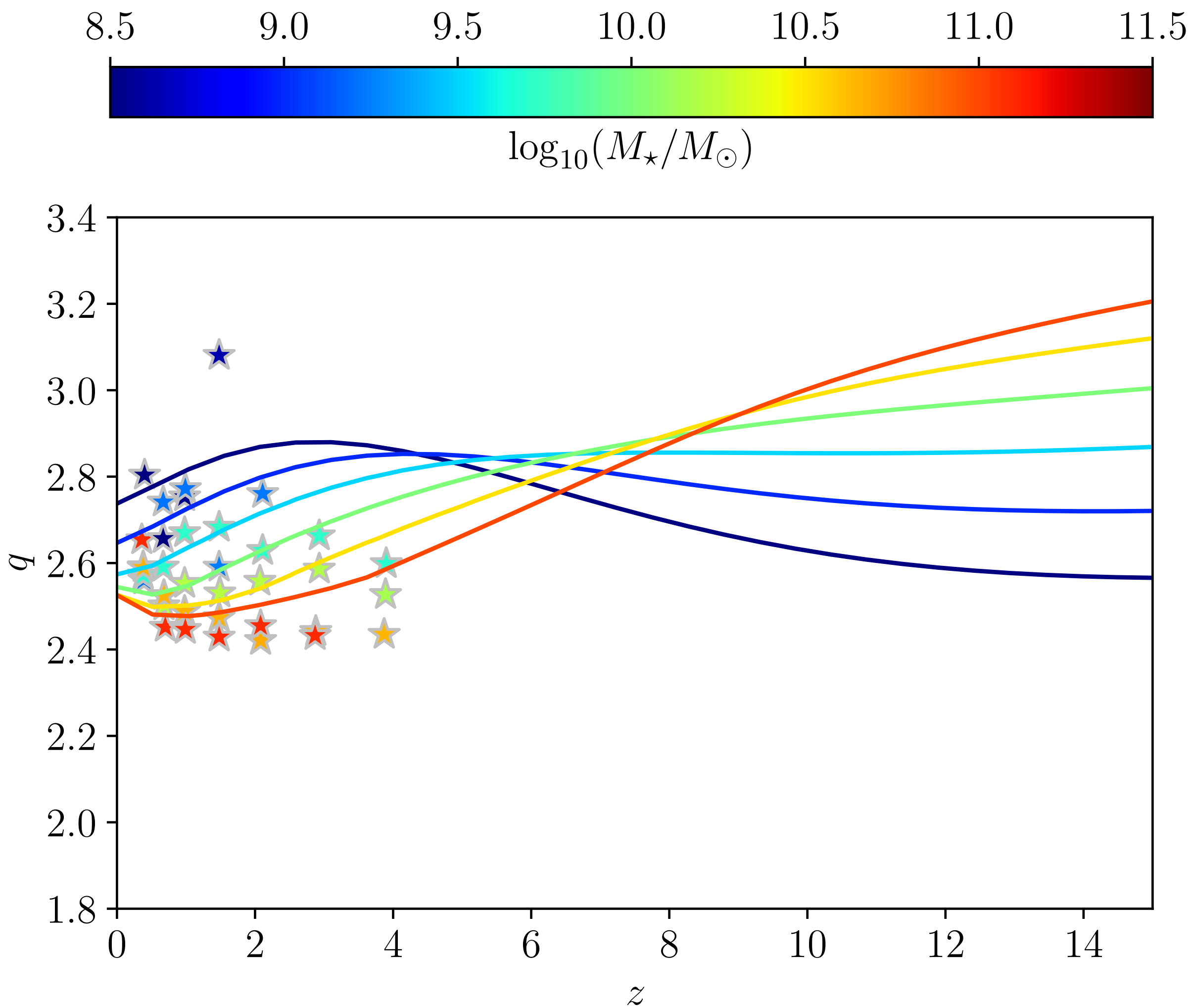

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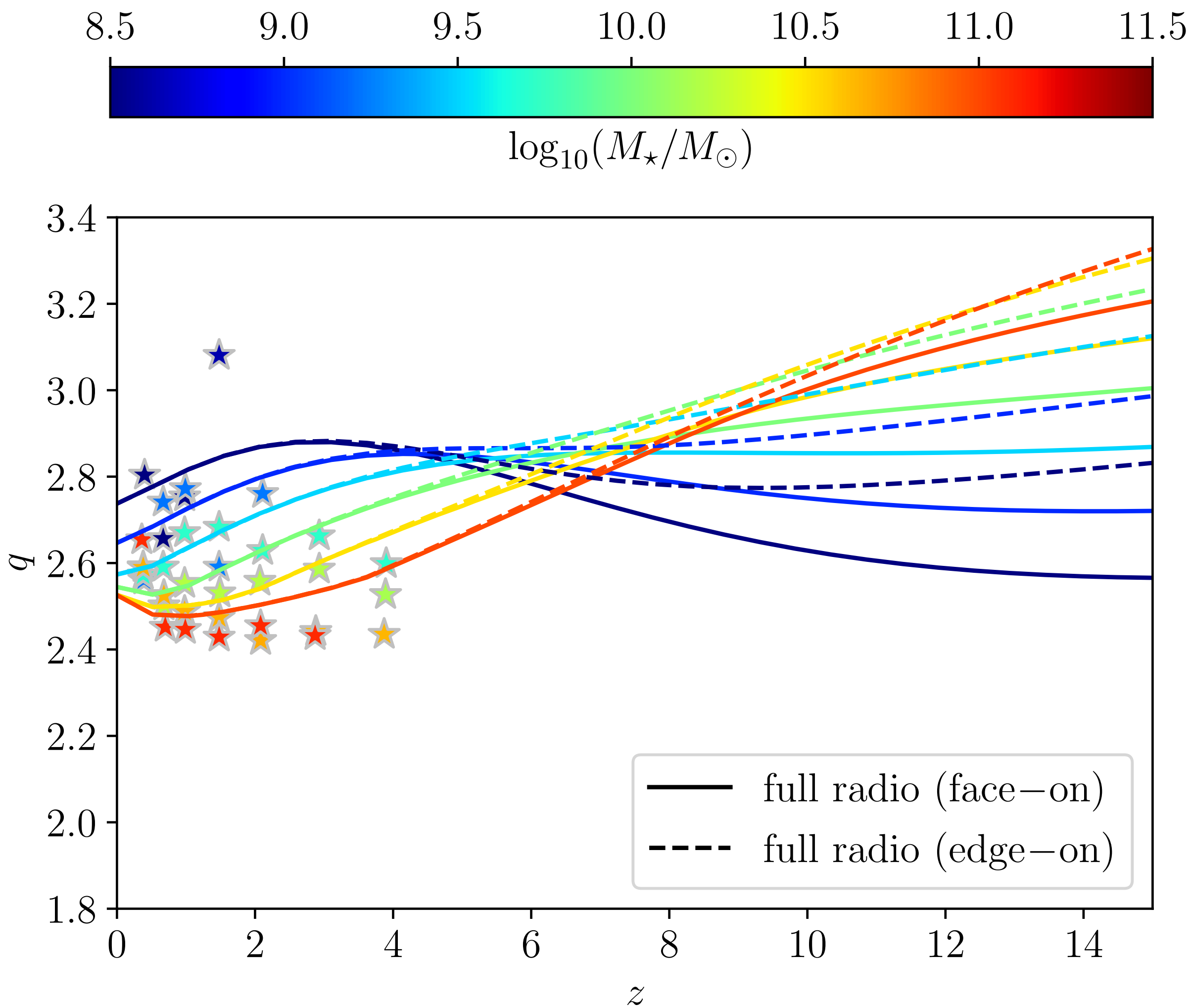


Conclusions

- The observed IR-radio correlation depends on stellar mass but is independent of redshift up to z ~ 4.
- This observation can be reproduced with a steady state cosmic ray model and the assumption of a saturated small-scale dynamo.
- The exact evolution of q depends on the choice of the free parameters.
- A calibration of the star formation rate at radio wavelengths should include a dependence on stellar mass.

