CAN MASSIVE STELLAR FEEDBACK DISPERSE GIANT MOLECULAR CLOUDS?

SAM GEEN (ITA/ZAH HEIDELBERG)
WITH PATRICK HENNEBELLE
PASCAL TREMBLIN
JOAKIM ROSDAHL

BASED ON GEEN ET AL (2016)

CLOUD SELF-REGULATION

Stars form inside molecular clouds

Massive stars produce energy in a number of ways
Radiation, winds, jets, supernovae

These energetic processes heat and disperse cloud material

Competition between gravity and "feedback"

The problem is complex – turbulence, MHD, interaction between feedback processes, scales, etc

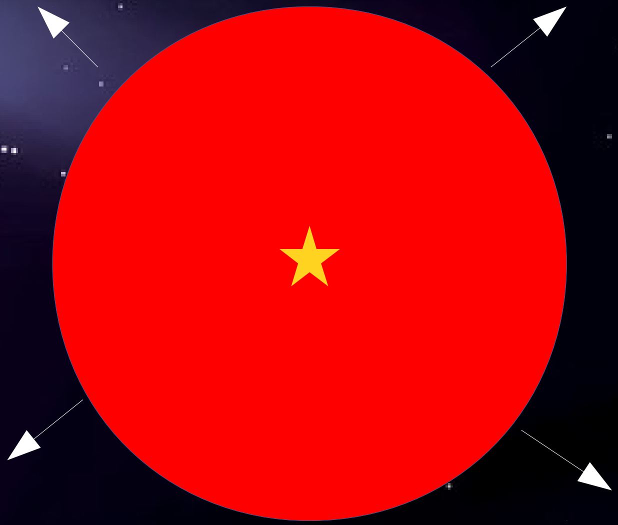
There's a reason that this is an open question spanning whole careers

Focus on **two** questions:
- Can we explain how **photoionisation** shapes the cloud?
- How does this affect **supernova** efficiency?

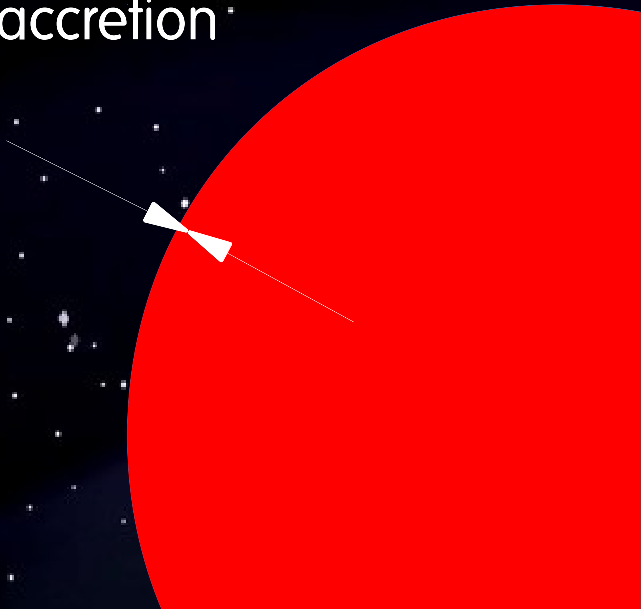
PHOTOIONISATION: THE BASICS

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 be stopped or even reversed by turbulence or accretion



See Kahn (1954), Spitzer (1978), Dyson & Williams (1980), Hosokawa (2006), Raga (2012)

PHOTOIONISATION: THE BASICS

We can solve the expansion algebraically (see Raga+ 2012)

$$n_0(\dot{r_i} + v_0^2) = n_i c_i^2$$

Ram pressure in neutral gas
(ionisation front expansion r_i,
external velocity v_0
external density n_0)

Thermal pressure
in ionised gas
(c_i ~ 10 km/s,
ionised gas density n_i)

(See paper or ask me
for derivations)

We can solve with this (assuming also photoionisation equilibrium, a turbulent, virialised cloud)

This gives us:

$$\frac{\dot{R}}{R} = 0.86 \frac{\alpha_{vir}^{1/2}}{t_{ff}} \left(R^{-3/4} - 1 \right)$$

R is a scale-free radius, r_i divided by the "stall" radius, where $dr_i/dt \rightarrow 0$, so $R \rightarrow 1$

Ionisation fronts expand on a timescale of the freefall time in the cloud and its virial parameter

