# <span id="page-0-0"></span>3D mapping of the ejecta of SN1987A from ALMA data

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### SN1987A exploded on 23 February 1987, at a distance of 51.4 kpc



## It was a core-collapse supernova, but with a blue supergiant progenitor



## After the explosion, preexisting rings of circumstellar material were discovered



#### The distance to SN1987A allows its expanding ejecta to be spatially resolved



## The 3D distribution and velocities of the material within the ejecta are predictions of explosion models



We have analysed ALMA observations of the remnant tracing CO 2-1 (230GHz) and 6-5 (691GHz), and SiO 5-4 (217GHz) and 6-5 (260GHz),  $\sim$ 10,000 -  $\sim$  12,000 days after the explosion



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The data cubes have a spatial resolution of 0.06 arcsec (3000 AU), and velocity resolutions of 100 or 300 km/s



To calculate the 3D distribution of these molecules, we first mask out data below a noise threshold estimated from regions beyond the equatorial ring



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CO 2-1

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### SiO 6-5



SiO 5-4



SiO 6-5

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SiO 5-4

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#### We then calculate the radial mass distribution for each molecule



Table: Stellar models

Name	Type	mass	$E_{\text{expl}}$	$\beta$ -decay	sim. time	Ref.
		[ $M_{\odot}]$	$[10^{51}$ erg]		[d]	
$B15_{without}$	<b>BSG</b>	15	1.39	no $\beta$ -decay	361	Woosley et al. 1998
<b>B15</b>	<b>BSG</b>	15	1.39	without tracer	361	Woosley et al. 1998
B15x	<b>BSG</b>	15	1.39	including tracer X	358	Woosley et al. 1998
<b>N20</b>	<b>BSG</b>	20	1.65	without tracer	362	Shigeyama et al. 1990
L15	<b>RSG</b>	15	1.75	without tracer	321	Limongi et al. 2000
W15	<b>RSG</b>	15	1.47	without tracer	373	Woosley et al. 1995

 $10^{-1}$ **R15**  $10^{-1}$ R15 (without)  $10^{-1}$ **B15X**  $0.02 - 1$  $CO<sub>2-1</sub>$  $CO 2-1$  $CO<sub>6-5</sub>$  $CO<sub>6-5</sub>$  $CO 6 - 5$  $10^{-2}$  $10^{-2}$  $10^{-7}$  $M/M_{tot}$ M/M<sub>tot</sub>  $10^{-3}$  $10^{-3}$  $10^{-5}$  $10^{-4}$  $10^{-4}$  $10^{-4}$ ไก่เรื่อง **Sudan**  $10^{-5}$  $10^{-}$  $10<sup>10</sup>$ 1000 2000 3000 4000 5000 6000 ó 1000 2000 3000 4000 5000 6000  $\frac{1}{2}$ 1000 2000 3000 4000 5000 6000  $V_r$  (km/s)  $V_r$  (km/s)  $V_r$  (km/s)  $\overline{u}$  $10^{-1}$  $10^{-1}$ N20  $10^{-1}$  $W15$  $CO<sub>2-1</sub>$  $CO 2-1$  $CO 2-1$ **Carpenter**  $CO<sub>6-5</sub>$  $CO<sub>6-5</sub>$  $CO 6-5$  $10^{-2}$  $10^{-2}$  $10^{-2}$ M/M<sub>tot</sub> W/M<sub>tt</sub>  $10^{-3}$  $10^{-3}$  $10^{-3}$  $10^{-4}$  $10^{-4}$  $10^{-4}$  $10^{-5}$  $10^{\circ}$ 10  $\overline{0}$ 1000 2000 3000 4000 5000 6000  $\ddot{\mathbf{0}}$ 1000 2000 3000 4000 5000 6000  $\ddot{o}$ 1000 2000 3000 4000 5000 6000  $V_r$  (km/s)  $V_r$  (km/s)  $V_r$  ( $km/s$ )

