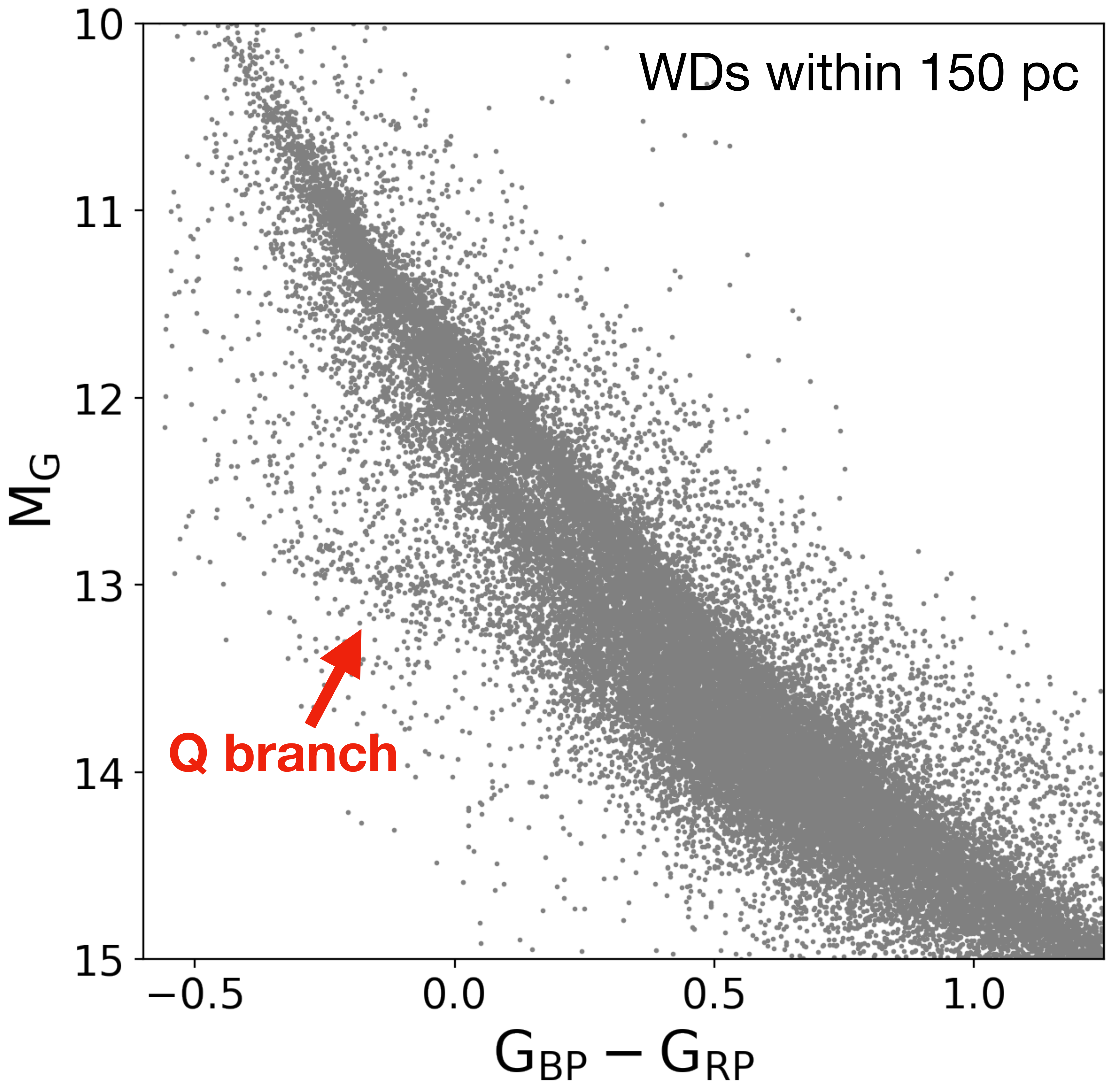
The Q branch: where white dwarfs stop cooling

Part I: observations

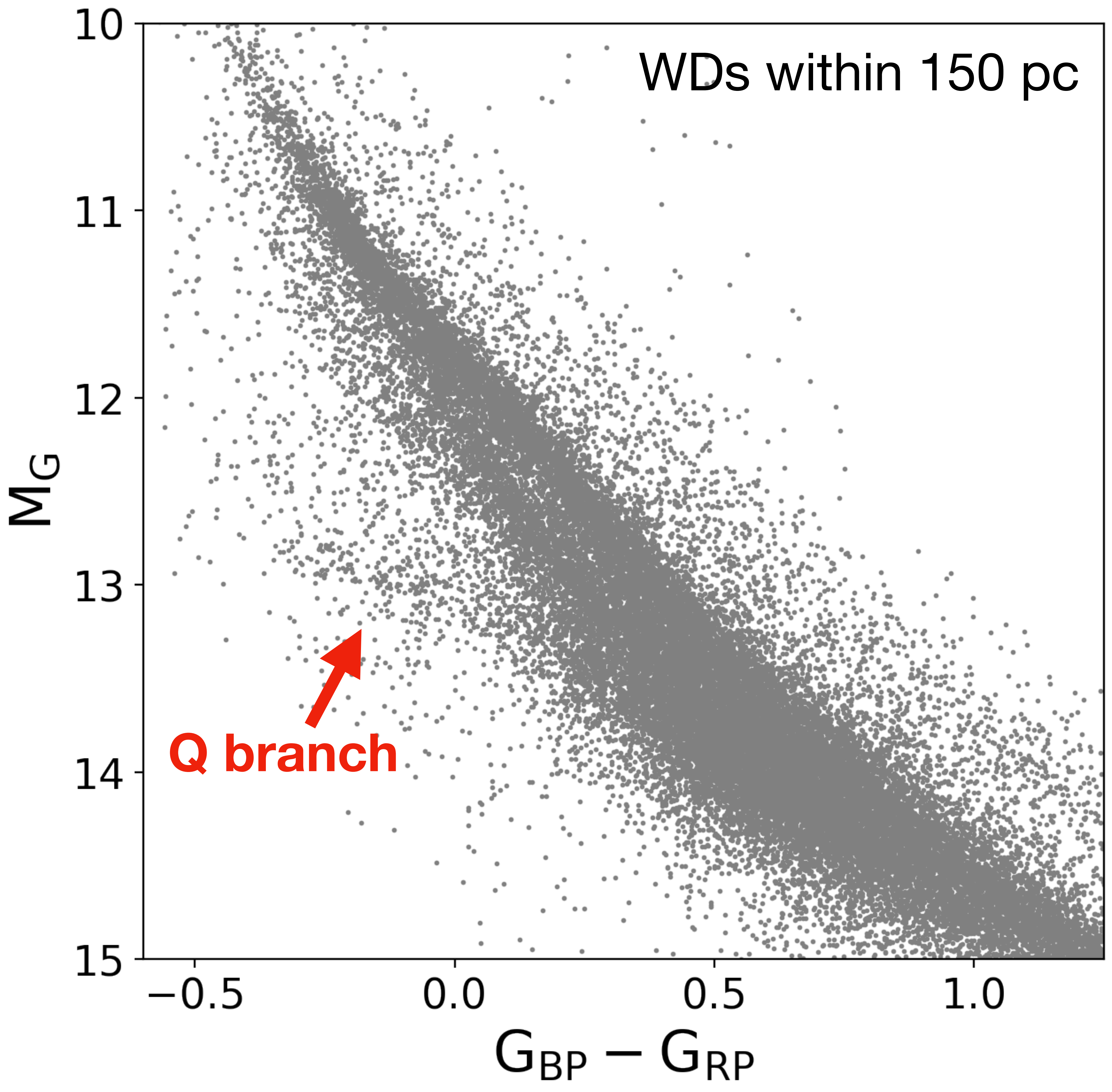
Mar 29th, 2021
KITP

Sihao Cheng (程思浩)
Johns Hopkins University

white dwarfs in *Gaia*



the Q branch

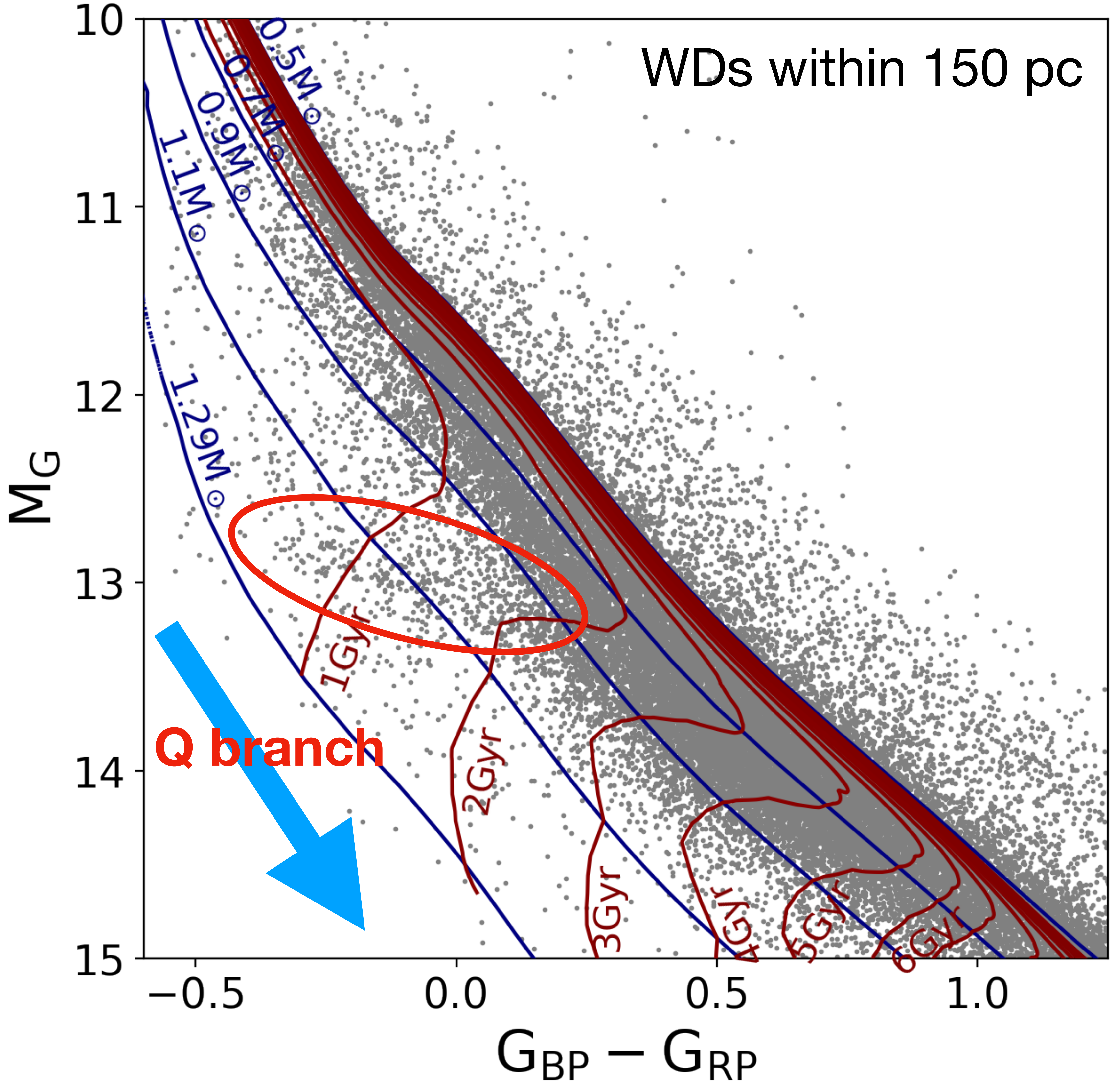


Properties of the Q branch:

Over-density

Gaia Collaboration et al. (2018)

the Q branch

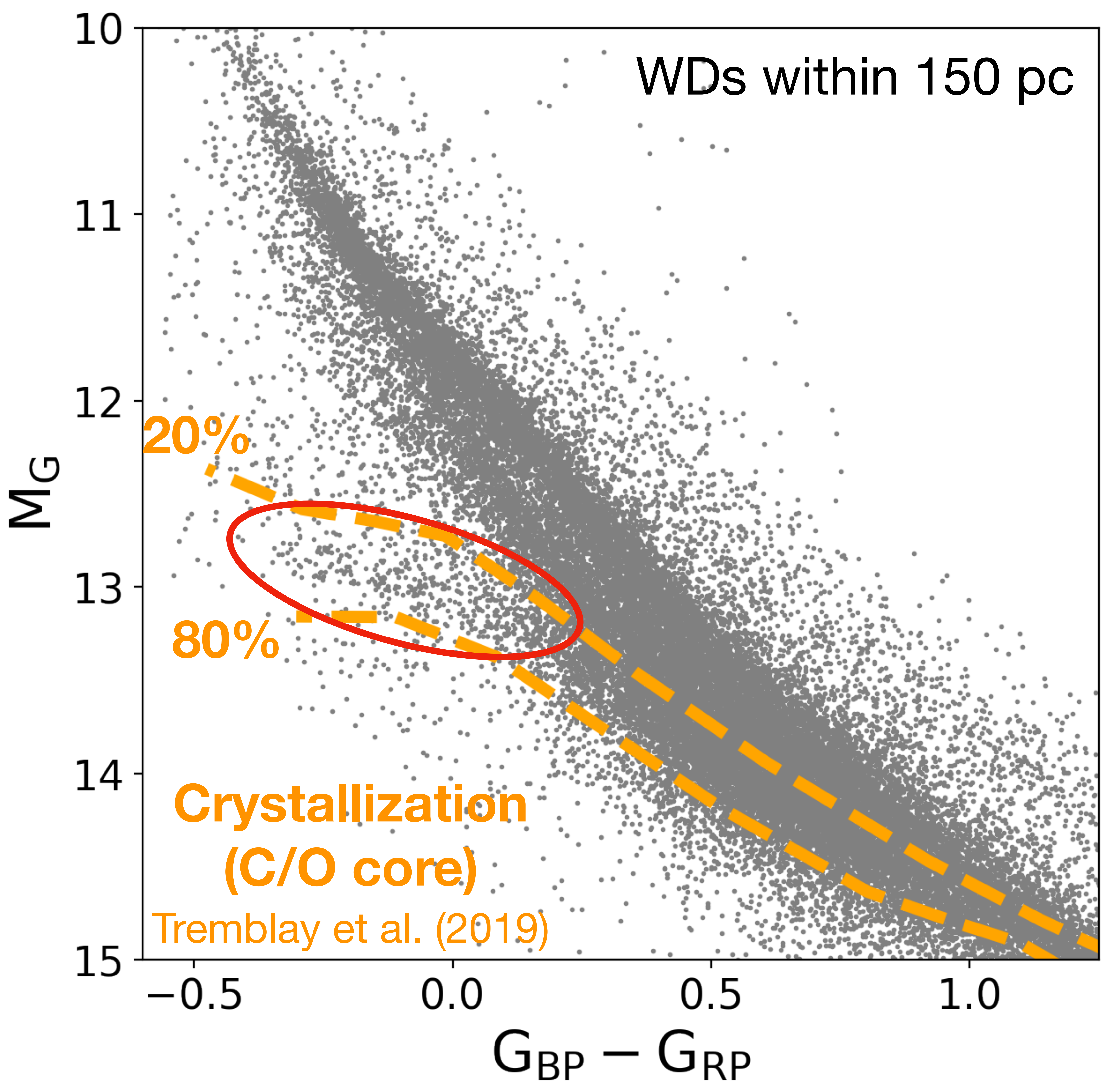


Properties of the Q branch:

Over-density

Gaia Collaboration et al. (2018)

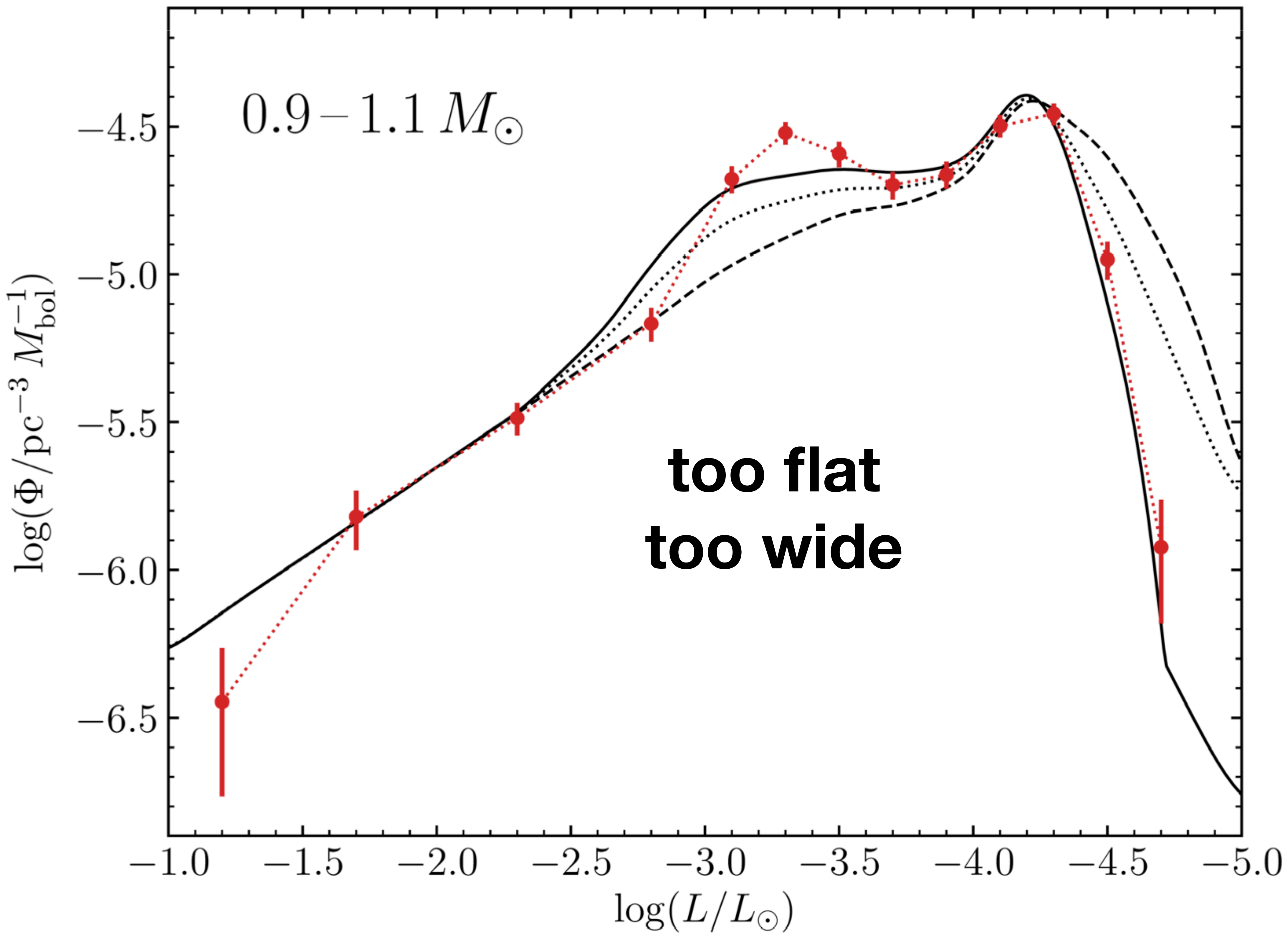
the Q branch



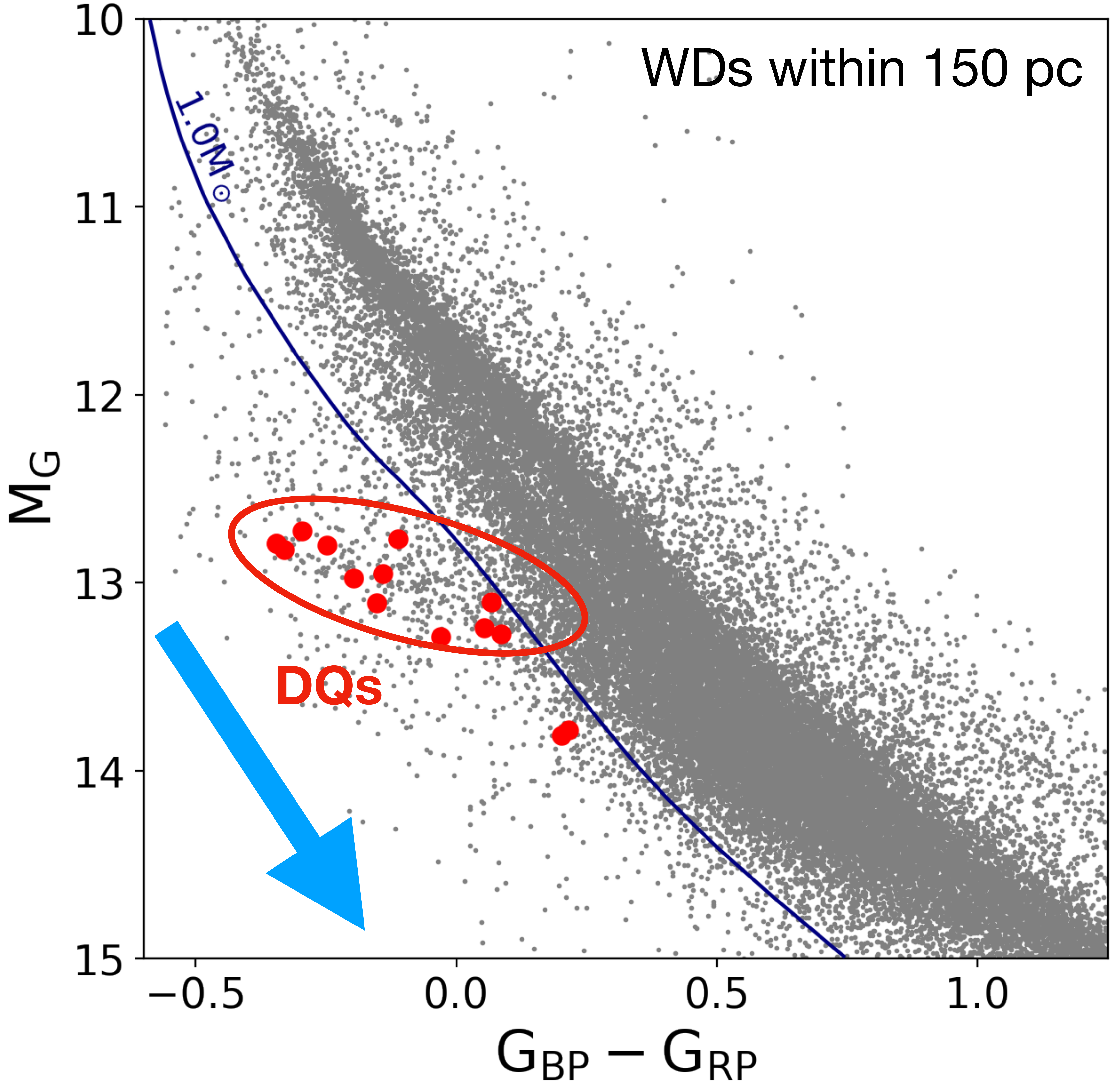
Properties of the Q branch:

Over-density

Gaia Collaboration et al. (2018)
Tremblay et al. (2019)



the Q branch



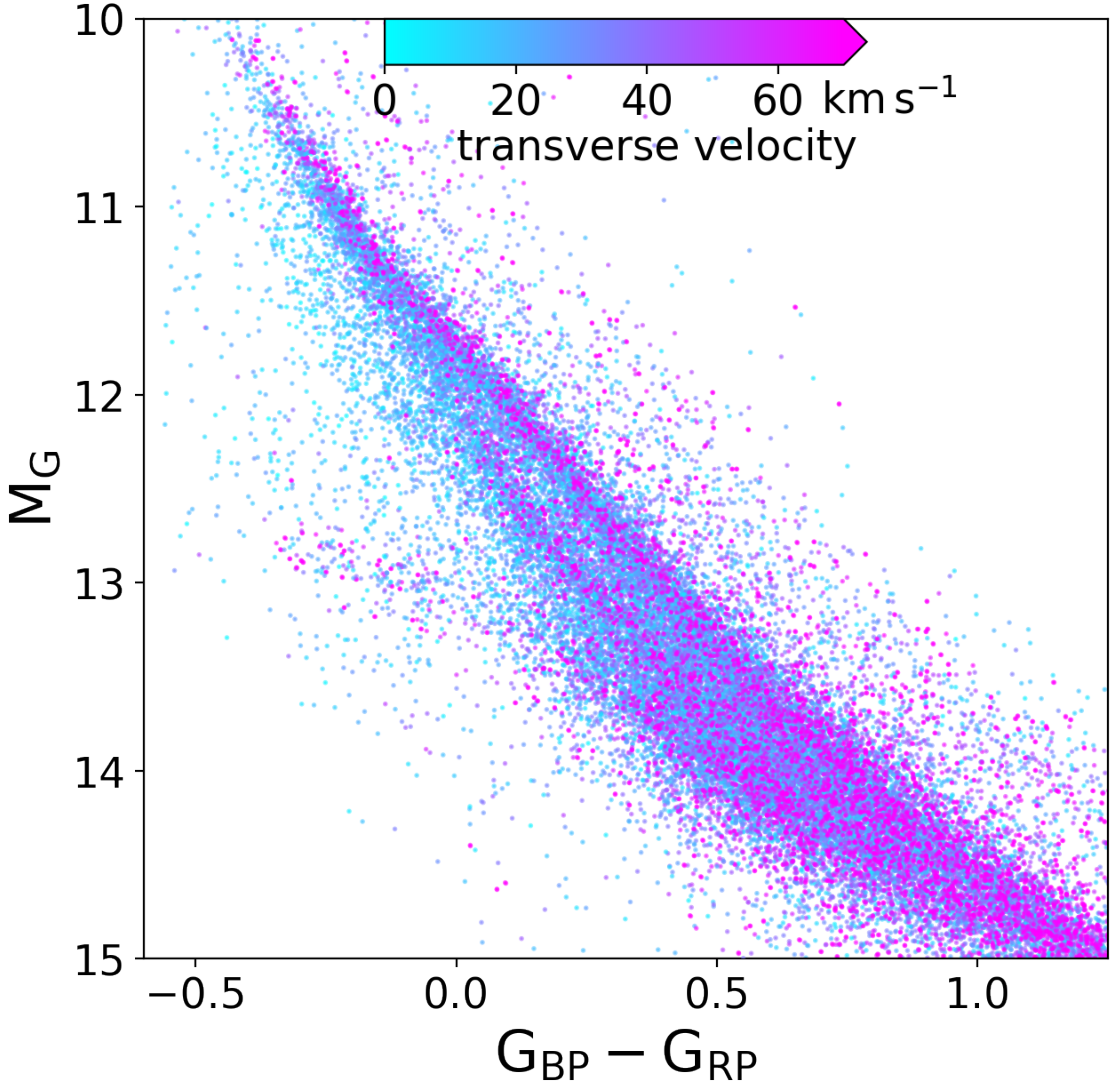
Properties of the Q branch:

Over-density

DQ white dwarfs

Gaia Collaboration et al. (2018)

a cooling anomaly!



