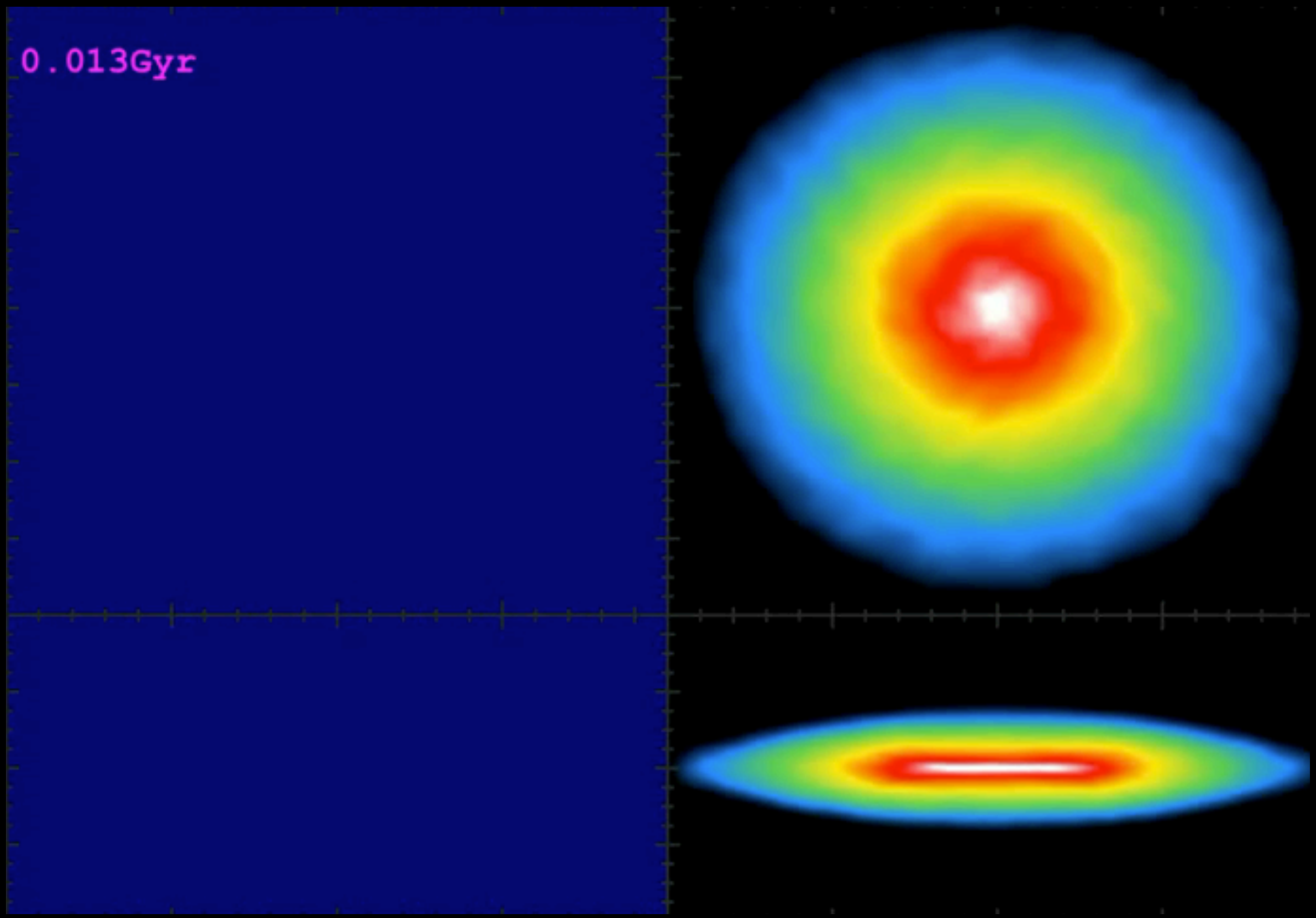
Chemo-dynamical modelling of thick/thin disks

Sergey Khoperskov[1]



in collaboration with: Misha Haywood[1], Paola Di Matteo[1], Owain Snaith[2], Matt Lehnert[3], Francoise Combes[4]

[1]GEPI, Observatoire de Paris, Meudon, France, [2]KIAS, Seoul, South Korea, [3]IAP, Paris, France, [4]LERMA, Observatoire de Paris, Paris, France

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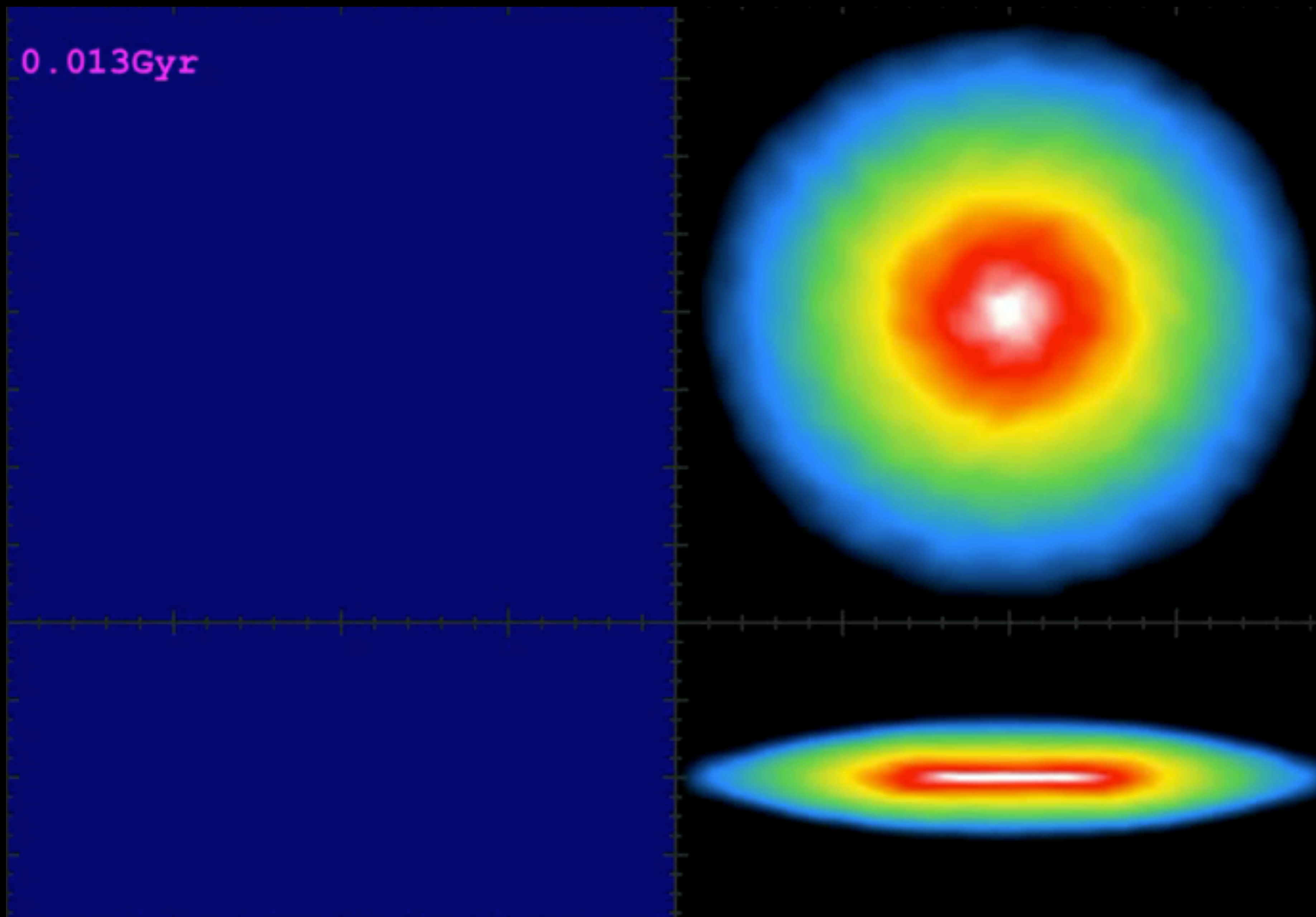

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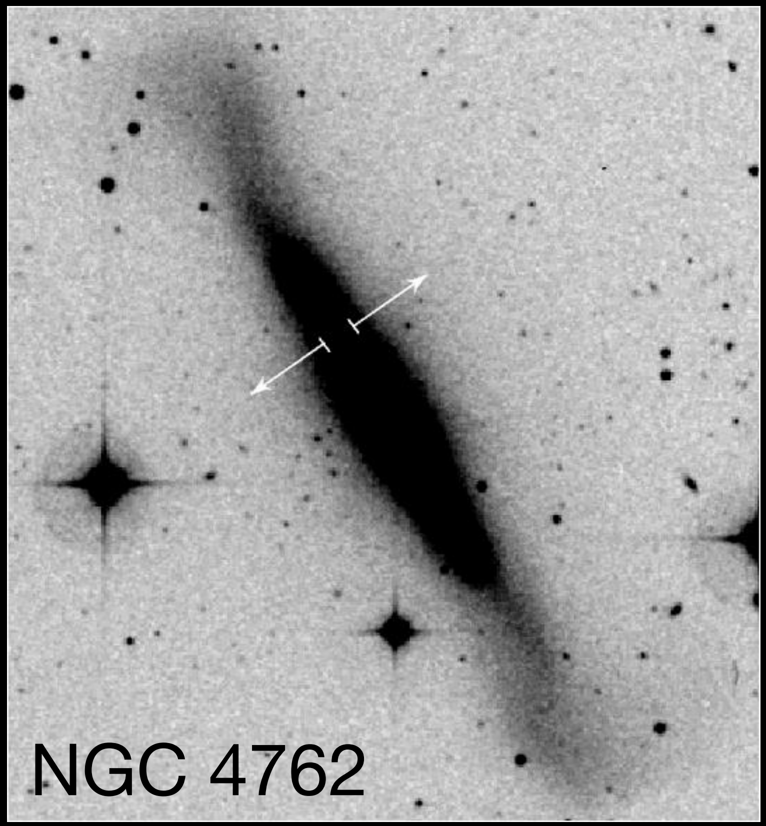
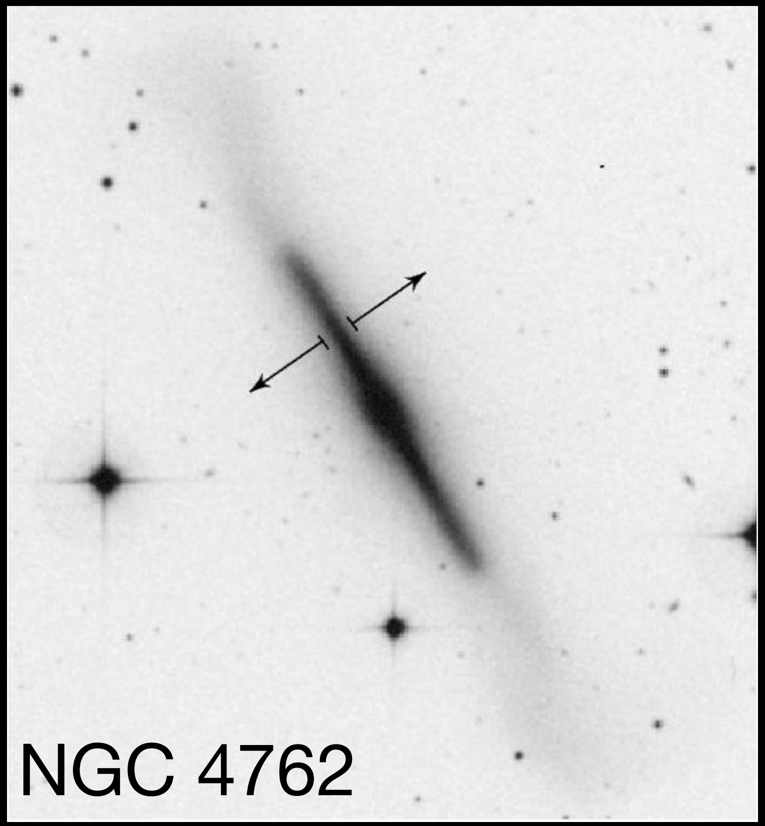
Galactic disks

Most spirals have two disk components

Thicker disk:
very common in other galaxies
appears to be old (> 6-10 Gyr)
moderately metal-poor

Thin disk:
relatively younger
moderately metal-rich
dynamically colder





Thick disk recognizable as relict of the early galaxy

ISM conditions at epoch of galaxy formation: mass, chemical composition, turbulence

Thick disk formation

- Perturbation by merging satellites and/or dark matter (e.g. Di Matteo+ 2011). The orbital energy of the satellite goes into thickening the disk.
- Accretion of satellites (e.g. Abadi+ 2003). Thick disk stars come in from outside.
- Gas rich mergers (e.g. Brook+ 2004, 2005). The thick disk stars are born in-situ.
- Formation in turbulent gas-rich thick gas disk (e.g. Bournaud+ 2009). Dissolution of giant gas agglomeration in clumpy galaxies (Kroupa 2002, Bournaud+ 2008).

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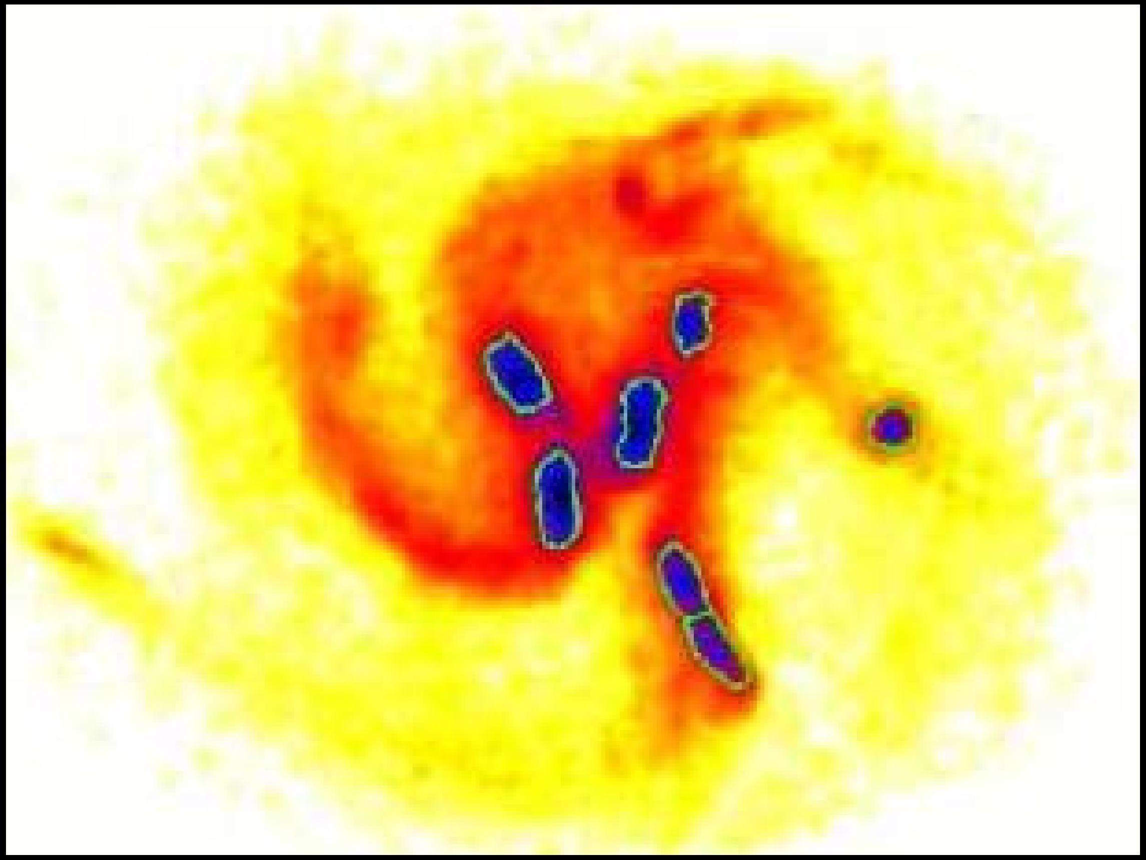
Thick disk formation in gas-rich disk

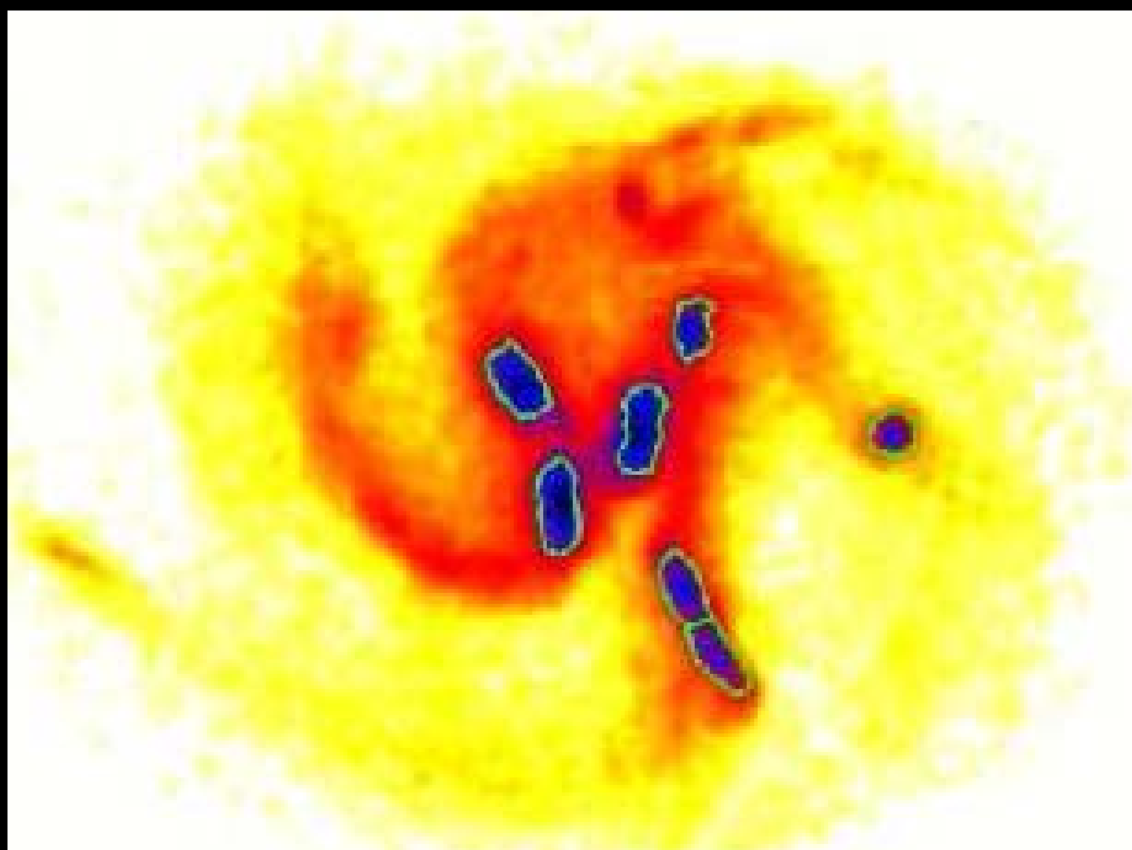
Clumpy disk



Noguchi 1998,1999
Bournaud, Elmegreen et al 2007

Thick disk formation in gas-rich disk

Clumpy disk



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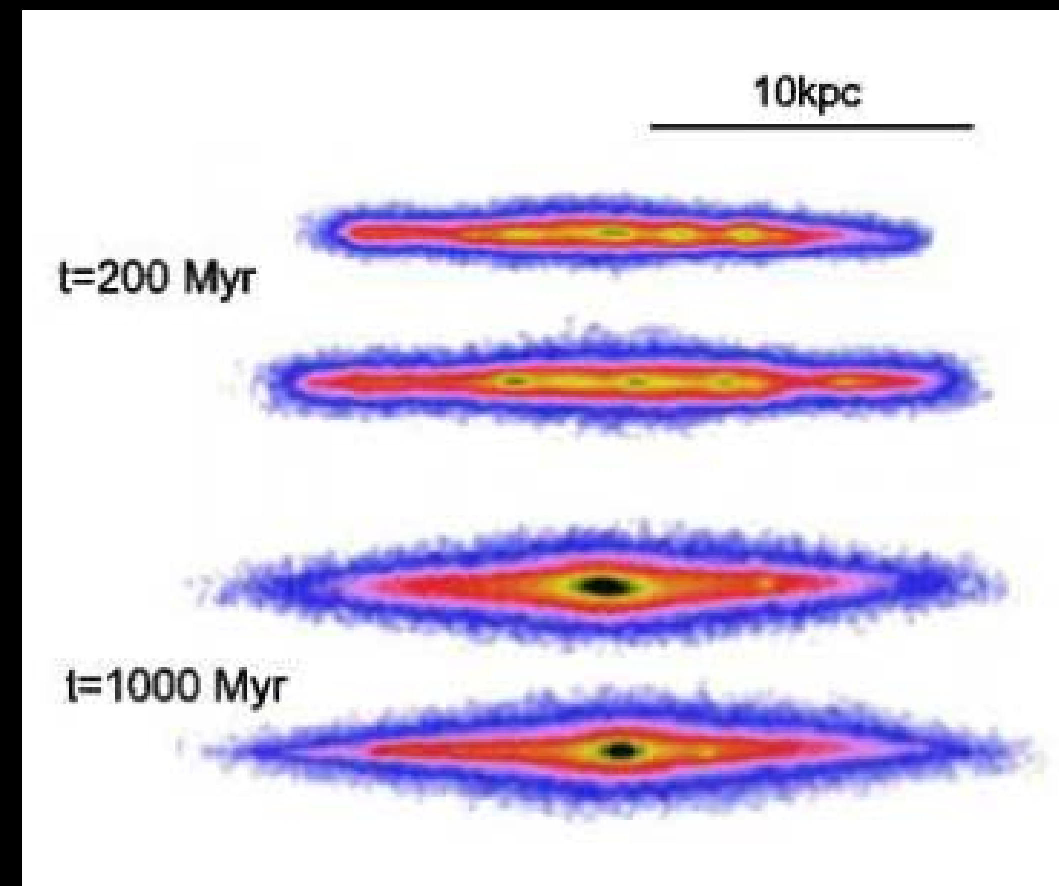
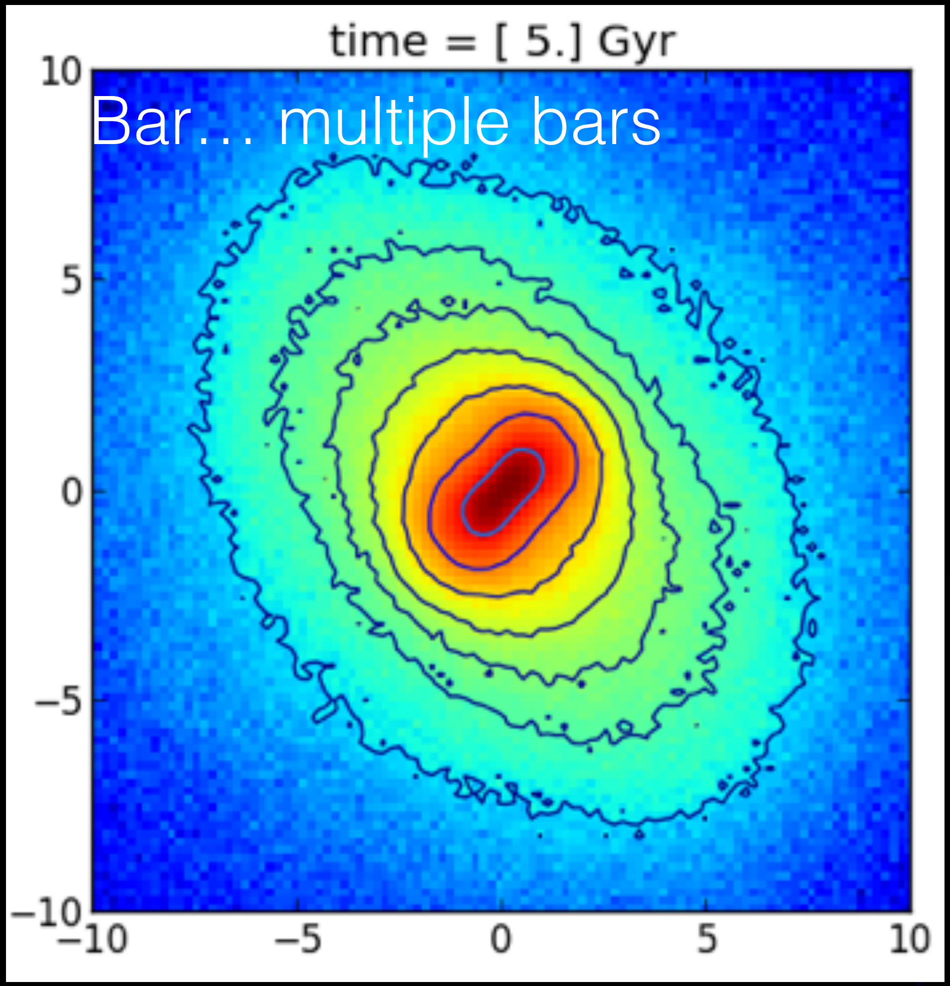
Thick disk

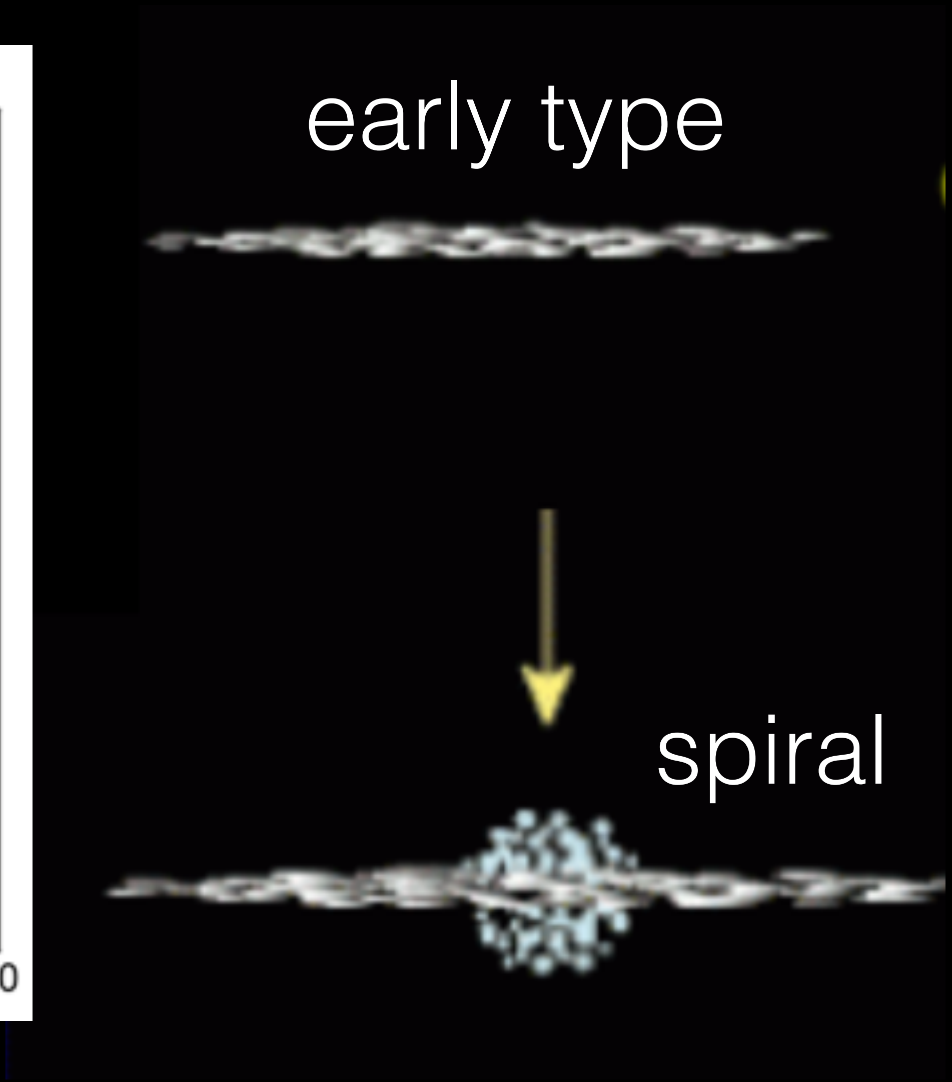


Rapid formation of exponential disk (and bulge), through dynamical friction

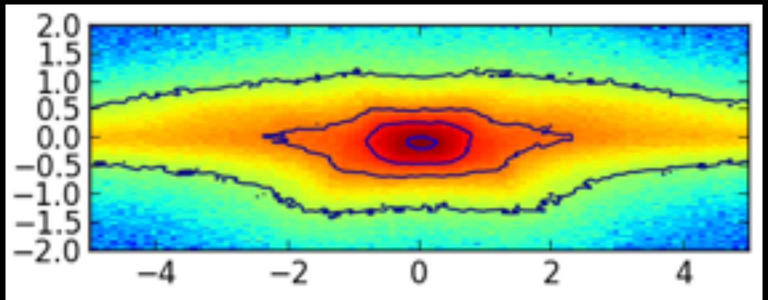
- Secular evolution affects galactic disk dynamics
- Dynamical information can be vanished through disk heating processes



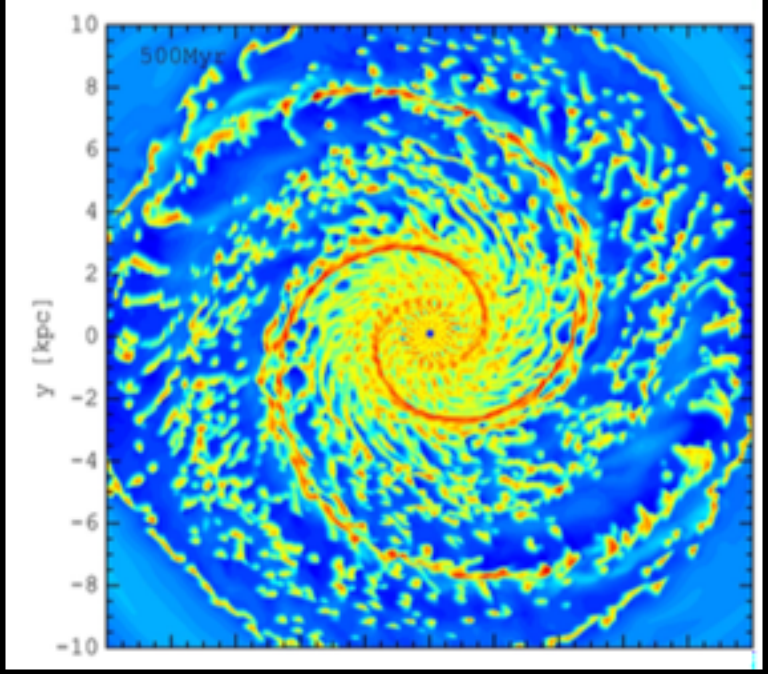
Khoperskov+ in prep.



Disk/bar buckling



Spirals and clouds



Khoperskov & Khrapov 2018

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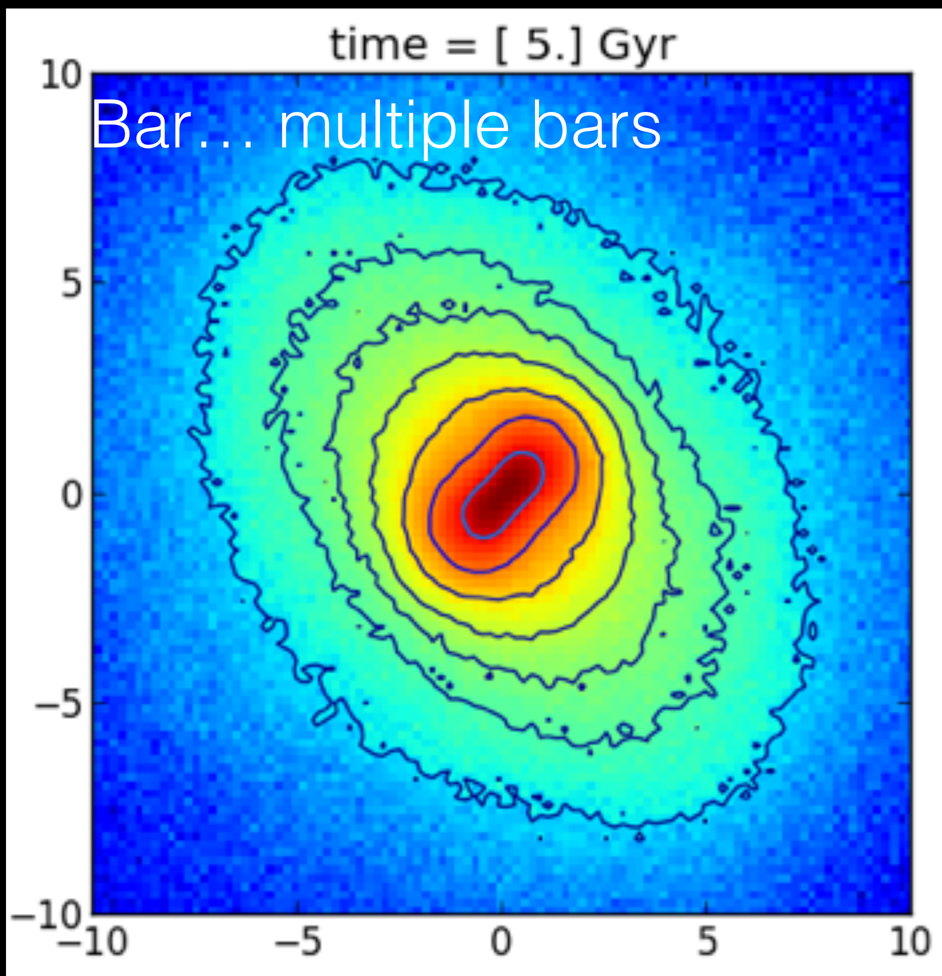

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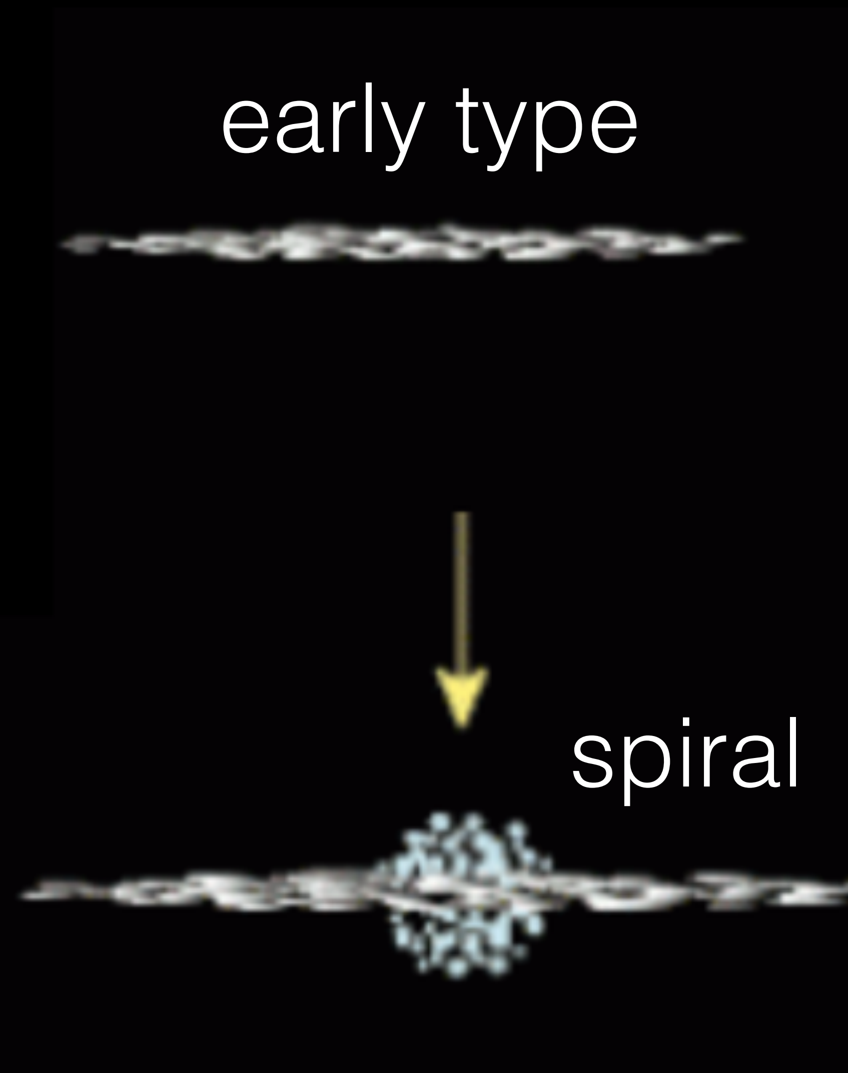

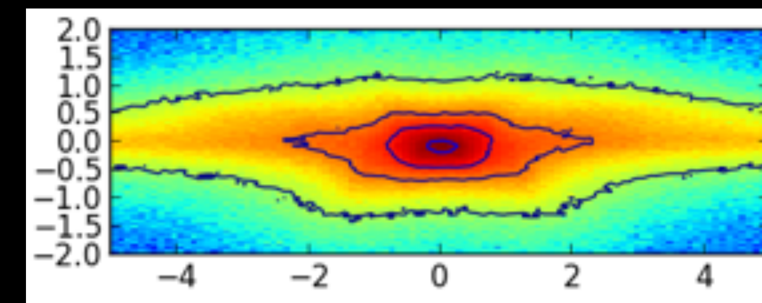

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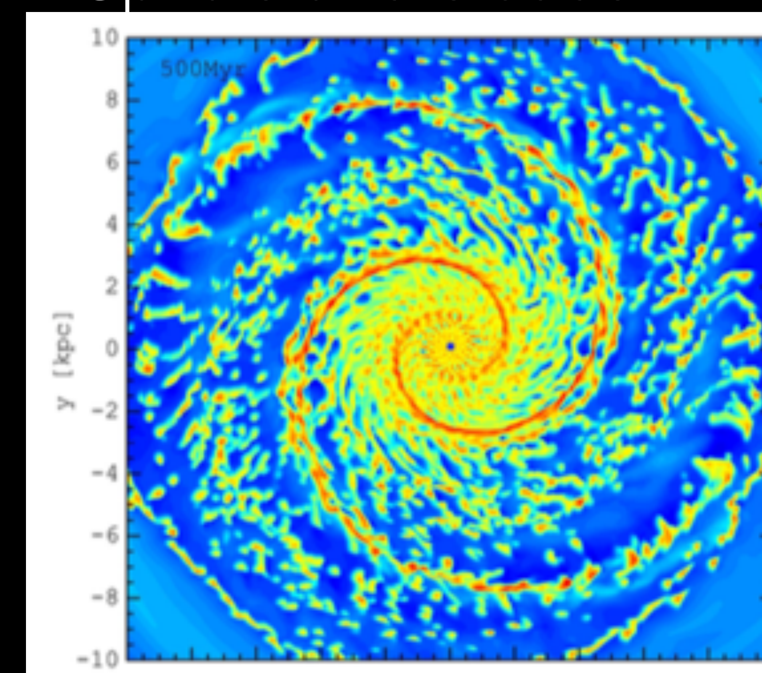


Khoperskov & Khrapov 2018

- The detailed abundance pattern reflects the chemical evolution of the gas from which the aggregate formed.

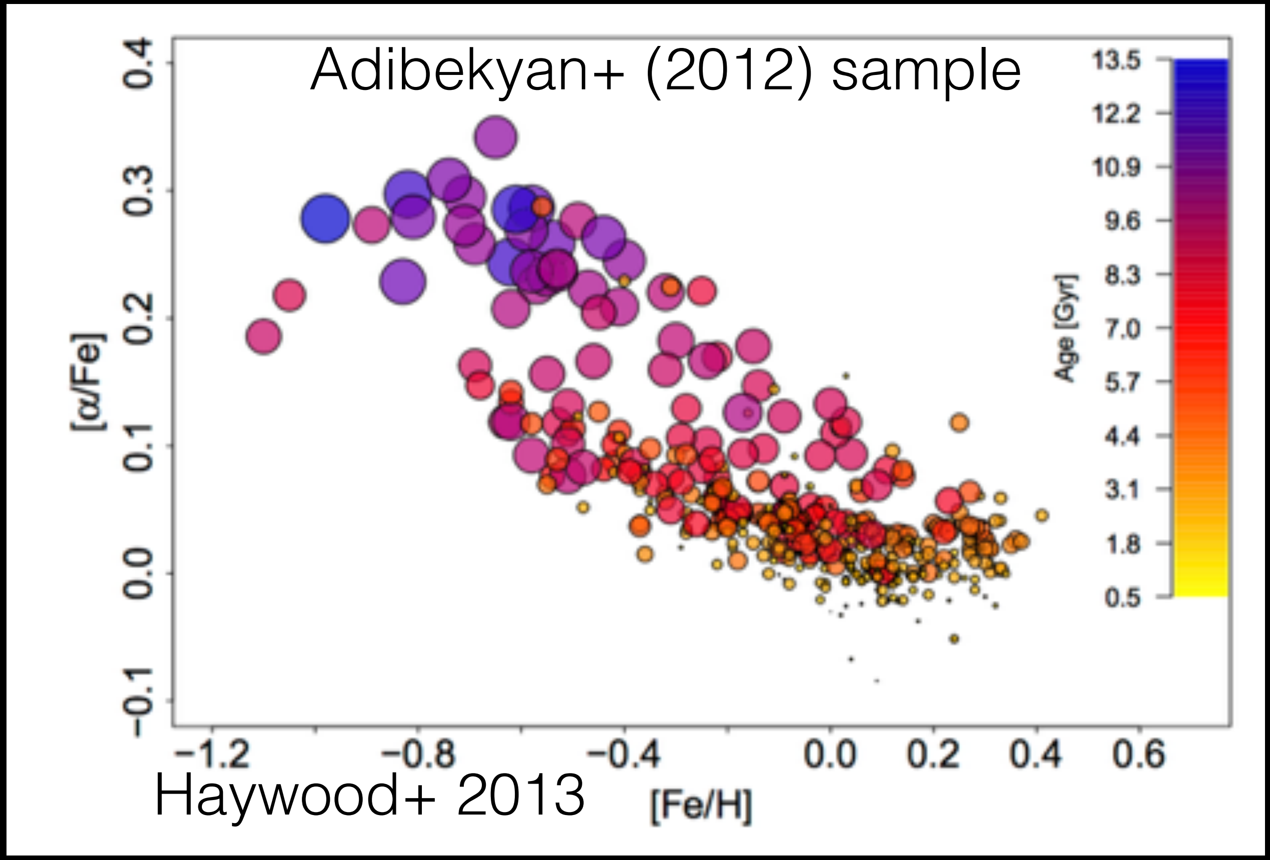
- Disks formation/evolution are still recognizable by their chemical signatures

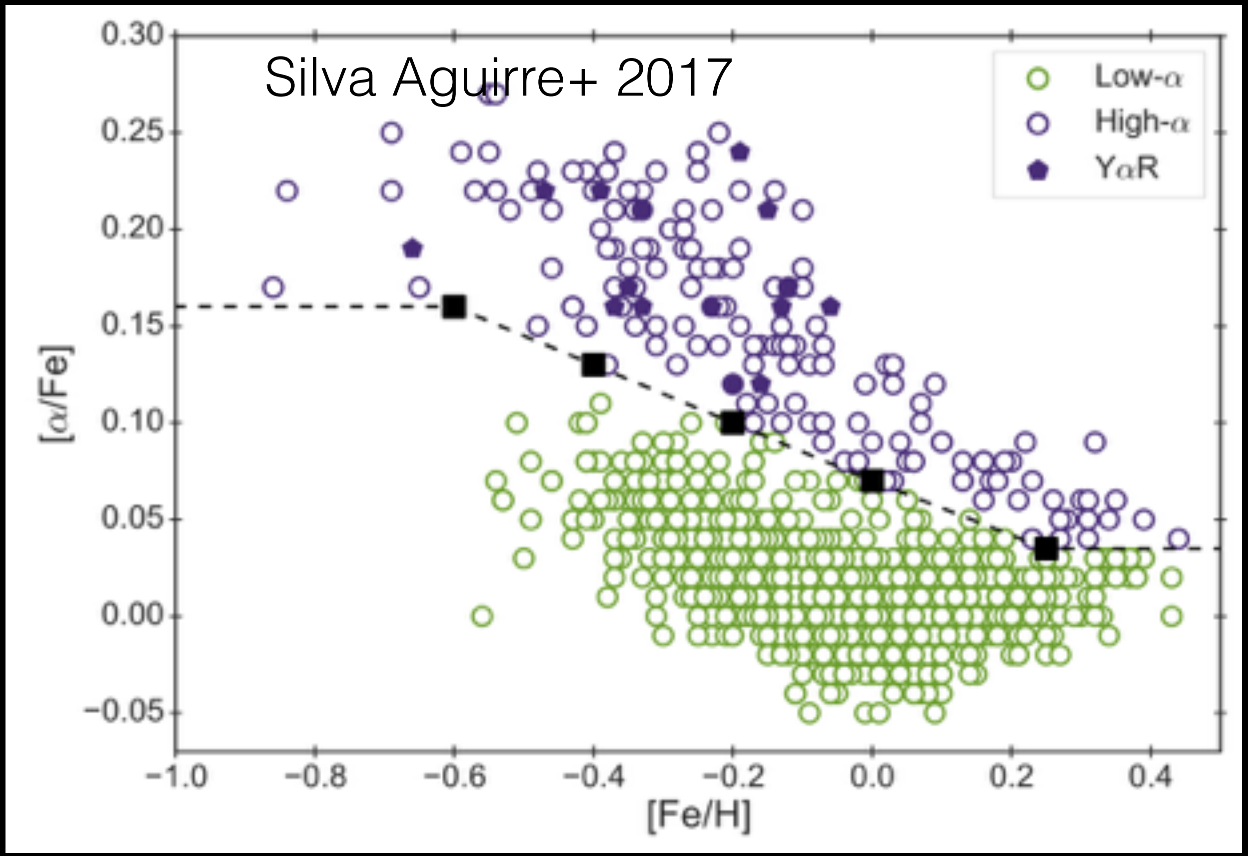
Chemical composition of the Milky Way

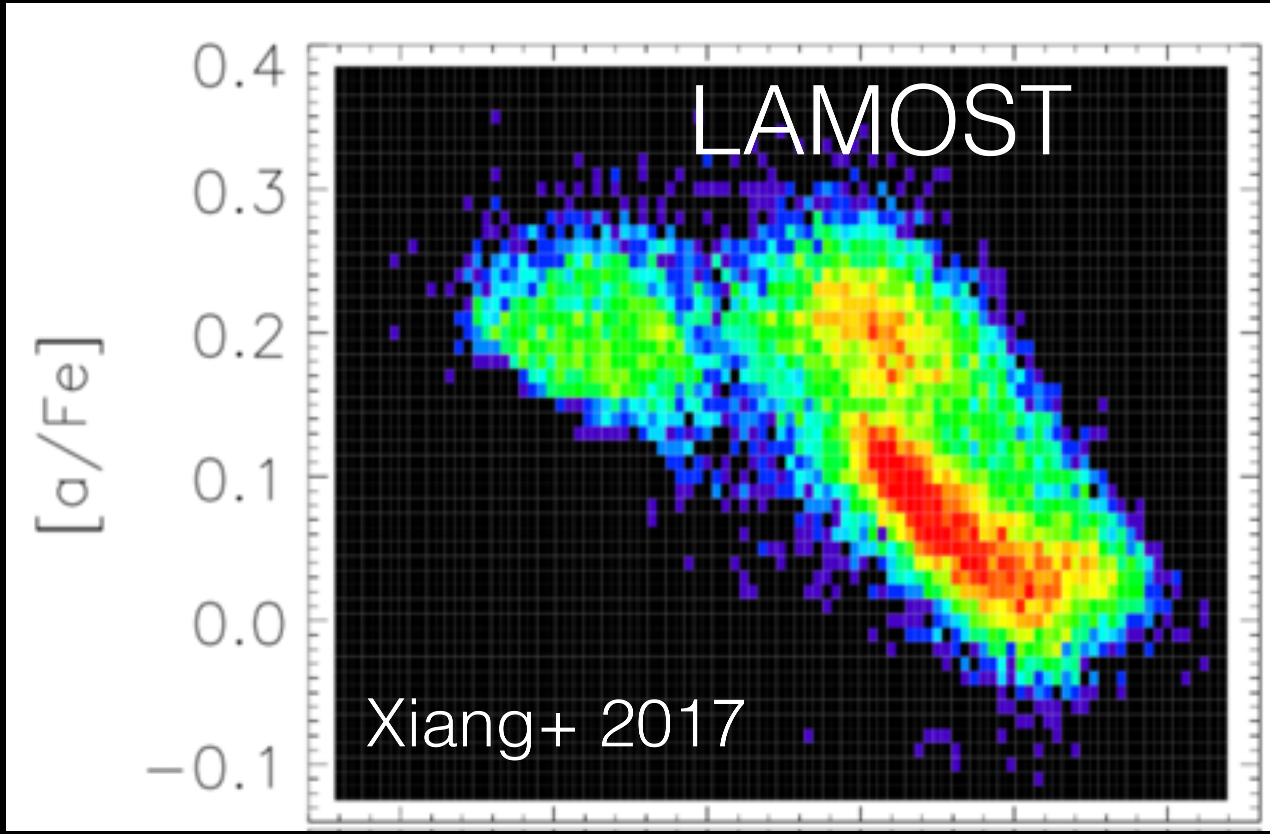
- [α/Fe]-[Fe/H] bimodality
- thick/thin disks?

