Lecture 2

Evolution of Primordial Protostars

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ADVANCED SUMMER SCHOOL 2019 "FIRST LIGHT"

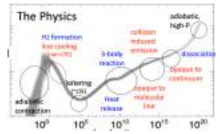
Recap: We have learned

1. From Big Bang ripples to a protostar

2. Physical processes in a primordial gas

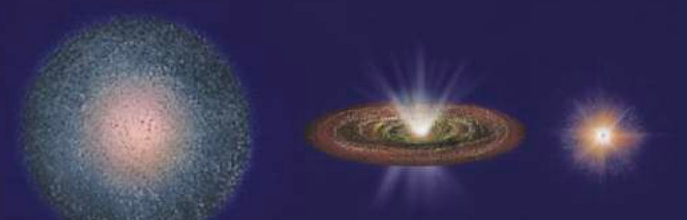
$$H^- + H \rightarrow H_2 + e \qquad \Gamma_{\rm dyn} = \alpha M_{\rm halo}^{-1/3} \frac{k_B}{\gamma - 1} \frac{dM_{\rm halo}}{dt}$$

3. Thermal evolution



STAR FORMATION

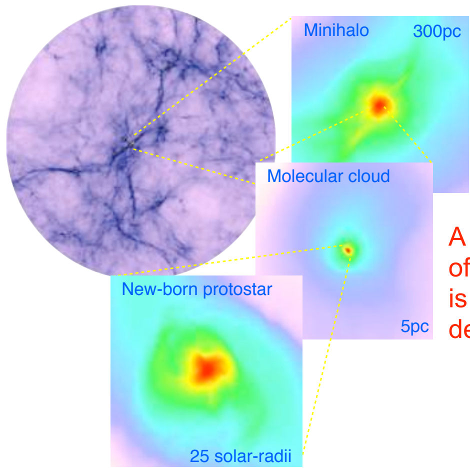
molecular cloud protostar star



today (Lecture 2)

monday (Lecture 1)

An *ab initio* simulation



Resolving planetary scale structures in a cosmological volume!

A complete picture of how a protostar is formed from tiny density fluctuations.

NY, Omukai, Hernquist 2008

Protostellar evolution

The surrounding hot gas is rapidly accreted onto the central proto star.

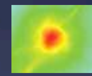
Mass accretion rate
dM/dt ~ soundspeed^3 / *G*
~ temperature$^{1.5}$ / *G*

Very large for *T* = 1000 K. Compare with the present-day environment.

One remaining question: "One protostar in a cloud ?"

This is actually two, **separate** questions:

1. *Does a pre-stellar cloud fragment into multiple clumps ?*
   (Thermal, or chemo-thermal instability.)



2. *Does a circum-steller disk fragment ?*
   (Gravitational instability)

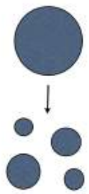
Unfortunately, these two processes are often confused with each other, and also mis-interpreted in many papers.
The short answer is NO for 1, and YES for 2.

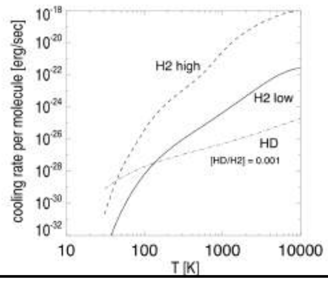
Thermal instability

For cooling rate $L\,(\rho,\,T)$, the Field criterion

$$-\rho\left(\frac{\partial L}{\partial \rho}\right)_T + T\left(\frac{\partial L}{\partial T}\right)_\rho > 0$$

dictates the stability of the gas.





H_2 cooling rate is density-independent at high densities (n >> 10^5). The above condition is satisfied for
$L \sim T^{\alpha}$ with $\alpha > 1$
for a fixed molecular fraction.

Chemo-thermal instability

Recall this reaction: $H + H + H \rightarrow H_2 + H$
The strong density dependence of 3-body reactions can trigger *chemo-thermal instability*:

Gas condensation
→ higher density
→ higher molecular fraction
→ higher cooling rate

Yoshii & Sabano (1977) Silk (1983)

It is very important whether or not the instability occurs and multiple (small-mass) clouds are formed.

Linear analysis and dispersion relation

For perturbations of the form $\delta T, \delta\rho, \delta x \propto \exp(\omega t)$

$$\boxed{A\omega^2 + B\omega + C = 0}$$

$$A = 1 + \frac{6-f}{2(2-f)}$$

$$B = \frac{\mu m_p}{kT}(TL_T - \rho L_\rho - L) - \frac{\mu\chi}{2kT}(TF_T - \rho F_\rho - F) - A\left(F_f + \frac{\mu}{2}\rho F_\rho + \frac{\mu F}{2}\right)$$

L : cooling rate, F : reaction (formation) rate
f : molecular fraction. Subscripts denote partial derivatives.

