The Origin of Massive Stars: Compact H II Regions and ZAMS as Clocks of Massive-Star Formation

Paolo Padoan

Dartmouth College & Institute of Cosmos Sciences

Mark Gieles *(University of Barcelona)*

Fabrice Martins *(University of Montpellier)*

William Lake *(Dartmouth College)*

Samuel Shipkoff *(Waterville Valley Academy)*

Padoan & Gieles 2026, ApJL (arXiv:2602.06196)

WHY MASSIVE STARS MATTER

- **Feedback:** ionization, winds, supernovae
- **Enrichment:** metals and dust
- **Early galaxies:** massive stars at $z > 10$
- **Globular clusters:** multiple populations

Key questions

- How is their mass assembled?
- On what timescale?
- What is the maximum mass?

1. The Inertial-Inflow Model

THE MASS-SUPPLY PROBLEM

$\langle M_\mathrm{J} \rangle \sim 1 - 10\, M_\odot$ —> *Massive stars need mass from larger scales*

Massive-core *(McKee & Tan 2002, 2003)*

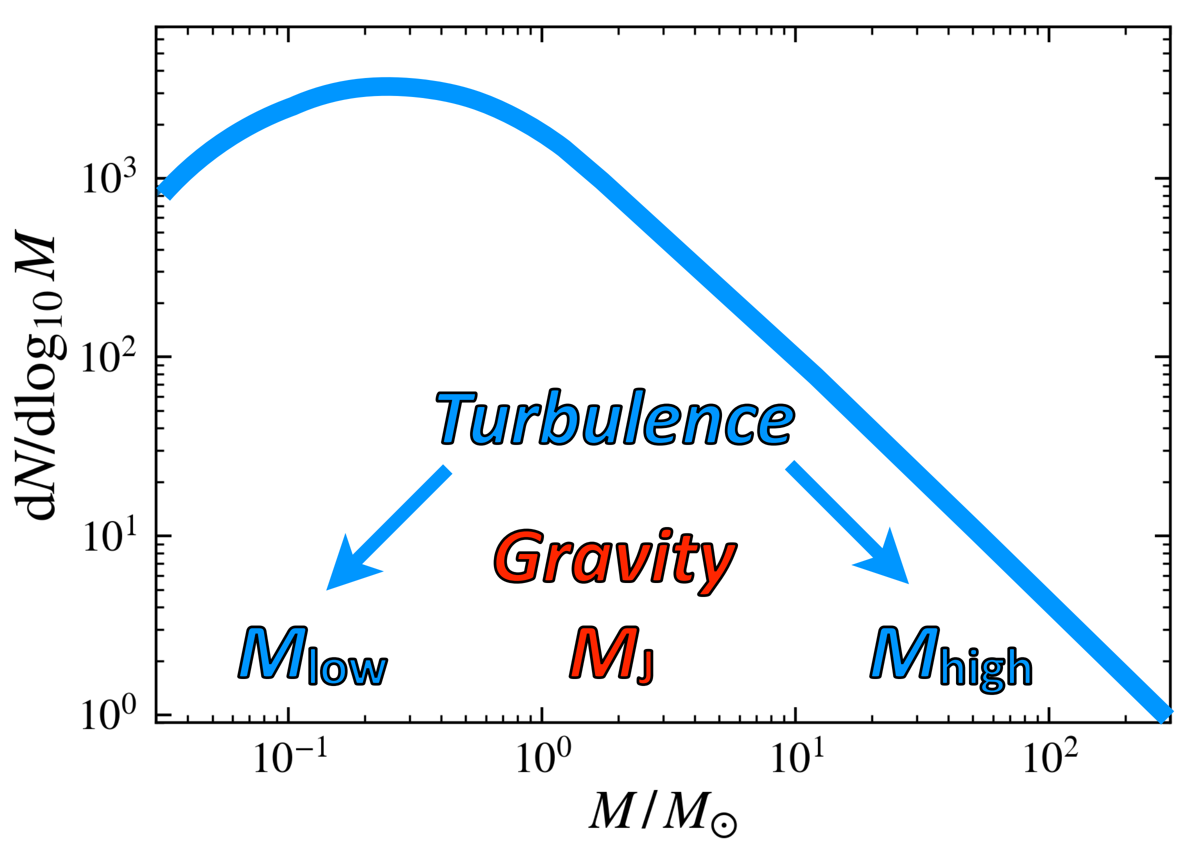
$M_\mathrm{core} \gg M_\mathrm{J}$

rapid collapse: $\sim 0.1\,\mathrm{Myr}$

Inertial-inflow *(Padoan et al. 2020)*

$M_\mathrm{core} \sim M_\mathrm{J}$

growth after collapse: $\gtrsim \mathrm{Myr}$

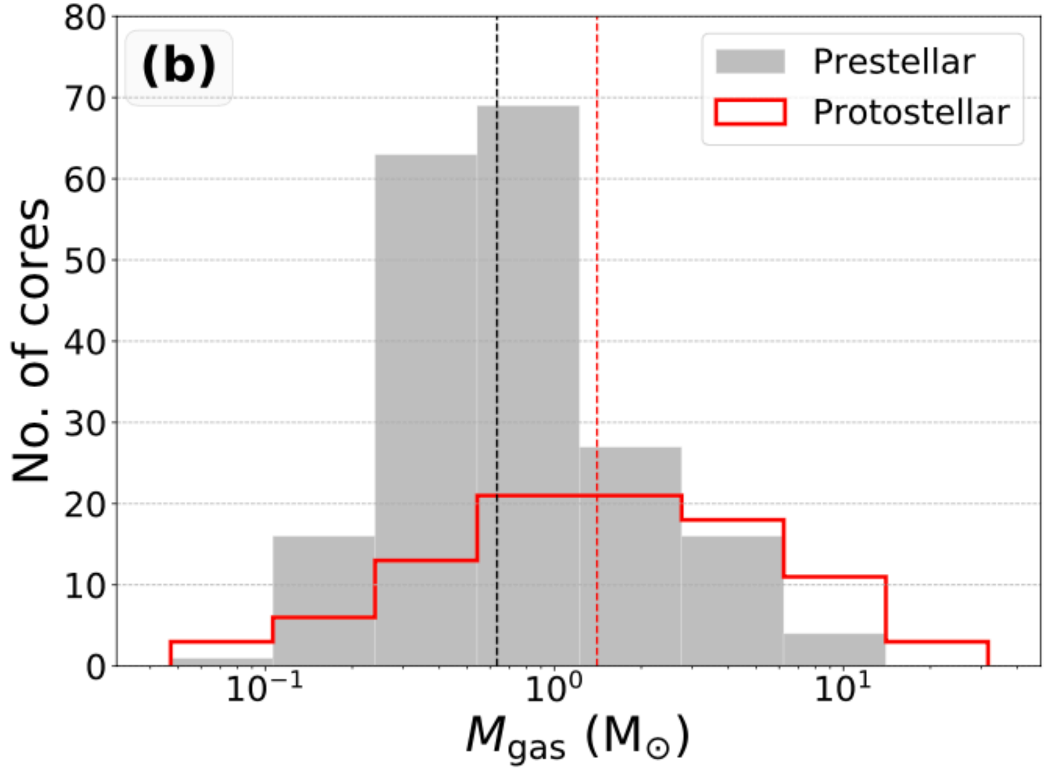


THE MASS OF PRESTELLAR CORES

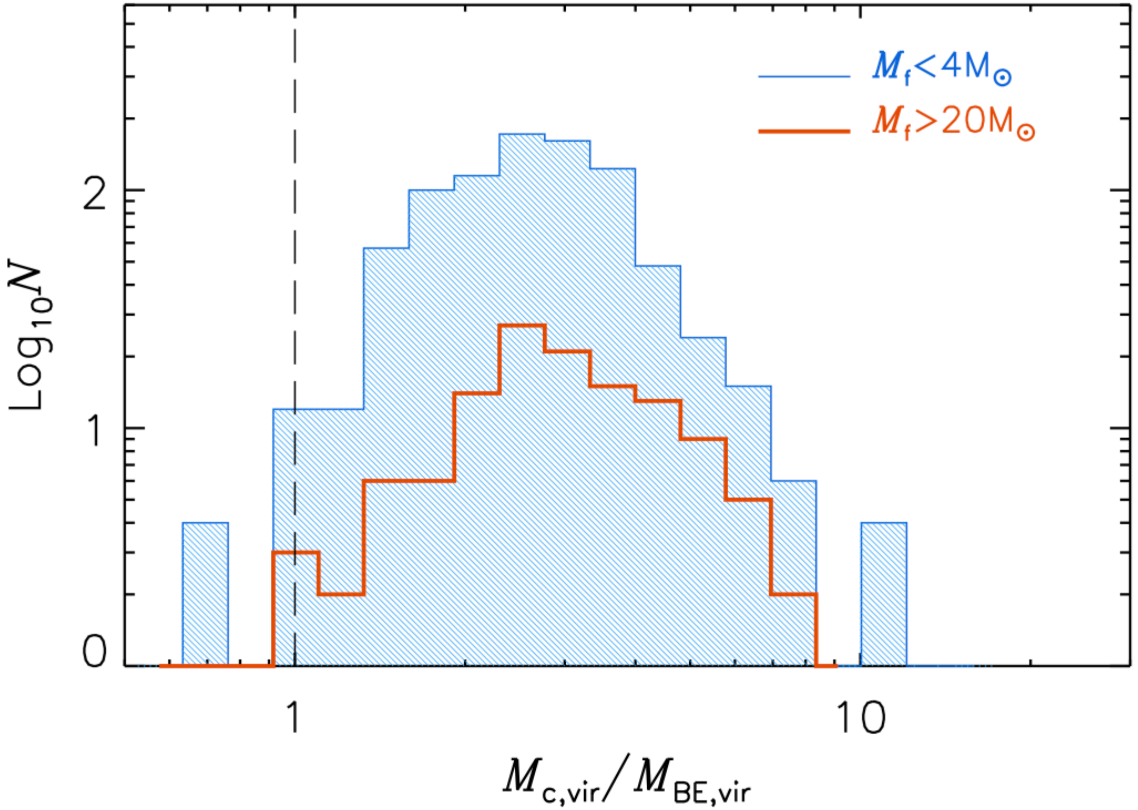
Massive cores are already mostly PROTO-stellar.

The initial core mass poorly predicts the final stellar mass.

Li et al. (2023) - ALMA **observations**



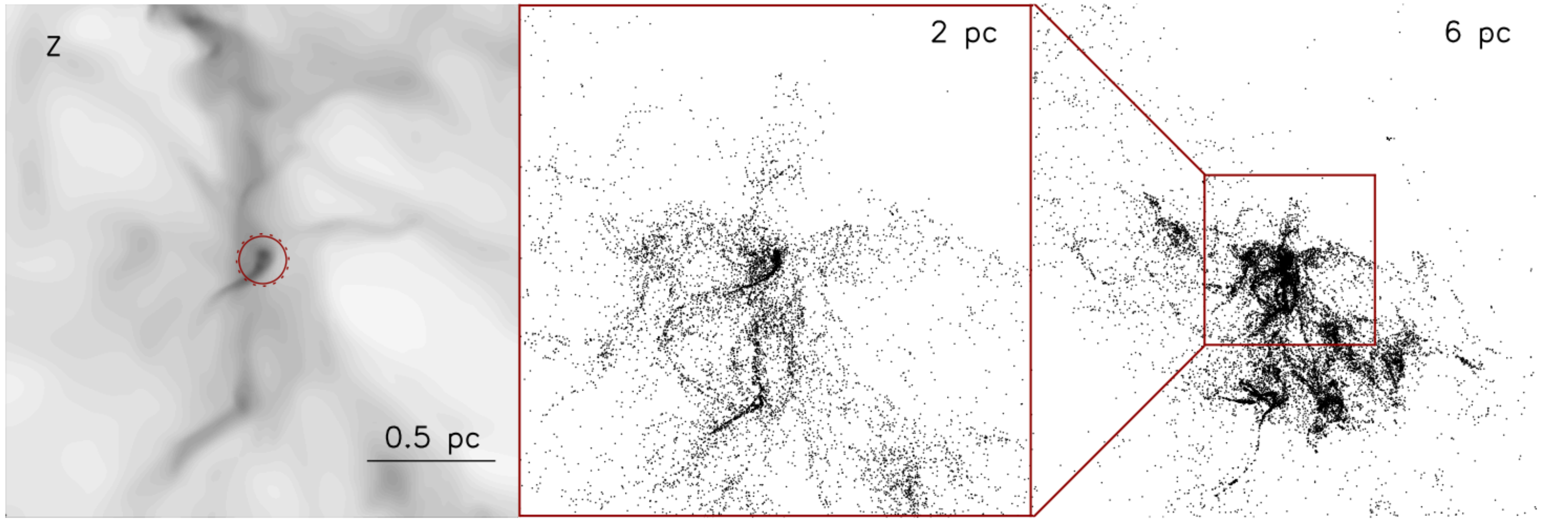
Padoan et al. (2020) - SN-driven **simulations**



—> Most of the stellar mass is accreted after the initial collapse.

INERTIAL-INFLOW MODEL — Main Ingredients

Guido Garay's talk



Padoan et al. (2020)

- Parsec-scale turbulent inflow sets the mass supply.
- The initial core is not the main reservoir.

