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The Dark Ages of the Universe

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  A missing piece in cosmic history
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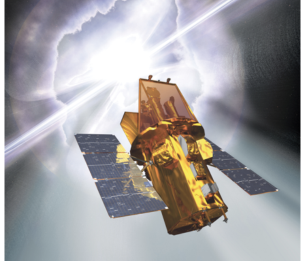
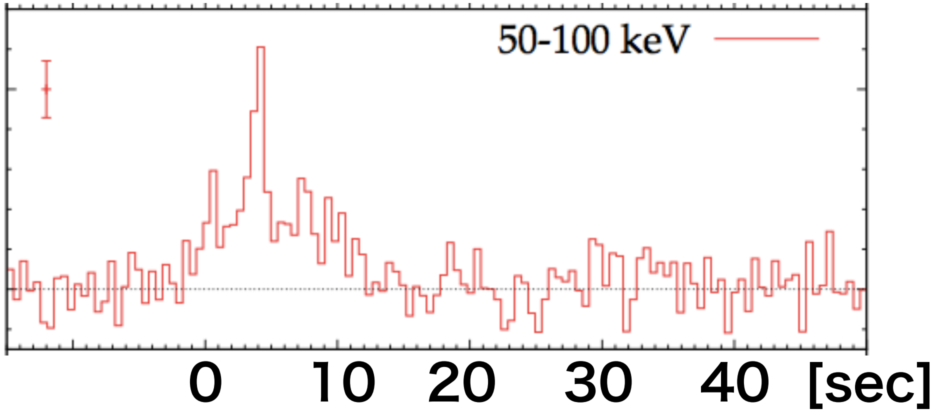
  Setting the scene for galaxy formation

References:
Hosokawa, Omukai, NY, Yorke, 2011, Science
Bromm, NY, 2011, ARAA
Hosokawa, Yorke, Omukai, Inayoshi, NY, 2013, ApJ
Tanaka, Moriya, NY, 2013, MN
Hirano et al. 2014, ApJ

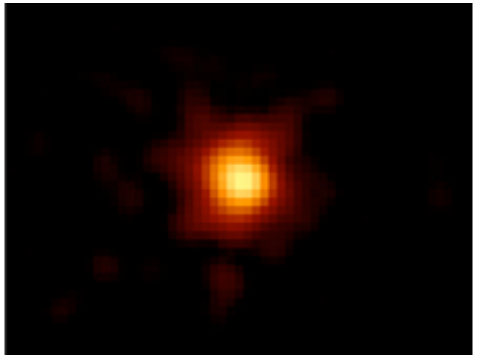


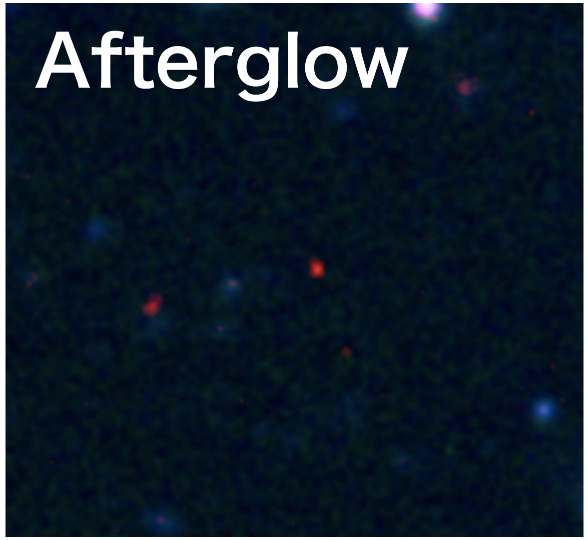
γ-ray burst

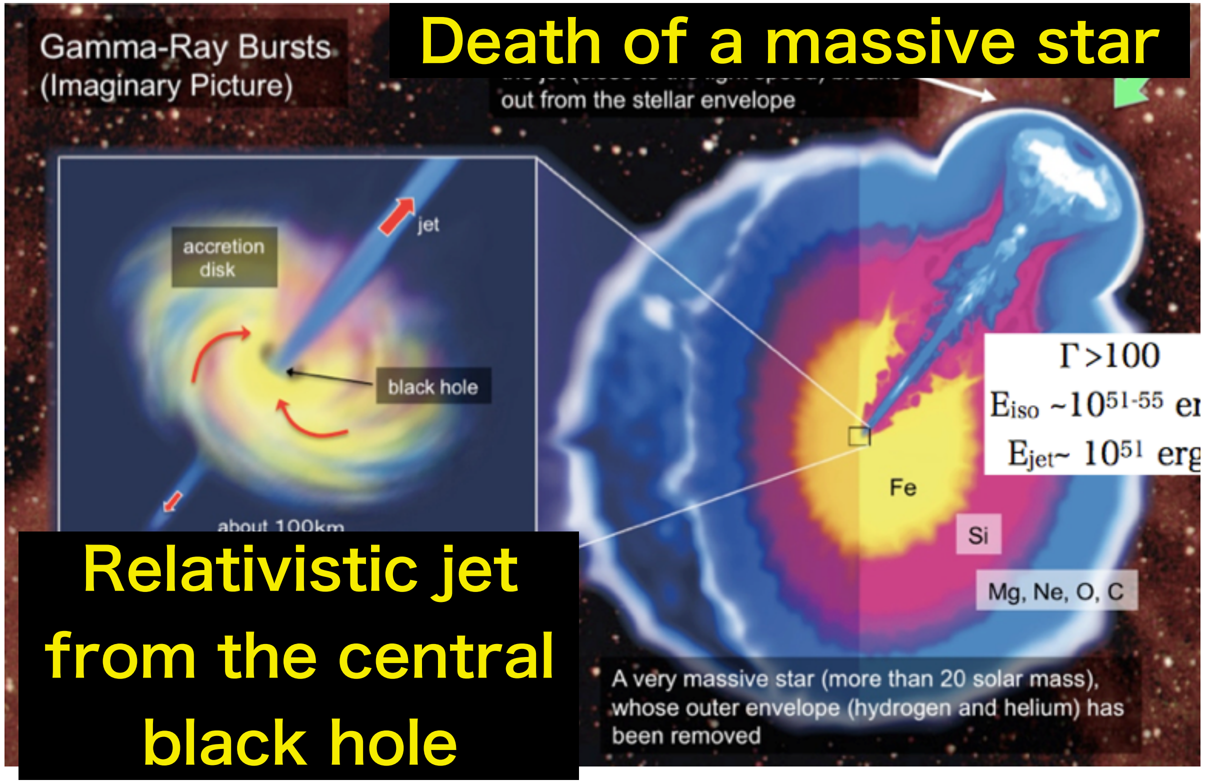
Photon count by Swift sat.



X-ray image





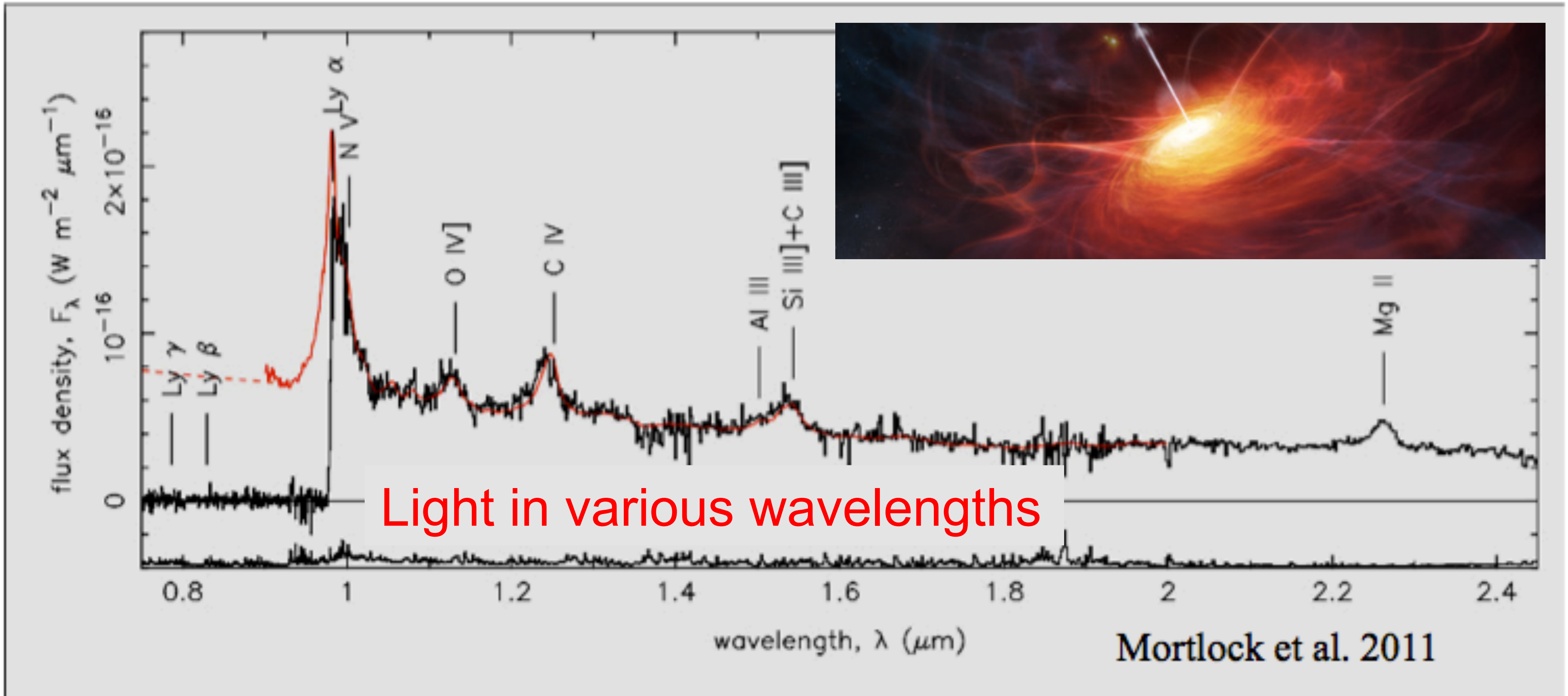


- Every few days
- From all directions on the sky (=extragalactic)
- The record redshift of $z=9.4$!
  ~ 13.5 billion light yrs

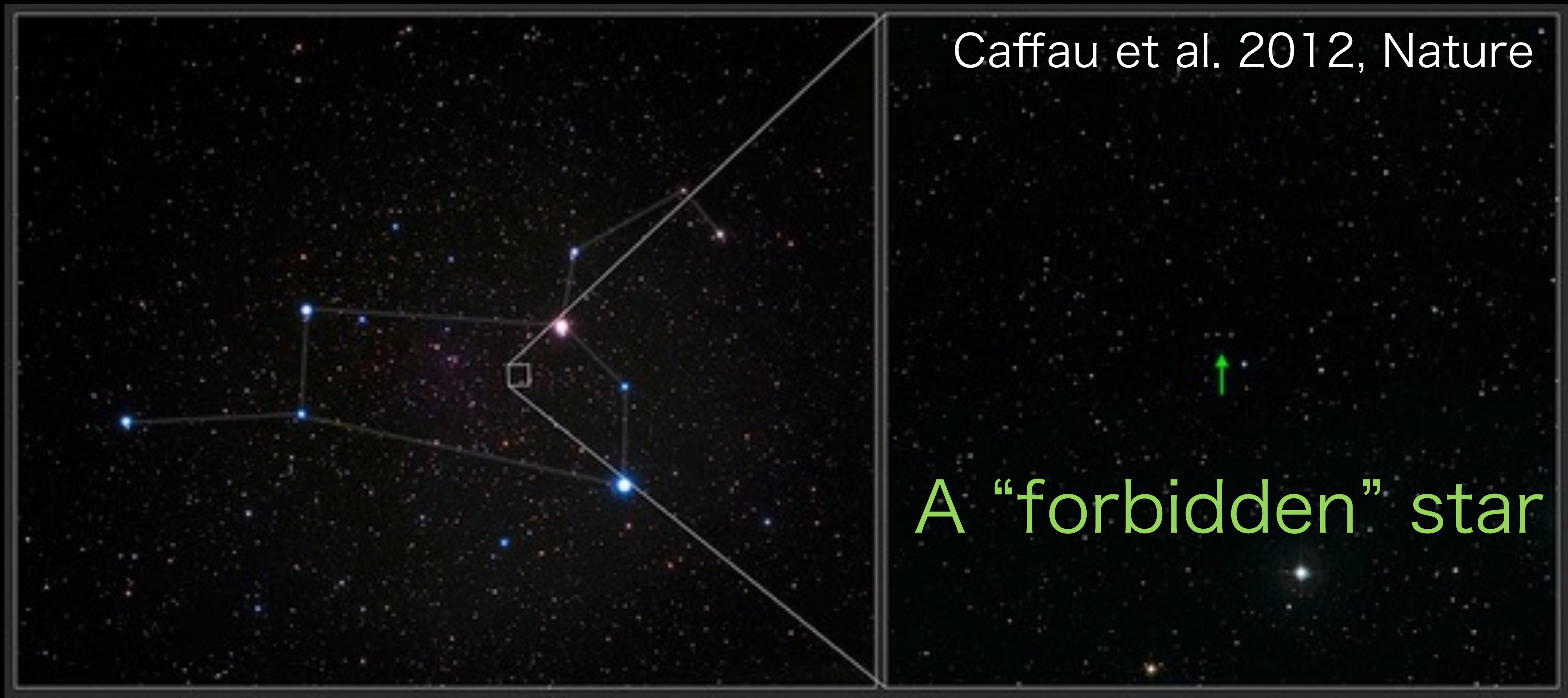
A YOUNG BUT BIG! BLACKHOLE

2 billion times heavier than the sun

13 billion light years away (130億光年彼方)



Stellar relics in the Milky Way

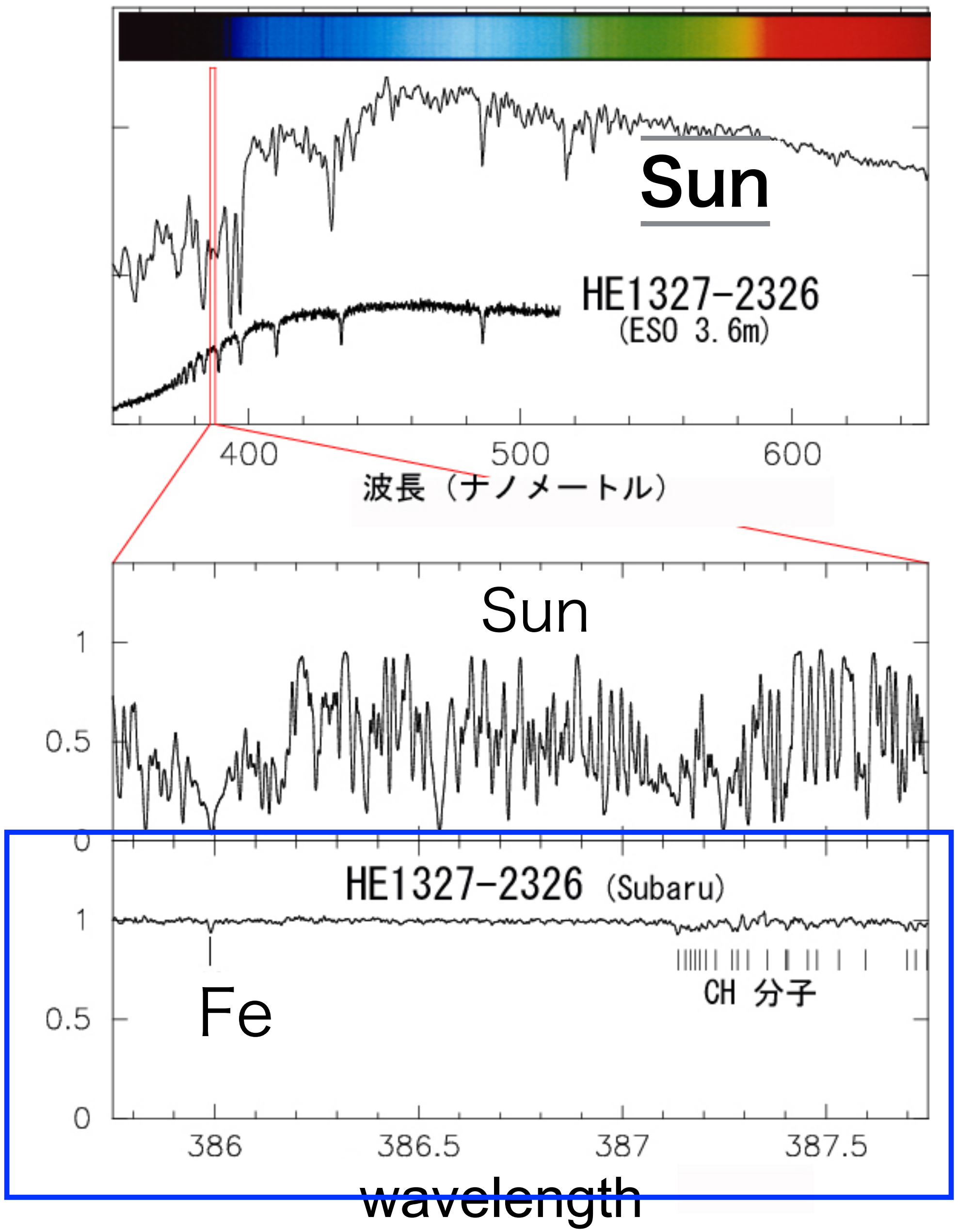


Low-mass ($<1 M_{sun}$),

extremely metal-poor (not only iron-poor)

Metallicity below 4.5×10^{-5} *that of the sun.*

No spectral features



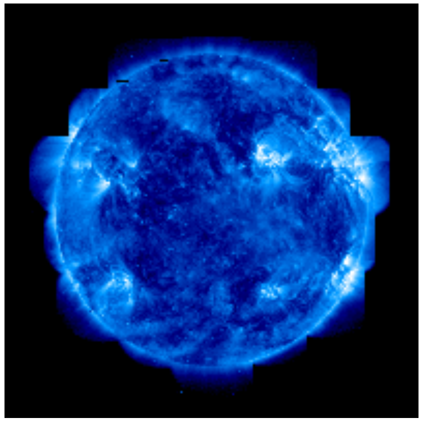
Ordinary stars like the sun contains a few percent (in mass) of heavy elements
→ many lines in the spectrum

There are many stars in Galaxy that contain less amount of heavey elements

A few of them contain almost no elements other than hydrogen and helium.