- The thick disk is not a mono-age population: 9-13 Gyr
- The thick disk is alpha-enhanced
- Thick disk chemically homogeneous

- Two regimes of abundance variations, corresponding to two regimes of star formation

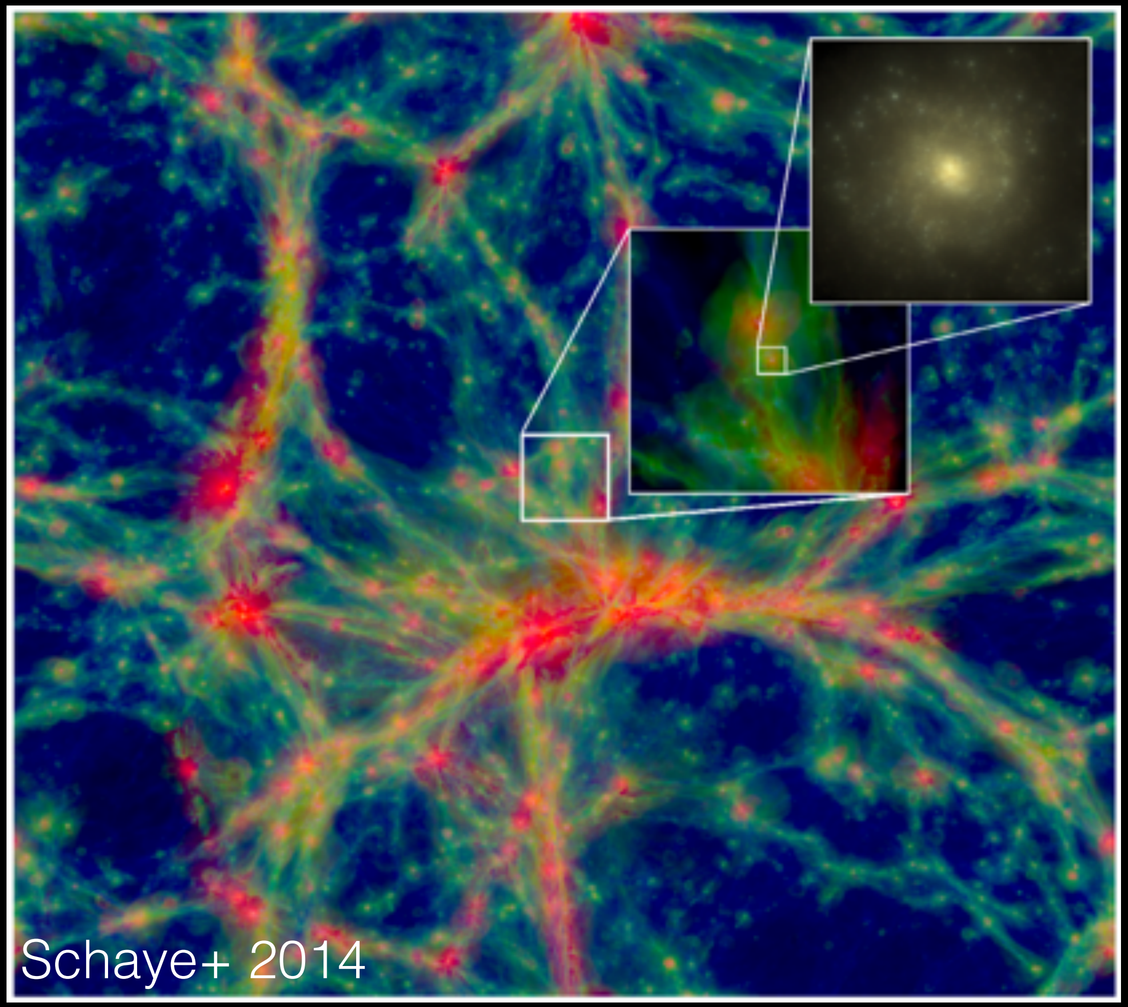






Cosmological simulations

EAGLE simulation



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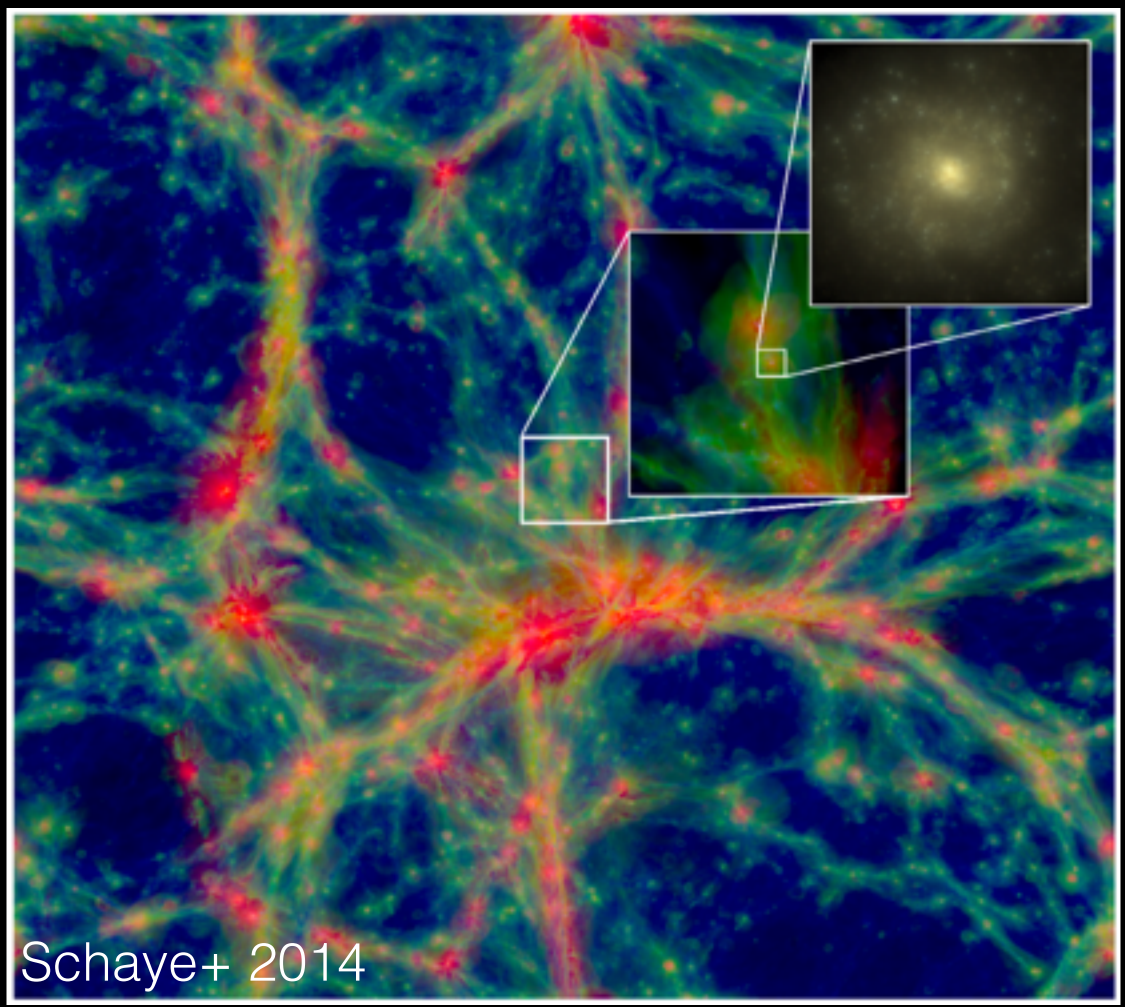
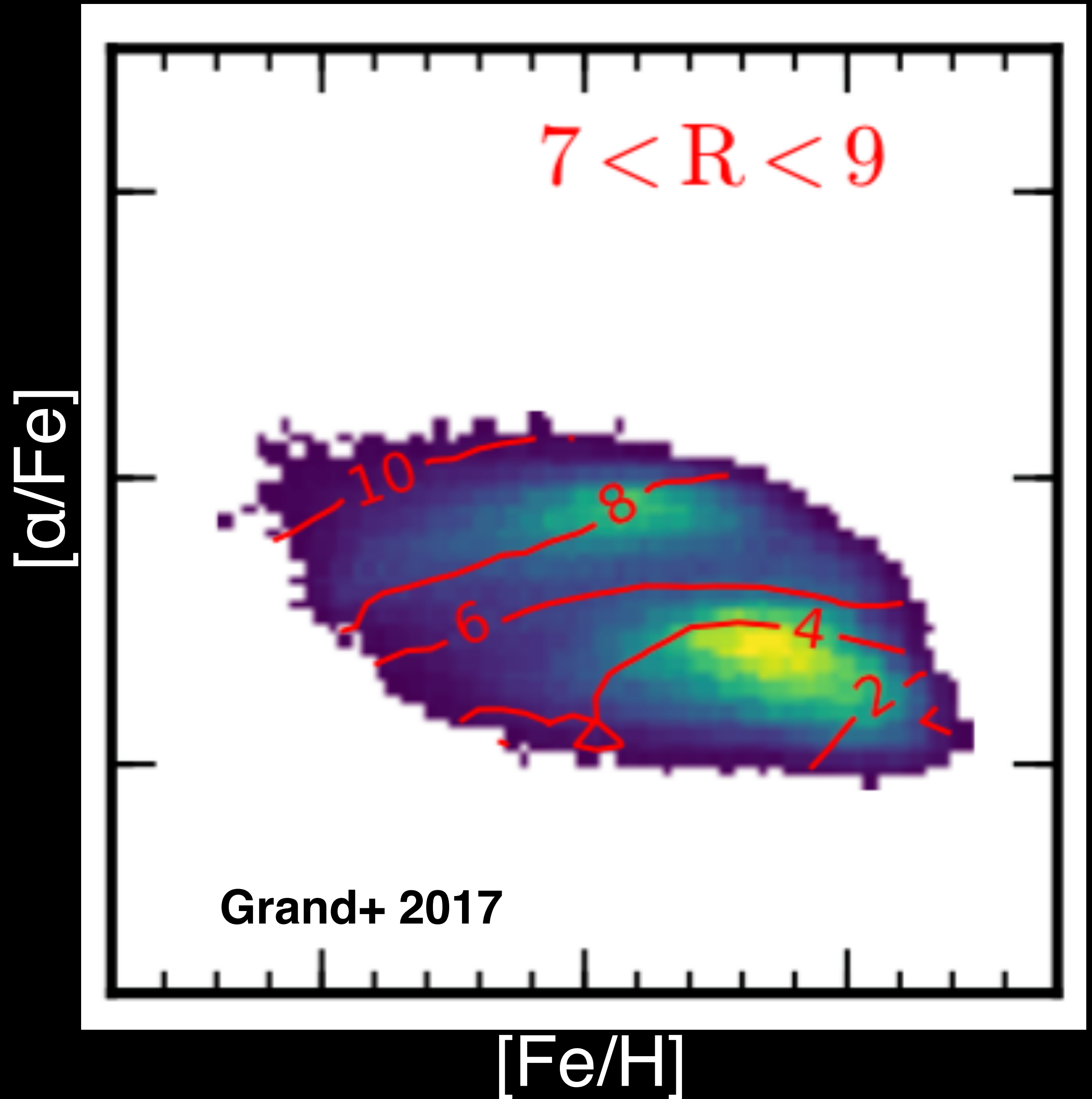


AURIGA project



Cosmological simulations

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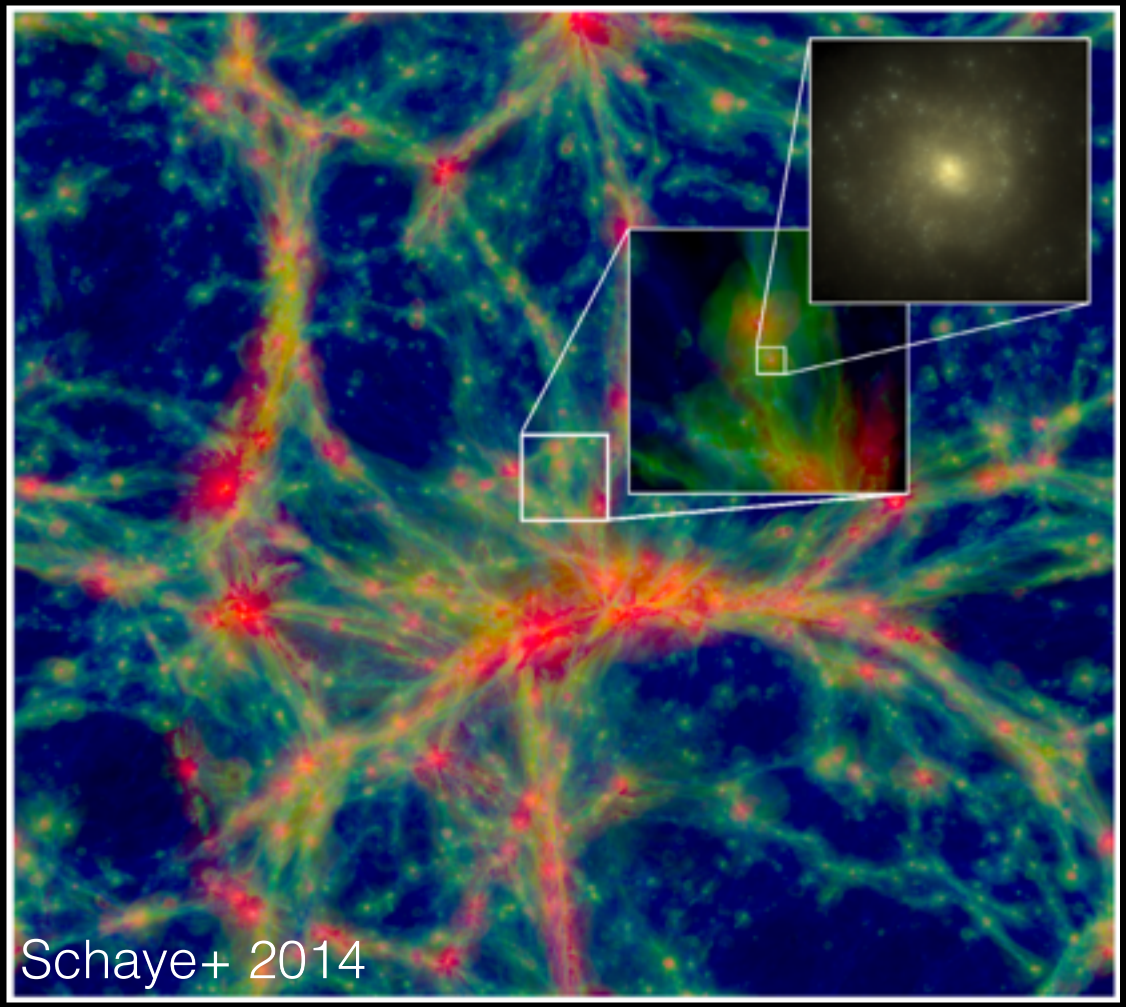

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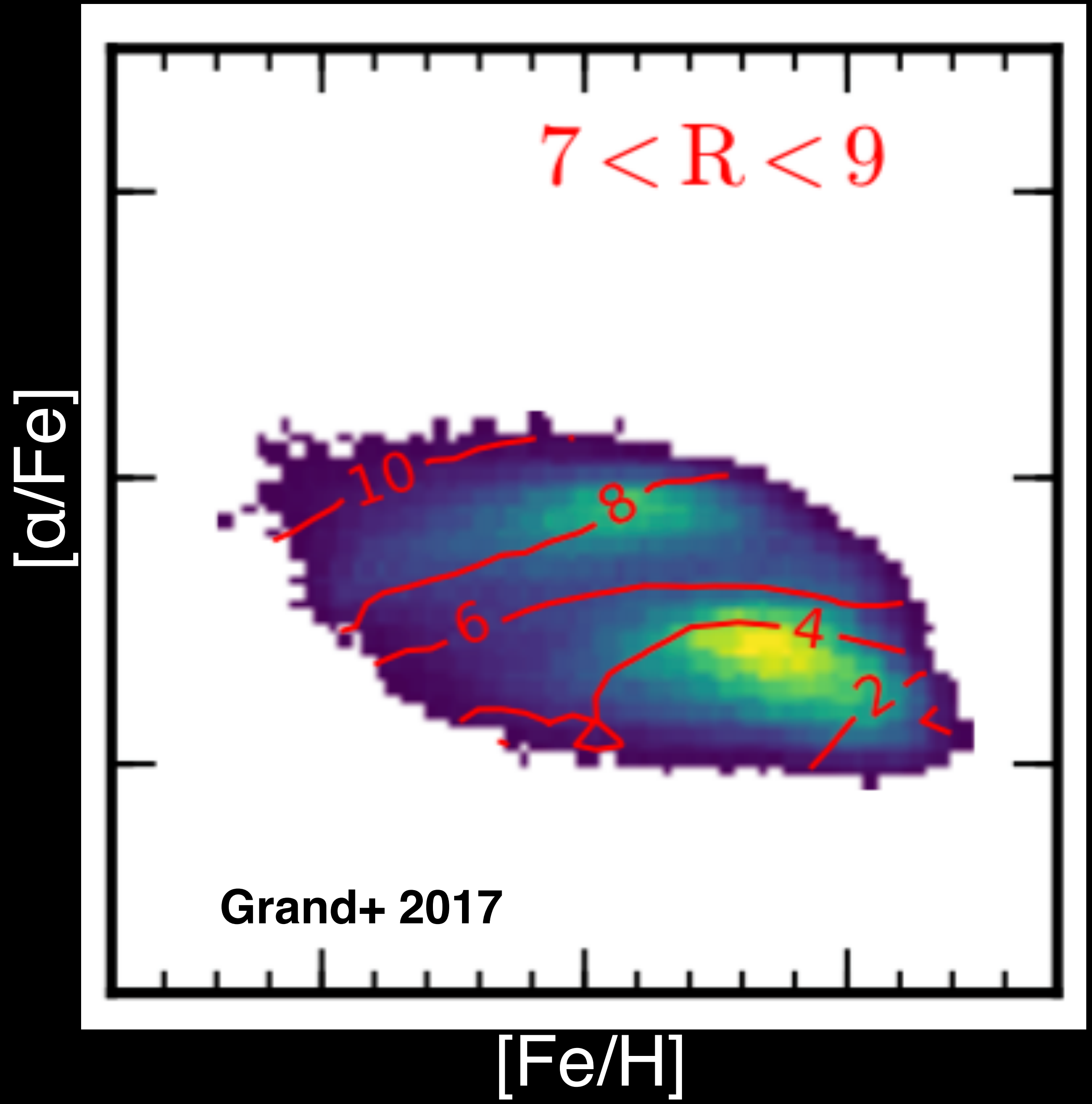

All (6) simulations
develop a clear bimodality

Merger plays an important role

Cosmological simulations

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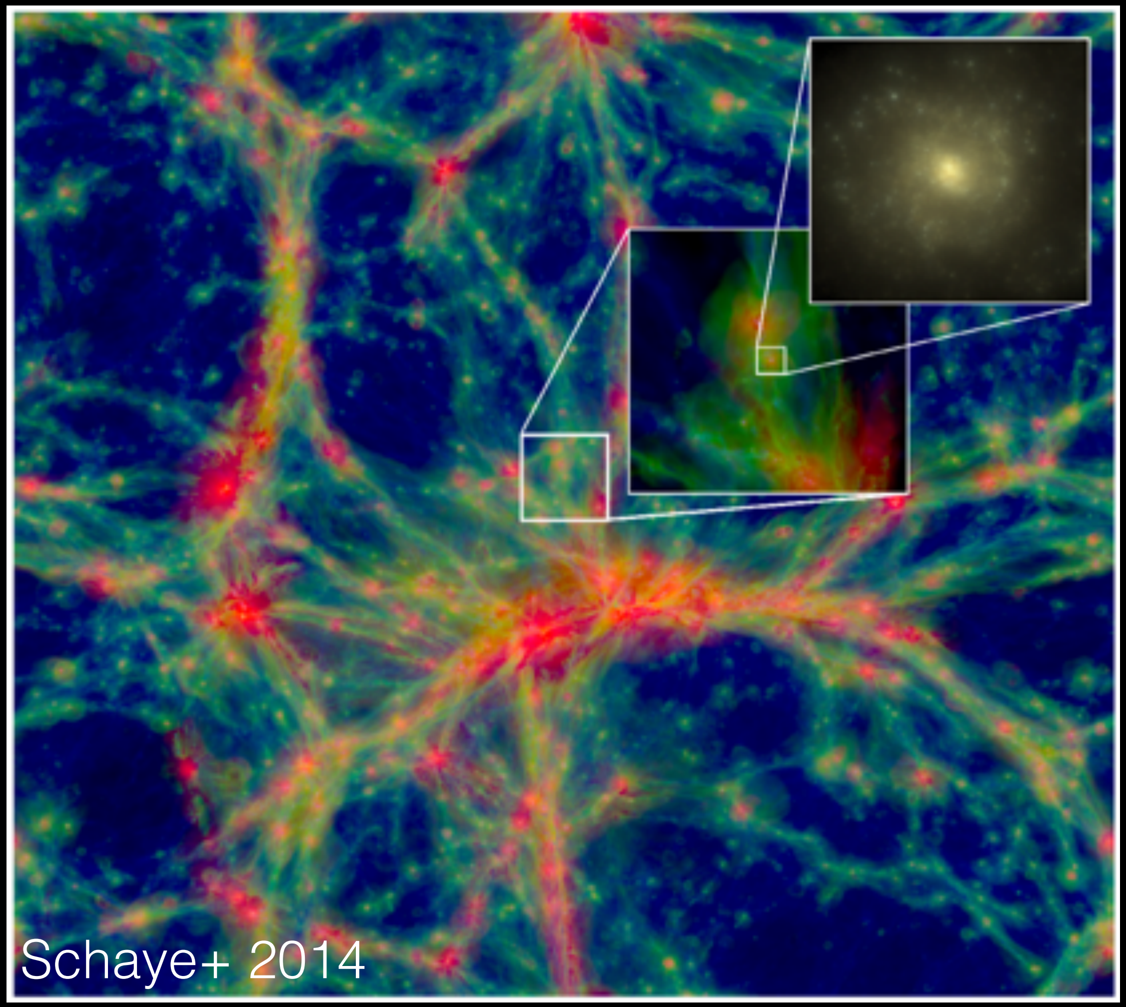

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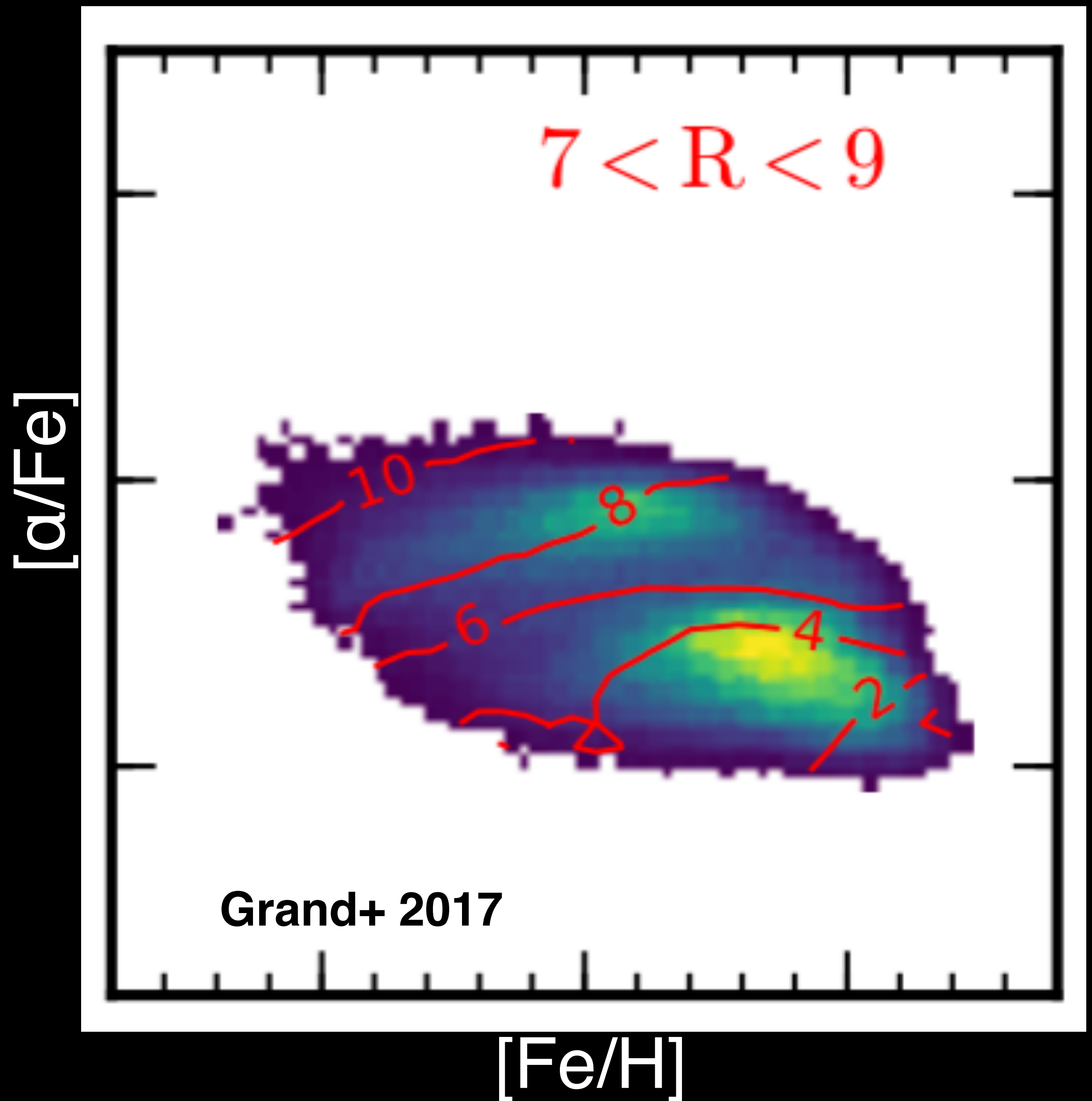


Milky Way case?

No significant classical bulge

No significant merger after thick disk formation

e.g. Shen+ 2010; Kunder+ 2012; Di Matteo+ 2014

All (6) simulations develop a clear bimodality

Merger plays an important role

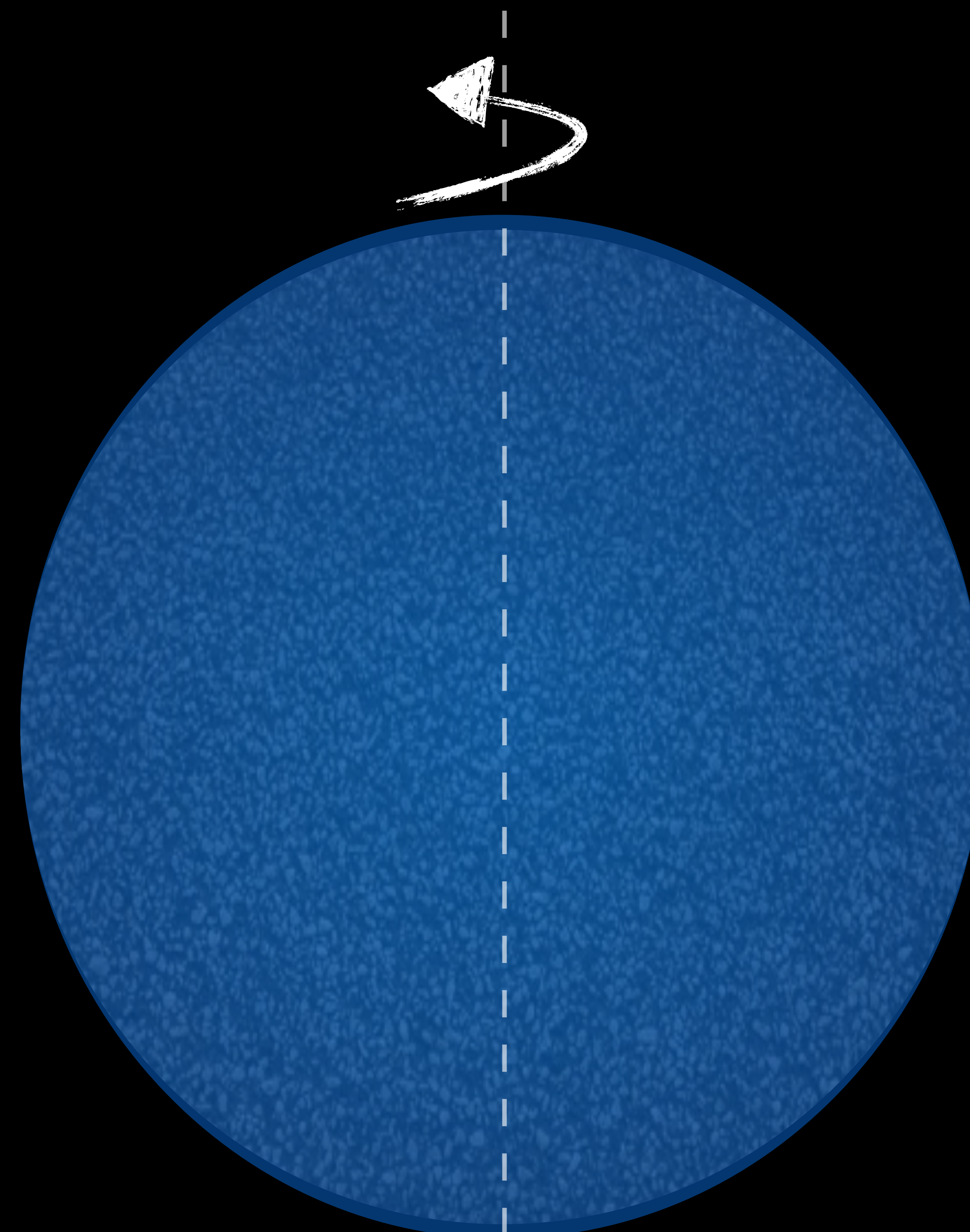
Outline

Isolated galaxy formation model
Starting from turbulent gas rich disk…

- can we reproduce realistic thick / thin disks?
- what do we need to separate thin and thick disks formation phases?
- chemical evolution?

live DM halo

live DM halo
rotating gaseous halo
$T_{ini} \sim 10^5 - 10^6$ K



similar to Cole+2013,
Aumer & White 2013, Marasco+ 2015

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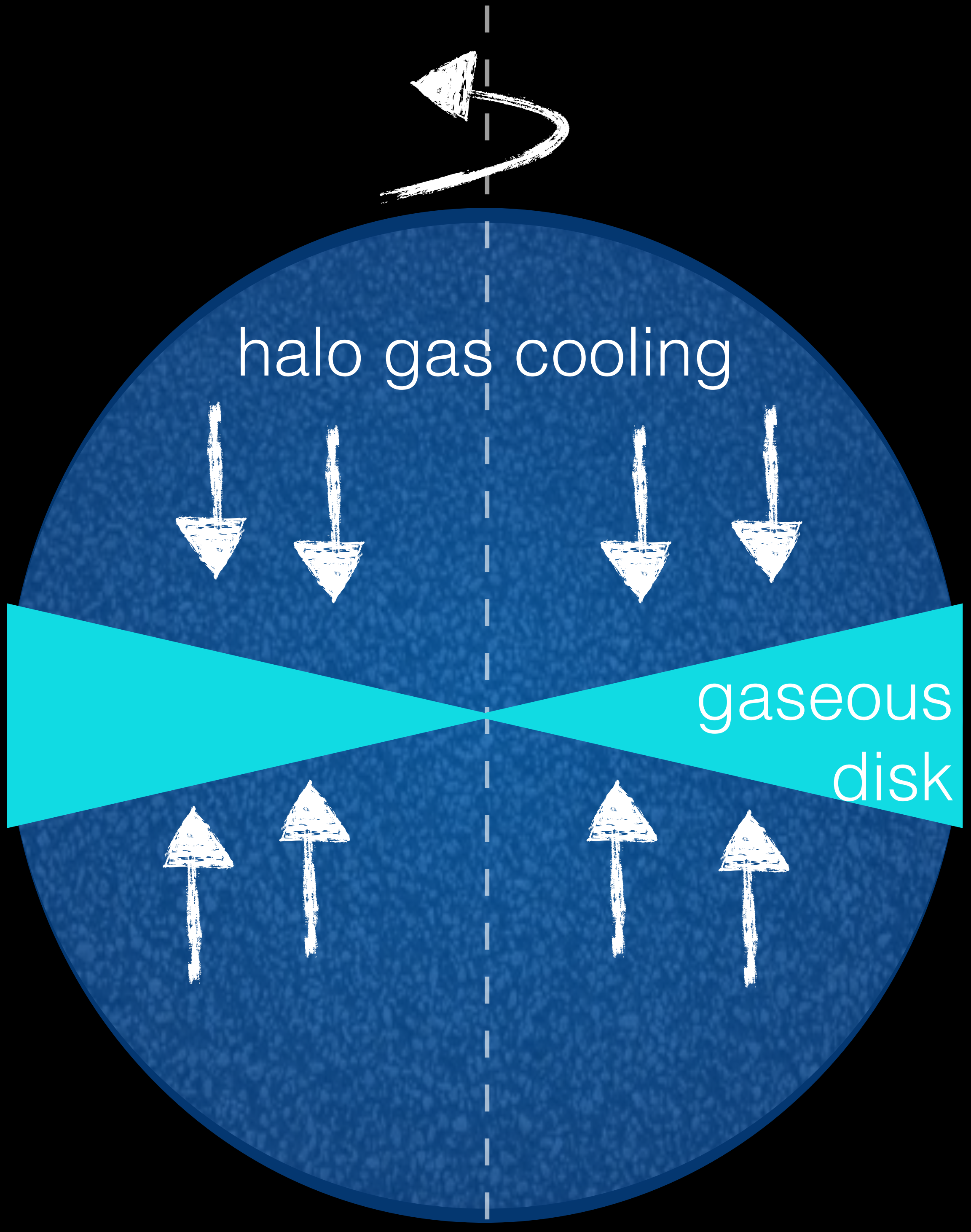

similar to Cole+2013,
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- Gasdynamics (grid based)
  - static mesh refinement
  - TVD MUSCL, 2nd order in time, 3rd in space
  - Riemann solvers (HLLC)
  - passive scalars advection
    - (H, He, Si, Fe, Mg, O… 8 species in total)
  - radiative cooling/heating (metallicity dependent)
  - stellar feedback (only thermal:
    - SNI, SNII, AGB stars, metallicity dependent)
  - star formation ($T<100$ K, $M^*_{ini}>10^3\ M_o$, div $V<0$)

- Stellar component (N-body)
  - stellar yields (Nomoto+ 2006)
  - mass loss
  - IMF (Kroupa 2001)

- Dark matter (N-body)

- Gravity: TreeCode
  ($\theta=0.5$, $\Delta t=10^4$ yr, AVX instructions)
  Khoperskov & Berczik in prep

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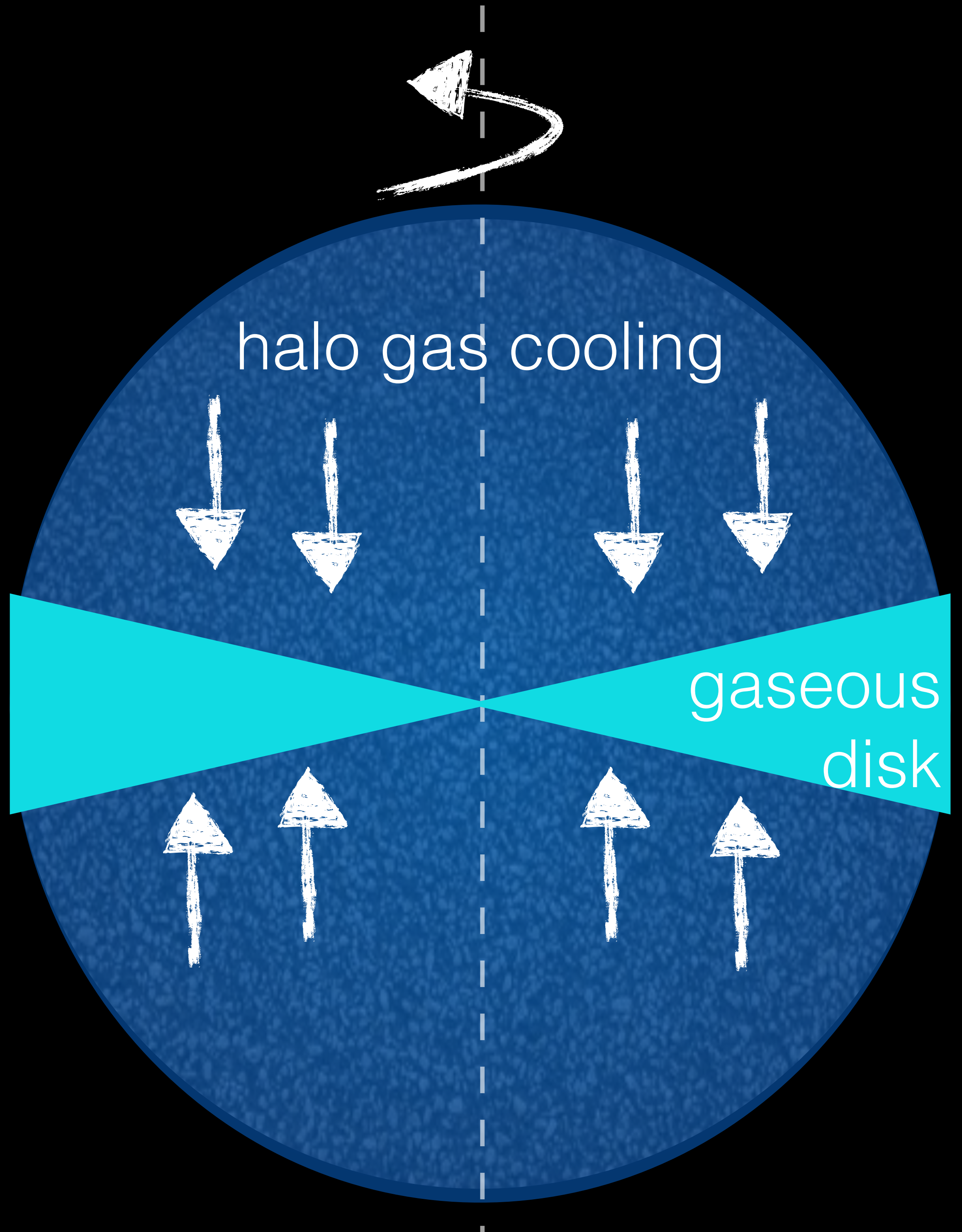

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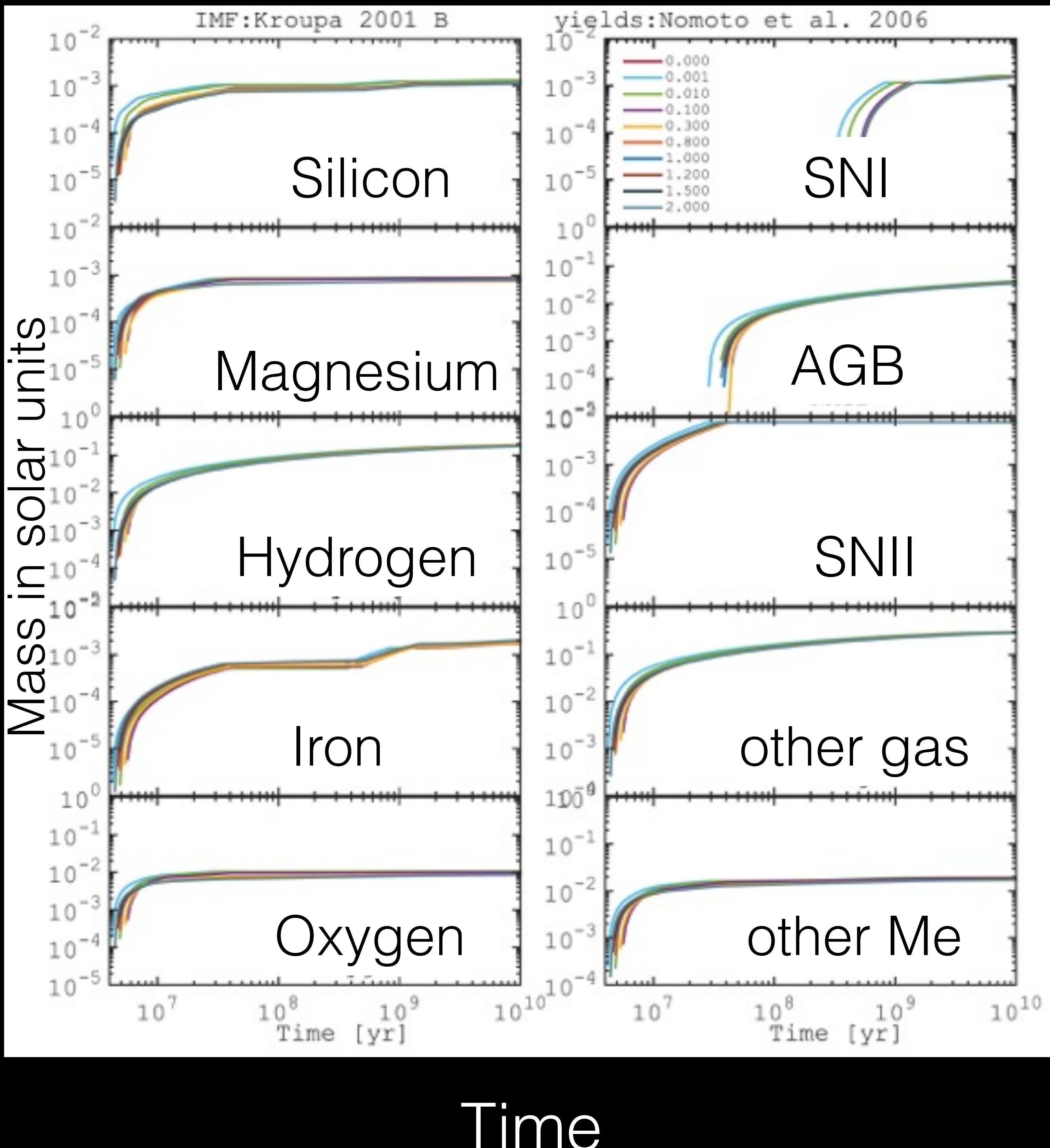
Chemical model



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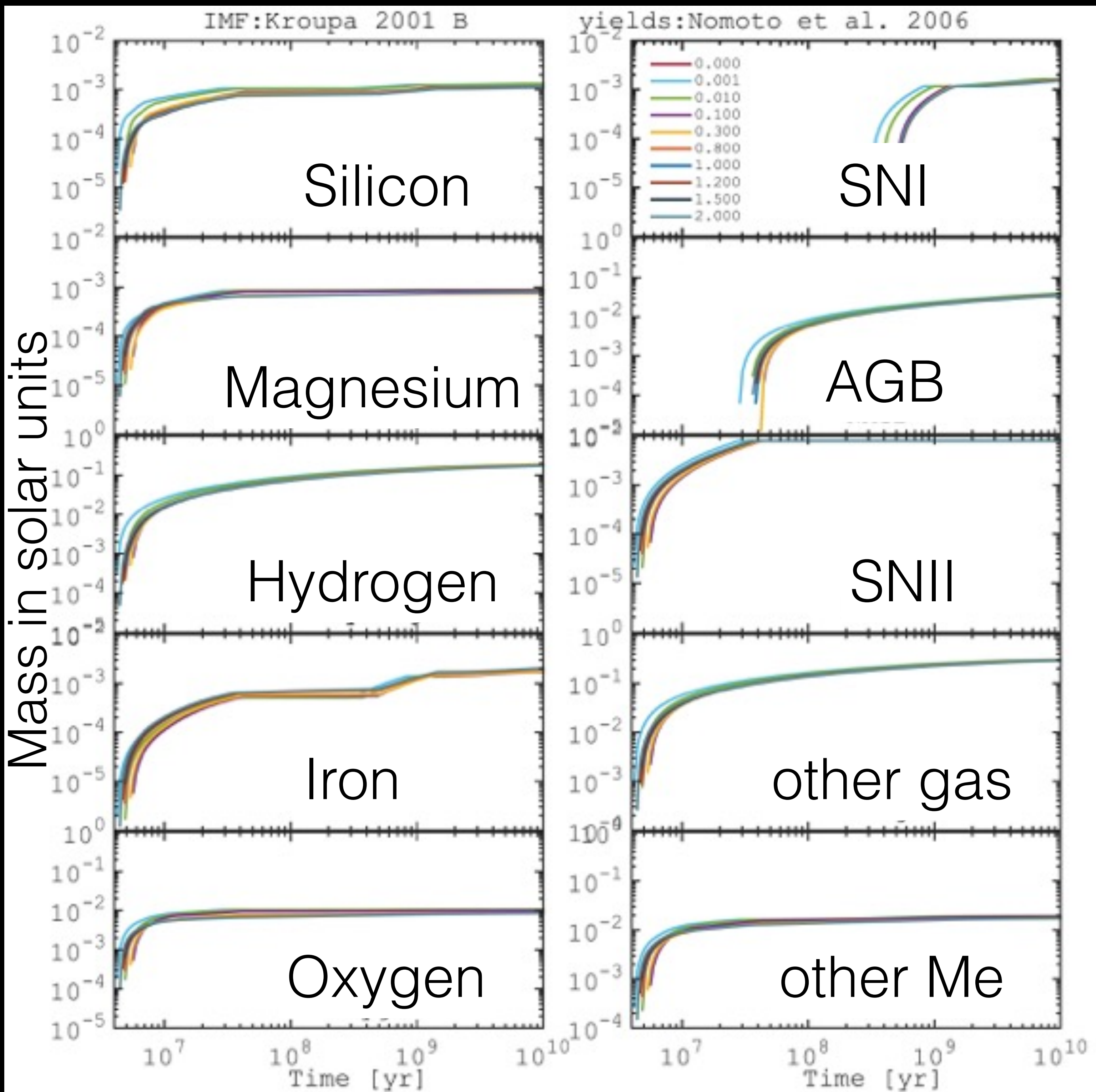
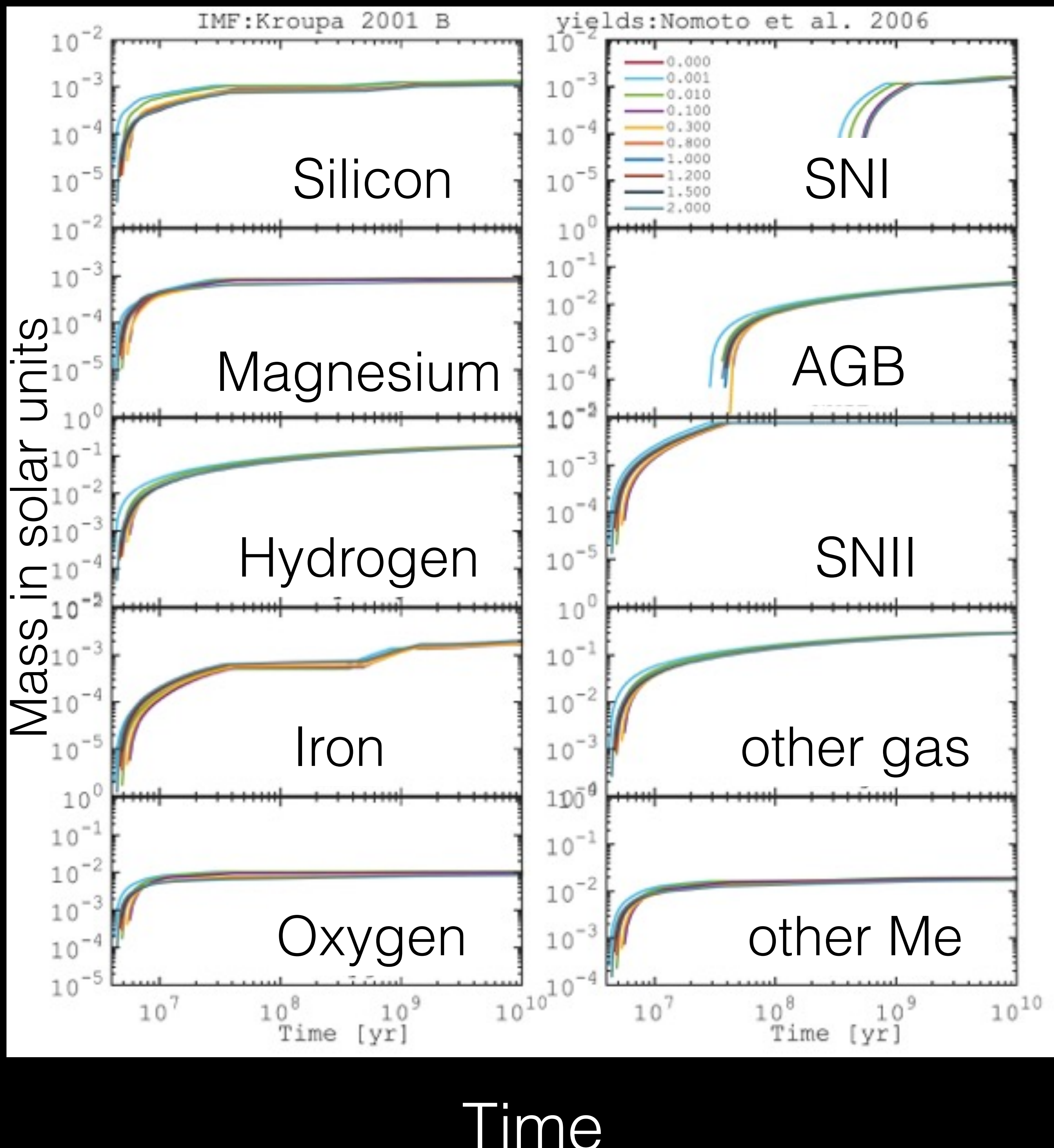


Mass in solar units

Time

Chemical model



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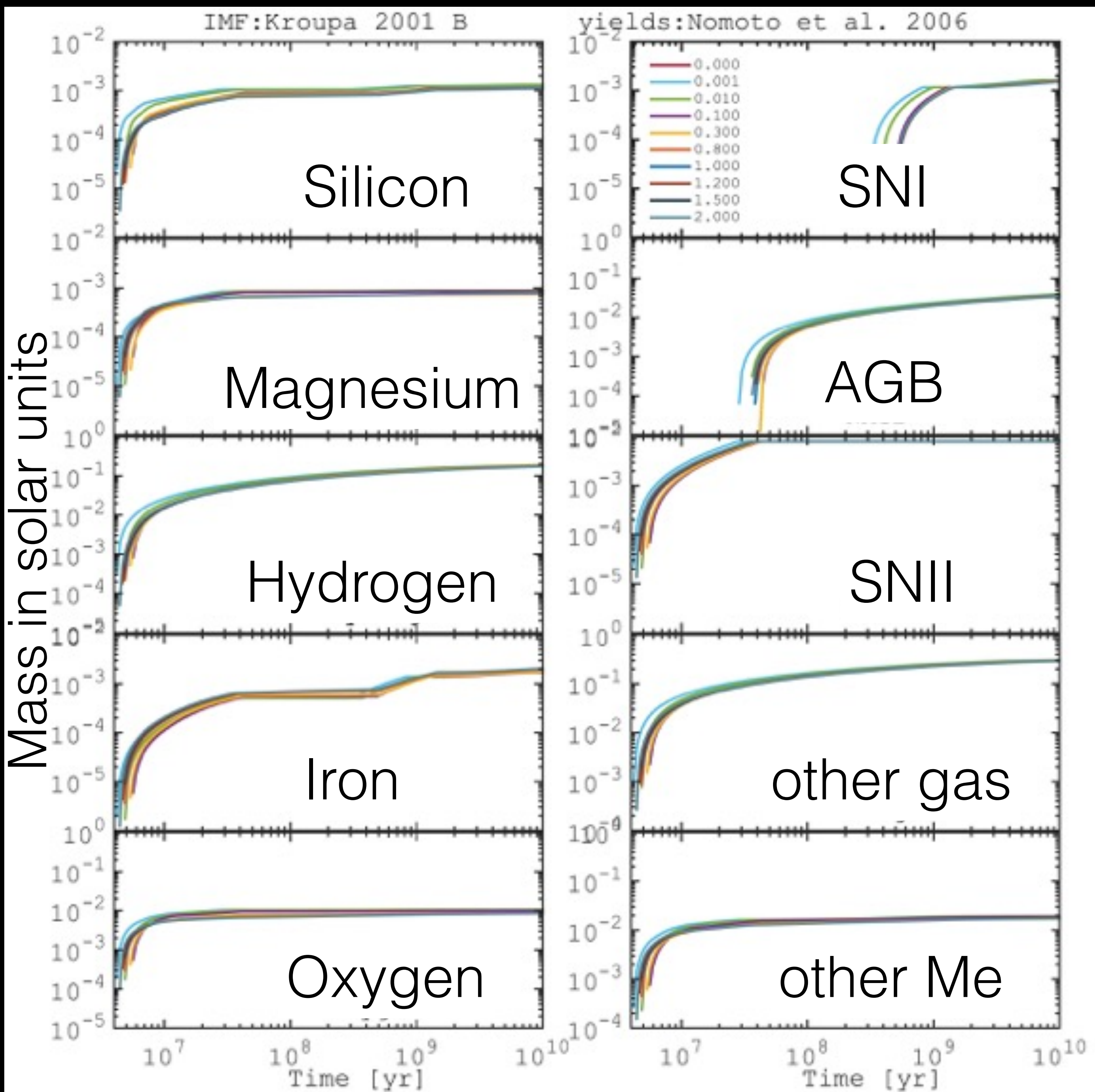
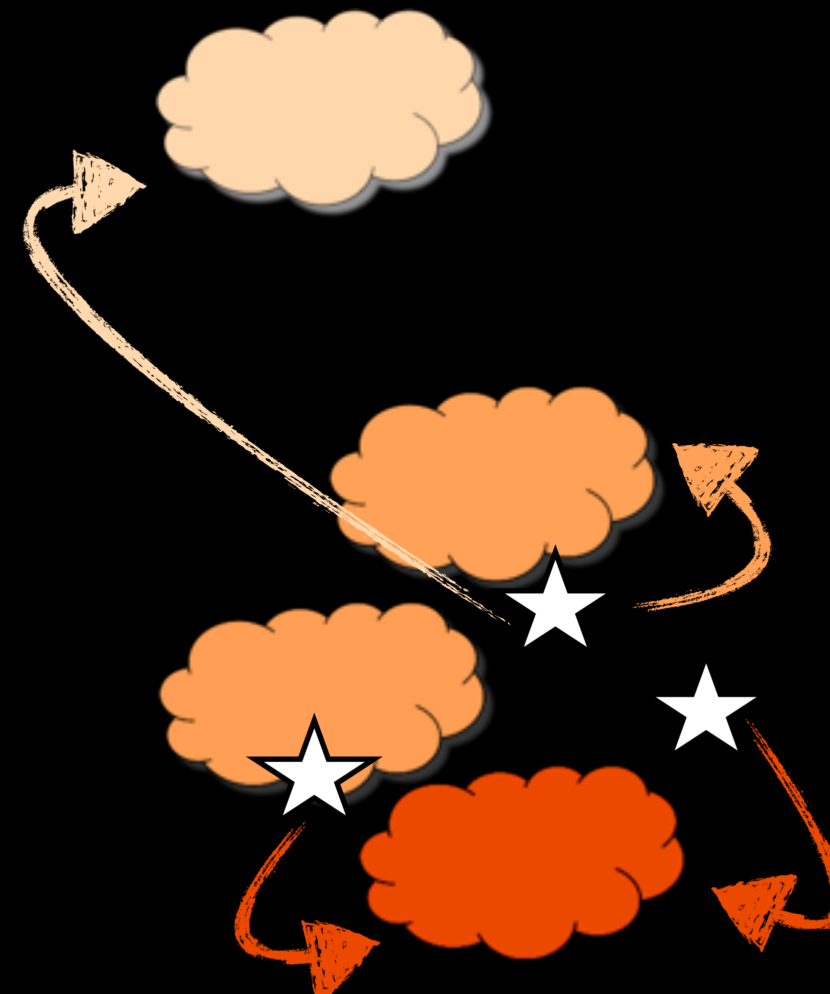
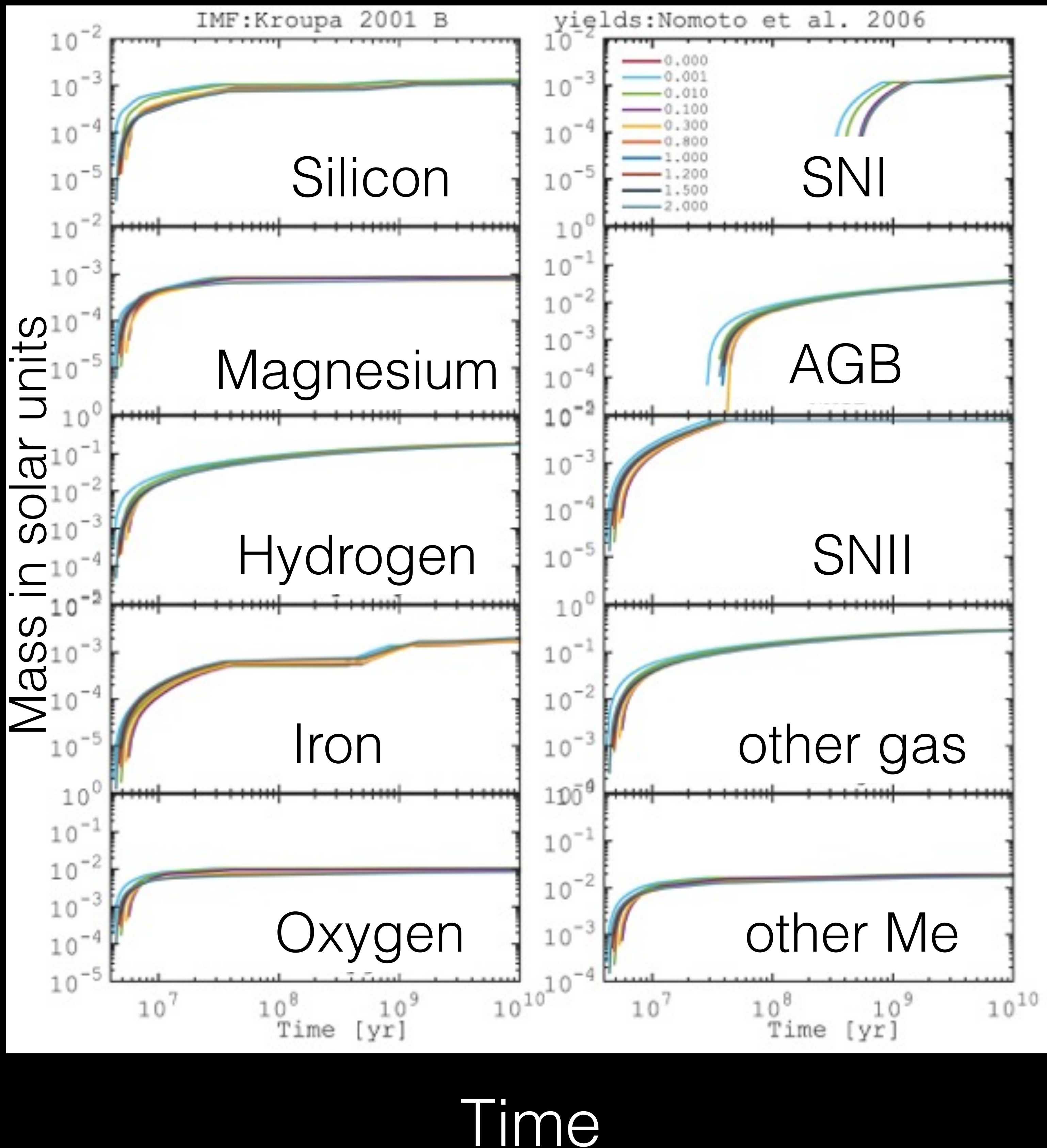




