STELLAR FEEDBACK IN MOLECULAR CLOUDS

EPISODE IV: THE RETURN TO

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AND JOAKIM ROSDAHL

UV FEEDBACK IN CLOUDS

HII regions, supernovae,
Molecular clouds

Outline of talk:

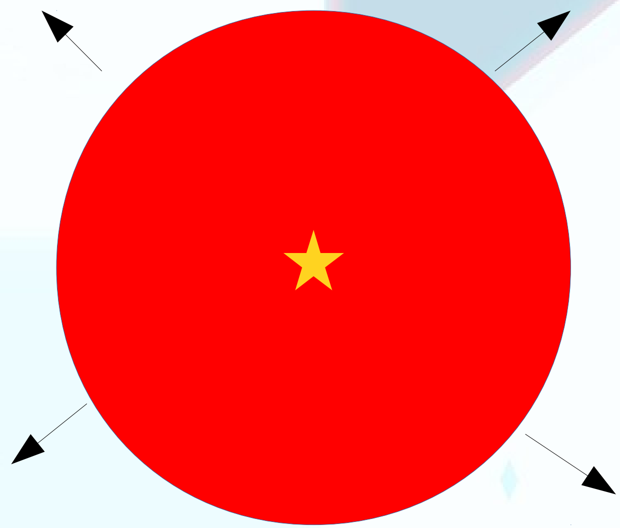
- How does photoionisation drive outflows in star-forming clouds?
- How do supernovae interact with HII regions and clouds?
- Can we explain self-regulation of star formation?
- Interaction between observational techniques and simulations

PHOTOIONISATION

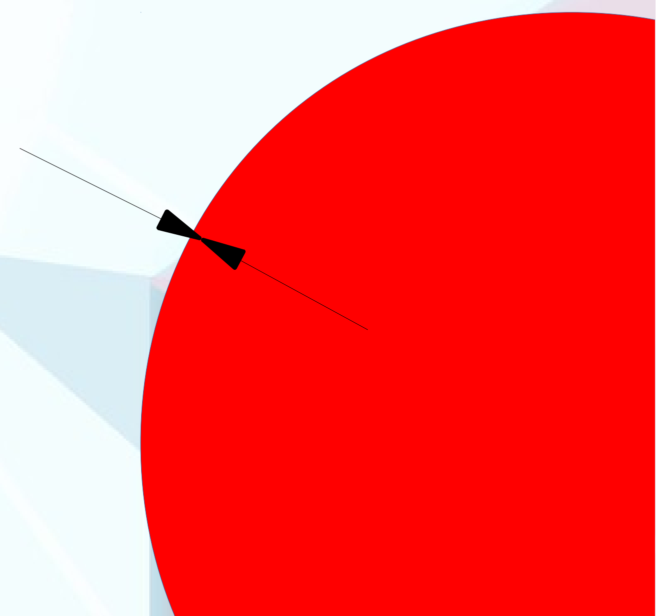
HOW TO MAKE AN HII REGION

1) UV photons stream out of the star, ionising hydrogen until all the photons are used to keep the gas ionised (called the "Strömgren radius")

2) The photoionised gas is at ~ 10,000 K so a shock begins to expand at ~ 10 km/s (still in photoionisation equilibrium)



3) The expansion can "stall" or even collapse via turbulence or accretion



Example:
Initial Strömgren radius is ~0.3 pc for a source of 10^{48} UV photons/s in a cloud of density 1000 cm^{-3}

See Geen et al, 2015 a, b, 2016 for more detailed models of this

SIMULATIONS

Use AMR code **RAMSES-RT + MHD** (Teyssier 2002, Fromang et al 2006, Rosdahl et al 2013, 2015)

Take an **isothermal gas sphere** (can vary mass, density, etc)

Include Kolmogorov **turbulence, self-gravity, B-field** (20 µG peak in Fiducial run)

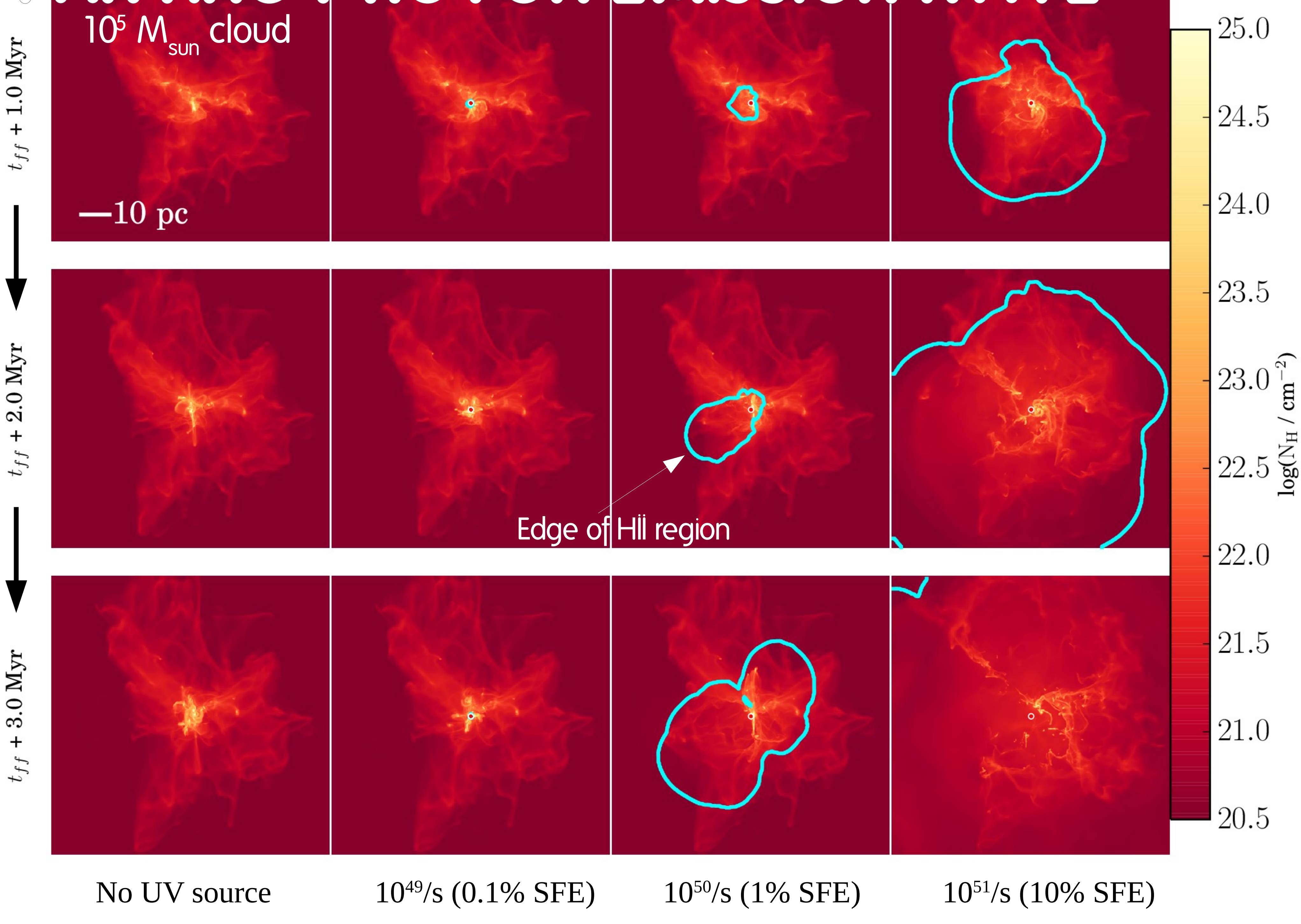
Use a 256^3 coarse grid with 2 levels of AMR on Jeans unstable cells (effective resolution 1024^3)
In the Fiducial run, the box is 25 pc → max resolution **0.025 pc**

Evolve the cloud for 1 freefall time, then put in a source of **photons** (Vacca et al, 1996, Sternberg et al, 2003)

Trace ionising photons with M1 method → treats photons as a fluid on the AMR grid

See **Geen, Hennebelle, Tremblin & Rosdahl, 2015 or 2016**

VARYING PHOTON EMISSION RATE



HII Regions and

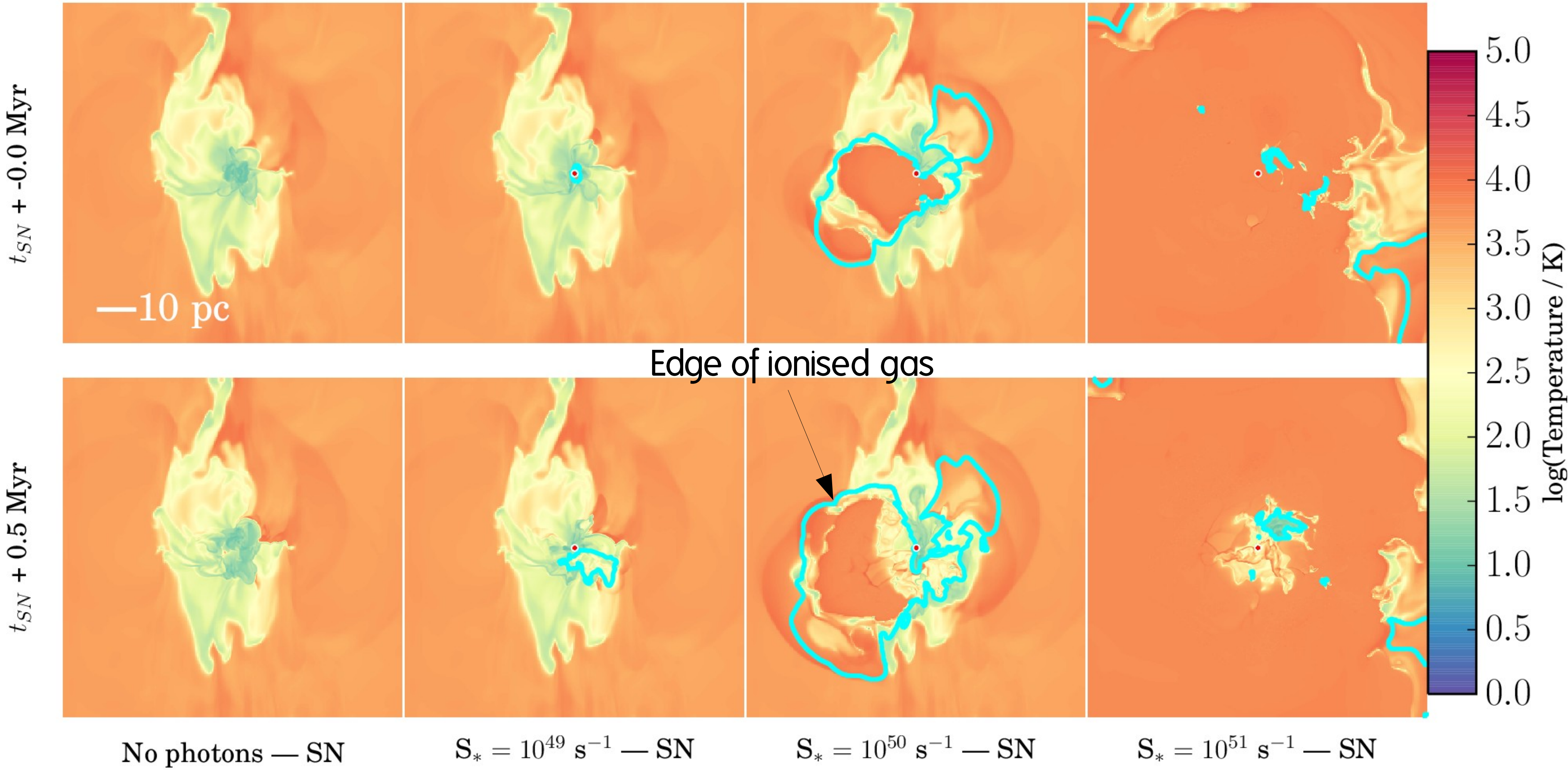
SUPERNOVAE

What happens when you put a supernova in a **very turbulent cloud**?
Our **10^5 M_{sun} cloud** has ~ **10^{44} g cm / s** in turbulent flows
Embedded **dense clumps up to 10^8 cm^{-3}, despite HII radiation** beforehand