(coefficients continued...)

$$\begin{aligned} C = &-\frac{\mu m_p}{kT}(TL_T - \rho L_\rho - L)\left(F_f + \frac{\mu}{2}\rho F_\rho + \frac{\mu F}{2}\right) \\ &+ \frac{\mu m_p}{kT}\left(L_f + \frac{\mu}{2}\rho L_\rho + \frac{1}{6-f}L\right)(TF_T - \rho F_\rho) \\ &+ \frac{\mu}{2}F\left[\frac{\mu}{3-f/2}\left(\frac{1}{2} + \frac{\chi}{kT}\right)(TF_T - \rho F_\rho) - \frac{\chi}{kT}\left(F_f + \frac{\mu}{2}\rho F_\rho + \frac{\mu F}{2}\right)\right] \\ &- \frac{\mu}{(3-f/2)\,t_{\rm dyn}}(TF_T - \rho F_\rho). \end{aligned}$$

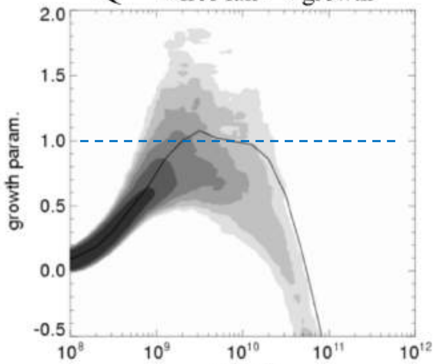
Further details given in Yoshii & Sabano (1977); Silk (1983)

We compare the real root of the dispersion relation (growth time) with the free fall time:

$$Q = \frac{t_{\rm dyn}}{t_{\rm g}} = \omega t_{\rm dyn} \quad \text{where} \quad t_{\rm dyn} = \sqrt{\frac{3\pi}{32G\rho}}$$

3D simulation result

$Q = t_{\text{free fall}} / t_{\text{growth}}$



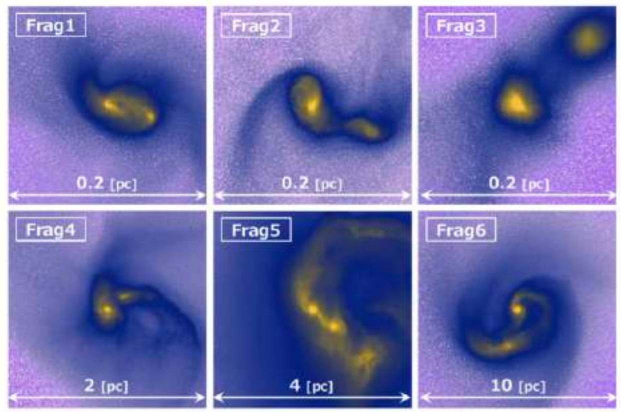
Q gets larger than 1, but not much larger.

Pertubation growth comparable to gravitational collapse.

Collapse is just accelerated and no fragmentation.

Note again that this is a different process from disk fragmentation in the post-collapse, accretion phase.

"Cosmological" samples



Out of 100 clouds from Hirano et al. (2014)

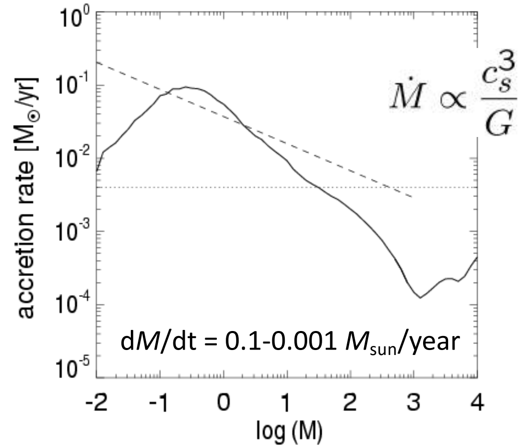
Protostellar evolution

The surrounding hot gas is rapidly accreted onto the central proto star.

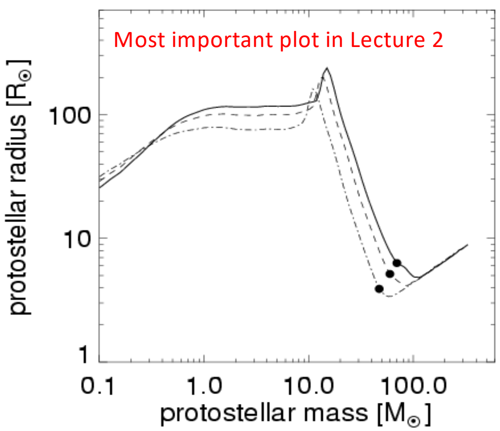
Mass accretion rate
$dM/dt \sim \text{soundspeed}^3 / G$
$\sim \text{temperature}^{1.5} / G$

Very large for T = 1000 K. Compare with the present-day environment.