 $CO + 10054$  days

 $SiO + 10054$  days





SiO +11216/11855 days

#### B15 models can be brought into somewhat better agreement with  $1.5\times$  higher velocities.

**R15 B15** (without) **B15X**  $10^{-1}$  $10^{-1}$  $10^{-7}$  $0.02 - 1$  $CO<sub>2-1</sub>$  $CO 2-1$  $CO<sub>6-5</sub>$  $CO<sub>6-5</sub>$  $CO 6 - 5$  $10^{-7}$  $10^{-2}$  $10^{-7}$  $M/M_{tot}$ **MIMo**  $10^{-3}$  $10^{-3}$  $10^{-3}$  $10^{-4}$  $10^{-4}$  $10^{-4}$  $10^{-5}$  $10^{-}$  $10<sup>10</sup>$ 1000 2000 3000 4000 5000 6000 1000 2000 3000 4000 5000 6000  $\frac{1}{2}$ 1000 2000 3000 4000 5000 6000  $V_r$  (km/s)  $V_r$  (km/s)  $V_r$  (km/s)  $10^{-1}$  $L15$  $10^{-1}$ N20  $10^{-1}$  $W15$  $CO 2-1$  $CO 2-1$  $CO 2-1$ **Committe**  $CO<sub>6-5</sub>$  $CO<sub>6-5</sub>$  $CO 6-5$  $10^{-2}$  $10^{-2}$  $10^{-7}$ **M/M<sub>tot</sub>** WIM,  $10^{-3}$  $10^{-3}$  $10^{-3}$ š  $10^{-4}$  $10^{-4}$  $10^{-4}$  $10^{-5}$ 10<sup>-</sup> 10  $\overline{0}$ 1000 2000 3000 4000 5000 6000  $\ddot{\mathbf{0}}$ 1000 2000 3000 4000 5000 6000  $\ddot{o}$ 1000 2000 3000 4000 5000 6000  $V_r$  (km/s)  $V_r$  (km/s)  $V_r$  (km/s)

CO +10054 days, predicted velocities scaled by 1.5x

#### B15 models can be brought into somewhat better agreement with  $1.5\times$  higher velocities.

SiO +10054 days predicted velocities scaled by 1.5x

 $---$  R15X  $10^{-1}$  $\overline{\phantom{a}}$  $10^{-1}$  $10^{-7}$  $SiO<sub>5-4</sub>$  $-$  sio 5-4  $SiO<sub>6-5</sub>$  $SiO<sub>6-5</sub>$  $10^{-7}$  $10^{-2}$  $10^{-7}$  $M/M_{tot}$  $\sum_{x=1}^{10} 10^{-3}$  $10^{-3}$  $10^{-3}$  $10^{-4}$  $10^{-4}$ R15 (without)  $10^{-4}$  $SiO<sub>5-4</sub>$  $sin 6.5$  $10^{-5}$  $10^{-1}$  $10<sup>10</sup>$ 1000 2000 3000 4000 5000 6000  $\overline{a}$ 1000  $2000$ 3000 4000 5000 6000  $\frac{1}{2}$ 1000 2000 3000 4000 5000 6000  $V_r$  (km/s)  $V_r$  (km/s)  $V_r$  (km/s)  $10^{-1}$  $10^{-1}$  $--$  W<sub>15</sub>  $10^{-1}$  $N20$  $-$  SiO 5-4 مخص  $-$  SiO 5-4 SiQ 6-5  $-$  SiO 6-5 **STAND**  $10^{-2}$  $10^{-2}$  $10^{-2}$ M/M<sub>tot</sub> W/M<sub>tt</sub> Wilwi  $10^{-3}$  $10^{-3}$  $10^{-1}$  $10^{-4}$  $10^{-4}$  $-- 115$  $10^{-4}$  $-$  SiO 5-4  $-$  SiO 6-5  $10^{-5}$  $10<sup>7</sup>$ 10  $\ddot{\mathbf{0}}$ 1000 2000 3000 4000 5000 6000  $\ddot{\mathbf{0}}$ 1000 2000 3000 4000 5000 6000  $\ddot{o}$ 1000 2000 3000 4000 5000 6000  $V_r$  (km/s)  $V_r$  (km/s)  $V_r$  (km/s)

#### B15 models can be brought into somewhat better agreement with  $1.5\times$  higher velocities.

SiO +11216/11855 days predicted velocities scaled by 1.5x



#### **Summary**

- From ALMA observations of the remnant of SN1987A, We have determined the 3D distribution of CO 2-1 and 6-5 transitions, and SiO 5-4 and 6-5 transitions
- We calculate the fractional mass distribution against velocity for each transition and compare it to the predictions of state of the art simulations
- None of the models provides a good match to the observations "out of the box".
- However, B15 models can be brought into somewhat better agreement by scaling velocities by 1.5×, while N20, L15 and W15 models still disagree.
- This would imply a rather implausible increase of the explosion energy by  $\times 2$

### Postscript: I travelled here overland from the UK



- CO<sub>2</sub> emissions from return flight Cardiff to Chania: 0.96t
- CO<sup>2</sup> emissions from trains, buses and ferries: 96% less, only **42kg**!

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