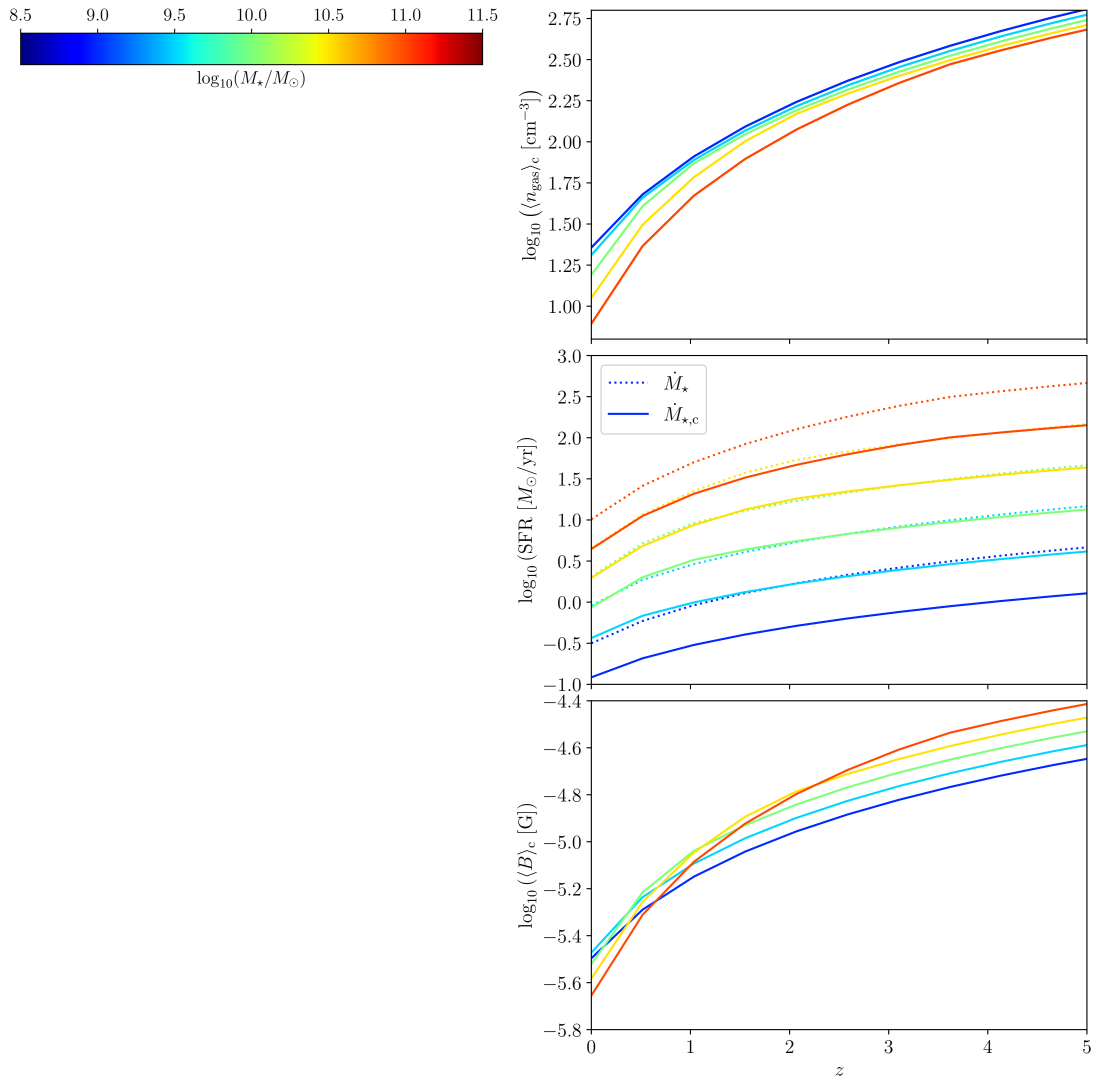
Thank you for your attention!