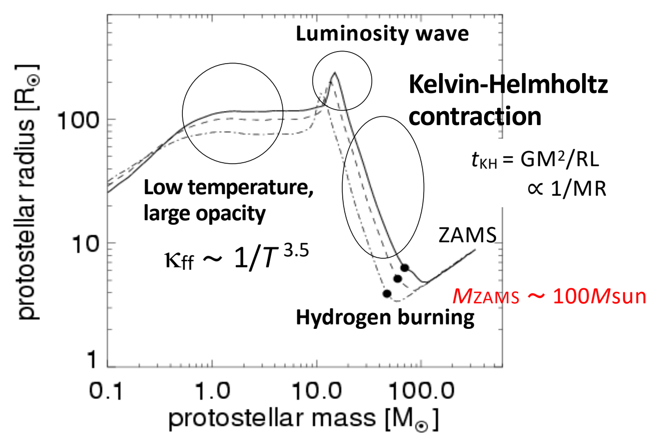
Gas mass accretion rate



Growth of a protostar



Growth of a protostar



Early Universe: Ideal environment for massive star formation

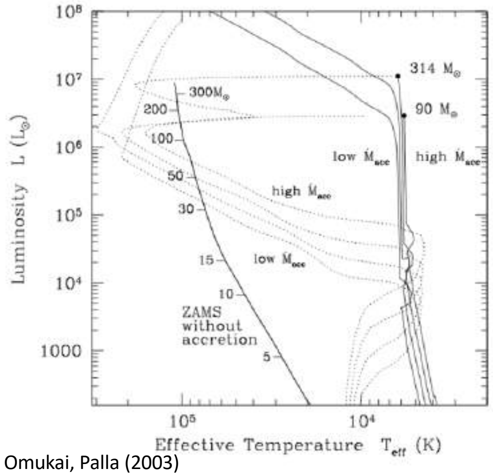
1 Large cloud mass at the onset of collapse
$M_{jeans} \sim$ 1000 solar-masses available (at most)

2 Not many stellar seeds (protostars)

3 Large accretion rate (rapid growth)
$dM/dt \sim$ 0.01 - 0.001 solar mass per year

4 Lack of opacity source
No efficient way of stopping accretion

H-R diagram: *T* - *L* evolution



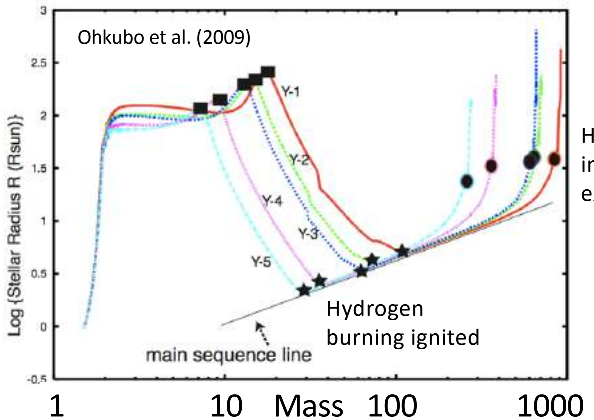
Omukai, Palla (2003)

An accreting protostar ascends vertically in the H-R diagram.

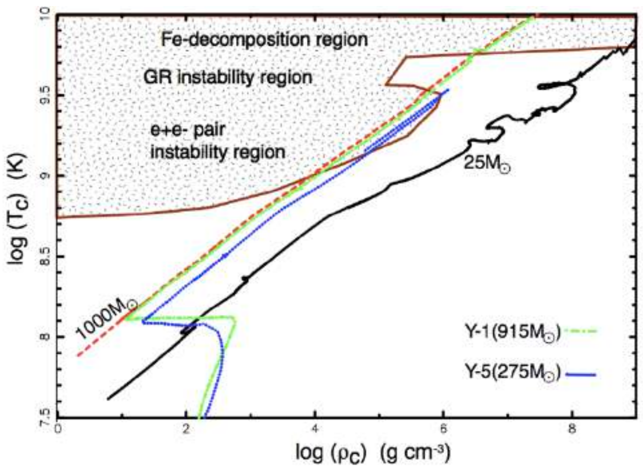
The atmosphere remains bloated, i.e., low T_{eff}.

Compare with the Hayashi track for ordinary protostars

Post-main sequence evolution



Core evolution and e+/e- creation



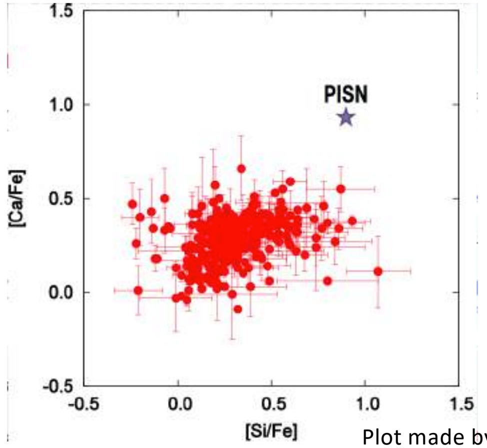
So far, so good…

Mystery #1

Models and numerical simulations suggest that the first stars are rather massive, even greater than 100 Msun.

However, there is no indication, and no single evidence that very massive Stars appreciably contributed to Galactic chemical Evolution.

Elemental abundances of metal-poor stars

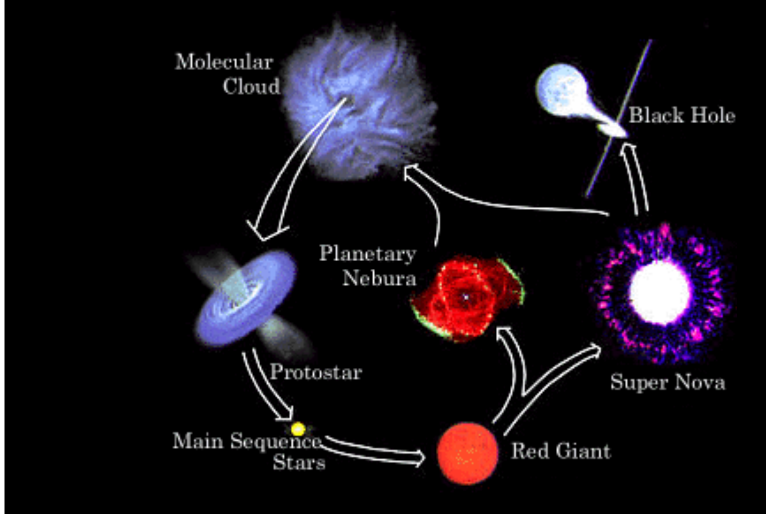


Plot made by N. Tominaga

The characteristic mass of the first stars

- our “Holy Grail”

