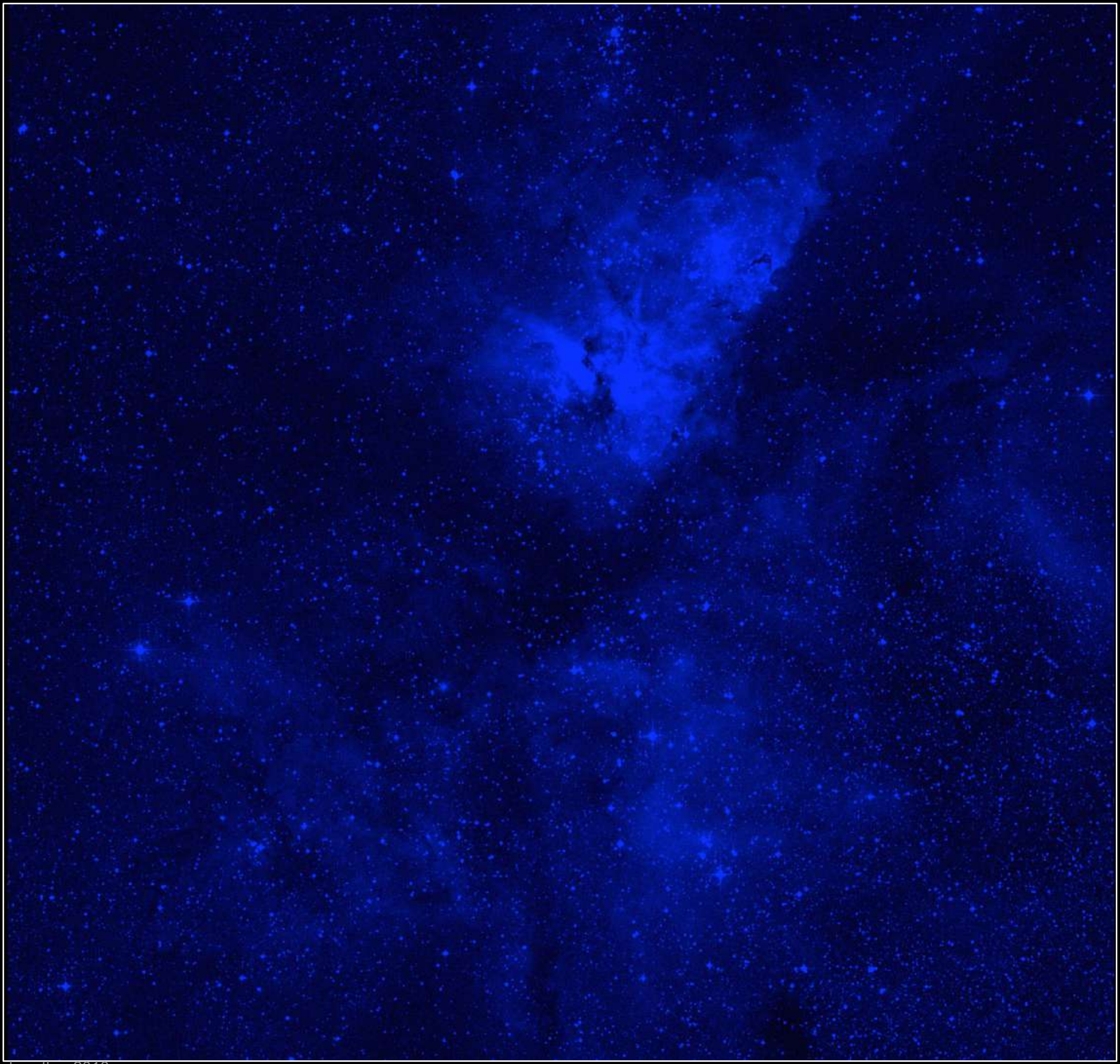
Massive Star Formation

Christoph Federrath

Canberra – 08 May 2018

Australian Government
Australian Research Council

Australian National University



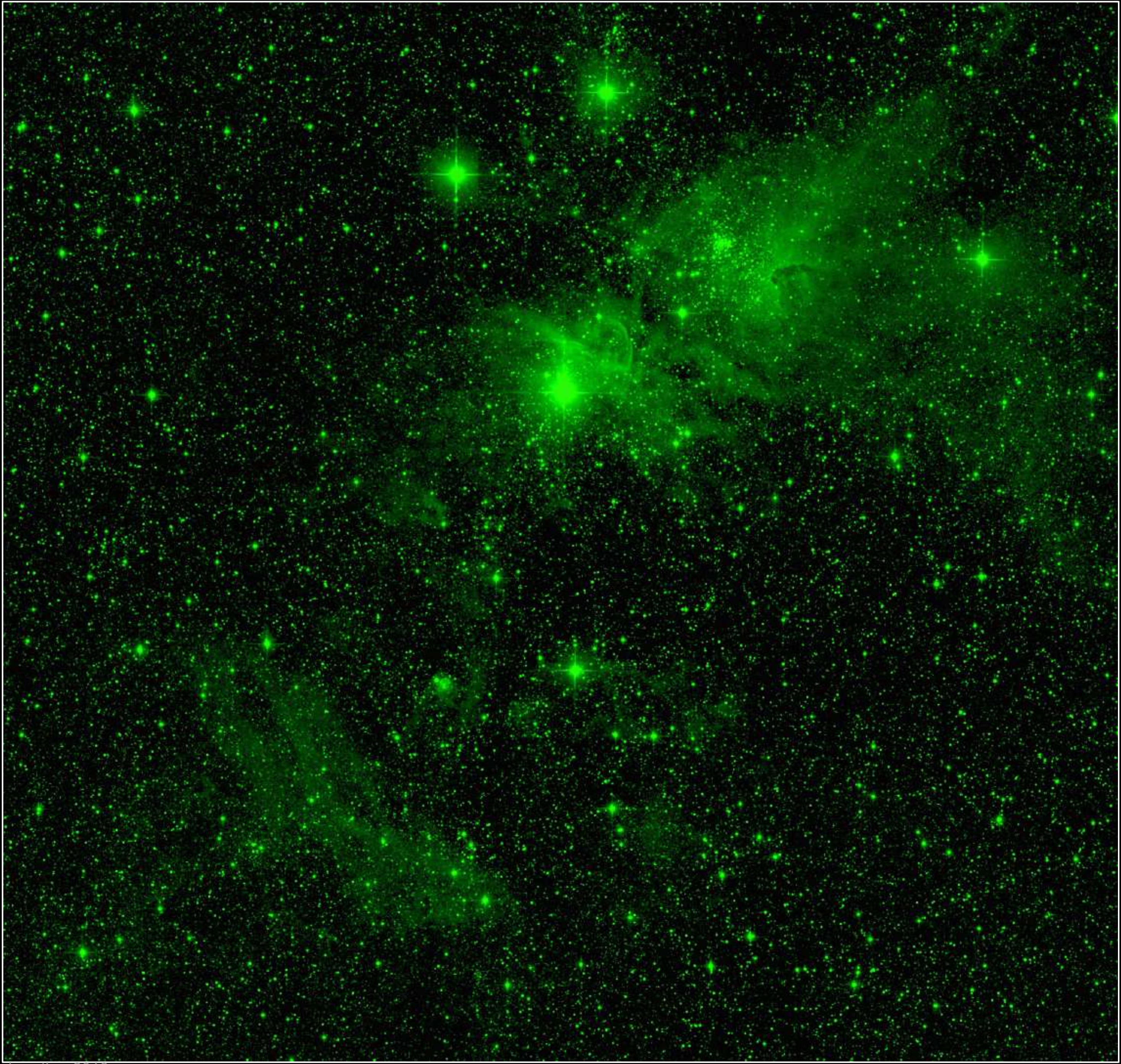
The Great Nebula in Carina

Visible Light
Digitized Sky Survey

Dark regions within the Visible nebula are obscured by dust.

New Massive Stars Found Hiding in Famous Nebula

M. S. Povich



The Great Nebula in Carina

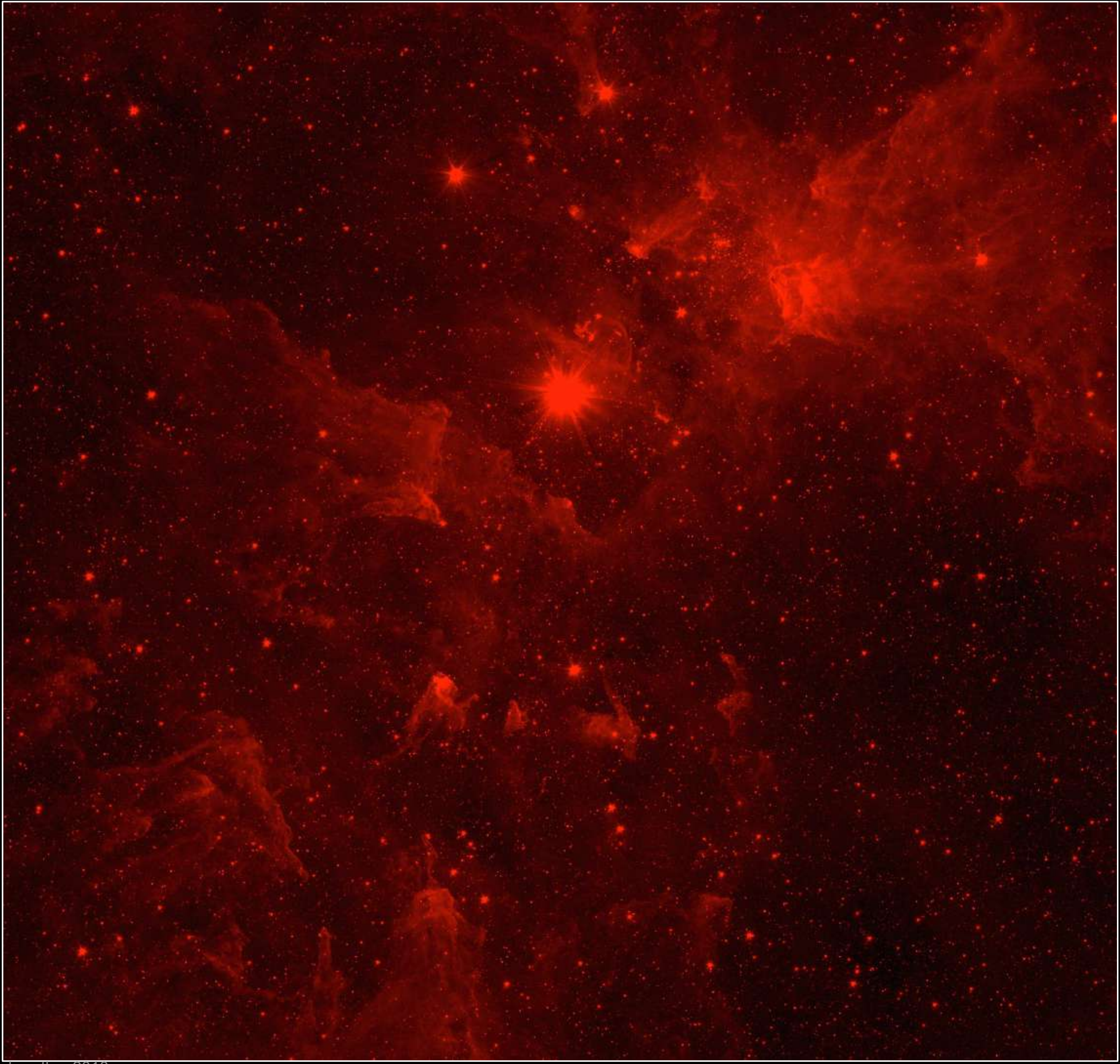
Near-Infrared

Two-Micron All-Sky Survey

Near-infrared light passes through the dust, revealing more stars.

New Massive Stars Found Hiding in Famous Nebula

M. S. Povich



The Great Nebula in Carina

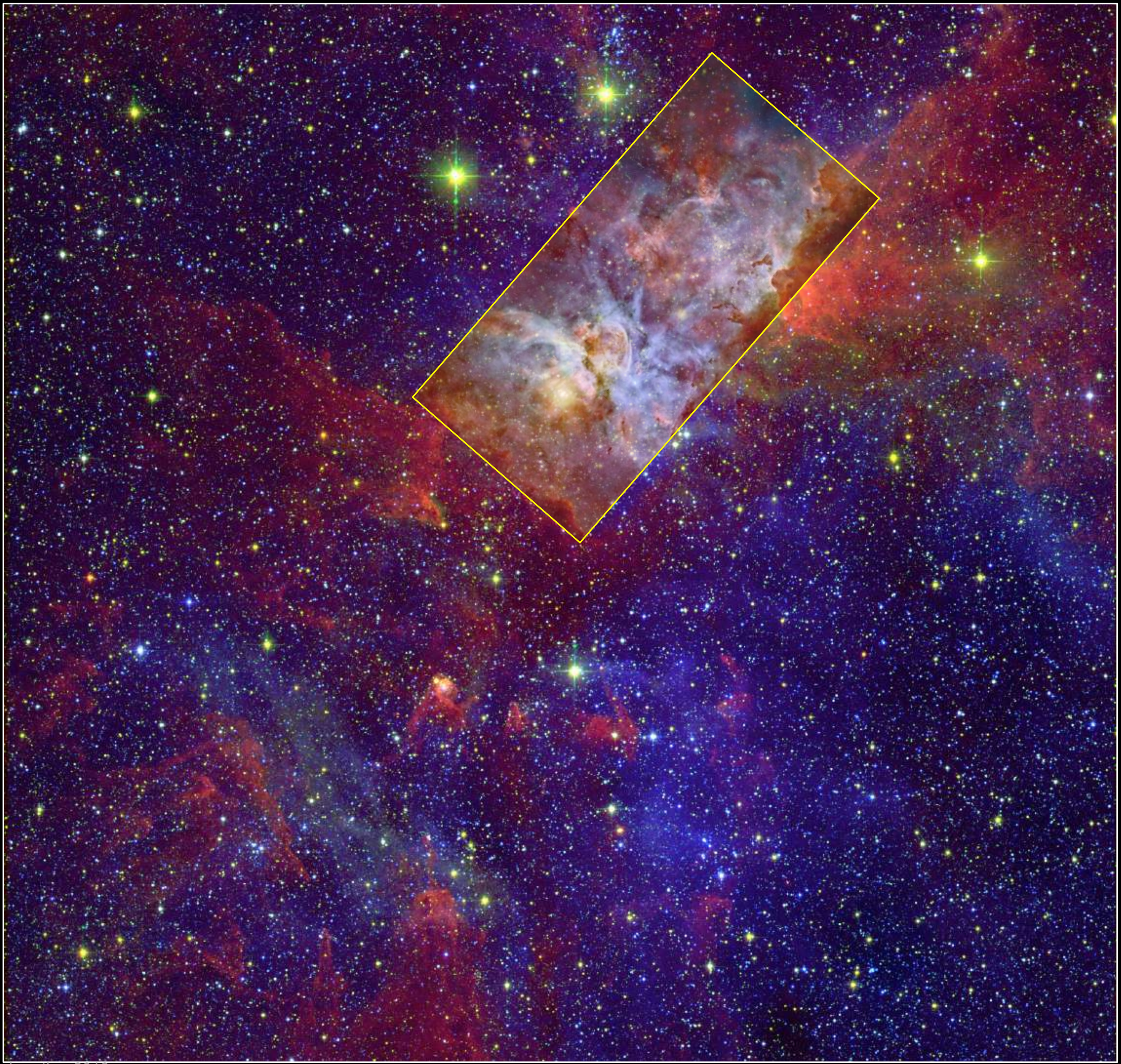
Mid-Infrared

Spitzer Space Telescope

The dust clouds themselves glow in mid-infrared light.

