Masers

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What is a maser?

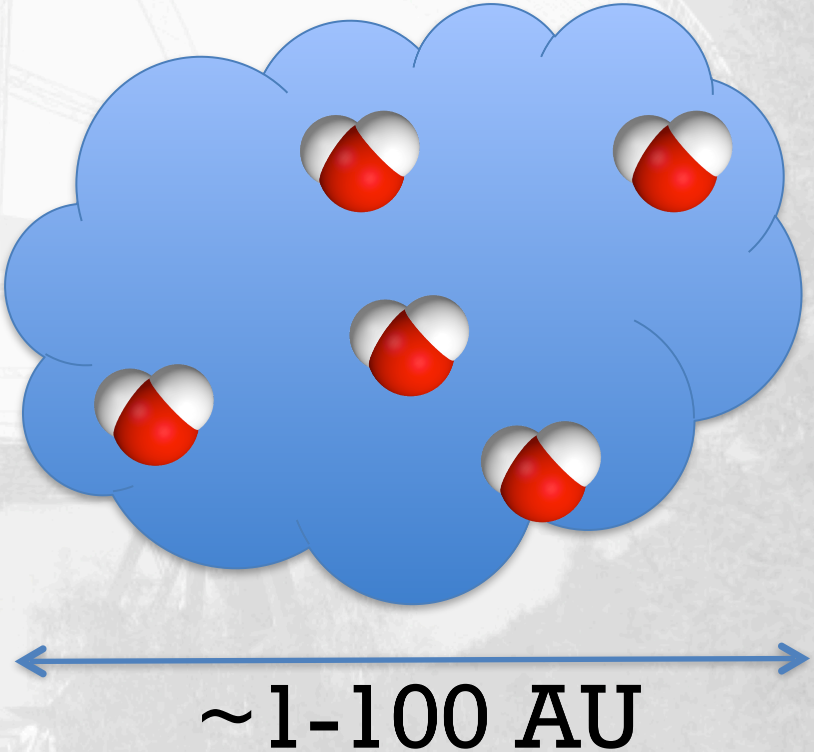
What is a maser?

Essentially, a cloud of molecular gas

With "population inversion"

Full list of known astrophysical masers (from WikiPedia)
But many are quite rare and not discussed further

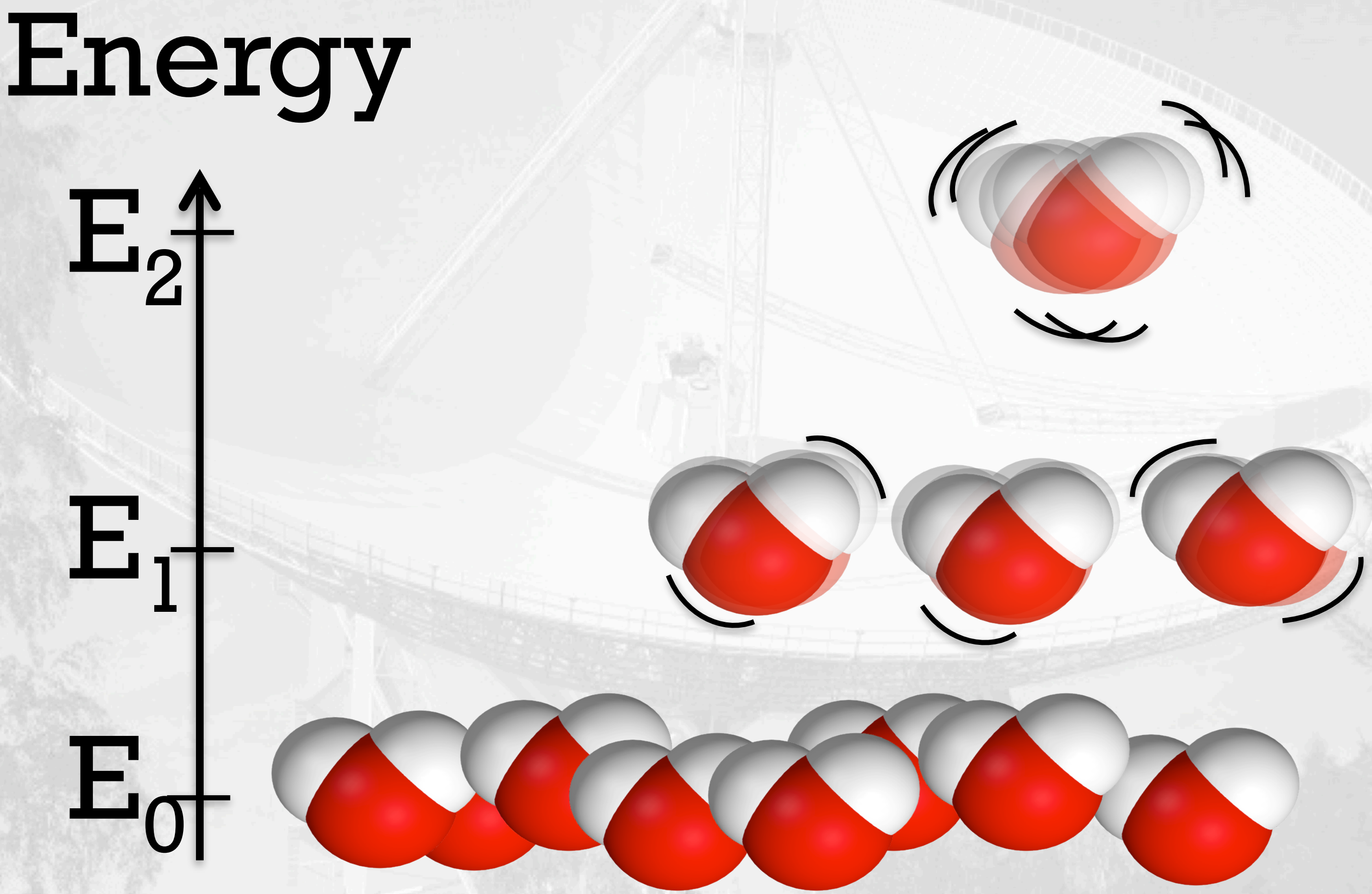
OH	CH_3OH	^{30}SiO
CH	HNCNH	HCN,
H_2CO	SiS	$H^{13}CN$
H_2O	HC_3N	H
NH_3,	SiO,	CS
$^{15}NH_3$	^{29}SiO,	



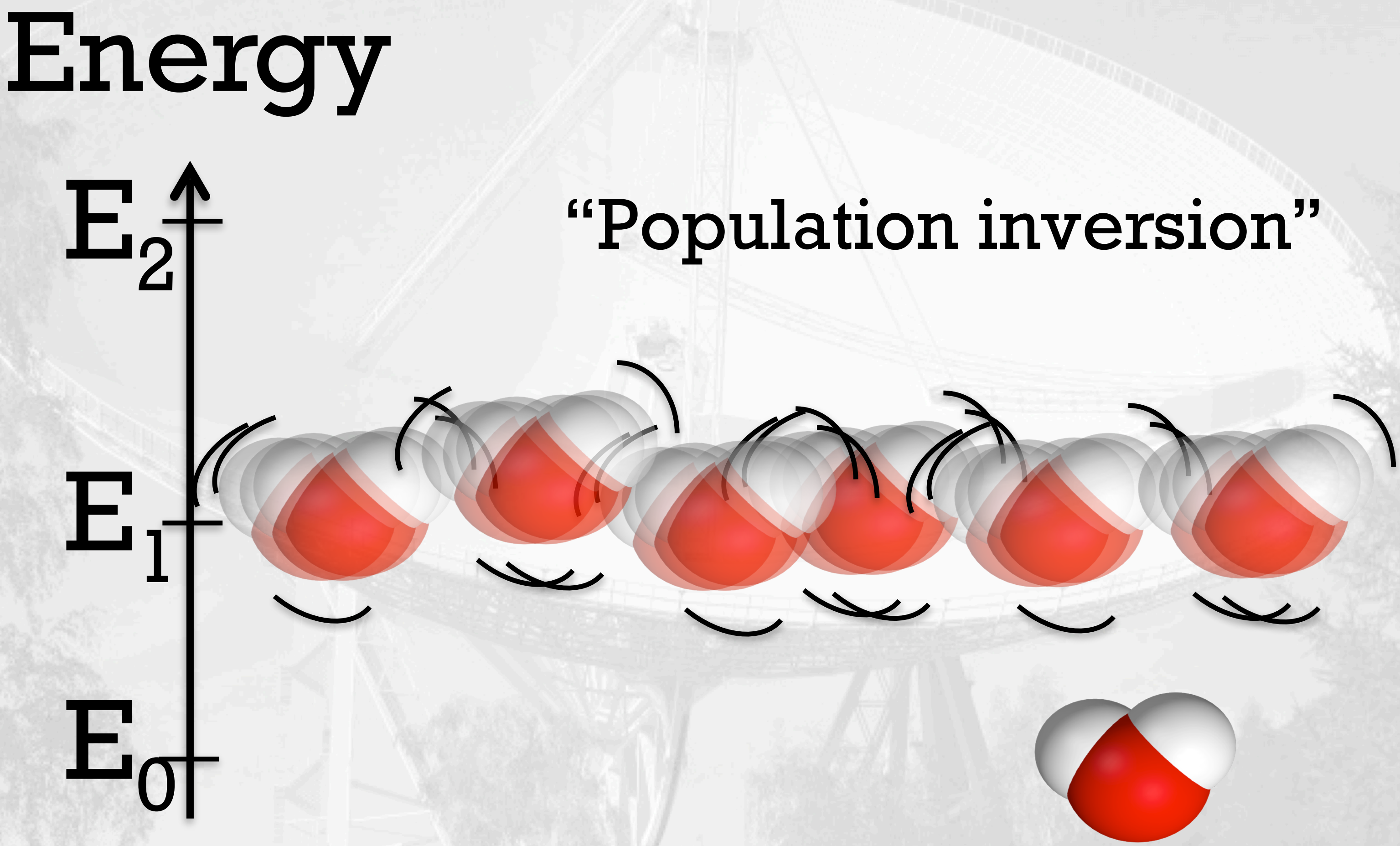
Molecules that <u>commonly</u> produce masers (in astrophysical contexts):
OH, CH_3OH, H_2O, SiO

Excited molecules

Boltzmann “Thermal” distribution



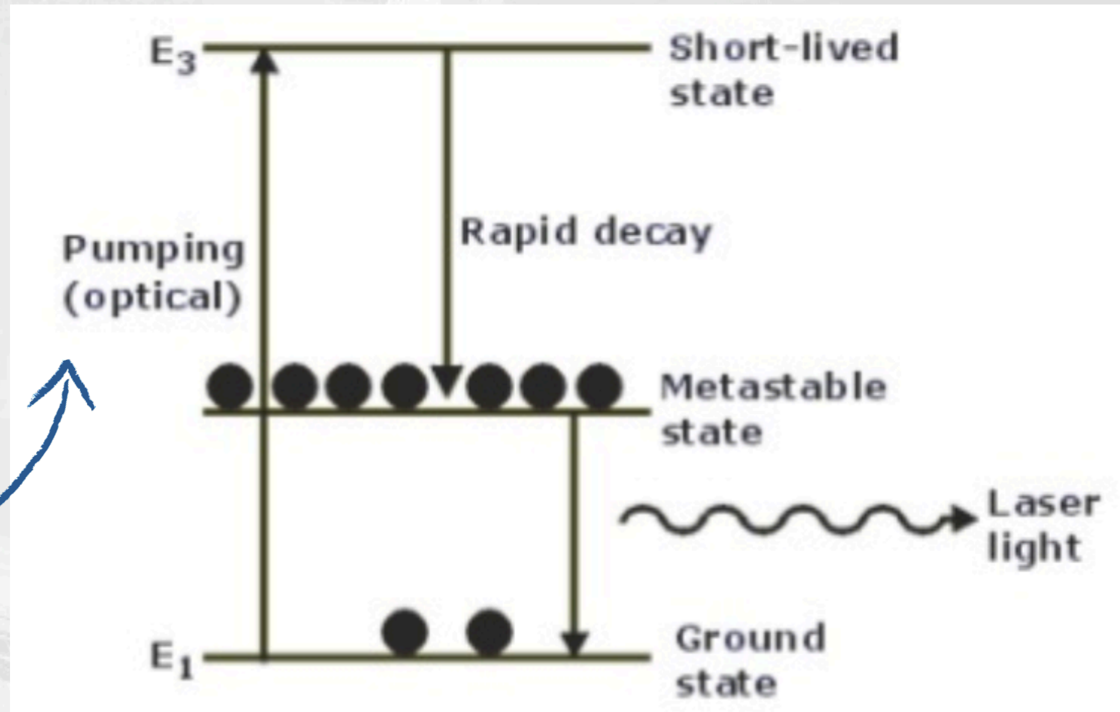
Excited molecules



Population inversion, how?

Energy input:

- Radiation
- Collisions



<u>Very important</u>: Incoming photon of $E=h\nu$ will stimulate emission of a photon of $h\nu$ – production of many photons of the same frequency.

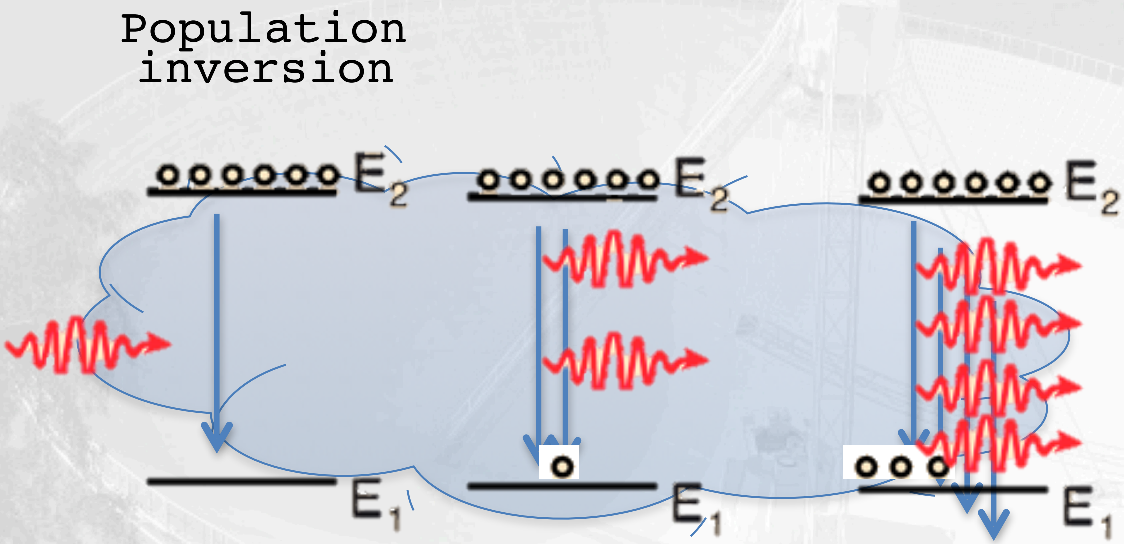
➔ Need velocity coherence for ampl. <u>Turbulent cloud is no good</u>

➔ Spectrum is a bright, narrow spike

What determines maser brightness?

