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

2nd generation stars?

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

THE SIMULATION SETUP BIT


The YULE Simulations

- 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_{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
- Winds from those tables (similar to Gatto+ 2017)

Gonna talk about two suites:

- YULE: 26 simulations of clouds with just UV
- AMUN: lots of physics (winds, RT pressure)

Why choose between quality and quantity when you can have both?

STELLAR SOURCES

New Fortran/F2PY module for coupling stellar evolution tables to RAMSES

Use "virtual" stellar objects attached to sink particles (via Olivier Iffrig)

Single stars from Geneva tables
Extract spectra from Starburst 99
0.1 and 1 Zsolar (plans to expand to BPASS for binaries, more metals)

Make cumulative emission tracks from each star in the table over time:

- Photons emitted (IR, Optical, HII, HeII, HeIII)
- Winds (mass loss, energy injected, yields)

Also:

- Stellar lifetimes, supernova energy, yields

For a star of mass M at step t → t+dt

- Normalise every track to a lifetime of 1
- Interpolate tracks either side of M
- Find f(t+dt) – f(t) for each output
- Inject onto the grid elastically (energy-driven in high density, momentum-driven in low-density)

Table creation in Python
Module in Fortran
F2PY interface to allow analysis code to read the same values as RAMSES

THE YULE SUITE

The Icelandic Yule Lads

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

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

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

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

Arrival: December 16
Pottasleikir Pot-Licker
Steals leftovers from pots

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

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

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

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

Arrival: December 21
GluggagægirWindow-Peeper
A voyeur who would look through windows in search of things to steal

Arrival: December 22
Gáttaþefur Doorway-Sniffer
Has an abnormally large nose and an acute sense of smell which he uses to locate laufabrauð

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

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

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

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

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?)

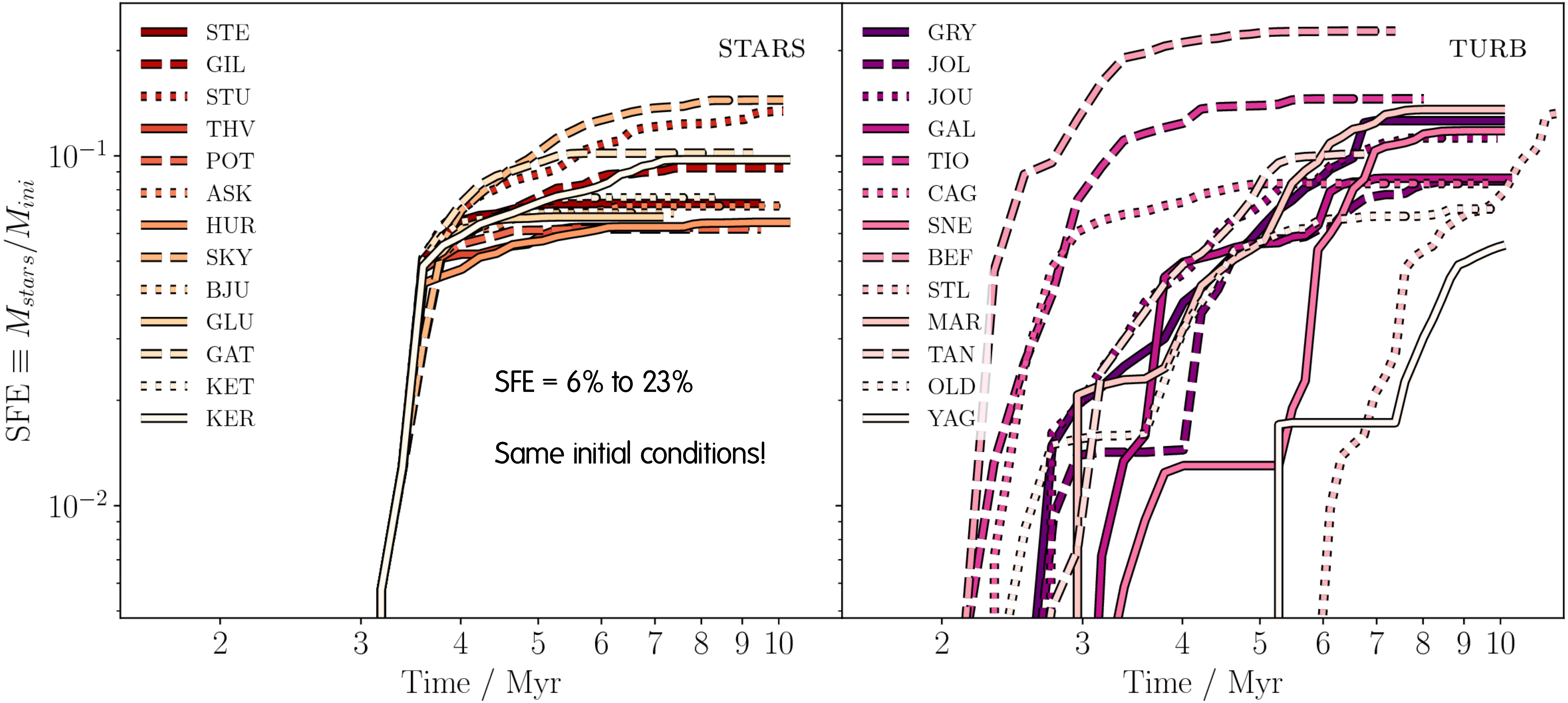
Introducing the **YULE** simulations

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

STAR FORMATION EFFICIENCY

tiny.cc/yule



SFE = 6% to 23%

Same initial conditions!

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.

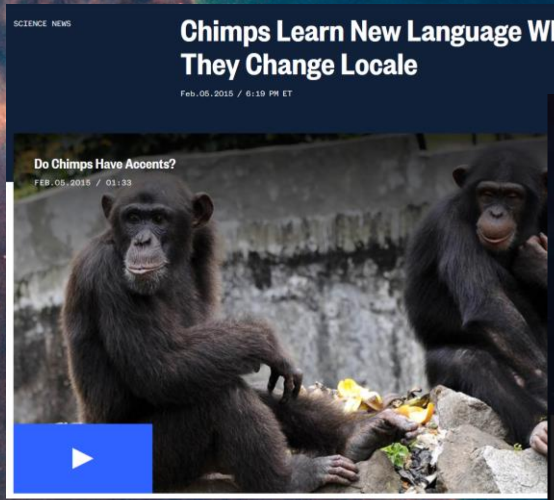
I can do statistics! Also use Bayesian methods instead

Stuart Watson, Zurich, studies social learning between chimpanzees

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

Basically:

$$\log(\mathrm{SFE}) = \mathrm{const} \times \log(???)$$



SCIENCE NEWS

Chimps Learn New Language When They Change Locale

Feb.05.2015 / 6:19 PM ET

Do Chimps Have Accents?

FEB.05.2015 / 01:33

Chimp Science Reveals How Society's Losers Become Influencers

Credit: NASA/HST

IS THE SFE COMPLETELY RANDOM?