New Massive Stars Found Hiding in Famous Nebula

M. S. Povich



The Great Nebula in Carina

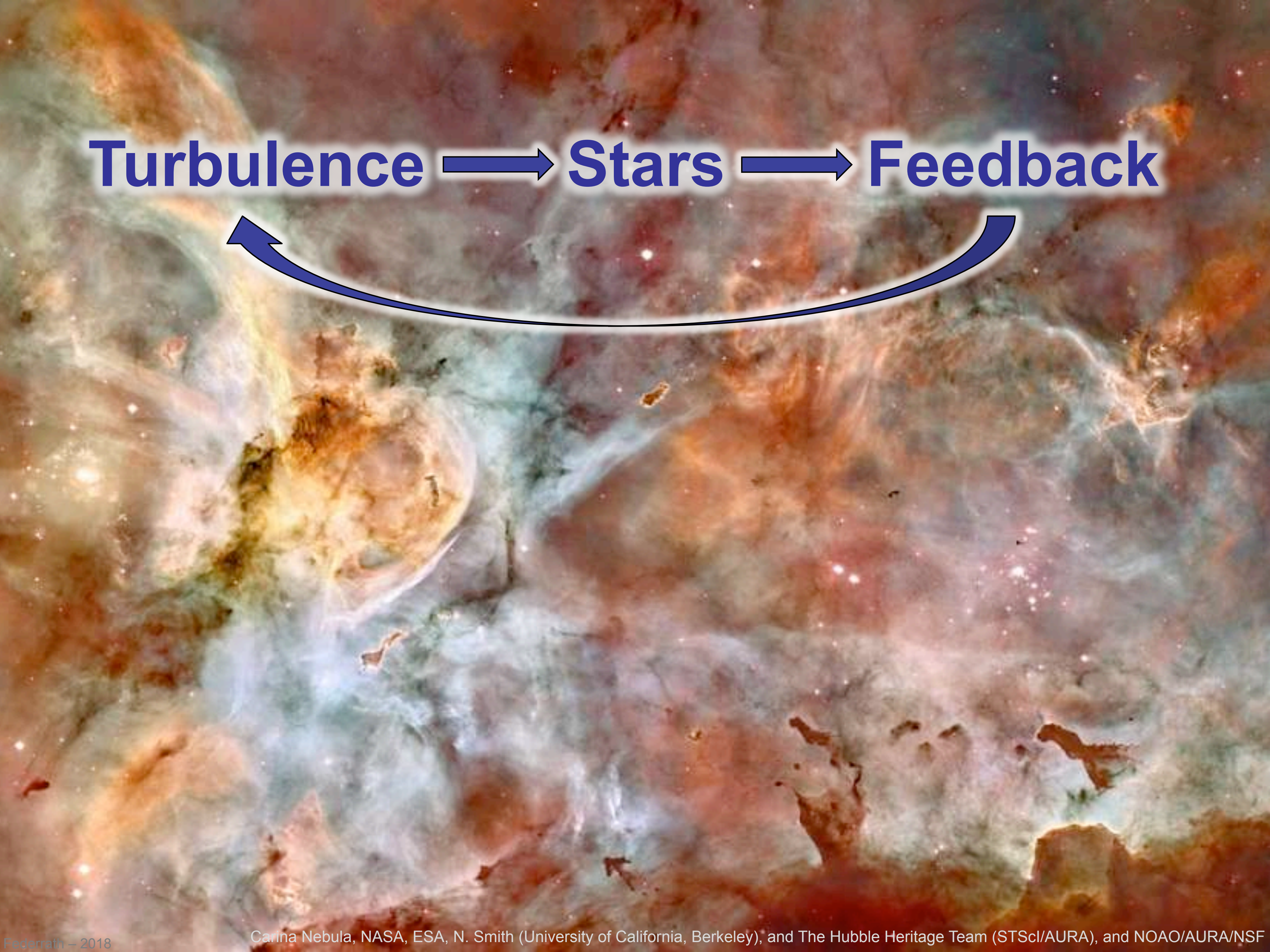
Visible Light
Digitized Sky Survey

Near-Infrared
Two-Micron All-Sky Survey

Mid-Infrared
Spitzer Space Telescope

New Massive Stars
Found Hiding in
Famous Nebula

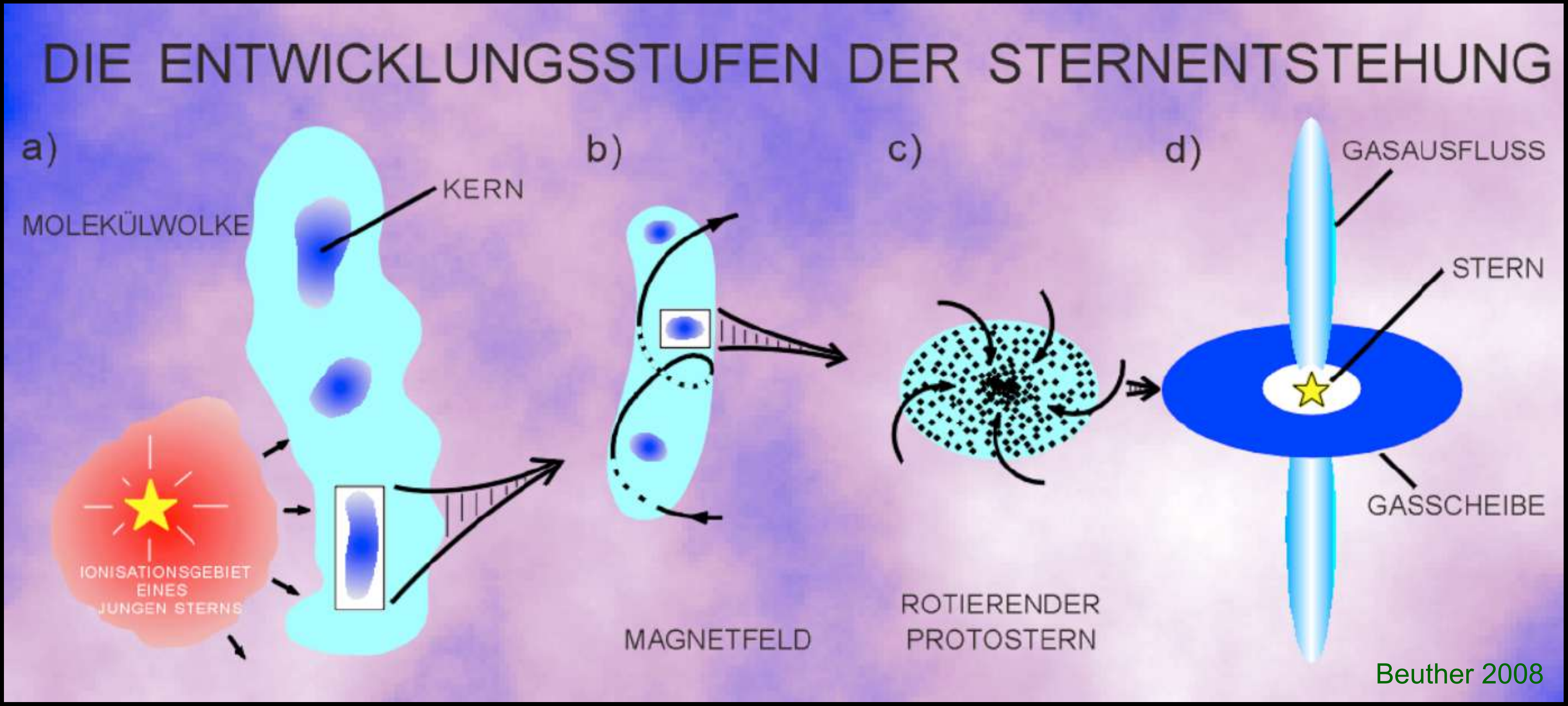
M. S. Povich



Carina Nebula, NASA, ESA, N. Smith (University of California, Berkeley), and The Hubble Heritage Team (STScI/AURA), and NOAO/AURA/NSF

The Star Formation Paradigm

Clouds ➔ Cores ➔ Disk + Star + Jet / Outflow



Beuther 2008

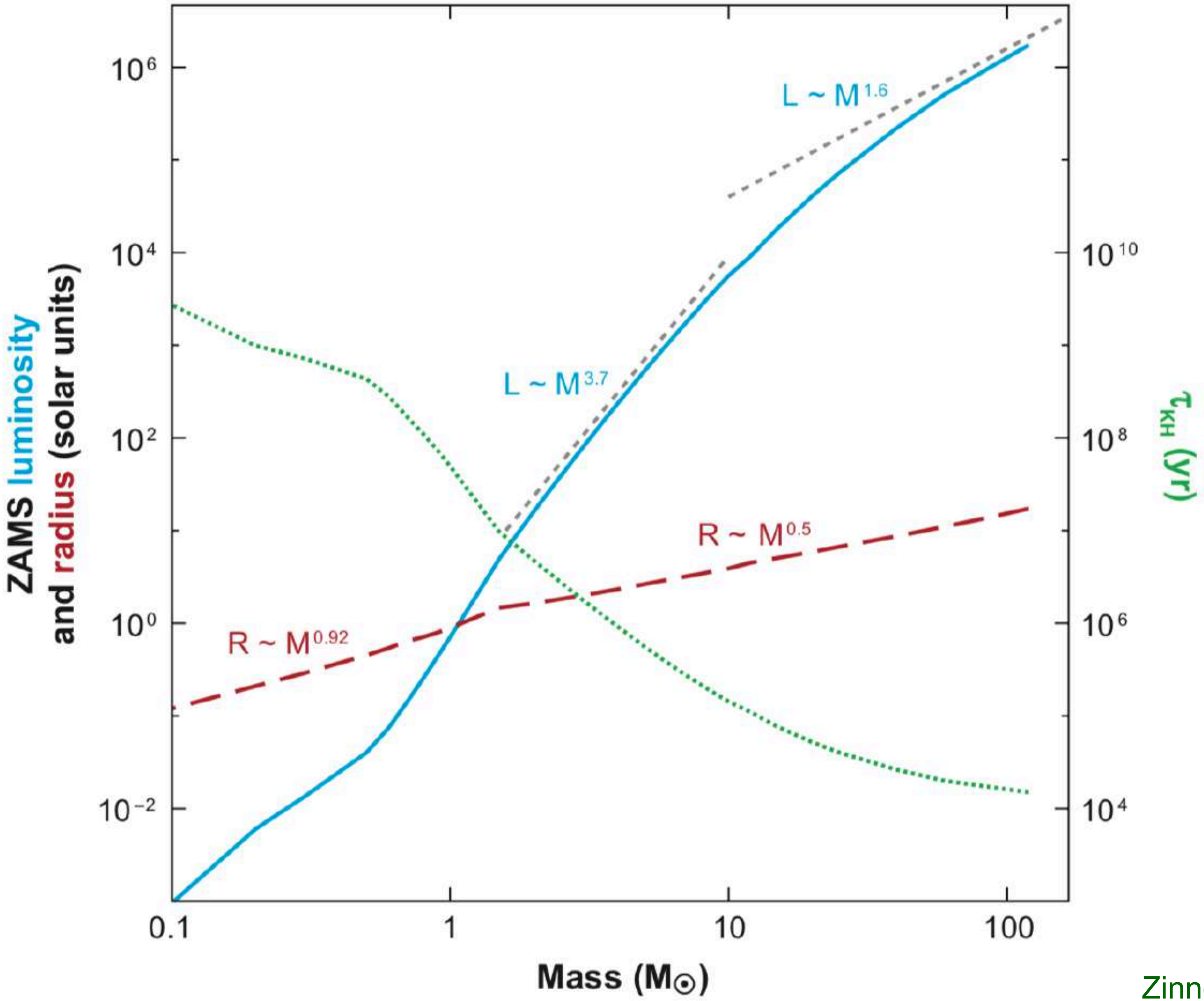
Literature:

- Zinnecker & Yorke (2007, Annual Reviews of Astronomy and Astrophysics)
- Tan et al. (2014, Protostars & Planets VI)

Table 1 Main-sequence massive star definition (logarithmic mass ranges)

Mass	Designation	Sp. type
8–16 $M_\odot$	Early B-type massive stars	B3V to B0V
16–32 $M_\odot$	Late O-type massive stars	O9V to O6V
32–64 $M_\odot$	Early O-type massive stars	O5V to O2V[a]
64–128 $M_\odot$	O/WR-type massive stars	WNL-H[b]

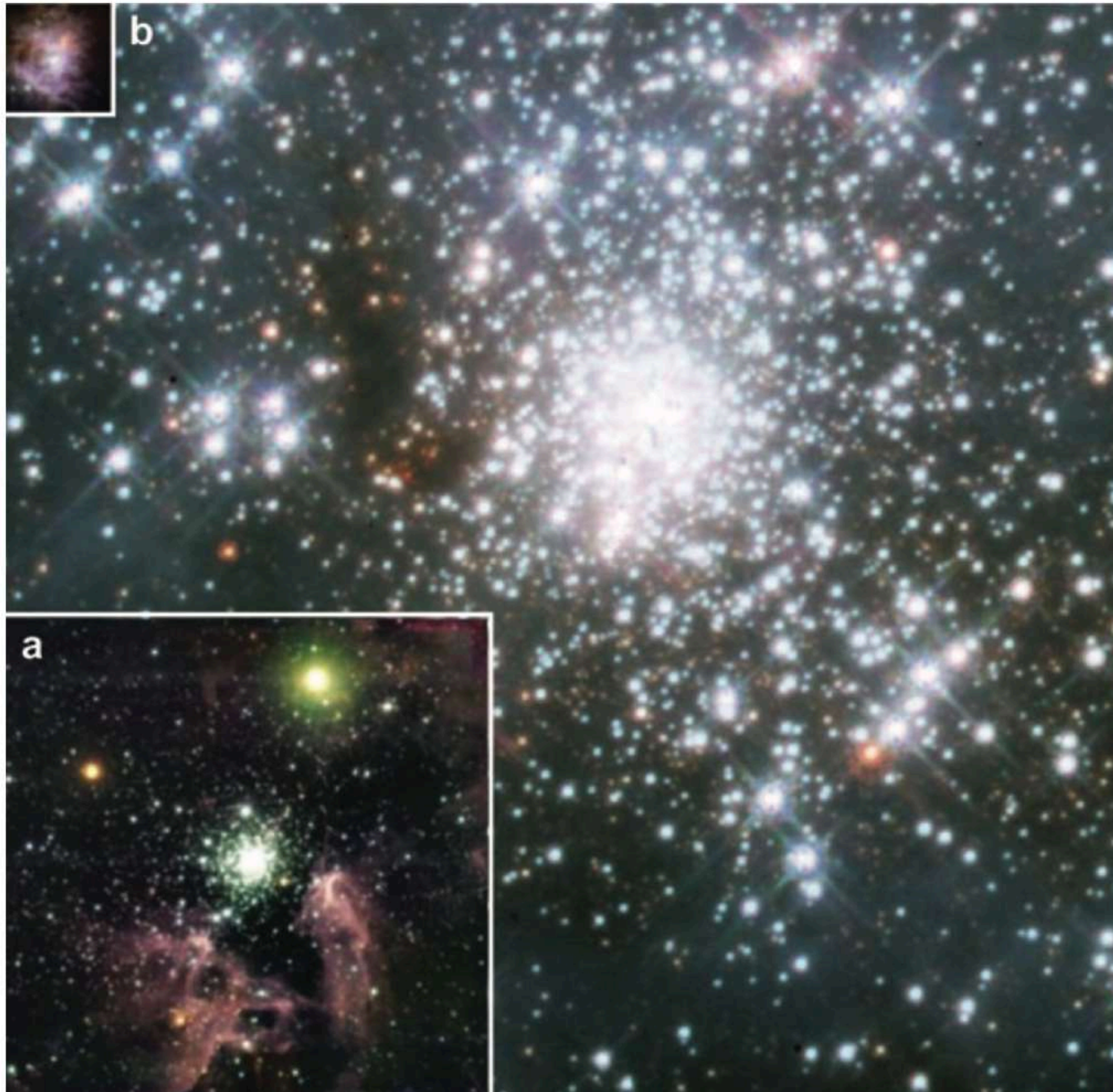
Massive Star Formation



Zinnecker & Yorke (2007)
Annu. Rev. Astron. Astrophys.