Time

Chemical model



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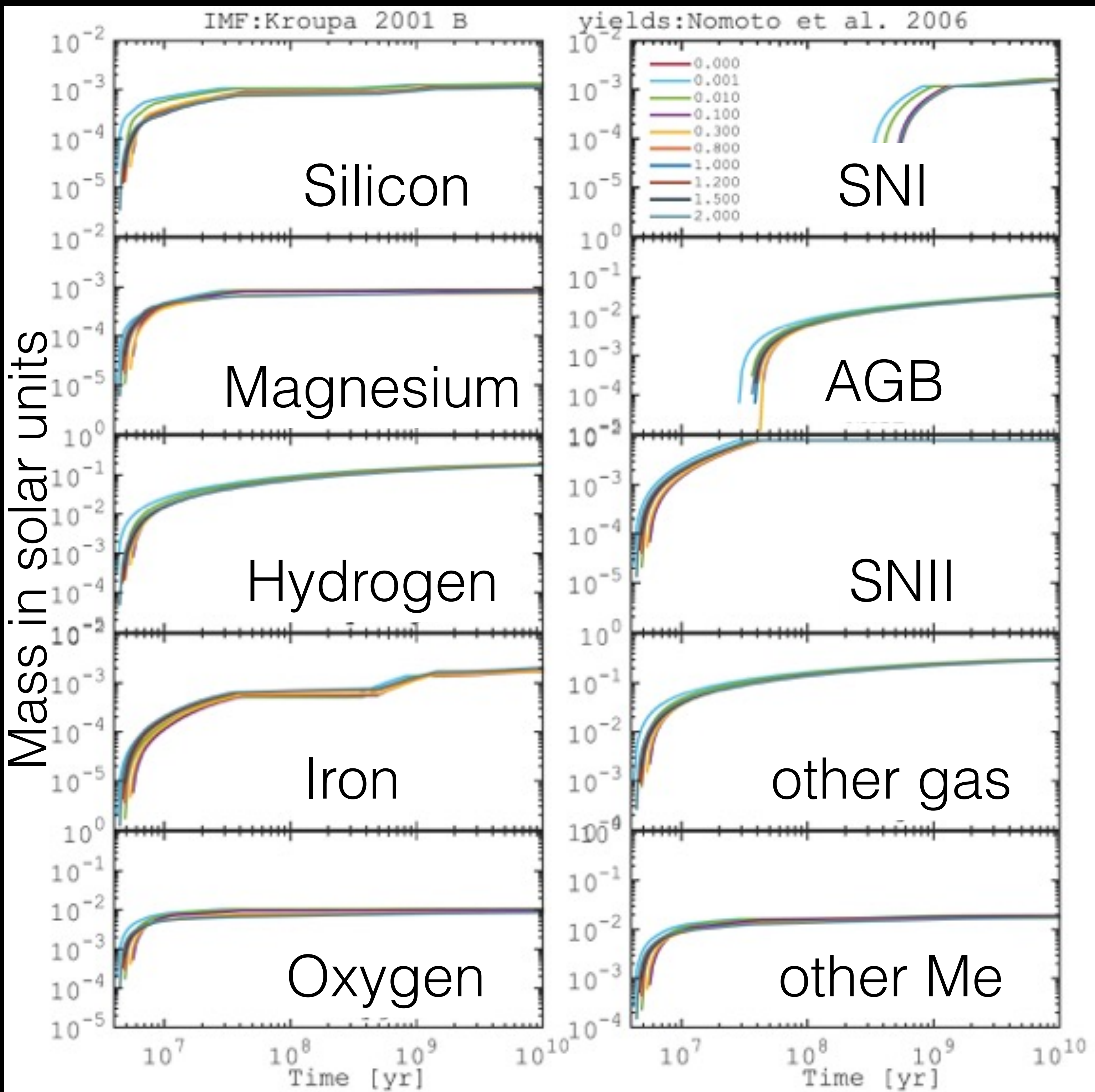

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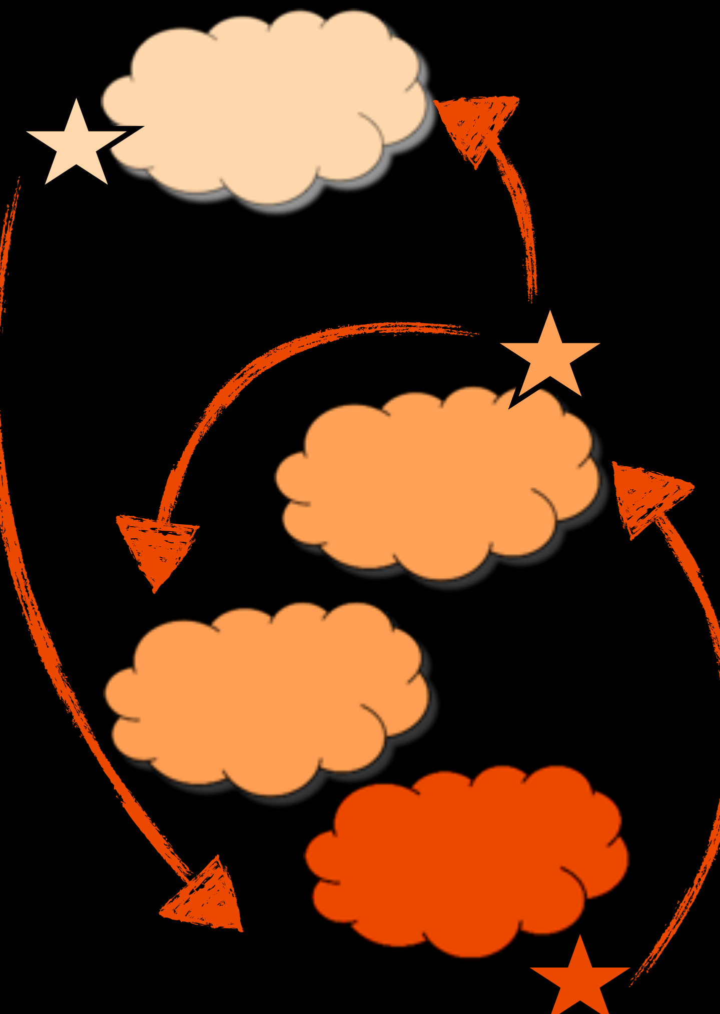

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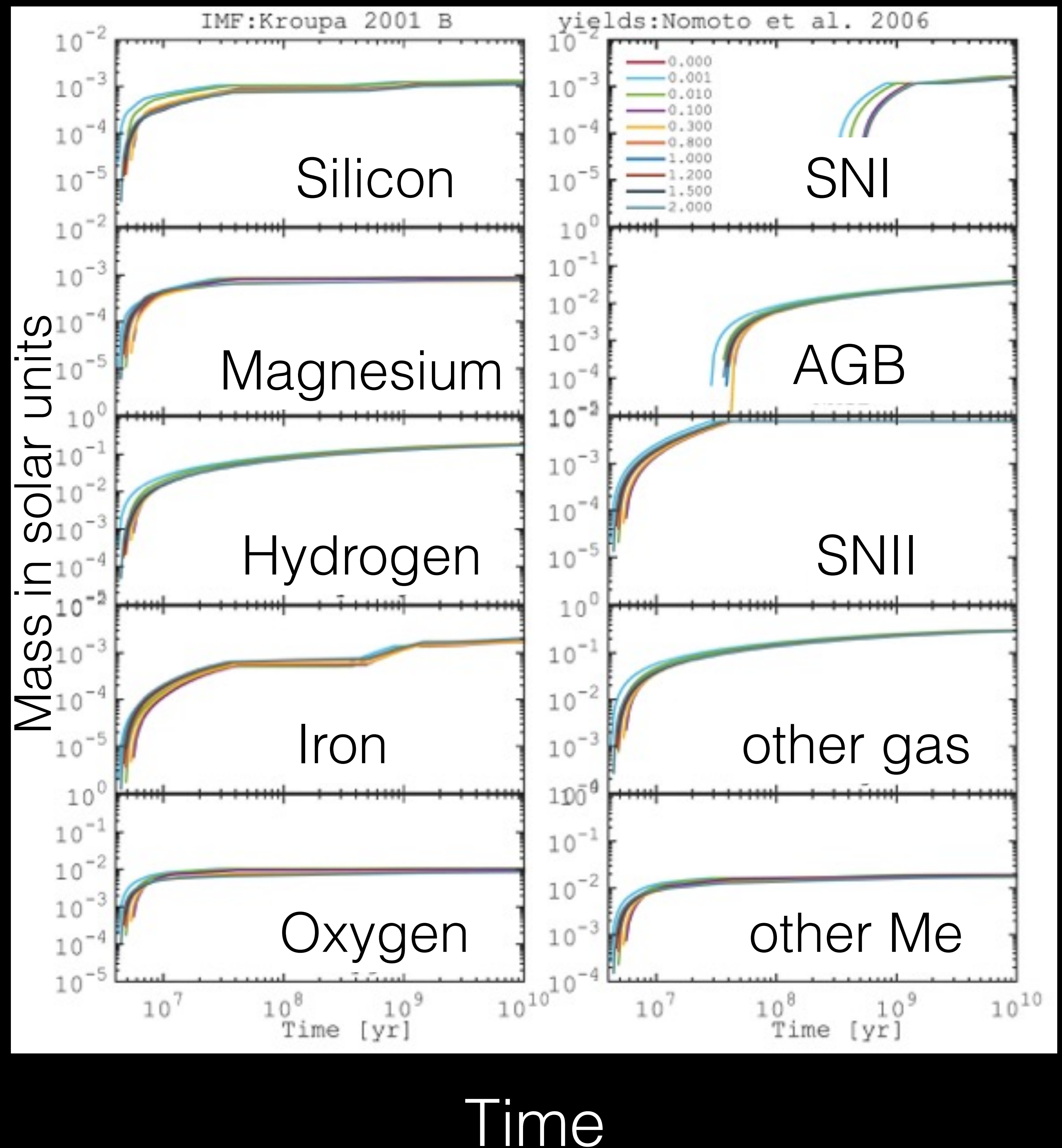
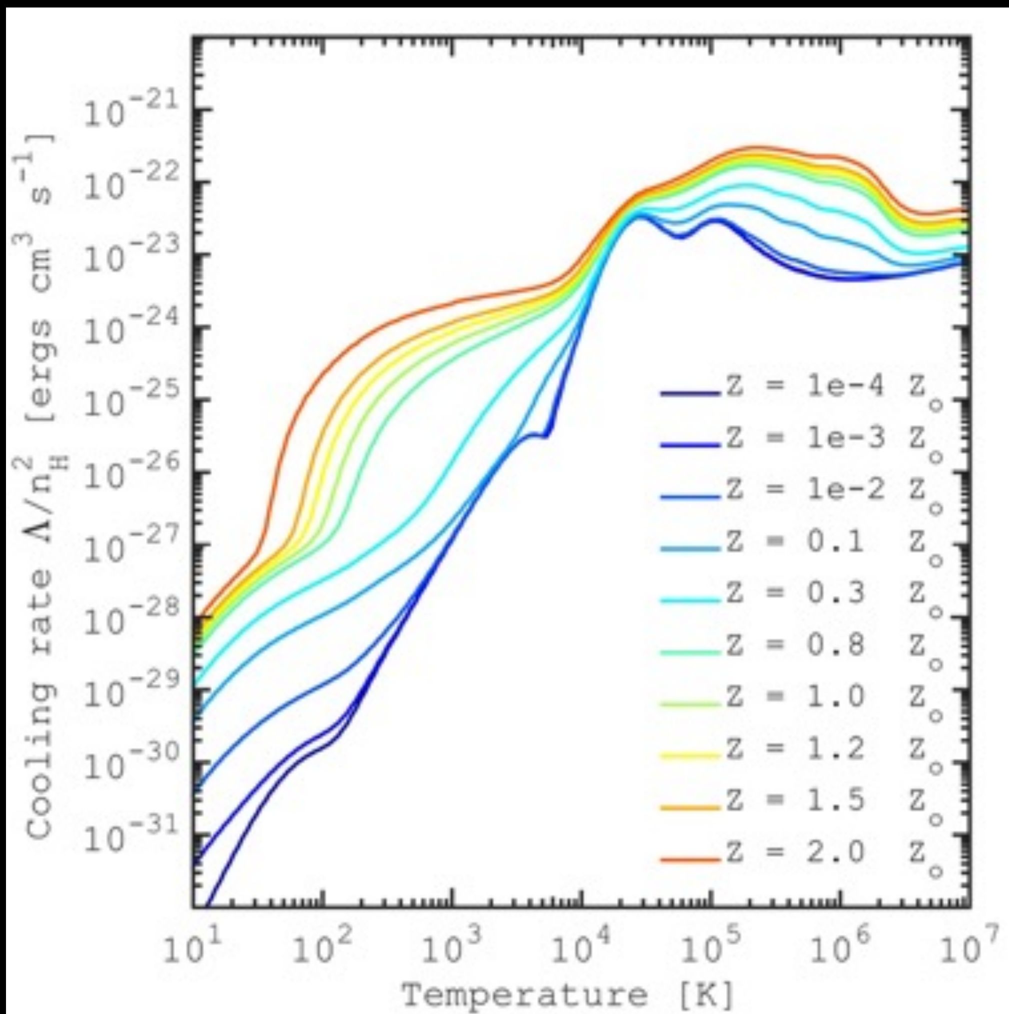
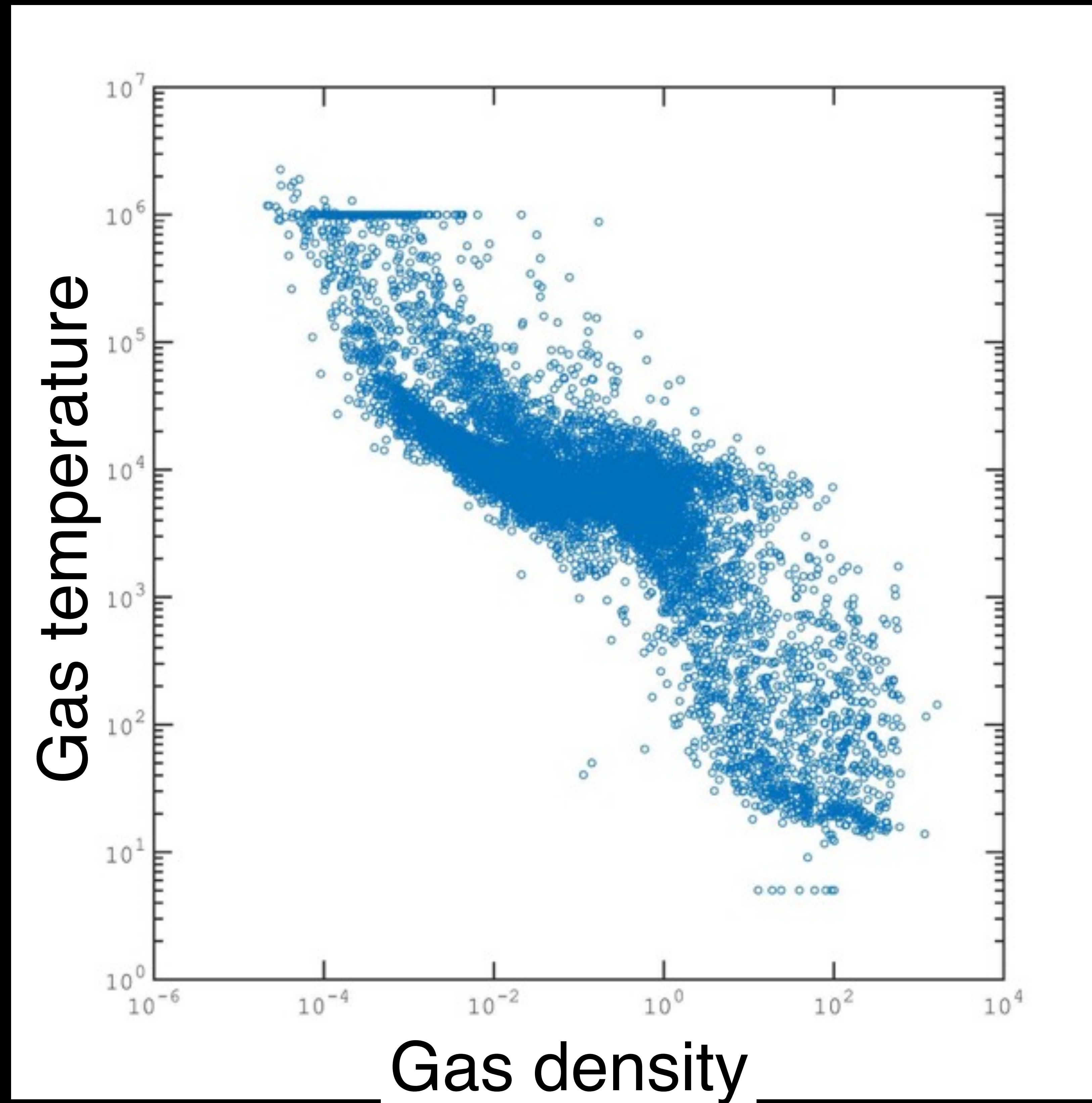


ISM and star formation

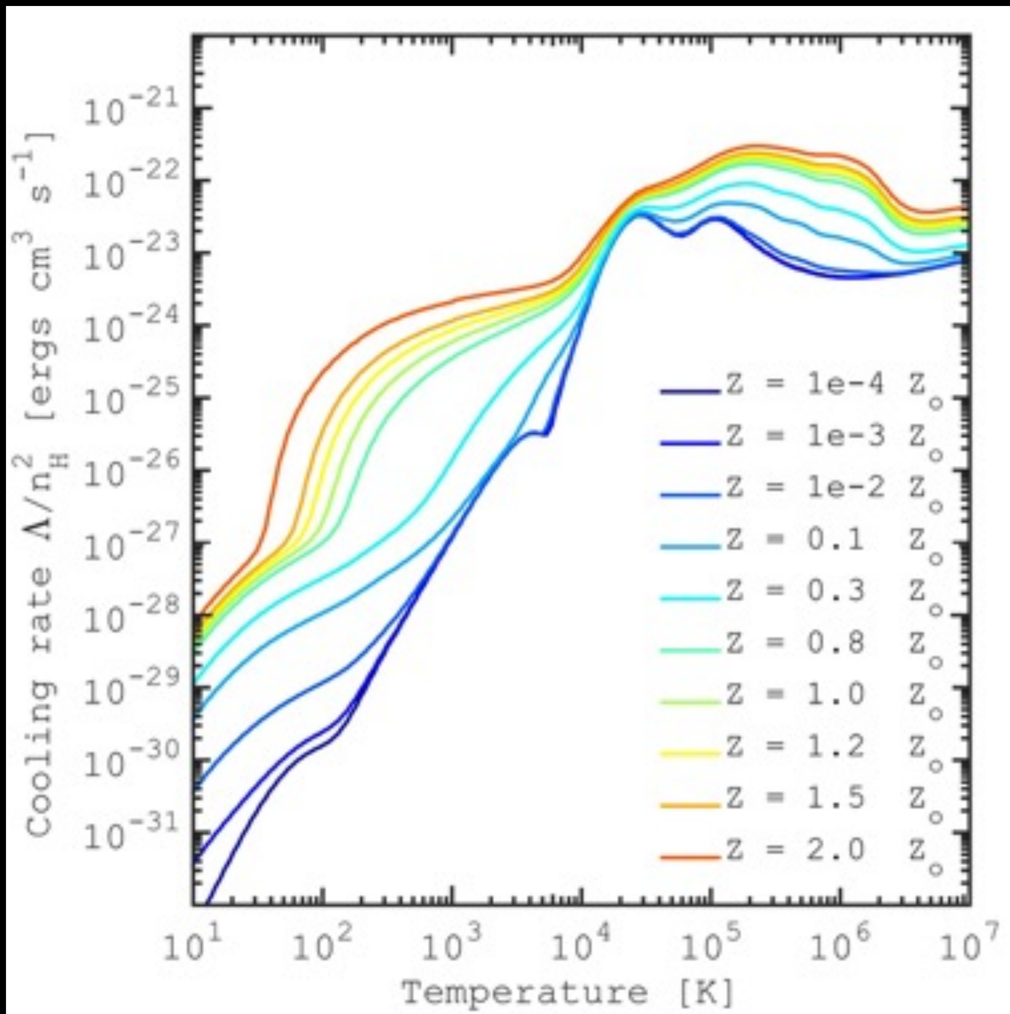


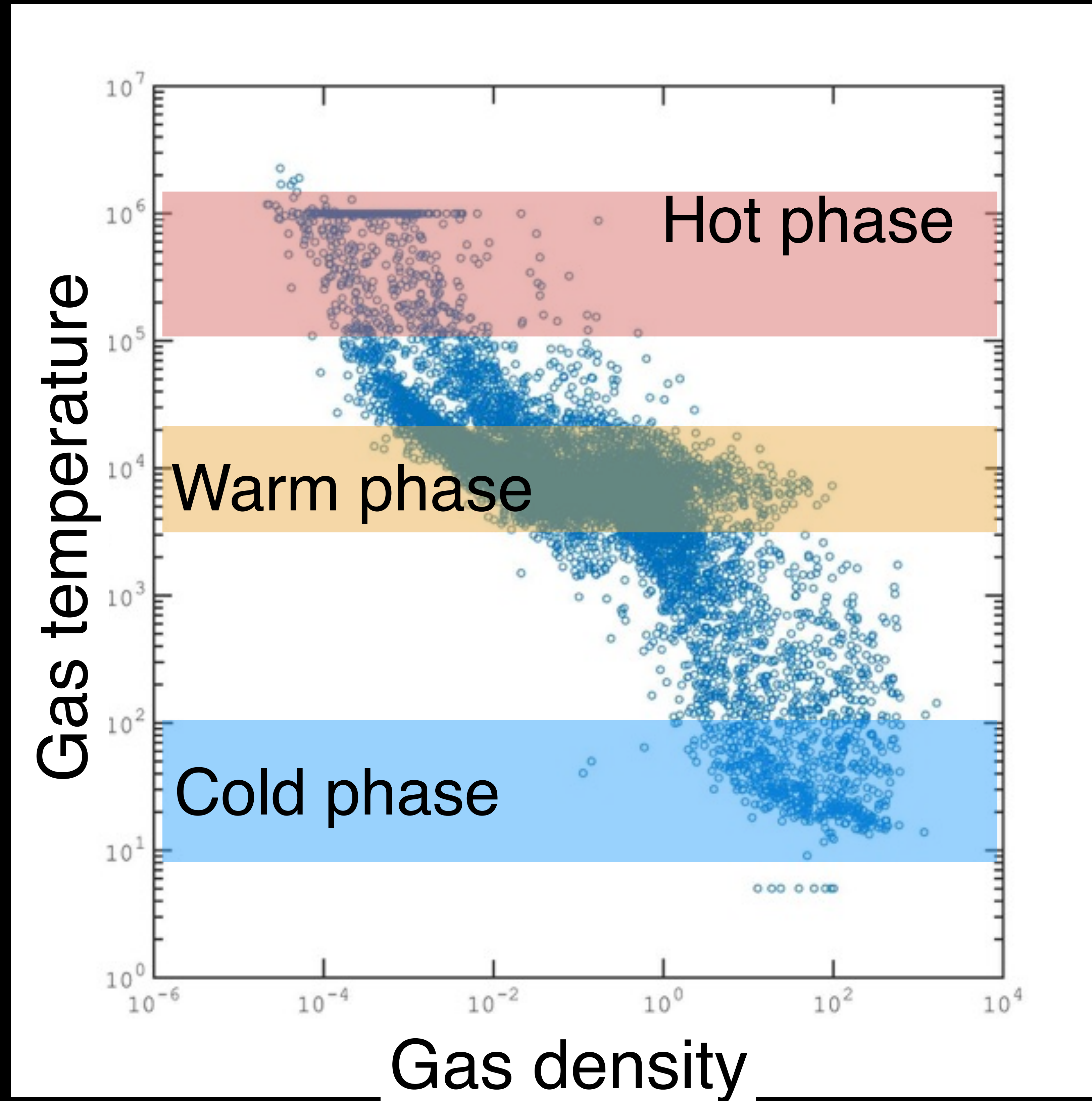


Long depletion time scale because gas spends most of the time in the non-star-forming state

see also: Semenov, Kravtsov, Gnedin 2017

ISM and star formation





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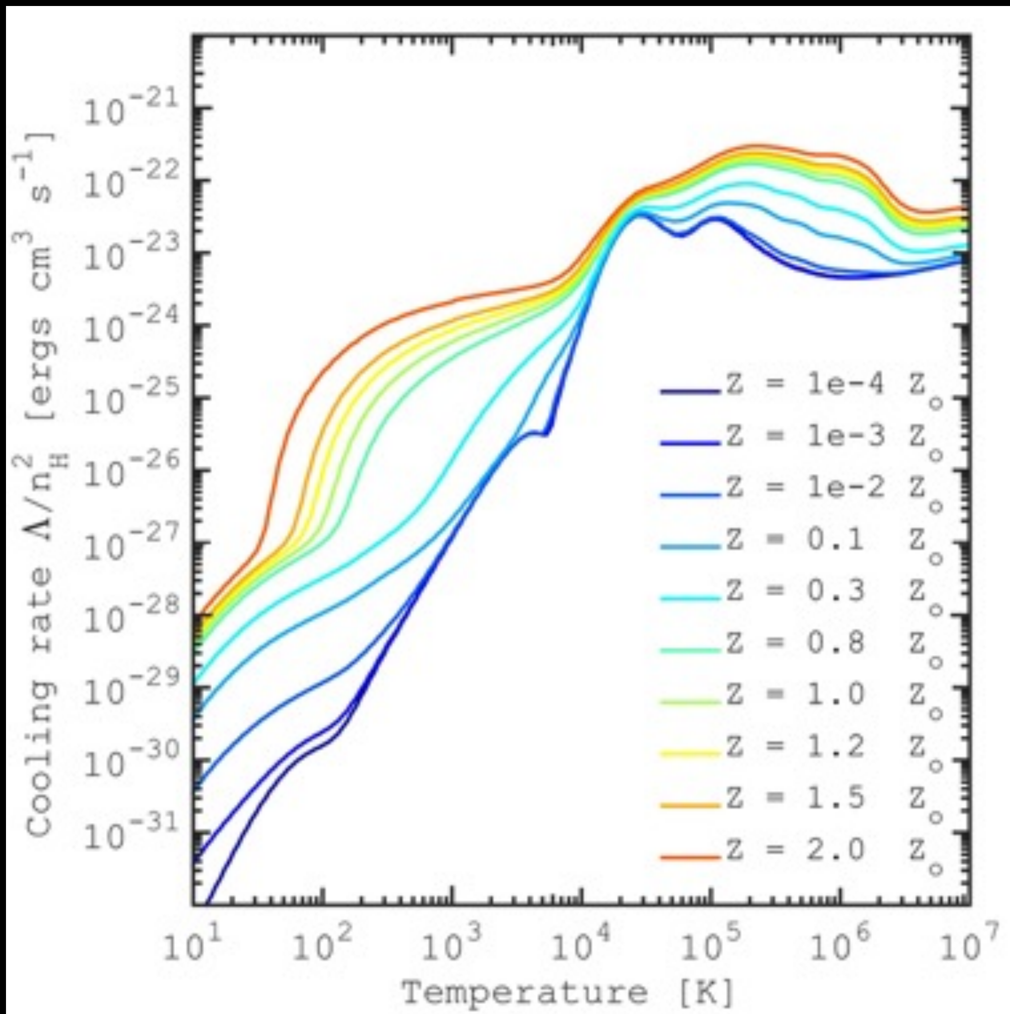

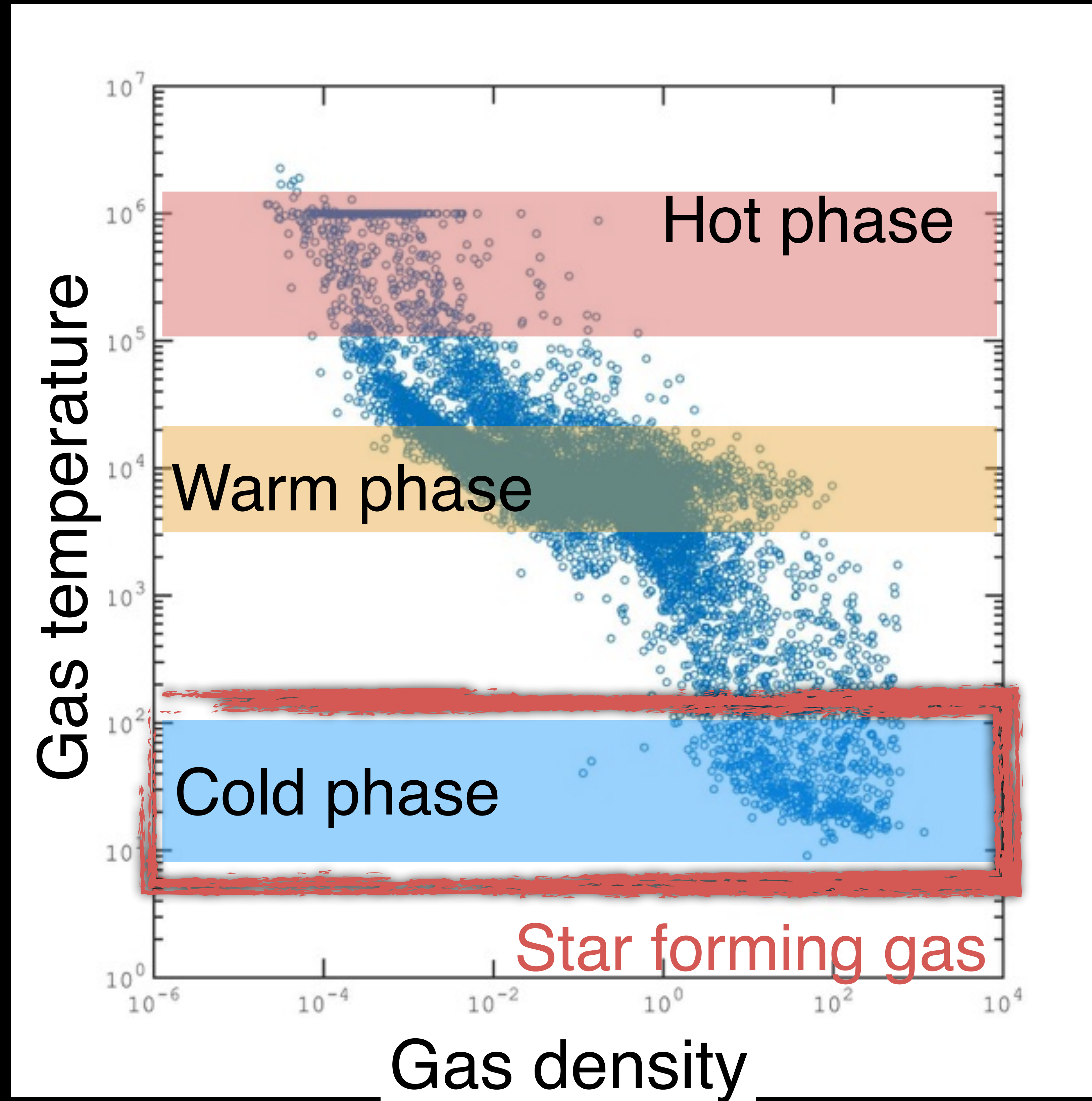

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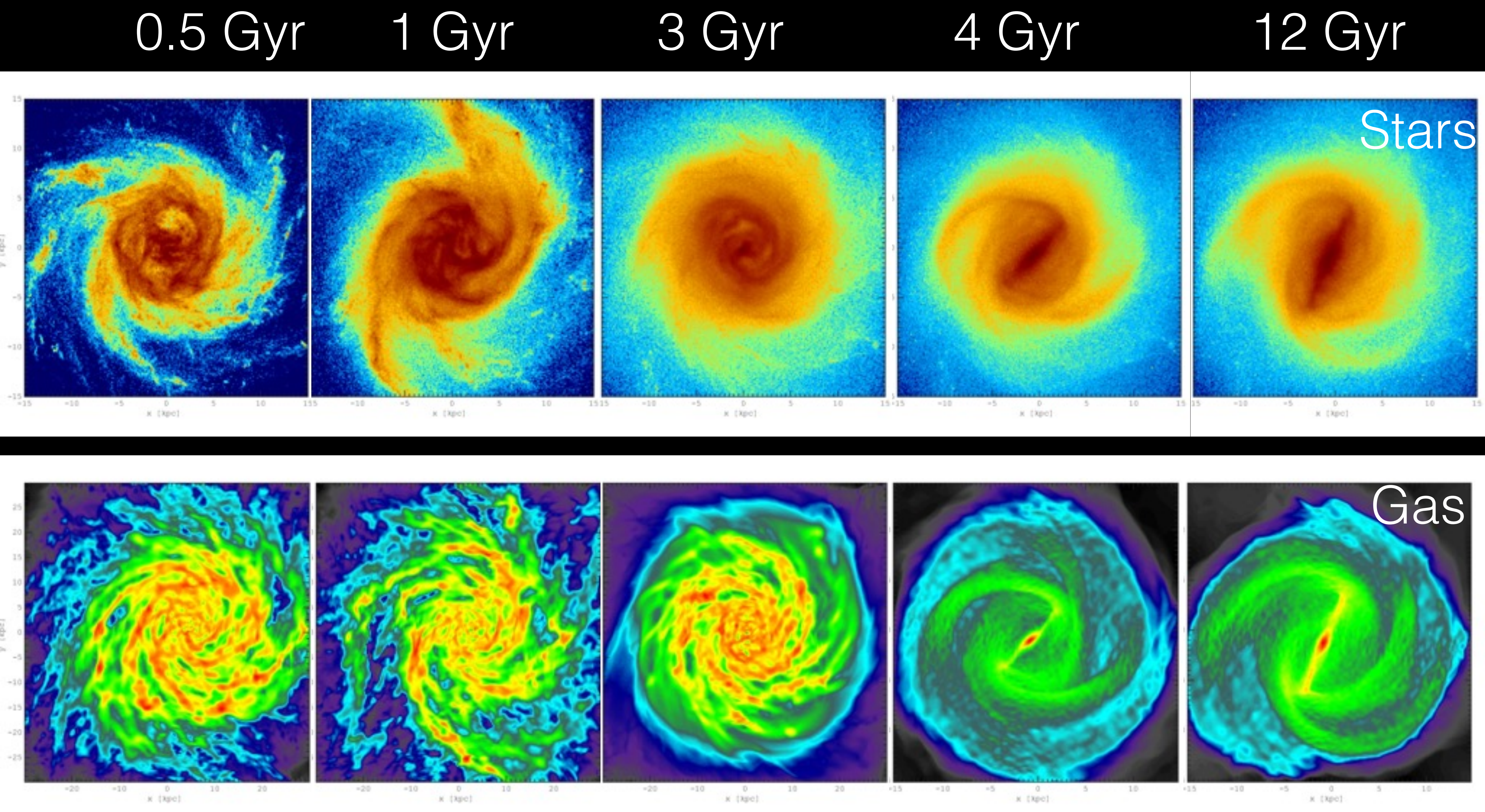
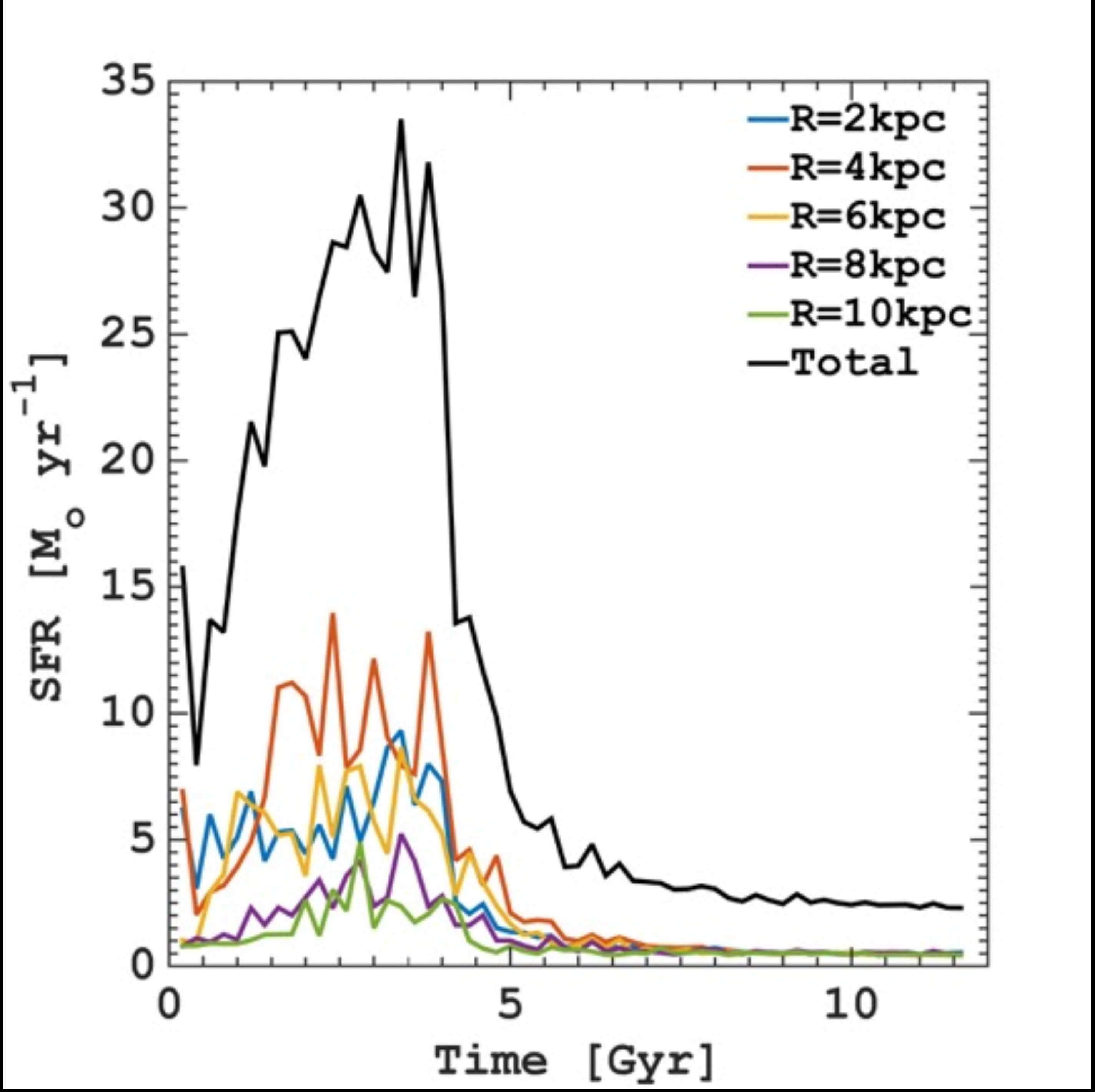
Self-consistent model: disk(s) formation



Self-consistent model: SFH



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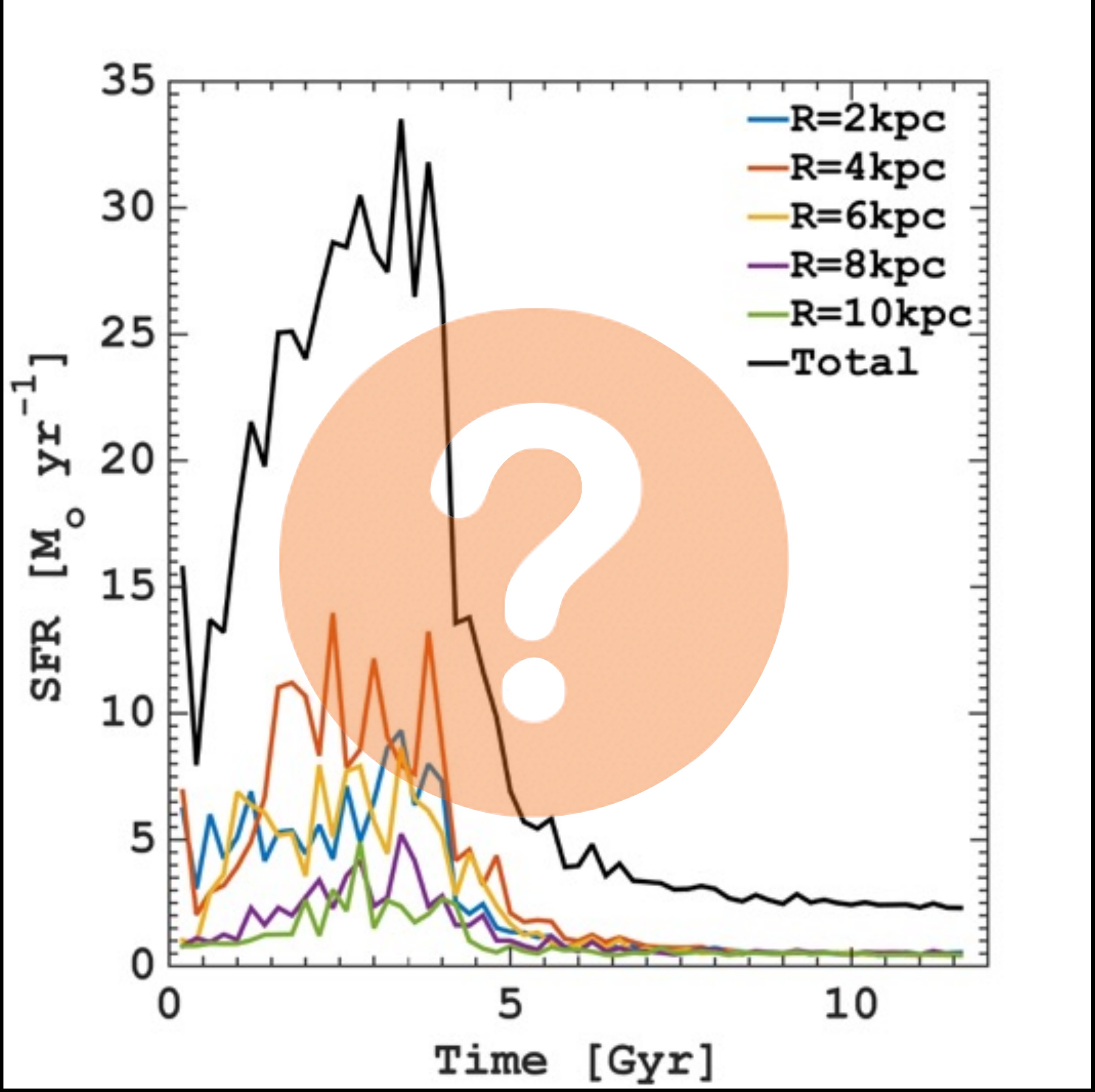
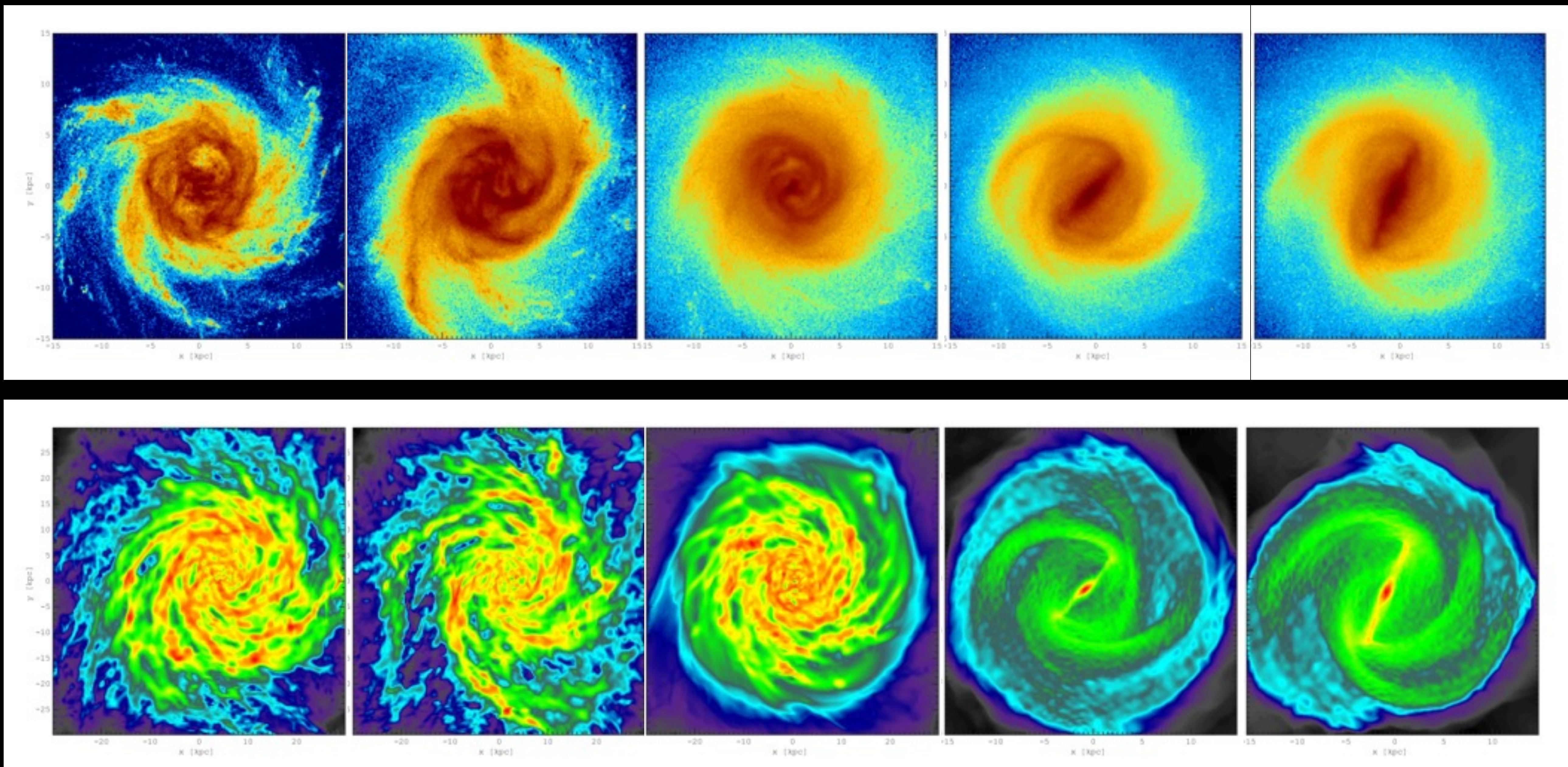


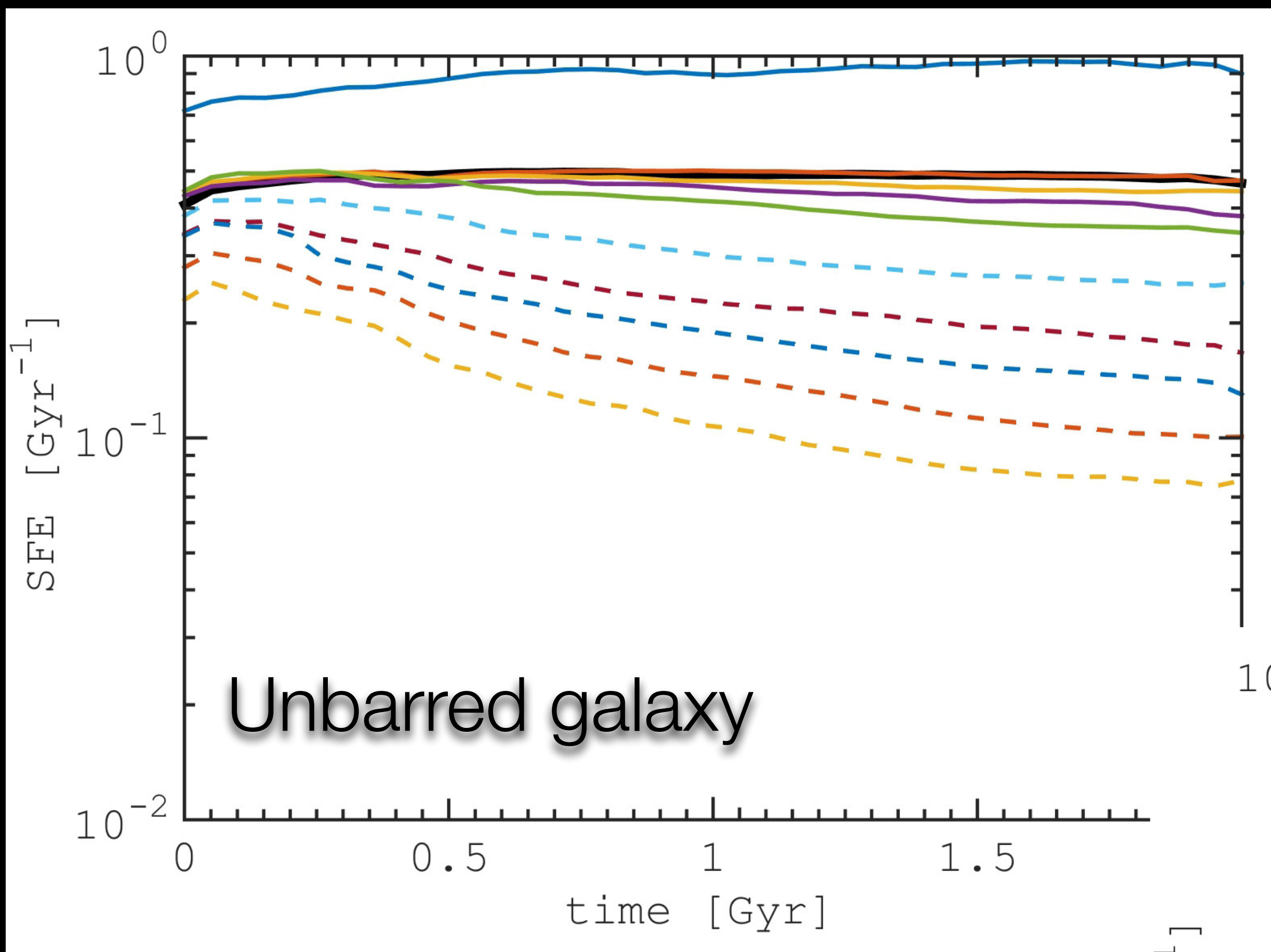
Rapid decrease of the star formation rate