1.1 Path length

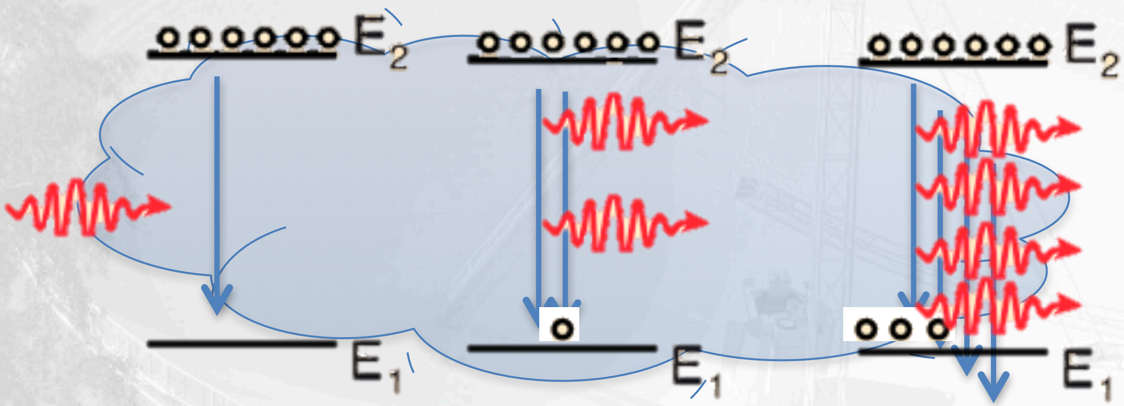
Masers in space



Common masers:
OH, CH_3OH, H_2O, SiO

Masers in space

Stimulated emission



Common masers:

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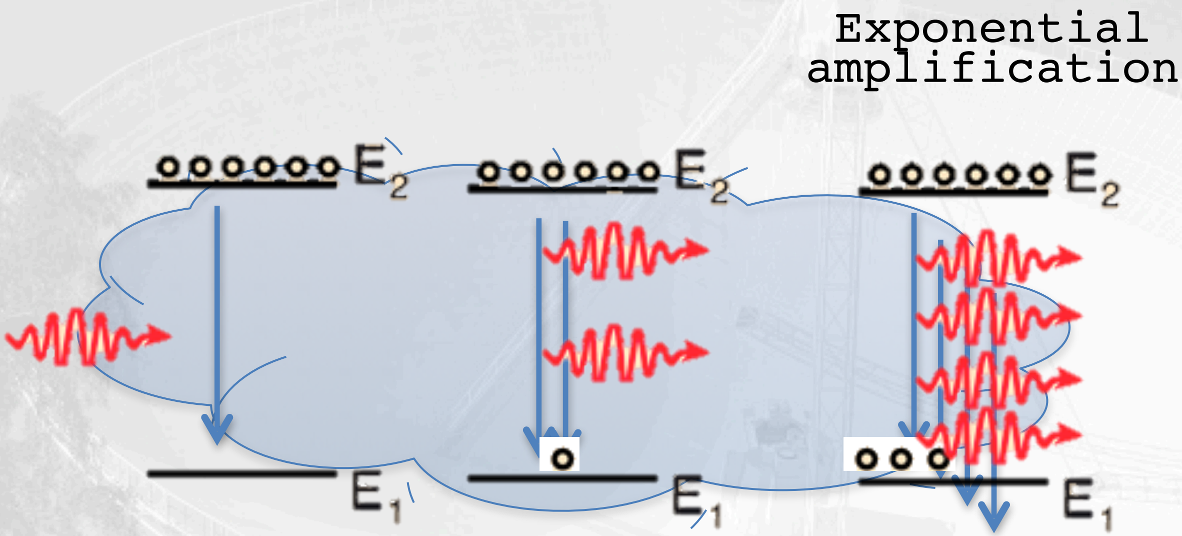
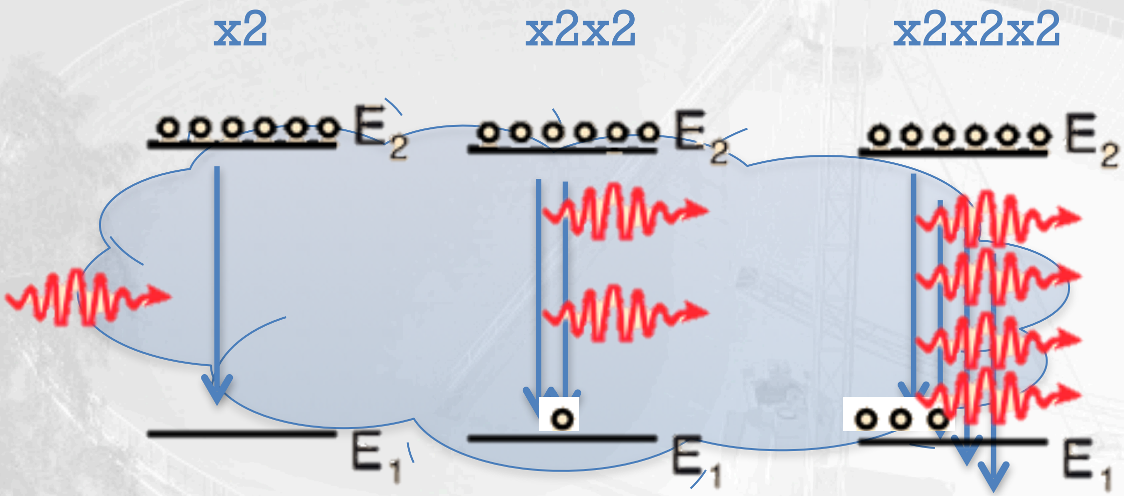
Masers in space



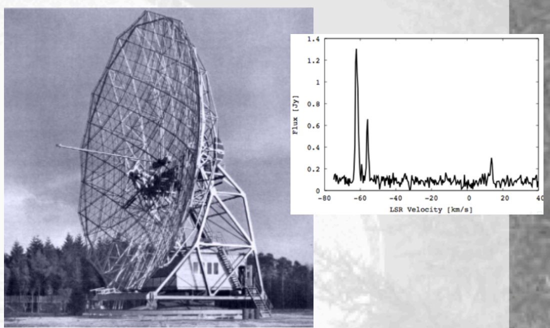
Common masers:
OH, CH_3OH, H_2O, SiO

- Amplification α e $^{\text{path length}}$

Masers in space



Observer



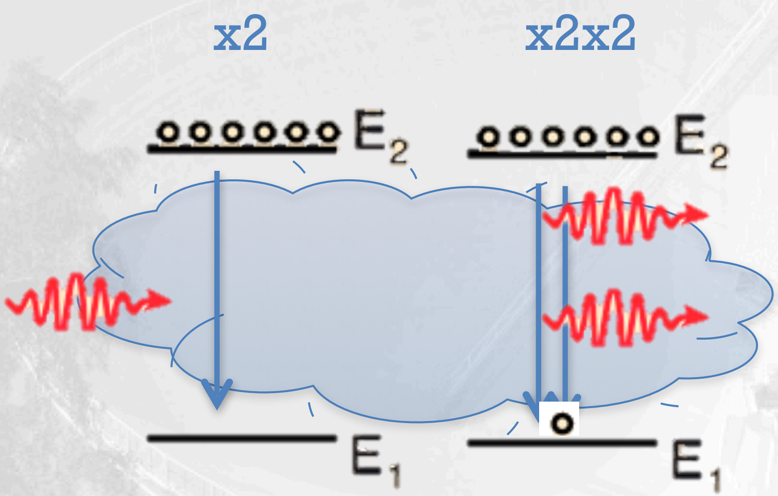
If the orientation of the maser is **long** in the line-of-sight of the observer then there will be **many** instances of stimulated emission and **exponential amplification**

Common masers:
OH, CH_3OH, H_2O, SiO

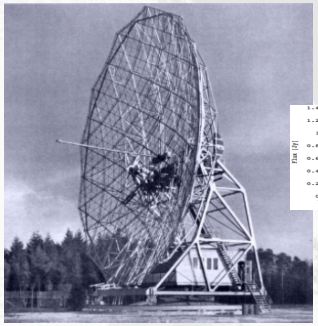
Therefore a **bright** maser will be observed

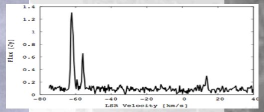
- Amplification α $e^{\text{path length}}$

Masers in space



Observer





If the orientation of the maser is **short** in the line-of-sight of the observer then there will be **few** instances of stimulated emission and **exponential amplification**

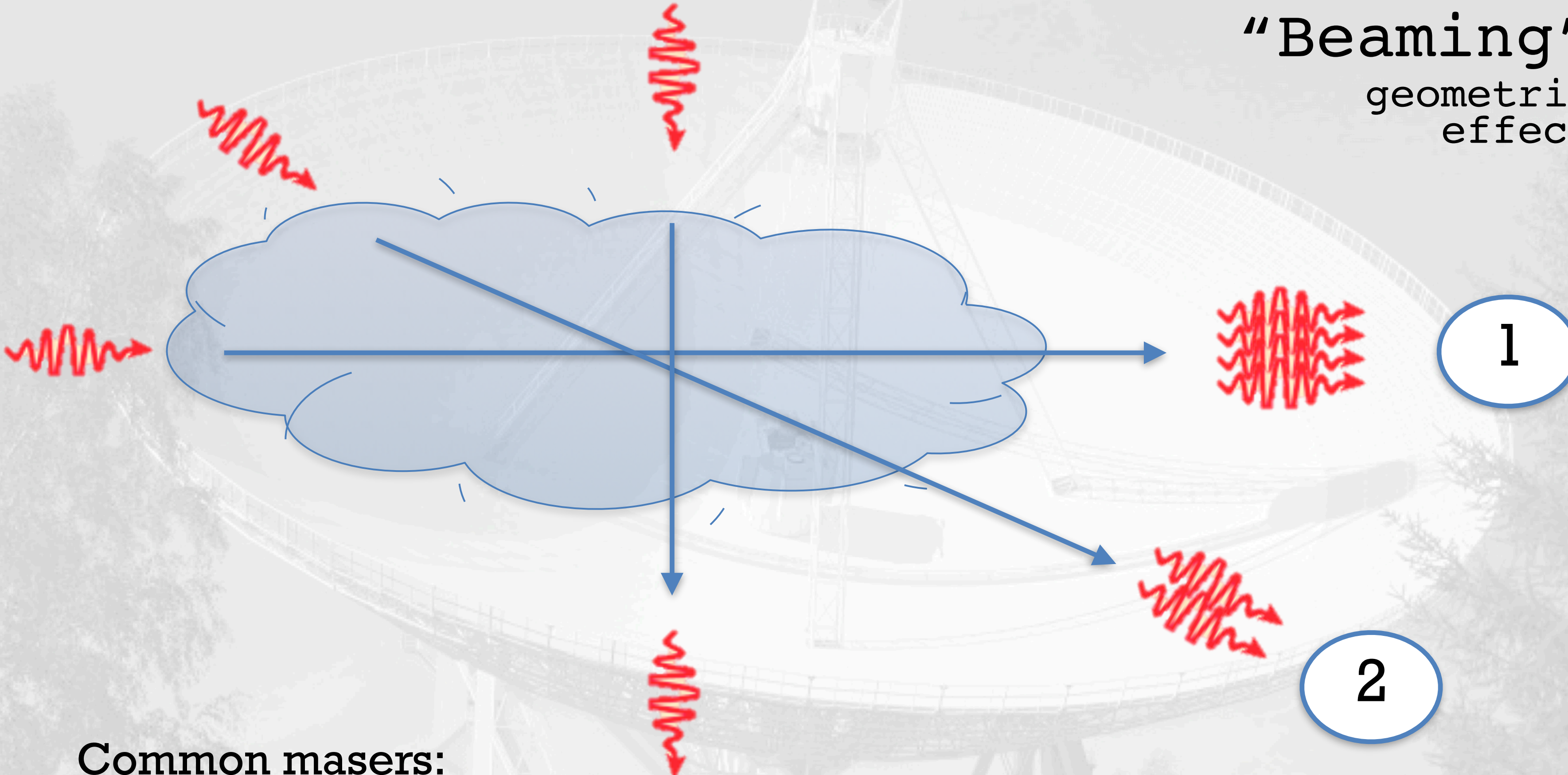
Therefore a **weak** maser will be observed