(See Iffrig & Hennebelle, 2015 for less massive cloud with a similar setup
Also Martizzi et al, 2014, Kim & Ostriker 2015, Li et al 2015, Walch & Naab 2015)

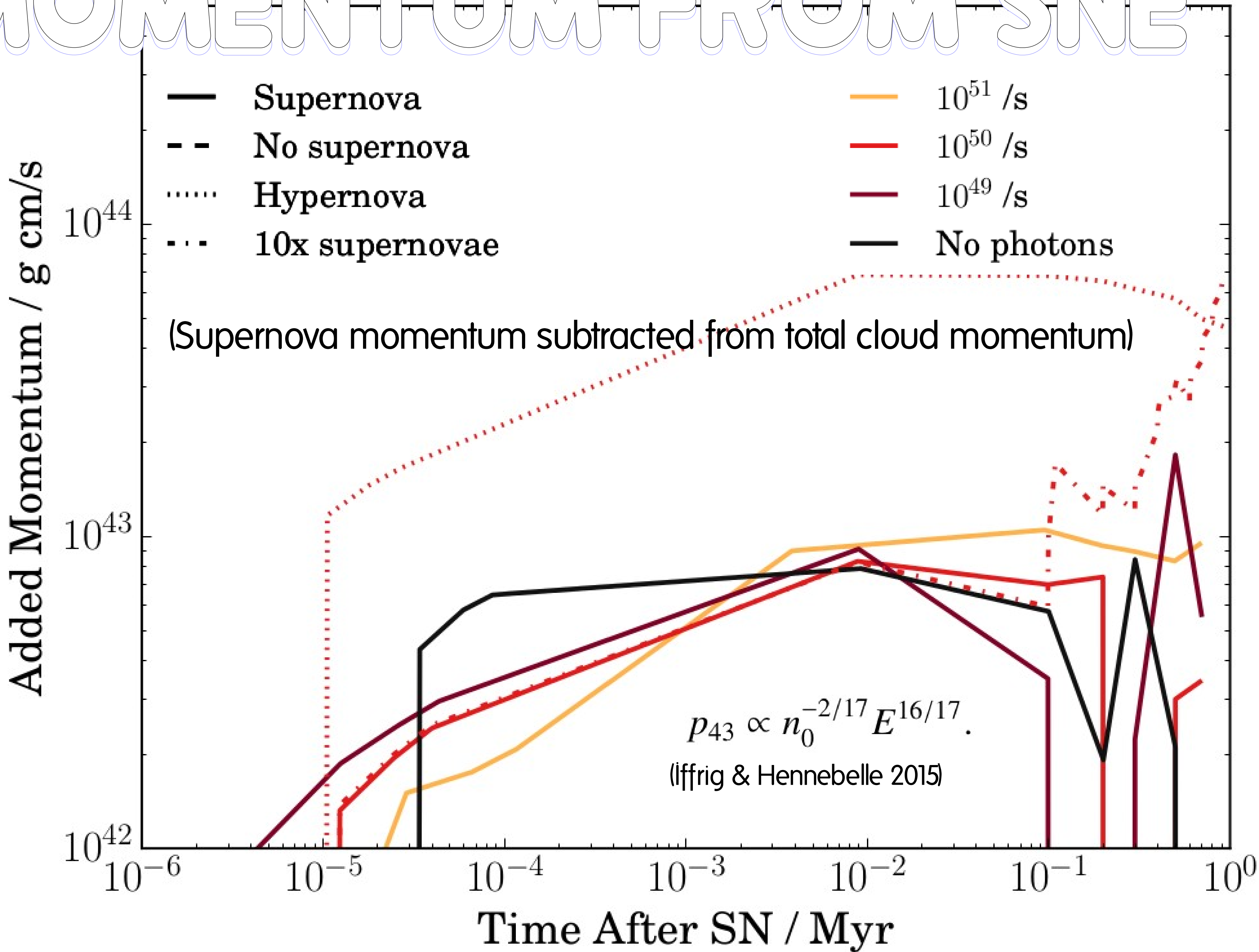
Credit: Steven Sugar

HII REGIONS AND SUPERNOVAE



Cooling time ~ 10^4 years
Very little hot gas remaining

MOMENTUM FROM SNE



MOMENTUM FROM SNE

We get ~ 10^{43} g cm/s per 10^{51} ergs of SN energy

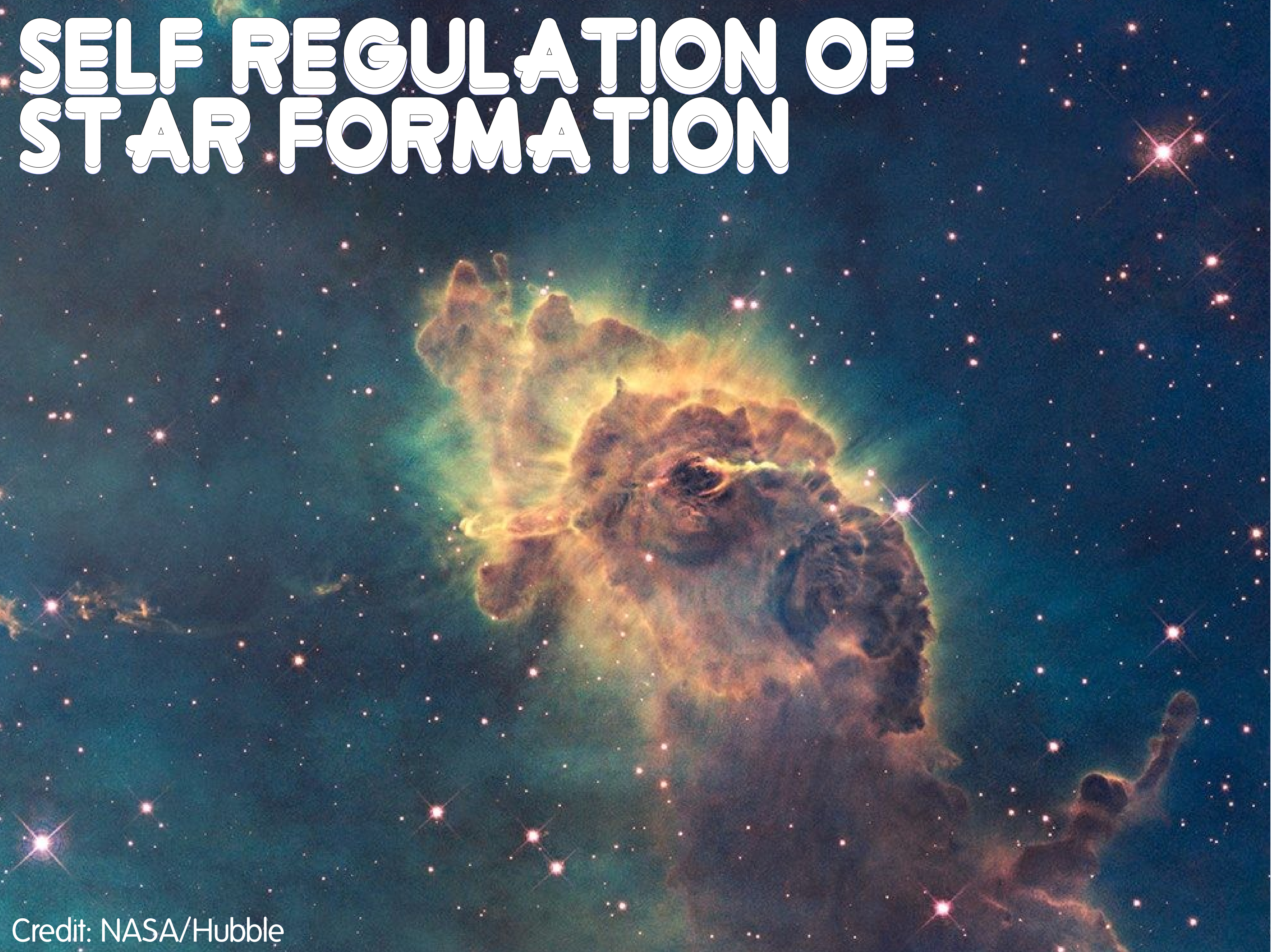
This is perhaps 2-3 times lower than other authors (Review by Thorsten Naab, in prep)

Why? Iffrig & Hennebelle 2015 use similar code and initial conditions and get better agreement with others

Some hypotheses (see Geen et al, 2016)
→ Explodes in/next to gas > 10^4 cm^{-3}
→ Shock cools within 1-5 pc, inside cloud
→ High ram pressure inside cloud
→ Out-of-equilibrium ionised gas cooling
→ Difficulty resolving cooling scales in very dense gas
→ Signal from supernova is too weak compared to total cloud momentum

Still lots of open questions
Supernovae very sensitive to conditions
Be careful with your sub-grid models!