OUR SIMULATIONS

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

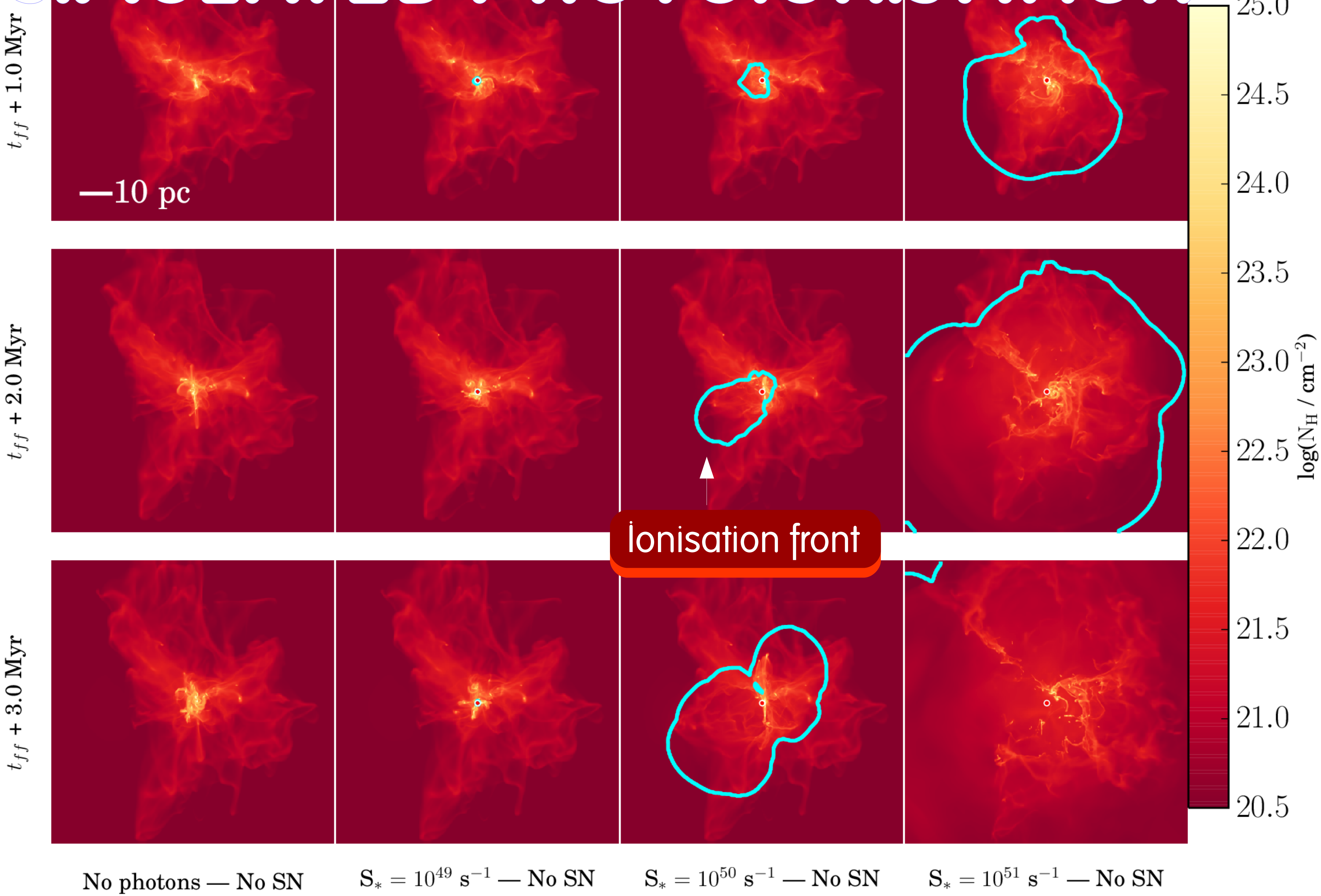
Take an **isothermal gas sphere** of a given mass
Include Kolmogorov **turbulence, self-gravity, B-field**

Put it in a box, refine in the central volume and on Jeans unstable cells up to some maximum resolution

EITHER put in a **fixed source** of energy (winds, radiation, supernovae) → focus of this talk
OR form "**sink particles**" - particles that accrete dense material around them (see paper on arXiv)
Sink particles emit photons – treat cluster as a population and distribute photons across sinks
Trace ionising photons with M1 method → photons are a fluid on the AMR grid

