THE (UN)PREDICTABILITY OF STAR FORMATION ON A CLOUD SCALE

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with Stuart Watson, Joakim Rosdahl, Rebekka Bieri, Ralf Klessen, Patrick Hennebelle
(and many more)

SOME CONTEXT

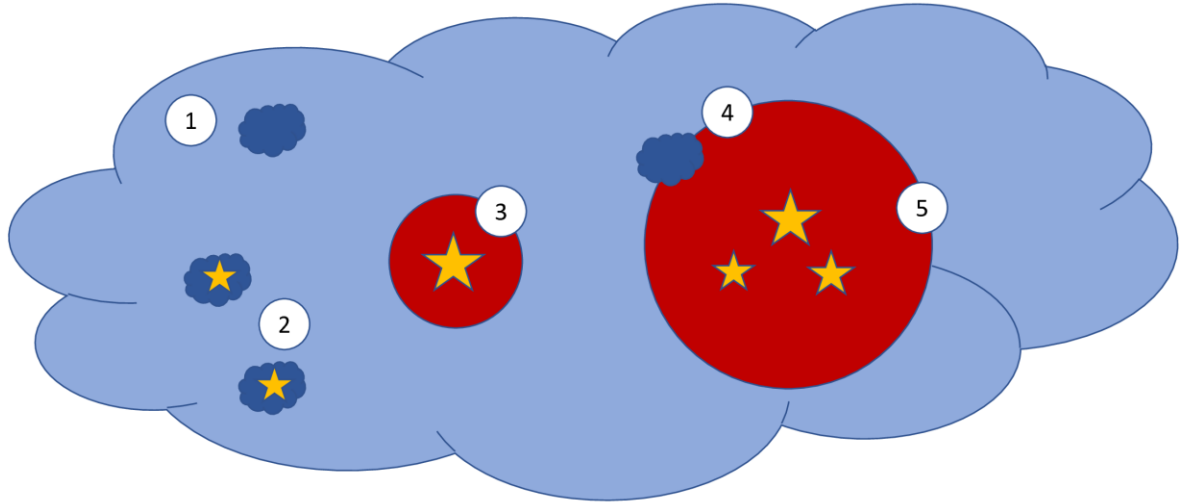
Star formation is messy and complicated – turbulence, feedback, lots of physics

Does chaos reign supreme?

Image credits: Grant Ritchie, Steven Sugar

STAR FORMATION IN CLOUDS

Stars form by accreting from dense cores
It ends locally when feedback drives away accreting gas



The total SFE is found by averaging over these local bursts BUT feedback links spatial locations

(Image taken from Laws of Star Formation Conference in July)

Question: what value do we get when this star formation is frozen out, and how does it relate to the value found by observers?

IS SFE PREDICTABLE?

Molecular clouds are highly chaotic:

- gravity, MHD both nonlinear
- Feedback loops from OB stars

Question: are there linear relationships between initial cloud state and final state (e.g. SFE) or are these systems dominated by chaos?

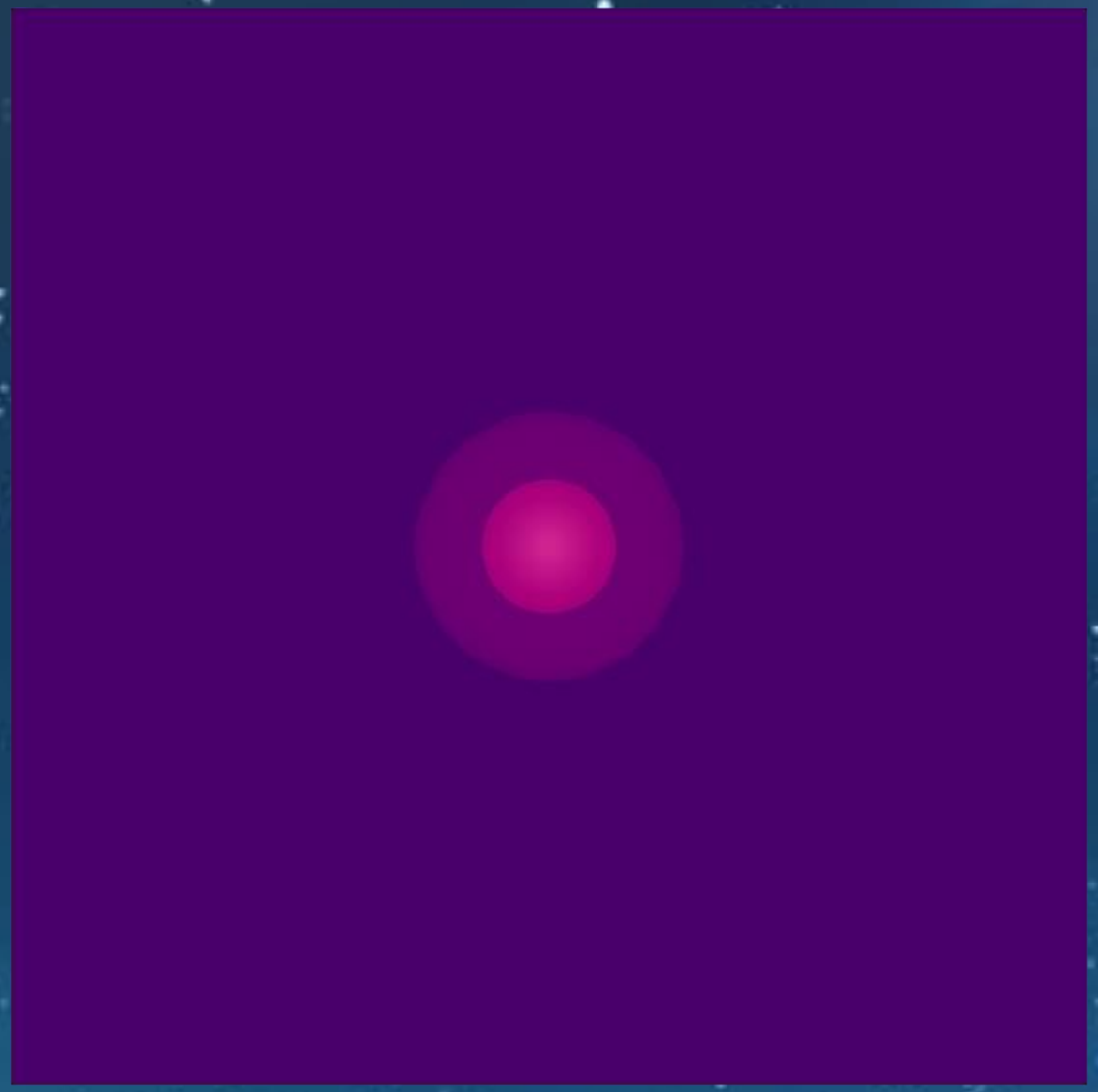
(Is the SFE systematic or statistical?)