Life cycle of stars

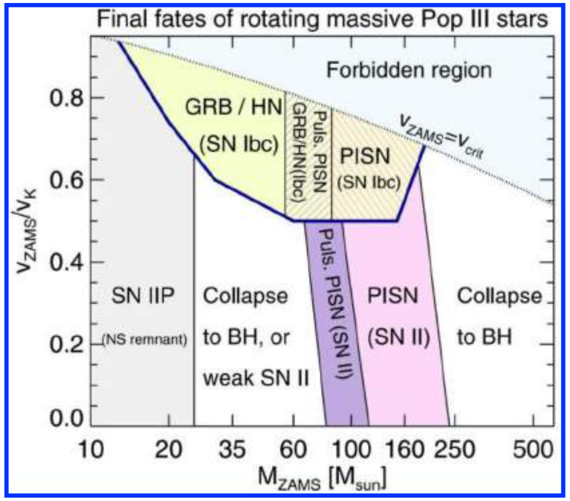


The mass and the fate of a star

mass	lifetime	fate
1 solar	~ 10 billion years	white dwarf
10	~ 10 million years	supernova
200	~ 2 million years	energetic supernova

> 1 million times brighter than the sun

Fate of the first stars



From Yoon (2009)

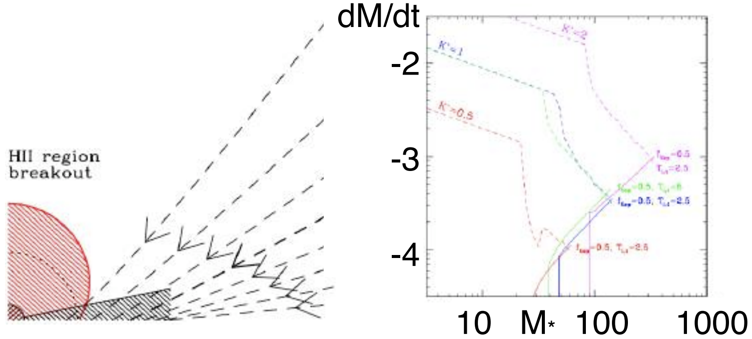
Protostars grow through gas accretion, mergers, plus, protostellar feedback over ~ 100,000 years

The Key Question

How and when does a first star stop growing ?

Protostellar feedback

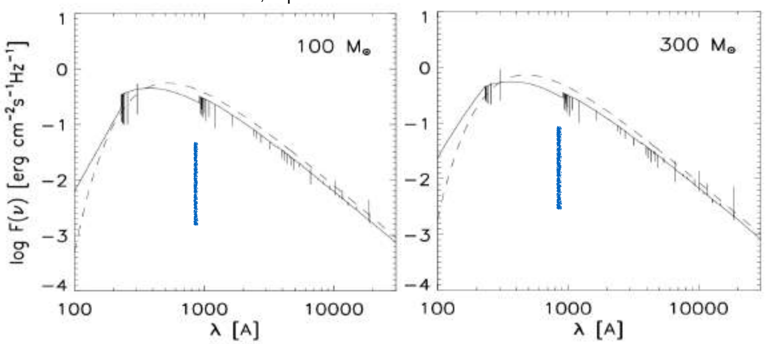
A disk evaporation model by Tan & McKee



Dipoar HII regions breaks out and eventually evaporates the geometrically thin disk

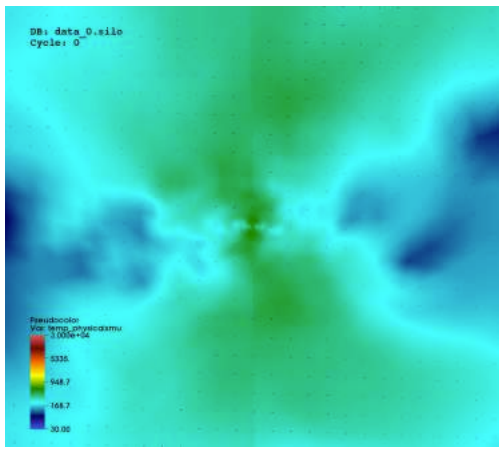
Pop III Spectral Energy Distribution

Bromm et al. 2001, ApJ

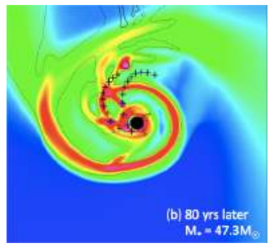


Pop III stars are more compact, and so *hotter* than the Pop I counterpart with the same mass.