Properties of the Q branch:

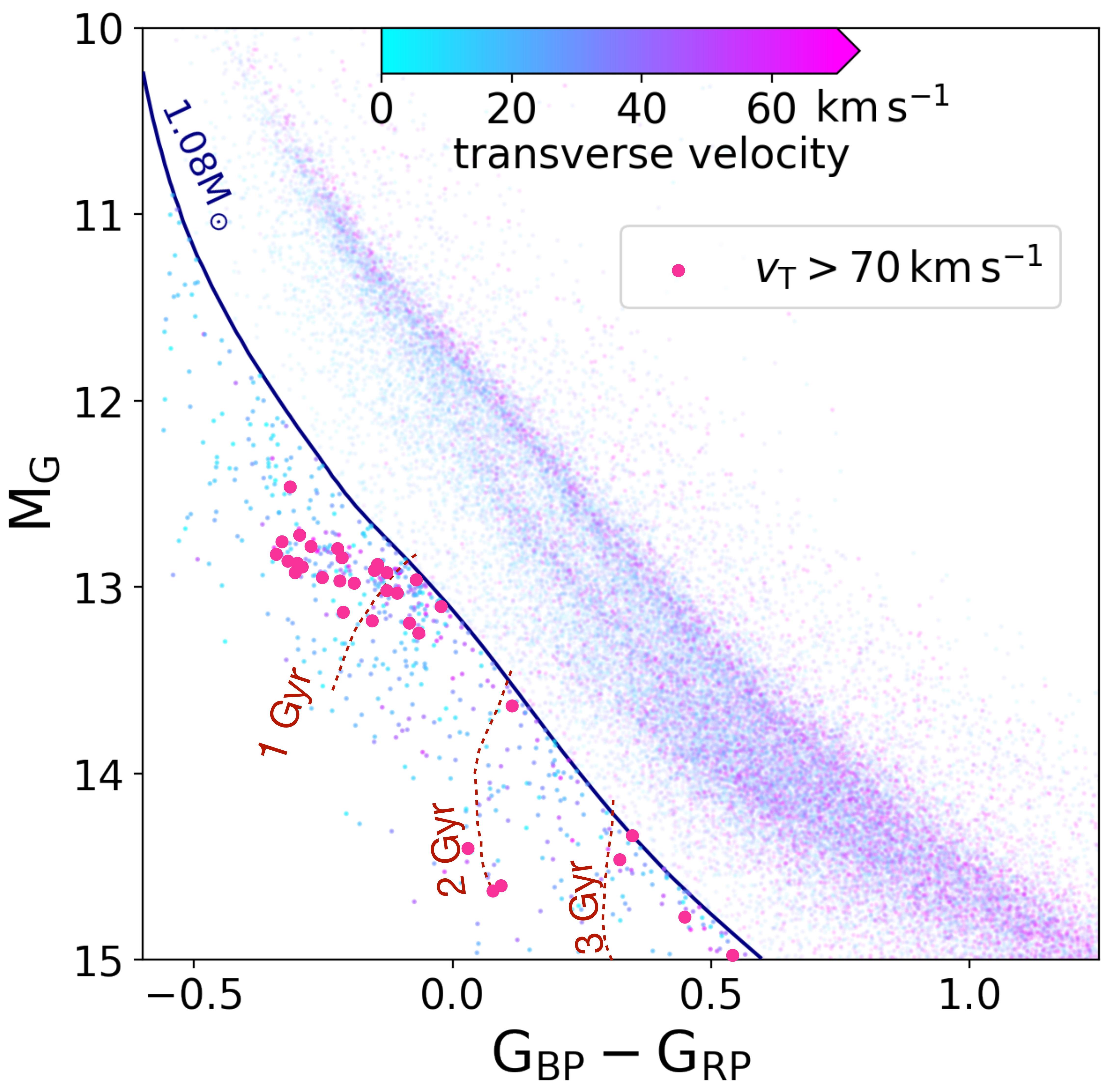
Over-density

DQ white dwarfs

Velocity excess

Cheng, Cummings, & Ménard (2019)

a cooling anomaly!



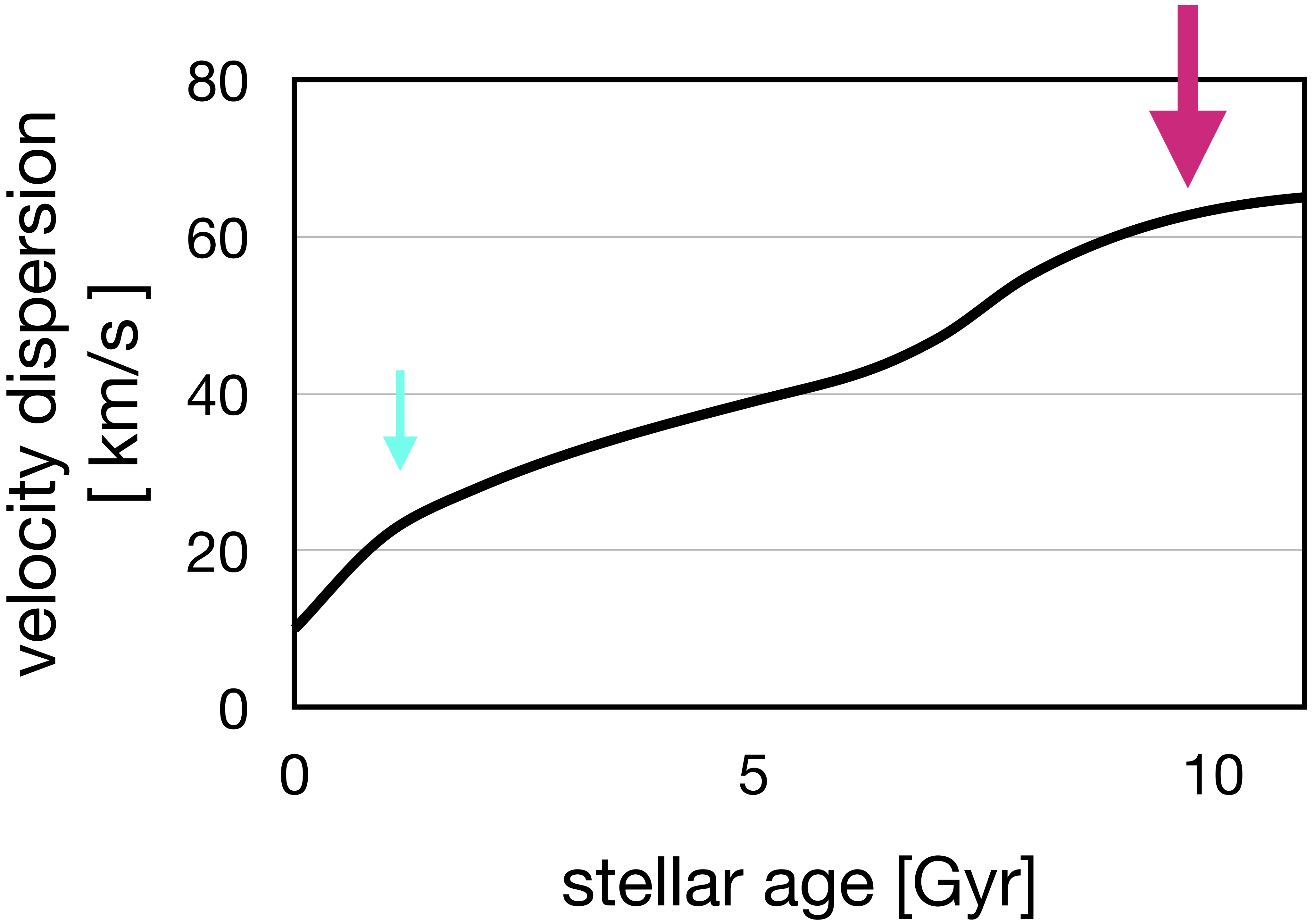
Properties of the Q branch:

Over-density

DQ white dwarfs

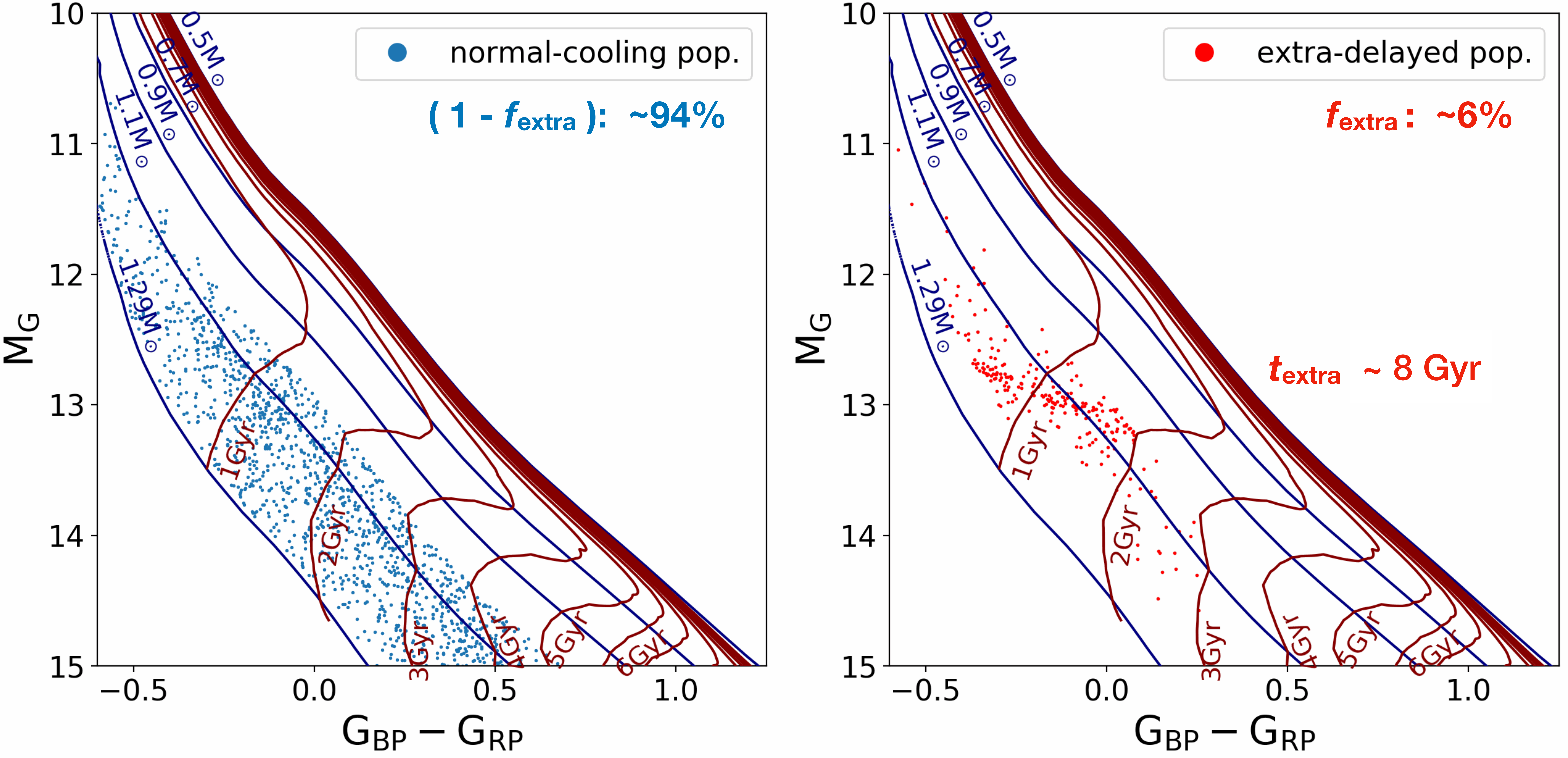
Velocity excess

Cheng, Cummings, & Ménard (2019)



