



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

Dense gas

Massive O stars

HII Regions

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

Does chaos reign supreme?

2nd generation stars?

Image credits: Grant Ritchie, Steven Sugar

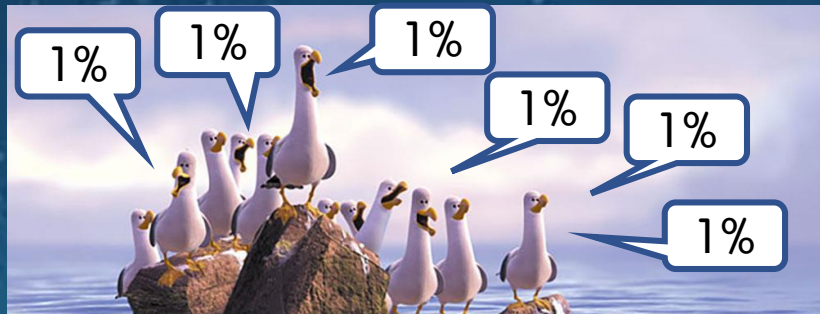
STAR FORMATION IN CLOUDS



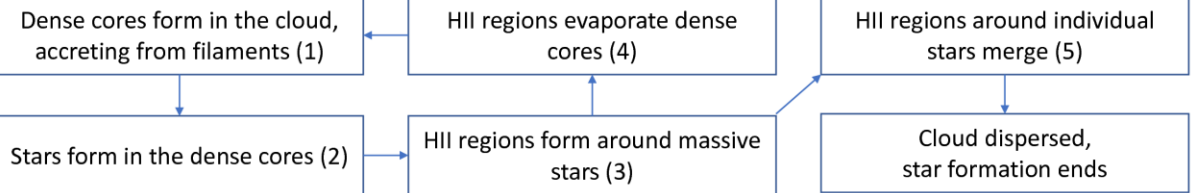
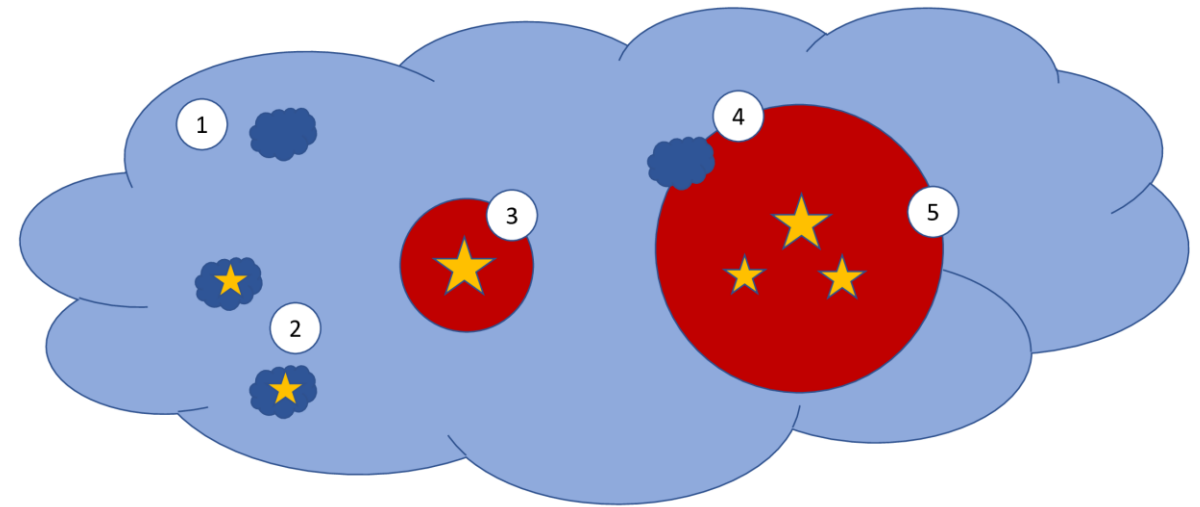
Orion nebula (credit: Tony Hallas)

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)



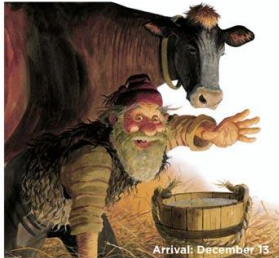
Question: what value do we get when this star formation is frozen out, and how does it relate to the value found by observers?

IS SFE PREDICTABLE?

The Icelandic Yule Lads



Stekkjastaur (Sheep-Cote Clod)
Harasses sheep, impaired by his stiff peg-legs
Arrival: December 12



Giljagaur (Gully Gawk)
Hides in gullies, waiting for an opportunity to sneak into the cowshed and steal milk.
Arrival: December 13



Stúfur (Stubby)
Abnormally short. Steals pans to eat the crust left on them
Arrival: December 14



Þvörusleikir (Spoon-Licker)
Steals þvöur (a type of a wooden spoon) to lick. Is extremely thin due to malnutrition
Arrival: December 15



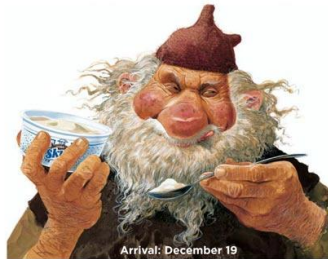
Pottasleiki (Pot-Licker)
Steals leftovers from pots
Arrival: December 16



Askasleikir (Bowl-Licker)
Hides under beds waiting for someone to put down their 'askur' (a type of bowl), which he then steals
Arrival: December 17



Hurðaskellir (Door-Slammer)
Likes to slam doors, especially during the night
Arrival: December 18



Skyrgámur (Skyr-Gobbler)
A Yule Lad with an affinity for skyr
Arrival: December 19



Bjúgnakrækir (Sausage-Swiper)
Would hide in the rafters and snatch sausages that were being smoked
Arrival: December 20



Gluggagægir (Window-Peeper)
A voyeur who would look through windows in search of things to steal
Arrival: December 21



Gáttapefur (Doorway-Sniffer)
Has an abnormally large nose and an acute sense of smell which he uses to locate laufabraud
Arrival: December 22



Ketkrókur (Meat-Hook)
Uses a hook to steal meat
Arrival: December 23



Kertasníkir (Candle-Stealer)
Follows children in order to steal their candles (which in those days was made of tallow and thus edible)
Arrival: December 24



Grýla
The mother of the Yule Lads. Icelandic parents did scare their children from misbehaving by telling them that Grýla could come and abduct them



Leppalúði
The husband of Grýla. Not that evil, but a lazy one.
Arrival: December 12

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?

