3:55 pm ~

磁化した星間媒質における分子雲形成・進化・破壊と分子雲衝突に誘起された星形成

Star Formation Induced by Cloud-Cloud Collisions and Galactic Giant Molecular Cloud Evolution in the Magnetized ISM

(Kobayashi+ 2017 in ApJ, 2018 in revision in PASJ, 2018 in progress.)

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Outline

- ✓ **Background**
  - ◆ **Multiple Episodes of Compression** in magnetized ISM
- ✓ **Time Evolution of GMCs on Galactic Scales**
  - ◆ **Network of expanding shells**
  - ◆ Formulation of GMC MF evolution with Cloud-Cloud Collisions (CCC)
- ✓ **CCC-driven (Massive) Star Formation**
  - ◆ **Rapid dispersal of GMCs**
- ✓ **Towards Galactic-Scale Studies**
  - ◆ Shock propagation in the multiphase ISM
- ✓ **Summary**

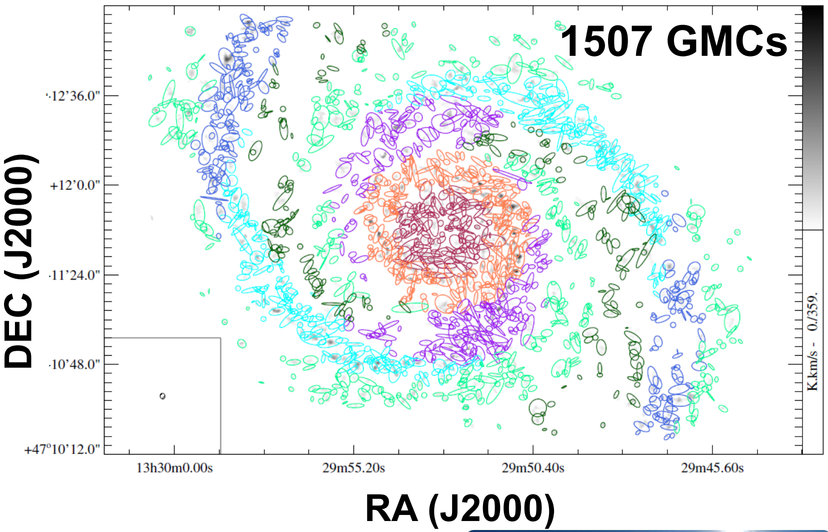
Backgrounds

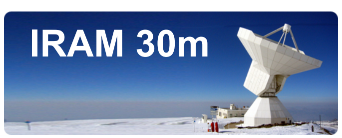
- ✓ Observed GMC MF
- ✓ Multiphase Simulations
- ✓ Multiple Episodes of Compressions

IRAM: GMC Distribution in M51

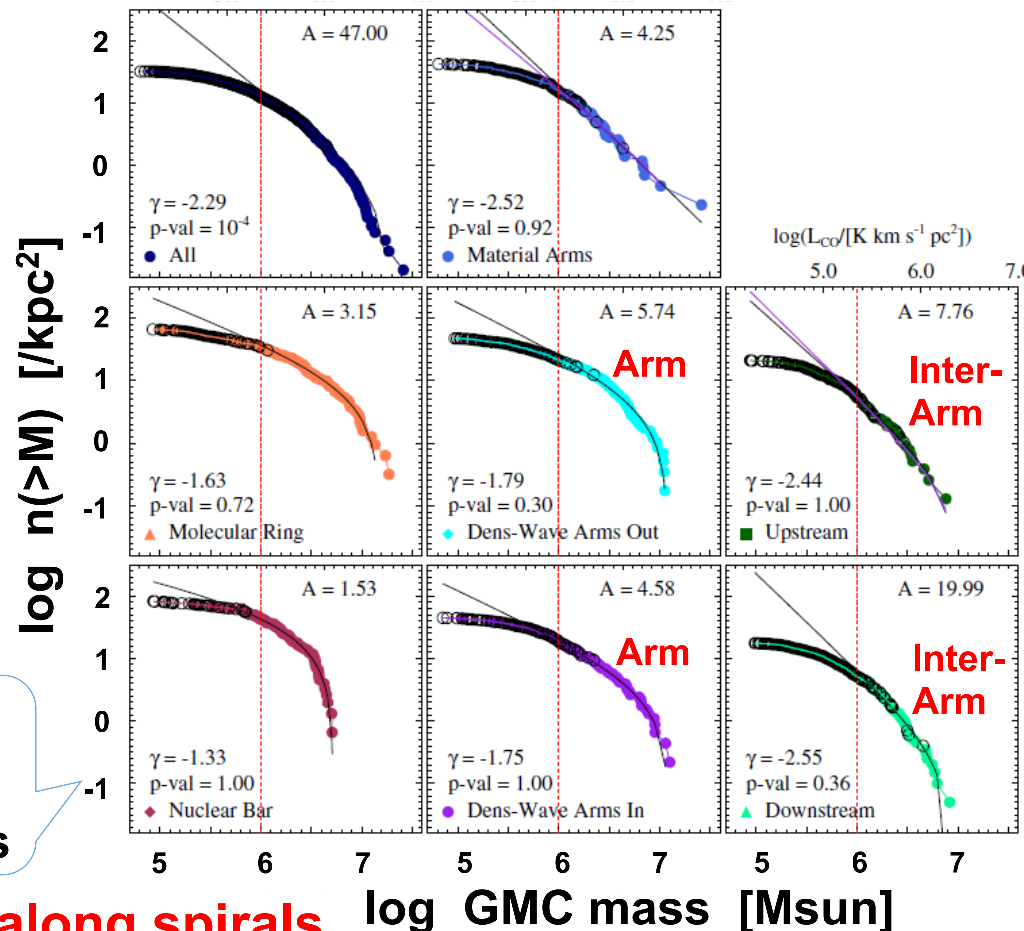
Sub-division in the galactic disk (Colombo+ 2014a)

1) Face-on view of identified GMCs





2) Cumulative mass function of GMCs



Power-law slope variation:
shallower (<-2) in arm regions,
steeper (>-2) in inter-arm regions

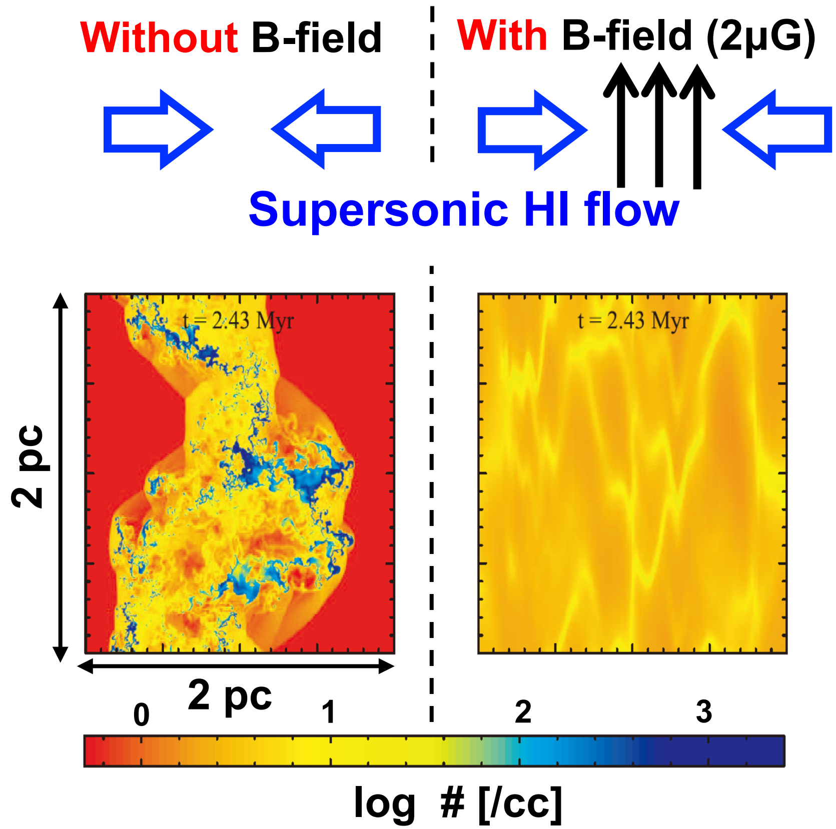
⇨ **Larger GMCs tend to reside along spirals.**
(Consistent trend from Koda+ 2009)

ISM Simulations

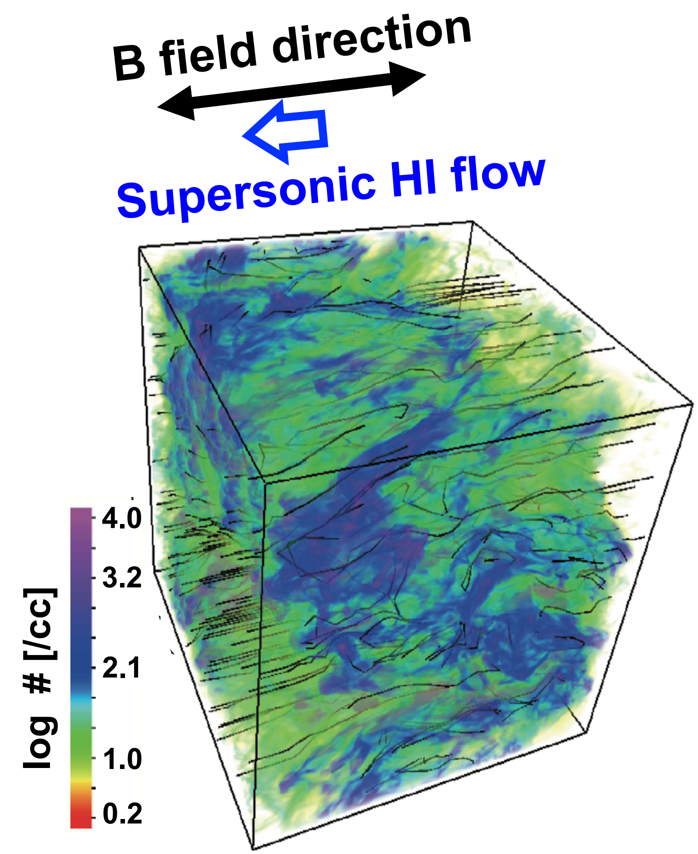
Similar results (e.g., Heitsch+ 2009, Körtgen & Banerjee 2015, Valdivia+ 2016)