PROTO-STELLAR FEEDBACK



Hosokawa et al. 2016, ApJ



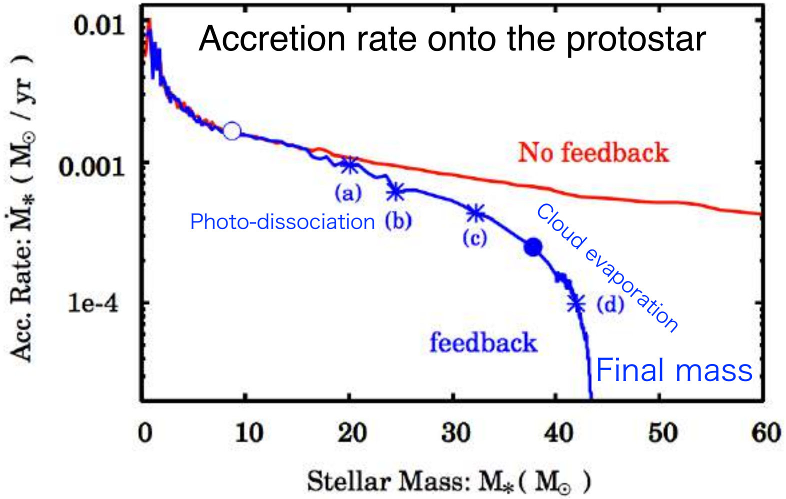
Accretion vs bi-polar HII regions

Self-regulation mechanism:

McKee-Tan08; Hosokawa+11; Stacey+12

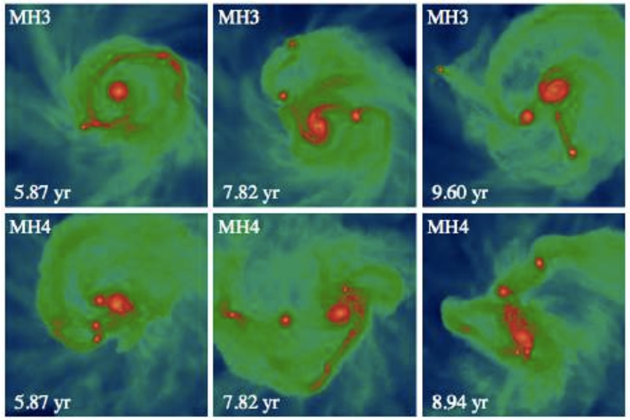
Final mass of a first star

Hosokawa, Omukai, NY, Yorke, 2011, Science



POST-COLLAPSE PHASE

Fragmentation of a proto-stellar disk

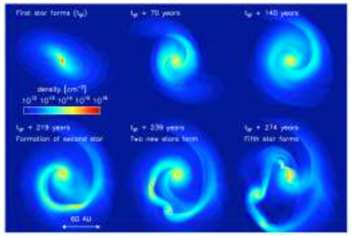


Small fragments migrate onto the central protostar on an orbital time scale

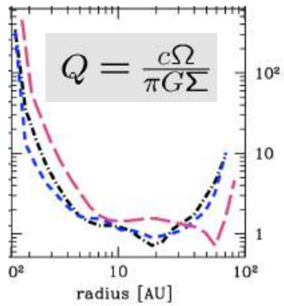
"Gravo-viscous accretion"

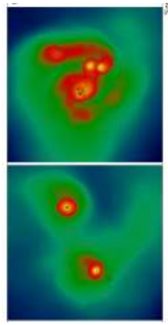
Greif et al. 2012, MNRAS

STAR CLUSTER FORMATION ?

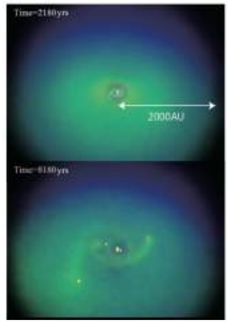


Clark+2011





Stacy+2014



Susa+2014

Toomre analysis

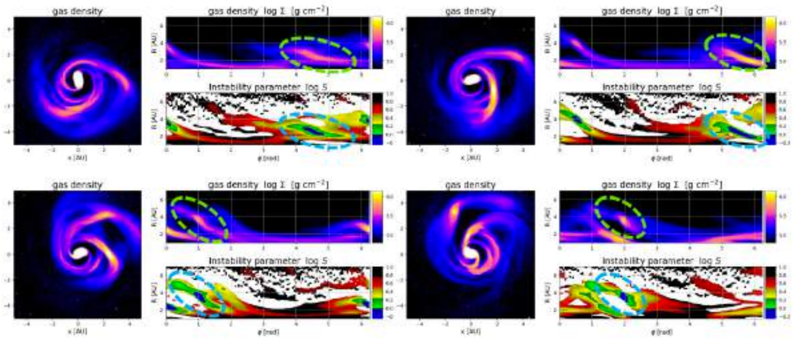
$f_1 \propto e^{i(kR-\omega t)}$

→ stability against radial perturbation i.e., formation of spiral arms in a differentially rotating disk (and not fragmentation!!!)

WHETHER OR NOT A SPIRAL ARM PRODUCES PROTOSTARS IS A SEPARATE QUESTION!!!

SPIRAL ARM INSTABILITY

Stability against perturbations along the arm (ring)



Linear analysis → critical wavenumber

$$\omega^2 = \left[\sigma^2 - \pi G \Upsilon f(kW)\right] k^2 + 4\Omega^2$$

$$f(kW) \equiv [K_0(kW)L_{-1}(kW) + K_1(kW)L_0(kW)]$$

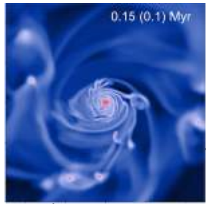
$$S \equiv \frac{\sigma^2 k^2 + 4\Omega^2}{\pi G f(kW) \Upsilon k^2} = 1$$