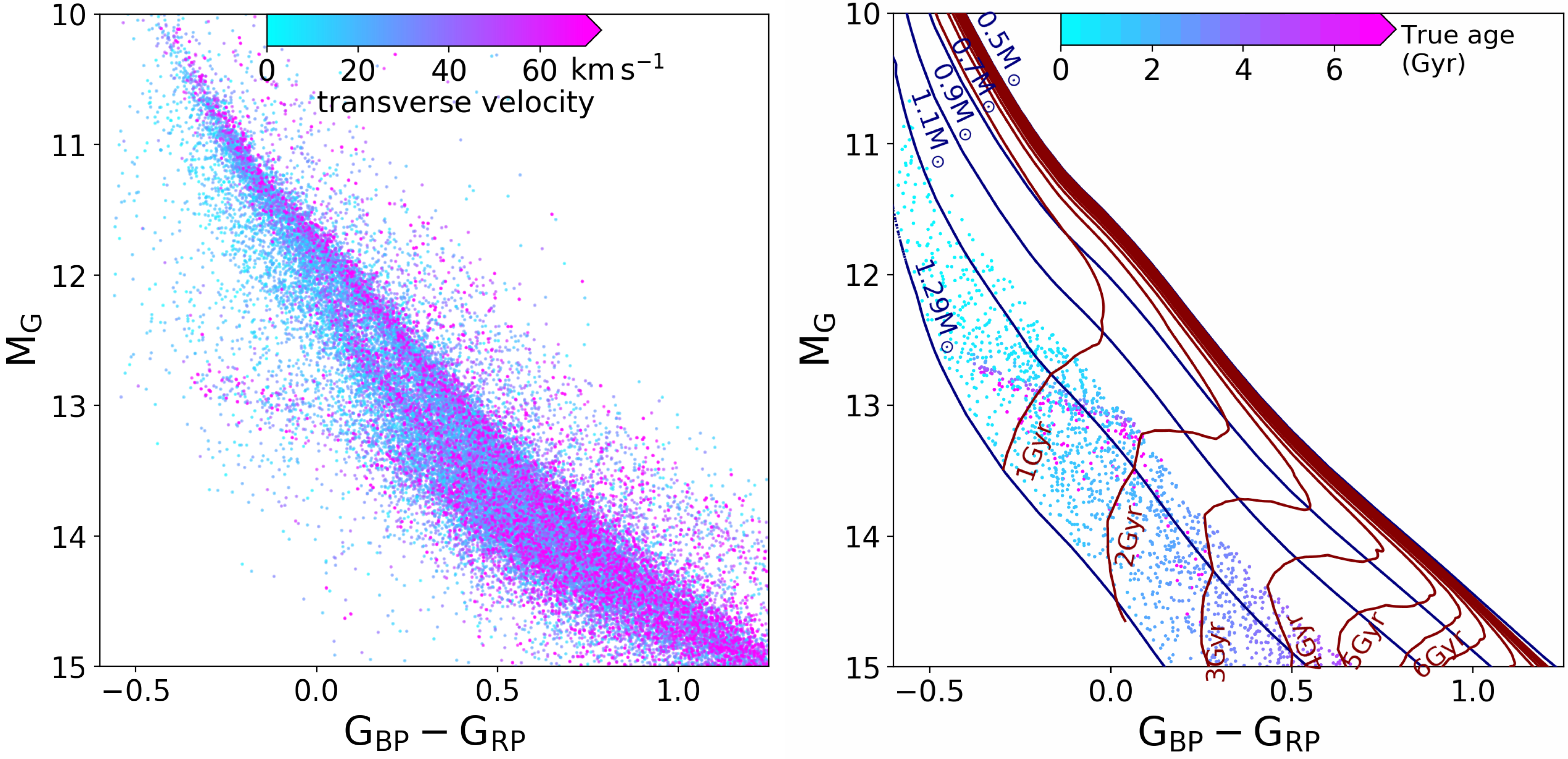
multiple populations

more animations: https://sihaocheng.github.io/Qbranch

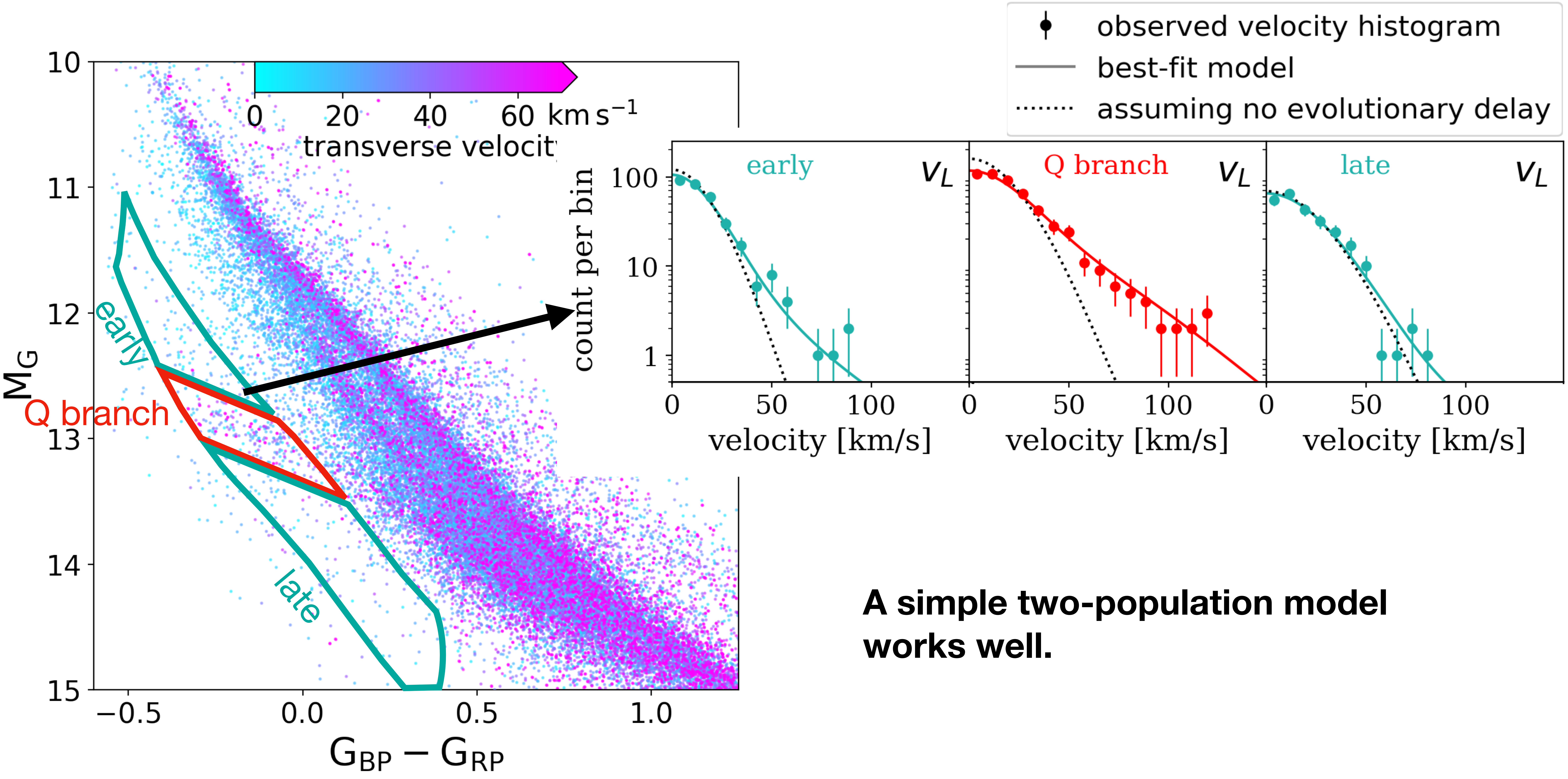


multiple populations

more animations: https://sihaocheng.github.io/Qbranch

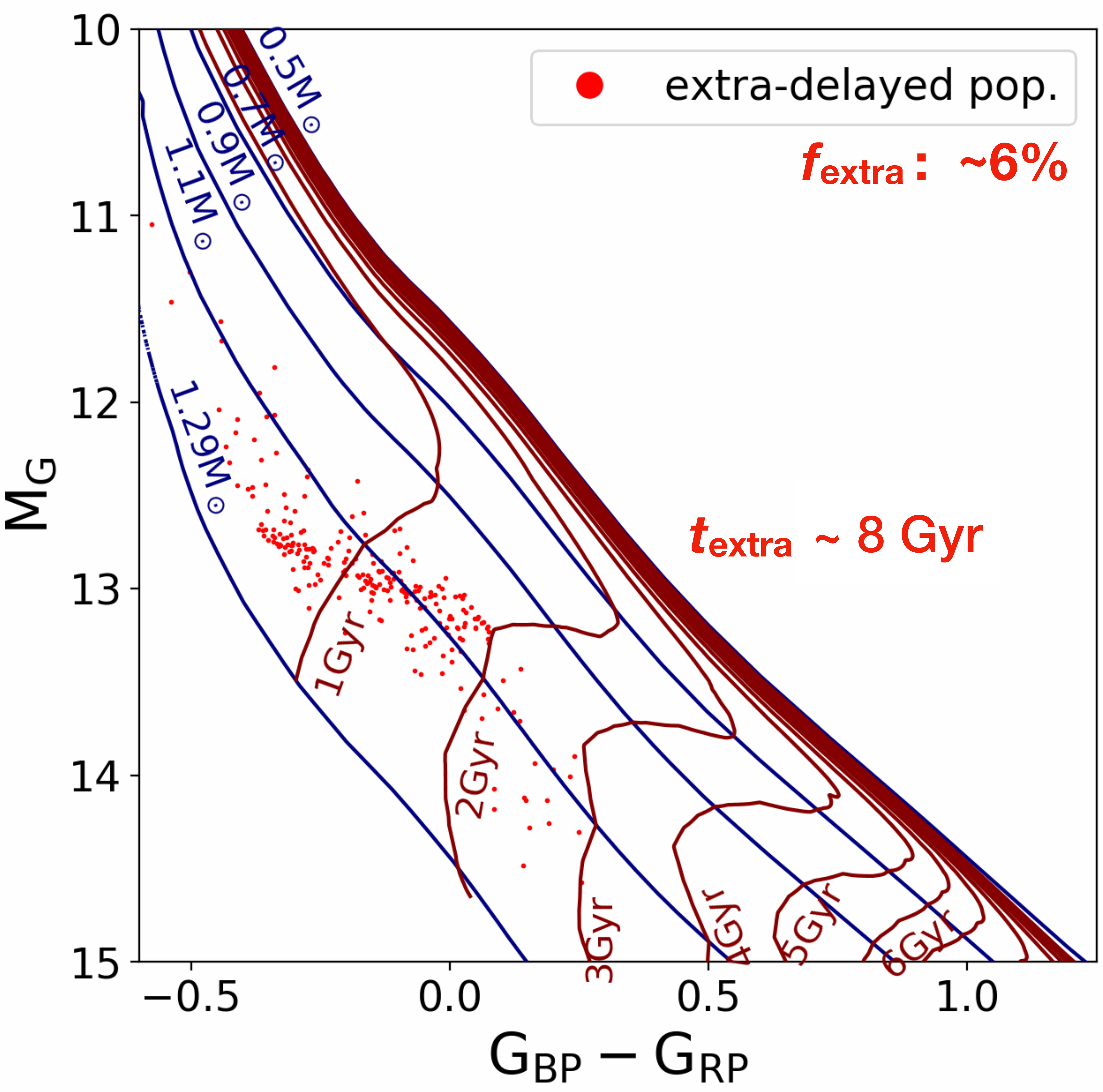


multiple populations



A simple two-population model works well.

What is the physics?



What is the energy source?

- 6%, 8 Gyr
- narrow branch

^{22}Ne plays an important role!

What is this population?

- C/O core
- DQs, DAQs: thin He layer? Hollands et al. 2020
- half DQ + half DA
- hot DQs?
- **merger products?** Schwab 2021, Althaus et al. 2021

A real challenge, but also opportunity!

CENTER FOR ASTROPHYSICS
HARVARD & SMITHSONIAN

Part II: Theoretical Progress toward Understanding the Cooling Delay

White Dwarfs from Physics to Astrophysics @ KITP

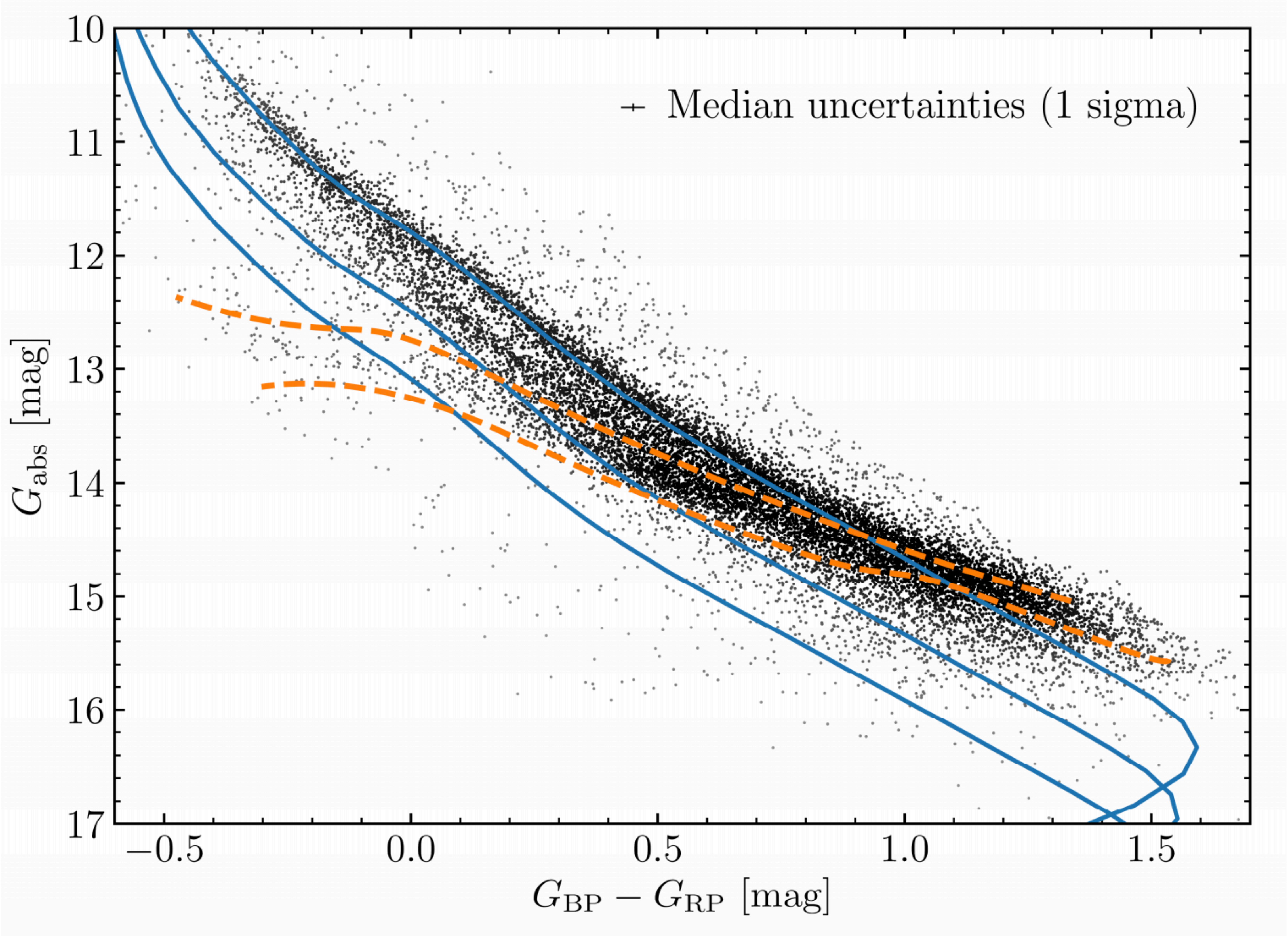
Evan Bauer (Center for Astrophysics | Harvard & Smithsonian)