Common masers:
OH, CH_3OH, H_2O, SiO

- Amplification α $e^{\text{path length}}$

Viewing angles

"Beaming"
geometric
effect

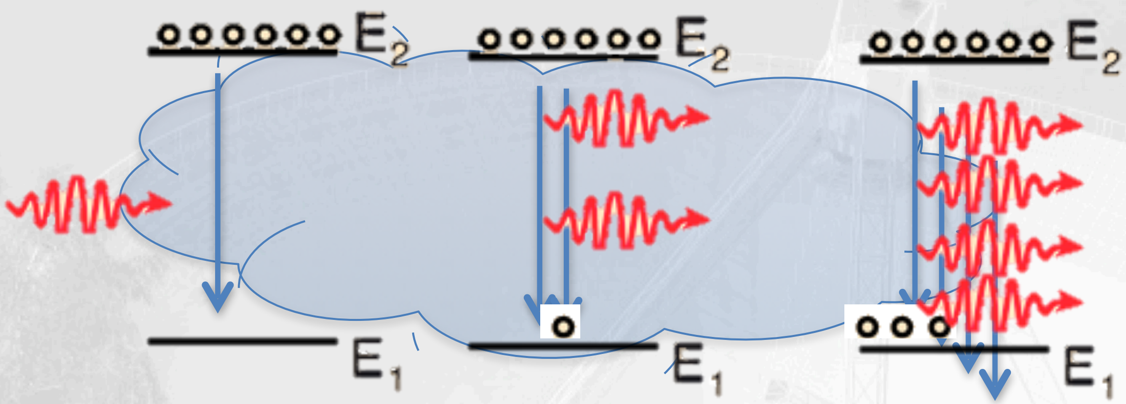


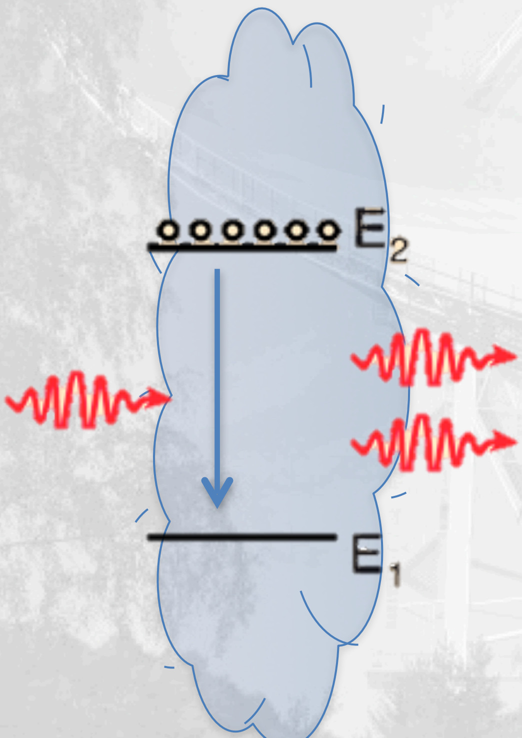
Common masers:
OH, CH_3OH, H_2O, SiO

- Amplification $\propto e^{\text{path length}}$

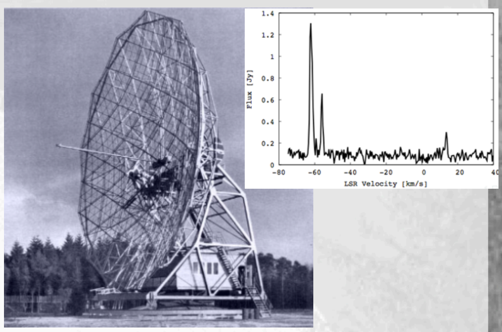
Consider the maser brightness observed from the following perspectives:
1 - bright
2 - moderate
3 - weak

Another example

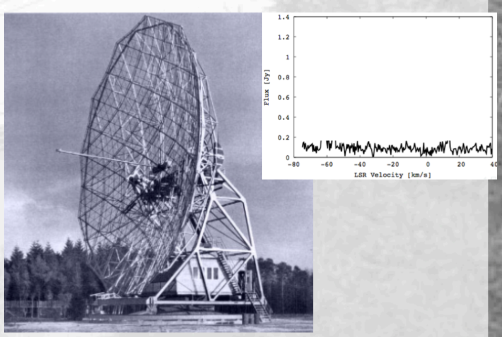




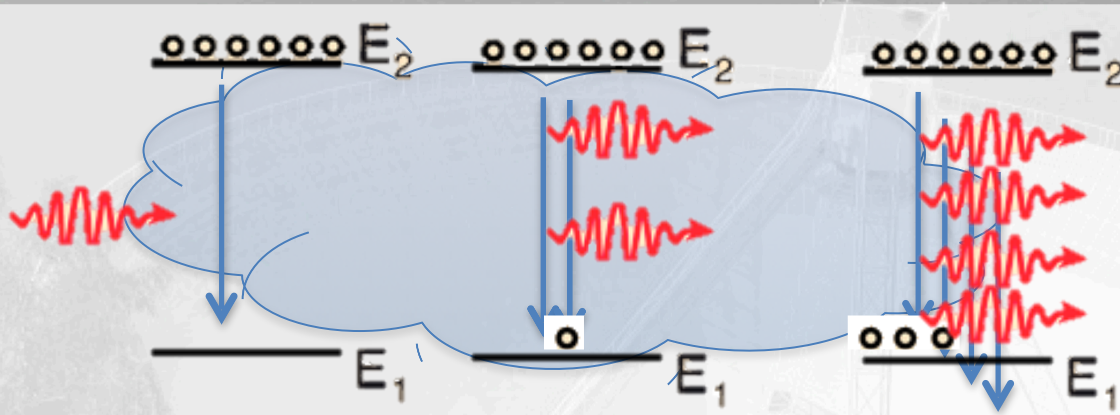
Observer 1



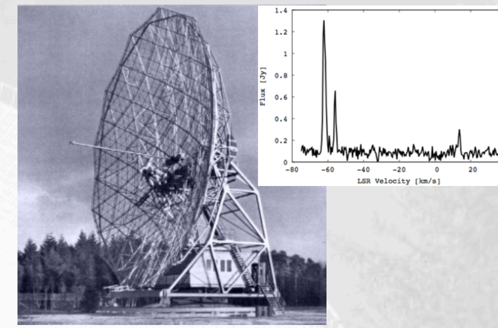
Observer 2

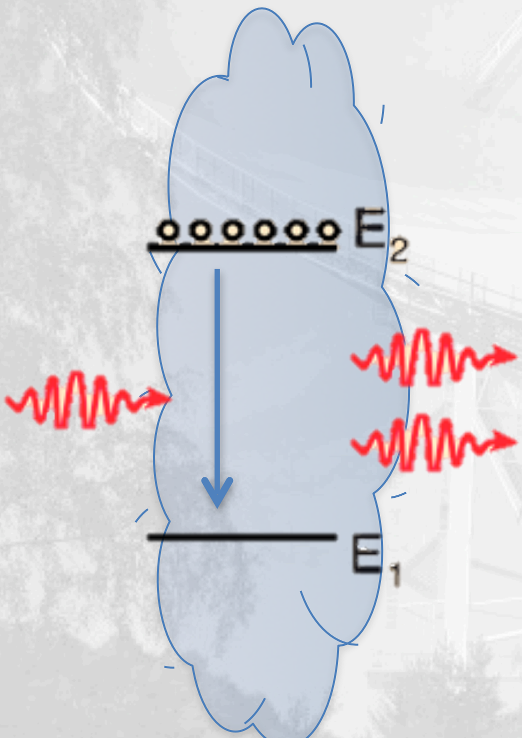


Another example



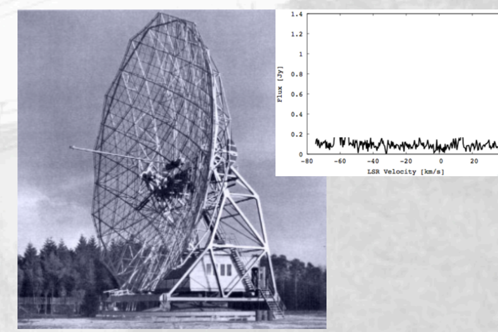
Observer 1





Despite the two masers being the same length Observer 1 sees much brighter maser emission than Observer 2

Observer 2



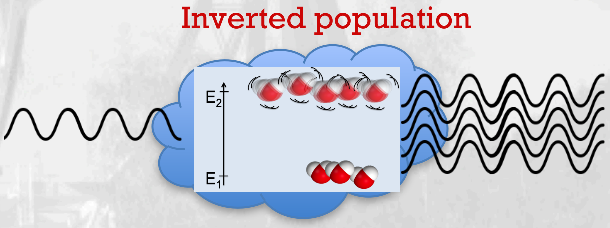
Longer path length leads to brighter masers

Discuss: LASERS

- What is the acronym for LASER?
- How does a LASER work?
- What is its energy source?
- What determines its colour?

- What is the difference between a LASER and a MASER?

(size / natural or manmade / wavelength)

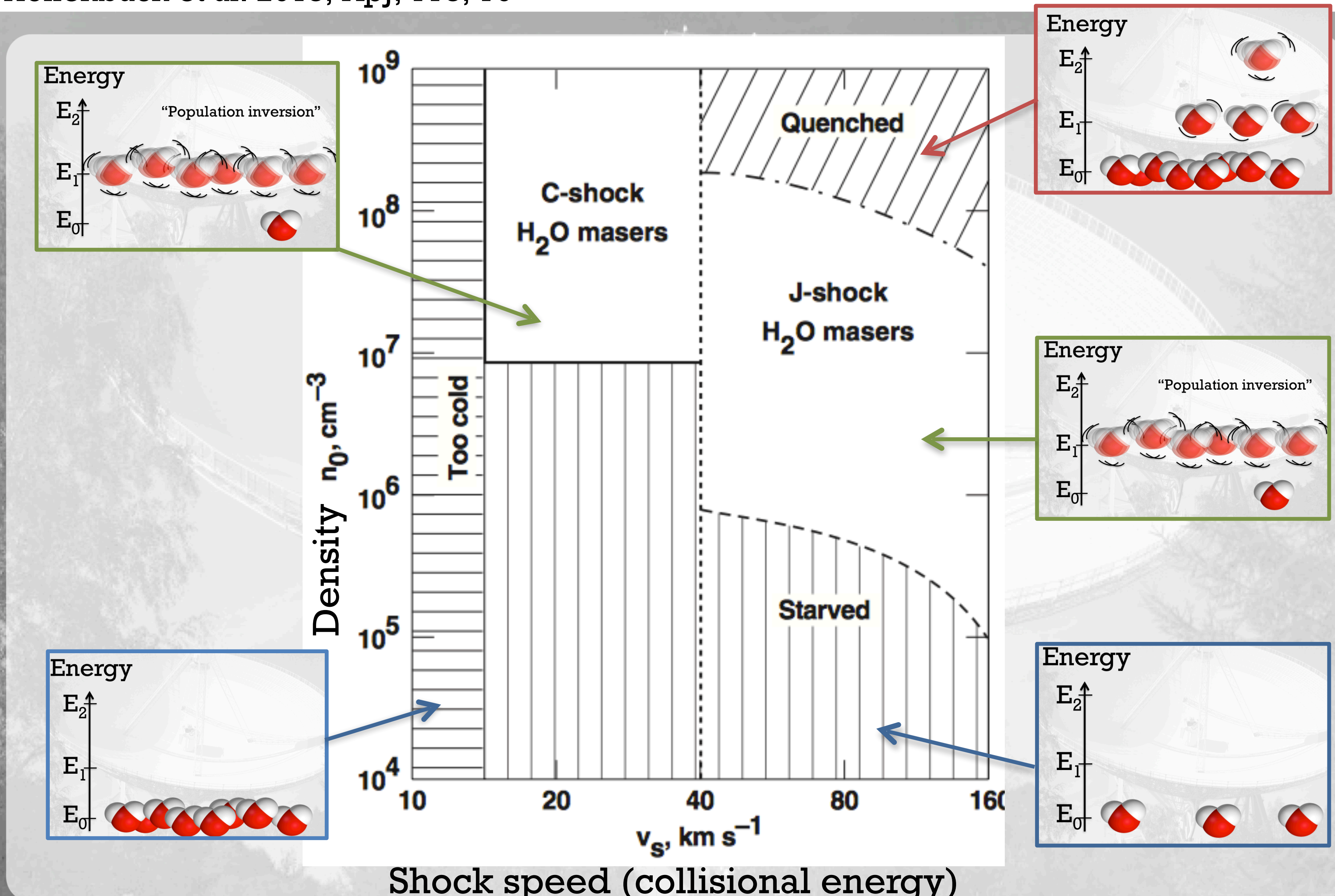


What determines maser brightness?

