A Search for Age Spreads in Synthetic Hertzsprung-Russell Diagrams of Young and Forming Clusters

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Why measure age spreads?

- ★ The distribution of ages of a stellar population directly measures the star formation history
- ★ Though the members of star clusters have formed together, it may be possible to measure an age spread that corresponds to the duration of the cluster's formation
- ★ The speed of star cluster formation is currently not well-constrained
- ★ Age spread is typically measured by comparing to isochrones, but this method has significant uncertainties

Simulations of young stellar clusters

Farias et al. (2019) and Farias & Tan (in prep.) present a suite of NBODY6 simulations with a Kroupa IMF, gradual star formation, and implementation of binaries. The simulations include a wide range of initial gas clump masses, densities, and star formation rates (ϵ_{ff}). The overall star formation efficiency is fixed at a fiducial value of 50%, and the primordial binary fraction is 50%.

Set Name	ϵ_{ff}	Σ_{cloud} [g cm^{-2}]	M_{cl} [$M_\odot$]	$\langle N_* \rangle$	t_* [Myr]	t_{ff} [Myr]	R_{cl} [pc]	σ_s [km s^{-1}]
	0.01	0.1	300	400	10.91	0.22	0.36	0.96
	0.03	0.1	300	400	3.64	0.22	0.36	0.96
m300L	0.1	0.1	300	400	1.09	0.22	0.36	0.96
	0.3	0.1	300	400	0.36	0.22	0.36	0.96
	1.0	0.1	300	400	0.11	0.22	0.36	0.96
	0.01	0.1	3,000	4,000	19.40	0.39	1.15	1.71
	0.03	0.1	3,000	4,000	6.47	0.39	1.15	1.71
m3000L	0.1	0.1	3,000	4,000	1.94	0.39	1.15	1.71
	0.3	0.1	3,000	4,000	0.65	0.39	1.15	1.71
	1.0	0.1	3,000	4,000	0.19	0.39	1.15	1.71
	0.01	0.1	30,000	40,000	34.50	0.69	3.65	3.04
	0.03	0.1	30,000	40,000	11.50	0.69	3.65	3.04
m30000L	0.1	0.1	30,000	40,000	3.45	0.69	3.65	3.04
	0.3	0.1	30,000	40,000	1.15	0.69	3.65	3.04
	1.0	0.1	30,000	40,000	0.34	0.69	3.65	3.04

In this work, we focus on the following simulations:

$$M_{clump} = 3000\ M_\odot$$

$$\Sigma_{cloud} = 0.1\ \mathrm{g/cm^2}$$

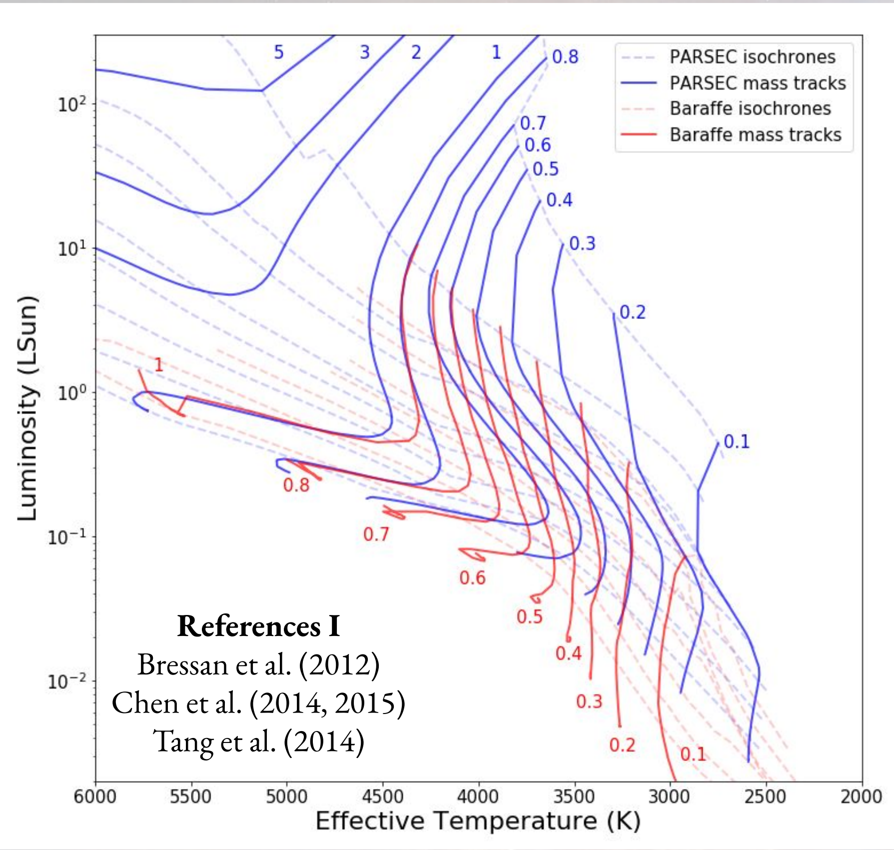
Various values of ϵ_{ff} lead to different formation durations t_*.

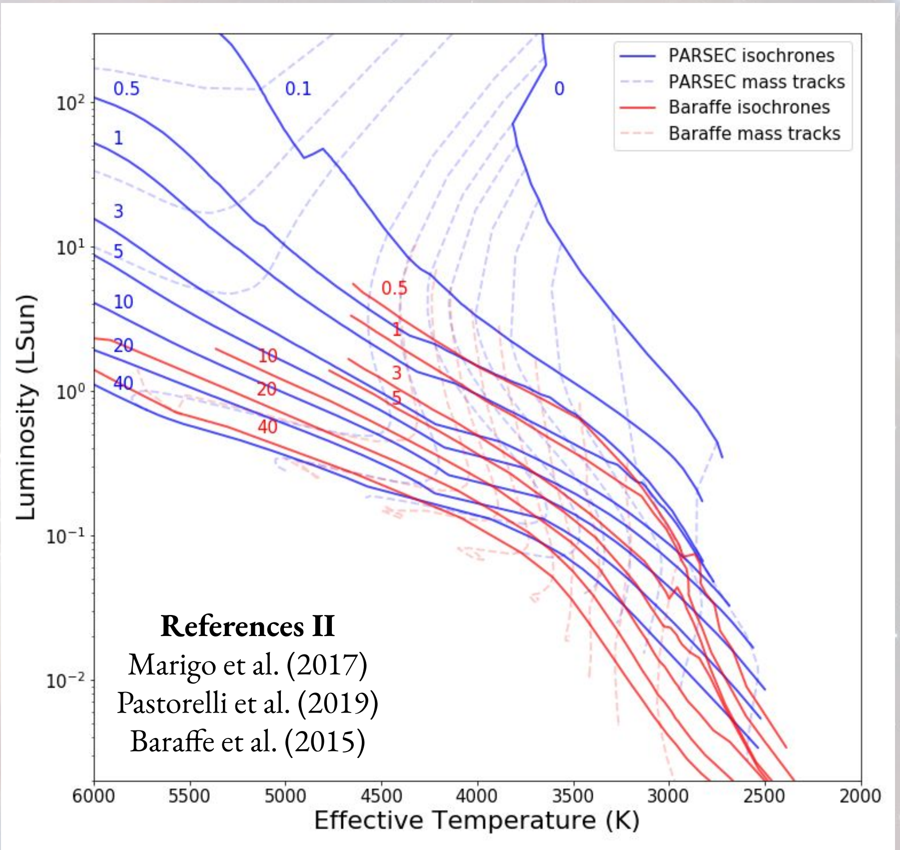
Methods for probing age spreads

Measurement of age spread: We aim to constrain the age spread of a given cluster by deriving metrics related to the cluster's luminosity spread on the Hertzsprung-Russell diagram.

Deriving temperatures and luminosities: The masses and ages of the simulated stars are placed on a grid of isochrones and mass tracks. Interpolation is used to derive the properties of interest.