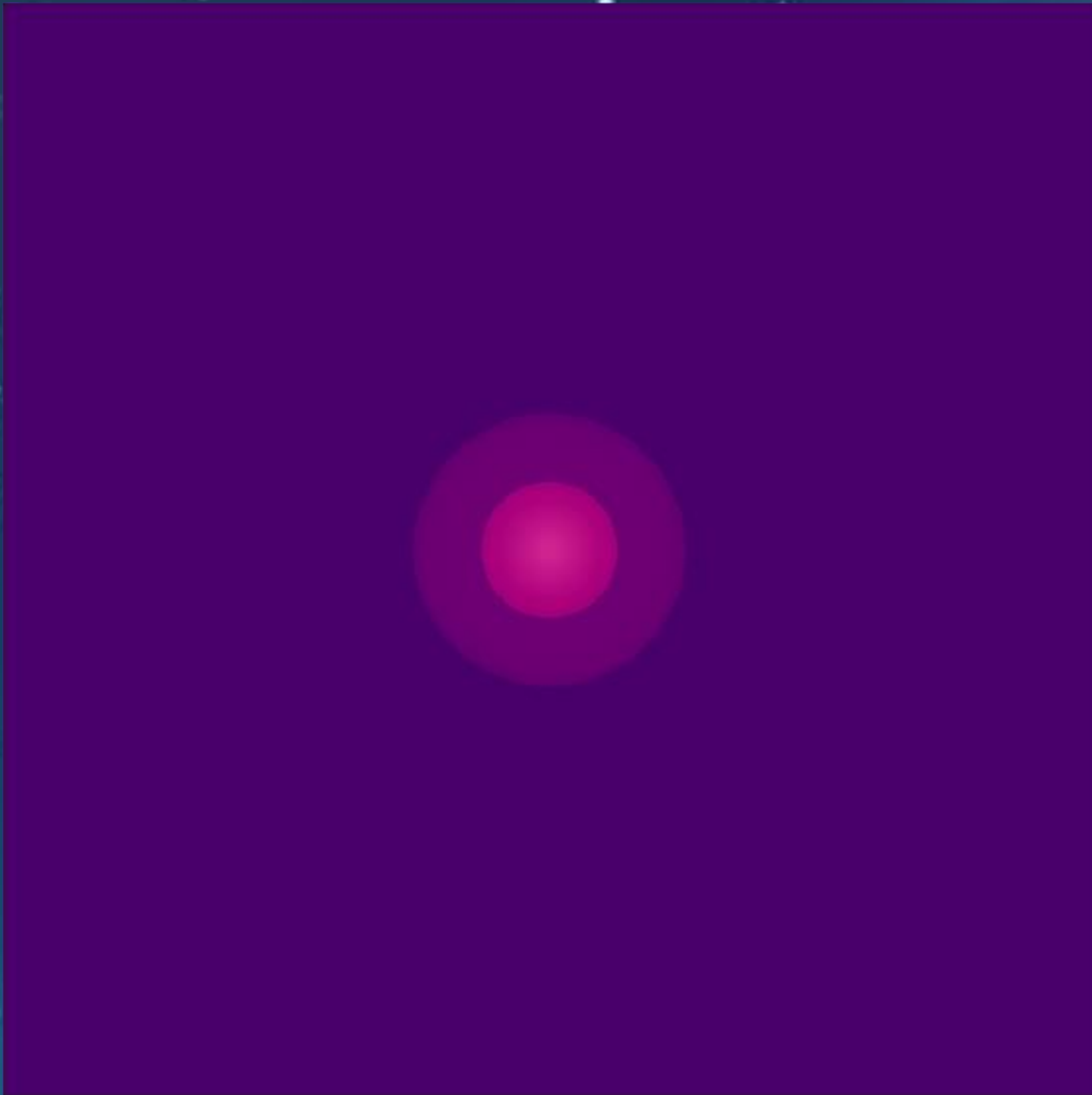
(Is the SFE systematic or statistical?)

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)
- Initial isothermal sphere, turbulent velocity field
- "Relax the cloud" for $0.5 t_{\text{ff}}$ then turn on gravity
- Form sink particles above Jeans mass limit
- OB Stars form when cluster accretes 120 M_{sun}
- Stars emit radiation in 3 bins (H α , HeI, HeII)
- Starburst 99/Geneva spectra for individual stars