1.2 Pumping conditions

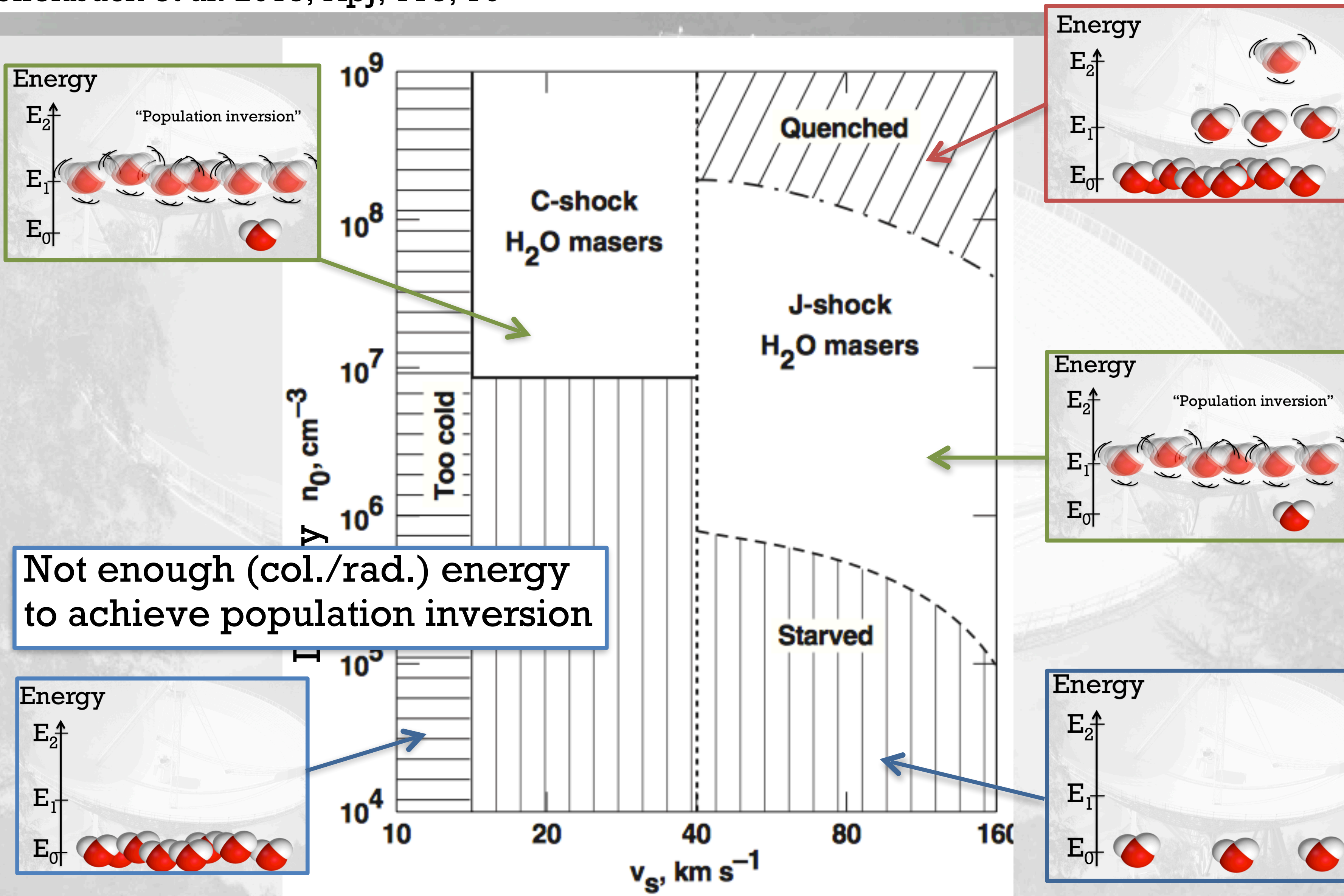
Pumping conditions

Hollenbach et al. 2013, ApJ, 773, 70



Pumping conditions

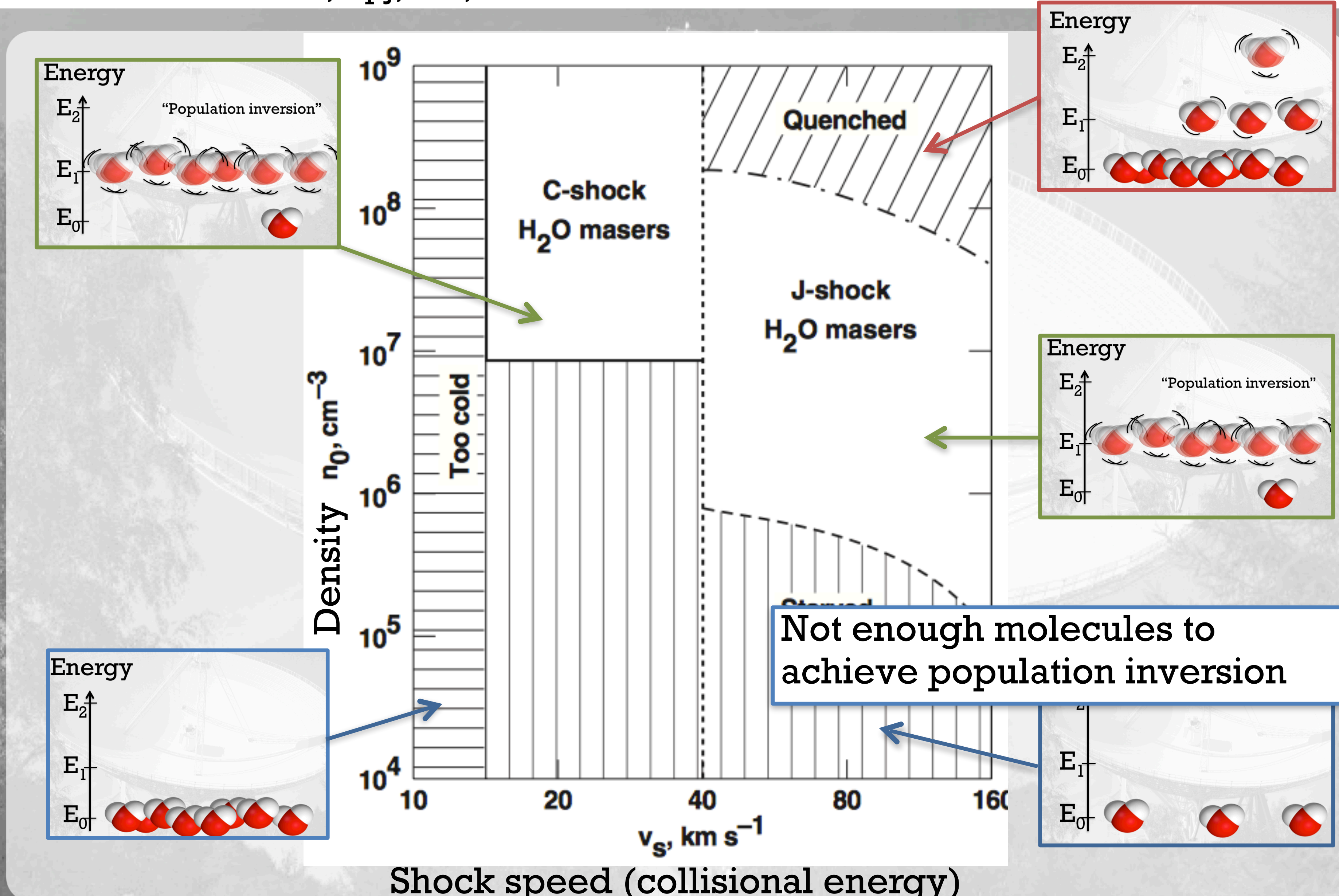
Hollenbach et al. 2013, ApJ, 773, 70



Shock speed (collisional energy)

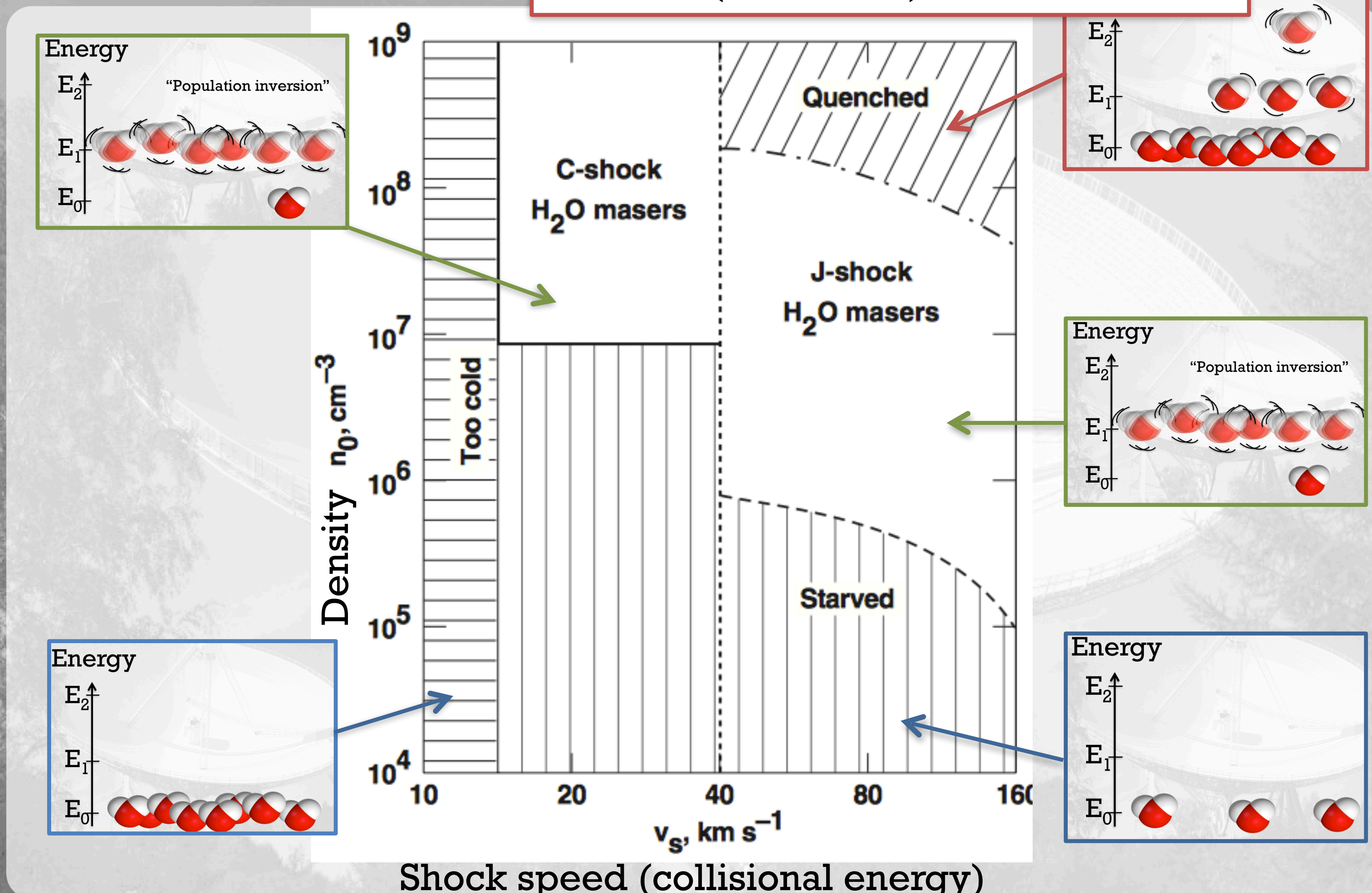
Pumping conditions

Hollenbach et al. 2013, ApJ, 773, 70



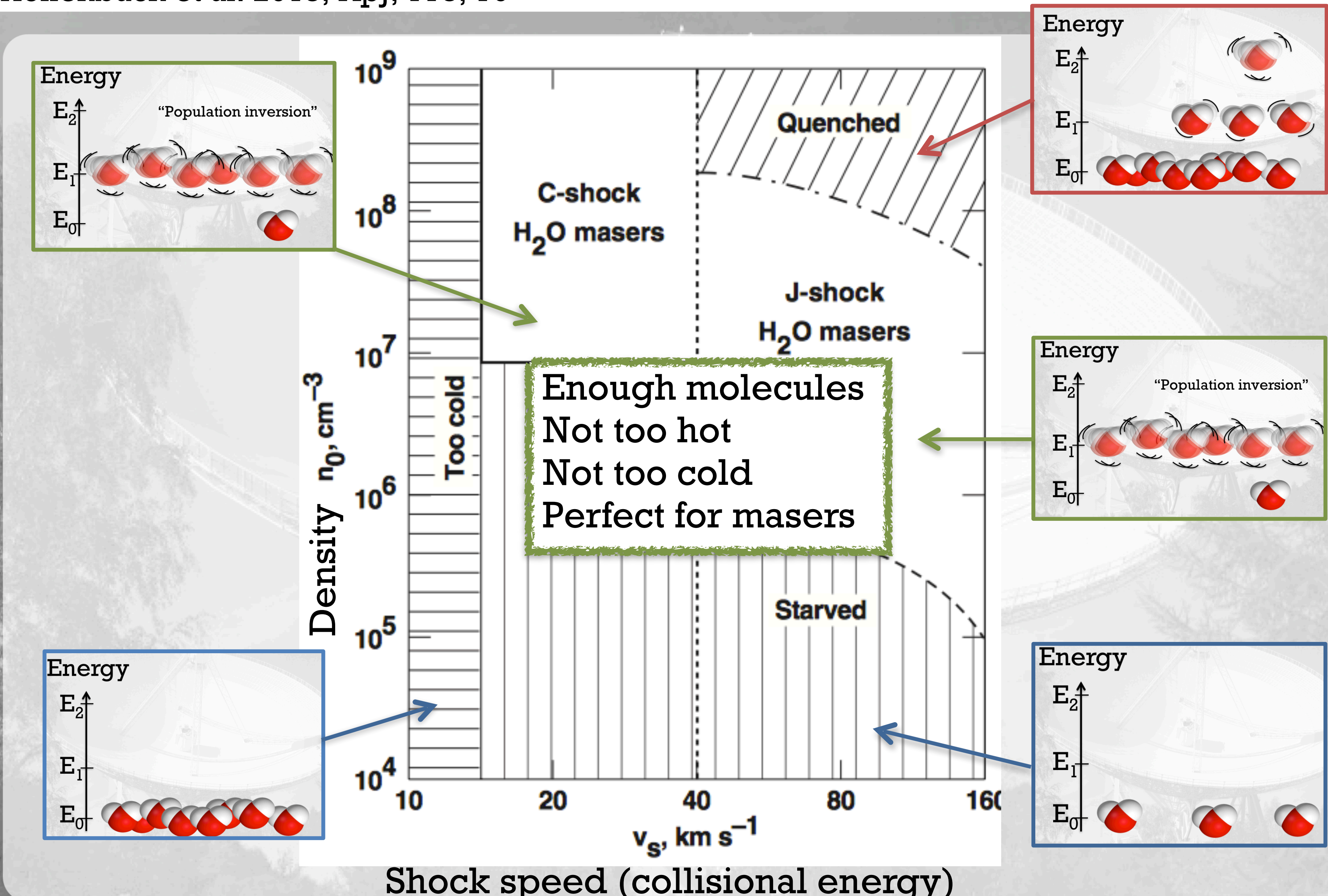
Hollenbach et al. 2013, ApJ, 773, 70

Too much (col./rad.) energy, molecules become ‘thermal’ (Boltzmann) distribution



Pumping conditions

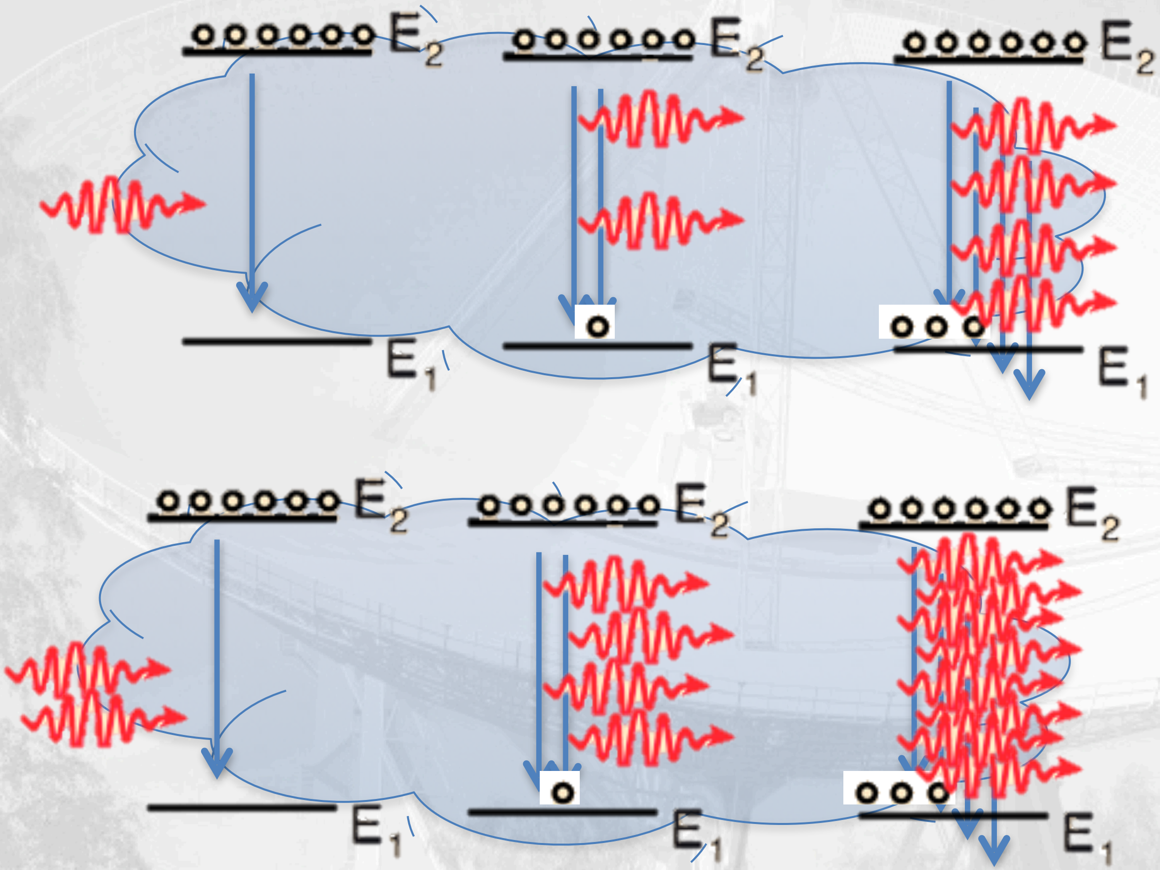
Hollenbach et al. 2013, ApJ, 773, 70



What determines maser brightness?