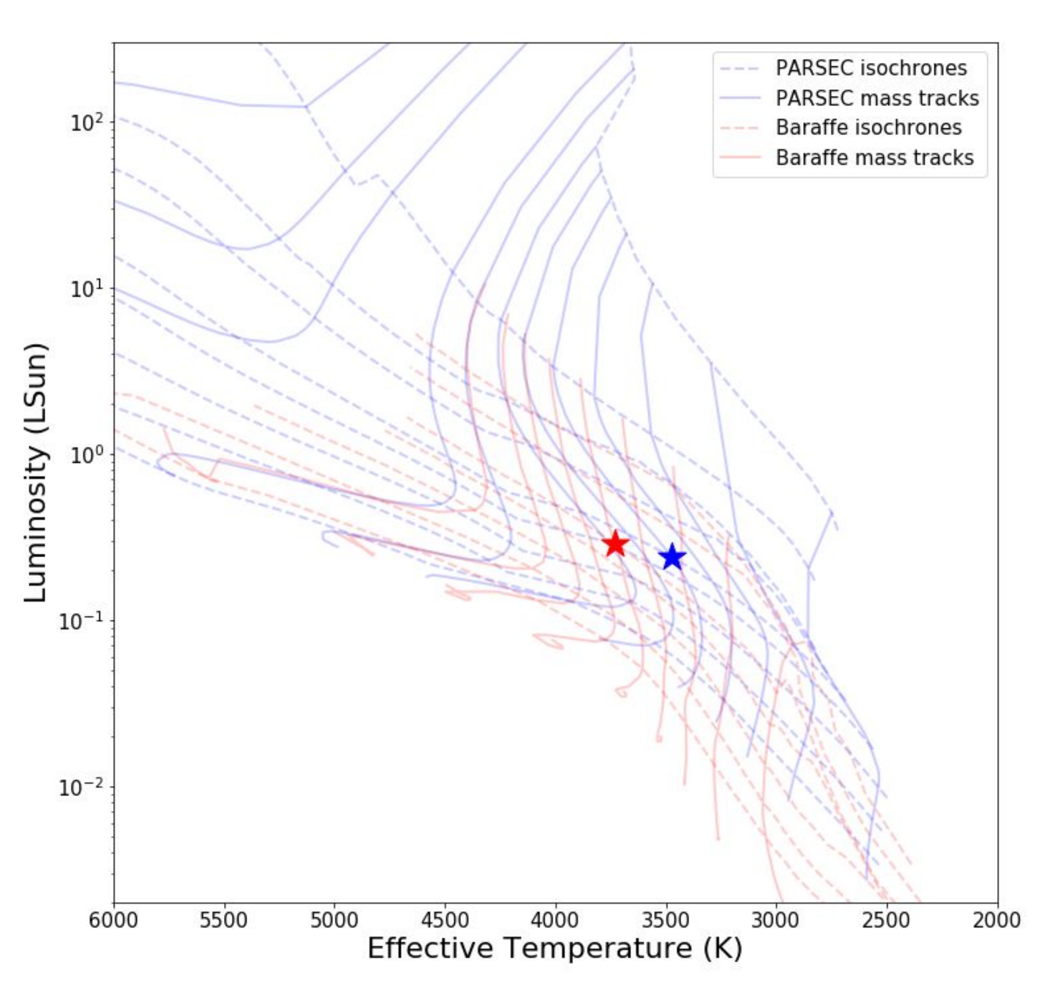
Treatment of binaries: The stars in each binary system are interpolated separately. Then, the luminosities are summed, and the system is assigned the temperature of the primary.





PARSEC **mass** range: 0.1 to 350 $M_\odot$
Baraffe **mass** range: 0.01 to 1.4 $M_\odot$

PARSEC **age** range: ~0 to 70 Myr
Baraffe **age** range: 0 to 10,000 Myr

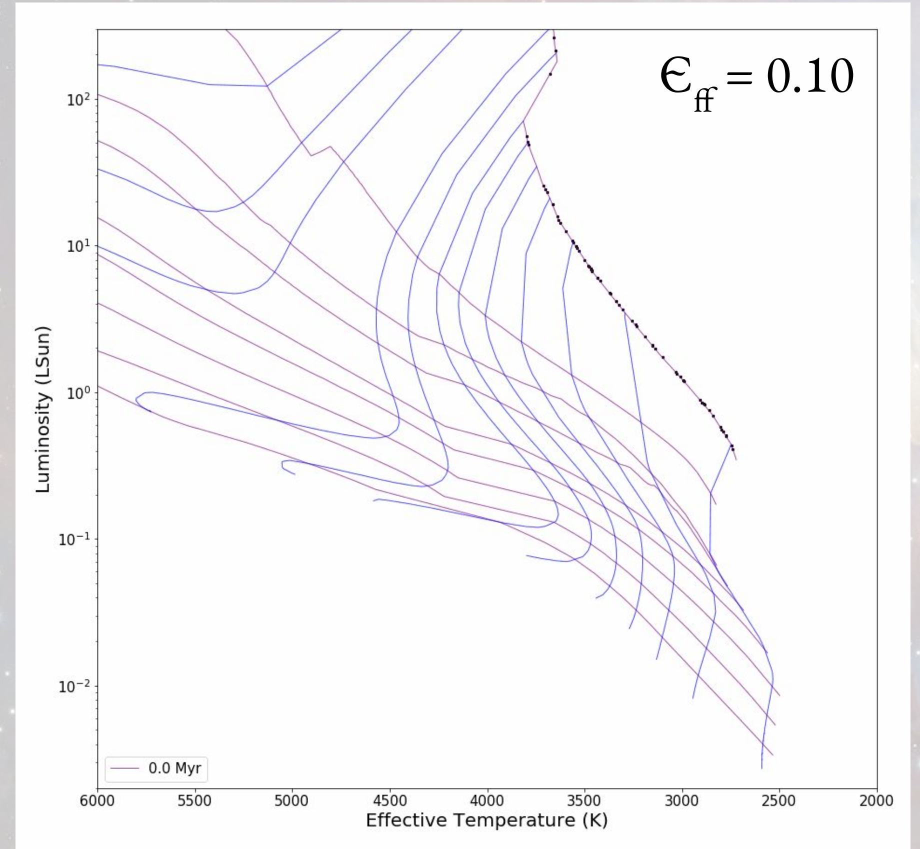


Differences in the tracks lead to slightly different results when interpolating into the temperature-luminosity space.

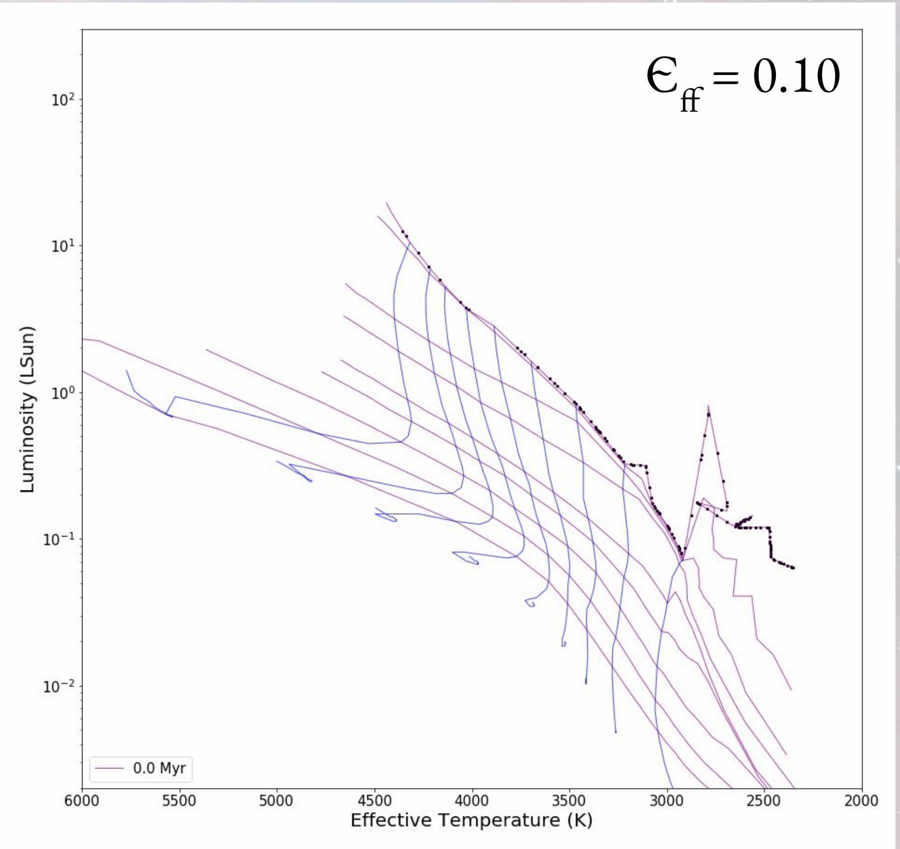
For example, a star with mass = 0.5 $M_\odot$ and age = 3 Myr will be interpolated as follows:

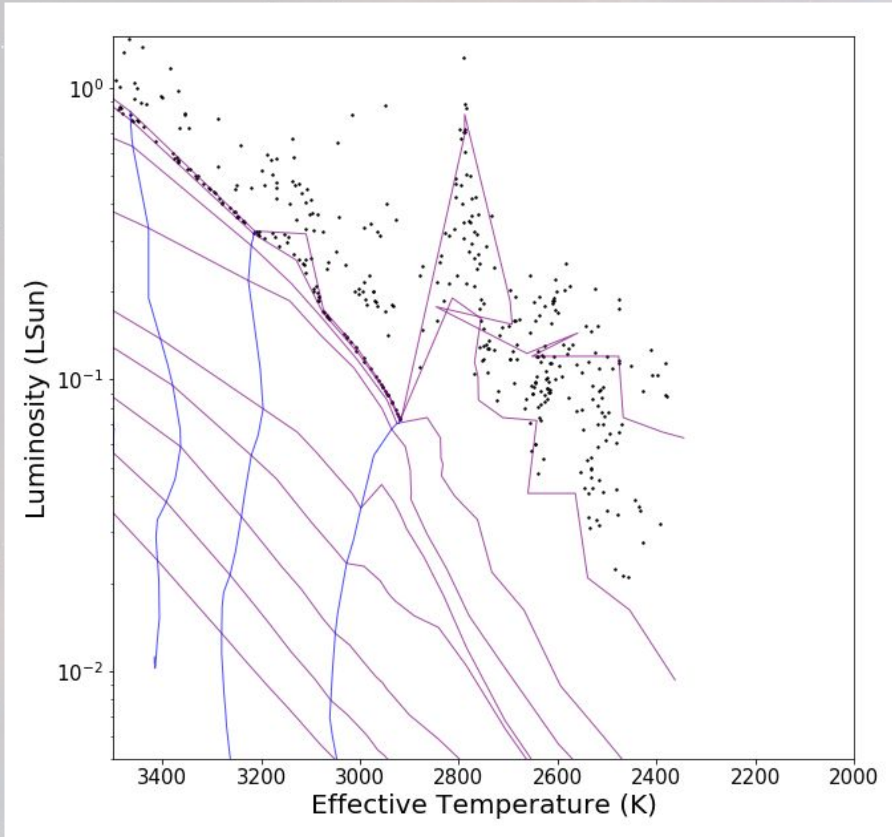
	PARSEC	Baraffe
T_{eff} (K)	3475	3731
L ($L_\odot$)	0.240	0.288

PARSEC

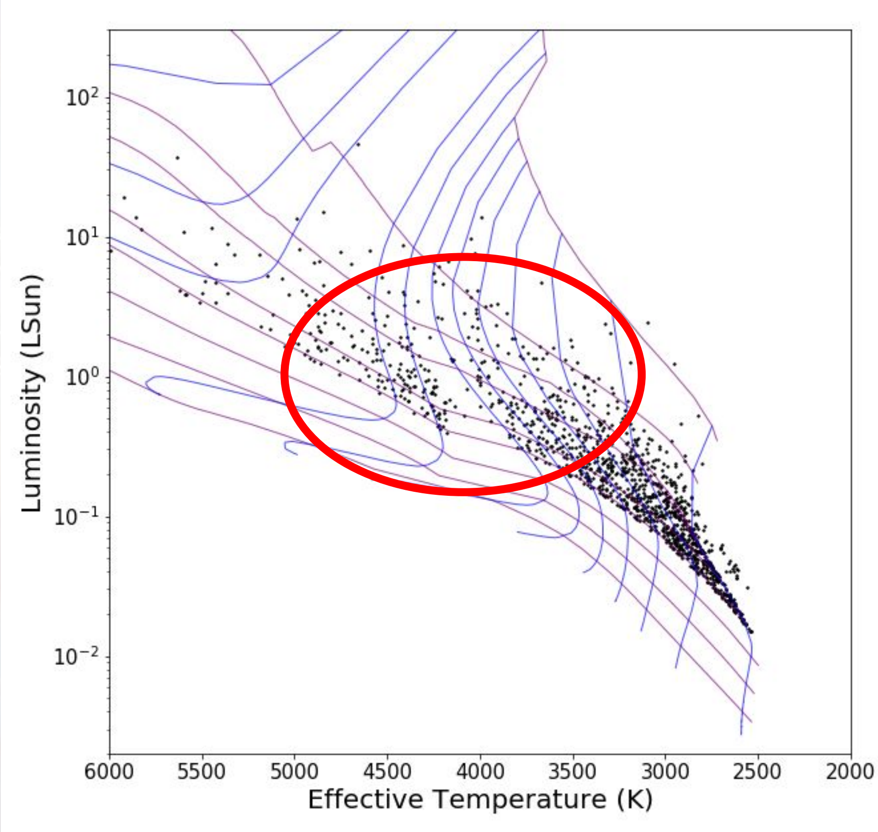


Baraffe



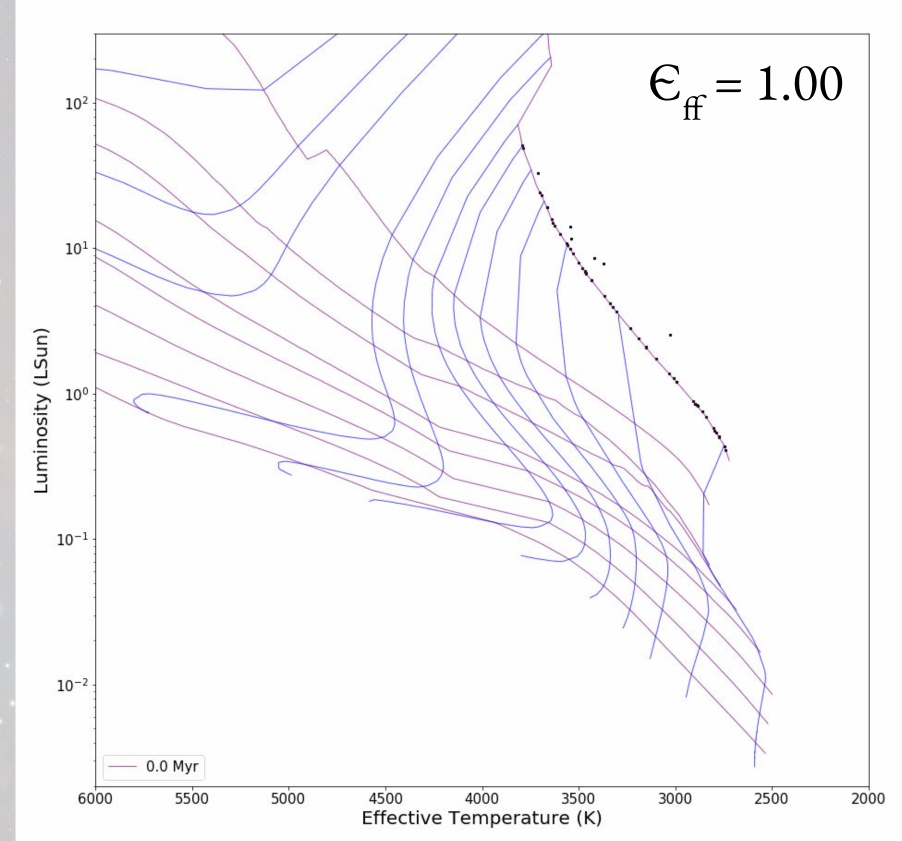


The PARSEC mass tracks from 0.6 to 0.8 $M_\odot$ have a widened spacing in temperature, which causes a gap in the distribution around 4000 K. This spacing is not present in the Baraffe tracks.