Seemingly different phenomena

- Prompt emission of high-energy photons
- Emergence of a super-massive blackhole
- A nearby star with very low metal content

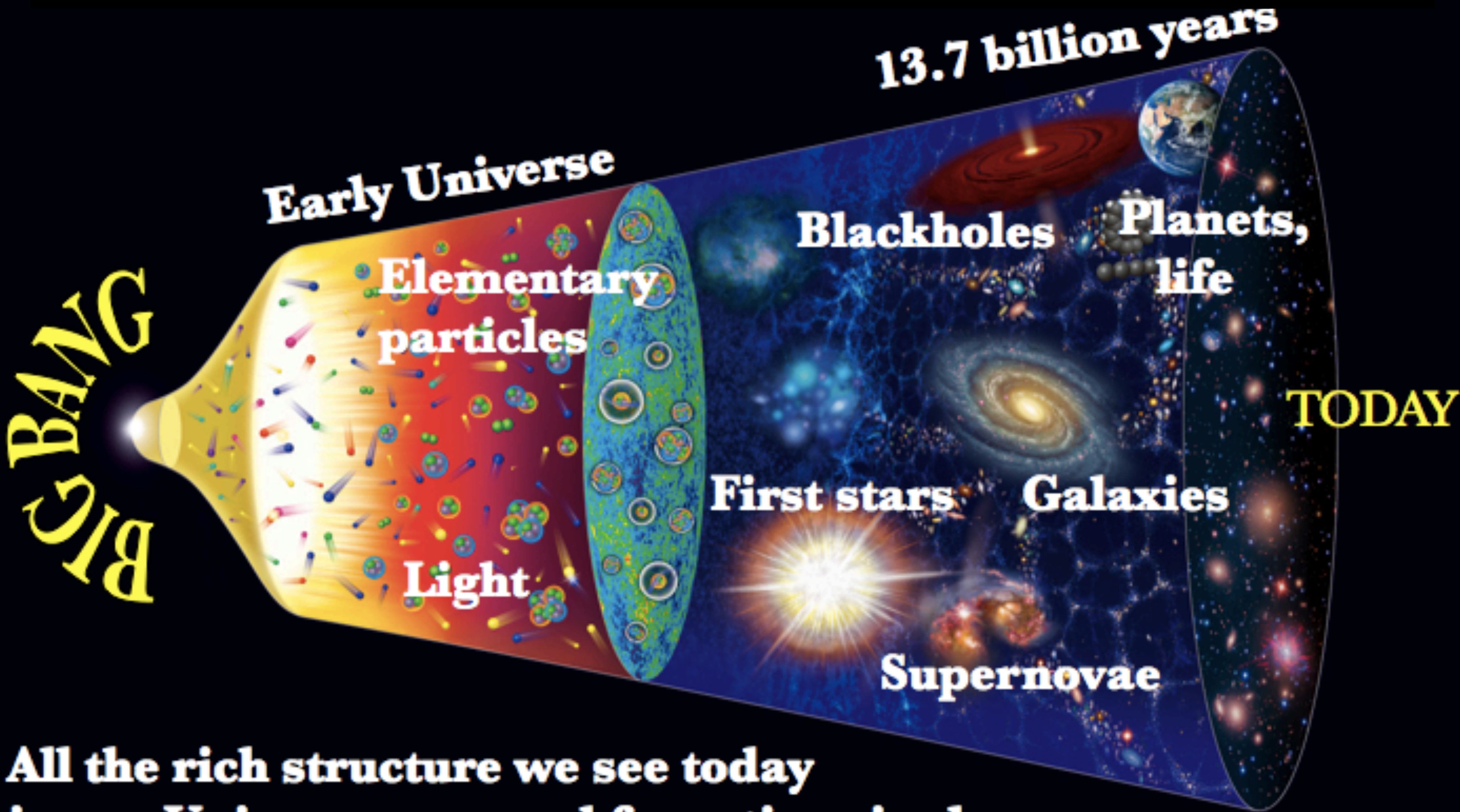


They may have the same origin,

which is also related, ultimately,

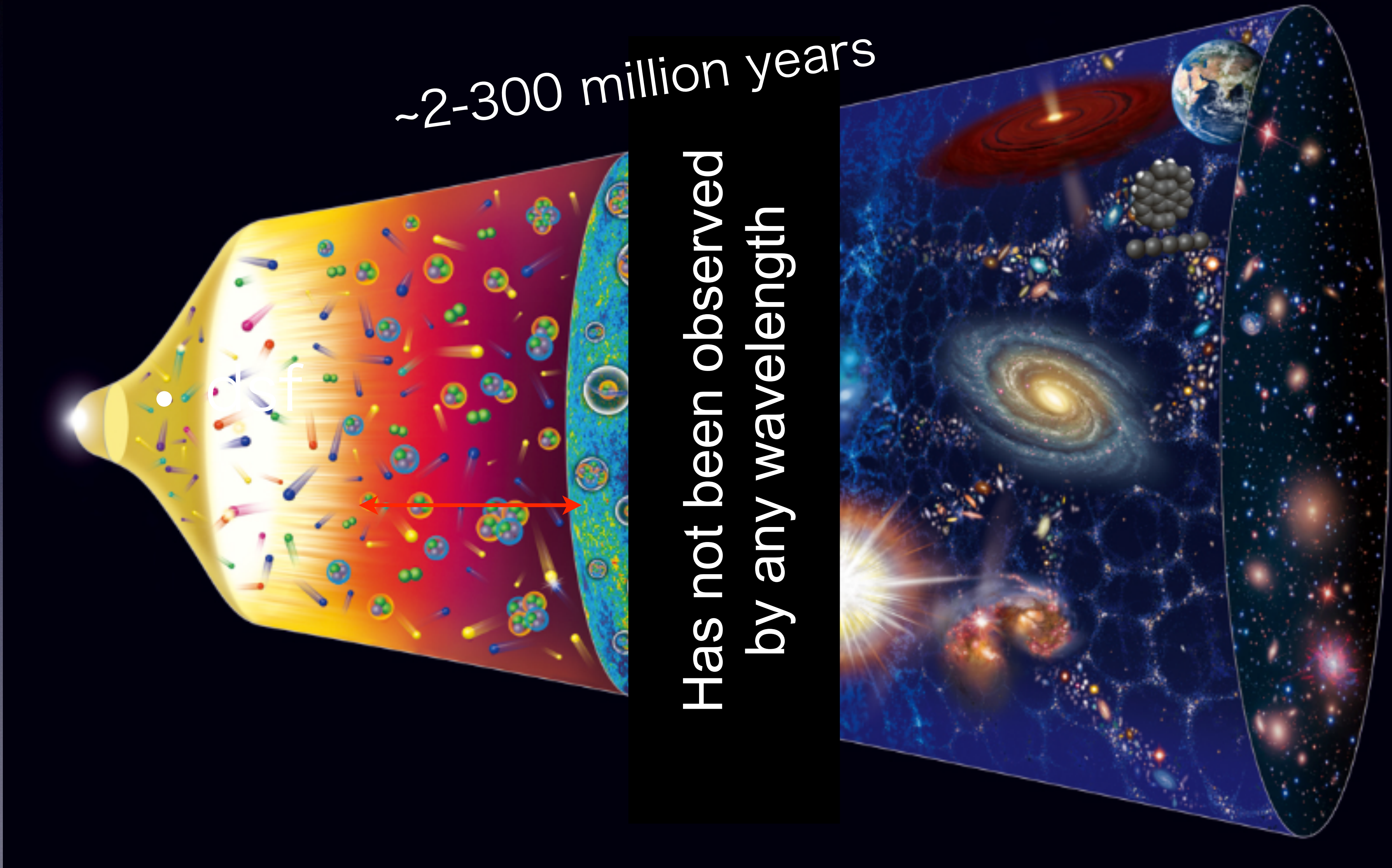
to the beginning of our own existence.

THE COSMIC HISTORY



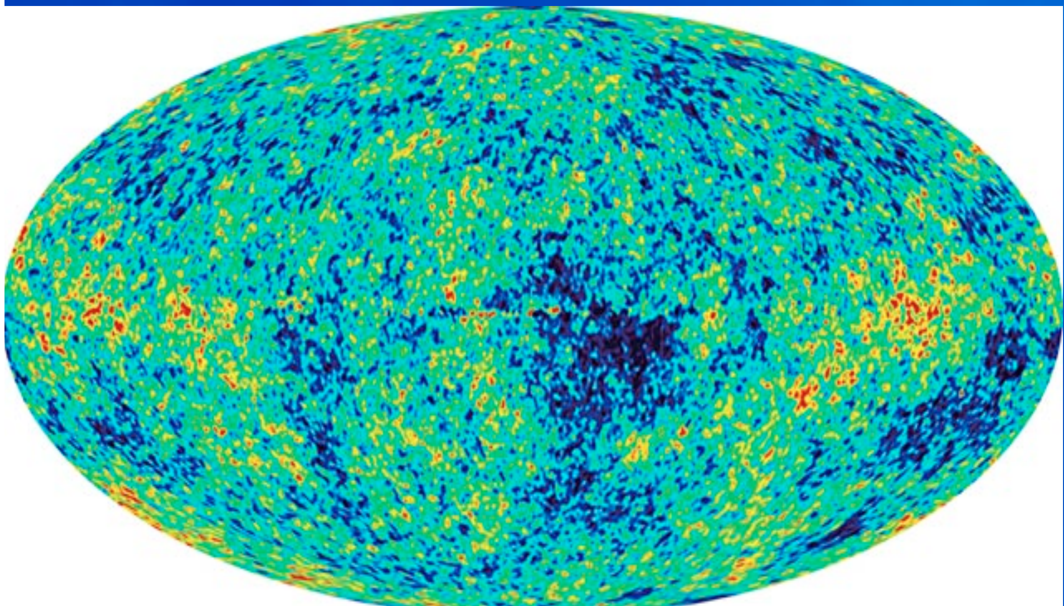
All the rich structure we see today in our Universe emerged from tiny ripples left over from the Big Bang

The Dark Ages

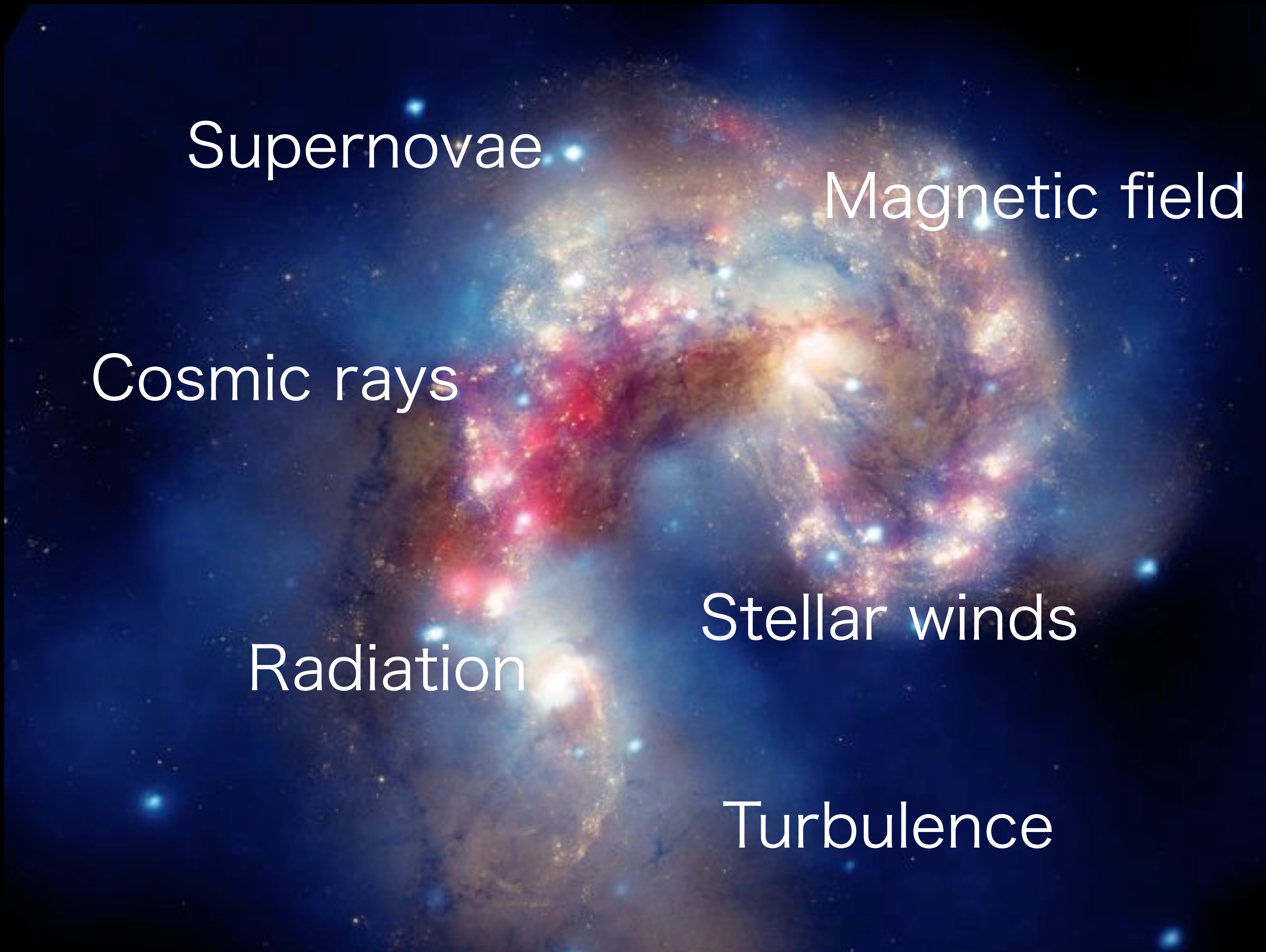


In the beginning,
there was a sea of light elements
and dark matter…

and tiny ripples left over
from the Big Bang

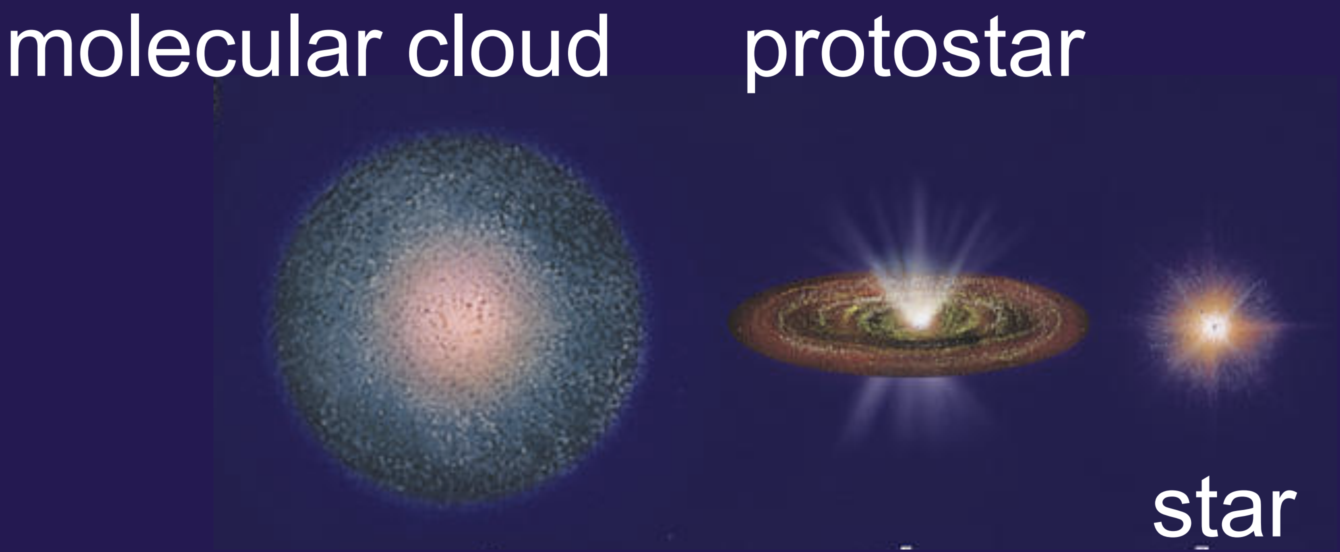


Compare with present-day star formation

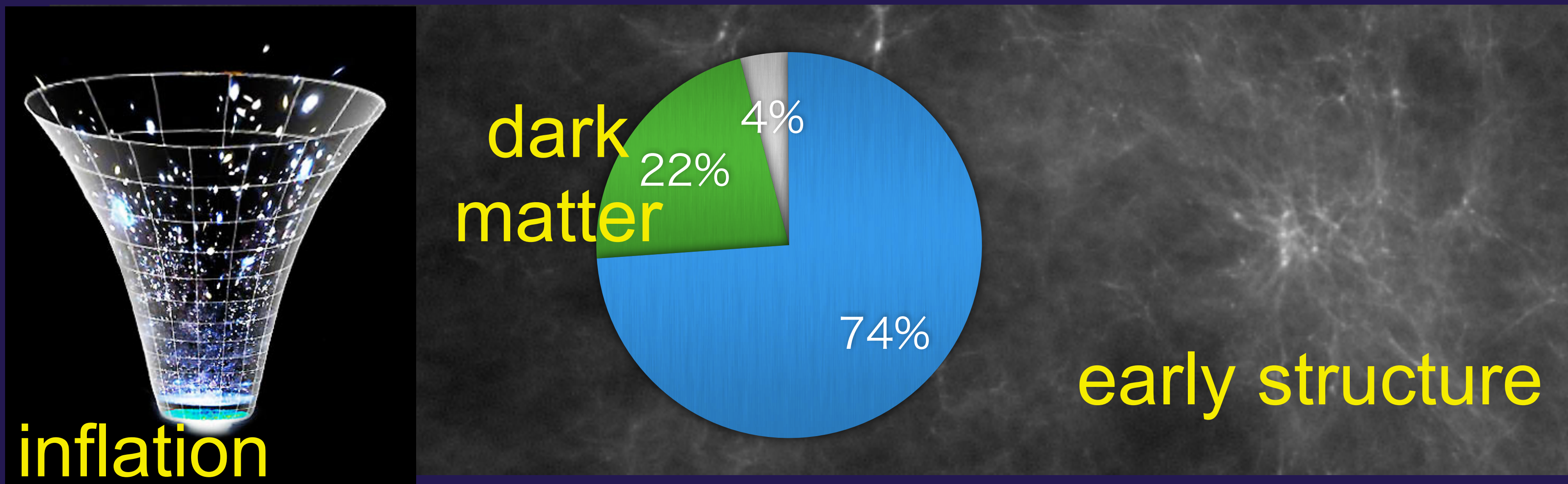


Early universe

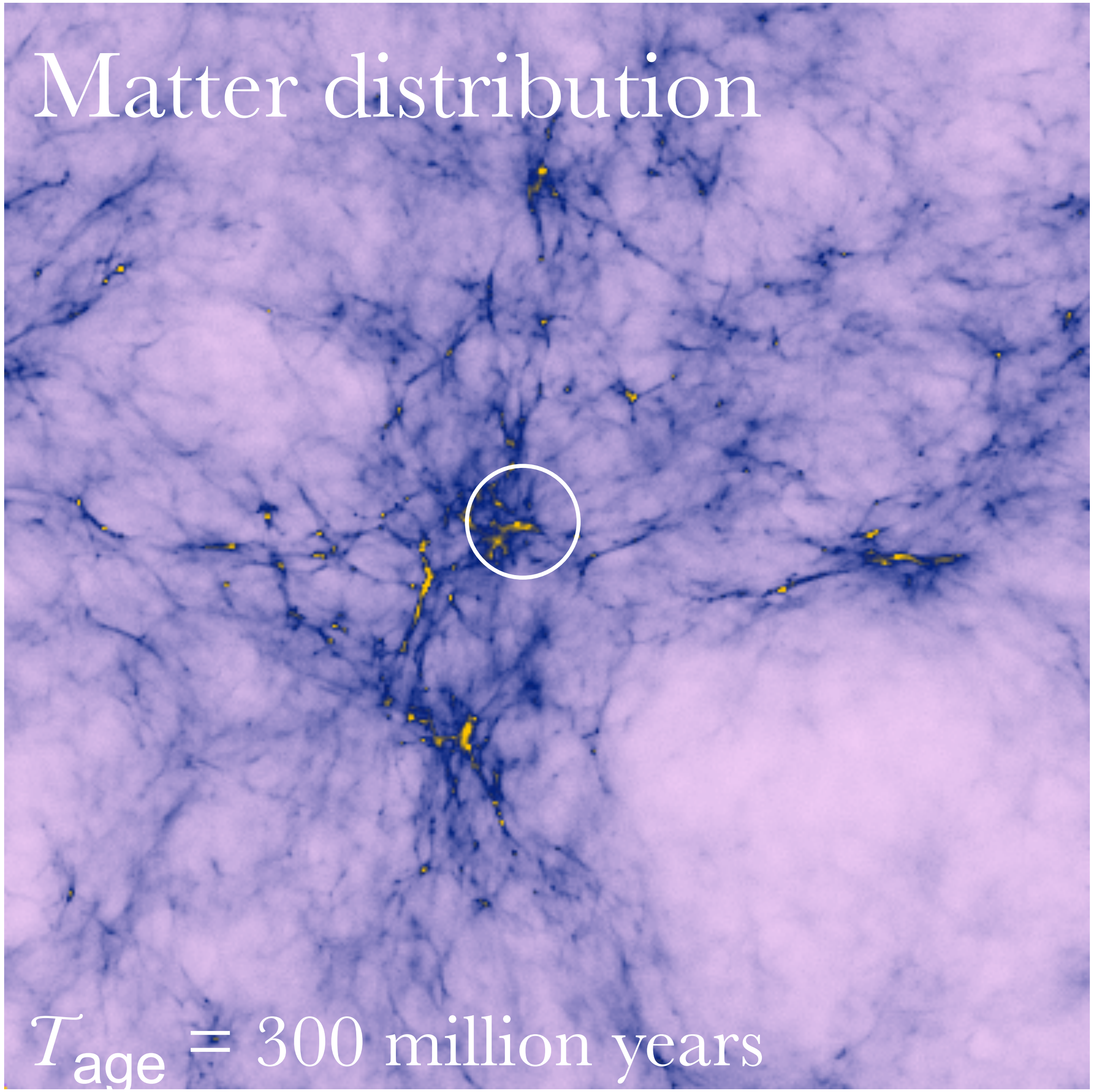
THEORY OF STAR FORMATION



STANDARD COSMOLOGICAL MODEL



First Star Nurseries



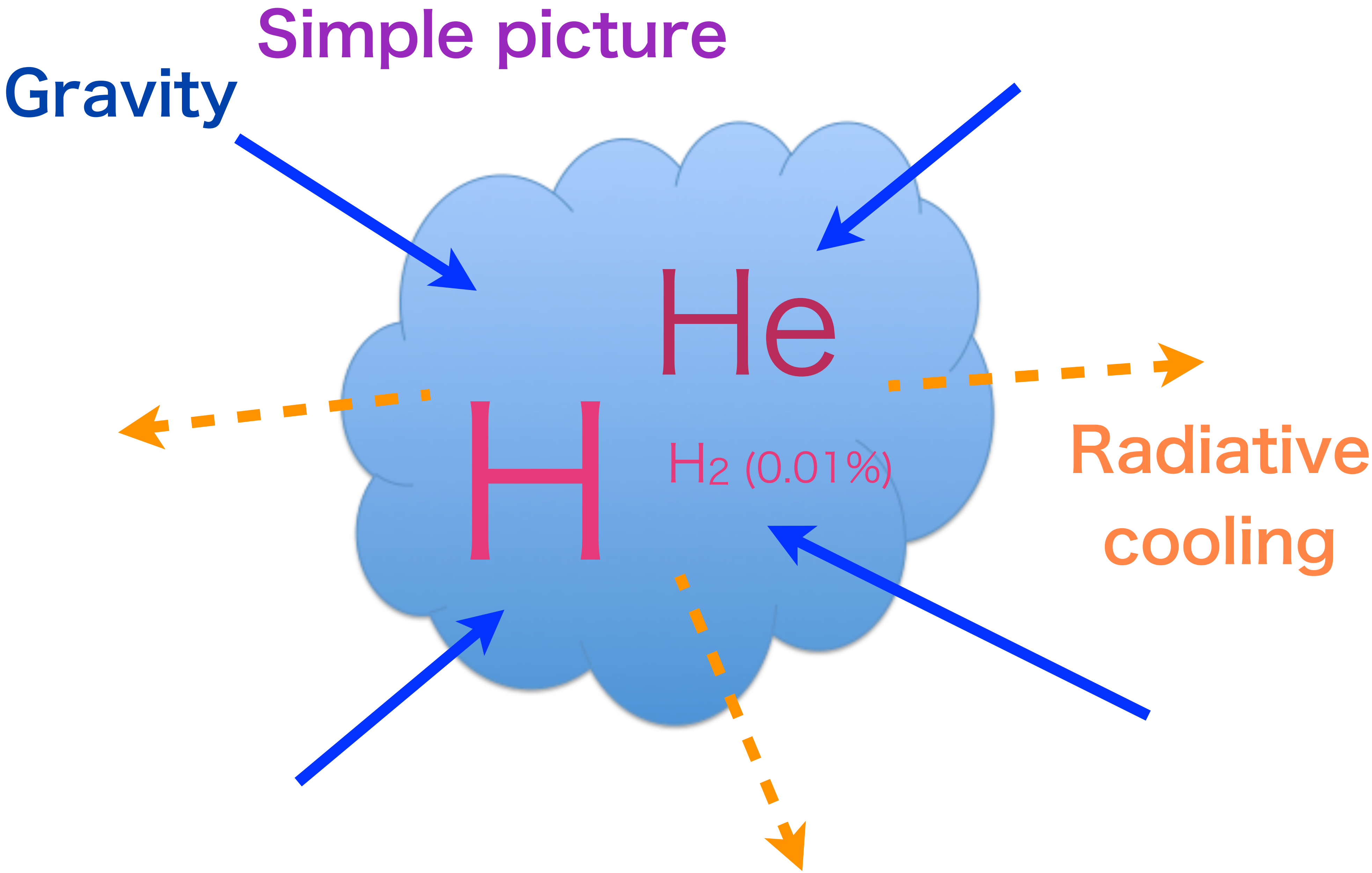
Web-like structure
in the early universe.