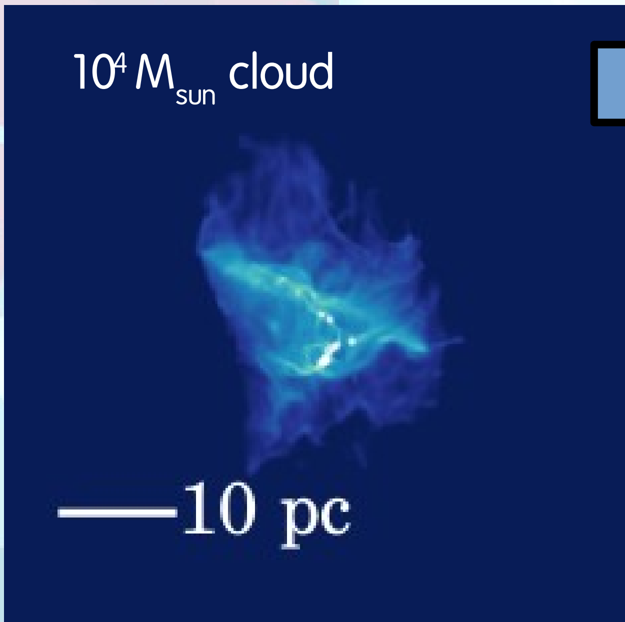
SELF REGULATION OF STAR FORMATION



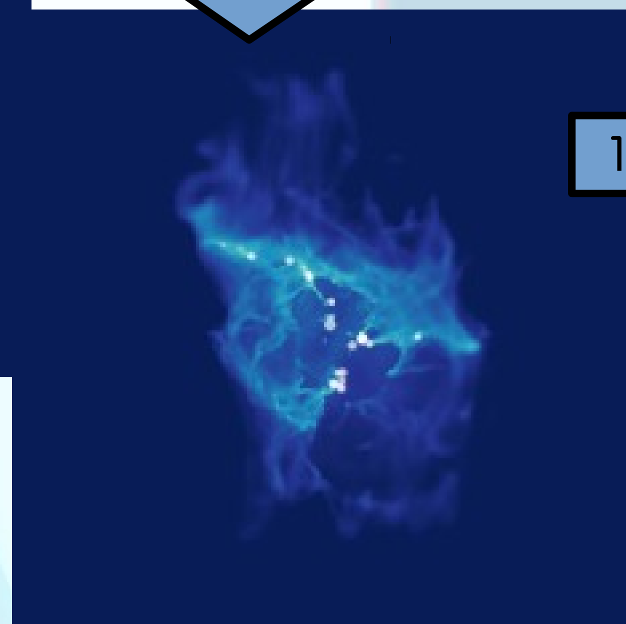
Credit: NASA/Hubble

CLOUD SELF DESTRUCTION WITH UV

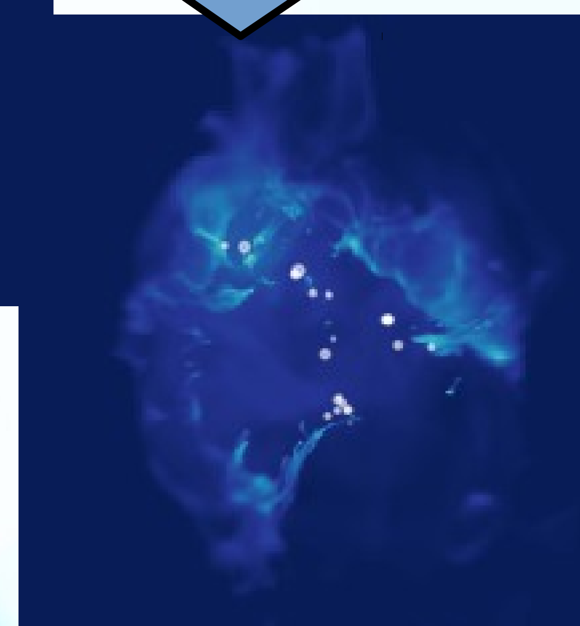
(for other work with feedback on sinks, see review by Dale, 2015)



1 freefall time



1 freefall time



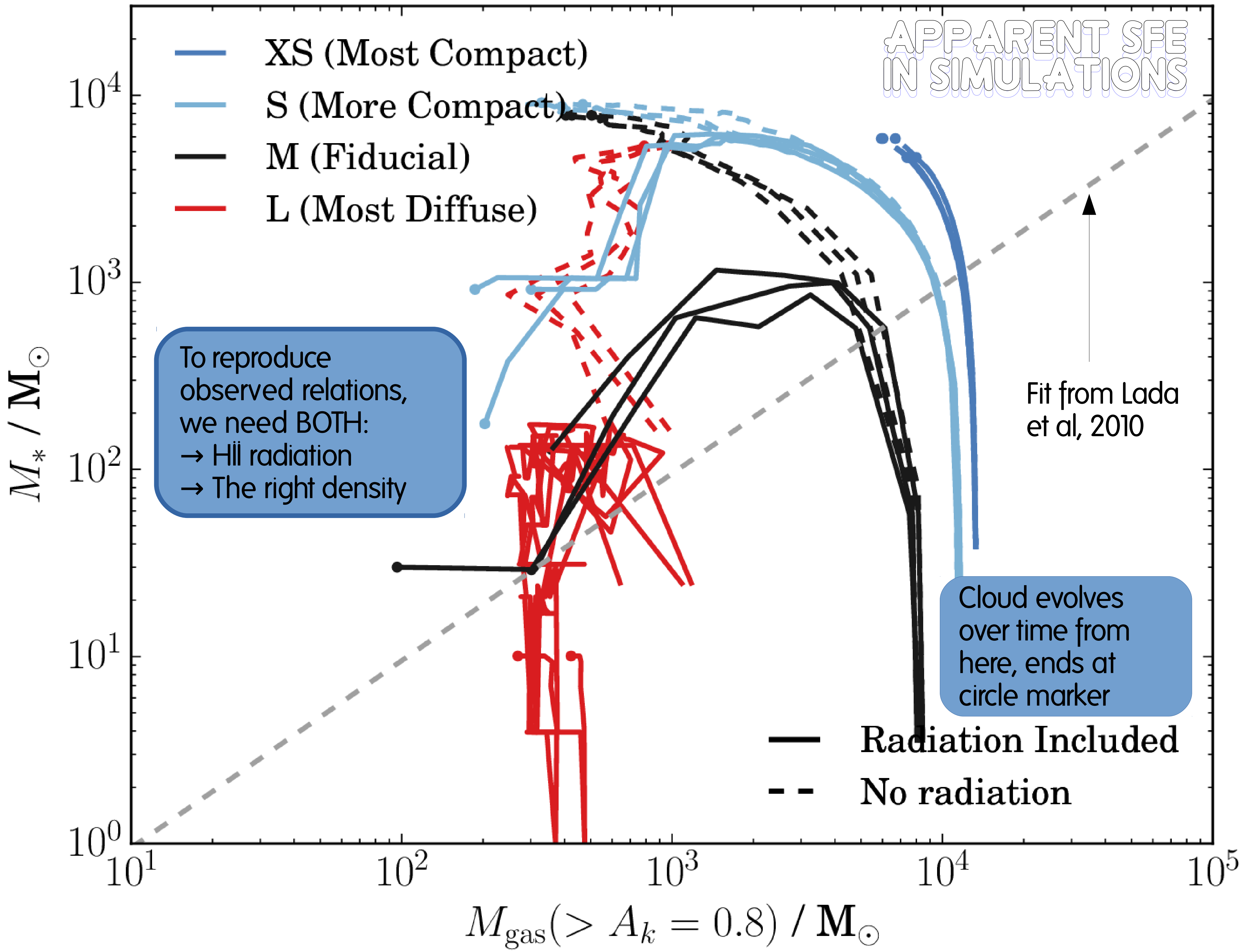
Sink particles accrete gas above Jeans limit

Particles emit radiation ($S_* = 9 \times 10^{46}$ /s / M_{sun})

- Sinks form in dense peaks
- More radiation from stars as gas is accreted
- Cloud is dispersed, accretion cut off
- Star formation ends

How does this compare to observational estimates of SFE?

- Take column density maps
- Use 6 lines of sight
- Finds stars inside $A_k = 0.1$



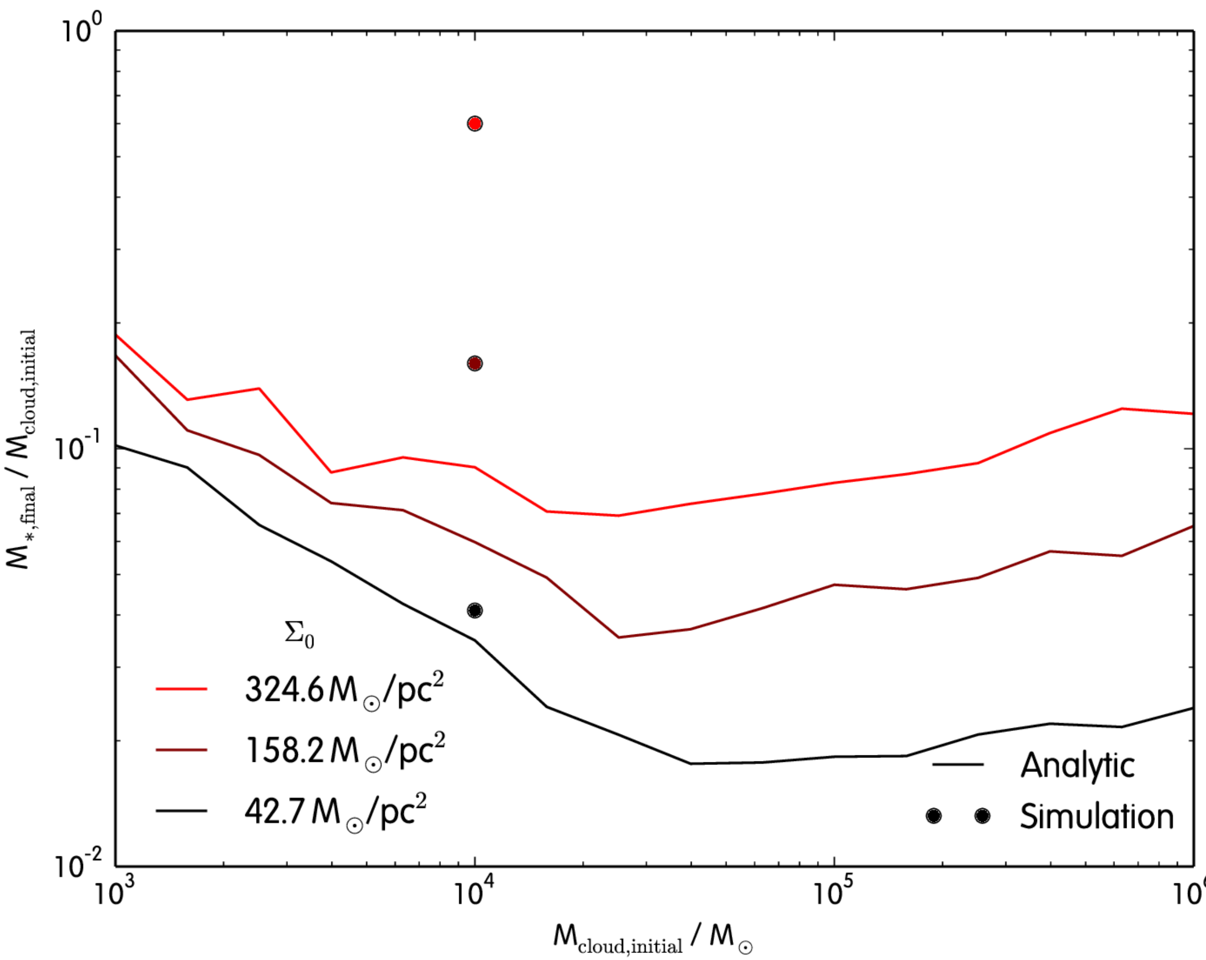
APPARENT SFE IN SIMULATIONS
XS (Most Compact)
S (More Compact)
M (Fiducial)
L (Most Diffuse)
To reproduce observed relations, we need BOTH:
→ HII radiation
→ The right density
Fit from Lada et al, 2010
Cloud evolves over time from here, ends at circle marker
Radiation Included
No radiation
M_* / M$_\odot$
$M_{gas}(> A_k = 0.8)$ / M$_\odot$
10^0
10^1
10^2
10^3
10^4
10^5

ANALYTIC MODELLING

With Antoine Verliat (masters student this summer with Patrick Hennebelle)

Some success explaining expansion of HII regions with constant photon sources (Geen et al 2015a,b, 2016)

Can we extend this to explaining the regulation of star formation inside molecular clouds?



Fairly easy to get ~1 to 10% SFE (star formation efficiency), but accurate predictions are harder...

