Larson's laws and the universality of molecular cloud structures

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Section 1

Introduction

Molecular clouds and star formation

Failure

Our incomplete understanding of how stars and planets form represents one of the longest-standing problems in astronomy today.

Crucial phenomenon with a lot of implications

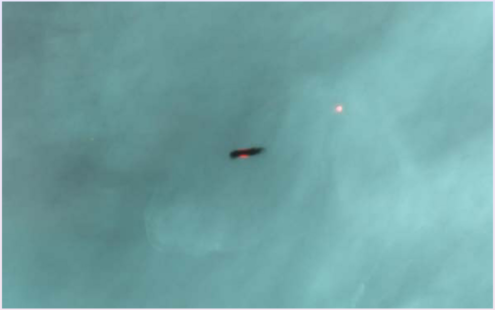
- Formation of a single stellar and planetary system.
- Formation of star clusters.
- Global evolution of an entire galaxy.
- Observable properties of galaxies at cosmological redshifts.

This failure is mainly linked to the difficulty to detect cold ($T \sim 10$ K) molecular hydrogen, the main component of molecular clouds.

Molecular clouds

- Stars form within the densiest regions of molecular clouds.
  - Microphysics: individual star formation from dense cores (protostellar disk, jets, outflows, dynamics).
  - Macrophysics: formation of systems of stars (giant molecular clouds, SFR, properties of the ISM, IMF)
- Star formation is inextricably linked to the molecular clouds!

Molecular clouds



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Tracers

Problem

H_2 is symmetric molecule, therefore cold H_2 has no emission line spectrum and remains essentially invisible.

Solution: use tracers

Molecular clouds are know to contain more than 100 molecules (CO, H_20, HCN, CO_2...) that glow at microwave radio frequencies, with thousands lines observed!

Can we trust radio observations?

A lot of data

- Lots of molecules with lots of emission lines provide a unique diagnostic tool: each transition probes different physical conditions within the cloud.
- Doppler shifts provide dynamical information too and allow one to disentangle different clouds that overlap along the line of sight.

Difficult interpretation

- Several poorly constrained effects (opacity variations, chemical evolution, depletion of molecules. . .) make the ratio between radio line intensity and H_2 non constant.
- Different molecules probe different regions, but each line has a limited dynamic range and data from different lines are often in contradiction.

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Optical picture

- Optically, molecular clouds appear as "holes" in the sky (and indeed originally they were mistaken as such).
- This happens because the dust present in dense molecular clouds absorbs photons in the optical wavelength.
- Extinction is higher for the bluer frequencies: IR light can often penetrate even the densiest regions of molecular clouds.

Structure of molecular clouds

Clouds have often a filamentary structure, with regions of significantly higher density. Filaments can connect relatively distant regions, like in a web.

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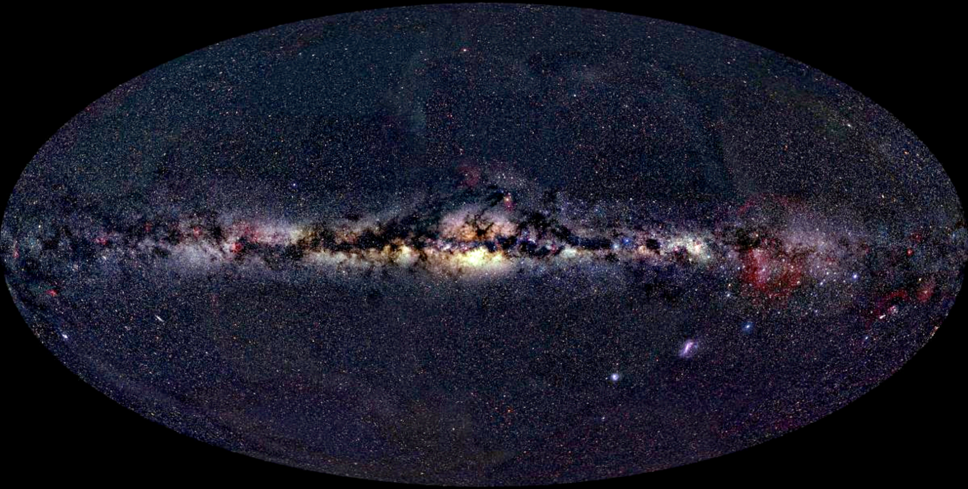
Molecular clouds show inhomogeneities at various scales:

GMC: Giant Molecular cloud: $M \sim 10^5\ \mathrm{M}_\odot$, $R \sim 10$ pc, $\rho \sim 10^2\ \mathrm{cm}^{-3}$.

Clump: Site of formation of star clusters: $M \sim 10^3\ \mathrm{M}_\odot$, $R \sim 1$ pc, $\rho \sim 10^3\ \mathrm{cm}^{-3}$.

Core: Site of formation of an individual star: $M \sim 10^1\ \mathrm{M}_\odot$, $R \sim 0.1$ pc, $\rho \sim 10^4\ \mathrm{cm}^{-3}$.

Gould belt



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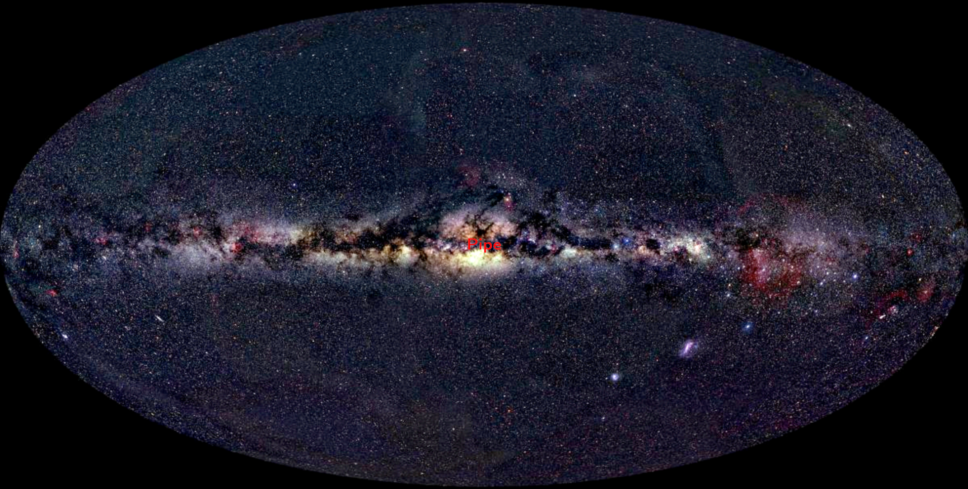

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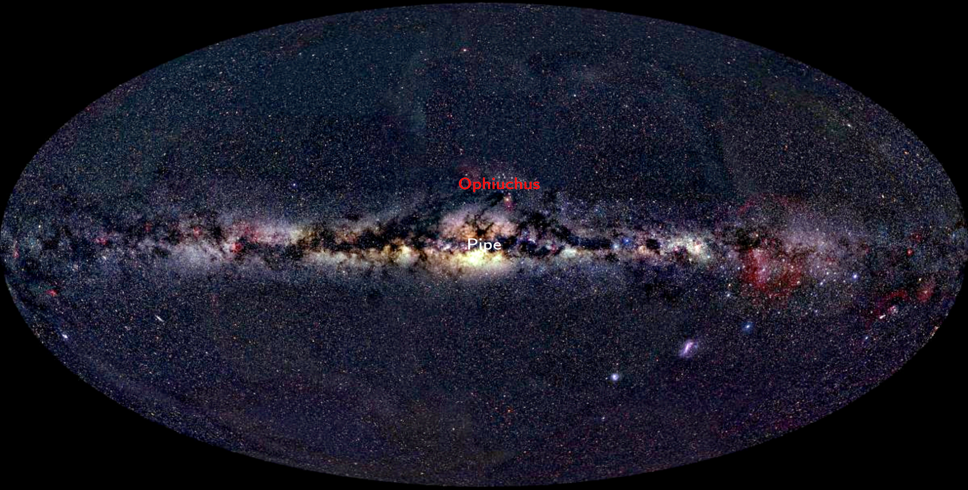

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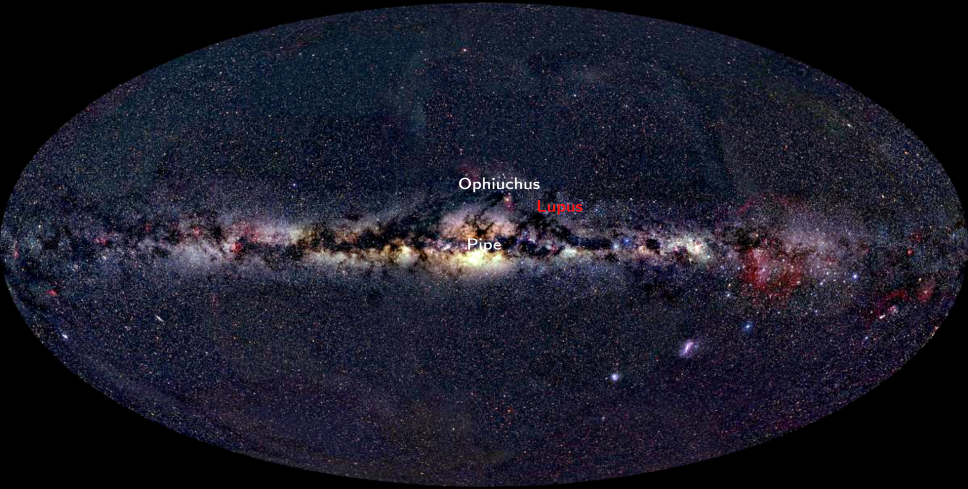

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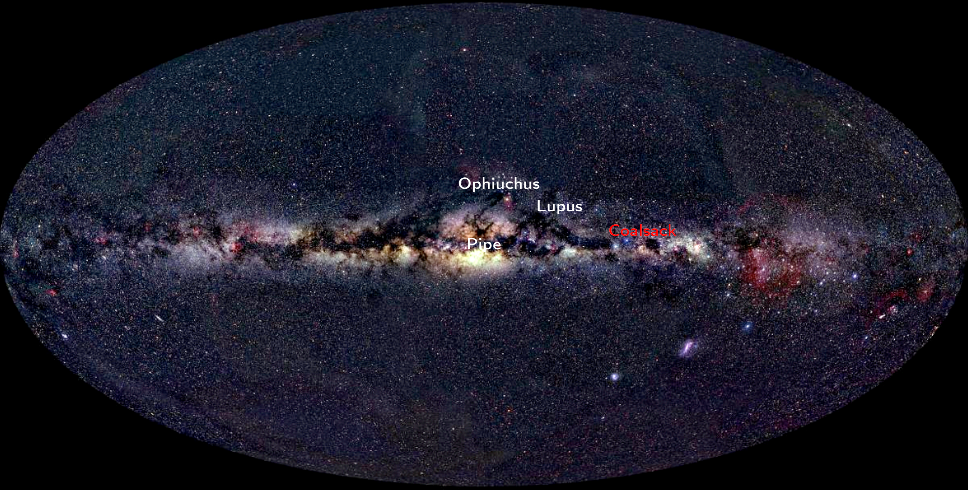

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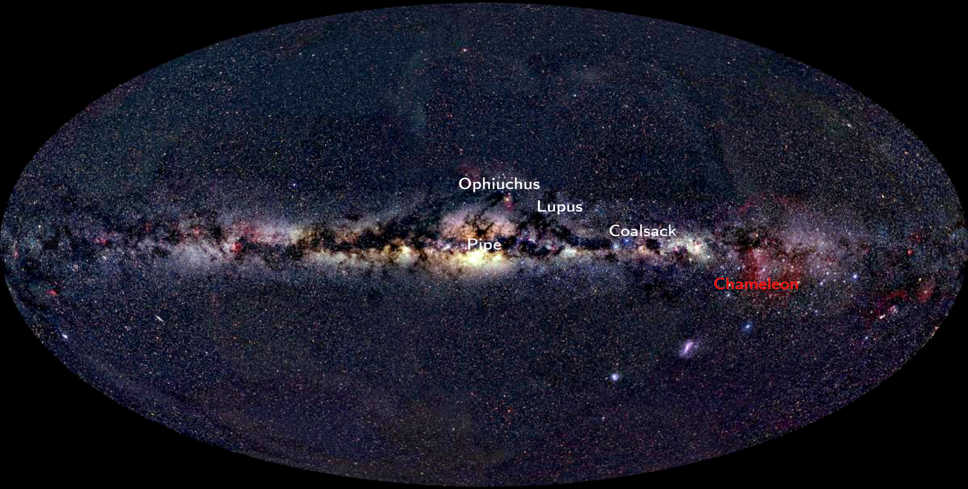