Magnetic fields retard cloud formation

Inoue & Inutsuka, 2008



Inoue & Inutsuka, 2012

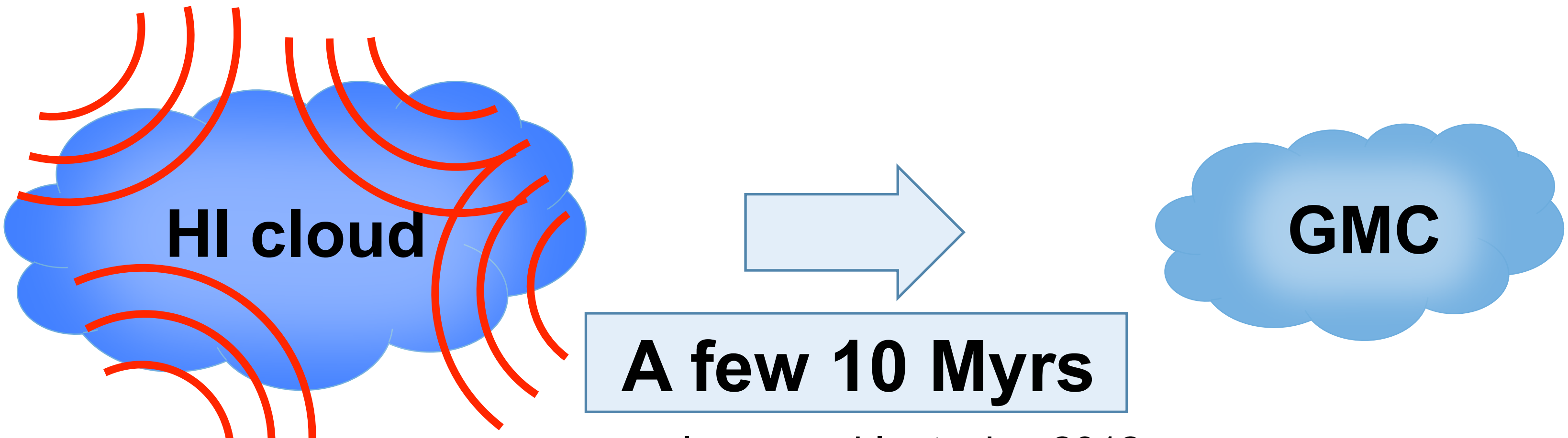


Cloud formation take place after supersonic compression with multiple times.

ISM Simulations

Typical time scale for GMC formation

Multiple episodes of compression is essential to form molecular clouds from magnetized WNM, which occupy most of the volume in galactic disks.



e.g., Inoue and Inutsuka, 2012
Inutsuka+ 2015

Goal: determine how this multiple compression governs the observed variation in GMC mass functions.

Time Evolution of GMCs on Galactic Scales

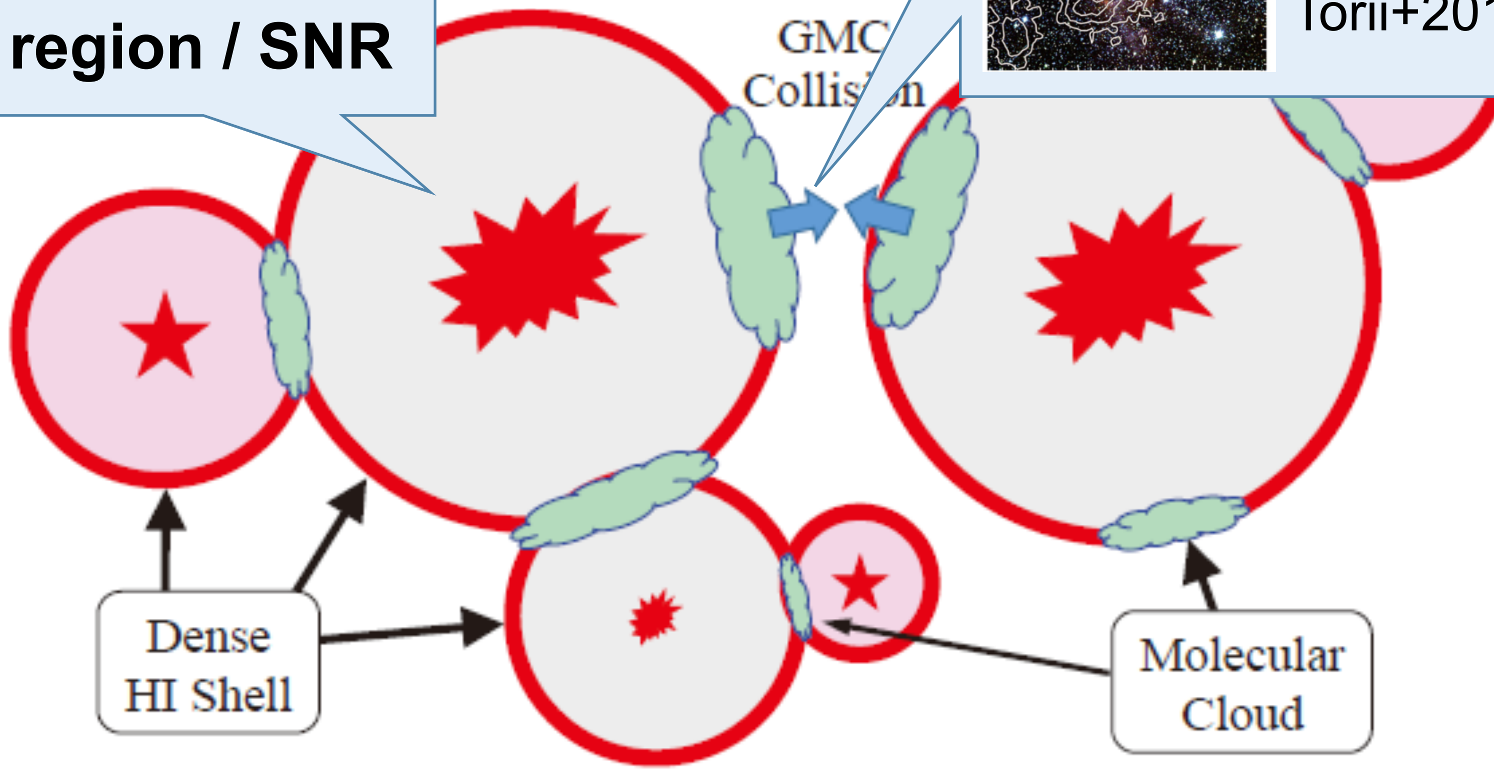
- ✓ Network of expanding shells
- ✓ Formulation of GMC MF evolution

GMC Formation & Evolution

Network of expanding shells on galactic scales

(Inutsuka+ 2015 A&A)

HII region / SNR



Cloud-Cloud Collisions (CCCs)

Fukui+ 2014
Nakamura+ 2012
Torii+2015

Formulation

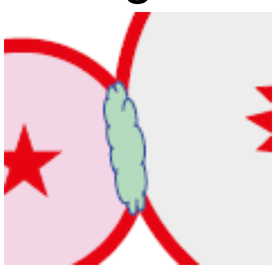
(c.f., Levinson & Roberts 1981, Kwan 1979, Scoville & Hersch 1979, Cowie 1980, Tomisaka 1984)

$n_{\rm cl}$: differential number density of GMCs with mass m

$$\frac{\partial n_{\rm cl}}{\partial t} + \frac{\partial}{\partial m}\left(n_{\rm cl}\frac{m}{T_{\rm f}}\right) = -\frac{n_{\rm cl}}{T_{\rm d}} + \frac{1}{2}\int_0^\infty\int_0^\infty K(m_1,m_2)n_{\rm cl,1}n_{\rm cl,2} \times \delta(m-m_1-m_2){\rm d}m_1{\rm d}m_2 - \int_0^\infty K(m,m_2)n_{\rm cl}n_{\rm cl}{\rm d}m_2 + \frac{1}{m}\frac{\partial(n_{\rm cl}m)}{\partial t}\bigg|_{\rm res}$$

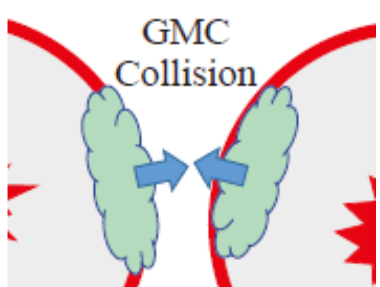
GMC self-dispersal
due to radiation by massive stars
(Td ~ 14 Myr; c.f. radiation hydrodynamics simulation: Inutsuka 2015)

GMC formation/growth
through compressions

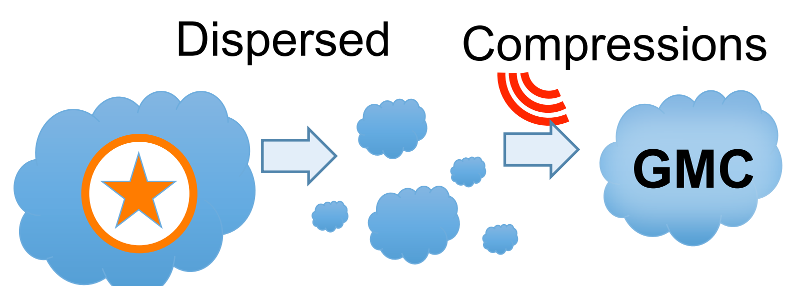


(Tf ~ 10 Myr; c.f. Inoue & Inutsuka 2012)

Cloud-Cloud Collisions (CCCs)
(coagulation)



Gas Resurrection
(Replenishment of minimum-mass population)



Kernel Function (Collision Rate)