1.3 Input “Seed” photons

Input "seed" photons

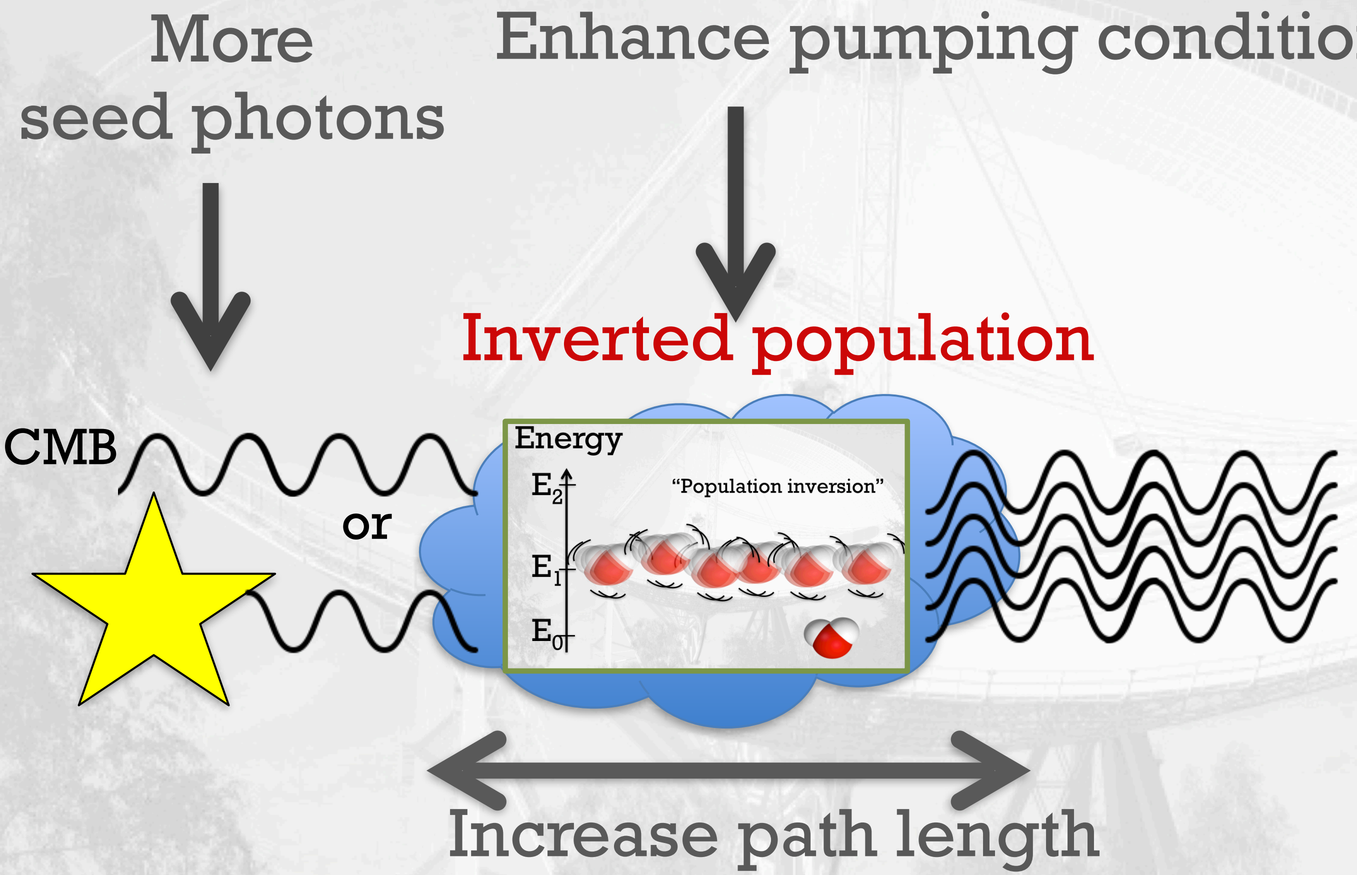


More input "seed" photons leads to more output photons

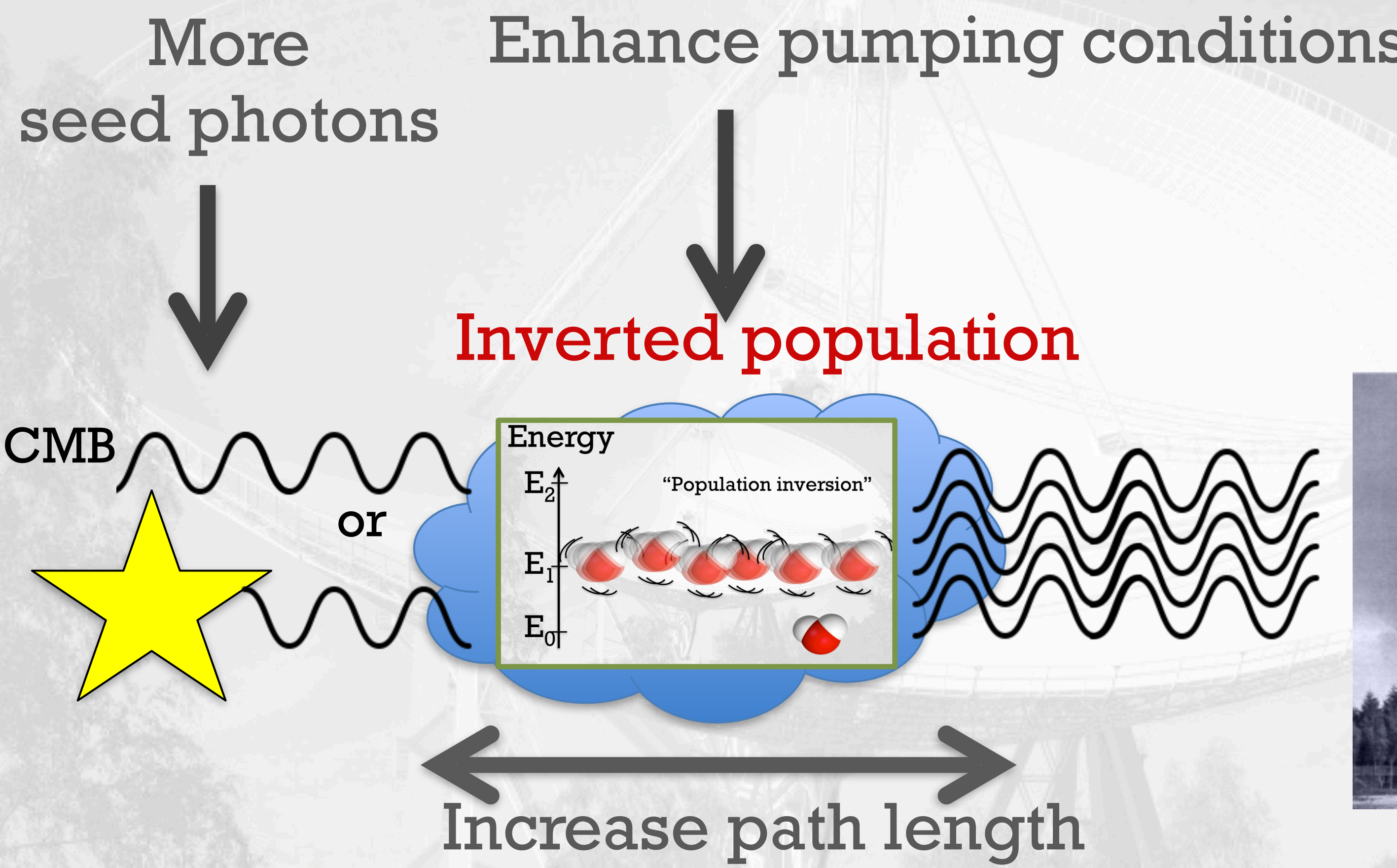
What determines maser brightness?

1.1 Path length
1.2 Pumping conditions
1.3 Seed photons

What determines the maser brightness?



What determines the maser brightness?

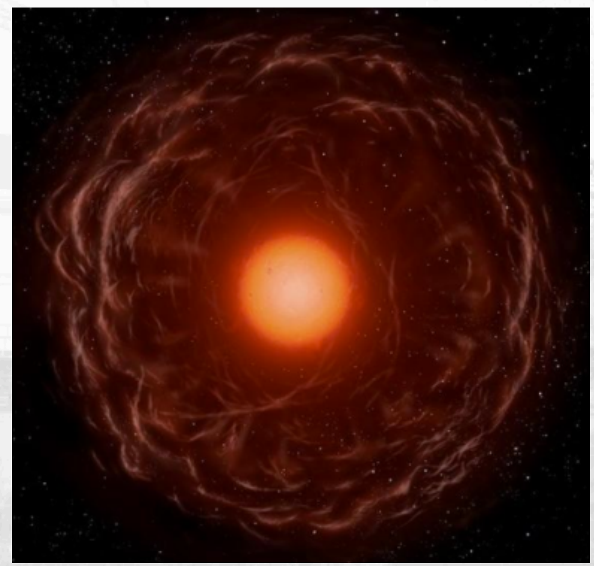


Discuss each of these for a minute with your colleagues to check your understanding

What do masers trace?