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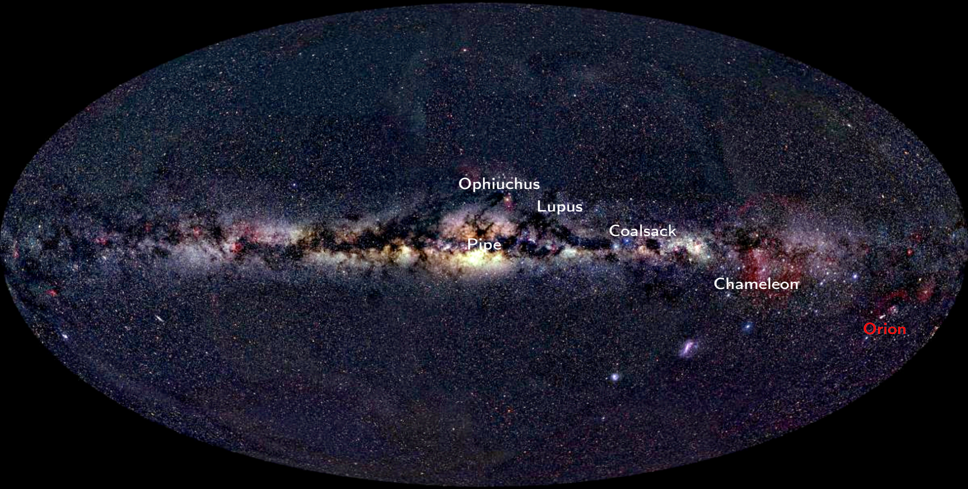

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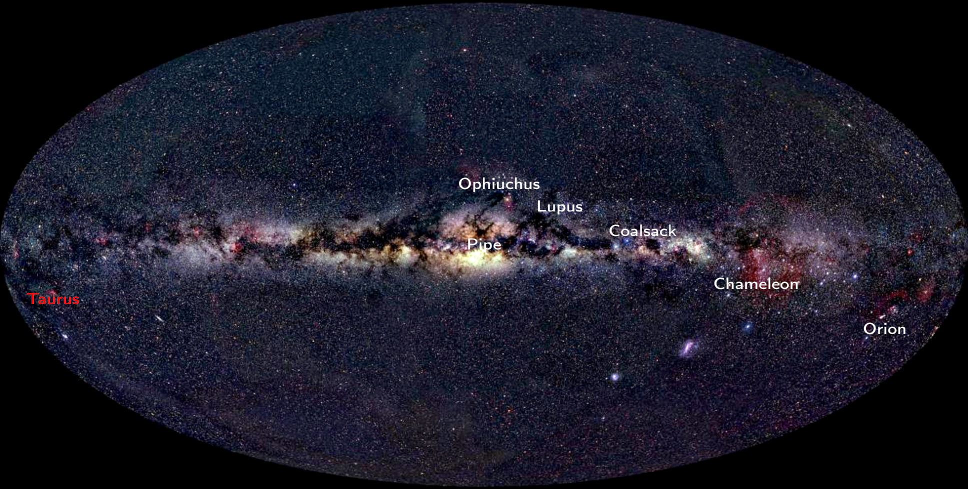

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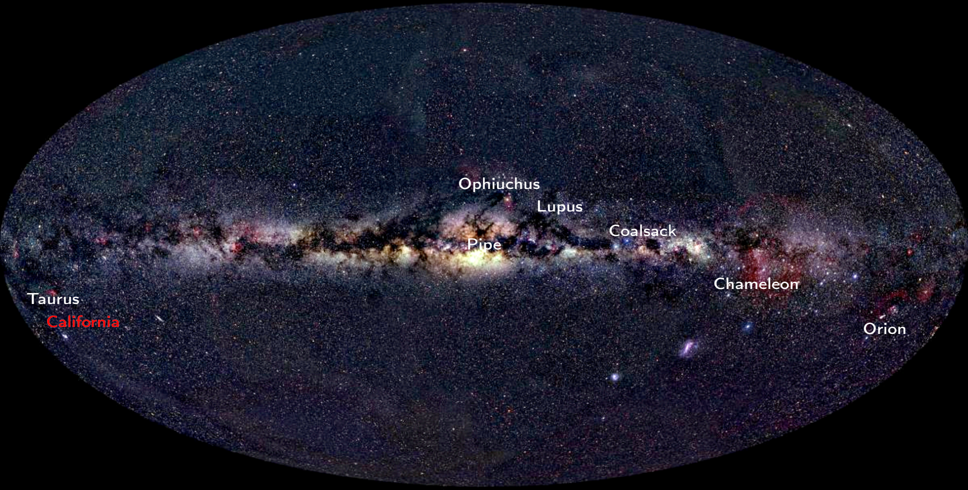

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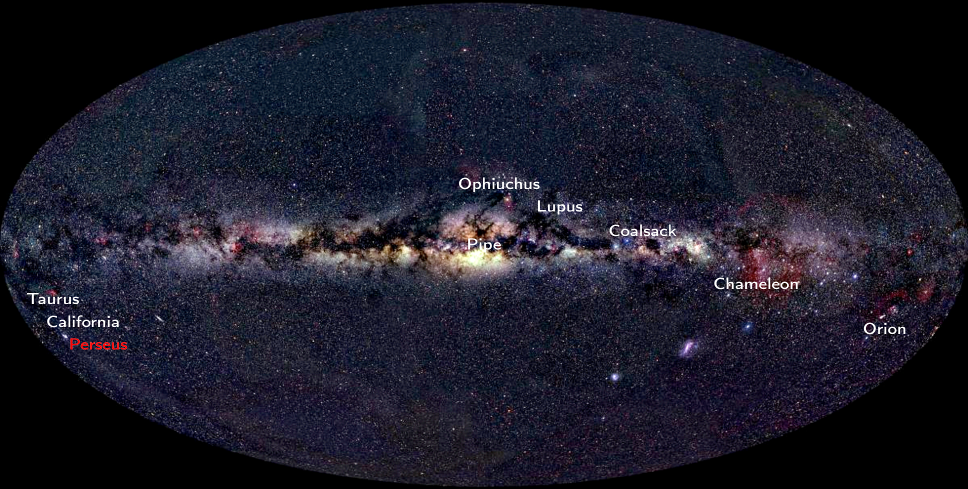

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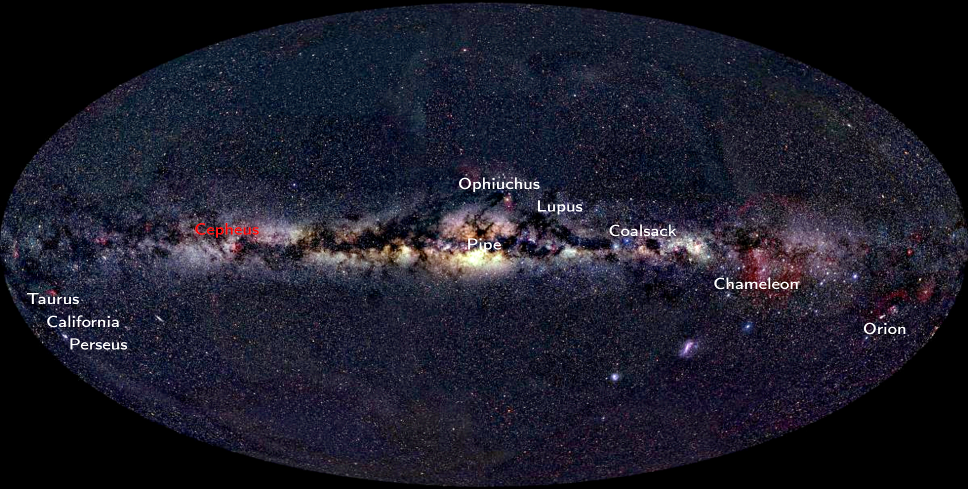

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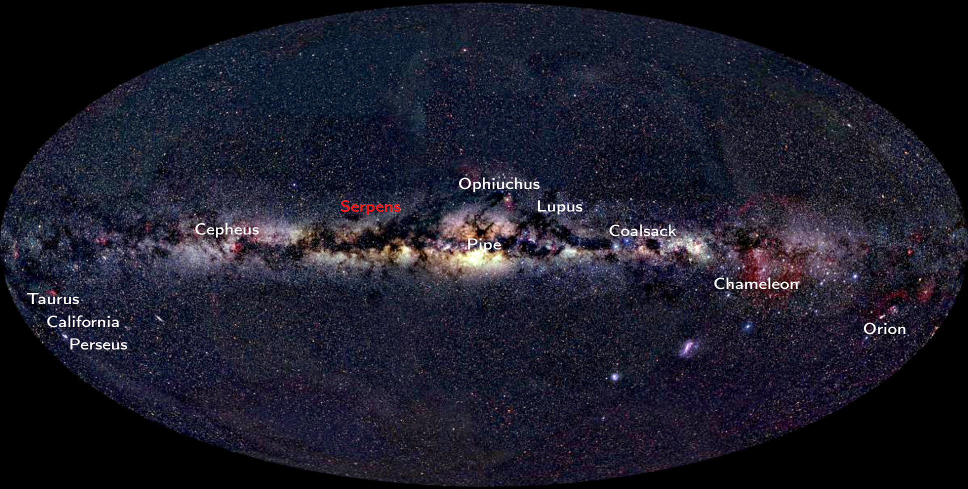

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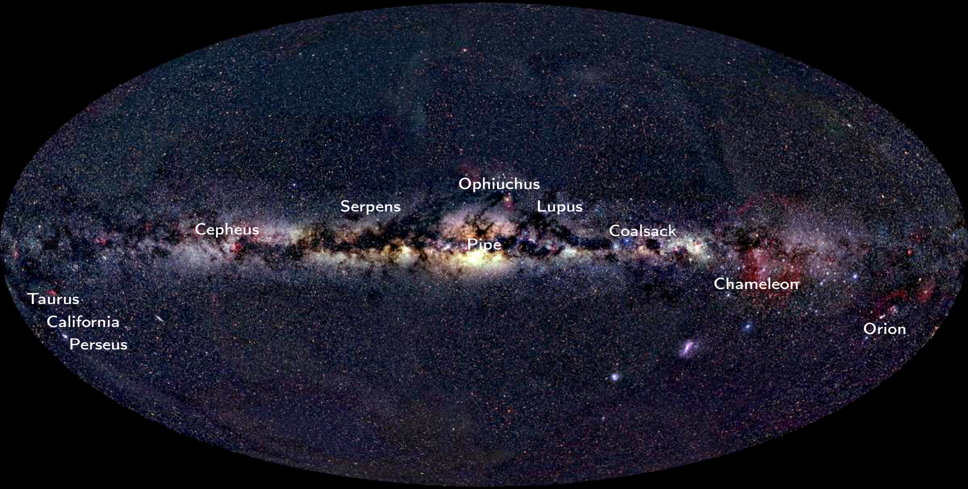


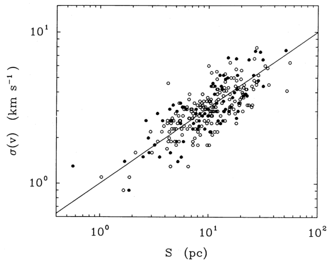
A. Melliger

Larson's 1st law

First law Larson, 1981

The internal motions of GMCs are chaotic, with their internal velocity dispersions σ systematically increasing with cloud size R (Sanders et al., 1985; Dame et al., 1986; Solomon et al., 1987):

$$\sigma \propto R^{0.5\pm0.1} \ .$$



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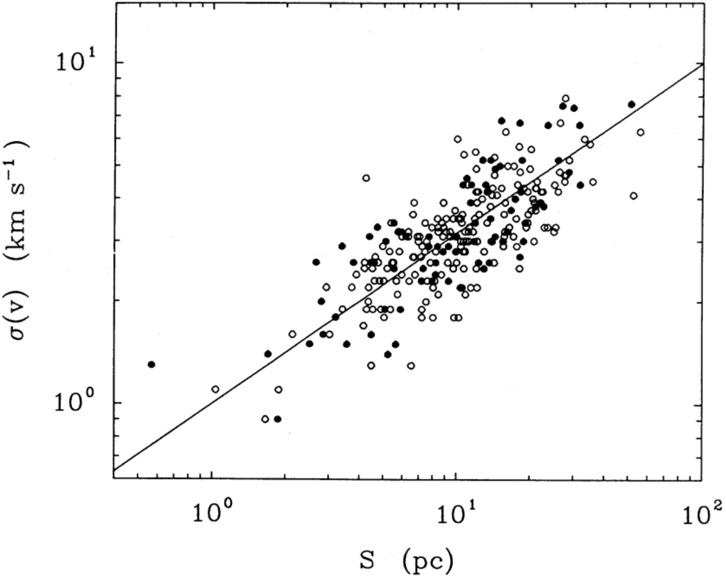

Size-linewidth relation and turbulence

Turbulence

Larson's law holds on a wide range and has no preferred scale, a fact which is interpreted as a signature of turbulence.

Exponent?

Larson's original exponent was $\sim 1/3$, corresponding to turbulence of incompressible fluids (Kolmogorov, 1941). The measured exponent is now $\sim 1/2$ corresponding to Burgers turbulence or *Burgulence*.

Universality!

Burgulence explains the exponent *within* a cloud, not why *all* GMCs follow the same size-linewidth relation. Turbulence in GMCs is universal, an unexplained result (Bolatto et al., 2008).