Josiah Schwab (UCSC), Sihao Cheng (JHU), Lars Bildsten (KITP)

March 29, 2021

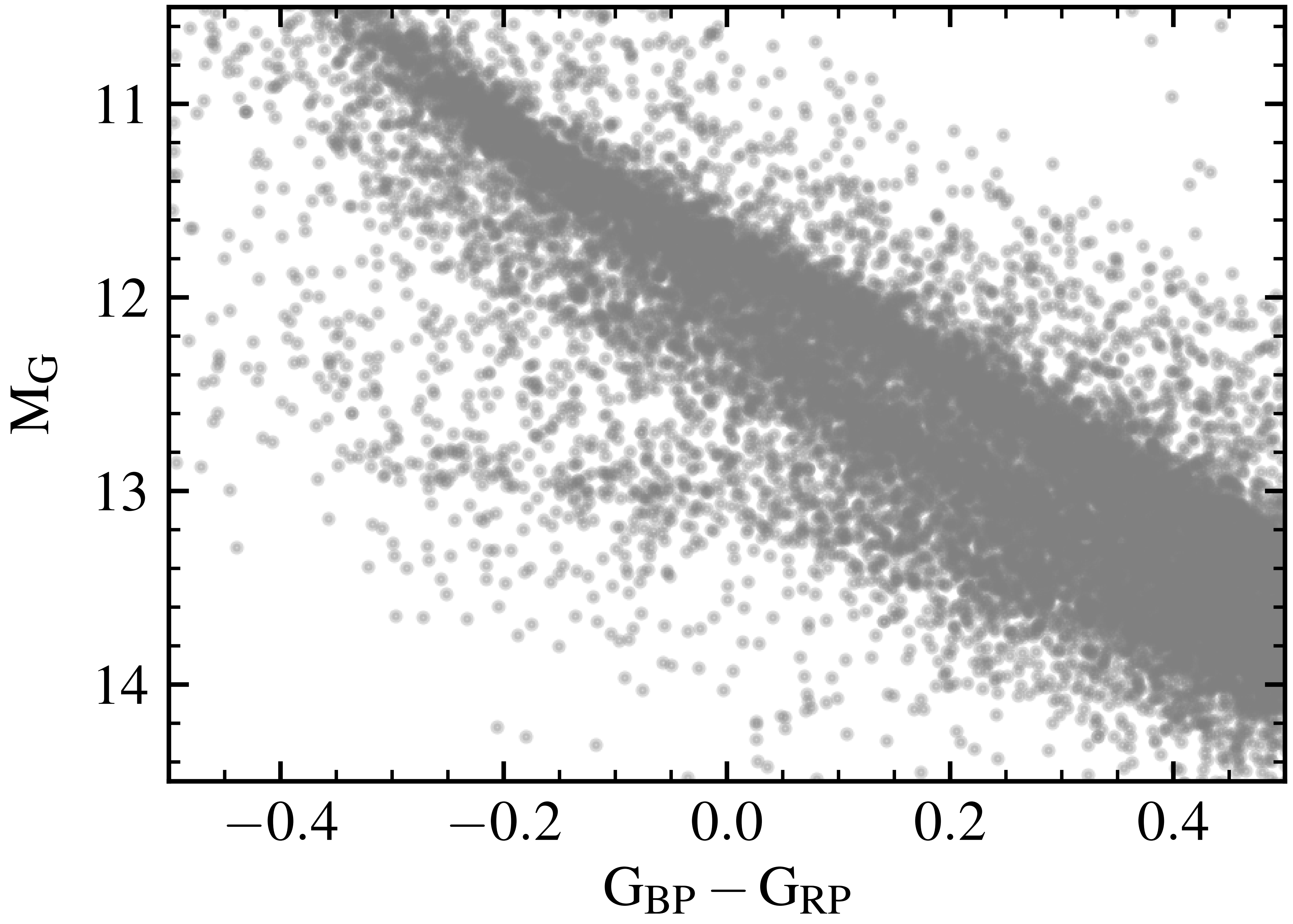
The Q Branch Coincides with C/O Crystallization

See also:
Tremblay et al. (2019), Nature 565:7738
Camisassa et al. (2021), submitted
Blouin et al. (2020, 2021), A&A 640:L11 & ApJL in press



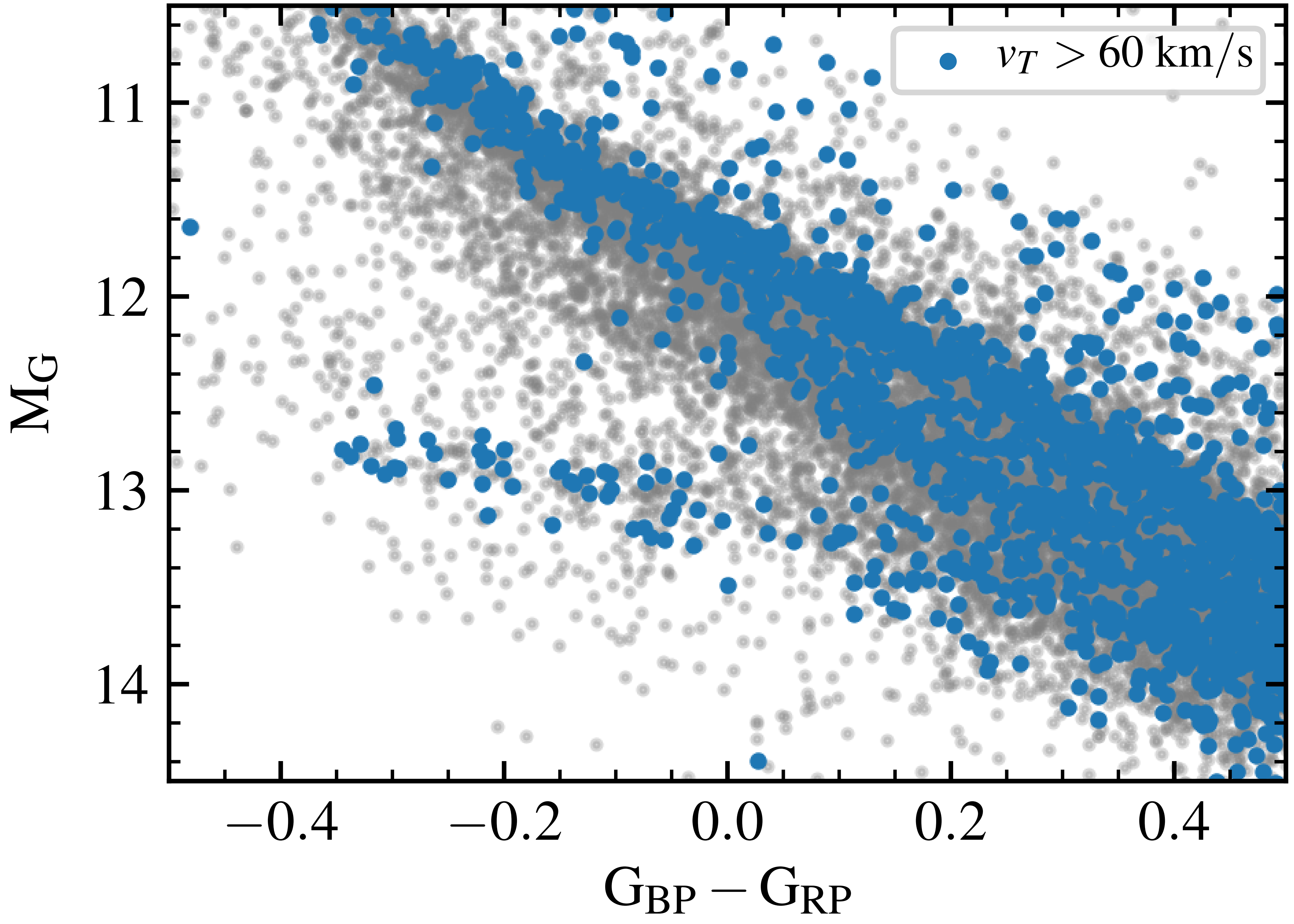
The Q Branch Coincides with C/O Crystallization

See also:
Tremblay et al. (2019), Nature 565:7738
Camisassa et al. (2021), submitted
Blouin et al. (2020, 2021), A&A 640:L11 & ApJL in press



The Q Branch Coincides with C/O Crystallization

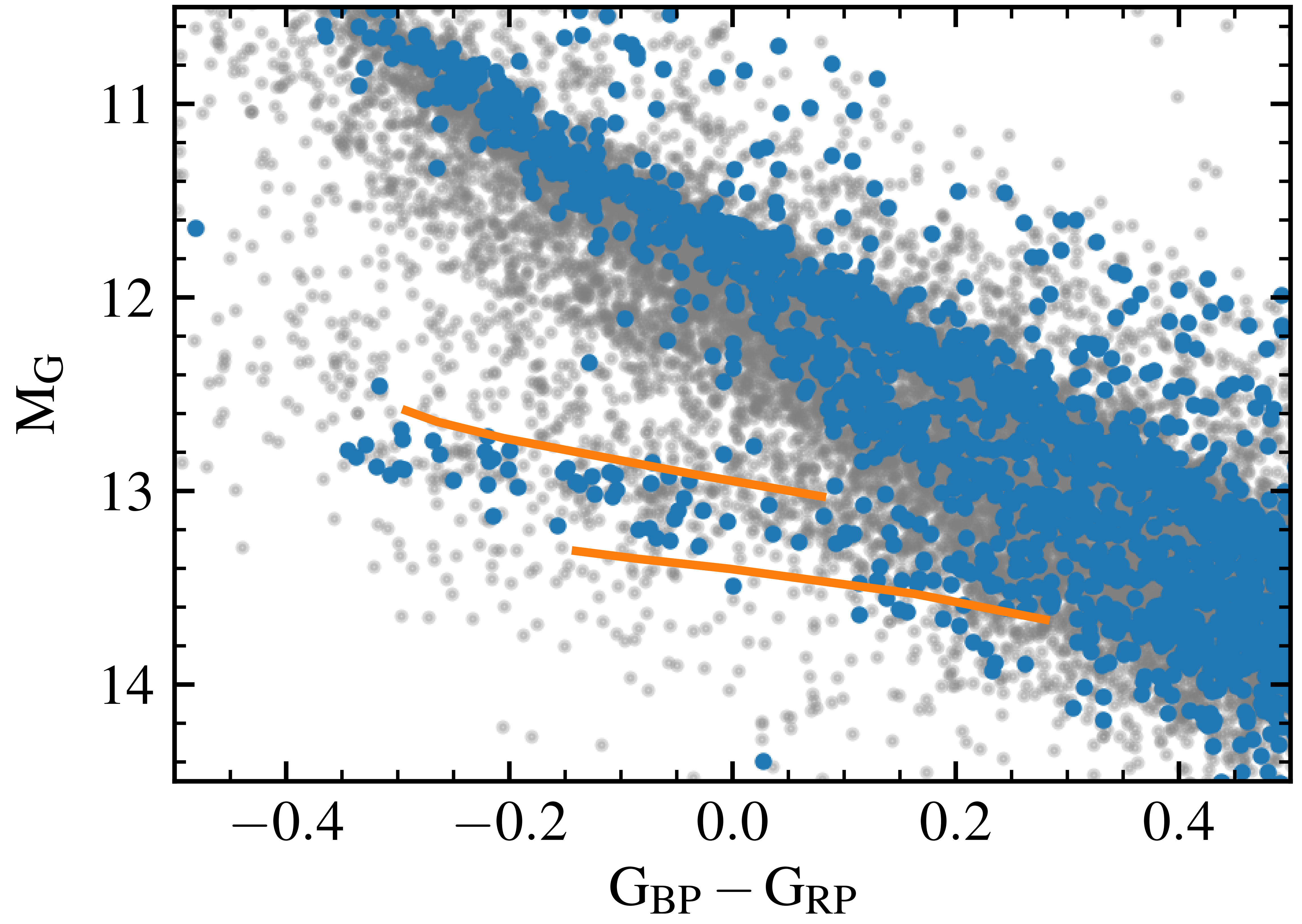
> See also:
> Tremblay et al. (2019), Nature 565:7738
> Camisassa et al. (2021), submitted
> Blouin et al. (2020, 2021), A&A 640:L11 & ApJL in press



