UNIVERSITY OF COLOGNE

Detection and Characterisation of Molecular Outflows

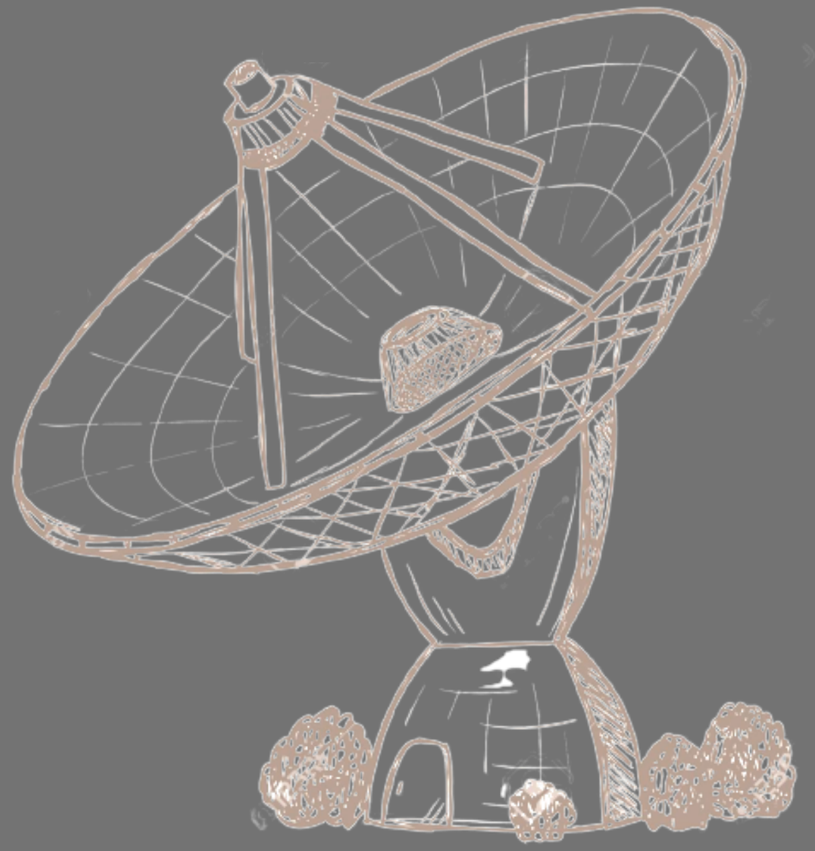
G327.3-0.6

Name : Niraj Kandpal

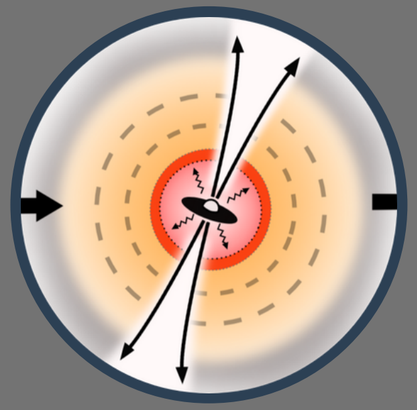
Supervisors : Prof. Dr. Peter Schilke

: Priv. Dr. Markus Roellig

Table of Contents



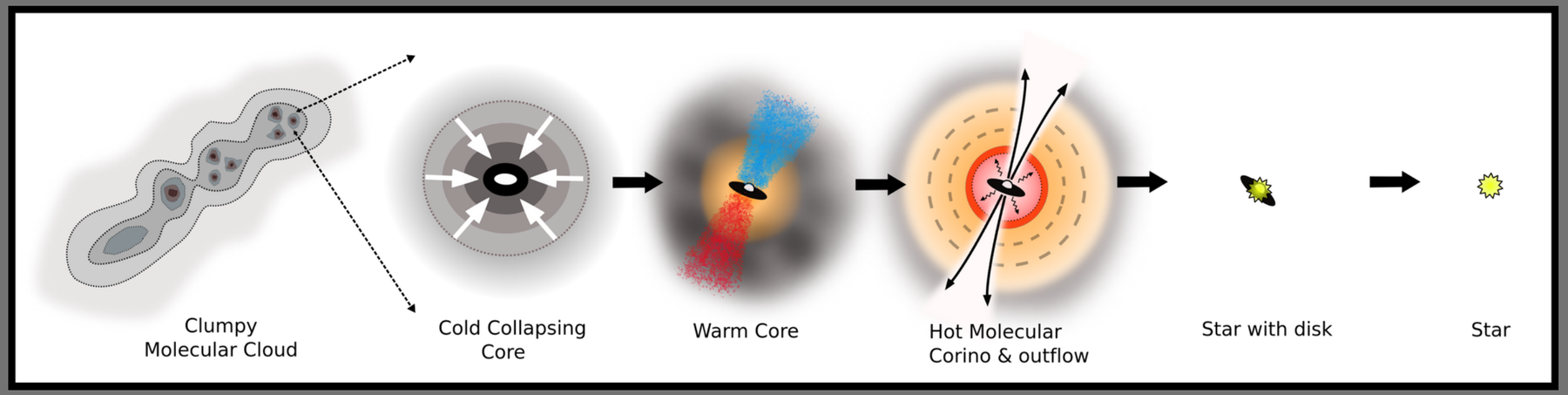
INTRODUCTION



- Stages of Low and High mass stars
- Molecular Outflows

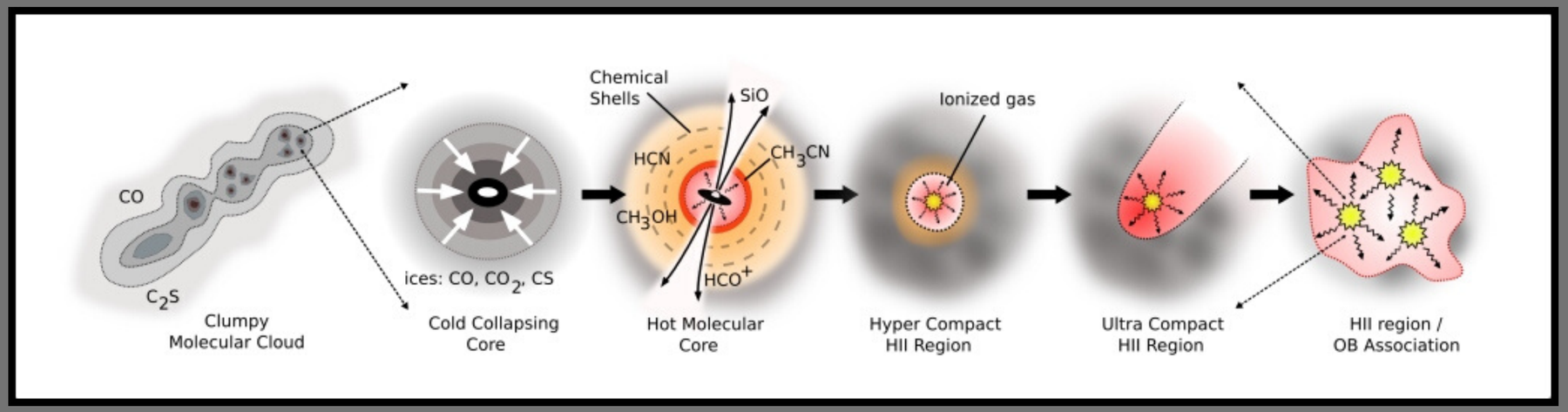
Stages of Low and High Mass Stars

$M \leq 8M_\odot$



Source : A. Ginsburg

$M > 8M_\odot$

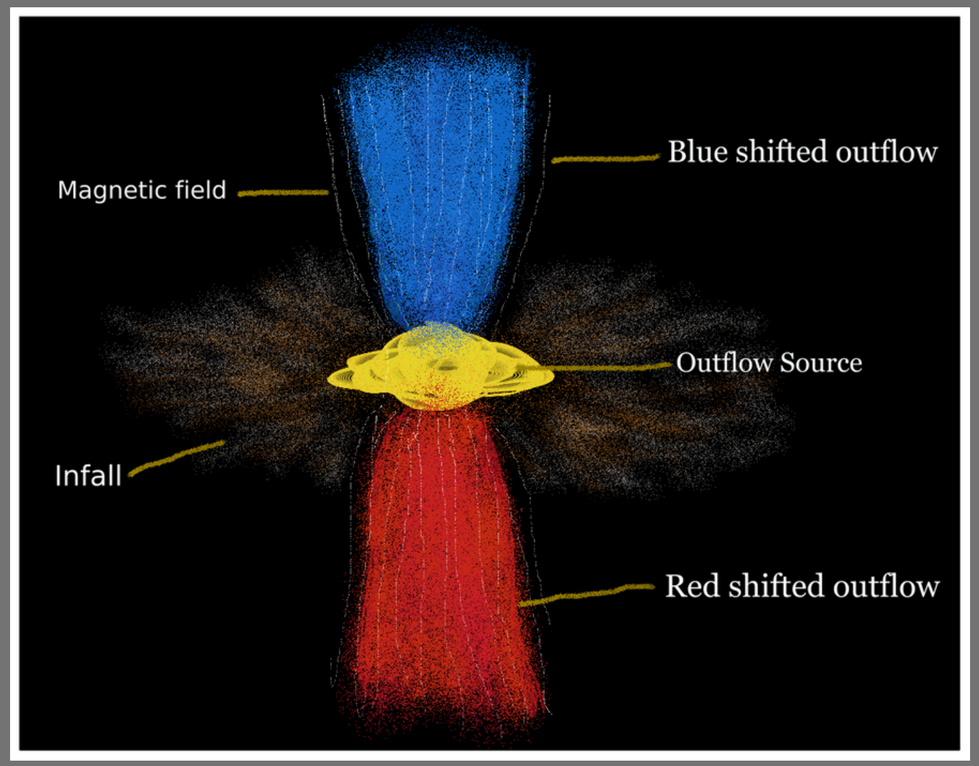


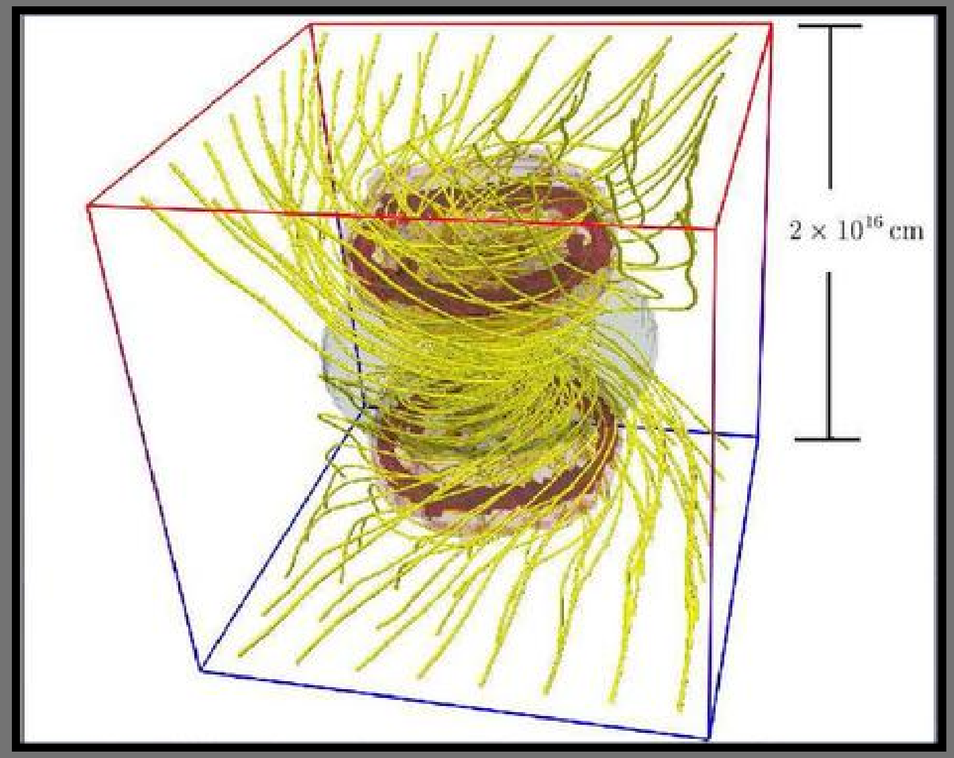
Source : Cormac Purcell

- Gravitational collapse
- Cold collapsing core
- Molecular outflows

$M_\odot$: Solar Mass

Molecular Outflows



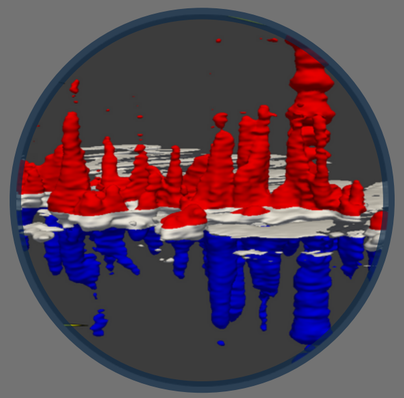


(Pudritz and Banerjee(2005))

- Mass ejection phenomena
- Doppler shift (blue and red)
- Conservation of angular momentum

- Magnetic field (assumption : B ll L)
- Outflows have physical and chemical impact