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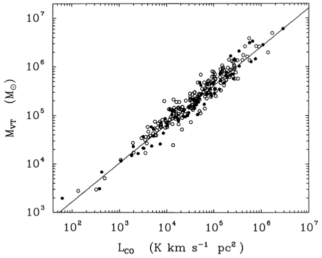
Larson's 2nd law

Second law Larson, 1981

GMCs are in approximate virial equilibrium: the gravitational potential energy is approximately twice the total kinec energy:

$$\frac{GM^2}{R} \simeq M\sigma^2 \, .$$



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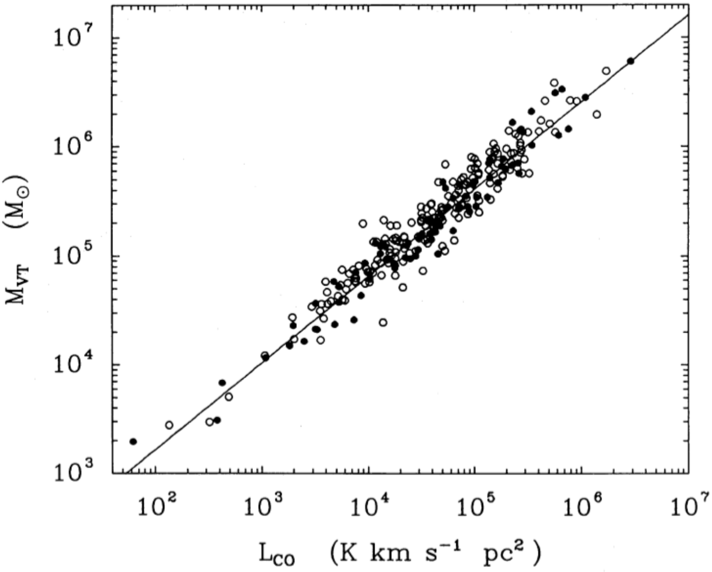

Gravity role at different scales

- Larson's concluded that GMCs, and also clumps within them, are gravitationally bounds.
- Recent studies show that most likely this applies only to clouds with $M > 10^4$ $M_\odot$ (Heyer et al., 2001).
- Smaller clumps must be either transient, or confined with other mechanisms, such as pressure.
- However, among the small clumps, the few that appear to be gravitationally bound contain most of the mass, and are the only one with active star formation.
- Clouds cores are gravitationally bounds but also pressure confined (Alves et al., 2001).

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Larson's 3rd law

Third law Larson, 1981

Molecular clouds have approximately constant column densities, or equivalently their masses scale as $M \propto R^2$.

Relation with the other laws

The three laws are related: since $\sigma \propto R^{1/2}$ (1st law) and $M \propto \sigma^2 R$ (2nd law), we must have $M \propto R^2$.

Average density

In our Galaxy, (bond) molecular clouds have surface densities around 100 $M_\odot$ pc^{-2}, corresponding to ~ 7 mag of visual extinction (Blitz, 1993).

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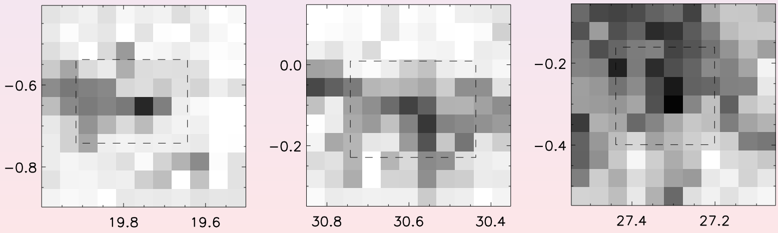
All simple? Not quite...

Solomon et al. (1987)

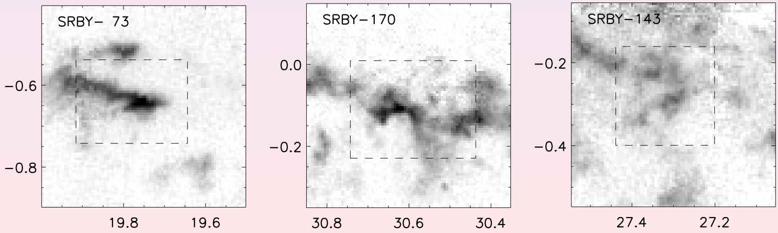
- The data used by are undersampled with respect to the beam FWHM;
- The ^{12}CO line is optically thick under most prevailing conditions in molecular clouds.
- This result in an average density $\Sigma \simeq 170\ M_\odot\ pc^{-2}$.



All simple? Not quite. . .

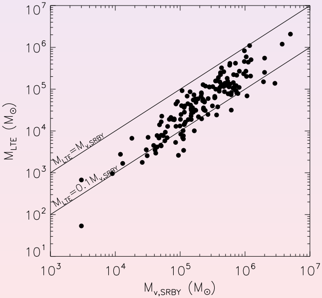
Heyer et al. (2009)

- The data used by are correctly sampled and have a much higher spatial resolution.
- The measurements are based on the ^{13}CO line, which is almost always optically thin.
- This result in an average density $\Sigma \simeq 40\ M_\odot\ pc^{-2}$.



Consequences

- Data seem to indicate that clouds masses might be lower than virial masses, suggesting that molecular clouds are unbound.
- The quantity $\sigma/R^{1/2}$, which is in principle constant (Larson's 1st law), correlates with the surface density Σ.



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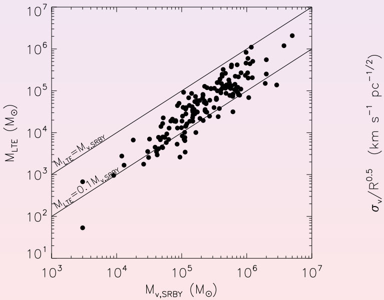

Larson's laws in external galaxies

Agreements

Larson's type relationships seem to holds in other galaxies too:

- Rosolowsky et al. (2003) found that molecular clounds in M33 have a surface density of $\sim 120\ \mathrm{M}_\odot\ \mathrm{pc}^{-2}$ (comparable to the Milky Way one).
- Mizuno et al. (2001) studied the LMC and confirmed Larson's laws there.

Differences

Bolatto et al. (2008) studied a sample of clouds in nearby galaxies and found that "more or less" Larson's laws hold there: clouds seem to have a factor 2 smaller surface density and a lot of scatter.

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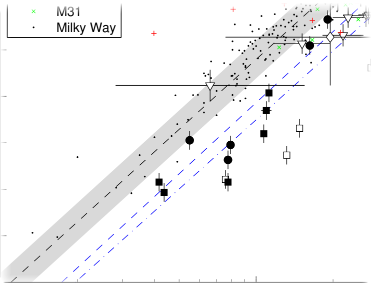

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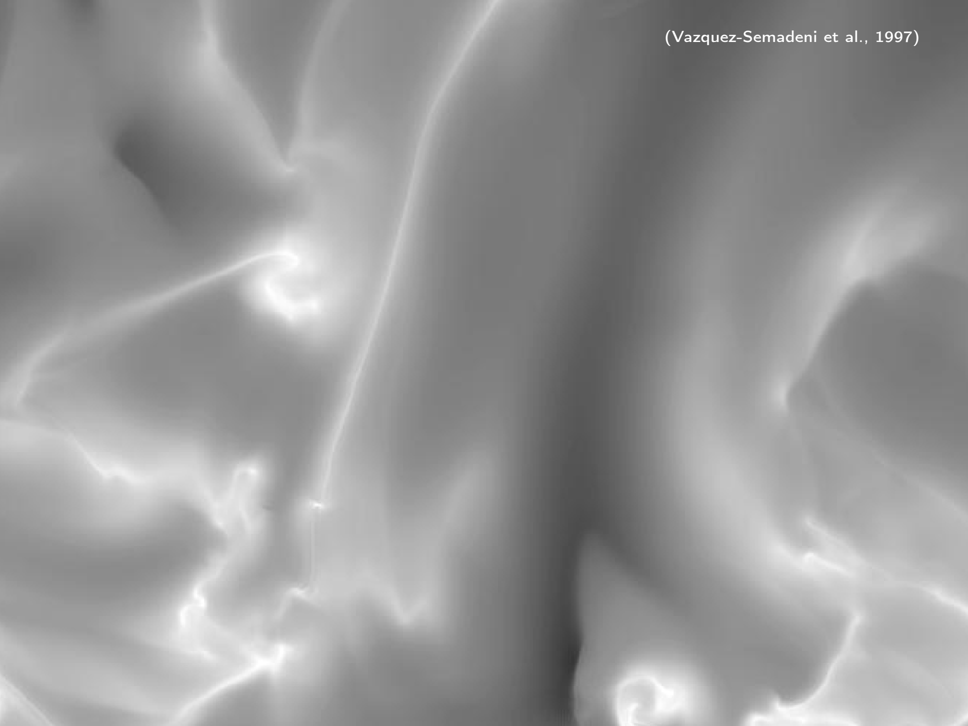
(Vazquez-Semadeni et al., 1997)

Dynamic range

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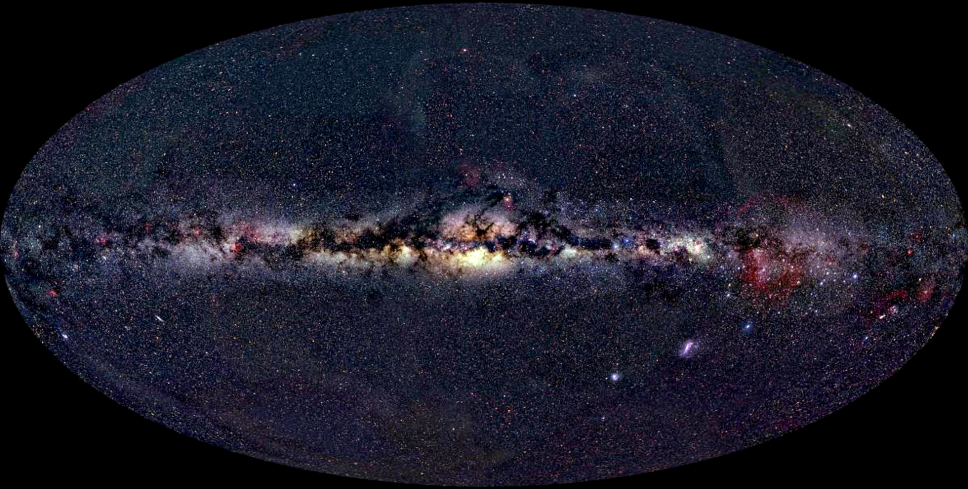
2. Observations have a limited dynamic range:
   - Minimum column density for H_2 and CO self-shielding from UV radiation field.
   - High-optical depth and chemical depletion of high-density regions.
3. It has been suggested that Larson's 3rd law is merely the result of this limited dynamic range, and that real clouds span at least 2 orders of magnitude in surface density.


Solution: use HDR imaging!

Section 2

Molecular clouds

Gould belt



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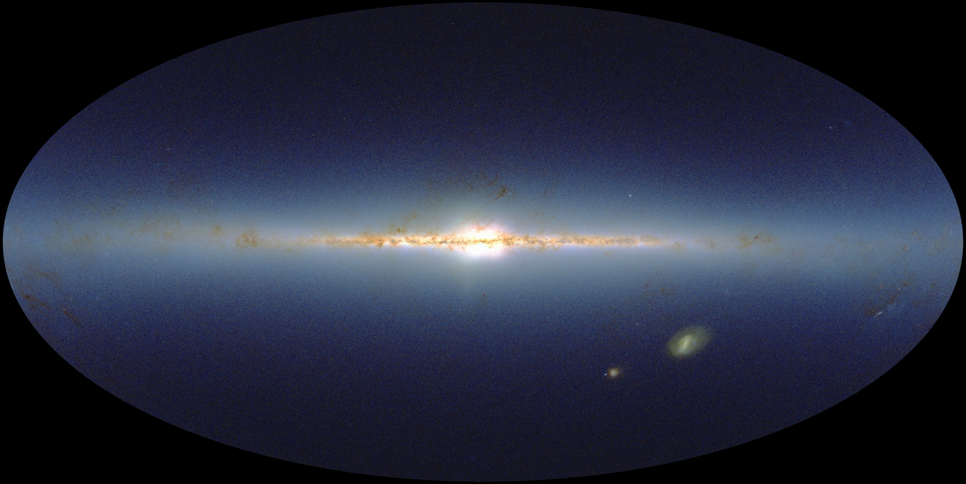

2MASS point sources

NICER
(Lombardi and Alves, 2001)

Idea

Use NIR color excess of background stars to measure the cloud column density (Lada et al., 1994).

Advantages

- Easy measurements with modern IR array (simple imaging).
- Reliable dust-to-gas ratio (Bohlin et al., 1978).
- Standard NIR reddening law (Rieke and Lebofsky, 1985) relatively stable.
- Tight NIR colors of un-reddened stars: NIR bands close to the Rayleigh–Jeans limit, where $B_\lambda \propto T/\lambda^4$.