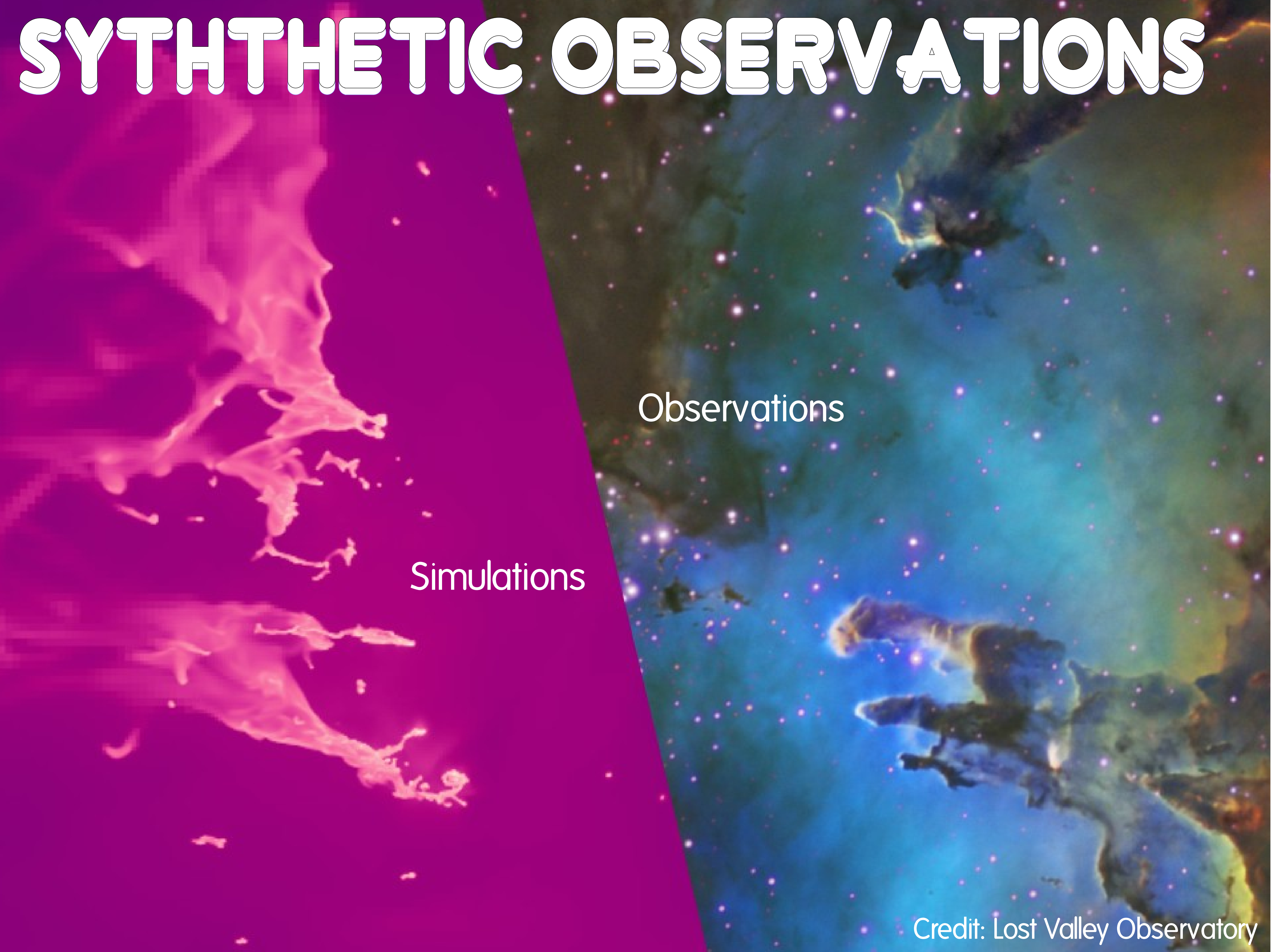
Open questions:

- How best to compare to simulations?
- What does the analytic model mean?
- Can we be sure of our results? i.e. are they degenerate with another way of getting the same SFE?

More work to be done

Feedback cycles in astrophysics are complex spatial, multivariate problems to describe precisely (quantitatively and qualitatively)

SYTHTHETIC OBSERVATIONS



SYTHTHETIC OBSERVATIONS

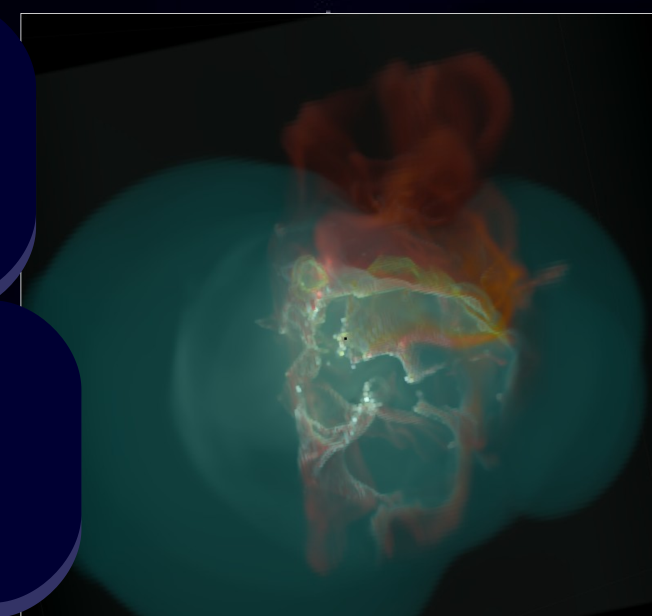
New project at İTA, Heidelberg

Couple OPİATE by Eric Pellegrini to RAMSES
(Optimized Post-processing İterative Approach To Emissivities)

Multi-variate calculations of emission/extinction
Allow synthetic observations of simulations
İmprove cooling of photoionised gas

Anticipated projects:
- Explore geometry & evolution of observed HII regions
- Model wider spectrum of UV photons in RAMSES
- İnsights into star formation laws (e.g. Lada+ 2010)

3D tools for RAMSES outputs:
- Use programmable shaders on graphics cards
- Compute emission/extinction maps in real time


Cyan: İonised, Orange: Neutral

THOUGHTS

We use RAMSES to model UV photoionisation and supernovae in star-forming regions

The combination of simulations and analytic theory is vital to understanding feedback

Exciting new possibilities for coupling simulations and observations

Still a lot to understand on the small scale before it can be applied to galaxies

THANK YOU

ANY QUESTİONS?

References:
GEEN, HENNEBELLE, TREMBLİN, ROSDAHL (2015)
GEEN, HENNEBELLE, TREMBLİN, ROSDAHL (2016)

EXTRA SLIDES

HIDDEN SECRETS

MODELLING HII REGIONS

In the most extreme case, if v_{esc} ~ 10 km/s (sound speed in ionised gas) front cannot expand beyond the initial Strömgren radius (Dale, 2012)

But in order for the ionisation front to escape the cloud, we need the stall radius to be larger than the cloud. v_{esc} can be lower and still create an ultracompact HII region.

Assuming a uniform, virialised cloud, we need at least this many photons:

$$S_* > 4\times10^{48}s^{-1}\left(\frac{\Sigma_0}{100\mathrm{M}_\odot\mathrm{pc}^{-2}}\right)^{5/2}\left(\frac{M}{10^5\mathrm{M}_\odot}\right)^{3/2}$$

Photon emission rate

Surface density of cloud

Mass of cloud

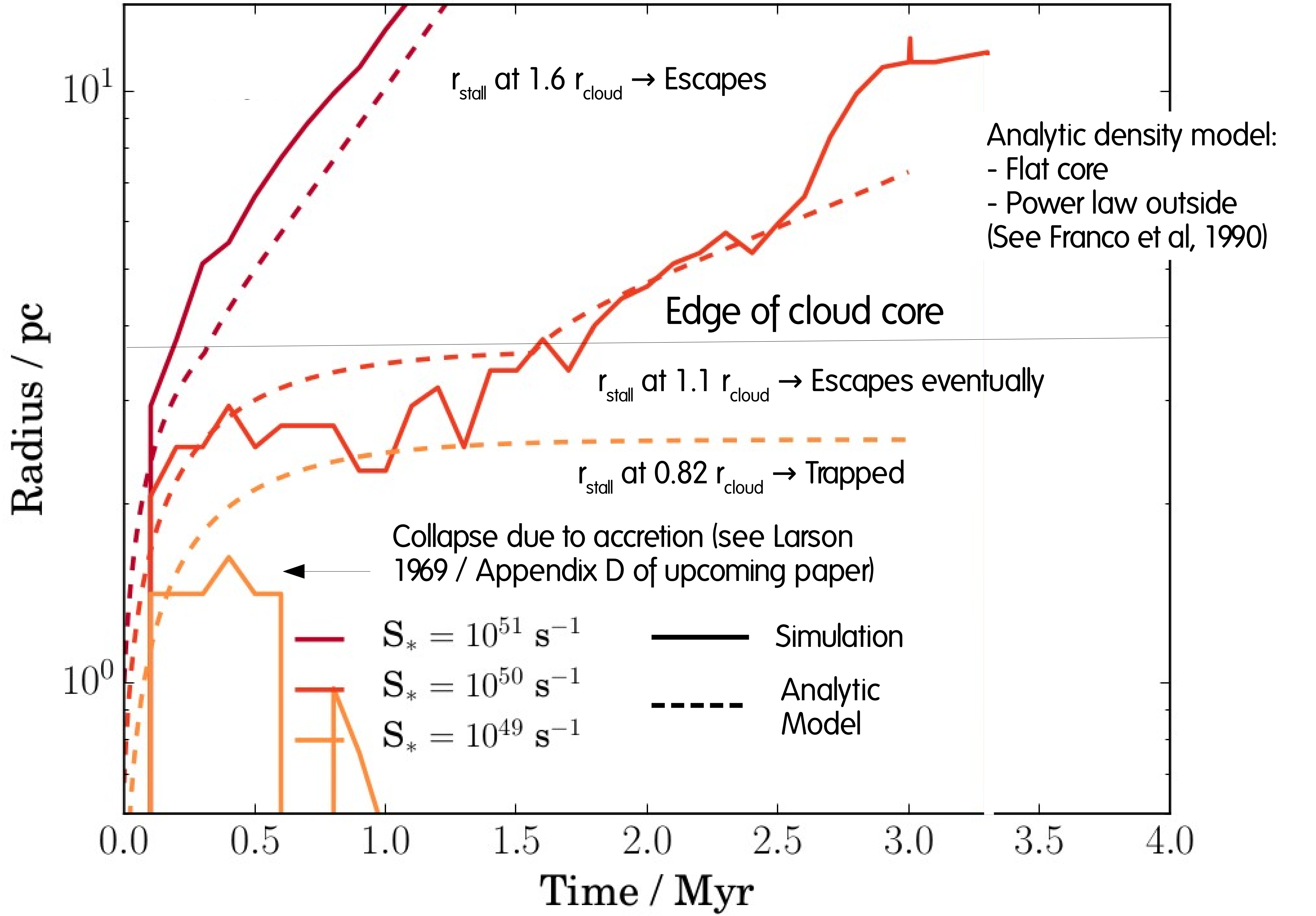
See Geen, Hennebelle, Tremblin & Rosdahl (2015) for details

If we assume a population of stars, this corresponds to a mass in stars of:

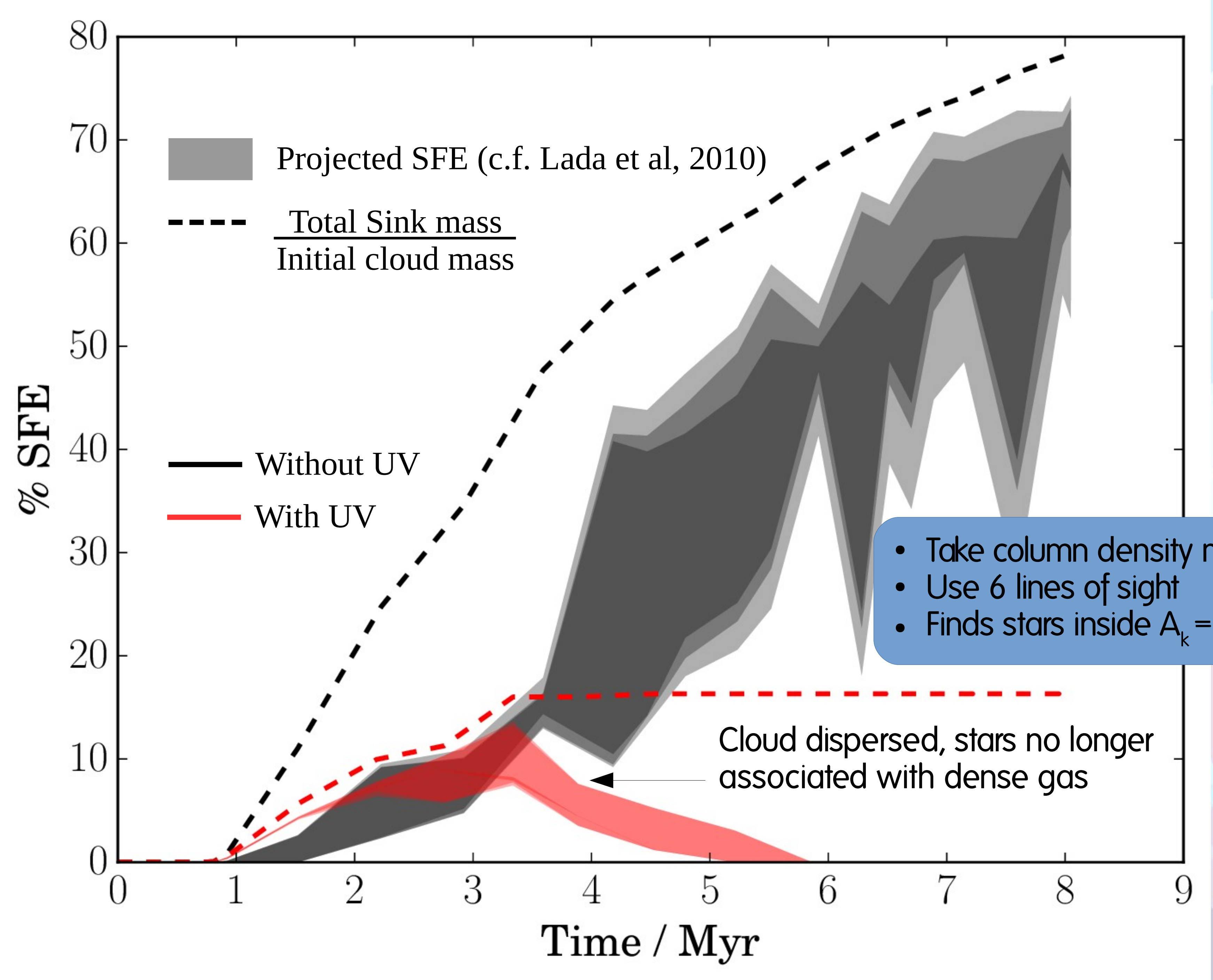
$$\frac{M_*}{M_{gas,0}} > 0.045\%\left(\frac{\Sigma_0}{100\mathrm{M}_\odot\mathrm{pc}^{-2}}\right)^{5/2}\left(\frac{M}{10^5\mathrm{M}_\odot}\right)^{1/2}$$

So what does this mean in practice? Let's look at an example from simulations:

VARYING PHOTON EMISSION RATE

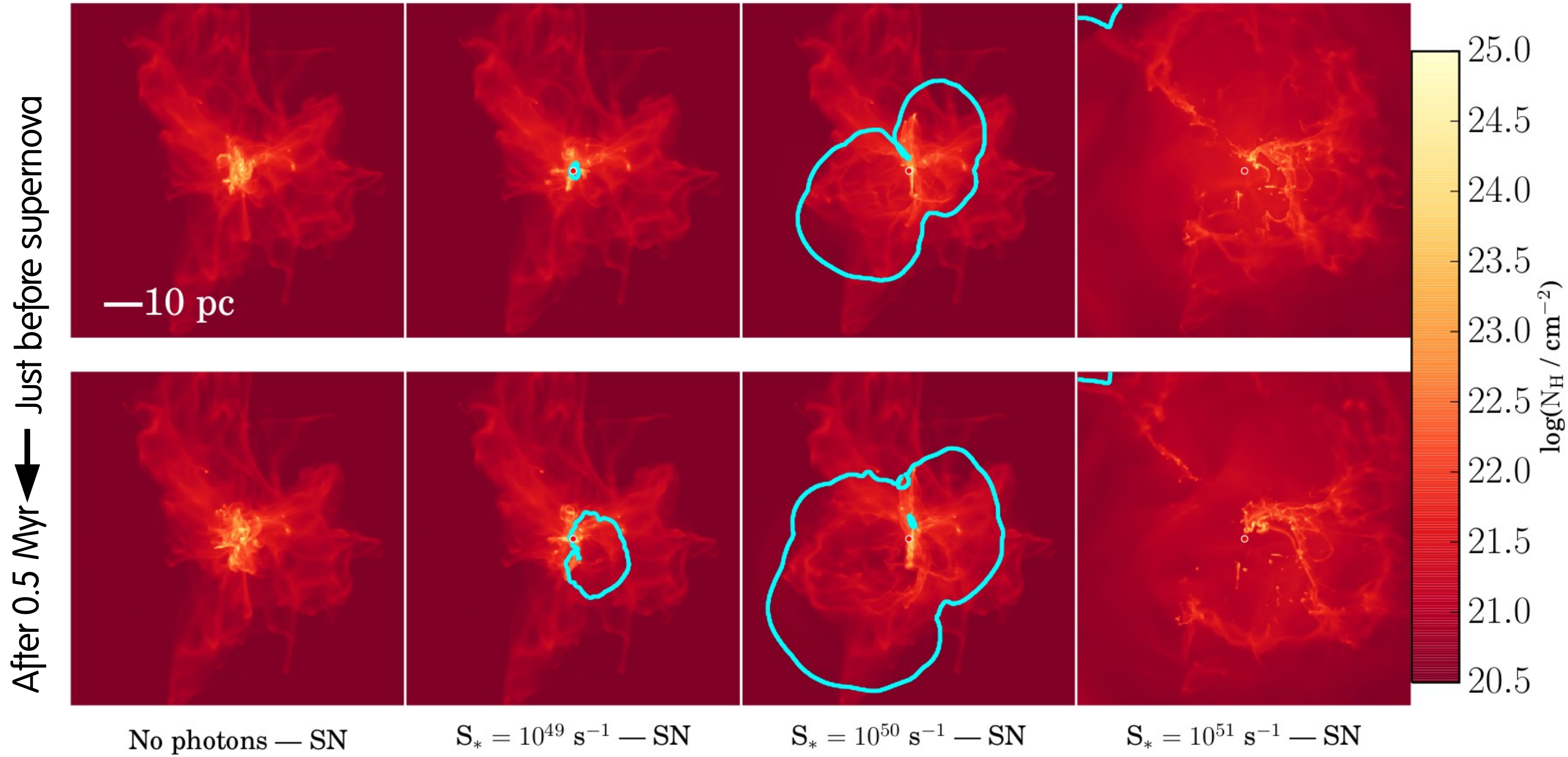


APPARENT SFE IN SIMULATIONS



- Take column density maps
- Use 6 lines of sight
- Finds stars inside $A_k = 0.1$

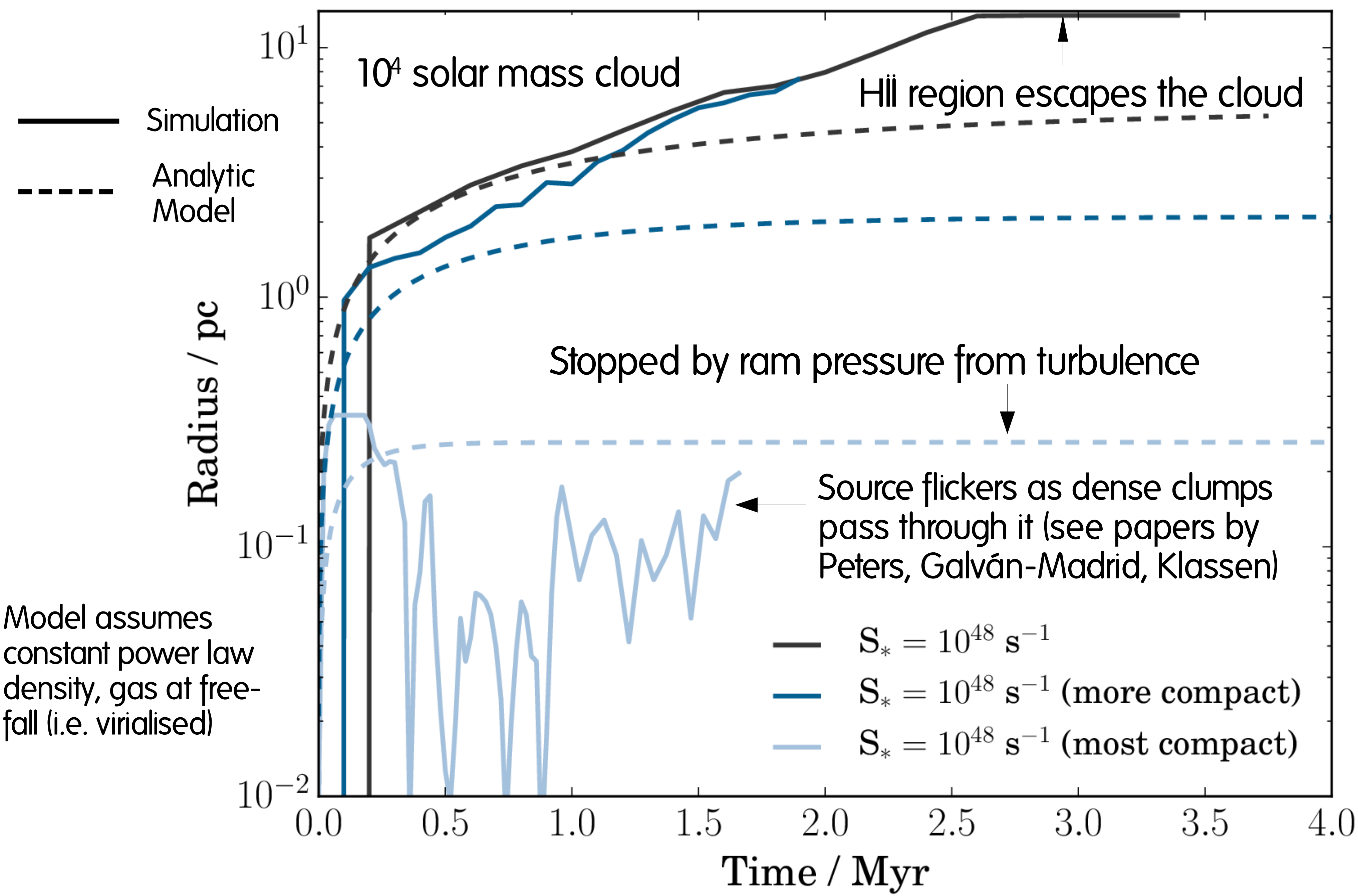
SUPERNOVAE IN CLOUDS



Following the first supernova from a massive star in a 10^5 solar mass cloud
Evolve cloud for 2.5 Myr, then add UV radiation for 3 Myr, then inject a supernova