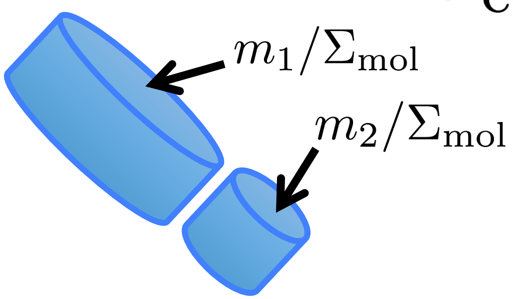
Kernel = cross section x relative velocity

$$K\left(m_1, m_2\right) = \sigma_{\mathrm{col}\,1,2} V_{\mathrm{rel}} \sim \frac{m_1 + m_2}{\Sigma_{\mathrm{mol}}} V_{\mathrm{rel}}$$

Column Density: $\Sigma_{\mathrm{mol}} \sim 2 \times 10^{22} \mu m_{\mathrm{H}} / \mathrm{cm}^2$

(Onishi+ 1999, Tachihara+ 2000)

Cross Section: $\sigma_{\mathrm{col}\,1,2} \sim \left(m_1 + m_2\right) / \Sigma_{\mathrm{mol}}$



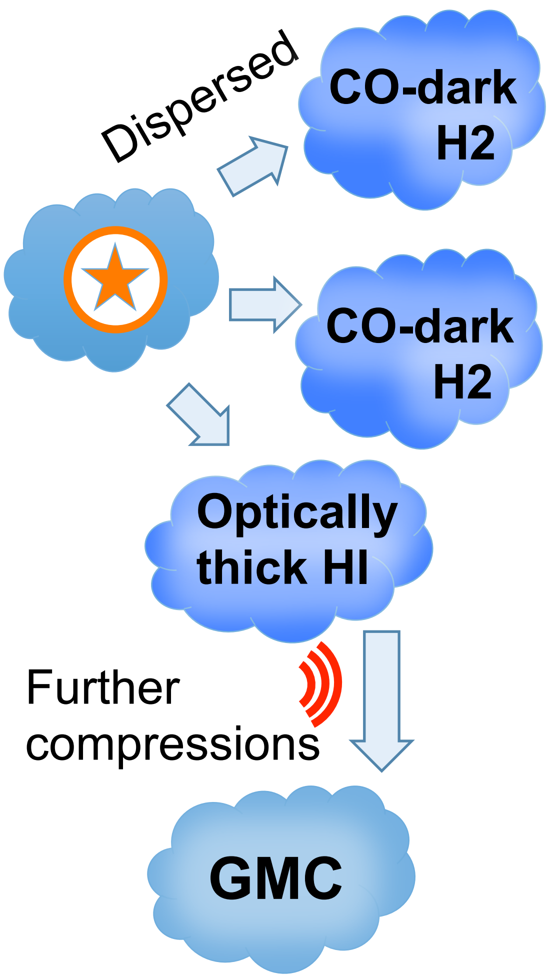
~ 7.5^2 pc^2 for collisions between 10^4 Msun GMCs

Relative Velocity: $V_{\mathrm{rel}} \sim 10\mathrm{km/s}$

(Stark & Lee, 2005, 2006)

Fate of Dispersed Gas

Dispersed gas may resurrect to replenish the minimum-mass population.



Total gas dispersal rate due to stellar feedback

Minimum-mass in the system

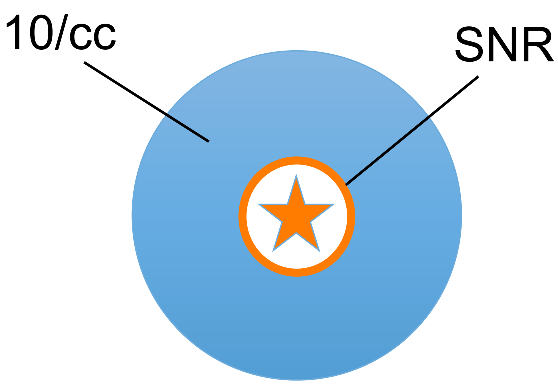
$$\left.\frac{\partial\left(n_{\rm cl} m\right)}{\partial t}\right|_{\rm res} = \varepsilon_{\rm res}\, \dot{\rho}_{\rm total,disp}\, \delta(m - m_{\rm min})$$

Resurrecting factor (0.01-1)
The rate to generate new generation minimum-mass GMCs out of the total dispersed gas.

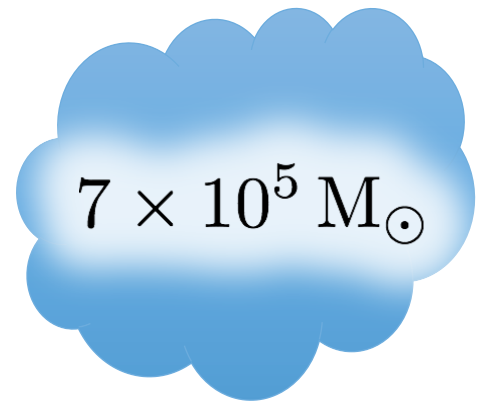
N.B.: In a steady state, $1-\varepsilon_{\rm res}$ can be understood as a rate to accrete onto pre-existing GMCs out of the total dispersed gas.

Self-growth Timescale T_f

Maximum GMC created in the bubble paradigm:



If swept up up to 100pc and pile them up into one gigantic cloud…



$$T_\mathrm{f}(m) = T_\mathrm{f,fid}\left(1 + \frac{m}{m_\mathrm{trunc}}\right)^\gamma$$

$T_\mathrm{f,fid}$ = 10 Myr

$\gamma = 10$

$m_\mathrm{trunc} = 7.7 \times 10^6 M_\odot$

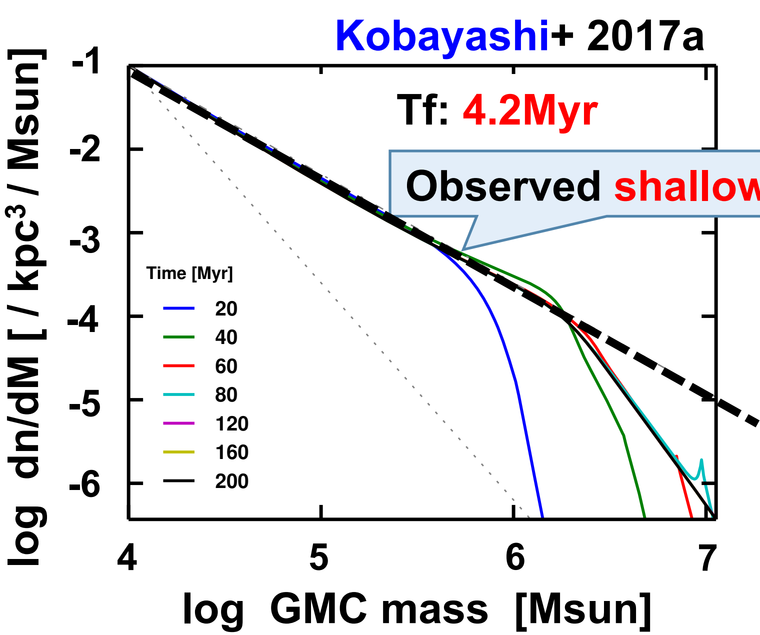
Results

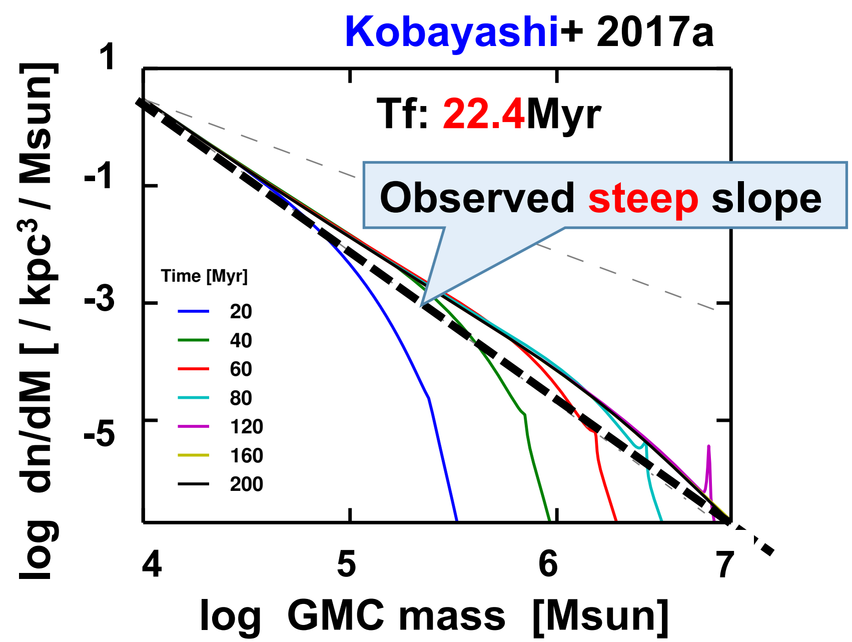
- ✓ **Slope of GMC MF**
- ✓ **Gas Resurrection**

Steady State with different Tf

CCC affects only the massive-end evolution…

$$\frac{\partial n_{\mathrm{cl}}}{\partial t} + \frac{\partial}{\partial m}\left(n_{\mathrm{cl}}\frac{m}{T_{\mathrm{f}}}\right) = -\frac{n_{\mathrm{cl}}}{T_{\mathrm{d}}} \quad \Rightarrow \quad n_{\mathrm{cl}}(m) = n_0\left(\frac{m}{M_\odot}\right)^{-1-\frac{T_{\mathrm{f}}}{T_{\mathrm{d}}}}$$





Arm regions: short Tf due to many massive stars/supernovae. Large surveys may put unique constraints on GMC formation/ dispersal timescales on galactic scales by measuring slopes.

