A Galactic radio survey of jets from MYSOs: An unobscured insight into massive star formation

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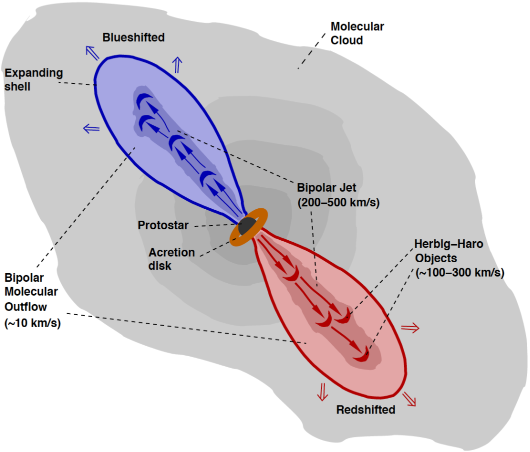
Tracing the Flow
Friday, 6th July 2018
10:00 –10:15

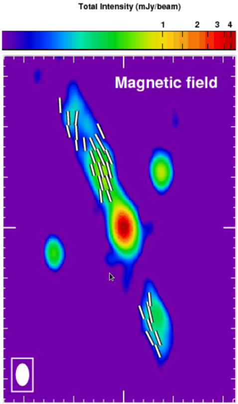
Introduction

Ionised Jets



Carrasco-González (2010)

Ionised Jets



Credit: Carrasco-González et al. (2010)

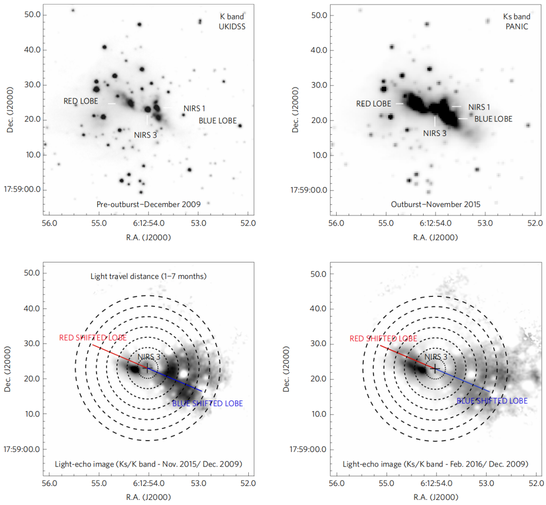
What we know

- Collimated structures over several pc
- Alignment with molecular outflows
- Shock emission
- Magnetic origins

What we don't

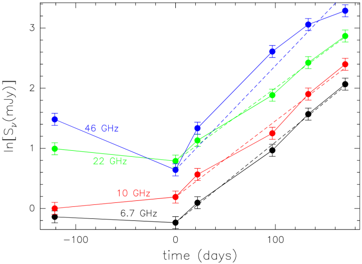
- Formation mechanisms
- Kinematics
- Precession/Variability
- Ionisation fractions
- Ionisation mechanisms

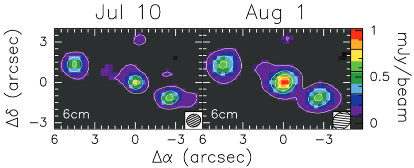
The Accretion/Ejection Link



Caratti o Garatti et al. (2017)

The Accretion/Ejection Link





Cesaroni et al. (2018)

- Episodic accretion/NIR burst of 20 $M_\odot$ MYSO (June 2015)
- Subsequent ejection/radio jet burst (July 2016)

Open questions about jets

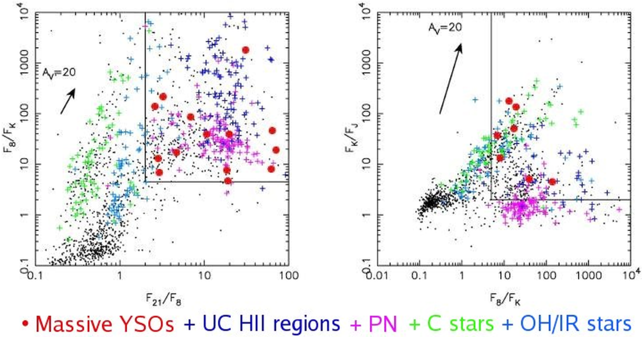
- How common are ionised jets towards high-mass YSOs? (lack of statistical surveys)
- Which launching/collimation mechanism? Disc-wind (Blandford and Payne, 1982; Pelletier and Pudritz, 1992), X-wind (Shu et al., 1994), something else?
- What are representative ionisation fractions and other parameters?