Figure 2

Hubble Space Telescope optical/IR image of the dense massive young cluster R136/30Dor (courtesy of M.J. McCaughrean; FOV ~30 arcsec × 30 arcsec or 7.5 pc × 7.5 pc). Dozens of massive O stars are found crowded within the half-light radius of 2 pc (Brandl et al. 1996). (*a*) A VLT image of NGC 3603 (Brandl et al. 1999) and (*b*) a VLT image of the Trapezium Cluster in Orion (McCaughrean 2001) are shown as these two galactic clusters would be seen if they were located at the distance of R136 in the Large Magellanic Cloud (50 kpc) and imaged with similar angular resolution (see Zinnecker 2002).



Zinnecker & Yorke (2007)
Annu. Rev. Astron. Astrophys.

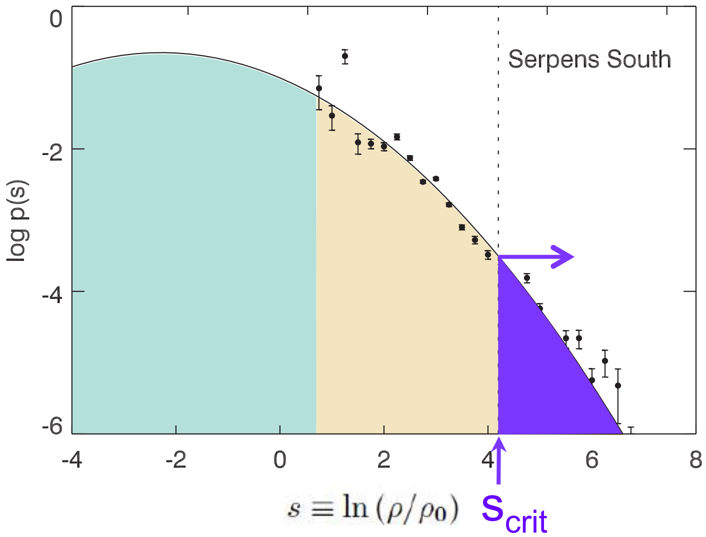
Why care about the virial parameter?

Statistical Theory for the Star Formation Rate:

SFR ~ Mass/time

freefall time **mass fraction**

$$\mathrm{SFR}_{\mathrm{ff}} = \epsilon \int_{s_{\mathrm{crit}}}^{\infty} \frac{t_{\mathrm{ff}}(\rho_0)}{t_{\mathrm{ff}}(\rho)} \frac{\rho}{\rho_0} p(s)\,\mathrm{d}s$$



Hennebelle & Chabrier (2011) : “multi-freefall model”

Federrath & Klessen (2012)

Why care about the virial parameter?

Statistical Theory for the Star Formation Rate:

$$p(s) = \frac{1}{\sqrt{2\pi\sigma_s^2}} \exp\left(-\frac{(s-s_0)^2}{2\sigma_s^2}\right)$$

$$s = \ln(\rho/\rho_0) \qquad t_{\mathrm{ff}}(\rho) = \left(\frac{3\pi}{32G\rho}\right)^{1/2}$$

SFR ~ Mass/time

freefall time **mass fraction**

$$\mathrm{SFR}_{\mathrm{ff}} = \epsilon \int_{s_{\mathrm{crit}}}^{\infty} \underbrace{\frac{t_{\mathrm{ff}}(\rho_0)}{t_{\mathrm{ff}}(\rho)}}_{\text{freefall time}} \underbrace{\frac{\rho}{\rho_0}}_{\text{mass fraction}} p(s)\,\mathrm{d}s = \epsilon \int_{s_{\mathrm{crit}}}^{\infty} \exp\left(\frac{3}{2}s\right) p(s)\,\mathrm{d}s$$

$$= \frac{\epsilon}{2} \exp\left(\frac{3}{8}\sigma_s^2\right)\left[1 + \mathrm{erf}\left(\frac{\sigma_s^2 - s_{\mathrm{crit}}}{\sqrt{2\sigma_s^2}}\right)\right]$$

Hennebelle & Chabrier (2011) : “multi-freefall model”

Federrath & Klessen (2012)

Why care about the virial parameter?

Statistical Theory for the Star Formation Rate:

$$p(s) = \frac{1}{\sqrt{2\pi\sigma_s^2}} \exp\left(-\frac{(s-s_0)^2}{2\sigma_s^2}\right)$$

$$s = \ln(\rho/\rho_0) \qquad t_{\rm ff}(\rho) = \left(\frac{3\pi}{32G\rho}\right)^{1/2}$$

SFR ~ Mass / time

freefall time — **mass fraction**

$$\mathrm{SFR_{ff}} = \epsilon \int_{s_{\rm crit}}^{\infty} \frac{t_{\rm ff}(\rho_0)}{t_{\rm ff}(\rho)} \frac{\rho}{\rho_0} p(s)\,\mathrm{d}s = \epsilon \int_{s_{\rm crit}}^{\infty} \exp\left(\frac{3}{2}s\right) p(s)\,\mathrm{d}s$$

$$= \frac{\epsilon}{2} \exp\left(\frac{3}{8}\sigma_s^2\right) \left[1 + \mathrm{erf}\left(\frac{\sigma_s^2 - s_{\rm crit}}{\sqrt{2\sigma_s^2}}\right)\right]$$

Hennebelle & Chabrier (2011) : “multi-freefall model”

From sonic and Jeans scales:

$$s_{\rm crit} \propto \ln\left(\alpha_{\rm vir}\mathcal{M}^2\right)$$

(Krumholz & McKee 2005, Padoan & Nordlund 2011)

$$\mathrm{SFR_{ff}} = \mathrm{SFR_{ff}}\left(\alpha_{\rm vir}, b, \mathcal{M}\right)$$

$$\sigma_s^2 = \ln\left(1 + b^2\mathcal{M}^2\right)$$

(e.g., Federrath et al. 2008)

$2\,E_{\rm kin}/E_{\rm grav}$ — **forcing** — **Mach number**

Federrath & Klessen (2012)

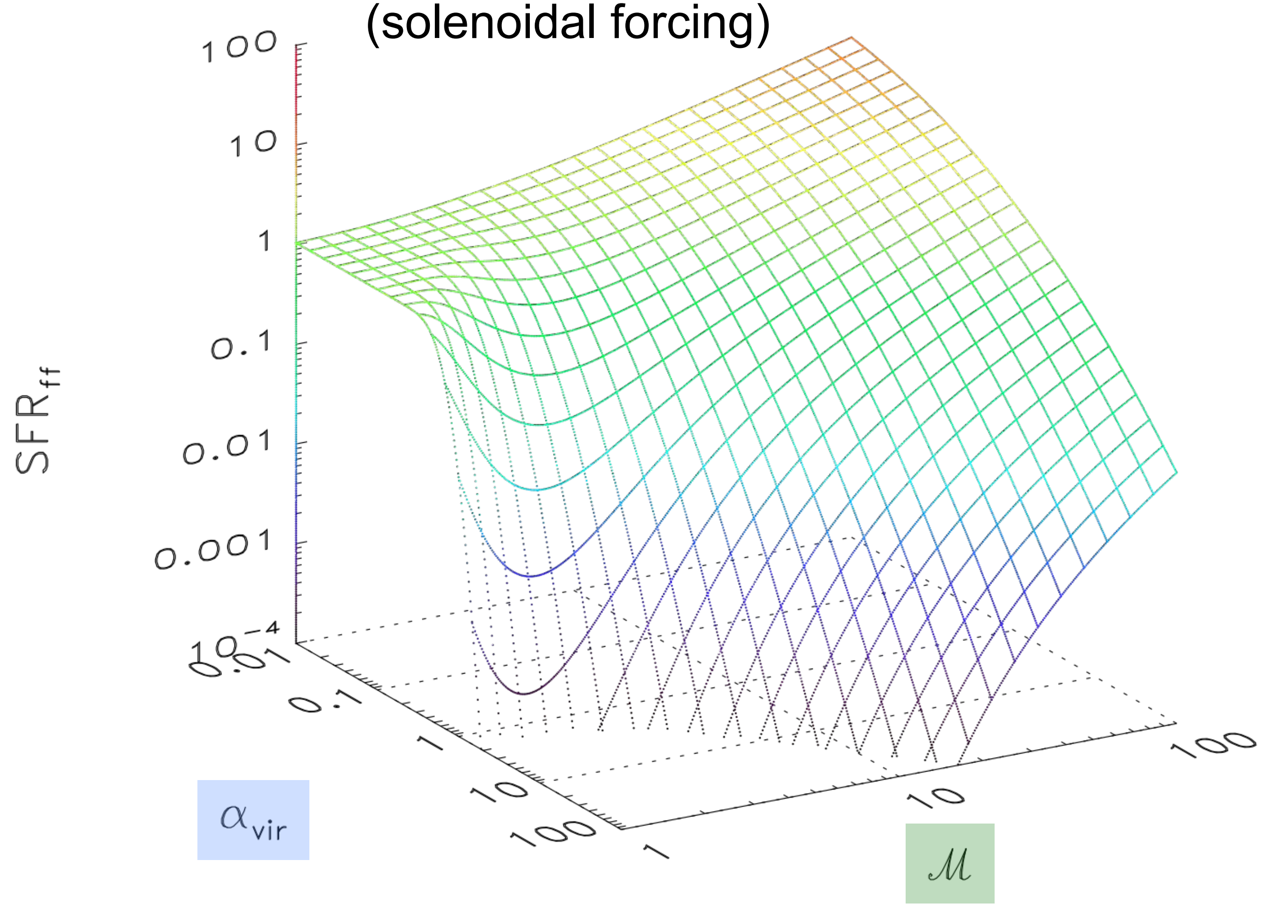
Why care about the virial parameter?

$$\mathrm{SFR_{ff}} = \mathrm{SFR_{ff}}\,(\alpha_{\mathrm{vir}}, b, \mathcal{M})$$

$2\,E_{kin}/E_{grav}$ **forcing** **Mach number**

forcing parameter $(b=0.33)$ multi−freefall

(solenoidal forcing)

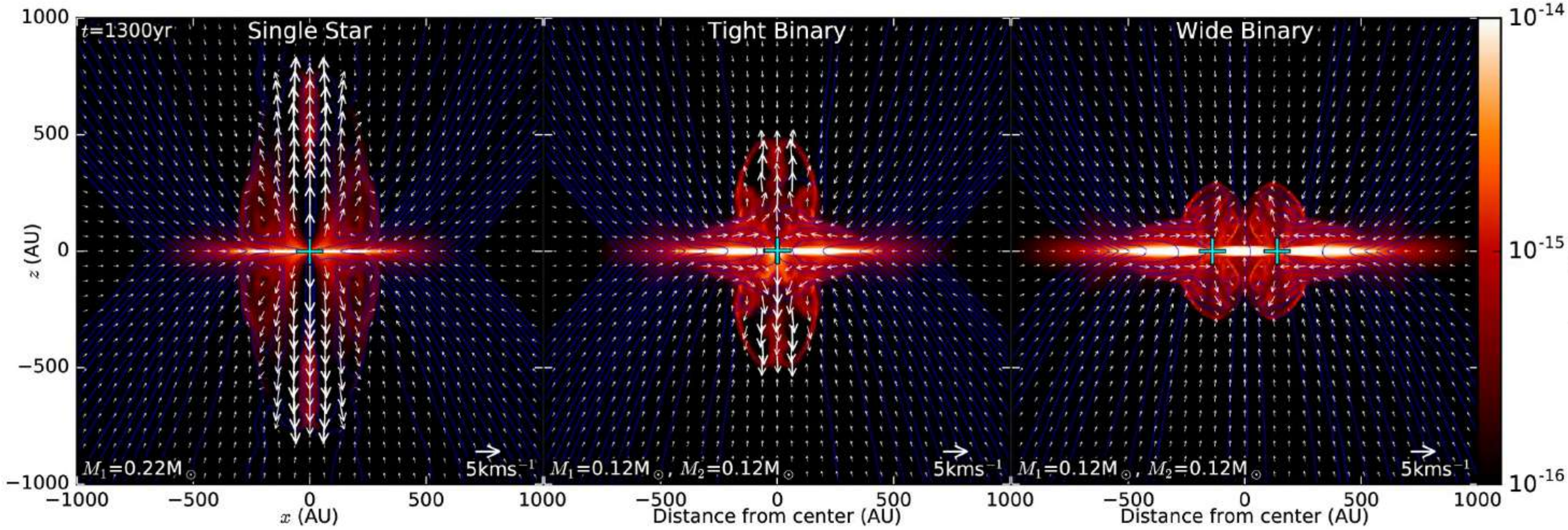


Federrath & Klessen (2012)

Jet Feedback in Binary Star Formation

Kuruwita, Federrath, Ireland (2017, MNRAS 470, 1626)

Movies available:
https://www.mso.anu.edu.au/~chfeder/pubs/binary_jets/binary_jets.html



Jet structure and power depend on binary separation → different star mass

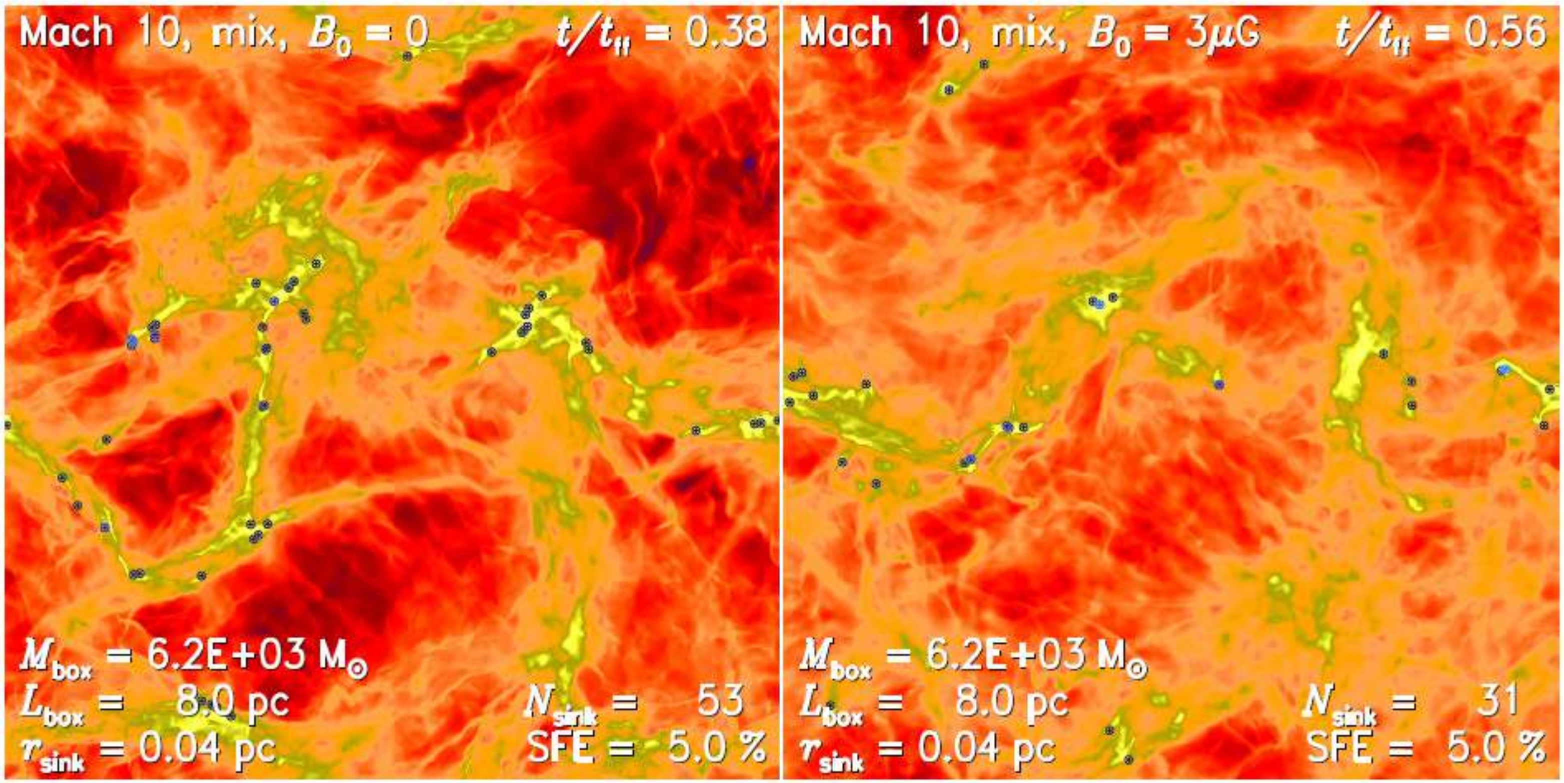
→ Challenge for understanding and modelling the IMF!