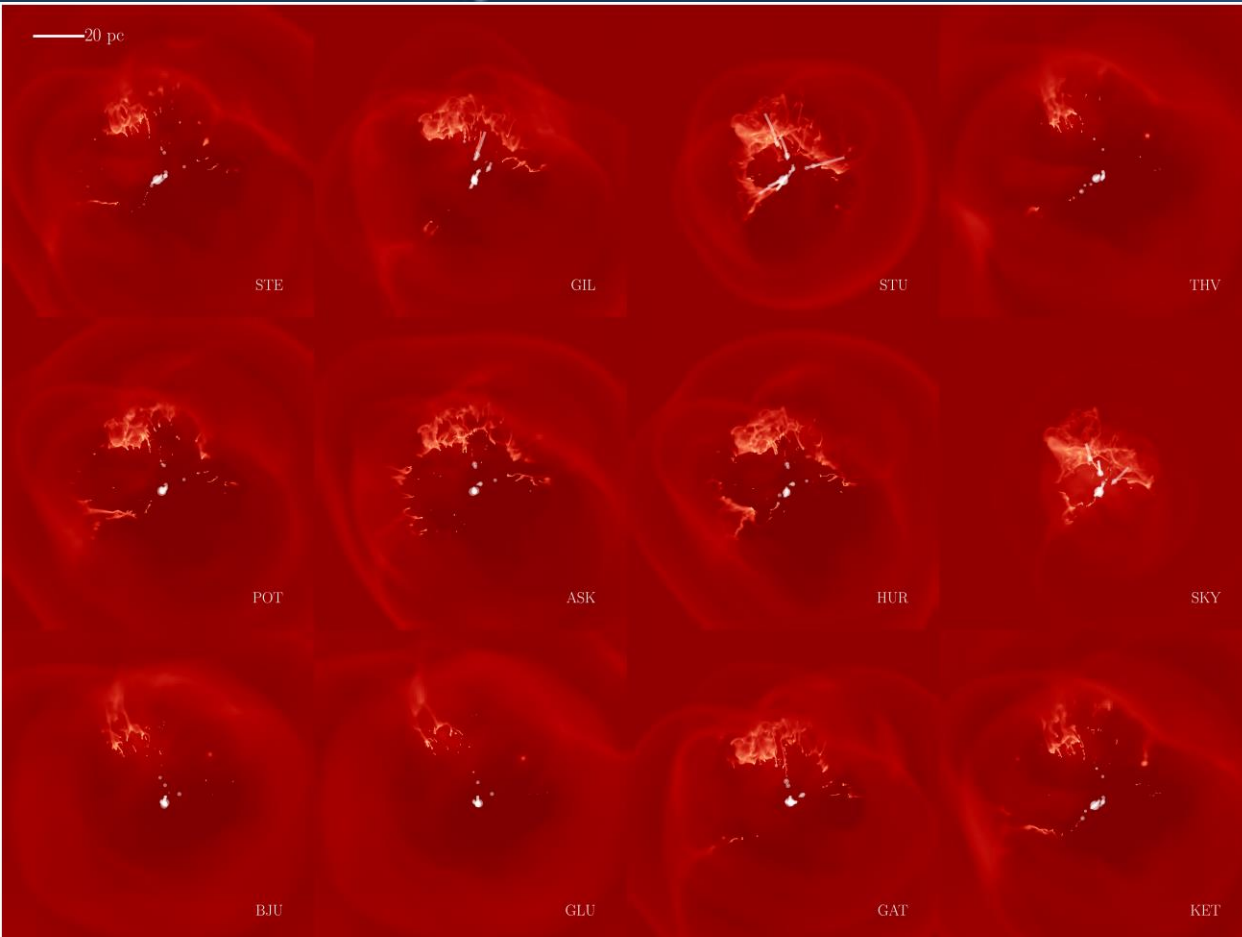
Two sets of 13 simulations

Randomise:

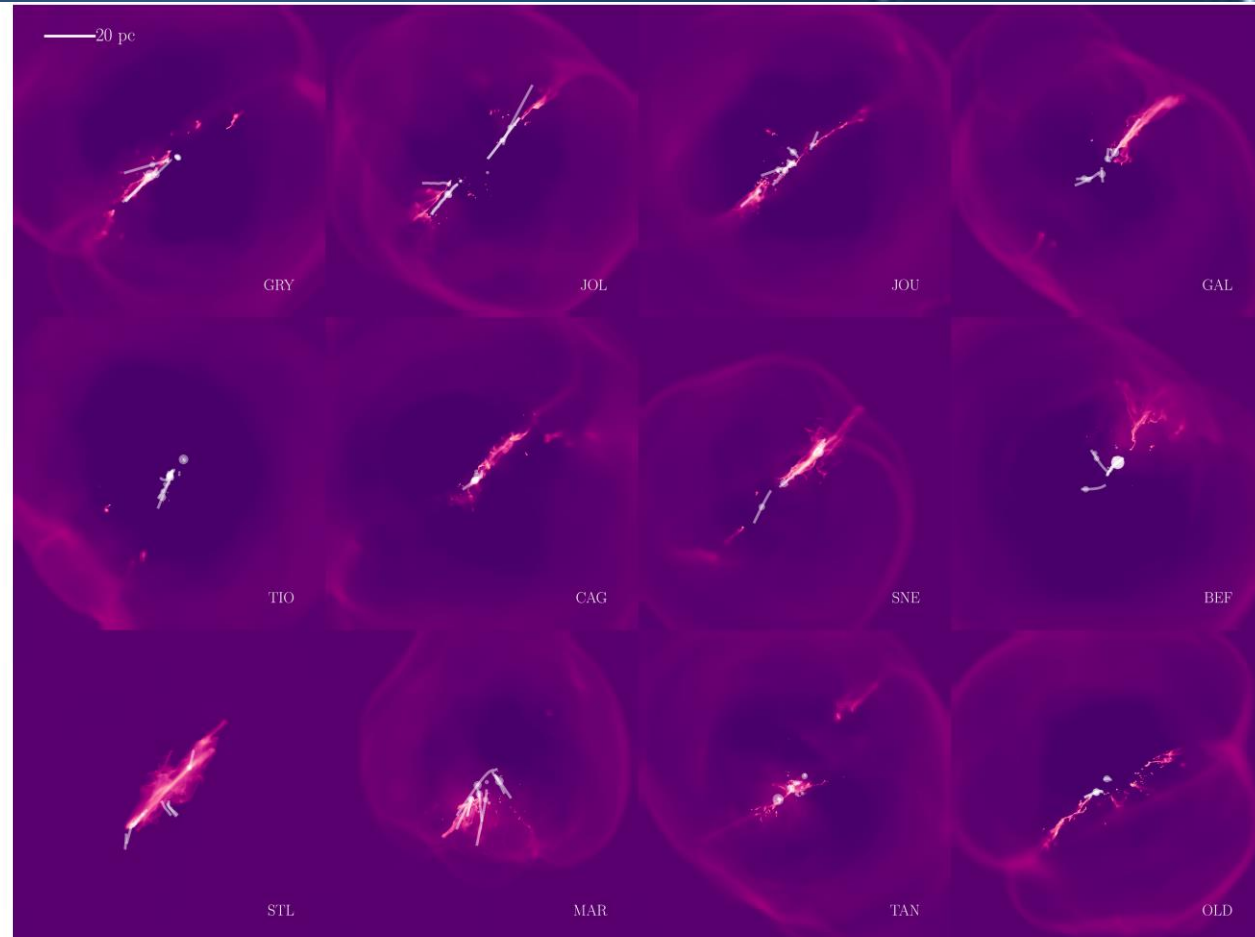
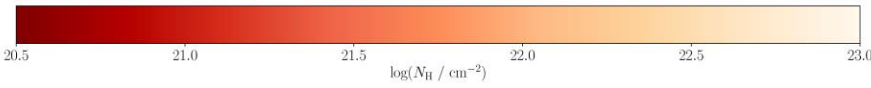
- Sampling of the IMF
- The initial turbulent velocity structure

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

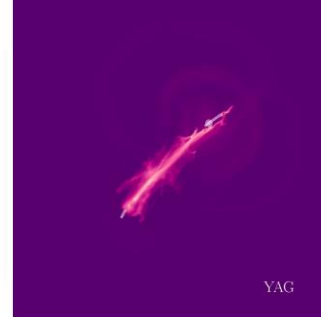
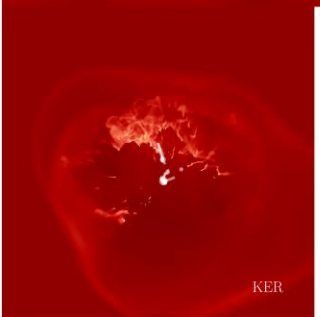
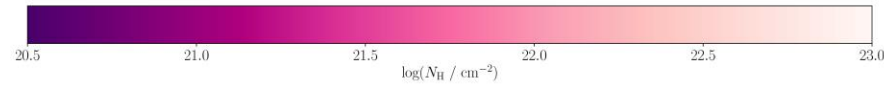
ALL OF THE SIMULATIONS