A galactic radio survey of jets from MYSOs

The Red MSX Source Survey - *Lumsden et al. (2013)*

Purpose:

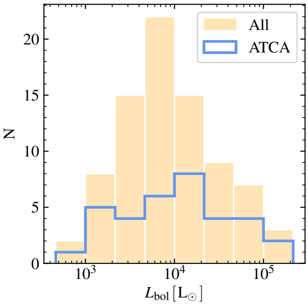
"To increase the known sample of massive young stellar objects (MYSOs) by an order of magnitude."

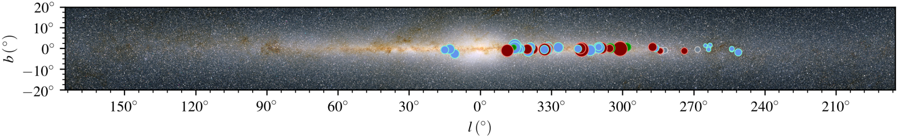


Lumsden et al. (2002)

Southern Sample - *Purser et al. (2016)*

- Total of 34 southern ($\delta_{J2000} < -30°$) RMS objects:
  - RMS classification: YSO or YSO/HII
  - Distance limited ($d < 7$ kpc)
  - 10^3 L$_\odot$ < L_{bol} < 10^5 L$_\odot$

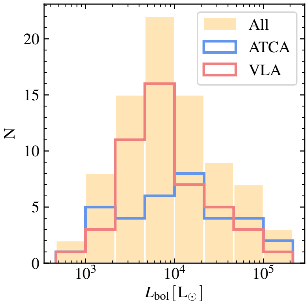


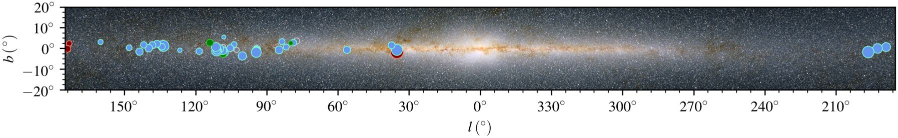


Credit: NIR Image from SDSS/APOGEE

Northern Sample - *Purser et al. (in prep)*

- Total of 47 northern ($\delta_{J2000} > -10^\circ$) RMS objects:
  - RMS classification: YSO or YSO/HII
  - Distance limited ($d < 7$ kpc)
  - 10^3 L$_\odot$ < L_{bol} < 10^5 L$_\odot$
- Concurrent sample of 8 IRDCs harbouring 14 luminous cores (Rathborne et al., 2010)

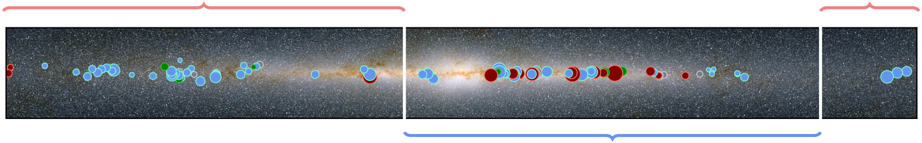




Credit: NIR Image from SDSS/APOGEE

VLA (2012–2014)

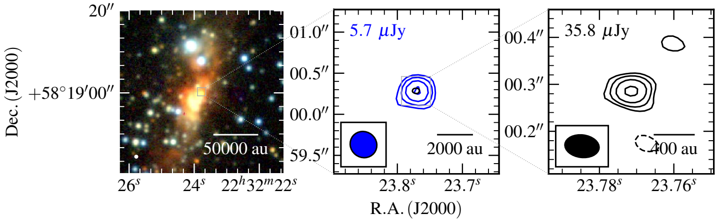
- 6 and 44 GHz
- 0″.33 and 0″.04
- ~ 7 and 40 µJy



