Nuclear Astrophysics meets Asteroseismology

Hannah Brinkman, Postdoctoral Researcher
Institute of Astronomy (IvS), KU Leuven, Belgium
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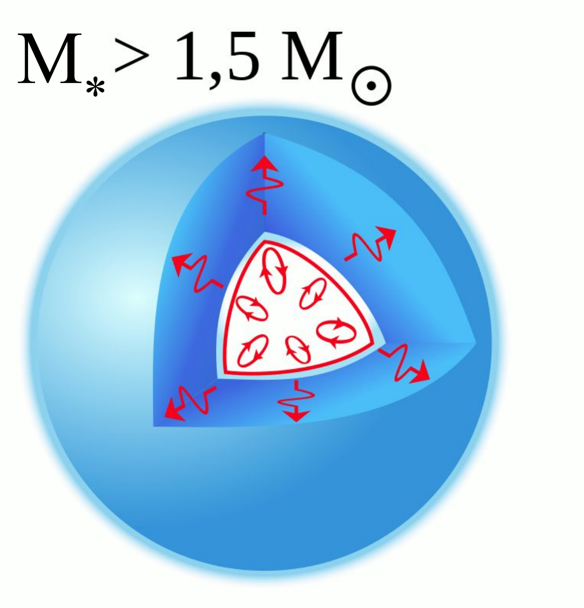
How do isotopes move inside a star?

Internal mixing processes for massive stars:

- ❑ Convective boundary mixing
- ❑ Envelope mixing

Project input:

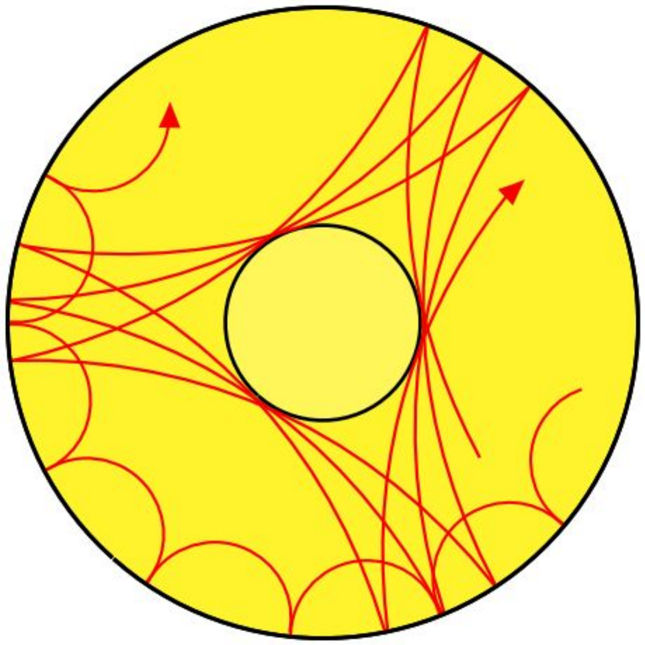
- ❑ Ledoux criterion for convection
- ❑ **Asteroseismically inferred values for convective boundary mixing and envelope mixing**



Connection to asteroseismology

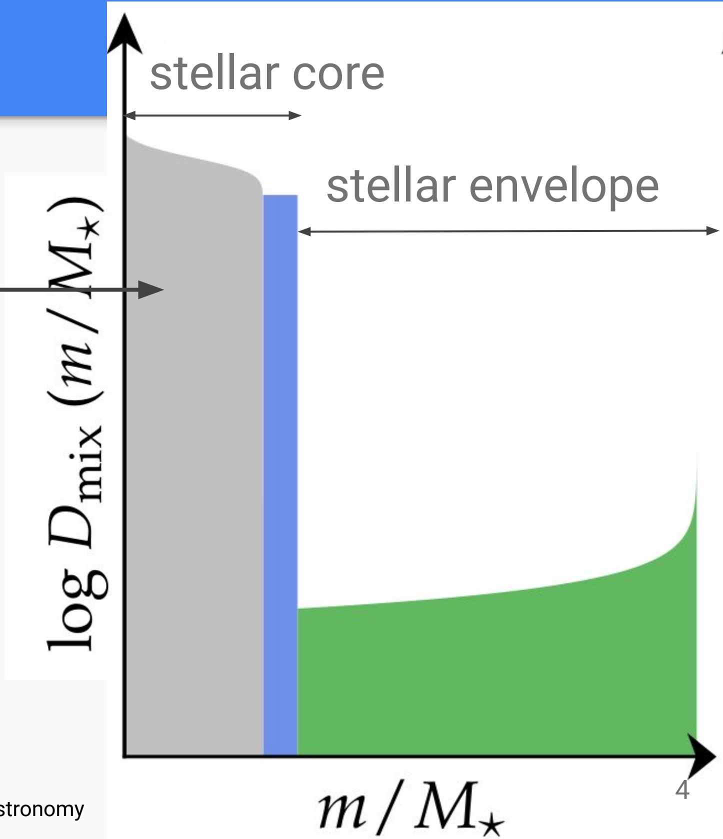
What is asteroseismology?