Typical environments

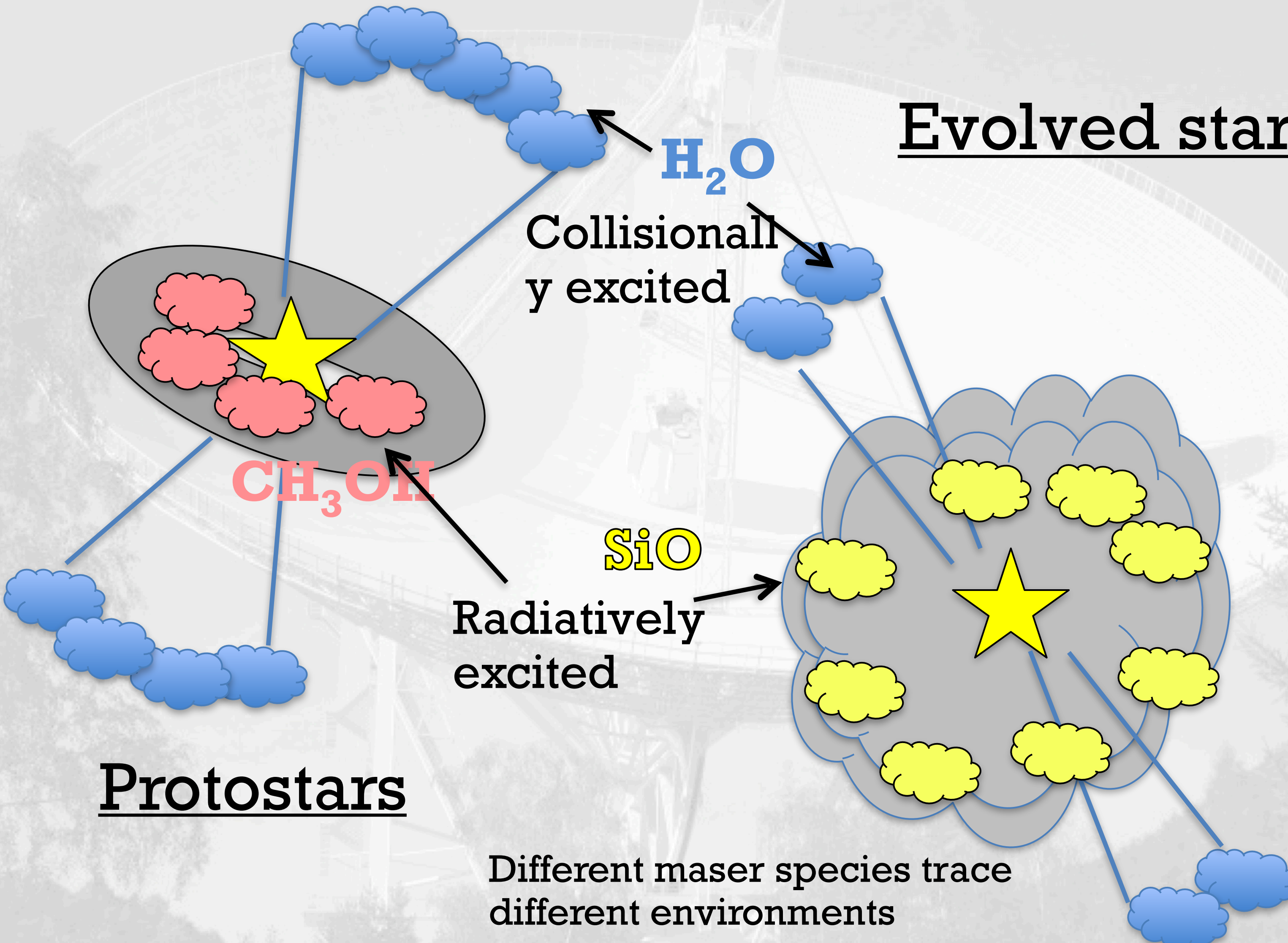
Evolved stars



Protostars

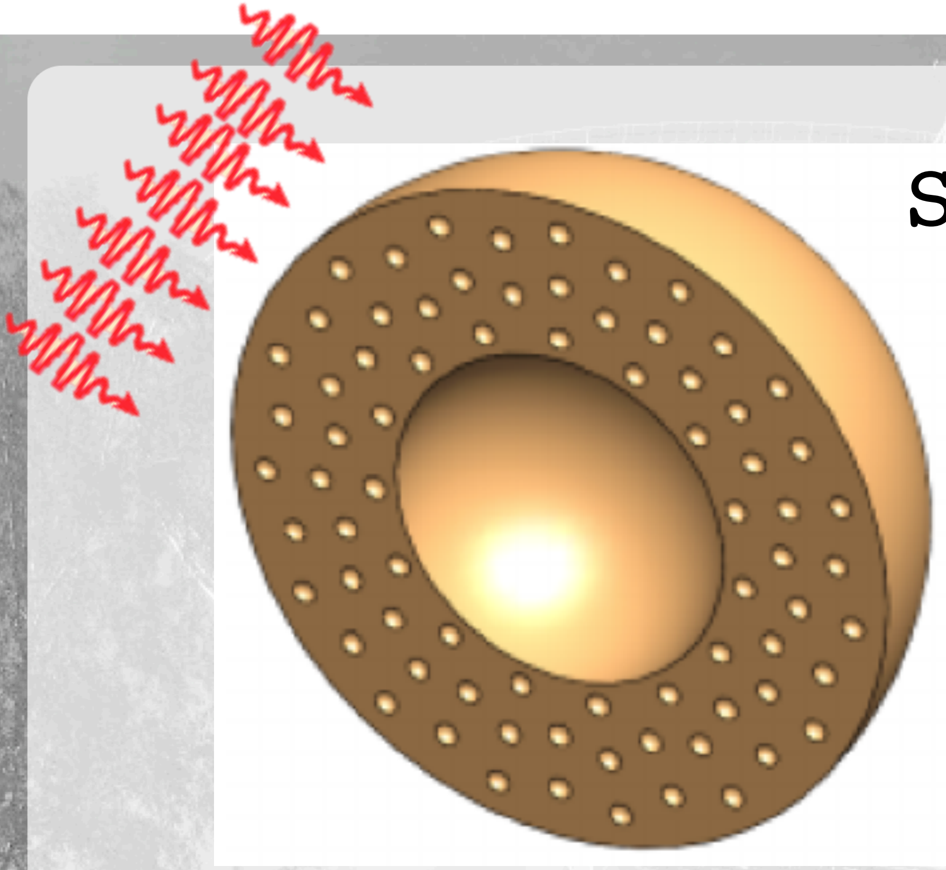
Also: comets, planetary atmospheres, supernova, extragalactic disks

Typical environments



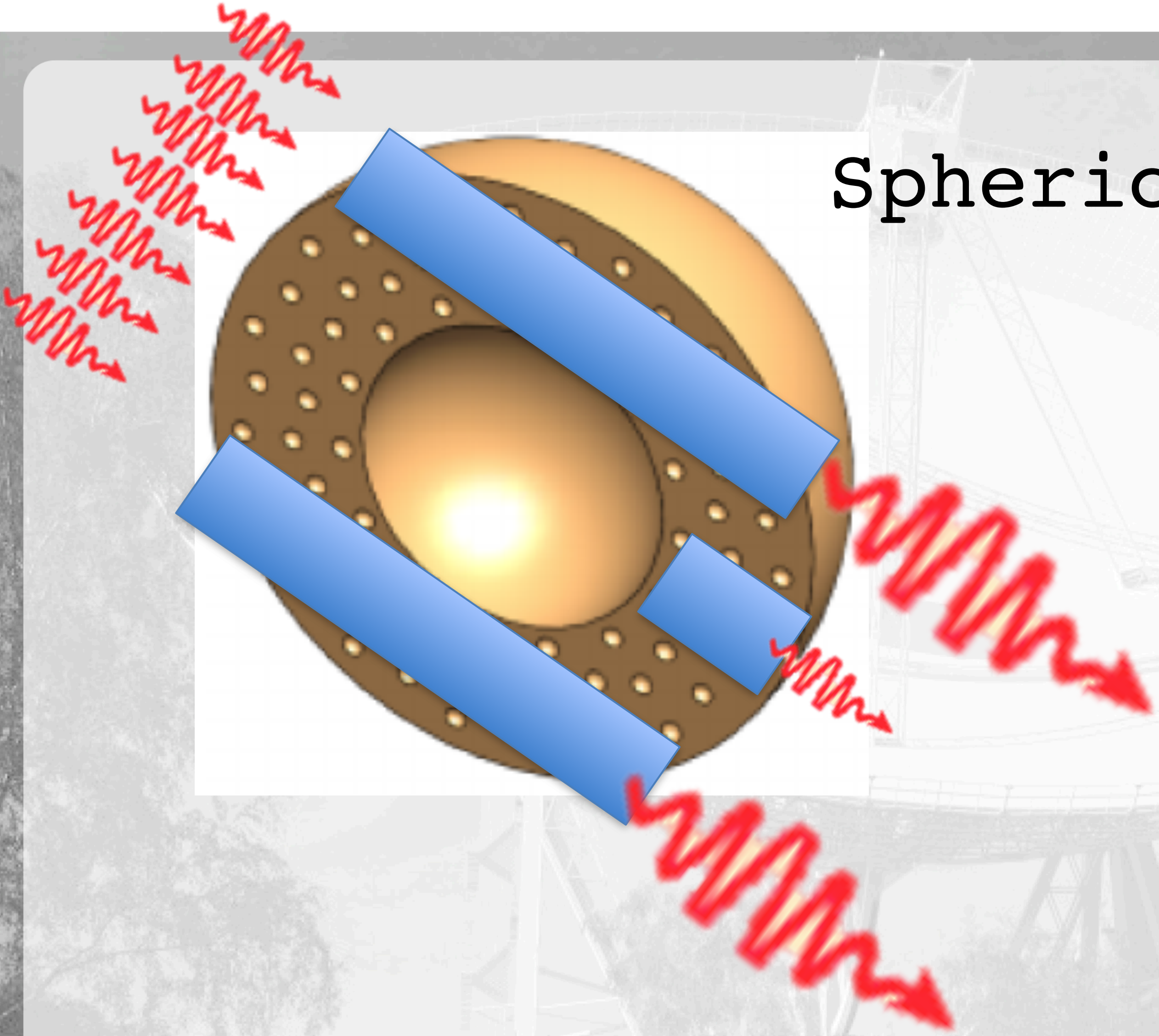
Different maser species trace
different environments