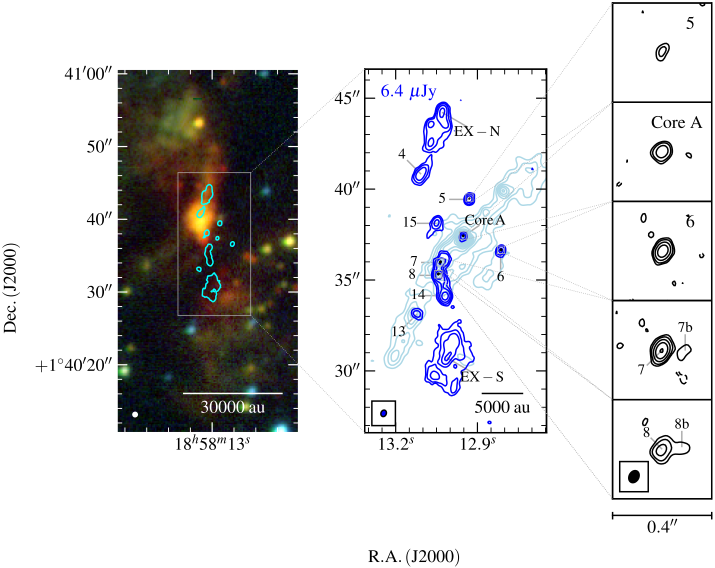
ATCA (2010–2013)

- 5.5, 9.0, 17.0 and 22.8 GHz
- 2″.0, 1″.2, 0″.6 and 0″.5
- ~ 17, 20, 40 and 100 µJy

Classification - ‘Jet’

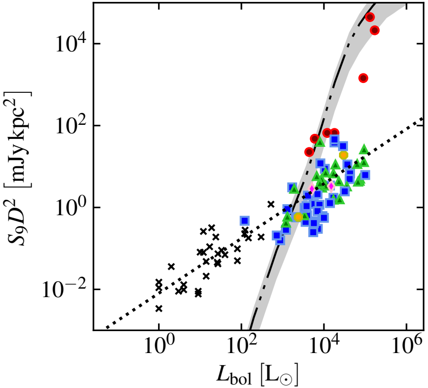


Classification - ‘Jet with lobes’ e.g. G35.2N



Results

Class.	ATCA	VLA	All-sky
DW	1	1	2
HII	6	3	9
N/D	3	3	6
U/K	2	2	4
Jet	3	4	7
Jet(C)	9	21	30
Jet(L)	7	10	17
Jet(L,C)	3	3	6
	34	47	81



≤ 74% of MYSOs harbour jets → 'Jet-phase' lasts ≤ 74000 yr (assuming formation timescale of 10^5 yr, McKee and Tan, 2003)

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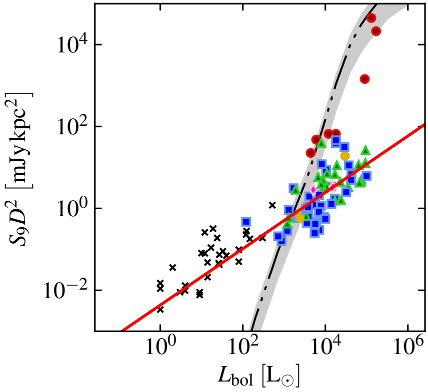
The low/high mass bridge?