1. Growth Law

$$t_{\rm form} = \tau_0\,(m_{\rm f}/m_0)^{\alpha}$$

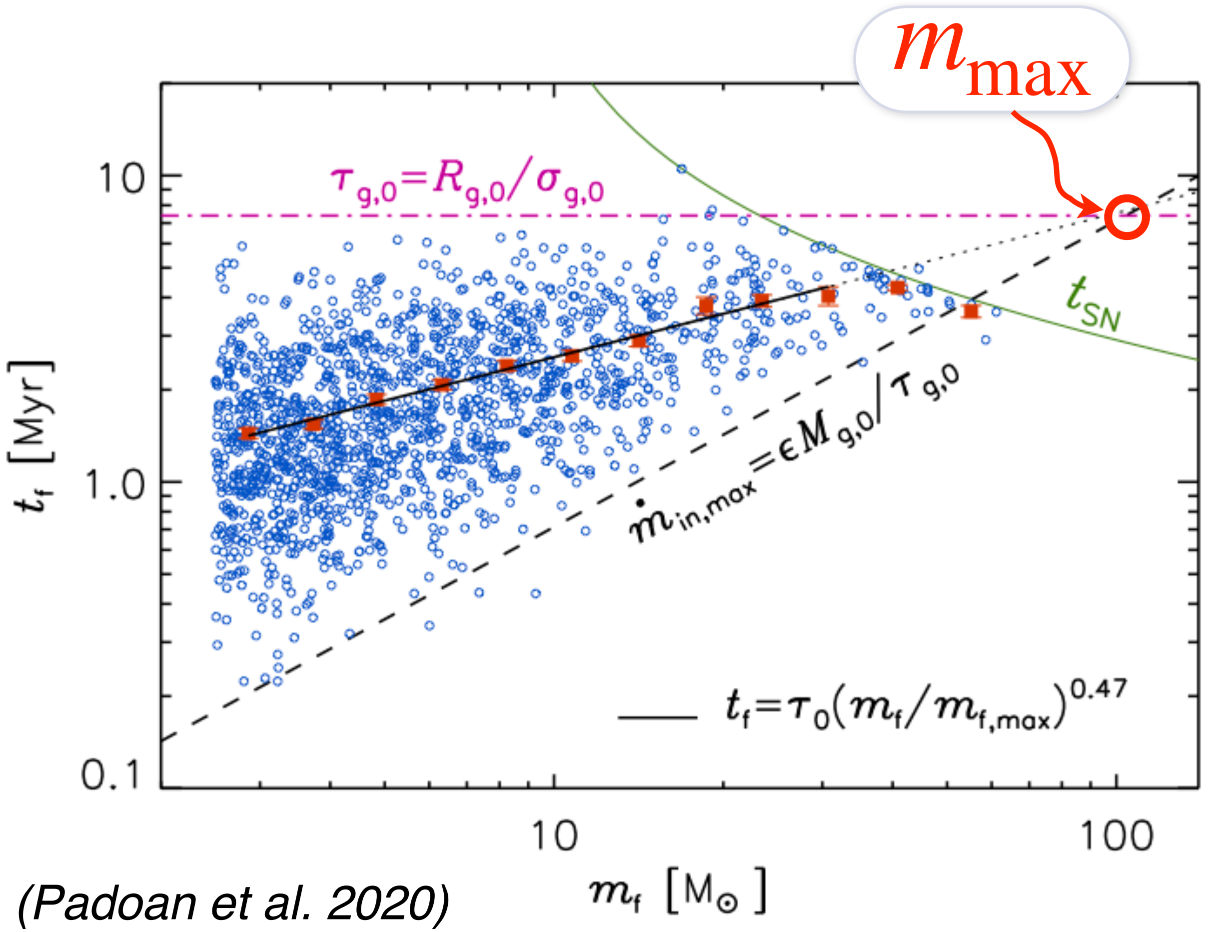
$$\tau_0 \sim 1\,{\rm Myr}\,,\quad \alpha \simeq 0.5$$

2. Maximum mass

$$m_{\rm max} \;\simeq\; \varepsilon_{\rm max}\,M_{\rm cloud}$$

$$\varepsilon_{\rm max} \simeq 2.5 \times 10^{-3}$$

INERTIAL-INFLOW MODEL — Growth time is set by the turbulent scale



(Padoan et al. 2020)

$$t_{form} = t_{dyn}\,(m_f/m_{max})^{\alpha}$$

$\alpha \simeq 0.5$ $\quad t_{dyn} \sim$ few Myr

- α: slope of turbulent scaling
- t_{dyn}: outer-scale dynamical time
- m_{max}: set by cloud mass

TWO CLOCKS FOR MASSIVE-STAR GROWTH

The inertial-inflow model predicts prolonged growth after collapse.

How can observations measure that time?

Compact HII regions

- Ionization turns on while the star is still accreting
- Comparison with the OB-star LF measures the growth time

ZAMS discrepancy

- Massive stars already burn H during the embedded growth
- Distance from the ZAMS constrains the growth time

Two independent clocks of the embedded growth phase

2. Compact H II regions as clocks

CLOCK 1: THE COMPACT H II REGION LIFETIME PROBLEM

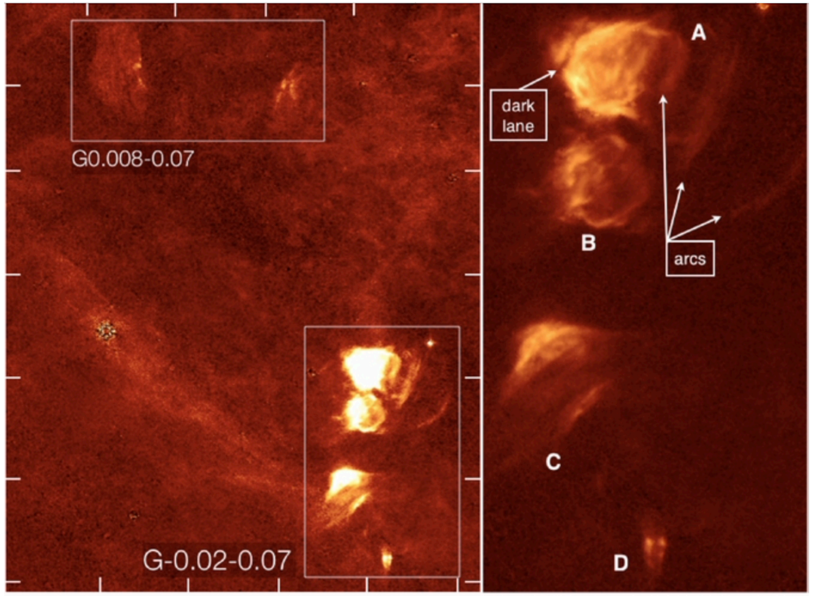
Number counts: too many compact H II regions relative to OB stars *(Wood & Churchwell 1989)*

Demographics imply:

$$t_{\rm HII} \sim \frac{N_{\rm HII}}{N_{\rm OB}}\, t_{\rm MS,OB} \sim 10^5\ {\rm yr}$$