CENTER FOR ASTROPHYSICS
HARVARD & SMITHSONIAN

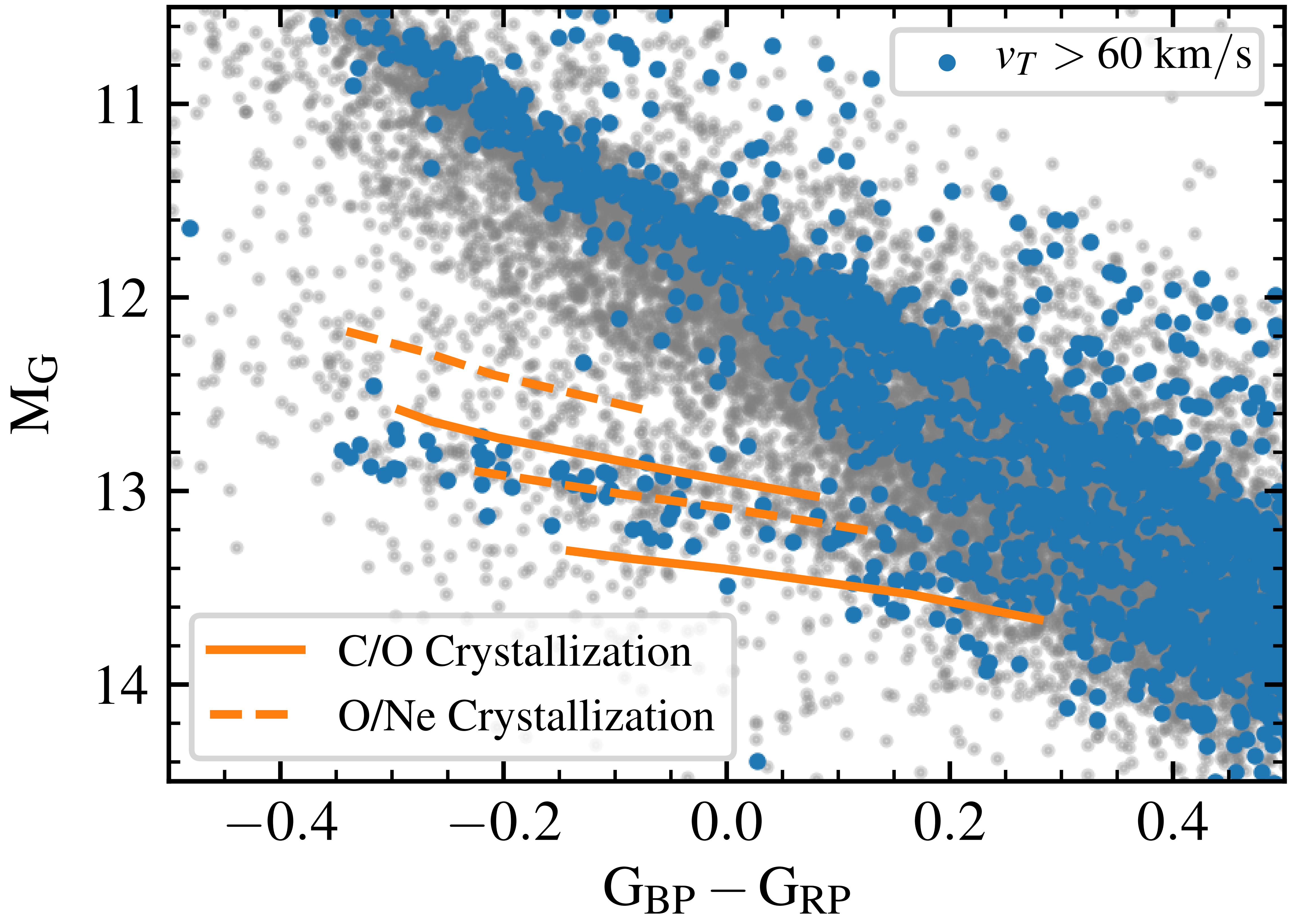
The Q Branch Coincides with C/O Crystallization

See also:
Tremblay et al. (2019), Nature 565:7738
Camisassa et al. (2021), submitted
Blouin et al. (2020, 2021), A&A 640:L11 & ApJL in press



The Q Branch Coincides with C/O Crystallization

> See also:
> Tremblay et al. (2019), Nature 565:7738
> Camisassa et al. (2021), submitted
> Blouin et al. (2020, 2021), A&A 640:L11 & ApJL in press



CENTER FOR ASTROPHYSICS
HARVARD & SMITHSONIAN

Energy required for 8 Gyr cooling delay rules out many candidate mechanisms.

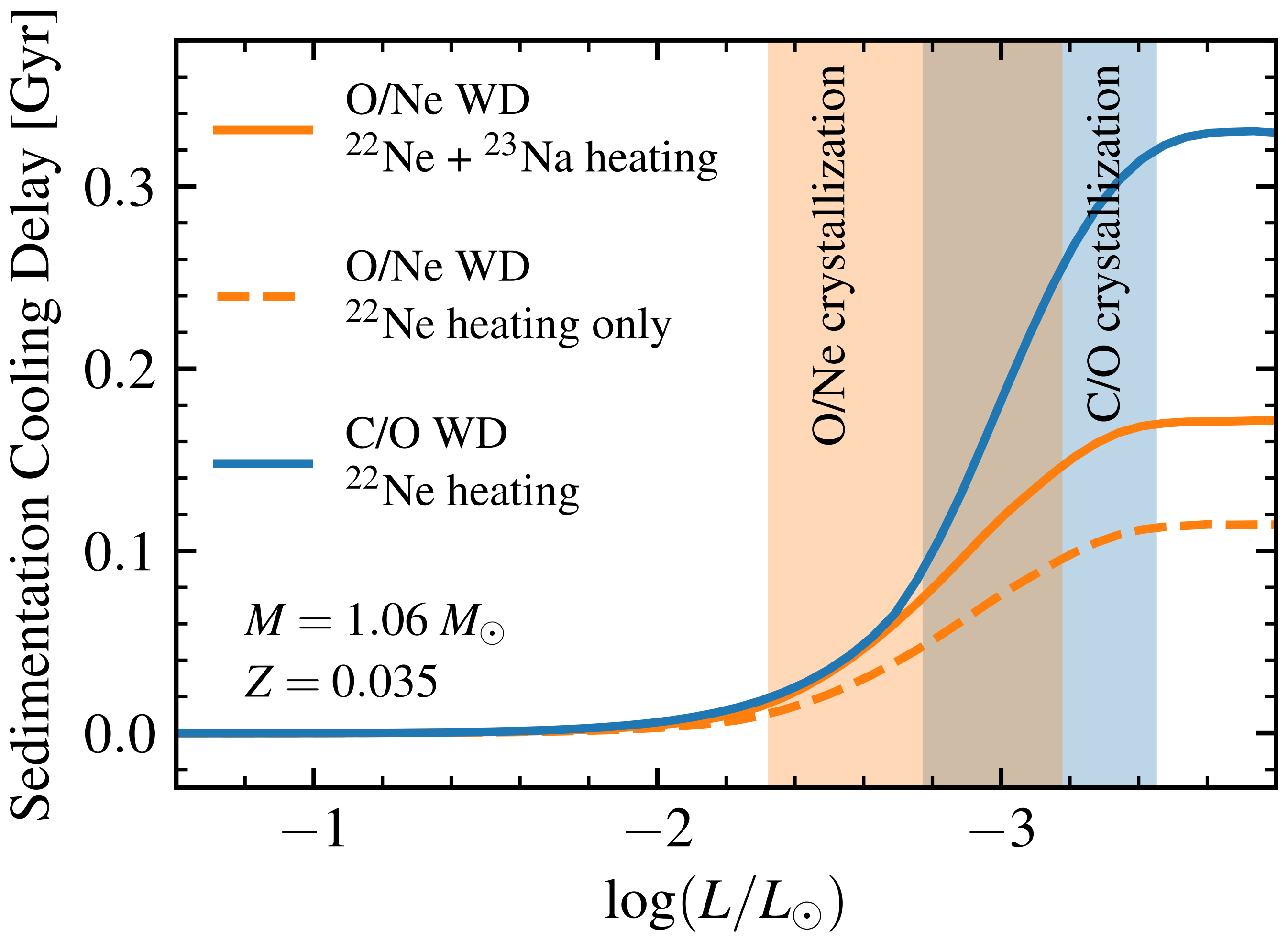
Well-defined narrow range of luminosities on the Q branch requires $E \gtrsim (10^{-3}\ L_\odot)(8\ \mathrm{Gyr})$ to maintain observed luminosity for the length of the cooling delay required by observations.

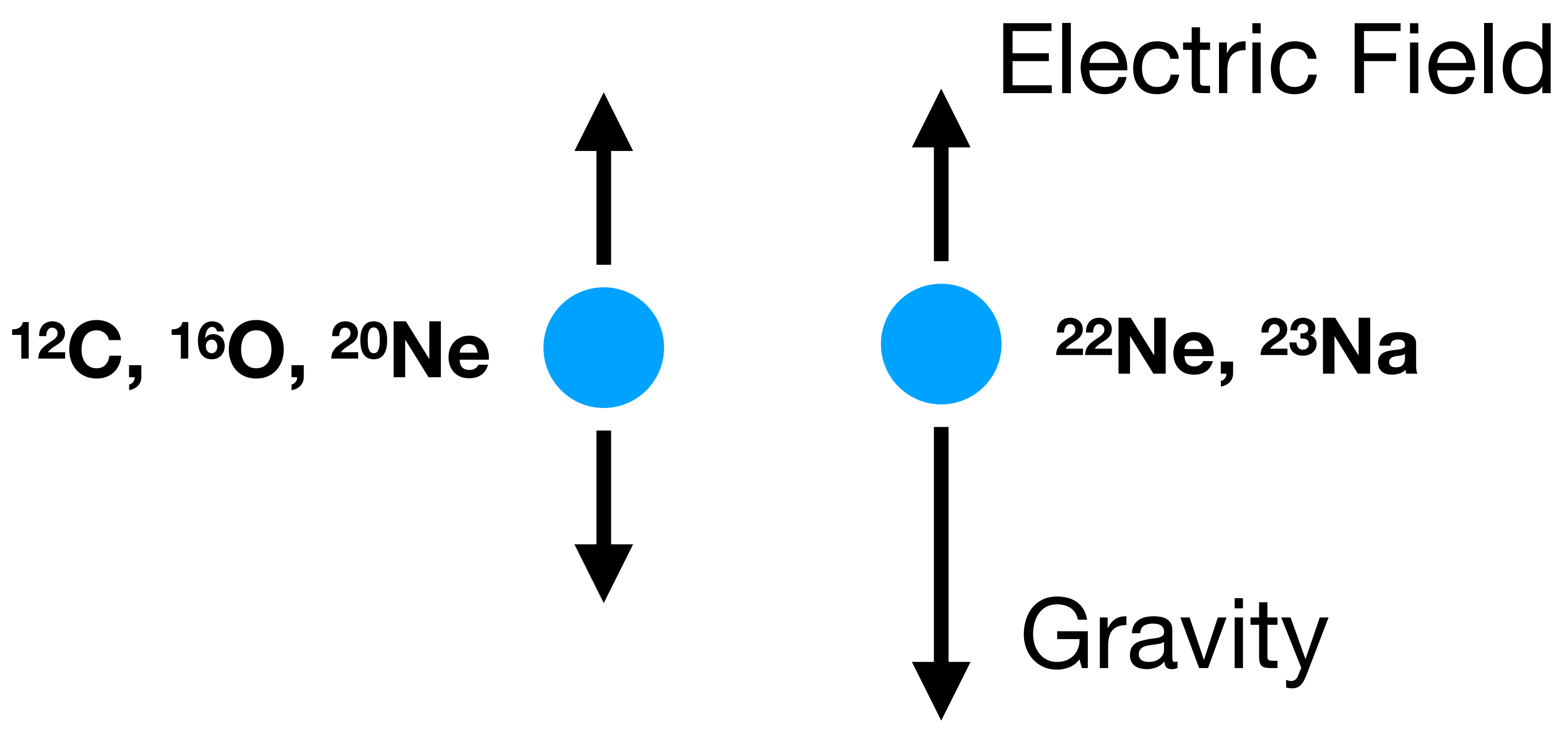
This rules out:

- Latent heat released by crystallization ✗
- C/O phase separation during crystallization ✗

Leaving only:

- Sedimentation of "heavy" (neutron-rich) elements like 22Ne and 23Na, which can release gravitational binding energy on the order of $E \sim m_p g R_{WD} X_j M_{WD}/(A_j m_p)$. ✓



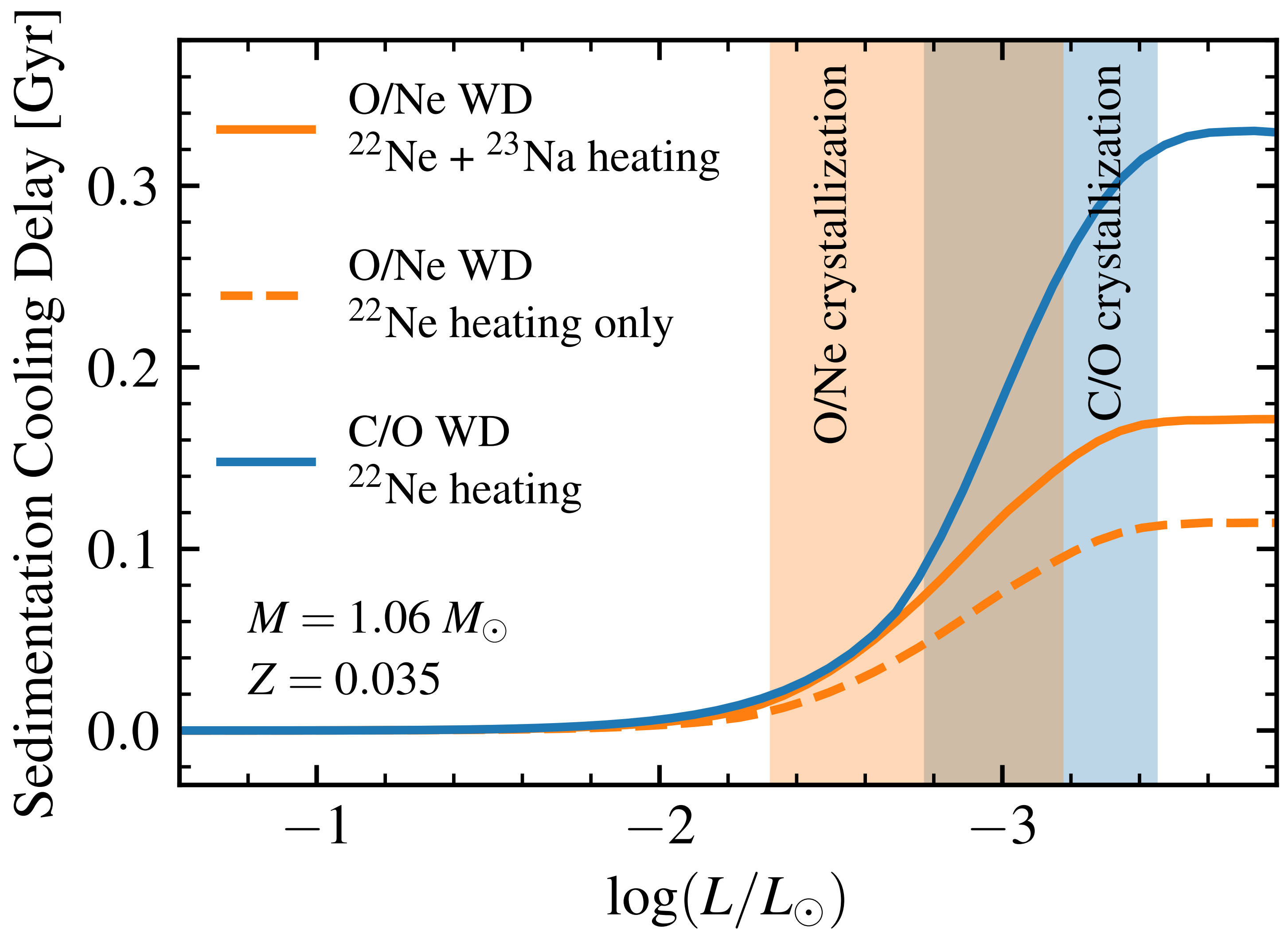


CENTER FOR ASTROPHYSICS
HARVARD & SMITHSONIAN

BUT: Standard 22Ne Sedimentation is too slow to provide cooling delay before frozen out by crystallization.