Optimal Steady State Resurrection

Coagulation equation for mass evolution

$$\frac{\partial mn}{\partial t} + \frac{\partial}{\partial m}\left(\frac{m^2 n}{T_{\rm f}(m)} - \int_{m_{\rm min}}^{m} \frac{mn{\rm d}m}{T_{\rm f}(m)} + \int_{m_{\rm min}}^{m} \frac{nm{\rm d}m}{T_{\rm d}}\right) = 0$$

Net mass flux

(in case of $n_{\rm cl}(m) = Am^{-\alpha}$)

$$F_{\rm total} = \frac{m_{\rm max}^2 n(m_{\rm max})}{T_{\rm f}(m_{\rm max})} - \frac{m_{\rm min}^2 n(m_{\rm min})}{T_{\rm f}(m_{\rm min})} - \int_{m_{\rm min}}^{m_{\rm max}} \frac{mn{\rm d}m}{T_{\rm f}(m)} + \int_{m_{\rm min}}^{m_{\rm max}} \frac{mn{\rm d}m}{T_{\rm d}}$$

$$= \frac{Am_{\rm max}^{2-\alpha}}{T_{\rm f}(m_{\rm max})} - \frac{Am_{\rm min}^{2-\alpha}}{T_{\rm f}(m_{\rm min})} - \int_{m_{\rm min}}^{m_{\rm max}} \frac{Am^{1-\alpha}{\rm d}m}{T_{\rm f}(m)} + \int_{m_{\rm min}}^{m_{\rm max}} \frac{Am^{1-\alpha}{\rm d}m}{T_{\rm d}}$$

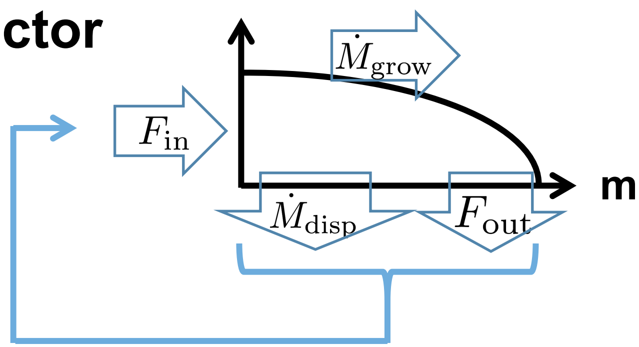
$$= F_{\rm out} - F_{\rm in} - \dot{M}_{\rm grow} + \dot{M}_{\rm disp}$$

Outgoing flux

Incoming flux

Define the resurrecting factor

$$\varepsilon_{\rm res} = \frac{F_{\rm in}}{F_{\rm out} + \dot{M}_{\rm disp}}$$



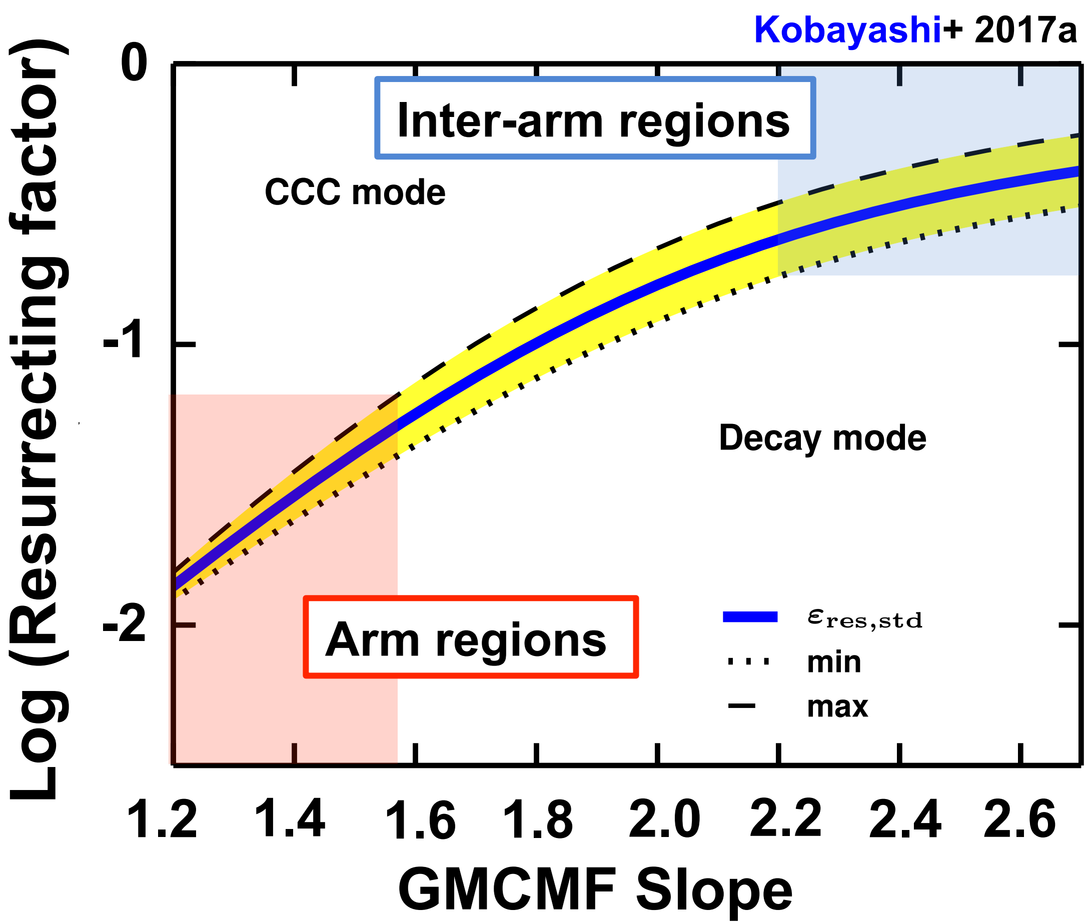
$F_{\rm total} = 0$

Resurrecting factor depends on α

$$\varepsilon_{\rm rec,std} = \frac{F_{\rm in}}{F_{\rm in} + \dot{M}_{\rm grow}} = \frac{Am_{\rm min}^{2-\alpha}}{T_{\rm f}(m_{\rm min})} \Big/ \left(\frac{Am_{\rm min}^{2-\alpha}}{T_{\rm f}(m_{\rm min})} + \int_{m_{\rm min}}^{m_{\rm max}} \frac{Am^{2-\alpha}{\rm d}m}{T_{\rm f}(m)}\right)$$

Optimal Steady State Resurrection

Relation between resurrection and GMCMF slope

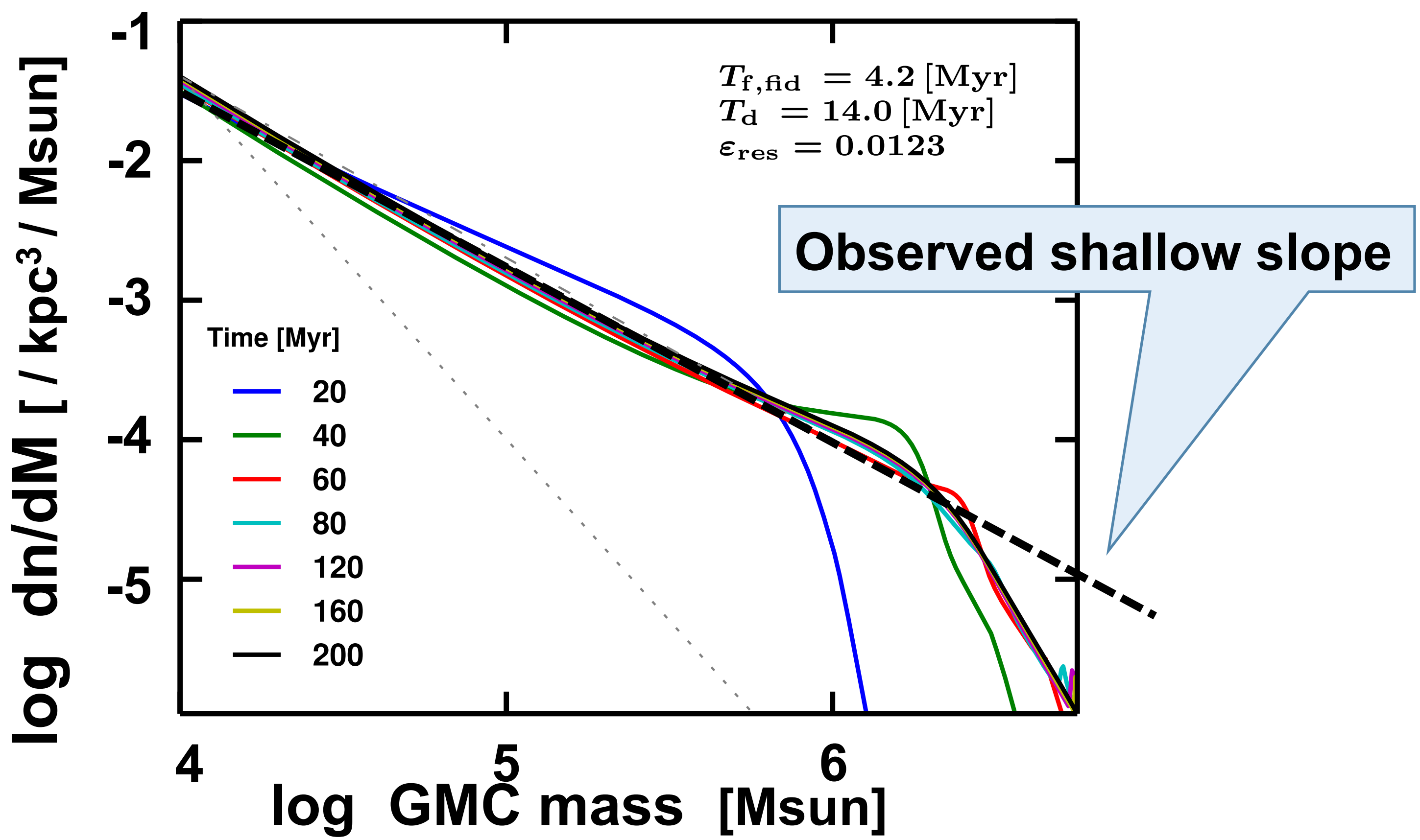


⇨ **Resurrecting factor: Arm ~ 1%, inter-arm ~30%**

Resurrection in arm regions

Little resurrection (~1%)

