The Life and Times of Giant Molecular Clouds

Authors: M. **Chevance** et. al.
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Presenters

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Stony Brook University

Thursday, April 20, 2023; 13:15-14:35

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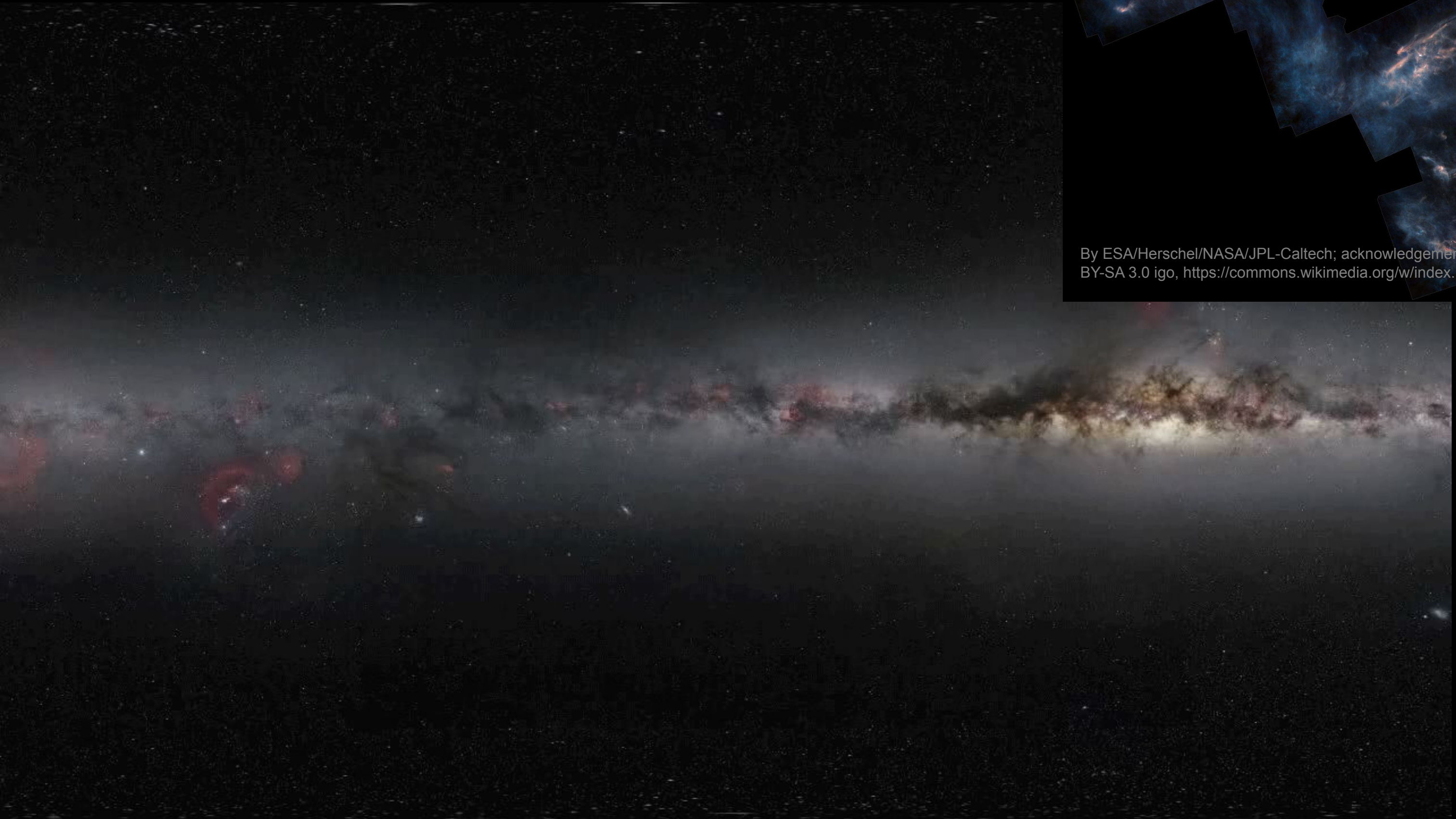
Giant molecular clouds (GMCs) are the sites of star formation and stellar feedback in galaxies. Their properties set the initial conditions for star formation and their lifecycles determine how feedback regulates galaxy evolution. In recent years, the advent of high-resolution telescopes has enabled systematic GMC-scale studies of the molecular interstellar medium in nearby galaxies, now covering a wide range of physical conditions and allowing for the first studies of how GMC properties depend on galactic environment. These observational developments have been accompanied by numerical simulations of improving resolution that are increasingly accurately accounting for the effects of the galactic-scale environment on GMCs, while simultaneously improving the treatment of the small-scale processes of star-formation and stellar feedback within them. The combination of these recent developments has greatly improved our understanding of the formation, evolution, and destruction of GMCs. We review the current state of the field, highlight current open questions, and discuss promising avenues for future studies.

Gallery - Taurus molecular cloud



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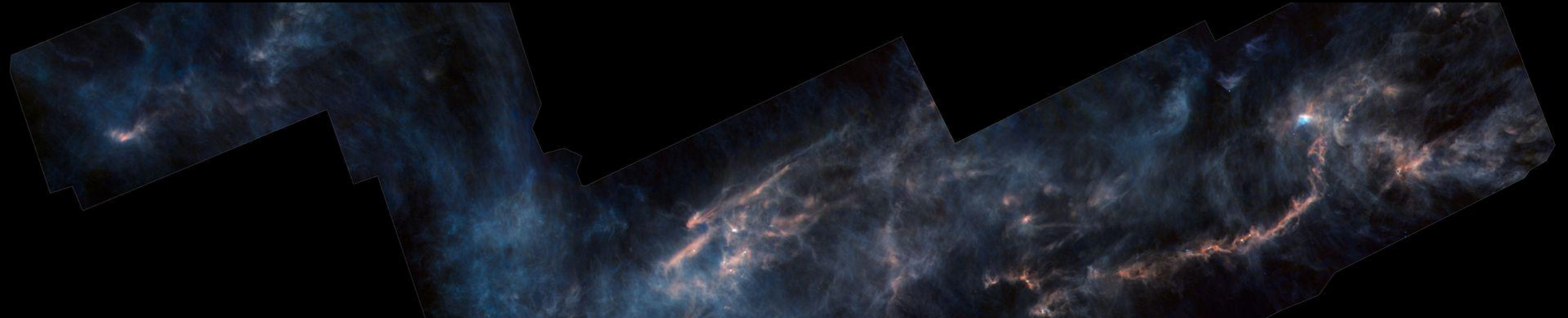
ESO/APEX (MPIfR/ESO/OSO)/A. Hacar et al./Digitized Sky Survey 2/Nick Risinger