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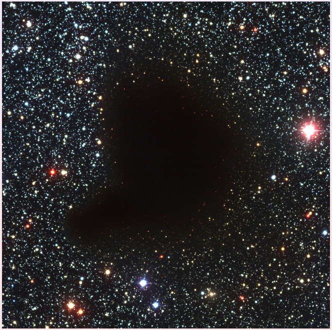

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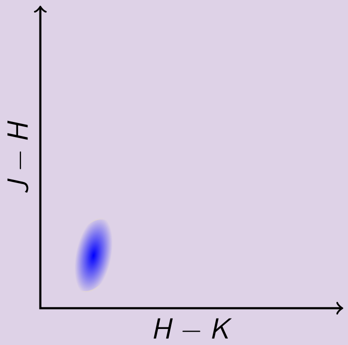
The method

Control field: Stars w/o significant extinction occupy a small region of the color-color plane

Science field: Reddening shifts stars along the reddening vector

Optimal extinction: Takes into account colors and errors of each star.



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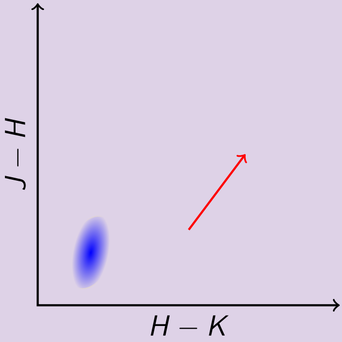

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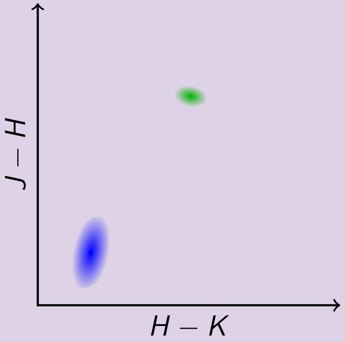


From extinction to surface density

Factors

The extinction A_K is converted into a mass column density using some factors:

- μ, the average molecular weight in the cloud ($\mu \simeq 1.37$);
- $\beta = \left[N(\mathrm{H}_I) + 2N(\mathrm{H}_2)\right]/A_K \simeq 1.67 \times 10^{22}\ \mathrm{cm}^{-2}\ \mathrm{mag}^{-1}$ (Savage and Mathis, 1979);

Reliability

Both conversions are considered quite robust, and little differences are expected among different clouds.

Distance

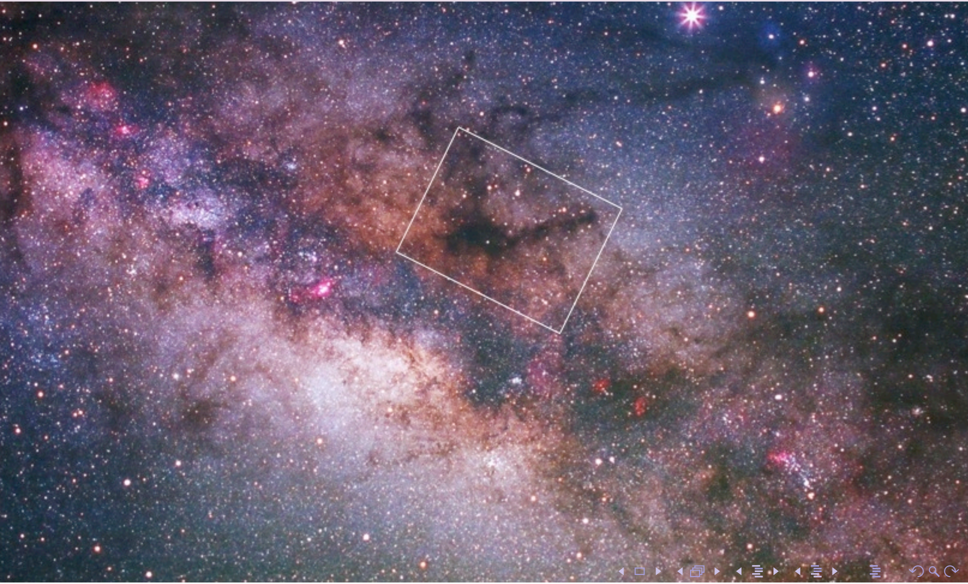
For the cloud mass, in addition we need a factor distance^2. This is typically the main source of errors for most clouds.

NICER advantages

- The method is based on a simple and well understood property of dust, reddening.
- It is unbiased (especially when a variant of it is used, NICEST, see Lombardi, 2009).
- NICER is optimized and produces maps that have a factor ~ 2 lower variance.
- It is simple to implement and very fast: can be easily used with several tens of millions stars

Example I: The Pipe nebula

Lombardi et al. (2006)



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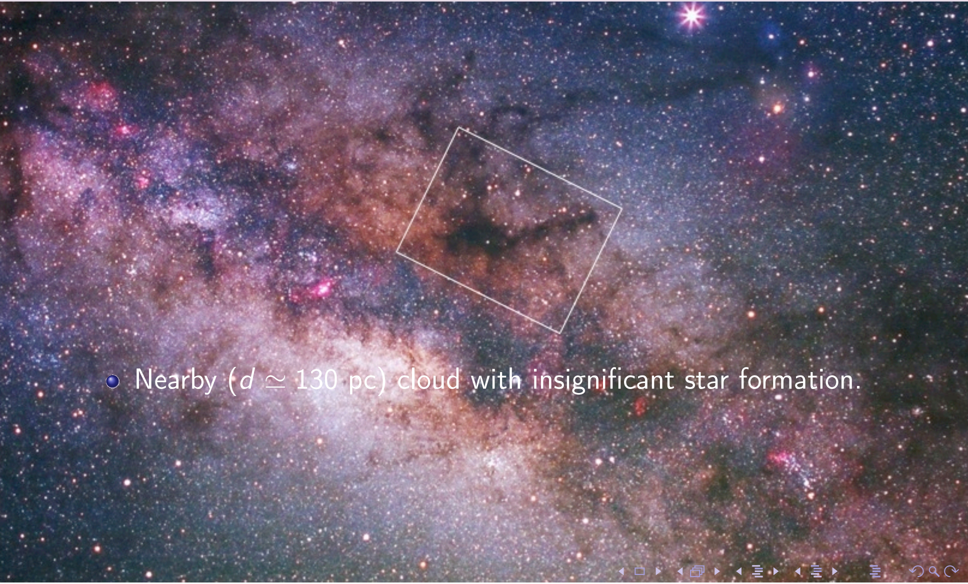

- Nearby ($d \simeq 130$ pc) cloud with insignificant star formation.

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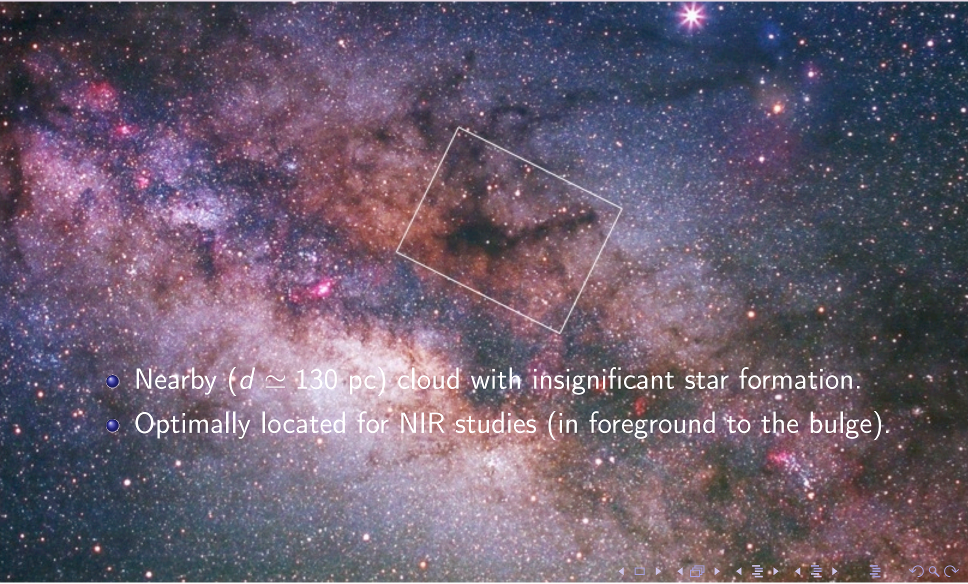

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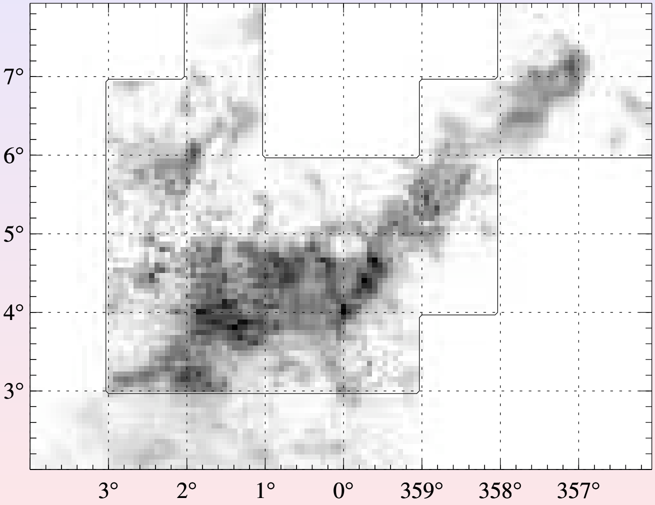
- Extinction map with RMS noise (K-band) 0.015 mag and resolution 1 arcmin.

Pipe nebula: CO vs. NICER



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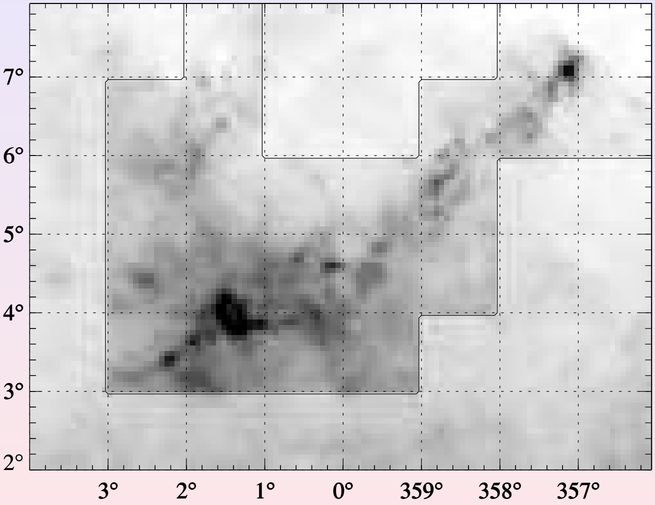

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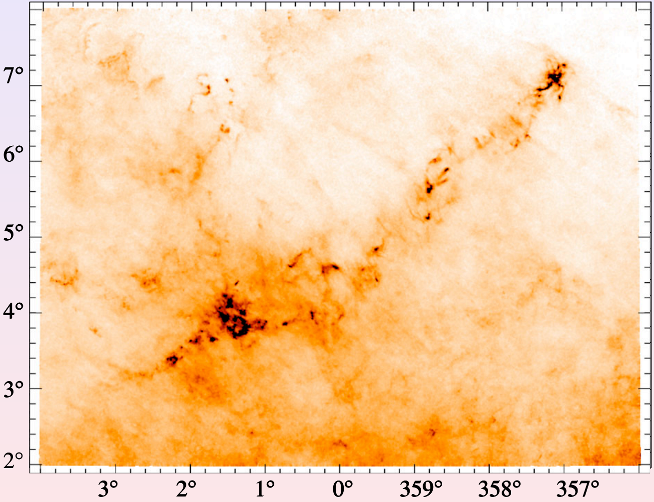
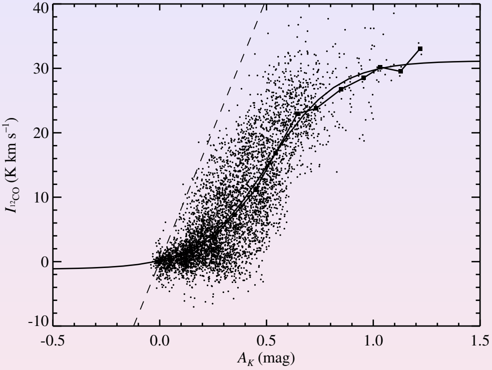


Detailed comparison



- ^{12}CO is insensitive below $A_V \sim$ 1–2 mag
- These data can be used for a robust determination of the ^{12}CO X-factor.