Kobayashi+ 2017a

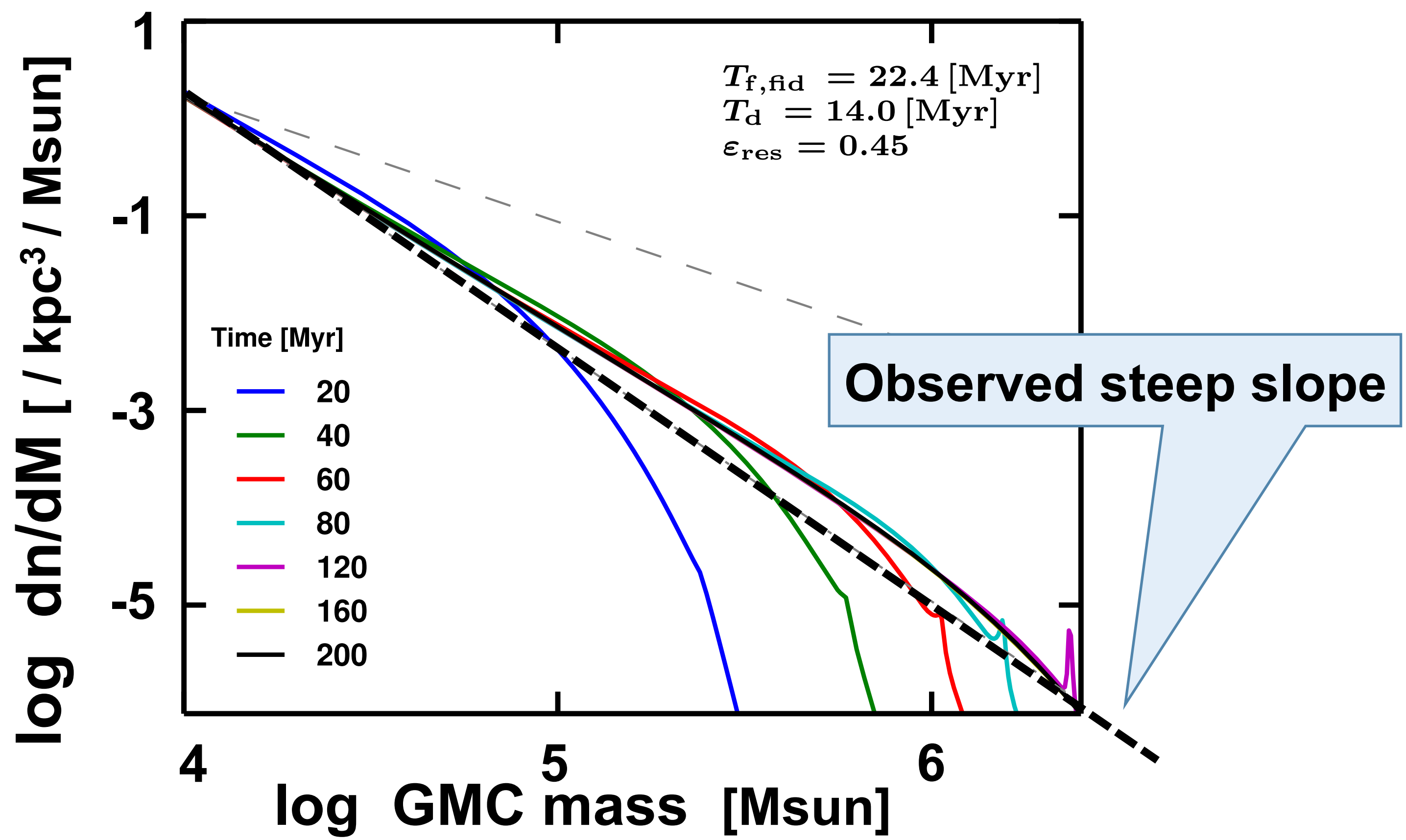


Only 1% is required in arm regions (because abundant massive GMCs capture dispersed gas).

Resurrection in inter-arm regions

Substantial resurrection (~45%)

Kobayashi+ 2017a

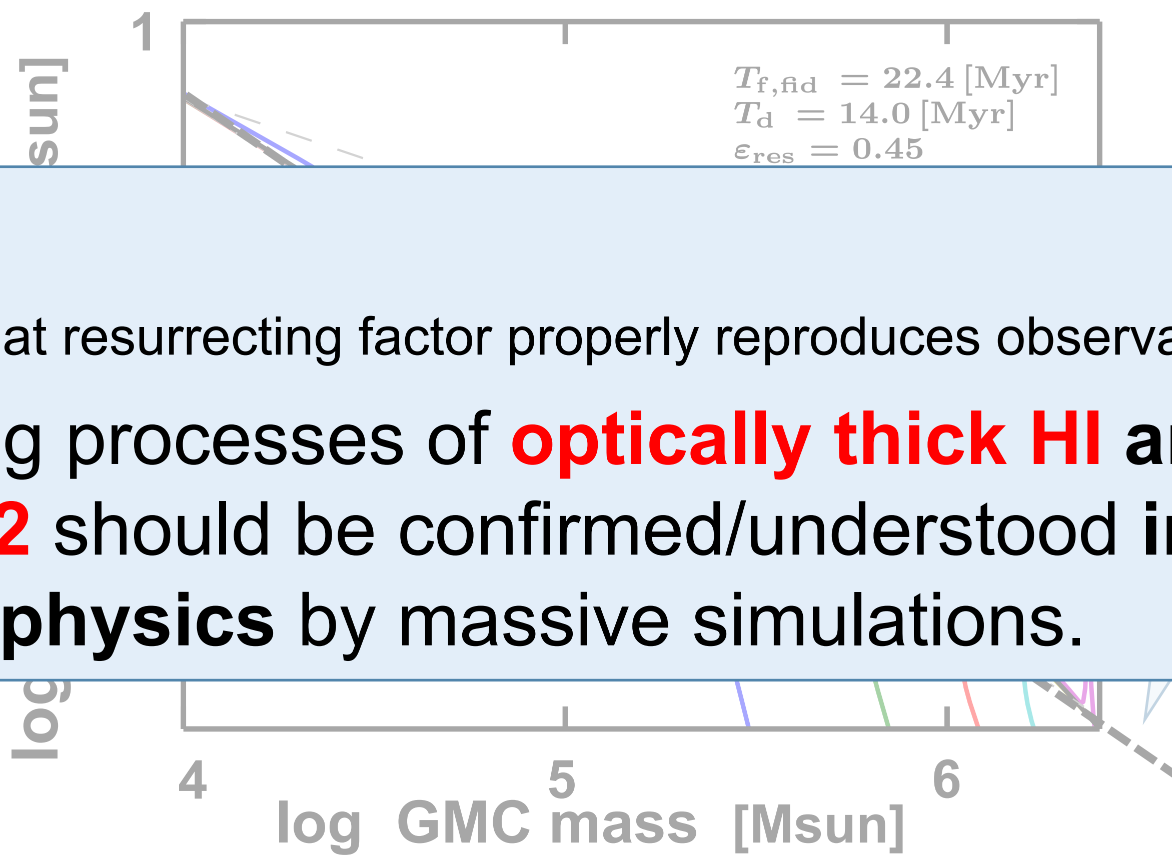


About 45% is required in inter-arm regions (lack of massive GMCs let dispersed gas easily resurrect).

Resurrection in inter-arm regions

Substantial resurrection (~45%)

Kobayashi+ 2017a



N.B.

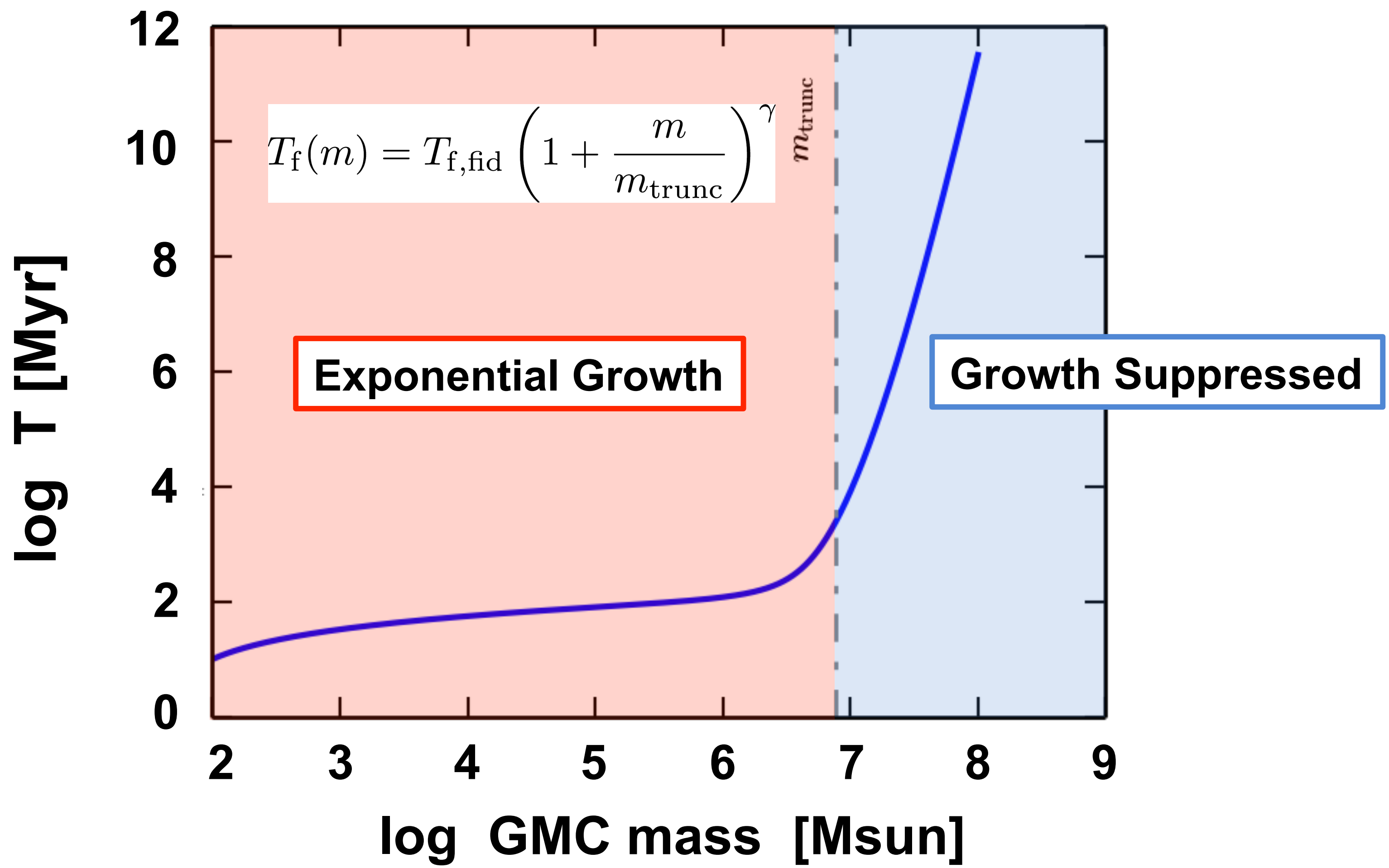
(We suggest what resurrecting factor properly reproduces observations.)