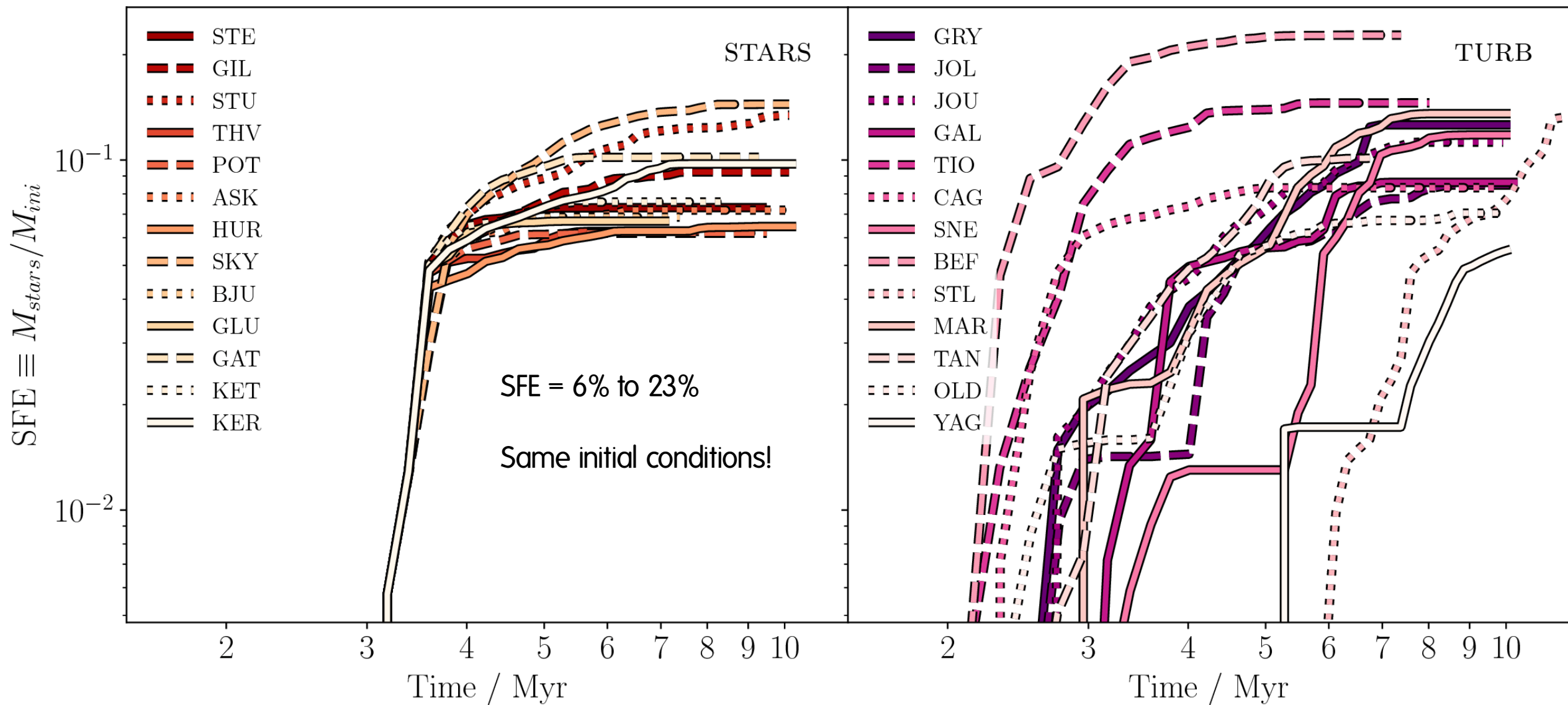
Randomly sample the IMF
(named after the Yule Lads)



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



STAR FORMATION EFFICIENCY



TIME FOR SOME HII REGION THEORY

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:

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

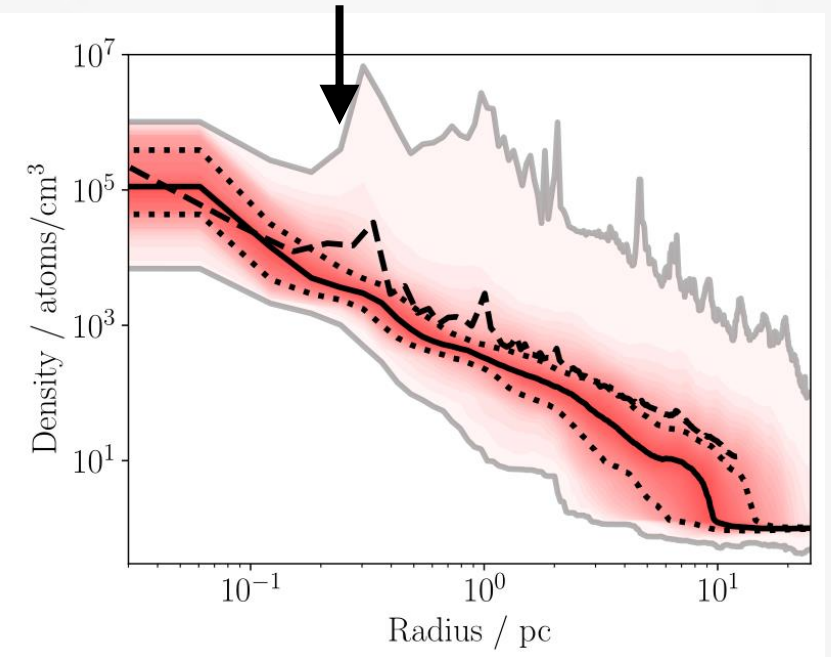
S_* is the photon emission rate
 $\psi = 4/7$ for a uniform density field
 $\psi = 4/3$ for an isothermal power law

For an isothermal field, the front accelerates!