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

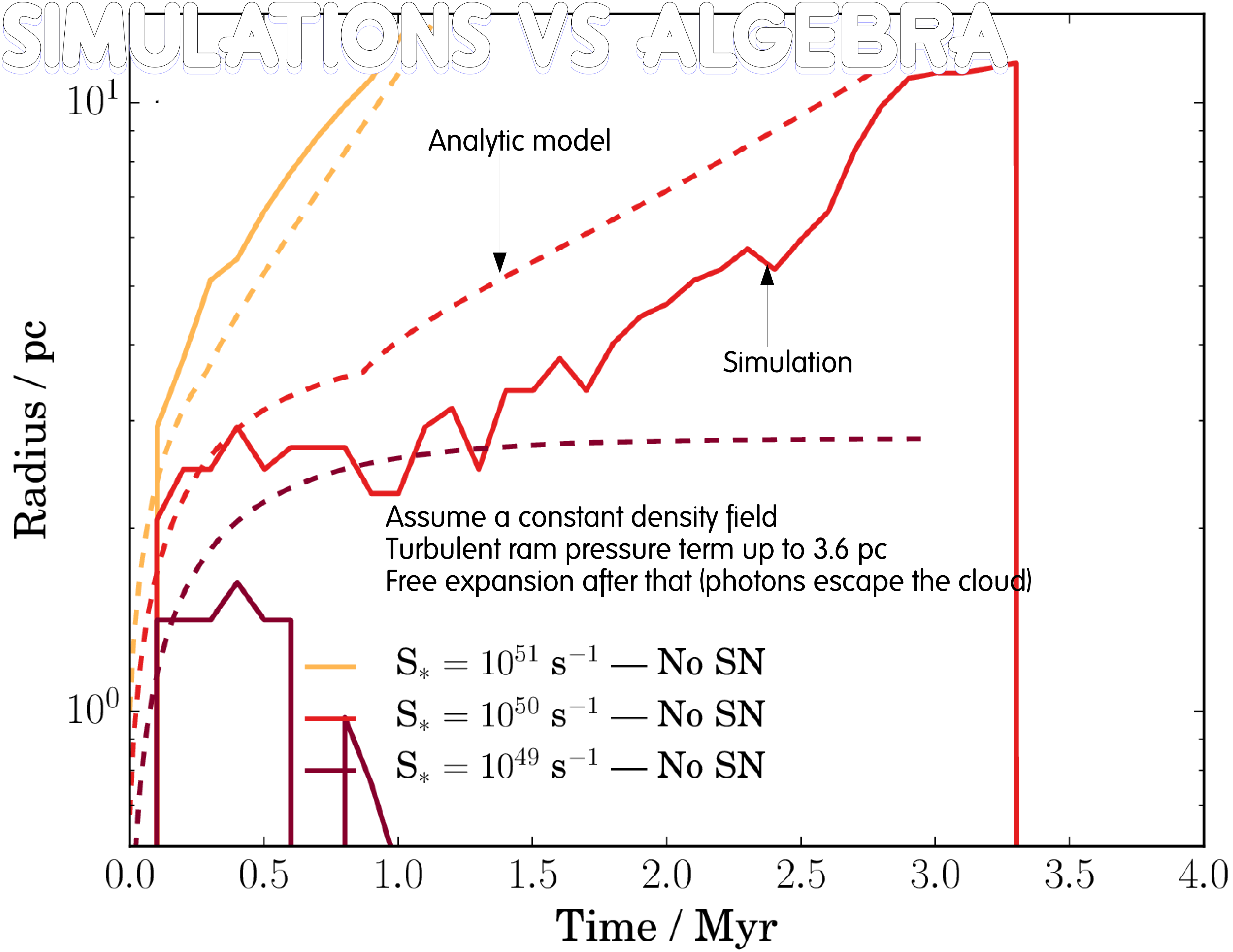
SIMULATED PHOTOIONISATION



Ionisation front

Cluster Mass: 0.1% Mcloud 1% Mcloud 10% Mcloud

SIMULATIONS VS ALGEBRA

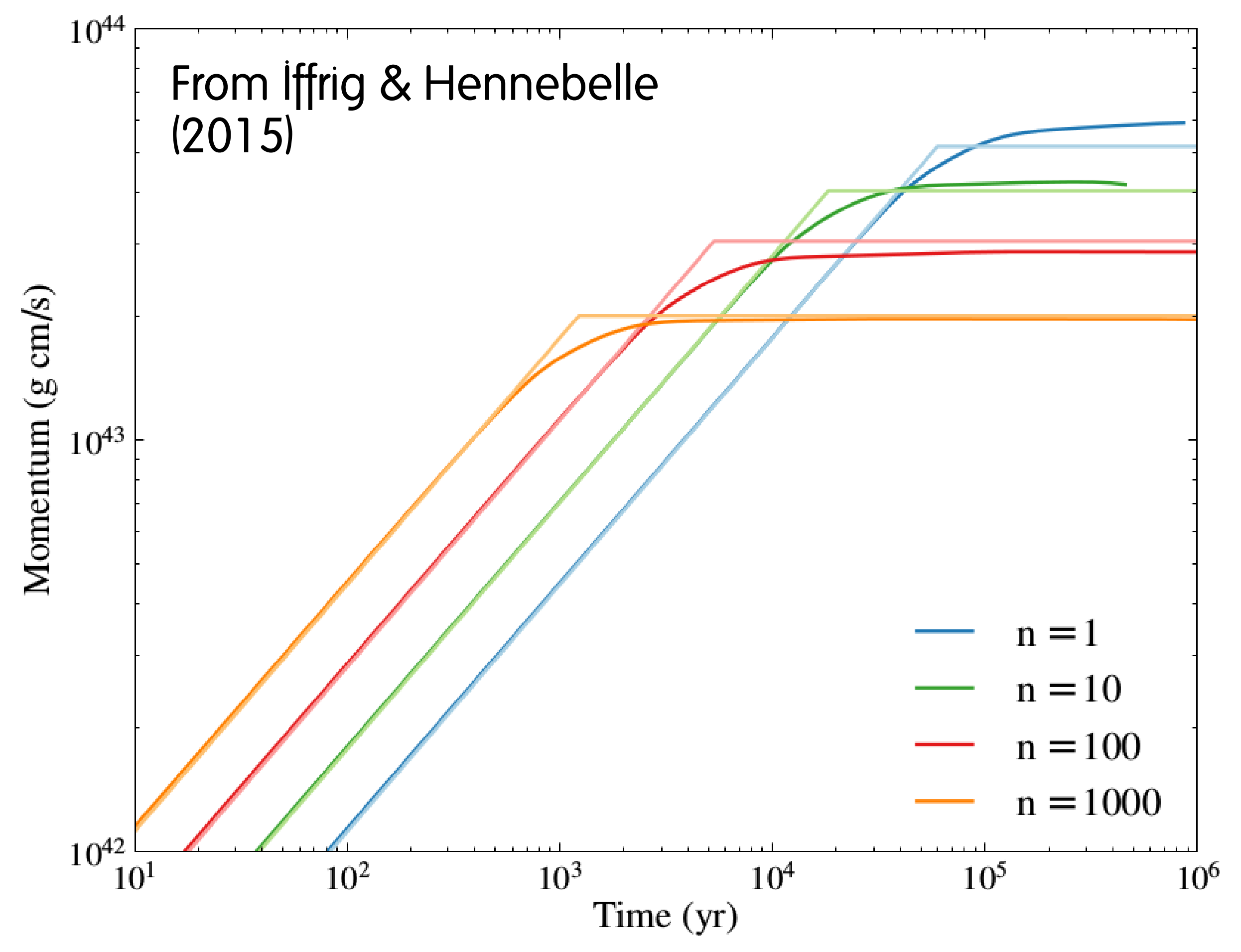


Assume a constant density field
Turbulent ram pressure term up to 3.6 pc
Free expansion after that (photons escape the cloud)

SUPERNOVAE

Lots of work has been done on supernovae
Early adiabatic phase follows Sedov / Taylor solution from the 1950s
Cooling is important for supernovae – see, e.g., Chevalier 1974, Cioffi 1988, Thornton 1998, Haid 2016)

Recent simulations in complex environments by İffrig & Hennebelle (2015); Kim & Ostriker (2015); Martizzi et al. (2015); Walch & Naab (2015); Körtgen et al. (2016)