If you have any questions, feel free to contact me:

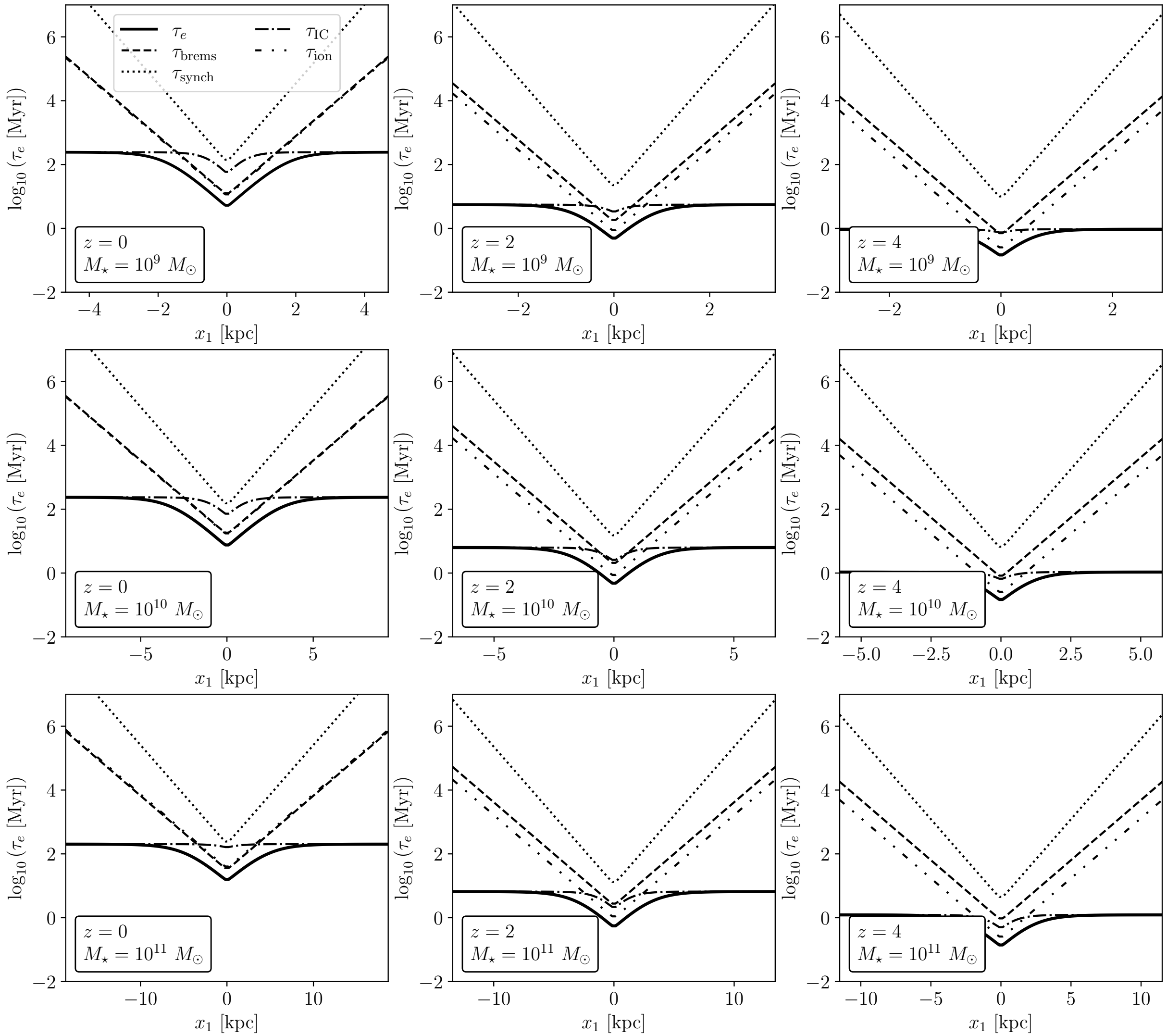
jennifer.schober@epfl.ch

Backup slides

Global input correlations



CR electrons: cooling timescales



IR-radio correlation