Eventually bursts out of the shell → "Champagne" flow

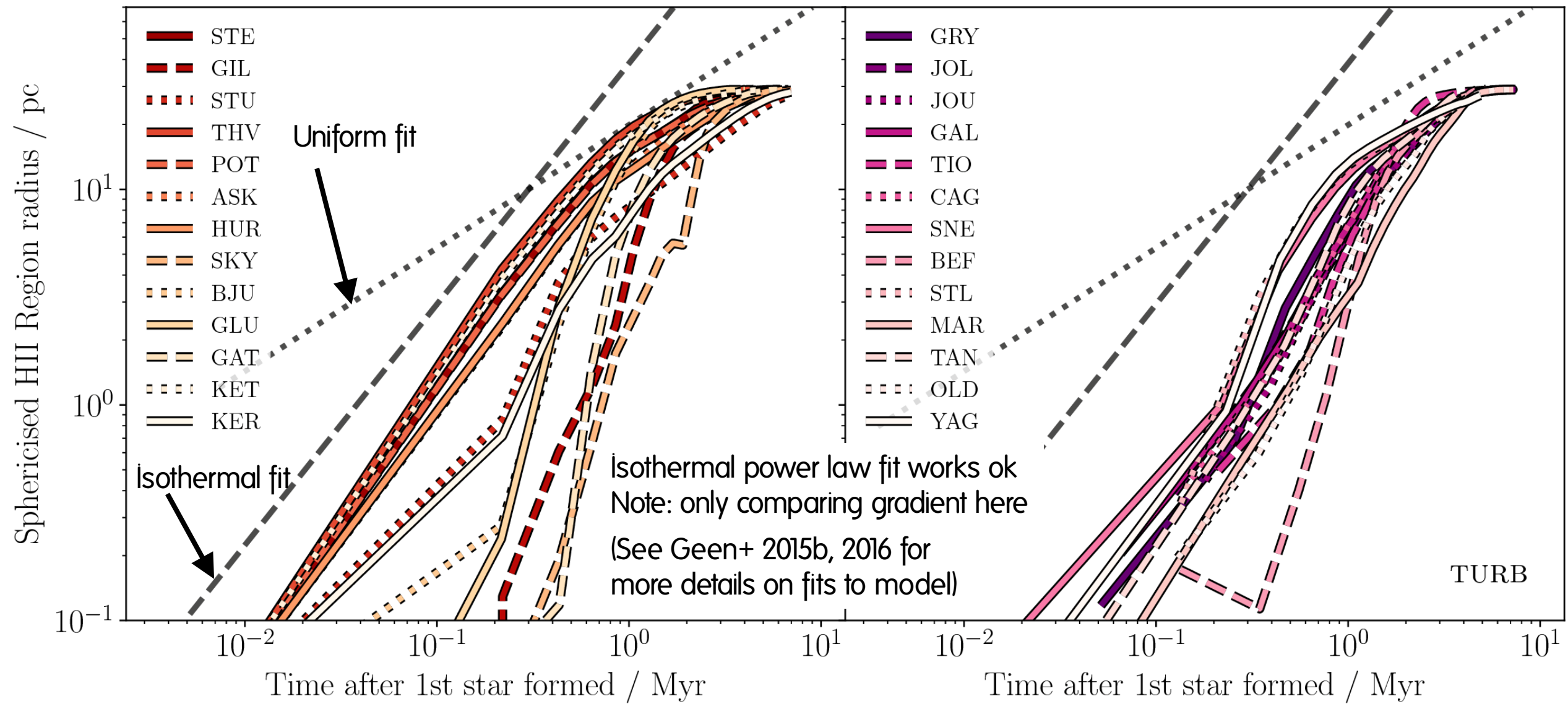
References: e.g., Kahn 1954; Spitzer 1978; Whitworth 1979; Franco et al. 1990; Williams & McKee 1997; Alvarez et al 2006, Hosokawa & Inutsuka 2006; Raga et al. 2012; Geen et al. 2015b

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



Density PDF per bin in red

COMPARE THIS TO OUR SIMULATIONS



IS THE SFE COMPLETELY RANDOM?

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.

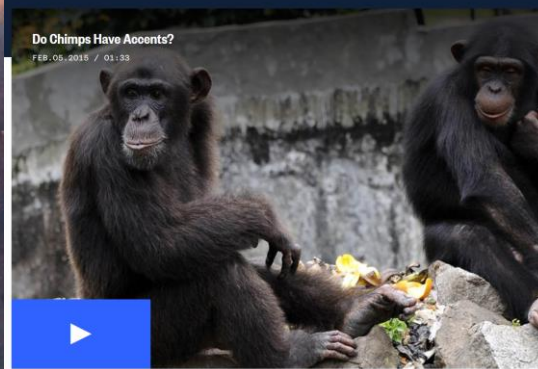
I can do statistics! Also use Bayesian methods instead



Stuart Watson, Zurich, studies social learning between chimpanzees

We use Bayesian generalised linear mixed models to predict SFE (details: <http://tiny.cc/yule>)
Basically:
 $\log(\text{SFE}) = \text{const} \times \log(\text{???})$

Chimps Learn New Language When They Change Locale
Feb. 05. 2015 / 6:10 PM ET



Chimp Science Reveals How Society's Losers Become Influencers

IS THE SFE COMPLETELY RANDOM?