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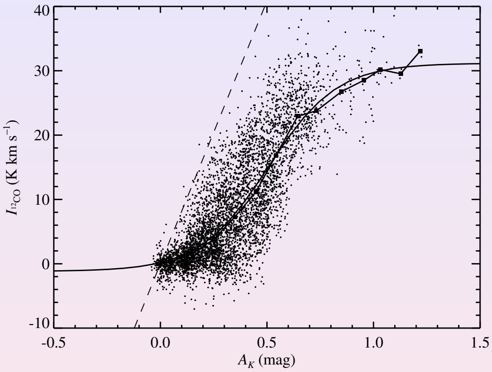

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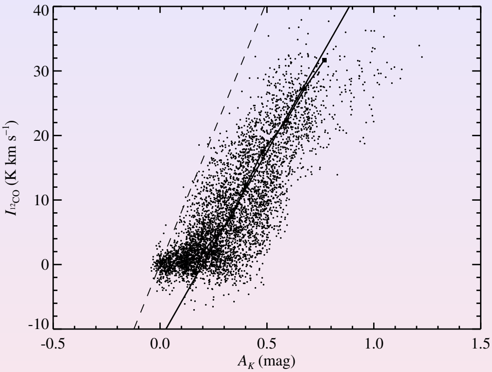

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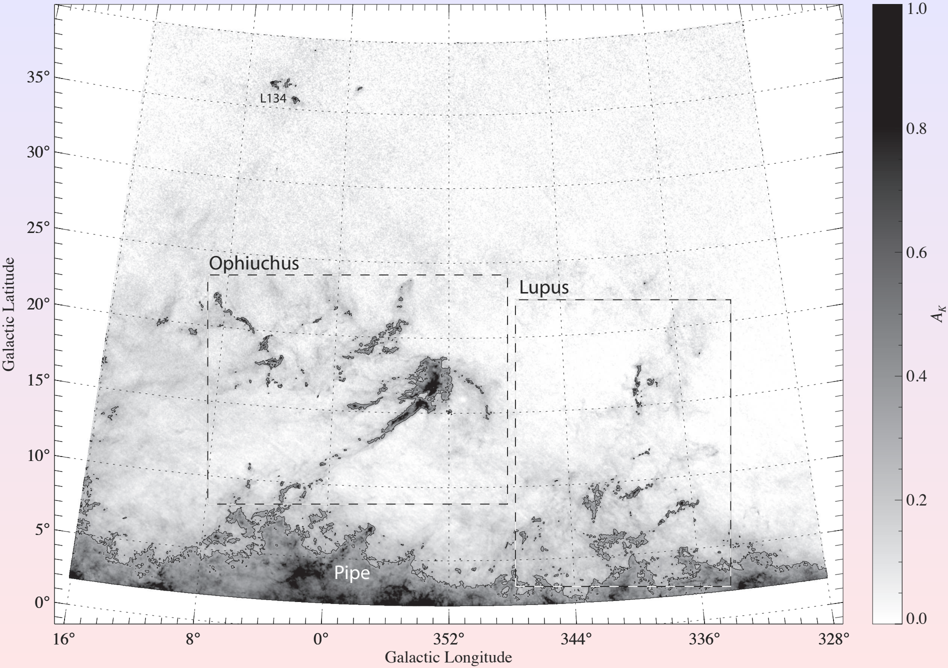
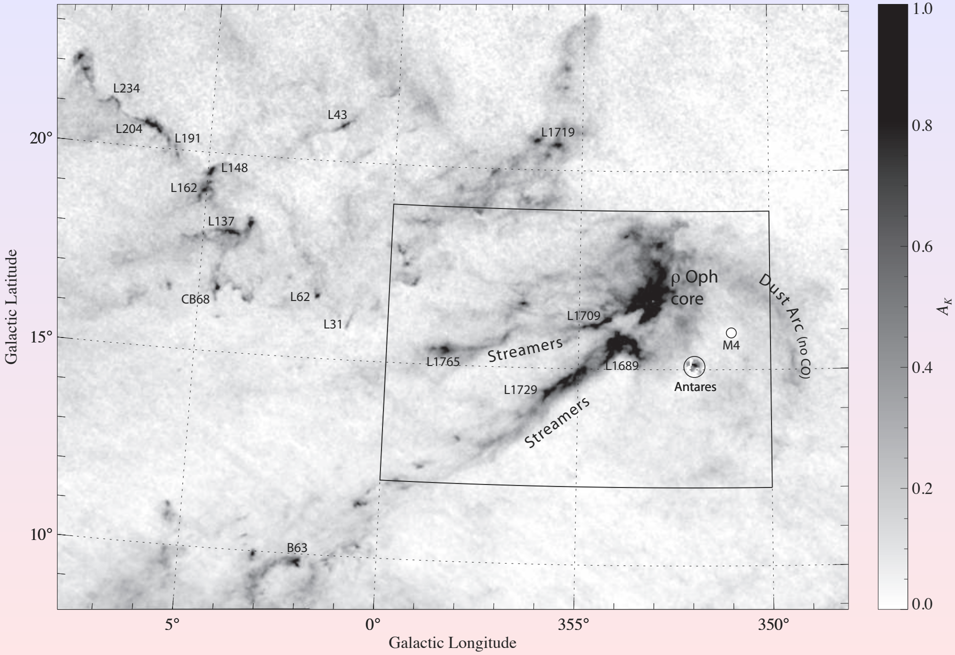
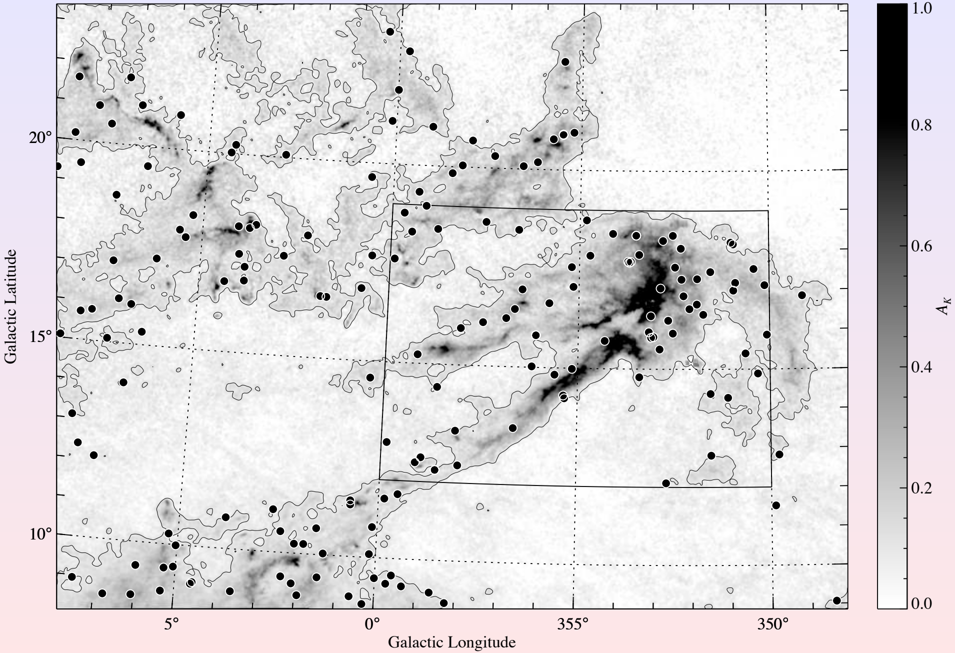


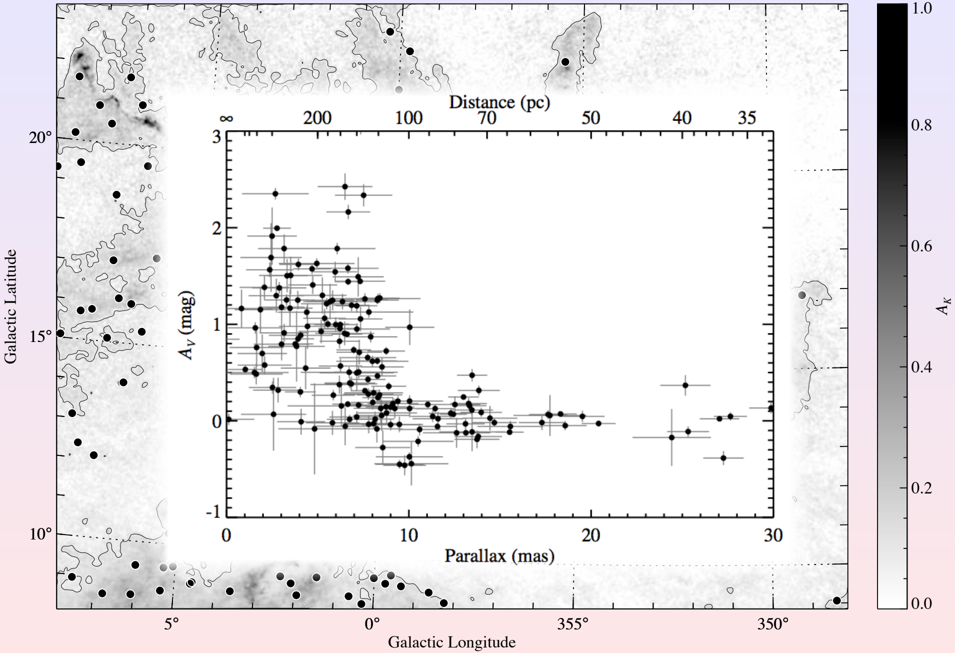
35°
30°
25°
20°
15°
10°
5°
0°
Galactic Latitude
L134
Ophiuchus
Lupus
Pipe
16°
8°
0°
352°
344°
336°
328°
Galactic Longitude
1.0
0.8
0.6
0.4
0.2
0.0
A_K



L234
L204
L191
L43
L1719
L148
L162
L137
CB68
L62
L31
ρ Oph
core
Dust Arc (no CO)
L1709
M4
Streamers
L1765
L1689
Antares
L1729
Streamers
B63
20°
15°
10°
5°
0°
355°
350°
Galactic Latitude
Galactic Longitude
1.0
0.8
0.6
0.4
0.2
0.0
A_K



20°
15°
10°
Galactic Latitude
5°
0°
355°
350°
Galactic Longitude
1.0
0.8
0.6
0.4
0.2
0.0
A_K



Distance (pc)
∞
200
100
70
50
40
35
3
2
1
0
-1
A_V (mag)
0
10
20
30
Parallax (mas)
20°
15°
10°
Galactic Latitude
5°
0°
355°
350°
Galactic Longitude
1.0
0.8
0.6
0.4
0.2
0.0
A_K

Orion revealed

A multiwavelength view

- Optical image (Wei-Hao Wang, IfA, Hawaii).
- 2MASS/NICER extinction map (Lombardi et al., 2011).
- Complementarity between red H II and green H_2 regions.
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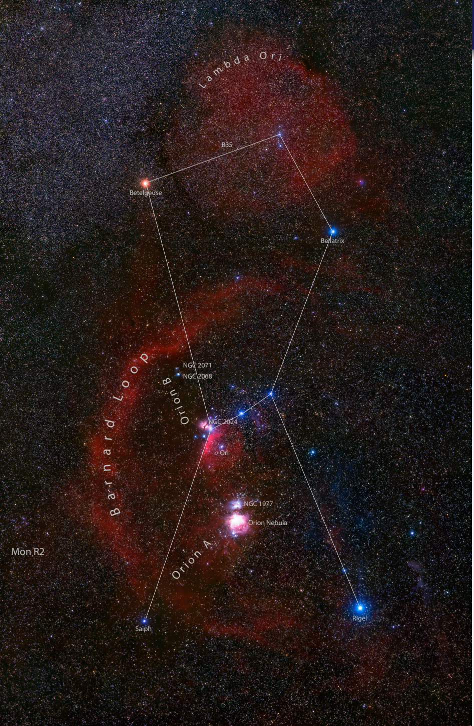

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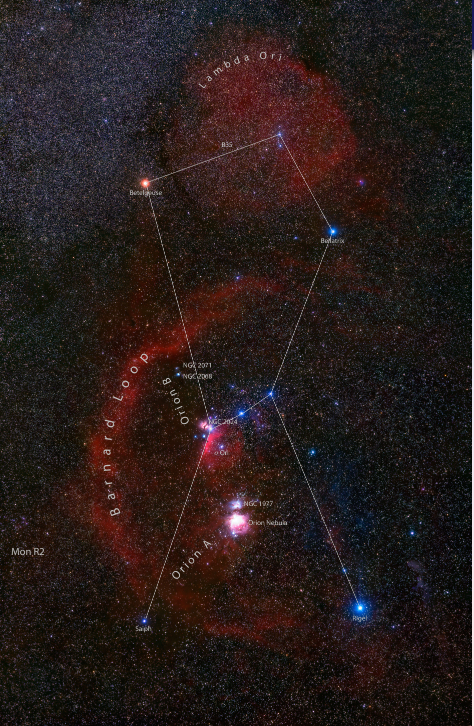

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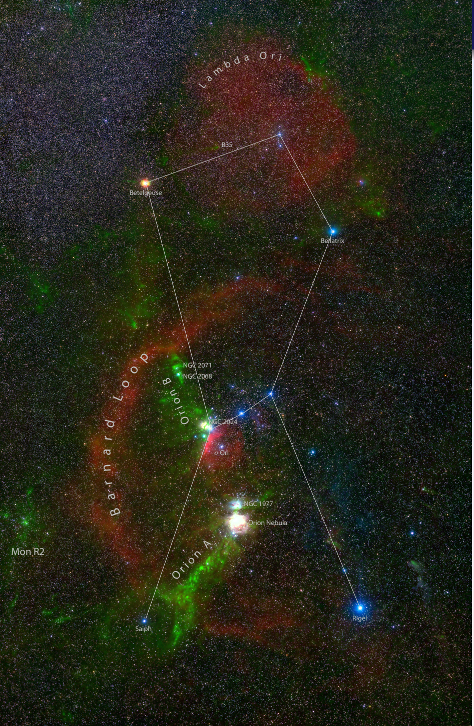