Introducing the **YULE** simulations

26 simulations of the same cloud but randomising the input parameters

Background: Every December, the 13 "Yule Lads" visit homes in Iceland to cause chaos

THE SIMULATION SETUP BIT



The YULE suite - Each simulation uses the same initial cloud mass and density, same physics

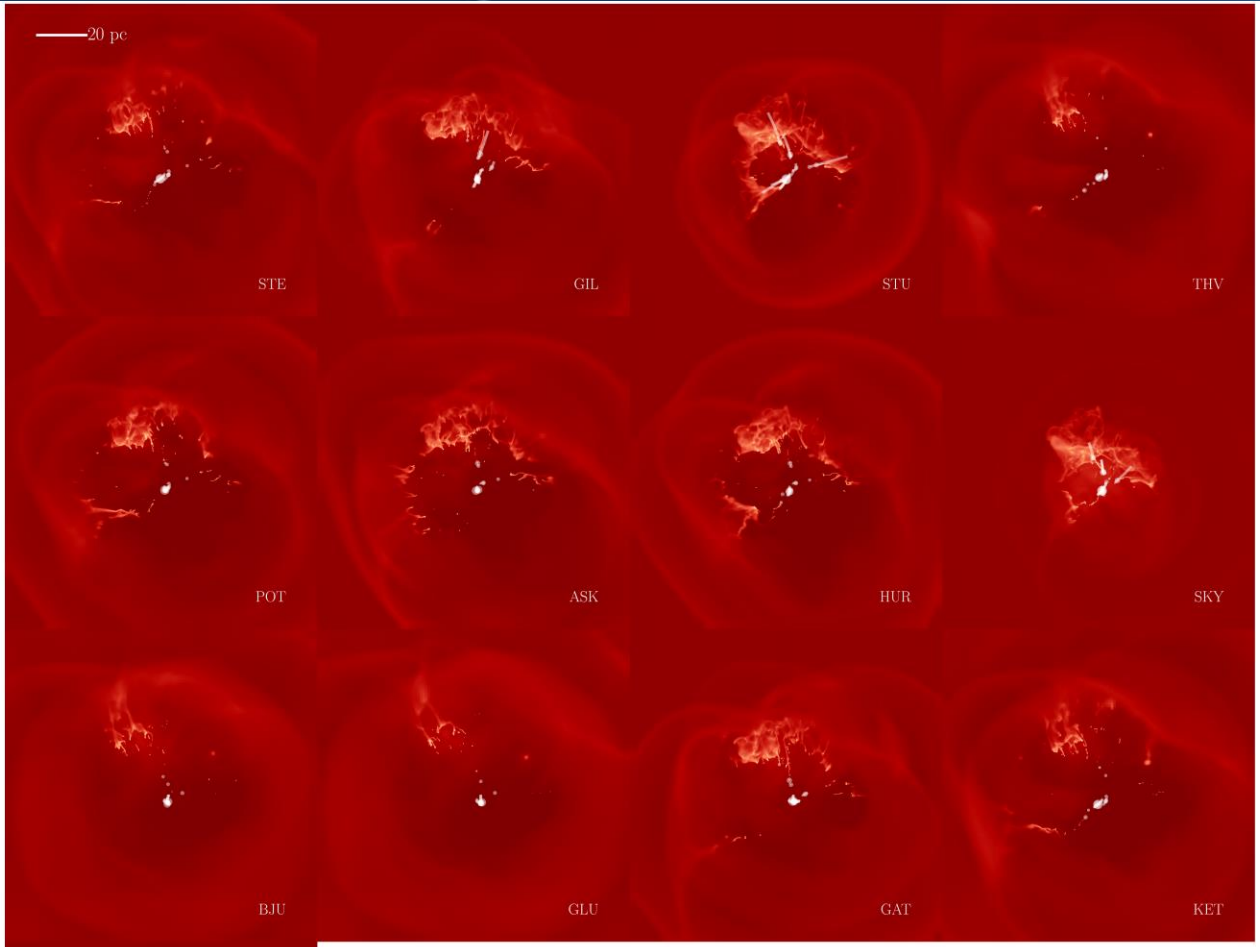
- Use RAMSES with RT & ideal MHD
- 112 pc box with 0.03 pc resolution (12 levels)
- İnitial isothermal sphere, turbulent velocity field
- "Relax the cloud" for 0.5 t_{ff} then turn on gravity
- Form sink particles above Jeans mass limit
- OB Stars form when cluster accretes 120 Msun
- Stars emit radiation in 3 bins (HI, HeI, HeII)
- Starburst 99/Geneva spectra for individual stars

Two sets of 13 simulations
Randomise:
- Sampling of the IMF
- The initial turbulent velocity structure

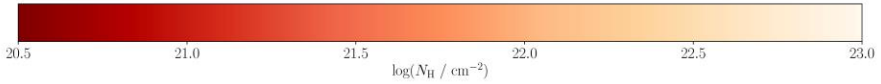
Paper as submitted on arXiv: http://tiny.cc/yule