The Star Formation Rate – Magnetic fields

Numerical Test for Mach 10 with mixed forcing

Movies available: http://www.mso.anu.edu.au/~chfeder/pubs/sfr/sfr.html

B=0 (M_A=∞, β = ∞) B=3μG (M_A=2.7, β = 0.2)



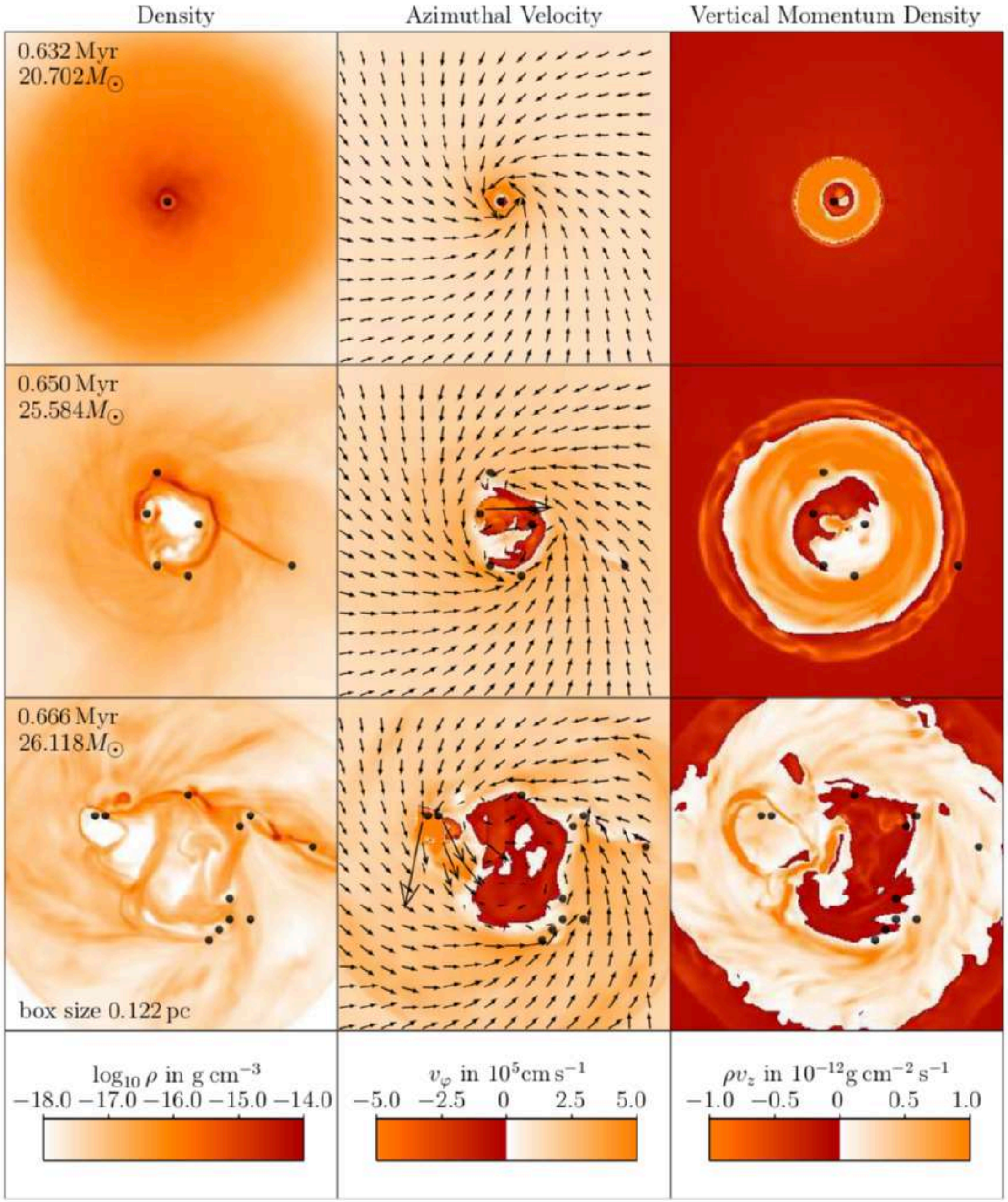
SFR_{ff} (simulation) = **0.46** x **0.63** SFR_{ff} (simulation) = **0.29**

SFR_{ff} (theory) = **0.45** x **0.40** SFR_{ff} (theory) = **0.18**

Magnetic field reduces SFR and fragmentation (by factor 2) → **IMF, Massive Stars**

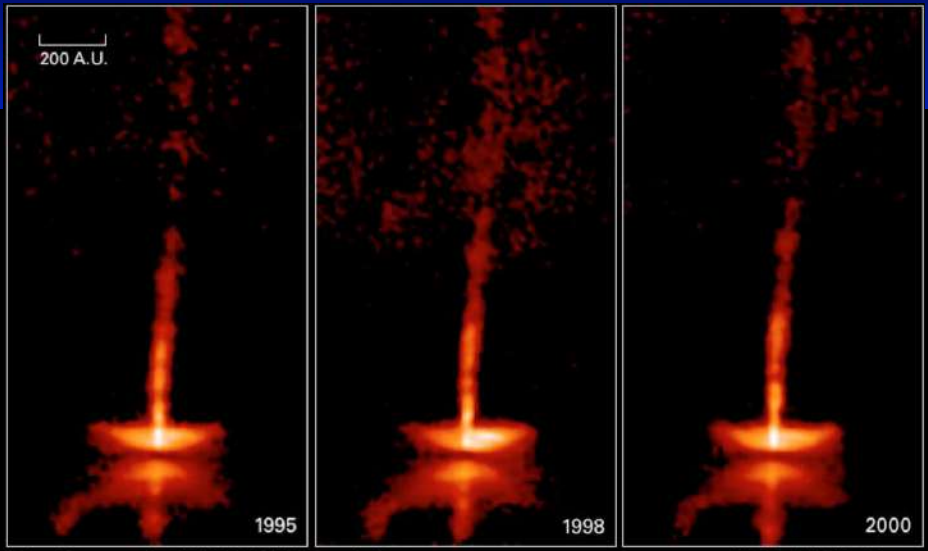
Padoan & Nordlund (2011); Padoan et al. (2012); Federrath & Klessen (2012)

Massive Star Formation – HII regions



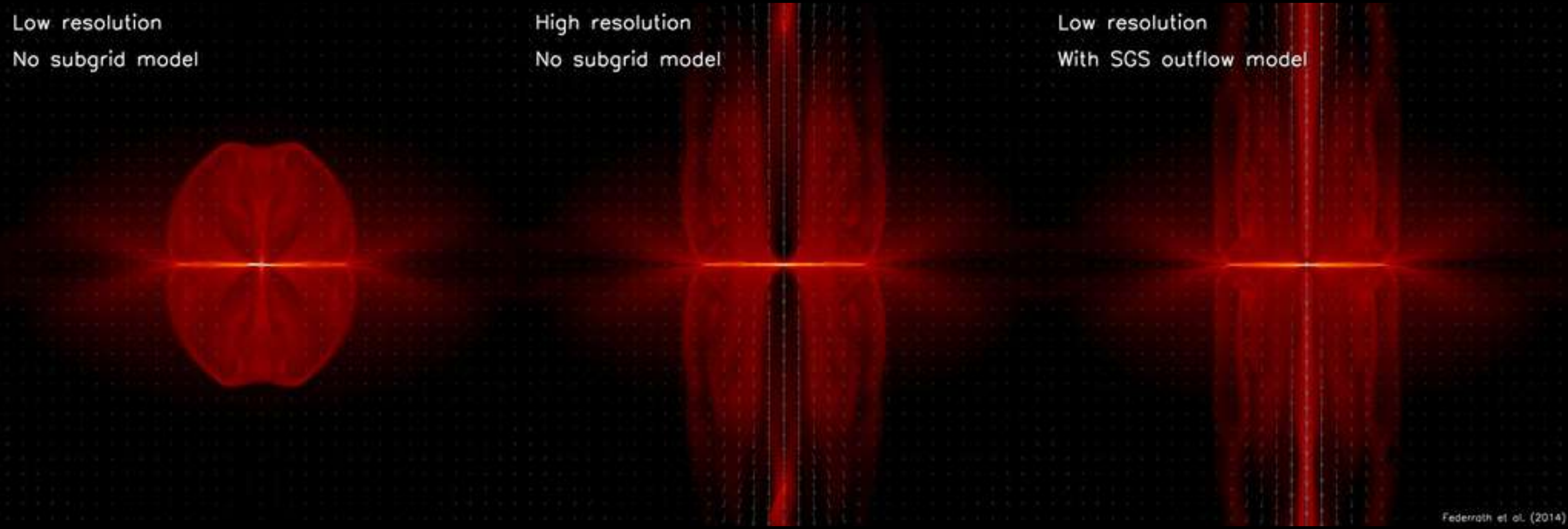
Peters et al. (2010)

Jet/Outflow Feedback



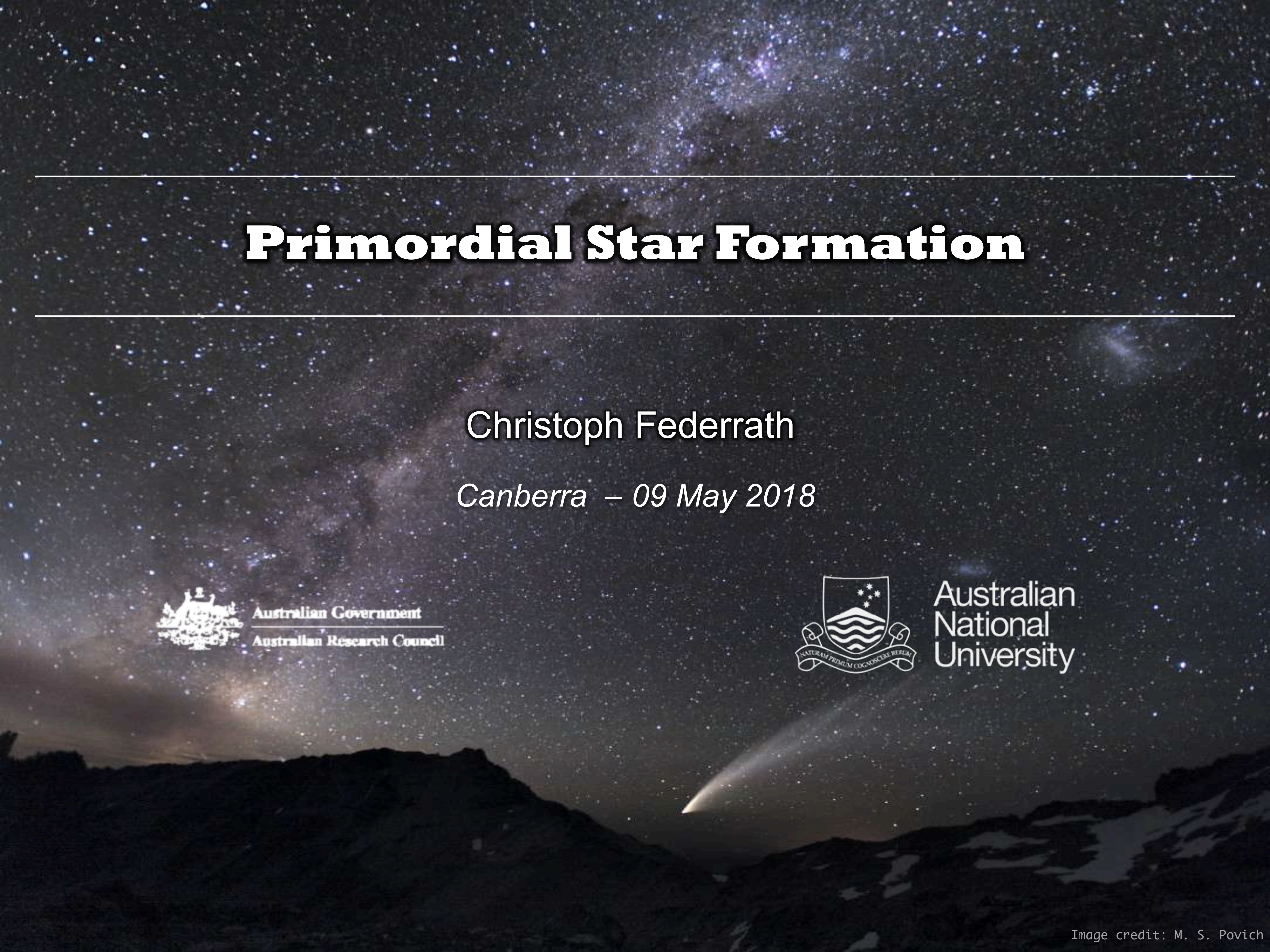
The Dynamic HH 30 Disk and Jet HST • WFPC2

NASA and A. Watson (Instituto de Astronomía, UNAM, Mexico) • STScI-PRC00-32b



Movies available: https://www.mso.anu.edu.au/~chfeder/pubs/outflow_model/outflow_model.html