Yellow spots are
clumps of dark matter.

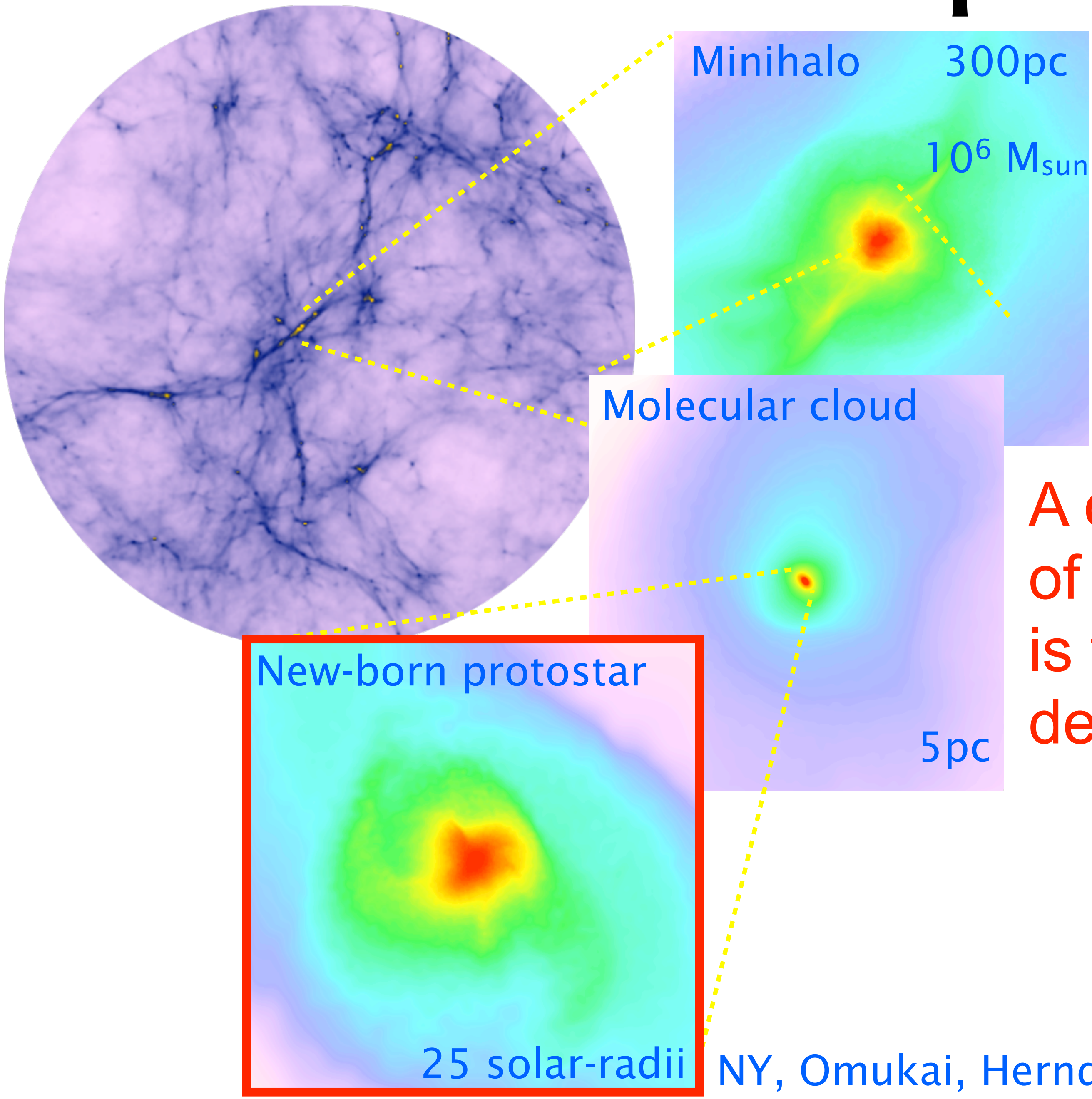
First star nurseries
are 1000 times
heavier than the sun.

Strongly clustered.

PRIMORDIAL GAS CLOUD



From primeval ripples to a protostar

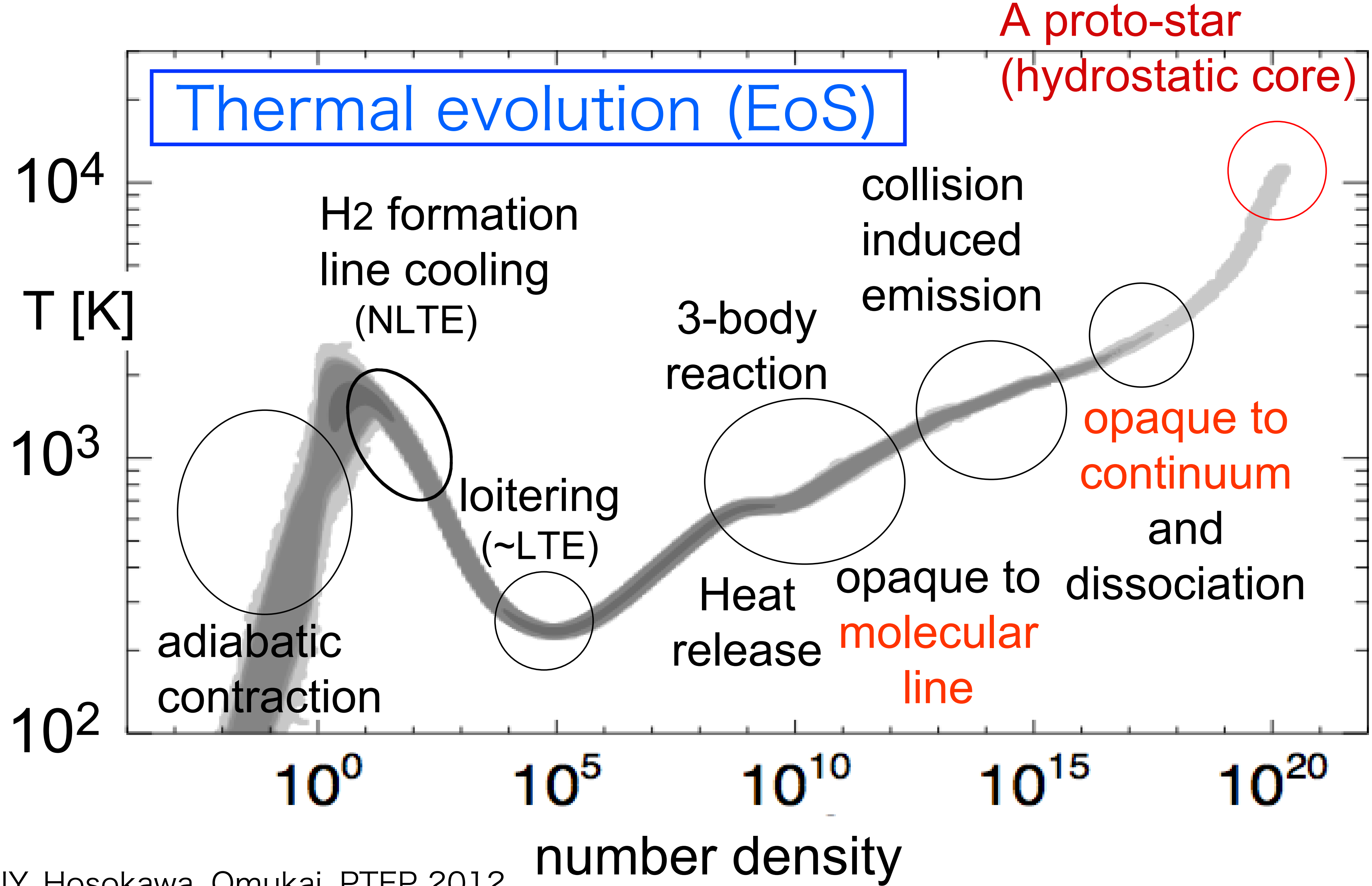


Resolving planetary scale structures in a cosmological volume!

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

NY, Omukai, Hernquist 2008

Physics is hard



NY, Hosokawa, Omukai, PTEP 2012

```
edot_3body_rate = 4.478 * eV_to_erg *
  ((k55_edot * SphP[ithis].HI * SphP[ithis].HI * SphP[ithis].HI
    + k57_edot * SphP[ithis].HI * SphP[ithis].HI * SphP[ithis].H2I)*base.numden*base.numden*base.numden
   -(k56_edot * SphP[ithis].H2I * SphP[ithis].HI
     + k58_edot * SphP[ithis].H2I * SphP[ithis].H2I)*base.numden*base.numden);
```

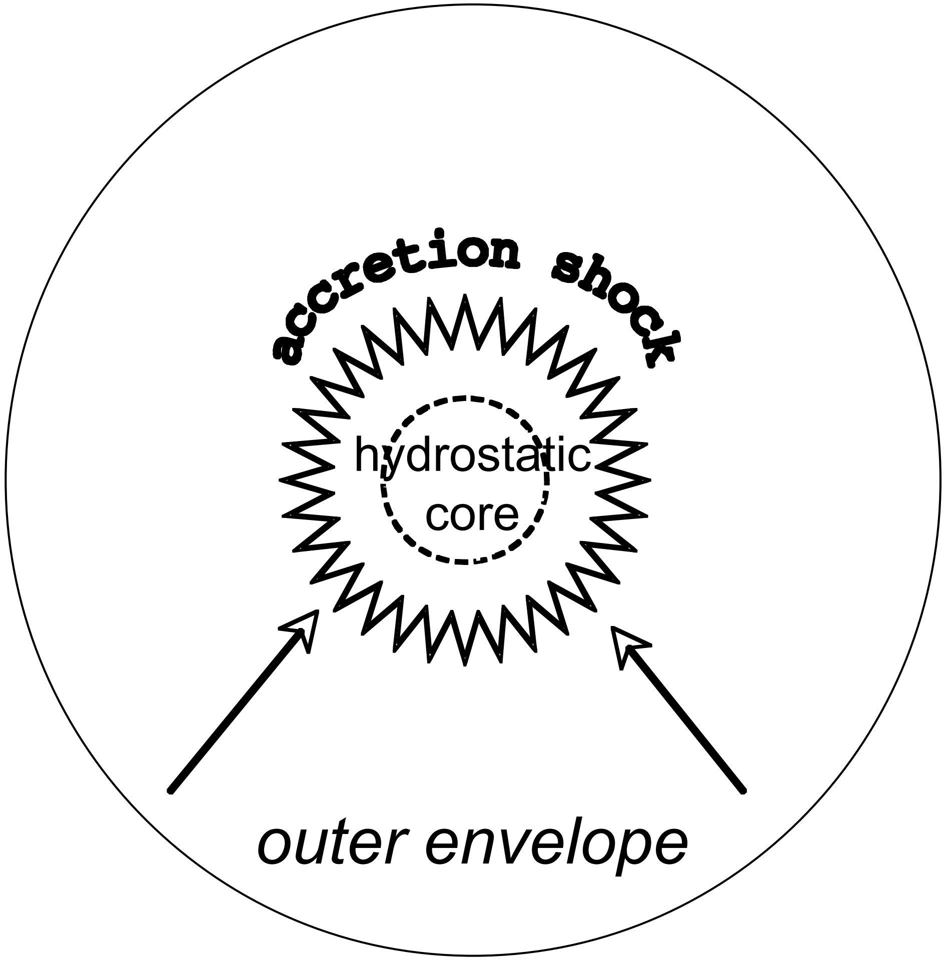
```
------- 60:  DI   + p    -> DII  + e      photo-ionization D
------- 61:  HDII + p    -> HI   + DII    photo-dissociation HD+
------- 62:  HDII + p    -> HII  + DI     photo-dissociation HD+
------- 63:  HD   + p    -> 2DI           photo-dissociation HD

3 body reactions

------- 71:  HI + HI + HI   -> H2I + HI
------- 72:  H2I + HI       -> HI + HI + HI  reverse reaction
------- 73:  HI + HI + H2   -> H2I + H2I
------- 74:  H2I + H2I      -> HI + HI + H2  reverse reaction
```

```
k_table[121][i]= 4.98e-11;     // H + CH  -> C + H2
k_table[122][i]= 2.7e-10;      // H + CH2 -> CH + H2

k_table[125][i]= 7.0e-14 * pow(T300, 2.80) * exp(-1950.0/T
k_table[126][i]= 6.83e-12 * pow(T300, 1.60) * exp(-9720.0/
k_table[127][i]= 3.3e-10 *  exp(-8460.0/T[i]);
k_table[128][i]= 6.64e-10 * exp(-11700.0/T[i]);
k_table[129][i]= 3.43e-13 * pow(T300, 2.67) * exp(-3160.0/
```

```
A[2][3][0][3]=1.29e-7;
A[2][3][0][5]=6.98e-8;
A[2][3][1][1]=4.98e-7;
A[2][3][1][3]=4.12e-7;
A[2][3][1][5]=3.18e-7;

A[2][3][2][1]=4.12e-10;

//JI = 4
//vI=0
A[0][4][0][2]=2.76e-9;

//vI=1
A[1][4][0][2]=3.98e-7;
A[1][4][0][4]=2.65e-7;
A[1][4][0][6]=1.50e-7;
A[1][4][1][2]=2.59e-9;

//vI=2
A[2][4][0][2]=2.38e-7;
A[2][4][0][4]=1.25e-7;
A[2][4][0][6]=4.72e-8;
A[2][4][1][2]=5.60e-7;
A[2][4][1][4]=3.91e-7;
A[2][4][1][6]=2.28e-7;
```

Hyper-accreting protostar

A “classic” picture



The central protostar accretes the surrounding gas at a very large rate:

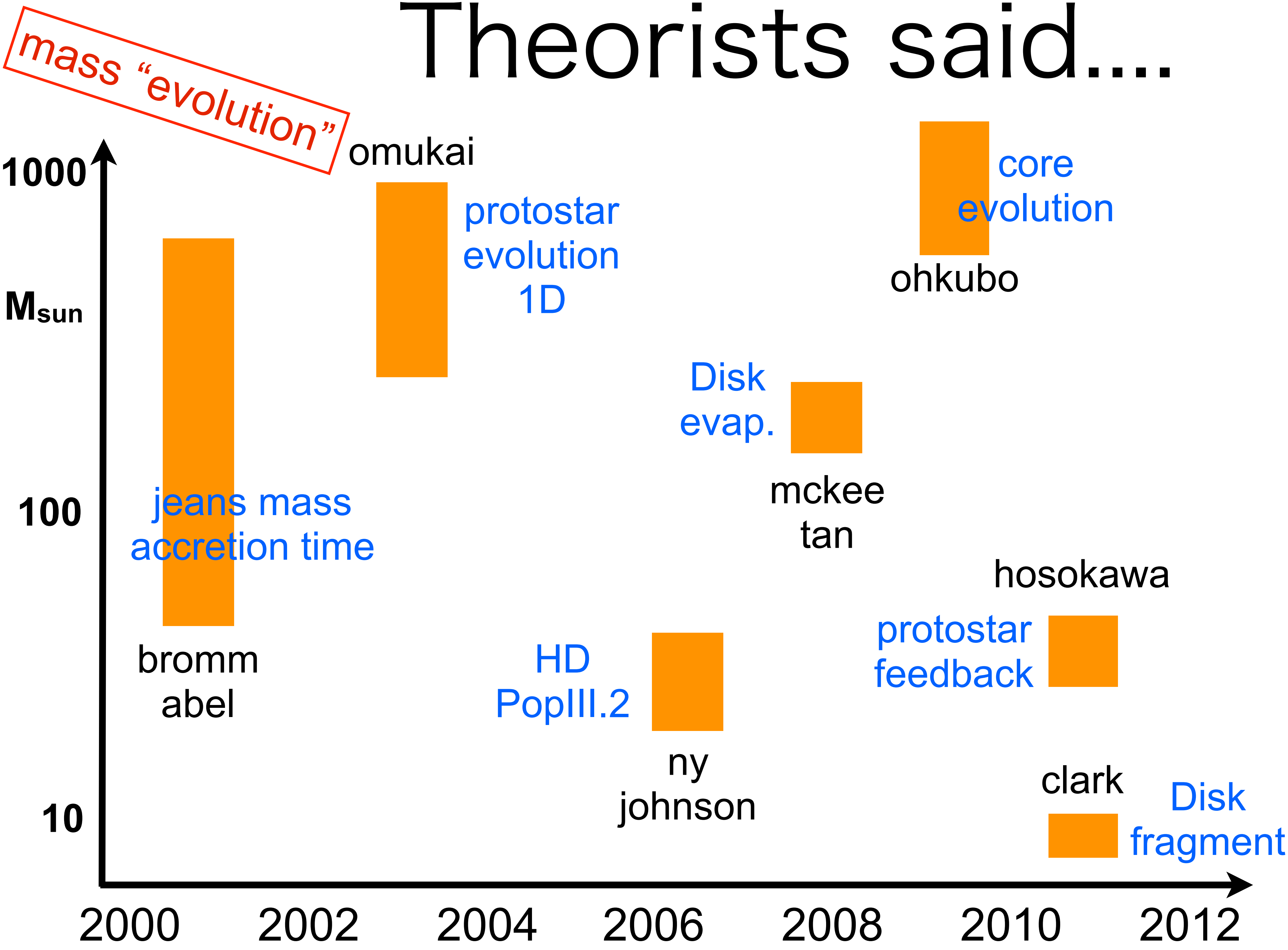
$$dM/dt \propto T^{1.5}/G$$
$$= 0.01\text{-}0.1\ M_{sun}/yr$$

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

Theorists said....

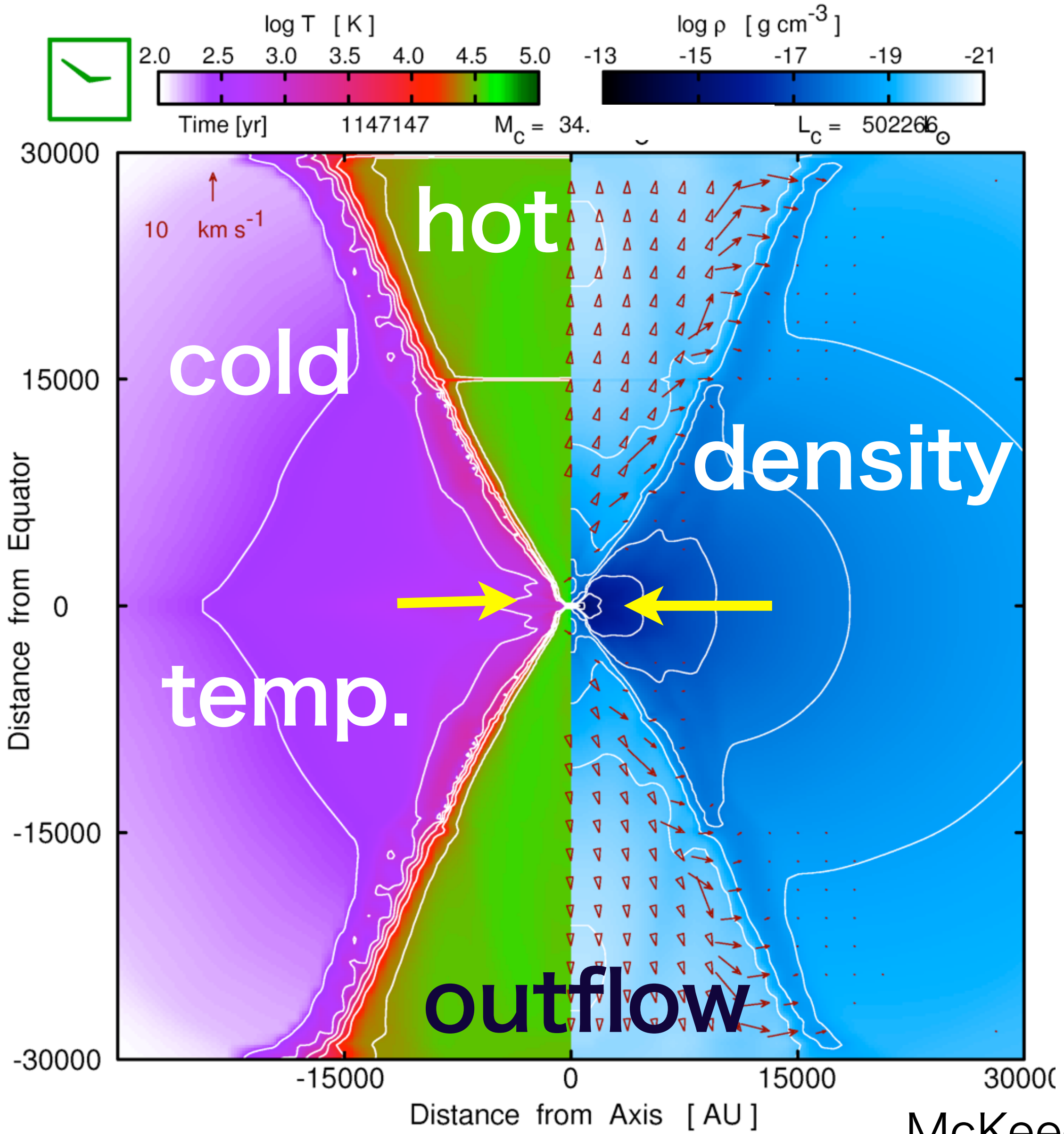


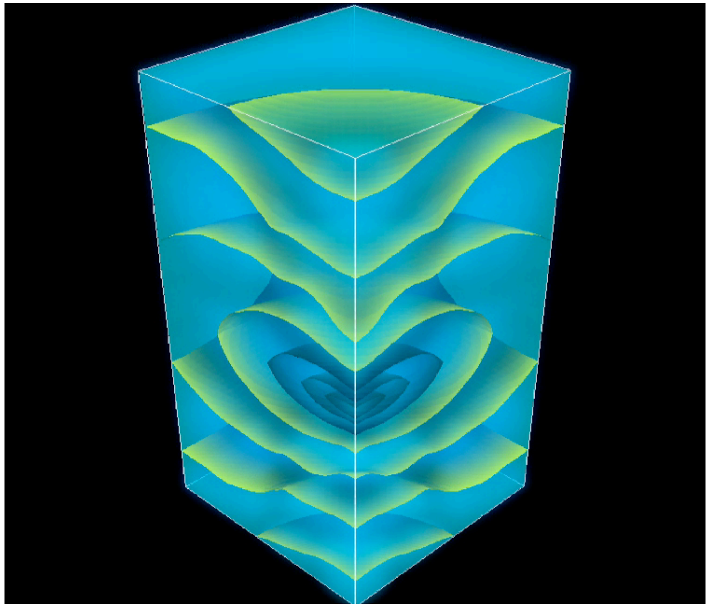
Protostars grow through gas accretion, mergers, plus, protostellar feedback over ~ 100,000 years

The Key Question

How and when does a first star stop growing ?