Radio luminosity vs. bolometric luminosity

$$\log_{10}\left(S_9 D^2{}_{\rm lm}\right) = (-2.09 \pm 0.14) + (0.67 \pm 0.10)\log_{10}\left(L_{\rm bol}\right)$$

$$\log_{10}\left(S_9 D^2{}_{\rm hm}\right) = (-2.36 \pm 0.41) + (0.69 \pm 0.10)\log_{10}\left(L_{\rm bol}\right)$$

Jet radio luminosities scale across 6 orders of magnitude in L_{bol}



Jet mass loss rate *(Reynolds, 1986)*

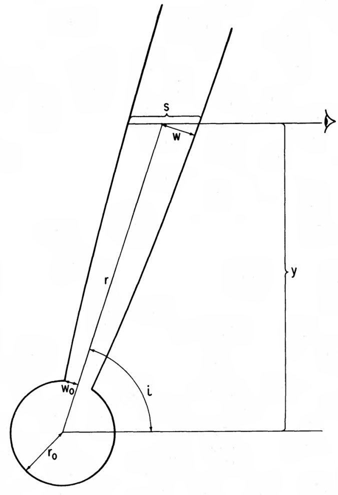
$$w(r) = w_0 \left(\frac{r}{r_0}\right)^{\epsilon} \qquad T(r) = T_0 \left(\frac{r}{r_0}\right)^{q_T}$$

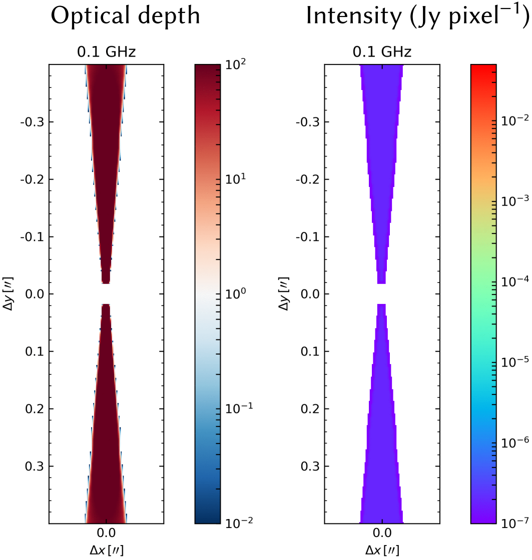
$$\tau(r) = \tau_0 \left(\frac{r}{r_0}\right)^{q_\tau} \qquad S_\nu(\nu) = S_0 \left(\frac{\nu}{\nu_0}\right)^{\alpha}$$

$$\dot{M}_{\mathrm{jet}} = \frac{9.38 \times 10^{-6}\, v_8\, \mu\, S_{\mathrm{mJy}}^{3/4}\, d_{\mathrm{kpc}}^{3/2}\, \theta_{\mathrm{OA}}^{3/4}}{\chi_0\, \nu_{10}^{\frac{3\alpha}{4}}\, \nu_{\mathrm{m10}}^{0.45-\frac{3\alpha}{4}}\, T_4^{0.075}\, \sin(i)^{1/4}\, F^{3/4}}$$

$$F = \frac{4.41}{q_\tau (\alpha - 2)(\alpha + 0.1)}$$

$$q_\tau = \frac{2.1(1 + \epsilon + q_{\mathrm{T}})}{\alpha - 2}$$

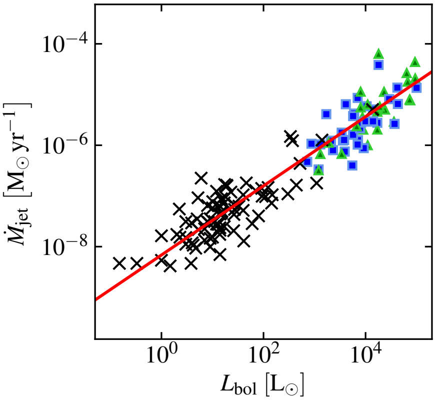



Optical depth
Intensity (Jy pixel^{-1})
0.1 GHz
0.1 GHz
-0.3
-0.2
-0.1
0.0
0.1
0.2
0.3
Δy [″]
0.0
Δx [″]
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}