Federrath et al. 2014, ApJ 790, 128



Primordial Star Formation

Christoph Federrath

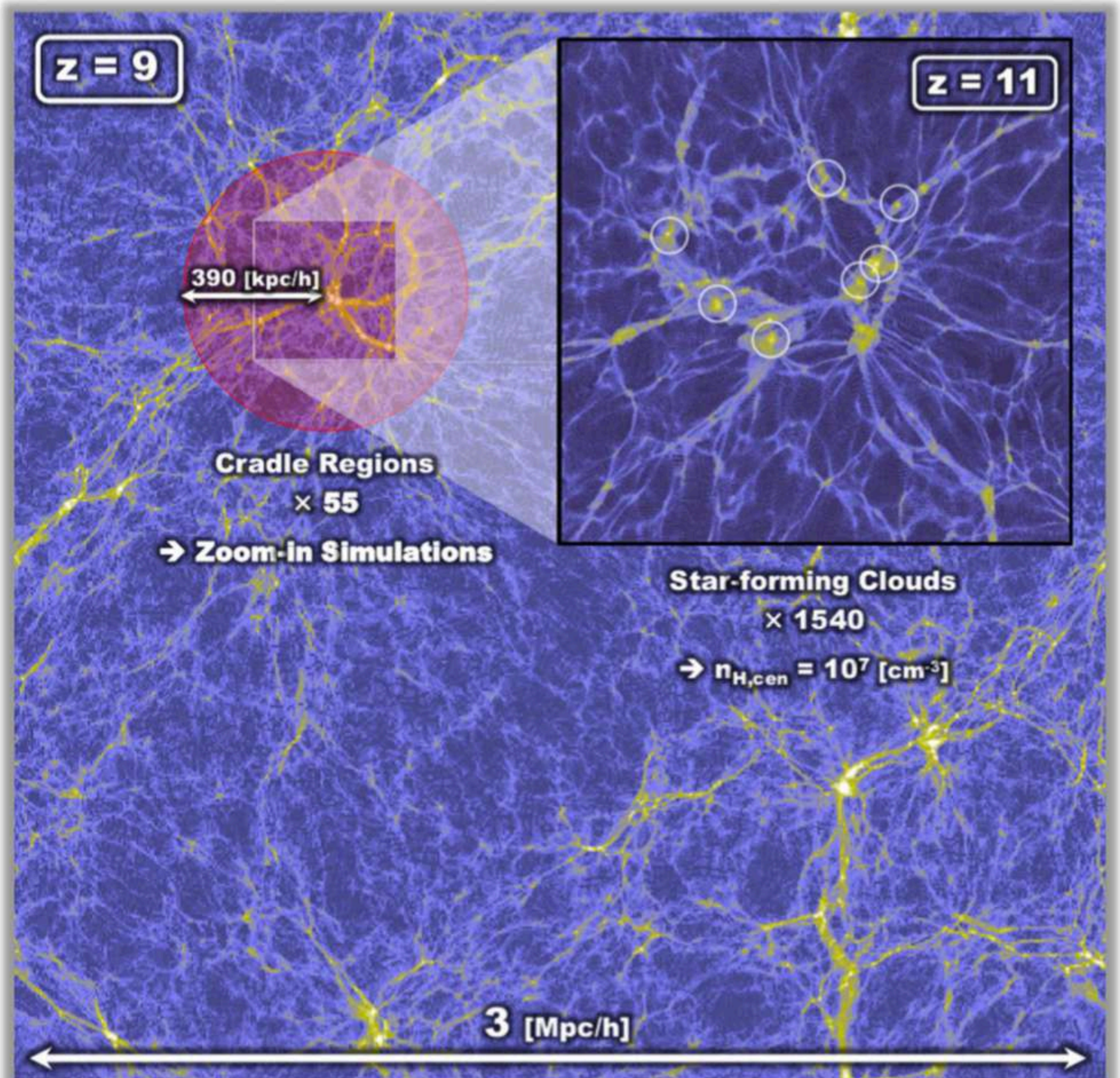
Canberra – 09 May 2018

Australian Government
Australian Research Council

Australian National University

Image credit: M. S. Povich

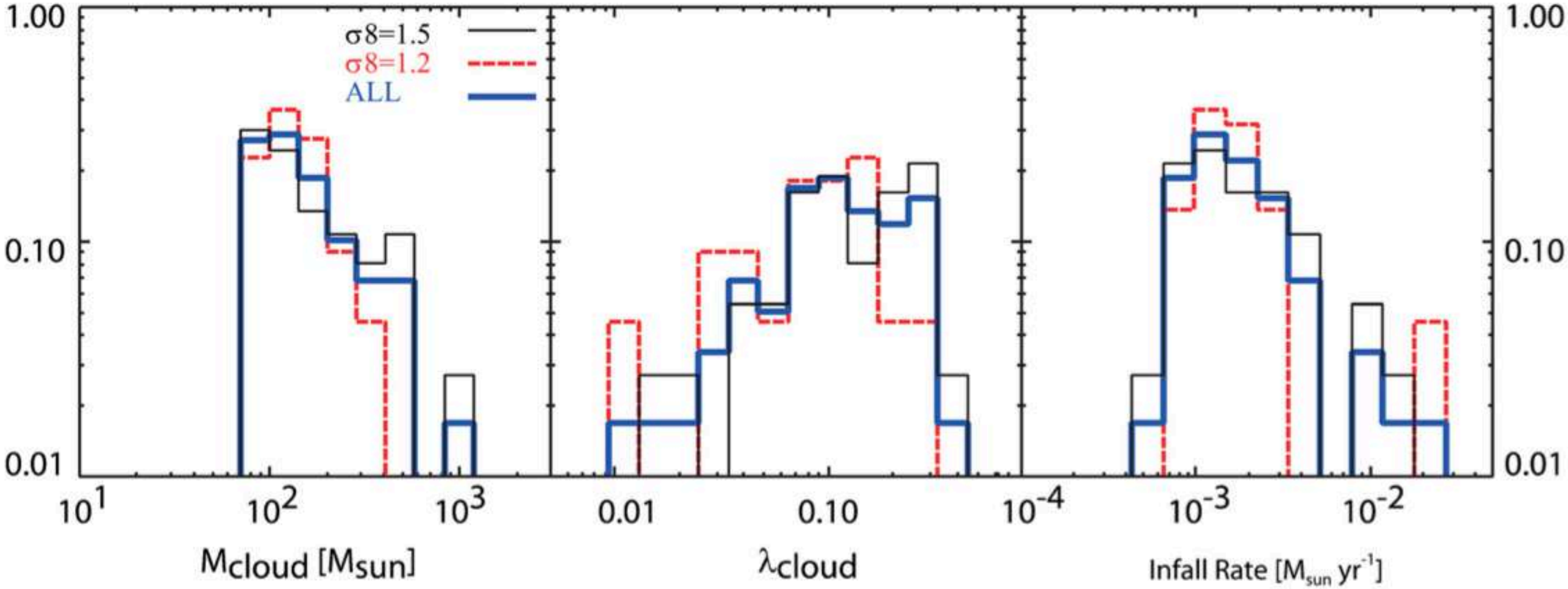
Formation of the First Stars in the Universe



mini haloes

Hirano et al. (2015)

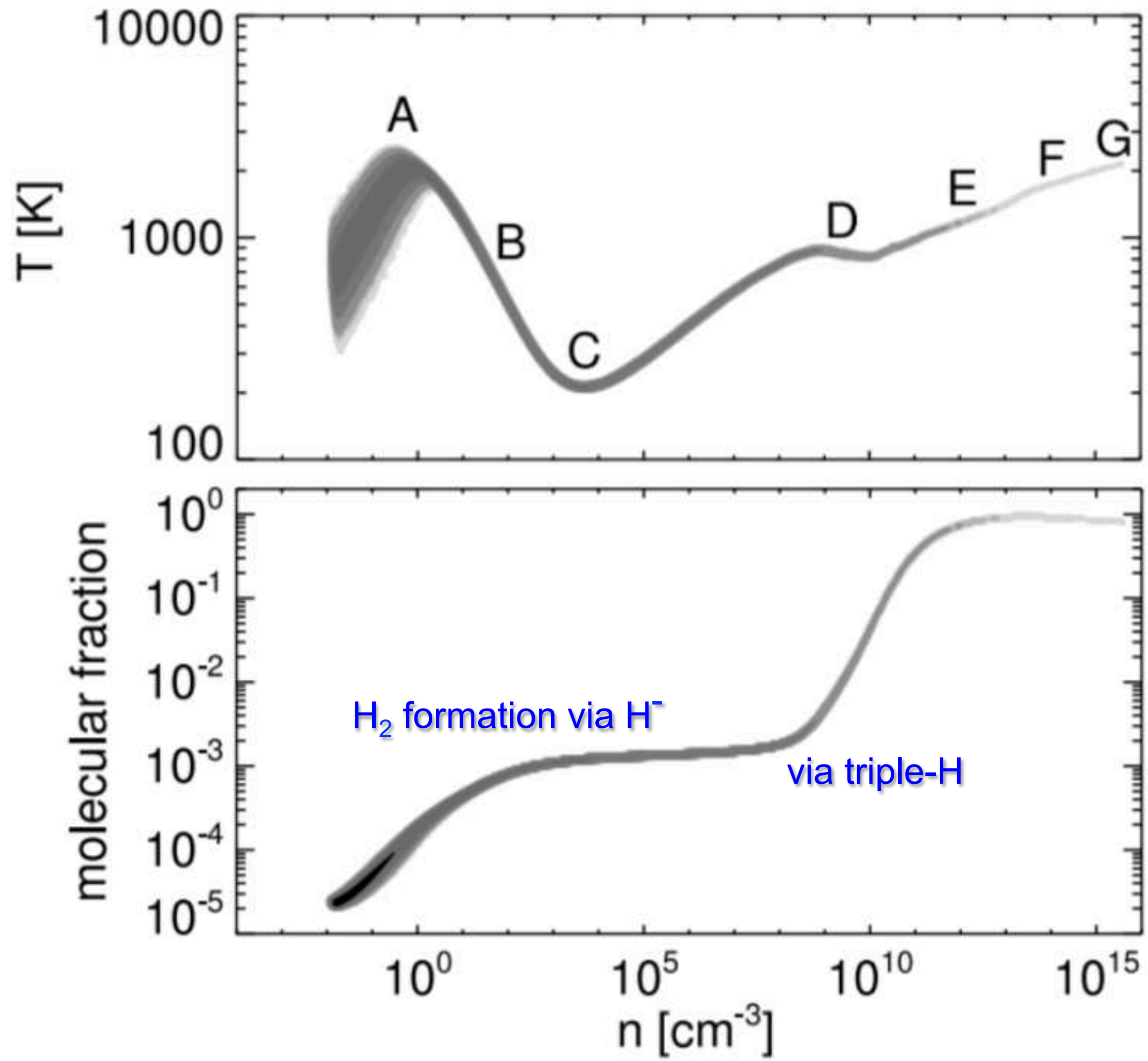
Physical Properties of Primordial Clouds



Similar to massive cores, but warmer (few hundred K)

Susa et al. (2014)

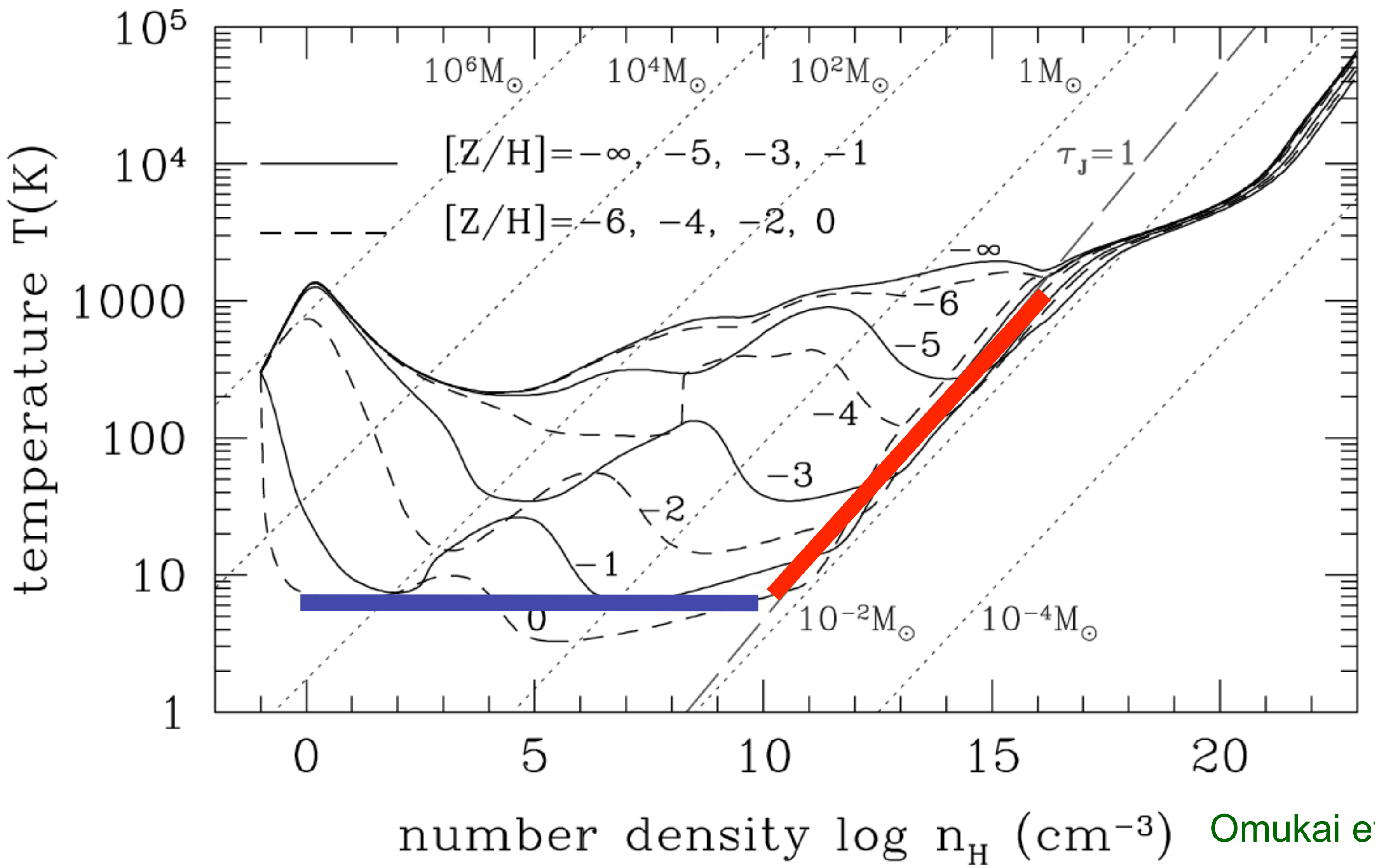
Star Formation – Chemistry / Heating / Cooling



Yoshida et al. (2006)

Star Formation – Chemistry / Heating / Cooling

Chemistry / Heating / Cooling: (Glover+07,10, Micic+12, Clark+12)

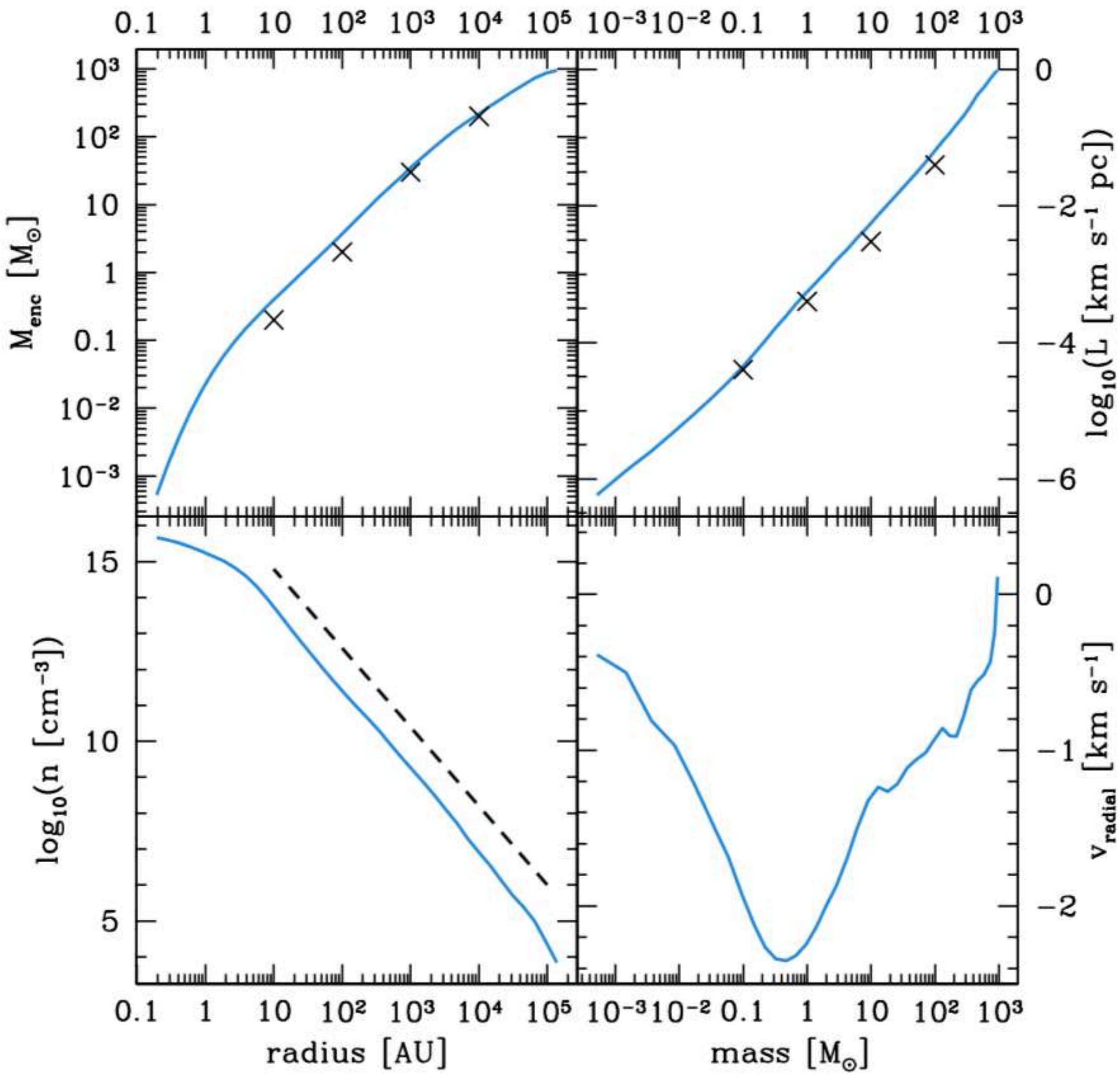


Omukai et al. (2005)