Detection and Characterization of Outflows



- G327 ALMA Data
- 2D Analysis Methods
- G327 data in 3D

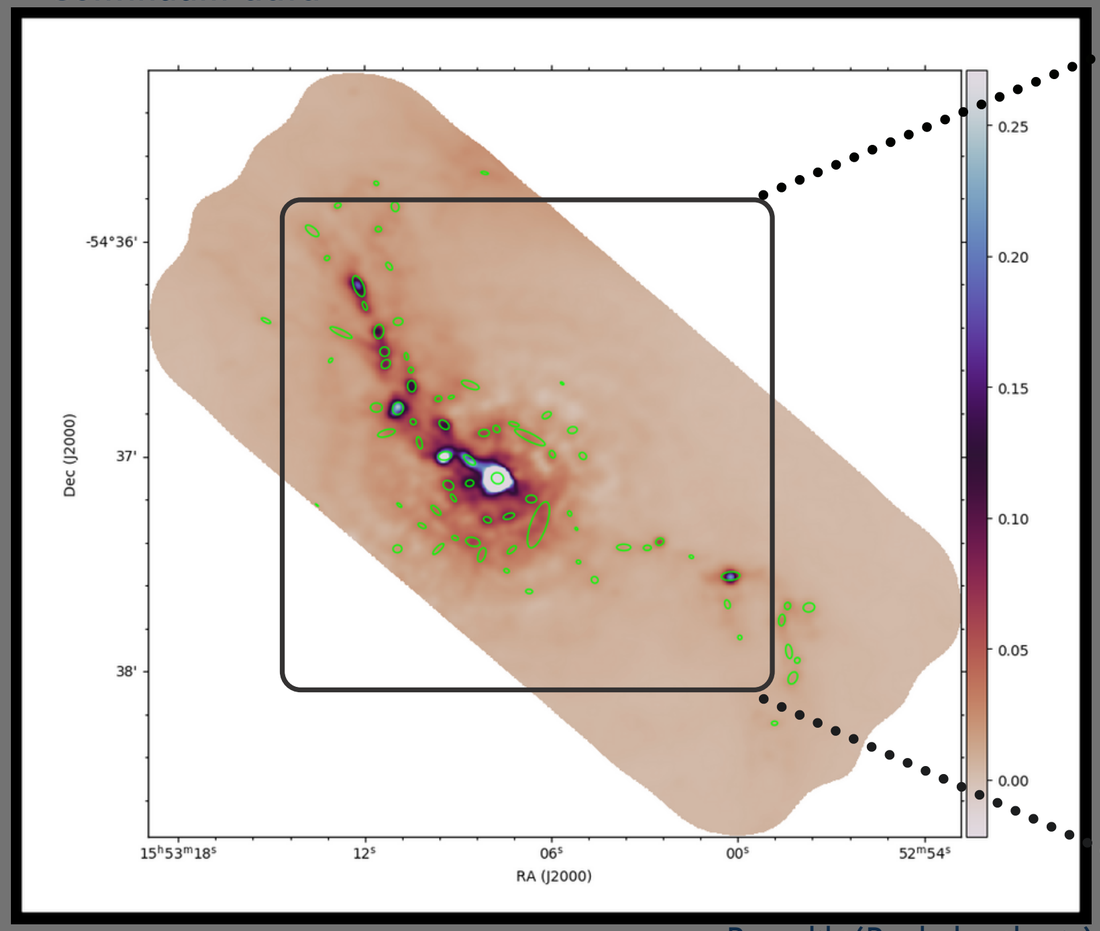
Detection

- Rotating Ellipsoid Method
- Outflow parameter Results
- Outflow vs. Core mass

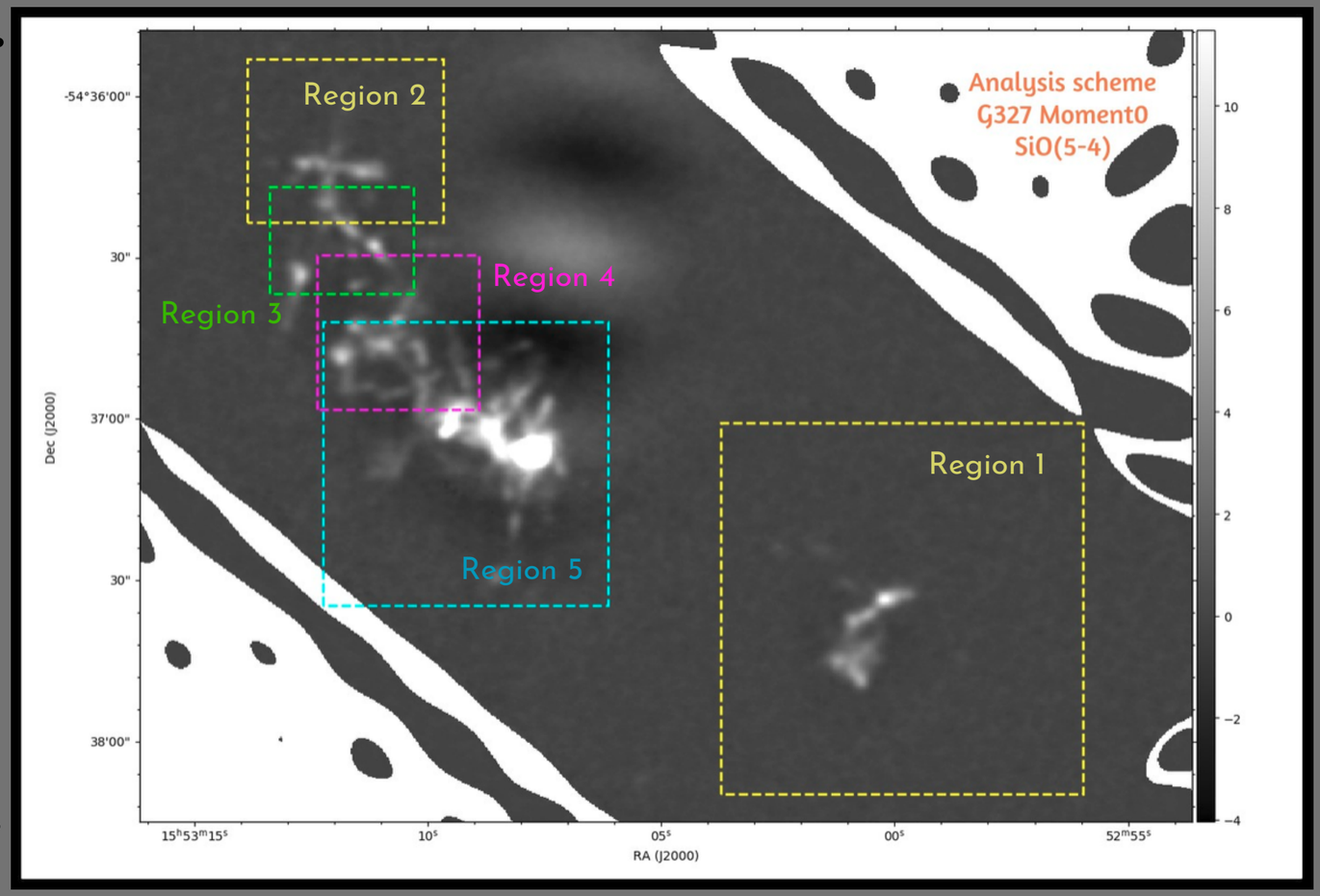
Characterization

G327 ALMA Data

Continuum data



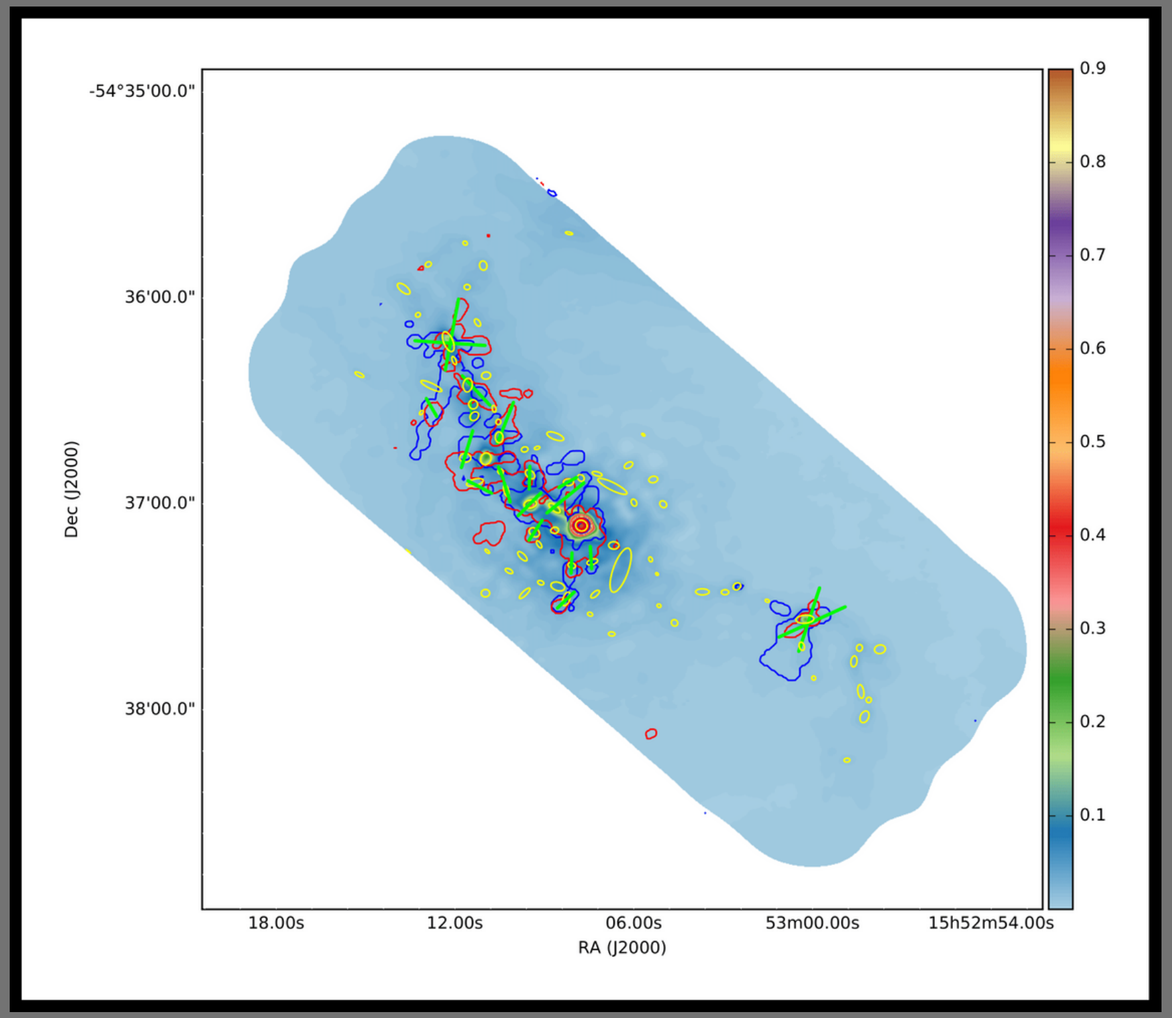
Line data



Benedikt(Bachelor thesis)

- Cycle 4 : ALMA Data
- 4 spectral windows
- SiO(5-4), CO(2-1), DCN(3-2), N2D+(3-2)
- Data : 3D FITS file : -144 km/s to 54.8 km/s
- SiO(5-4) 217 GHz
- Analysis Scheme

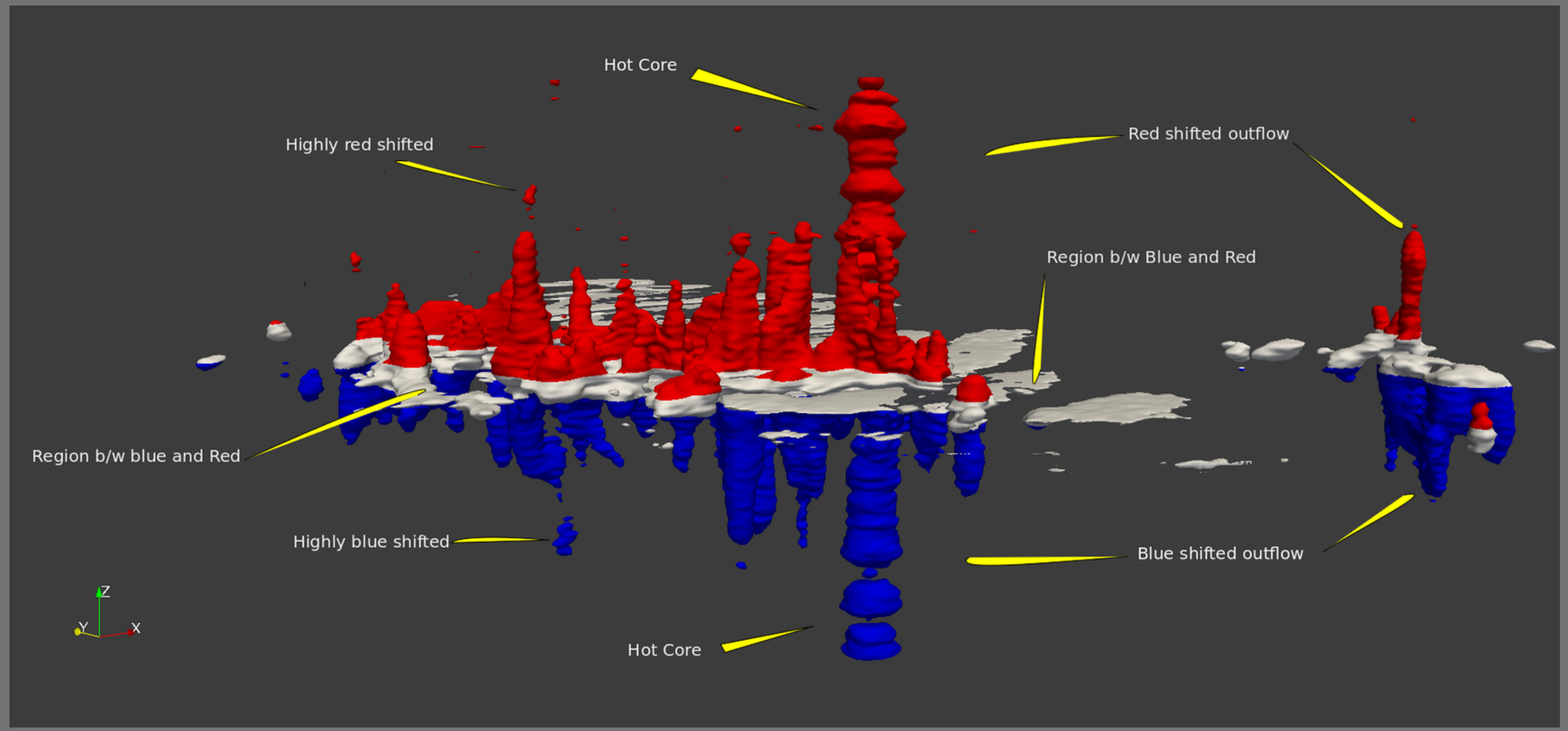
2D Analysis Methods



Continuum : ALMA Data, Contour : G327 SiO(5-4)

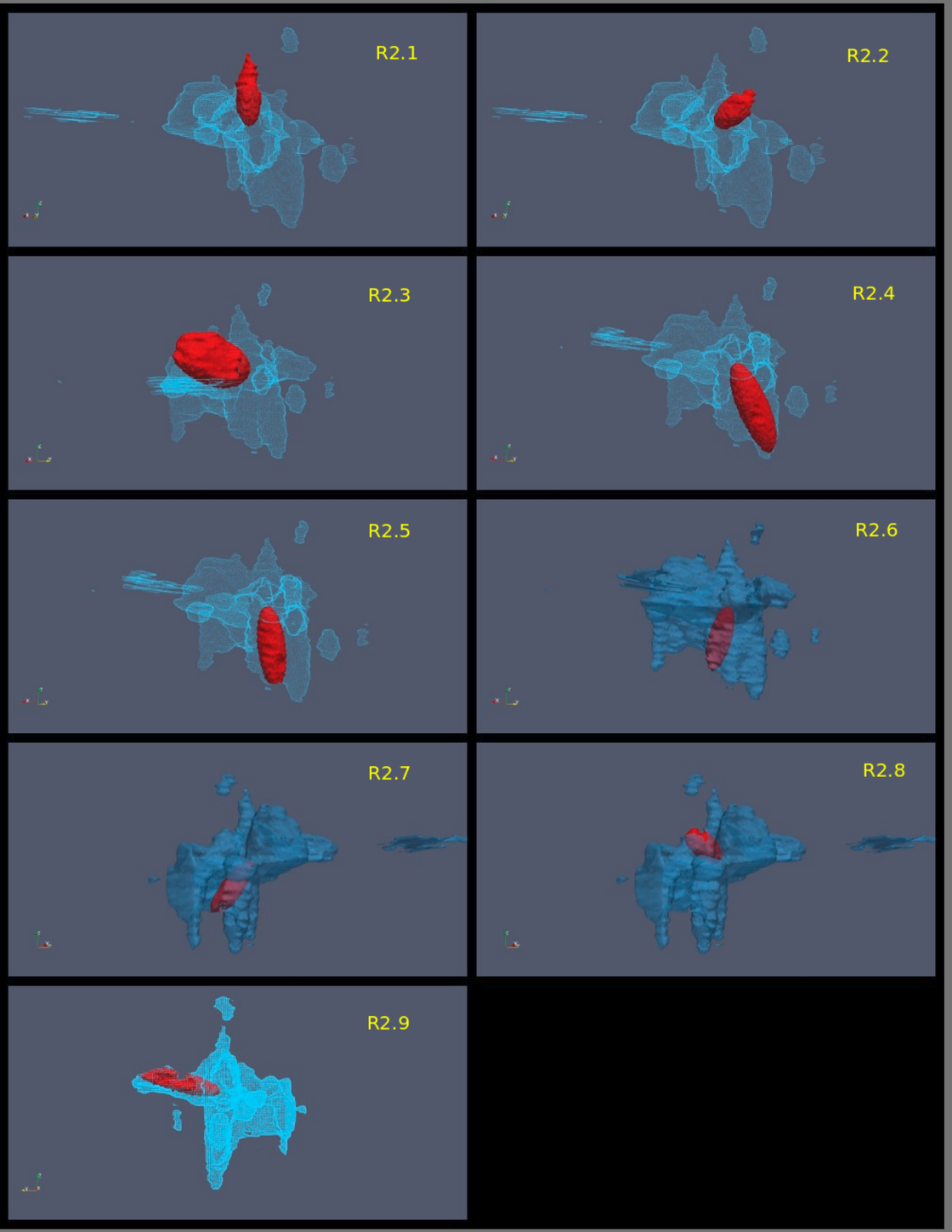
- Moment maps, PV plots, channel maps
- Blue : Velocity range
  (- 144 km/s to -51 km/s)
- Red : Velocity Range
  (-37.5 km/s to 54.8 km/s)
- Yellow : sources
  (-44.5 km/s : systemic velocity)
- Green : Outflow Directions
  (21 outflows found)
- Hard to detect every outflow !