Asteroseismology is the study of the internal structures of stars by means of their oscillations, comparable to how we learn about the interior of the Earth by studying earthquakes



Connection to asteroseismology

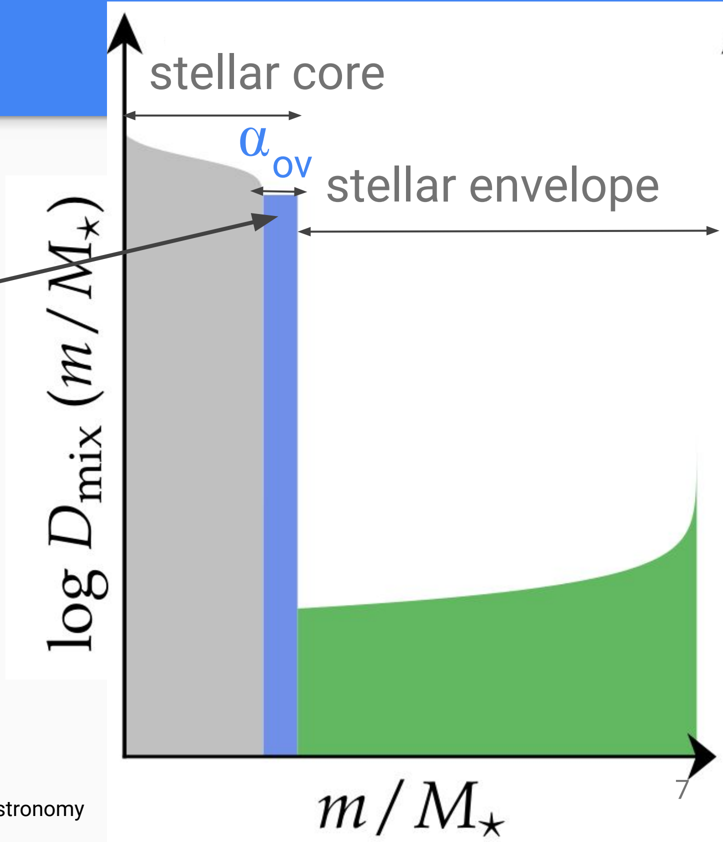
Based on observations, stars have larger $\boxed{\text{convective cores}}$ than standard stellar evolution models currently predict



Pedersen, M. G.et al., 2021, Nature Astronomy

Connection to asteroseismology

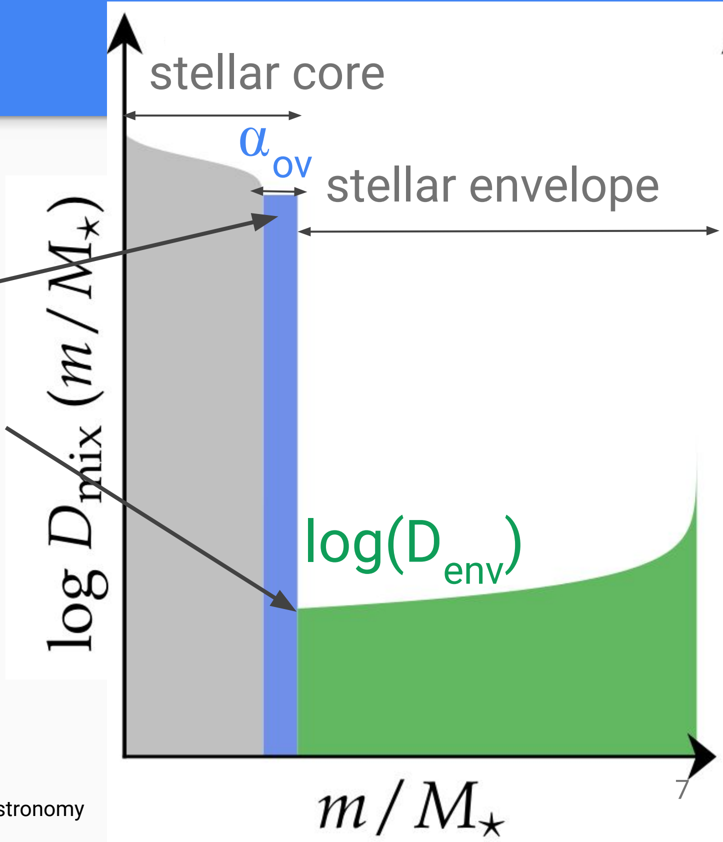
- How could this difference be solved?
  - Use of calibrated convective boundary mixing (CBM)