Molecule formation in high-density gas: $t_{form} \sim 1/n$

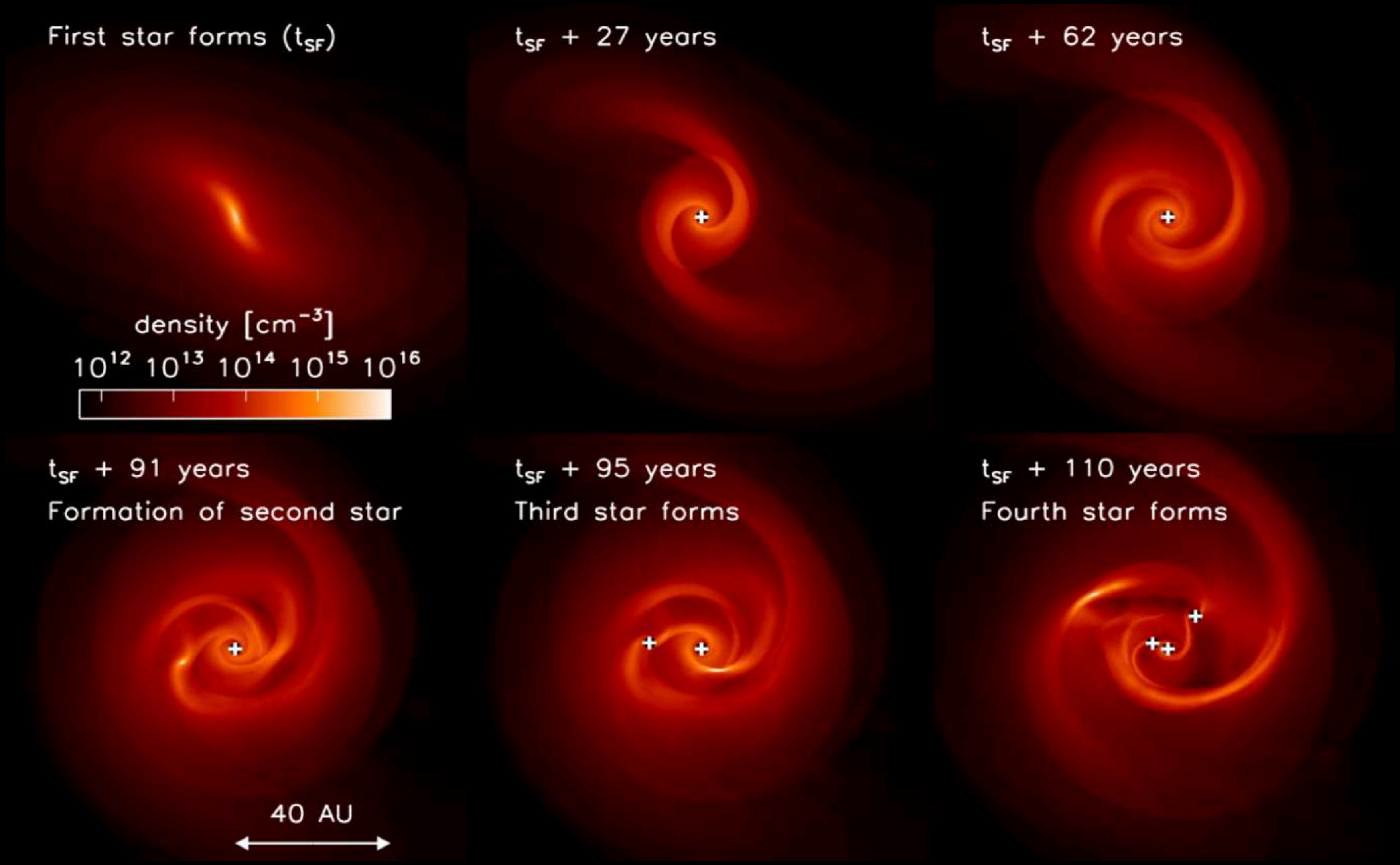
Micic et al. (2012), Hollenbach et al. (1971)

Physical Properties of Primordial Clouds



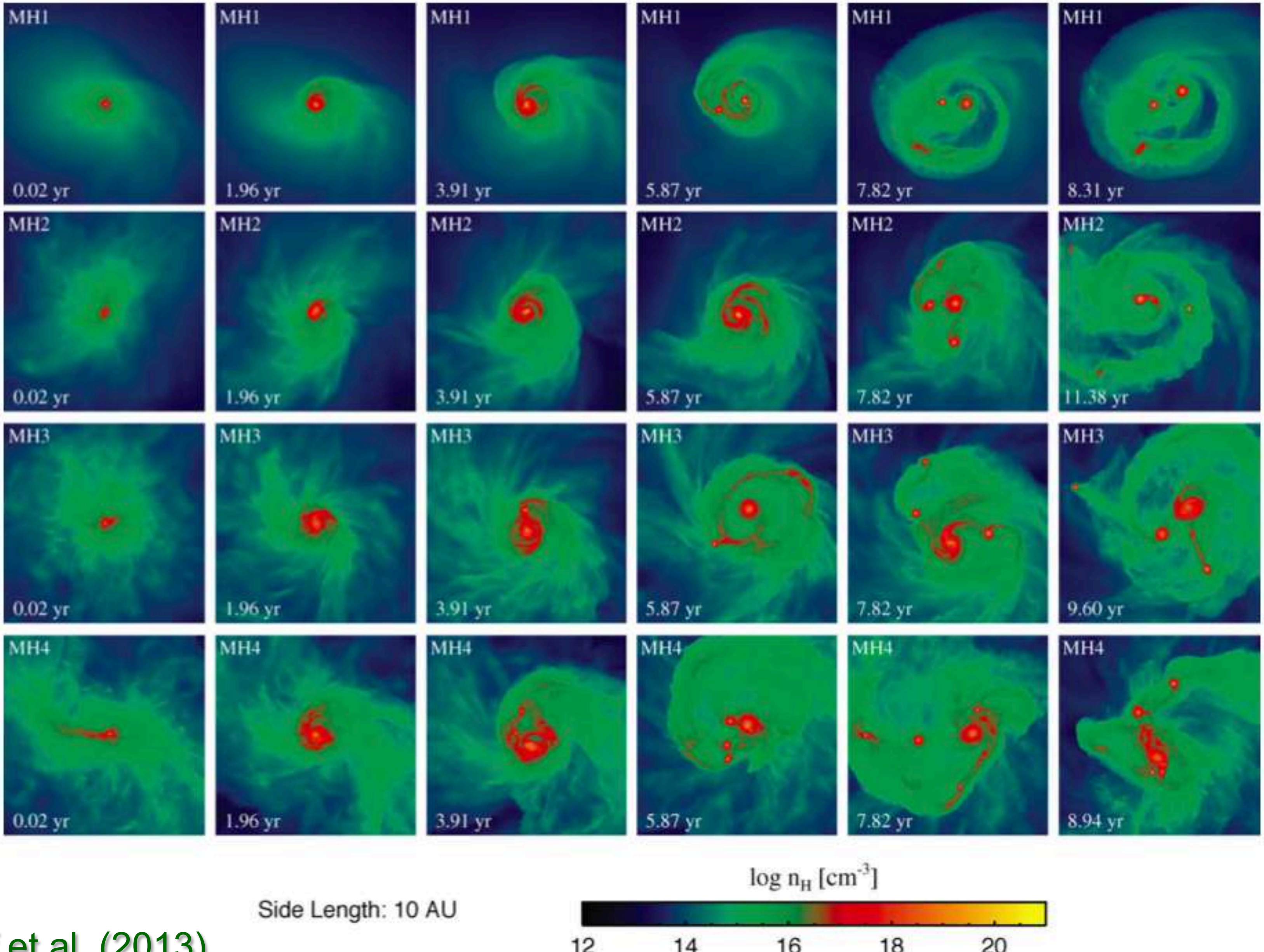
Clark et al. (2011)

Formation of the First Stars: Fragmentation



Clark et al. 2011, Science

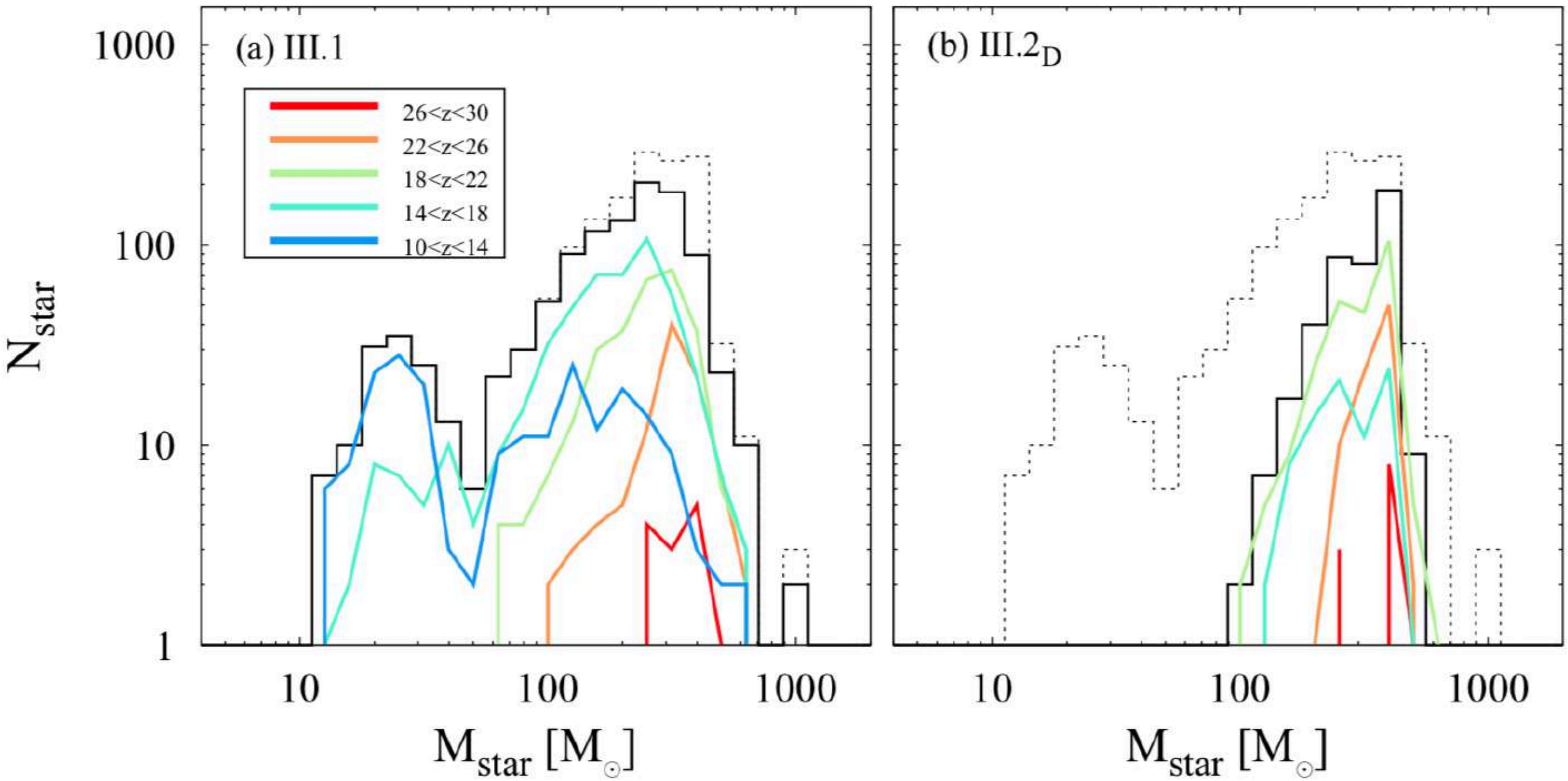
Formation of the First Stars: Fragmentation



Greif et al. (2013)

Formation of the First Stars: IMF

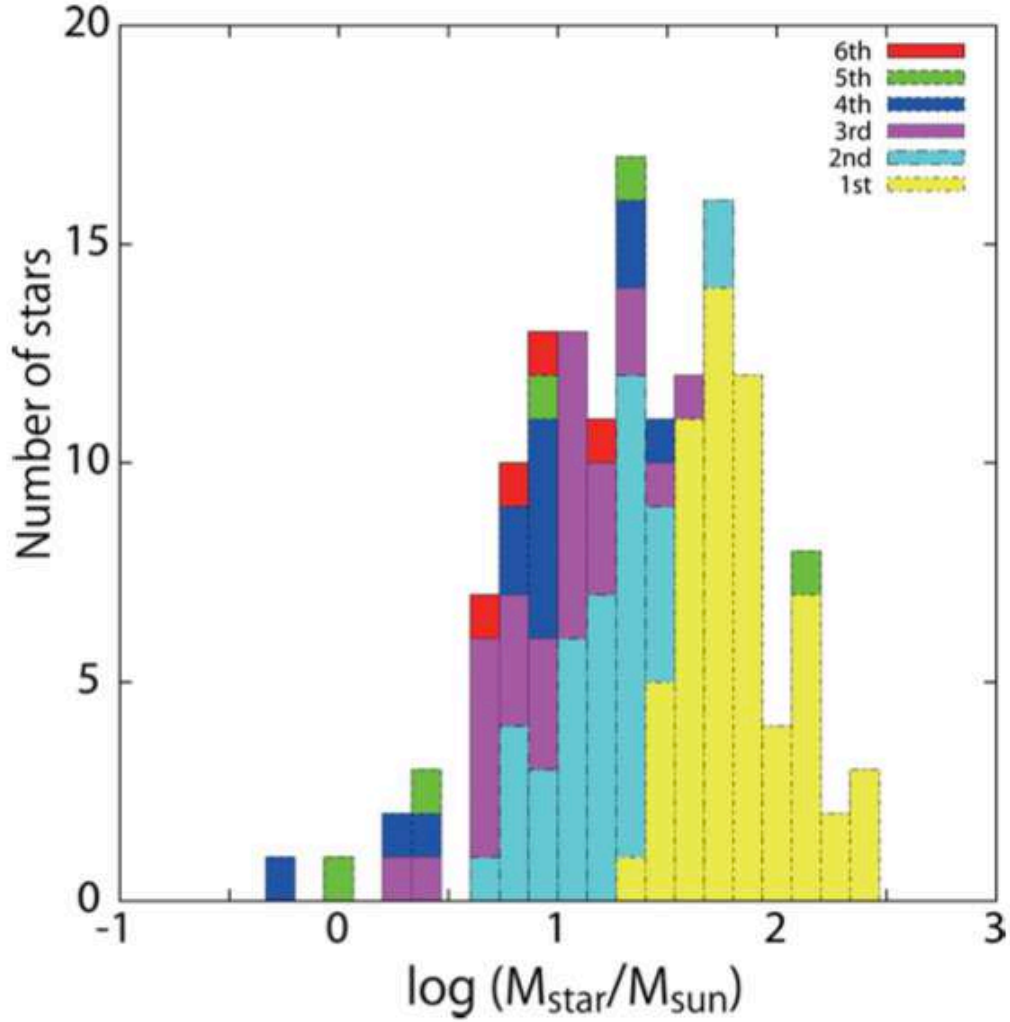
Primordial IMF from simulations so far...