Expansion is much faster:

$$\frac{R_{\rm HII}}{c_{\rm s}} \sim 10^4\ {\rm yr}$$



Mills et al. (2011) — Sgr A

Problem: *compact H II regions appear to live too long.*

CLOCK 1: The Lifetime Problem in Luminosity Space

Improved demographics from the LFs *(Mottram et al. 2011)*

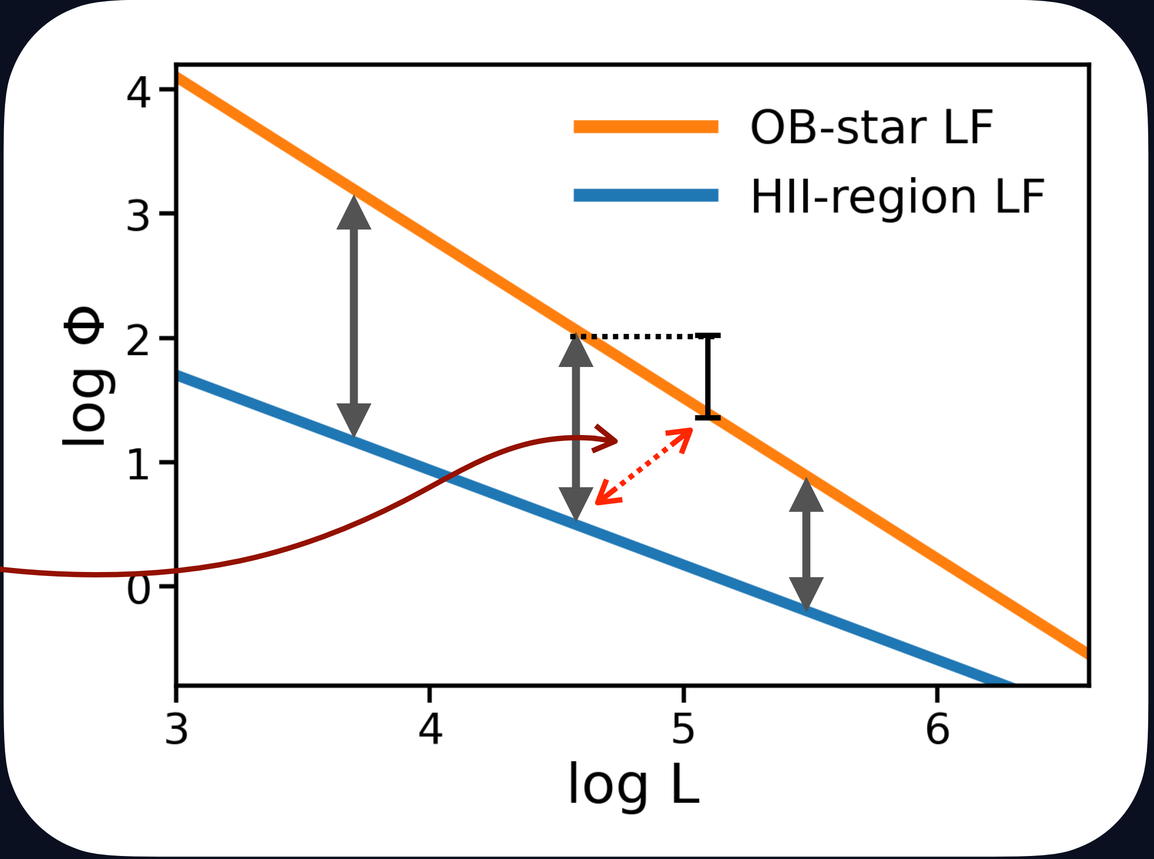
Key assumption: embedded stars are already at their **final mass and luminosity**.

- **At fixed luminosity:**

$$t_{\mathrm{HII}}(L) \;=\; t_{\mathrm{MS}}(L)\,\frac{\phi_{\mathrm{HII}}(L)}{\phi_{\mathrm{OB}}(L)}$$

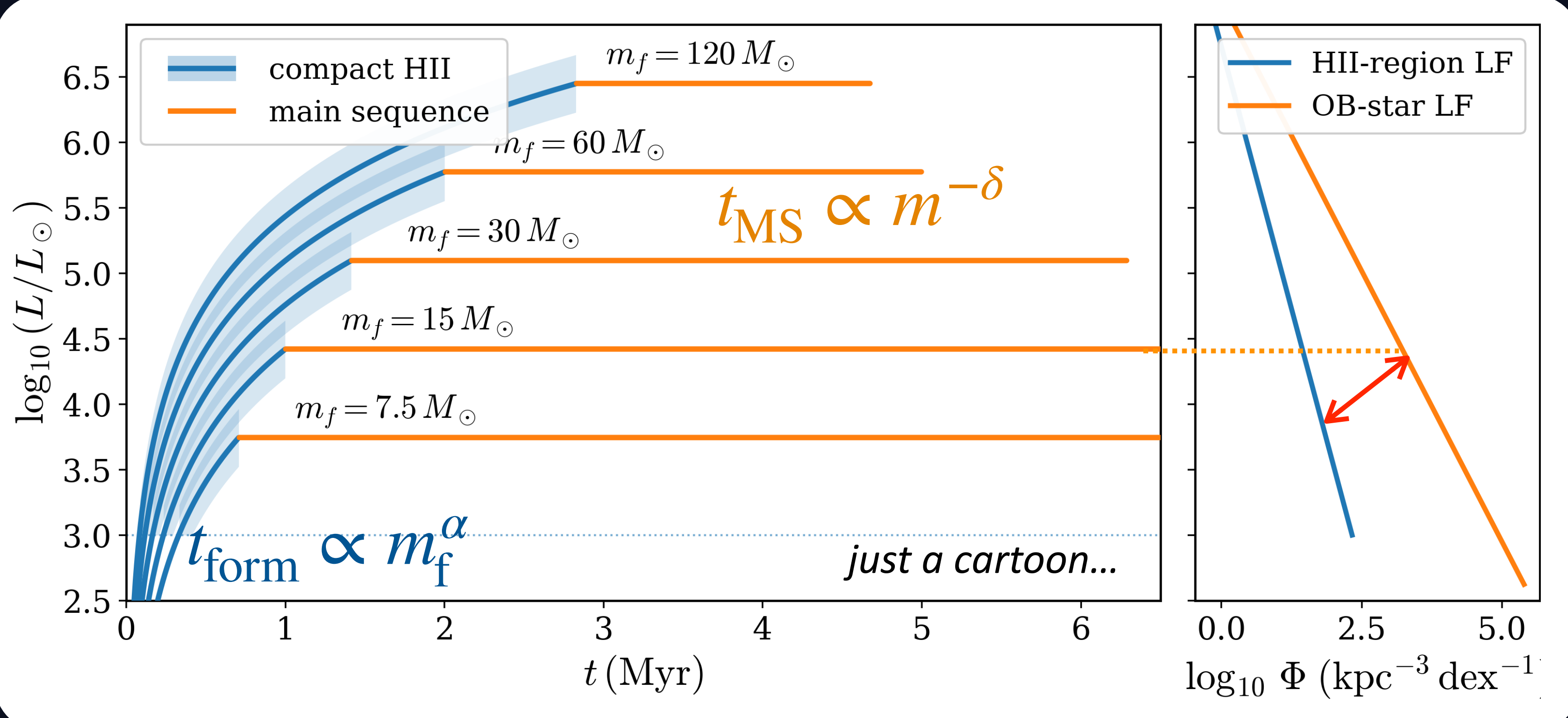
- **Result:** $t_{\mathrm{HII}} \simeq 3 \times 10^5\,\mathrm{yr}$

But if massive stars are still growing while ionizing, the equal-L mapping fails.



Why growth changes the HII-region LF

- OB stars count the time spent on the main sequence.
- Compact HII regions count the time spent growing while ionizing.
- Because growth time increases with final mass, the HII-region LF is shallower.