Pedersen, M. G.et al., 2021, Nature Astronomy

Connection to asteroseismology

- How could this difference be solved?
  - Use of calibrated convective boundary mixing (CBM)
  - Use of calibrated envelope mixing (Denv) at the bottom of the envelope



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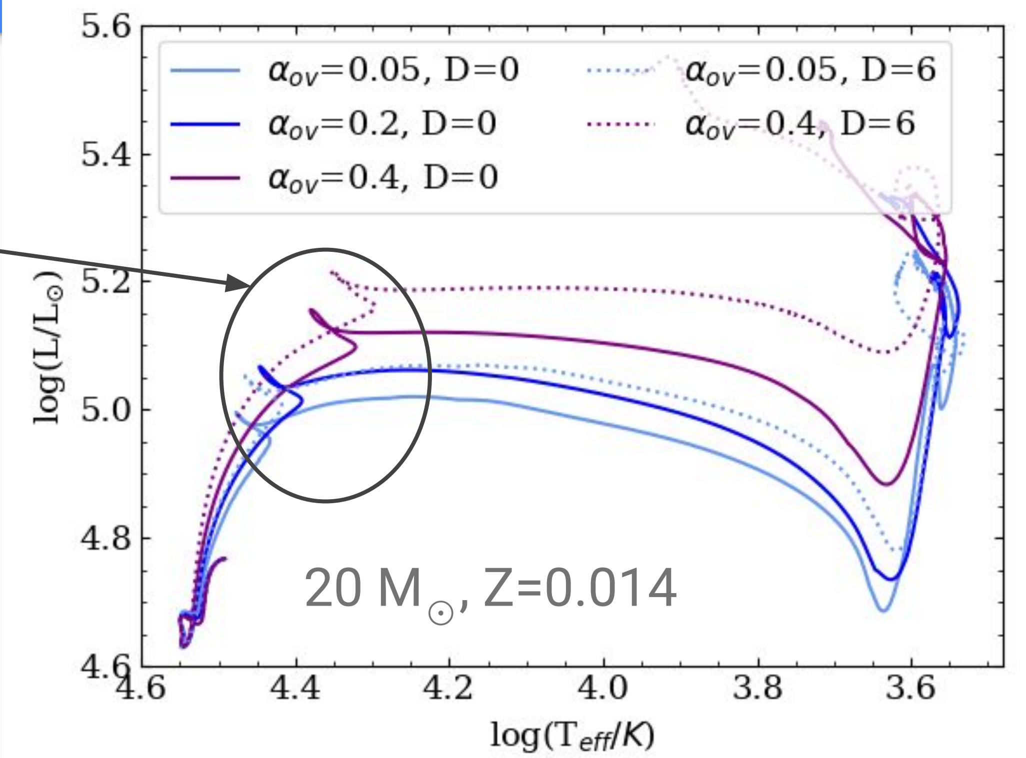
Linking back to stellar evolution

- Model ingredients:
  - Initial mass of 20 $M_\odot$
  - Initial metallicity Z=0.014
  - Nuclear network of 212 isotopes
  - α_{ov} and D_{env} are varied according to asteroseismology
  - Endpoint at $\log(T_c)=9$

Linking back to stellar evolution

- More CBM/a higher D_{env} leads to:
  - Higher luminosity at the TAMS
  - Lower temperature at the TAMS