MESA Models
Bauer et al. (2020) ApJ 902:93

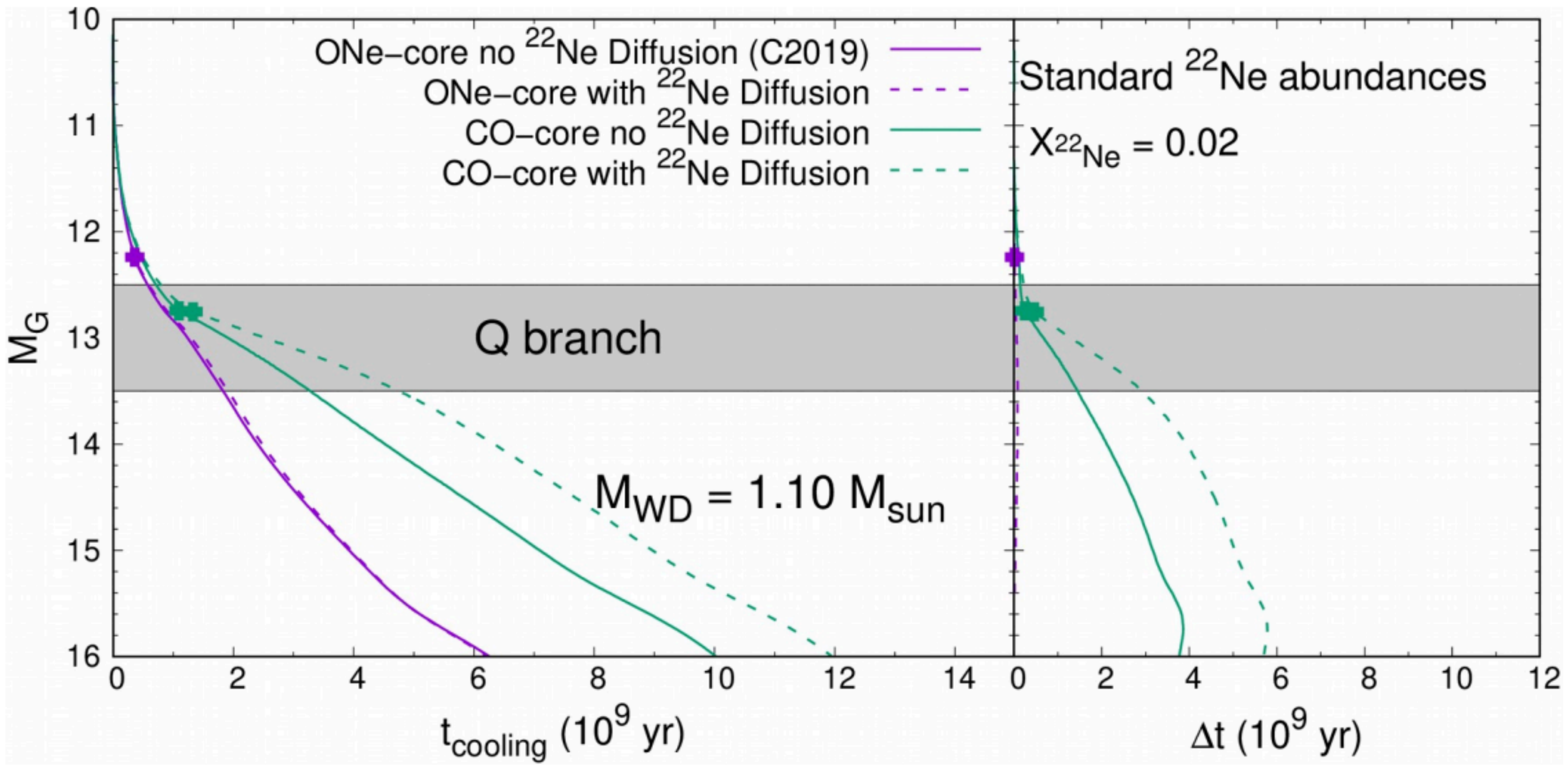
Cooling delay < 1 Gyr for standard 22Ne diffusion coefficients, which are well constrained by theory.



La Plata Models
Camisassa et al. (2021) submitted

Cooling delay up to a few Gyr, but still far short of what is required by observations.

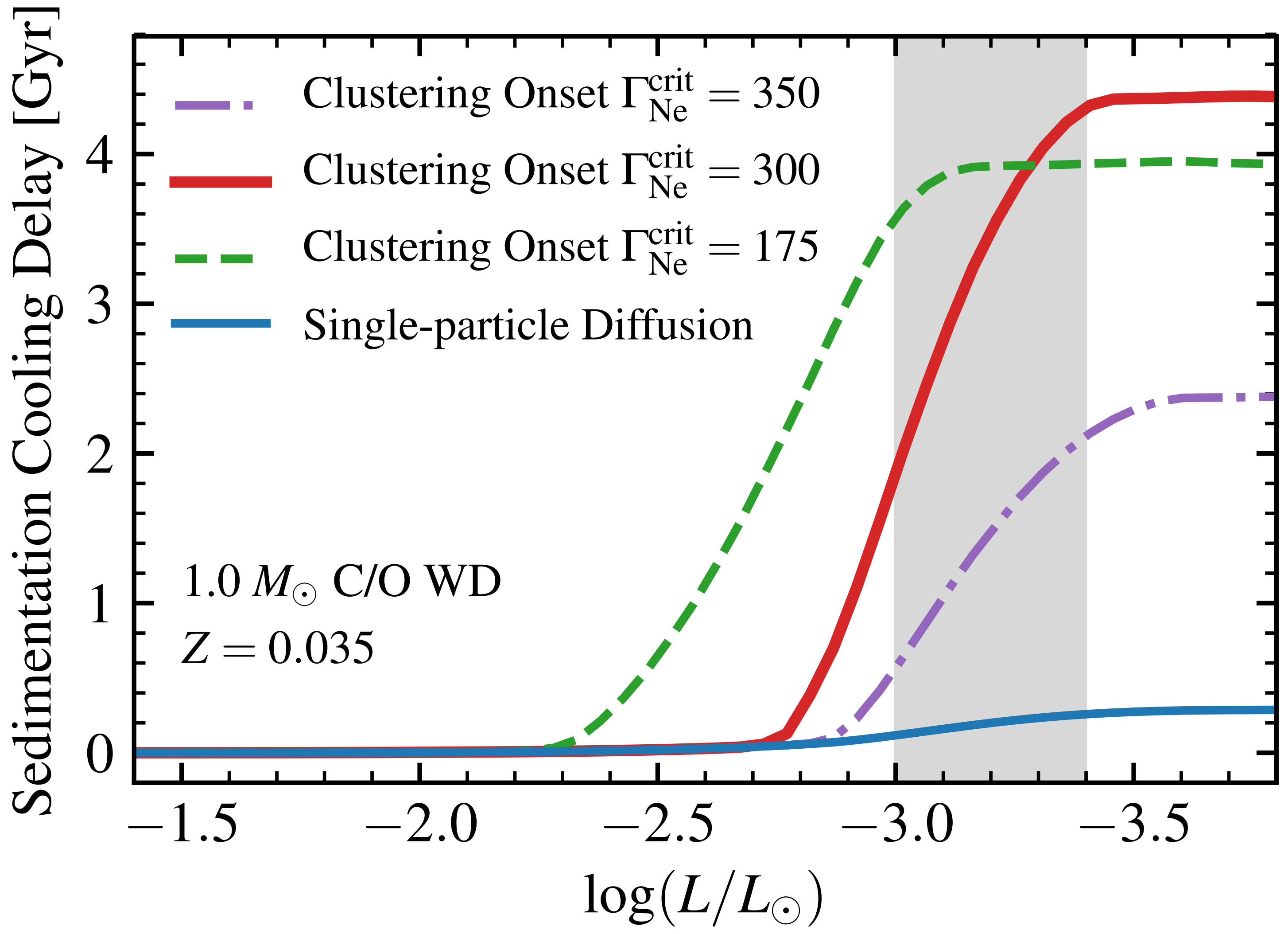
arXiv:2008.03028



Proposed Modifications to 22Ne Sedimentation

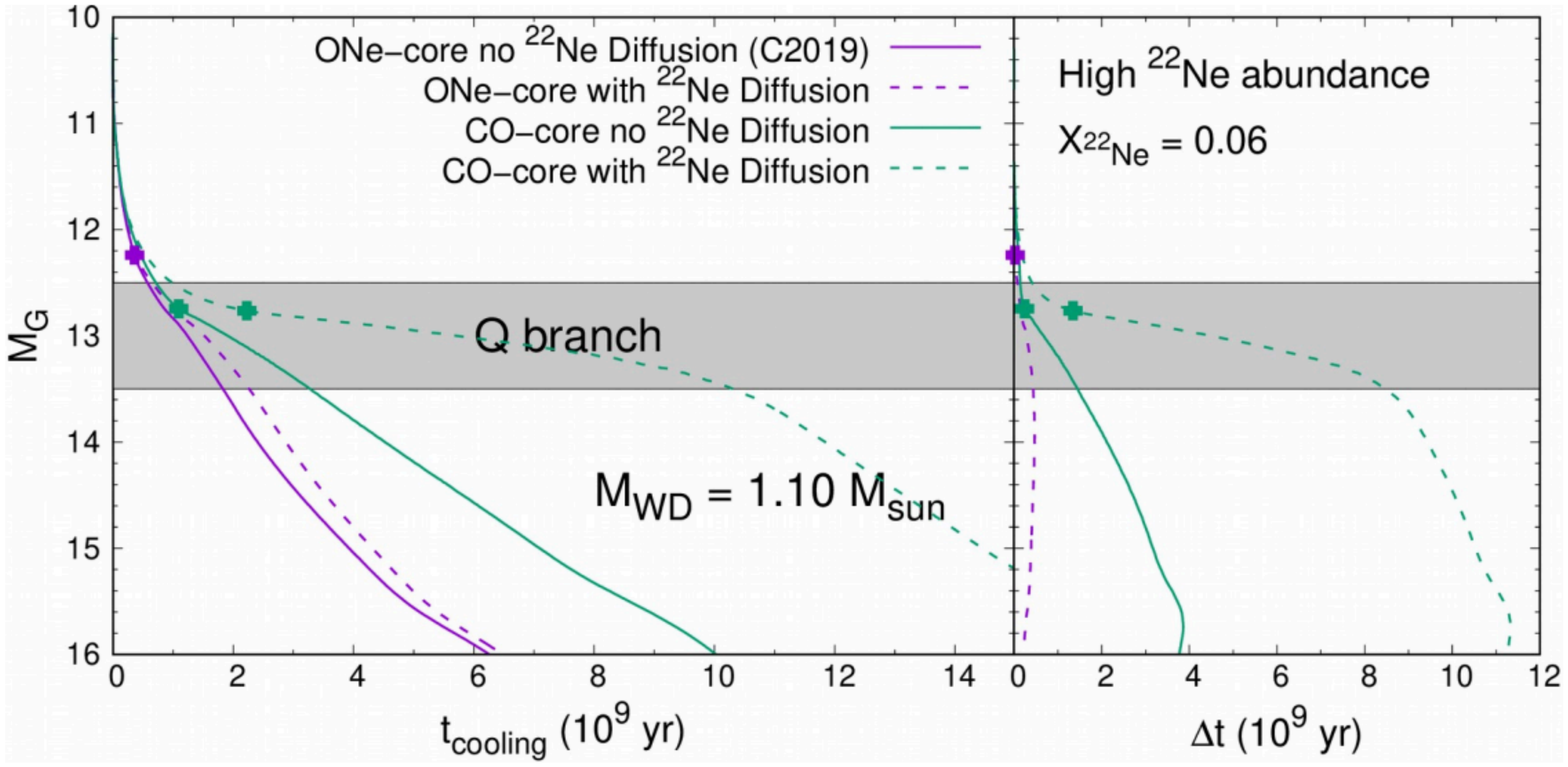
Proposal: Enhance Diffusion Speed
Bauer et al. (2020) ApJ 902:93

Form clusters of 22Ne in strongly coupled plasma that sink faster and enhance sedimentation heating.