The slope difference measures the growth law

For simple power laws: $L \propto m^{\gamma}, \quad t_{\mathrm{MS}} \propto m^{-\delta}, \quad t_{\mathrm{form}} \propto m^{\alpha}$

the luminosity functions (LFs) are: $\phi_{\mathrm{OB}}(L) \propto L^{\beta_{\mathrm{OB}}}, \quad \phi_{\mathrm{HII}}(L) \propto L^{\beta_{\mathrm{HII}}}$

$$\Delta\beta = \beta_{HII} - \beta_{\mathrm{OB}} = \frac{\alpha + \delta}{\gamma}$$

- HII-region LF is shallower than the OB-star LF
- Slope difference constrains α
- Relative normalization constrains τ_0

OBSERVATIONAL LFs — Common normalization at 3 kpc

We compare optically revealed OB stars with embedded massive stars using the same Galactic-structure correction, completeness correction, and scale height $h = 39\,\mathrm{pc}$.

OB-star LF — ALS III + Gaia DR3

$$\phi_{\mathrm{OB}}(G_{\mathrm{abs}})$$

- Revealed massive stars
- Gaia absolute magnitude, not L_{bol}
- $d \leq 12\,\mathrm{kpc}$
- 12,640 stars (5,958 used in the fit)

Embedded-source LF — RMS survey

$$\phi_{\mathrm{emb}}(L_{\mathrm{bol}})$$

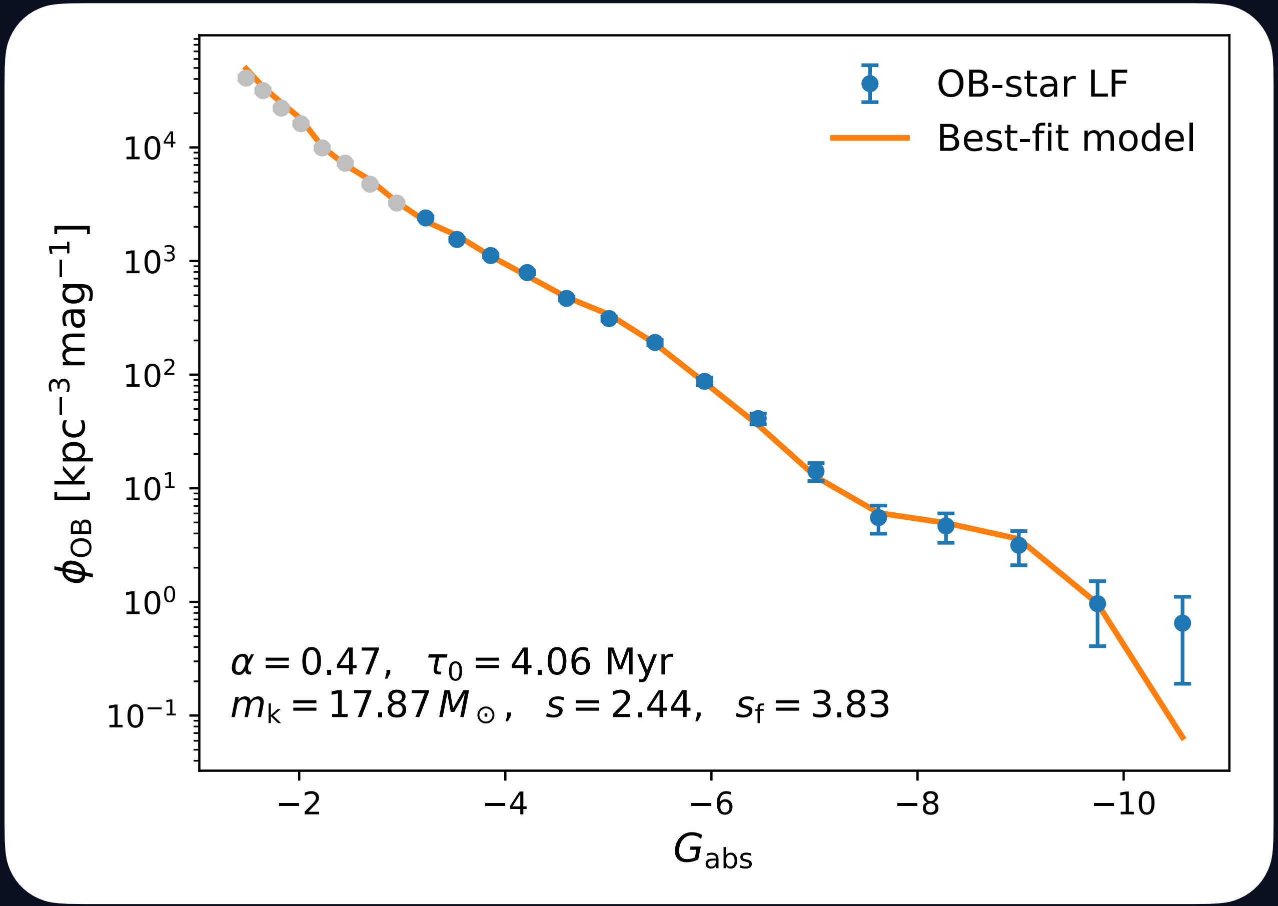
- Compact HII regions and MYSOs
- Observed in L_{bol}
- $d \leq 18\,\mathrm{kpc}$
- 1,800 sources

$\{\phi_{\mathrm{OB}}, \phi_{\mathrm{emb}}\} \Longrightarrow$ *joint constraints on IMF + growth law*

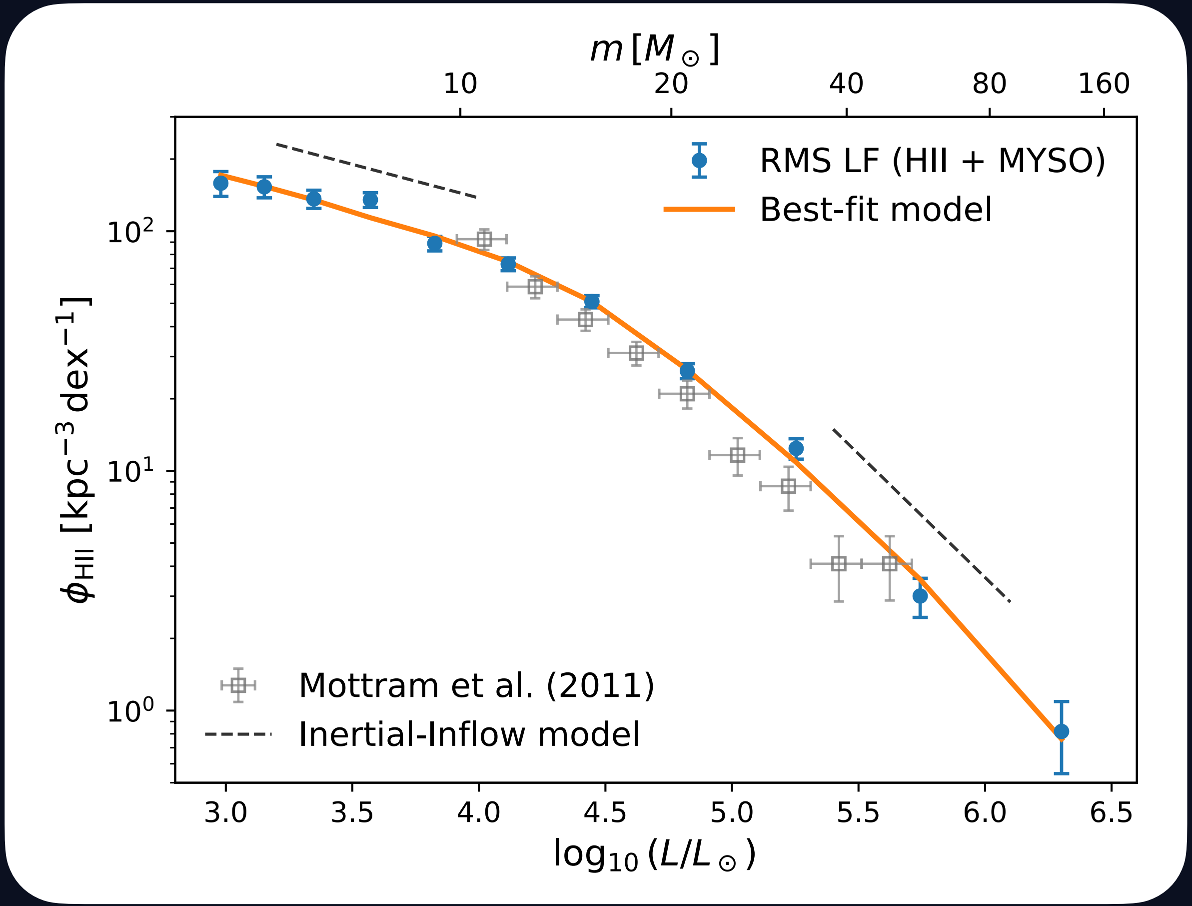
ALS III catalog: *Pantaleoni Gonzáles et al. (2025)* — RMS catalog: *Lumsden et al. (2013)*