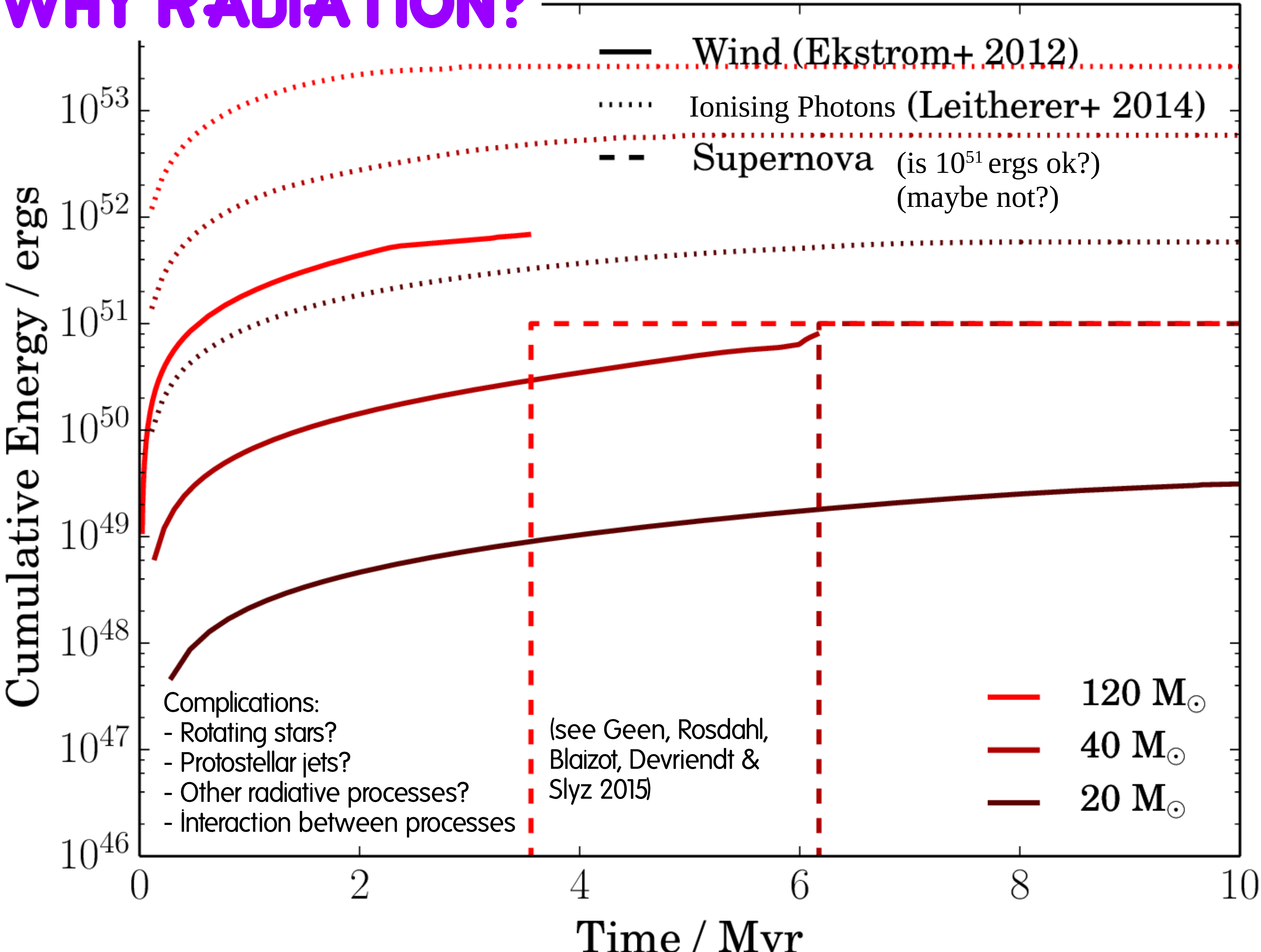
See also
Iffrig & Hennebelle 2015 (similar setup without HII radiation)
Walch & Naab 2015 (with HII radiation, less turbulence)

VARYING CLOUD DENSITY

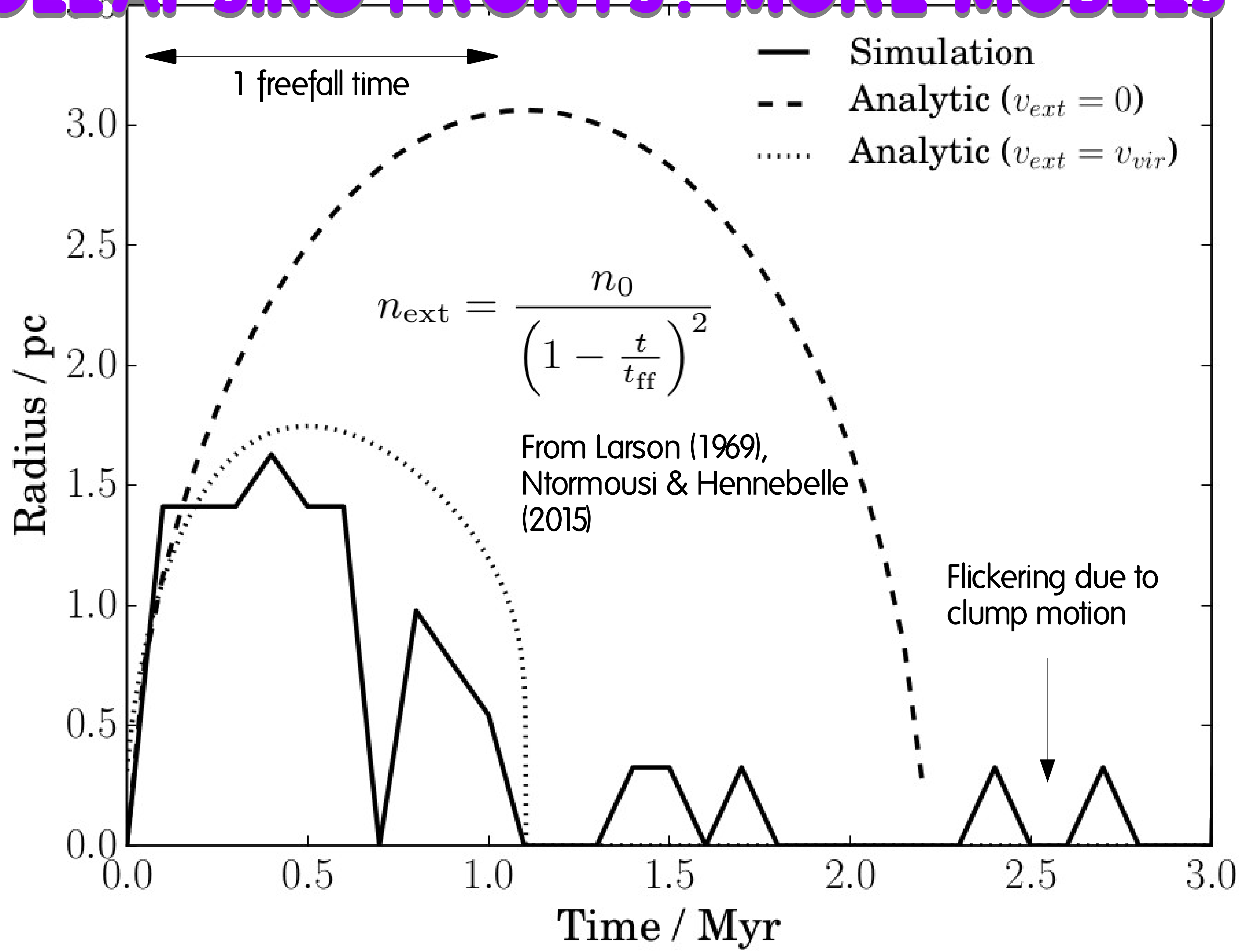


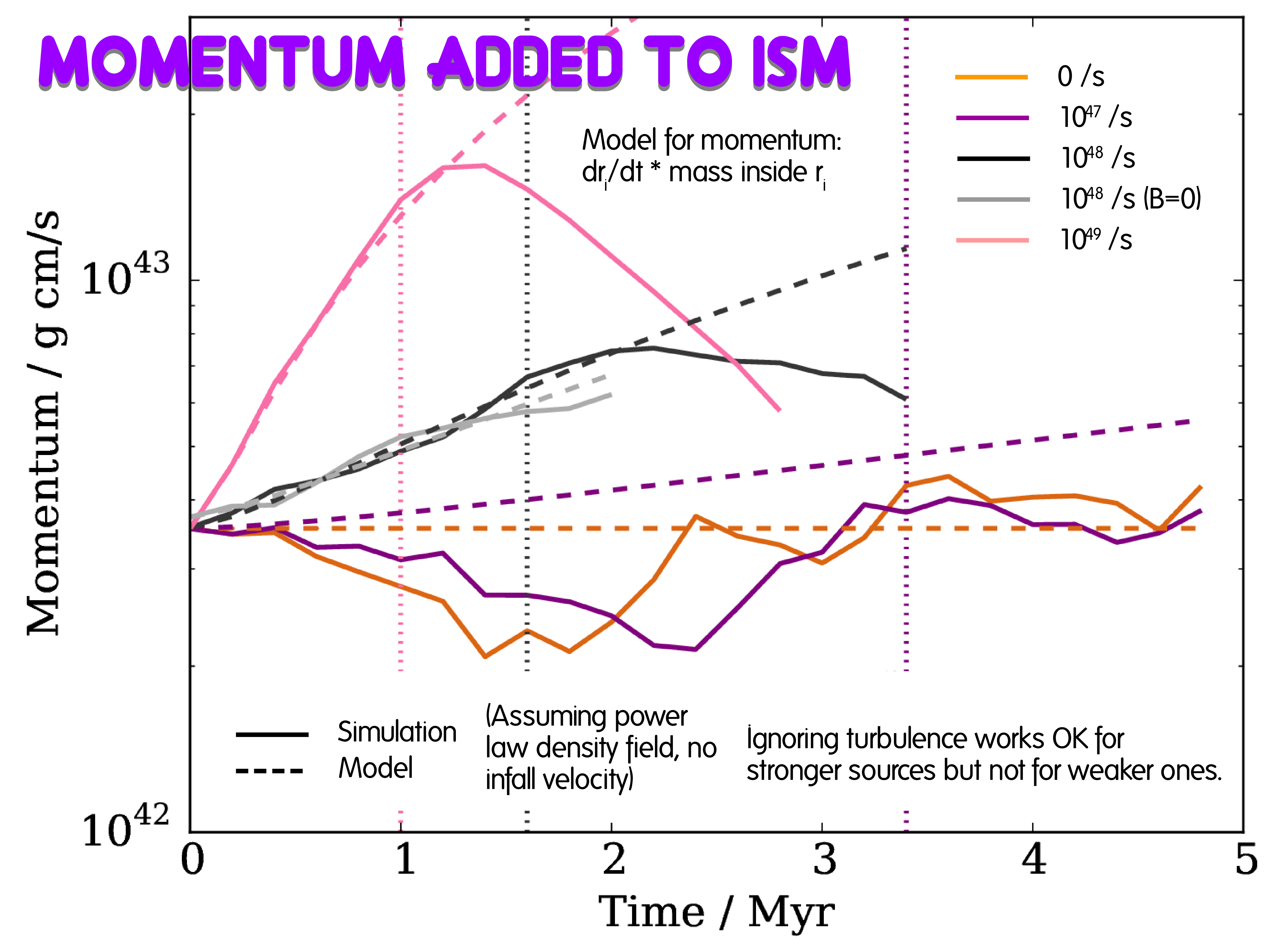
Model assumes constant power law density, gas at free-fall (i.e. virialised)

WHY RADIATION?