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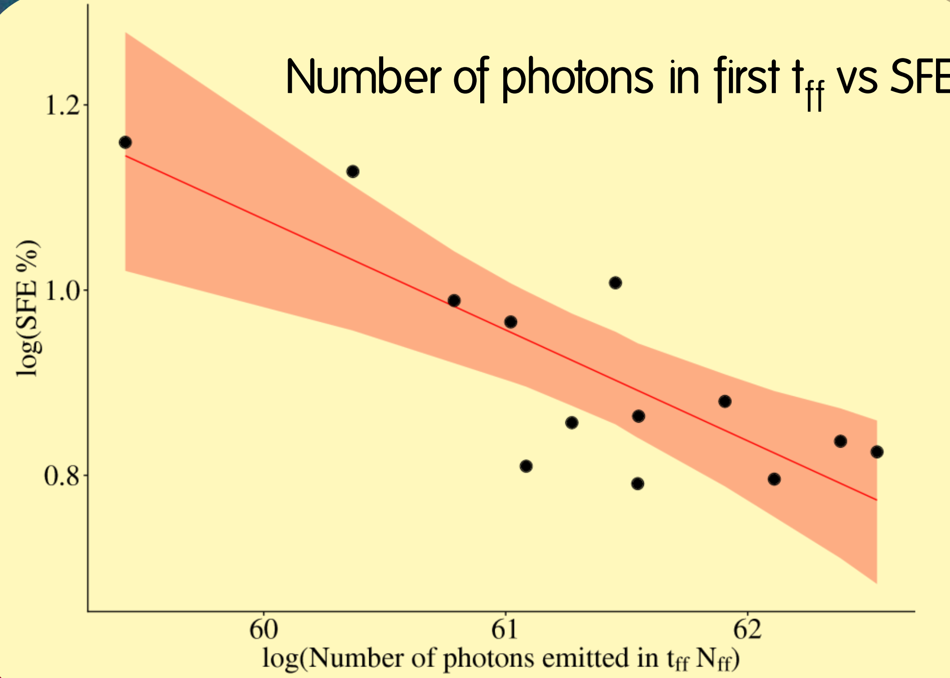
What's **not** important:

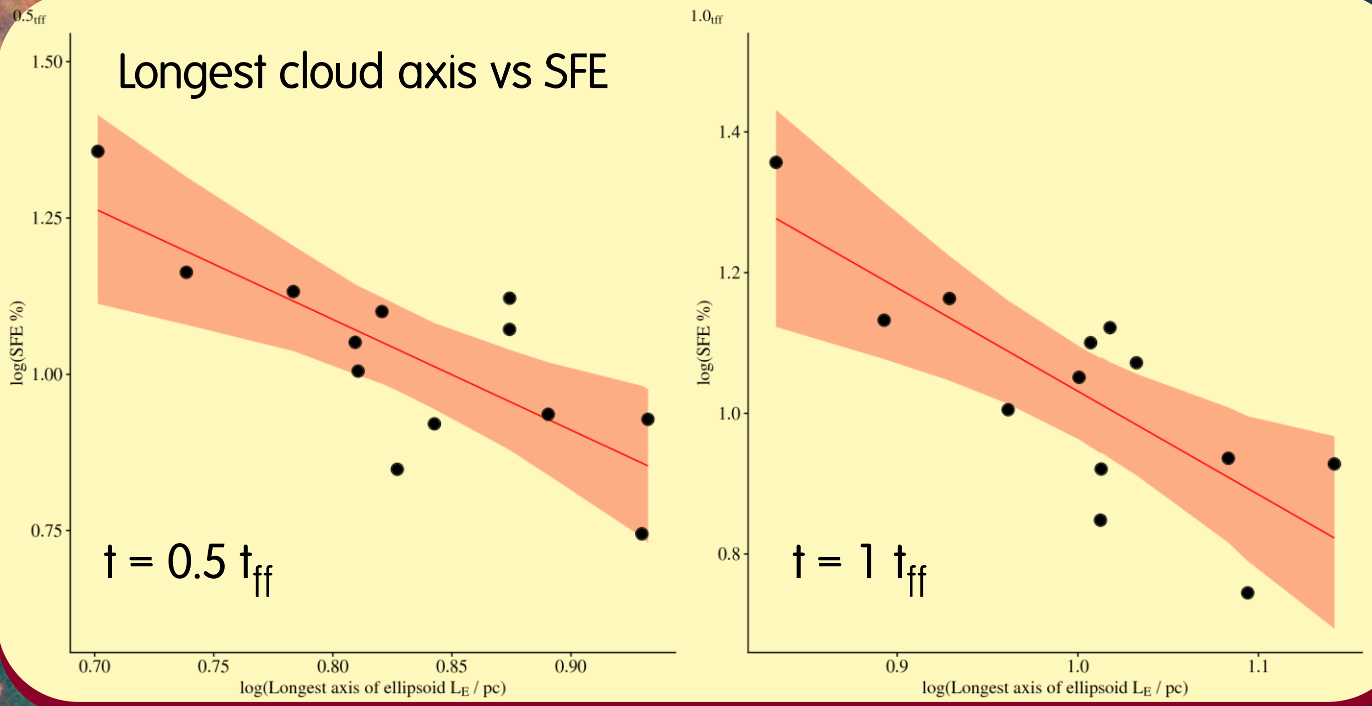
- Most massive star, cluster size, mass of 1st star, peak and total photon emission
- Shortest and "middlest" cloud axis (when fitting an ellipsoid)

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…)



Number of photons in first t_{ff} vs SFE



Longest cloud axis vs SFE

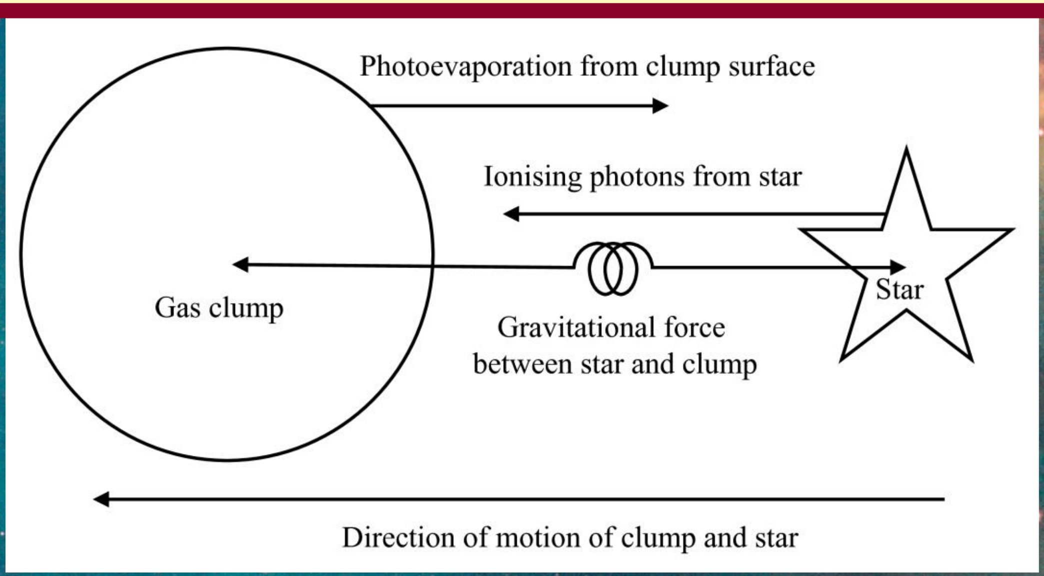
CLUSTER DISPERSAL BY WEAK FEEDBACK??