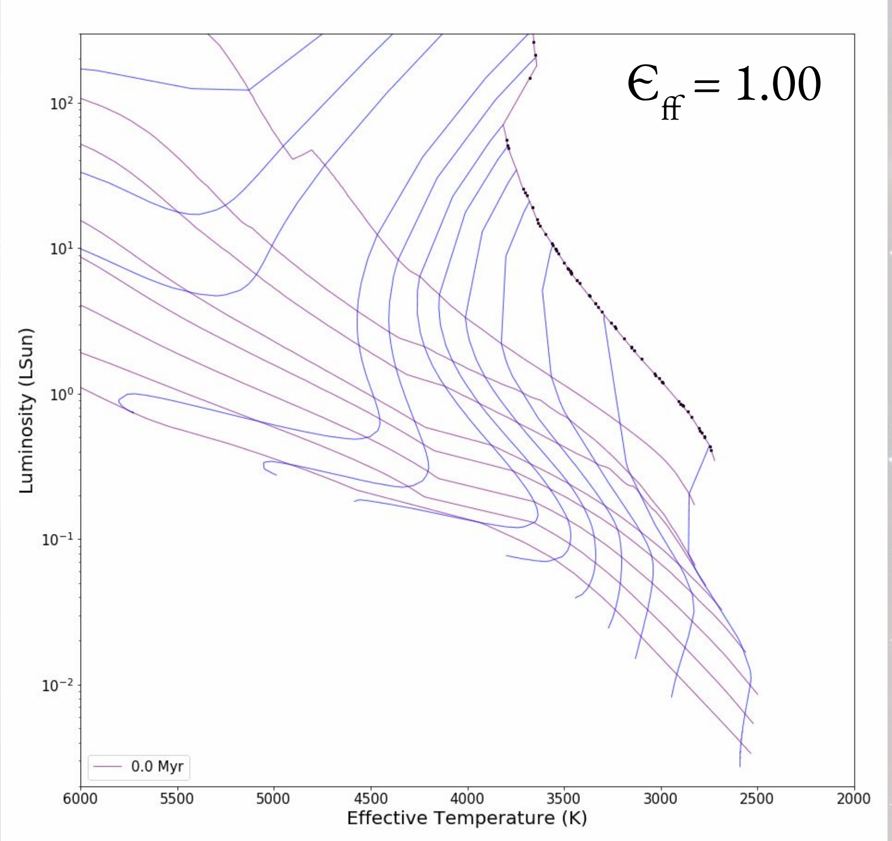


The Baraffe isochrones have discontinuous shapes at the lowest masses and earliest ages due to assumptions about initial conditions. The models have large uncertainties in this regime (Baraffe, priv. comm.).

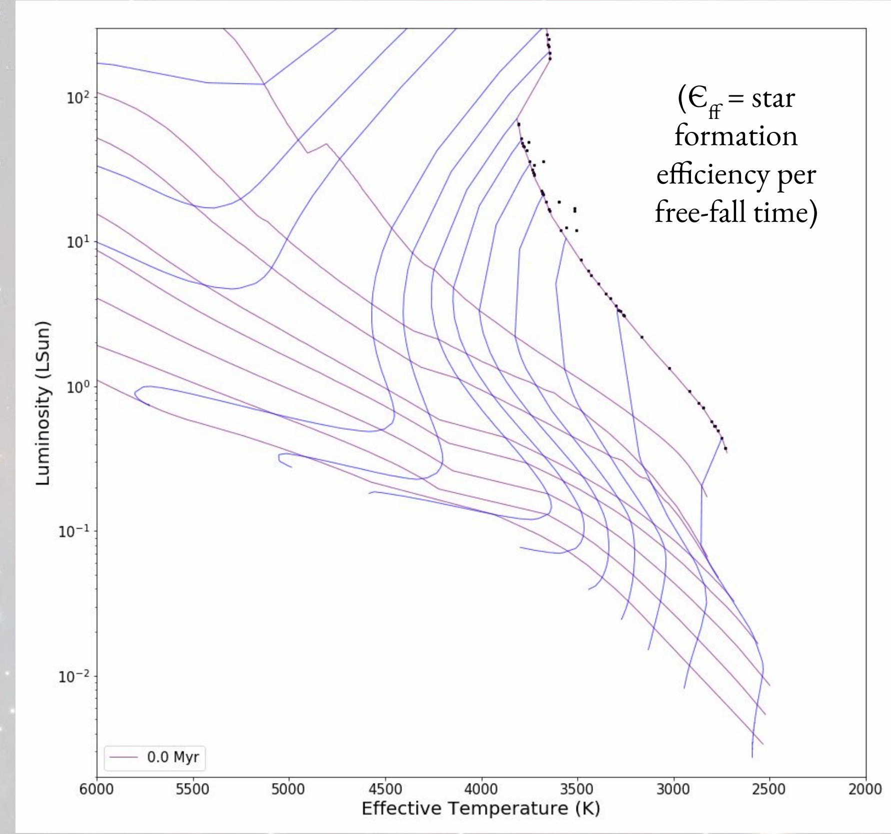
With binaries



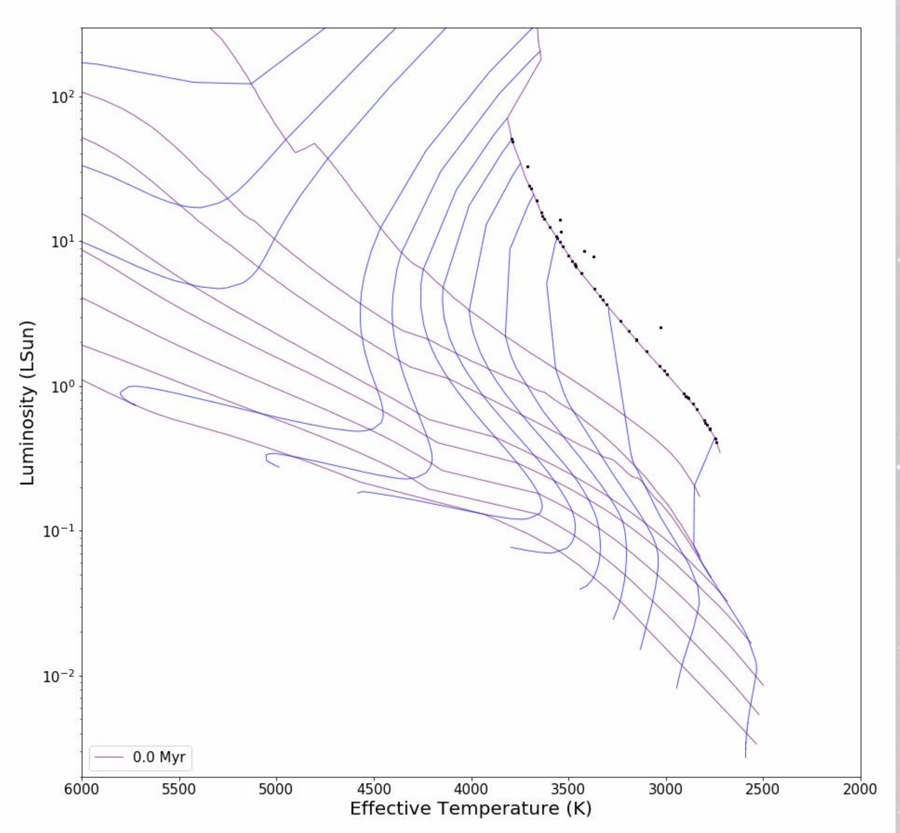
Without binaries



Slow formation: $\epsilon_{ff} = 0.03$ Fast formation: $\epsilon_{ff} = 1.00$



(ϵ_{ff} = star formation efficiency per free-fall time)