Pressure-driven outflow around a protostar





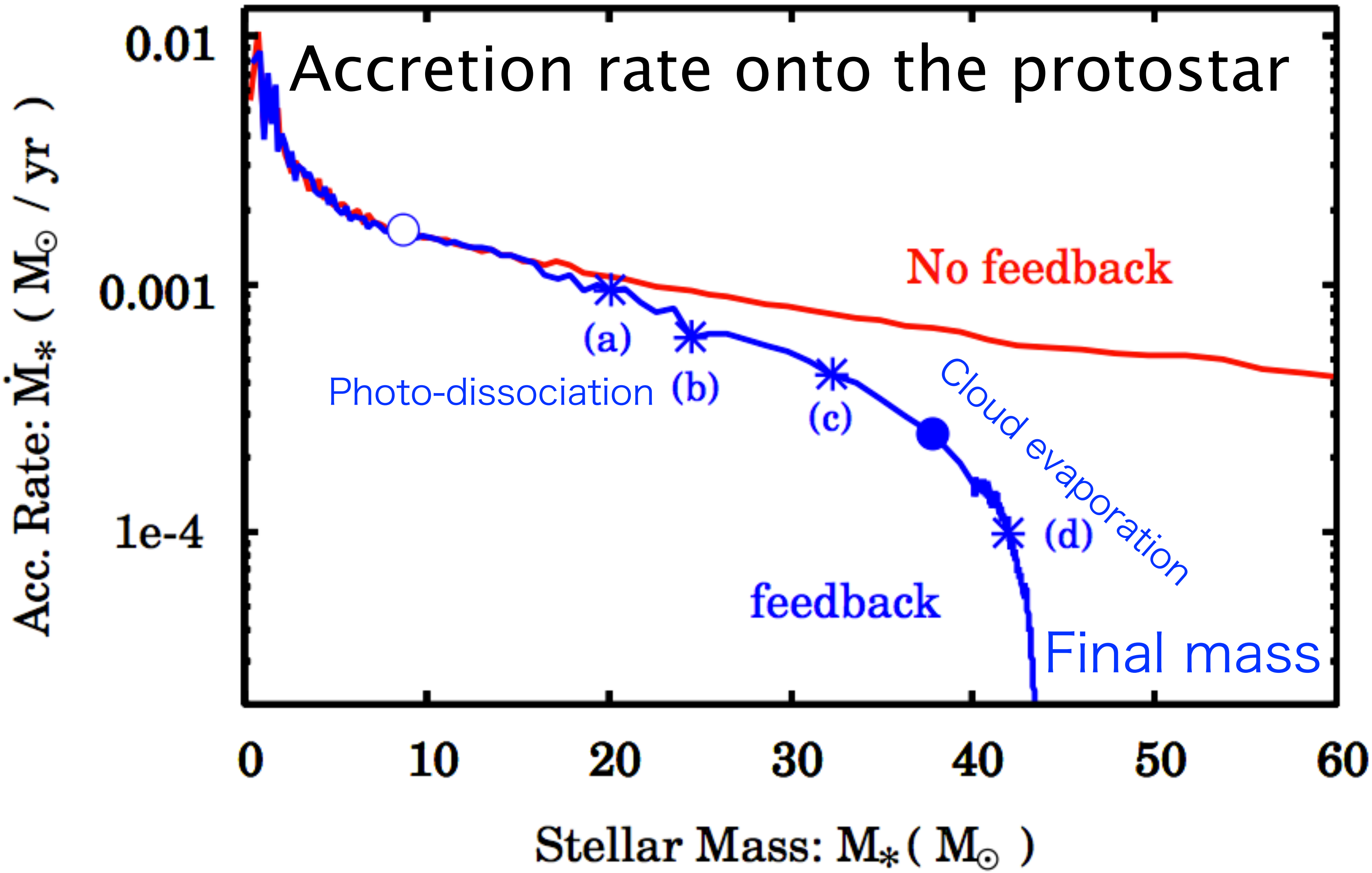
Bi-polar HII regions vs accretion flow.

Self-regulation mechanism.

McKee-Tan08; Hosokawa+11; Stacey+12

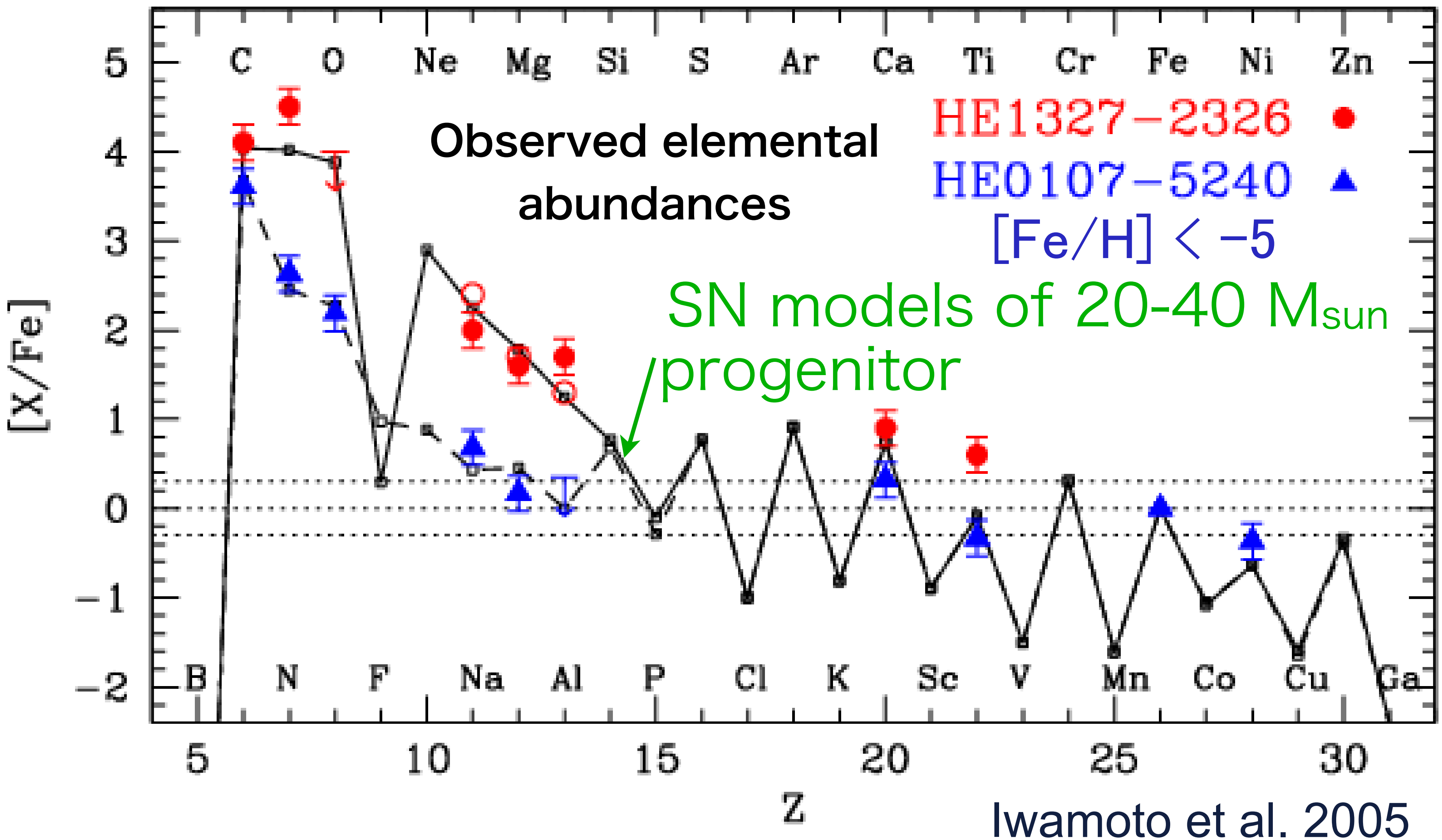
Final mass of a first star

Hosokawa, Omukai, NY, Yorke, 2011, Science



A long standing puzzle ··· resolved.

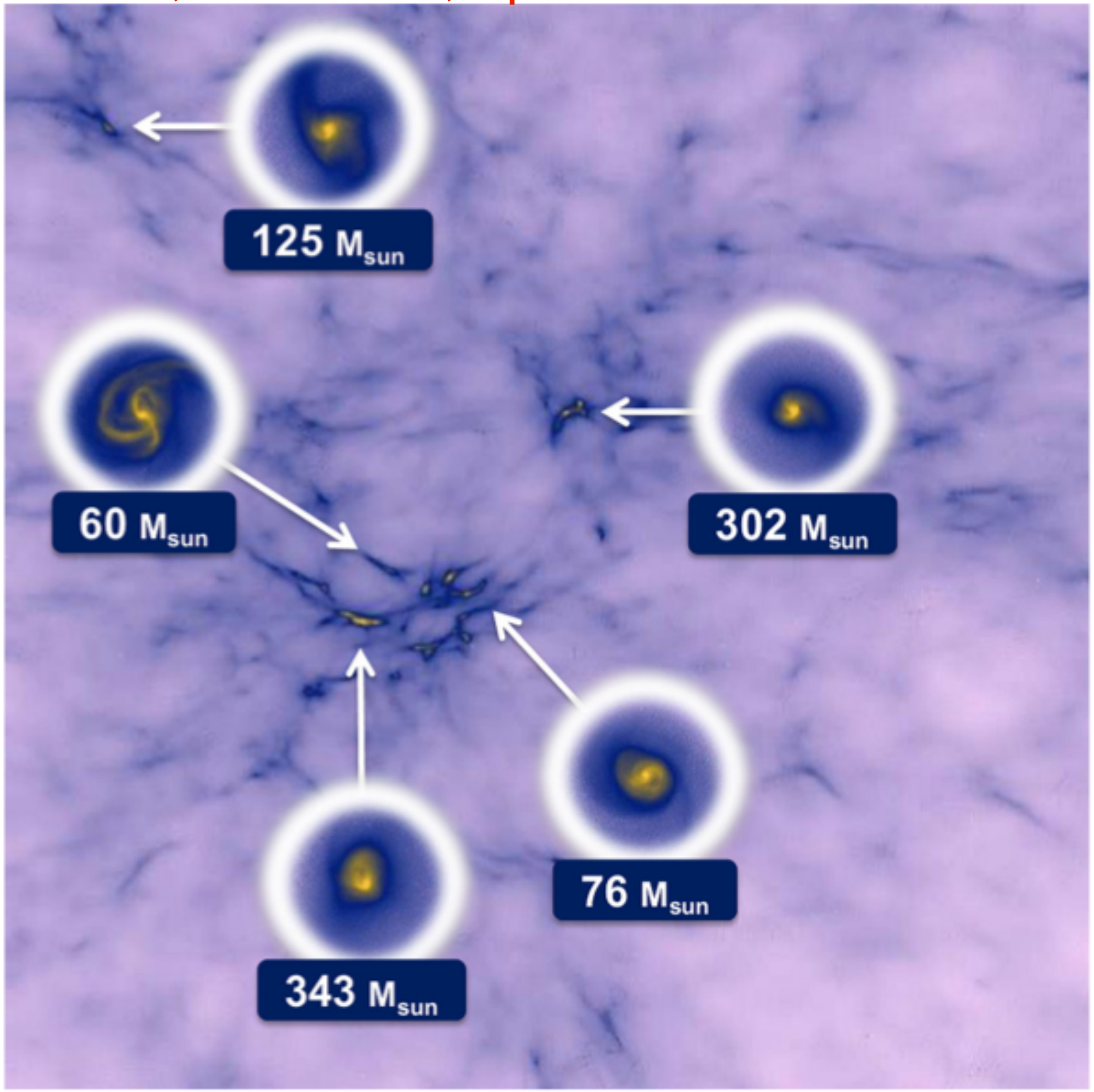
Metal-poor stars were formed from a gas cloud enriched by the first supernova explosions



Iwamoto et al. 2005

100 First Stars

Hirano, NY+ 2014, ApJ



Cosmological hydro simulation

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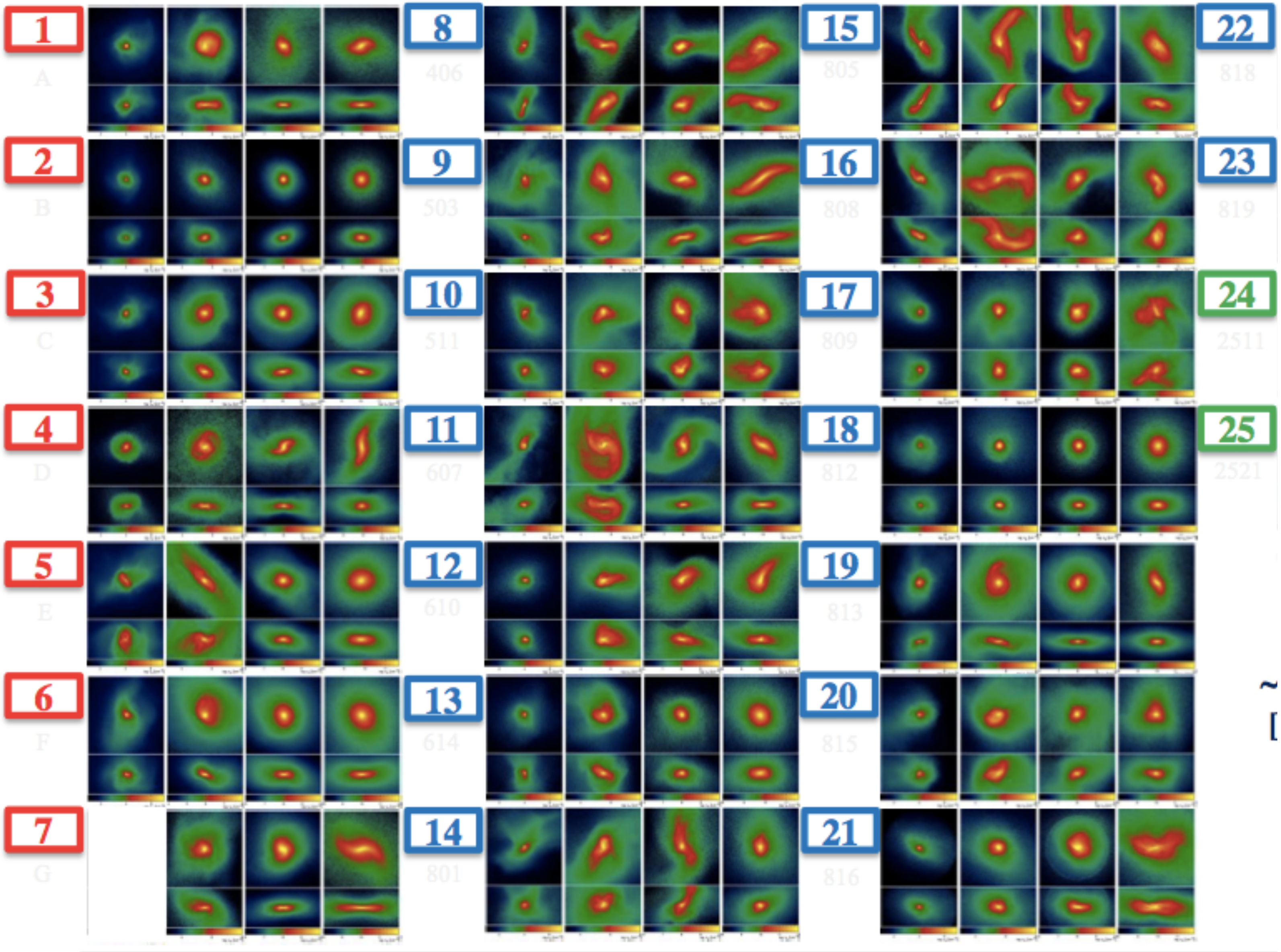
radiation-hydro calculation of protostellar evolution

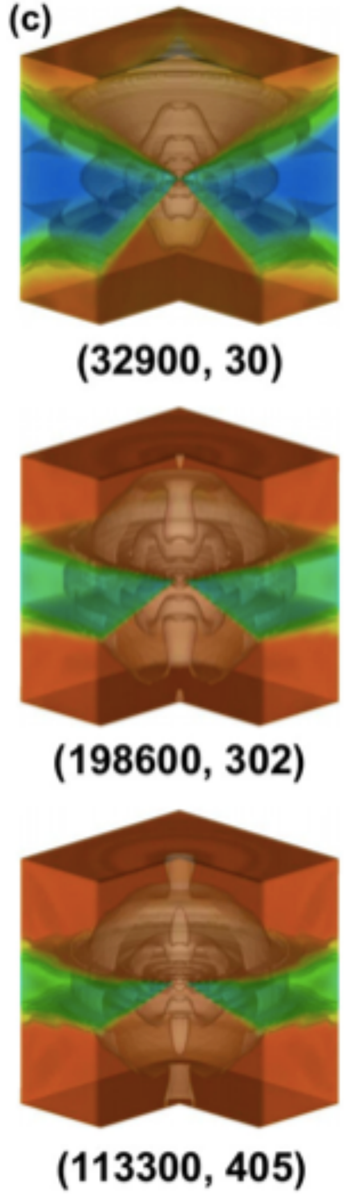
100 star forming clouds located in the cosmological volume.