Hirano et al. (2015)

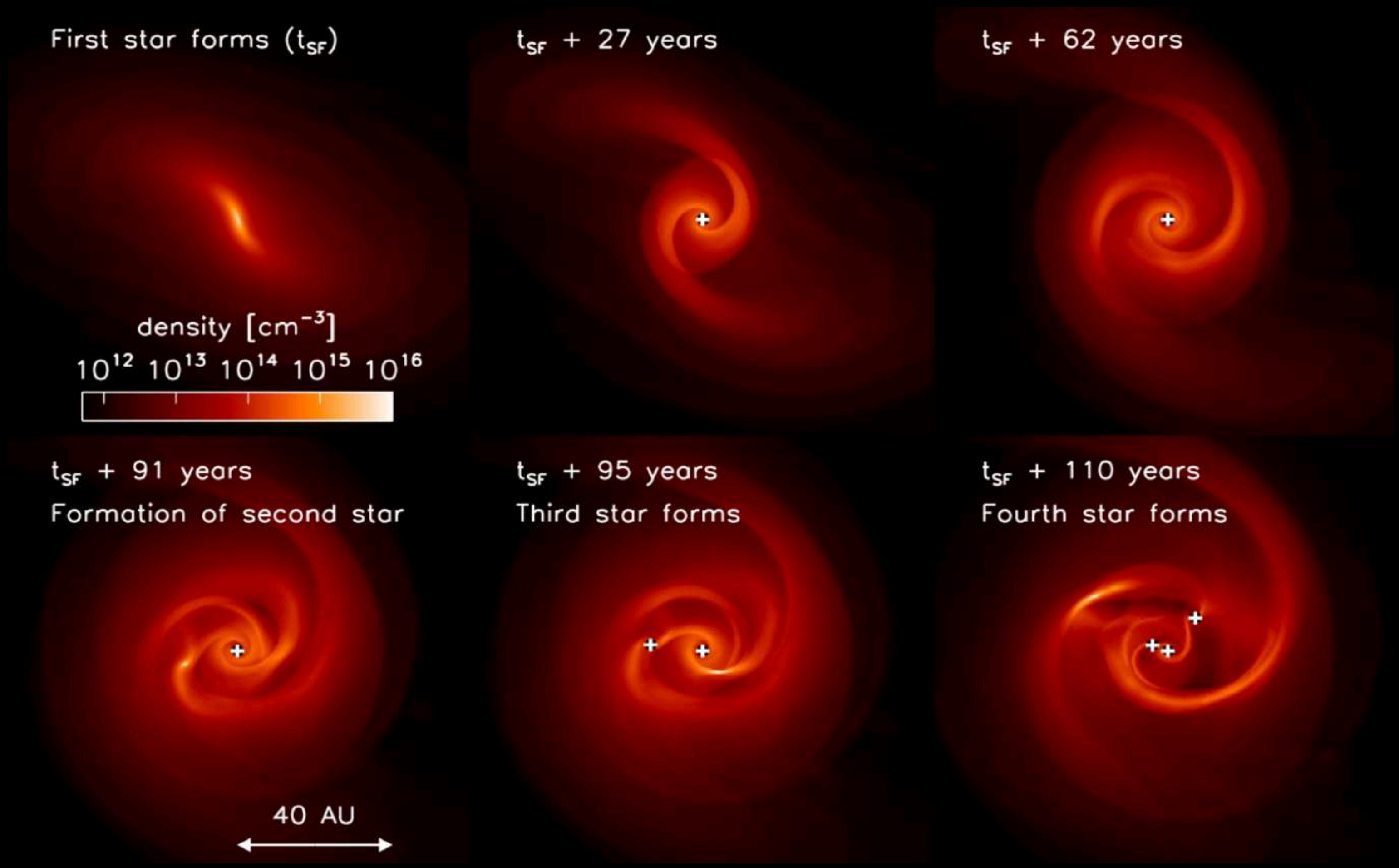
Formation of the First Stars: IMF

Primordial IMF from simulations so far...



Susa et al. (2014)

Formation of the First Stars in the Universe



Clark et al. 2011, Science

Important physics missing: **no magnetic fields, no jet feedback**

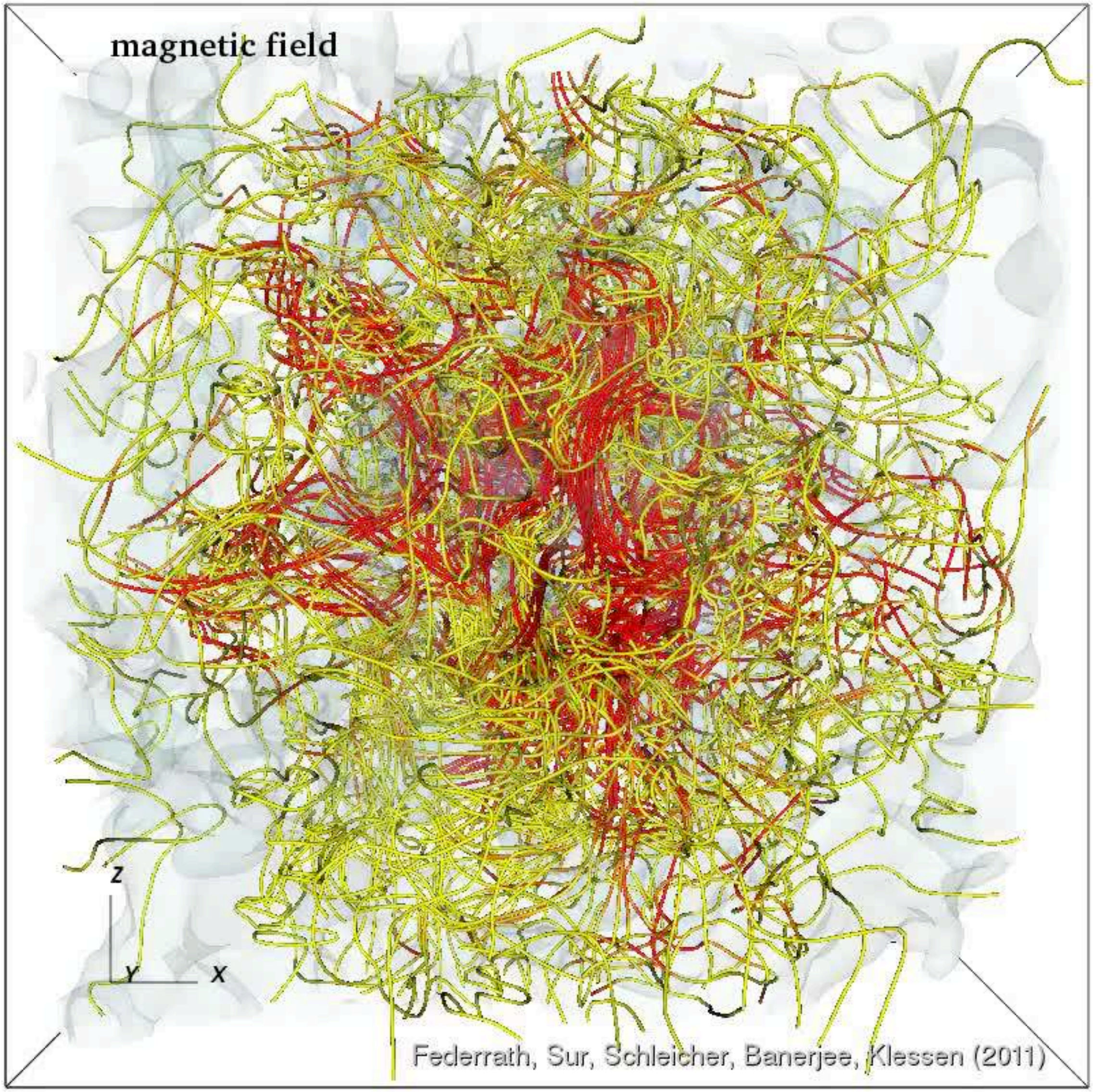
→ **Our simulation methods allow us to predict the IMF of the First Stars**

→ Indirect constraints on First Stars IMF: by e.g., Norris et al. (2013)

and near future observations with **LSST, JWST, GMT, E-ELT**

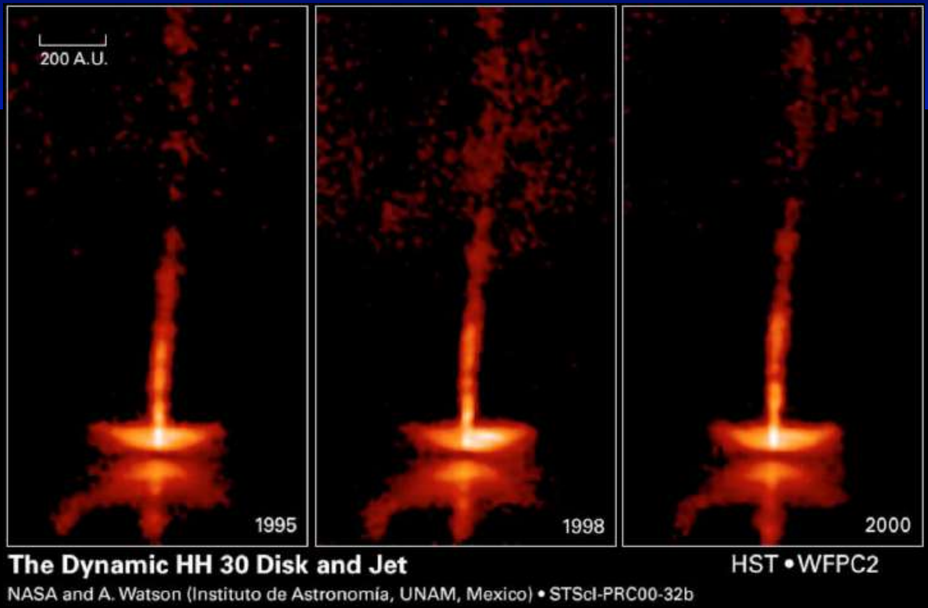
Dynamo-amplified Magnetic Fields

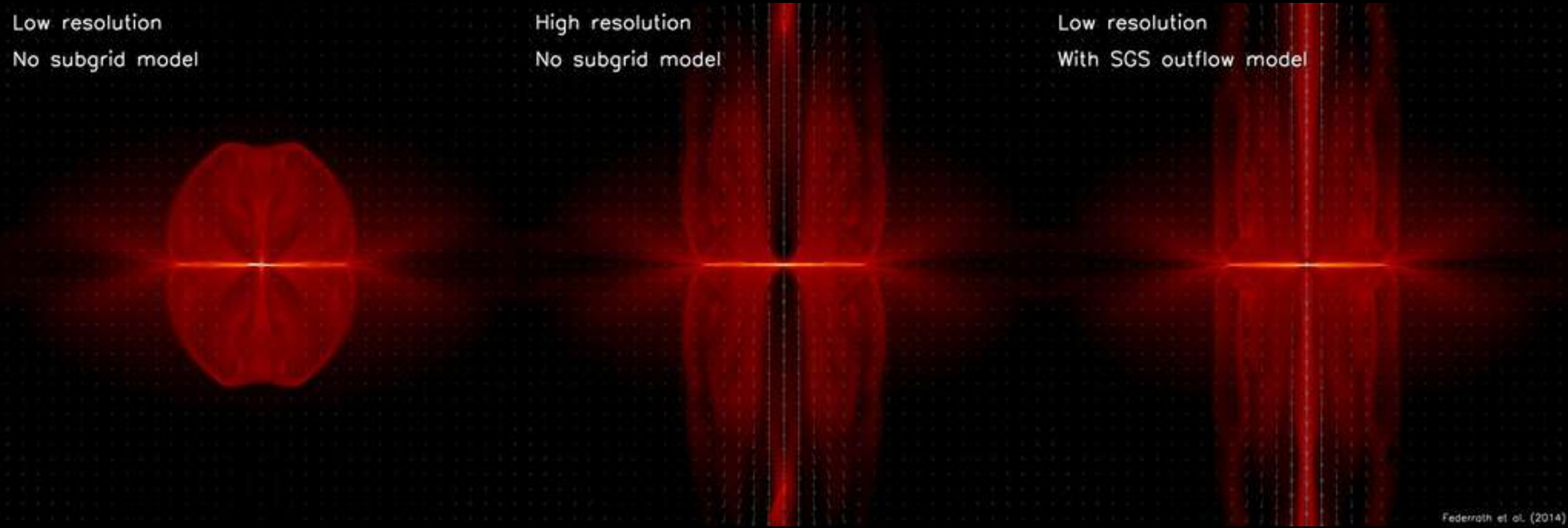
Movies available: **http://www.mso.anu.edu.au/~chfeder/pubs/dynamo_grav/dynamo_grav.html**



Federrath et al. (2011)

Jet/Outflow Feedback



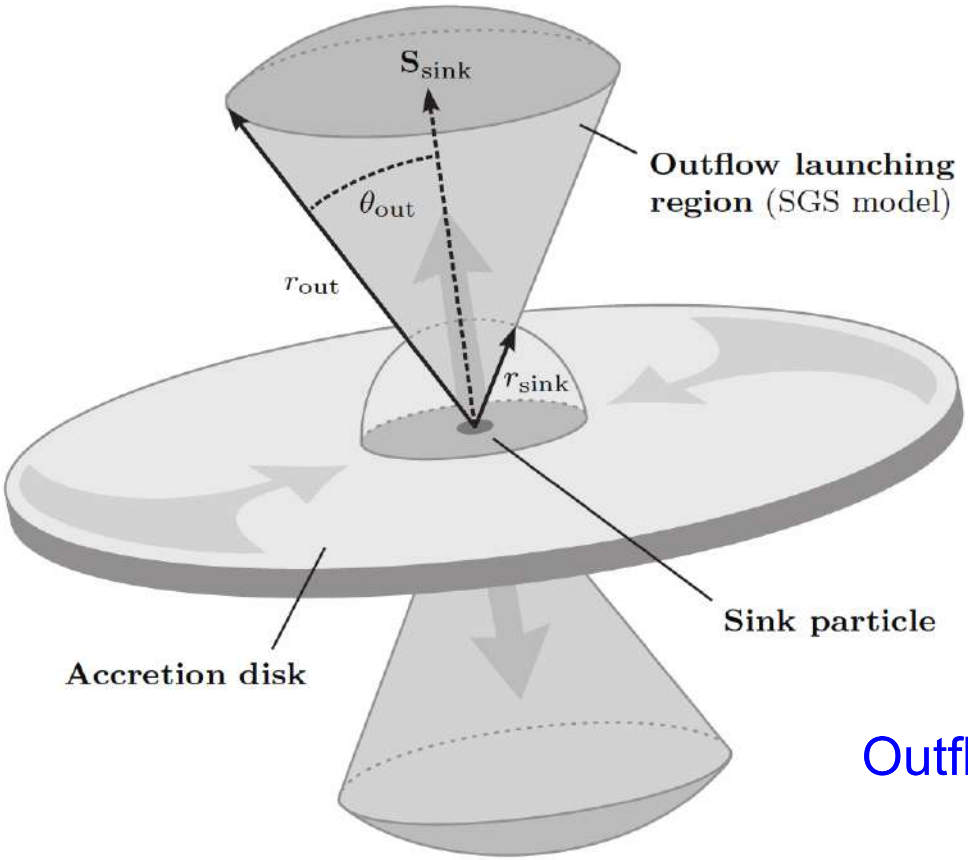


Movies available: https://www.mso.anu.edu.au/~chfeder/pubs/outflow_model/outflow_model.html

Federrath et al. 2014, ApJ 790, 128

Jet Feedback Subgrid Model

Federrath et al. 2014, ApJ 790, 128



List of SGS outflow parameters.