Resurrecting processes of **optically thick HI** **and** **CO-dark H2** should be confirmed/understood **in the context of physics** by massive simulations.

About 45% is required in inter-arm regions (lack of massive GMCs let dispersed gas easily resurrect).

Exponential self-growth

GMC mass grows exponentially by compression



Massive GMCs are long-lived;
Typical "Age" and typical "Lifetime" is different!

CCC-driven Star Formation

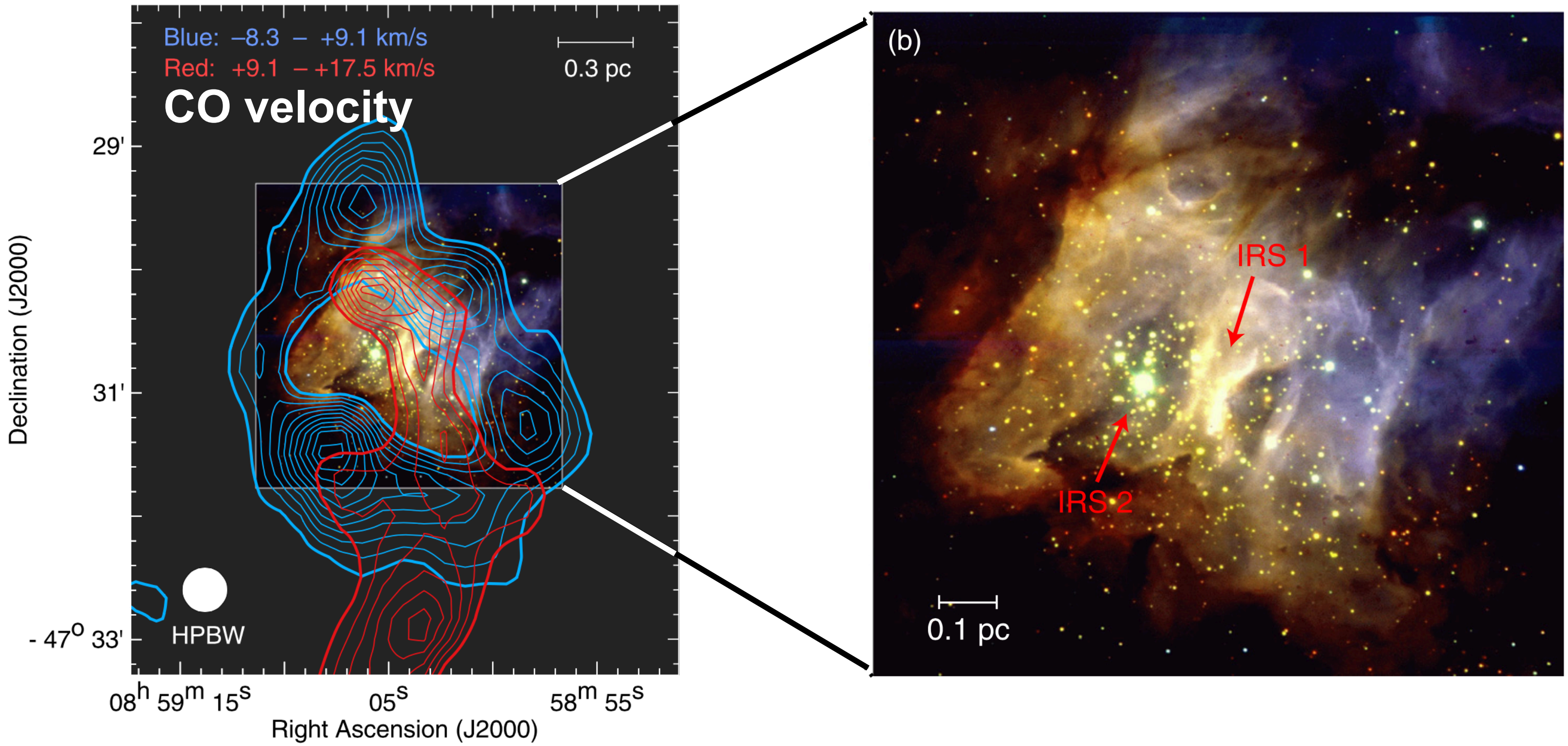
- ✓ Rapid Massive Star Formation
- ✓ Star Formation Rate
- ✓ Collision Frequency

Star Formation at CCC sites

O(B) stars and YSOs are often observed.

Ex.) RCW38 (Fukui+ 2016)

O(B) star candidates form at the intersection.



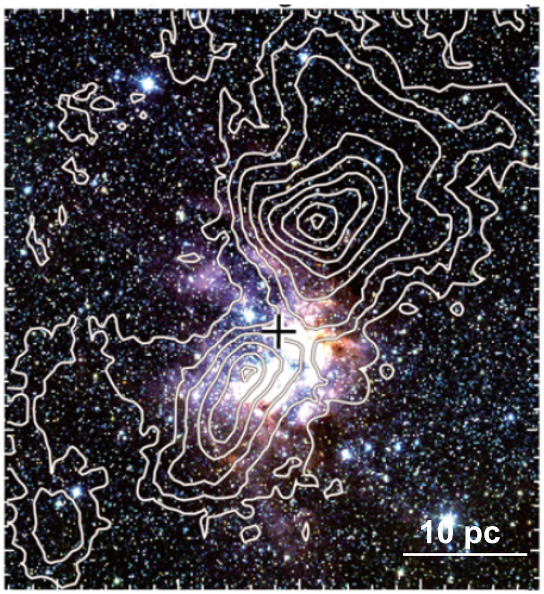
1) Complementary distribution on the sky and
2) bridging feature in CO position-velocity diagram
indicate a recent CCC event ~0.1 Myr ago.

Star Formation at CCC sites

O(B) star formation possibly triggered by CCC.

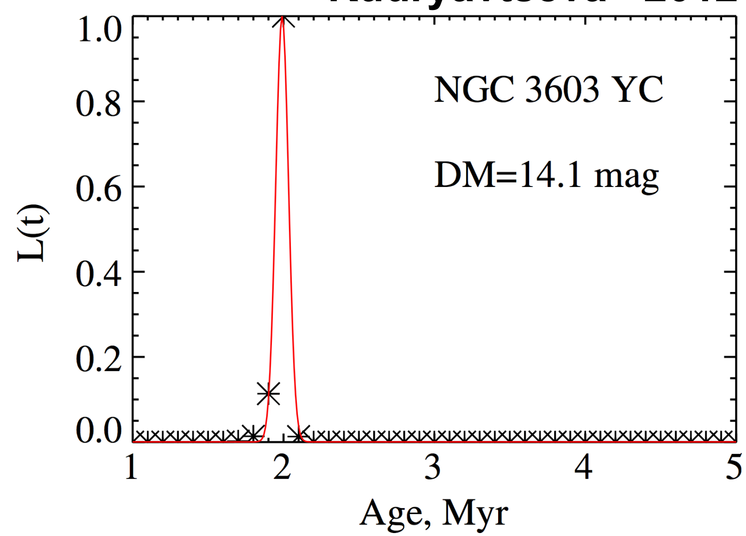
Ex.) NGC3603

12CO contour + JHK image
Fukui+ 2014



Probability of stellar ages
(with assumed isochrones).