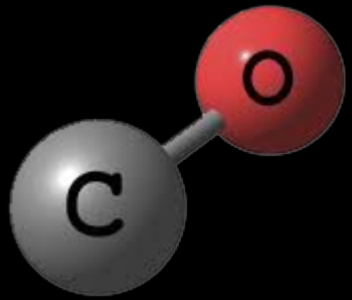
1 Introduction - Giant Molecular Clouds (1.1)

- GMC: a type of interstellar clouds
- Scale: Not clear, ~30 pc
- Mass: ~ $10^4 – 10^6$ solar masses (main budget of galactic ISM)
- Composition: Mainly (1) gas and (2) dust
  - Number density: H_2 molecules: $n \sim 100\ cm^{-3}$
  - Temperature: $T \sim 10\ K$



1 **Introduction** - Giant Molecular Clouds (1.2)

- 1970: CO (carbon monoxide) J=1–0 transition at 2.6 mm (radio)
- Line emission, molecular.
- Why?
  a. GMCs large complexes found
  b. **CO is a tracer of H_2 molecules**
  c. CO/H_2 may be linear



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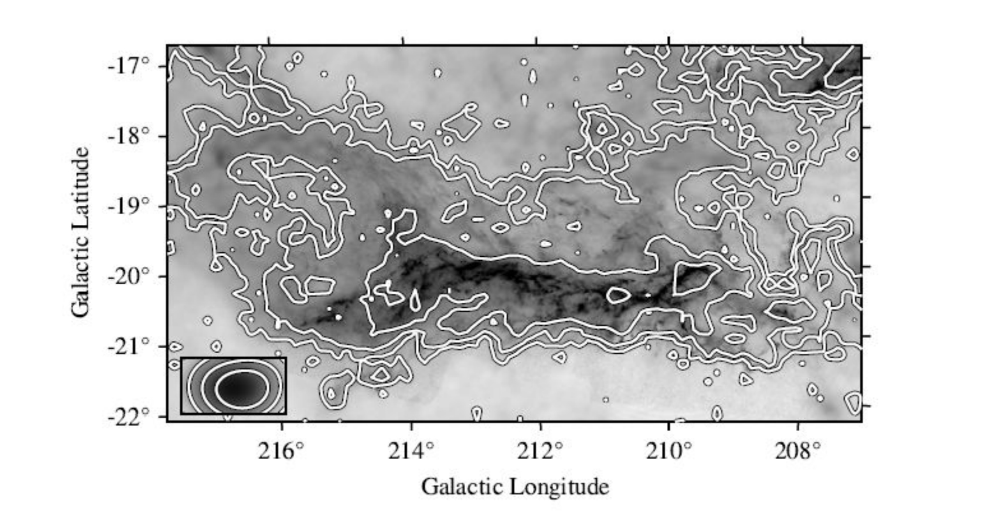
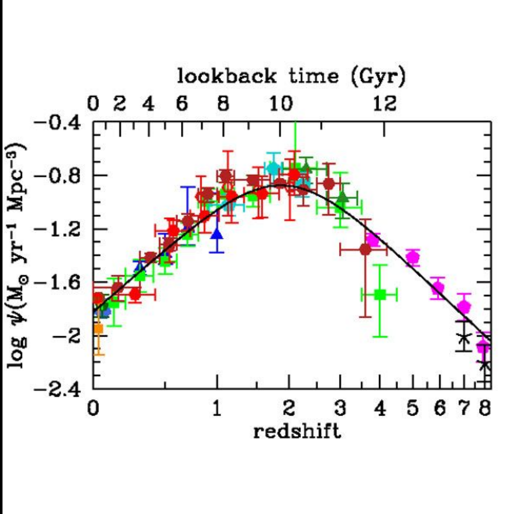
1 **Introduction** - Giant Molecular Clouds (1.3)

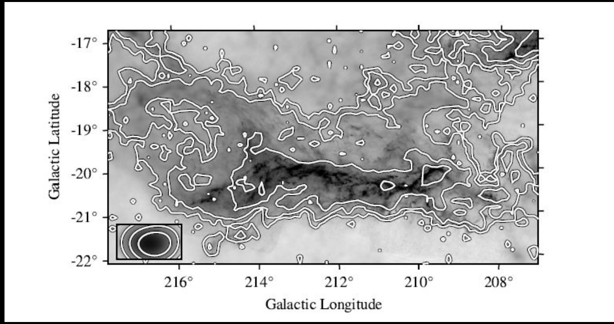
- Last slide: **CO** at **2.6 mm is a tracer of H_2 molecules**
- Other detection method:
  - Dust: 353 μm **(0.353 mm) emission**
- Cold + dense molecular gas at z~2 → SFR reaches maximum





1 **Introduction** - Paper Motivation (1.4)

- ALMA online enhanced resolving power
- MC problems:
  - Depletion time: $t_{dep} = M_{mol} / \dot{M}_*$ varies on scales
  - No enough observ. data, no secure lifetimes of individual clouds
  - Other questions… (properties, models, gravitational system assumptions)