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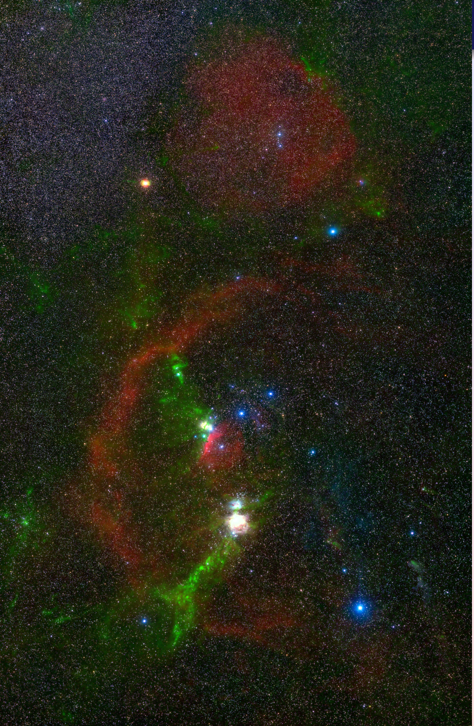

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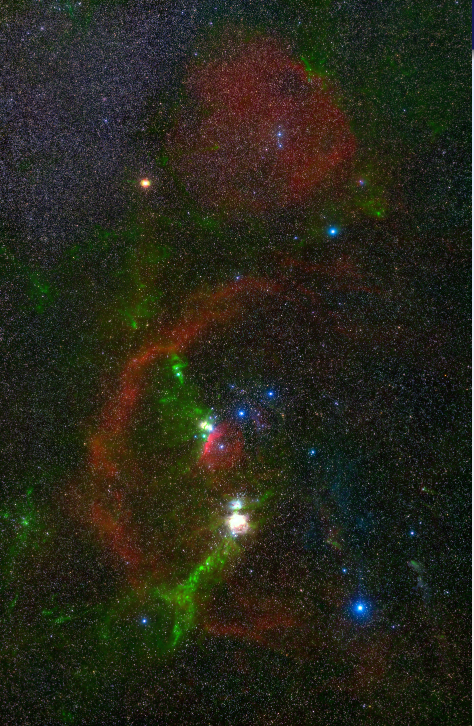

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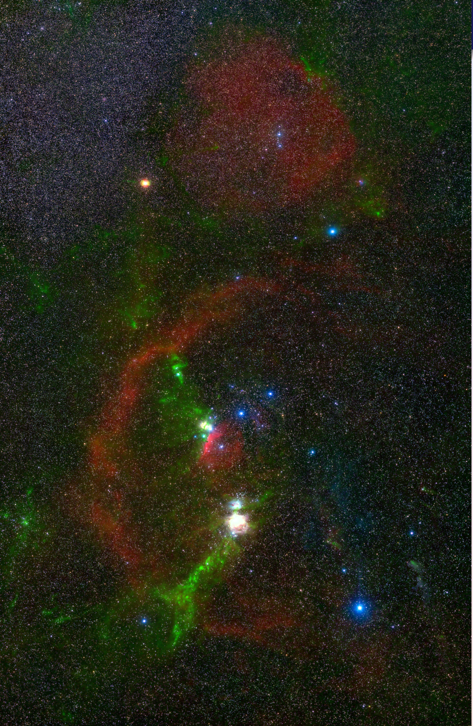

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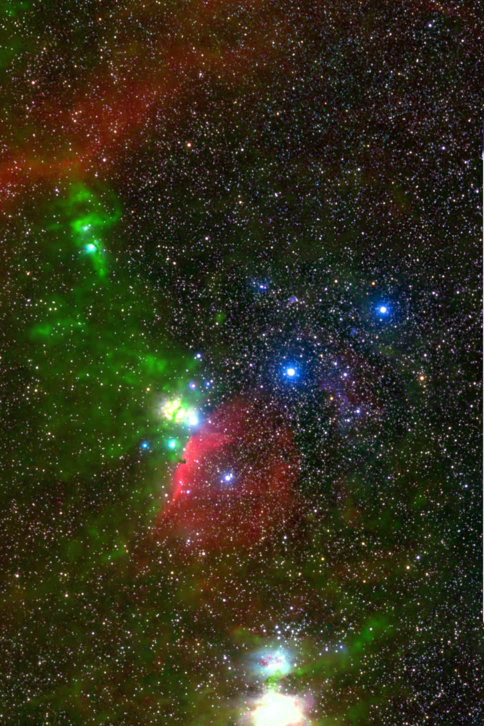

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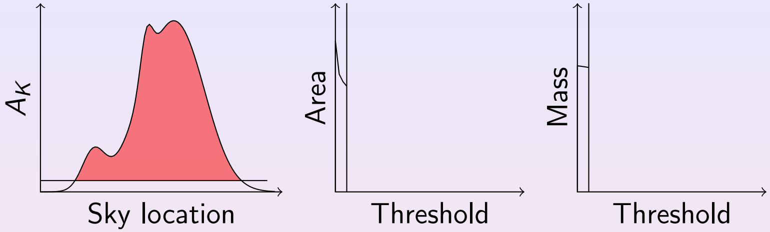
Section 3

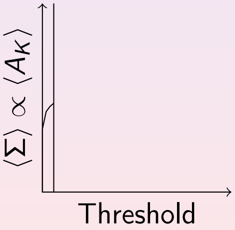
Analysis

An operative definition



Extinction threshold

- Take an extinction threshold, and consider all points in a cloud above the threshold.
- Calculate within this contour the area and the enclosed mass.
- Deduce the average surface density.



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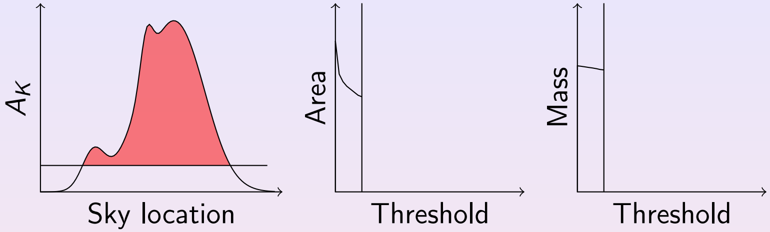

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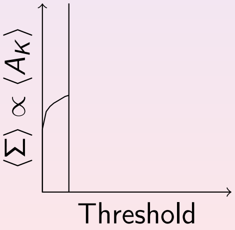

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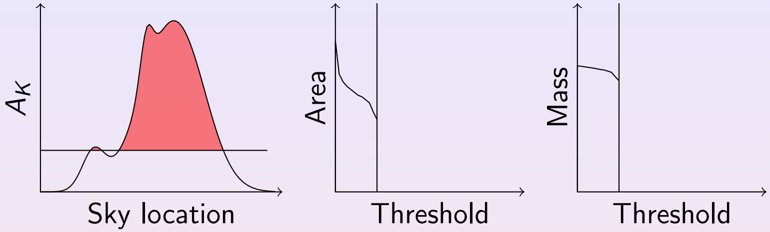

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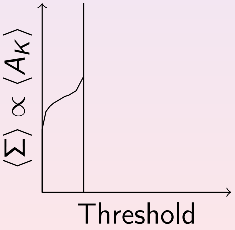

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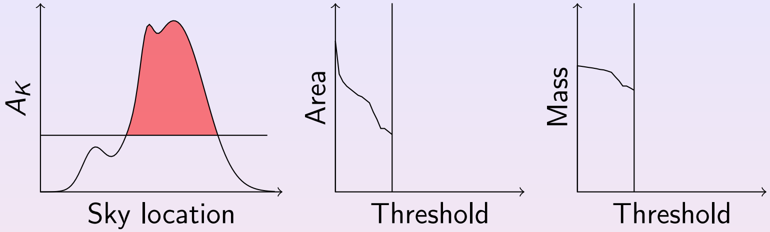

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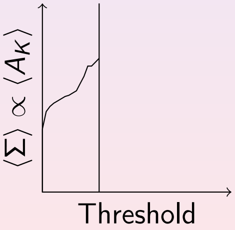

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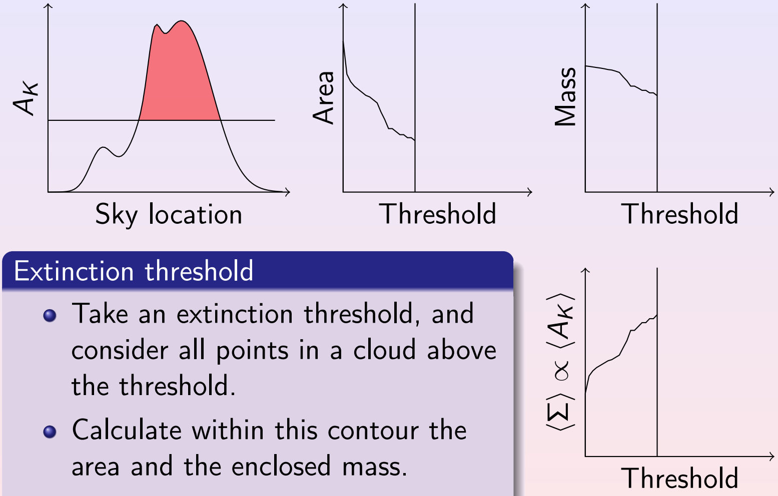

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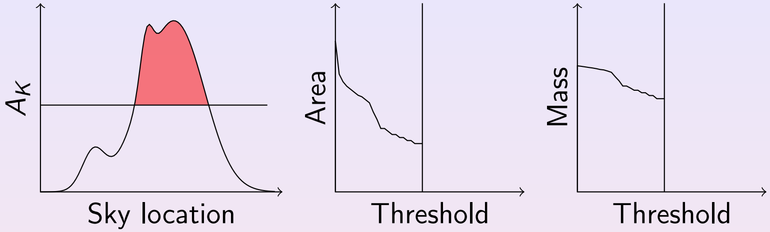

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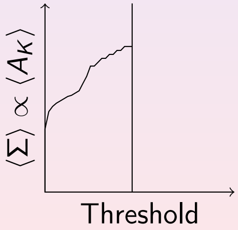

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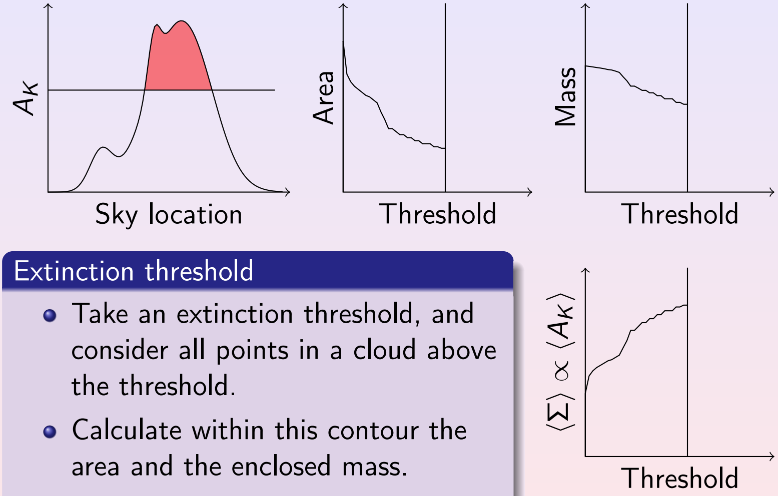

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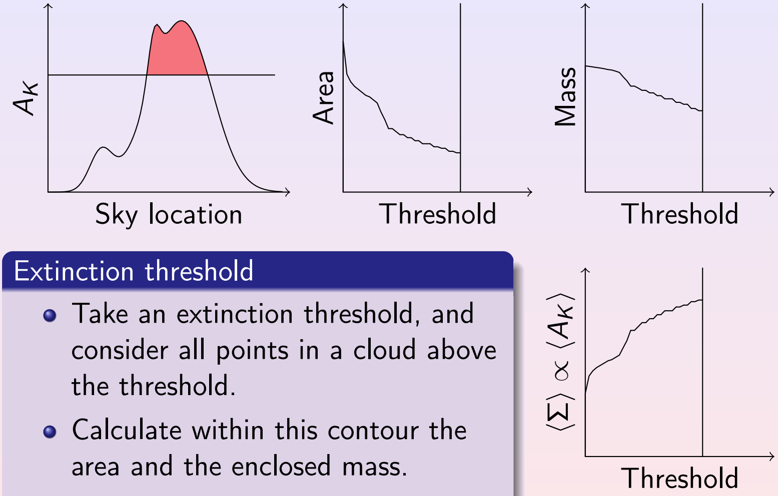

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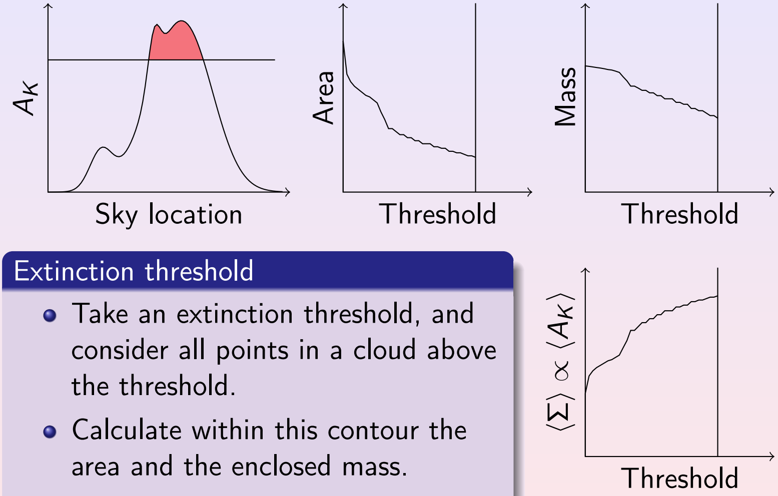