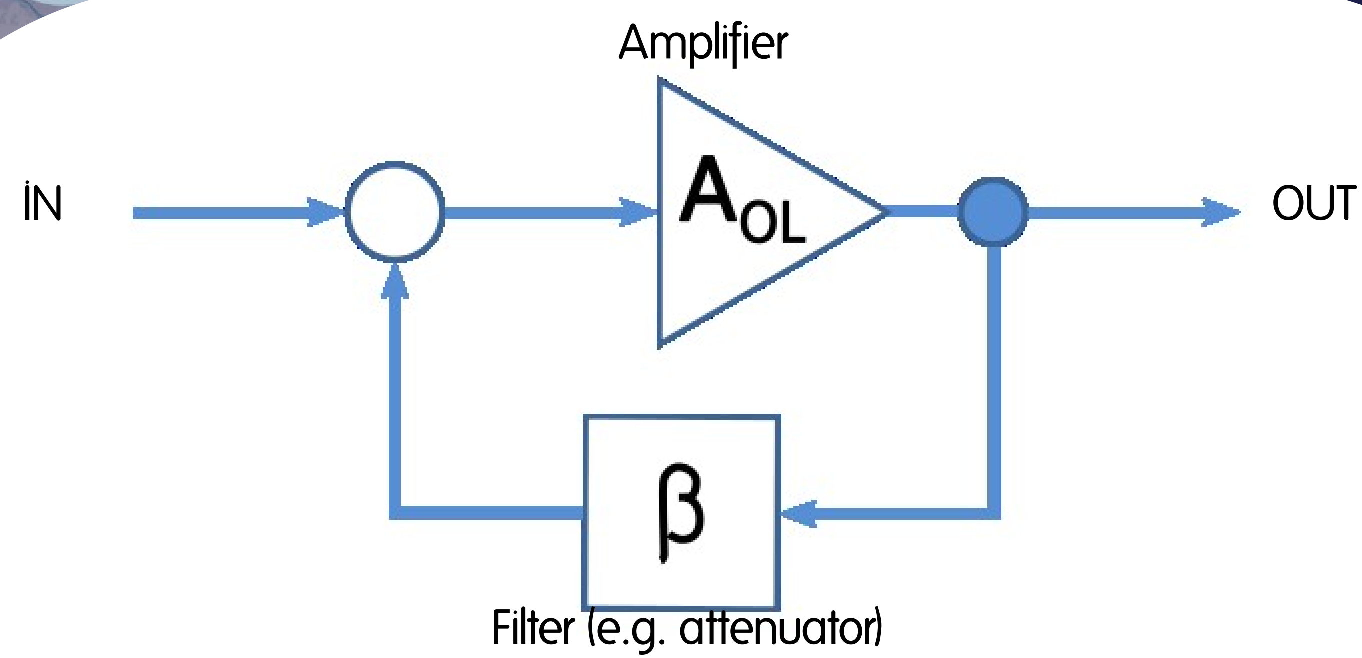
COLLAPSING FRONTS? MORE MODELS





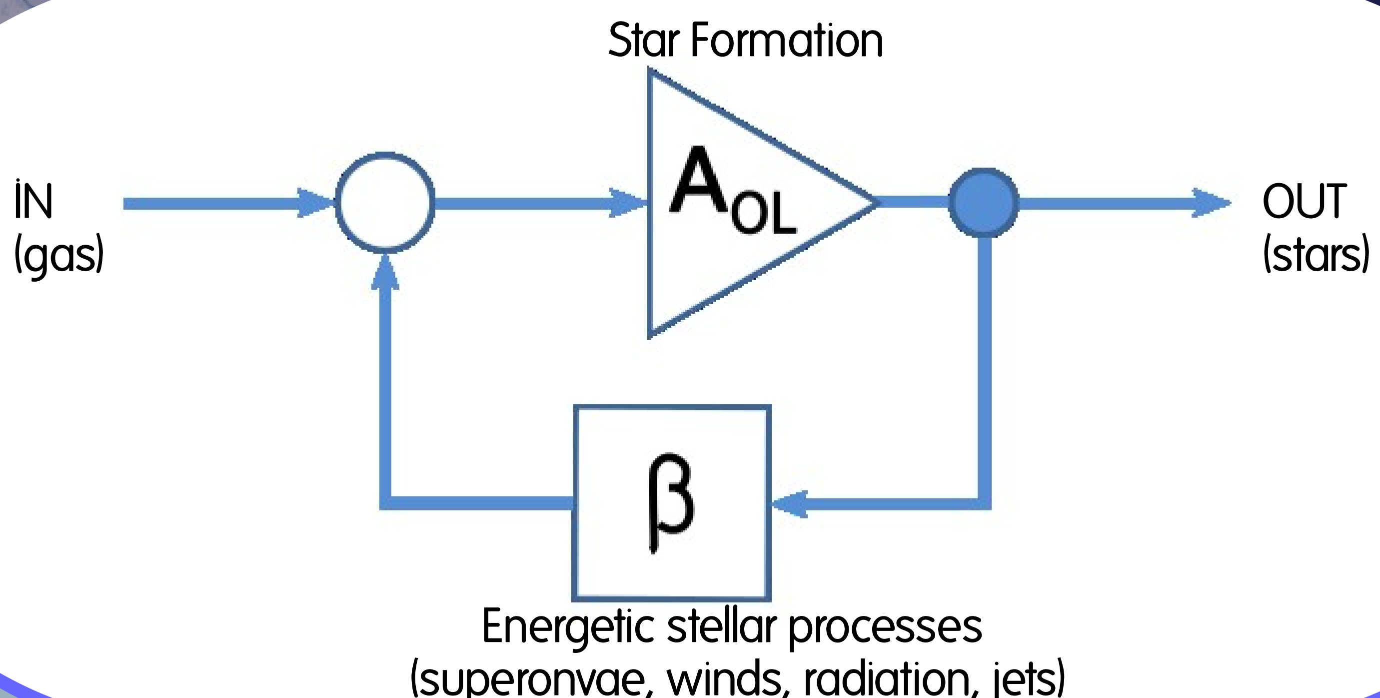
MOMENTUM ADDED TO ISM
0 /s
10^47 /s
10^48 /s
10^48 /s (B=0)
10^49 /s
Model for momentum:
dr_i/dt * mass inside r_i
Simulation
Model
(Assuming power
law density field, no
infall velocity)
Ignoring turbulence works OK for
stronger sources but not for weaker ones.
Momentum / g cm/s
10^43
10^42
0
1
2
3
4
5
Time / Myr

FEEDBACK



Can be **positive** (feedback increases signal strength)
or **negative** (feedback decreases signal strength)

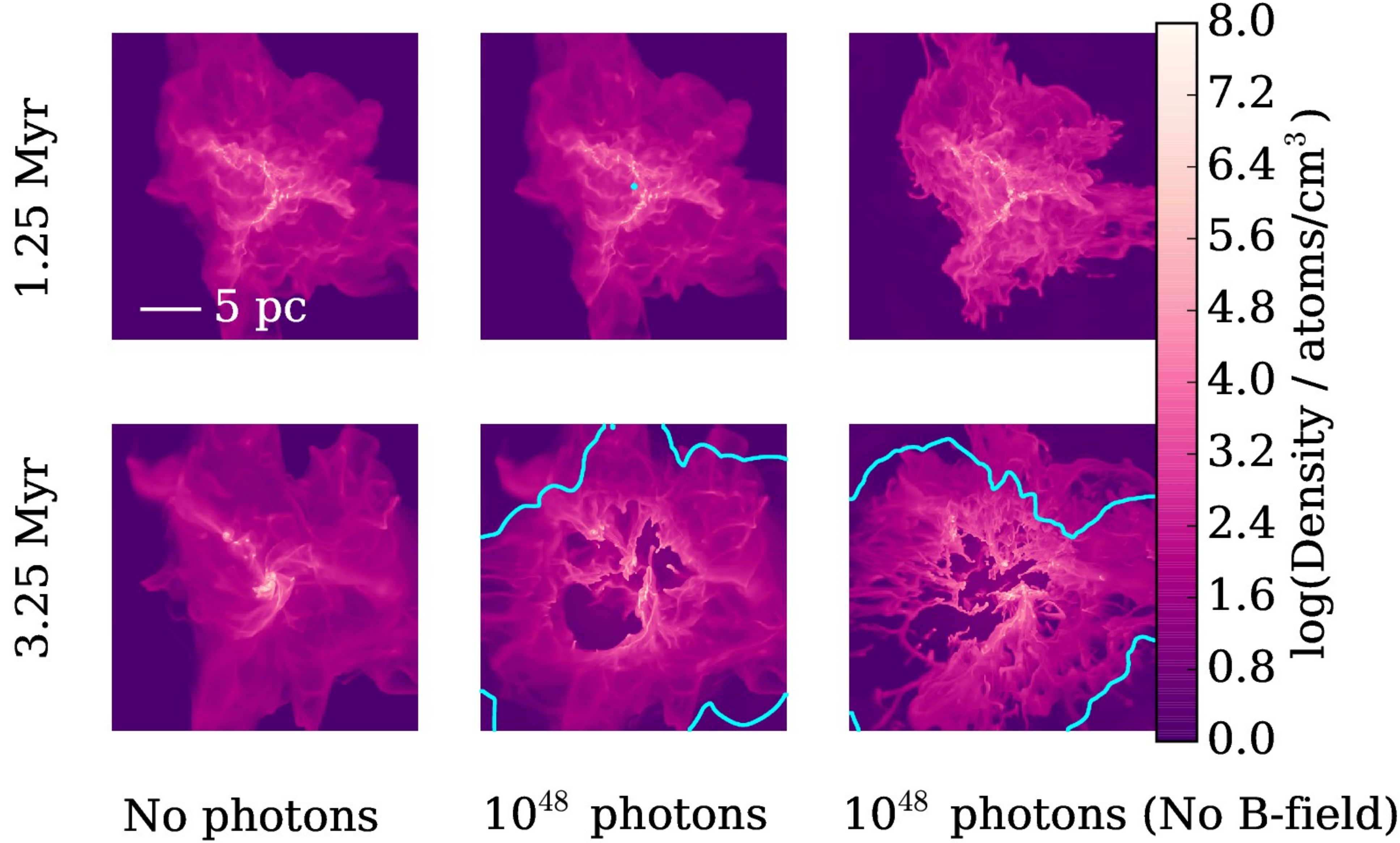
FEEDBACK



Can be **positive** (shock compression, metals from SNe → efficient cooling, source of turbulence) or **negative** (cloud destruction, galactic winds)

MAGNETS? HOW DO THEY WORK?