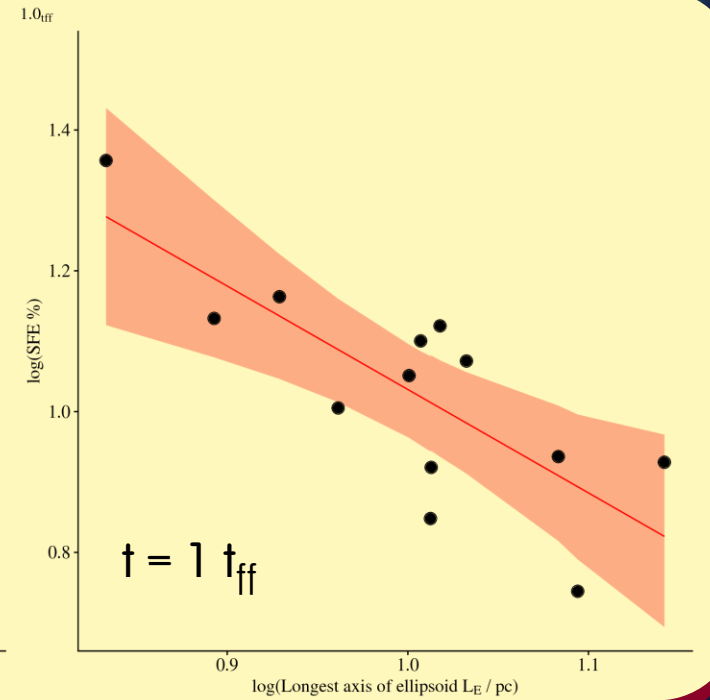
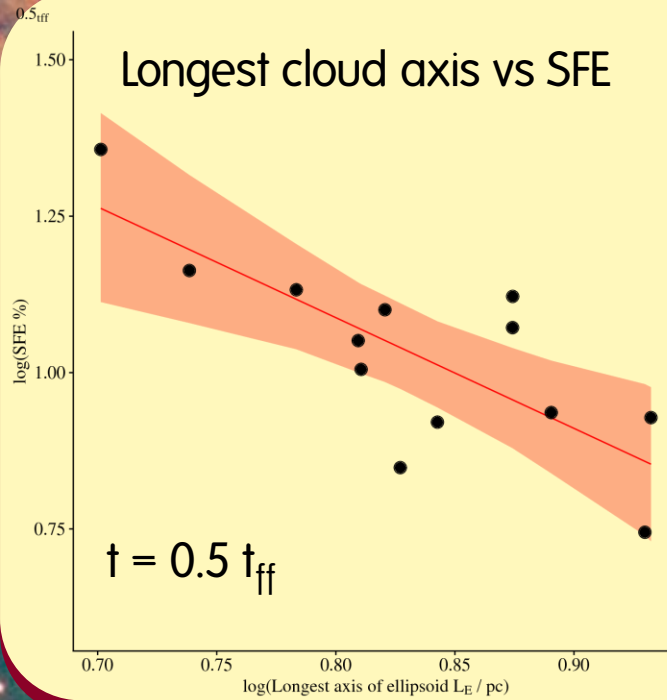
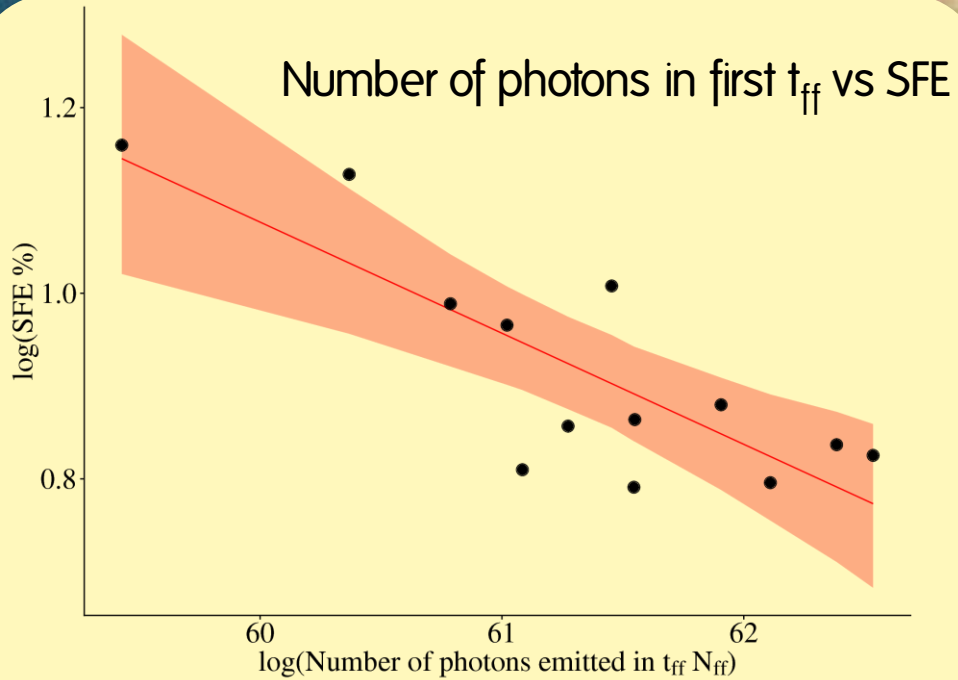
What's not important:

- 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...)



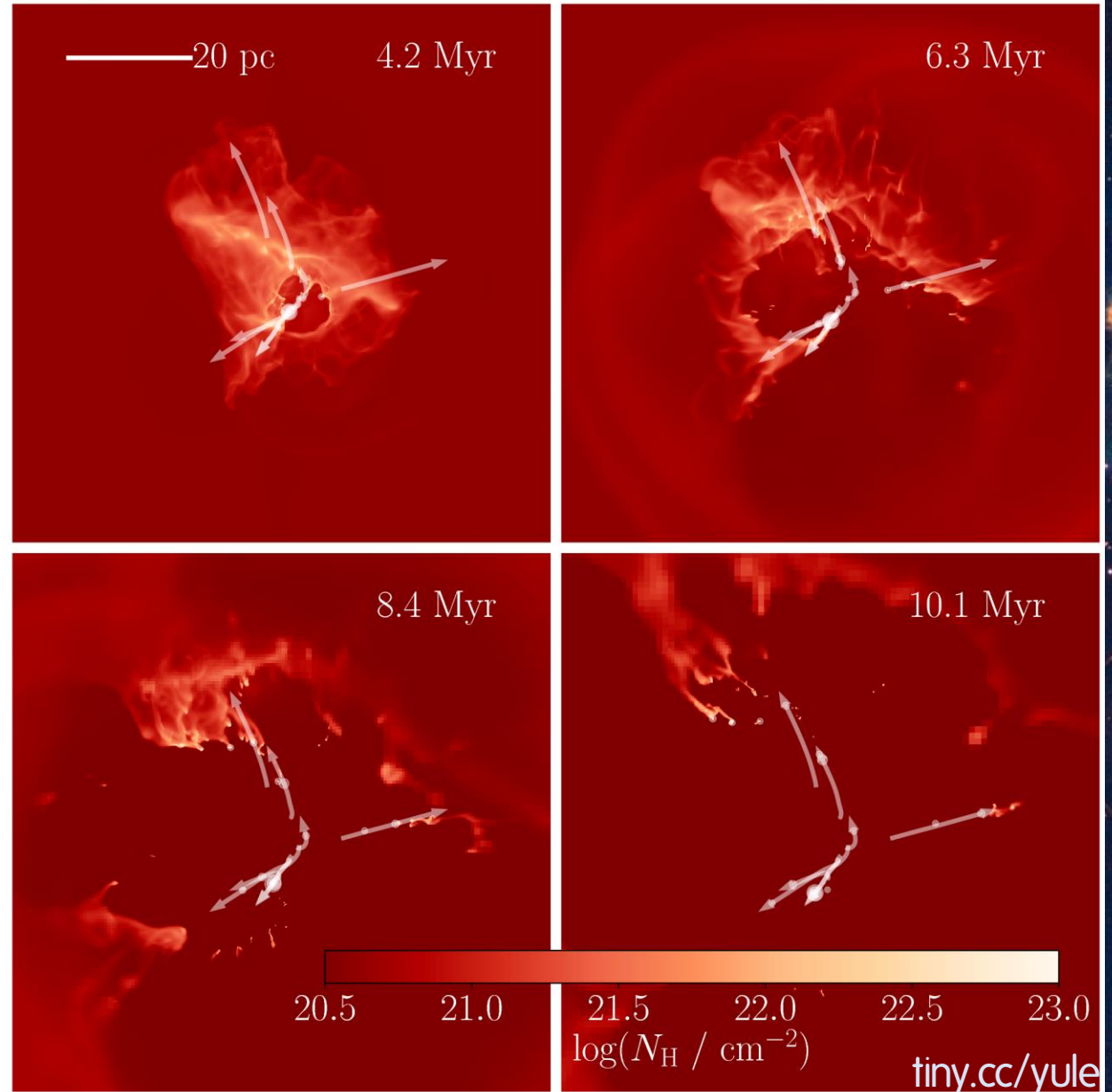
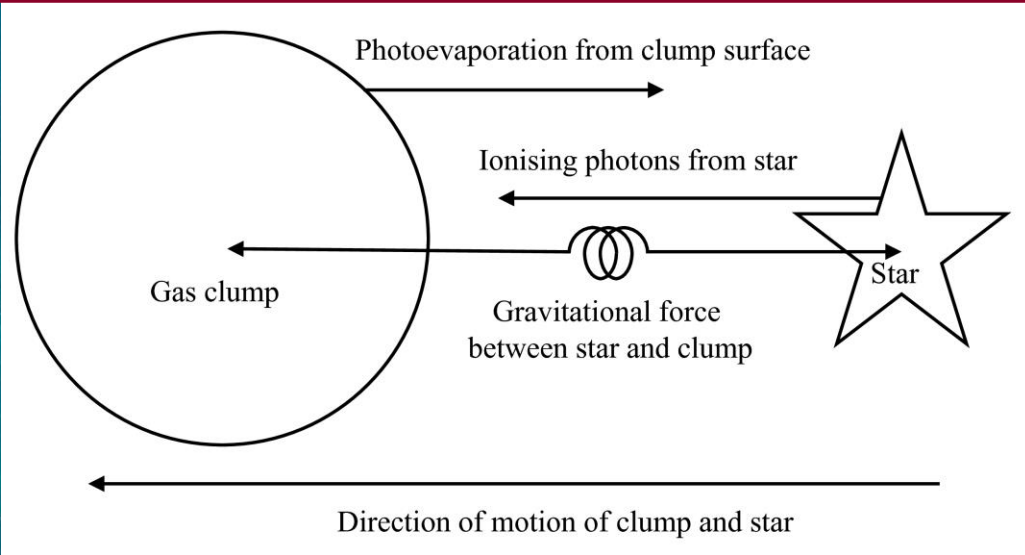
CLUSTER DISPERSAL BY WEAK FEEDBACK??