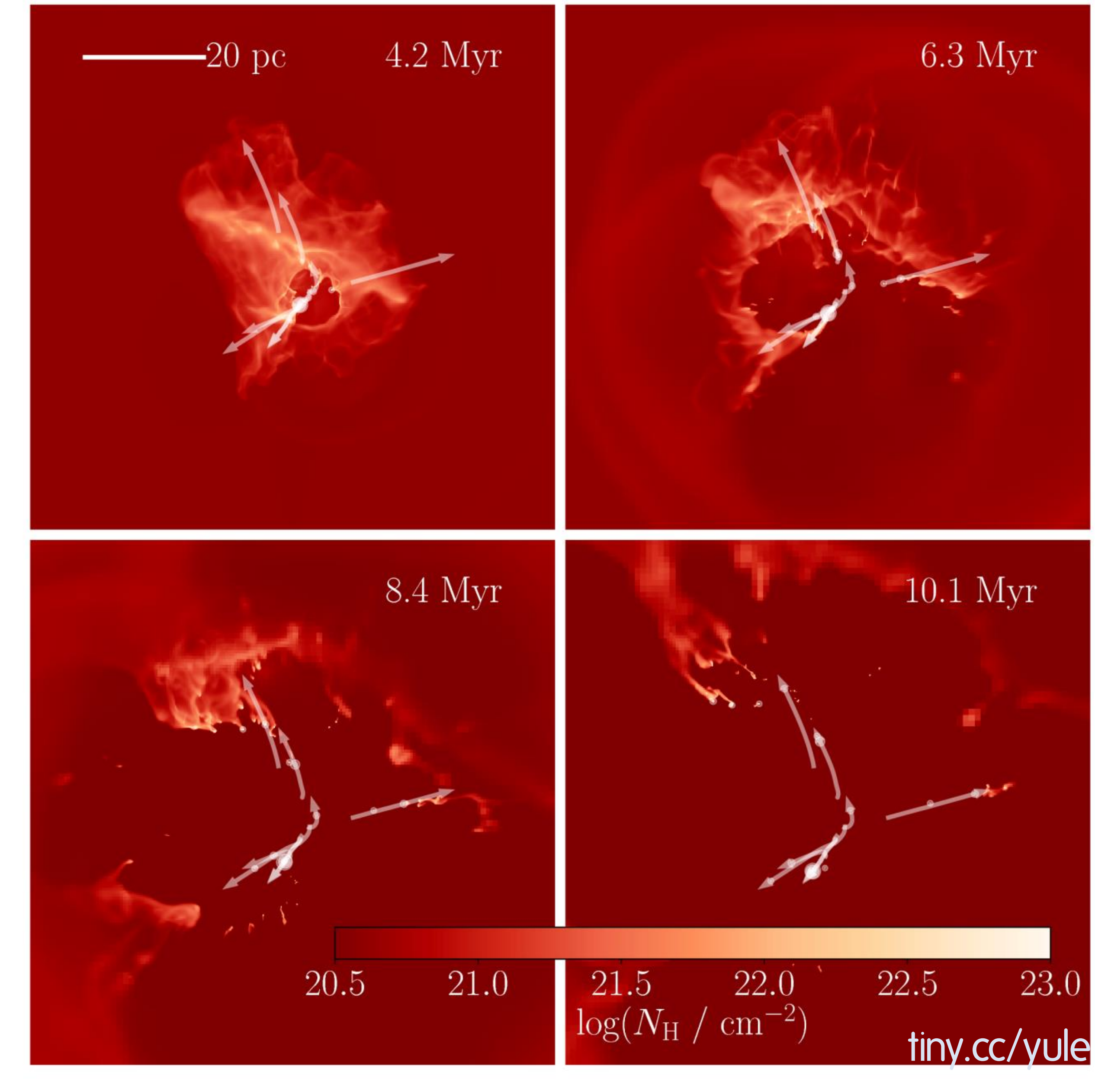
This seems weird, so let's unpack it

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





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THE AMUN SUITE

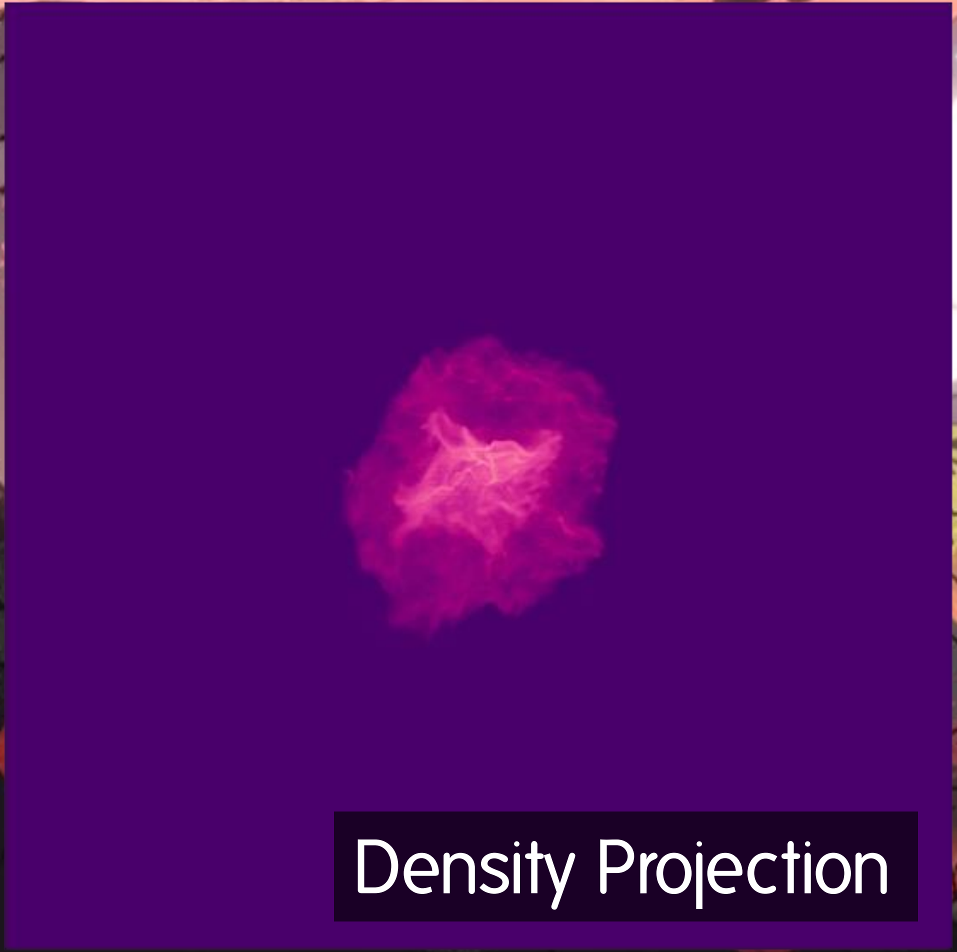
Collaboration with Rebekka Bieri

AMUN –
God of Wind

Question: what processes dominate? Under what conditions?

Stellar winds, UV pressure, IR pressure (+SN, jets, etc, etc?)