Characteristic mass of the first stars

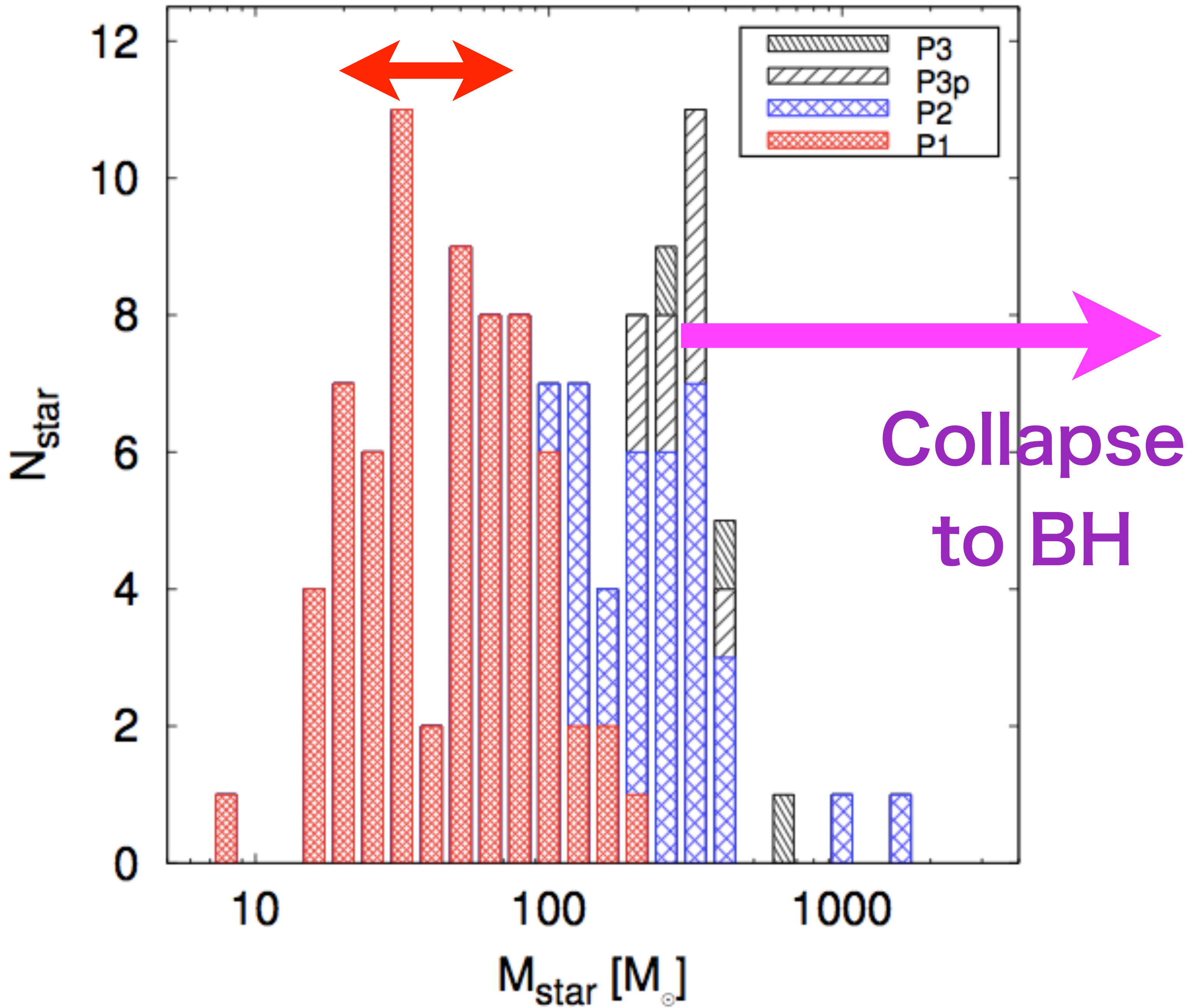
Toward Primordial IMF

Imagine this enormous effort…

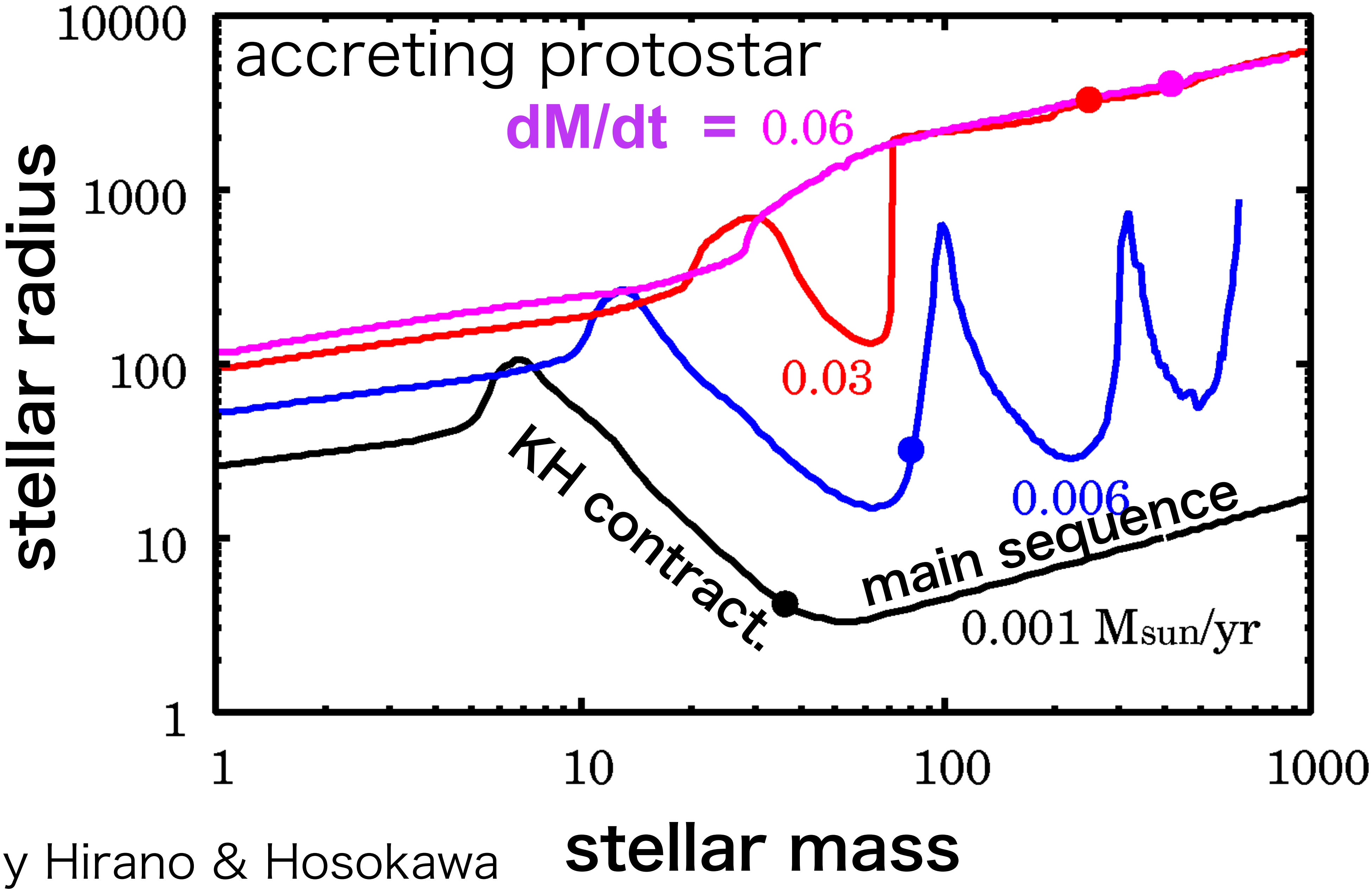




The result : final masses



3 evolutionary paths



By Hirano & Hosokawa

Hunting for the first supernova explosions

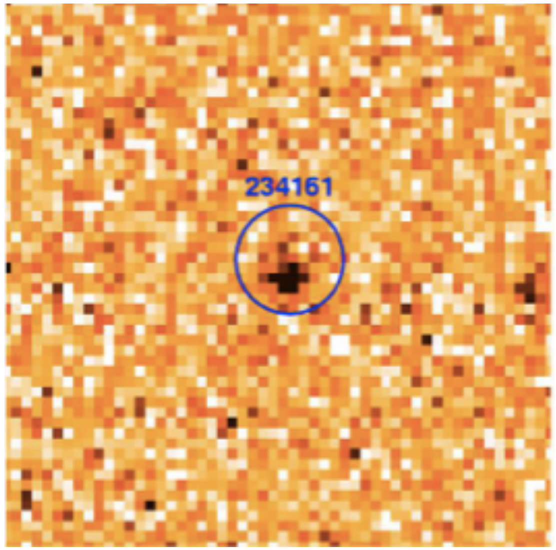
Tanaka, Moriya, NY, Nomoto 2012, MNRAS, 422, 2675

Moriya et al. 2013, MNRAS, 428, 1020

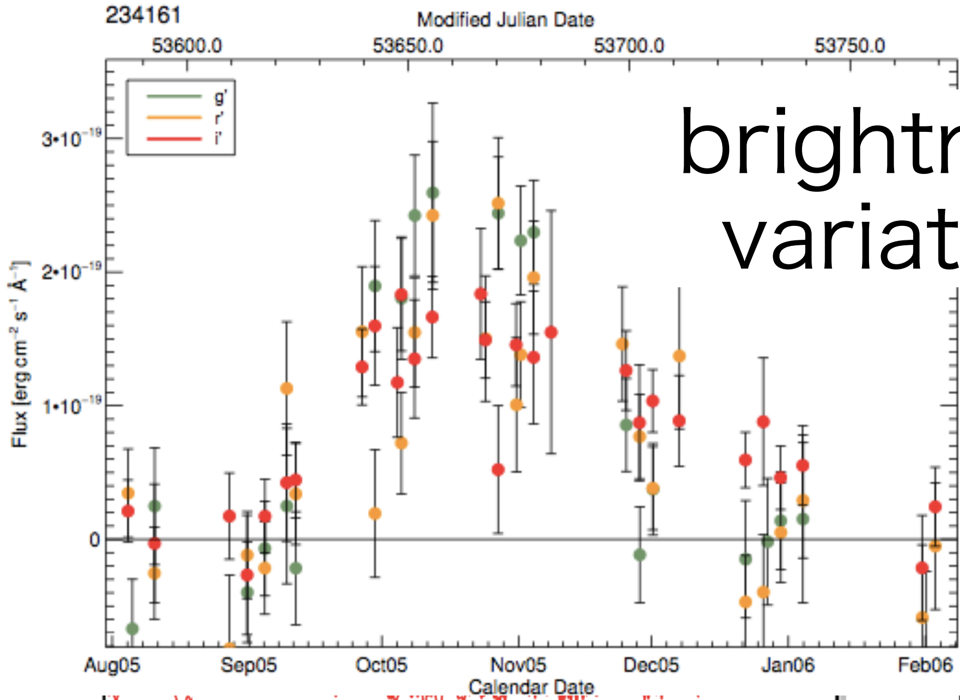
Tanaka, Moriya, NY, arxiv 1306.3743

Distant supernova

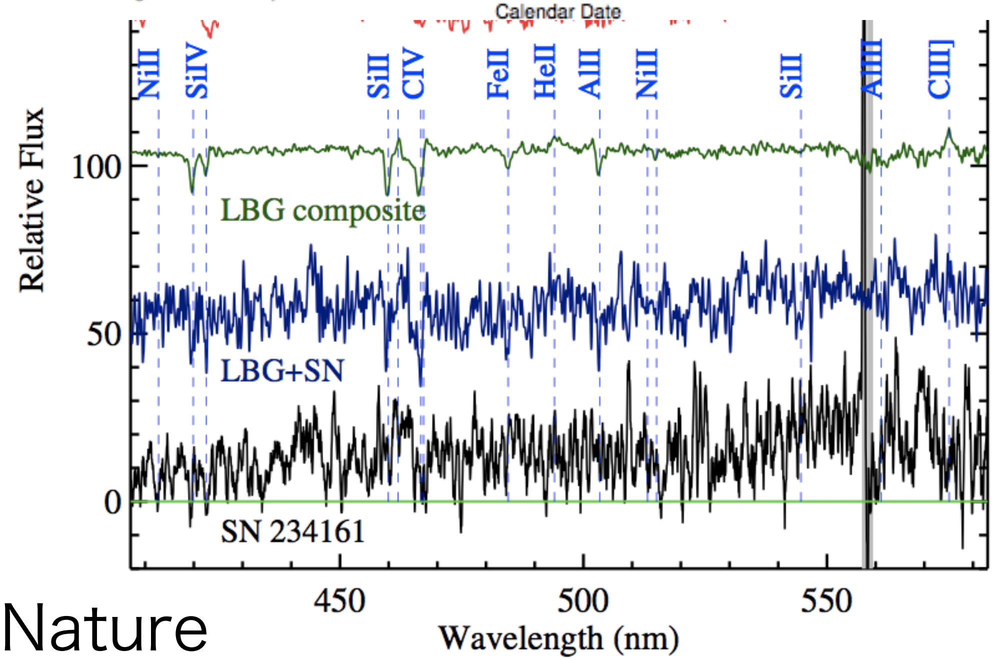
Type IIn at z=2.4



11 billion light years away

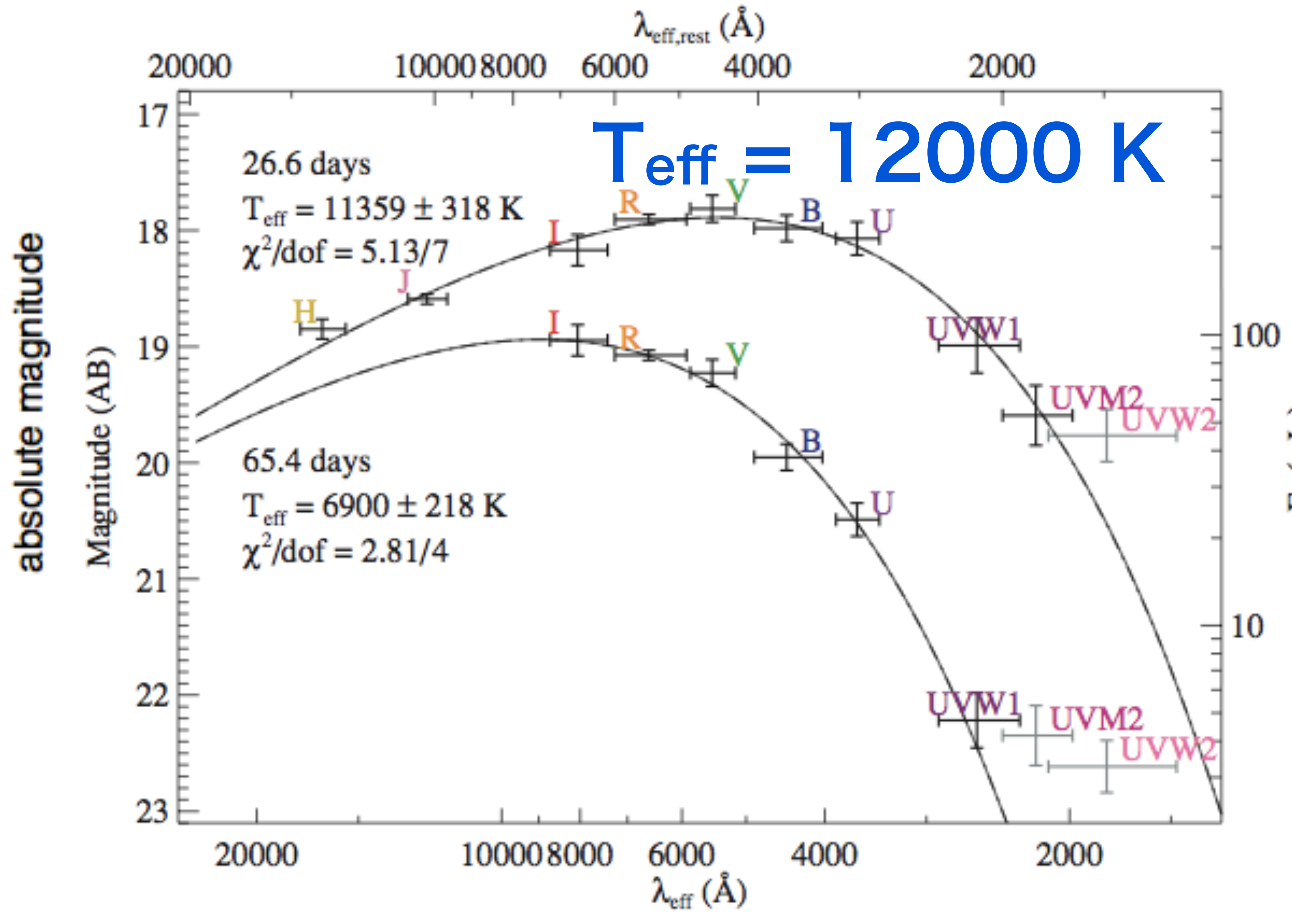


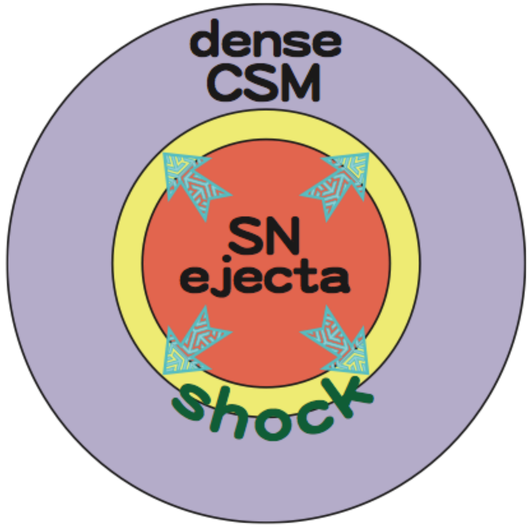
brightness variation



Cooke et al. 2009, 2012, Nature

Super-luminous supernovae





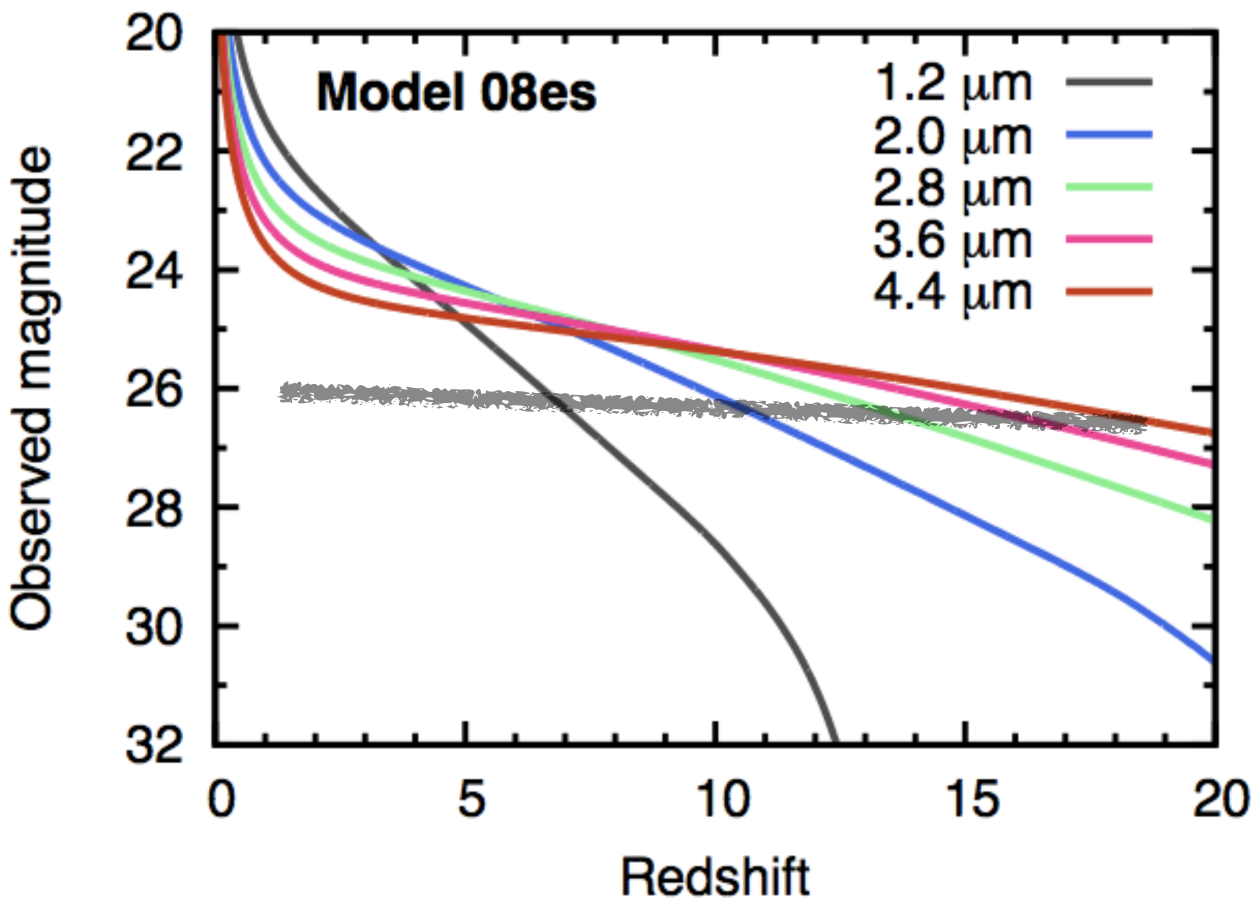
Powered by shock-interaction with dense gas cloud

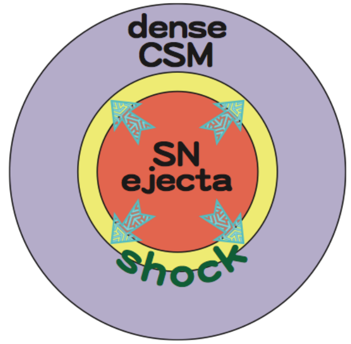
Bright in ultra-violet

Death of a very massive star (> 50 Msun?)

They will be visible to very high-z.

Super-Luminous SN





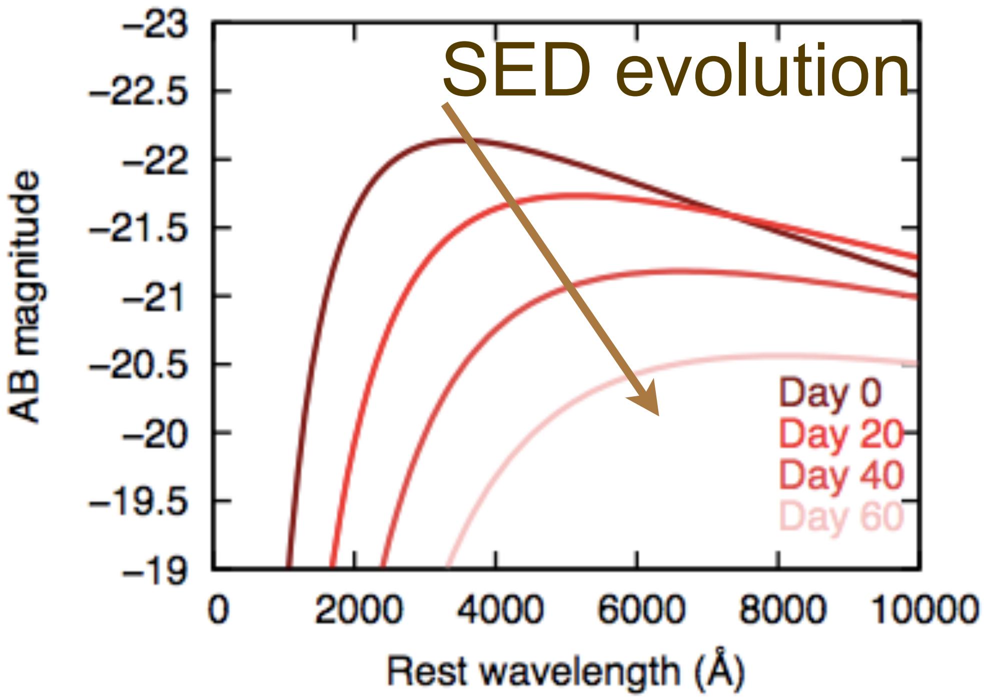
Powered by shock-interaction with dense CSM.