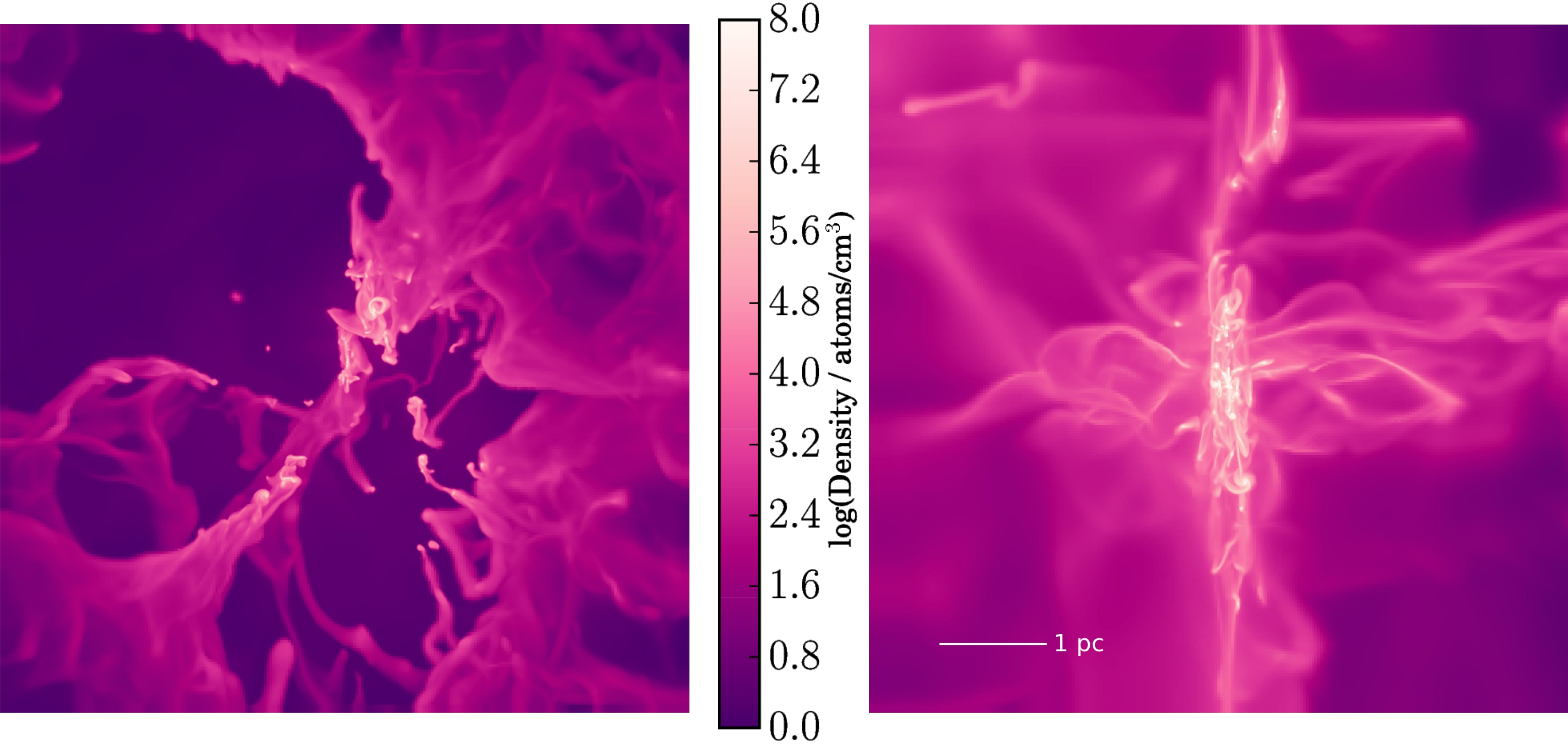
See also papers by Patrick Hennebelle and collaborators



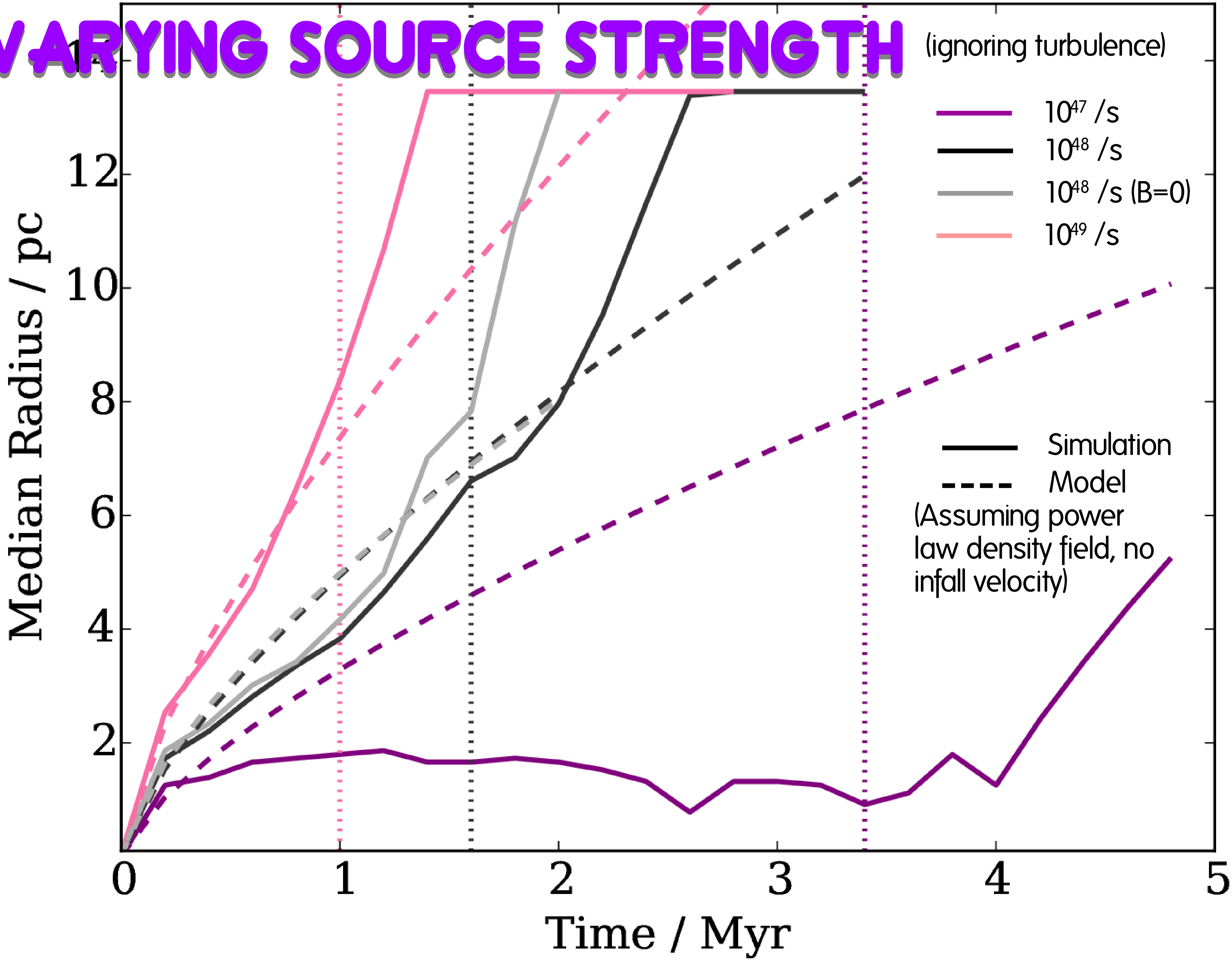
VARYING CLOUD DENSITY

Our "standard" cloud

Most compact cloud (1/8 freefall time)



VARYING SOURCE STRENGTH



POSITIVE FEEDBACK?

Our ionisation front causes mass to pile up around it as it expands

Can we trigger star formation in this dense shell?

Elmegreen (1994) says yes! If this is true...

$$\frac{\pi G \rho_0}{3 c_0} > \frac{8^{1/2} V_{\mathrm{shell}}}{r_{\mathrm{shell}}^2}$$

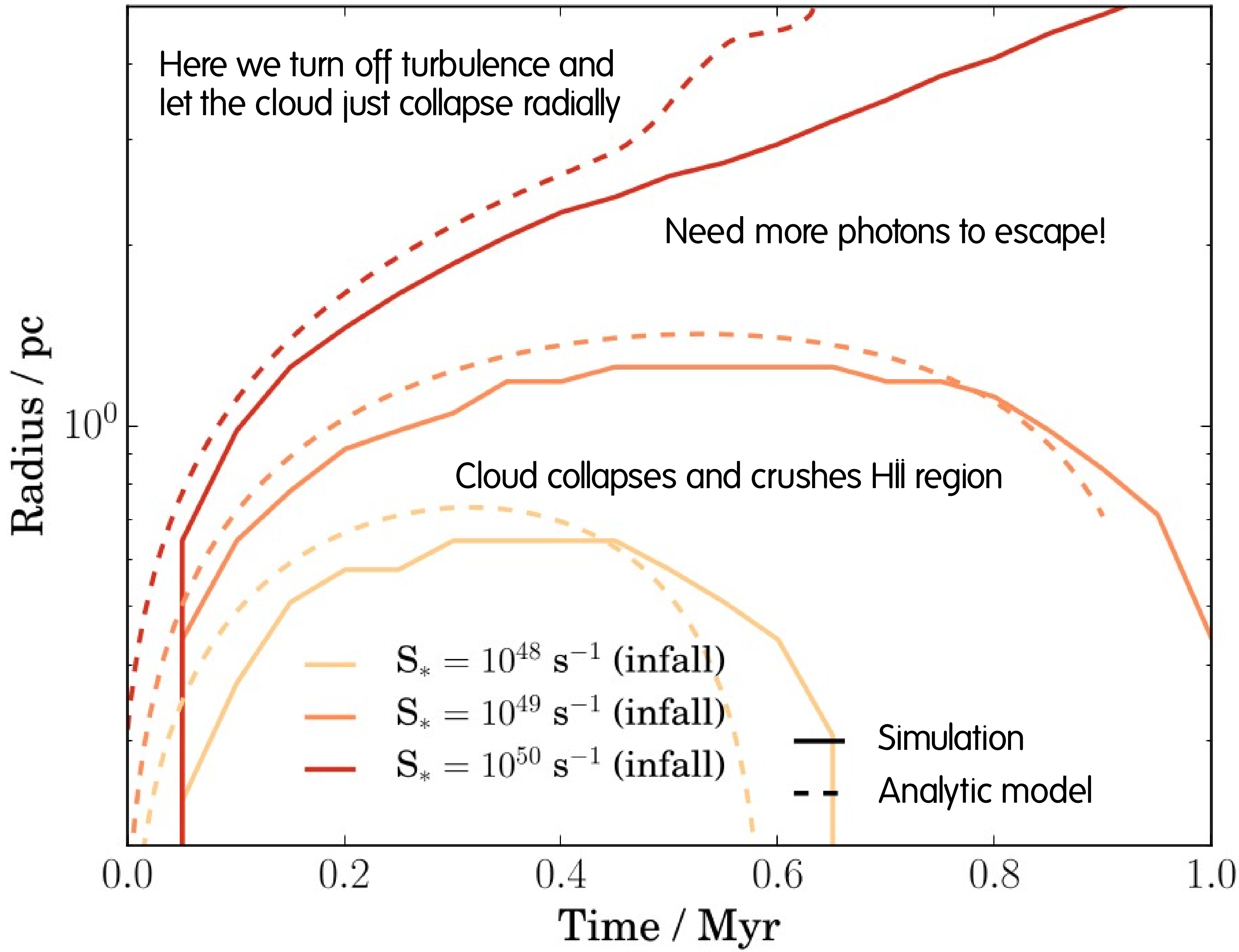
In our simulations this more or less means

$$r_{\mathrm{shell}} t > 100 \ \mathrm{pcMyr}$$

Which is just outside the time/size of our simulations

So we don't see it, but it's possible!

TURBULENCE VS INFALL



NO MORE SLIDES

WE ARE DONE