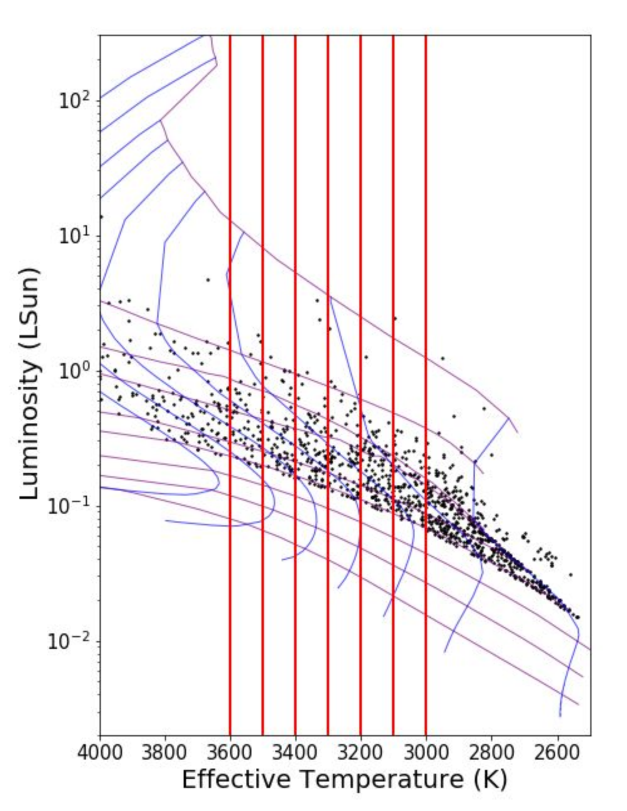
Luminosity and age metrics

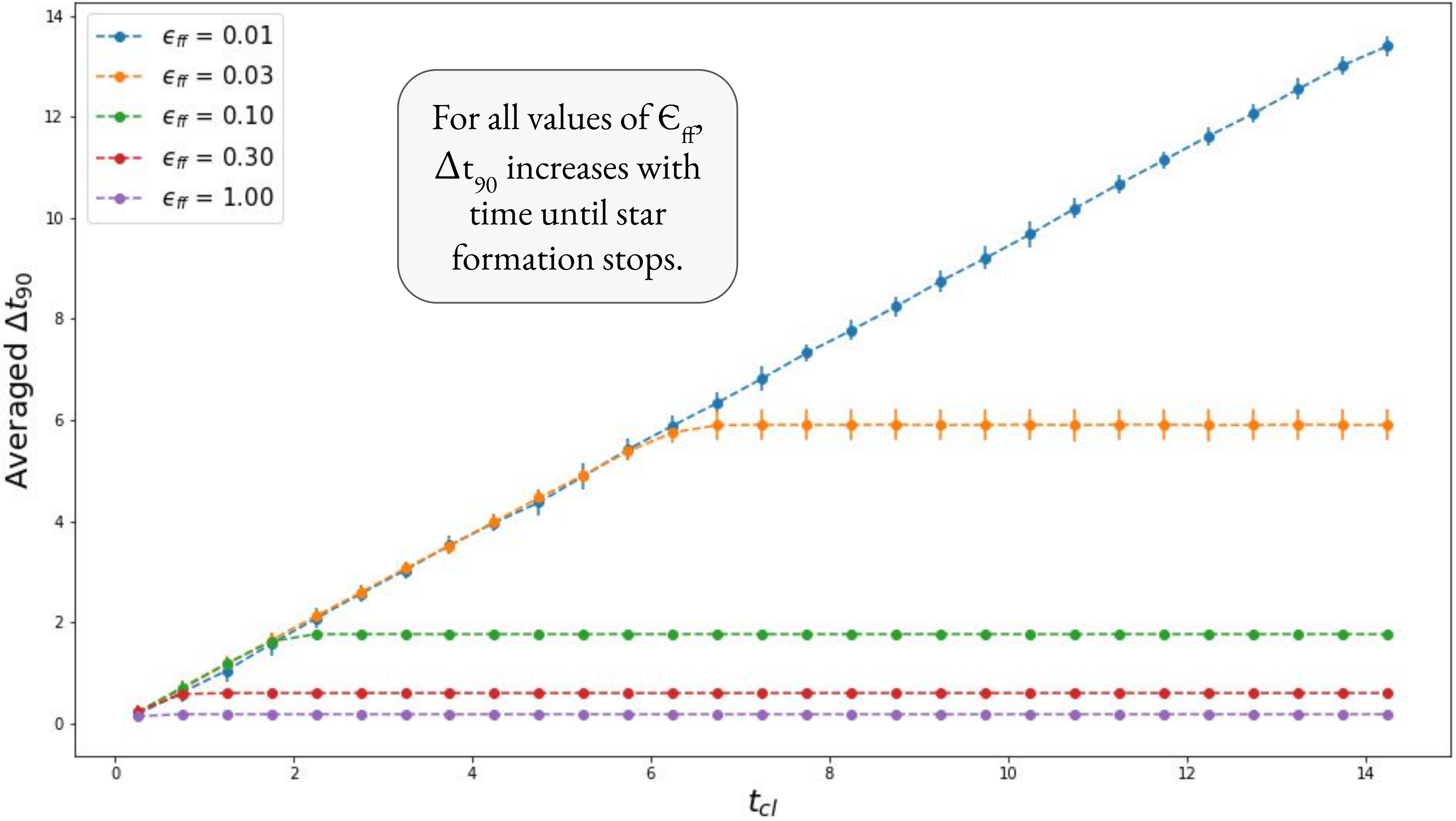
Luminosity spread (σ_L): Mean of the bottom 25% of the luminosities subtracted from the mean of the top 25% of the luminosities. Averaged across 6 bins in the temperature range 3000-3600 K (shown at right).

Age spread (Δt_{90}): The 5th percentile of all ages in the cluster subtracted from the 95th percentile.

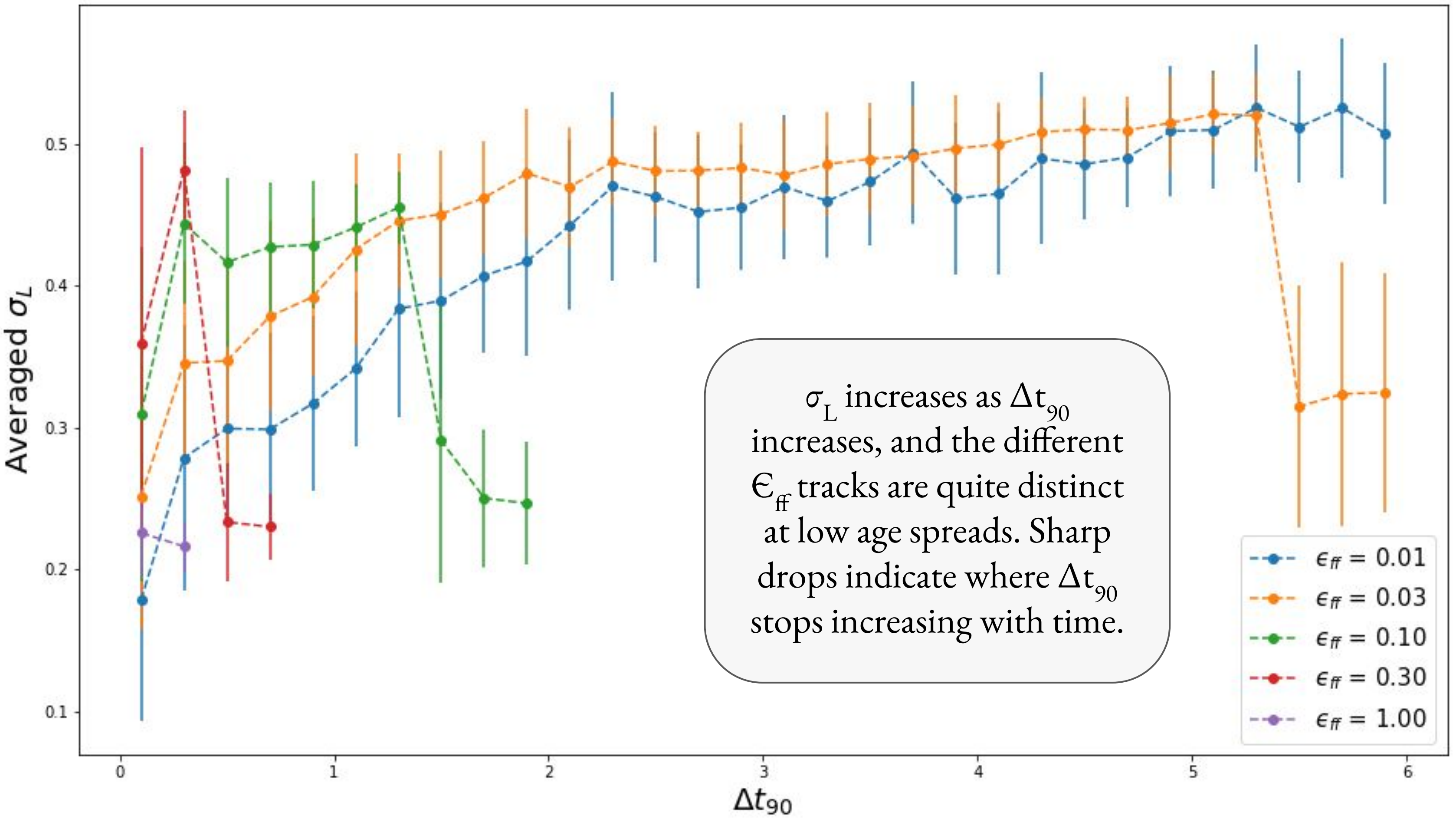
Mean luminosity (μ_L): Mean of the mean luminosities in each of the six temperature bins used for σ_L.