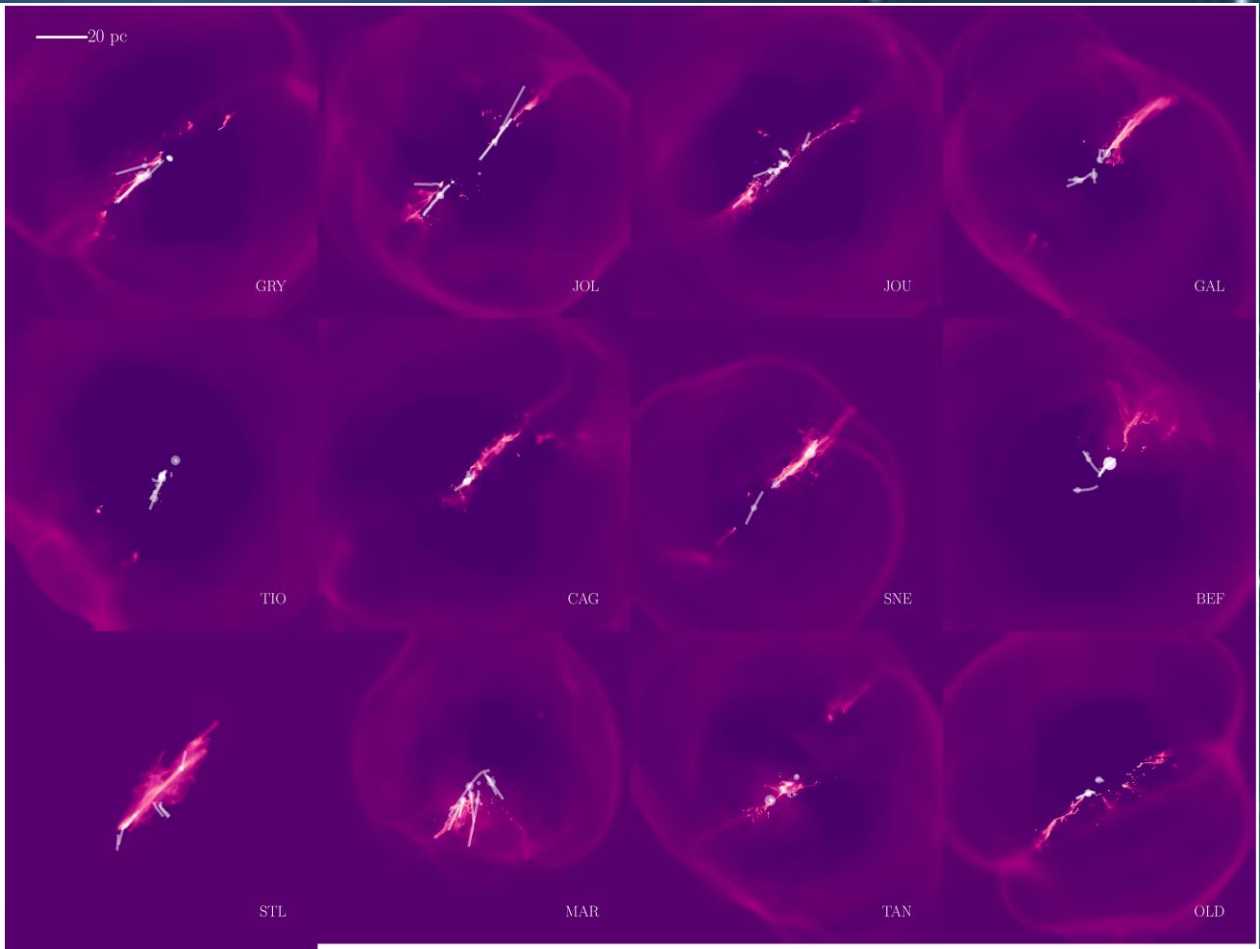
ALL OF THE SIMULATIONS

tiny.cc/yule

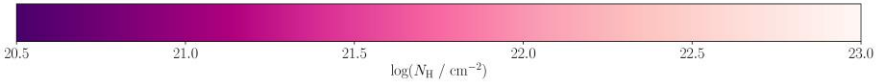


Randomly sample the IMF
(named after the Yule Lads)





Randomise the turbulent velocity field
(named after other winter figures)



STAR FORMATION EFFICIENCY

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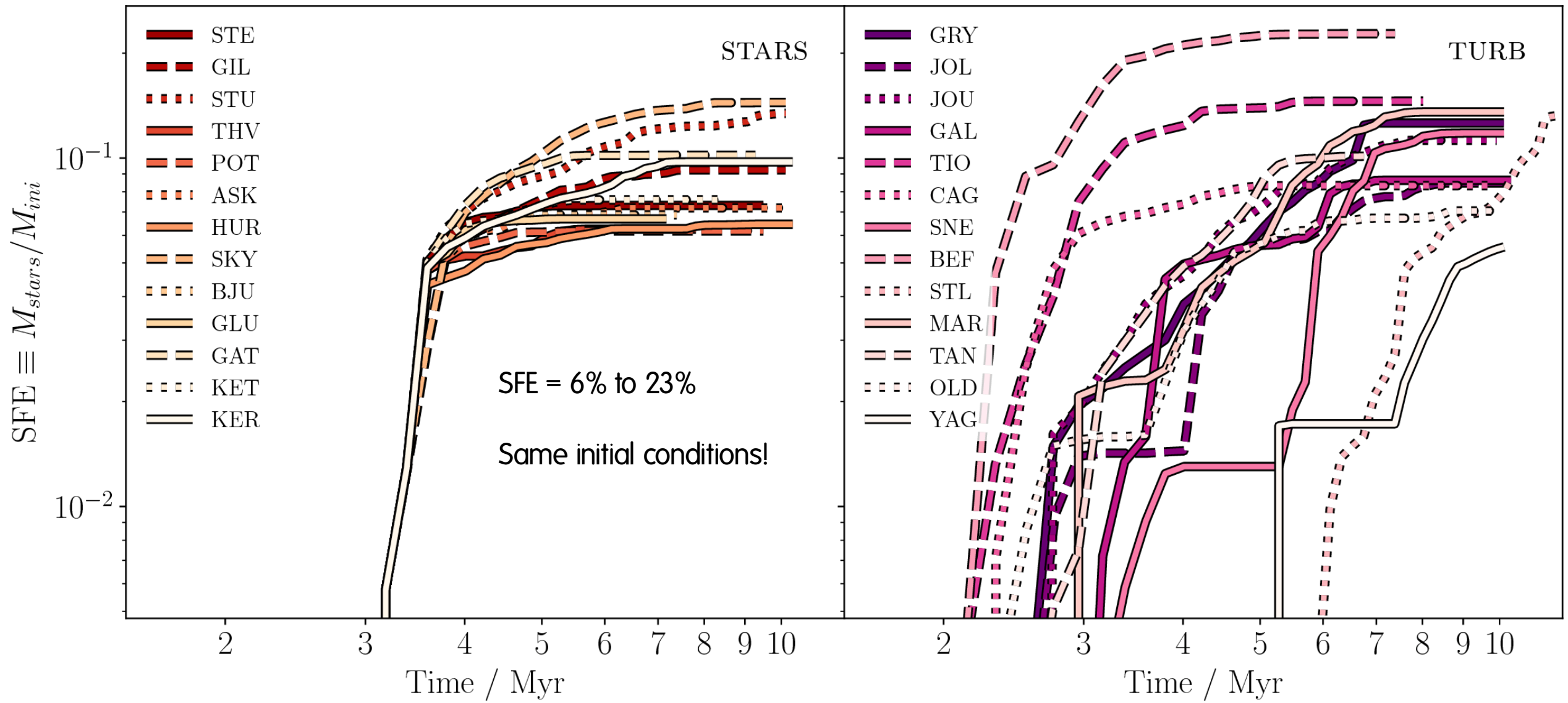

TIME FOR SOME HII REGION THEORY

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How do HII regions in clouds work?