SGS Parameter	Symbol	Default	Reference
Outflow Opening Angle	$\theta_{\rm out}$	$30°$	[1]
Mass Transfer Fraction	$f_{\rm m}$	0.3	[2]
Jet Speed Normalization[a]	$\lvert\mathbf{V}_{\rm out}\rvert$	$100\,{\rm km\,s^{-1}}$	[3]
Angular Momentum Fraction	$f_{\rm a}$	0.9	[4]
Outflow Radius	$r_{\rm out}$	$16\,\Delta x$	Section 4

Notes. [a] The outflow velocities are dynamically computed according to the Kepler speed at the footpoint of the jet, $\lvert\mathbf{V}_{\rm out}\rvert = 100\,{\rm km\,s^{-1}}(M_{\rm sink}/0.5\,M_\odot)^{1/2}$ (see Equation 13).
References: [1] Blandford & Payne (1982); Appenzeller & Mundt (1989); Camenzind (1990); [2] Hartmann & Calvet (1995); Calvet (1998); Tomisaka (1998); Bacciotti et al. (2002); Tomisaka (2002); Lee et al. (2006); Cabrit et al. (2007); Lee et al. (2007); Hennebelle & Fromang (2008); Duffin & Pudritz (2009); Bacciotti et al. (2011); Price et al. (2012); Seifried et al. (2012); [3] Herbig (1962); Snell et al. (1980); Blandford & Payne (1982); Draine (1983); Uchida & Shibata (1985); Shibata & Uchida (1985, 1986); Pudritz & Norman (1986); Wardle & Königl (1993); Bacciotti et al. (2000); Königl & Pudritz (2000); Bacciotti et al. (2002); Banerjee & Pudritz (2006); Machida et al. (2008); [4] Pelletier & Pudritz (1992); Bacciotti et al. (2002); Banerjee & Pudritz (2006); Hennebelle & Fromang (2008).

Outflow mass: $$M_{\rm out} = f_{\rm m}\dot{M}_{\rm acc}\Delta t$$

Outflow velocity: $$\lvert\mathbf{V}_{\rm out}\rvert = \left(\frac{GM_{\rm sink}}{10\,R_\odot}\right)^{1/2} = 100\,{\rm km\,s^{-1}}\left(\frac{M_{\rm sink}}{0.5\,M_\odot}\right)^{1/2}$$

Outflow angular momentum: $$\mathbf{L}_{\rm out} = f_{\rm a}\left(\mathbf{S}'_{\rm sink} - \mathbf{S}_{\rm sink}\right)\cdot\mathbf{S}'_{\rm sink}/\lvert\mathbf{S}'_{\rm sink}\rvert$$

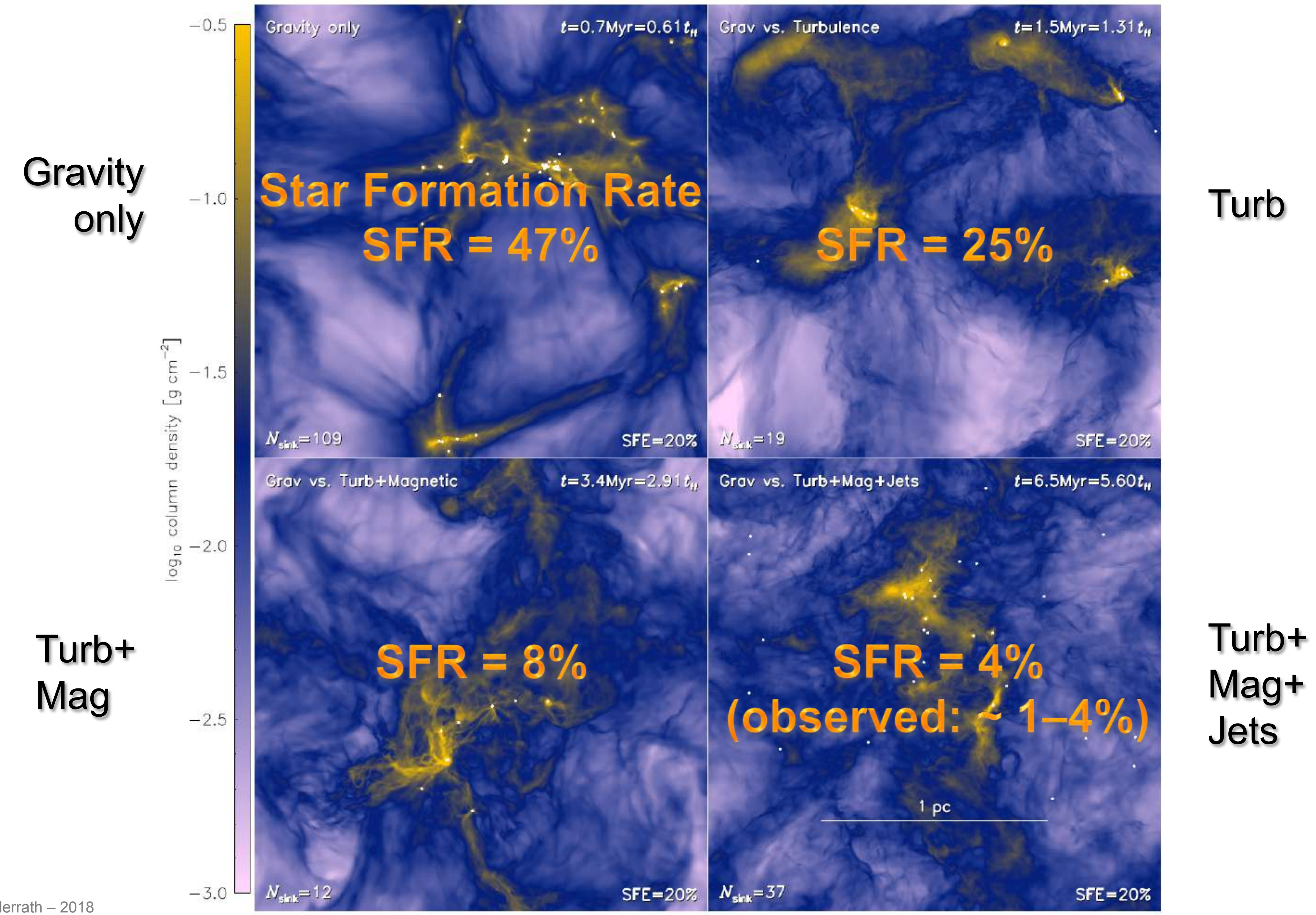
Outflow/Jet Feedback

NGC1333

Image credit: Gutermuth & Porras

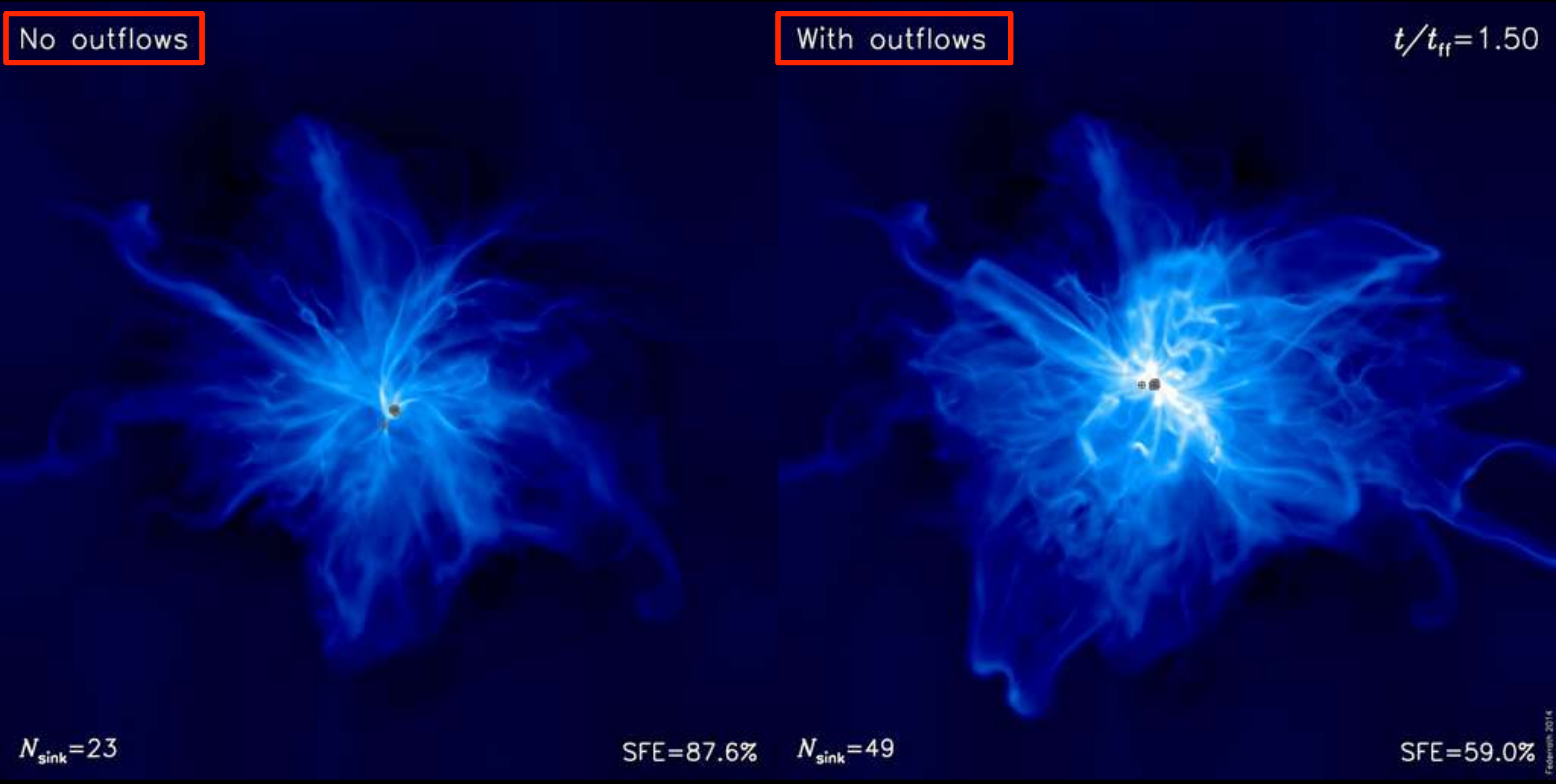
Star Formation is Inefficient (Federrath 2015, MNRAS 450, 4035)

Movies available: http://www.mso.anu.edu.au/~chfeder/pubs/ineff_sf/ineff_sf.html



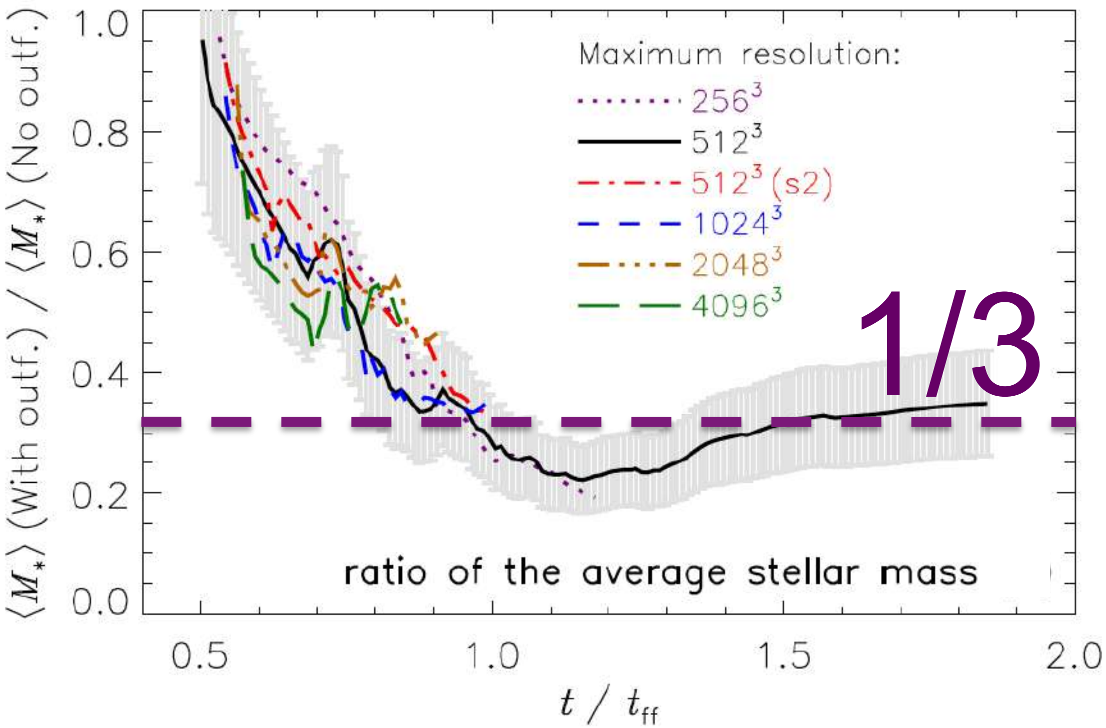
The role of outflow/jet feedback

Movies available: https://www.mso.anu.edu.au/~chfeder/pubs/outflow_model/outflow_model.html

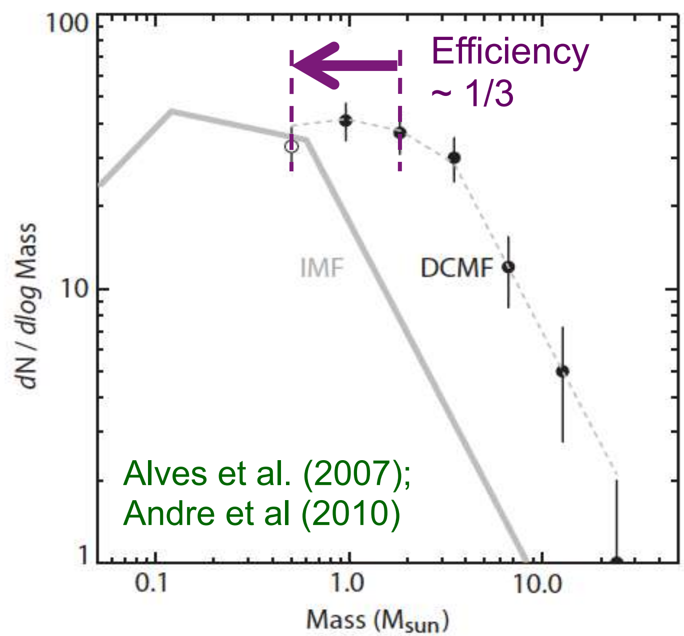


Federrath et al. 2014, ApJ 790, 128

Implications for the stellar initial mass function (IMF)



Federrath et al. 2014, ApJ 790, 128



Outflow/Jet feedback reduces average star mass by factor ~ 3 → IMF!