G327 Data in 3D



SiO(5-4)

- X, Y : Position
  (R.A. & DEC.)
- Z : Velocity axis
- 43 outflows



Rotating ellipsoid method

- In Blue : Region 2
- In Red : Outflow lobe
- Choosing center of rotation
- Rotation : towards each lobe
- Fitting 5 parameters manually
  (2 angles for 3D rotation & 3 ellipsoid parameters)
- Calculating total intensity
  (Flux also obtained)

Outflow parameter Results

Outflow mass

10^{-3} to 10^{3} $M_{\odot}$

(Wu et. el. 2004)

High mass stars
Mass : Few solar masses
(Y.Xu et. el. 2006)

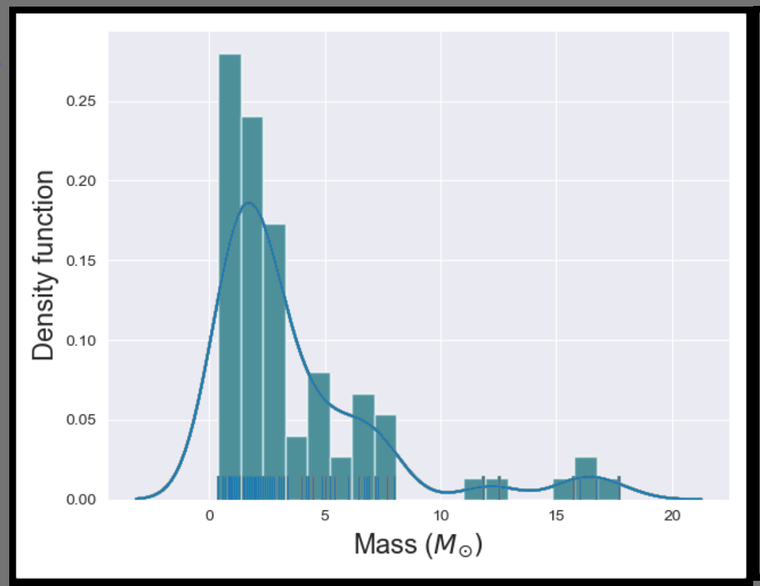
Outflow Energies

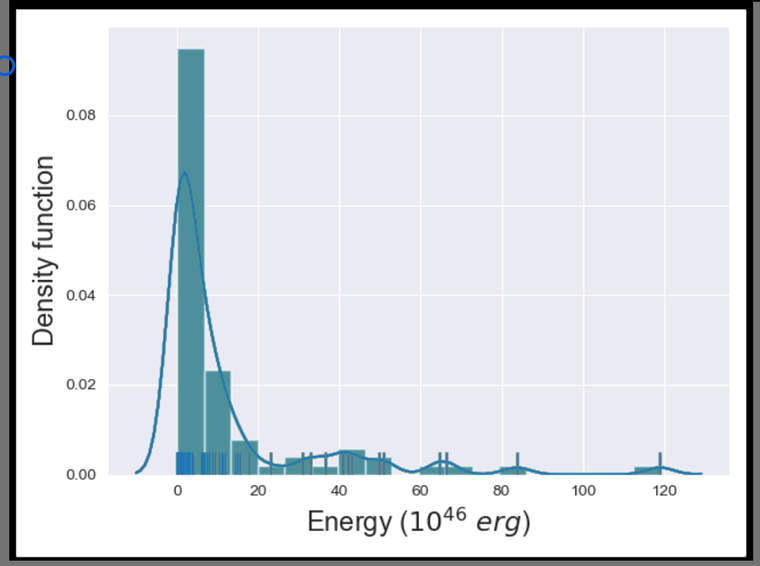
10^{38} to 10^{48} erg

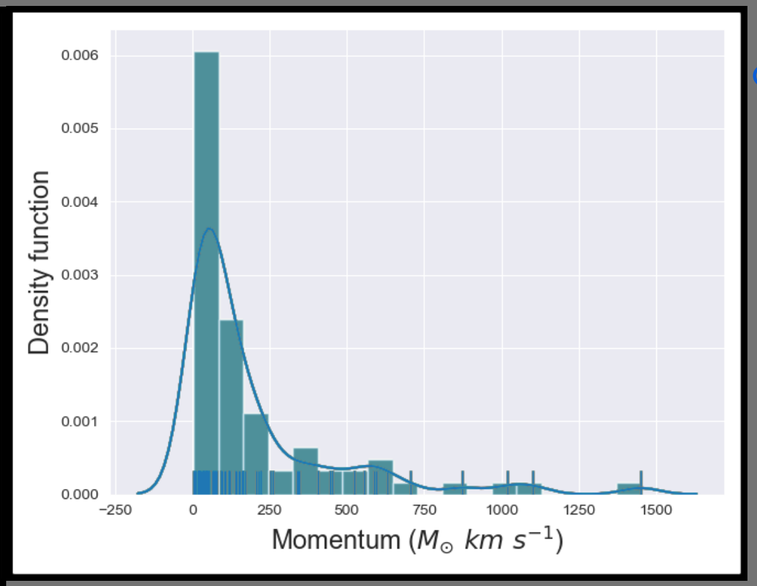
(Wu et. el. 2004)

$\sim 10^{45}$ ergs

(Y.Xu et. el. 2006)







Outflow Momentum

10^{-3} to 10^{4} $M_{\odot}$ km s^{-1}

(Wu et. el. 2004)

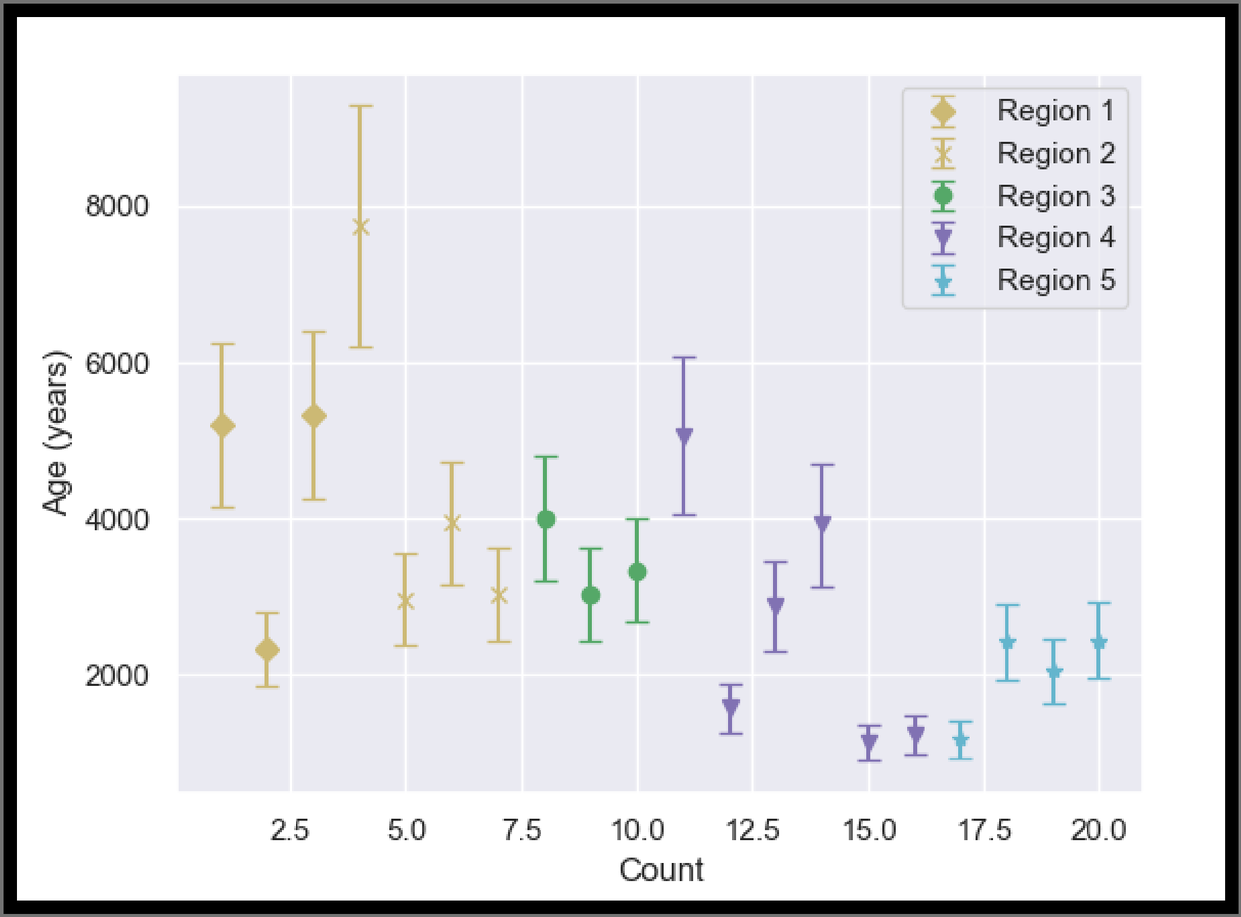
tens of $M_{\odot}$ km s^{-1}

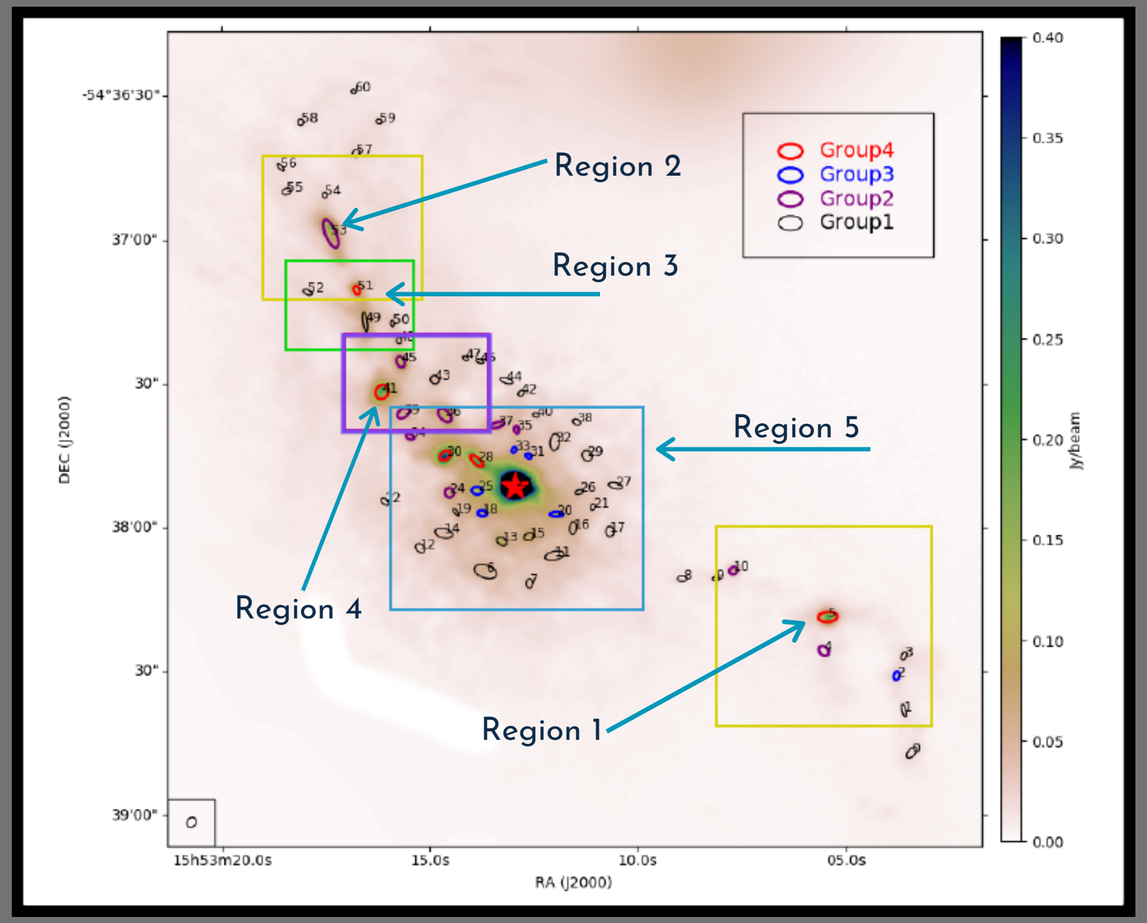
(Y. Xu et. el. 2006)