OBSERVATIONAL LFs — Best-fit model from growth law and IMF

OB-star LF



HII-region + MYSO LF



The same growth law and IMF provide an excellent fit to both the shape and normalization of both LFs.

JOINT FIT — One model for both luminosity functions

We fit the two LFs simultaneously with a deterministic forward model.

Physical Model

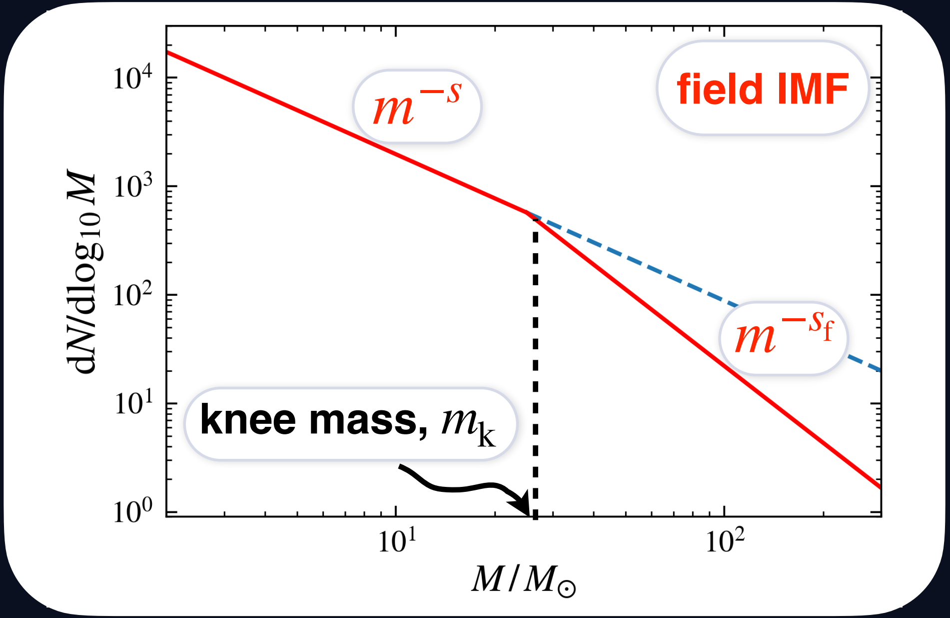
- Field IMF + Growth law
- $m_{\mathrm{k}},\ s,\ s_{\mathrm{f}},\ \alpha,\ \tau_0$

Predicted LFs

- $\phi_{\mathrm{OB}}(G_{\mathrm{abs}}),\quad \phi_{\mathrm{emb}}(L_{\mathrm{bol}})$

Joint fit to the observed LFs

- Shape + Normalization



The LF comparison is not a compact H II lifetime measurement; it is a clock for massive-star growth.

JOINT FIT — Growth law and field IMF

Growth Law

$$\alpha = 0.48^{+0.11}_{-0.11}, \quad \tau_0 = 4.15^{+0.90}_{-0.63}\ \mathrm{Myr}$$