Jet mass loss rate vs. bolometric luminosity

$$3 \times 10^{-7} \leq \dot{M}_{\rm jet} \leq 6 \times 10^{-5}\,{\rm M_\odot\,yr^{-1}}$$
$$\tilde{\dot{M}}_{\rm jet} = 3 \times 10^{-6}\,{\rm M_\odot\,yr^{-1}}$$
$$\bar{\dot{M}}_{\rm jet} = 6 \times 10^{-6}\,{\rm M_\odot\,yr^{-1}}$$

$$\dot{M}_{\rm jet}^{\rm lm} \propto L_{\rm bol}{}^{0.60\pm0.10}$$
$$\dot{M}_{\rm jet}^{\rm hm} \propto L_{\rm bol}{}^{0.74\pm0.16}$$
$$\dot{M}_{\rm jet}^{\rm all} \propto L_{\rm bol}{}^{0.68\pm0.04}$$



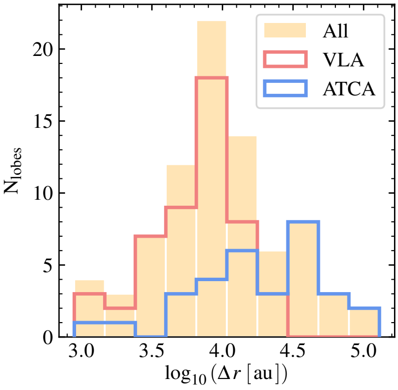
Mass loss rates in jets scale across 6 orders of magnitude in $L_{\rm bol}$

Jets with Lobes

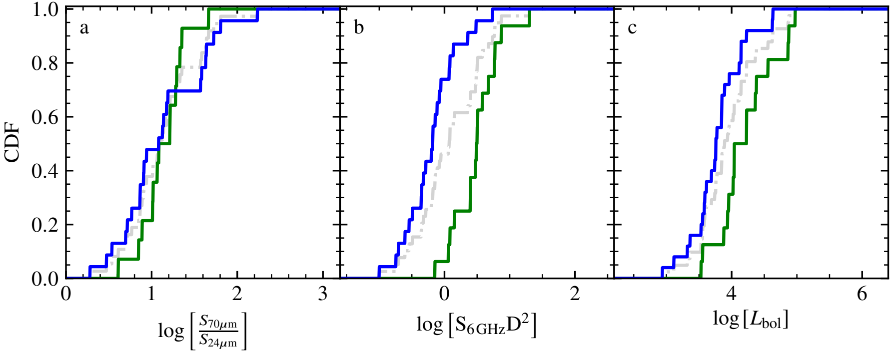
Lobe Separations

Shock-ionised lobes associated with thermal jets:

- Internal or external shocks resulting from variable ejection, or impingement upon surrounding material
- Negative spectral indices:
  1. Optically thin thermal emission ($\alpha \sim -0.1$)
  2. Optically thin non-thermal emission ($\alpha < -0.1$)
- Typical separation of $\sim 10^4$ au



Lobes... A different phenomena?



Different distributions:

- KS test statistic 0.253, 0.635, 0.555
- p-values of 0.500, <0.001, 0.003

Why?

- Evolutionary phase?
- Evidence for episodic accretion?
- Simply a sensitivity issue?

Non-Thermal Emission

Synchrotron Emission

$$N_e(E) \propto E^p$$

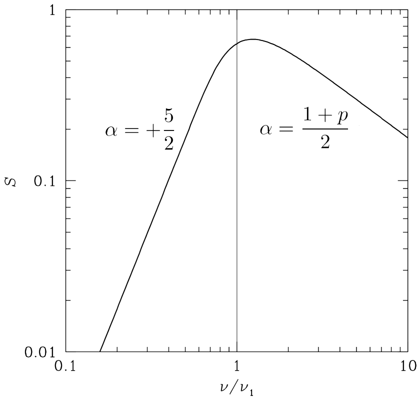
$$j_\nu \propto B^{\frac{1-p}{2}} \nu^{\frac{1+p}{2}}$$

$$S_\nu \propto \nu^\alpha$$

$$\Rightarrow \alpha = \frac{1+p}{2}$$

For head-on shocks, diffusive shock acceleration (1st order Fermi acceleration) produces $p \leq -2$ (Bell, 1978):