6 physical models
2 IMF samplings
2 cloud masses



10^5 Msun cloud

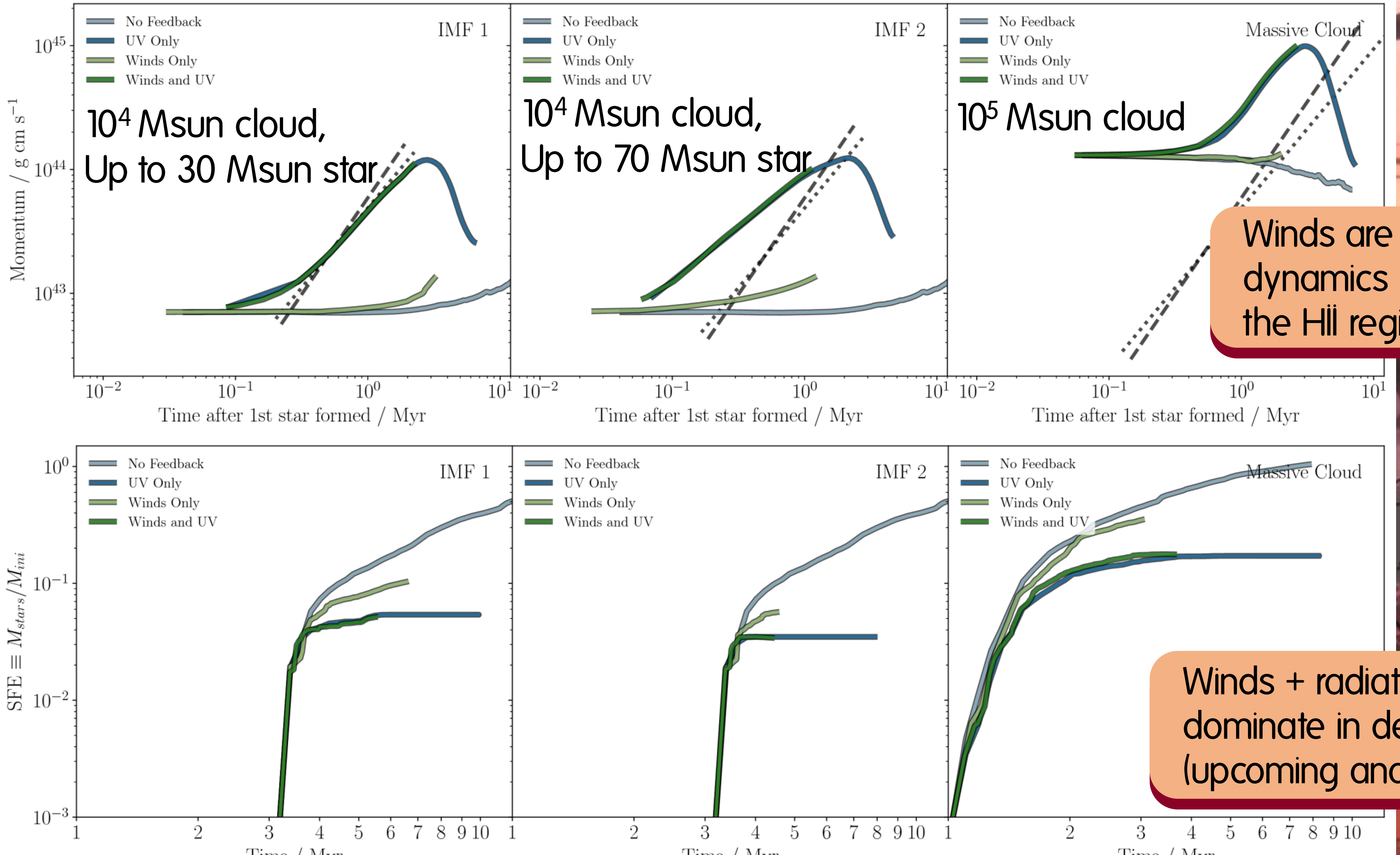
Pink = photoionised

White = stellar winds

THE AMUN SUITE

With Rebekka Bieri

Winds, UV pressure start to become important in more massive clouds, but photoionisation still dominates



10^4 Msun cloud,
Up to 30 Msun star

10^4 Msun cloud,
Up to 70 Msun star

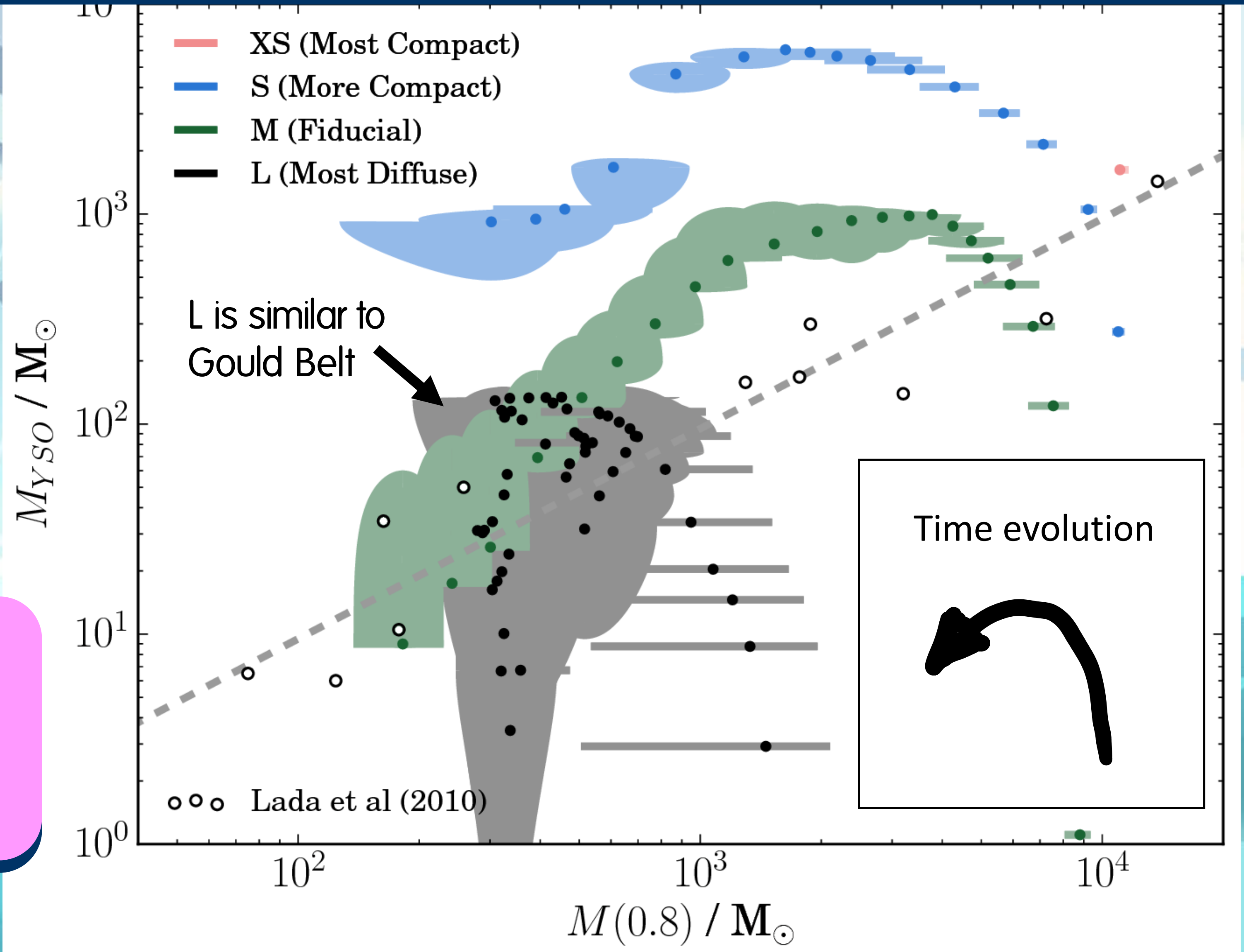
10^5 Msun cloud

Winds are not super important for dynamics (but lower the density in the HII region, important later?)

Winds + radiation pressure begin to dominate in dense, massive clusters (upcoming analytic paper)