Kudryavtseva+ 2012



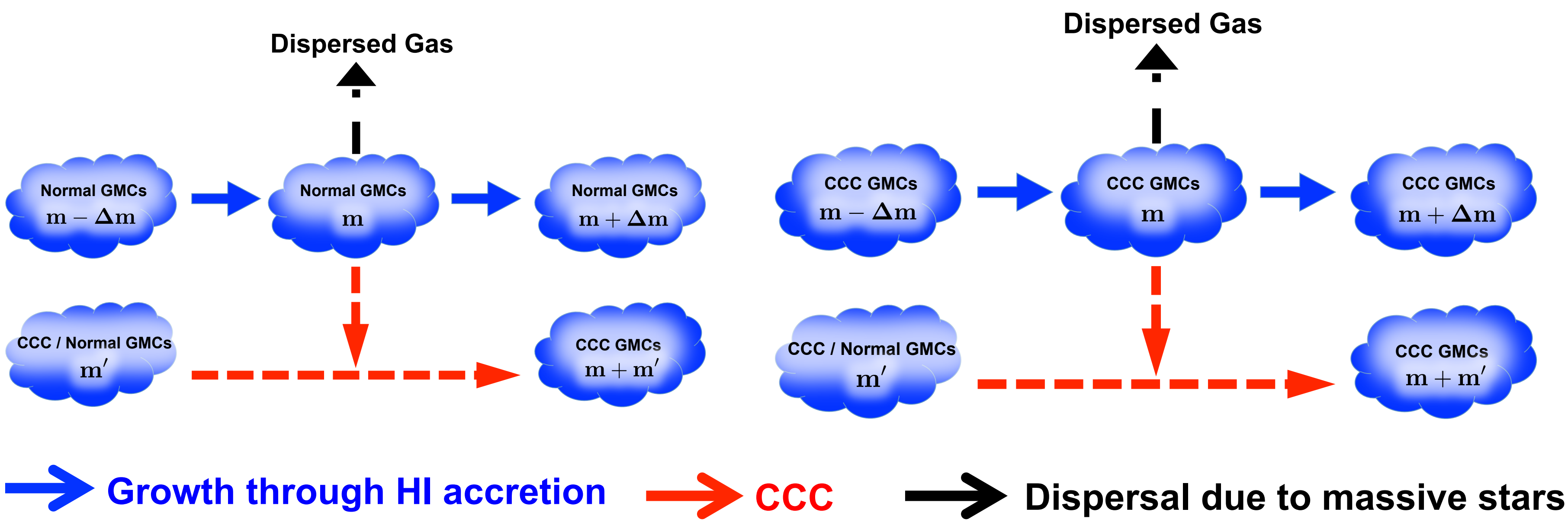
Multiple O stars might form ~0.5pc scale within 1Myr!

Similar trends observed in different sites (Westerlund2, W51, M17, NGC6334, NGC6357, M16, W33, M42, RCW166, S116, S117, S118, M43, RCW36, M20, RCW120, NGC2024, RCW34, … etc.)

Two GMC Populations

Short Td for GMCs undergoing CCC

1) Normal Population   2) CCC Population



- ✓ **GMCs join the CCC population once they experience CCC.**
- ✓ **CCC population has a short Td ~ 5Myr representing observed rapid massive-star formation.**

Two GMC Populations

Time evolution equation and star formation rate (SFR)

n_{acc}: normal population

n_{col}: CCC population

T_d = 14 Myr

$T_{d,col}$ = 5Myr

$$
\begin{aligned}
&\frac{\partial\left(n_{\rm acc,cl}+n_{\rm col,cl}\right)}{\partial t}+\frac{\partial}{\partial m}\left(\left(n_{\rm acc,cl}+n_{\rm col,cl}\right)\frac{m}{T_{\rm f}}\right)\\
&= -\frac{n_{\rm acc,cl}}{T_{\rm d}}-\frac{n_{\rm col,cl}}{T_{\rm d,col}}\\
&\quad+\frac{1}{2}\int_0^\infty\int_0^\infty K(m_1,m_2)\\
&\qquad\times\left(n_{\rm acc,cl,1}+n_{\rm col,cl,1}\right)\left(n_{\rm acc,cl,2}+n_{\rm col,cl,2}\right)\\
&\qquad\times\delta(m-m_1-m_2){\rm d}m_1{\rm d}m_2\\
&\quad-\int_0^\infty K(m,m_2)\\
&\qquad\times\left(n_{\rm acc,cl}+n_{\rm col,cl}\right)\left(n_{\rm col,cl,2}+n_{\rm col,cl,2}\right){\rm d}m_2\\
&\quad+\frac{1}{m}\frac{\partial\left(n_{\rm cl}m\right)}{\partial t}\bigg|_{\rm res}.
\end{aligned}
$$

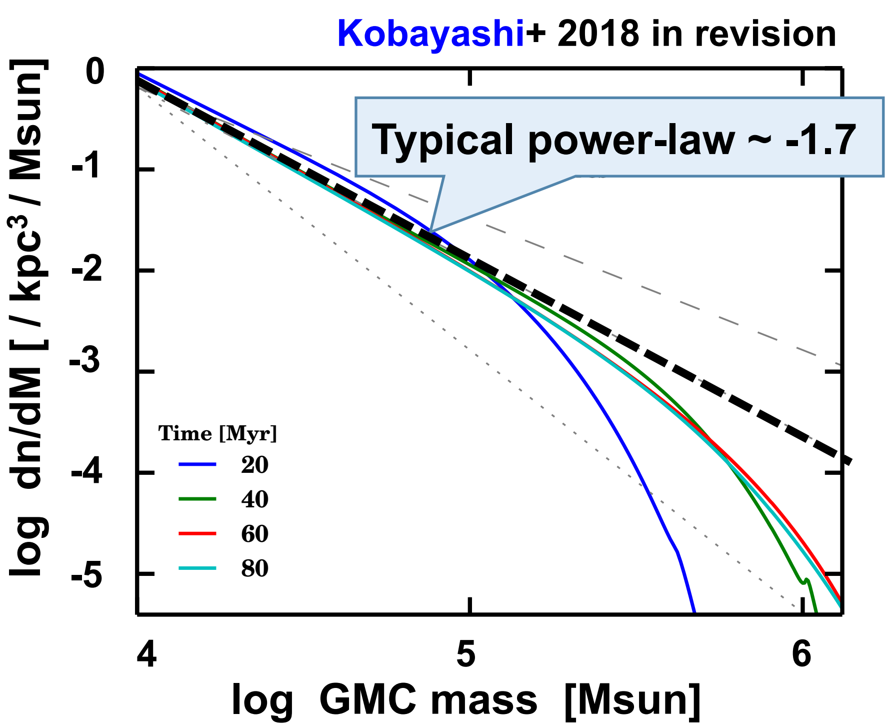
ε_{SFE} = 1%

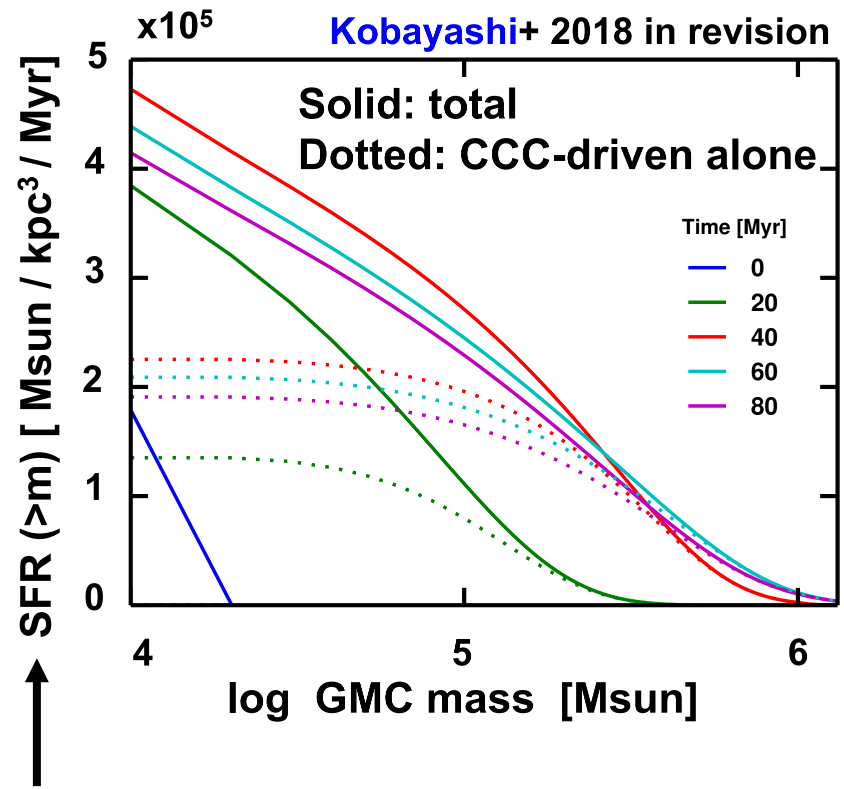
$$
{\rm SFR}(>m)=\varepsilon_{\rm SFE}\times\left(\int_m^\infty\frac{mn_{\rm acc,cl}}{T_{\rm d}}{\rm d}m+\int_m^\infty\frac{mn_{\rm col,cl}}{T_{\rm d,col}}{\rm d}m\right)
$$

CCC-driven star formation

Two GMC Populations

GMCMF and CCC-driven star formation rate





10kpc x 10kpc x 100pc disk (like Milky Way), this SFR = a few Msun per year.

⇨ **CCC-driven star formation may amount to a few 10 percent of the total star formation in the Milky Way and nearby galaxies, which is mostly driven by GMCs > 10^5 Msun.**

Which GMC mass is important?

e-folding timescales for GMCs of mass m

(with pure coagulation assumed)

Growth terms from the evolution equation

$$\frac{\partial n_{\rm cl}}{\partial t} = -\int K(m, m_2) n_{\rm cl} n_{{\rm cl},2}\, {\rm d}m_2 = -\int \underline{K(m, m_2) n_{\rm cl} n_{{\rm cl},2} m_2}\, {\rm d}(\ln m_2)$$

Number change by collision with population of mass m_2 with a bin width of e x m_2.

1) "Number" e-folding timescale due to collision with GMCs with mass m_2 alone.

$$T_{\rm col,num} = \frac{n_{\rm cl}}{K(m, m_2) n_{\rm cl} n_{{\rm cl},2} m_2}$$

2) "Mass" e-folding timescale due to collision with GMCs with mass m_2 alone.

$$T_{\rm col,mass} = \frac{n_{\rm cl} m}{\left(K(m, m_2) n_{\rm cl} n_{{\rm cl},2} m_2\right) m_2}$$

Note: **Number e-folding timescale** can be intuitively/easily understood, but it **does not necessarily mean how fast GMCs can move in the GMC mass-coordinate!** (Indeed, that is what mass e-folding timescale tells you.)