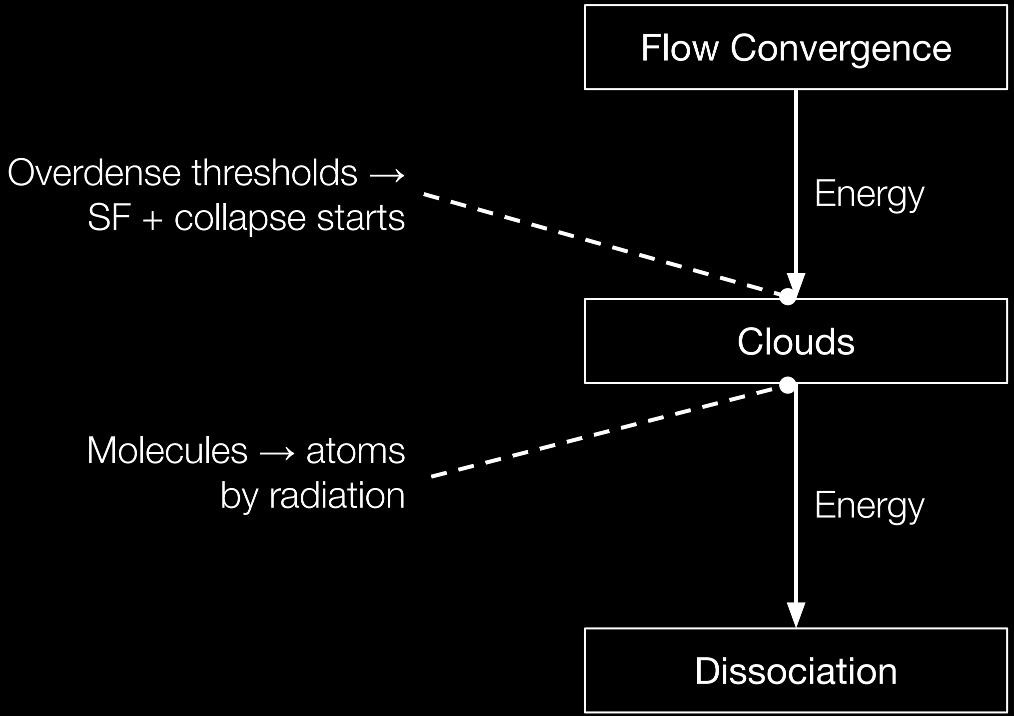


$$\alpha_{\mathrm{vir}} \equiv \frac{5\sigma_v^2 R}{GM}$$

1 **Introduction** - Paper Motivation (1.5)

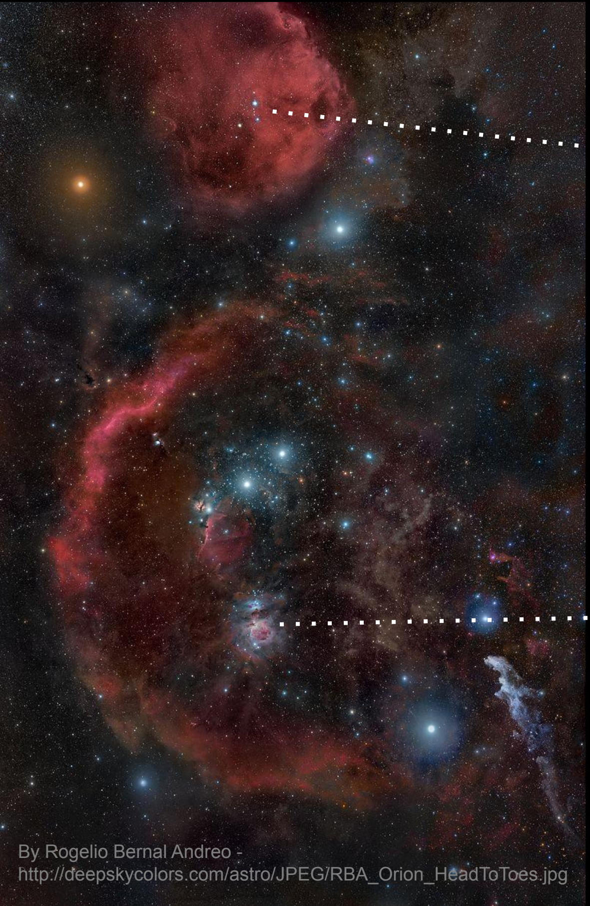
- Old models: look at magnetic fields or free-fall collapse
- Magnetic fields << support the collapse
- MHD simulations:
    - kinematics + structure + evolution became possible insights → star formation (SF) in GMCs
- Old MHD simulations did count feedback and parameters from individual GMCs.

1 **Introduction** - GMCs' Lifecycle (1.6)

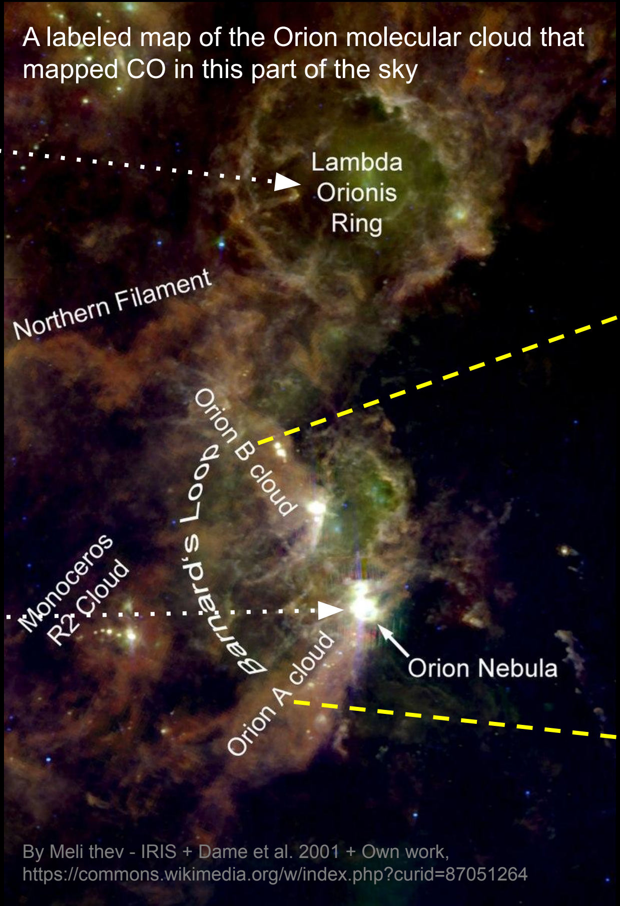


(SN feedback, stellar winds, radiation work done by gravity…)