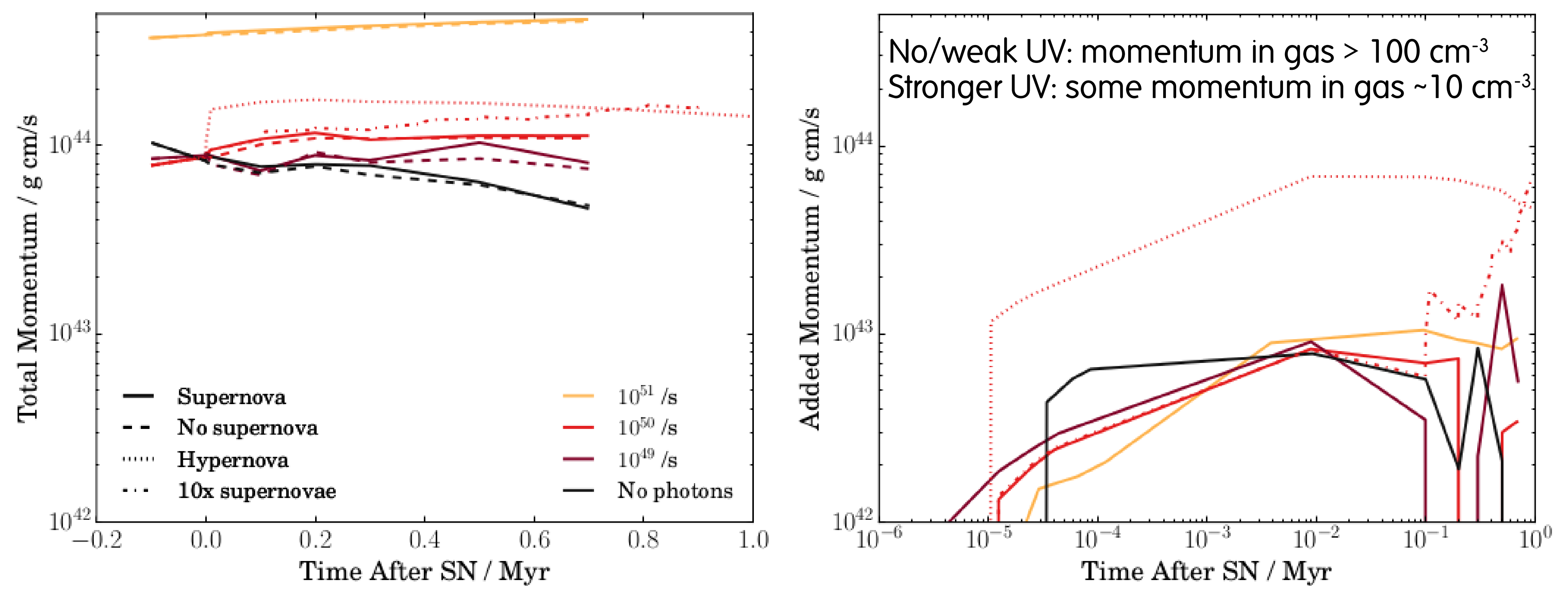

From İffrig & Hennebelle (2015)

Very simple picture:
1) Injection of energy
2) Momentum goes up:
> $E = \frac{1}{2}mv^2$
> As we gather mass, E = const but m goes up
mv = sqrt(2 E m)
So momentum goes up
3) Gas cools after 1 cooling time (Cox 1972)
After cooling time, shell becomes momentum conserving
4) Momentum freezes out

SUPERNOVAE

How does the environment affect the efficiency of supernovae?

In Geen+ (2016) we find less than half the momentum in other papers... (cough)



No/weak UV: momentum in gas > 100 cm^{-3}
Stronger UV: some momentum in gas ~10 cm^{-3}

It's a very dense, turbulent cloud – could be ram pressure? Evaporation of dense clumps? Resolution problems (I hope not)? Gravity? Noise from other flows in the cloud? (The whole cloud has 10x more momentum in turbulence than the supernova produces)

Other thoughts:
Supernovae happen too late to stop star formation in clouds (4-20 Myr typically)
Probably most important for the ISM pressure / galactic winds / metal enrichment

SOME THOUGHTS

Stars form in dense gas in molecular clouds.

They regulate their environment through different energetic processes

Photoionisation provides a lot of energy (at a low-ish temperature)
In clouds with a lot of turbulence, ionisation front can be trapped
Cloud less likely to be dispersed – higher SFE?

Supernovae are very inefficient in dense clouds
Pre-supernova feedback allows supernova to escape
Roughly constant momentum injection? Role of turbulence / cloud structure?

Analytic models can still explain the broad behaviour of more complex systems
Feedback loops complicate this → systems become very nonlinear
How will theorists tackle this problem in the decades to come?

THANK YOU

ANY QUESTİONS?