Proposal: Increase 22Ne Mass Fraction
Camisassa et al. (2021) submitted

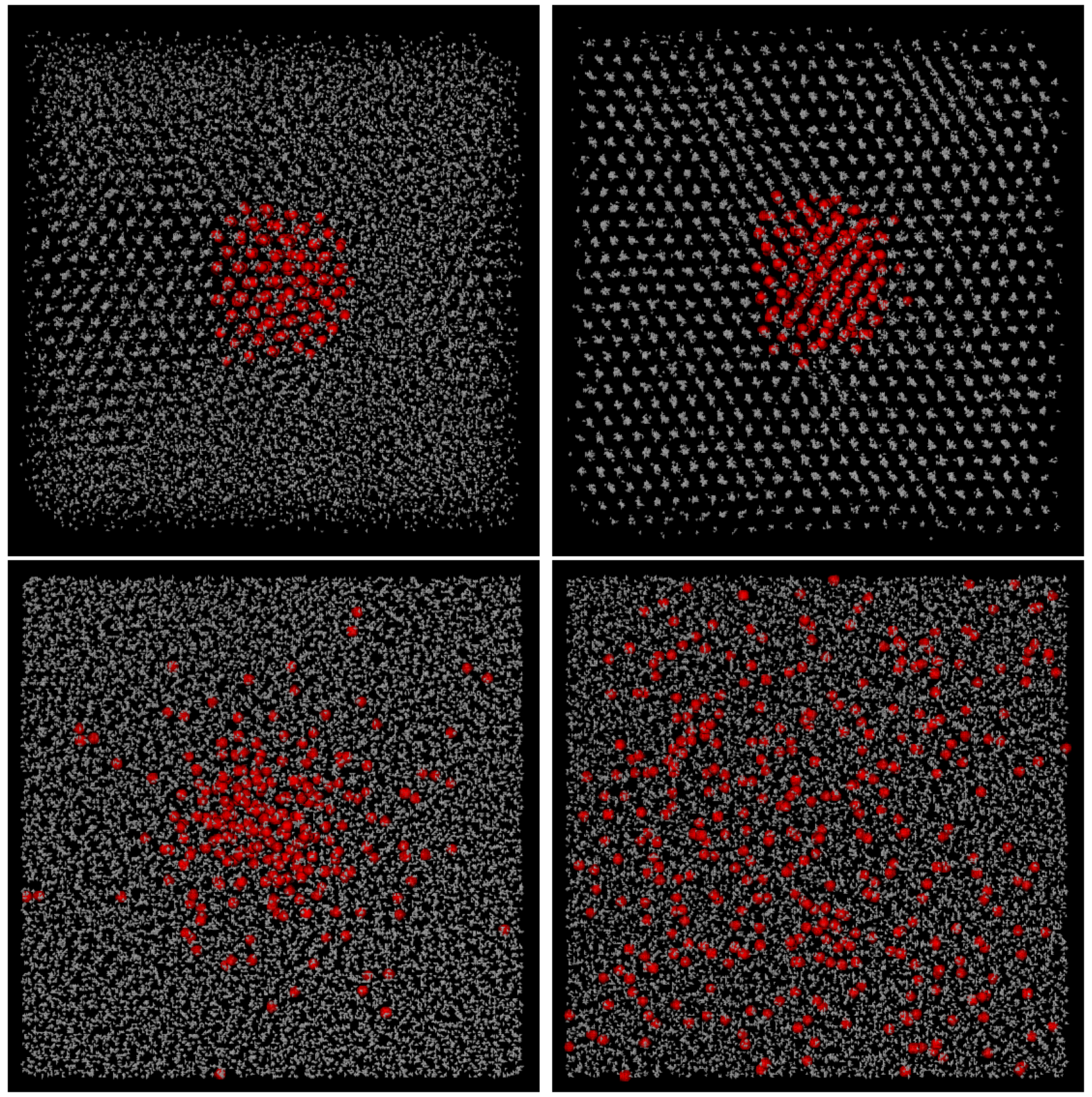
22Ne mass fraction of X > 0.06 appears sufficient to explain cooling delay in La Plata models.
arXiv:2008.03028



Difficulties for These Proposals

Proposal: Enhance Diffusion Speed
Bauer et al. (2020) ApJ 902:93

Caplan et al. (2020) ApJL 902:44
Molecular Dynamics simulations indicate that solid 22Ne clusters aren't stable in liquid WD interiors.



Proposal: Increase 22Ne Mass Fraction
Camisassa et al. (2021) submitted

Difficult to produce 22Ne mass fraction above primordial metallicity from $^{14}\mathrm{N}(\alpha,\gamma)^{18}\mathrm{F}(e^{+}\nu)^{18}\mathrm{O}(\alpha,\gamma)^{22}\mathrm{Ne}$

No detailed mechanism for producing 22Ne mass fraction > 0.06 has yet been demonstrated.

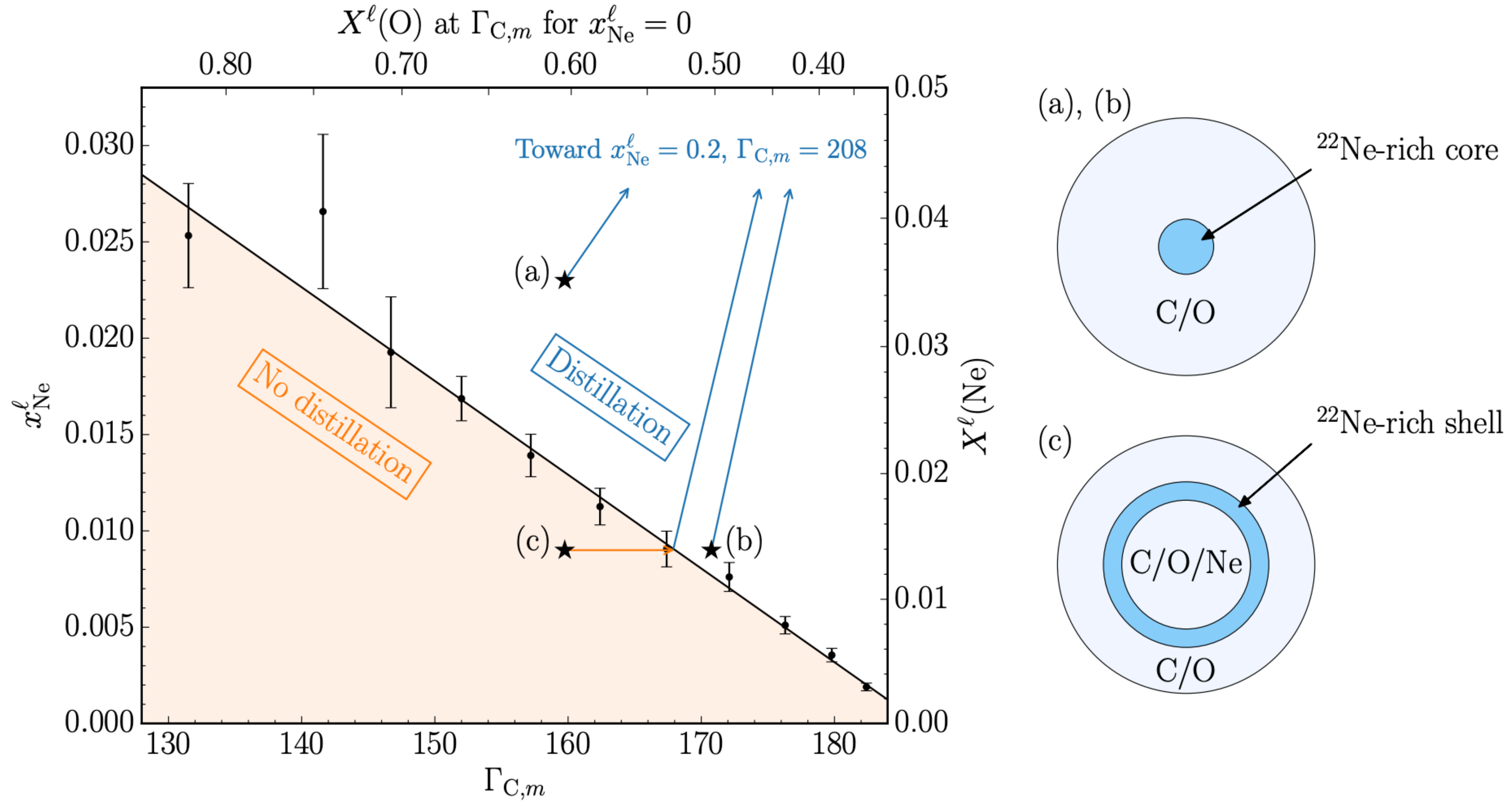
Mergers? Schwab (2021) ApJ 906:53 indicates that these will form O/Ne WDs, not the C/O WDs required to explain the Q branch.

A New Mechanism: Ne/C/O Phase Separation?

Blouin et al. (2021), ApJL in press

22Ne "distillation" possible for mass fractions ~ 0.03, forming crystals *depleted* of 22Ne that float upward and melt, leading to net transport of 22Ne toward the center.

Qualitative differences in overall mixing sensitive to relative proportions of C/O/Ne.



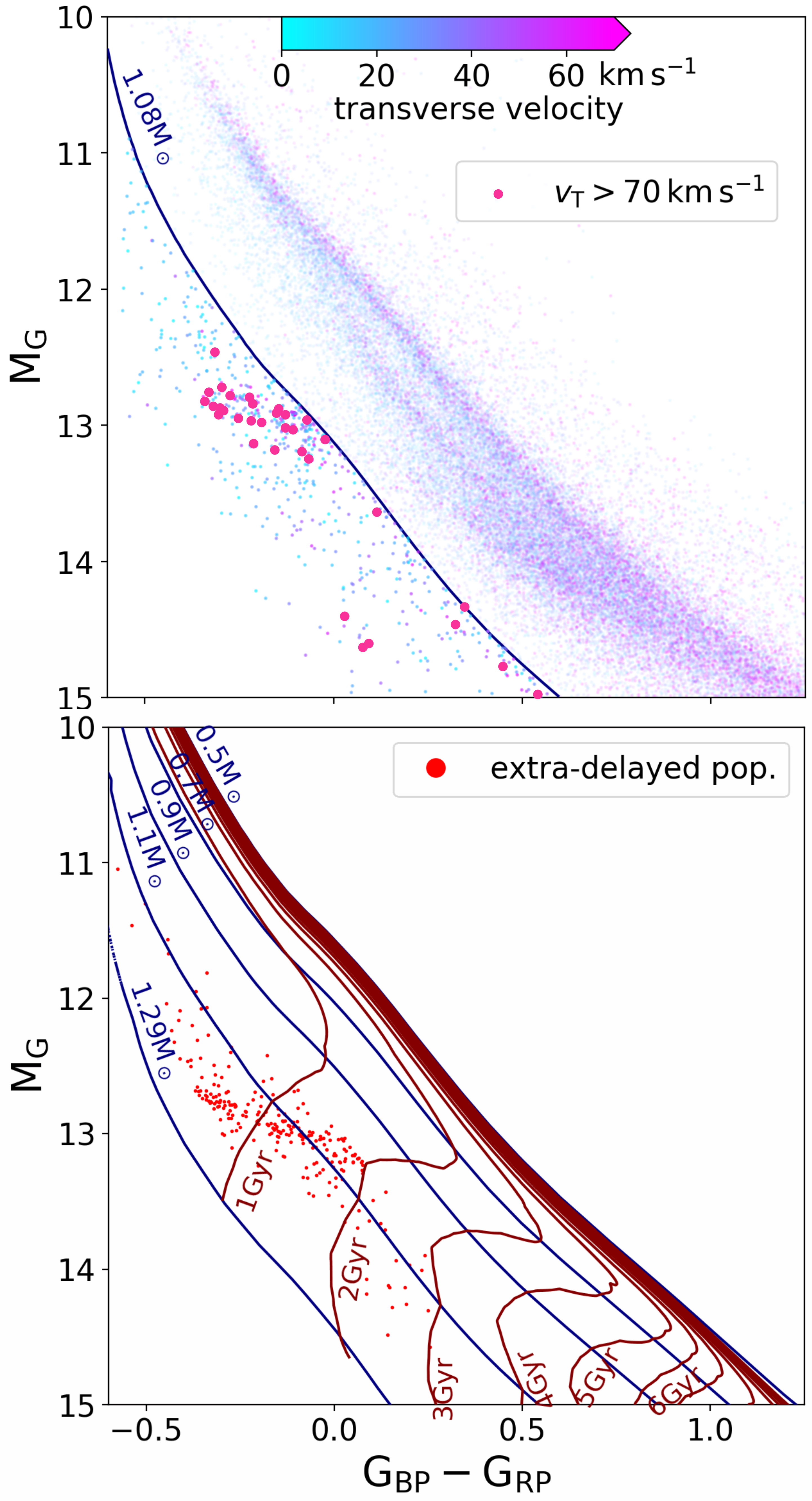
Summary

Models agree:

- Cooling anomaly requires ultra-massive WDs with C/O cores.
- Energy needed to power Q branch luminosity rules out latent heat or C/O phase separation alone during crystallization.
- Standard 22Ne sedimentation is not enough for 8 Gyr cooling delay.
- Some new physical mechanism (likely involving 22Ne) needed to explain the cooling delay on the Q branch.

Proposals:

- Speed up sedimentation by clustering. Disfavored by MD. 🤔
- Significantly increase 22Ne mass fraction. But how? 🤔
- Phase separation and distillation of 22Ne. Looks promising.



Models agree:

- Cooling anomaly requires ultra-massive WDs with C/O cores.
- Energy needed to power Q branch luminosity rules out latent heat or C/O phase separation alone during crystallization.
- Standard 22Ne sedimentation is not enough for 8 Gyr cooling delay.
- Some new physical mechanism (likely involving 22Ne) needed to explain the cooling delay on the Q branch.

Proposals:

- Speed up sedimentation by clustering. Disfavored by MD. 🤔
- Significantly increase 22Ne mass fraction. But how? 🤔
- Phase separation and distillation of 22Ne. Looks promising.