Gallery - Orion molecular cloud complex



By Rogelio Bernal Andreo - http://deepskycolors.com/astro/JPEG/RBA_Orion_HeadToToes.jpg



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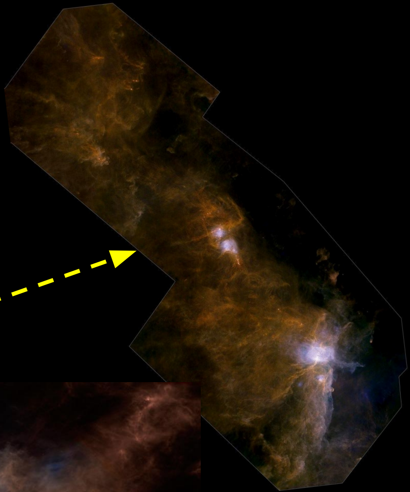

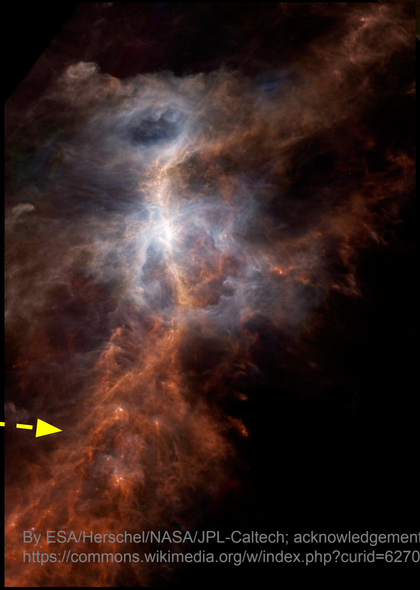

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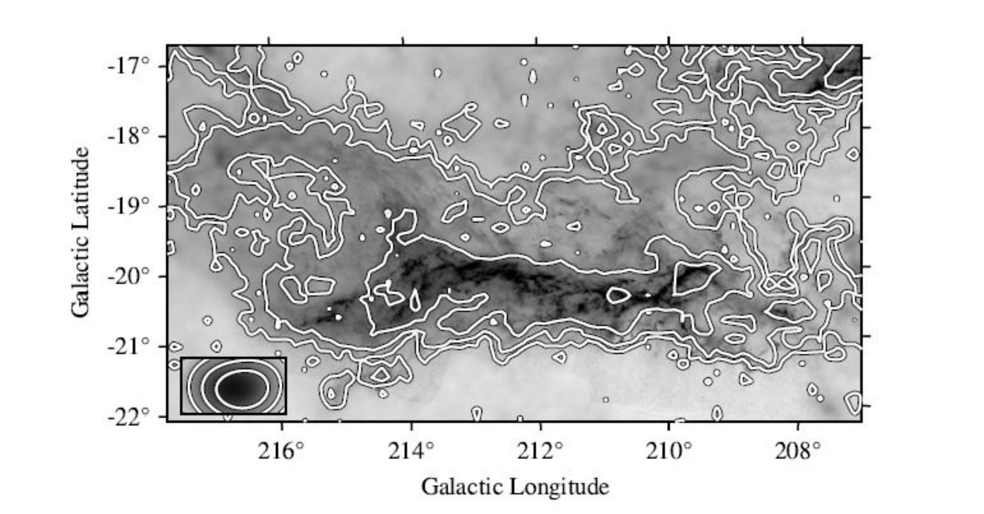
2 **GMC Properties** - Entity Definition? (2.1)

- GMC morphology: aspect ratio + filamentary shape
- High-M lead SF in filamentary w/ high column density
- Background = dust column density → GMC boundaries
- Contours = molecular gas emission → threshold identifying



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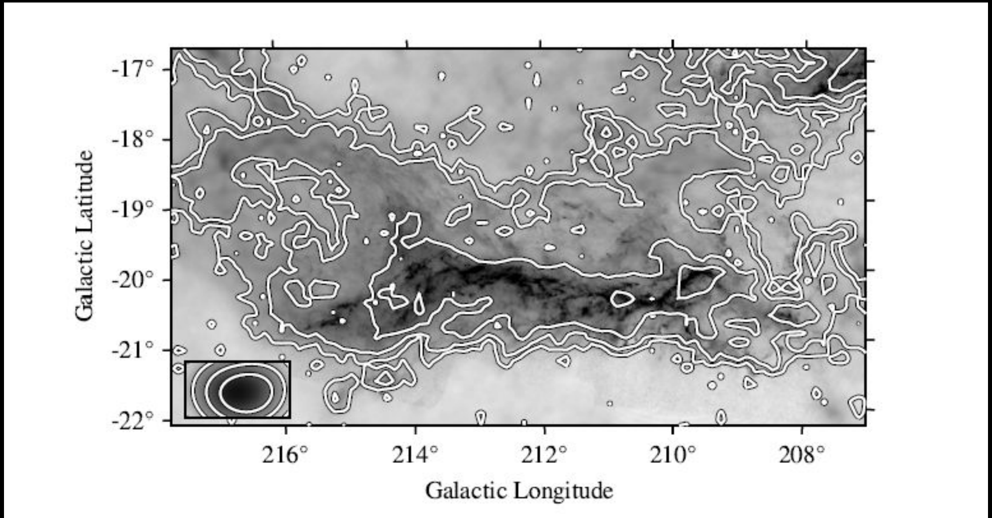
Temperature:	T ~ 10 K

2 **GMC Properties** - Entity Definition? (2.2)

- Problems:
  - Non-linear CO/H_2
  - Dust-based GMCs are observed in Solar neighborhood
- So, GMCs have no well-defined set of discrete entities to define itself.