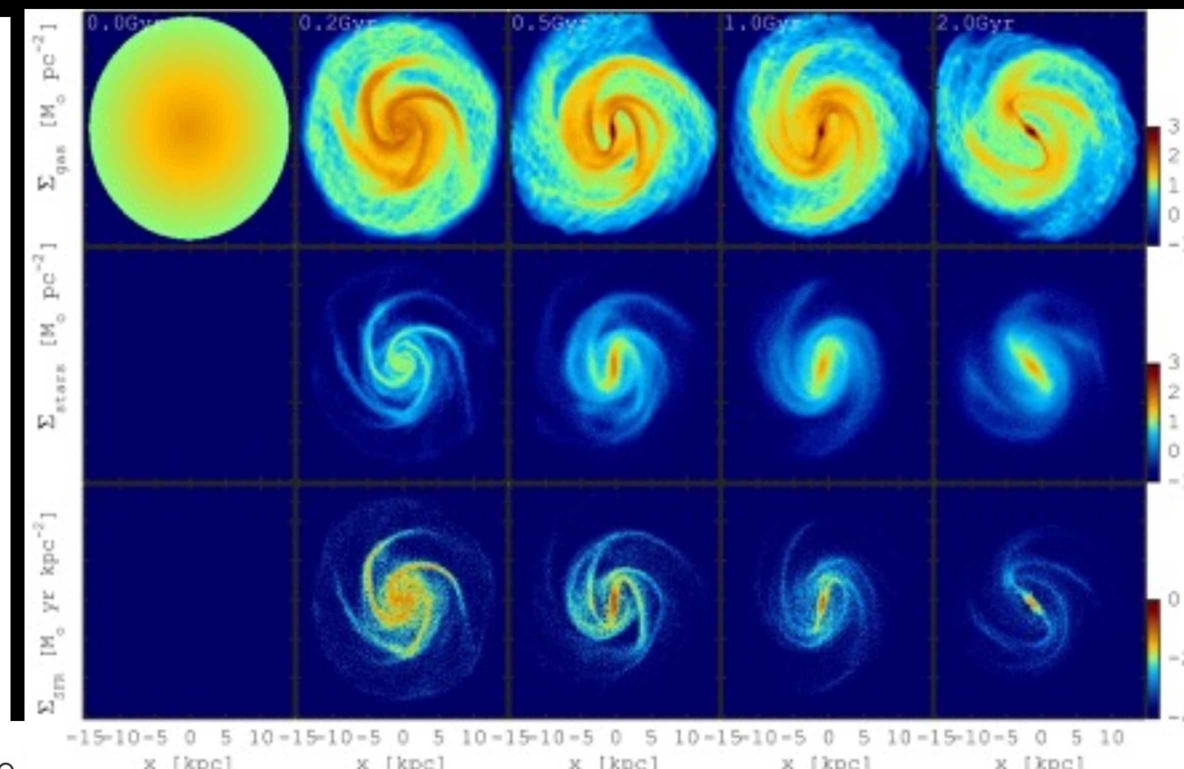
Stellar disk formation

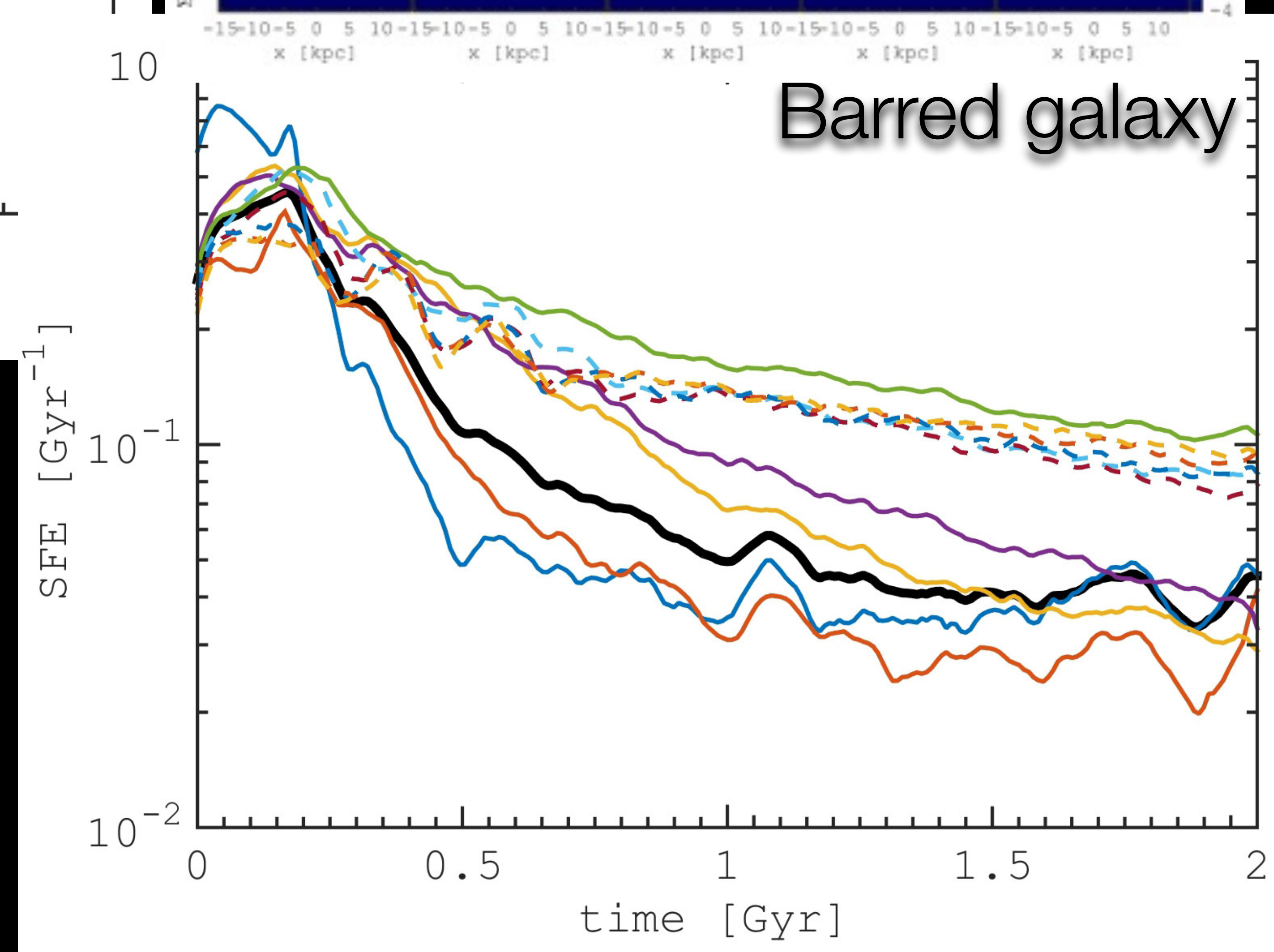
0.5 Gyr 1 Gyr 3 Gyr 4 Gyr 10 Gyr



Star formation efficiency. Toy models



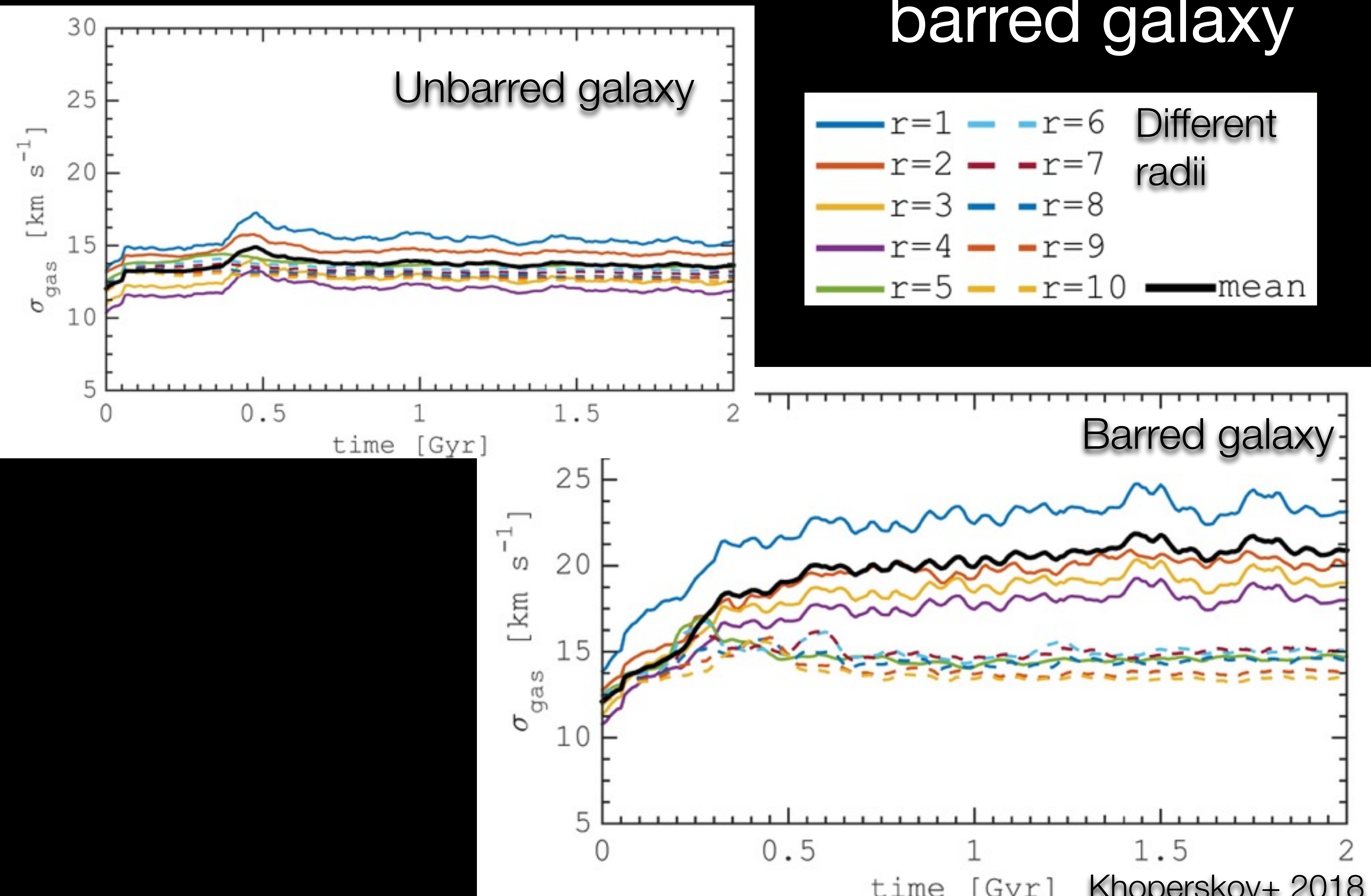




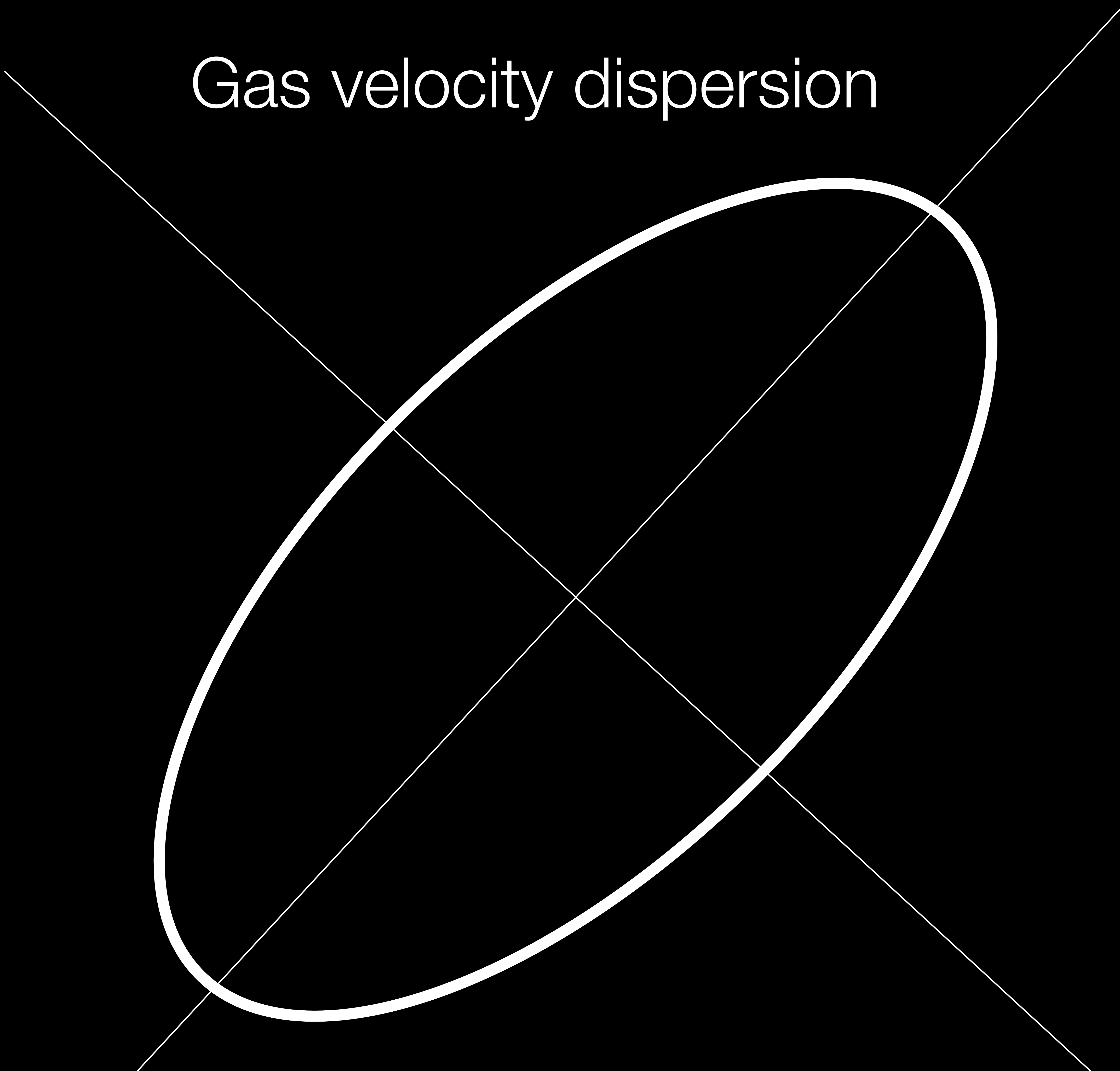
Star formation in gas-rich galaxies with rigid bar potential

Khoperskov+ 2018

Gas velocity dispersion in a gas-rich barred galaxy



Gas velocity dispersion



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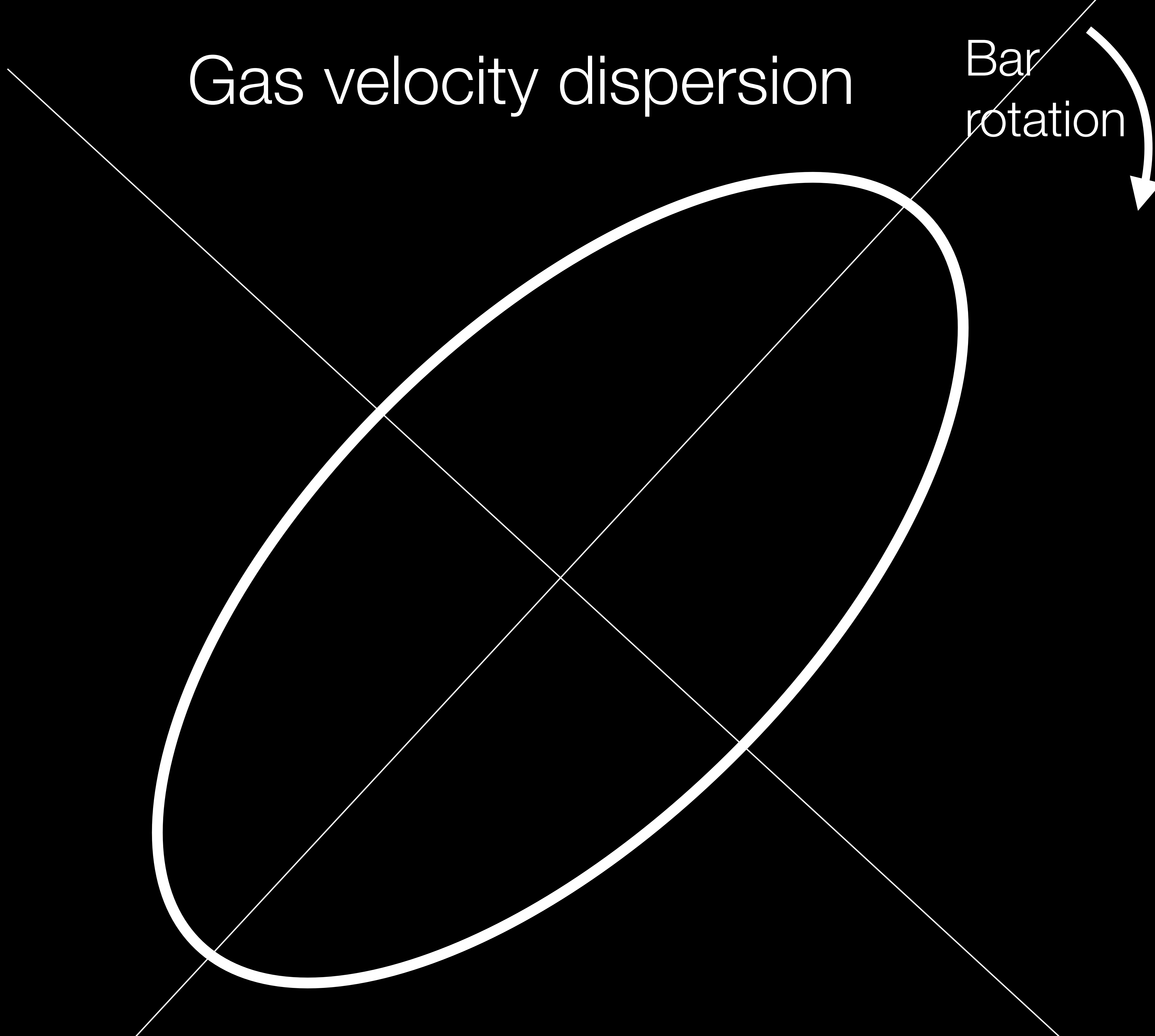

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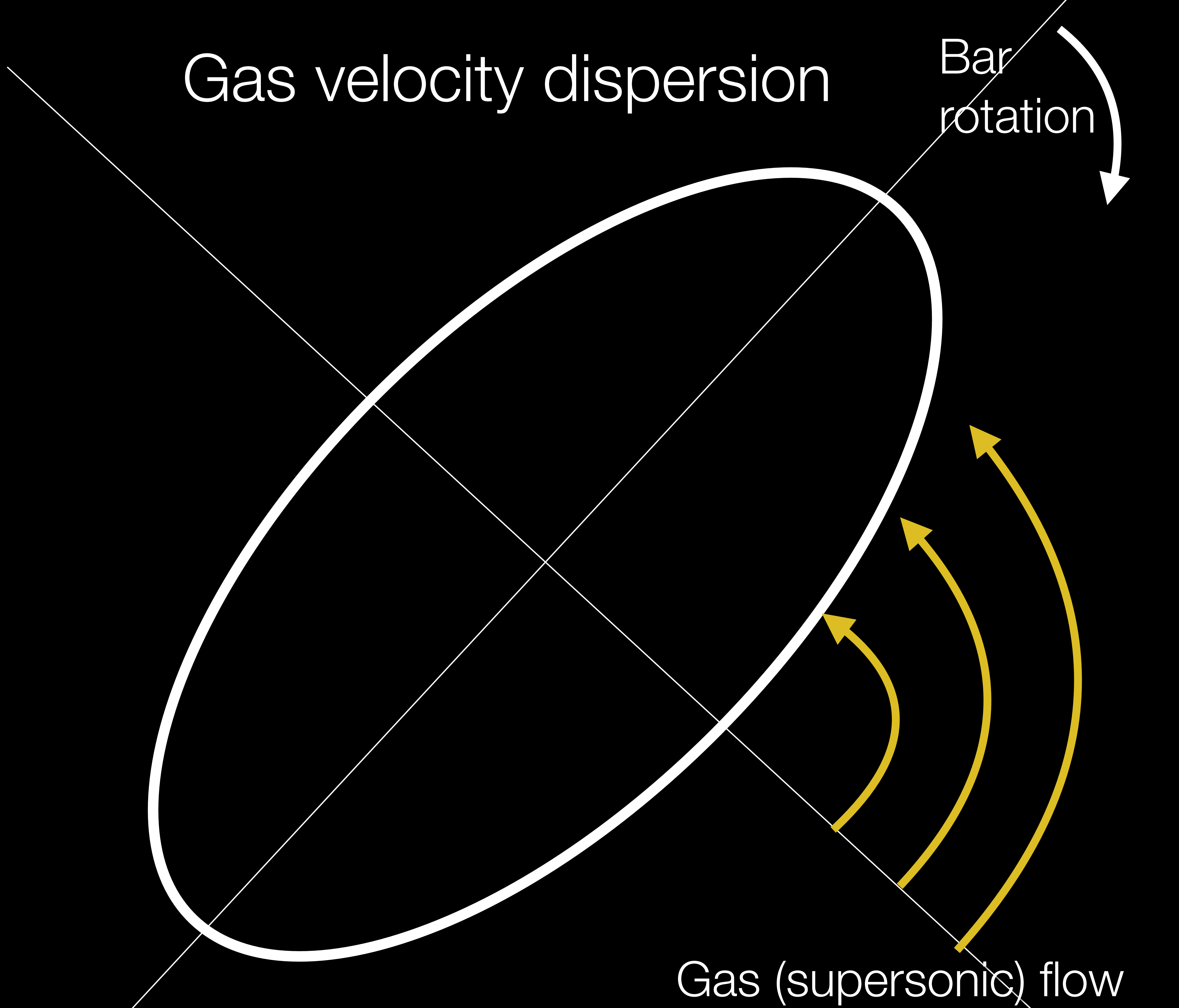
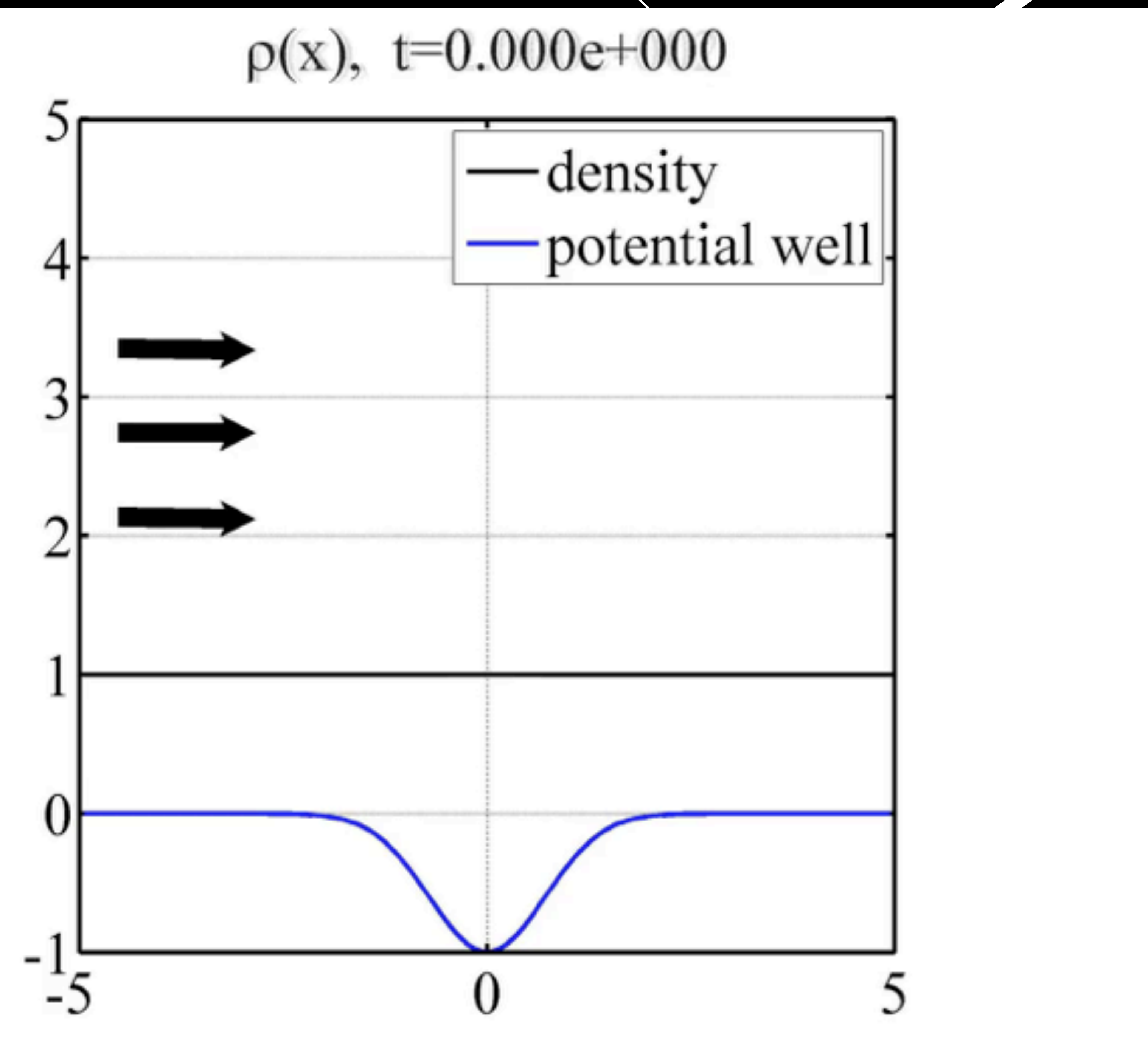
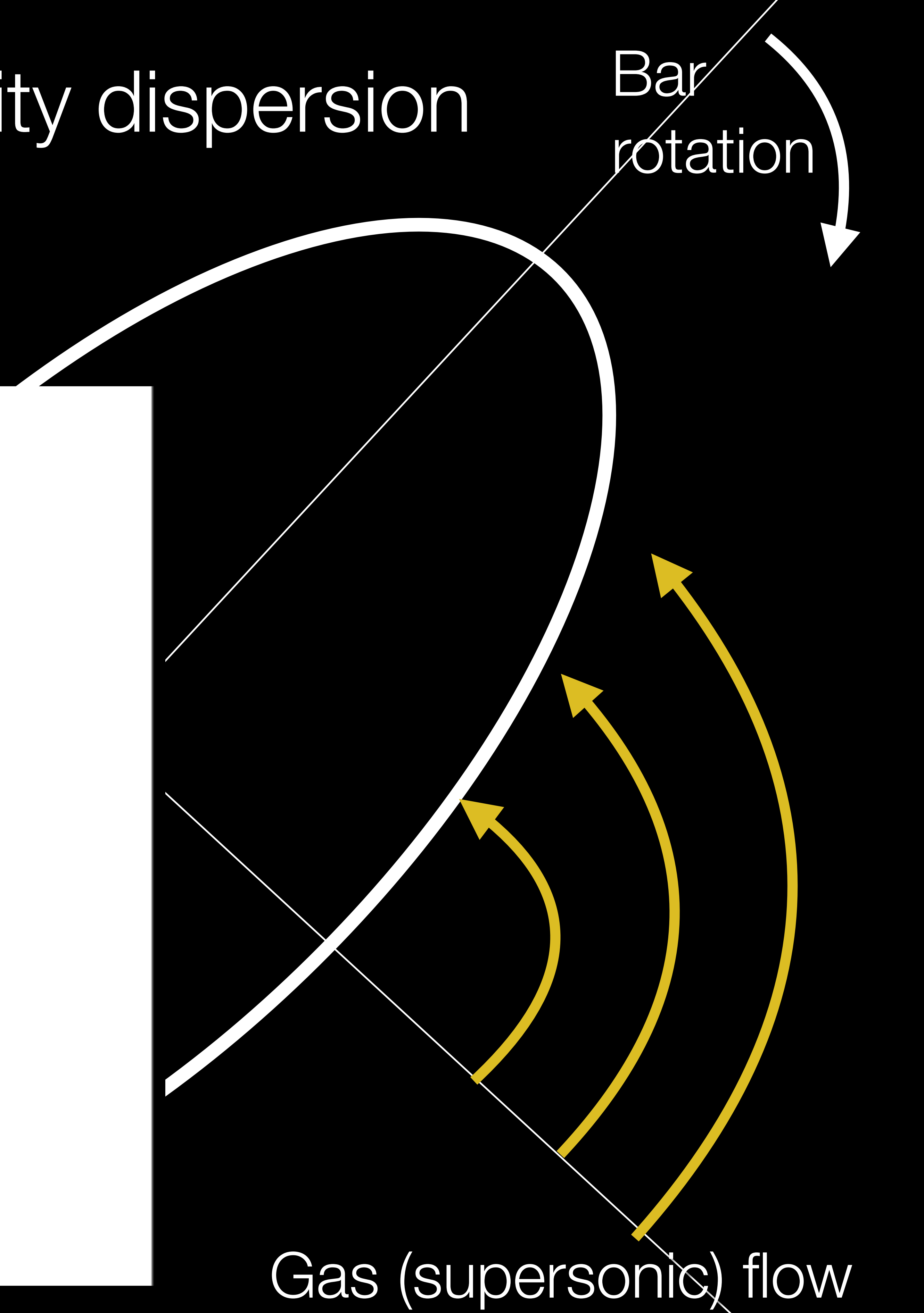


Gas velocity dispersion





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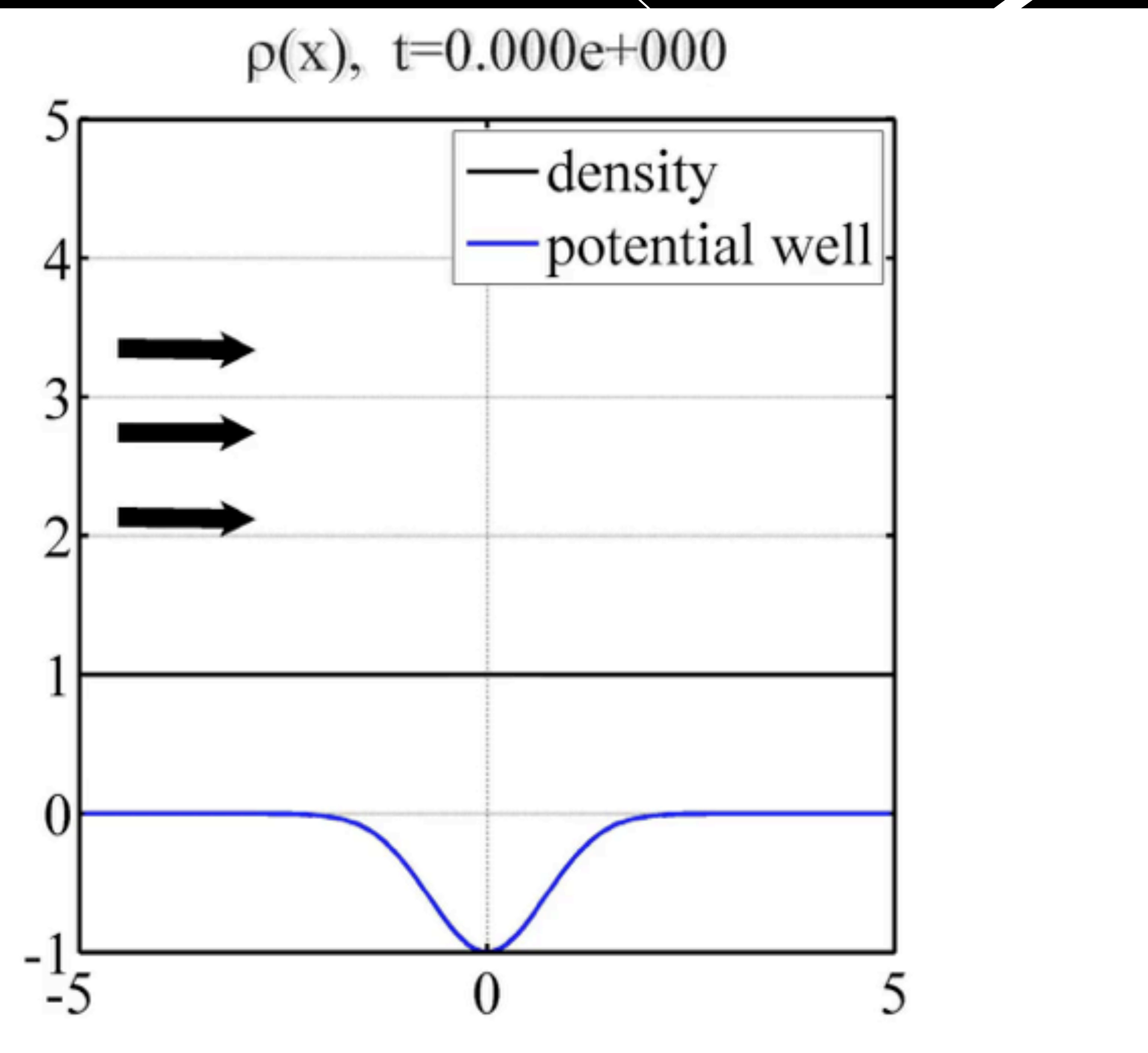
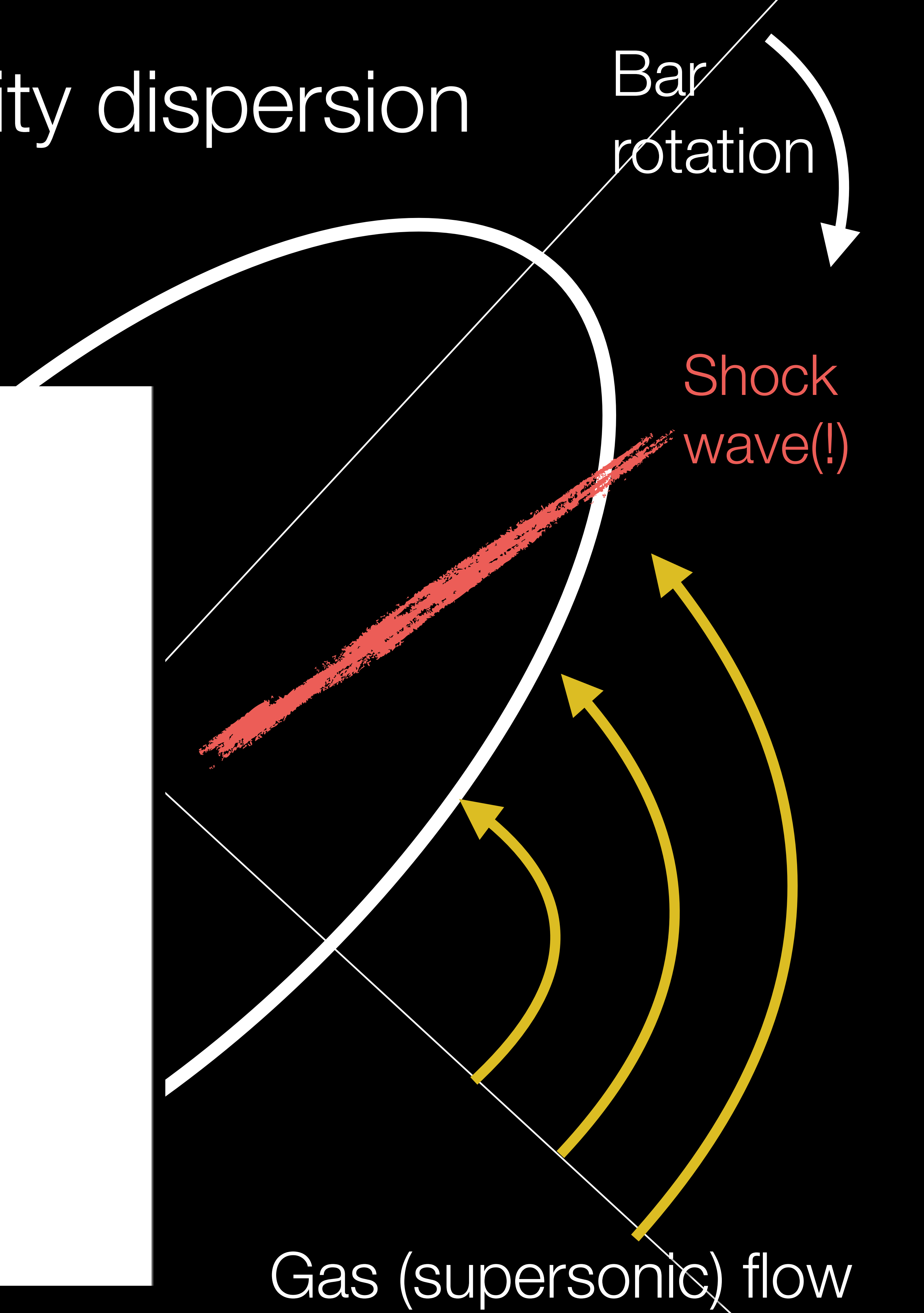
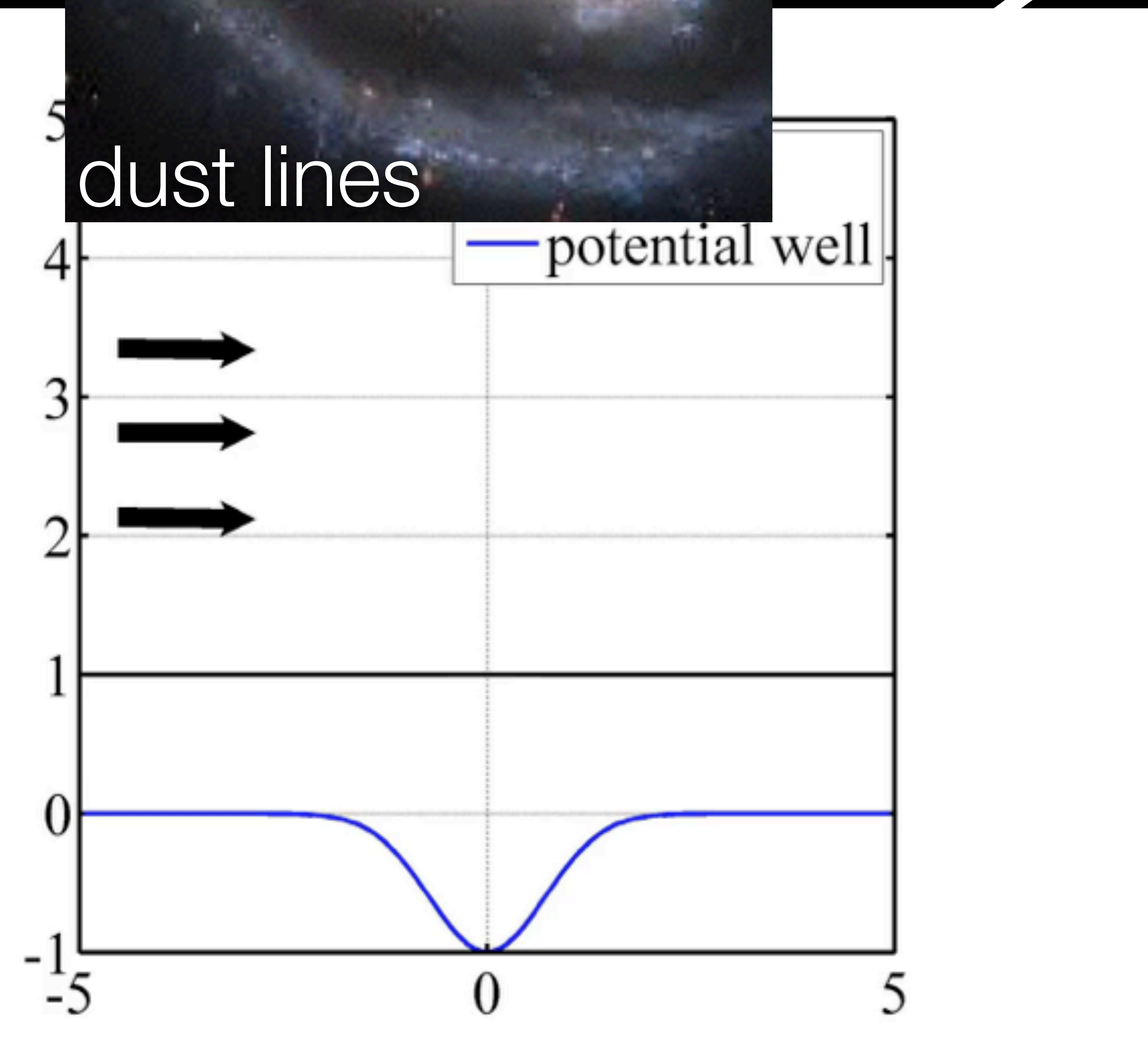
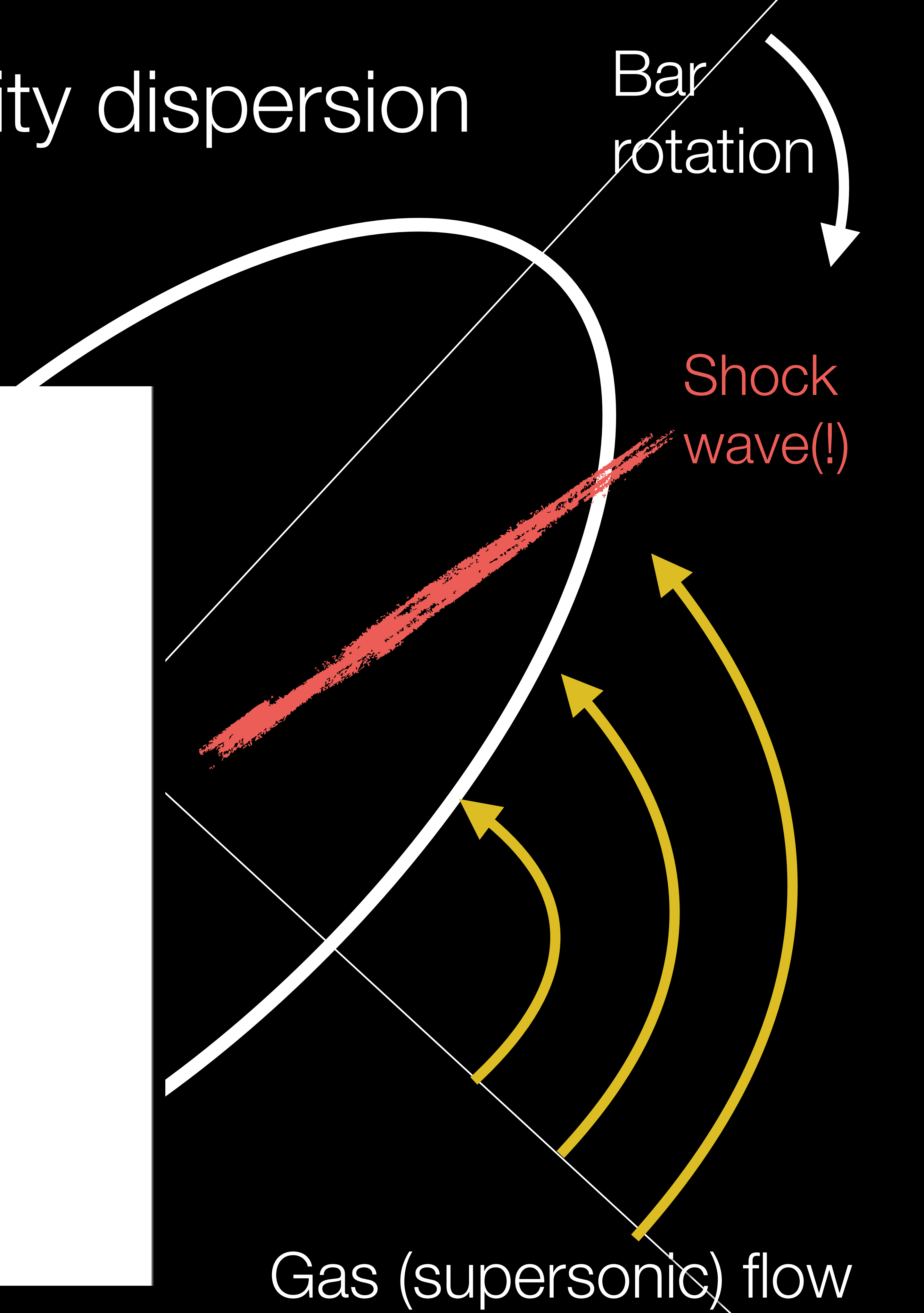