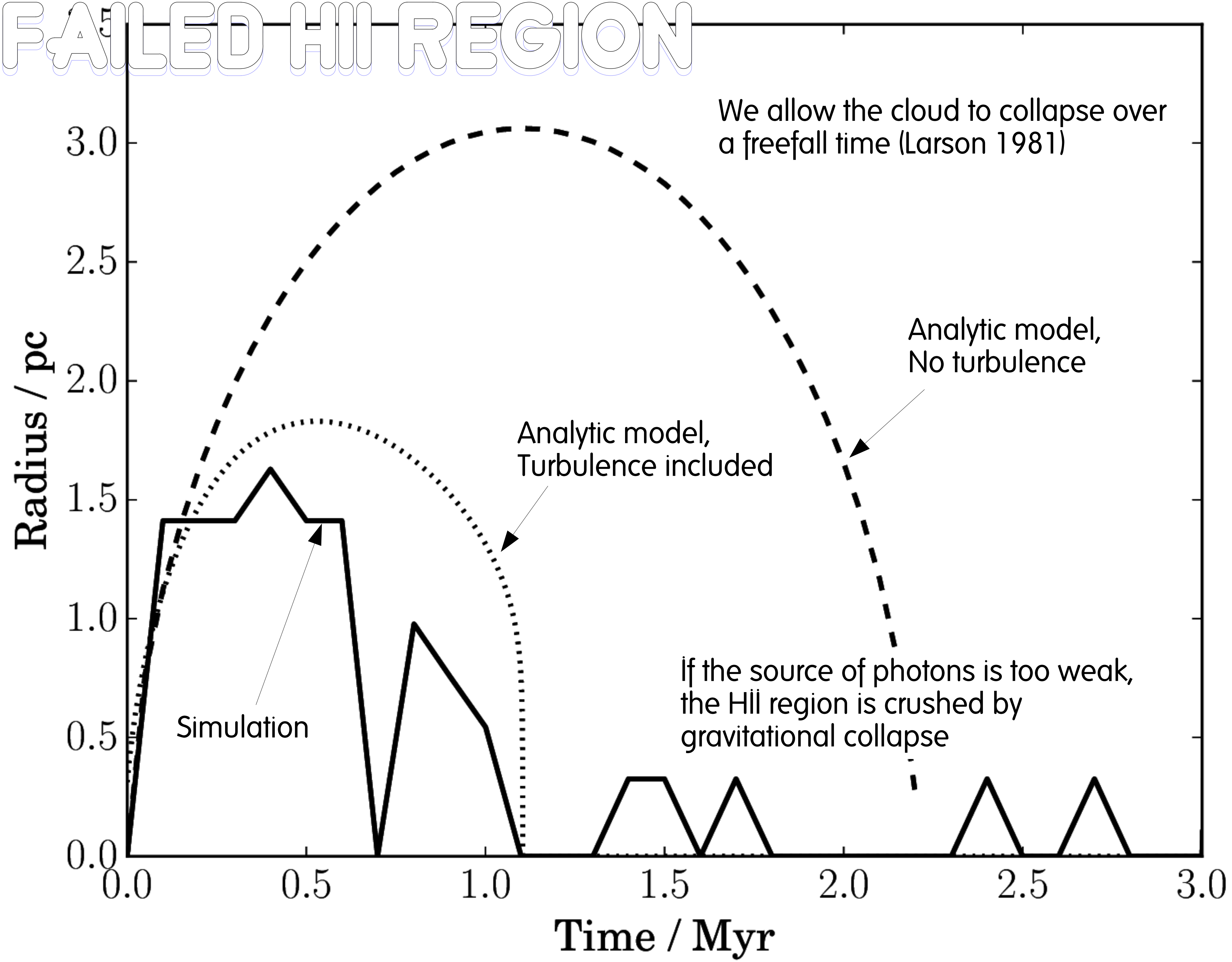
Relevant papers:

Geen et al (2015a,b, 2016)

EXTRA SLIDES

HİDDEN SECRETS

FAILED HII REGION



We allow the cloud to collapse over a freefall time (Larson 1981)