2 things needed:

- Pressure balance between HII region and cloud
- Photon emission rate = recombination rate in HII region

Solving this gives this radius:

$$r_i \propto t^{\psi} S_*^{\psi/4}$$

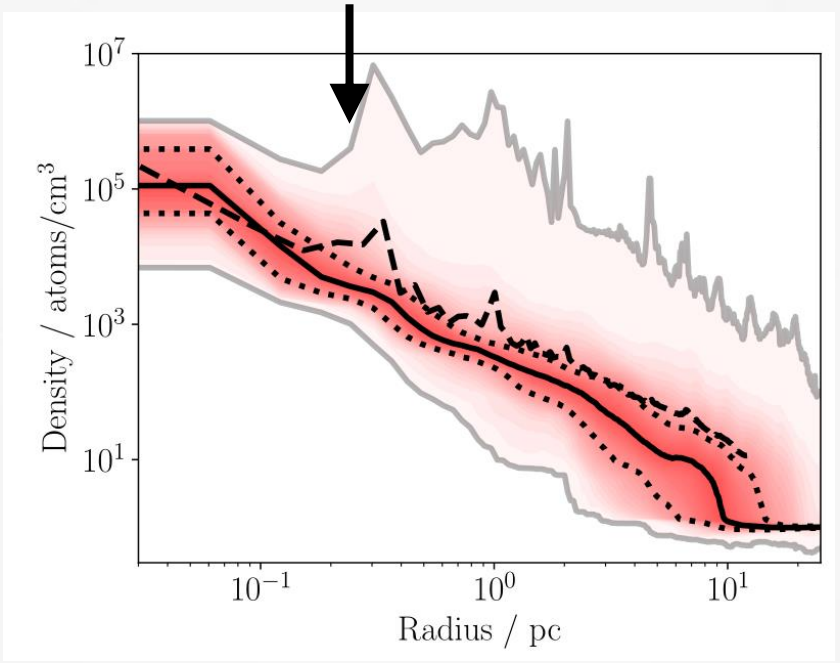
S_* is the photon emission rate
$\psi = 4/7$ for a uniform density field
$\psi = 4/3$ for an isothermal power law

For an isothermal field, the front accelerates!

Eventually bursts out of the shell → "Champagne" flow

References: e.g., Kahn 1954; Spitzer 1978; Whitworth 1979; Franco et al. 1990; Williams & McKee 1997; Alvarez et al 2006, Hosokawa & Inutsuka 2006; Raga et al. 2012; Geen et al. 2015b

In this simulation, the star "sees" a ~ isothermal density field



Density PDF per bin in red

COMPARE THIS TO OUR SIMULATIONS

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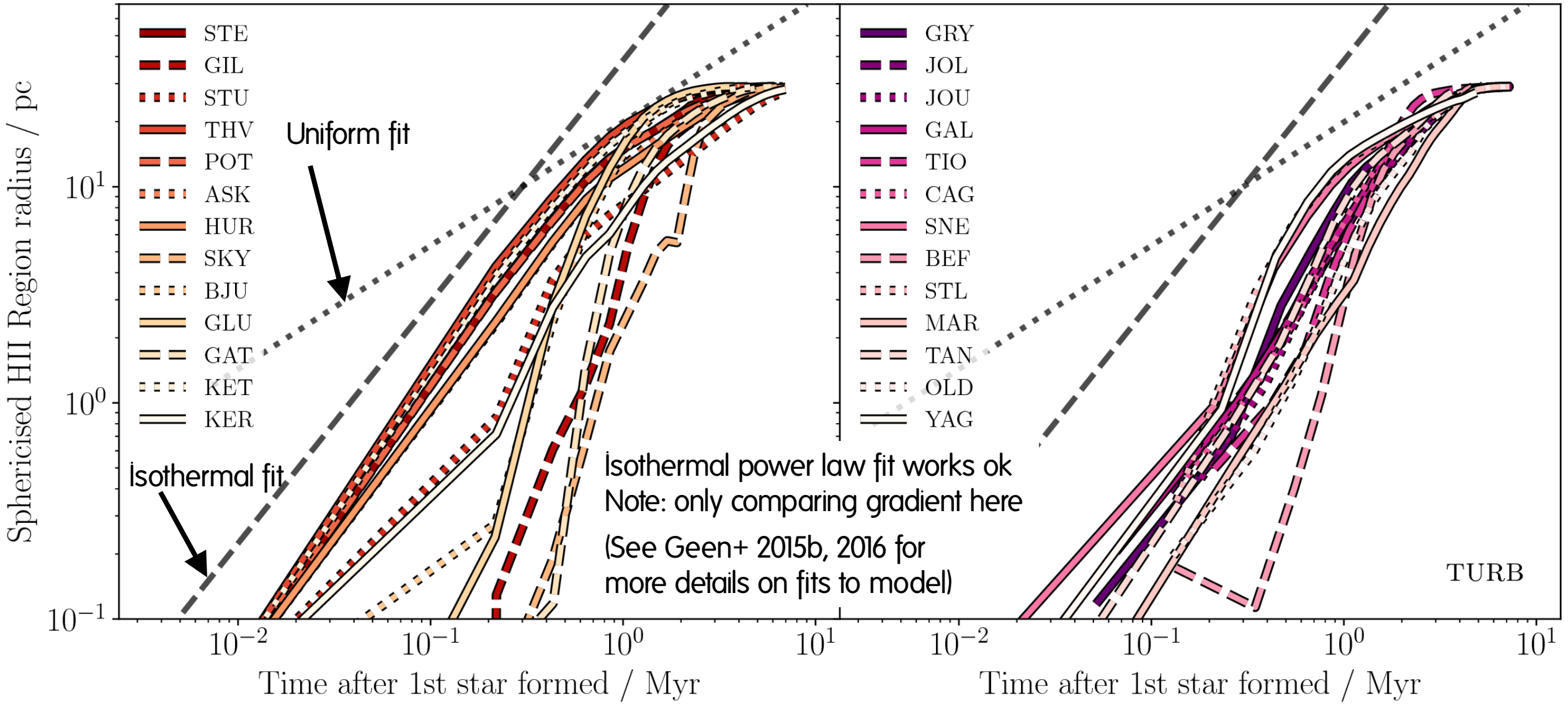

IS THE SFE COMPLETELY RANDOM?