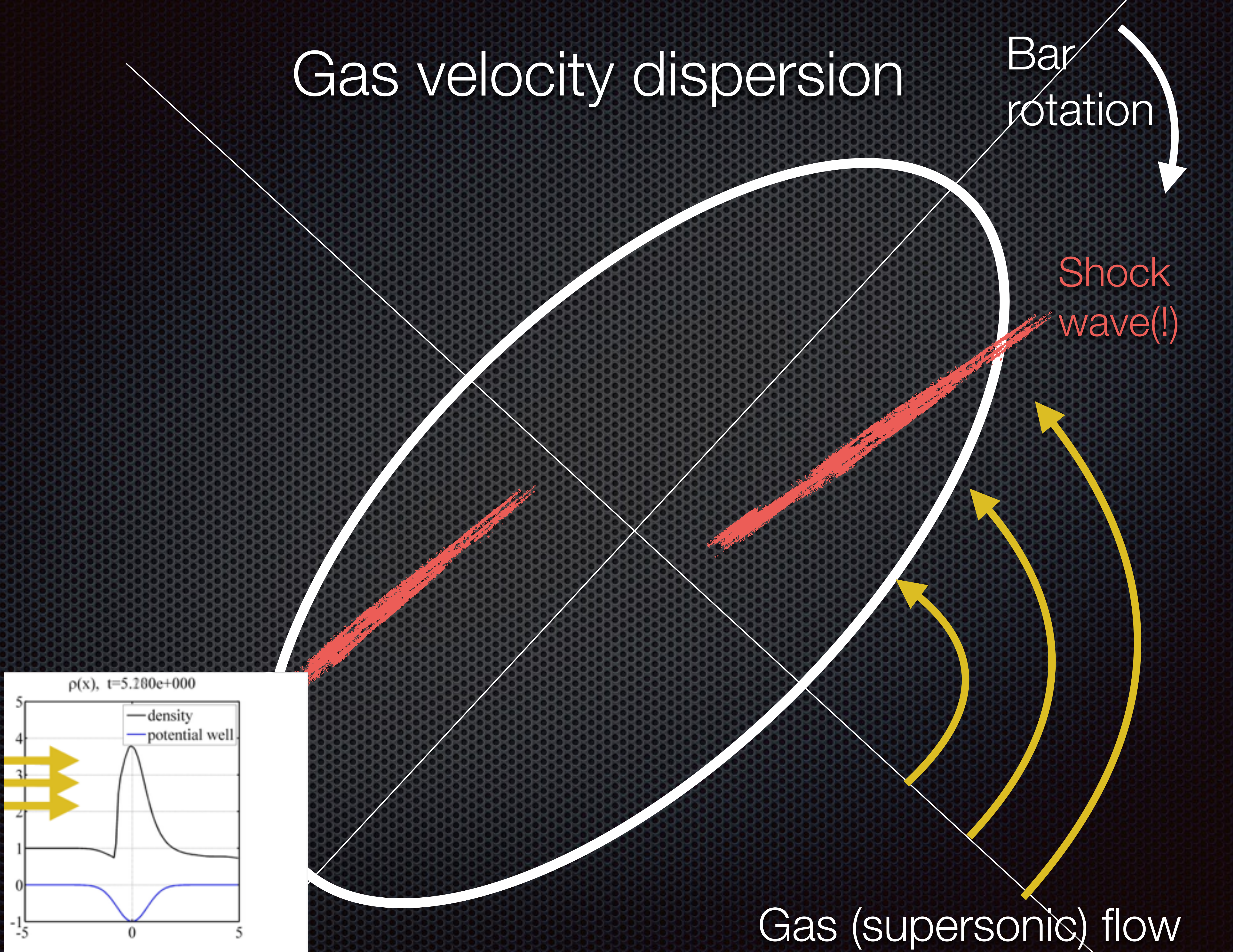


velocity dispersion

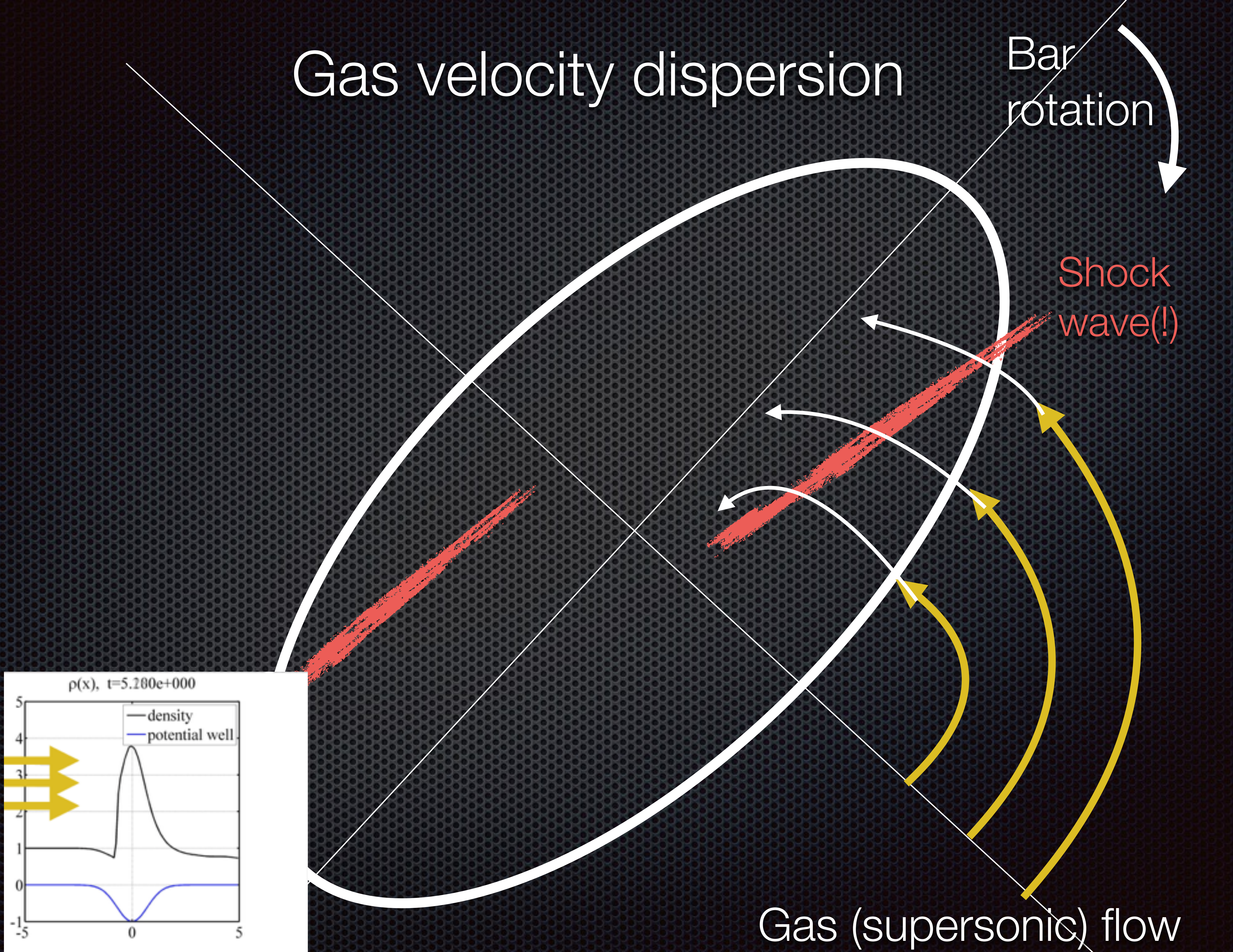




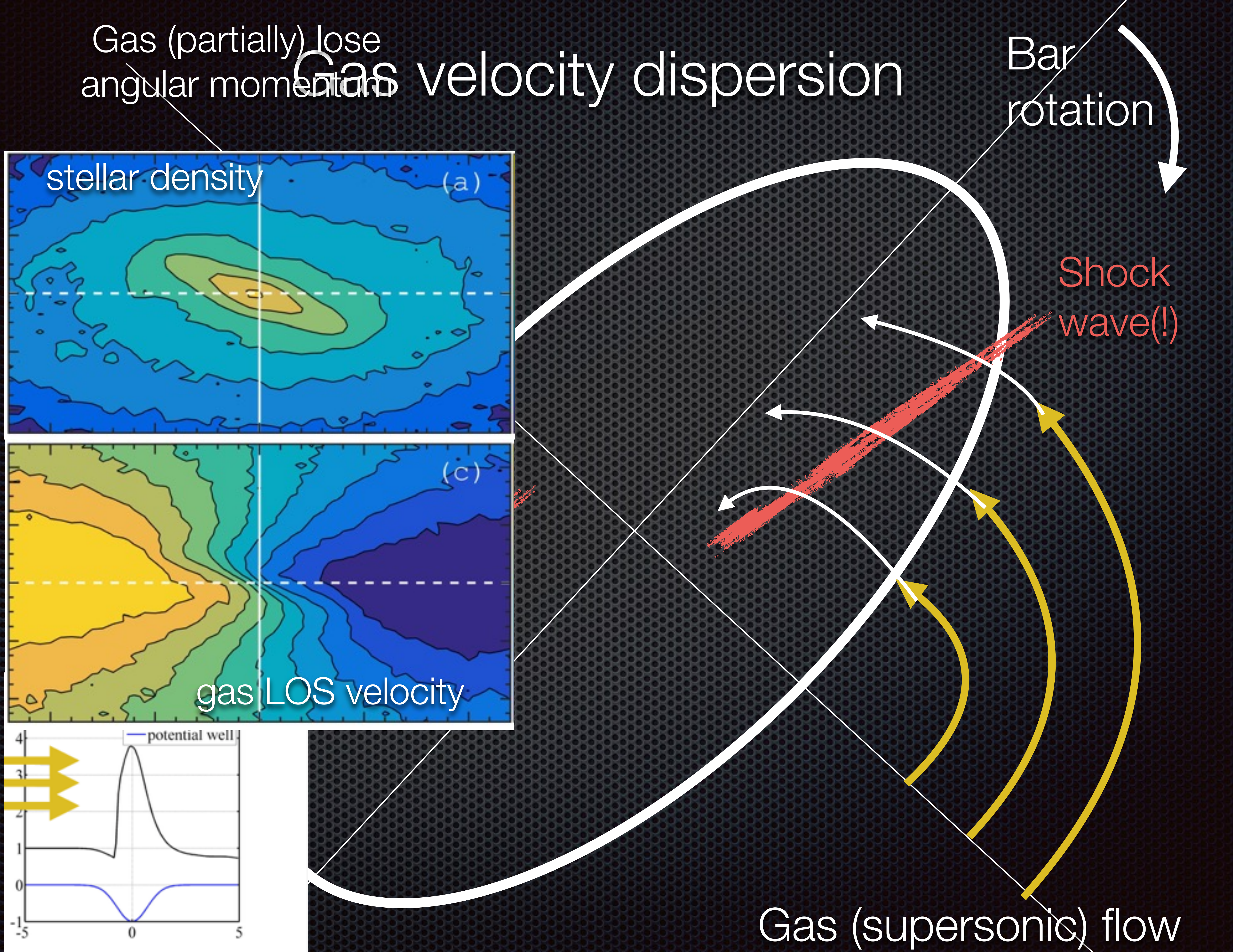
Gas velocity dispersion



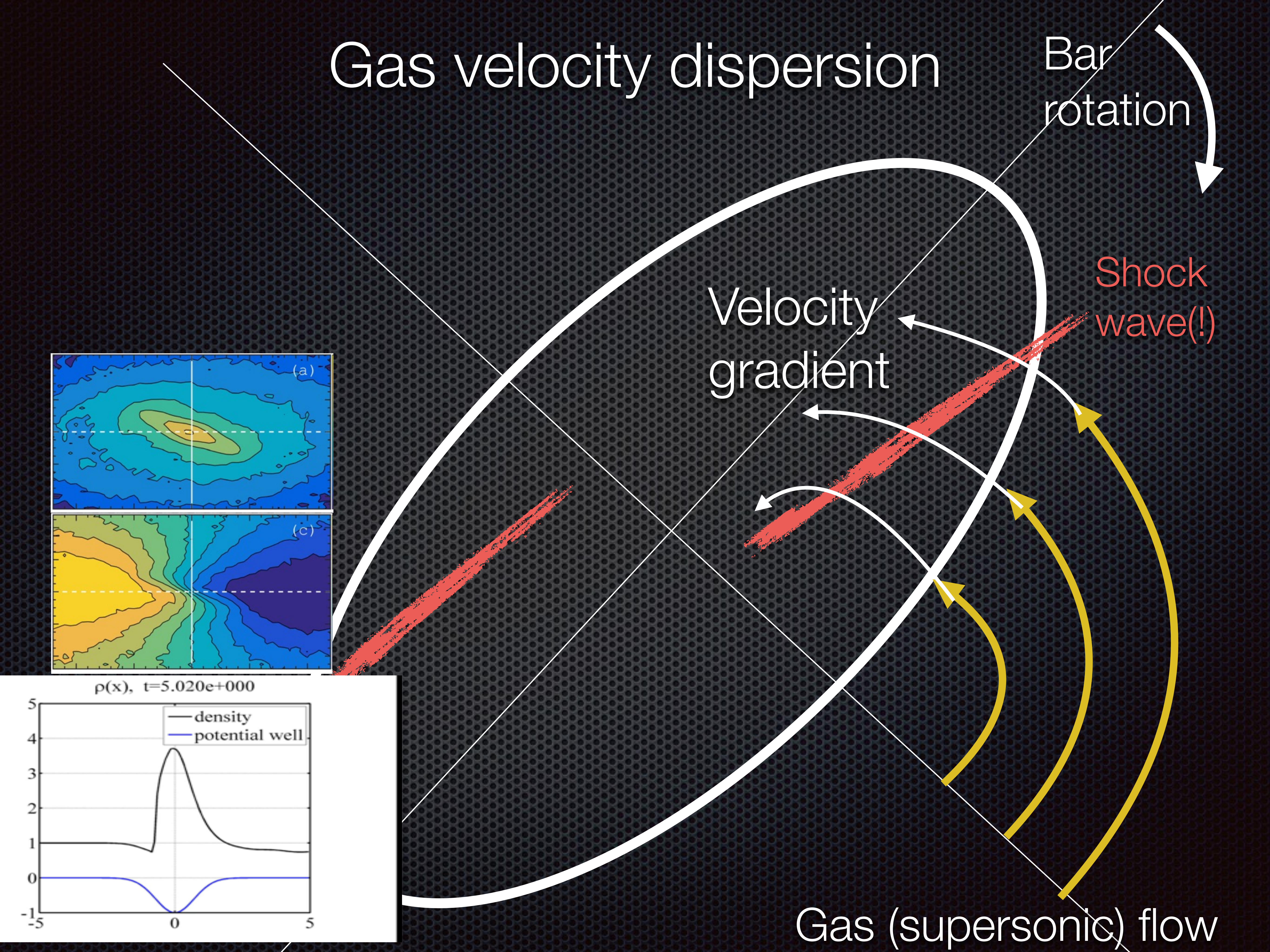
Gas velocity dispersion



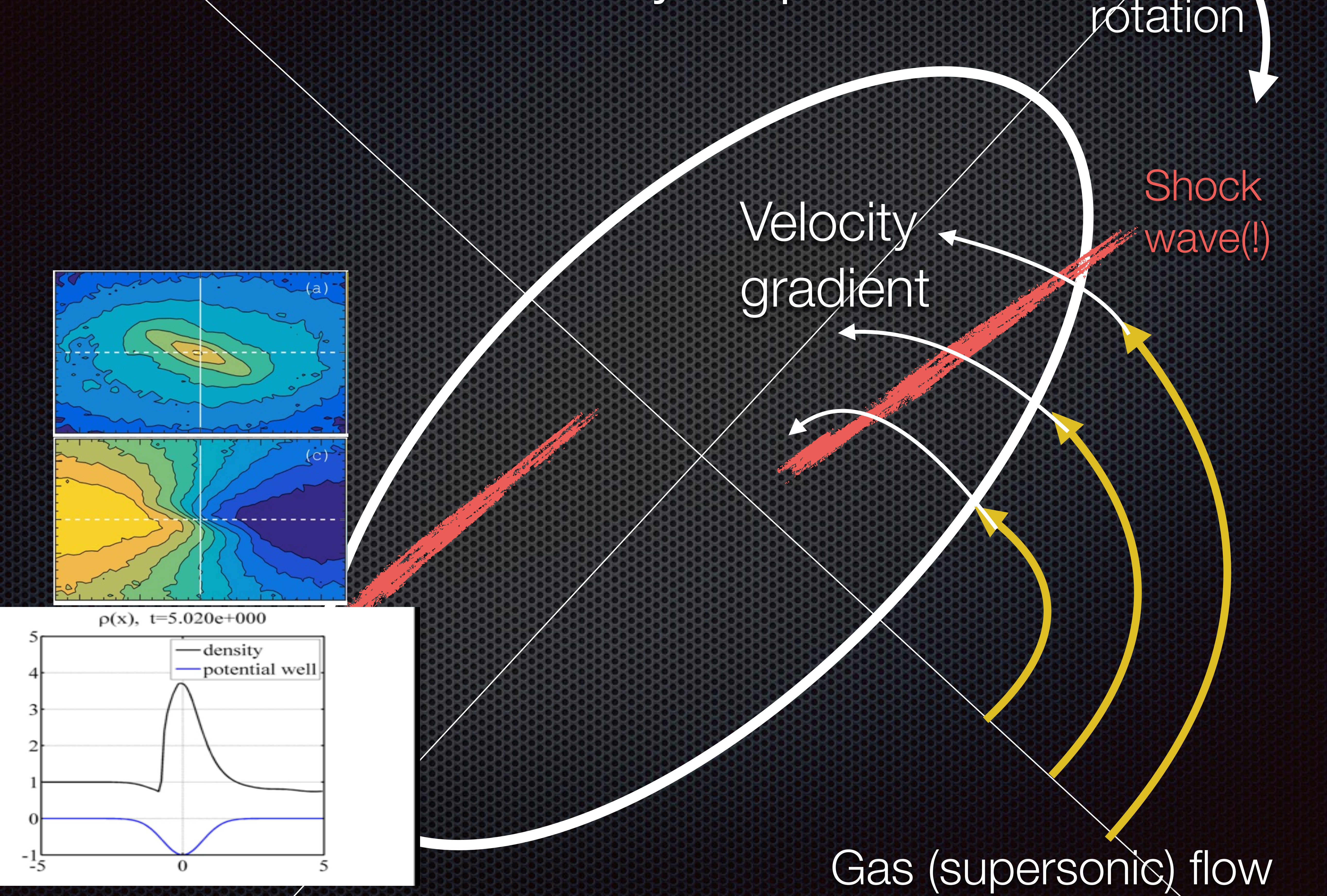
Gas velocity dispersion

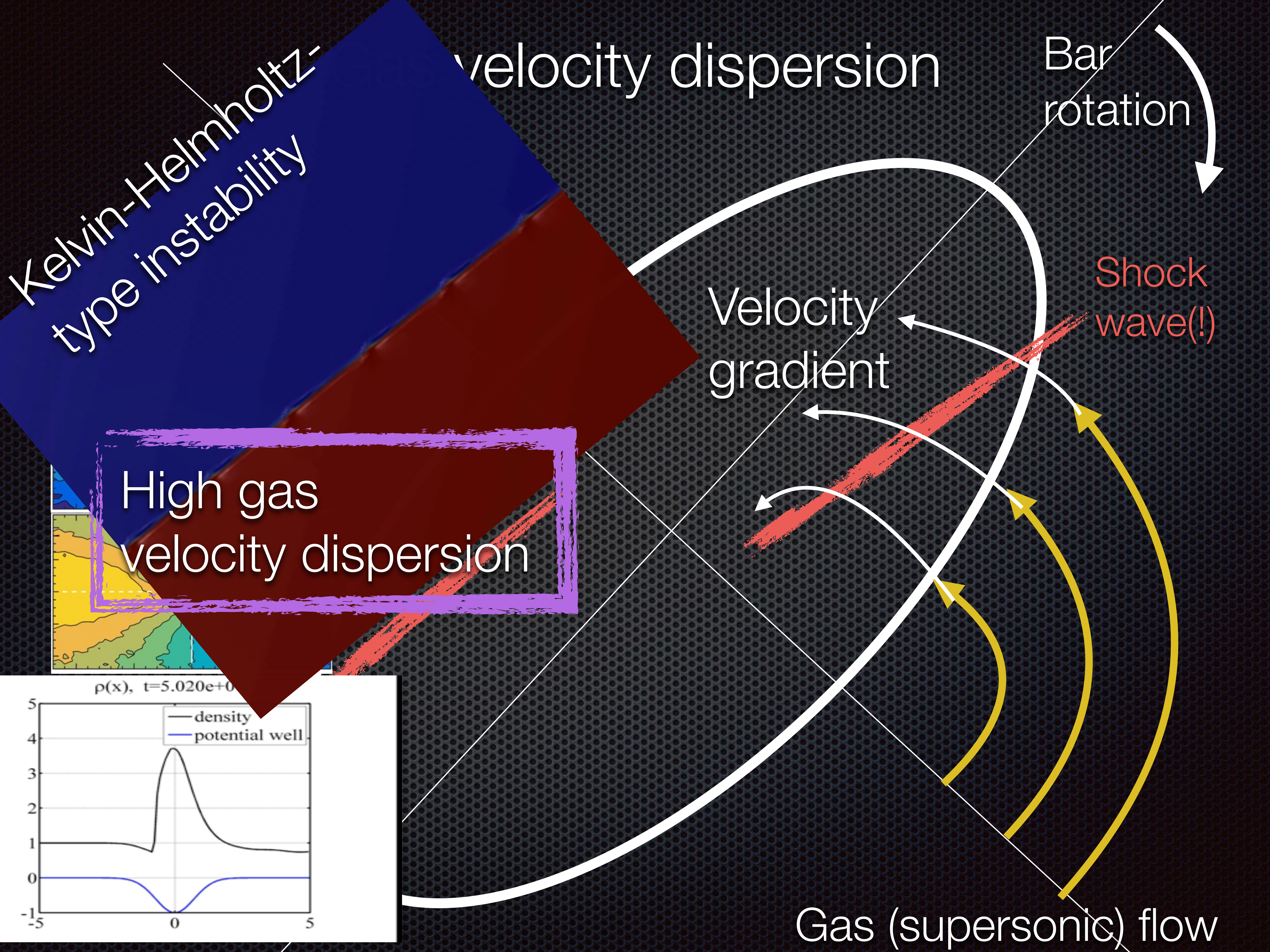


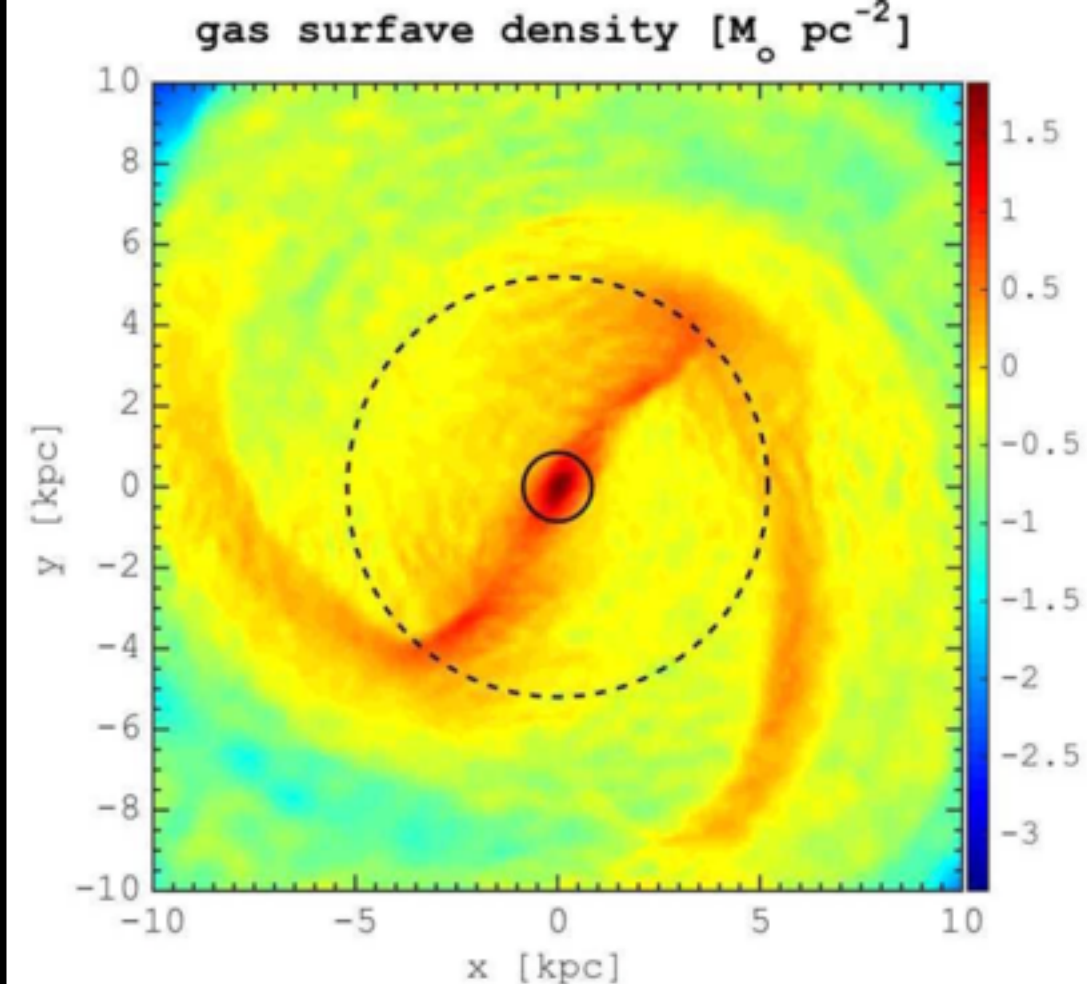
Gas velocity dispersion



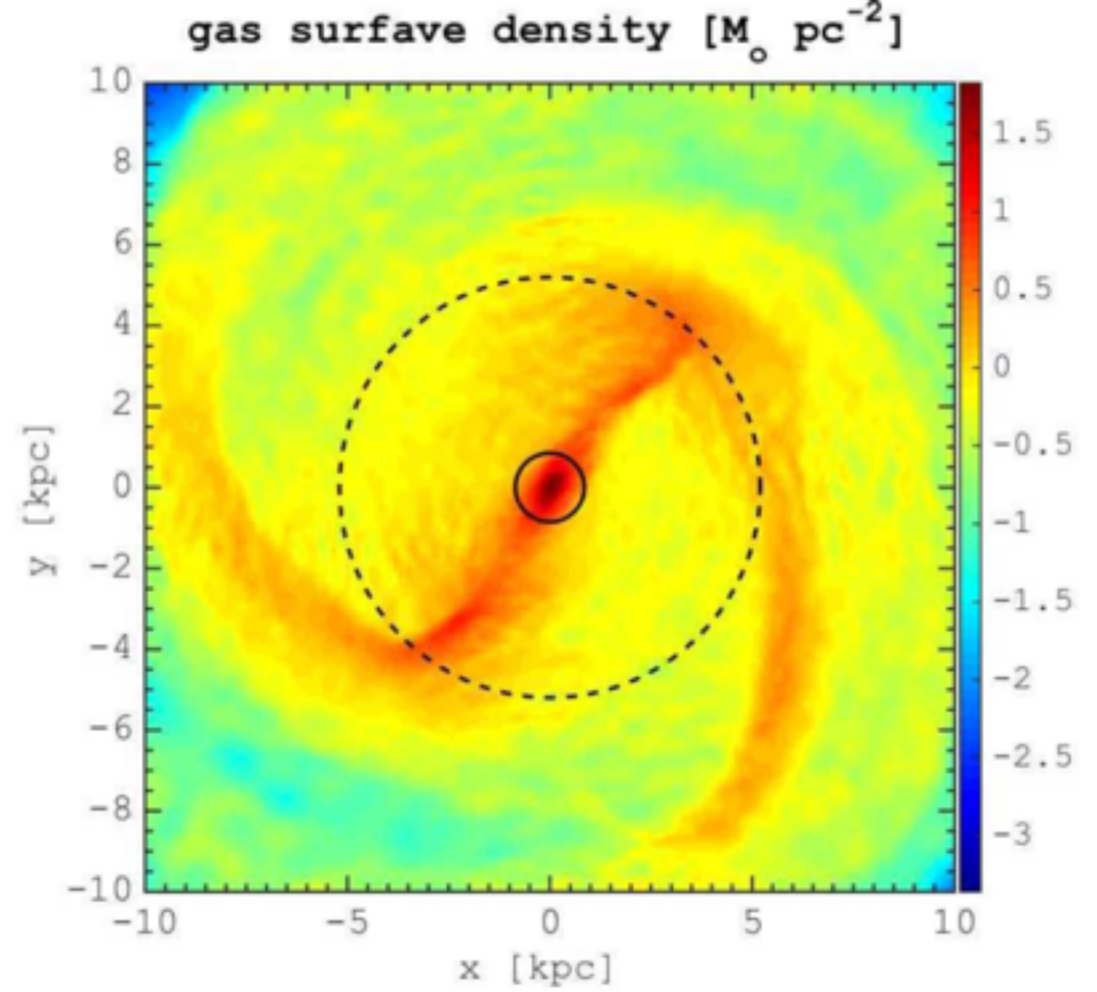
Gas velocity dispersion

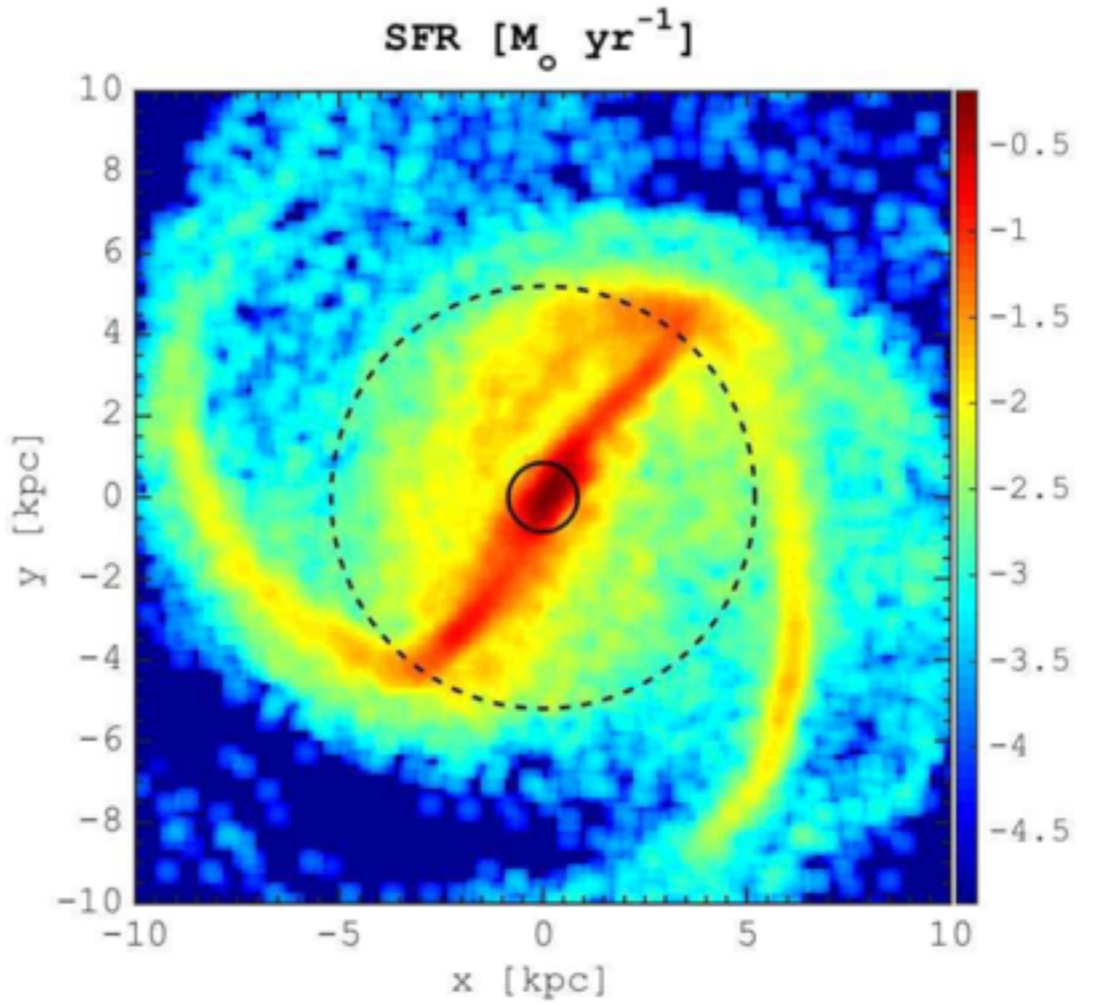


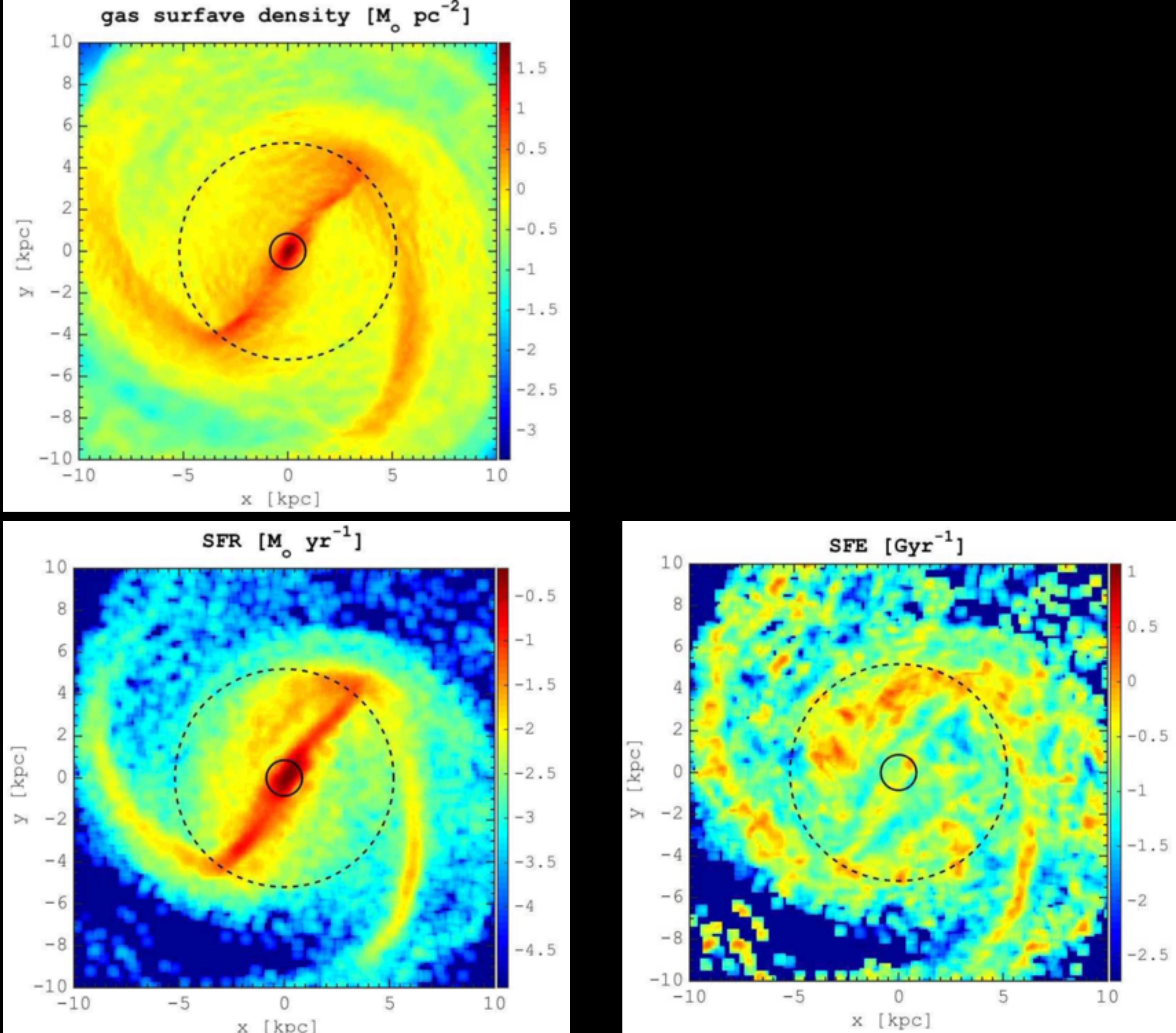

velocity dispersion
Bar rotation
Kelvin-Helmholtz-type instability
Shock wave(!)
Velocity gradient
High gas velocity dispersion
ρ(x), t=5.020e+0
density
potential well
5
4
3
2
1
0
-1
-5
0
5
Gas (supersonic) flow



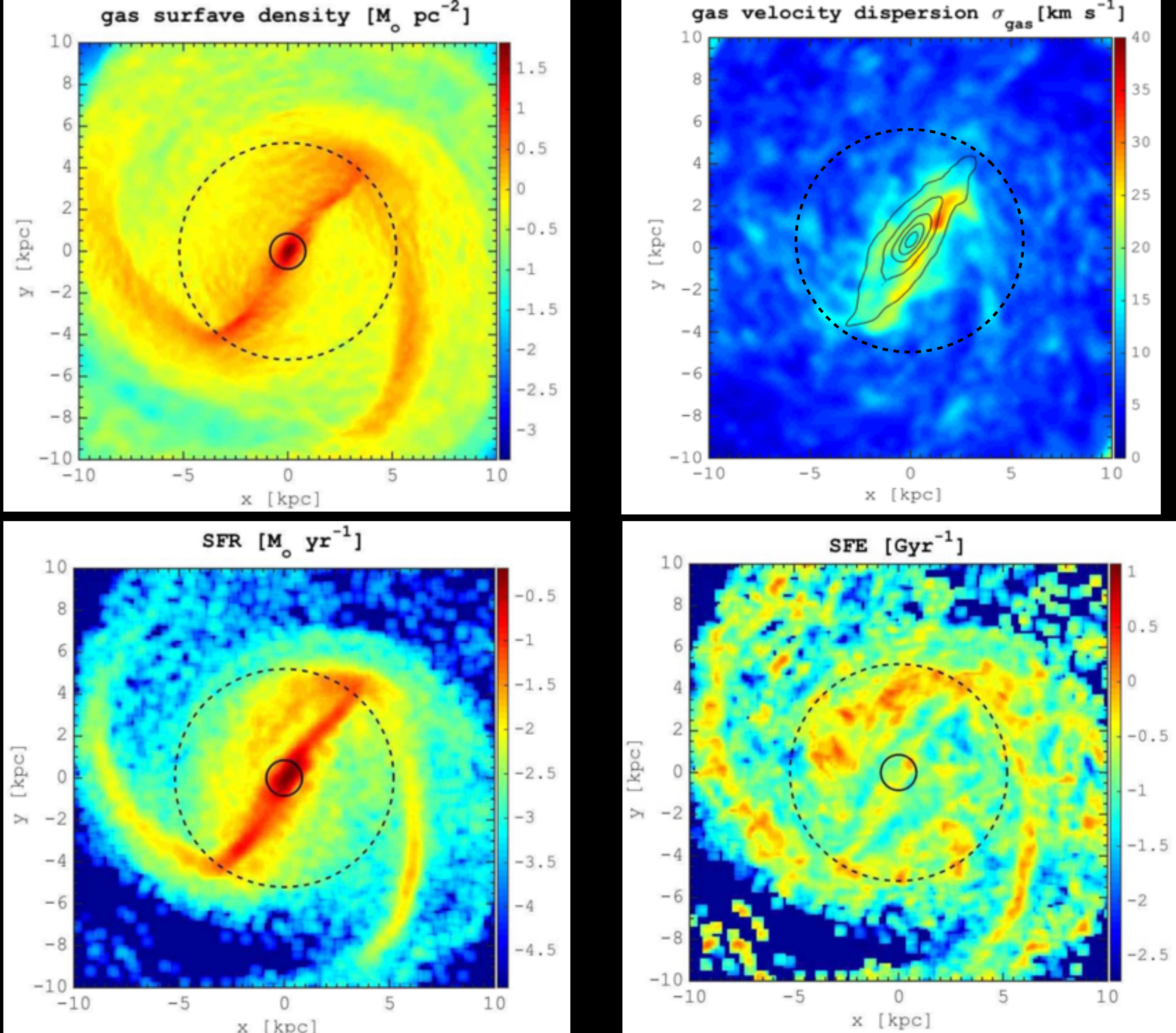
gas surfave density [M$_o$ pc^{-2}]
10
8
6
4
2
0
-2
-4
-6
-8
-10
y [kpc]
-10
-5
0
5
10
x [kpc]
1.5
1
0.5
0
-0.5
-1
-1.5
-2
-2.5
-3


gas surfave density [M$_o$ pc^{-2}]
y [kpc]
x [kpc]
10
8
6
4
2
0
−2
−4
−6
−8
−10
−5
5
1.5
1
0.5
−0.5
−1
−1.5
−2
−2.5
−3


SFR [M$_o$ yr^{-1}]
y [kpc]
x [kpc]
10
8
6
4
2
0
−2
−4
−6
−8
−10
−5
5
−0.5
−1
−1.5
−2
−2.5
−3
−3.5
−4
−4.5

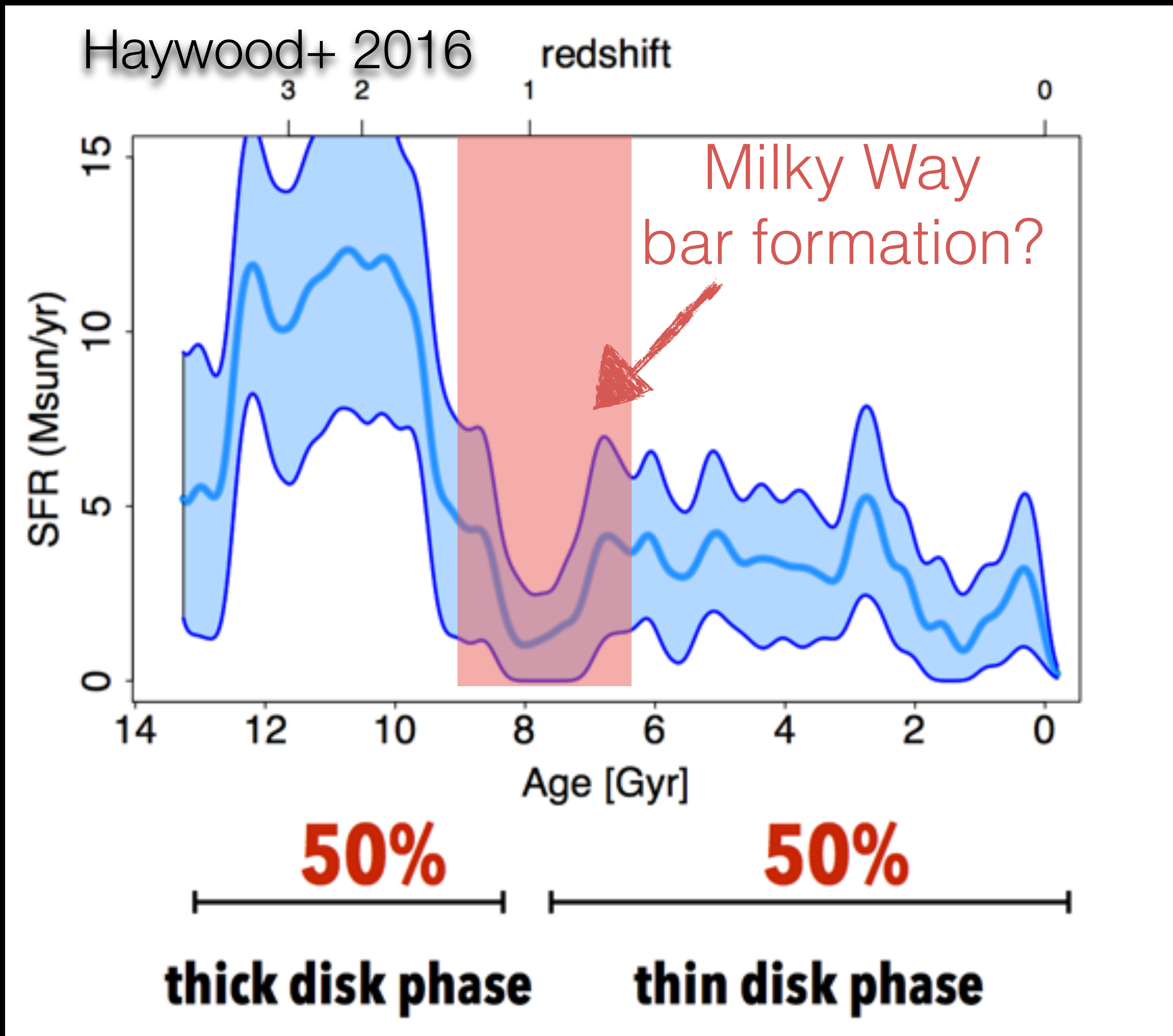


gas surfave density [M$_o$ pc^{-2}]
SFR [M$_o$ yr^{-1}]
SFE [Gyr^{-1}]
x [kpc]
y [kpc]



gas surfave density [M$_\odot$ pc^{-2}]
gas velocity dispersion σ_{gas} [km s^{-1}]
SFR [M$_\odot$ yr^{-1}]
SFE [Gyr^{-1}]
x [kpc]
y [kpc]

Milky Way star formation history



Chemical evolution model by Snaith et al 2015

Two distinct phases:

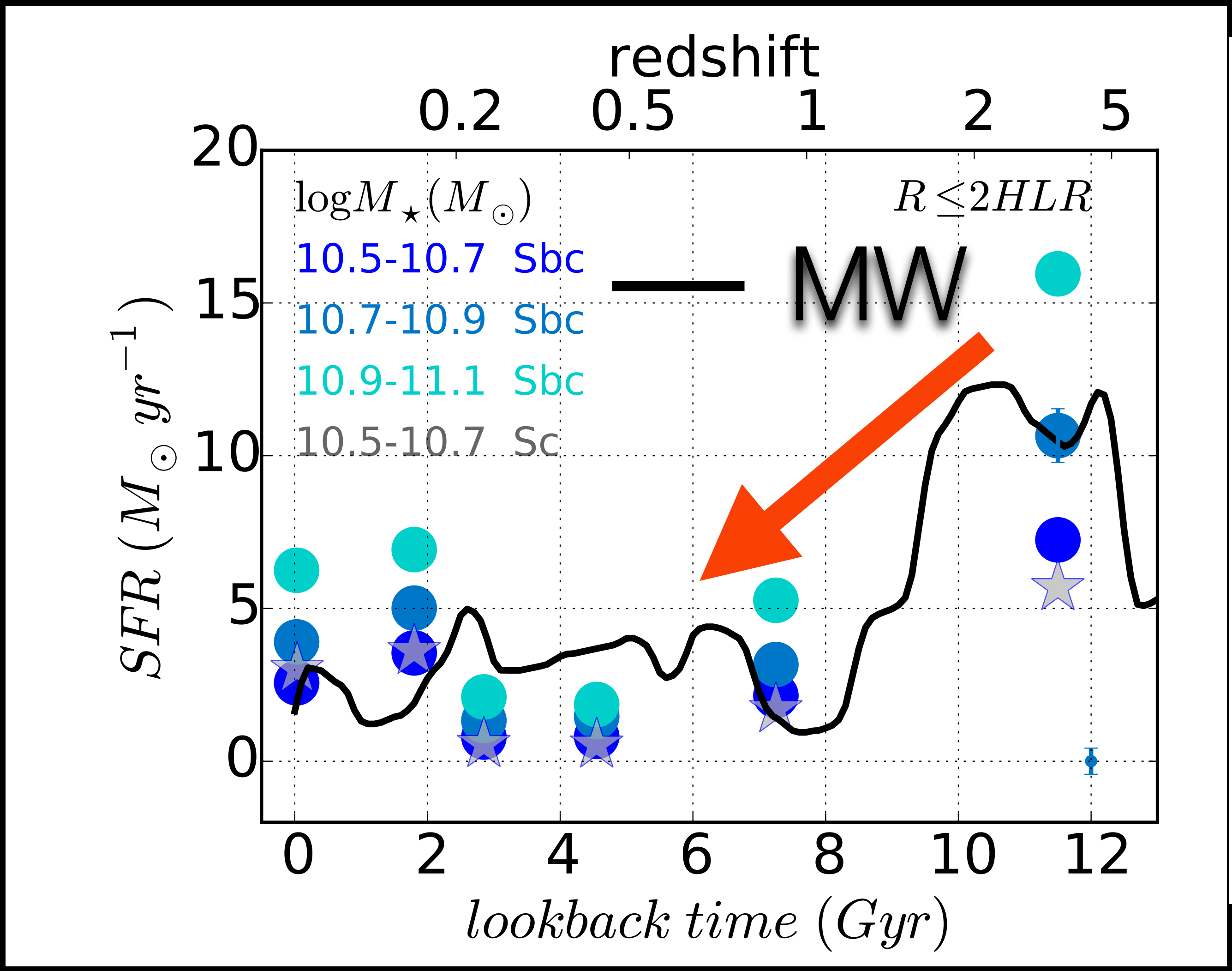
thick disk 12-9 Gyr
thin disk 8 Gyr-today

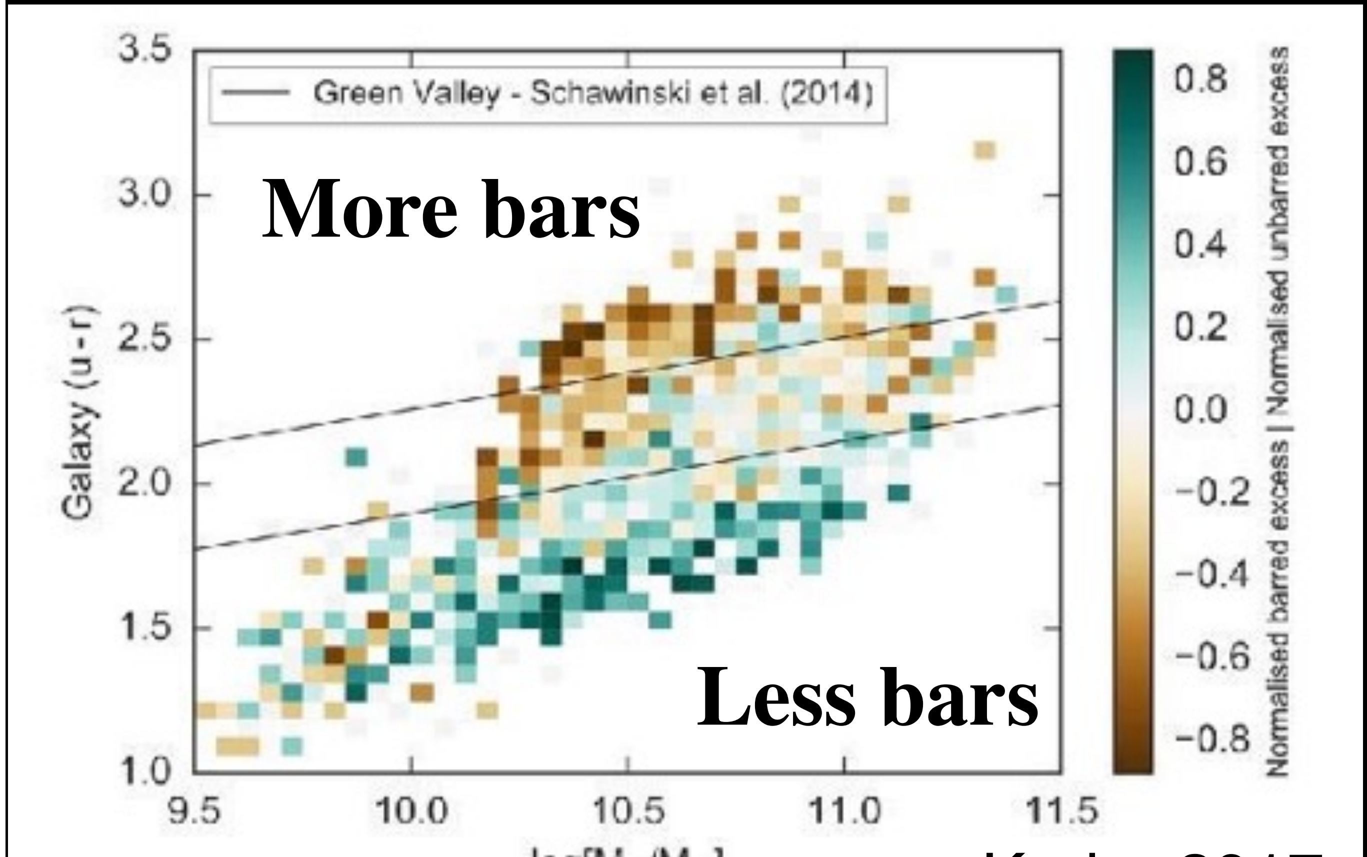
Rapid decrees of star formation can be explained by the formation of a bar in a gas-rich disk

SFH in barred galaxies

Observations indicate that 60% of bright disk galaxies have bars

(e.g., Knapen+ 2000; Barazza+ 2008)





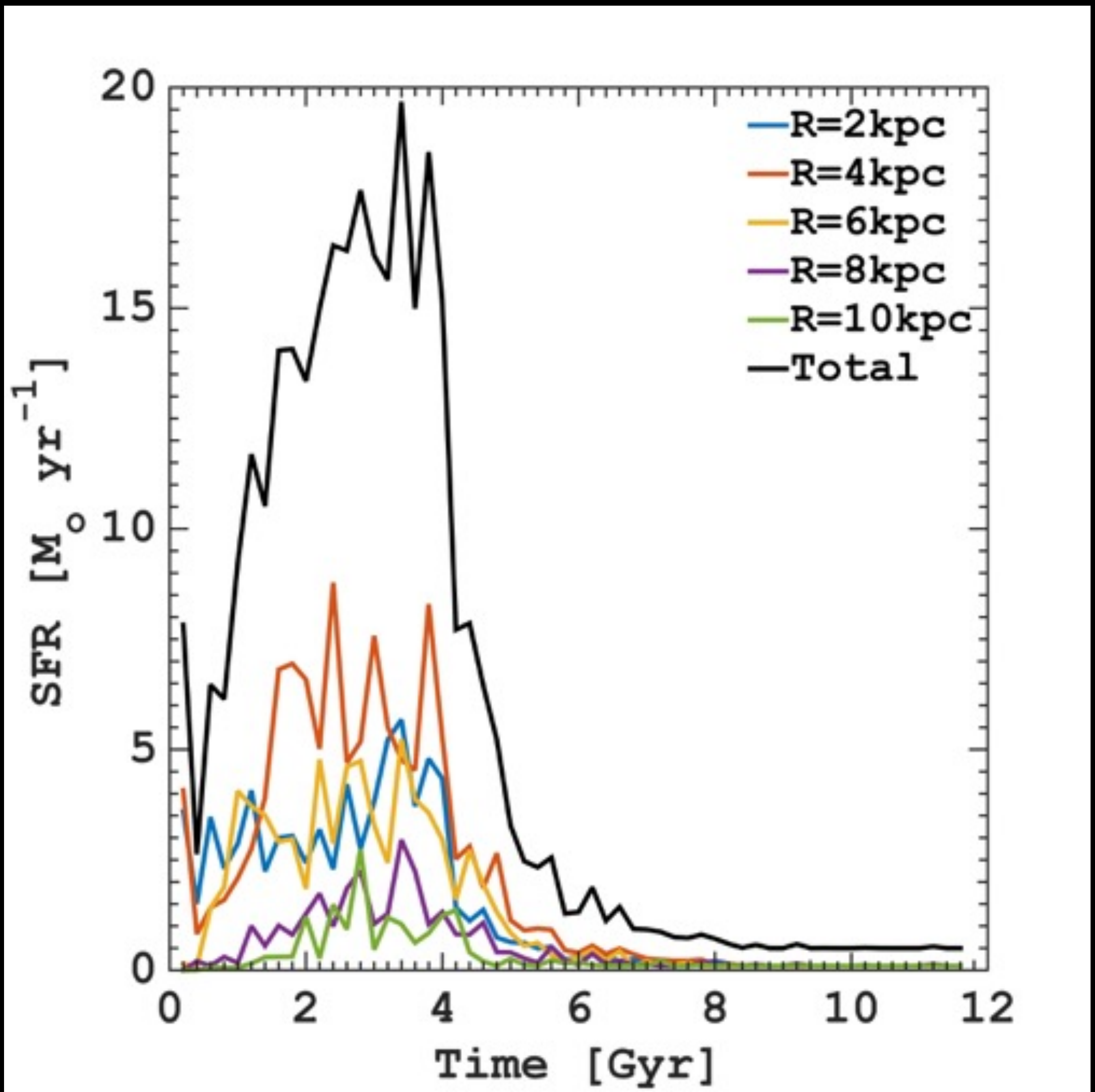
Kruk+ 2017

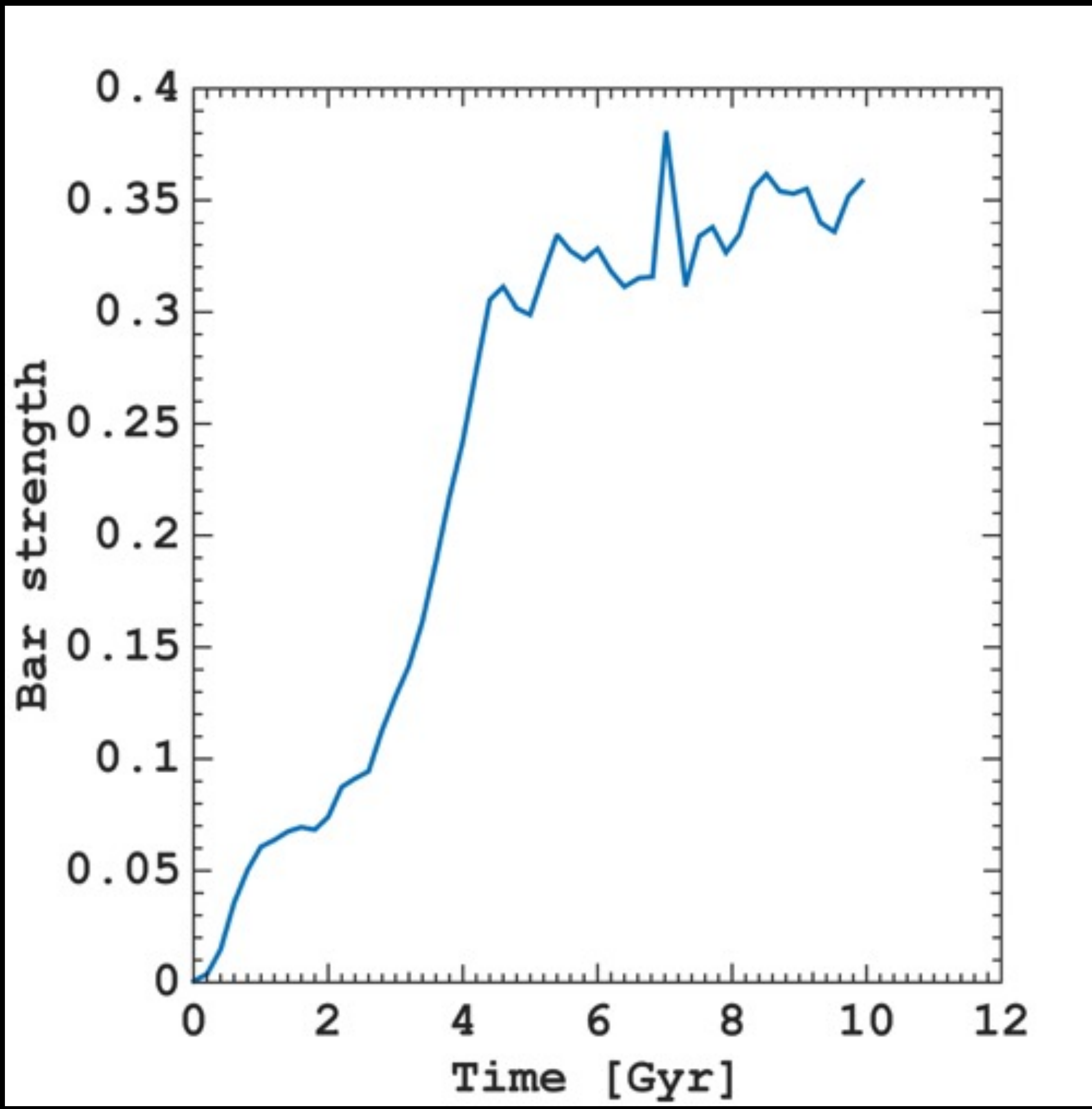
MW-mass galaxies form their bar at z=1-1.5 (Sheth+ 2008, Melvin+ 2014)