OBSERVATIONS? YES

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

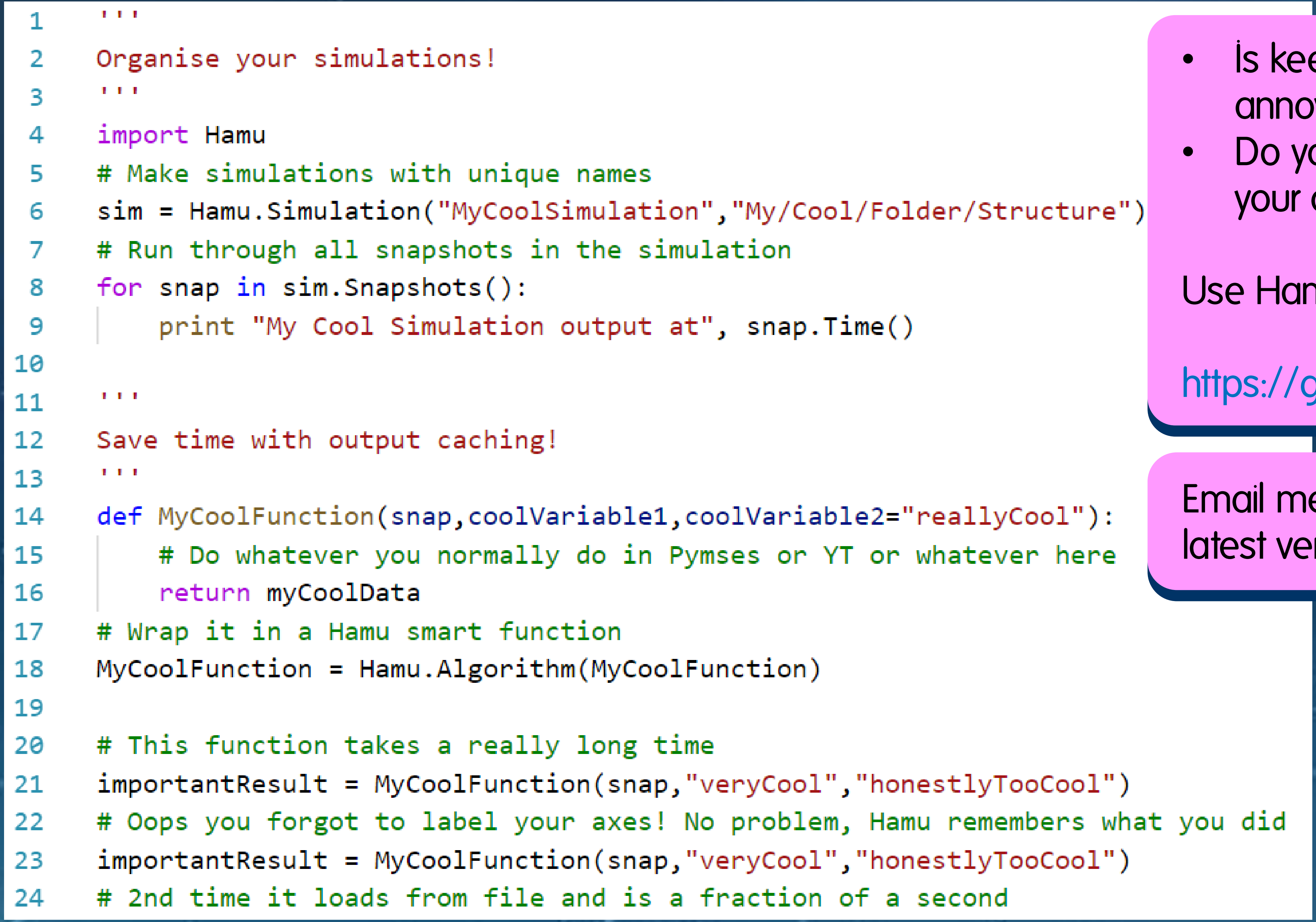


L is similar to Gould Belt

Time evolution

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

HAMU – ORGANISE YOUR ANALYSIS



```
'''
Organise your simulations!
'''
import Hamu
# Make simulations with unique names
sim = Hamu.Simulation("MyCoolSimulation","My/Cool/Folder/Structure")
# Run through all snapshots in the simulation
for snap in sim.Snapshots():
    print "My Cool Simulation output at", snap.Time()

'''
Save time with output caching!
'''
def MyCoolFunction(snap,coolVariable1,coolVariable2="reallyCool"):
    # Do whatever you normally do in Pymses or YT or whatever here
    return myCoolData
# Wrap it in a Hamu smart function
MyCoolFunction = Hamu.Algorithm(MyCoolFunction)

# This function takes a really long time
importantResult = MyCoolFunction(snap,"veryCool","honestlyTooCool")
# Oops you forgot to label your axes! No problem, Hamu remembers what you did
importantResult = MyCoolFunction(snap,"veryCool","honestlyTooCool")
# 2nd time it loads from file and is a fraction of a second
```

- Is keeping track of your simulations annoying?
- Do you spend forever re-running your analysis?

Use Hamu!

https://github.com/samgeen/Hamu

Email me if you get stuck / want the latest version!

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

UV photoionisation is the most important thing for small-medium molecular clouds near the Sun
- But: low Z? Higher pressure? Dense/massive clouds?

Tools:

- Fast simulations (~10k hours) x lots = statistics!
- Expensive simulations (100k-1M hours+) = physics!
- Analytic model & observational comparisons = necessary!

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)
Watch this space for AMUN papers!
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THANK YOU!

EXTRA SLIDES

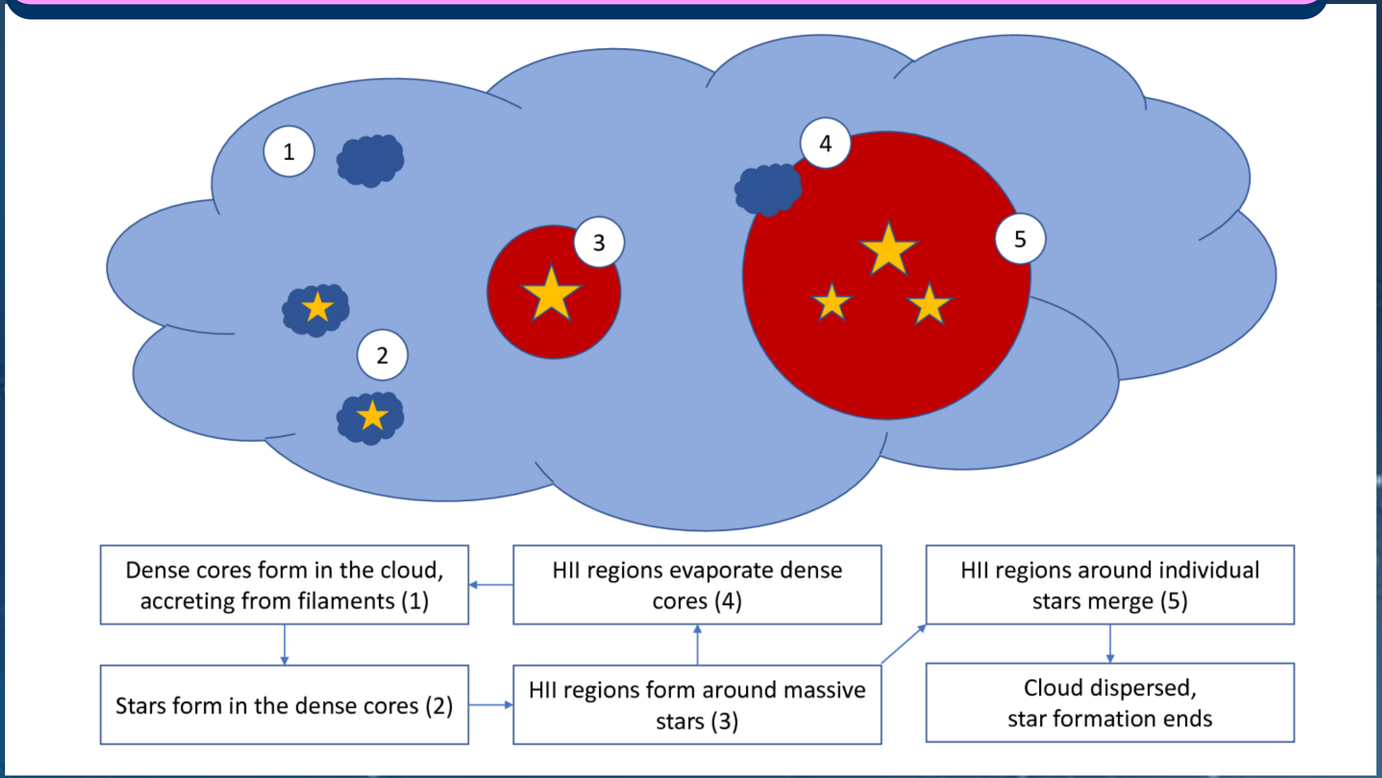
STAR FORMATION IN CLOUDS

Orion nebula (credit: Tony Hallas)

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)

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



Dense cores form in the cloud, accreting from filaments (1)

Stars form in the dense cores (2)

HII regions form around massive stars (3)

HII regions evaporate dense cores (4)