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Can we uncover relationships between emergent cloud properties and SFE?

Statistics is hard! I did this frequentist thing but unsure how to interpret it

Great! Here's a ton of numbers. Have fun.

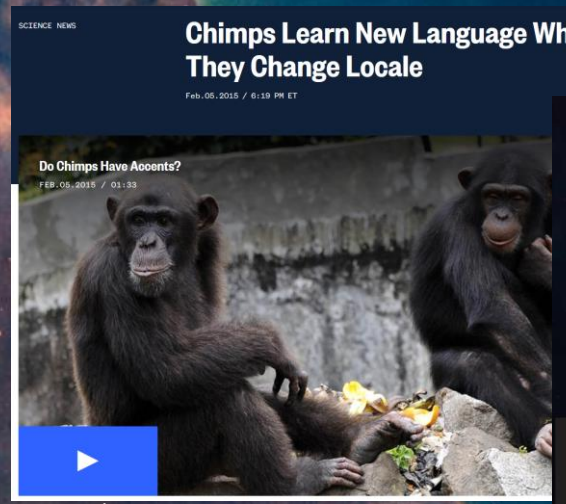
I can do statistics! Also use Bayesian methods instead

Stuart Watson, Zurich, studies social learning between chimpanzees

We use Bayesian generalised linear mixed models to predict SFE (details: http://tiny.cc/yule)

Basically:

log(SFE) = const x log(???)



Credit: NASA/HST

IS THE SFE COMPLETELY RANDOM?

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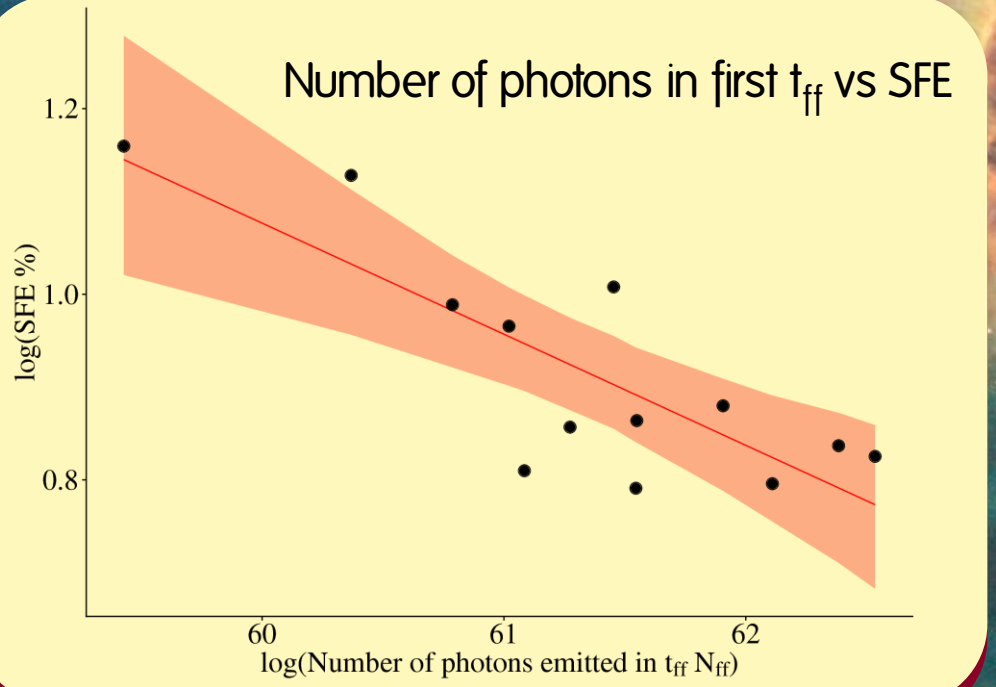
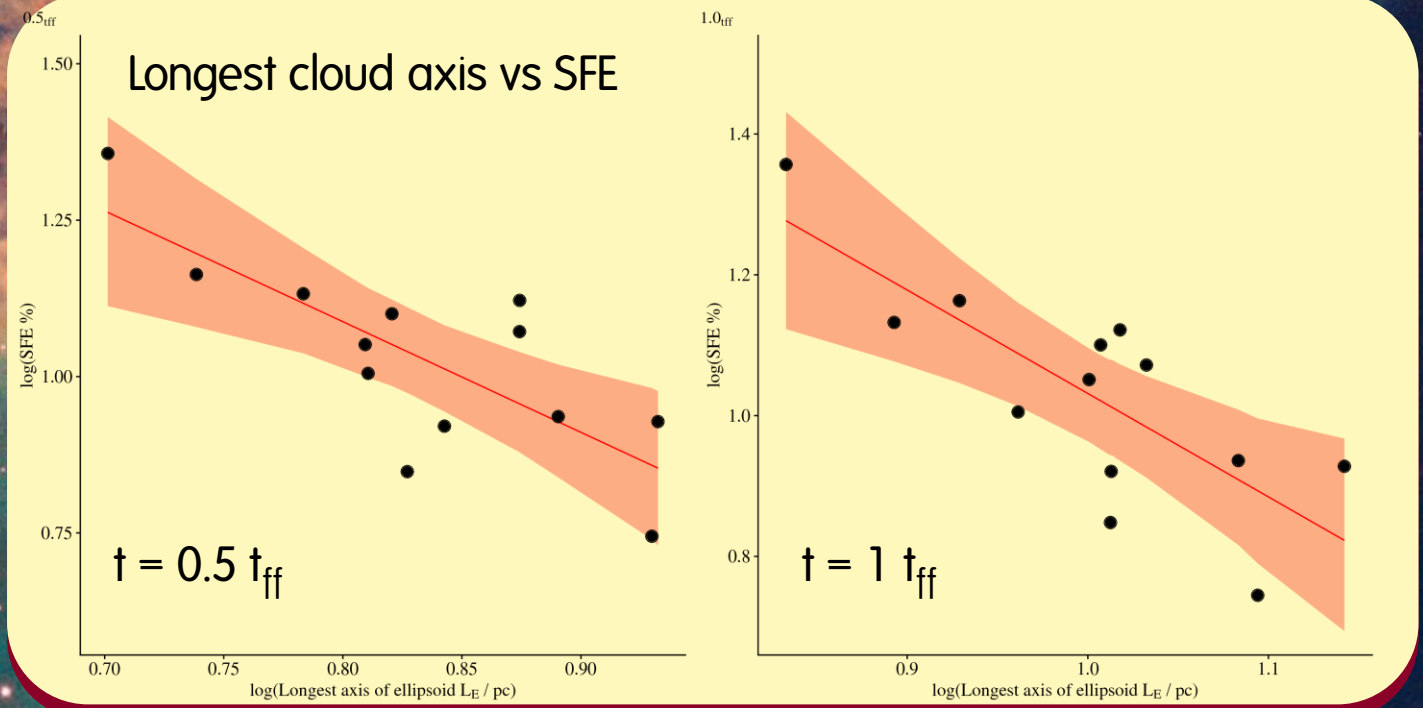
What's **not** important:

- Most massive star, cluster size, mass of 1st star, peak and total photon emission
- Shortest and "middlest" cloud axis (when fitting an ellipsoid)

What **is** important

- Number of photons emitted in first 0.5 t_{ff} (OK!)
- Length of the cloud (related to filament density?)
- How far massive stars travel on average (next slide...)





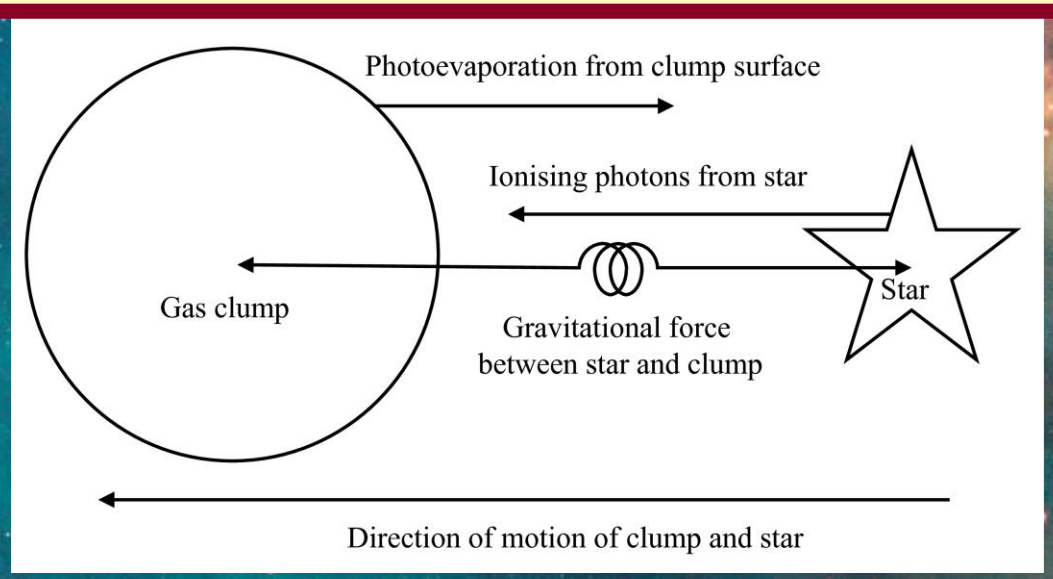
CLUSTER DISPERSAL BY WEAK FEEDBACK??