That’s also the epoch of the transition from the thick disk to the thin disk

Self-consistent model: SFH

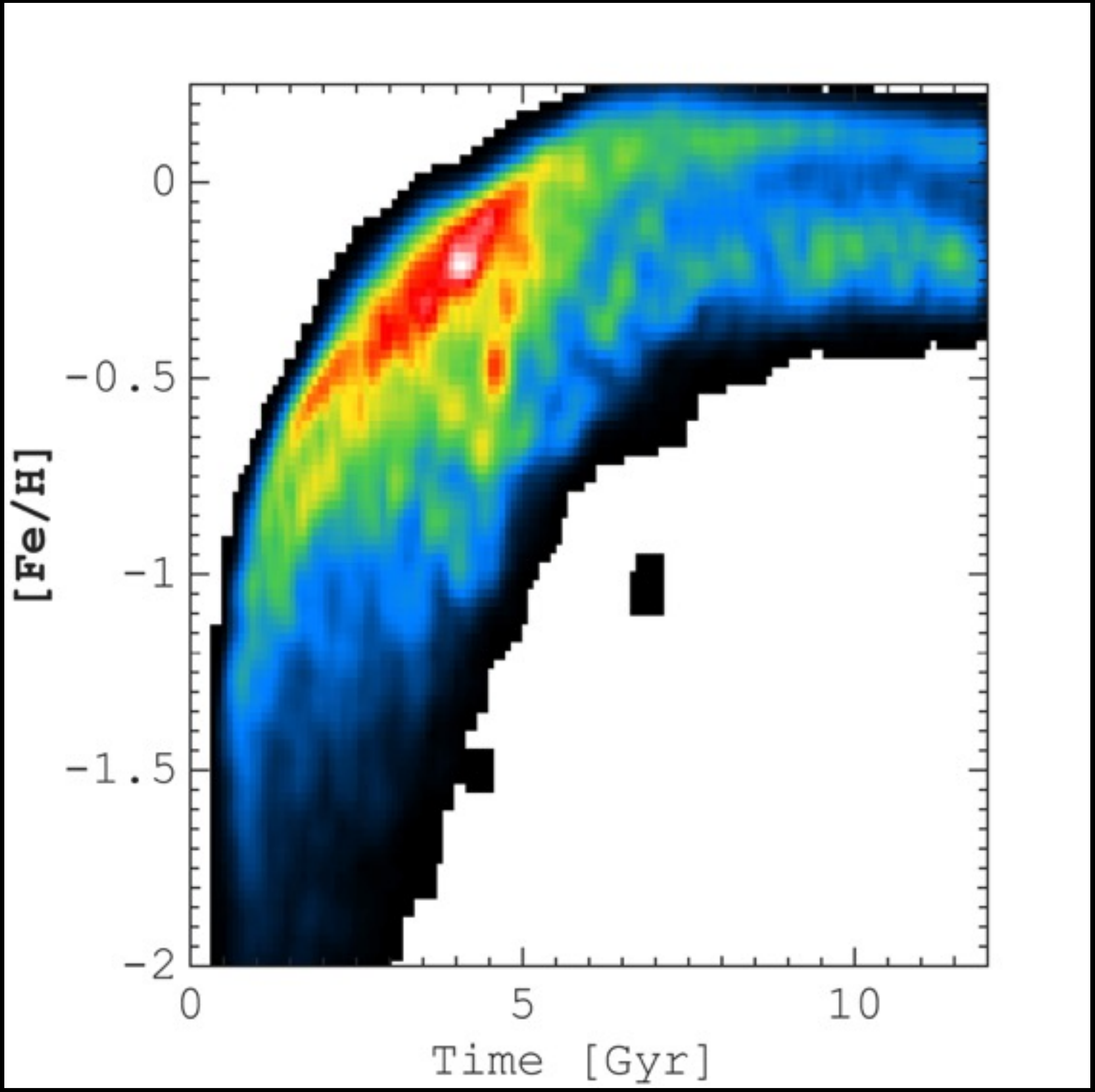
Bar is able to suppress the star formation



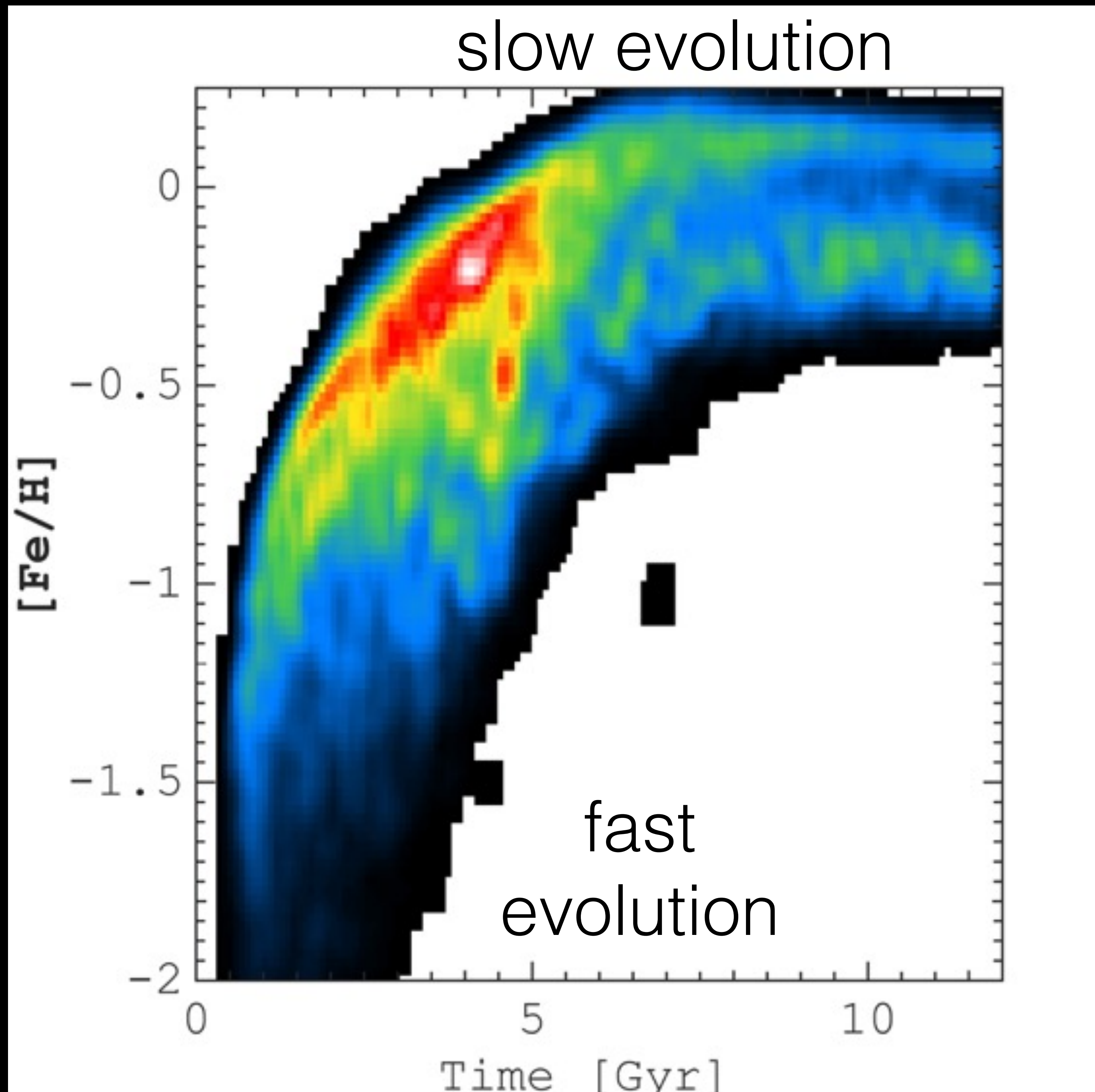


see also: Observations: James & Percival (2018) Simulations: Renaud+ (2015)

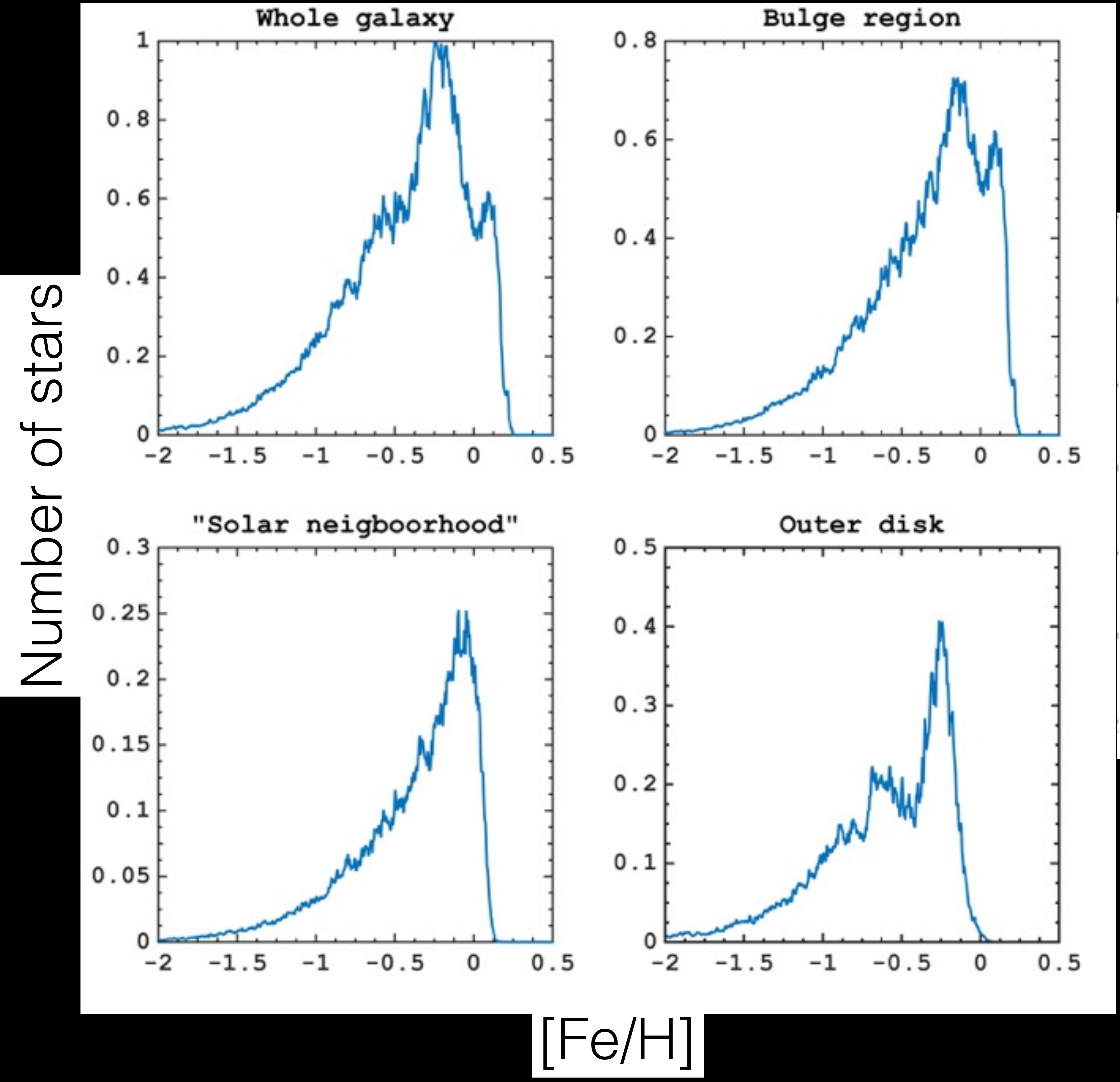
Self-consistent model: [Fe/H] evolution

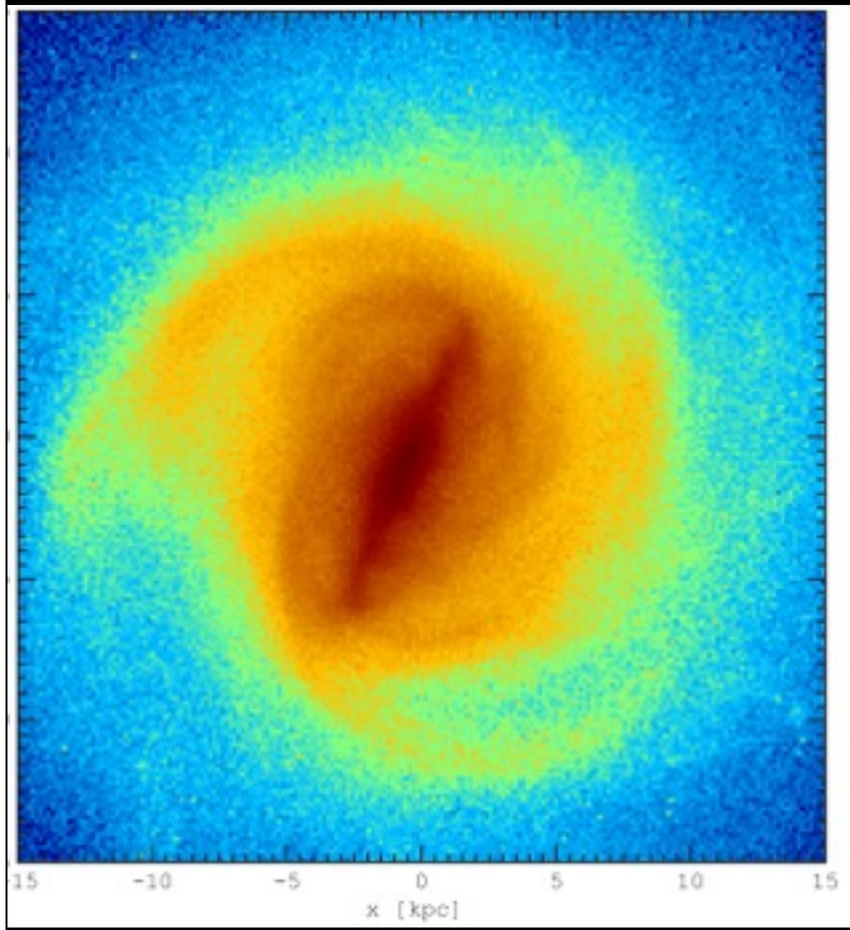


Self-consistent model: [Fe/H] evolution



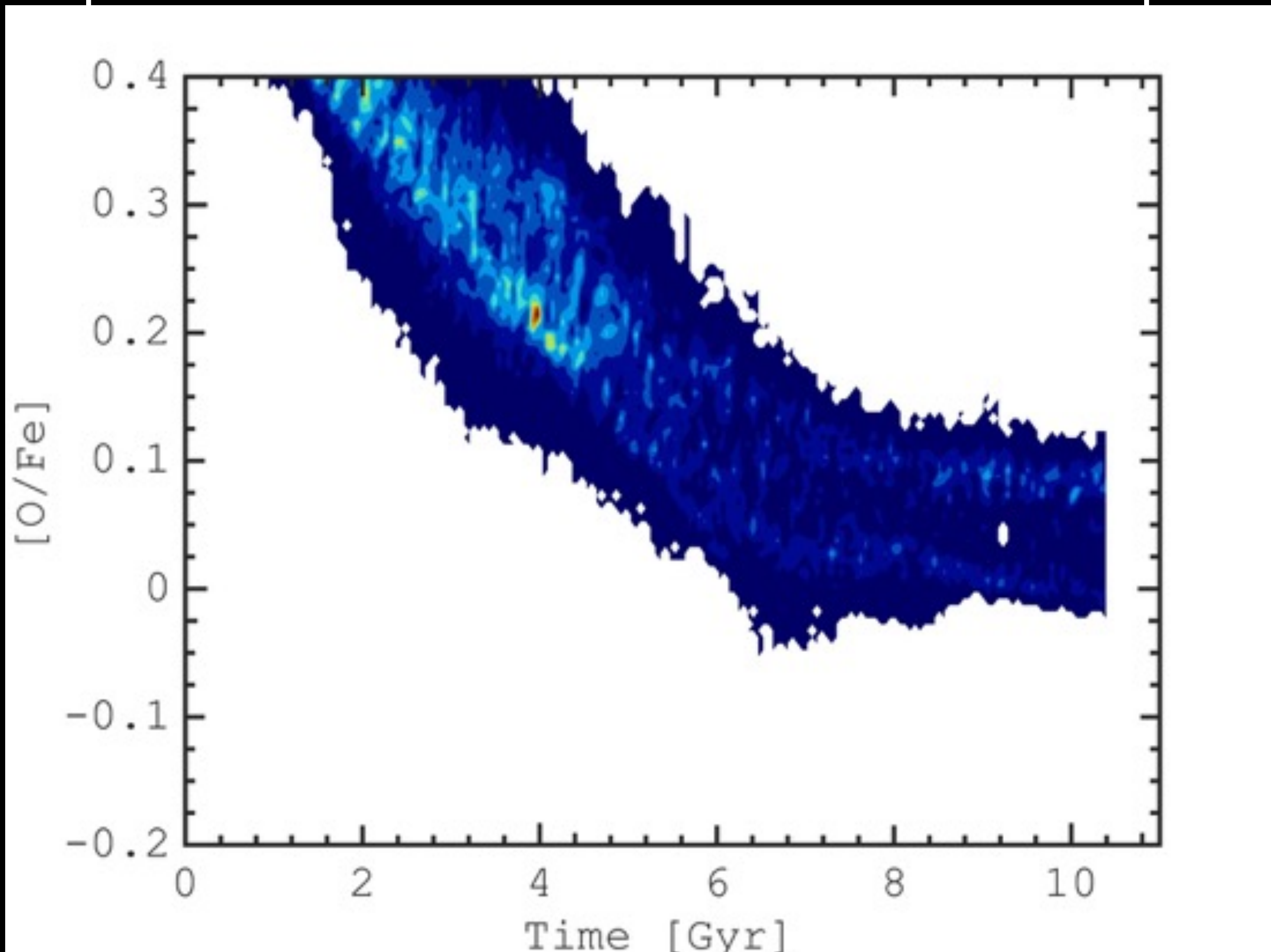
MDF in different disk regions





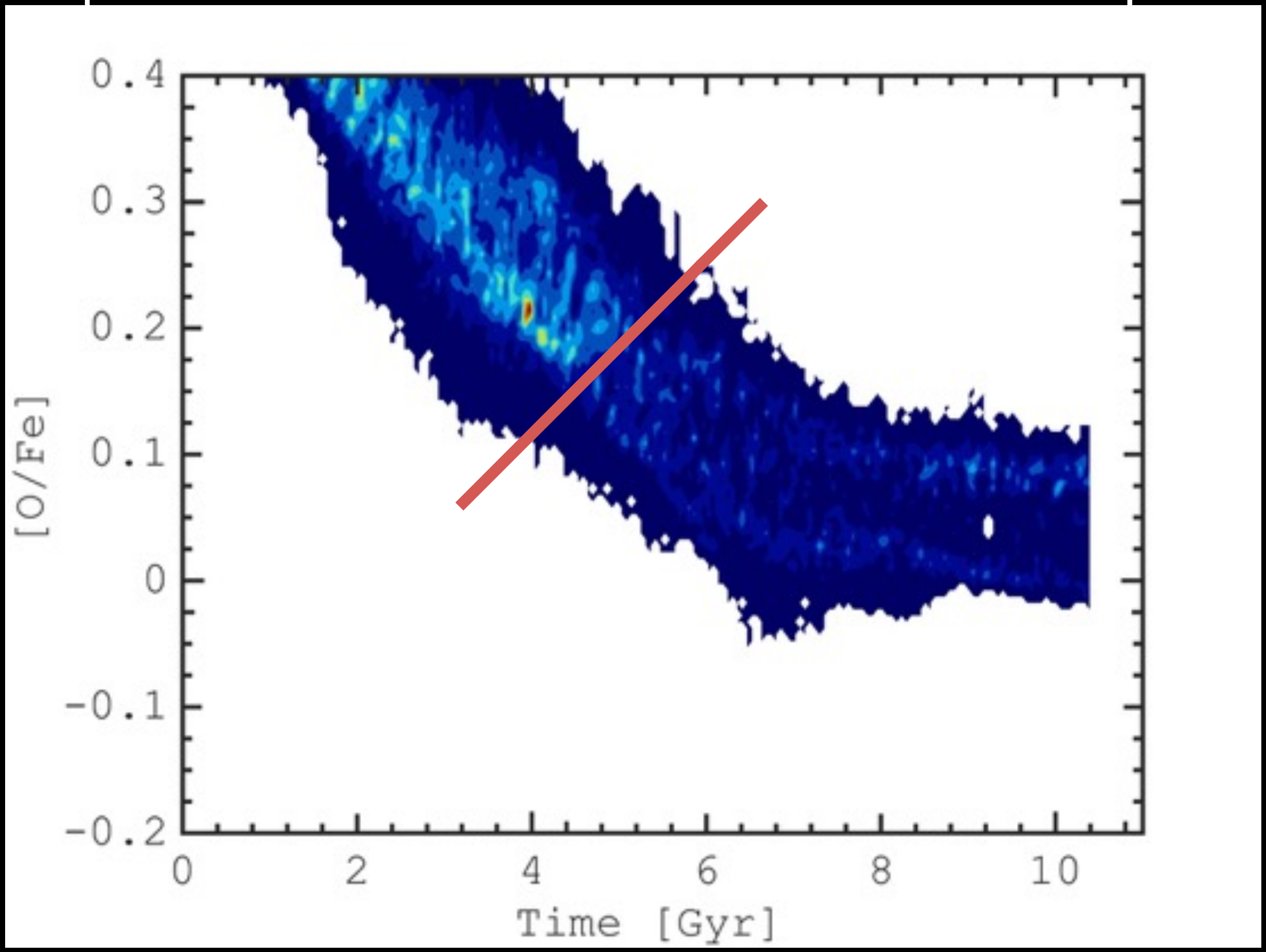
Self-consistent model: [O/Fe] evolution

alpha-enriched stars -> star formation was rapid



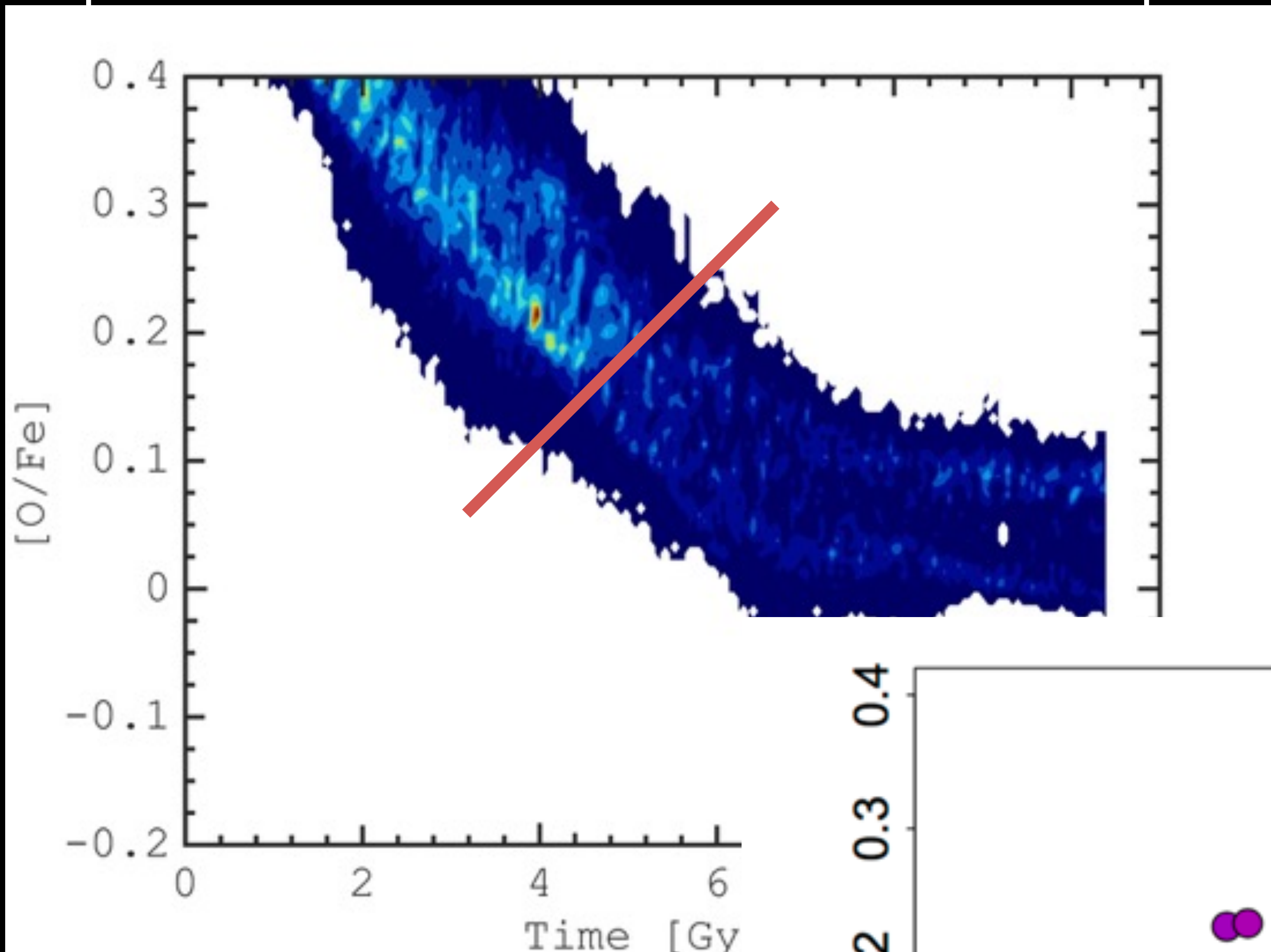
Self-consistent model: [O/Fe] evolution

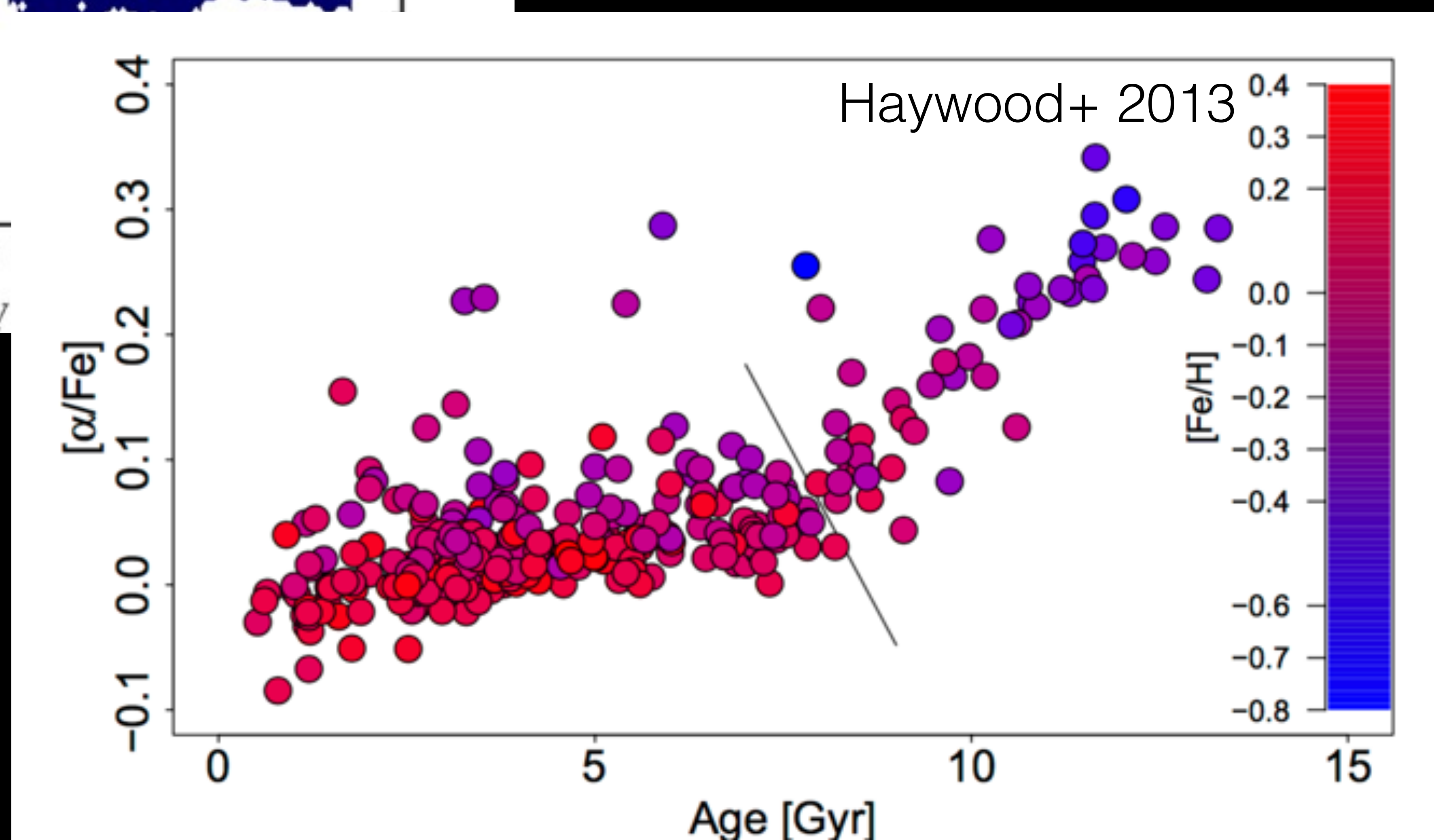
alpha-enriched stars -> star formation was rapid



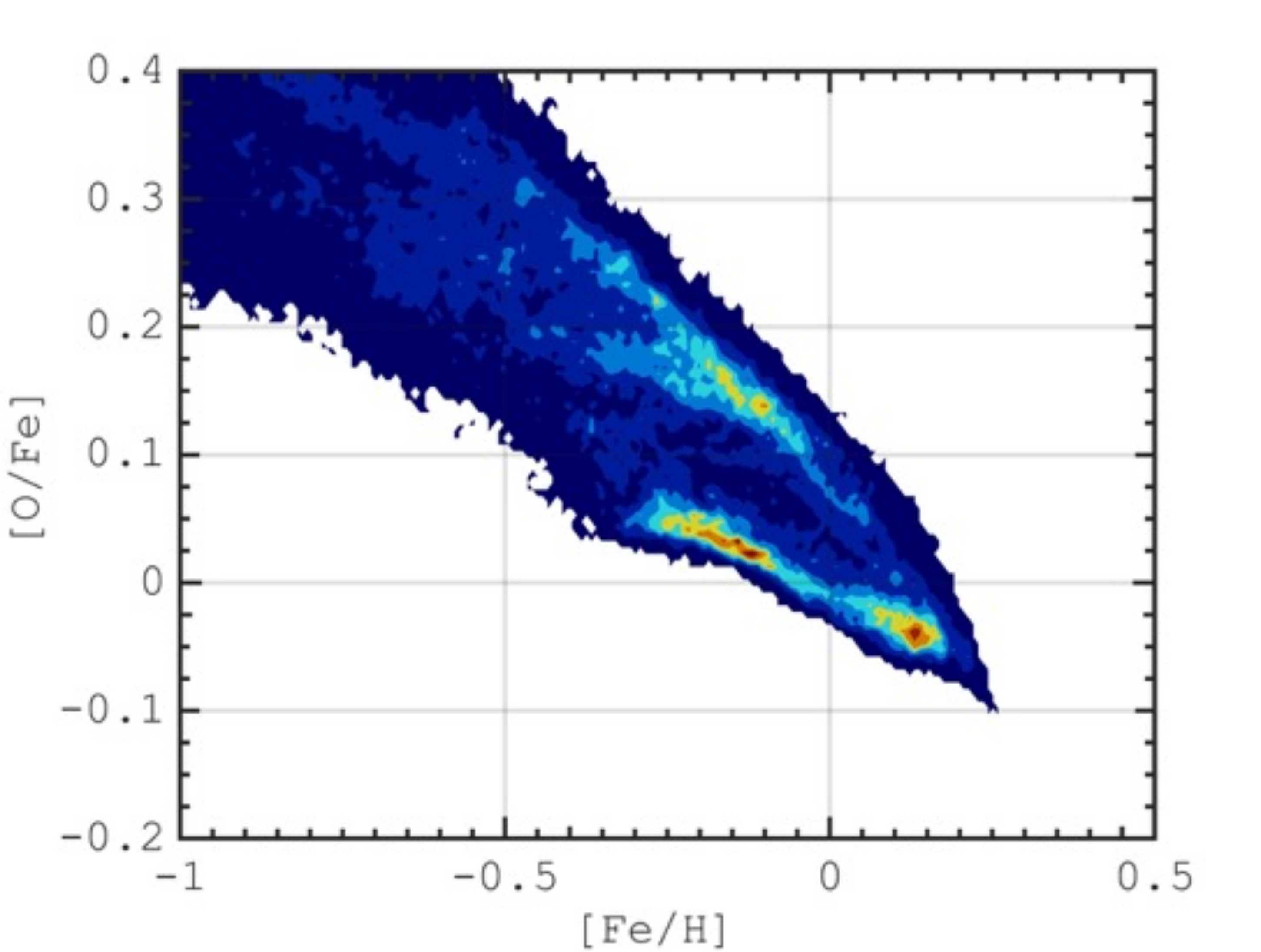
Self-consistent model: [O/Fe] evolution

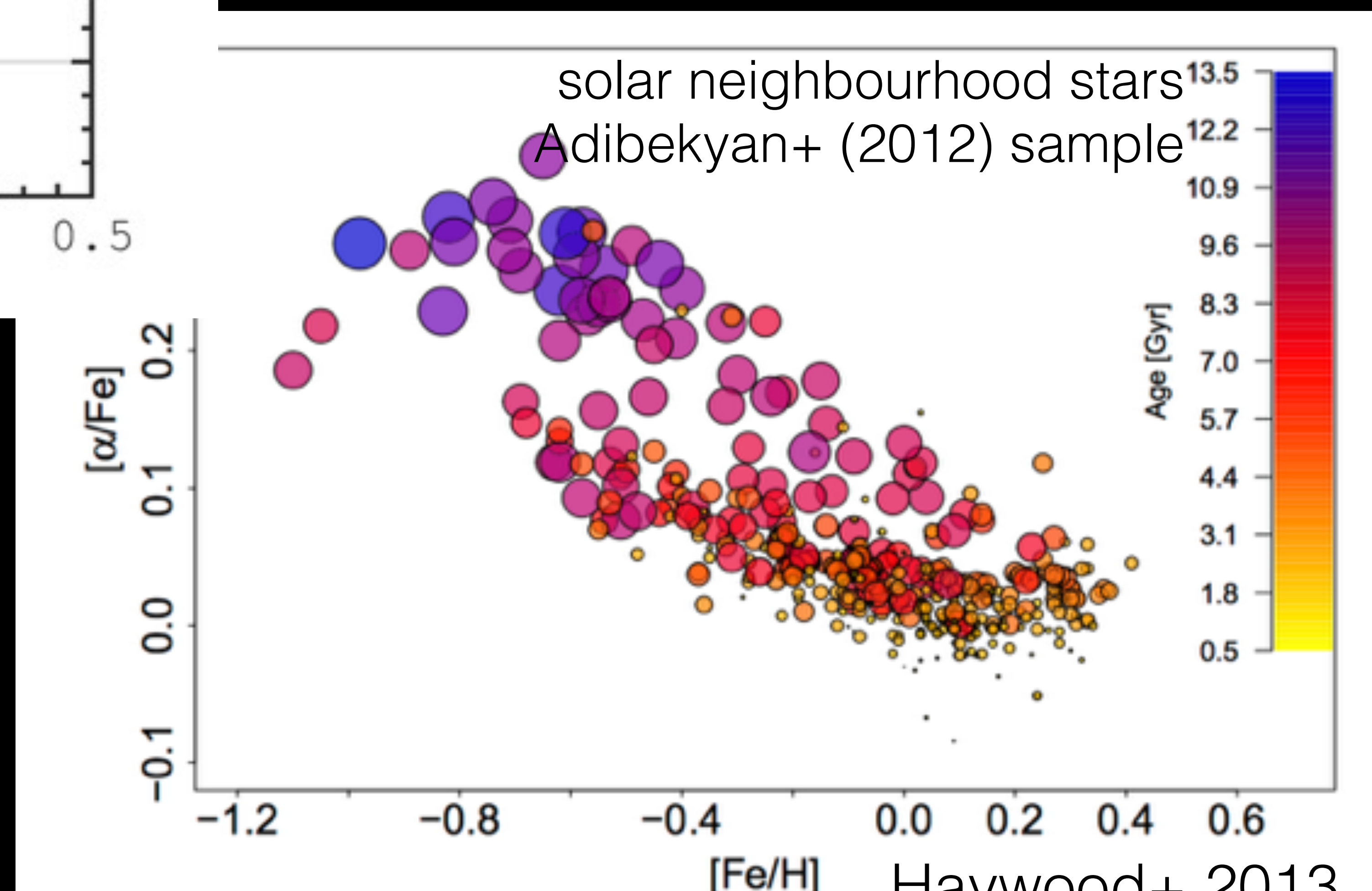
alpha-enriched stars -> star formation was rapid





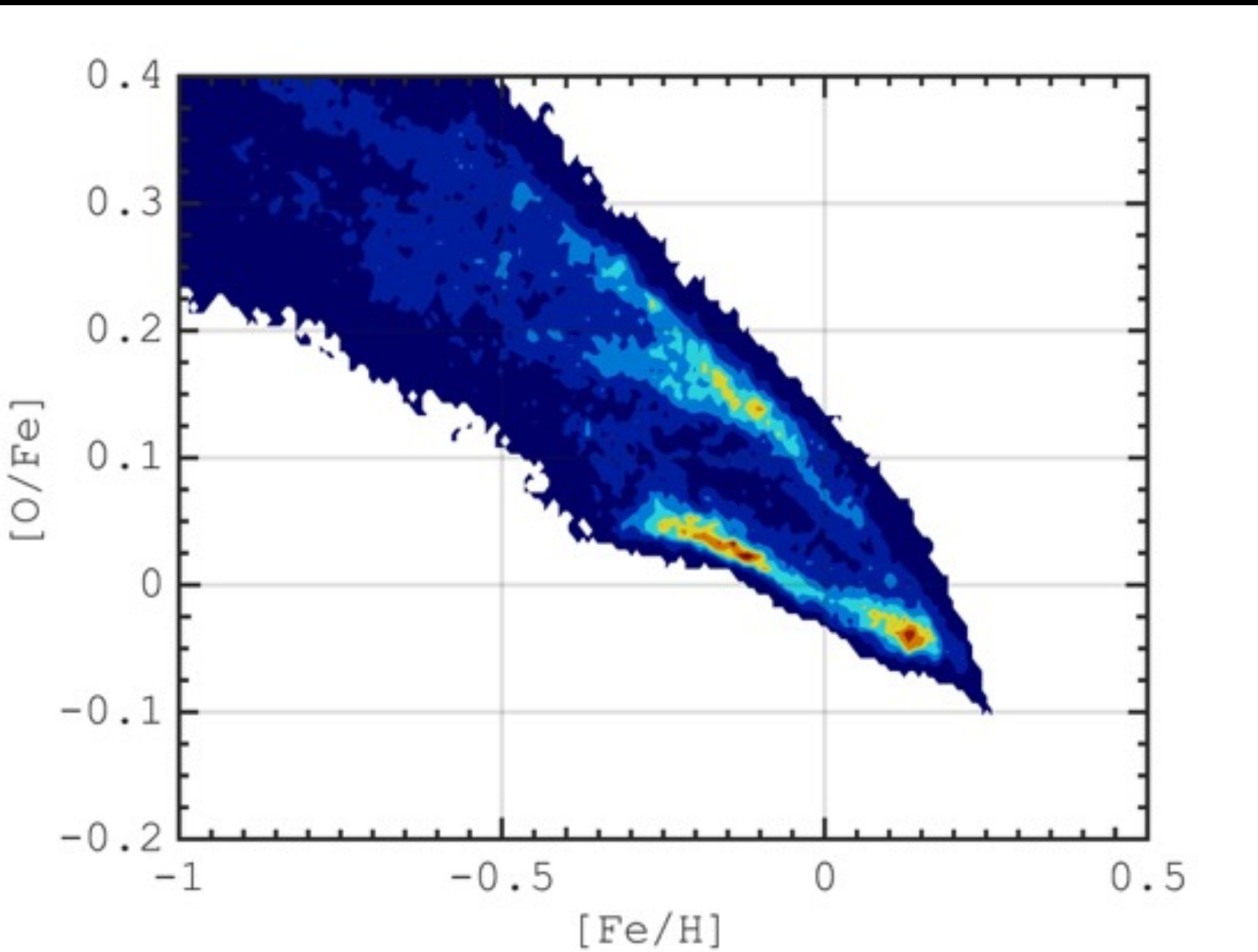
Self-consistent model: [O/Fe]-[Fe/H]

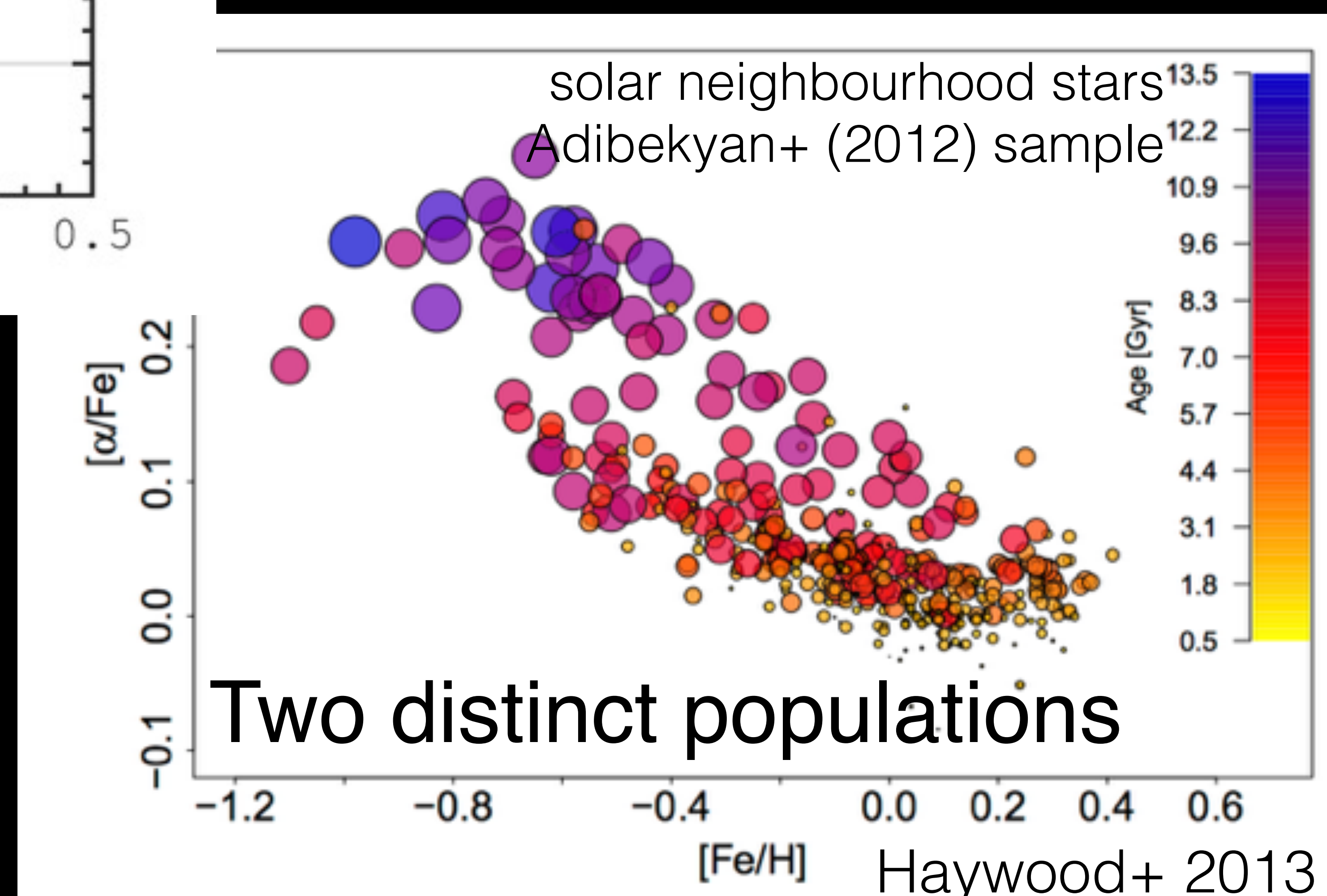




Haywood+ 2013

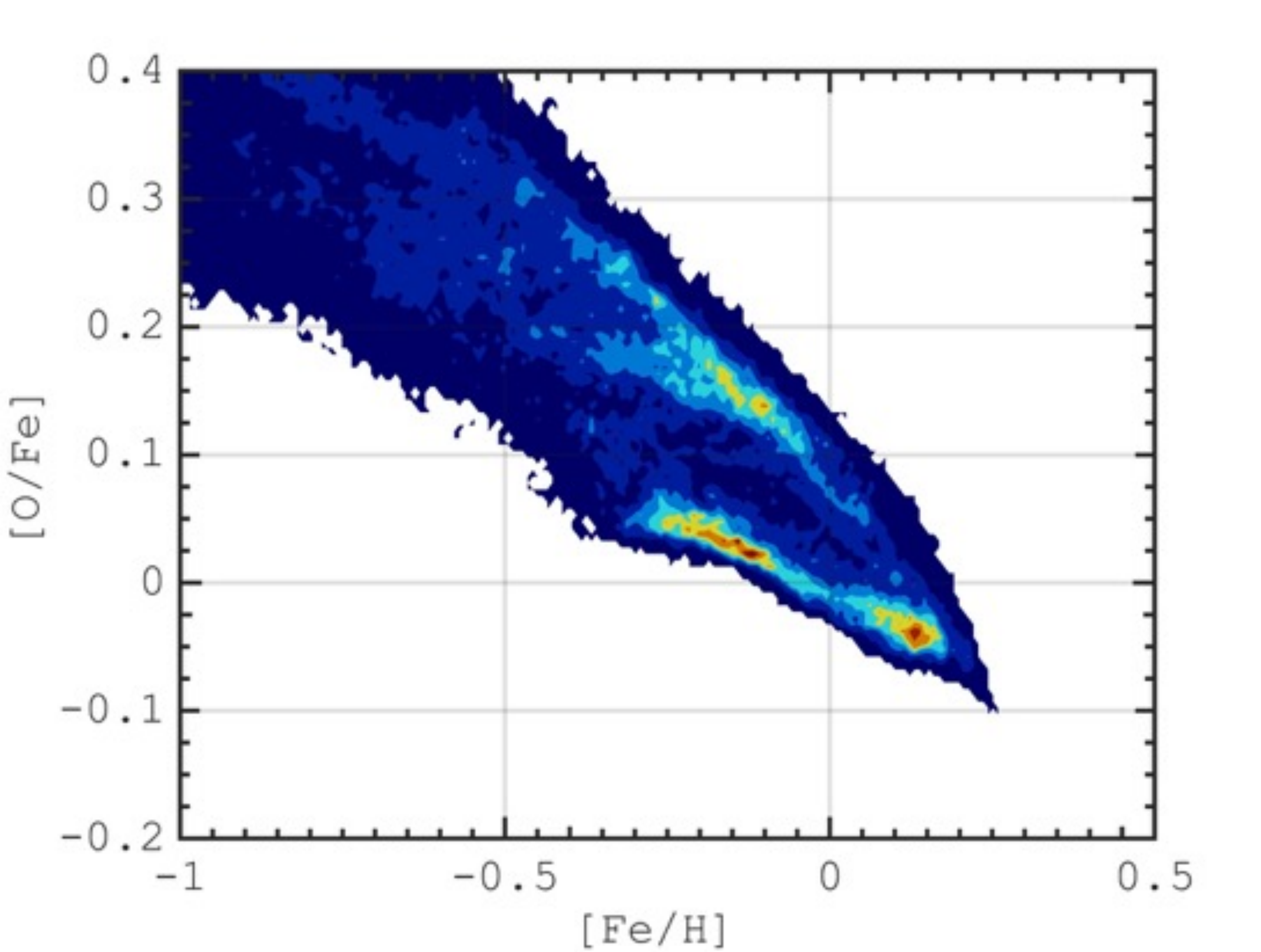
Self-consistent model: [O/Fe]-[Fe/H]