Masers in evolved star shells

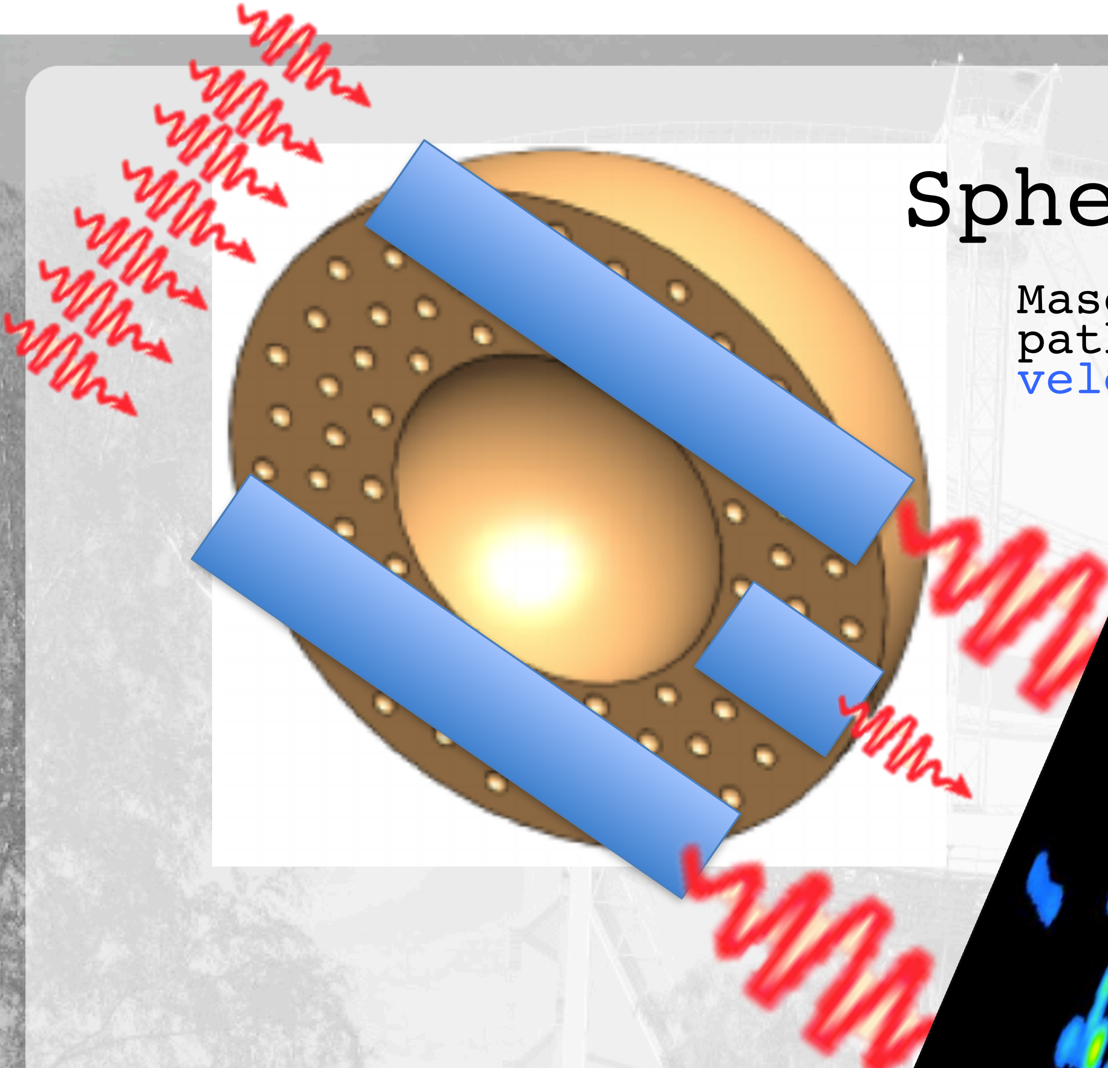


Spherical shell

Masers in evolved star shells

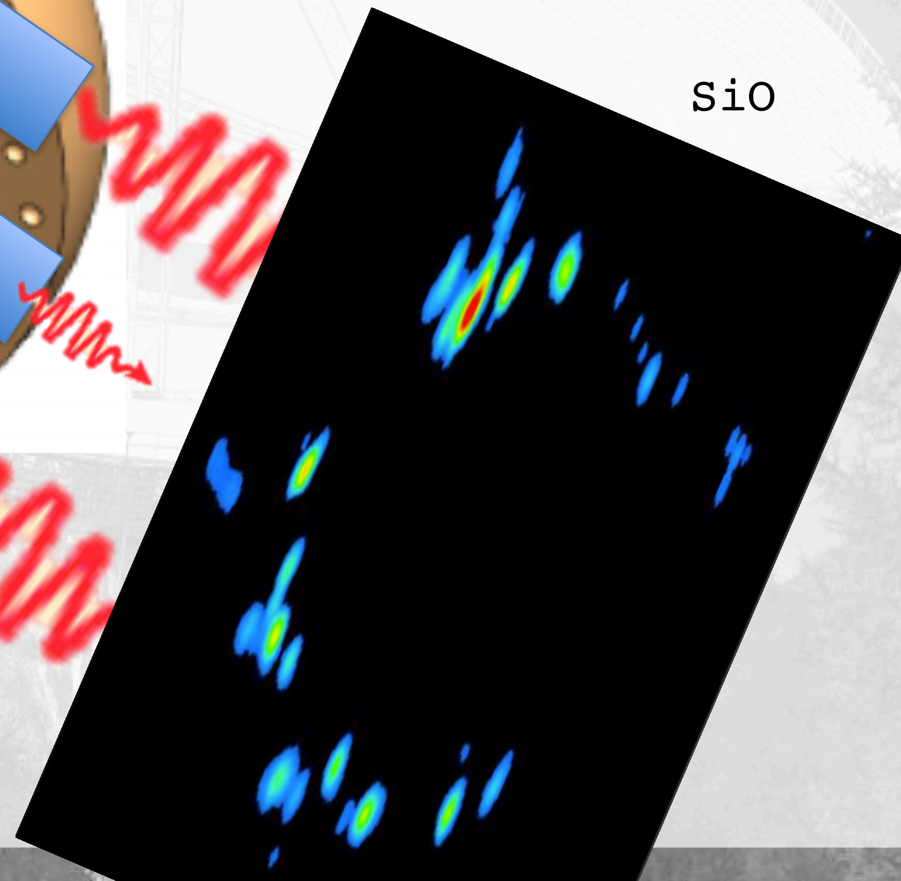


Masers in evolved star shells



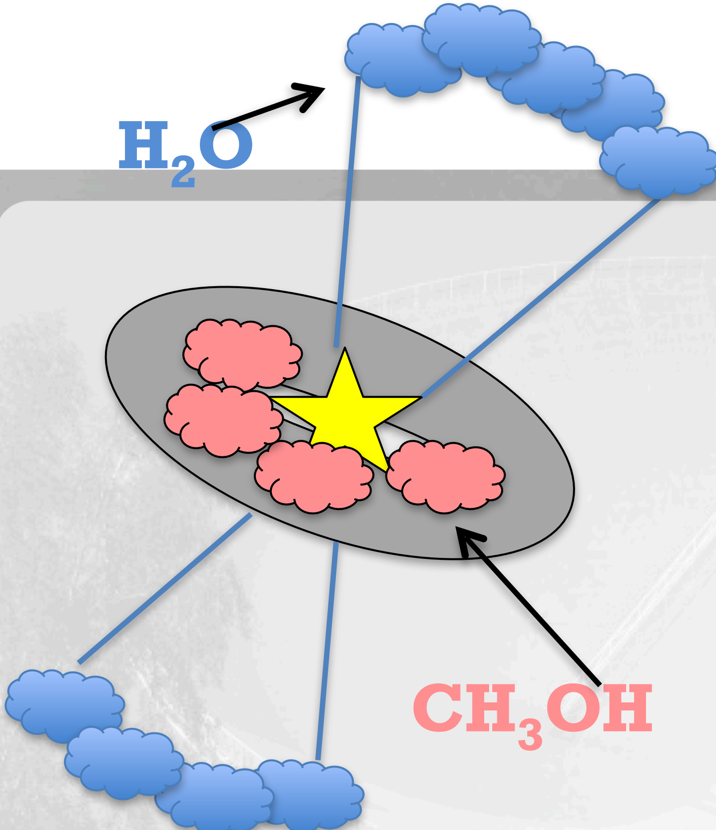
Spherical shell

Masers only seen when the path-length is long and velocity coherent

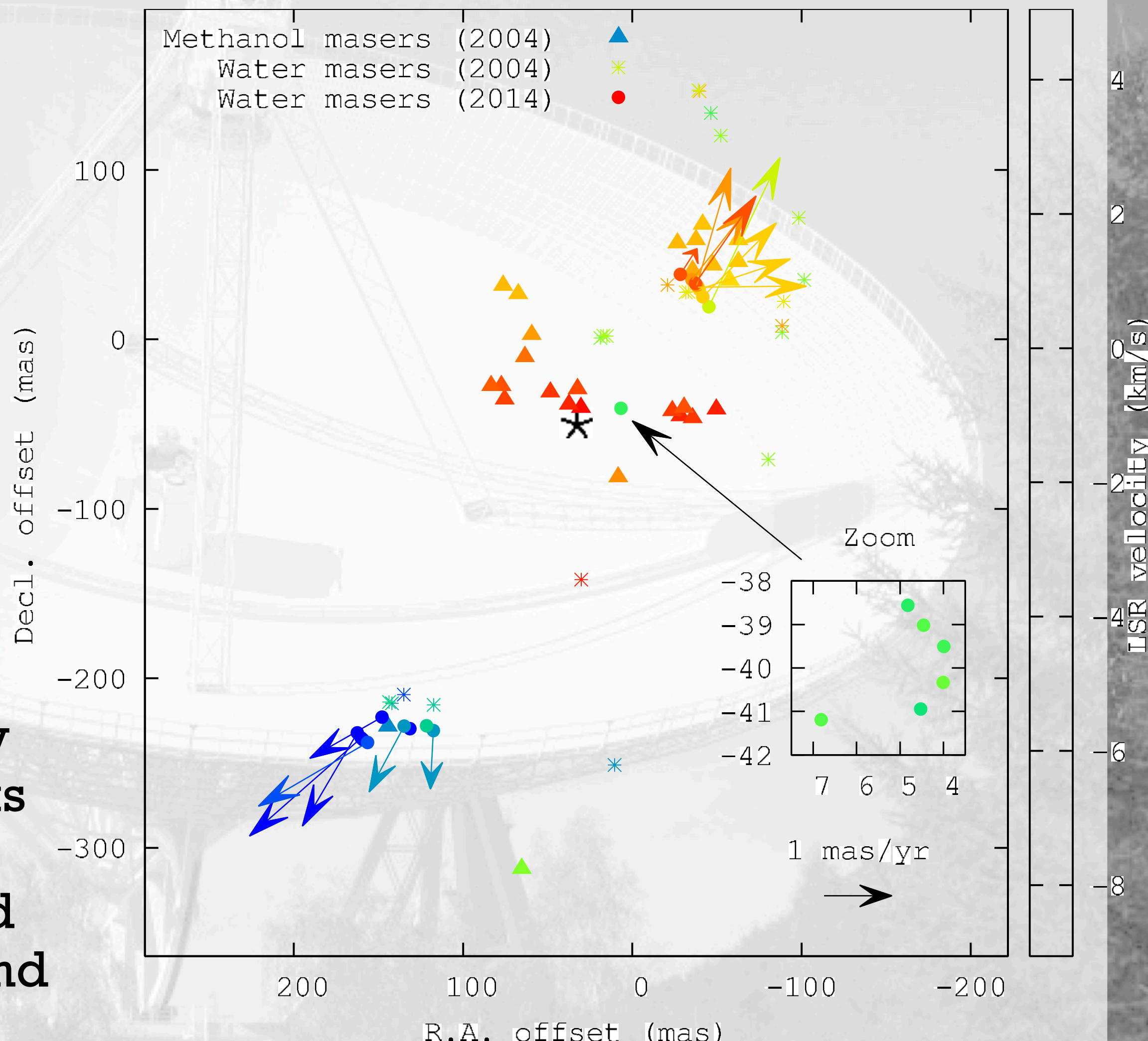


Circular image

High-mass protostars



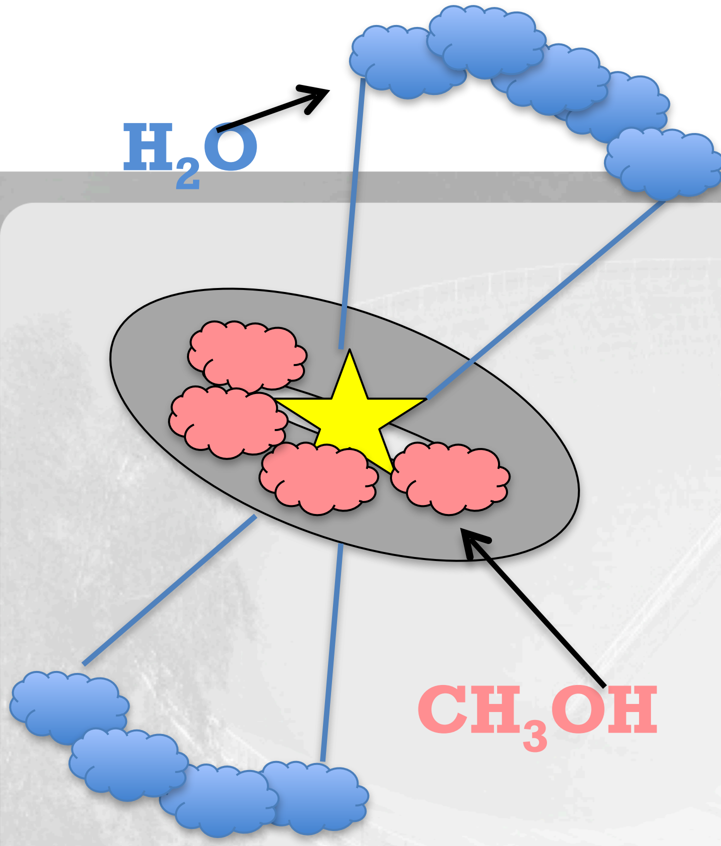
Burns et al. 2017, MNRAS, 467, 2367



Water masers are pumped by collisions and are found in jets

Methanol masers are pumped by warm infrared radiation and are found in disks

High-mass protostars



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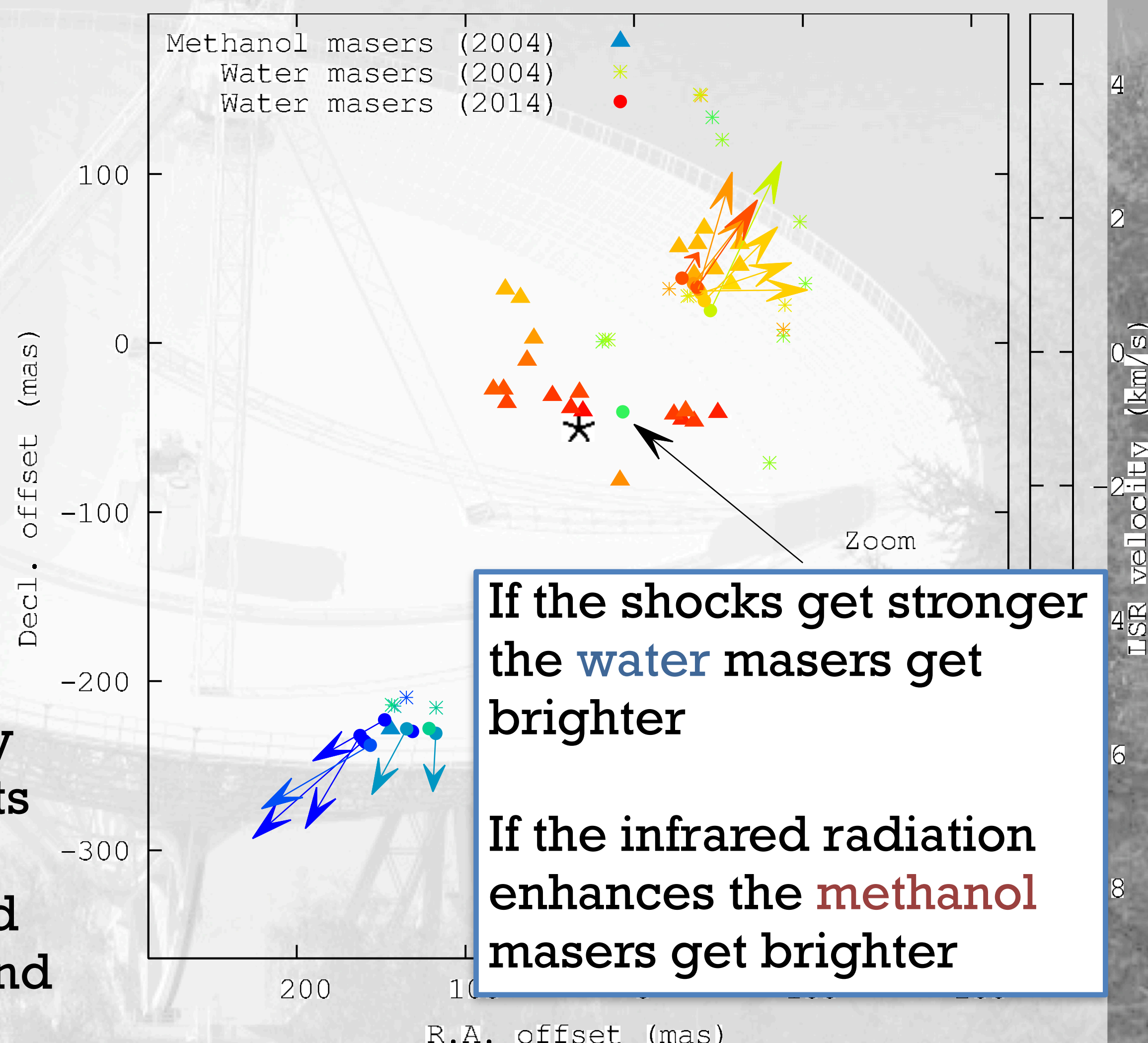


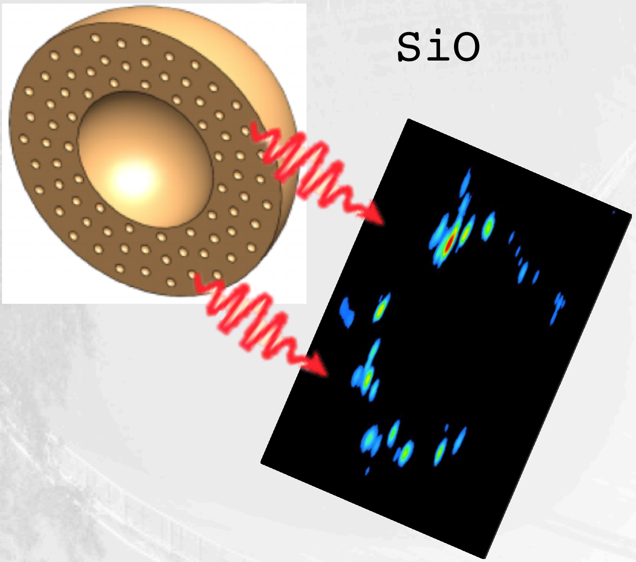
If the shocks get stronger the water masers get brighter

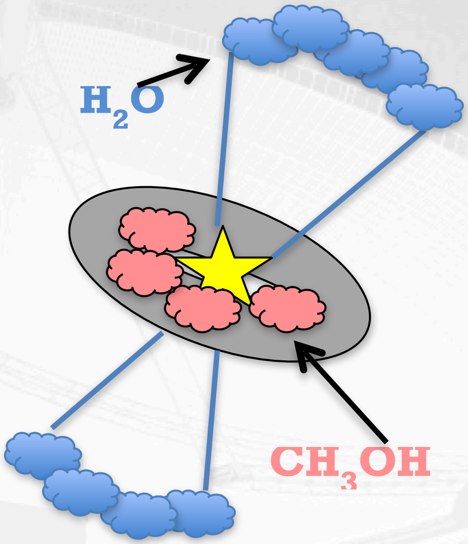
If the infrared radiation enhances the methanol masers get brighter

Water masers are pumped by collisions and are found in jets

Methanol masers are pumped by warm infrared radiation and are found in disks

Shocks and shells

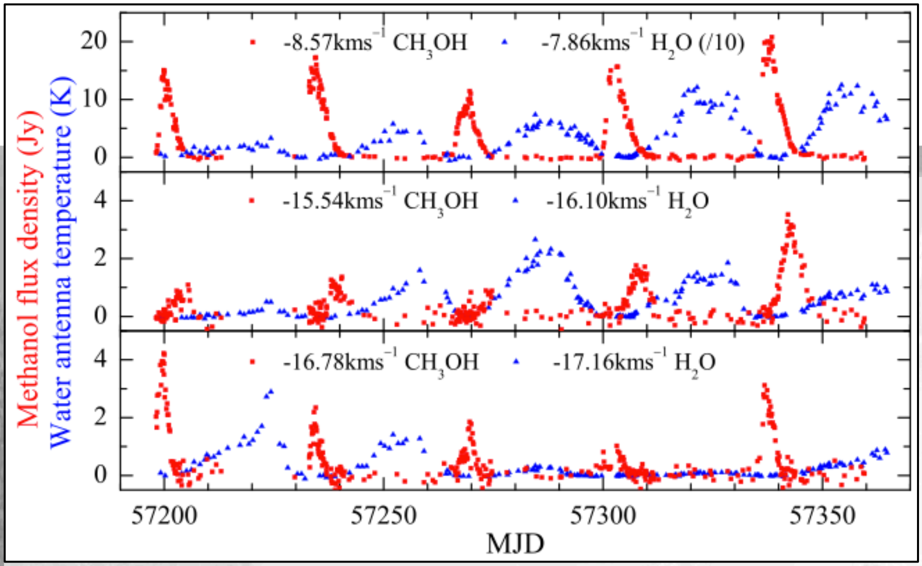




Conclusion 1: maser detections are strongly biased to regions that have a long path-length along the observer's line-of-sight; you almost always see a **cross-section** of your target.