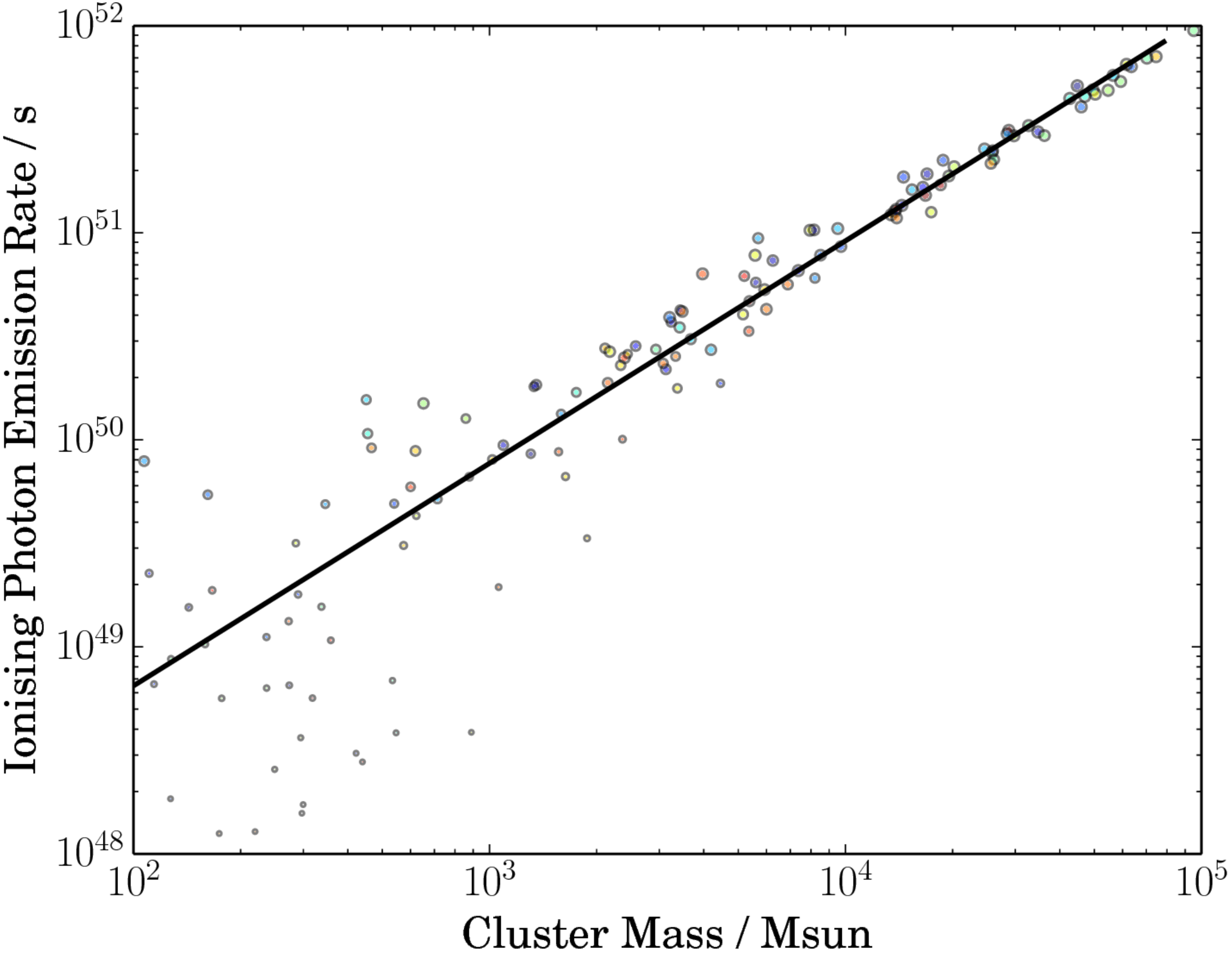
Analytic model, No turbulence

Analytic model, Turbulence included

Simulation

If the source of photons is too weak, the HII region is crushed by gravitational collapse