-> Comparable to the effect of rotationally induced mixing



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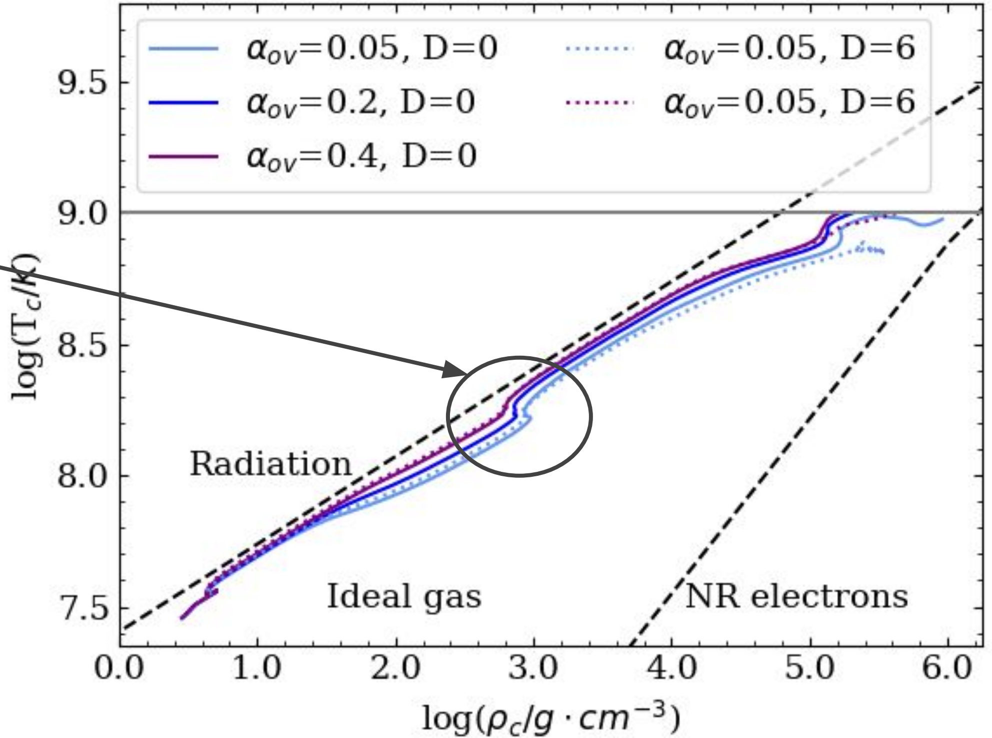
Linking back to stellar evolution

- More CBM/a higher D_{env} leads to:
  - Higher central temperature at helium burning



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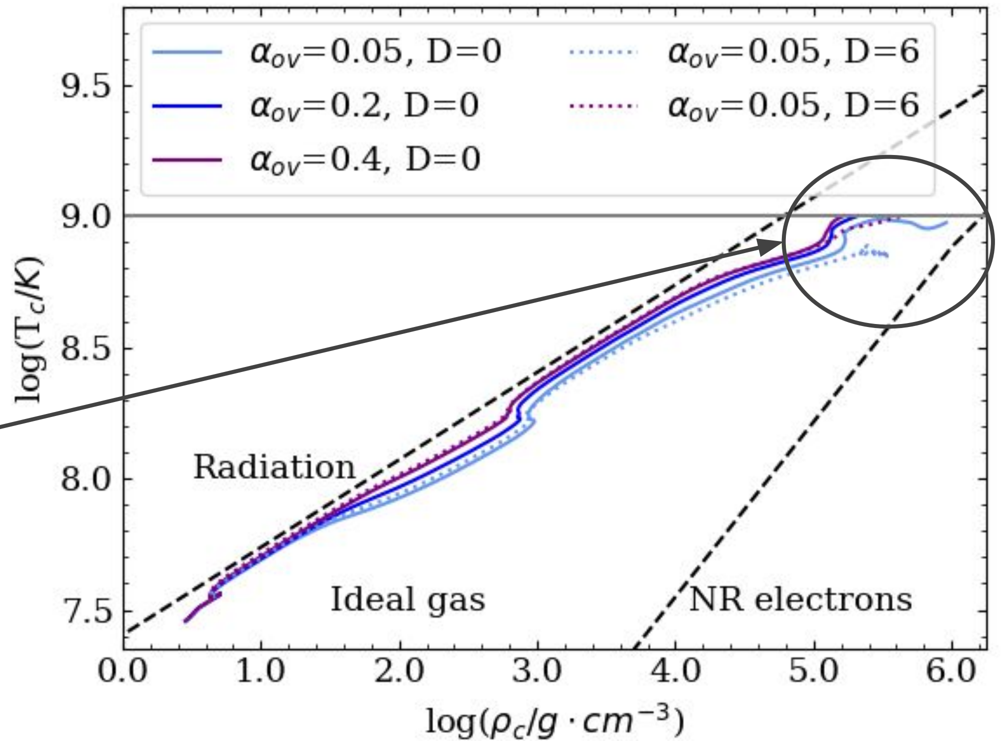
Linking back to stellar evolution