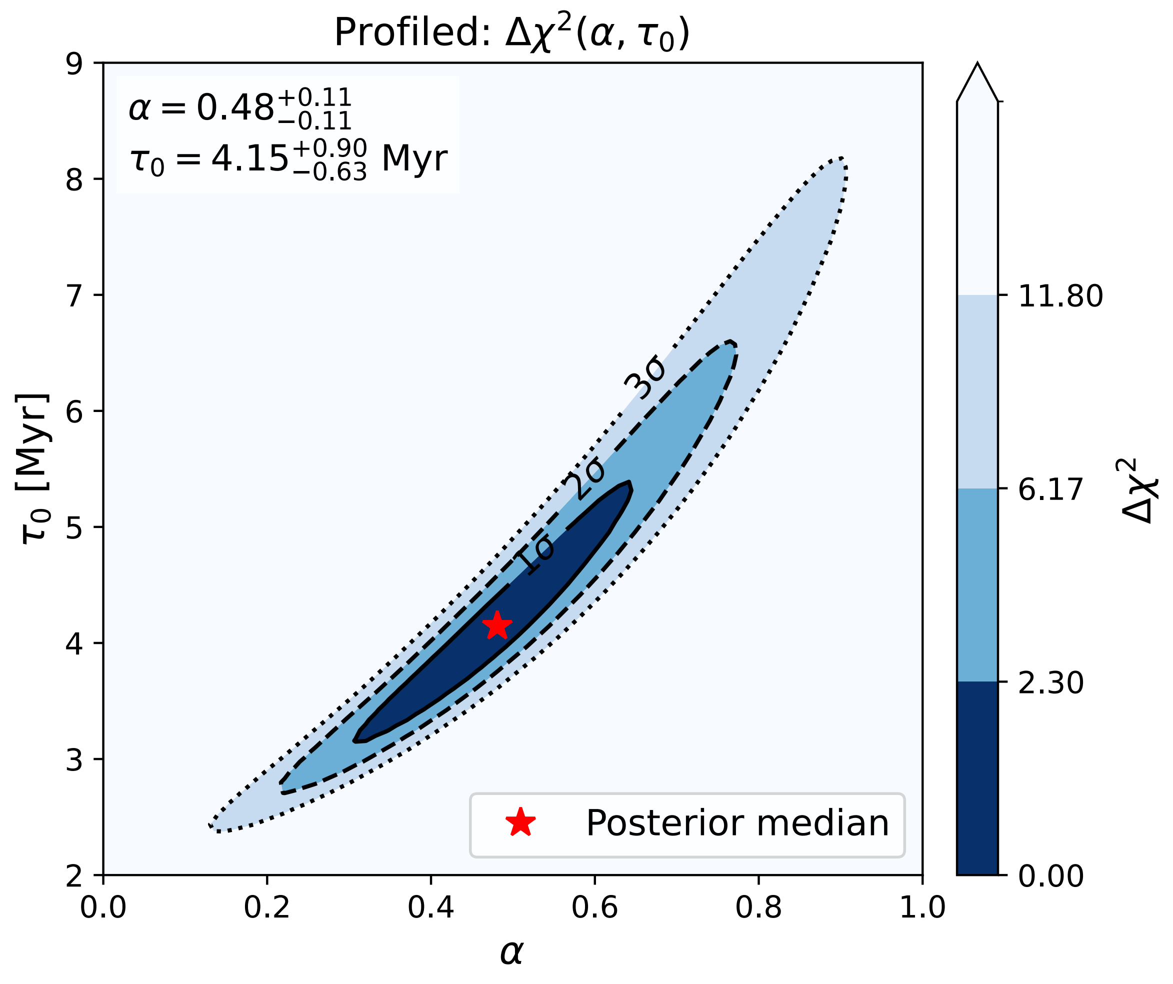
Field IMF

$$m_k = 18 \pm 2\, M_\odot$$

$$s = 2.45 \pm 0.09$$

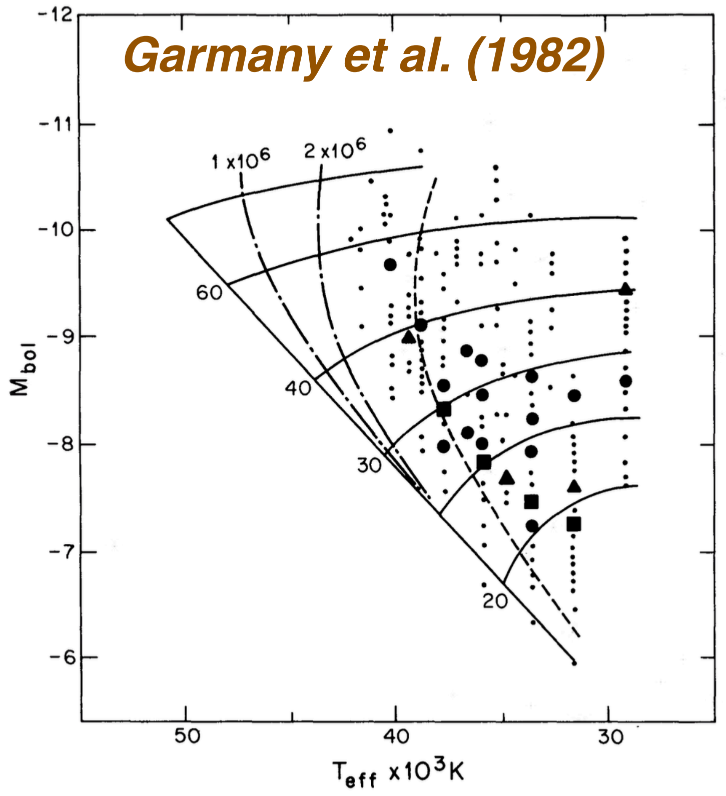
$$s_f = 3.86 \pm 0.18$$

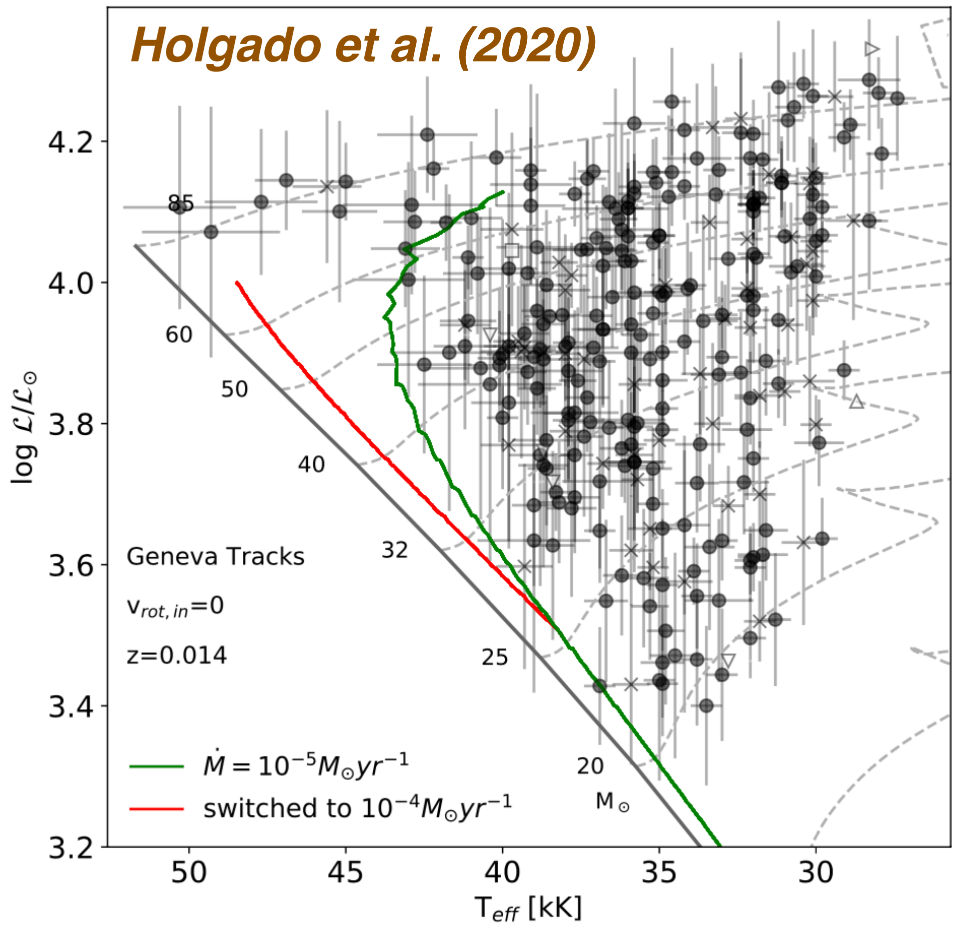
- *Formation time* $\approx 4\,\mathrm{Myr}$ *at* $60\,M_\odot$
- *Slope* ≈ 0.5