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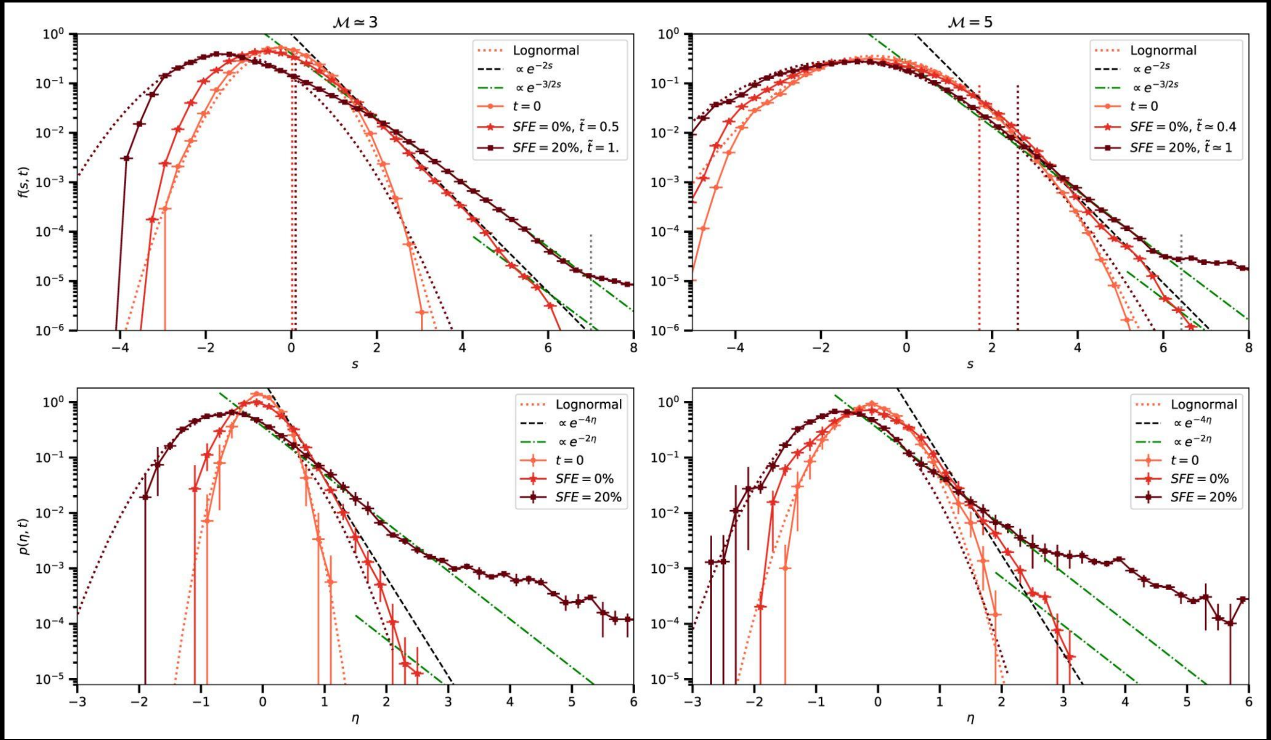
2 **GMC Properties** - Internal Structure (2.3)

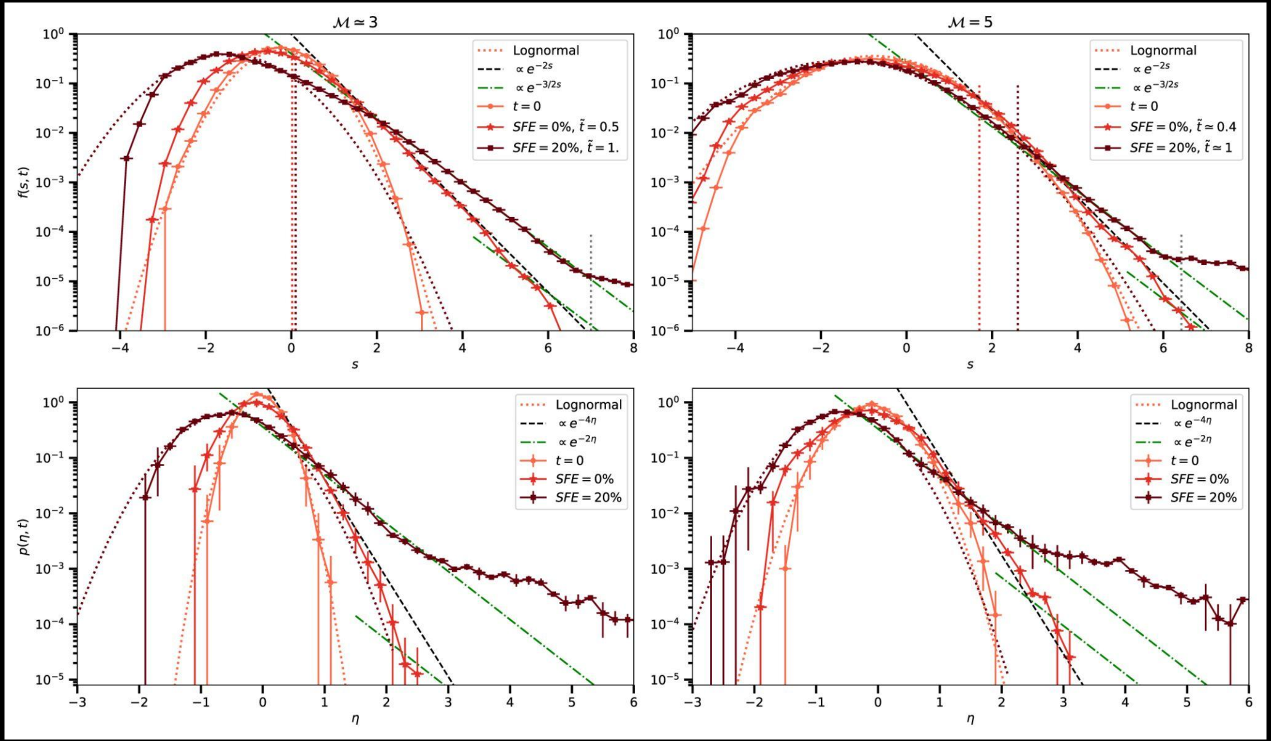
- Turbulent: Re > 10^8 ; Volume density follows $\log(\rho/\rho_0)$-normal distribution