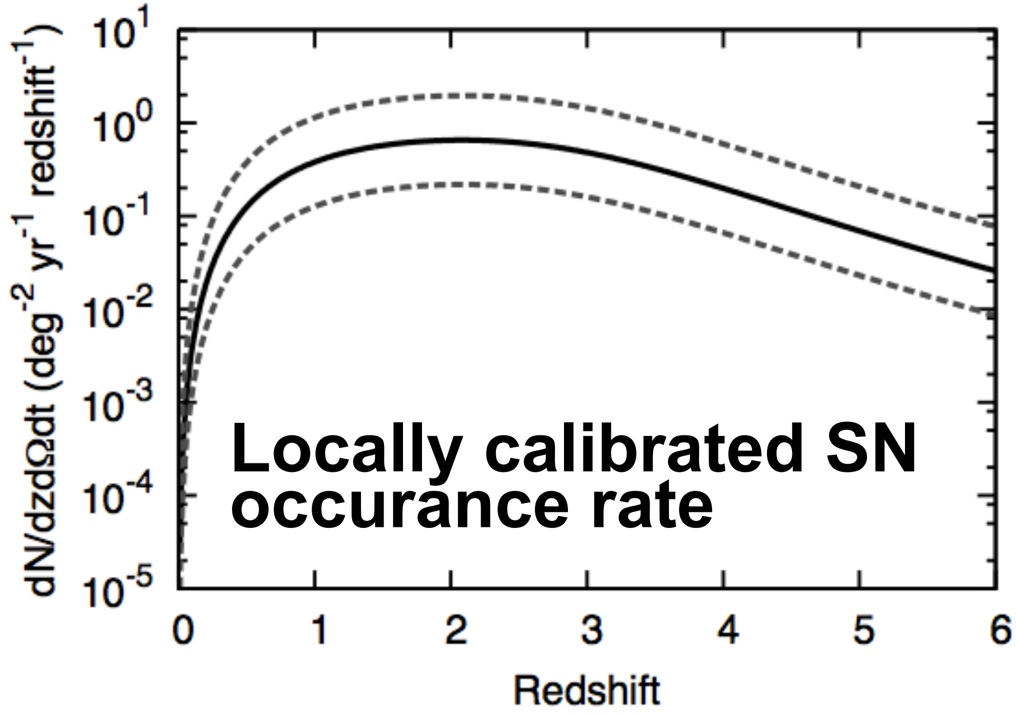
Bright in rest-UV

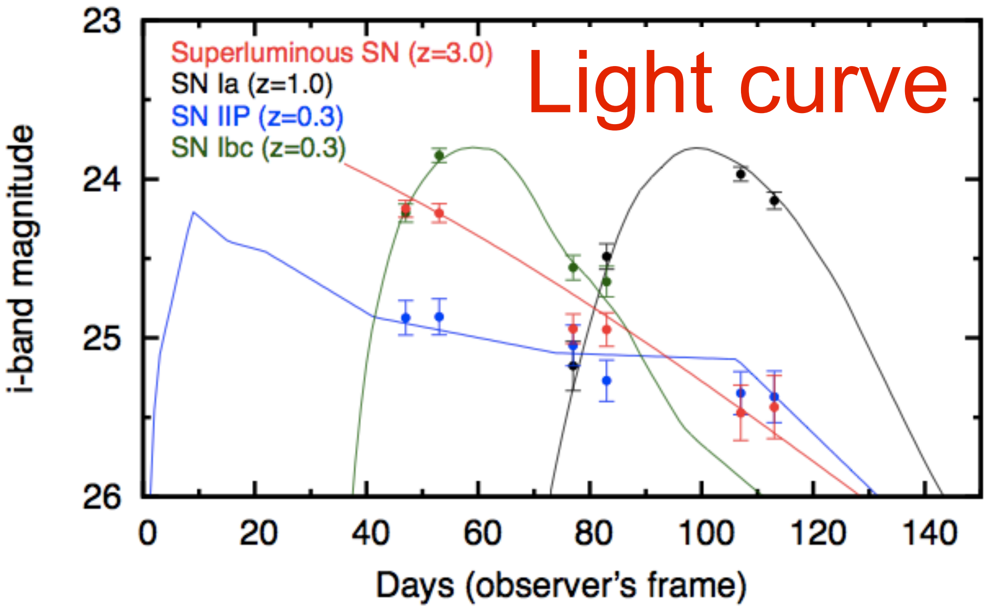
Death of a very massive star (> 50 Msun?)

They will be visible to very high-z.

Monte-Carlo Simulation







Model Spectra

+

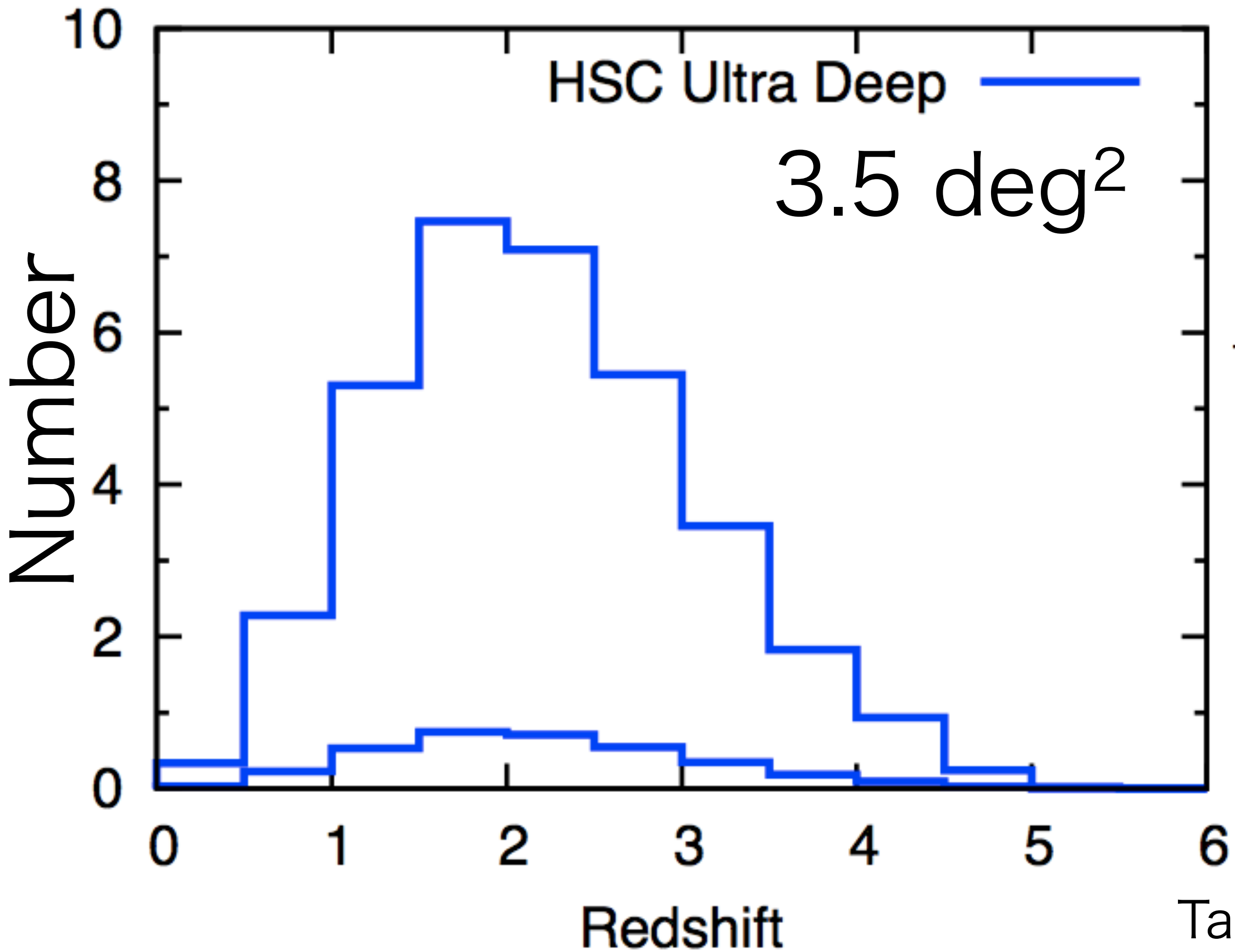
SN occurance rate

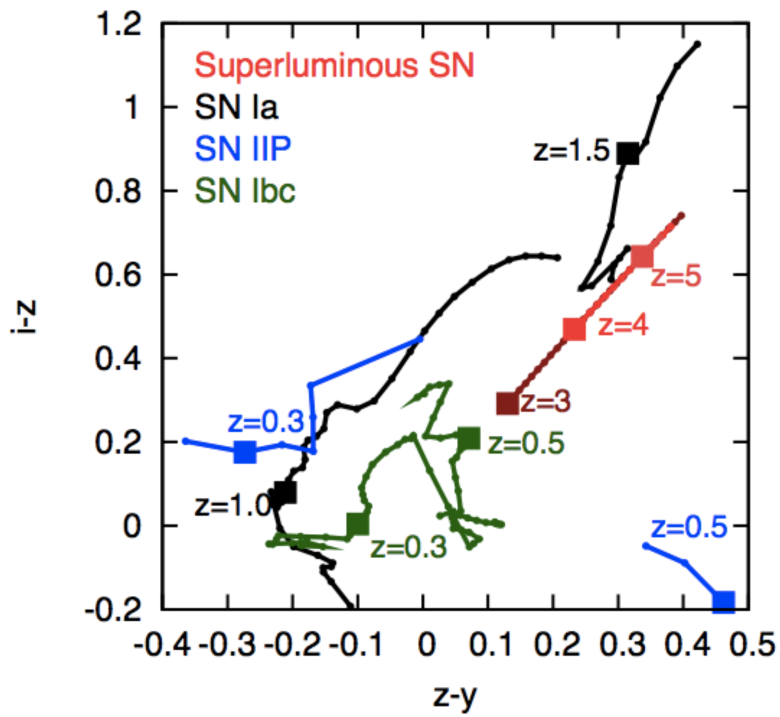
Distinguished from low-z SN

Tanaka, Moriya, NY, Nomoto 2012

Subaru-HSC 2014-

	Area (deg^2)	Δt (day)	n_1	n_2	Limiting magnitude* m_g	m_r	m_i	m_z	m_y
Subaru/HSC Deep	30	6	2	3	26.1	25.8	25.6	24.5	23.2
Subaru/HSC Ultra Deep	3.5	6	3	4	26.9	26.6	26.6	25.6	24.3