This seems weird, so let's unpack it

Stars travel further when SFE is higher

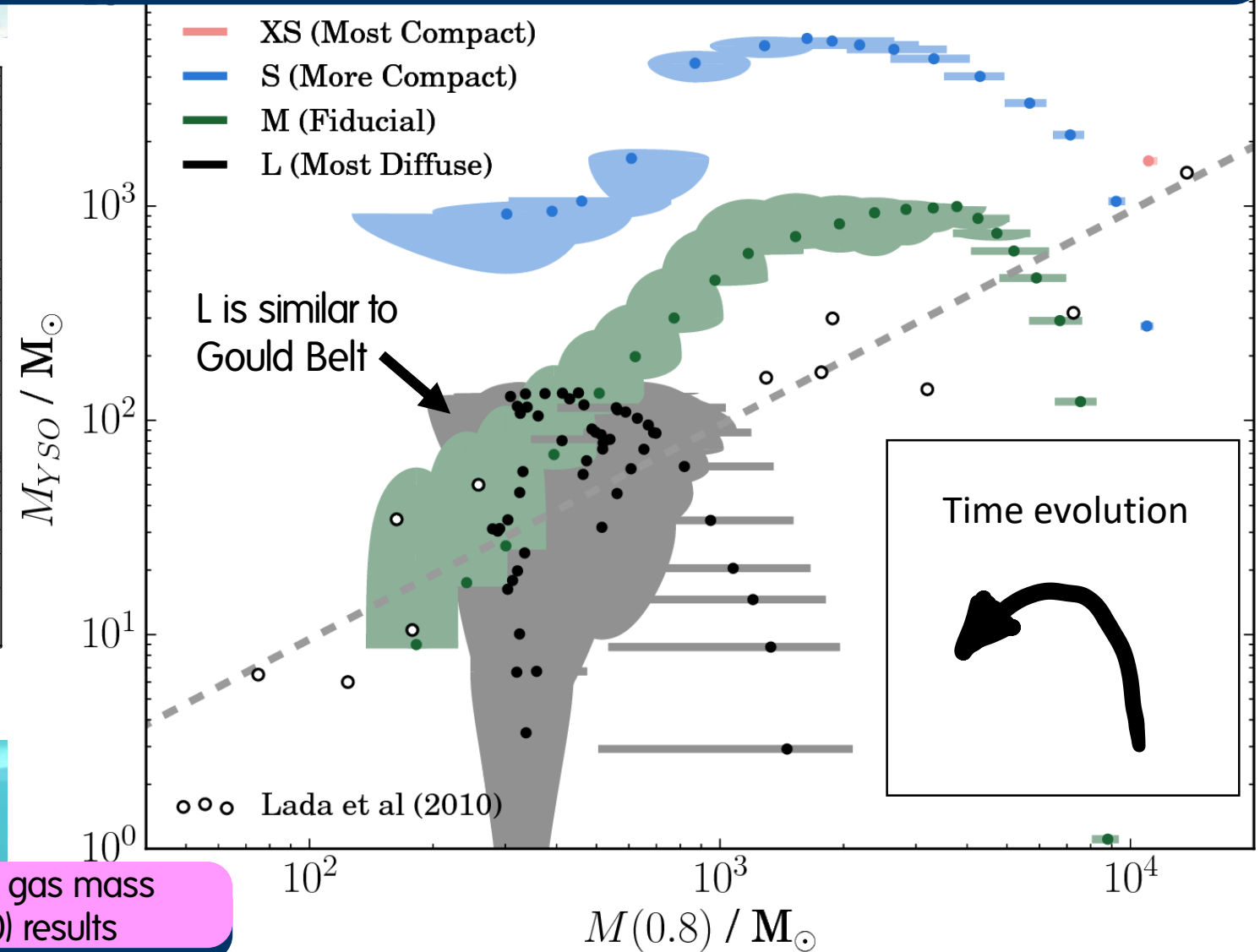
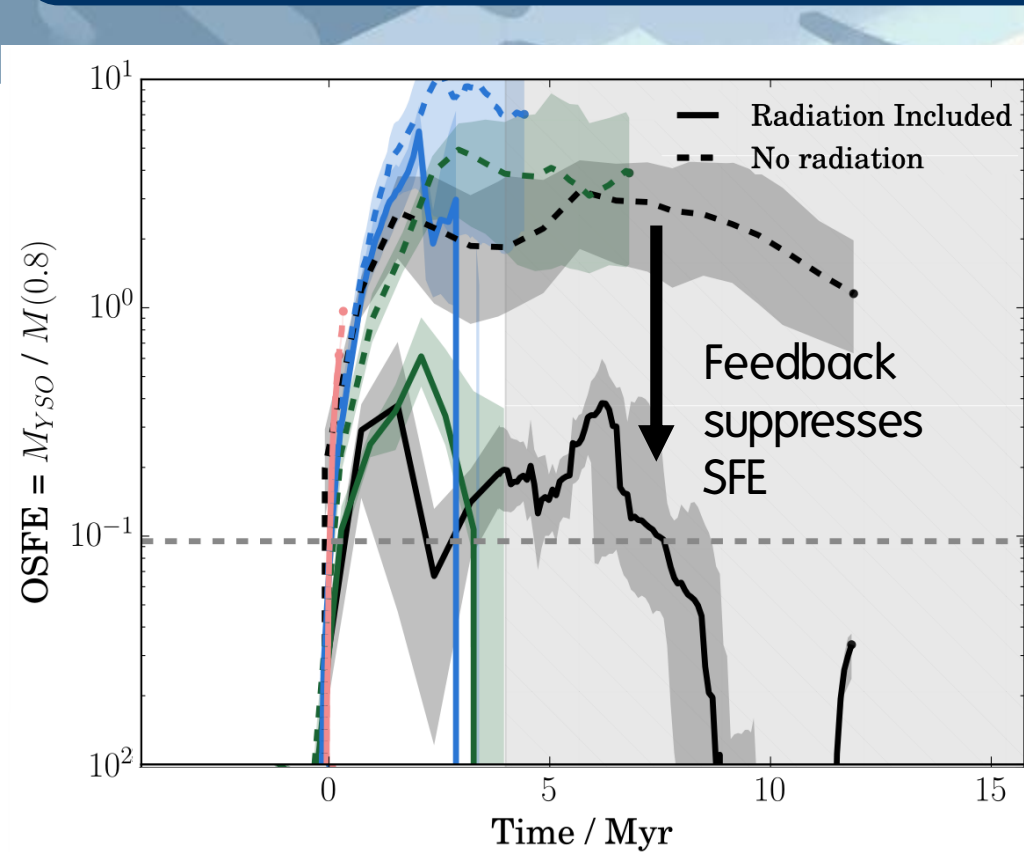
This means weak feedback = cluster dispersed