Cluster age (t_{cl}): The age of the cluster in a given frame.





For all values of ϵ_{ff}, Δt_{90} increases with time until star formation stops.

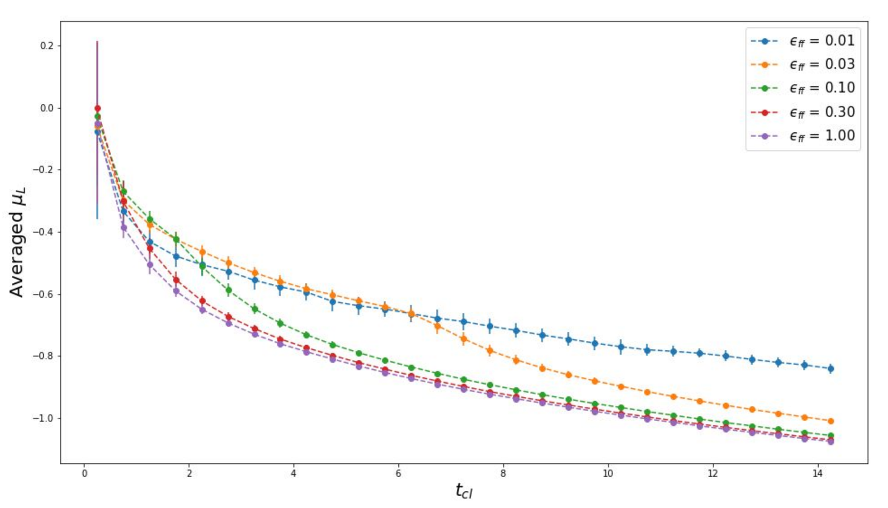

Averaged σ_L
Δt_{90}
0.1
0.2
0.3
0.4
0.5
0
1
2
3
4
5
6
ϵ_{ff} = 0.01
ϵ_{ff} = 0.03
ϵ_{ff} = 0.10
ϵ_{ff} = 0.30
ϵ_{ff} = 1.00
σ_L increases as Δt_{90} increases, and the different ϵ_{ff} tracks are quite distinct at low age spreads. Sharp drops indicate where Δt_{90} stops increasing with time.

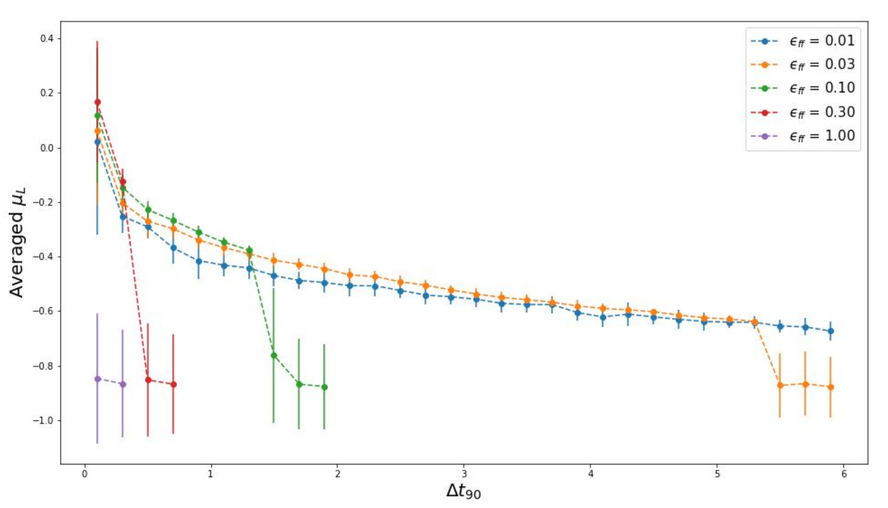
Other trends to note

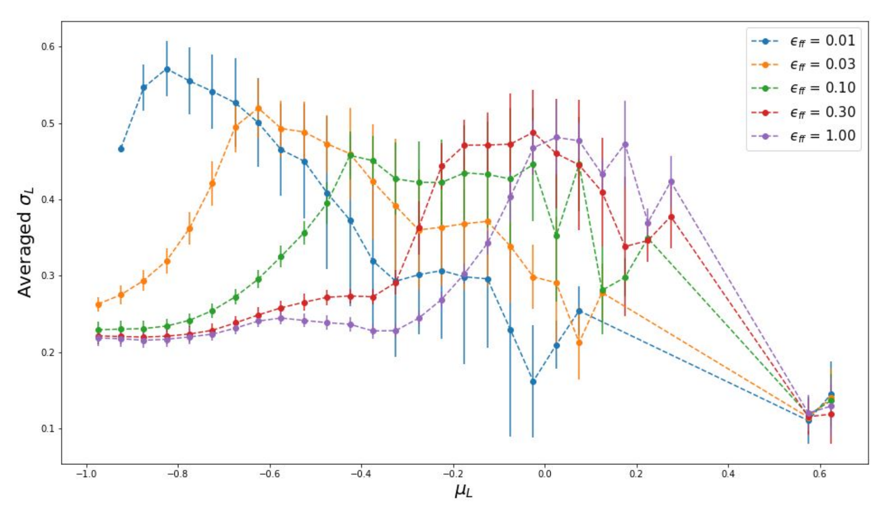
μ_L decreases as the clusters age (top left).

Similarly, μ_L decreases with Δt_{90}, dropping off when star formation stops (bottom left).

Each cluster forms a unique evolutionary track in μ_L-σ_L space (bottom right).







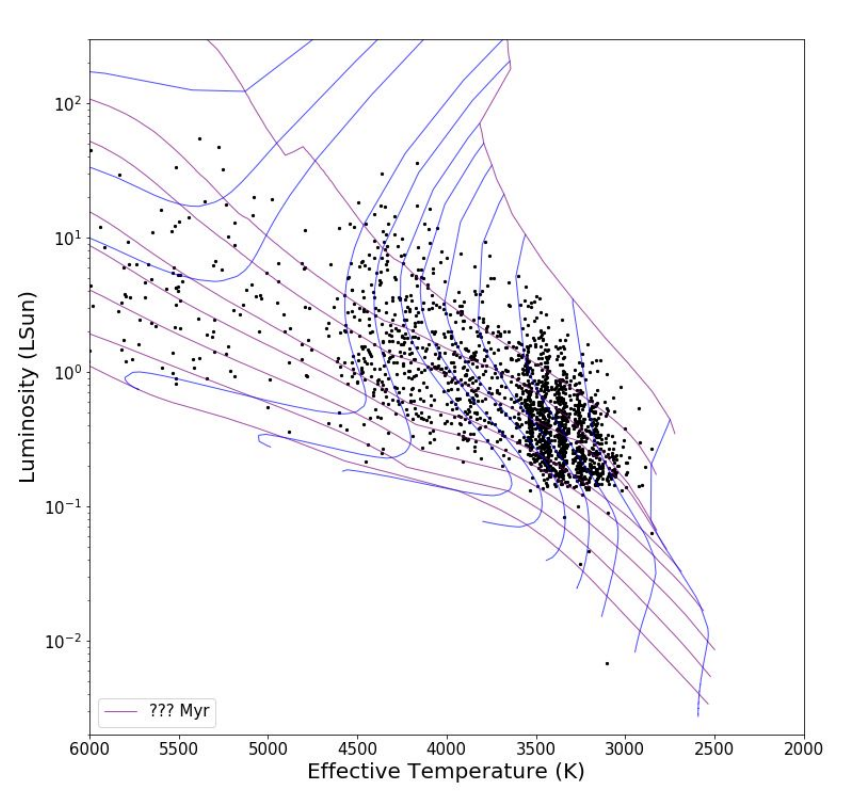
The Orion Nebula Cluster (ONC)

The ONC is one of the densest star-forming regions in the Orion complex.