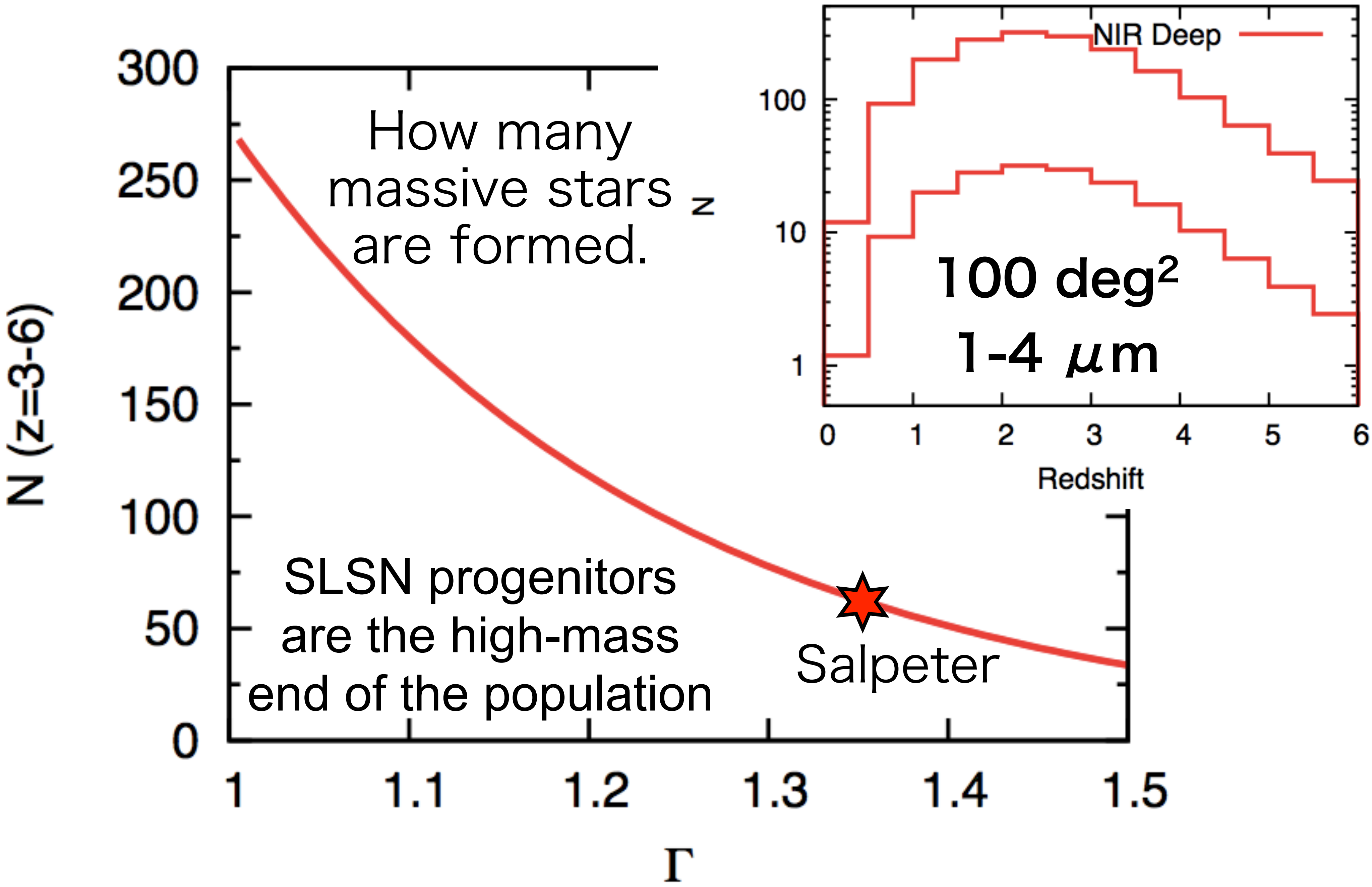




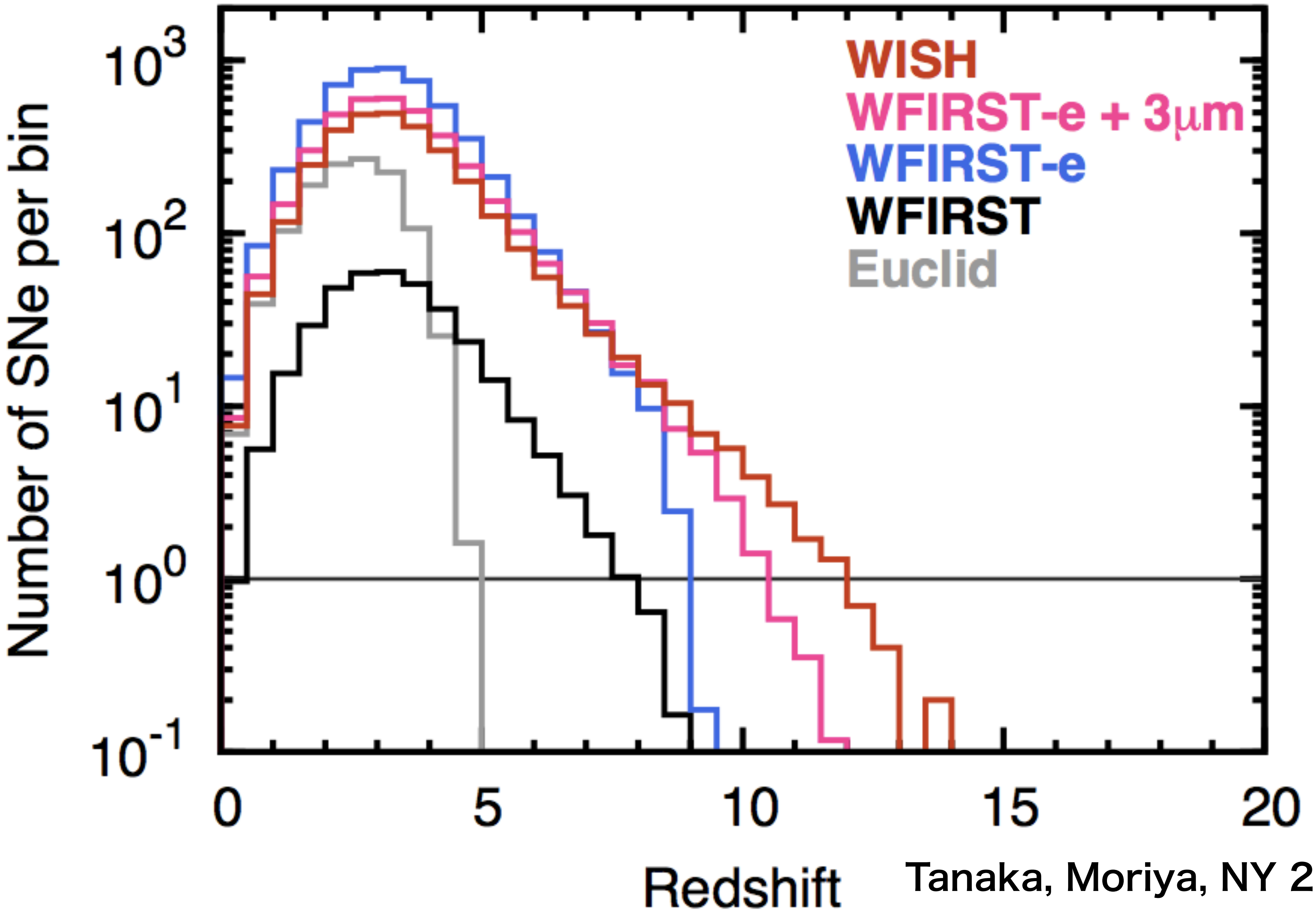
color selection

Tanaka, Moriya, NY, Nomoto, 2012

Probing stellar mass

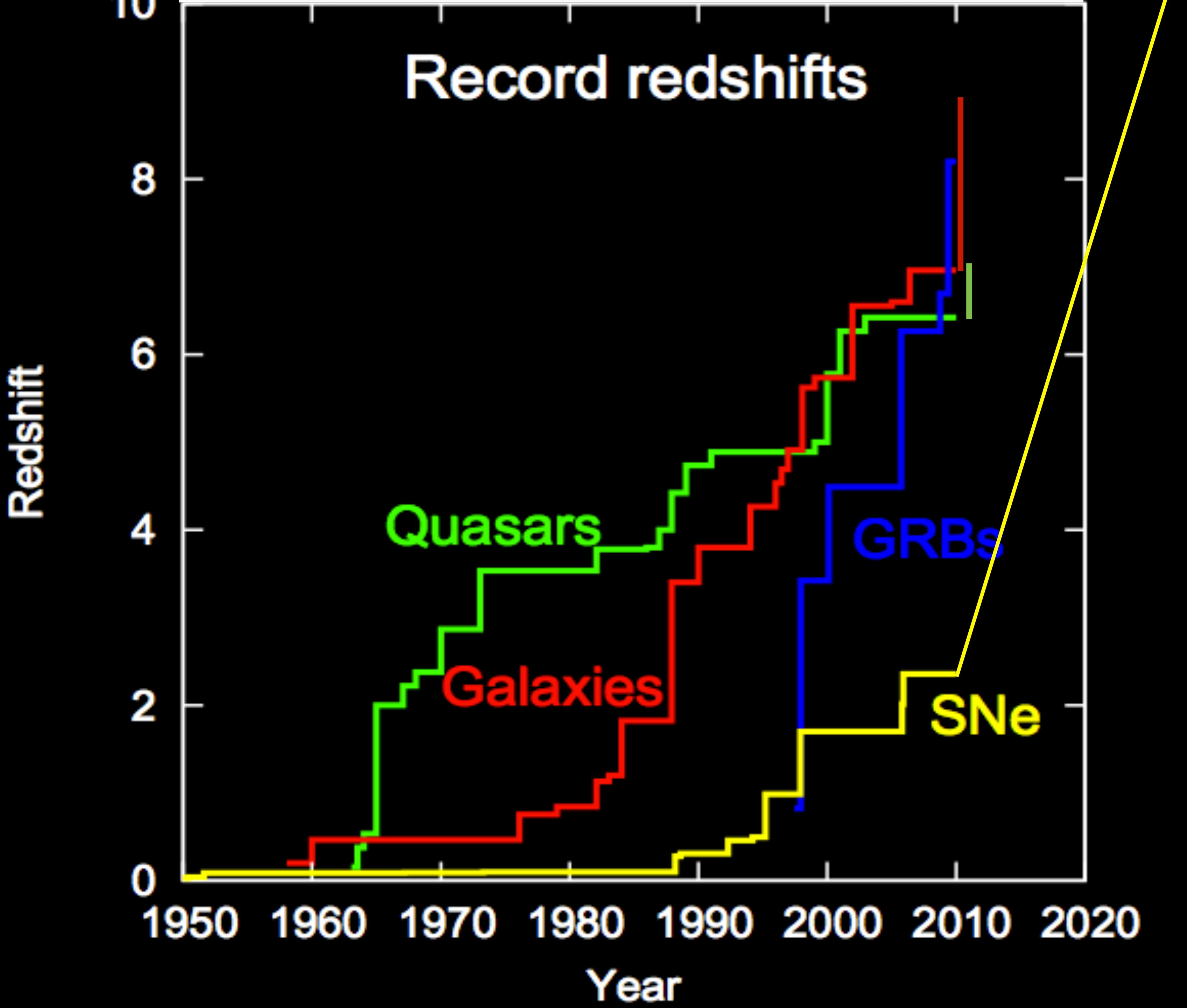


Future surveys



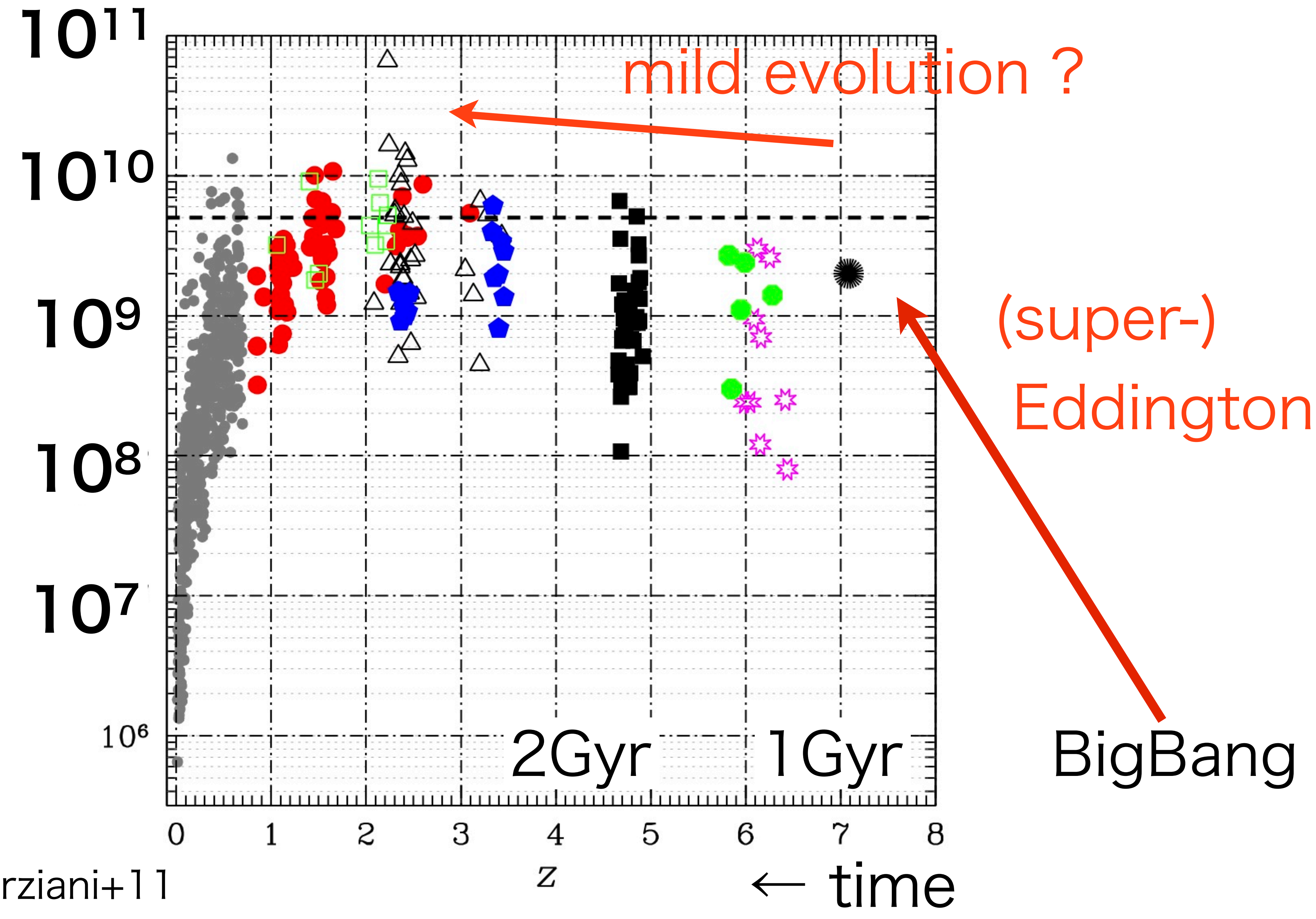
Tanaka, Moriya, NY 2013

Personal goal



First blackholes

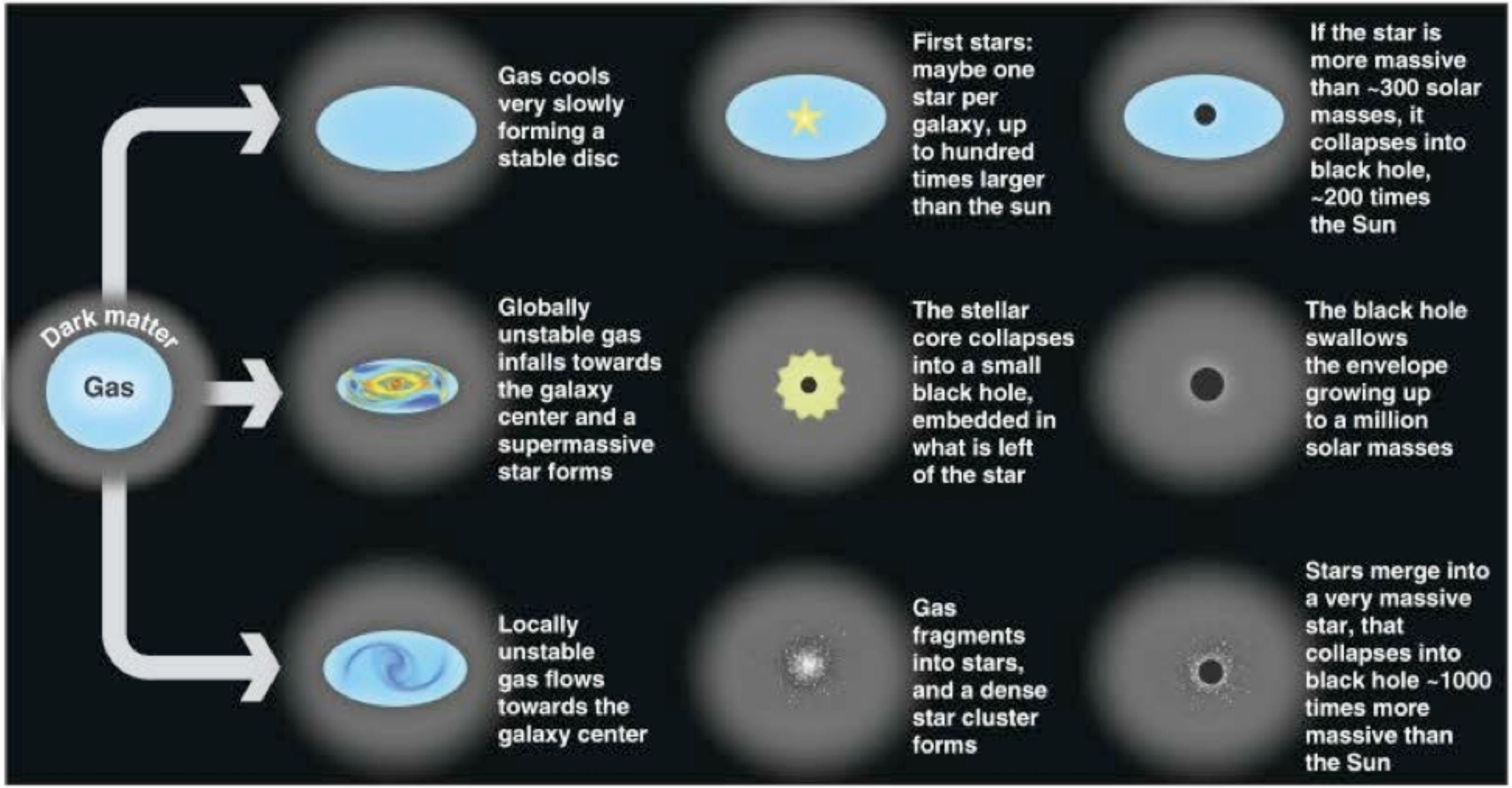
Blackhole mass



Marziani+11

Blackhole seeds: Rees diagram

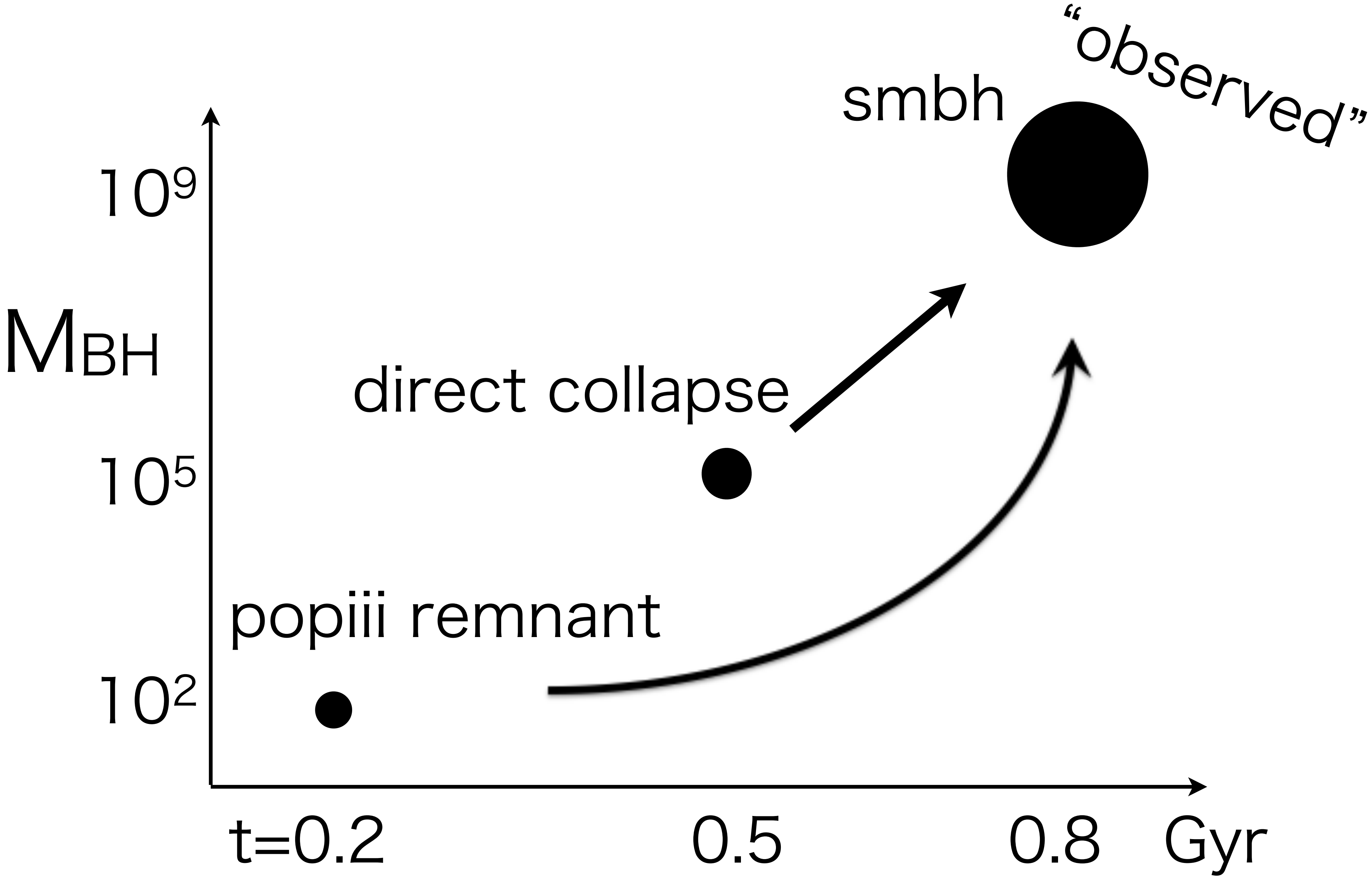
PopIII remnant



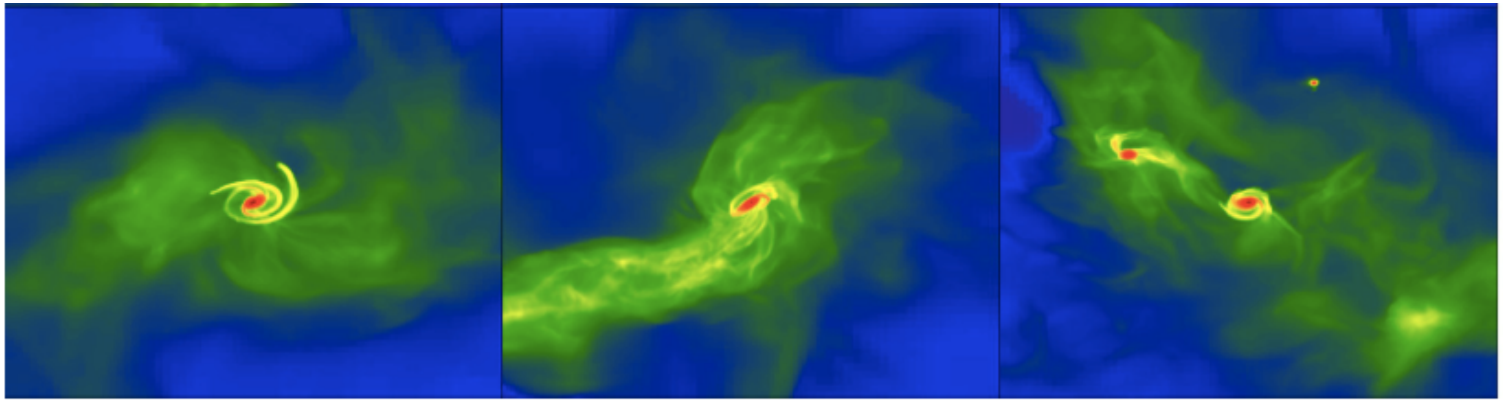
Volonteri 2012, Science

via a super-massive star

Blackhole growth

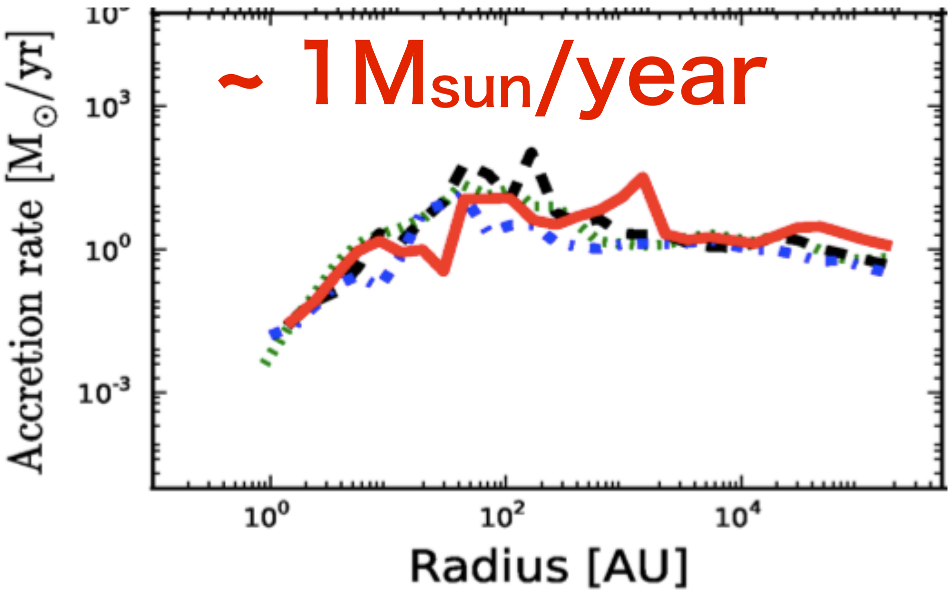


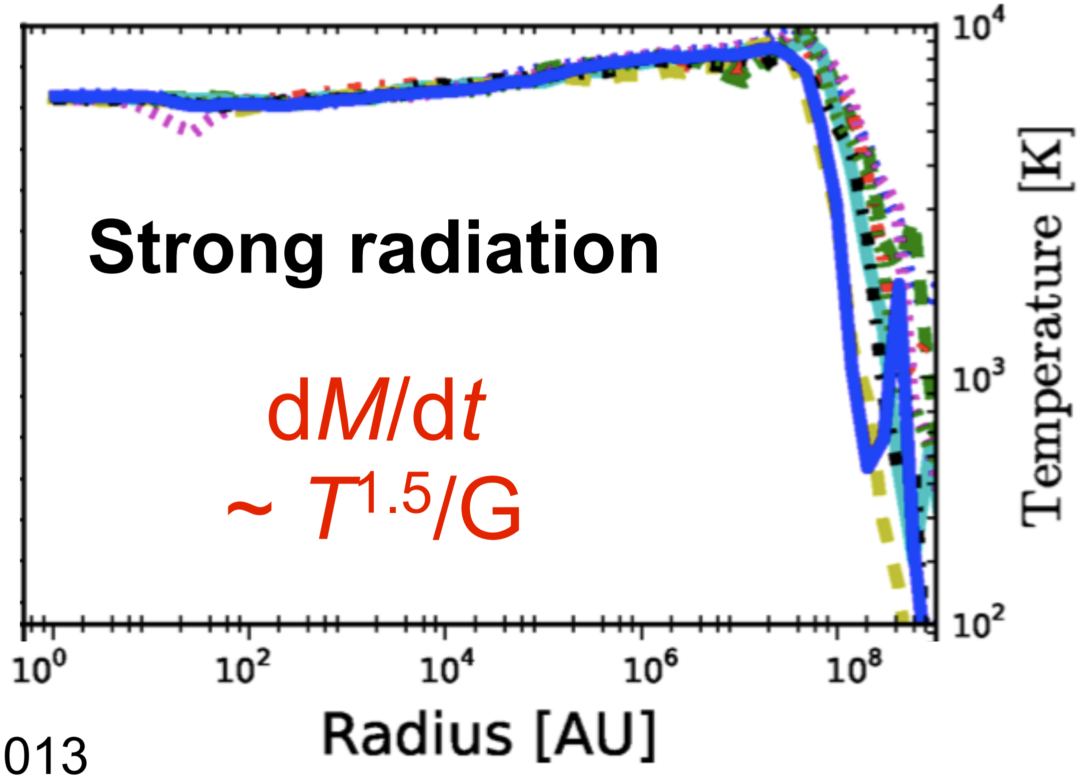
Direct collapse model



Super Massive Star $\sim 10^5\ M_{sun}$

Latif+13, A&A

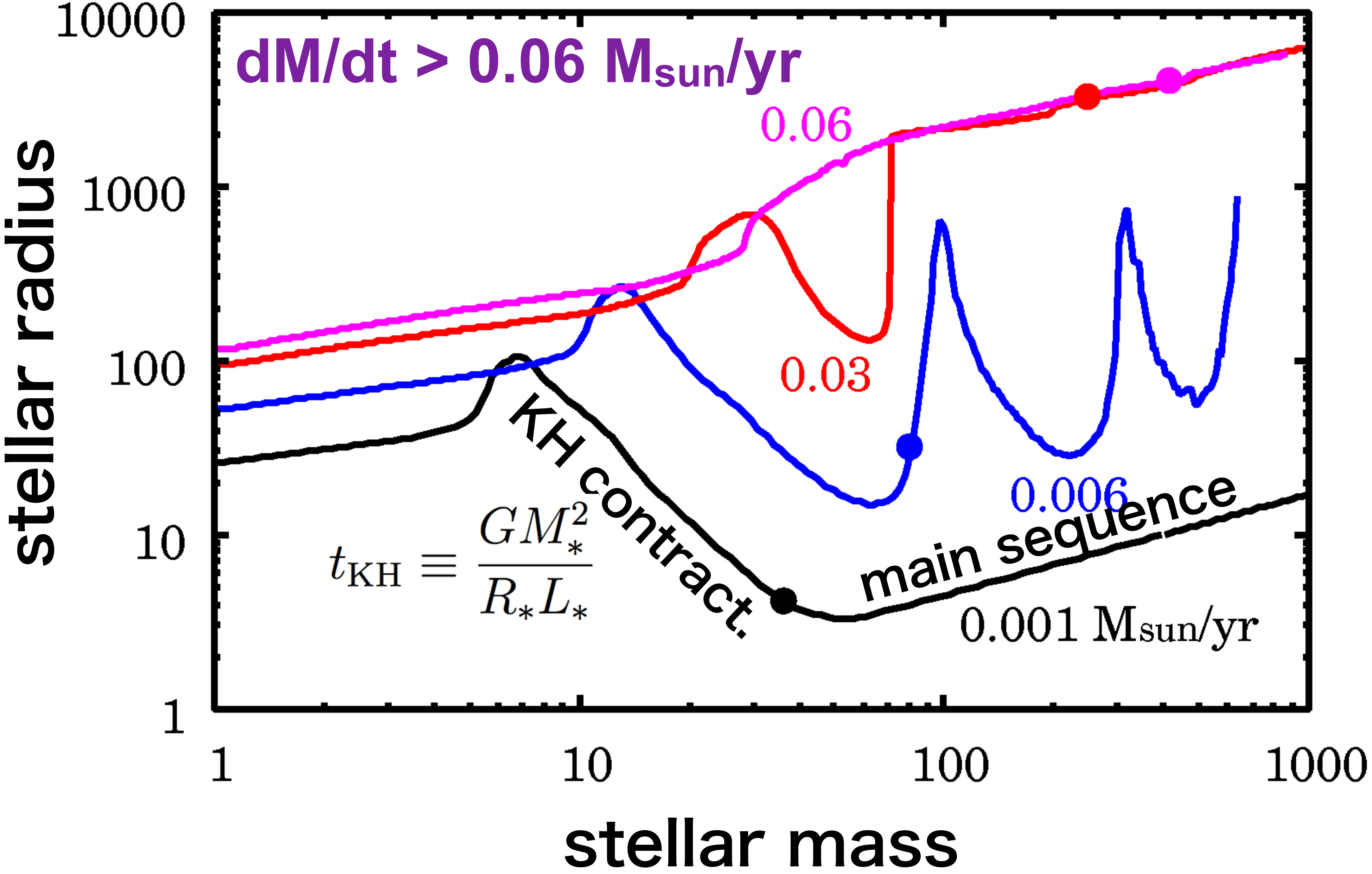




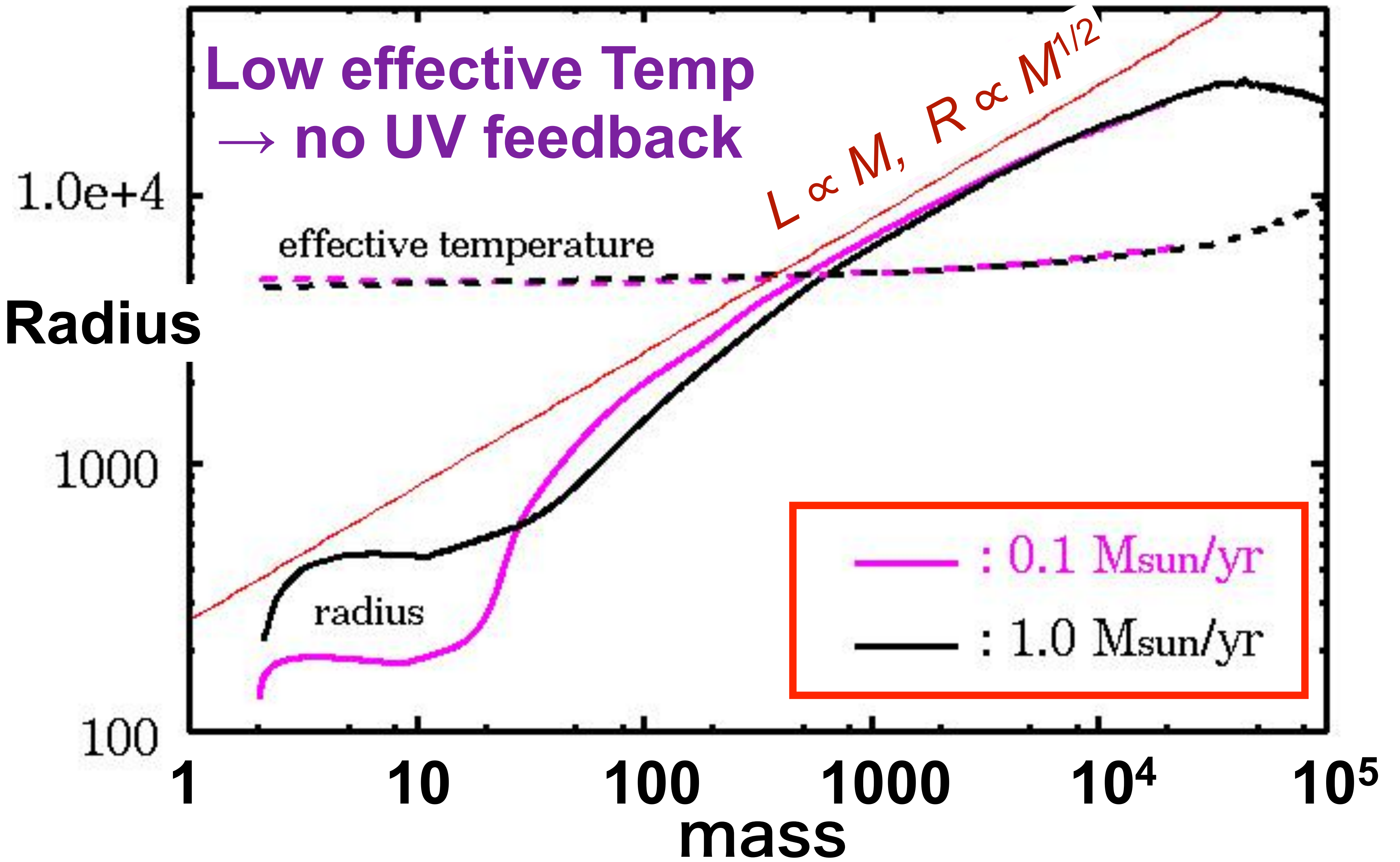
See also Regan & Haehnelt 2011; Choi+2013