(Jaupart & Chabrier, 2020)

2 **GMC Properties** - Internal Structure (2.4)

- Volume density follows log(ρ/ρ_0)-normal distribution: **describe internal conditions**



(Jaupart & Chabrier, 2020)

2 **GMC Properties** - Kinematics (2.5)

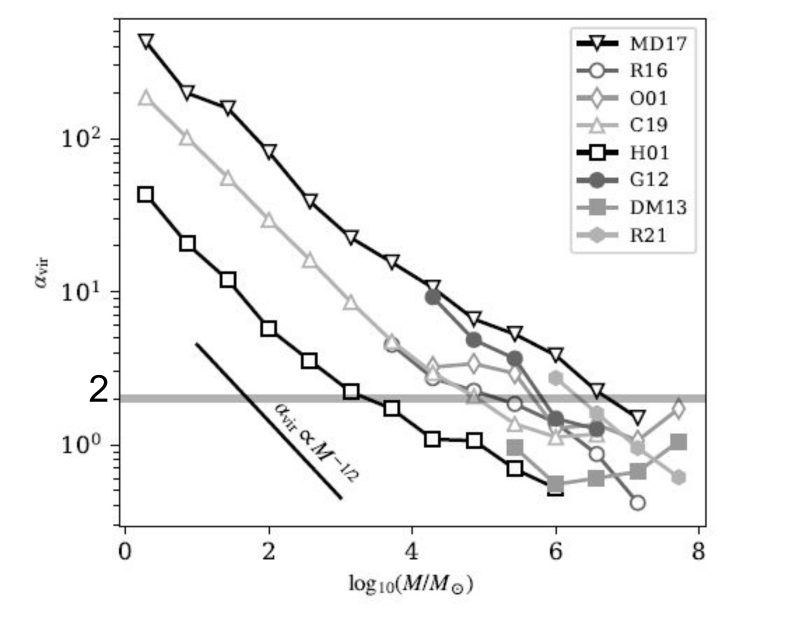
- CO + dust → Masses, Scales
- CO → velocity dispersions (σ_v)

$$\sigma_v = \sigma_0 \left(\frac{R}{1\ \mathrm{pc}}\right)^{c_1} \quad \text{and} \quad M = \Sigma_{\mathrm{mol}} \pi R^{c_2}, \qquad (2)$$

$$\alpha_{\mathrm{vir}} \equiv \frac{5\sigma_v^2 R}{GM} \propto \frac{\sigma_0^2}{\Sigma_{\mathrm{mol}}} \qquad (3)$$

$$\alpha_{\mathrm{vir}} = 2E_k/U_g$$

$$\frac{dN}{dM} \propto M^{c_3} \qquad (4)$$



3 GMC Formation

- Recall: GMCs are massive ($10^{4.5}$), gas-molecule conversion, collapse, and SF
- Triggers to form GMCs
- 1. Accretion
- 2. Neutral atom → molecular H_2 gas

$$t_{\rm eq} = \frac{1}{2Rn + D + \zeta} \qquad (5)$$

$$D_0 = 5.8 \times 10^{-11} I_{\rm UV}\ {\rm s}^{-1}$$

$$t_{\rm diss} \approx \frac{5 \times 10^2}{I_{\rm UV}} \quad {\rm yr} \qquad (7)$$

"Unattennuated"

$$t_{\rm diss} \approx \frac{5 \times 10^2}{I_{\rm UV}} \quad {\rm yr} \qquad (7)$$

"Shielded regions"

$$t_{\rm H_2} \approx \frac{1}{Z'_d} \times \frac{10^9}{n} \quad {\rm yr}\ . \qquad (8)$$

4. The Evolution of GMCs

Central Questions:

1. Is collapse local or global?
2. How long does it take for star formation to begin?
3. How long does it take for star formation to end?

Local vs. Global Collapse

Local

- Only a small fraction of the cloud collapses
- Large structure may not be bound
- Most gas doesn't collapse → low SFR efficiency

Evidence:

- Stellar velocities are mostly random
- Stellar positions trace "fractal structure"

Global

- The entire cloud collapses at once
- Large structure must be bound
- Destruction of cloud by feedback → low SFR efficiency
- Non-thermal motions may explain large linewidths

Evidence:

- Large-scale filaments
- Central "hubs"
- Large linewidths

Timescale for Phases of GMCs

Natural timescale: free-fall time

- Lower limit on the collapse time
  - Non-spherical geometry (filaments)
  - Magnetic fields
  - Differential rotation shear
  - Turbulence
  - Accretion of external material

$$t_{\rm ff} = \sqrt{\frac{3\pi}{32G\rho}},$$

Measuring the Lifetime of GMCs

- It is very difficult!
  - Object classification
  - Stellar age spreads
  - Evolution along orbital streamlines
- There is not enough data to give an exact answer
- Modern ideas:
  - CO and Hα are rarely coincident
    - Clouds cycle between GMC state and star forming state
    - Fit this with analytical model → ~10-30 Myr lifetime