It is well-studied, but its age has proven difficult to constrain due to pre-main sequence evolution uncertainties.

We use data from Da Rio et al. (2016), which includes stellar parameters for about 2700 pre-main sequence stars.

Da Rio et al. (2016): *IN-SYNC survey (part of SDSS III) of Orion using the APOGEE instrument for H-band spectroscopy.*



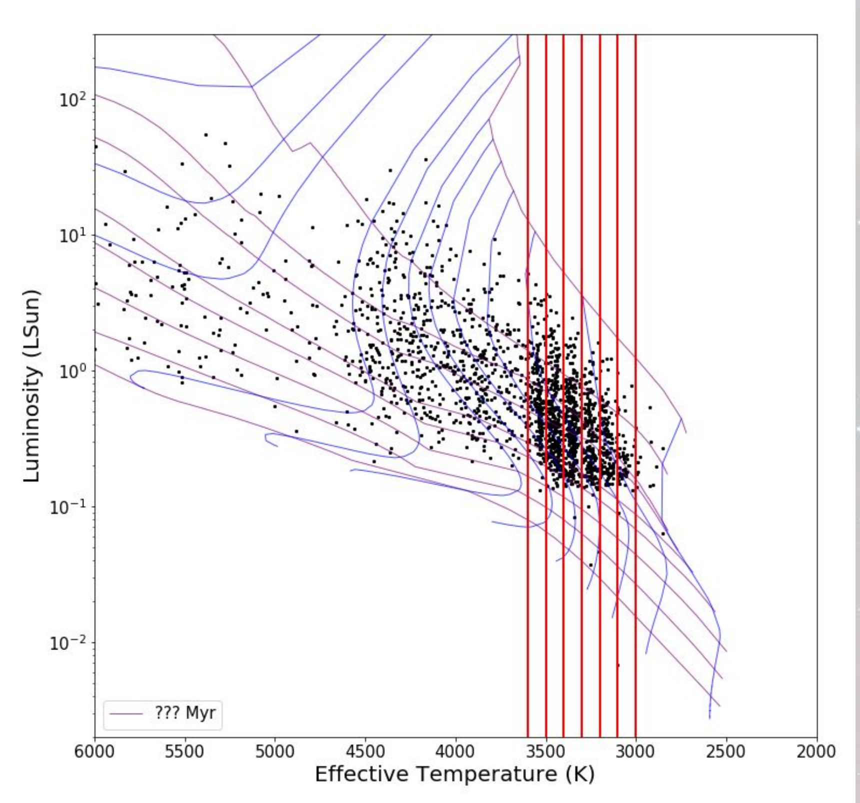
Measuring age and luminosity metrics in the ONC

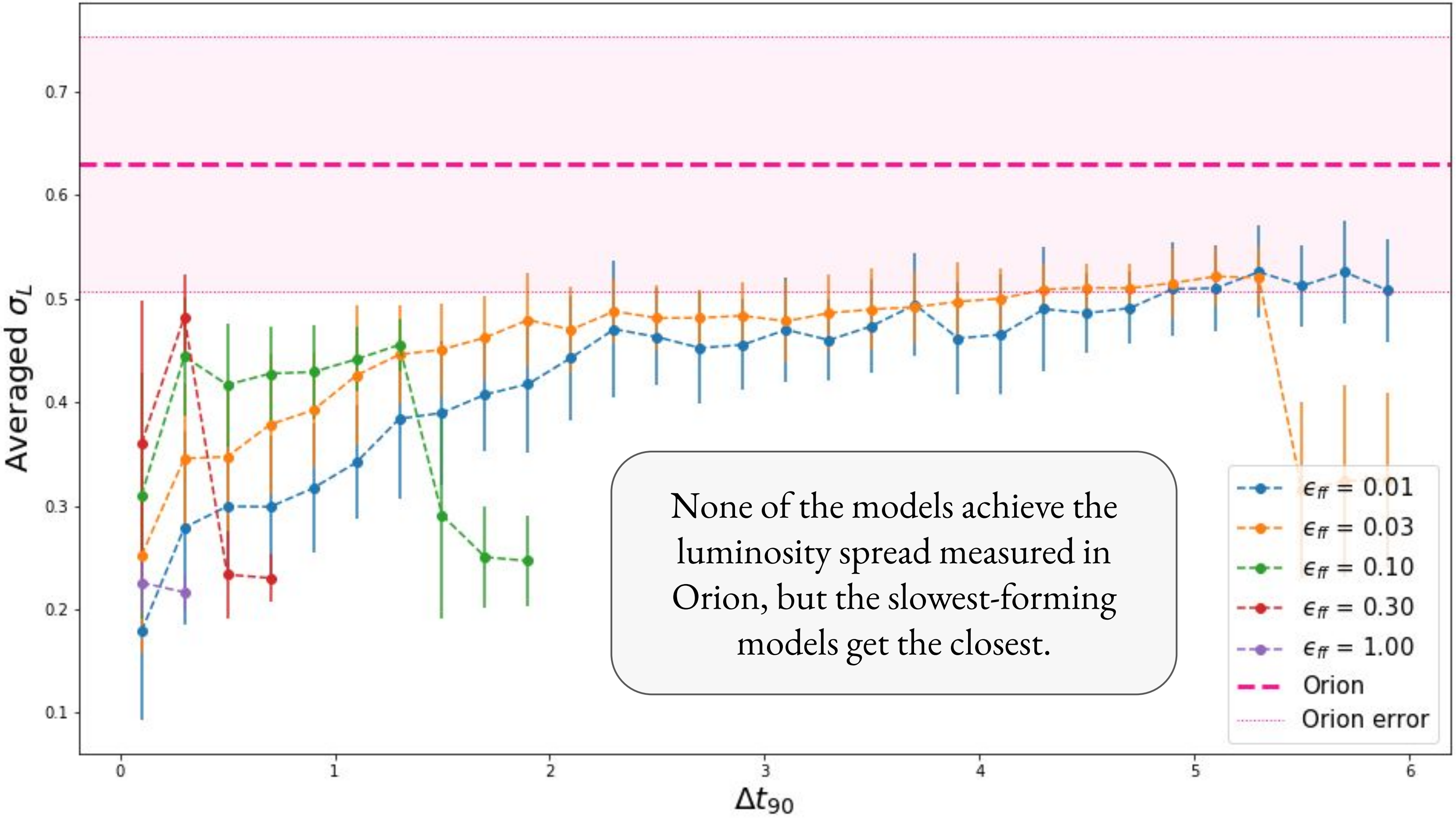
σ_L and μ_L are measured in the same temperature bins as for the simulated data (shown at right).

Only stars that are within the range of the PARSEC tracks are considered so that the metrics can be directly compared.