3. Modified ZAMS as clocks

CLOCK 2: THE ZAMS PROBLEM



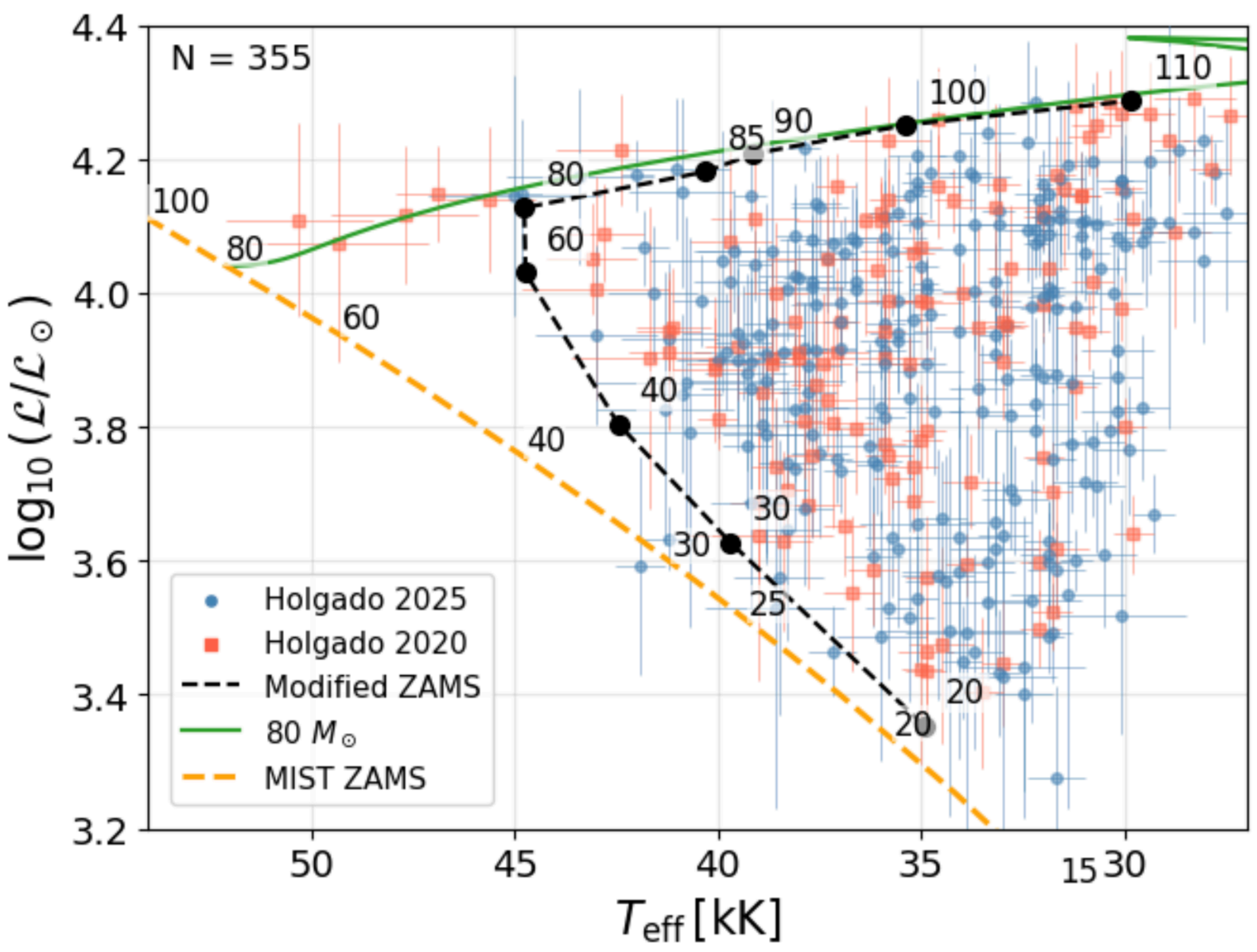


Problem: *The observed lower envelope lies above the classical ZAMS.*

Slow formation solution already proposed by *Bernasconi & Maeder (1995)* and *Holgado et al. (2020).*

CLOCK 2: A Modified ZAMS from Slow Growth

Growth Law: $t_{\rm form} = 4\,{\rm Myr}\,(m_{\rm f}/60\,M_\odot)^{0.5}$



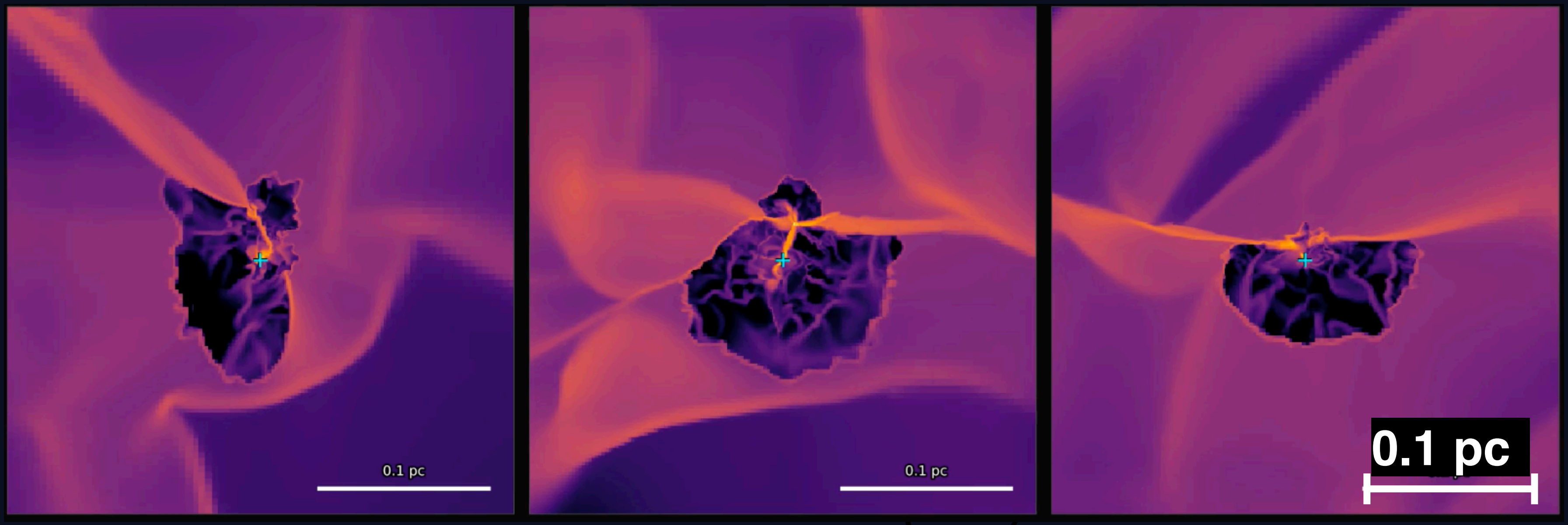
Sam Shipkoff
WV Academy

- Slow growth: H burning starts before the final mass is reached.
- Accreting tracks define a modified ZAMS.
- The modified ZAMS naturally follows the observed sHRD envelope.
- The required growth law is the same as for the LF clock.

NEXT STEP: H II regions around growing sinks

- Follow ionization feedback around accreting sinks.
- Connect t_{form}, ionizing luminosity, and compact-H II morphology
- Build synthetic-observation catalogs.

William Lake
Dartmouth



CONCLUSIONS — Two clocks, one growth time

$$t_{\rm form} = 4\,{\rm Myr}\left(\frac{m_{\rm f}}{60\,M_\odot}\right)^{0.5}$$

Clock 1: Compact H II regions

The LFs measure growth during ionization, not a single compact-H II lifetime.

Clock 2: ZAMS offset

Accreting tracks define a modified ZAMS that follows the observed sHRD envelope.

Physical picture

Massive stars grow mostly after collapse, through parsec-scale inertial inflow.

Massive stars grow over Myr timescales that increase with final mass.