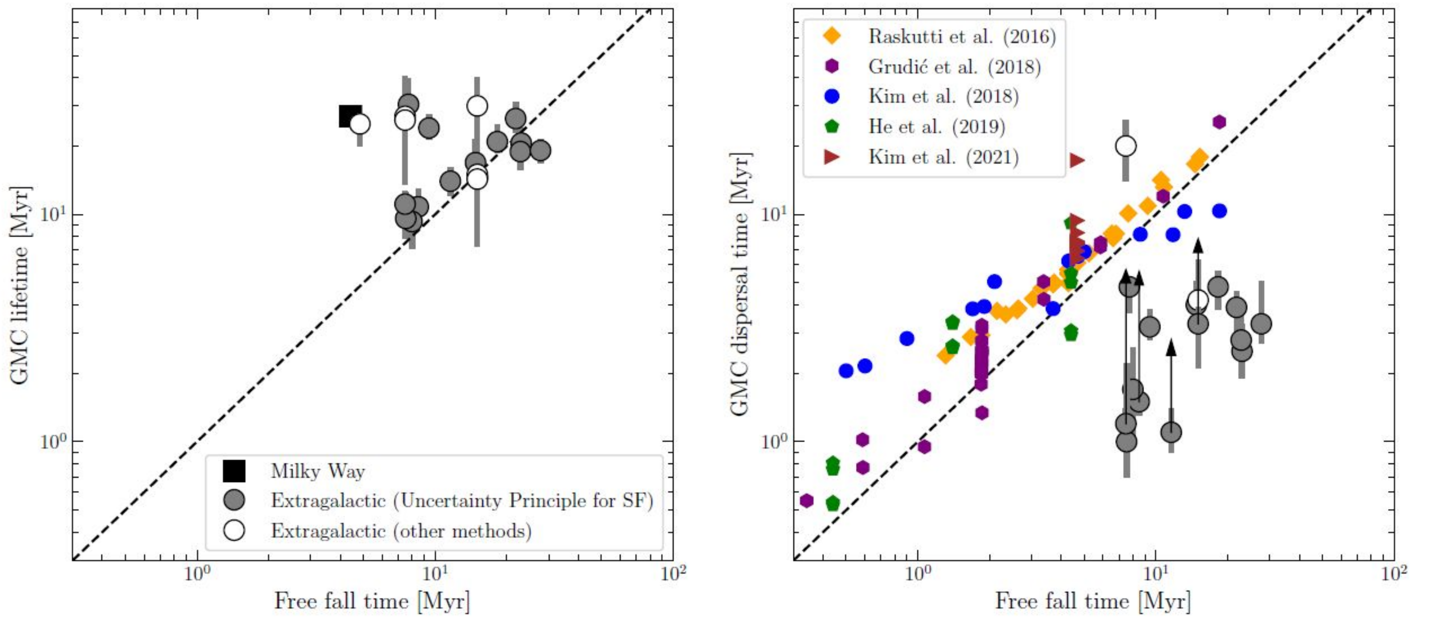


Fig. 3.— Measured GMC lifetime (*left*) and GMC dispersal time (*right*) in the Milky Way (black square; *Murray* 2011) and nearby galaxies, using the uncertainty principle for star formation (grey circles; *Kruijssen et al.* 2019; *Chevance et al.* 2020a; *Zabel et al.* 2020; *Kim et al.* 2021a) and other analysis methods (white circles; *Engargiola et al.* 2003; *Blitz et al.* 2007; *Kawamura et al.* 2009; *Miura et al.* 2012; *Corbelli et al.* 2017; *Meidt et al.* 2015). The dispersal time is measured from the moment where Hα emission from massive stars becomes visible. This neglects a potential phase of dust-obscured massive star formation. In the most nearby galaxies, *Kim et al.* (2021a) measured the duration of this embedded phase using 24μm emission. This increases the GMC dispersal time as indicated by the black arrows. In addition, beam dilution might results in longer measured cloud free-fall times. These two effects likely explain the longer duration of the GMC dispersal time found in simulations (*Raskutti et al.* 2016; *Grudić et al.* 2018; *Kim et al.* 2018; *He et al.* 2019; *Kim et al.* 2021b), measured from the formation of the first star.

Evolution of SFR

- In MW: extended star formation (stars older than t_{ff})
  - Long collapse times? →
  - Accretion? → “conveyor belt” picture
- Can we have clouds without any star formation?
  - Requires dispersal by external dynamics
  - Rare in simulations
  - ~20% of dark clouds don’t have stars, but they could be unobservable
    - “Inert” phase of cloud formation?
- SFR ends after feedback reverses gas inflow
  - Typically a few Myr (justification in next section)

Efficiency Rates

$$\epsilon_{\rm ff} = \frac{\dot{M}_*}{M_{\rm gas}/t_{\rm ff}}.$$

- Efficiency per free fall time
- Theory: depends on virial parameter, mach number, magnetization
- Current simulations: ε ~ 0.01-0.05
- **How to measure?**
    - Requires volume density
    - Various methods, most agree on median of ε ~ 0.01
    - Large variations in scatter estimates
    - We don’t know if it varies with environment

6. Lifetime Accomplishment

Central Questions:

1. How efficiently do GMCs convert mass to stars?
    a. Does it vary with environment or GMC properties?
2. When do we get bound vs. unbound stars?
3. How can we learn about GMCs by studying their produced stars?

Star formation efficiency

"Fraction of total cloud mass that is converted to stars"

- How to measure?
  - It is not an instantaneous quantity – requires gas mass early on and gas mass at end of life
  - Must use statistics of many GMCs
  - Current estimates: 0.02-0.10
- Theoretical models
  - Use stellar feedback
  - Toy model can kind of replicate measurements:
  - Dynamical disruption dominates at low densities
  - Photoionization dominates at high densities

$$\begin{aligned}\frac{M_{\rm phot}}{M_*} &\sim c_i m_{\rm H} t_i \left(\frac{\Xi^2}{M_* \alpha_{\rm B}^2 n_i}\right)^{1/3} \qquad (17)\\ &= 11 \left(\frac{n_i}{30\ {\rm cm}^{-3}}\right)^{-1/3} \left(\frac{M_*}{1000\ {\rm M}_\odot}\right)^{-1/3},\end{aligned}$$

Dynamical Disruption

- Efficiency is a function of *momentum per stellar mass provided by feedback, virial ratio, surface density*
- Simulations: can broadly reproduce observations of efficiency
- Why does (dp/dt)/M* affect ε so strongly?
  - Consider a nonuniform surface density

Main takeaway: ε proportional to surface density → this should be measurable!