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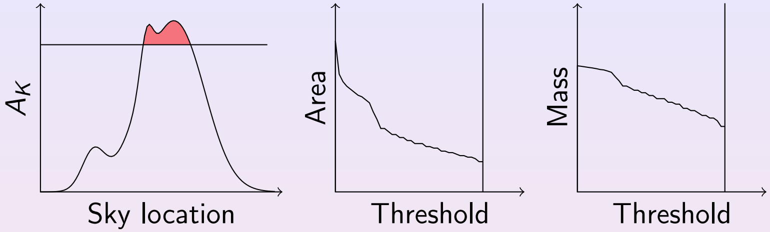

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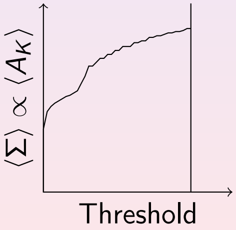

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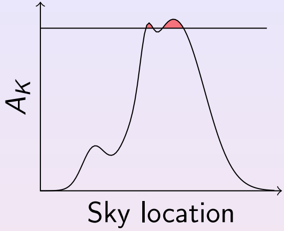

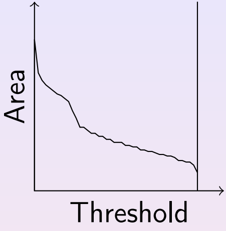

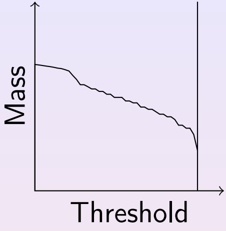

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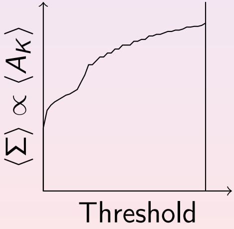

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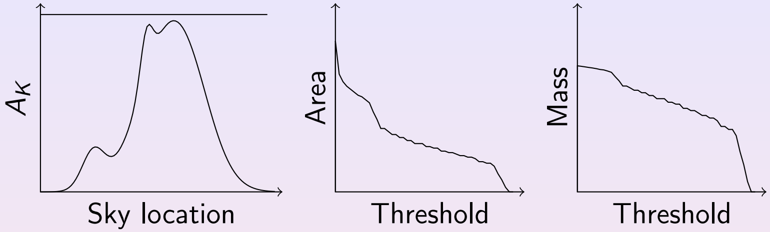

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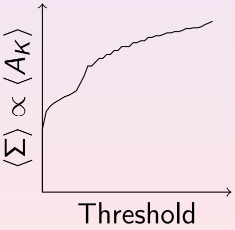

Larson's 3rd law revised
Lomnbardi et al. (2010)

Ambiguities

Two ways of considering Larson's 3rd law:

1. A "comparative" version, where one studies different clouds at the same extinction threshold.
2. An "internal" version, where one verifies the $M(R) \propto R^2$ prediction on a single clout at different extinction thresholds.

Larson used a mixture of the two!

Extinction helps!

- We have a complete description of the projected mass density of many different molecular clouds.
- Best conditions to revised the validity of both versions of Larson's 3rd law.

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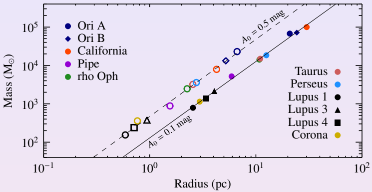
Different clouds at a constant extinction threshold

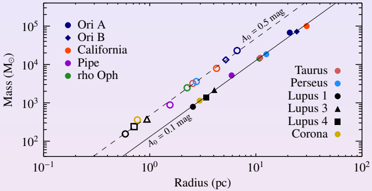


Threshold A_0 (mag)	a ($M_\odot$ pc$^{-\gamma}$)	γ	Scatter (percent)
0.1	41.2	1.99	11%
0.2	73.1	1.96	12%
0.5	149.0	2.01	14%
1.0	264.2	2.06	12%
1.5	379.8	2.07	14%

Results

- All clouds follow exquisitely a Larson-type relationship $M = aR^\gamma$, with $\gamma \simeq 2$.
- Clouds have very similar average surface densities within the same extinction threshold contour.
- The scatter is always below 15%.

Different clouds at a constant extinction threshold



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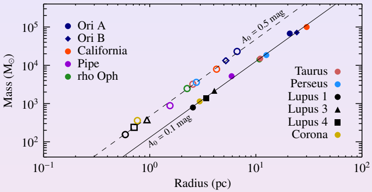

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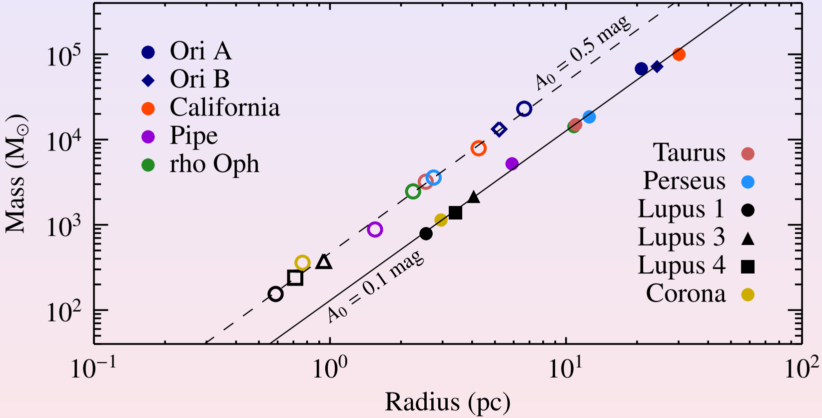
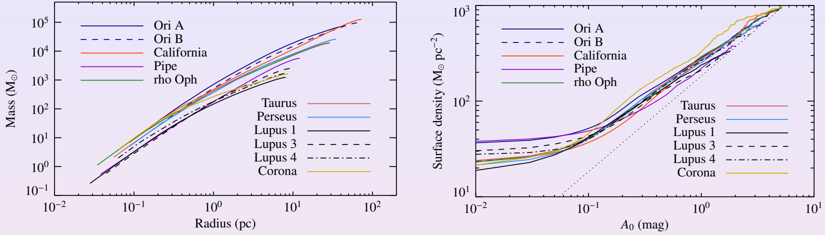


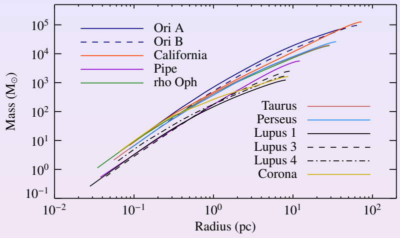
Larson's 3d law for single clouds

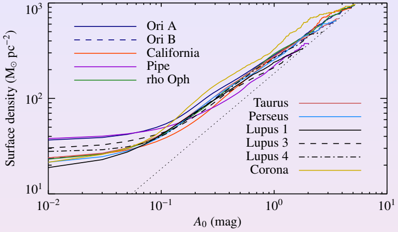


Results

- Cloud $M(R)$ plots have similar trends, but span a relatively large range of masses.
- Best fit for $R \in [0.1, 1]$ pc is $M(R) = 380\ M_\odot (R/\mathrm{pc})^{1.6}$ (see also Kayffmann et al. 2010).
- Small scatter in exponent, large in mass.
- Power-law index significantly different from 2!

Larson's 3d law for single clouds





Results

- Cloud $M(R)$ plots have similar thrends, but span a relatively large range of masses.
- Best fit for $R \in [0.1, 1]$ pc is $M(R) = 380\ M_\odot (R/\mathrm{pc})^{1.6}$ (see also Kayffmann et al. 2010).
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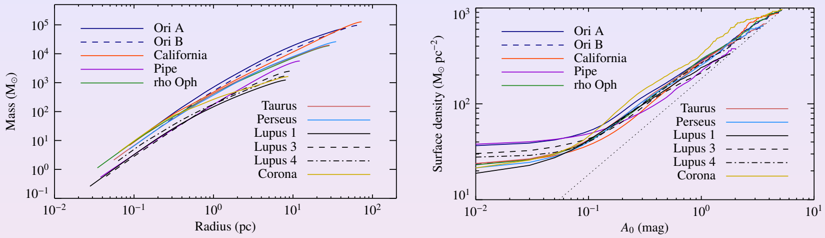

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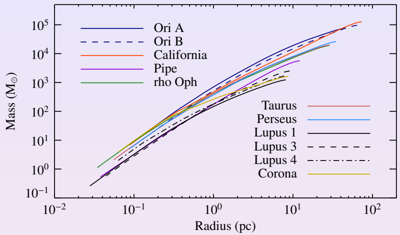

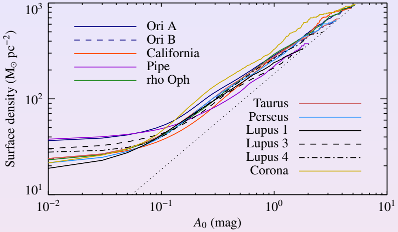

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A hint

Larson's 3rd law and cloud structure

- Observations have long established that many clouds have a log-normal distribution at low extinctions:

$$p(A_K) = \frac{1}{\sqrt{2\pi}\sigma A_K} \exp\left[-\frac{(\ln A_K - \ln A_1)^2}{2\sigma^2}\right] .$$

- Traditionally, log-normality is linked to supersonic turbulence, but it turns out it is a common feature of different classes of models (Tassis et al. 2010).
- We can express the mass M and the area S of a cloud above a threshold A_0 as simple integrals of $p(A_K)$:

$$M(A_0) \propto \int_{A_0}^{\infty} A_K \, p(A_K) \, \mathrm{d}A_K , \quad S(A_0) \propto \int_{A_0}^{\infty} p(A_K) \, \mathrm{d}A_K$$

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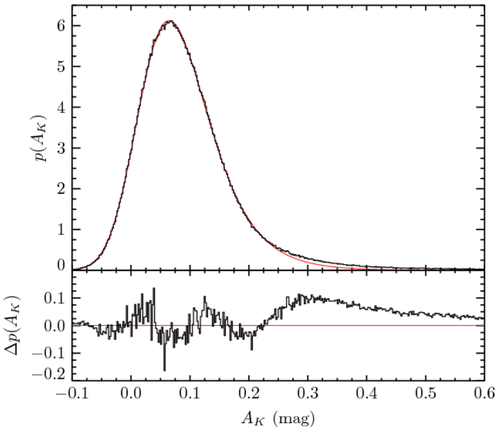

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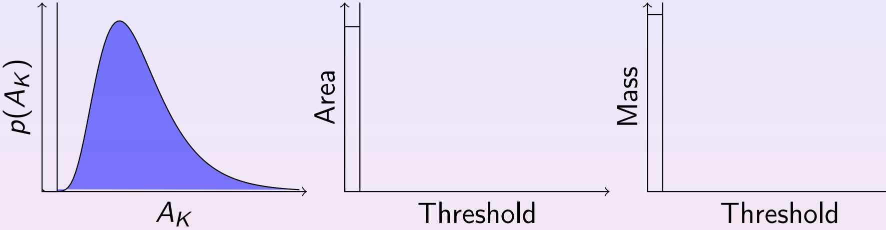
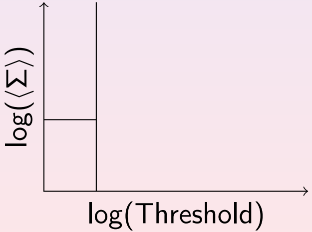
Larson's law and log-normal distributions



Extinction threshold

- Take an extinction threshold, and consider all points in the distribution at larger A_K values.
- Calculate from these the area and mass above the threshold.
- Deduce the average surface density.