- Very Energetic outflows
- Physical Impact
- Chemical Impact

Ages of the Outflows

chemical evolution

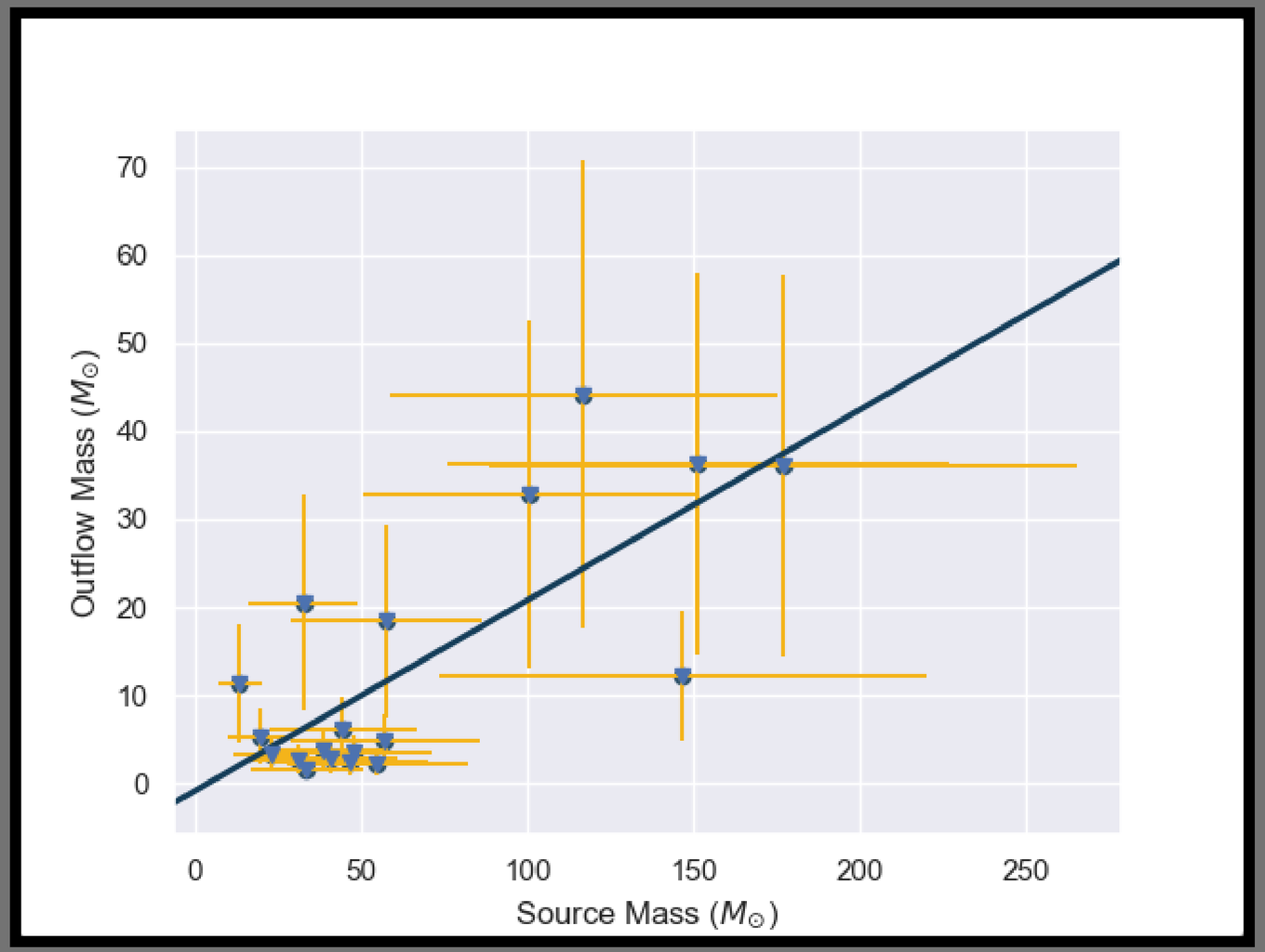




T. Zhang(2020)

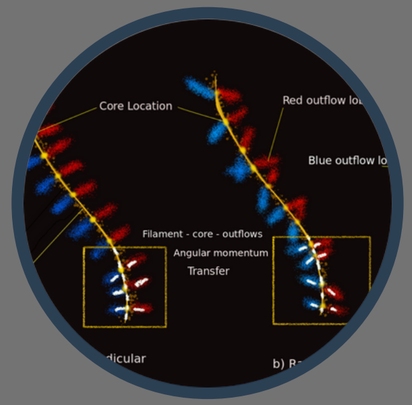
- Star formation in the Initial stages
- Decreasing : Region 1 - Region 5
- Group 4 most evolved Group 1 least
- Disparity Near Hot core

Outflow vs. Core mass



- Linear Relationship
- Slope : 0.22
- Slope = 0.8, (Beuther et. el.(2002)) Slope = 0.77 (L. T. Maud et. el.(2015))
- High mass stars (scale up of low-mass ?)
- Outflow properties ✔ (Scale up with core mass)

Implications for Star Formation

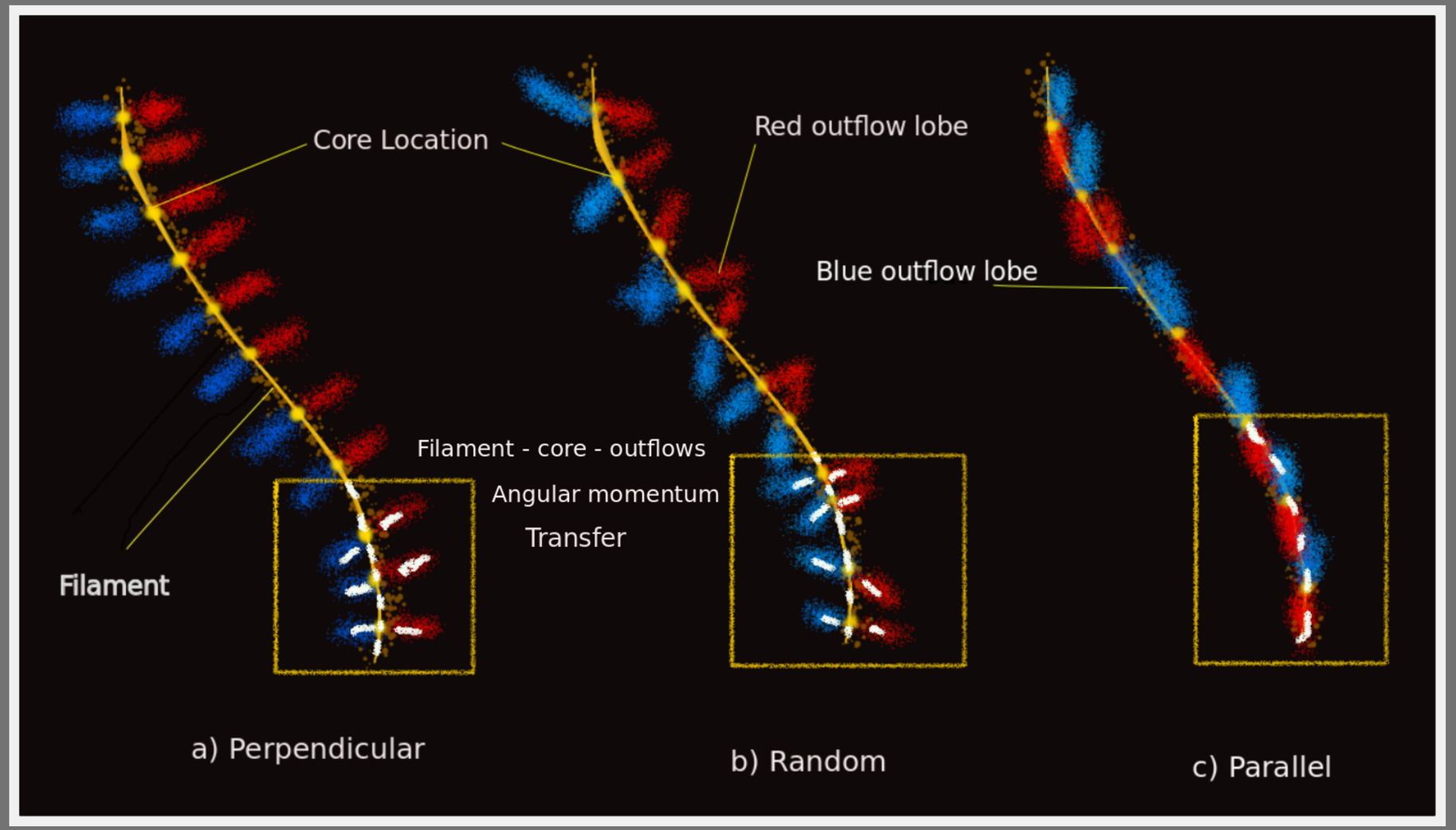


- Outflows and Filaments
- Position Angle w.r.t the filaments
- Monte carlo simulations

Filaments & Outflows

- Outflow orientation w.r.t the filament
- Angular momentum

(Filament - core - outflows)
(protostar)
(Bodenheimer (1995))



- Plot : 3 Different filaments (3 cases)
- Perpendicular senario

(Whitworth et el. 1995), Li et el. 2018
(Anatpindika&Whitworth 2008), (Kong et el. 2019)

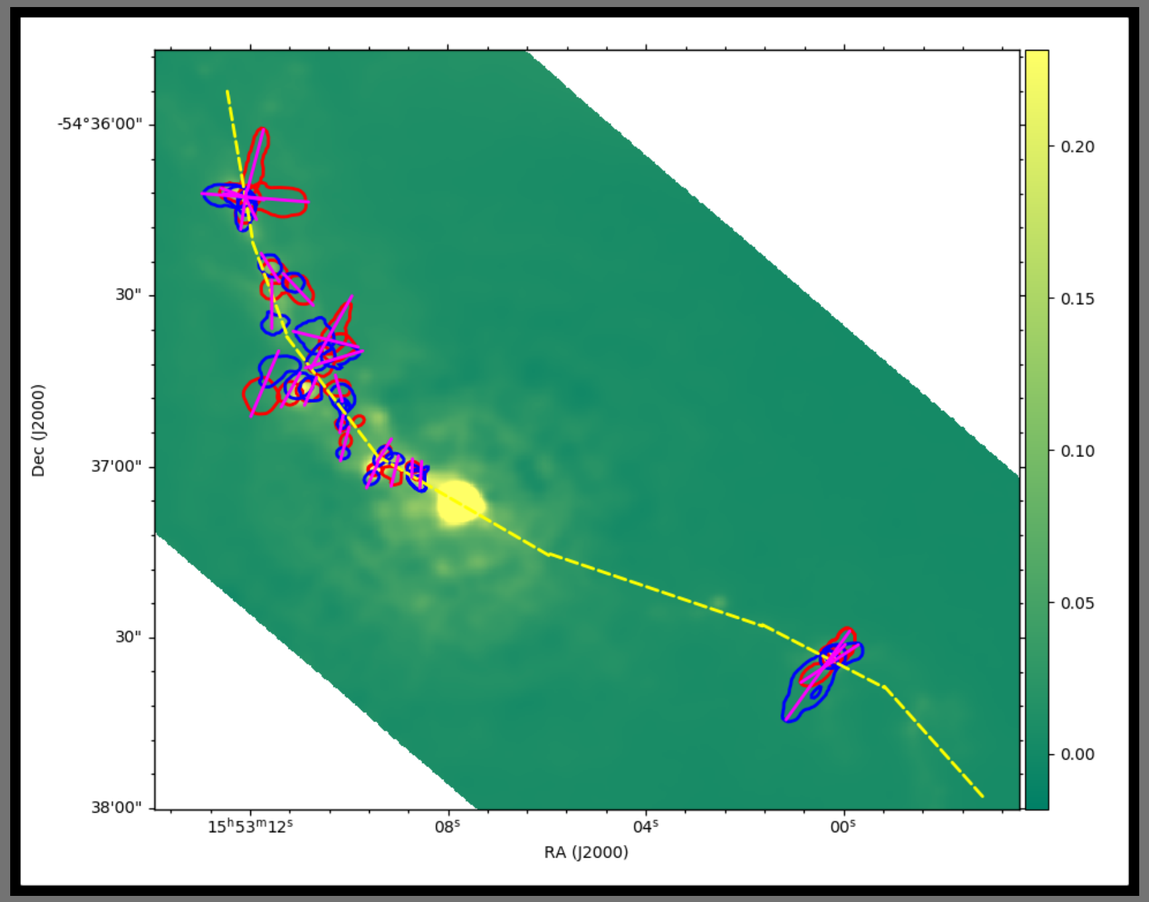
- Random scenario

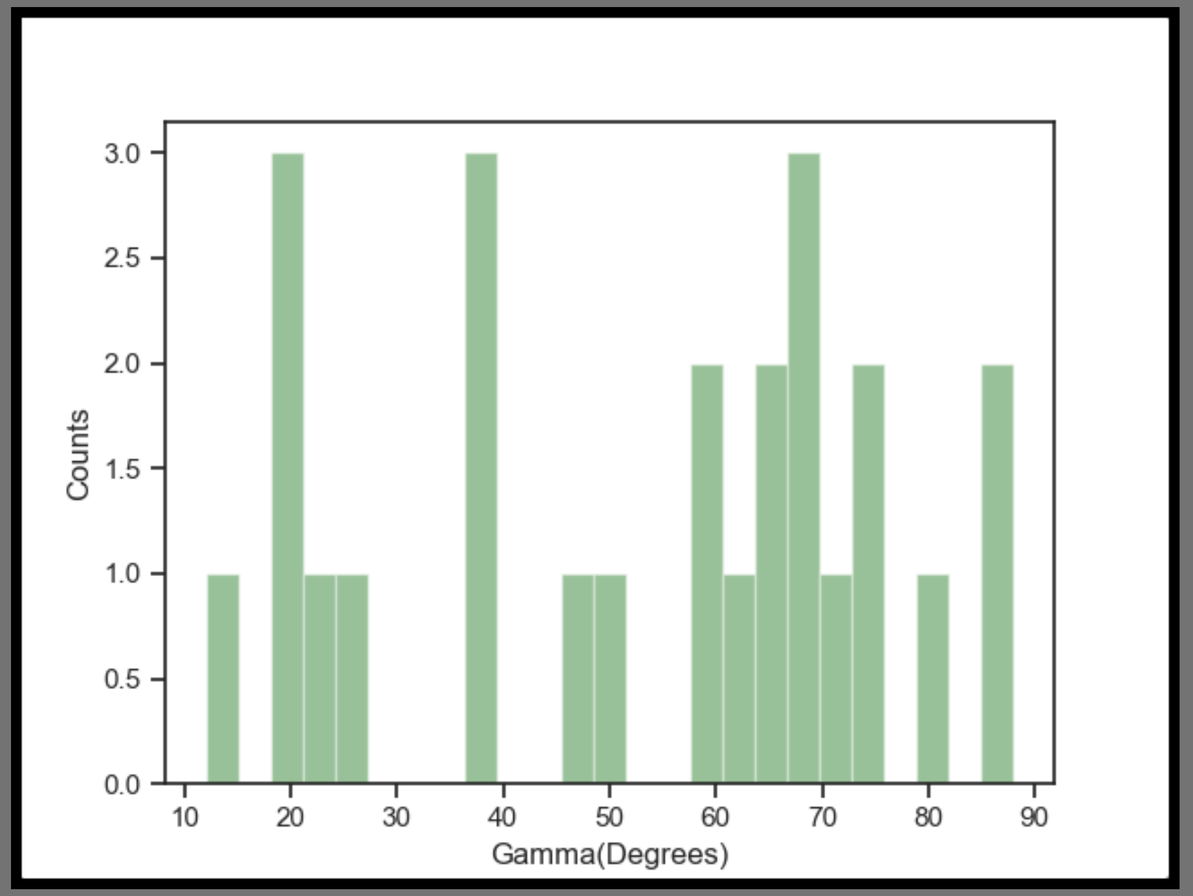
(Stephens et. el. 2017), (T. Baug et el. 2019)

- Parallel Scenario

(Banerjee et el. 2006), (offner et el. 2008)

Position Angle (P.A.)