- More CBM/a higher D_{env} leads to:
  - Higher central temperature at helium burning
  - An earlier transition to radiative carbon burning



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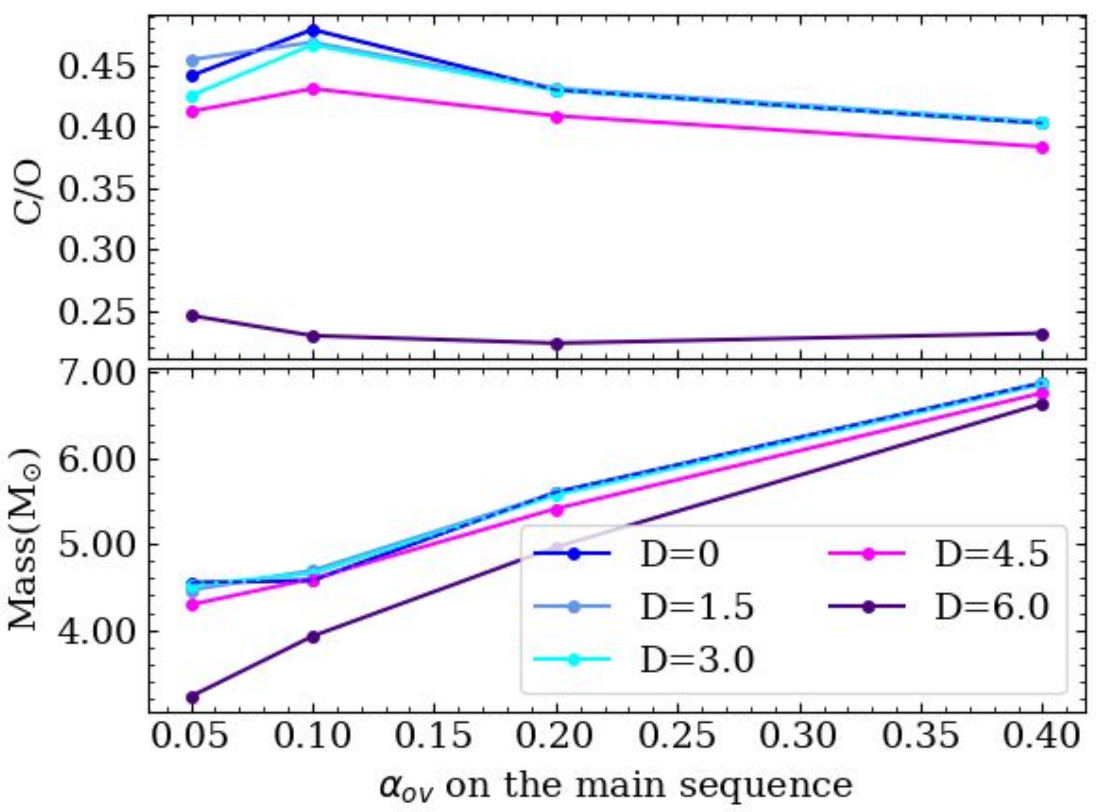
Linking back to stellar evolution

- More D_{env} leads to a lower CO-core mass and a lower C/O-ratio
- More CBM leads to a higher CO-core mass