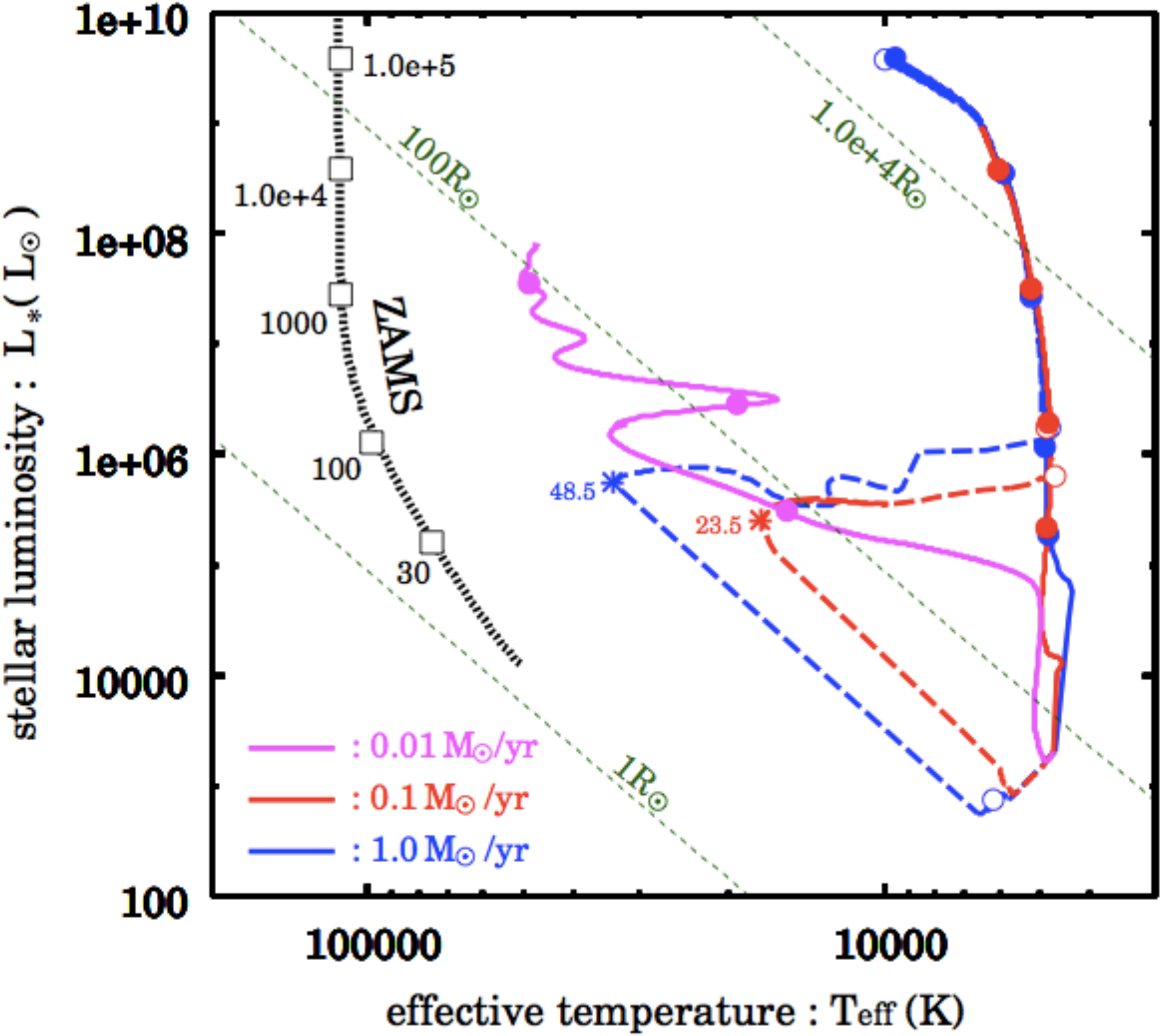
Supergiant star

Hosokawa, Yorke, Inayoshi, Omukai, NY 2013, ApJ



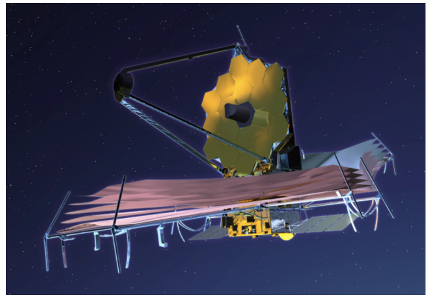
100,000 M_{sun} star

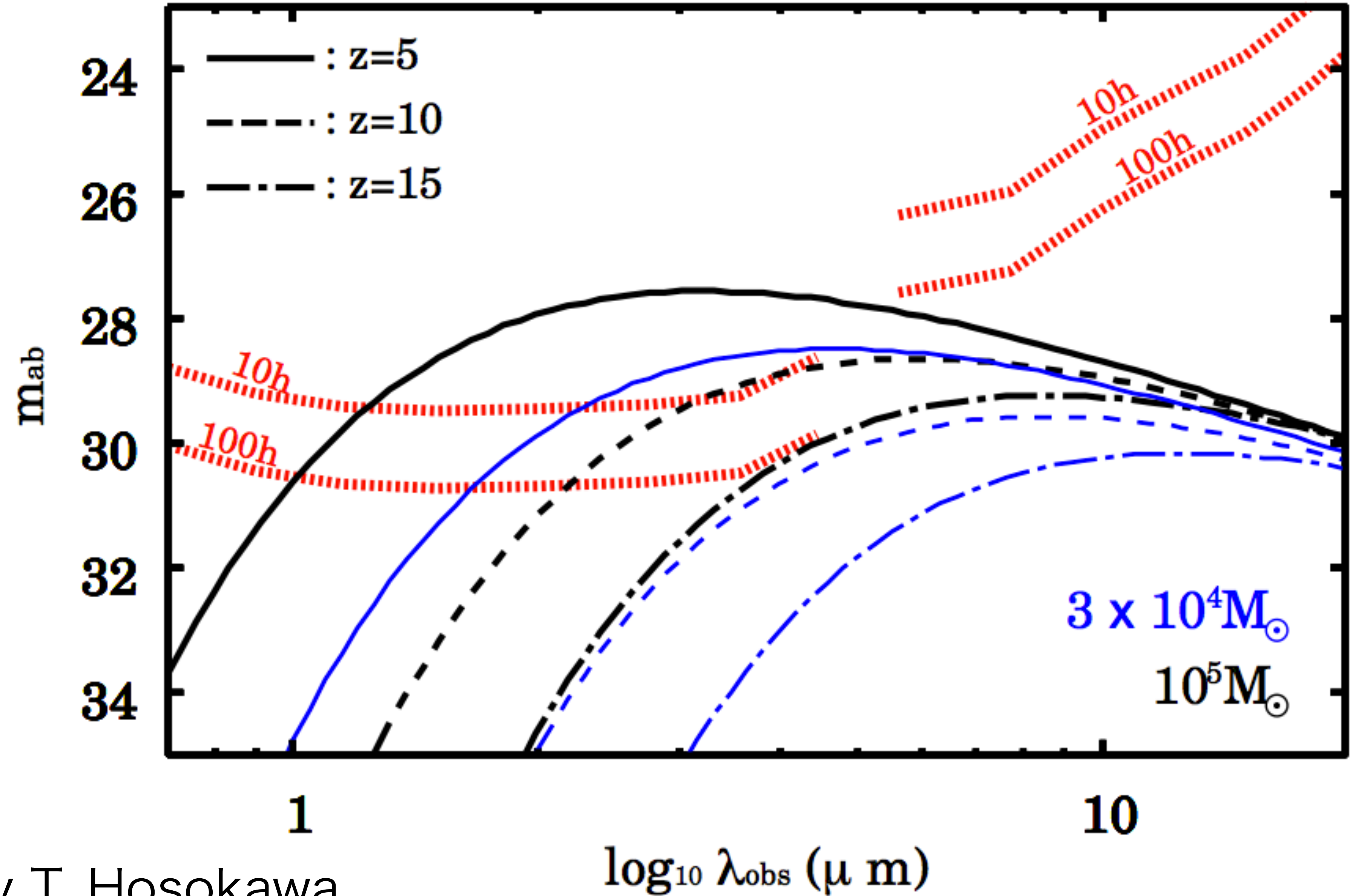




1e+10
1e+08
1e+06
10000
100
stellar luminosity : $L_*(L_\odot)$
100000
10000
effective temperature : T_{eff} (K)
1.0e+5
1.0e+4
1000
100
30
ZAMS
$100R_\odot$
$1.0e+4R_\odot$
$1R_\odot$
48.5
23.5
: 0.01 $M_\odot$/yr
: 0.1 $M_\odot$ /yr
: 1.0 $M_\odot$ /yr

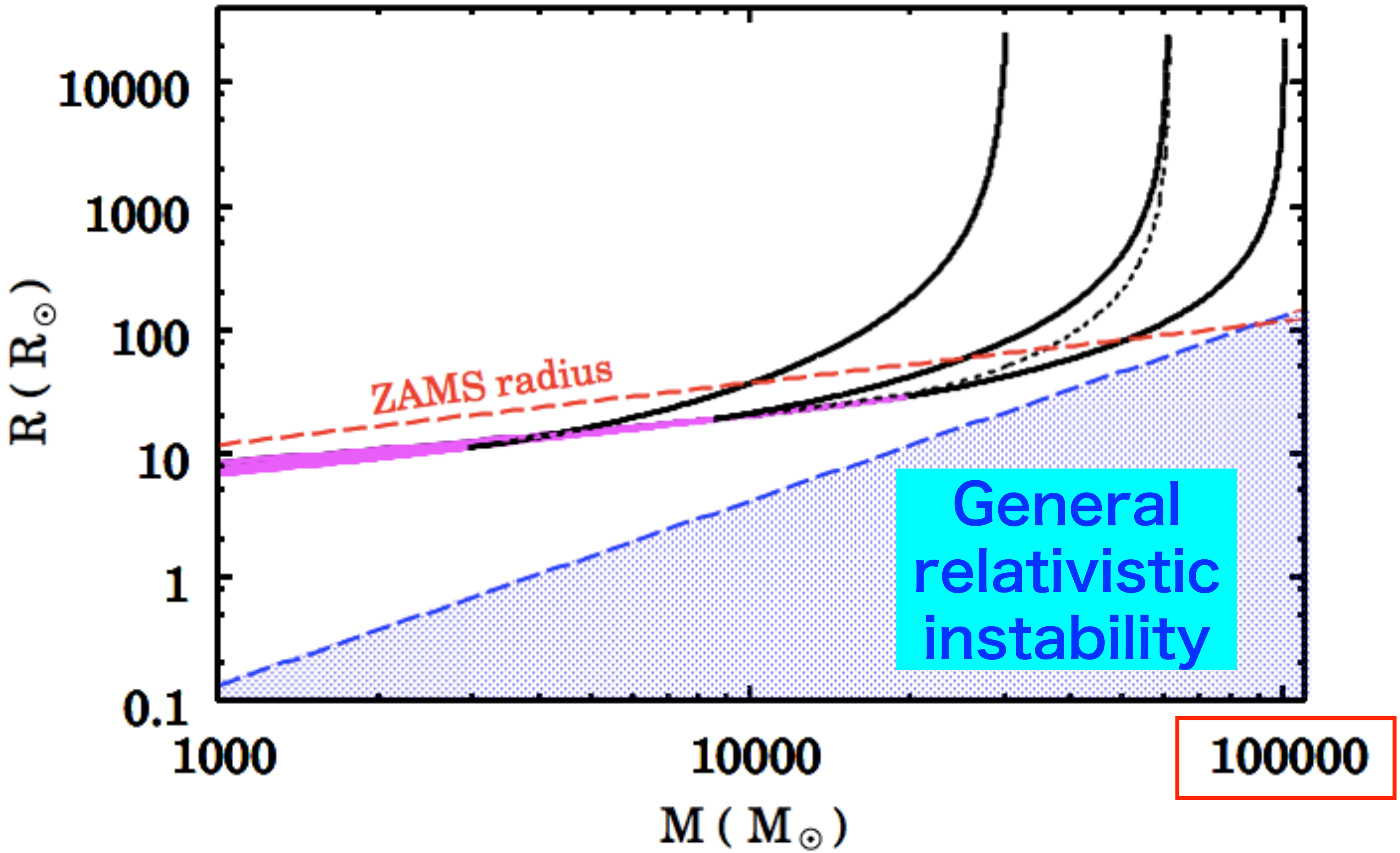
James Webb Space Telescope



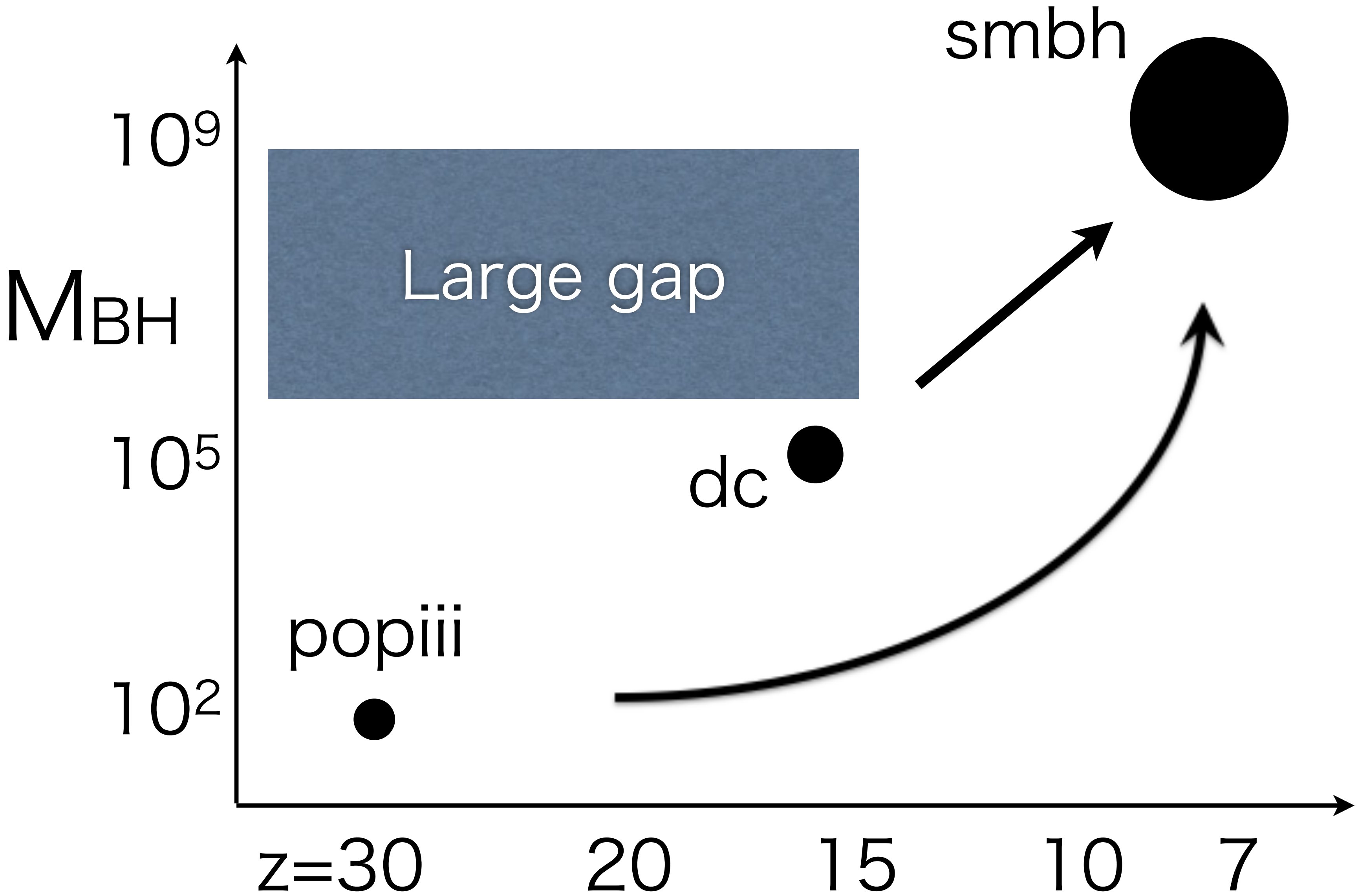


By T. Hosokawa

Gravitational stability



Blackhole growth



Summary

- Formation of massive primordial stars as origin of objects in the early universe
- Supernova explosions might be visible to the most distant places
- Rapid growth of a primordial star makes a supermassive star and possibly a BH