EMISSION FROM CLUSTERS



WINDS VS RADIATION

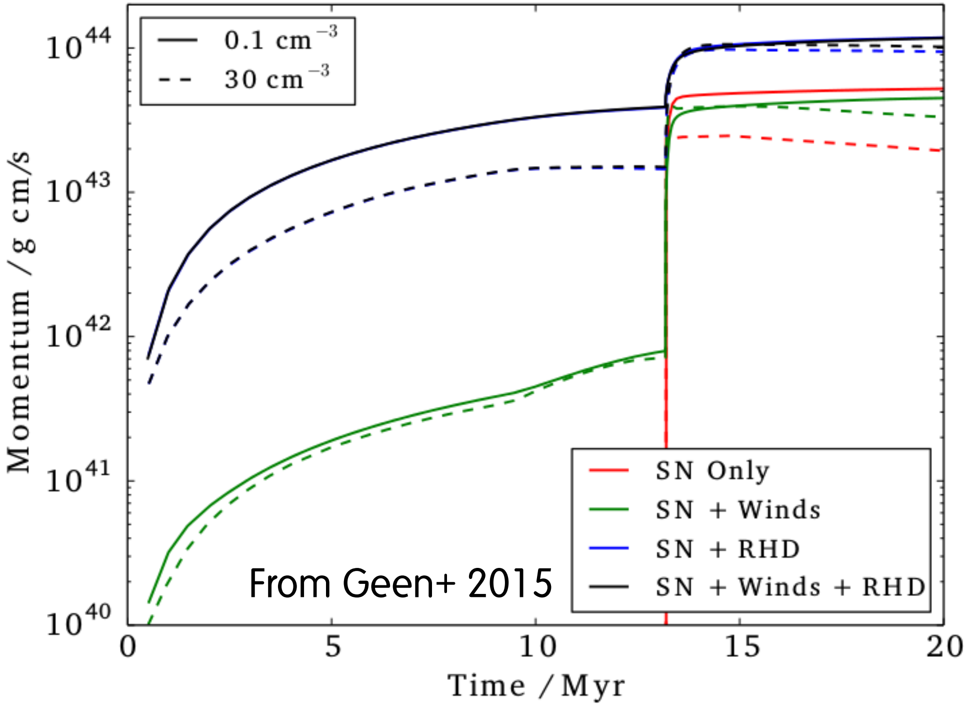
This also gets complicated!

Photoionisation pressure: density x temperature (= 10,000 K = constant)

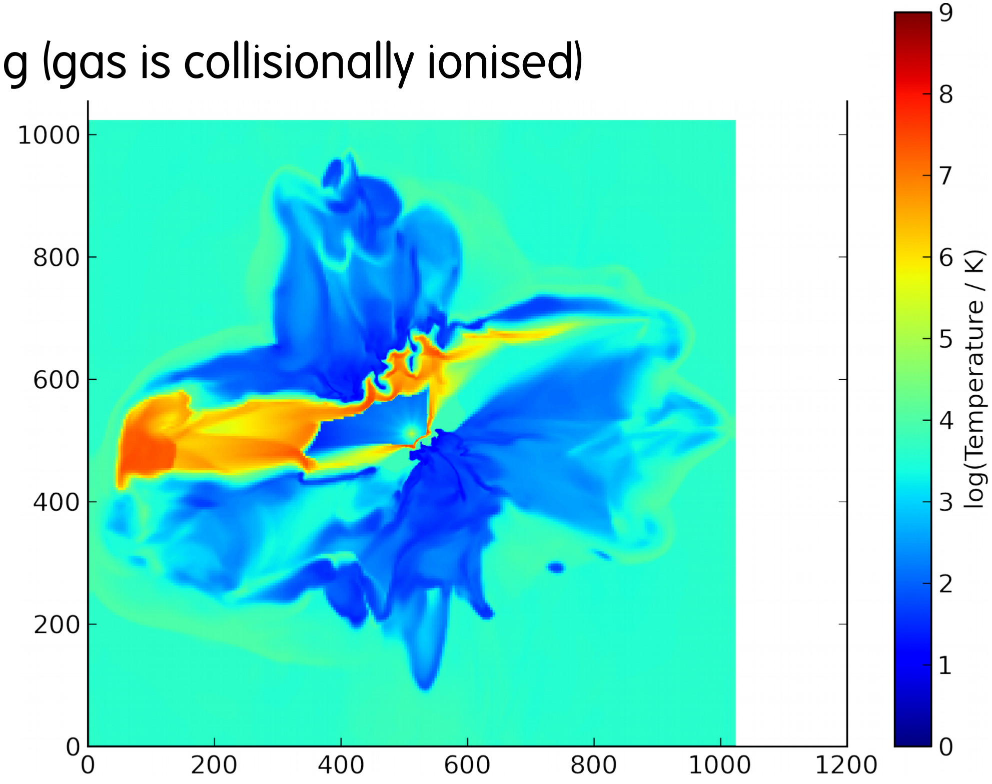
Wind pressure: Wind luminosity x time (builds up constantly)

There's a limit where one overpowers the other

When winds dominate, photoionisation does nothing (gas is collisionally ionised)



From Geen+ 2015



15 solar mass star
Winds are very weak, photoionisation dominates
Winds add almost nothing to the final momentum

10^4 solar mass cluster (preliminary results)
Winds dominate
Gas free-streams then shocks to up to 10^8 K

Credit: "Space Cats"

NO MORE SLIDES

WE ARE DONE