$$\Rightarrow \boxed{\alpha \leq -0.5}$$



Credit: NRAO

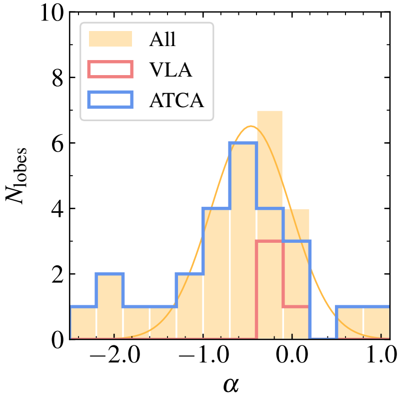
Shocked Emission

Means for spectral index:

$$\bar{\alpha}_{\mathrm{ATCA}} = -0.55 \pm 0.18$$
$$\bar{\alpha}_{\mathrm{VLA}} = -0.16 \pm 0.07$$
$$\bar{\alpha}_{\mathrm{All}} = -0.48 \pm 0.16$$

Assuming a normal distribution of lobe spectral indices:

$$\Rightarrow \boxed{\bar{\alpha}_{\mathrm{All}} = -0.46 \pm 0.08}$$



Purser et al. (in prep)

Summary

- Jets launched at the end of the MYSO phase, existing for $\sim 7 \times 10^4$ yr
- Radio luminosities and jet mass loss rates scale in the same way as for low-mass examples

Disc-based accretion processes form high-mass stars

- $\sim 40\%$ of jets are associated to non-thermal emission
- $\bar{\alpha}_{\rm lobe} \sim -0.5/p \sim -2 \longrightarrow$ typical of 1$^{\rm st}$ order Fermi acceleration at shocks (Bell, 1978)
- B-fields are present in the flow, as per magneto-centrifugal launching mechanisms

Non-thermal lobes are shock sites capable of accelerating particles to relativistic energies which emit synchrotron radiation due to acceleration by the jet's magnetic field.

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Questions

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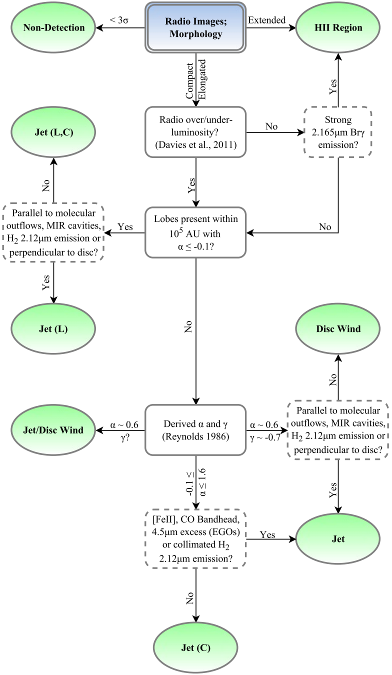
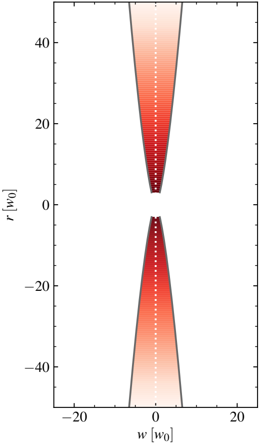

Radio Images; Morphology
< 3σ
Non-Detection
Extended
HII Region
Compact
Elongated
Radio over/under-luminosity? (Davies et al., 2011)
No
Strong 2.165μm Brγ emission?
Yes
No
Yes
Lobes present within 10^5 AU with α ≤ -0.1?
Yes
Parallel to molecular outflows, MIR cavities, H_2 2.12μm emission or perpendicular to disc?
No
Jet (L,C)
Yes
Jet (L)
No
Derived α and γ (Reynolds 1986)
α ~ 0.6
γ?
Jet/Disc Wind
α ~ 0.6
γ ~ -0.7
Parallel to molecular outflows, MIR cavities, H_2 2.12μm emission or perpendicular to disc?
No
Disc Wind
Yes
Jet
-0.1 ≤
α ≤ 1.6
[FeII], CO Bandhead, 4.5μm excess (EGOs) or collimated H_2 2.12μm emission?
Yes
No
Jet (C)