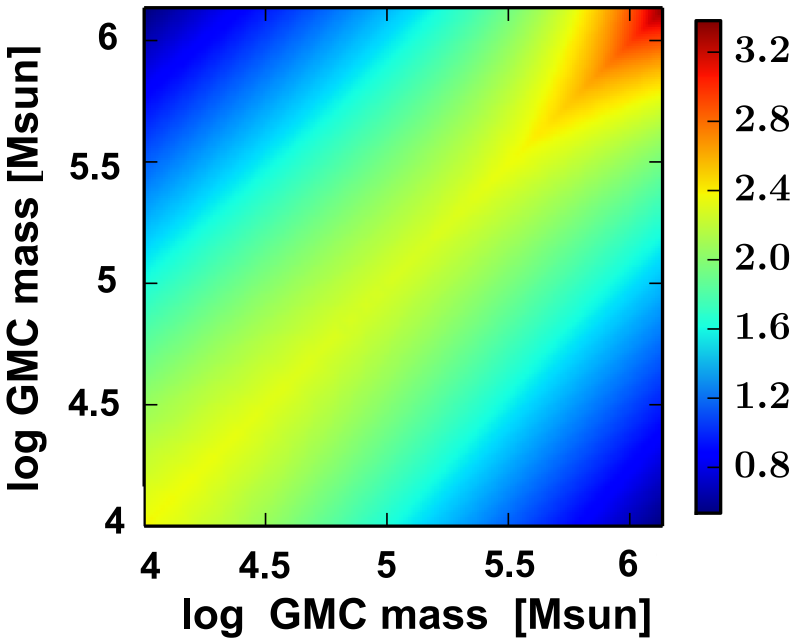
Which GMC mass is important?

e-folding timescales for GMCs of mass m

(with pure coagulation assumed)

log (Number e-folding timescale [Myr])

Kobayashi+ 2018 in revision



$$n_{\rm cl}(m) = Am^{-\alpha}$$ (now -α = -1.7)

$$T_{\rm col,num} \propto \frac{1}{m m_2^{1-\alpha}} \; (\text{for } m \gg m_2)$$

i.e., Smaller cloud population outnumbers larger one.

$$T_{\rm col,num} \propto \frac{1}{m_2^{2-\alpha}} \; (\text{for } m \ll m_2)$$

i.e., Larger clouds have larger surface area.

Clouds are often bombarded by smaller clouds

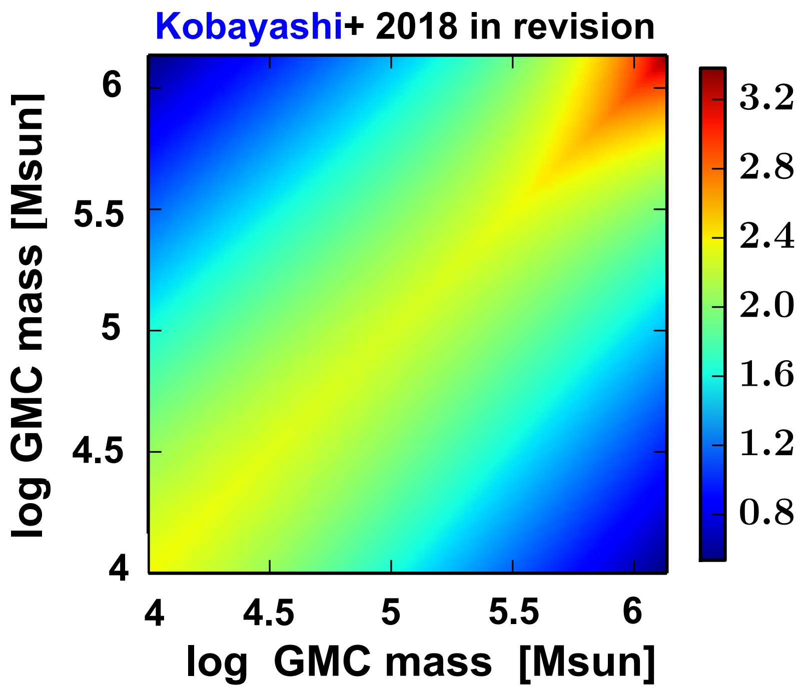
(smaller cloud population outnumbers, and larger clouds have larger surface area.)

Which GMC mass is important?

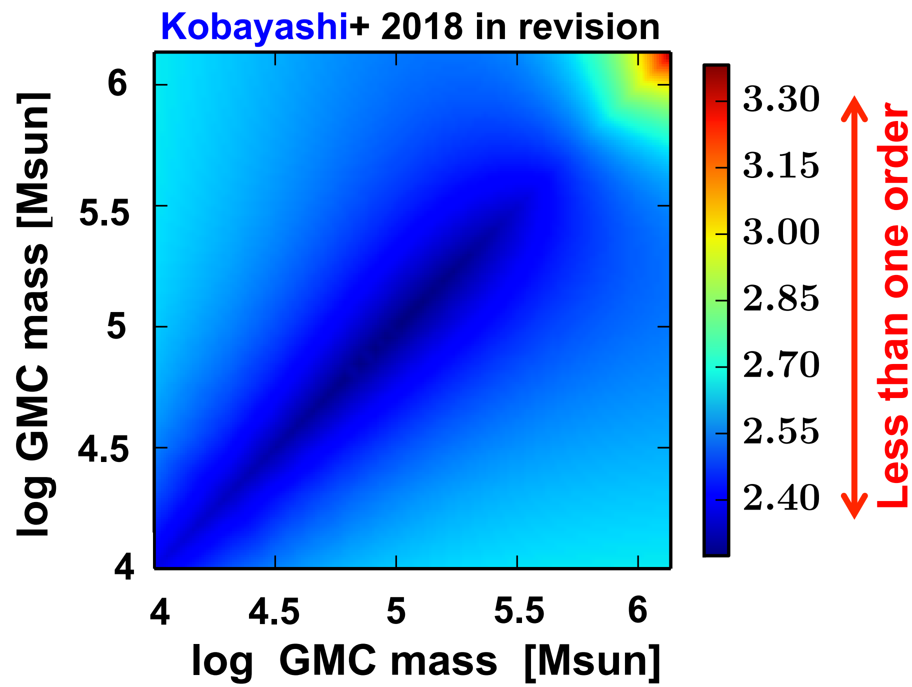
e-folding timescales for GMCs of mass m

(with pure coagulation assumed)

log (Number e-folding timescale [Myr])



log (Mass e-folding timescale [Myr])



GMCMF growth due to CCC is still dominated by small-large GMC collision, but **equal-mass CCC also contributes to GMC mass-growth!**

Which mass pair can we observe?

Observability

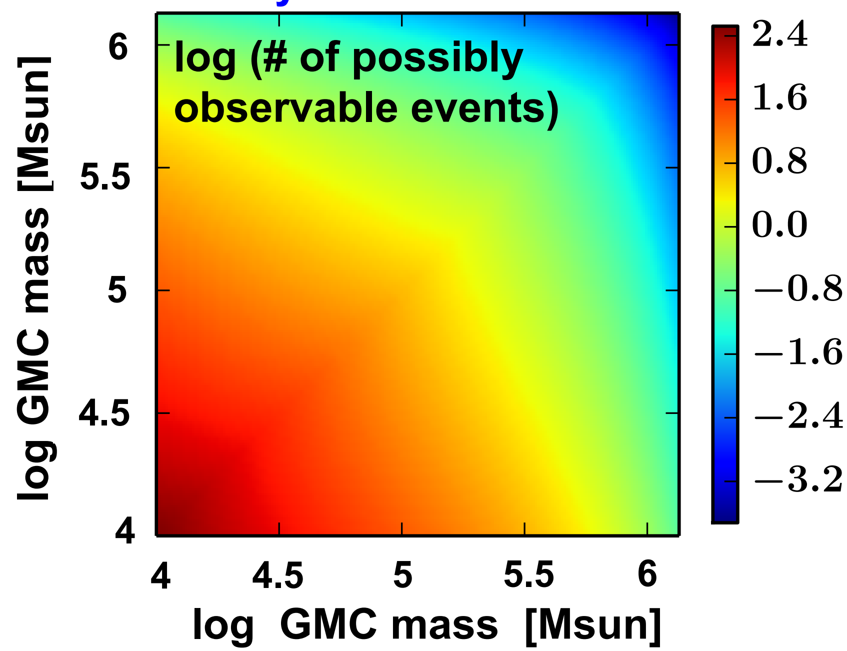
$$N_{\mathrm{obs}}(m, m_2) = \int \frac{\int_m^{m+\delta m} n_{\mathrm{cl}} \mathrm{d}m}{T_{\mathrm{col,num}}(m, m_2)} \Delta T_{\mathrm{CCC}} \, \mathrm{d}V_{\mathrm{survey}}$$

ΔT_{CCC} : Duration over which CCC can be identified as CCC

$V_{\mathrm{survey}} = \int \mathrm{d}V_{\mathrm{survey}}$: Survey volume

Let us optimistically assume ΔT_{CCC} = 1Myr, and survey the entire MW disk.

Kobayashi+ 2018 in revision



Mof the CCC pairs that current observations can probe must consist of GMCs ~10^4 Msun; it is desired to push observations further to pairs of >10^5 Msun, which are important for galactic star formation!

Summary

✓Backgrounds: Multiple Episodes of Compression

- Variation of GMC MF on galactic scales
- Magnetic fields retard molecular cloud formation

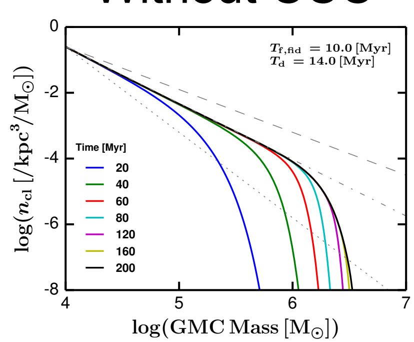
✓Formulation: Coagulation Equation with CCC

- **GMC MF slope is characterized by Tf/Td whereas its massive end is governed by CCC**
- **CCC-driven SF may amount to a few 10 per cent of total SF in the Milky Way galaxy.**

✓Future Prospects:

- The column density of star formation rate (SFR)
- Transition from arm regions to inter-arm regions

Without CCC



With CCC