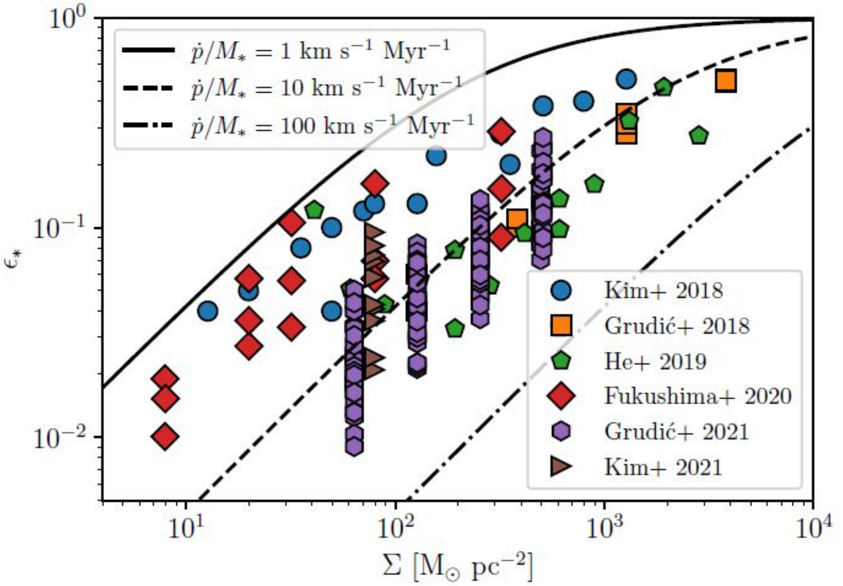


Fig. 4.— A compilation of integrated star formation efficiencies ϵ_* obtained in simulations of isolated GMCs with photoionization and other feedback processes; the data shown are from *Kim et al.* (2018), *Grudić et al.* (2018), *He et al.* (2019), *Fukushima et al.* (2020), *Grudić et al.* (2021), and *Kim et al.* (2021b) as indicated. Lines show Equation 18 evaluated with $\alpha_{\rm vir} = 1$ and $\dot{p}/M_*$ as indicated in the legend.

Binding of Star Clusters

- Only 10% of stars form in bound clusters
- Return to local vs. global collapse
    - If local, most stars will not be formed in main collapse hubs
    - If global, we require a lot of feedback to stop the collapse and unbind stars
- Local collapse seems more likely given observations

Using Stars to Learn about GMC

- Study positions of stars and gas from 2-point correlation function
- Young stars are more strongly clustered than the gas
  - This diminishes with age
  - Makes sense: denser gas will form stars more easily

7. Future Prospects

Large Surveys → better statistics, different environments

Better Resolution → different galaxies, different environments (low metallicity, interacting systems, high redshift, etc.)

Higher Resolution Simulations → better understanding of internal dynamics

Current areas of work

- Effect of the surrounding environment on cloud properties
  - Need to observe dust emission, surface density, more environments!
- Effect of the surrounding environment on star formation
  - Need to increase statistical power → estimate star formation efficiency for subpopulations
- Effect of the surrounding environment on GMC lifetime
  - Need high-resolution simulations and high-resolution imaging

Combining Observations and Sims

- Translate relation between gas and star formation to tracers of gas vs. star flux
  - Can run simulations and get detailed measurements
- Give empirical constraints → feed into future simulations

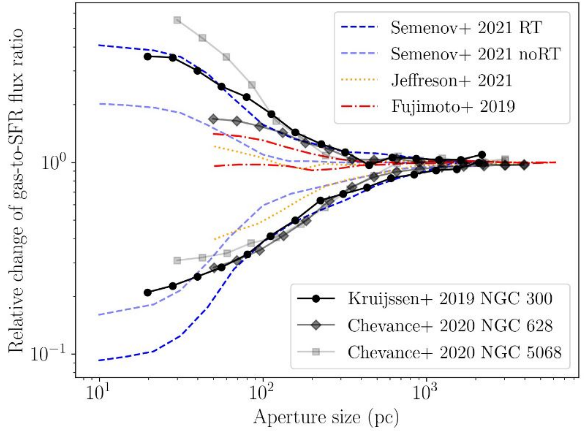


Fig. 5.— The so-called "tuning fork diagram" illustrating the spatial decorrelation between gas and stars, as traced by the gas-to-SFR flux ratio relative to the galactic average value as a function of aperture size, obtained from both observations (of NGC 300, Kruijssen et al. 2019; of NGC 628 and NGC 5068, Chevance et al. 2020a) and simulations (Fujimoto et al. 2019; Semenov et al. 2021 with and without explicit radiative transfer, RT, modeling; and Jeffreson et al. 2021b). The upper and lower branches are the result of focusing apertures on molecular gas and stellar peaks, respectively. The lines correspond to best-fit models of Kruijssen et al. (2018) to the synthetic and observed peaks, which yield molecular cloud lifetimes and feedback timescales. The comparison of simulated tuning fork diagrams to observations tests the adopted stellar feedback prescriptions, indicating the importance of early (pre-supernova) feedback in removing gas around emerging clusters, crucial to reproduce the observed decorrelation at small aperture sizes.

Main Paper

Chevance M., Krumholz M. R., McLeod A. F., Ostriker E. C., Rosolowsky E. W., Sternberg A., **2022**, arXiv, arXiv:2203.09570. doi:10.48550/arXiv.2203.09570

References

Jaupart E., **Chabrier** G., **2020**, ApJL, 903, L2. doi:10.3847/2041-8213/abbda8