Jet mass loss rate *(Reynolds, 1986)*

$$\dot{M}_{\rm jet} = \frac{5.24 \times 10^{-6}\, S_{\rm mJy}^{3/4}\, d_{\rm kpc}^{3/2}\, \theta_{\rm OA}^{3/4}}{\nu_{10}^{\frac{3\alpha}{4}}\, \nu_{\rm m10}^{0.45-\frac{3\alpha}{4}}\, F^{3/4}}$$

Case	α	ϵ	$q_{\rm T}$
Standard Collimated	< 0.4	$2/3$	0
Standard Spherical	$0.4 - 0.8$	1	0
Recombining Conical	> 0.8	1	$-1/2$



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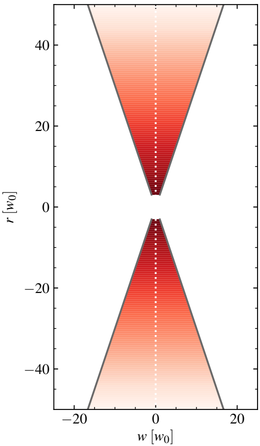

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Case	α	ϵ	$q_{\rm T}$
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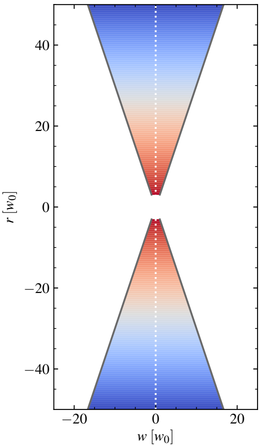
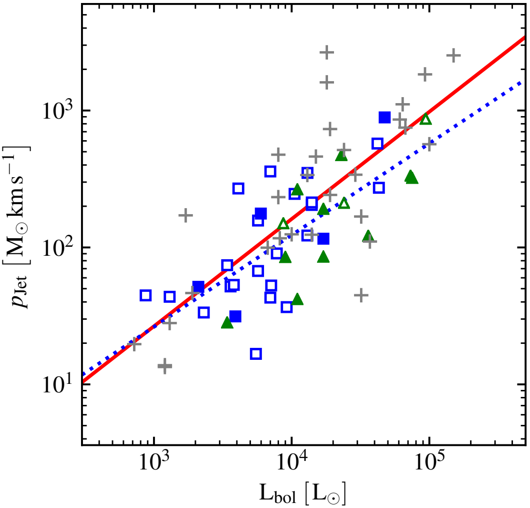
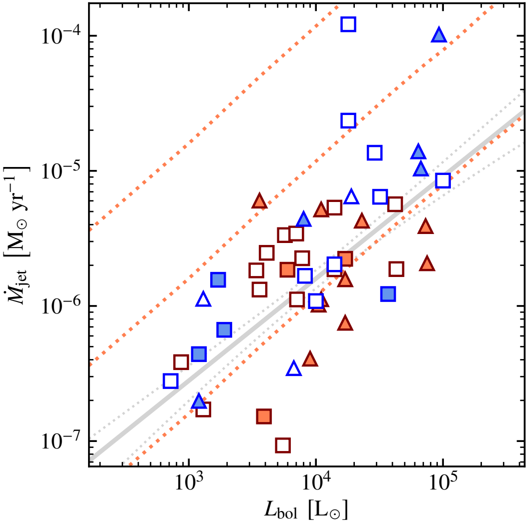



10^3
10^2
10^1
$p_{\rm Jet}\ [\rm M_\odot\,km\,s^{-1}]$
10^3
10^4
10^5
$\rm L_{bol}\ [L_\odot]$


10^{-4}
10^{-5}
10^{-6}
10^{-7}
$\dot{M}_{\rm jet}$ [$M_\odot$ yr^{-1}]
10^3
10^4
10^5
$L_{\rm bol}$ [$L_\odot$]