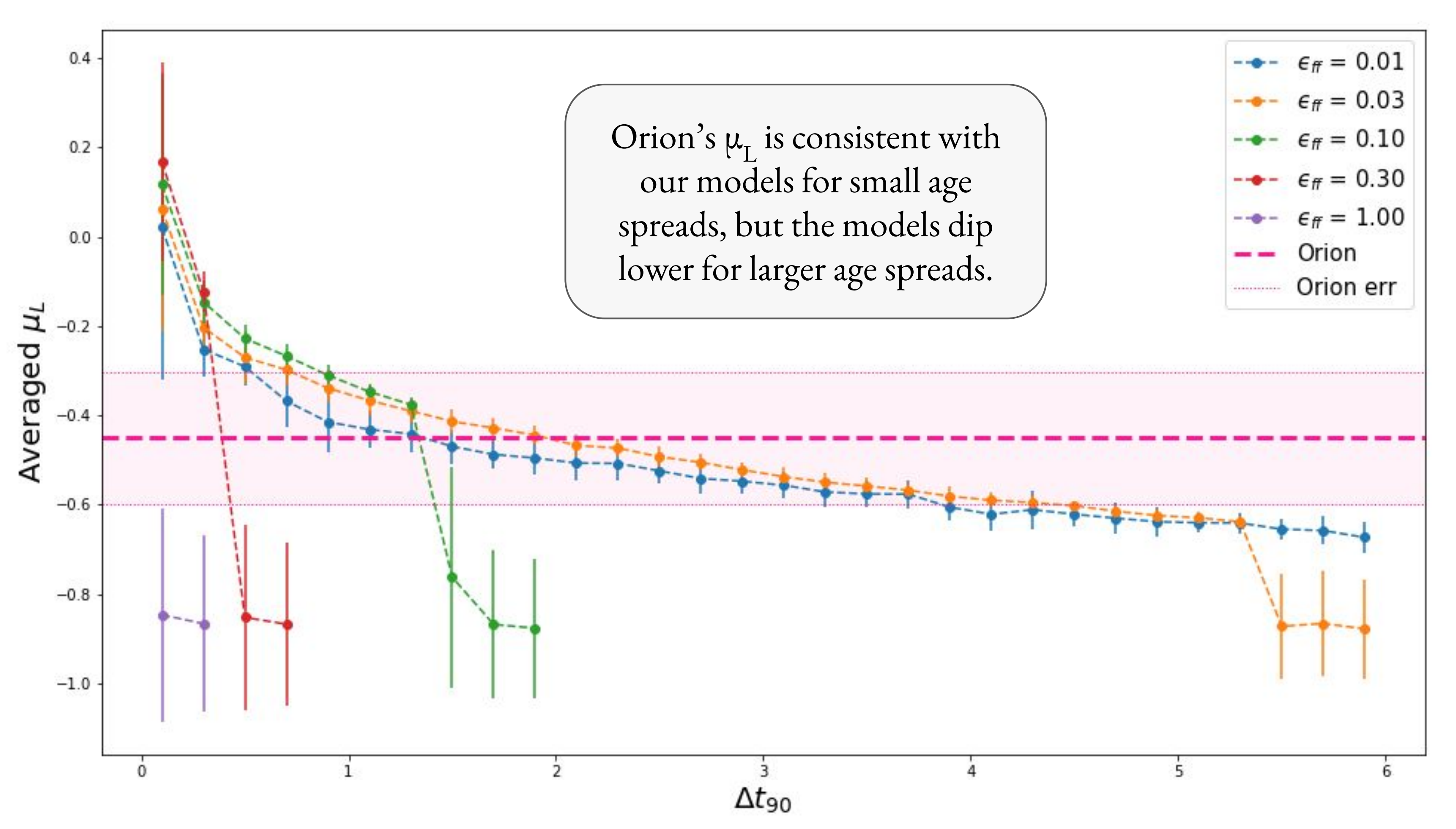
Measurements:
$\sigma_L = 0.62992 \pm 0.1233$
$\mu_L = -0.45042 \pm 0.1481$

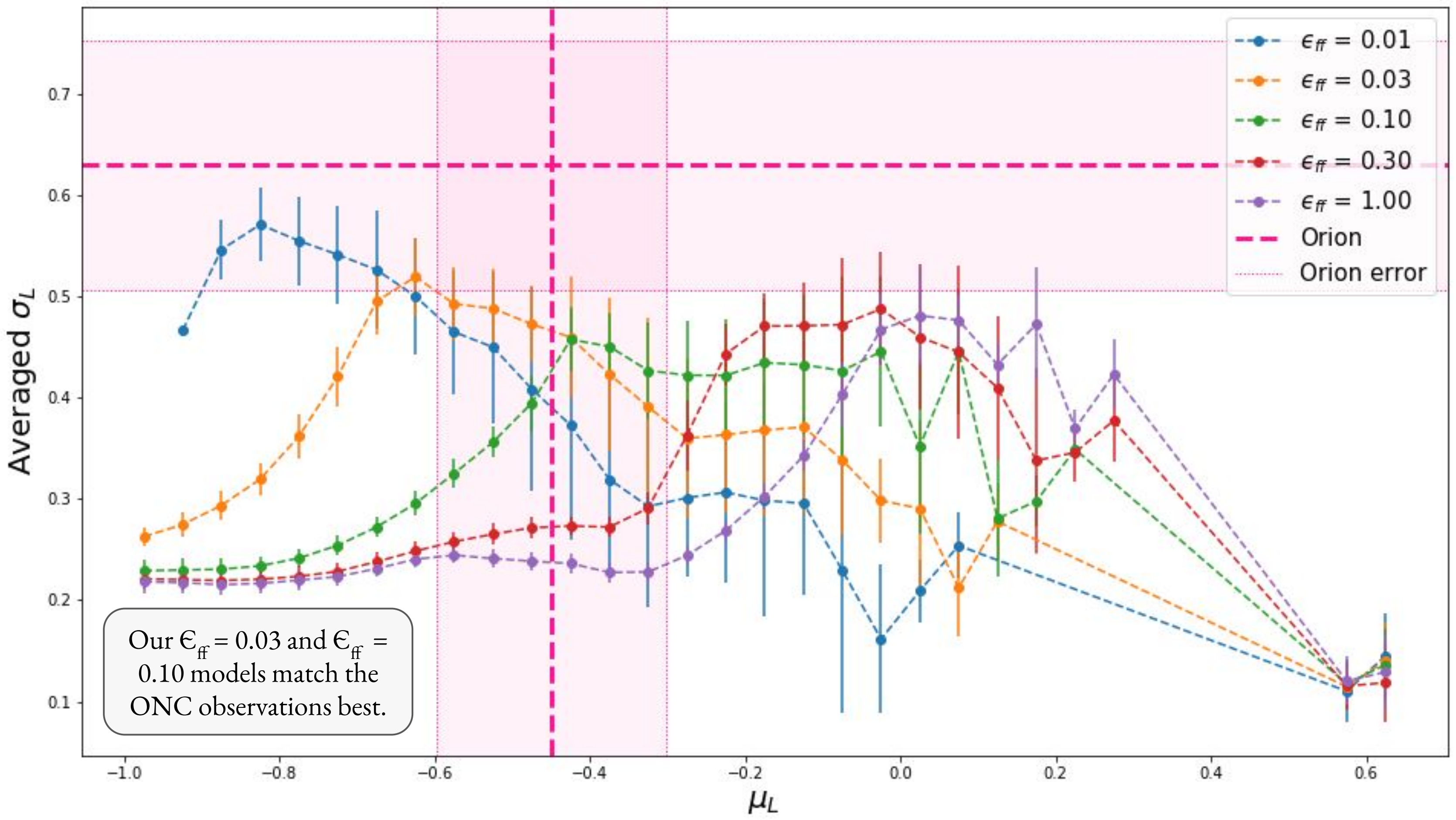
We have not yet produced a robust measure of age spread due to uncertainties in available age estimates from Da Rio et al. (2016).





None of the models achieve the luminosity spread measured in Orion, but the slowest-forming models get the closest.


Orion's μ_L is consistent with our models for small age spreads, but the models dip lower for larger age spreads.
Averaged μ_L
Δt_{90}
ϵ_{ff} = 0.01
ϵ_{ff} = 0.03
ϵ_{ff} = 0.10
ϵ_{ff} = 0.30
ϵ_{ff} = 1.00
Orion
Orion err



Our ϵ_{ff} = 0.03 and ϵ_{ff} = 0.10 models match the ONC observations best.

Other investigations and future work

- ★ Probing the full parameter space of the simulations, including the lower- and higher-mass clusters
- ★ Accounting for complex effects such as variable reddening, extinction errors, and variable luminosity accretion
- ★ Deriving age estimates for ONC members via reverse interpolation
- ★ Tracing radial variations of simulated Ha-R diagrams in order to probe radial age gradients, etc.
- ★ Extending luminosity spread metrics to color-magnitude diagrams

Conclusions

- ★ We have developed methods to produce synthetic H-R diagrams of simulated star clusters (including binaries)
  - ○ Choice of isochrone model can introduce systematic effects
  - ○ Limited by uncertainties in pre-main sequence tracks
- ★ We have developed simple luminosity metrics in the 3000–3600 K temperature range to characterize a cluster's evolutionary state
- ★ Comparison with the ONC data shows none of the current models can reach the observed luminosity spread, though the best-matching models have $t_* \sim 2$ Myr and $\epsilon_{ff} \sim 0.03$ to 0.01

Thank you!
Questions?

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