Typical Mass

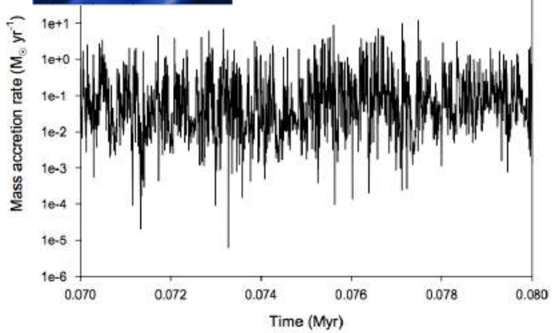
$$M_{\rm cl} \sim \frac{\Upsilon}{f_{\rm g}} \lambda_{\rm MU} = A \frac{\Sigma}{f_{\rm g}} W \lambda_{\rm MU}$$

Inoue & Yoshida, 2018; 2019 (see also Takahashi+2015)

ACCRETION BURSTS



Protostellar disk evolution (Vorobiov+ 2012)

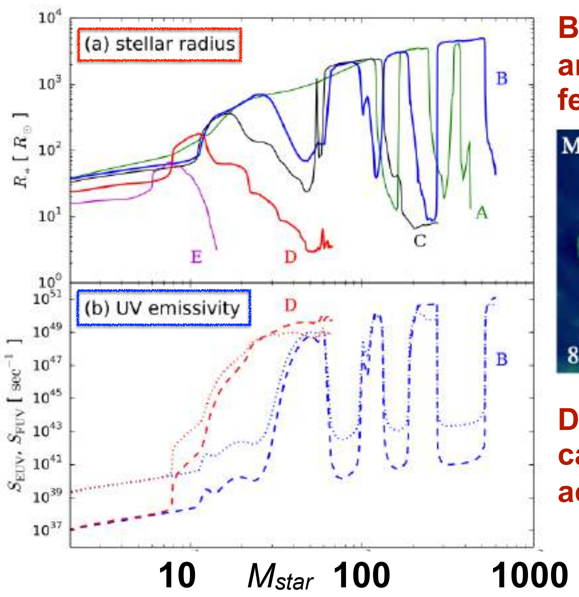


Sakurai, Vorobiev, in prep.

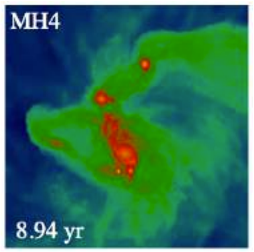
Accretion rate is highly time-dependent.

"Burst accretion" changes the strength of protostellar feedback.

It takes a KH time for the outer envelope to contract.



Burst accretion and proto-stellar feedback.

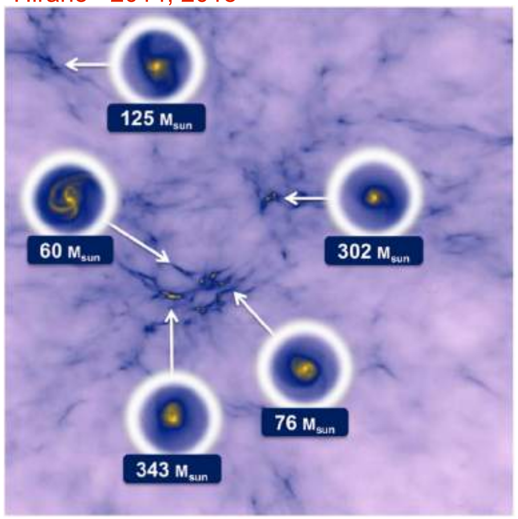


Disk fragmentation causes sporadic accretion "burst"