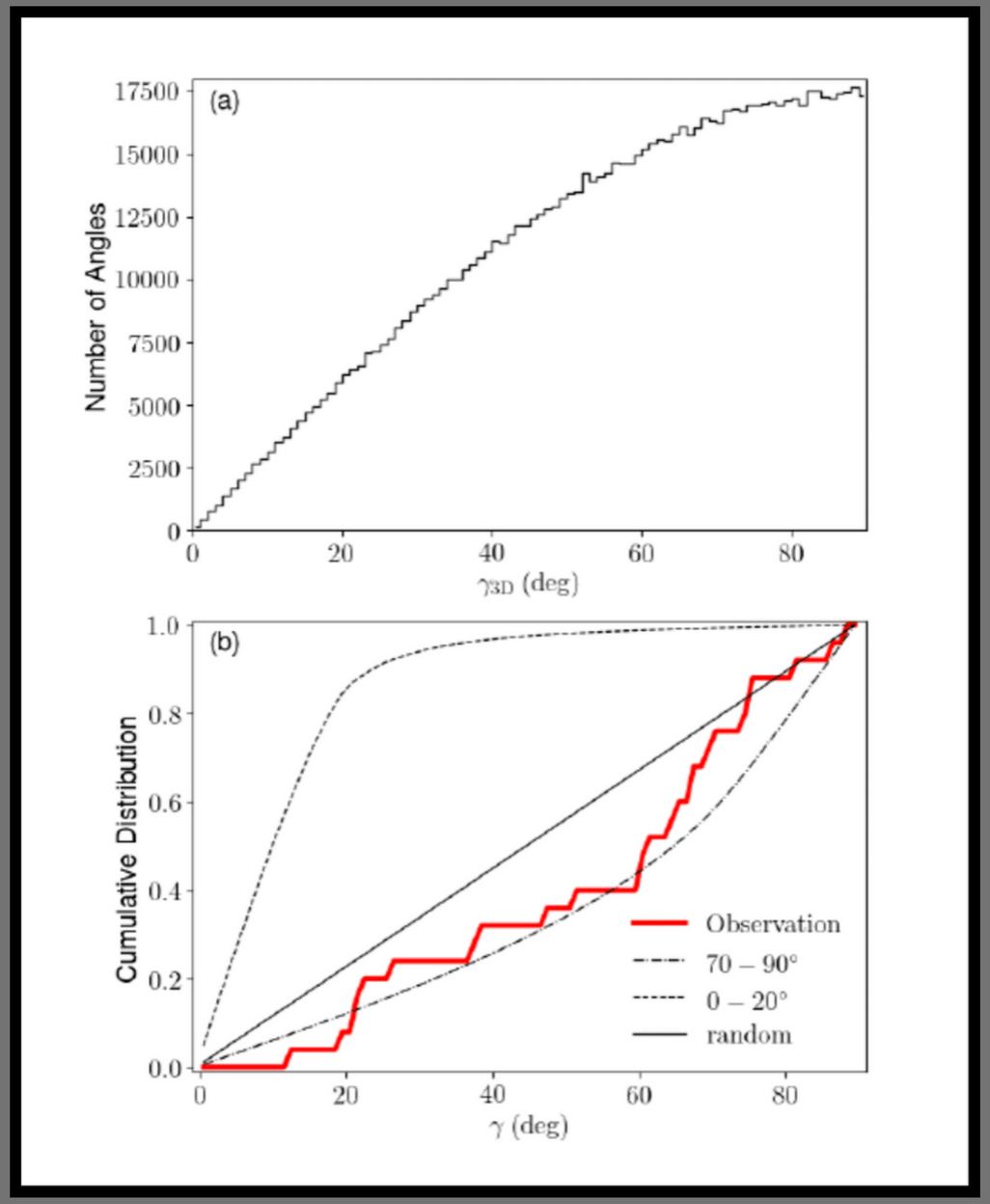




- Yellow : G327 filament
- Pink Line showing outflow direction

- Histogram for Gamma (i.e P.A. w.r.t. the filament)
- Most angles b/w 60-90 degrees

a) CDF (cumulative distribution) for simulated PA



b) CDF of 2D PA based on simulated PA

Monte carlo simulation

- Monte carlo simulations
  (Kong et el. 2019), (Stephens et. el. 2017)
- Angle b/w two random unit vectors in unit sphere
  (N = 1000000)
- Mapping each 3D angle into 2D projection
- Three different scenarios
  a) parallel, b) Perpendicular c) Random
- Anderson Darling Test
  (Test if data is from specific distribution)
  p-value : 0.32 (perpendicular case) ✔
  p-value : 0.09 (Random case)

(if p-value < 0.05 reject the distribution)

Perpendicular senario

(Anatpindika&Whitworth 2008), (Kong et el. 2019)

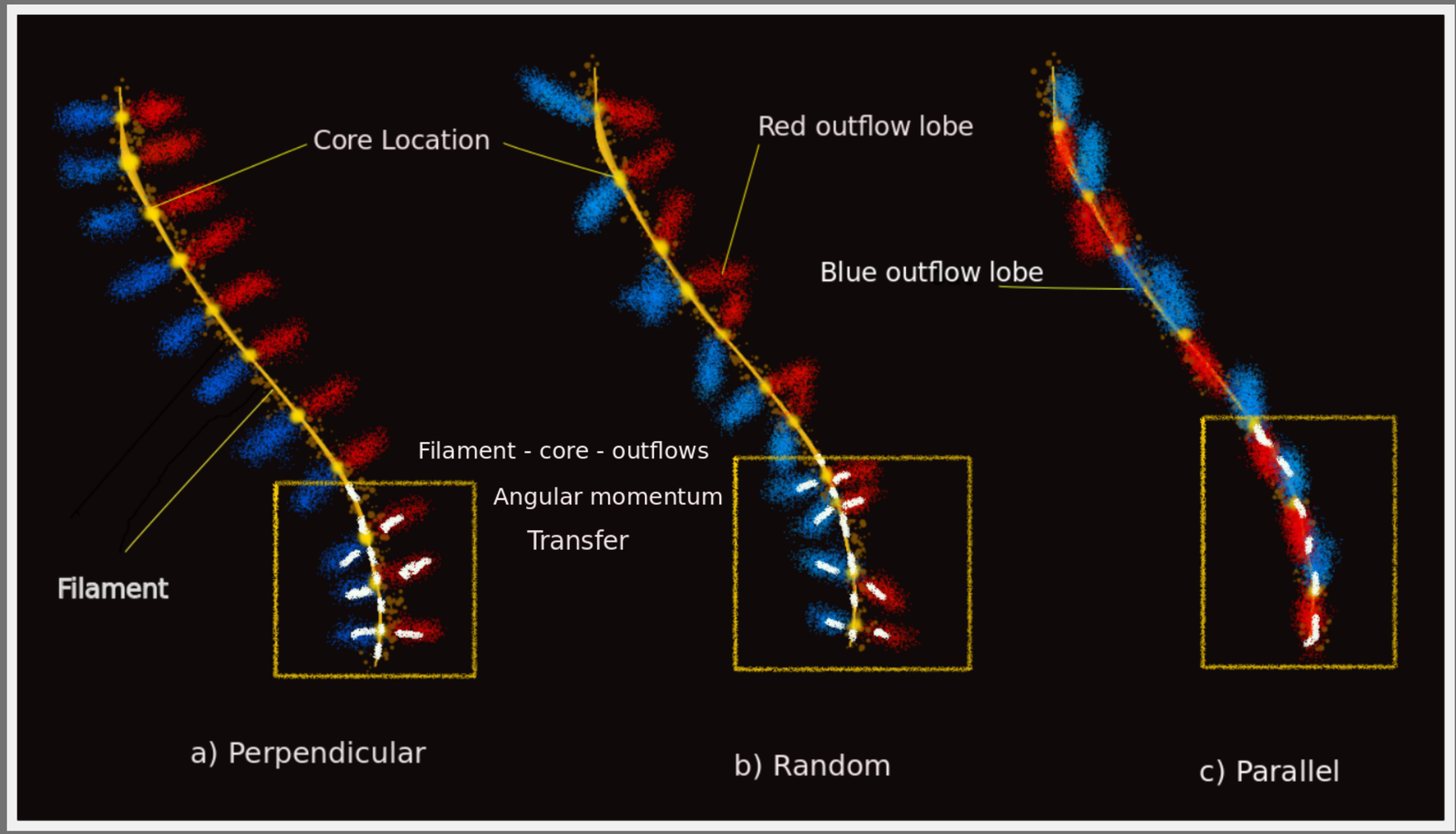
(Whitworth et el. 1995), (Li et el. 2018)

- Different stages
- Constant mass accretion from the filament to the core
- Gravitational fragmentation of shock compressed layer

Parallel Scenario

(Banerjee et el. 2006), (Banerjee&Pudritz 2007)

- Shear Instabilities in colliding HD and MHD flows



Random scenario

(Stephens et. el. 2017), (T. Baug et el. 2019)

Combination of different processes

Comments

- Studied by very few authors
- Fewer for HM star forming regions

Summary and Outlook

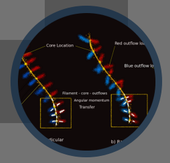
5 

Thank You All !

4 

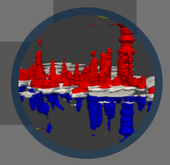
Future Outlook

- Automatic Detection - Magnetic field orientation

3 

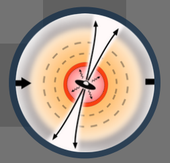
Implication for star formation

- Filaments and outflows - Position Angle - Monte Carlo simulation

2 

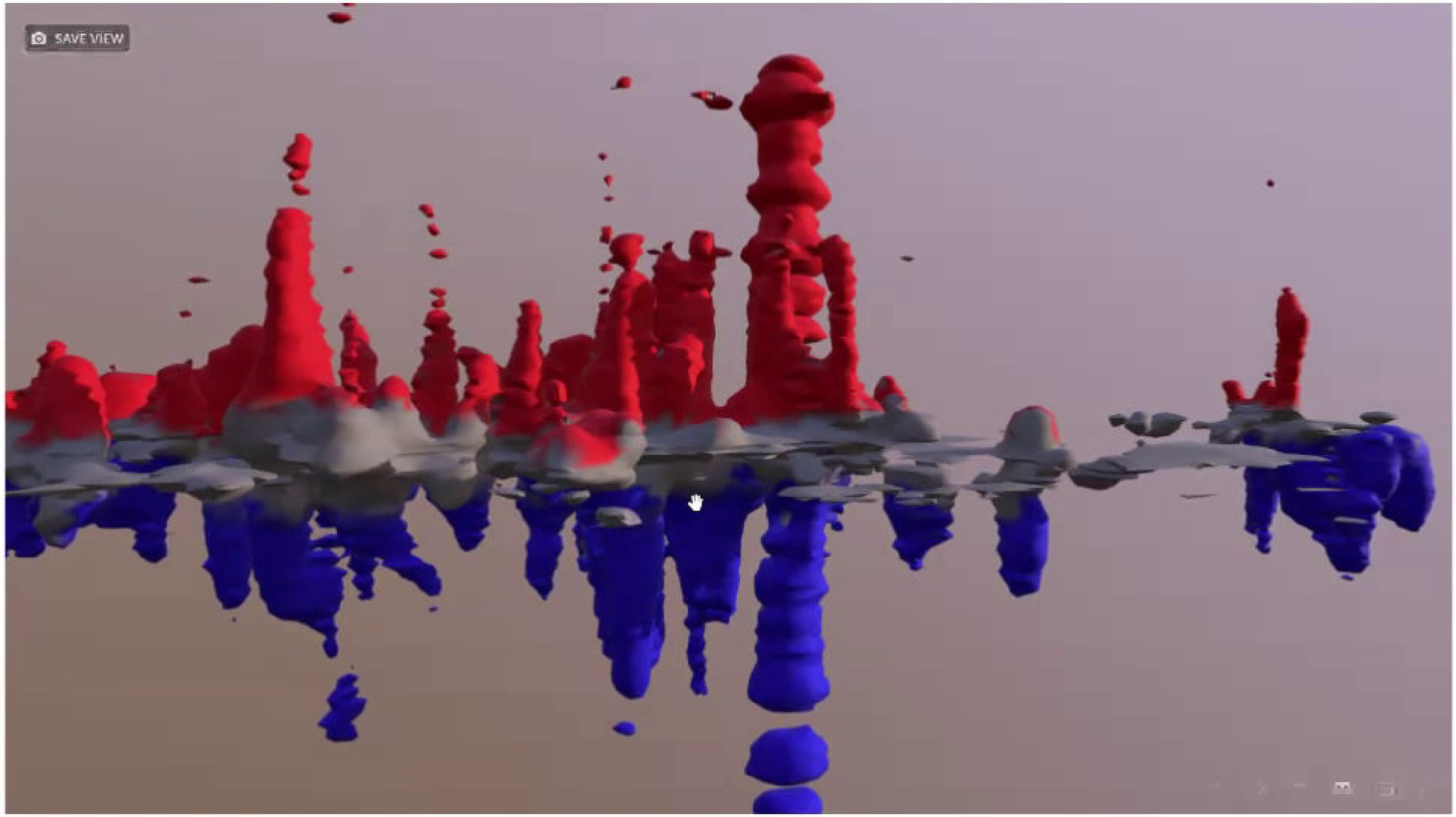
Detection and characterisation of outflows

- 2D Detection - 3D Detection - Rotating ellipsoid - Outflow parameters

1 

Introduction and Theory

- Star formation - Outflows


SAVE VIEW

G327 Region

3.3 kpc

(Urquhart et al. 2011)

450 μm

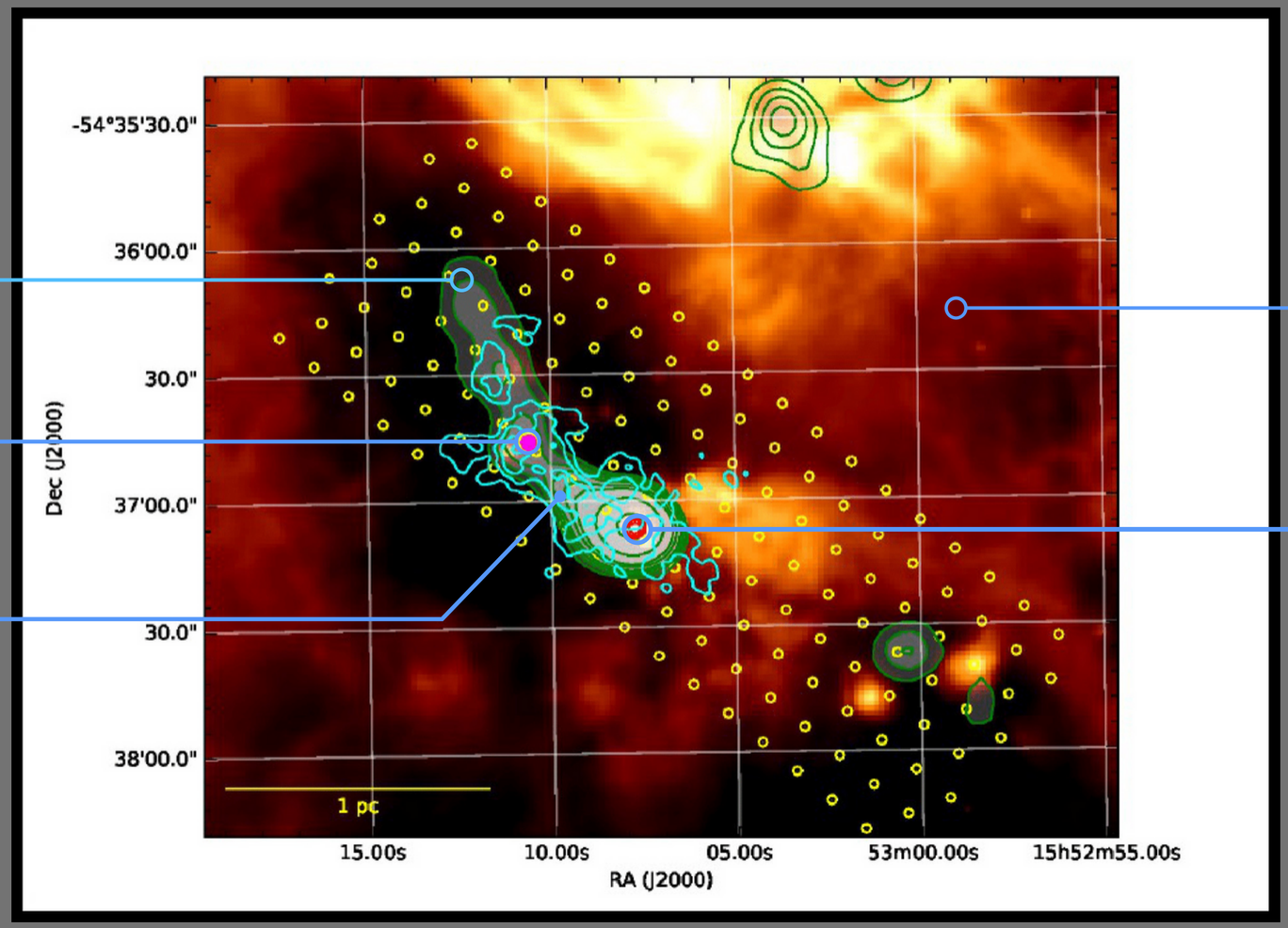
(Minier et el. 2009)