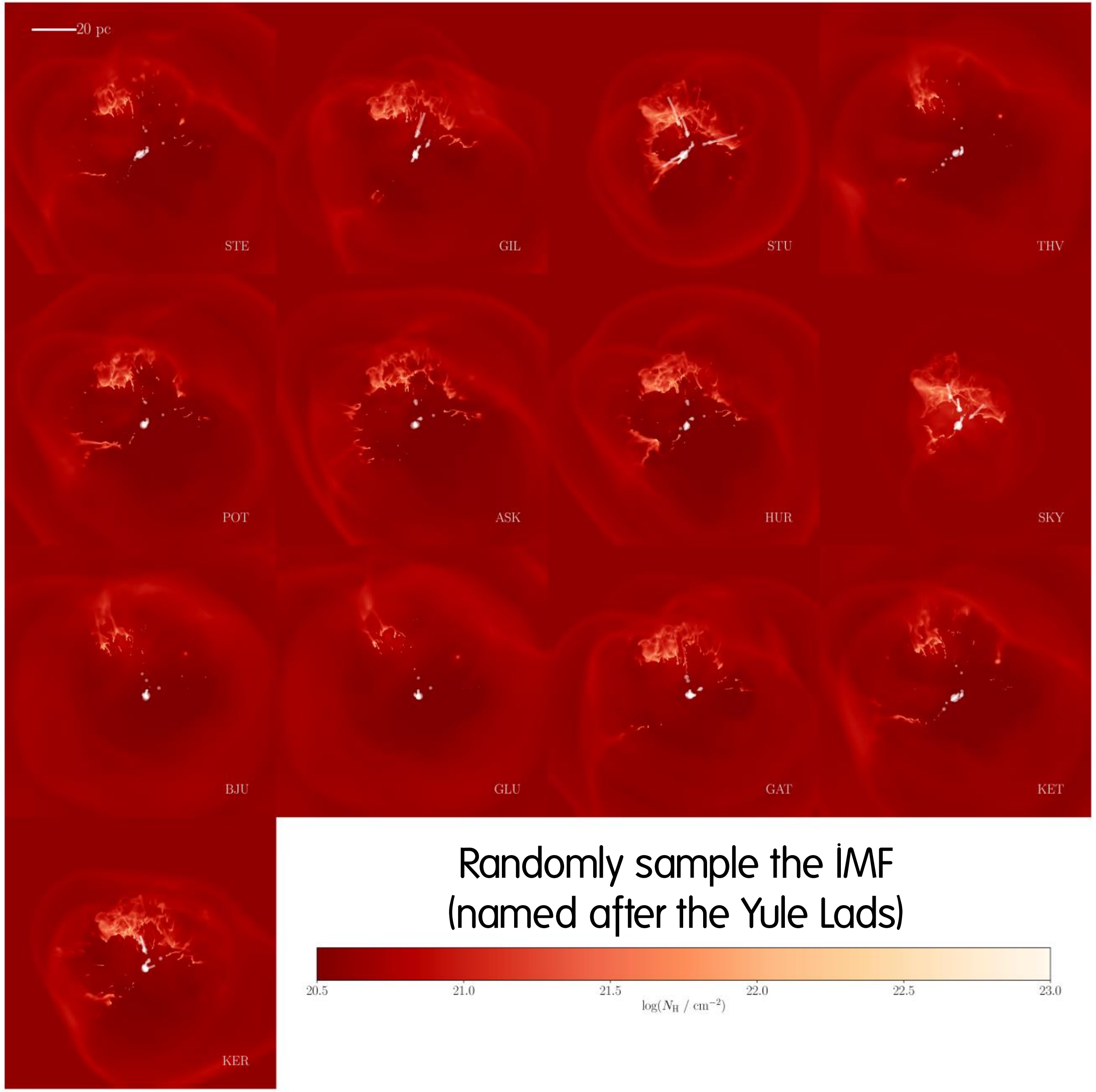
HII regions around individual stars merge (5)

Cloud dispersed, star formation ends

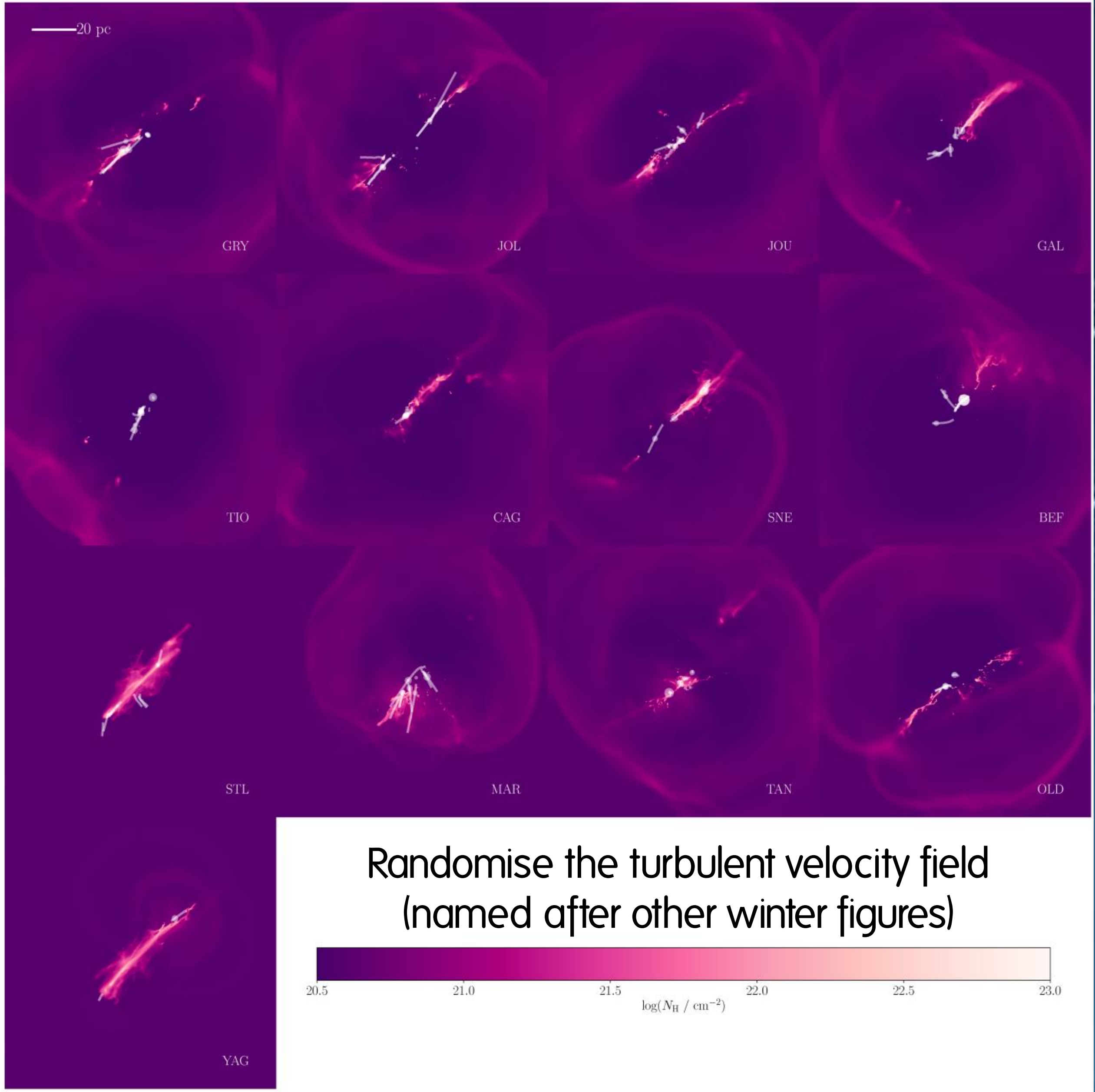
Question: what value do we get when this star formation is frozen out, and how does it relate to the value found by observers?