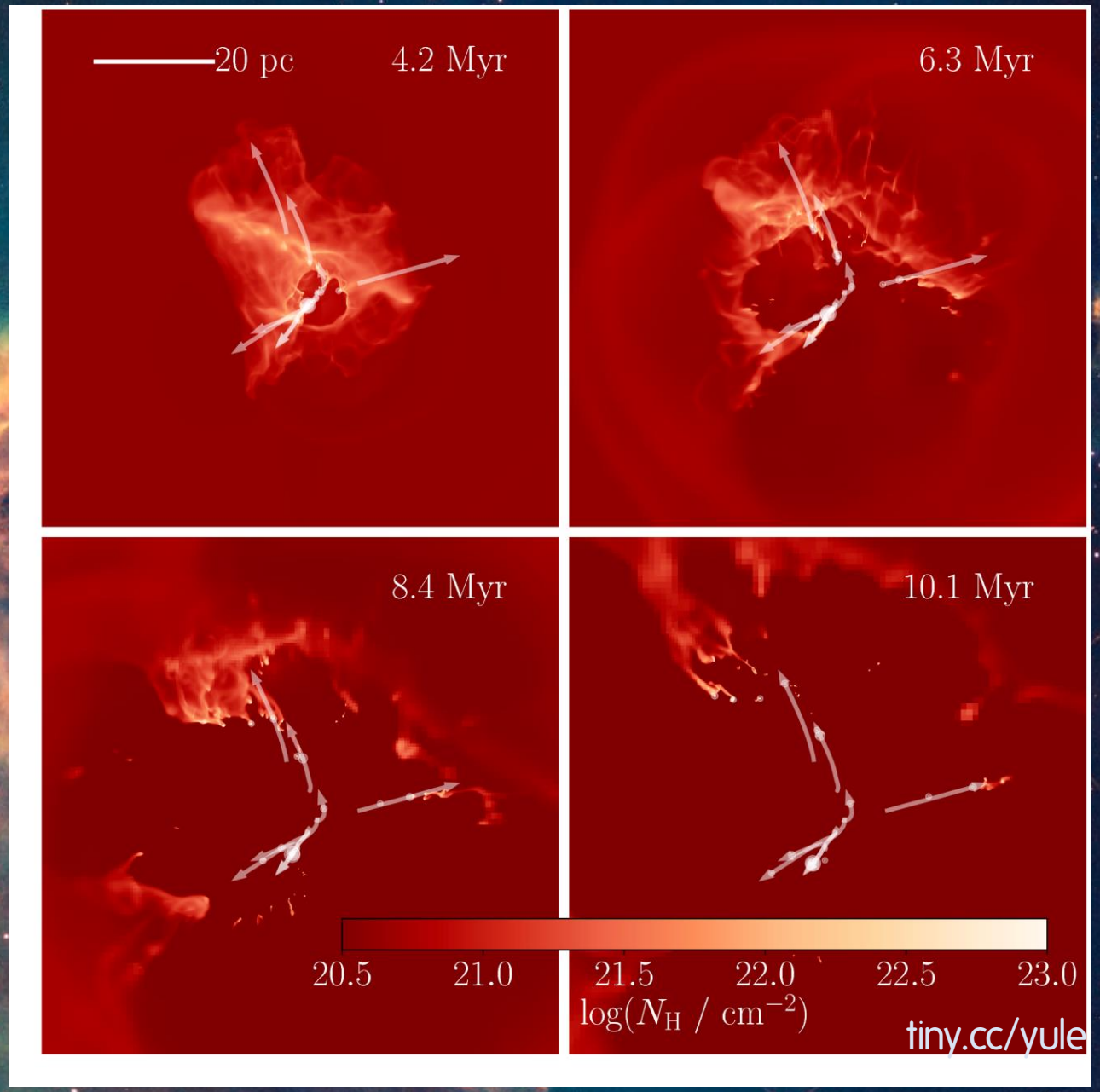
This seems weird, so let's unpack it

Stars travel further when SFE is higher

This means weak feedback = cluster dispersed

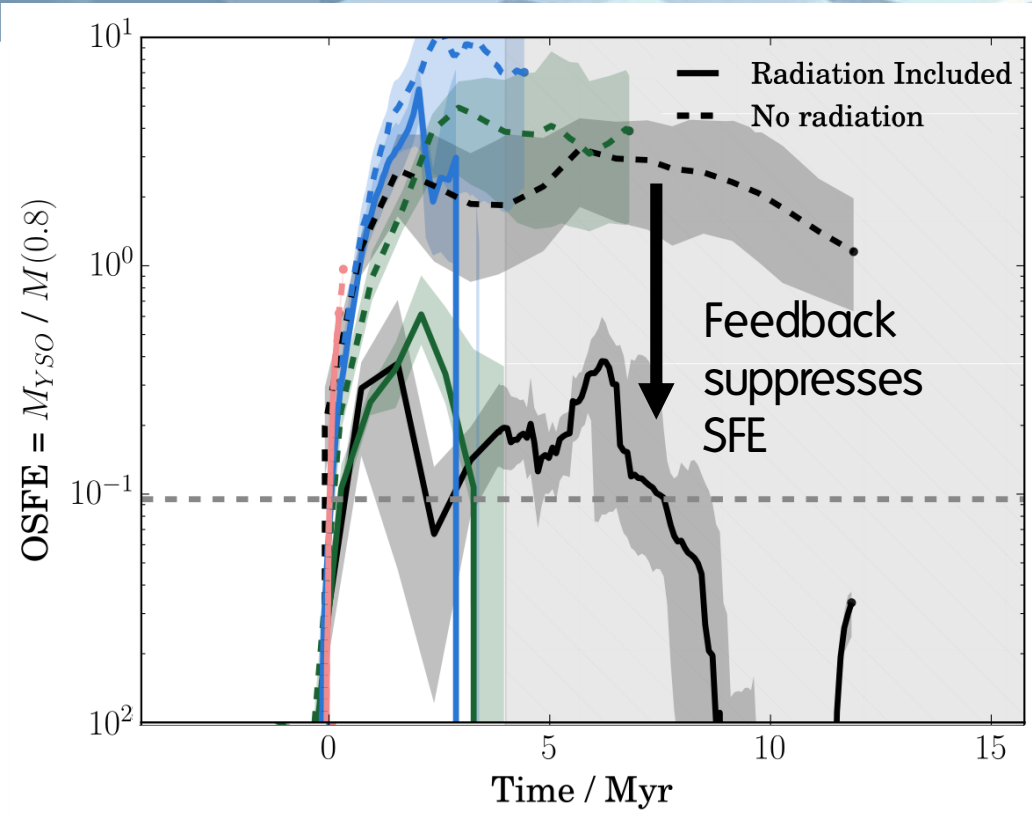
Our explanation: clumps accelerated by photoevaporation. Stars follow clumps as long as they exist. Weak feedback = clumps live longer