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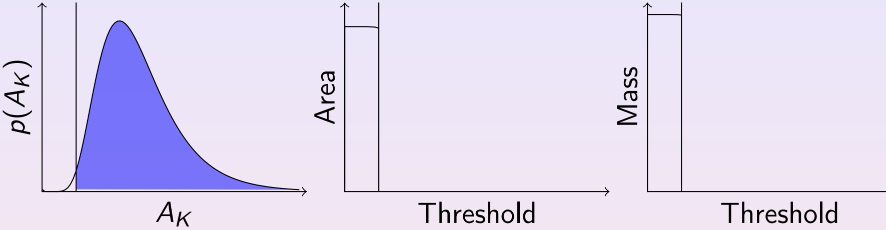

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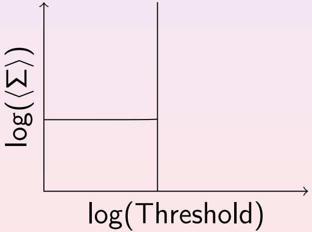

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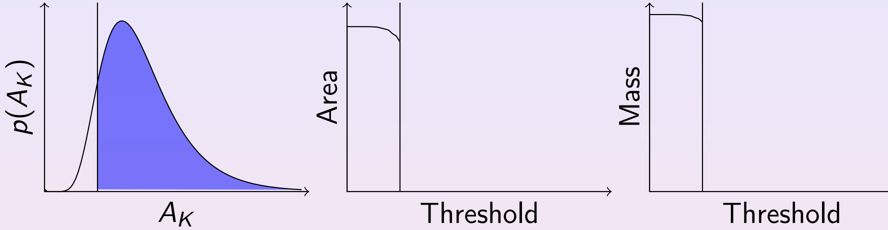

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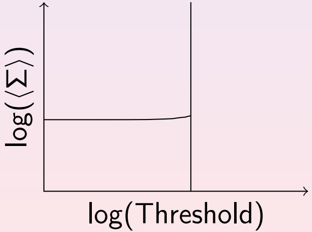

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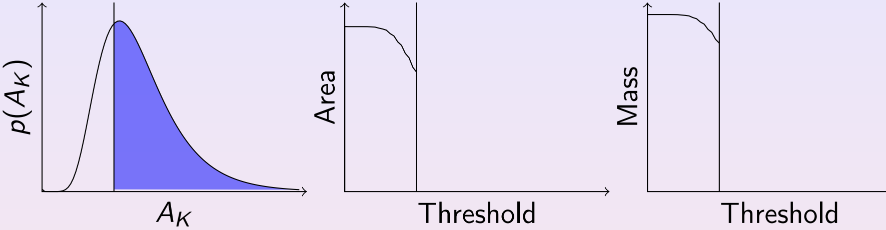

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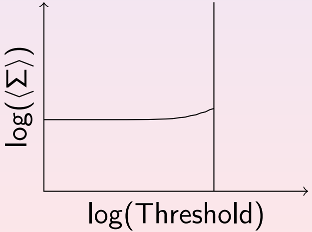

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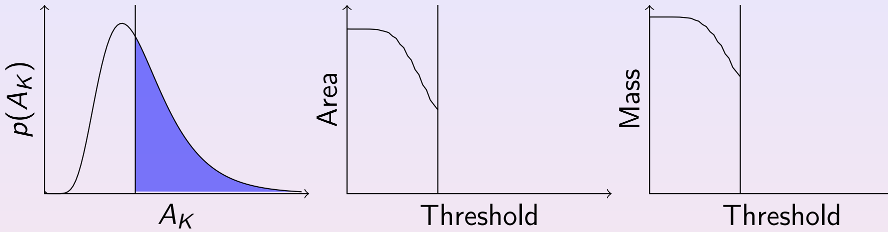

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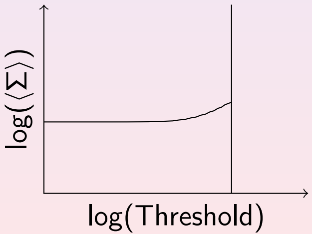

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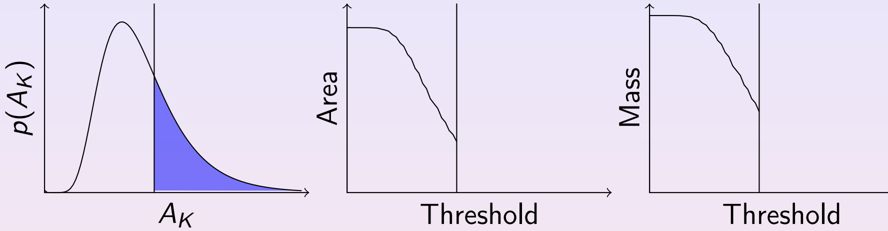

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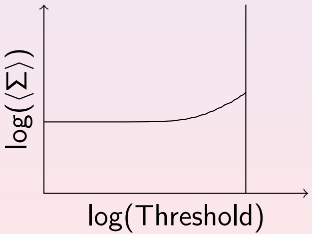

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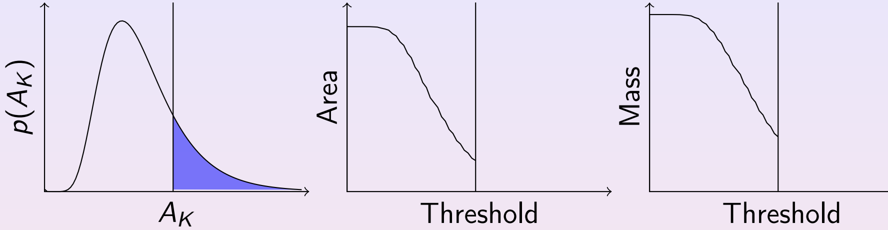

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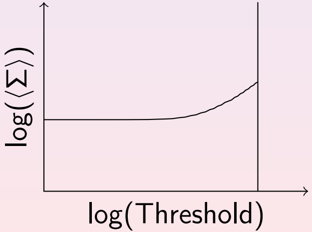

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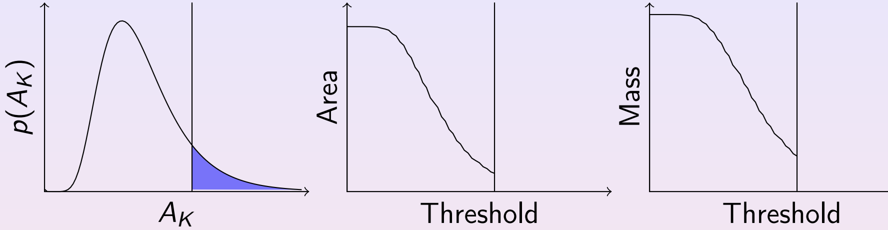

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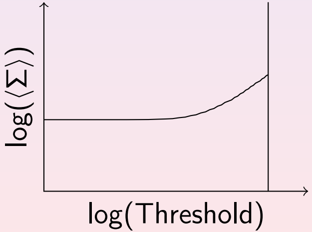

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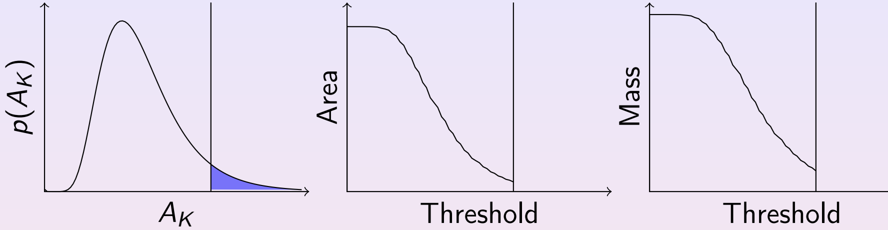

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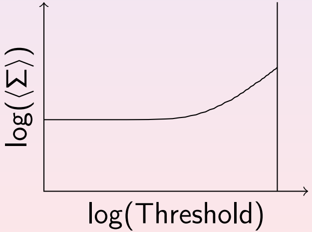

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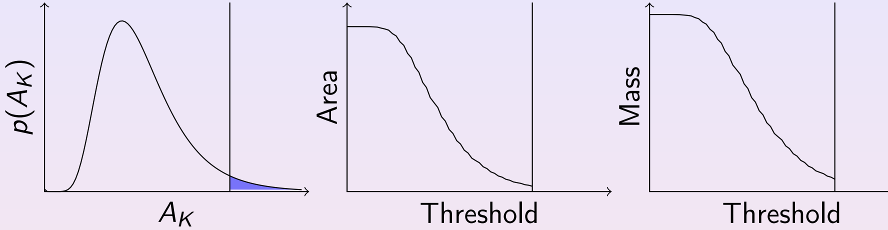

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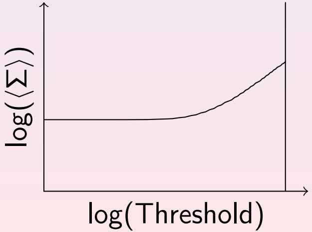

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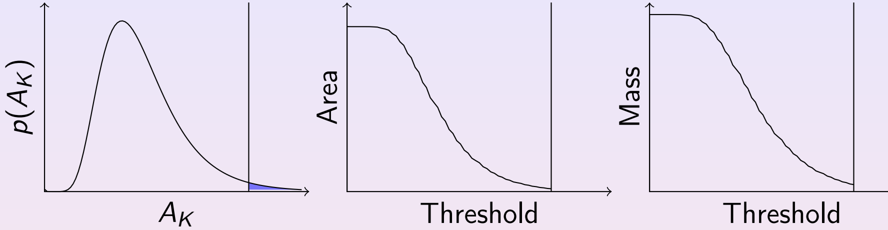

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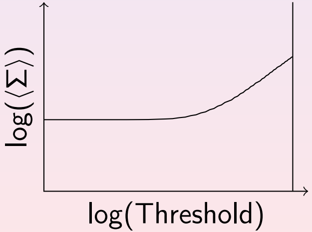

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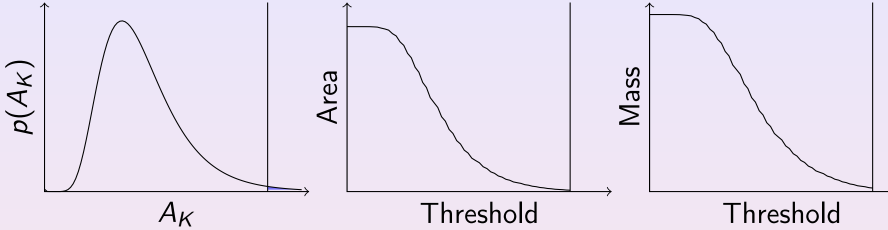

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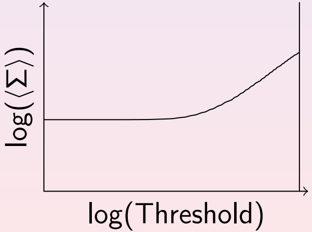

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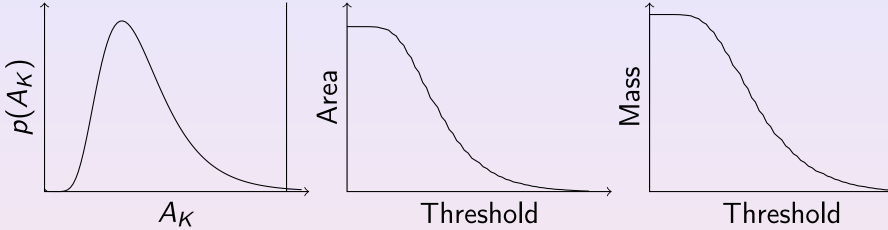

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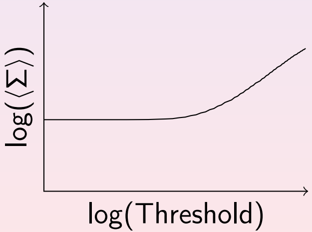
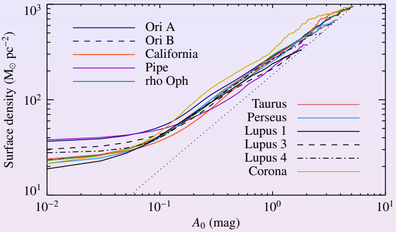
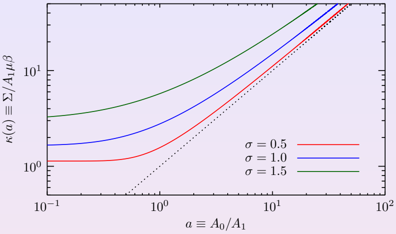


Log-normal distributions





Theoretical expectation

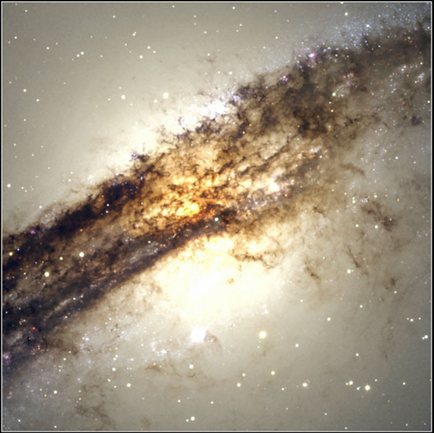
- This allows us to estimate the expected cloud surface density above an extinction threshold.
- Qualitatively, we recover the observed curves.
- The scatter among different clouds can be kept small if the relative scatter of the log-normal parameters A_1 and σ is small (which is).

Open issues

Still quite a lot. . .

1. Log-normality only works at low extinction:
   - What is the role of cores for Larson's law?
   - How is the deviation from log-normality related to stellar formation?
2. Why do clouds follow log-normal distributions?
   - What is the role of turbulence, isothermality, magnetic fields. . .
3. Why do cloud have relatively similar log-normal parameters A_1 and (especially) σ?
   - In turbulence models σ is related to the cloud Mach number. Are the similar σ related to universality of turbulence for the size-linewidth relation?
4. What is of Larson's 3rd law in external galaxies?
   - Can we use extinction techniques outside the Milky Way?

Centaurus A visible



Centaurus A infrared

Credit: Y. Beletsky

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