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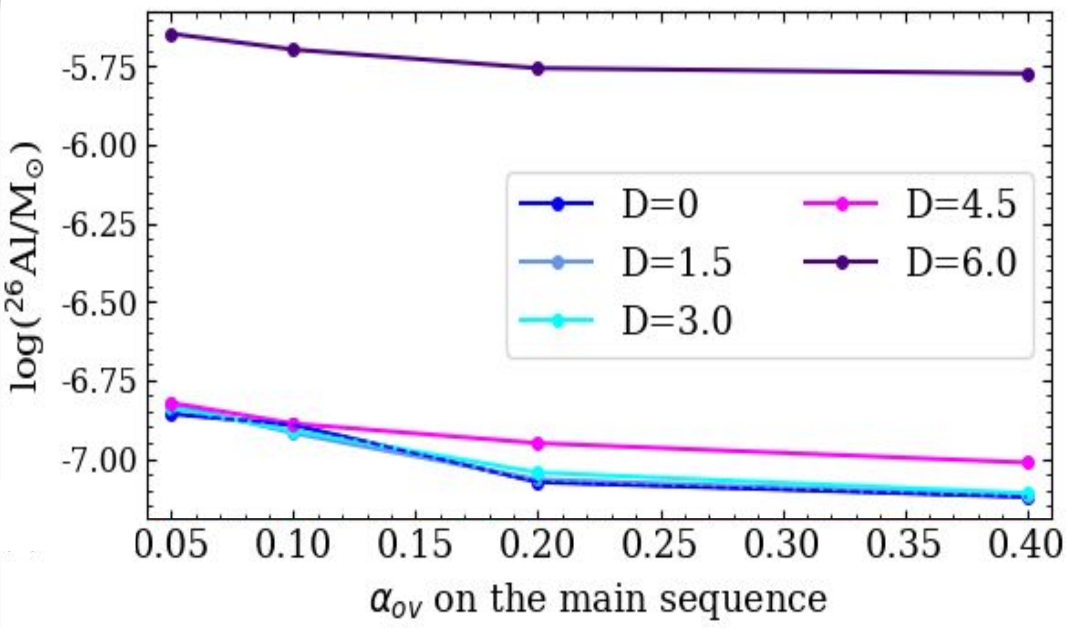
Linking back to nucleosynthesis: ^{26}Al

- More CBM leads to:
  - a lower ^{26}Al yield -> longer MS leading to more internal decay
- A higher D_{env} leads to
  - a higher ^{26}Al yield -> more mixing within the stellar envelope



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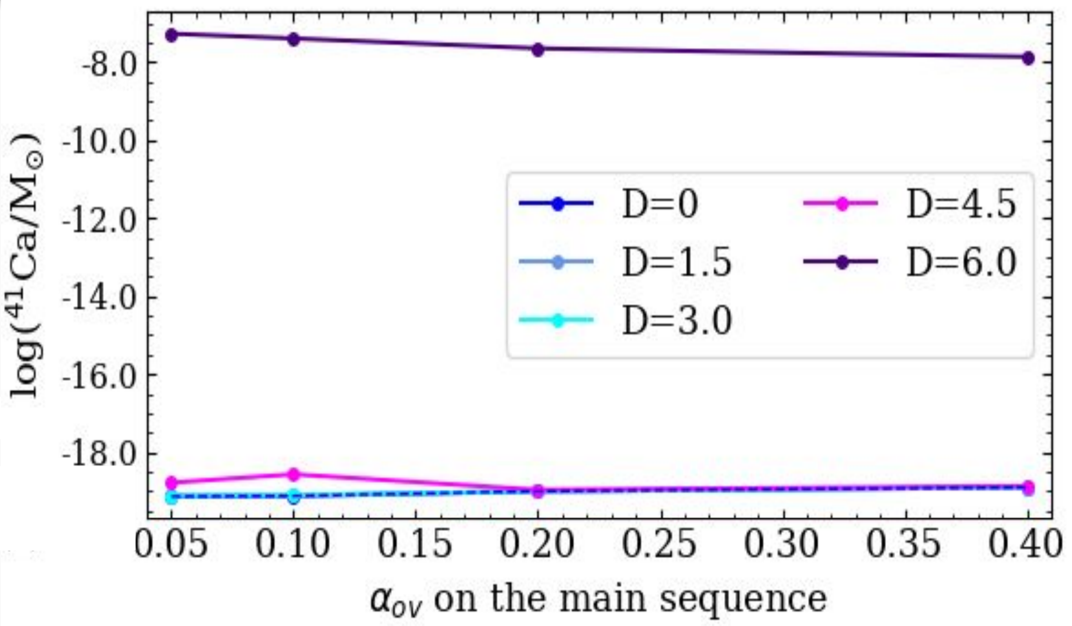
Linking back to nucleosynthesis: ^{41}Ca & ^{36}Cl

- More CBM leads to:
  - a comparable ^{41}Ca yield over the whole range
- A higher Denv leads to
  - a higher ^{41}Ca yield

-> ^{36}Cl behaves similarly



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Conclusions

- Conclusions:
  - Mixing induced by internal gravity waves and rotation have comparable results on the main-sequence
  - Internal gravity waves during helium burning have a strong effect on:
    - C/O-ratio at the end of helium burning
    - Yields of isotopes produced during this stage

Future work

- Future work will include:
  - A larger range of initial masses
  - Evolution to the end of silicon burning
  - Combining internal gravity waves and rotation
  - Time-dependent CBM and envelope mixing
  - Comparing model results with observations
  - Updated reaction rates (when relevant and available)