Cold core

(Wyrowski et el. 2008)

N2H+(1-0)

(Wyrowski et el. 2008)



8 μm

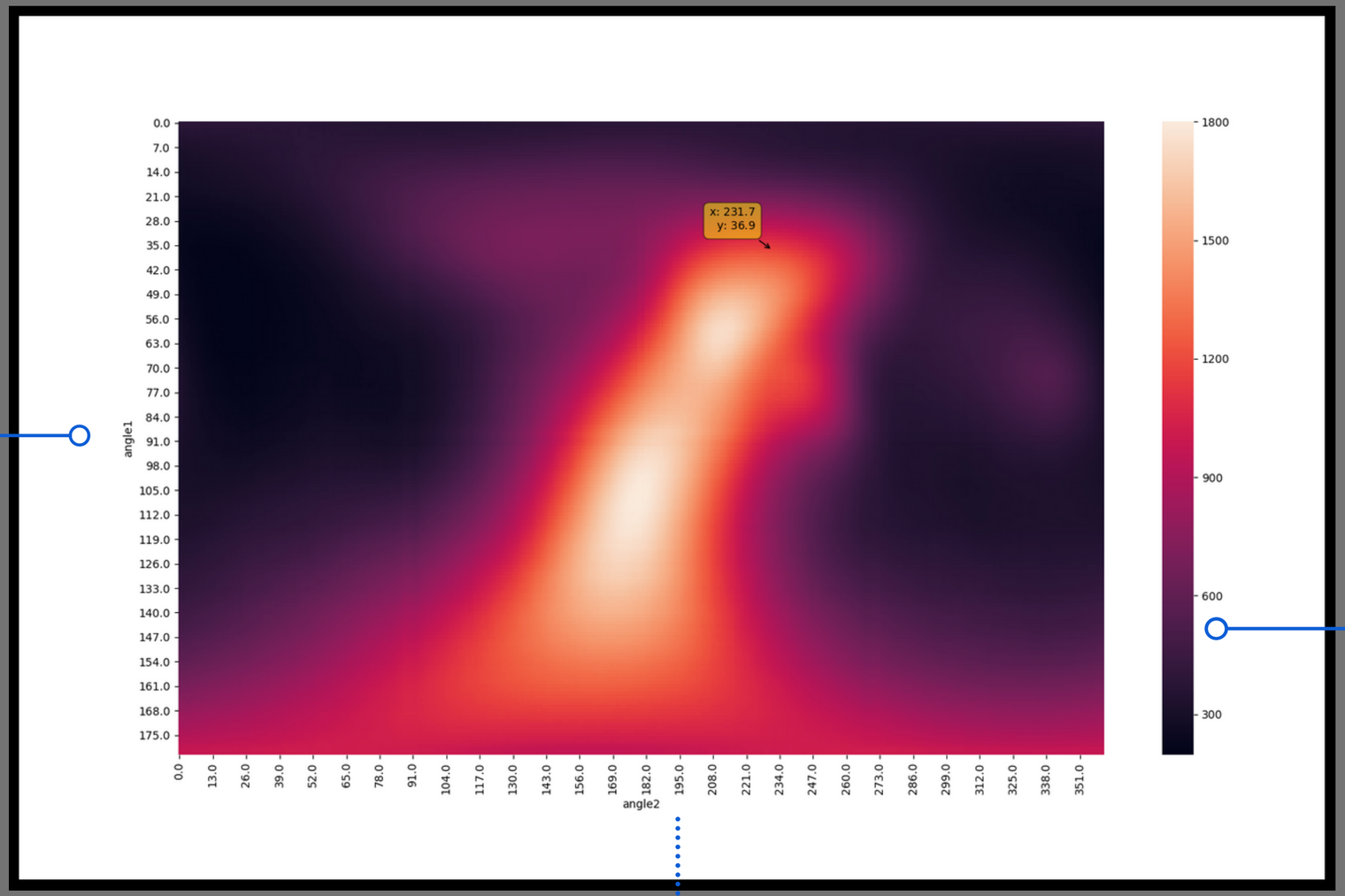
(Background)

3 mm continuum

(Wyrowski et el. 2008)

Source : G327 ALMA proposal

Automatic Rotation



5 Parameters :

2 Angles ✔

3 ellpsoid axis ✘

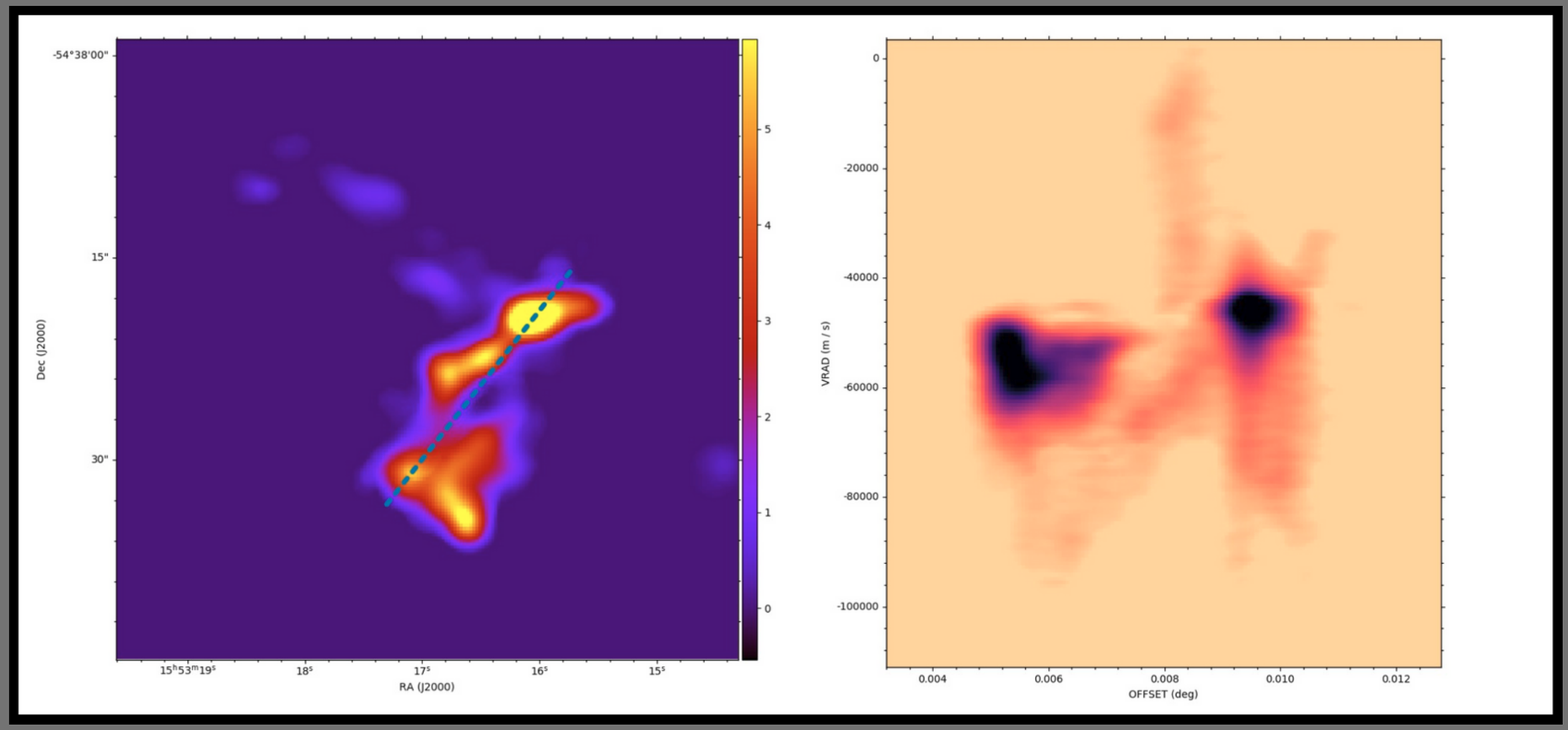
Angle 1 : (0 - 180)

Integrated intesity

- Higher intenstiy : Outflow location

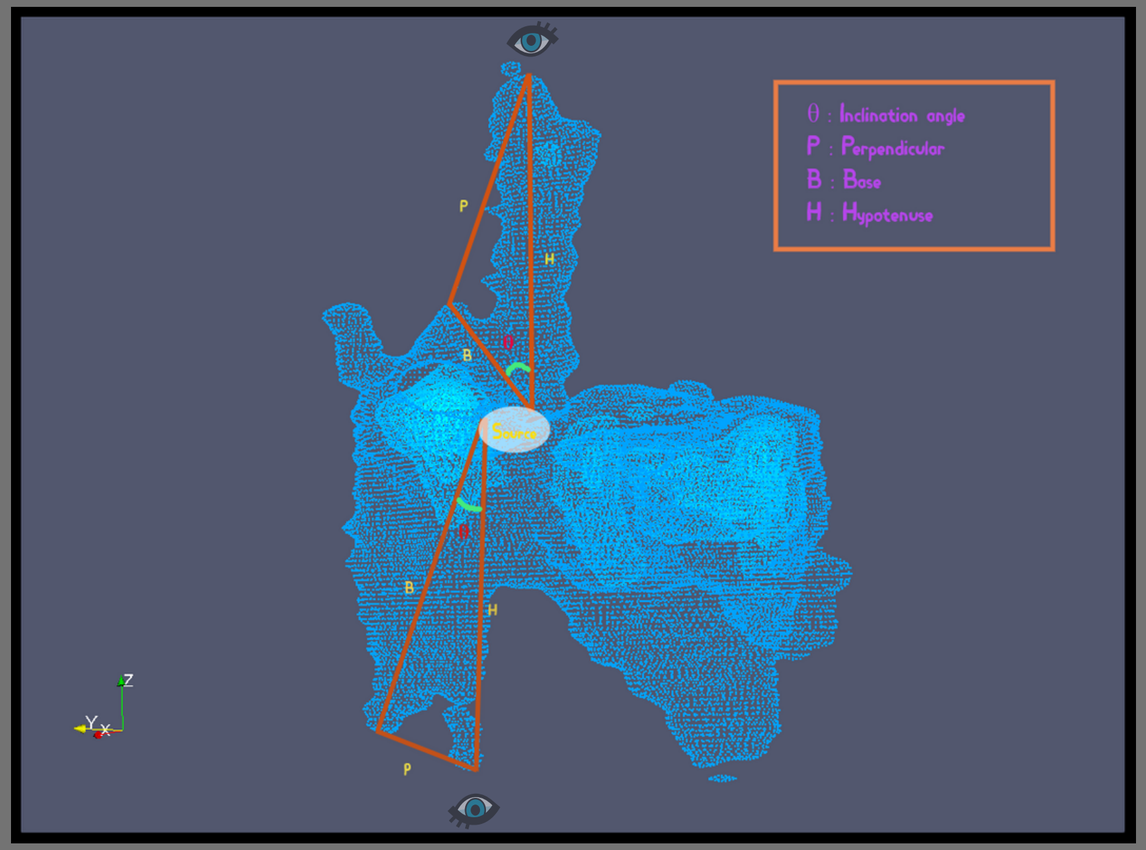
Angle 2 : (0 - 360)

Postion Velocity plots

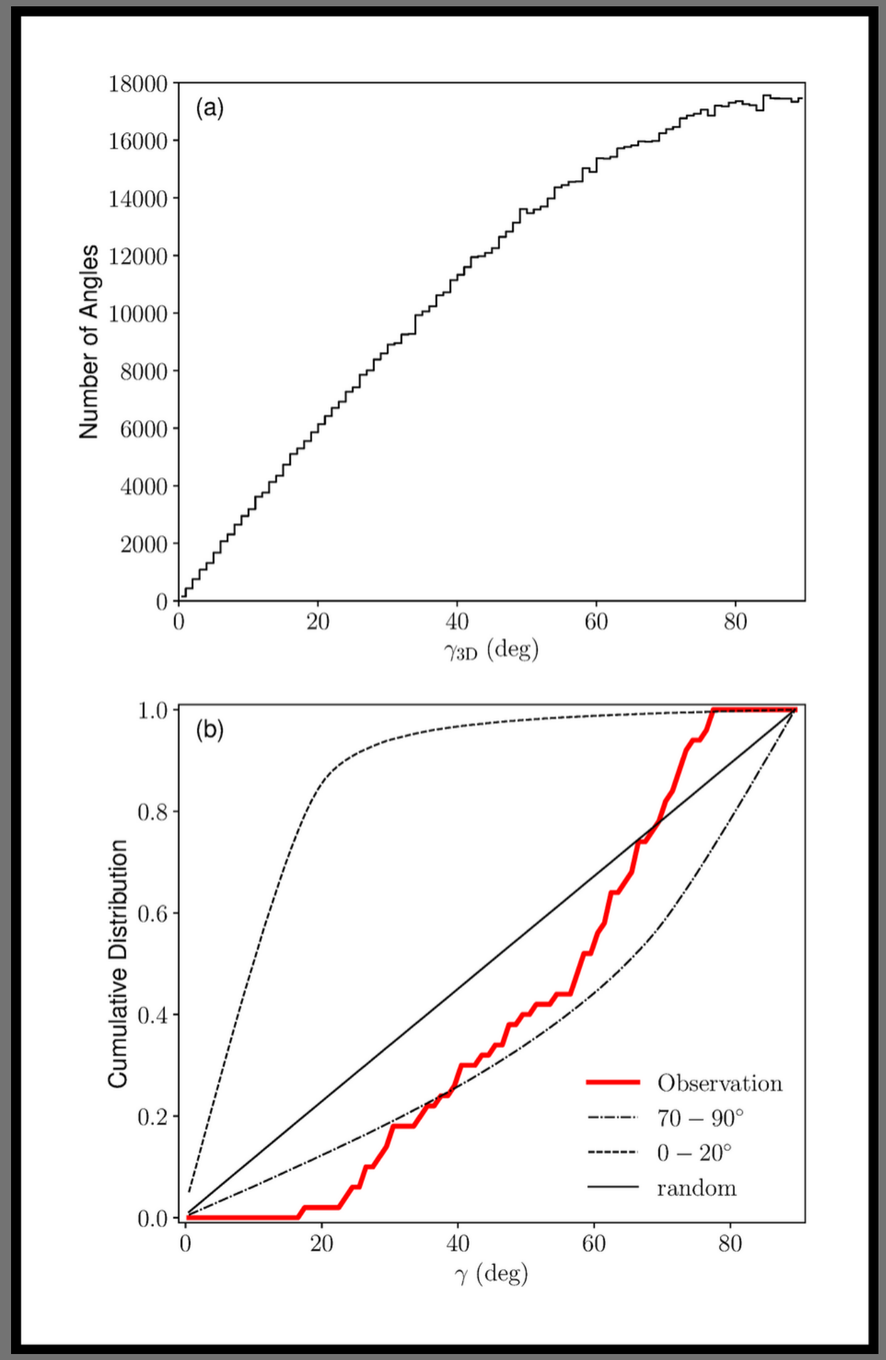


- Region 1 in Analysis scheme
- Slice : North west - South east
- PV plot for the slice
- Hubble's law