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)

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:

$$r_{\mathrm{i}} \propto t^{\psi} S_*^{\psi/4}$$

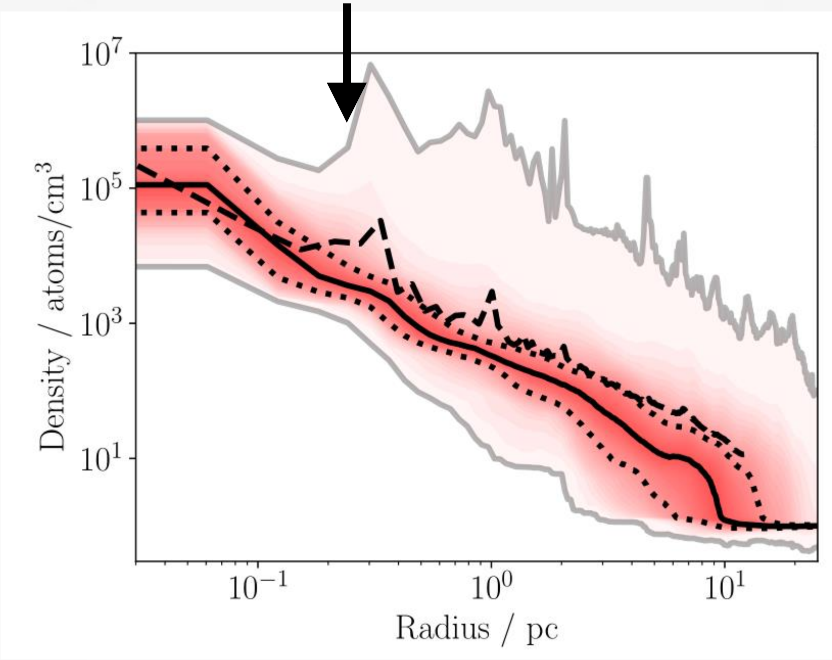
S_* is the photon emission rate
ψ = 4/7 for a uniform density field
ψ = 4/3 for an isothermal power law

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

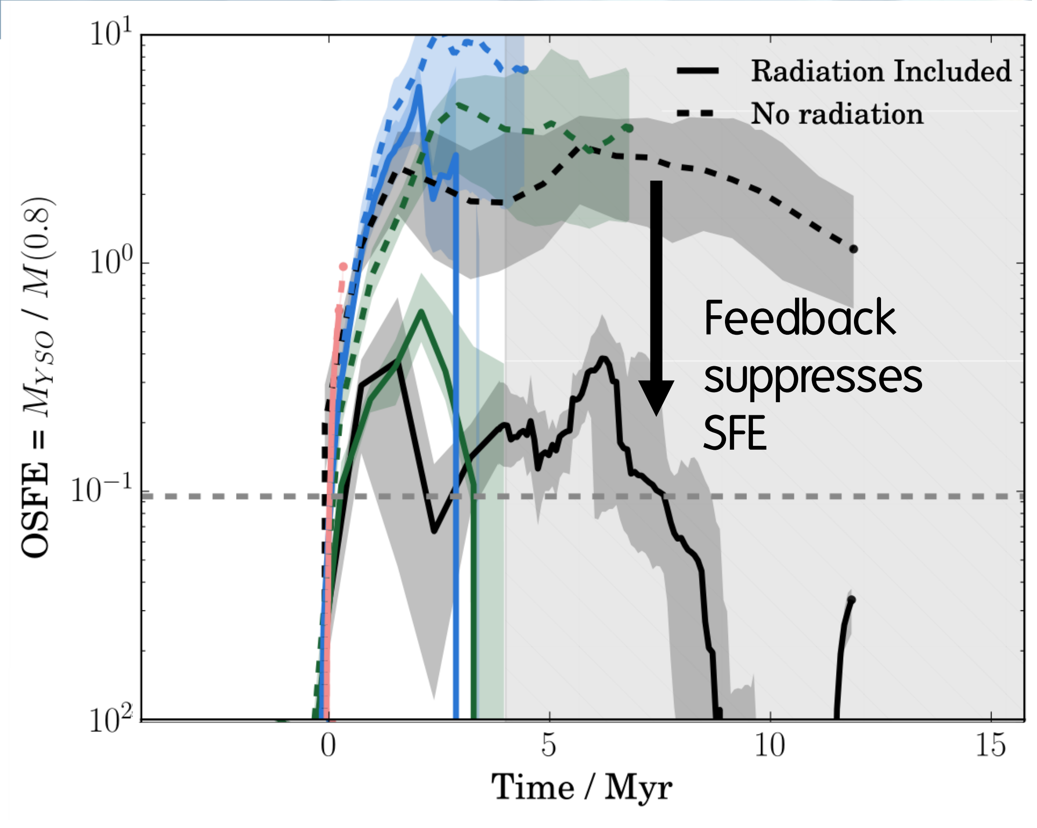
In this simulation, the star "sees" a ~ isothermal density field



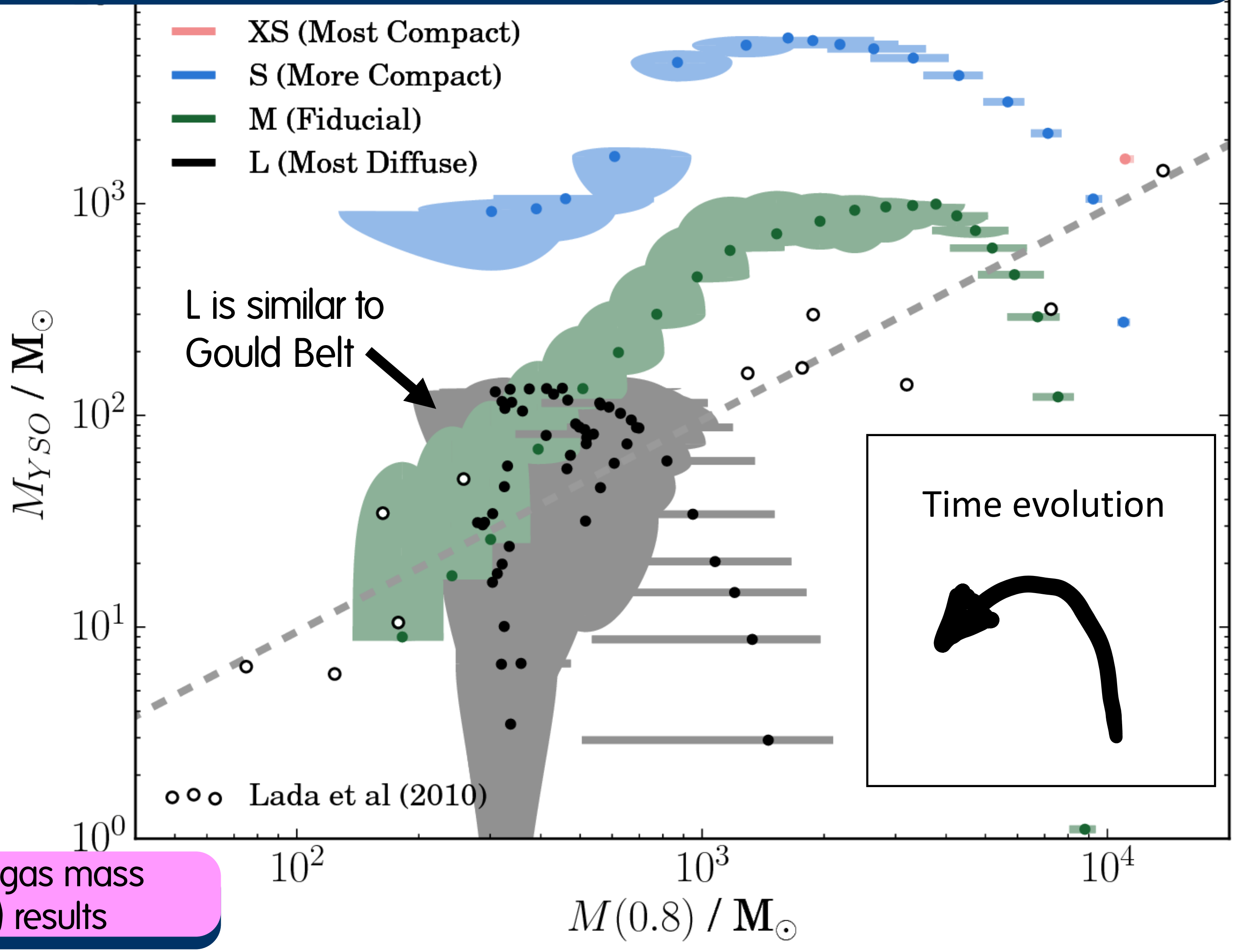
Density PDF per bin in red

OBSERVATIONS?