Greif+ 2012
Vorobyov+ 2014
Sakurai+2015

ONE HUNDRED FIRST STARS

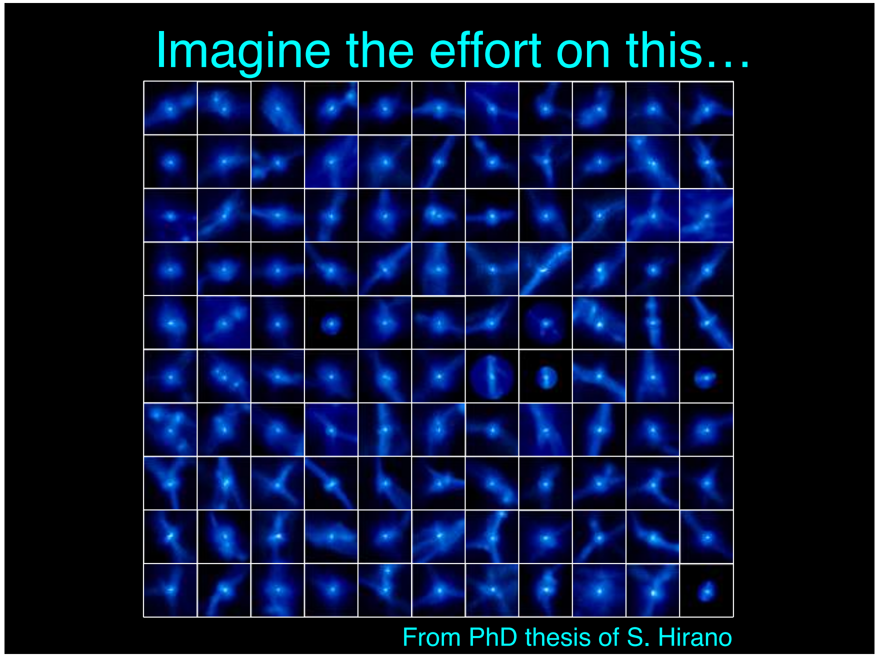
Hirano+ 2014; 2015

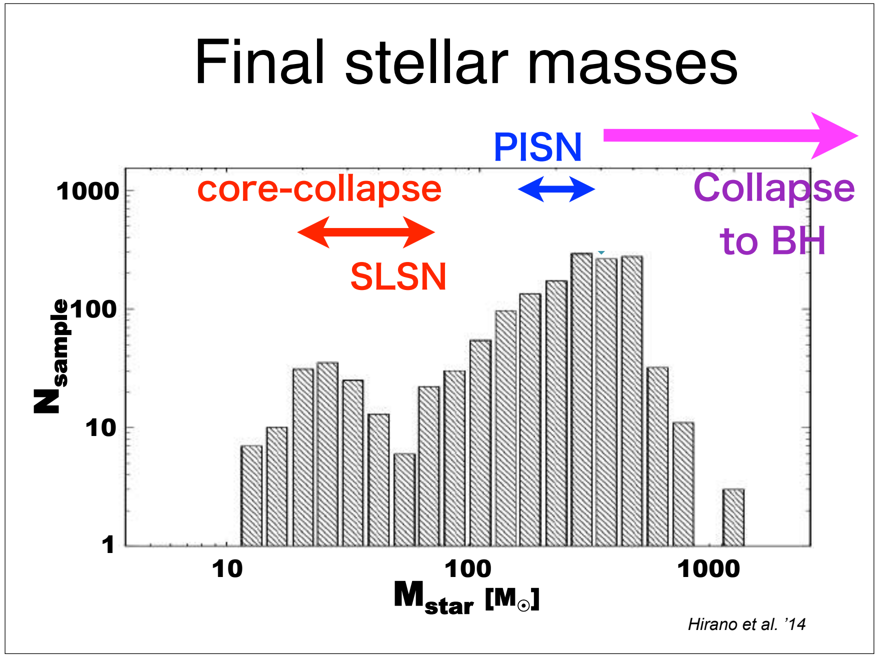


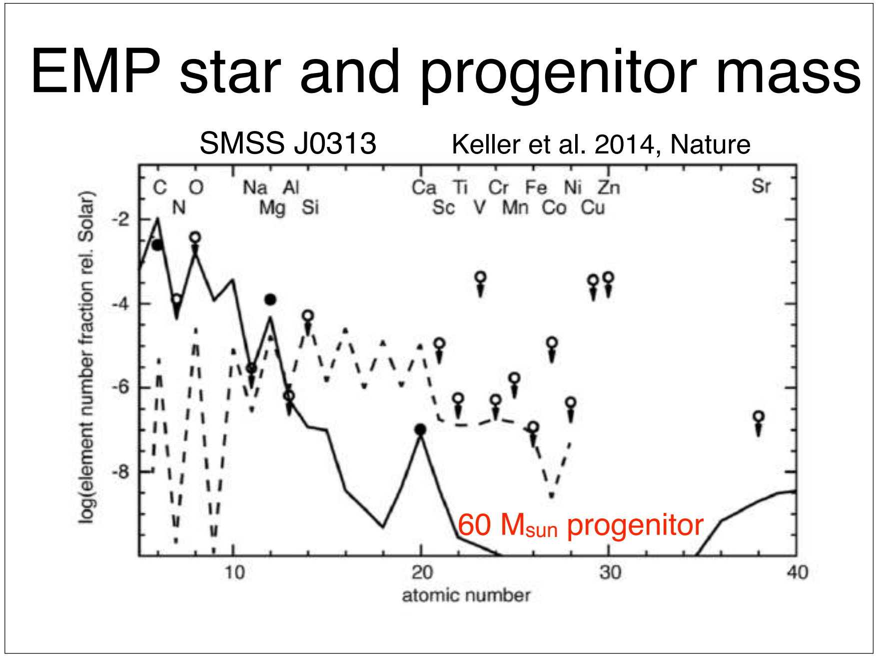
Cosmological hydro simulation
+
radiation-hydro calculation of protostellar evolution

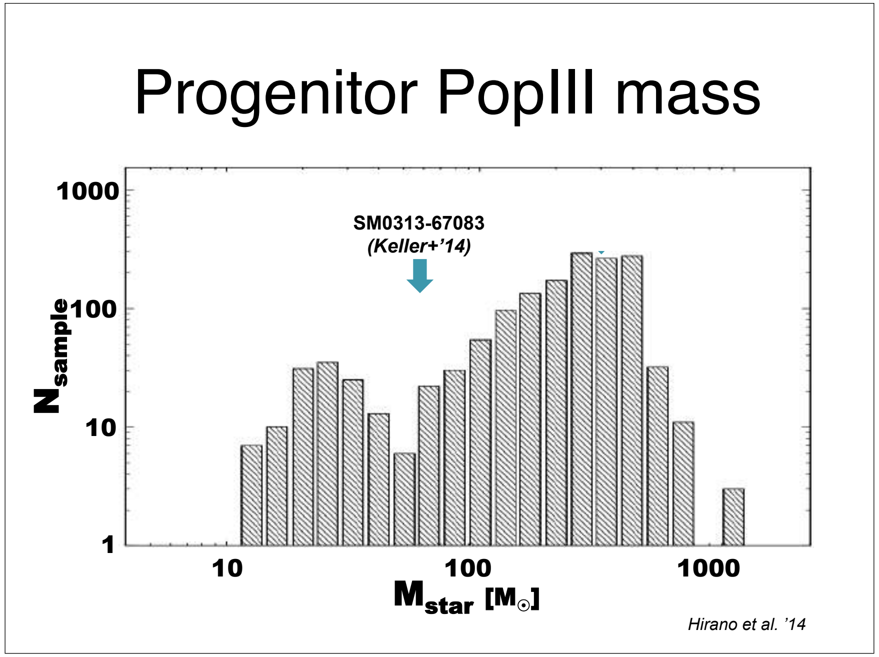
100 star forming clouds located in a cosmological volume.