Inclination Angle

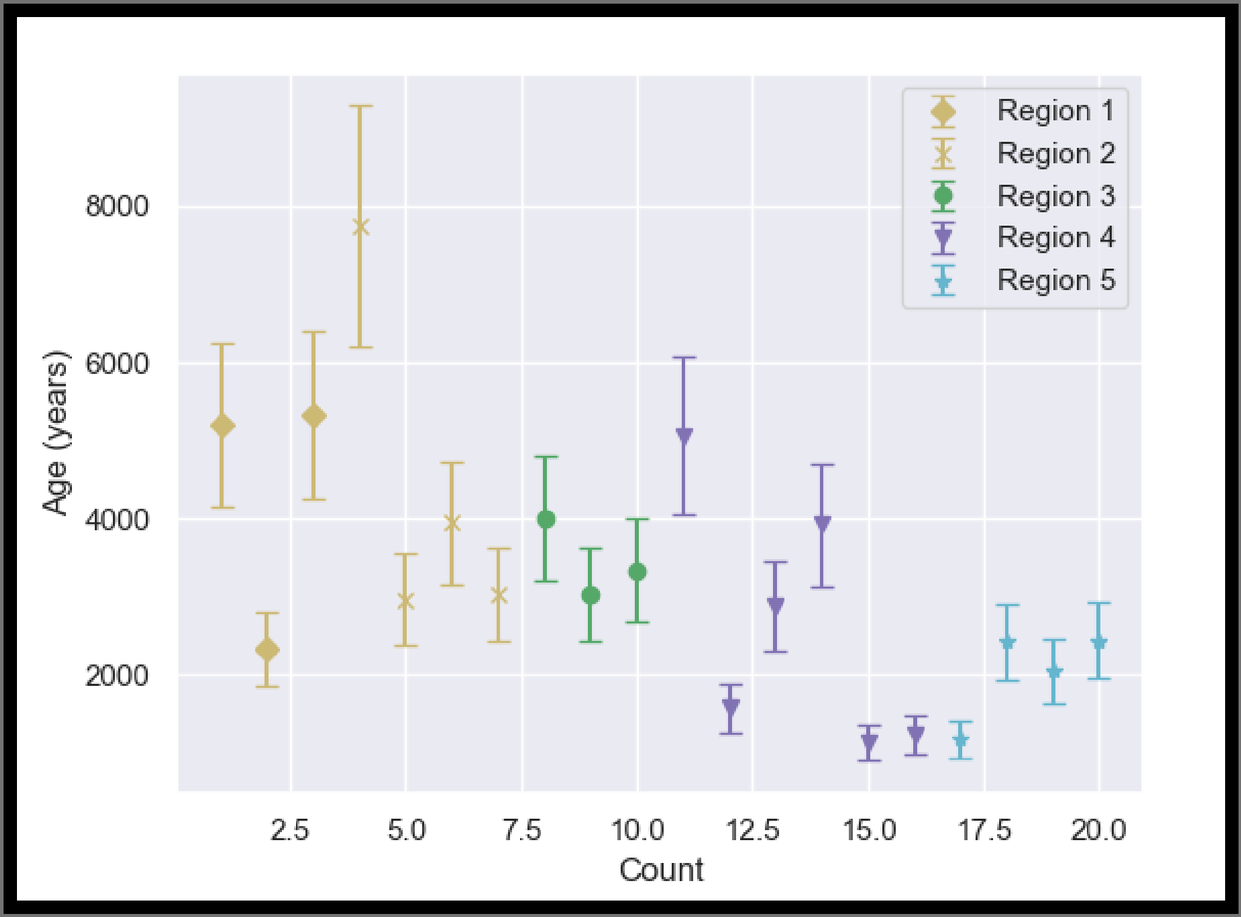


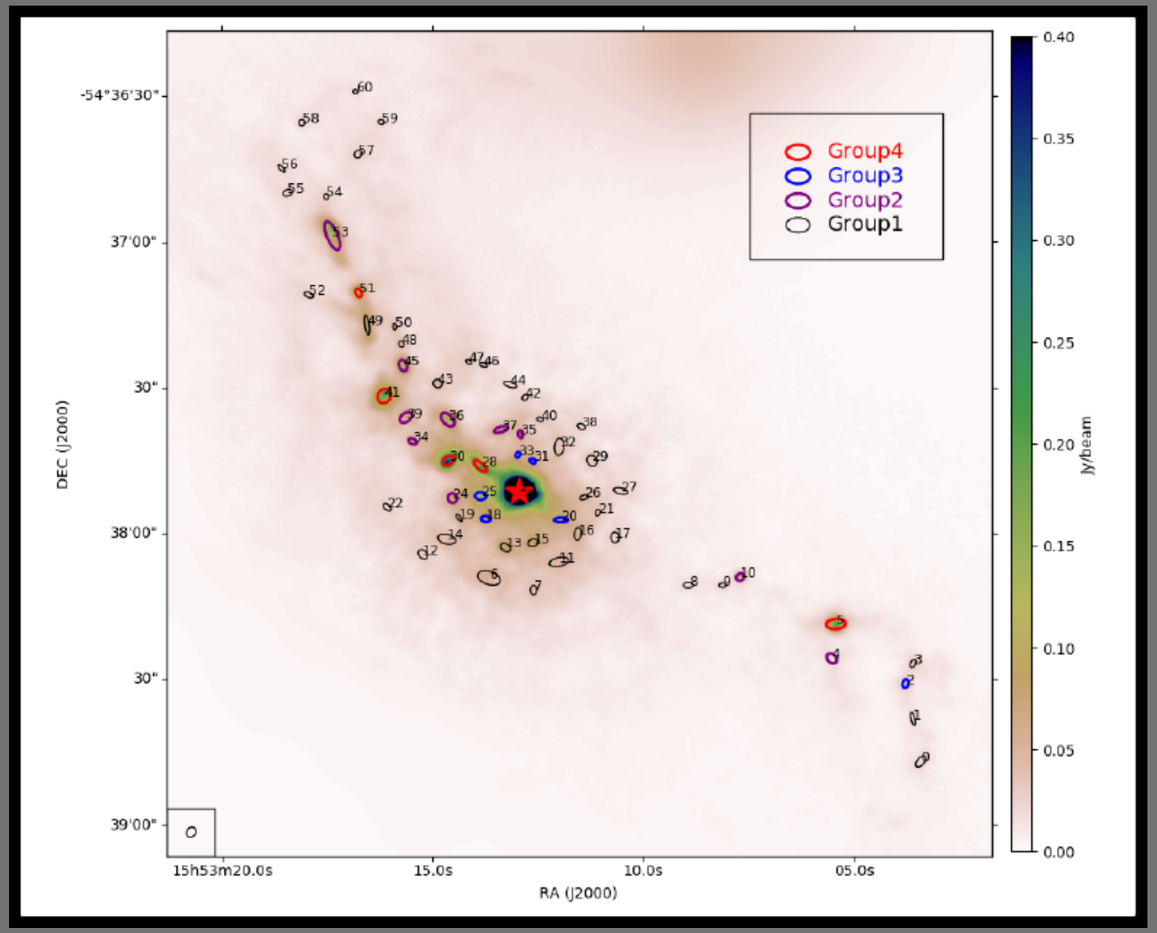
- H : line of sight
- θ : Inclination angle
- Both p-values < 0.05
- Mean θ : 53.6 deg



Ages of the Outflows

chemical evolution

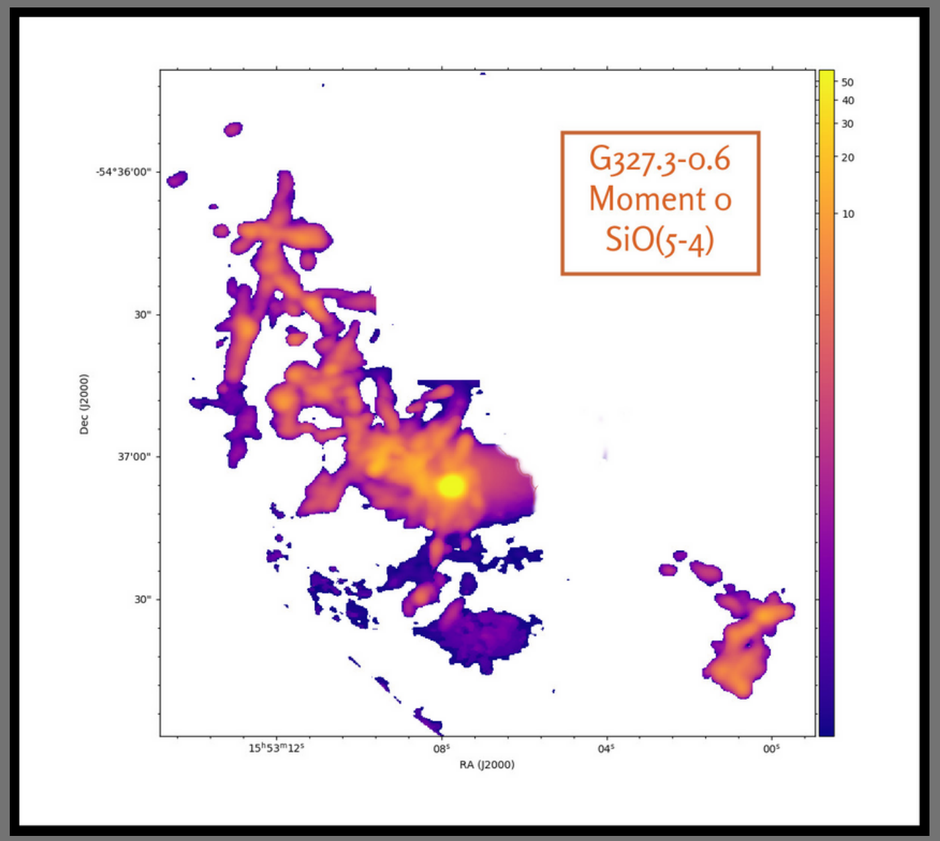


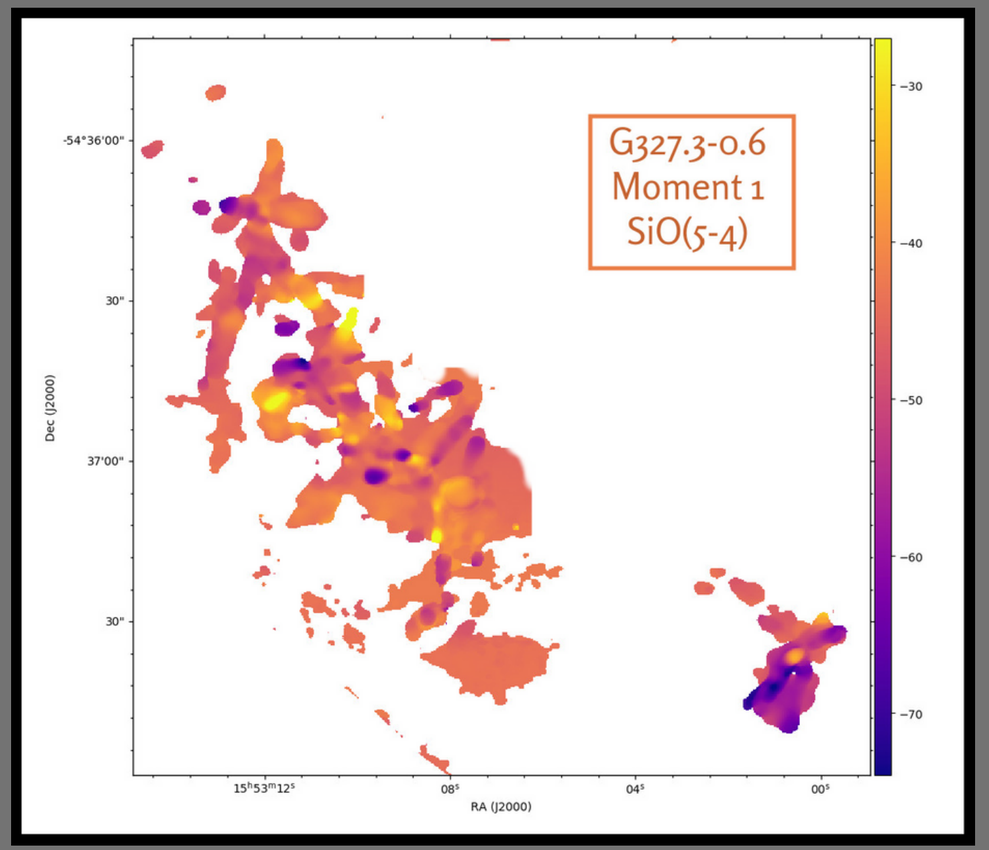


T. Zhang(2020)

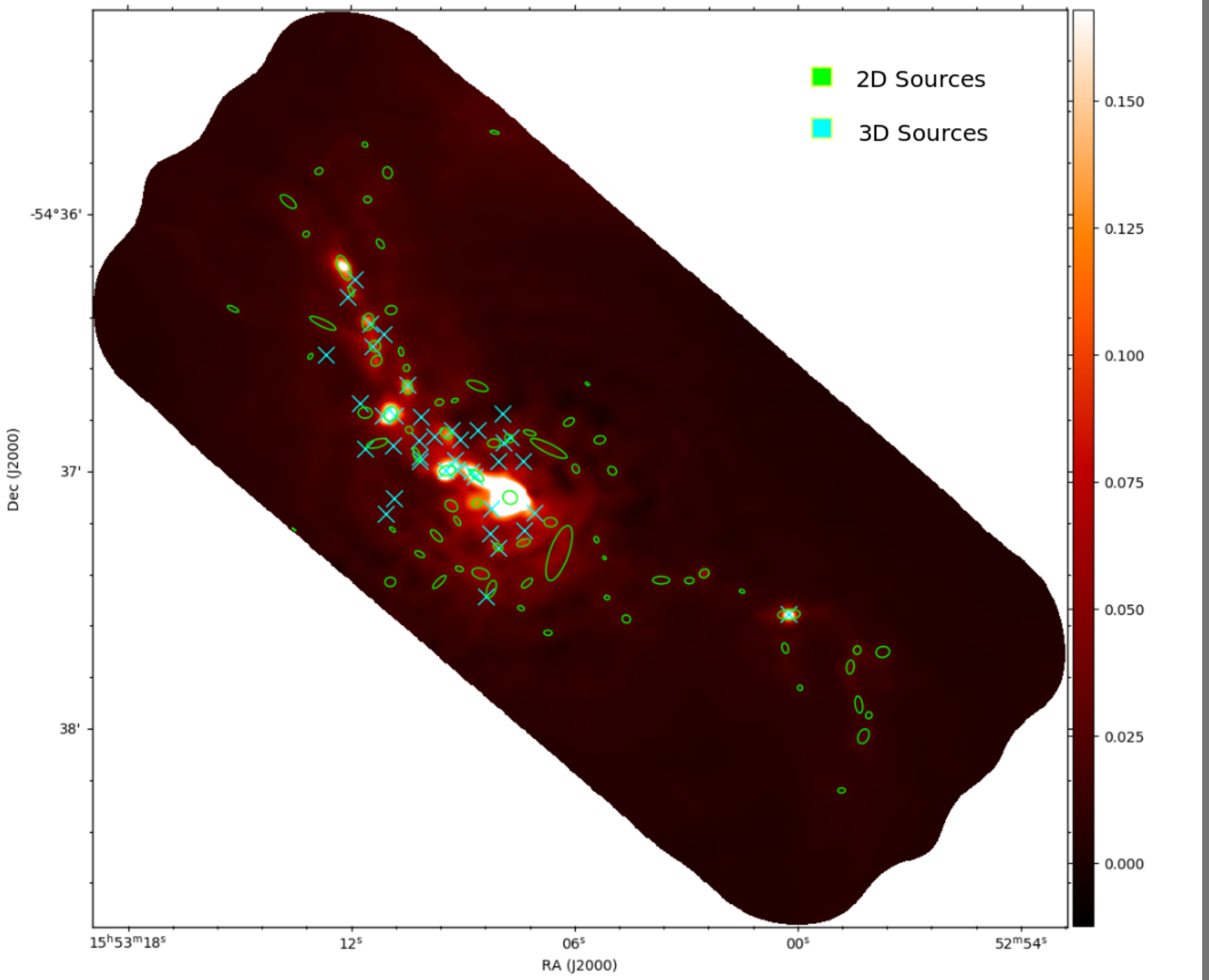
- Inclination angle correction
- Decreasing : Region 1 - Region 5
- Group 4 most evolved Group 1 least
- Disparity Near Hot core