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 \rightarrow recent SFE
Geen+ (2018) – all gas \rightarrow 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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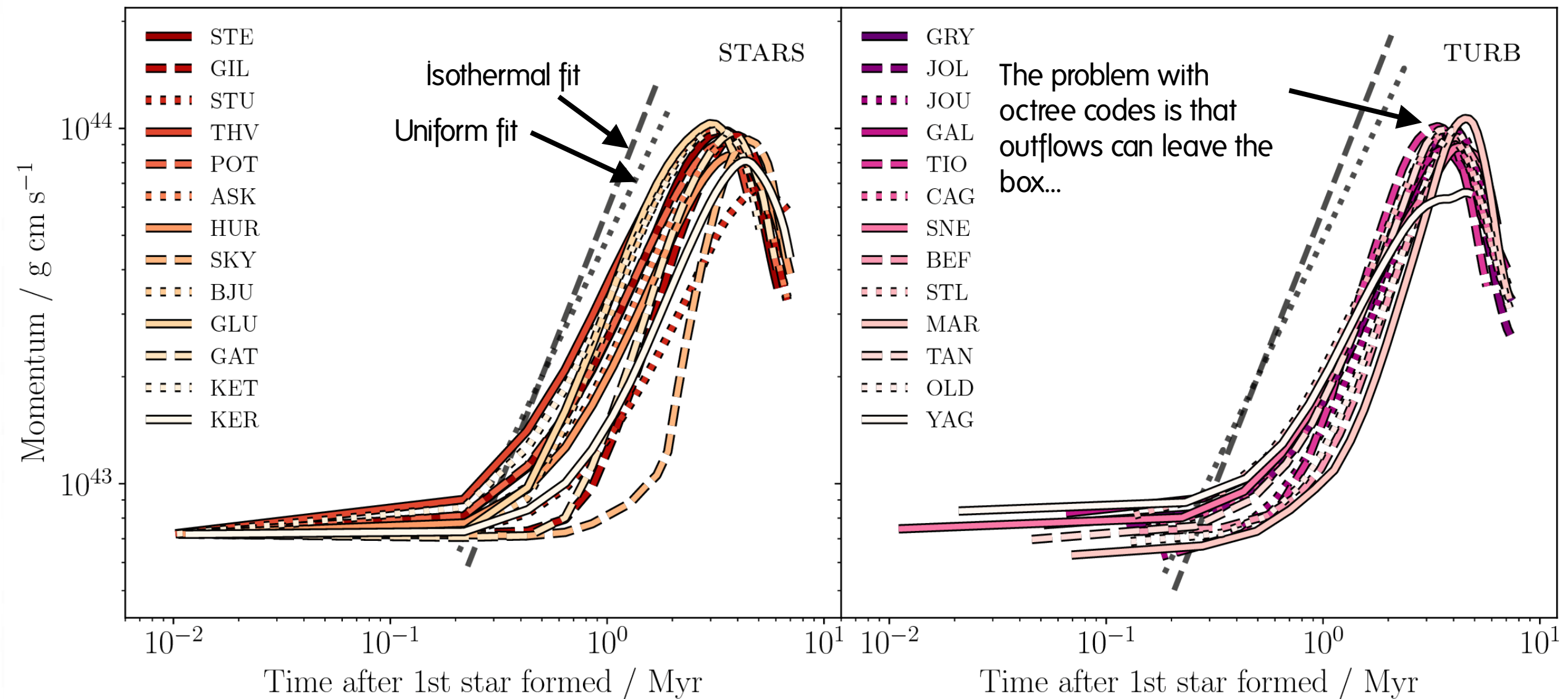
THANK YOU!

The background is a dark purple space-themed illustration. It features several stylized starburst patterns with glowing centers and radiating lines in shades of blue, purple, and pink. Scattered throughout are numerous small, white, diamond-shaped stars and larger, multi-pointed star shapes. The overall aesthetic is futuristic and cosmic.

EXTRA SLIDES

MOMENTUM INJECTED BY HII REGION

<http://tiny.cc/yule>





NOPE