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



Feedback suppresses SFE



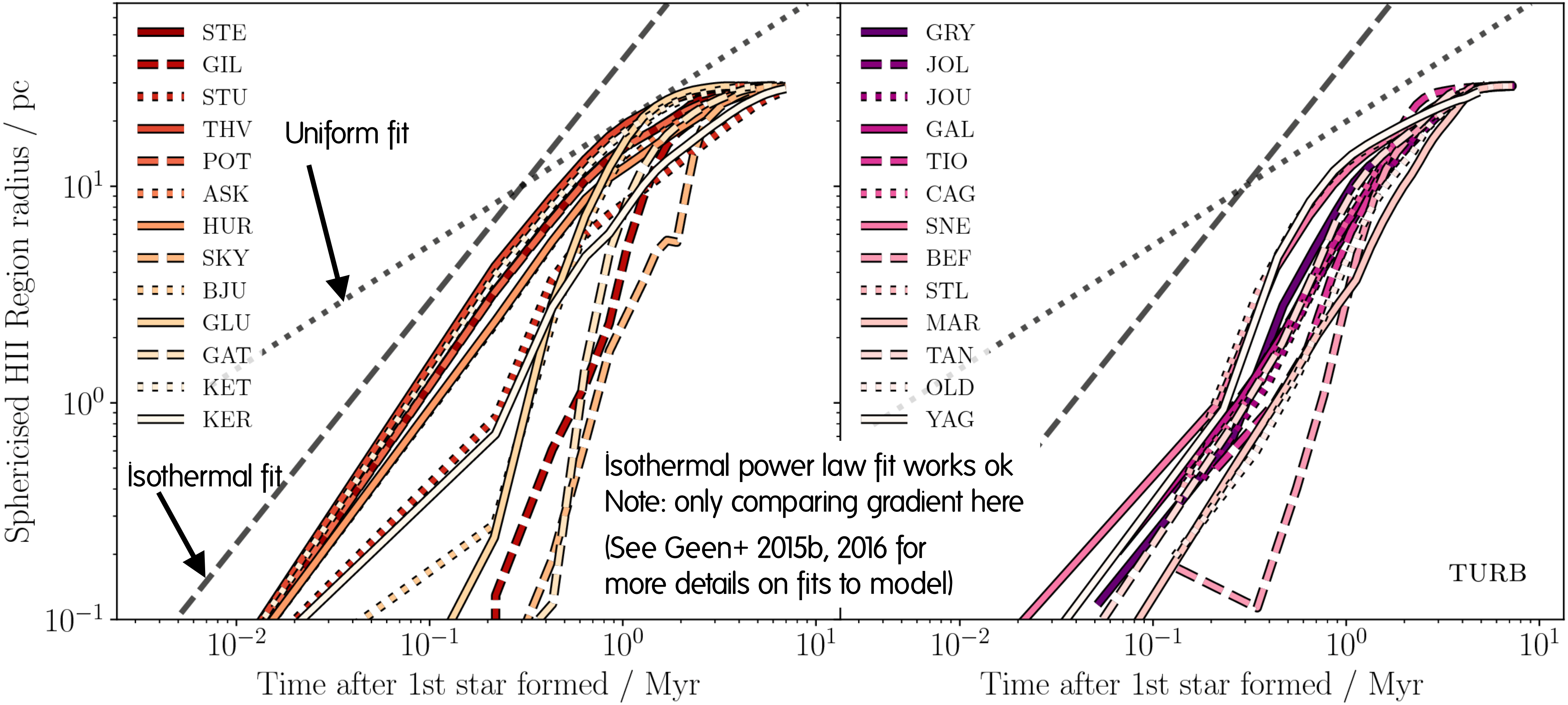
L is similar to Gould Belt

Time evolution

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

COMPARE THIS TO OUR SIMULATIONS

tiny.cc/yule

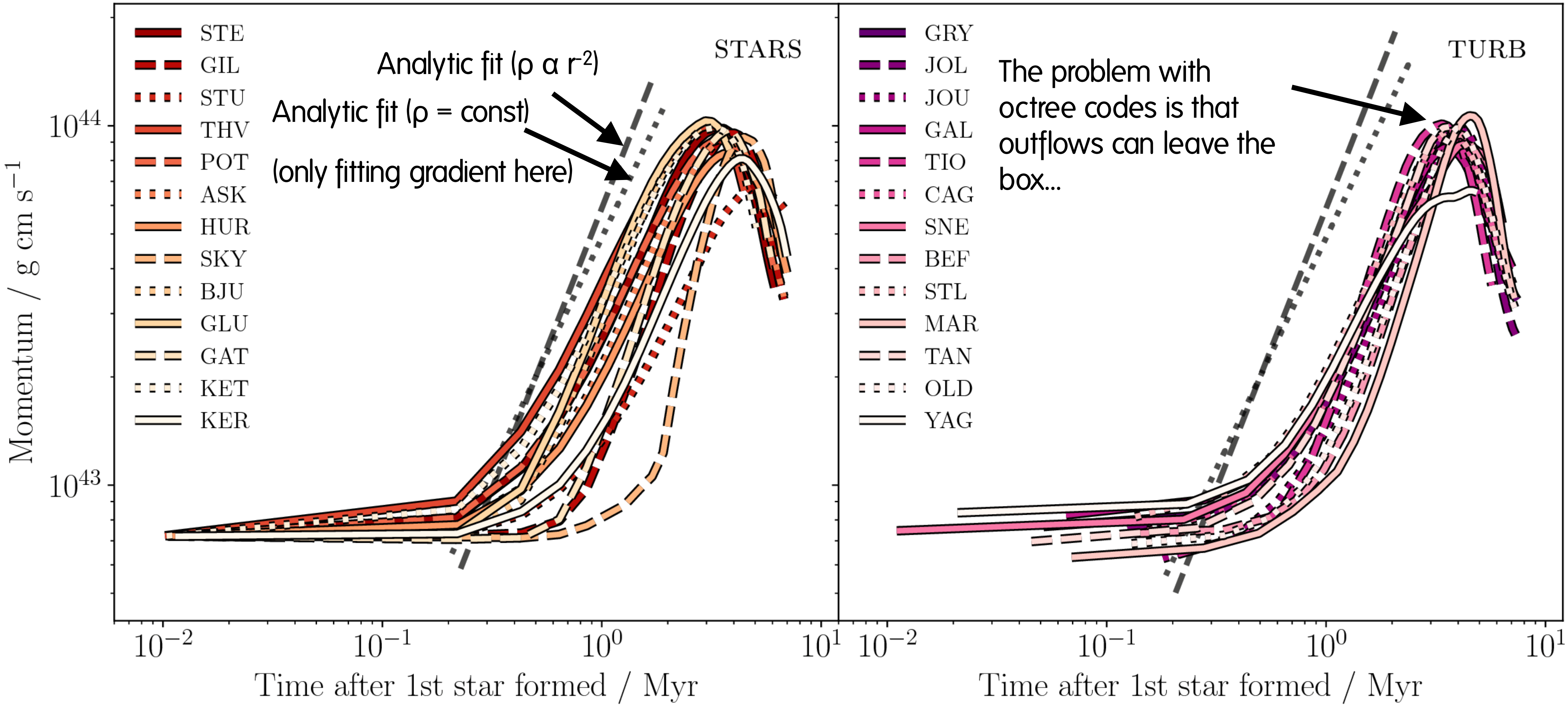


Isothermal power law fit works ok
Note: only comparing gradient here

(See Geen+ 2015b, 2016 for
more details on fits to model)

MOMENTUM INJECTED BY HII REGION

http://tiny.cc/yule



Analytic fit ($\rho \propto r^{-2}$)

Analytic fit (ρ = const)

(only fitting gradient here)

The problem with octree codes is that outflows can leave the box...

NOPE