Moment Maps





- Integrated Intensity map
- Velocity Field map



2D and 3D outflow sources

Outflow Parameter Calculation

$$N = \left(\frac{8\pi}{hcA_{ul}g_u}\right)\frac{Q_{rot}(T_{ex})\ e^{E_u/kT}}{2f}\ \frac{c^2}{2kv^2}\ \int S_\nu d\nu$$

Column Density (Zhang et. el. 2016)

$$M = \mu_{H_2} m_H A_{pixel} N_{H_2}$$

Mass

Mass

$$p = \sum_{ch=1}^{n} m_{ch}|v_{ch} - v_{sys}|$$

Momentum (A.Lopez 2009)

$$E = \frac{1}{2}\sum_{ch=1}^{n} m_{ch}(v_{ch} - v_{sys})^2$$

Energy

Tex : Excitation Temperature (assumed (- 40 K))

Qrot : Parition function

Sv : Flux

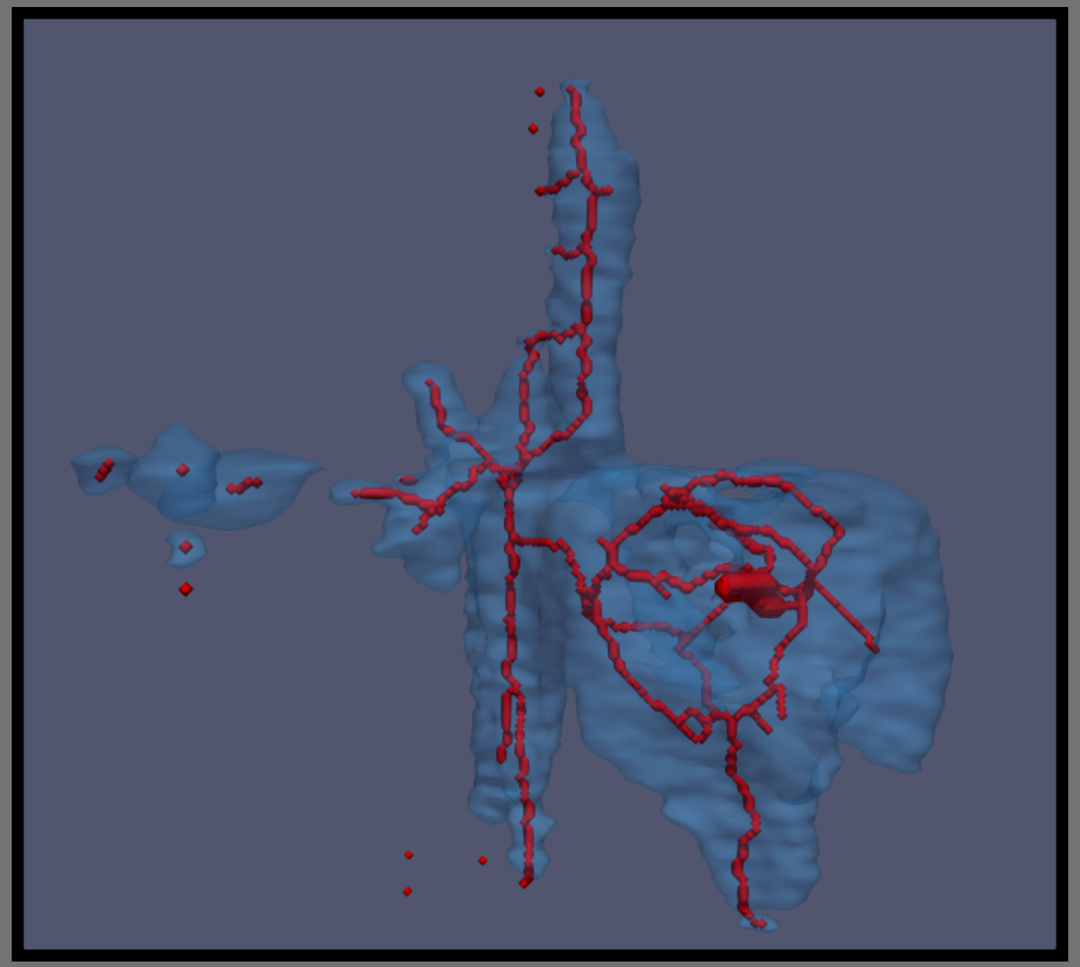
f : abundance ratio

mu_H2 : mean molecular weight

mH : mass of hydrogen

Apixel : Area of each pixel

Skeletonization

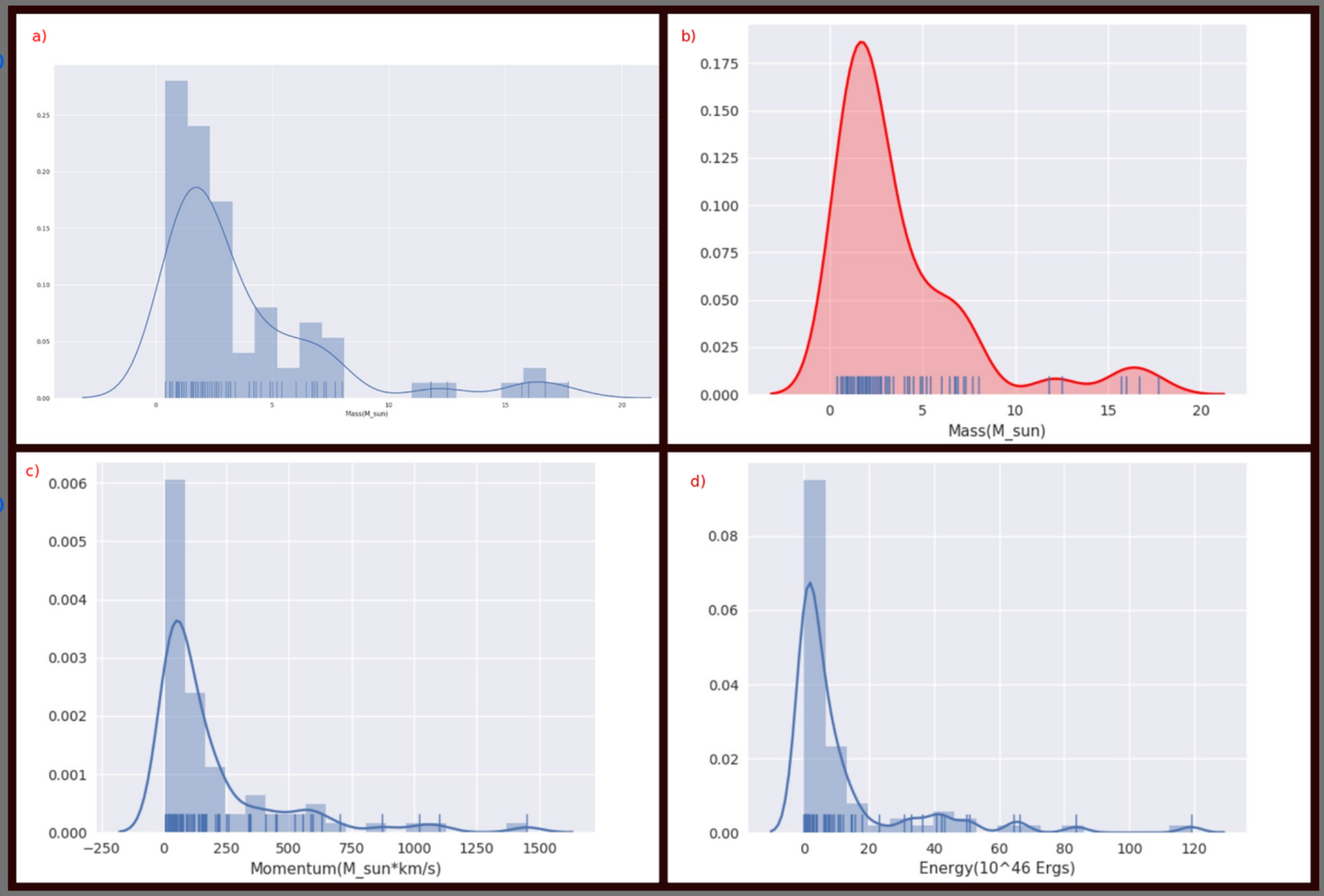


Outflow parameter Results

x-axis : Mass

y-axis : Probability

KDE and Histogram



x-axis : Mass

y-axis : Probability

Kernel Density Estimation (KDE)

x-axis : Momentum

y-axis : Probability

KDE and Histogram

High Momentum

(Wu et. el. 2004)

x-axis : Energy

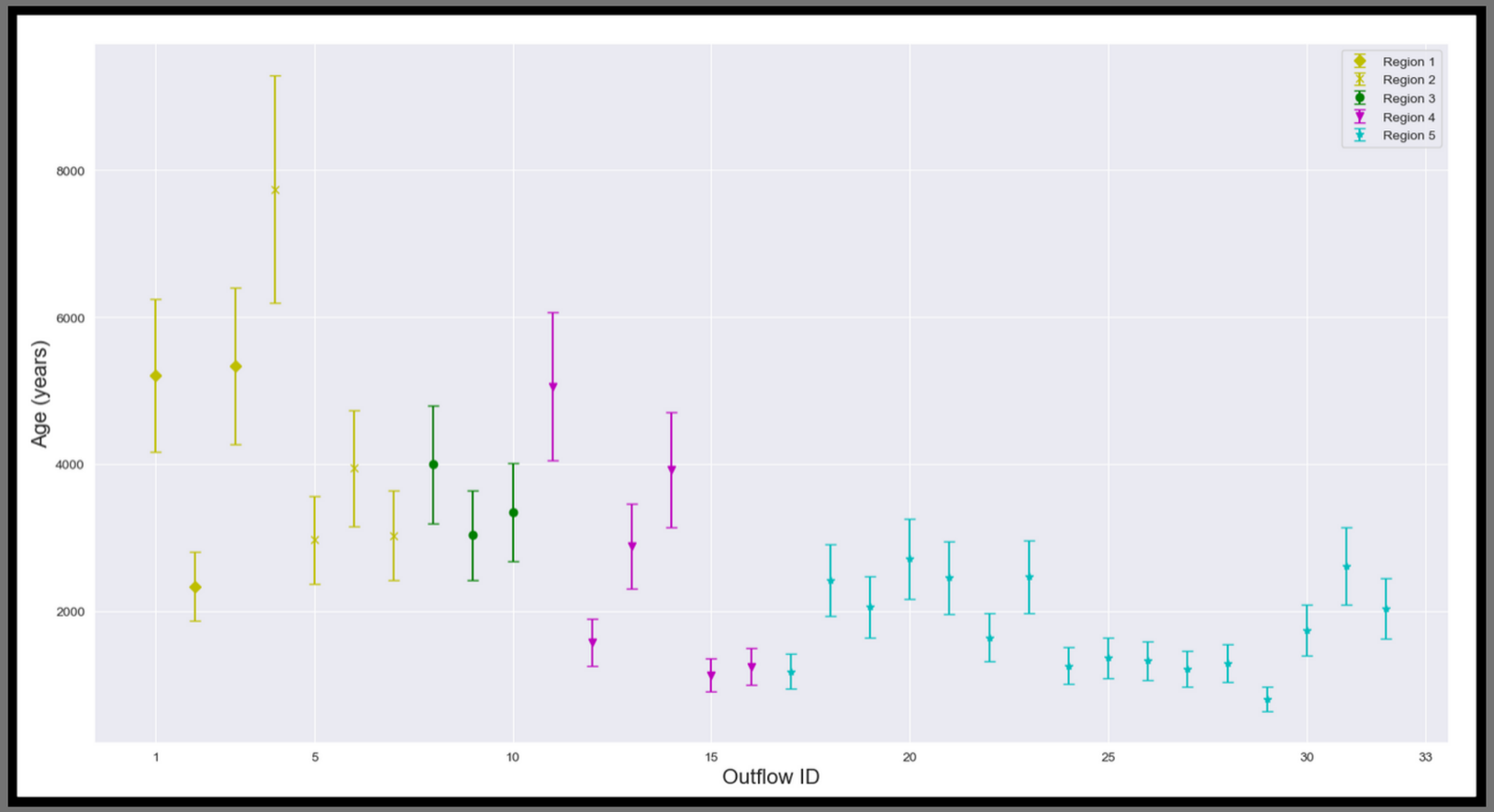
y-axis : Probability

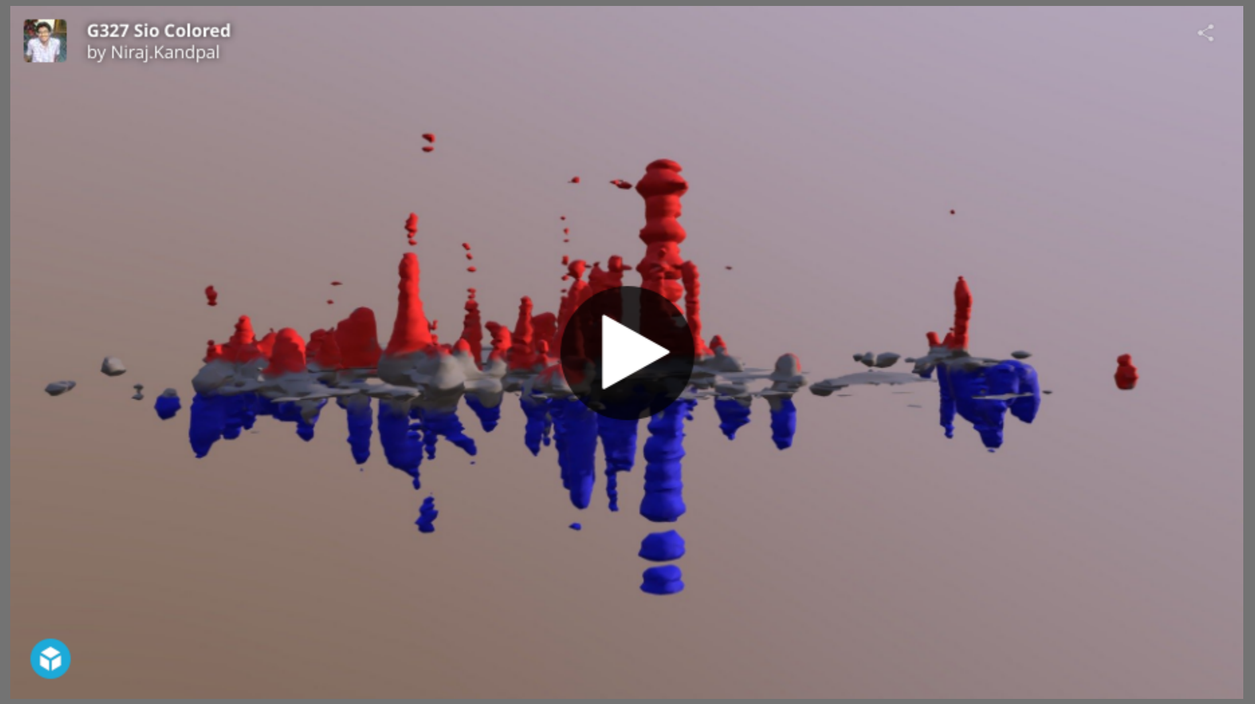
KDE and Histogram

High Energy

(Wu et. el. 2004)

Age Distribution




G327 Sio Colored
by Niraj.Kandpal