Mass distribution of the first stars


Imagine the effort on this…
From PhD thesis of S. Hirano


Final stellar masses
PISN
core-collapse
Collapse to BH
SLSN
1000
100
10
1
N_{sample}
10
100
1000
M_{star} [$M_\odot$]
Hirano et al. '14

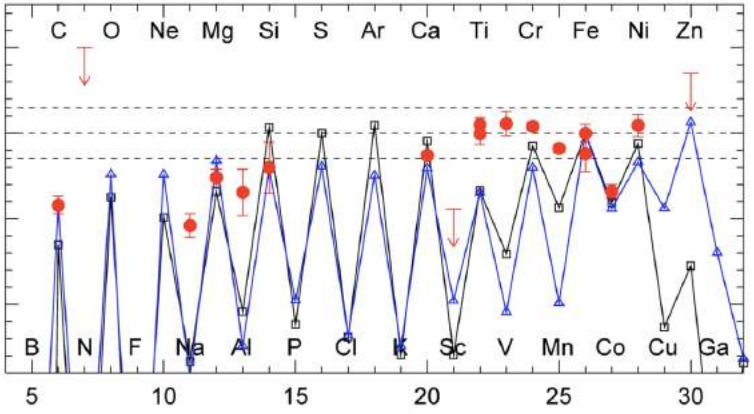

EMP star and progenitor mass
SMSS J0313
Keller et al. 2014, Nature
C O N Na Al Mg Si Ca Ti Cr Fe Ni Zn Sc V Mn Co Cu Sr
log(element number fraction rel. Solar)
-2
-4
-6
-8
10
20
30
40
atomic number
60 M_{sun} progenitor


Progenitor PopIII mass
SM0313-67083
(Keller+'14)
1000
100
10
1
N_{sample}
10
100
1000
M_{star} [$M_\odot$]
Hirano et al. '14

Another metal-poor star

SDSS J1820.5-093939.2

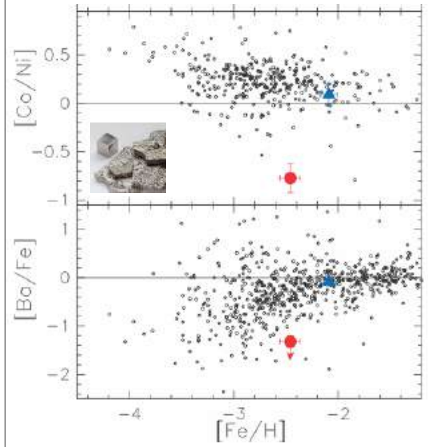
Aoki et al. 2014, Science



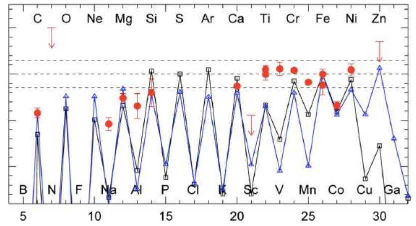
SN models of 300-1000 M_{sun} progenitor

Very massive star ?

Low-mass metal-poor star SDSS J001820.5-093939.2

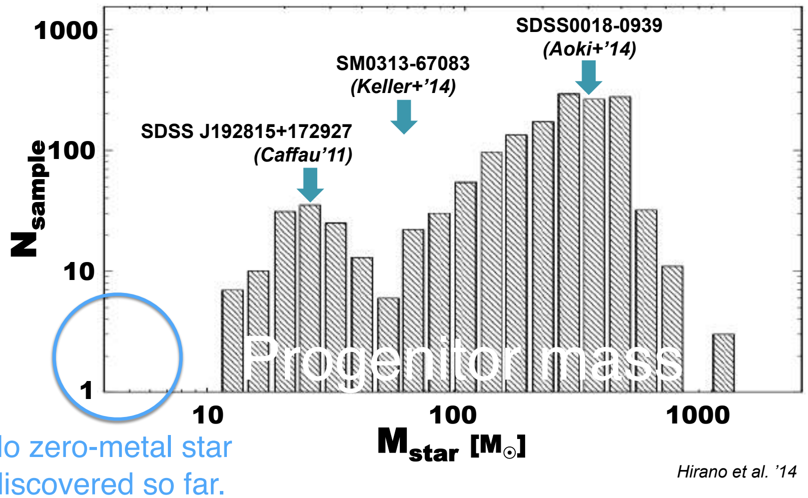


Very different yield from core-collapse supernova:
low α/Fe, low Co/Fe etc
Signatures of a pair-instability supernova of progenitor mass > 200 M_{sun}



Aoki et al. 2014, Science

Progenitor PopIII masses



No zero-metal star discovered so far.

Summary of Lecture 2

- Protostellar evolution
- Radiative feedback and self-regulation
- Disk fragmentation and arm instability
- Wide mass distribution and the final fates