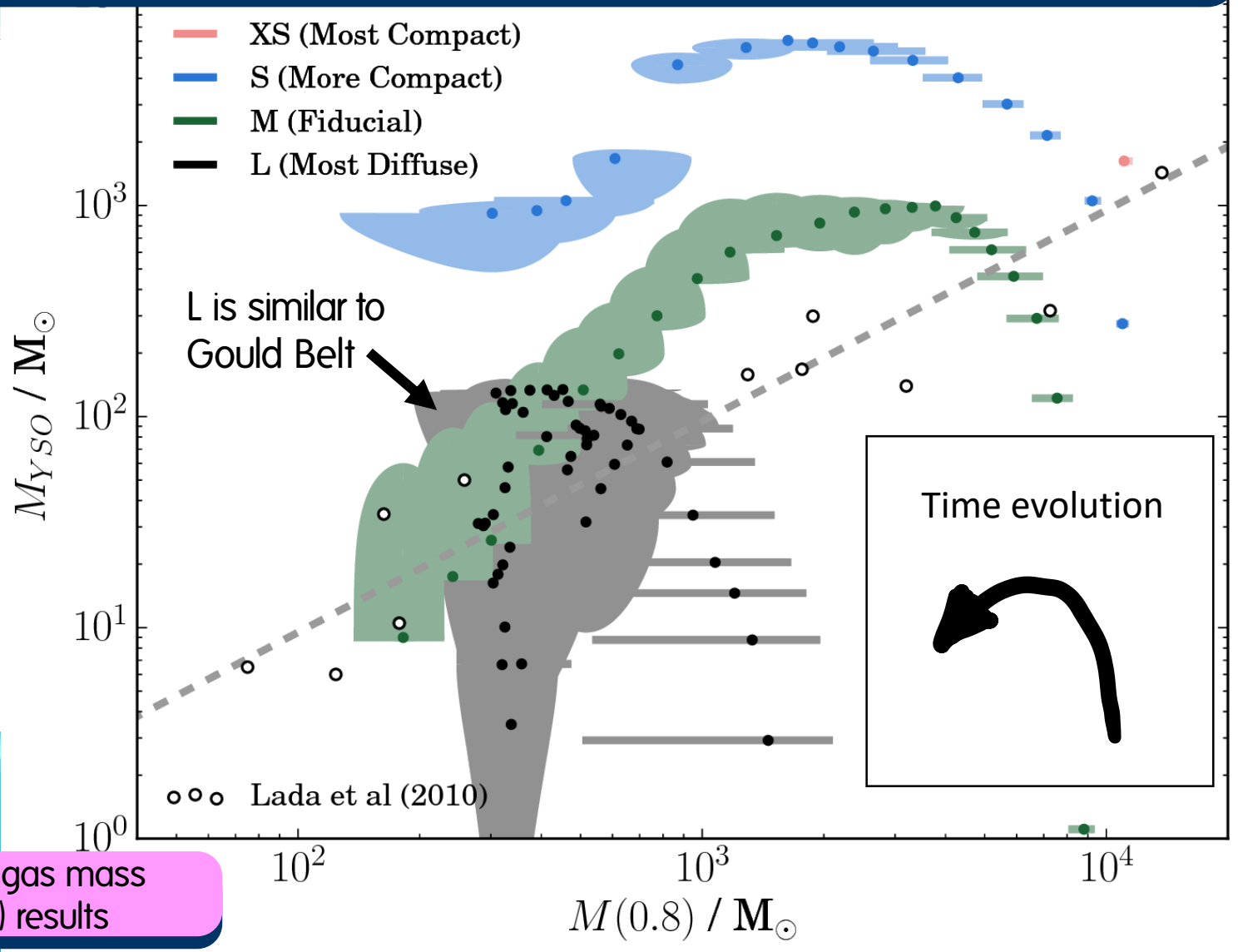




OBSERVATIONS?

In Geen+ 2017 (without a randomly sampled IMF) we compared these clouds to the nearby Gould Belt.





Simulation results for YSO mass, dense gas mass every 0.2 Myr compared to Lada+ (2010) results

SOME TAKEAWAY MESSAGES

Clusters < 10^4-10^5 Msun are influenced by random sampling in the IMF, modes of turbulence. We can recover trends that allow us to predict SFE

We can recover observed trends in SFE by invoking feedback
Is SFE universal in all clouds? Heavily dependent on assumptions about initial conditions

Lada+ (2010) – dense gas → recent SFE
Geen+ (2018) – all gas → total SFE
Is there something in this? Star formation fractal on different scales?

Simulations: powerful (expensive) virtual laboratories
Analytic models: fast, descriptive, but have to make assumptions
Observations: limited information but look at real objects
We need all three to really get a grip on these problems

References: Geen et al 2017 (MNRAS),
Geen et al 2018 (accepted to MNRAS) (http://arxiv.org/abs/1806.10575 - quick link: http://tiny.cc/yule)
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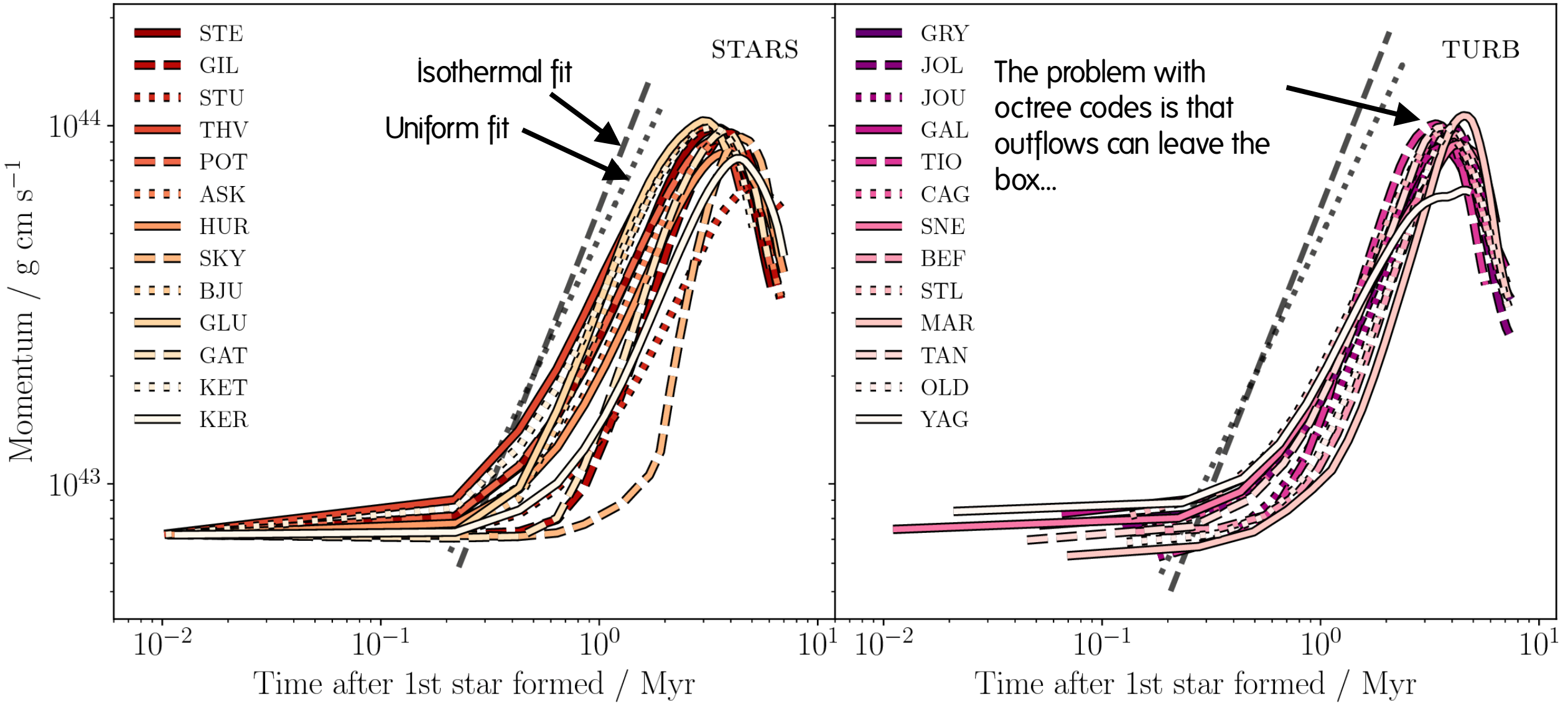
THANK YOU!

EXTRA SLIDES

MOMENTUM INJECTED BY HII REGION

http://tiny.cc/yule




NOPE