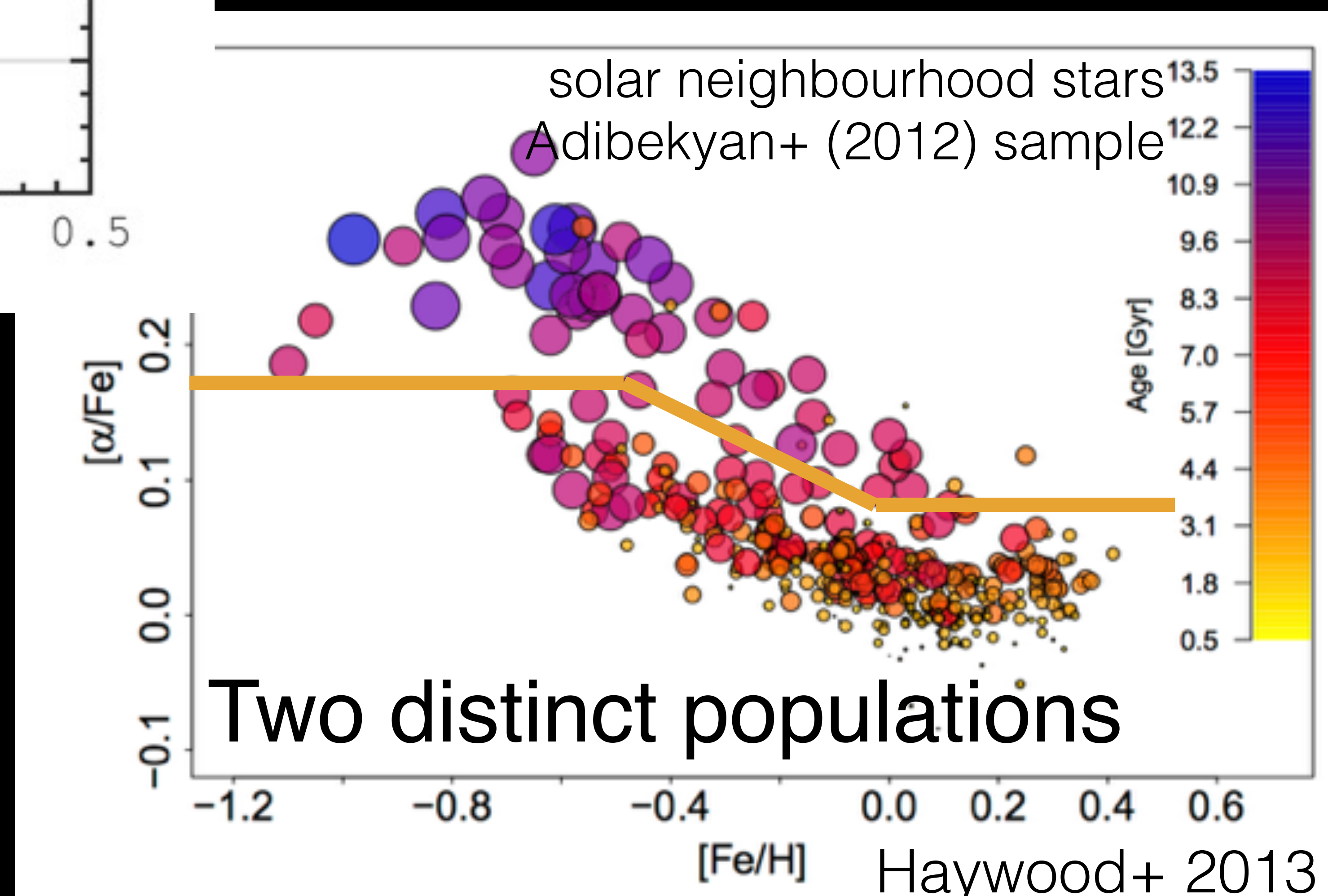




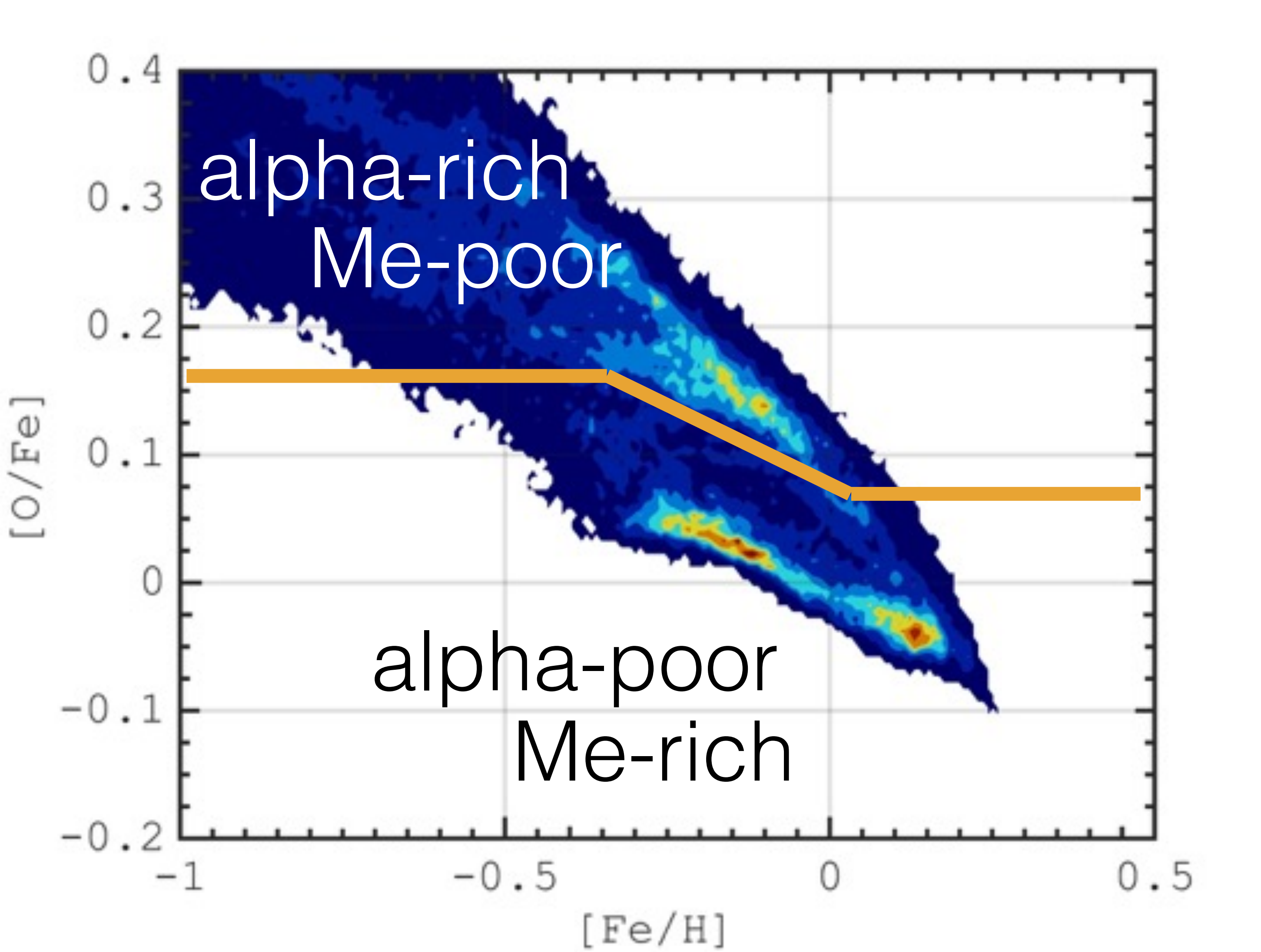
Haywood+ 2013

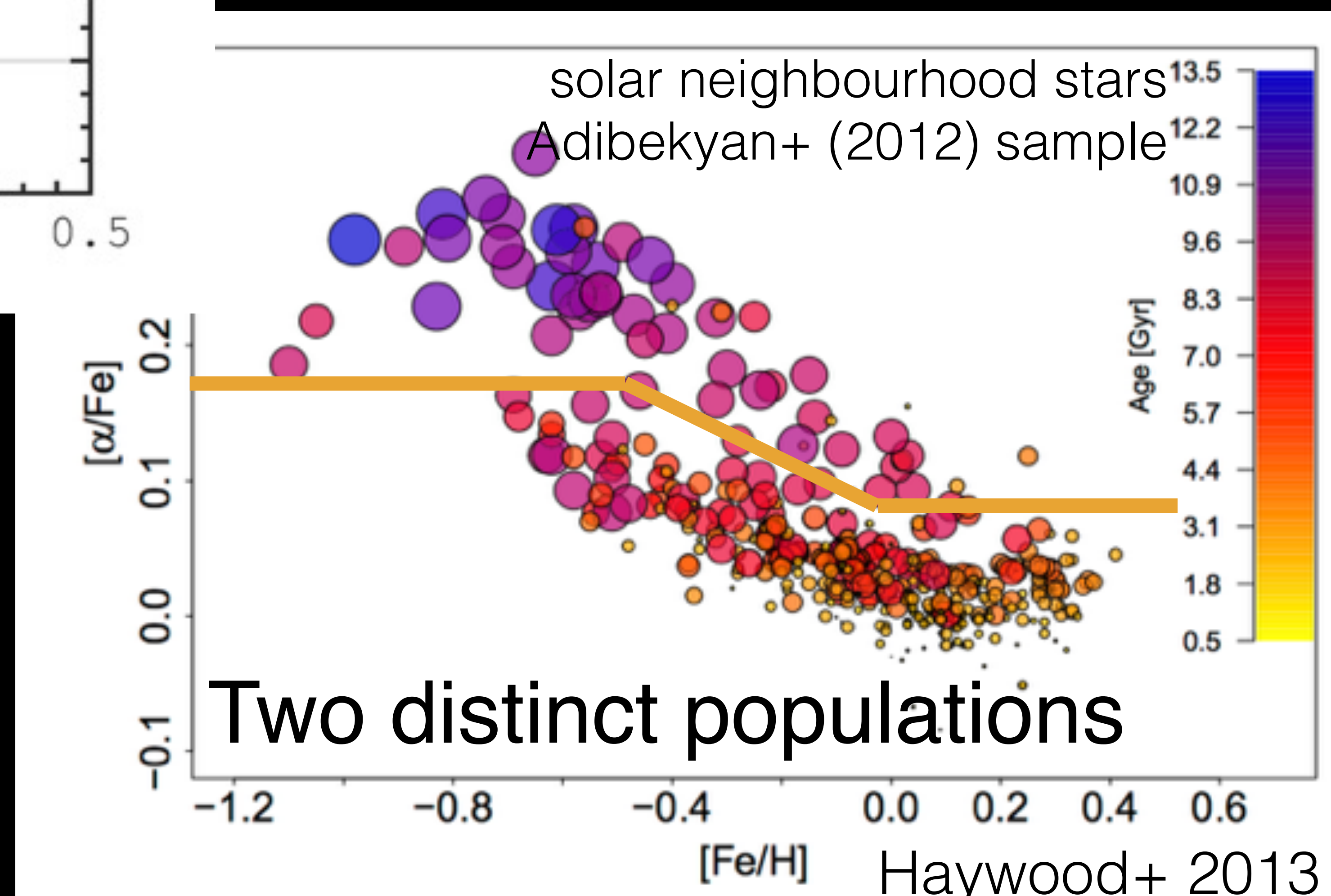
Self-consistent model: [O/Fe]-[Fe/H]





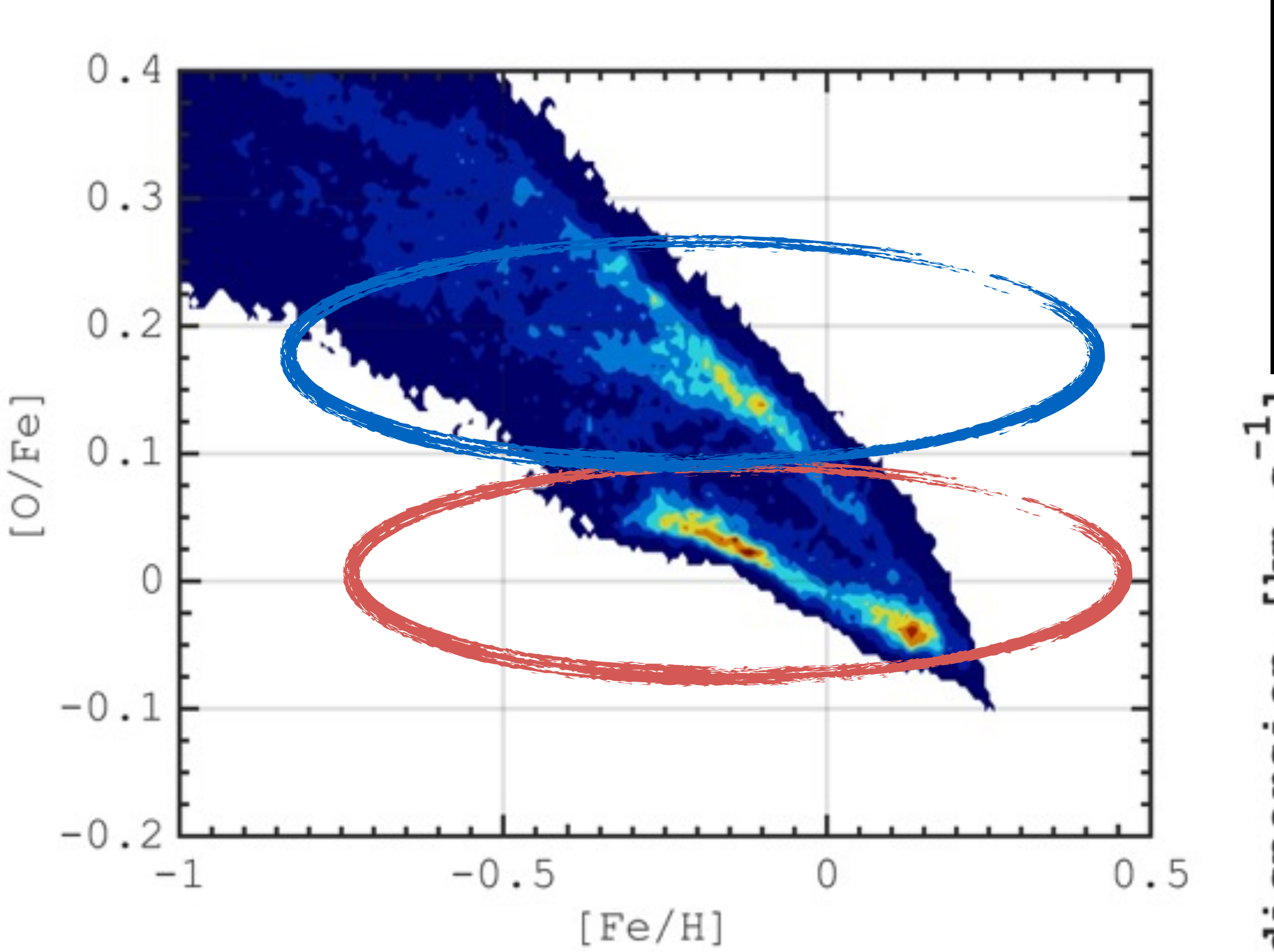
Self-consistent model: [O/Fe]-[Fe/H]

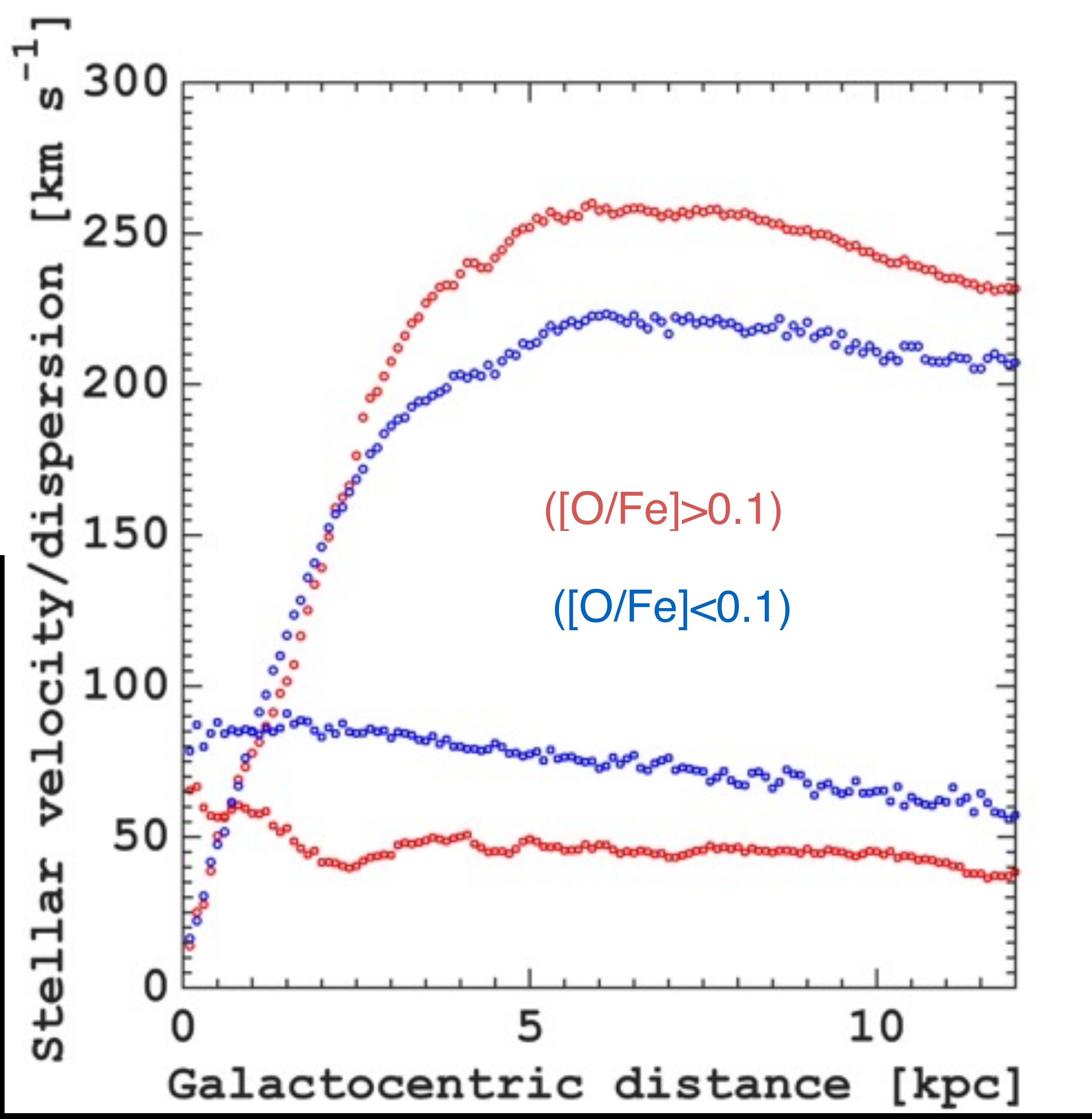




Haywood+ 2013

Self-consistent model: [O/Fe]-[Fe/H]

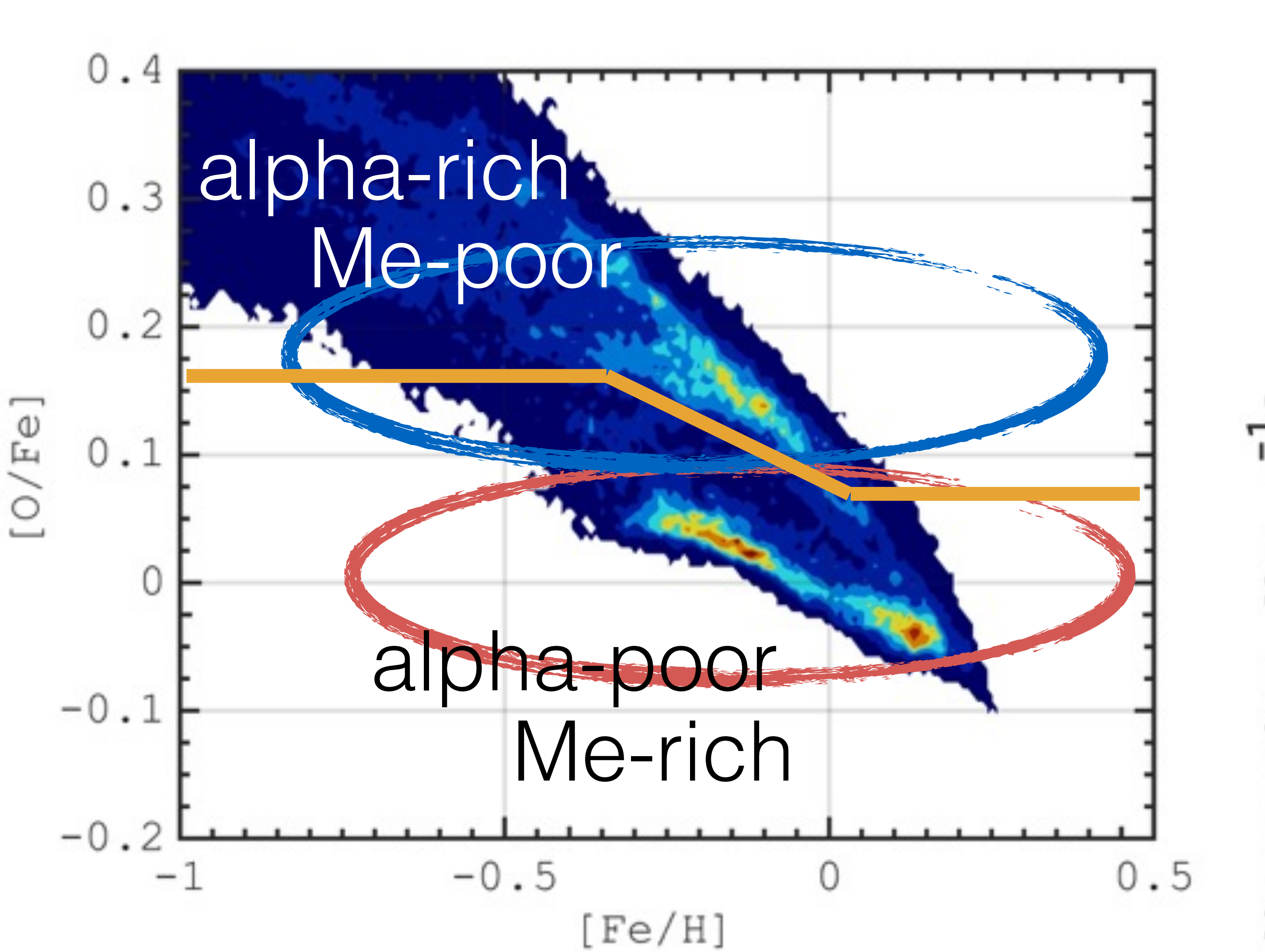


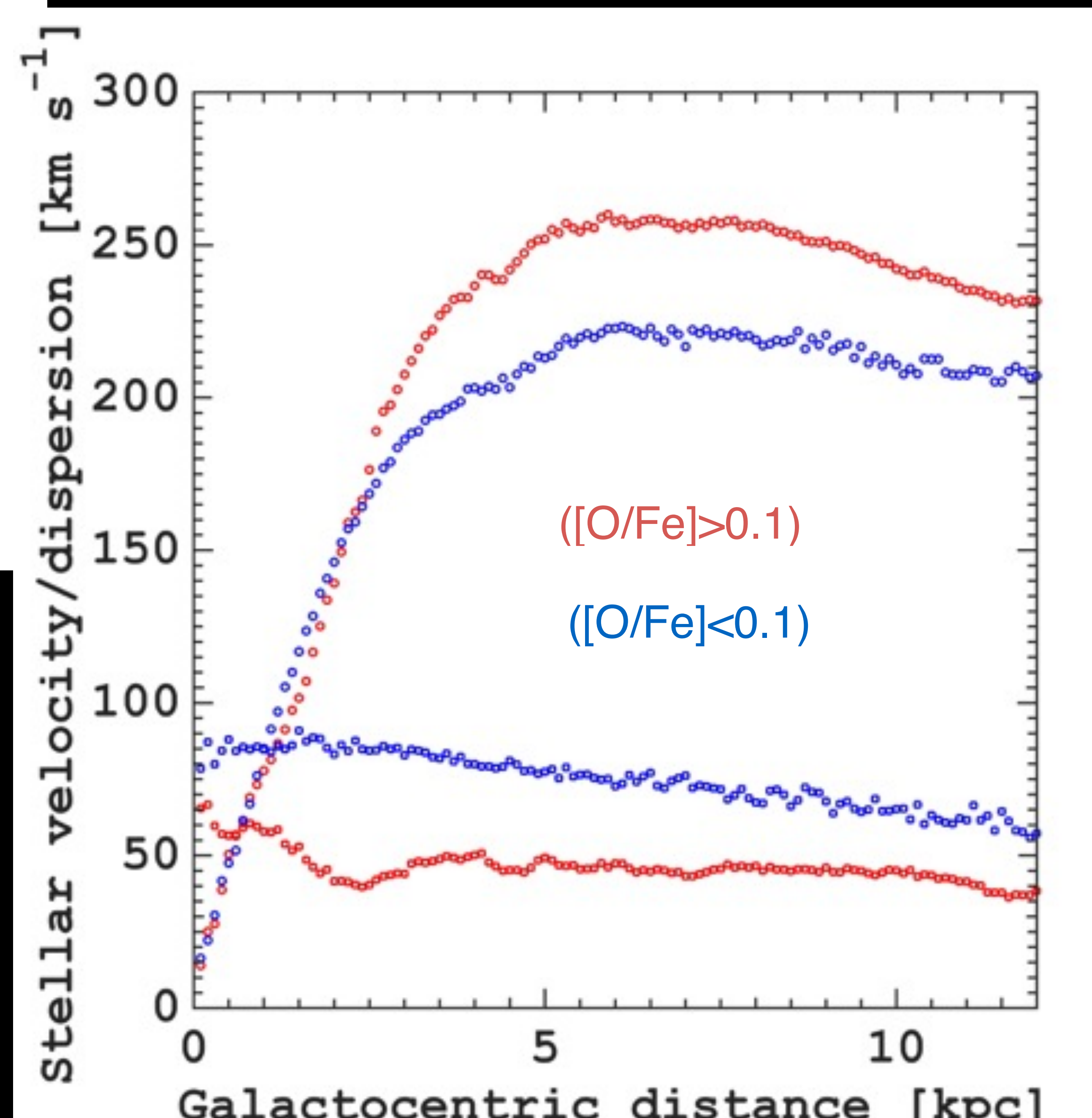


Alpha-enriched disk rotates slower and it is kinematically hotter

Two kinematically different populations

Self-consistent model: [O/Fe]-[Fe/H]

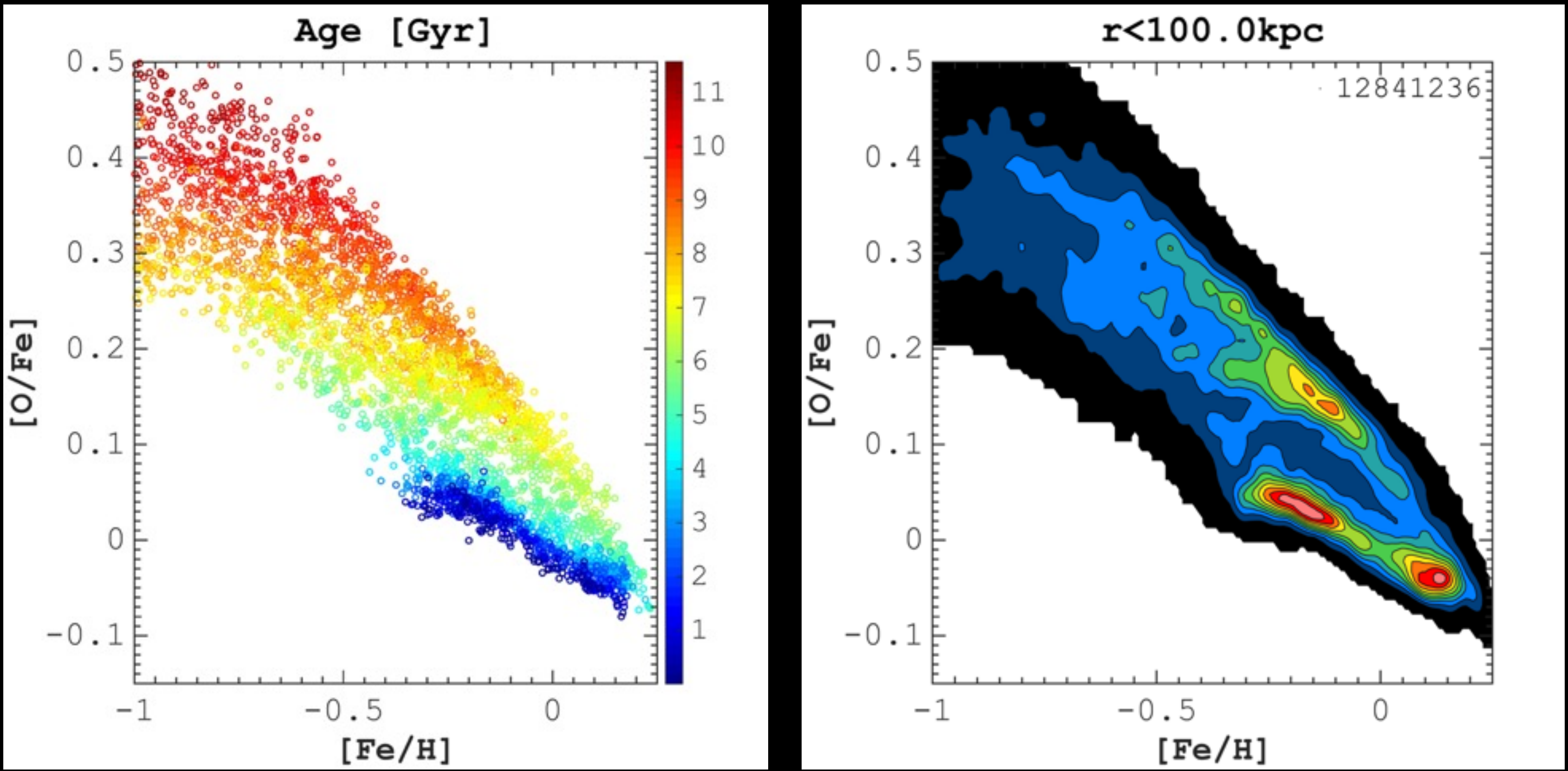




Alpha-enriched disk rotates slower
and it is kinematically hotter

Two kinematically
different populations

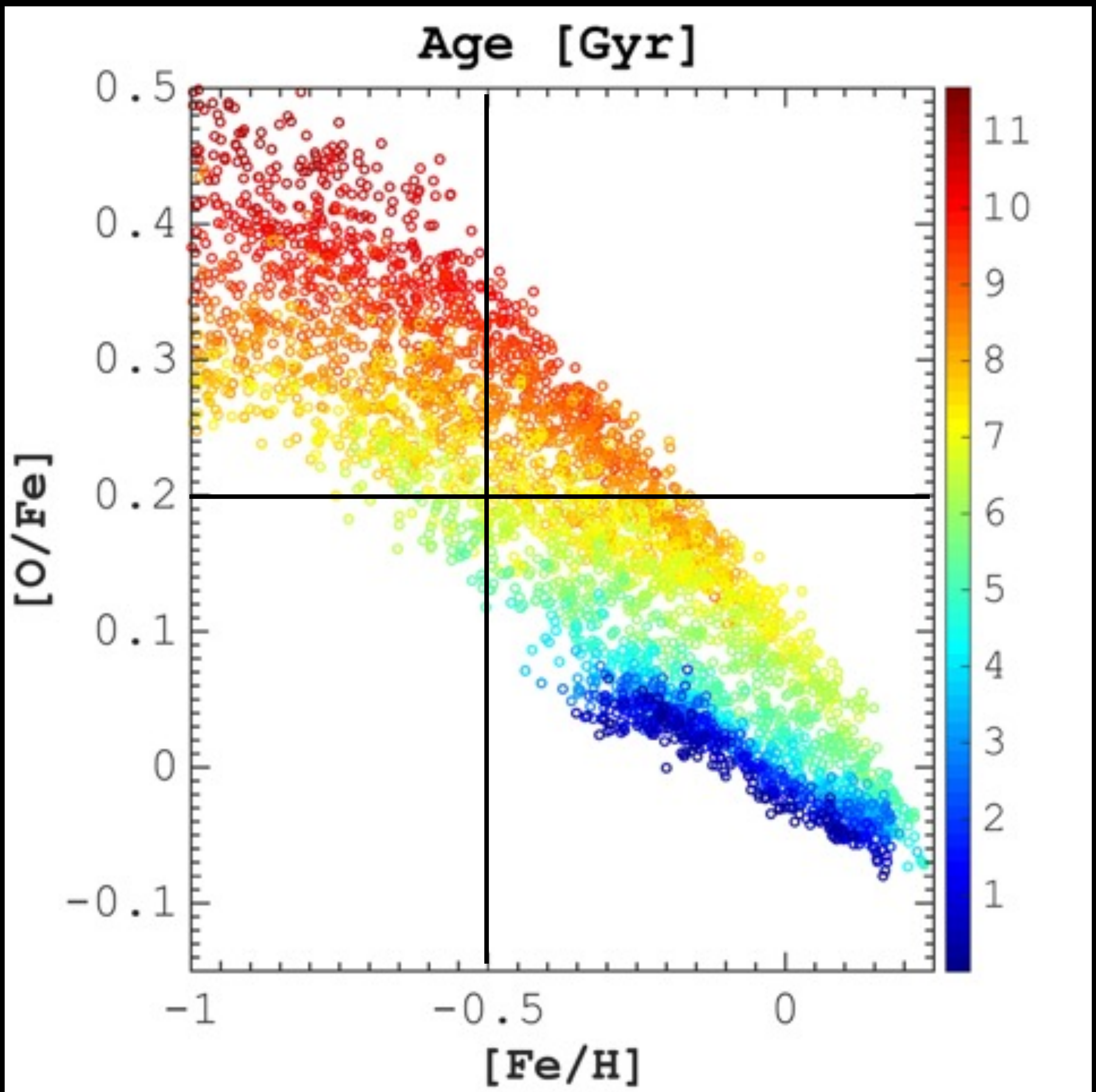
Alpha-age-metallicity relation

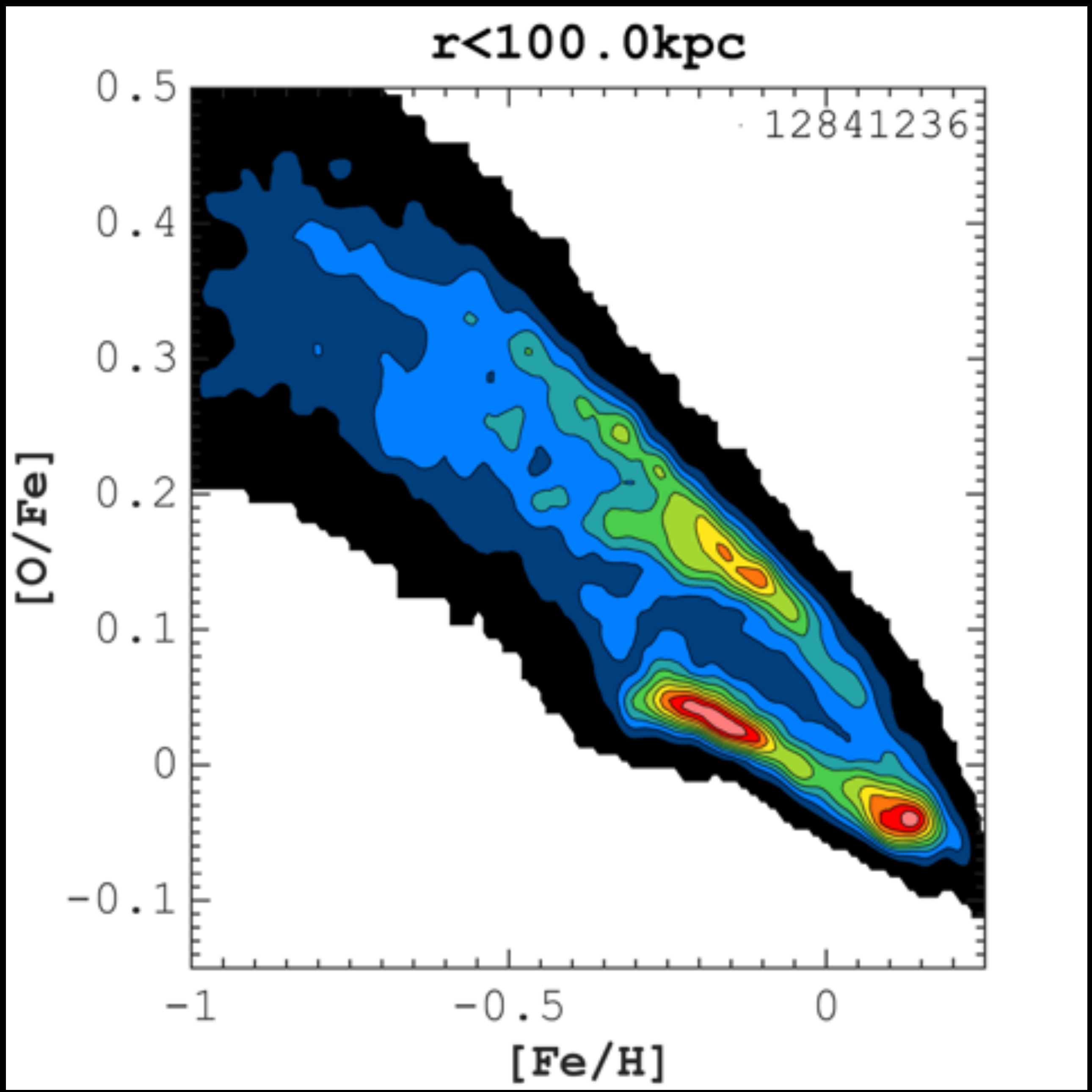


Stellar populations:

Mono-age ≠ Mono-abundance

Alpha-age-metallicity relation

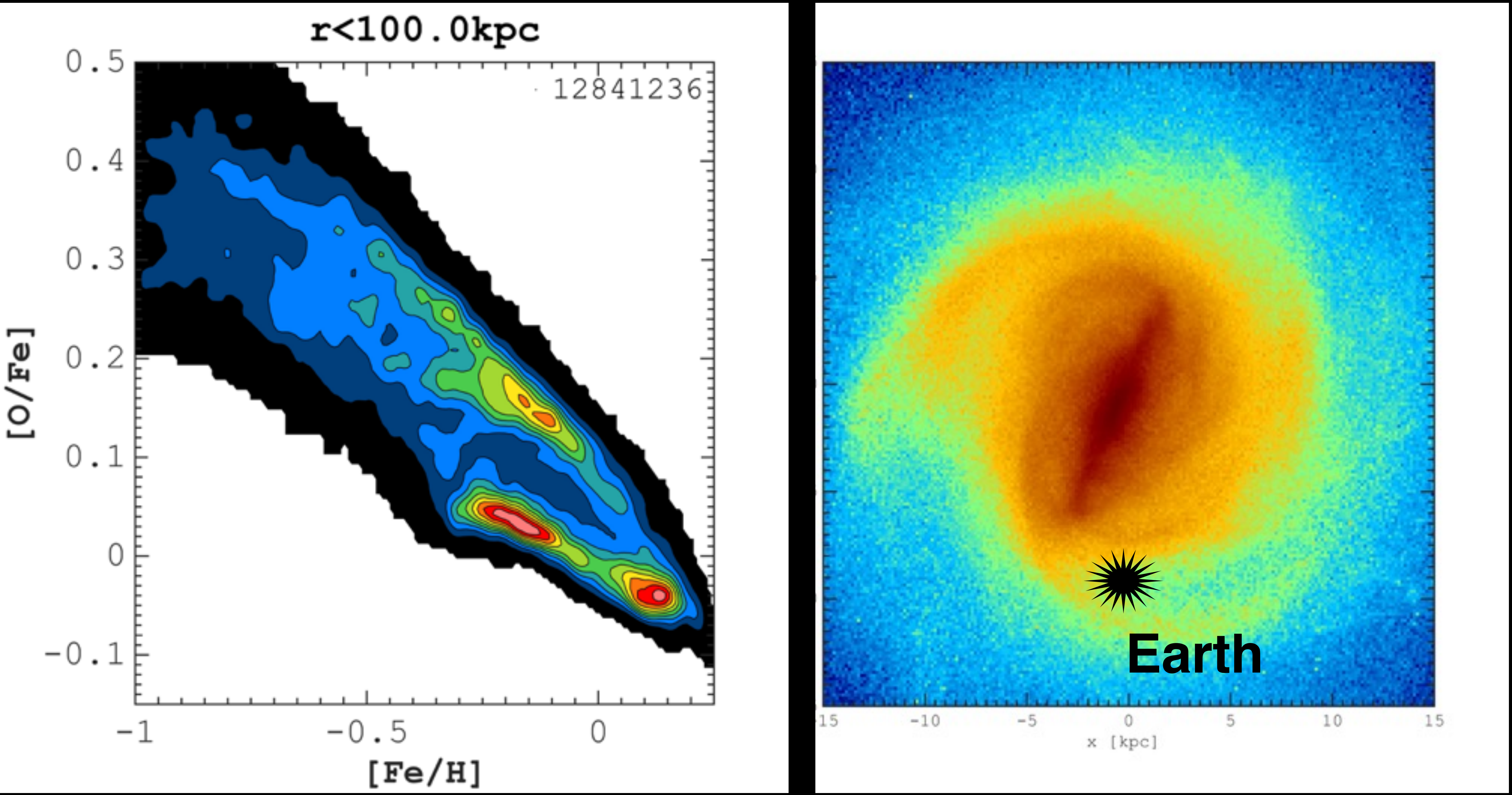




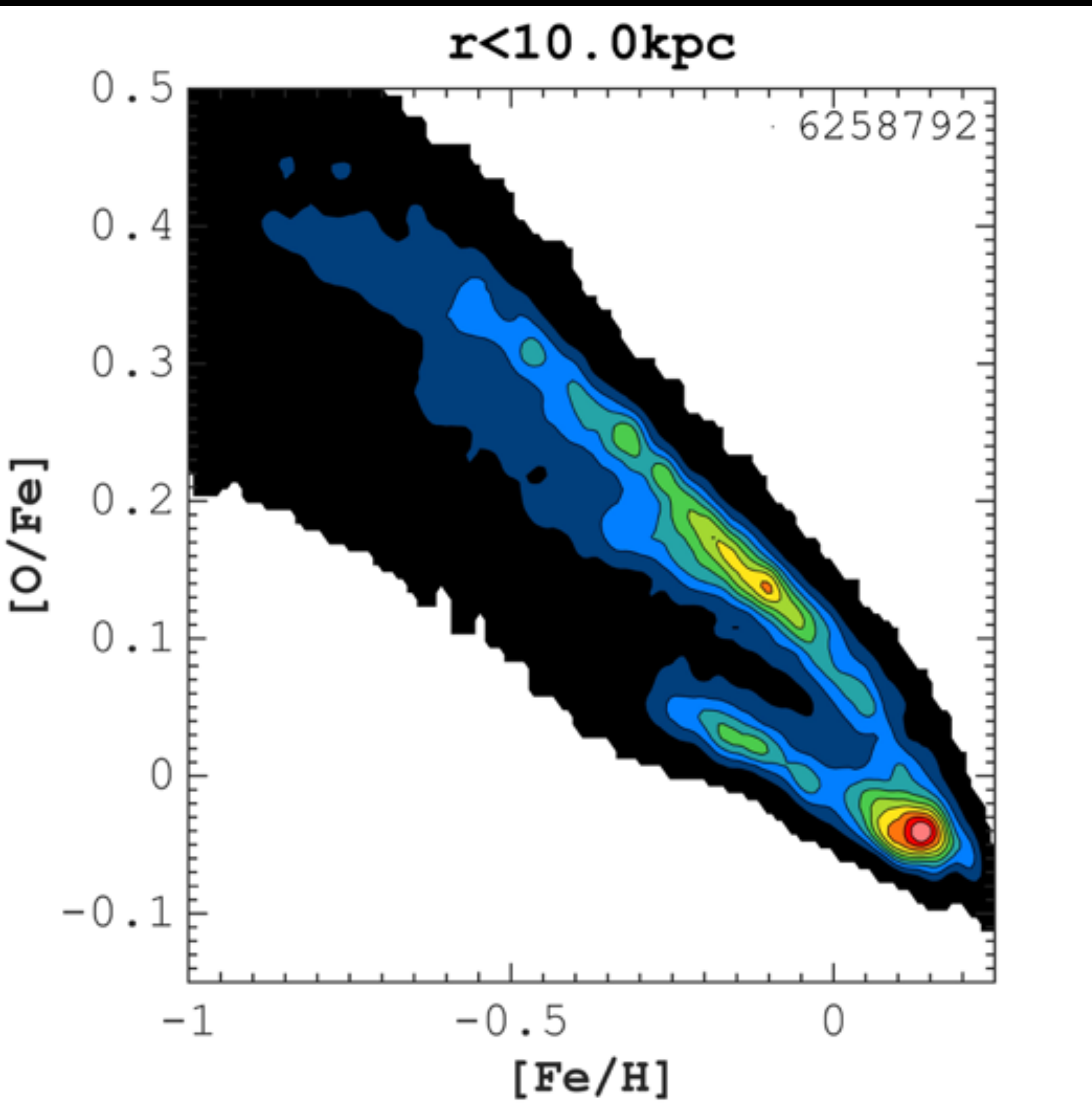
Stellar populations:

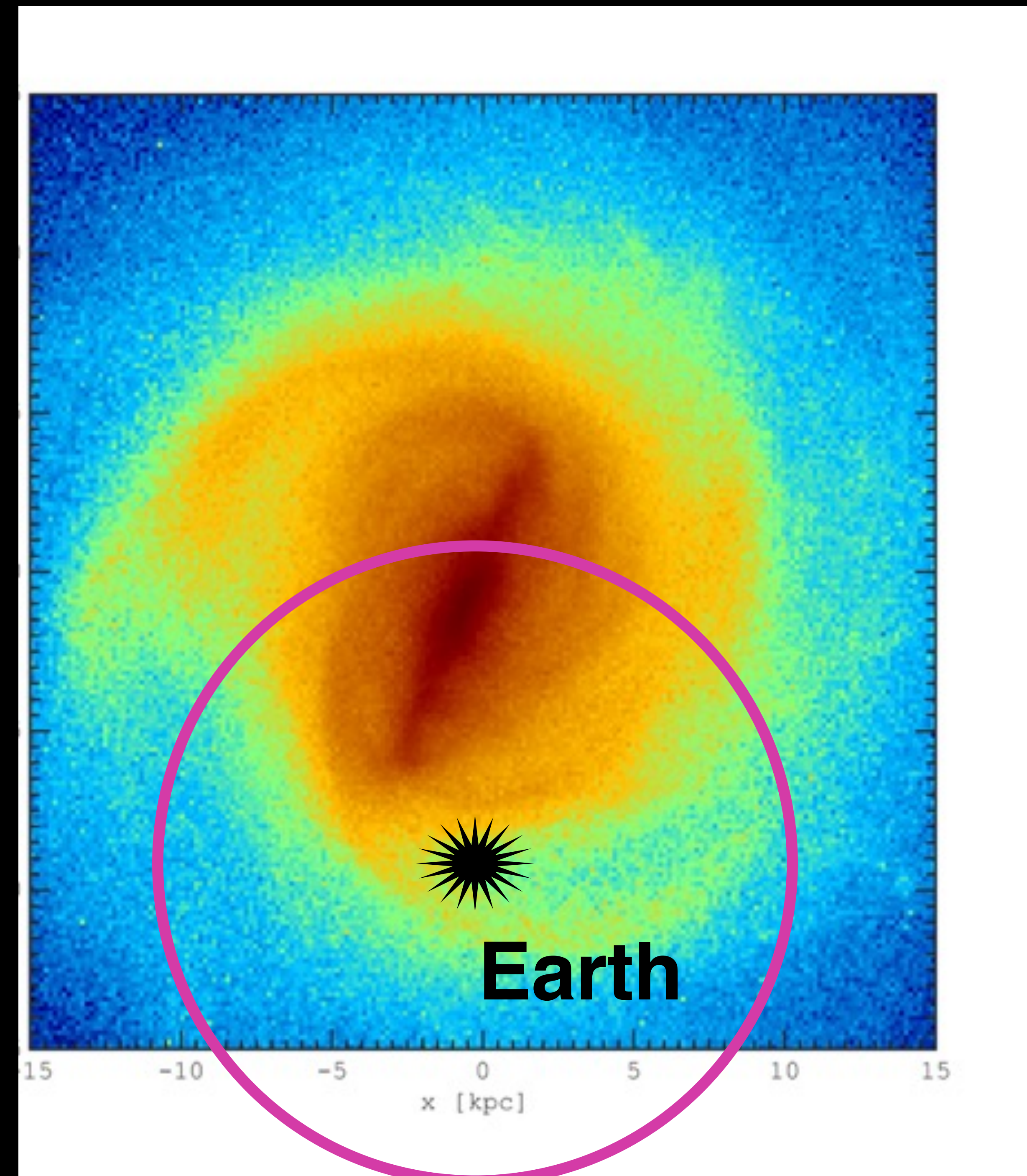
Mono-age ≠ Mono-abundance

Alpha-metallicity relation

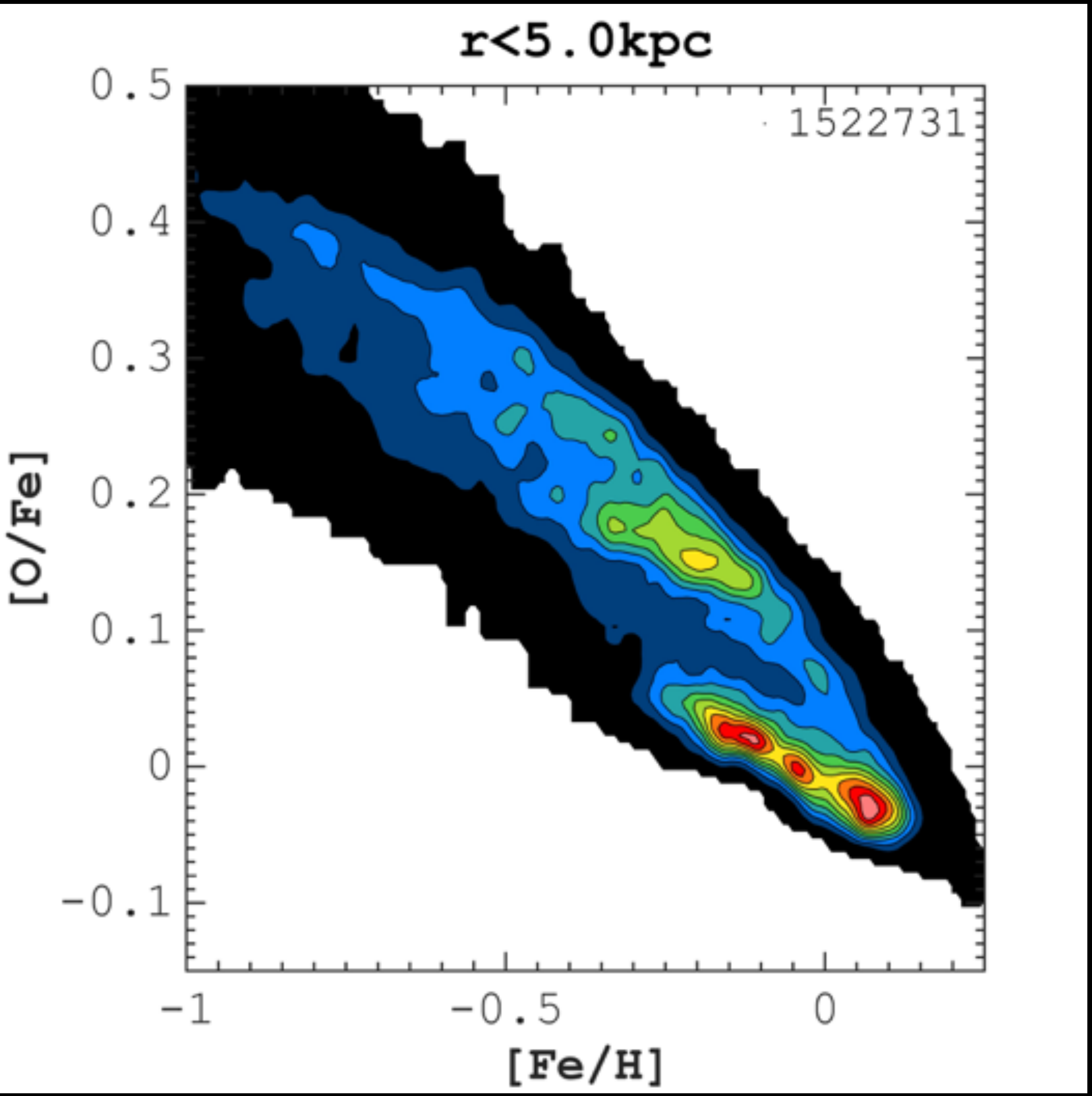


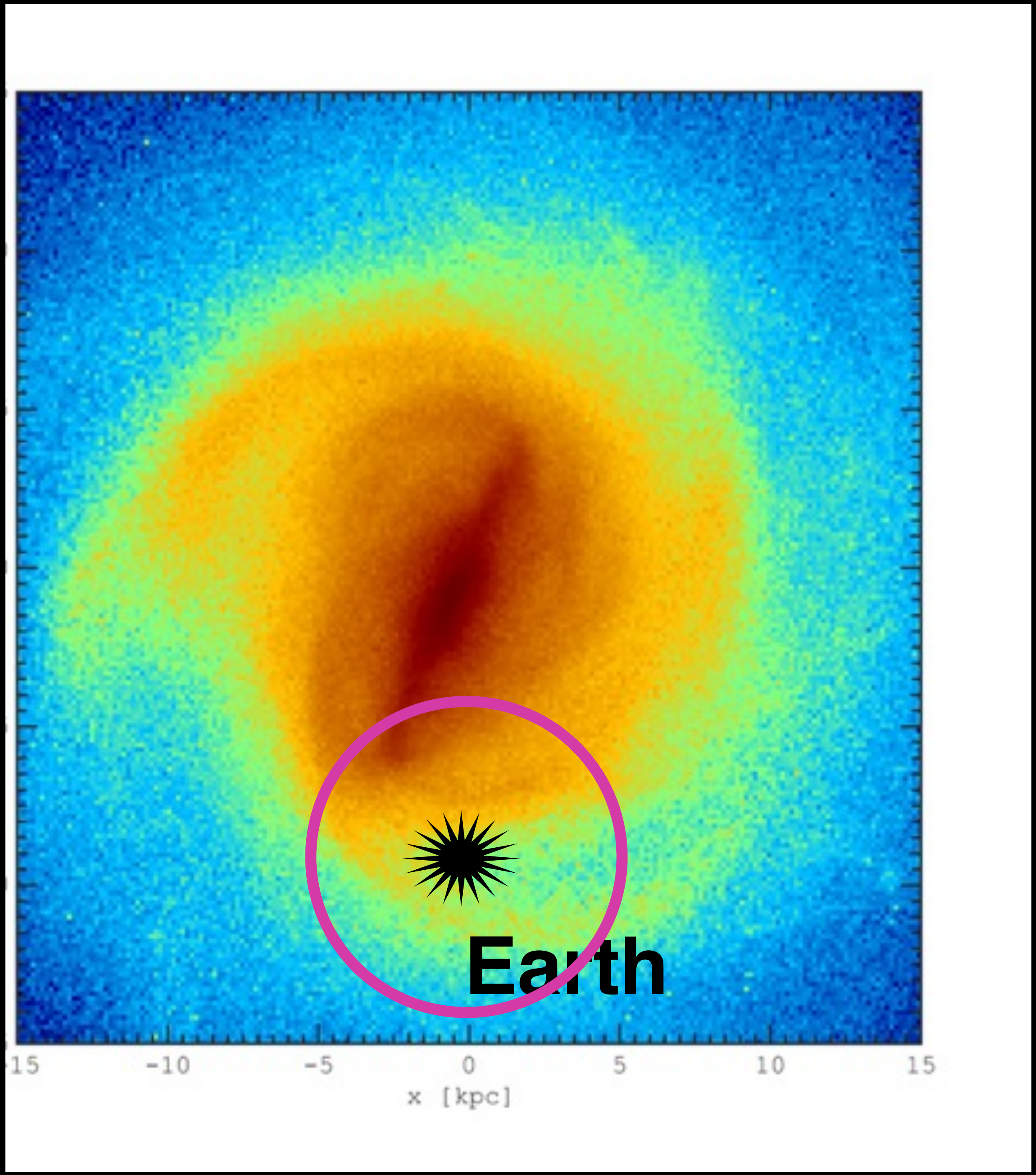
Alpha-metallicity relation



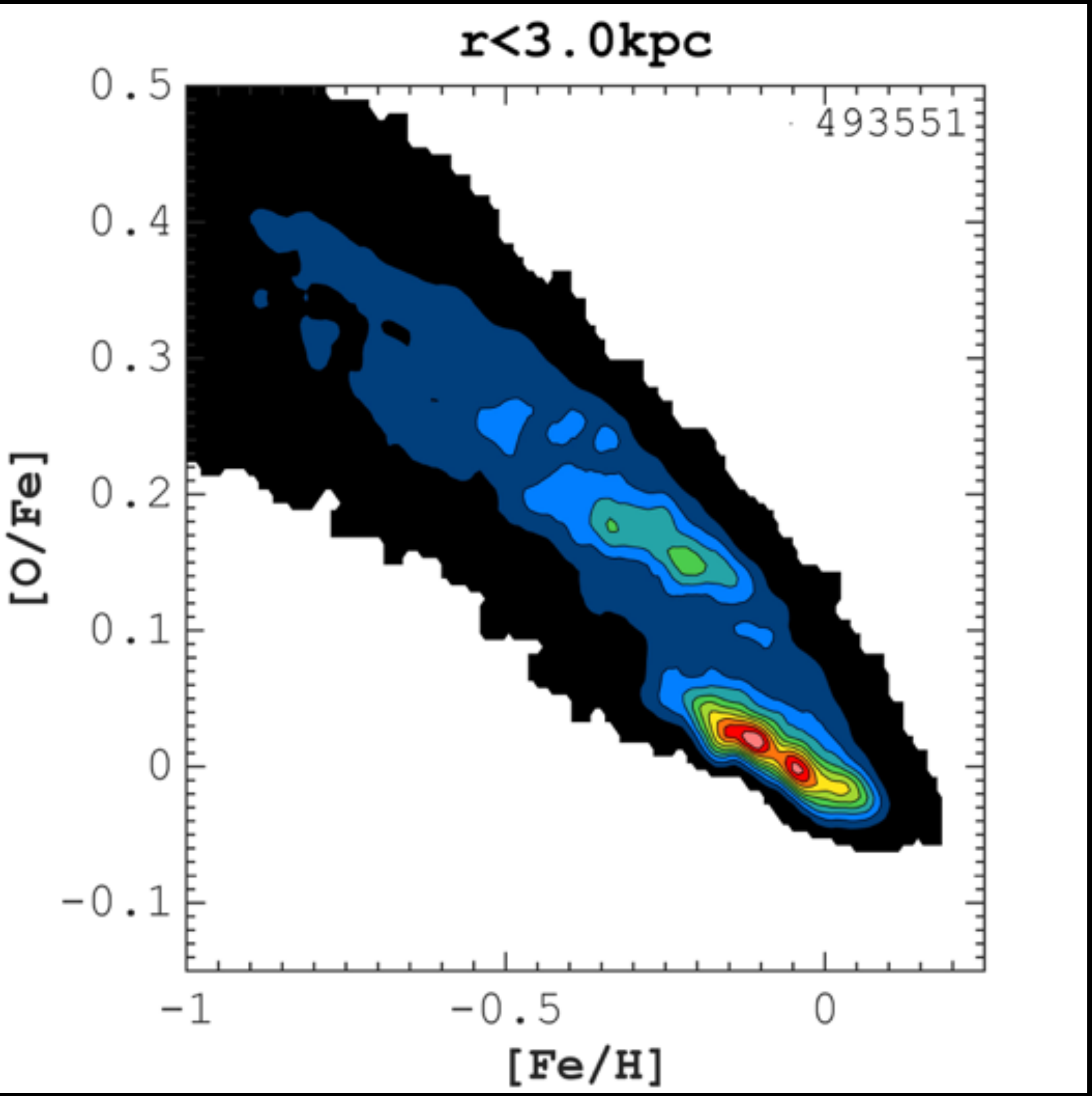


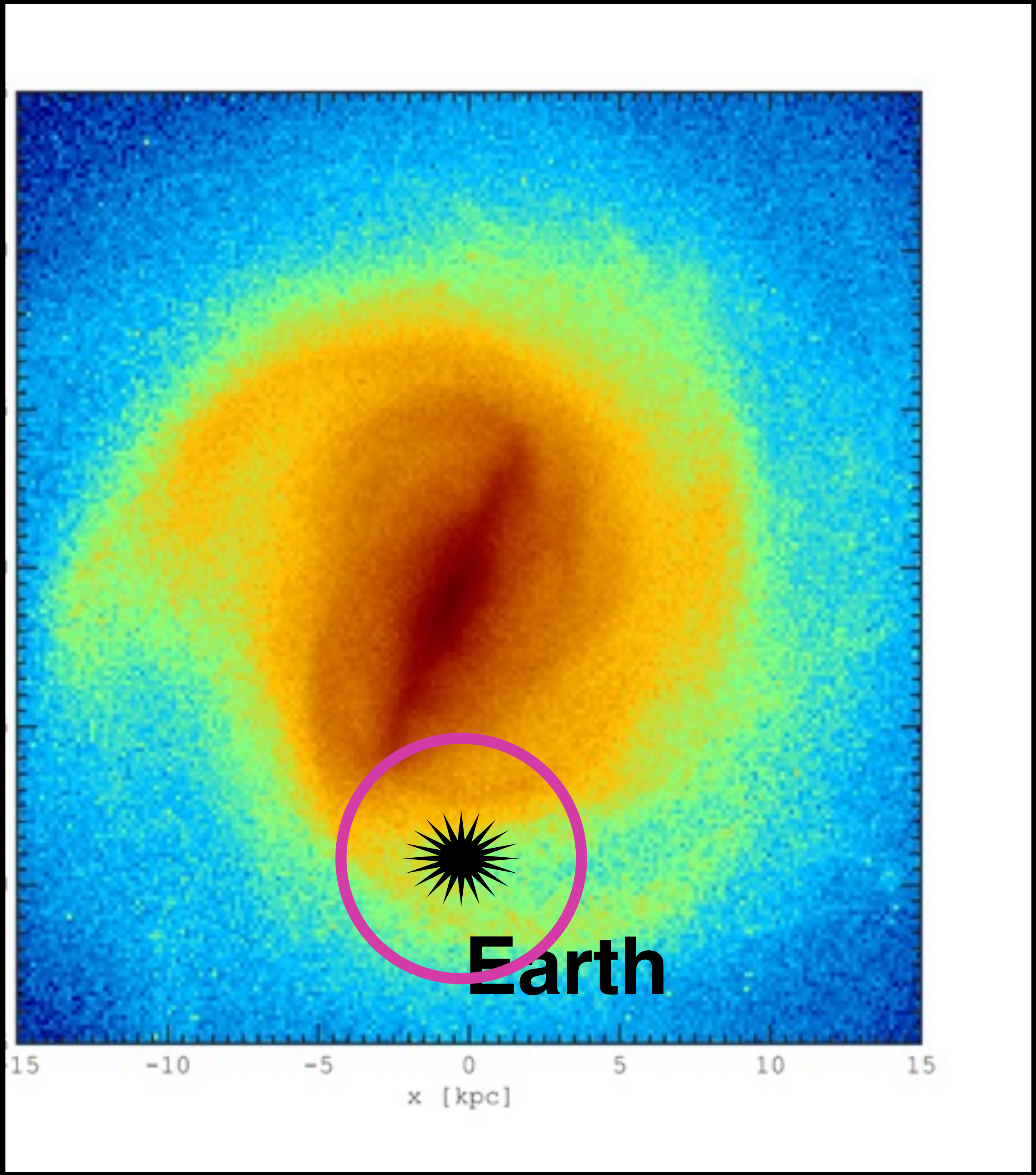
Alpha-metallicity relation



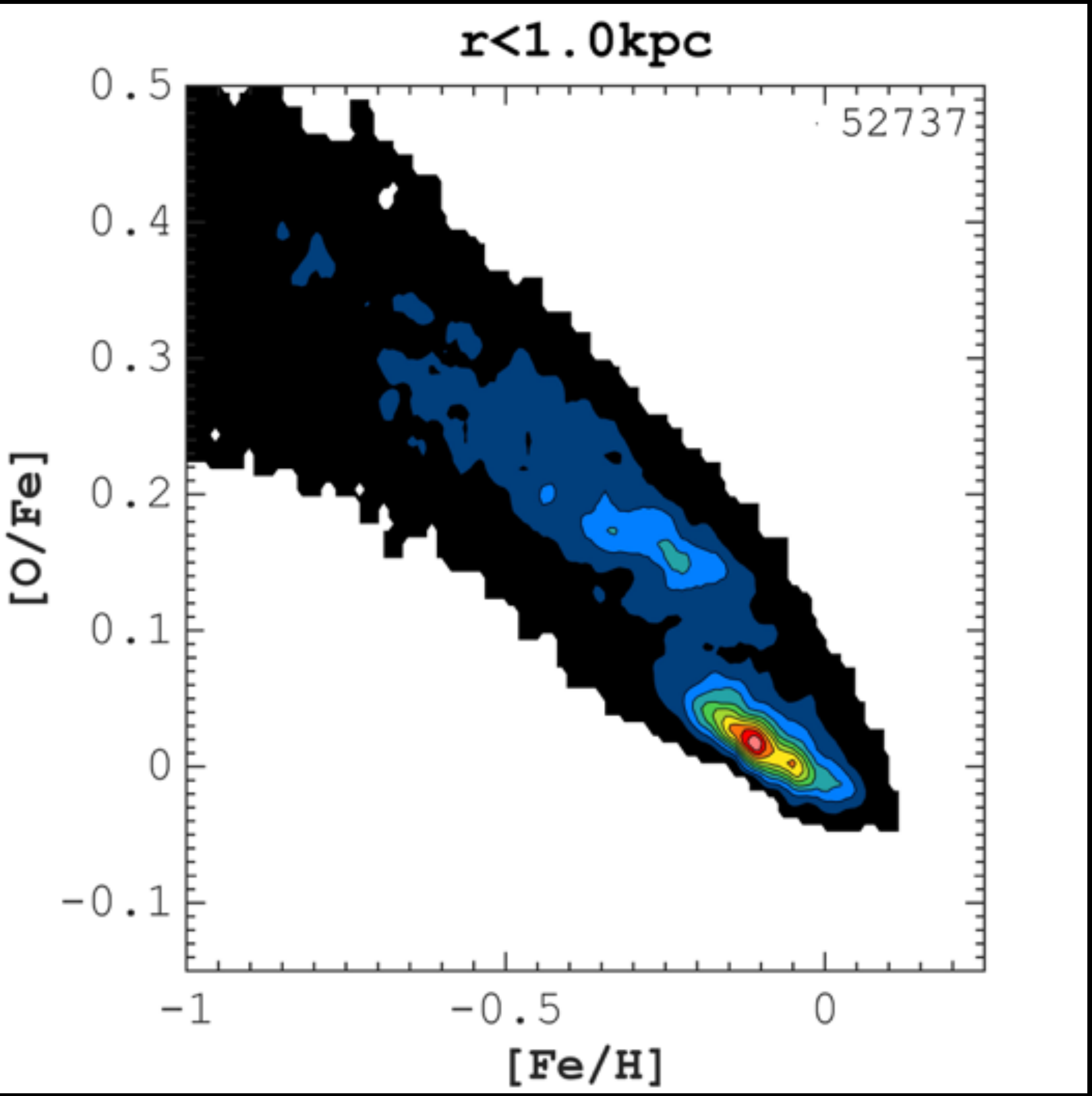


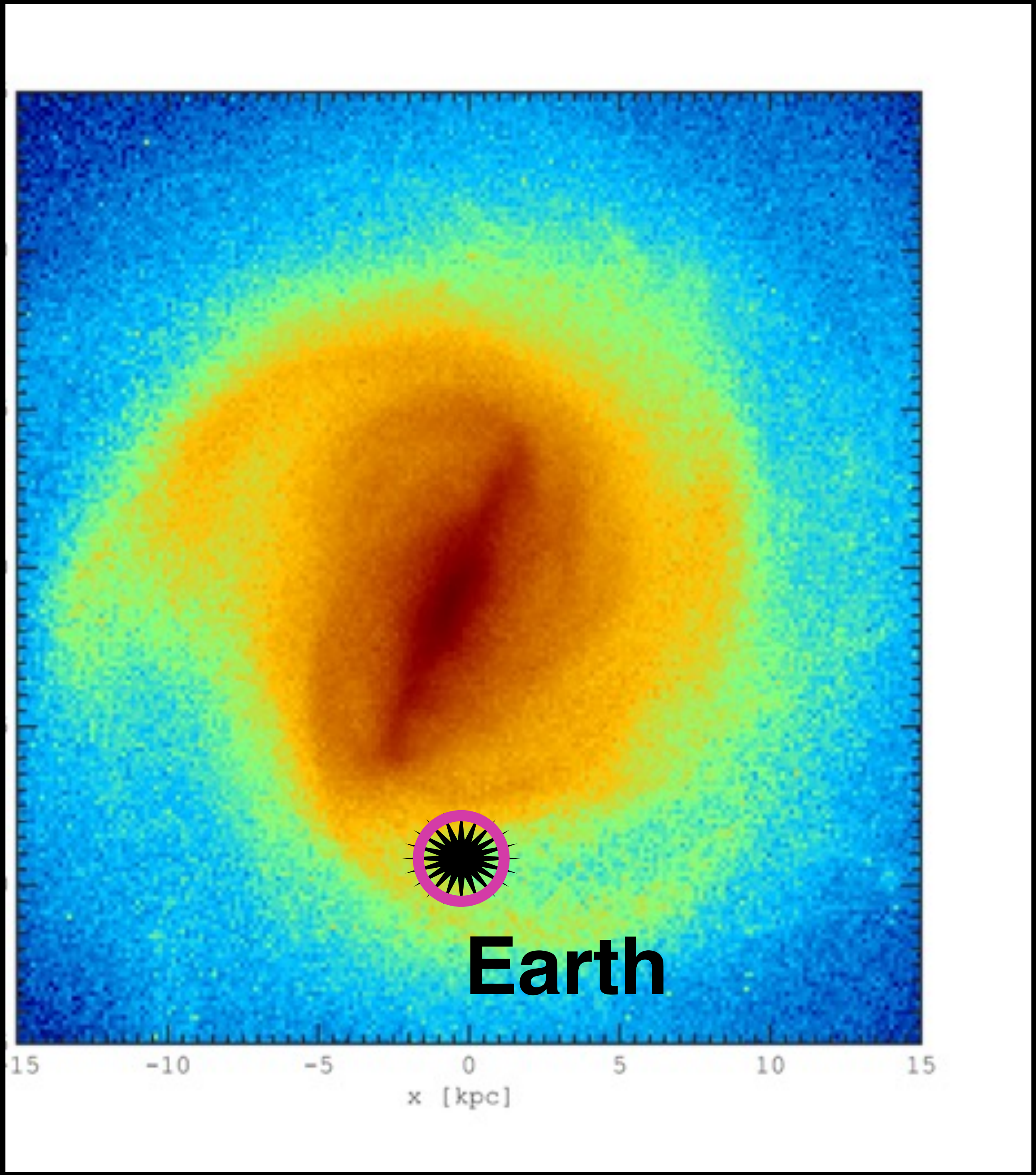
Alpha-metallicity relation



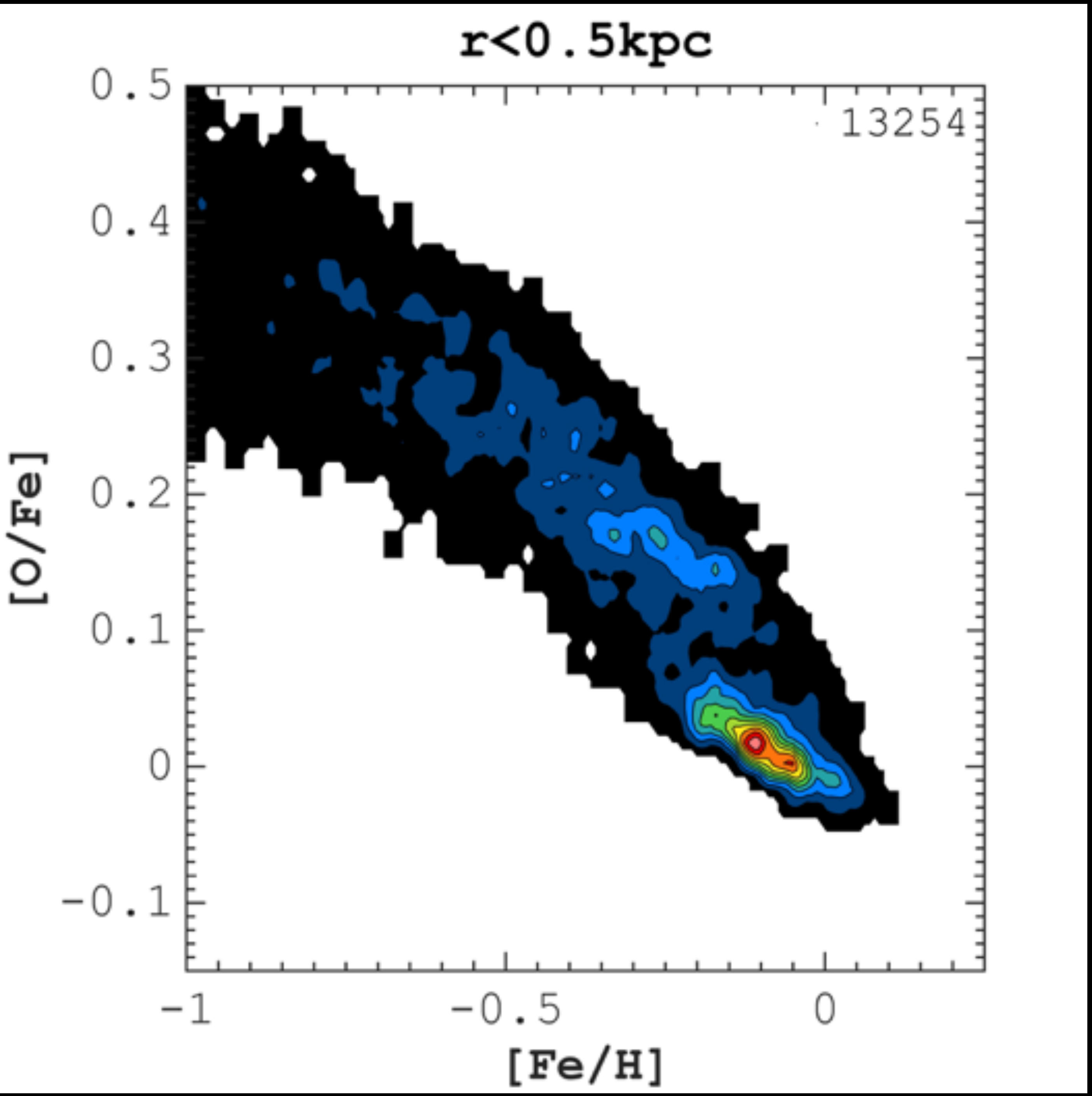


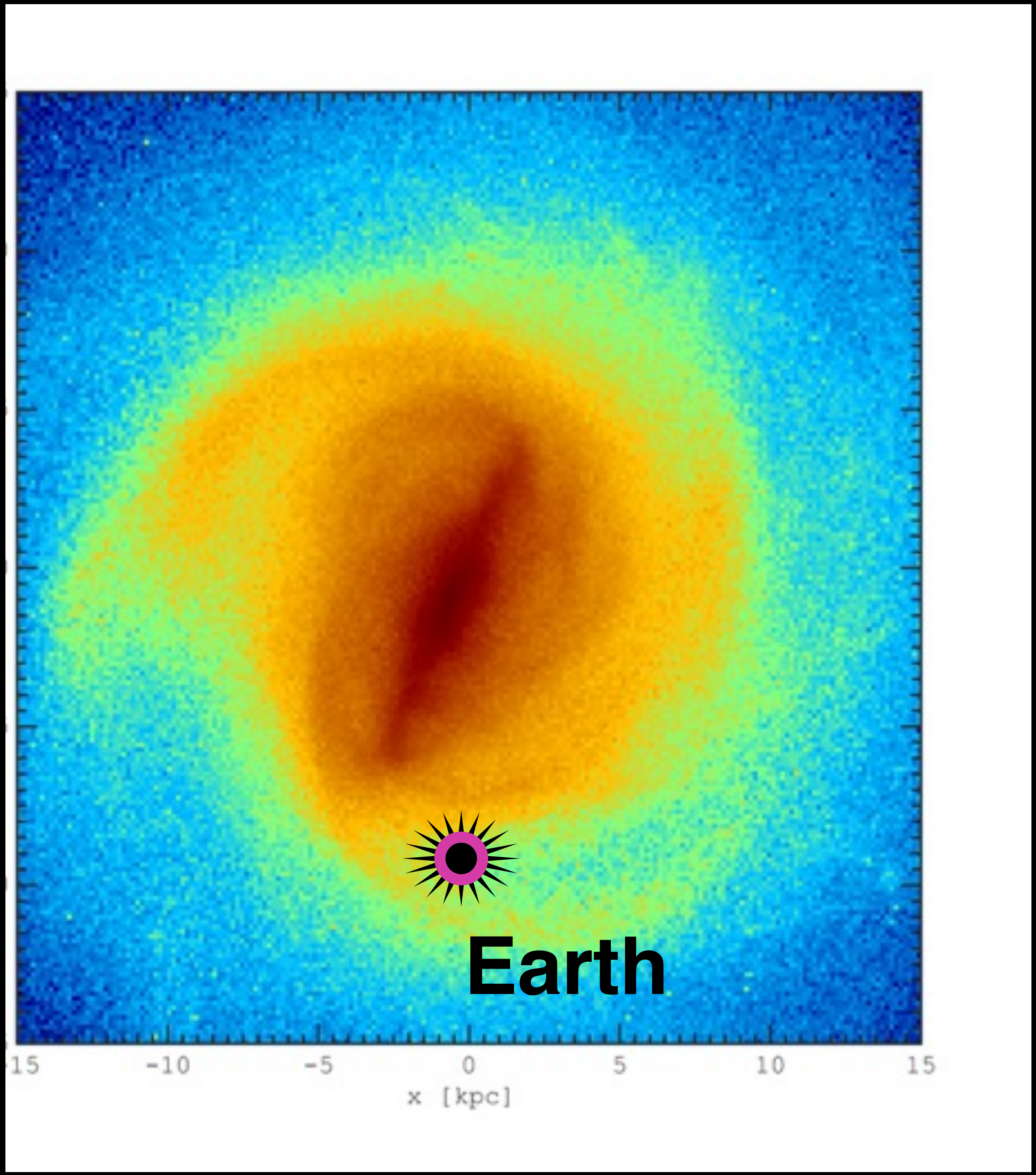
Alpha-metallicity relation





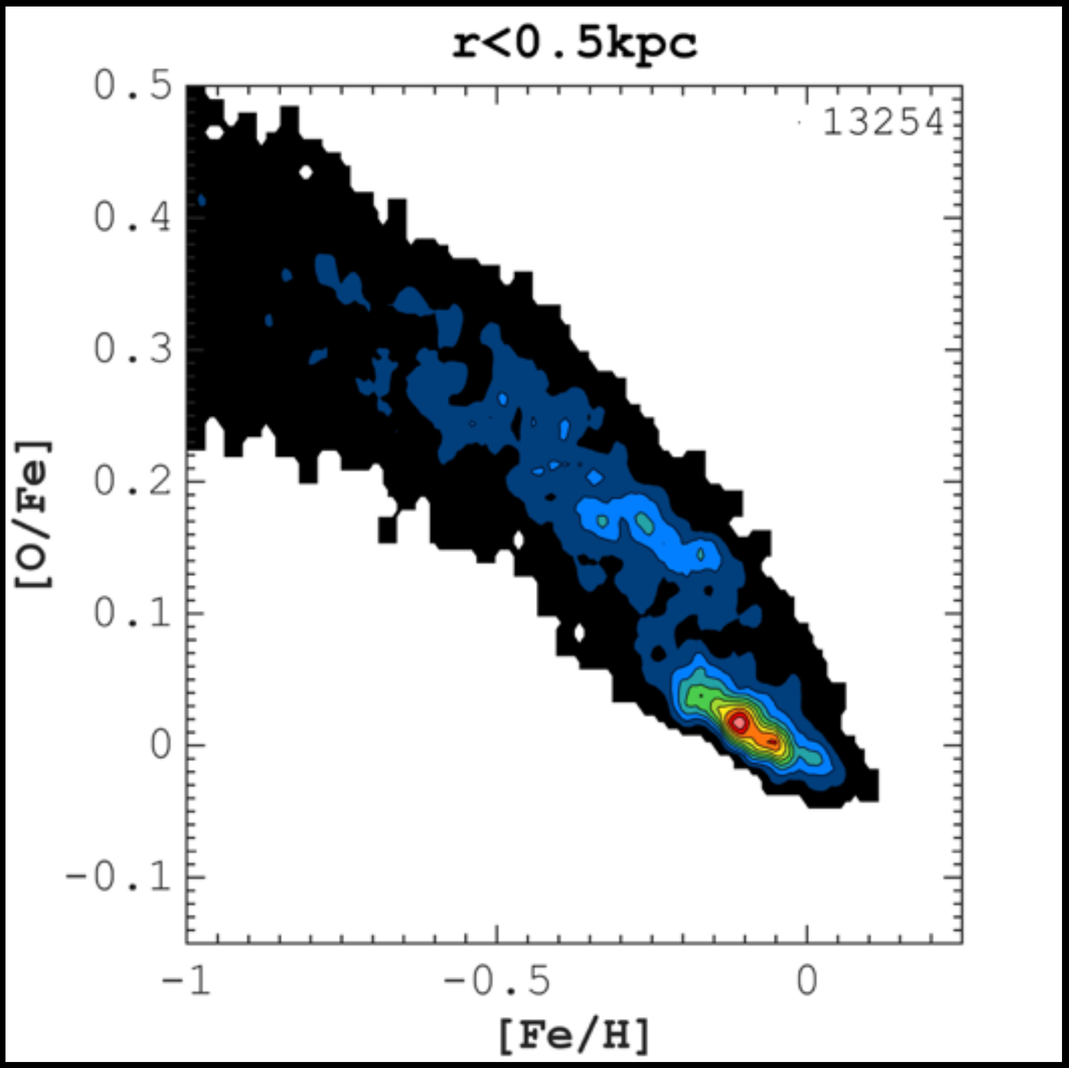
Alpha-metallicity relation



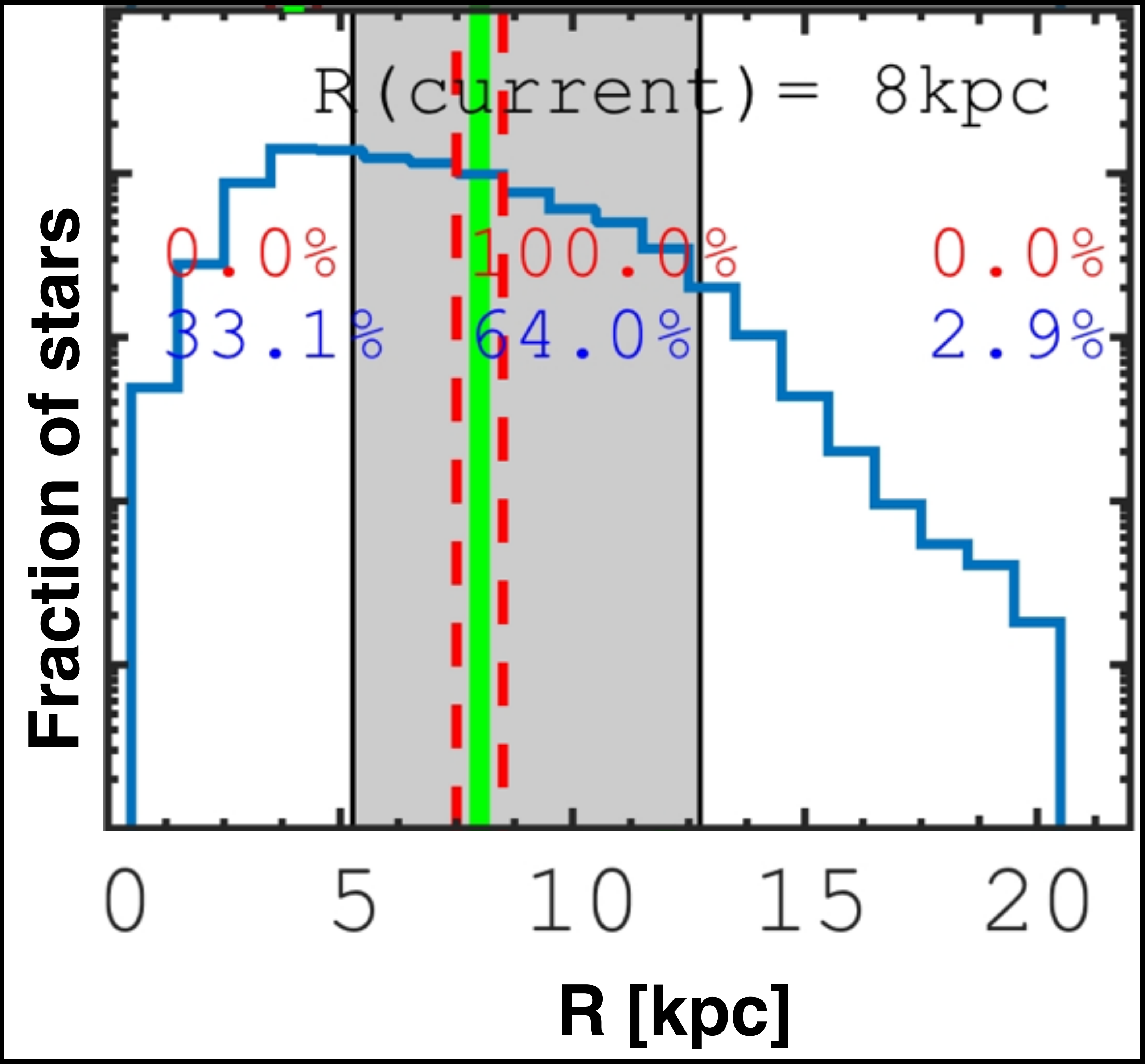


Why small patch of the disk
can tell us about the overall evolution?

because of *radial migration*

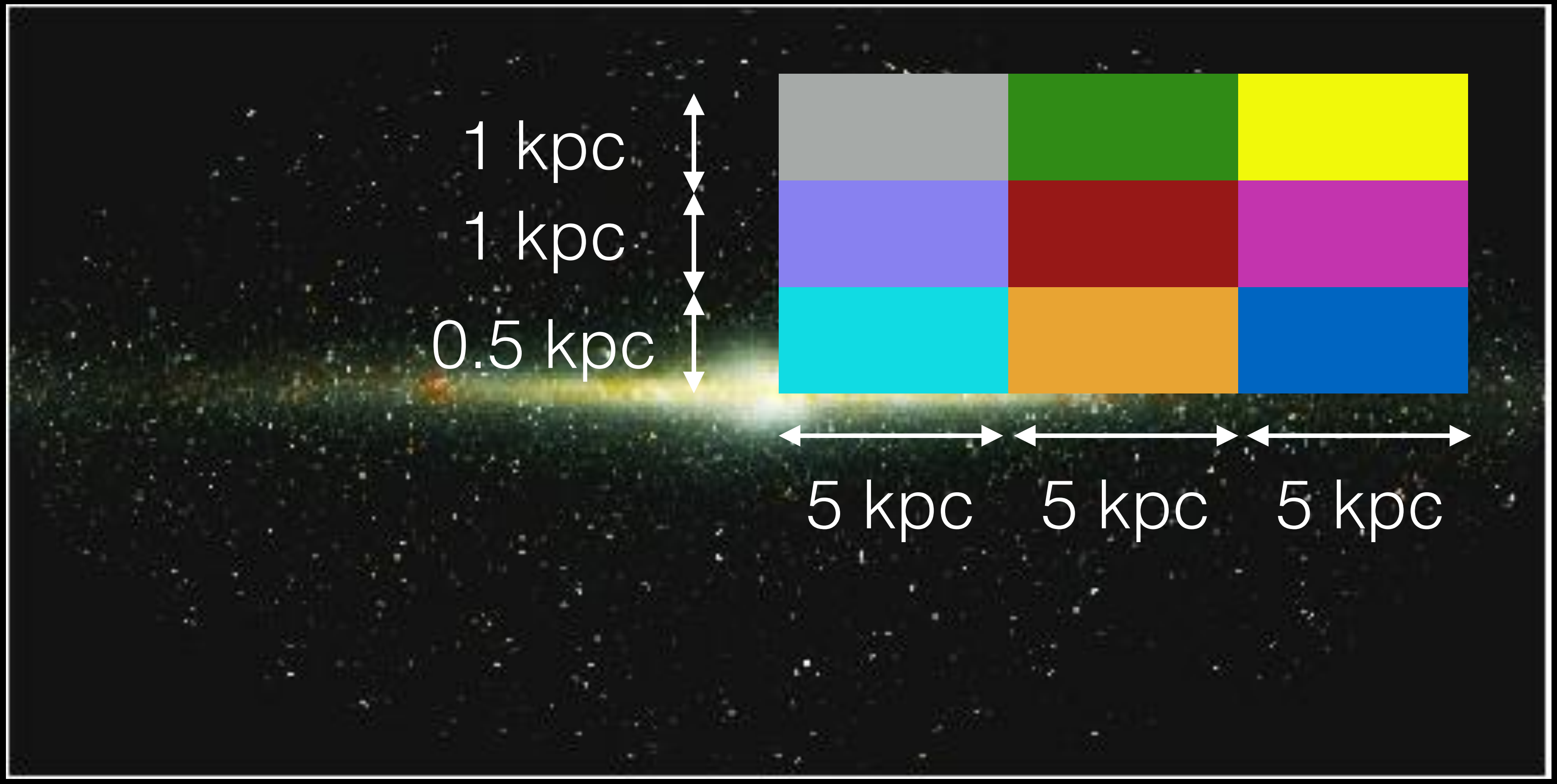


Distribution of star birth radii at a given radius

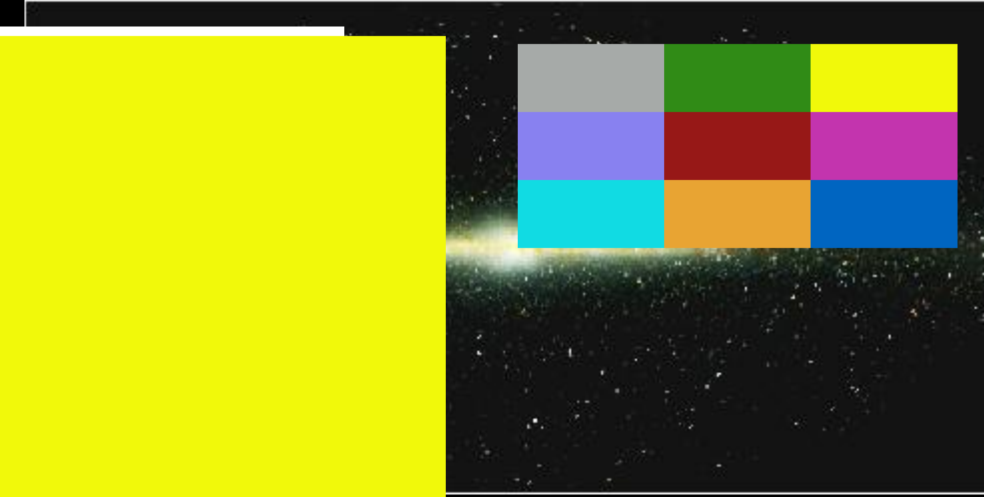


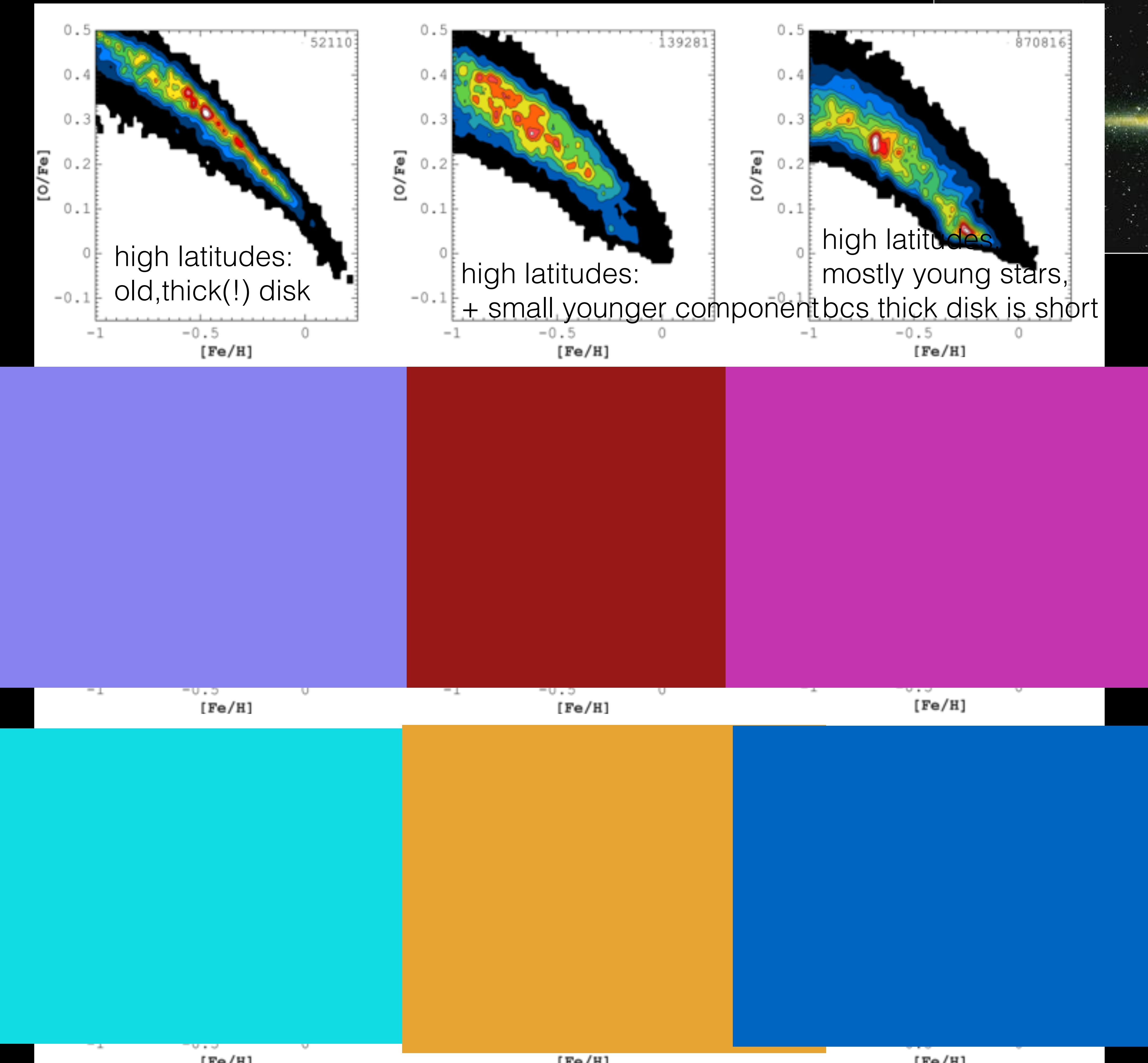
Khoperskov+ 2018 (submitted)

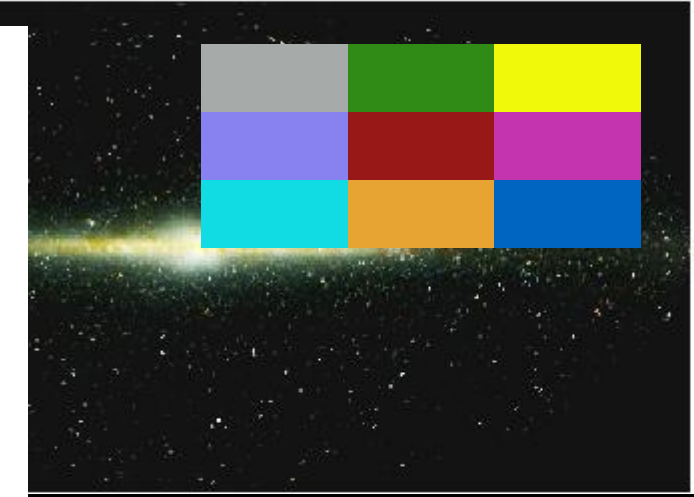
[O/Fe] spatial variations

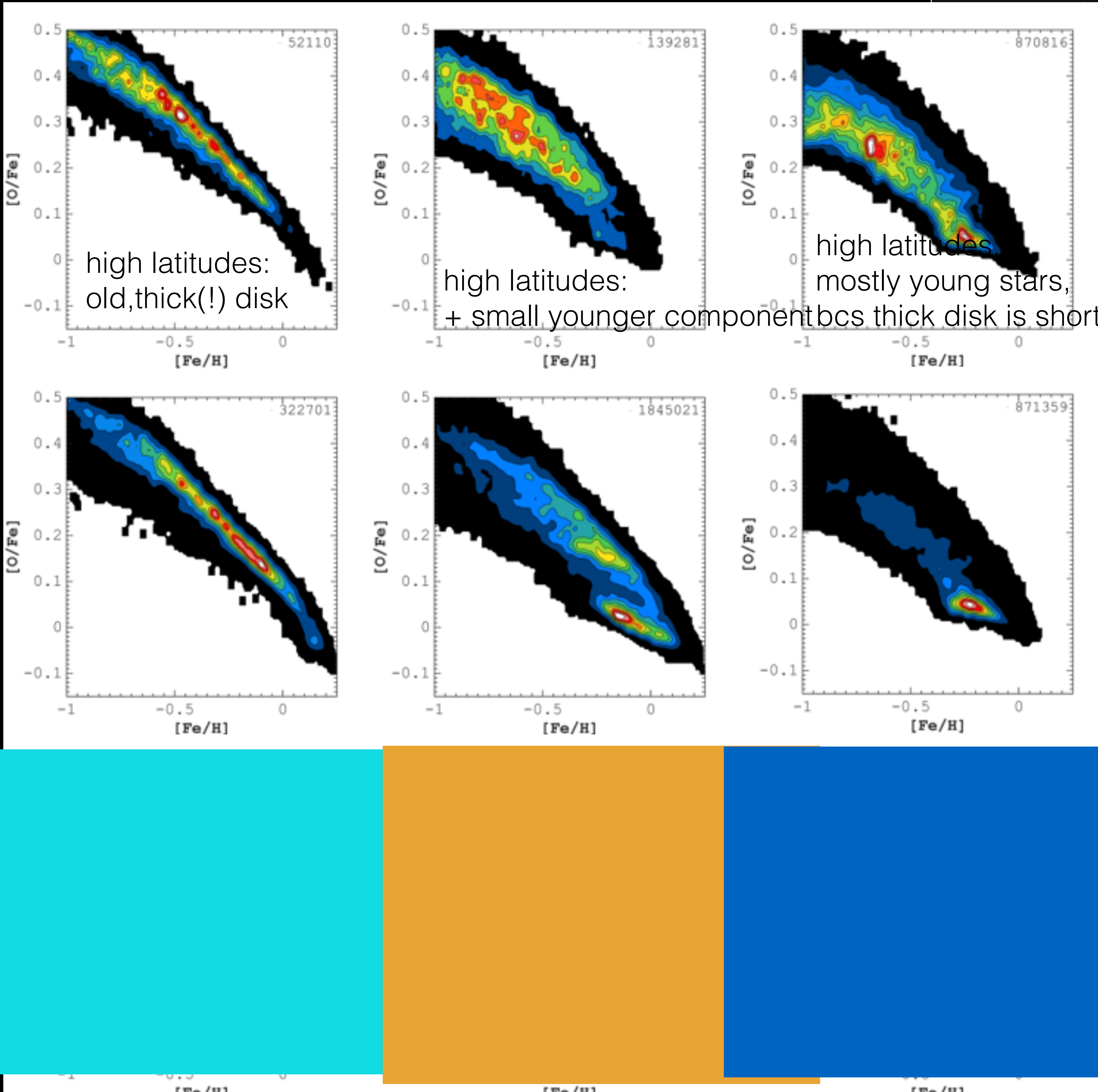



-1
-0.5
0
[Fe/H]
[Fe/H]
[Fe/H]
[Fe/H]
[Fe/H]
[Fe/H]
[Fe/H]
[Fe/H]
[Fe/H]




52110
139281
870816
[O/Fe]
[Fe/H]
high latitudes:
old,thick(!) disk
high latitudes:
+ small younger component
high latitudes,
mostly young stars,
bcs thick disk is short

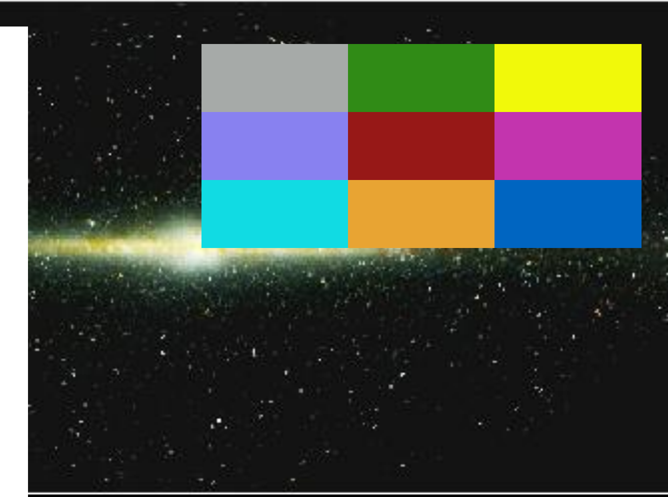


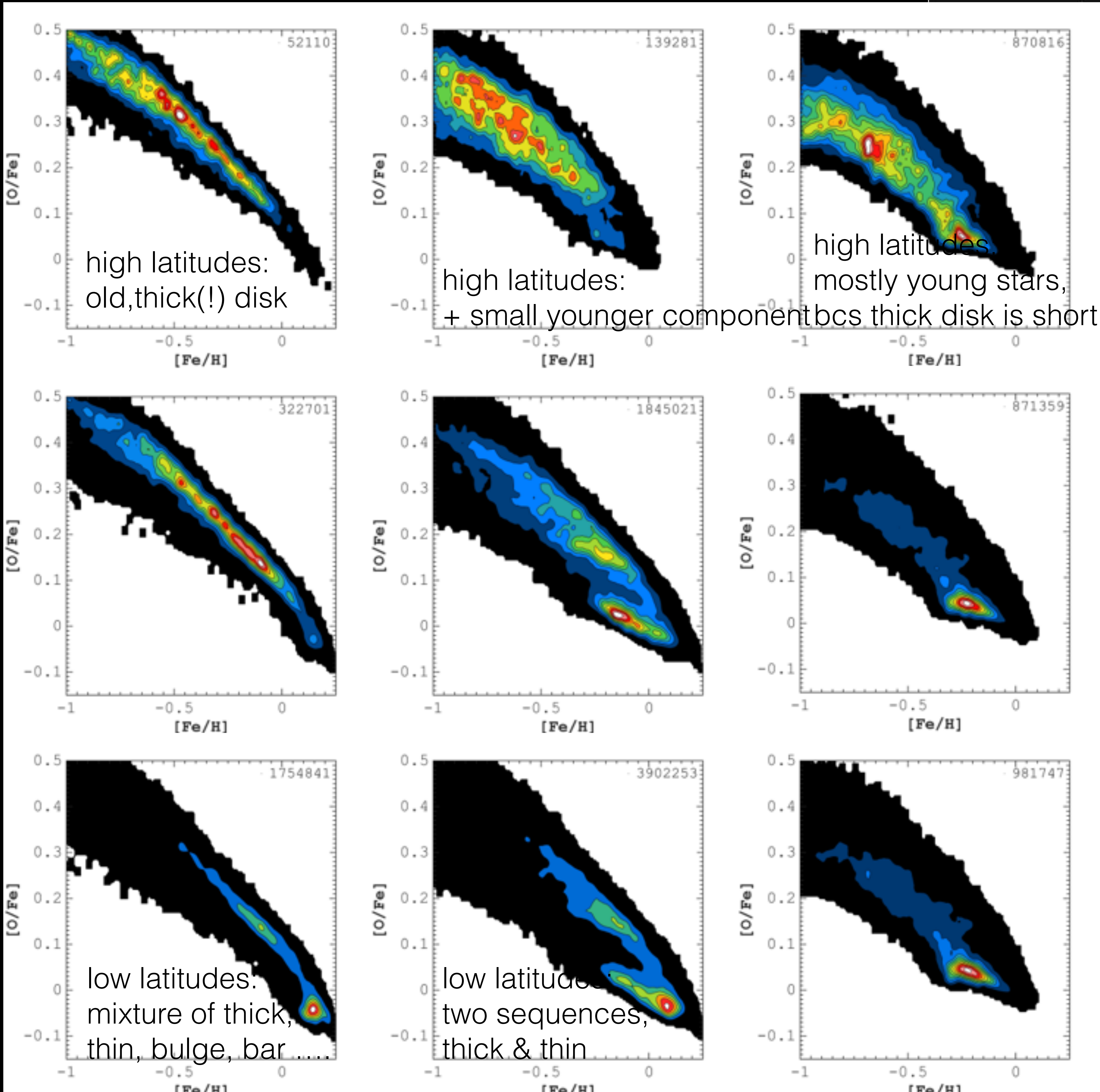


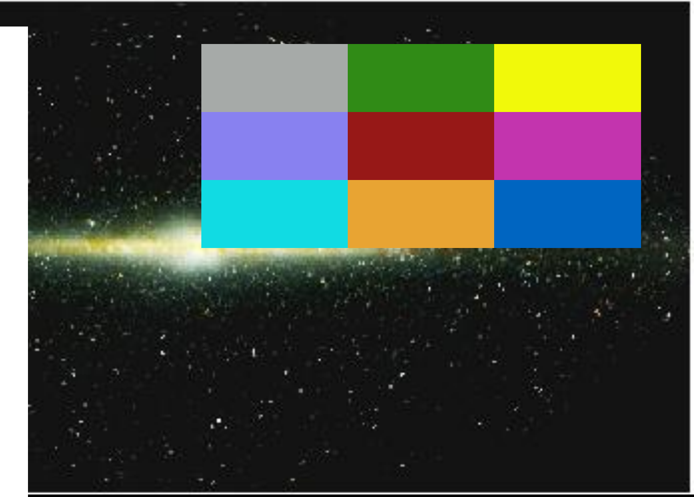
high latitudes:
old,thick(!) disk

high latitudes:
+ small younger component

high latitudes:
mostly young stars,
bcs thick disk is short




52110
139281
870816
322701
1845021
871359
1754841
3902253
981747
[O/Fe]
[Fe/H]
high latitudes:
old,thick(!) disk
high latitudes:
+ small younger component
high latitudes,
mostly young stars,
bcs thick disk is short
low latitudes:
mixture of thick,
thin, bulge, bar .....
low latitudes
two sequences,
thick & thin



Summary

- The thick disk formed in a well mixed turbulent gaseous disk which gave rise to a steep and monotonic chemical enrichment lasting a few Gyr

- Thin disk is the result of slow (and long) star formation

- Formation of the bar can separate these two phases decreasing global star formation rate. This provides evidence for the existence of two different epochs of star formation in the galaxy, which we have defined as the epochs of thick disk and thin disk formation.

- The transition between the two epochs is imprinted in [α/Fe] variation as a function of time/space/metallicity