Conclusion 2: Amplification is sensitive to changes in path length / radiation / collisions ➔ maser variability

Variability

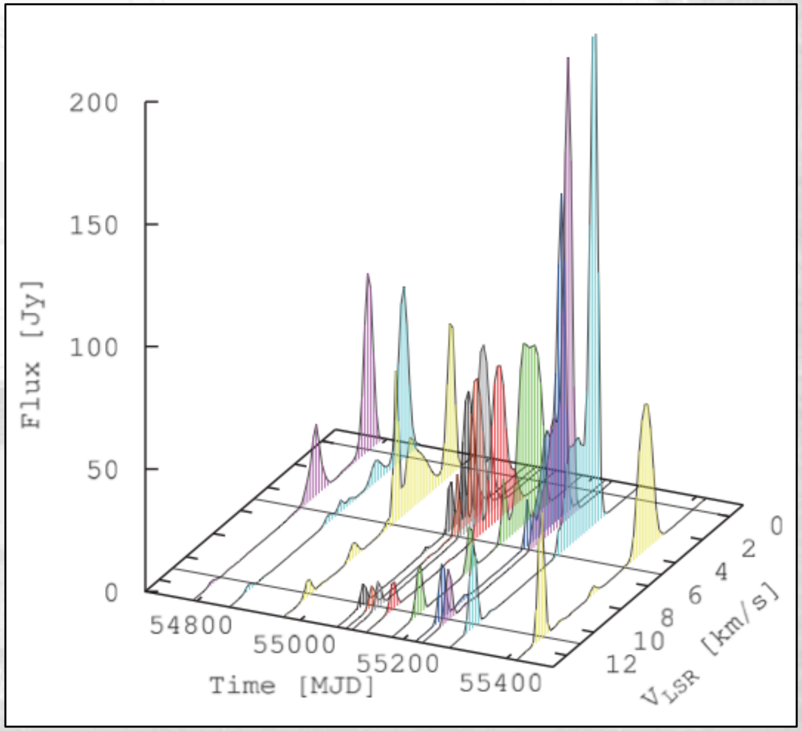


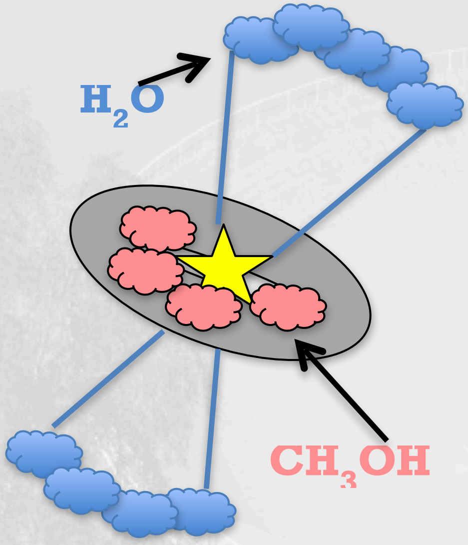
Periodic

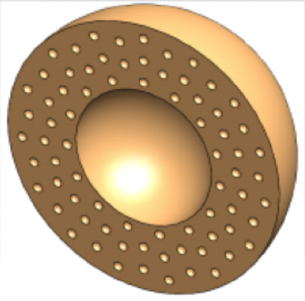
Gradual brightening

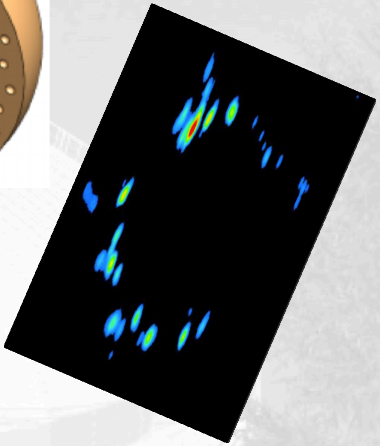
Gradual dimming

Bursts









Discuss

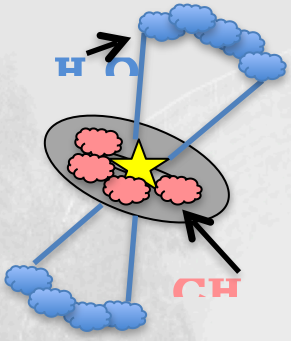
- What is the pumping energy source for water masers?
- Were are water masers often found?

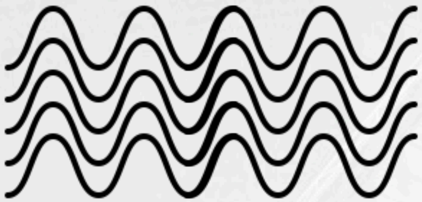
- What is the pumping energy source for methanol masers?
- Where are methanol masers often found?

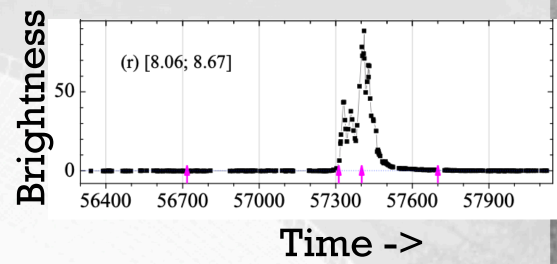
- What is the pumping energy source for SiO masers?
- Where are SiO masers often found?

Maser Monitoring

Maser Monitoring





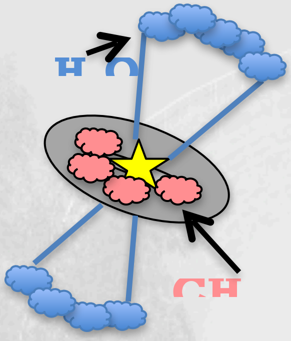


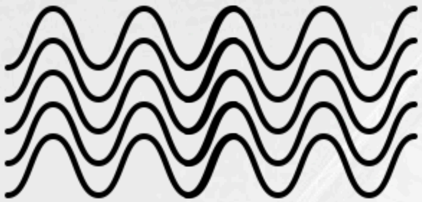
We already learned that the maser brightness can depend on Path length, pumping conditions, and input seed photons. Therefore, by monitoring the brightness of masers using a radio telescope we can interpret any changes in the maser brightness as physical changes in the maser region.

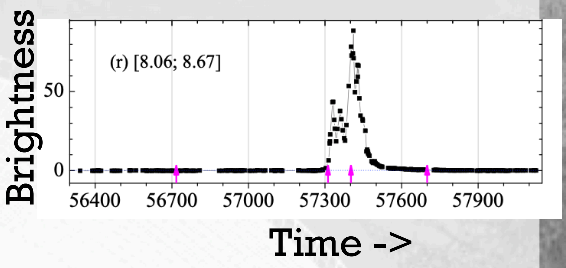
For this reason there are many radio telescopes monitoring many astrophysical maser sources. Examples of what they have found:

- Newly launched protostellar jets
- Pulsating evolved star shells
- Brightening of infrared sources due to protostellar accretion

Maser Monitoring







We already learned that the maser brightness … on
Path length, pumping conditions, and input see…
Therefore, by monitoring the brightness of masers u…
telescope we can interpret any changes in the maser brig…
physical changes in the maser region.

Can you say which maser **molecule** was used for each of these findings?

For this reason there are many radio telescopes monitoring many astrophysical maser sources. Examples of what they have found:

- Newly launched protostellar jets
- Pulsating evolved star shells
- Brightening of infrared sources due to protostellar accretion

Maser imaging observations

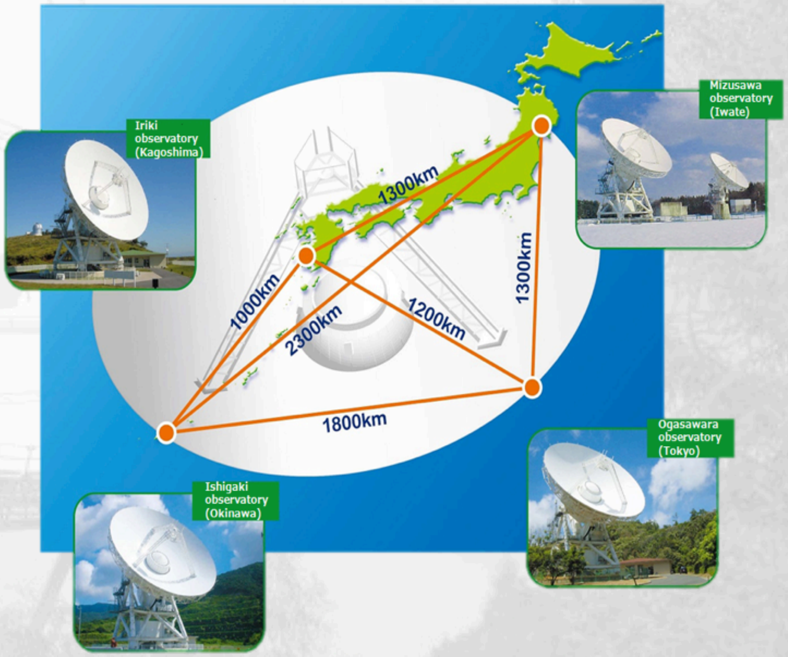
Maser imaging observations

The Very Large Array (VLA) is a collection of 27 radio antennas located at the NRAO site in Socorro, New Mexico. Each antenna in the array measures 25 meters (82 feet) in diameter and weighs about 230 tons. Credit: Alex Savello/NRAO

VLA / ALMA / ATCA
"Radio interferometers"

Baselines: ~ 1-100 km
Resolution: ~ 10-100s milliarcsecond

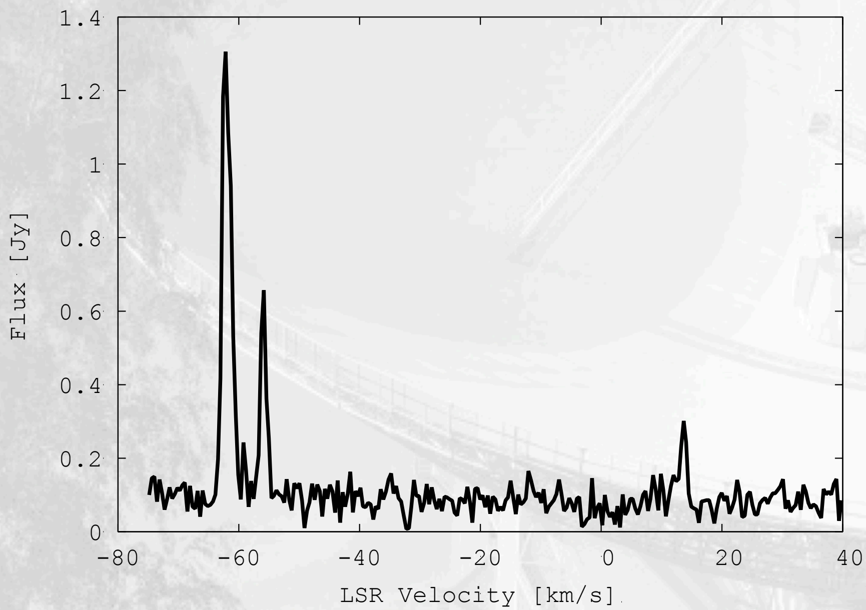
VLBI
Baselines: 1000s of km
Resolution: ~ milliarcsecond



Both provide different but complementary science

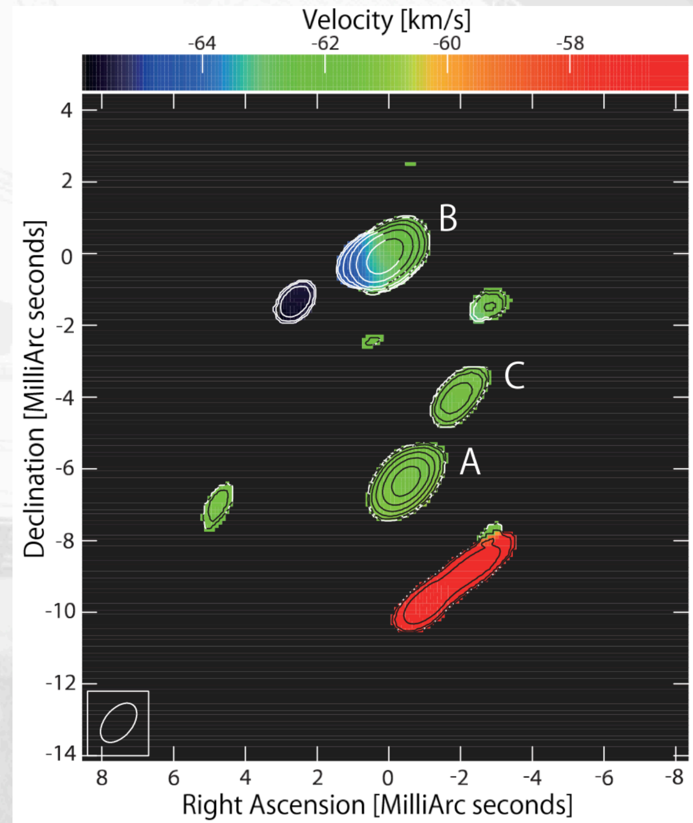
Maser observations

<u>Single dish radio telescope</u>
+ Easier to perform observations
- Only measures flux and frequency

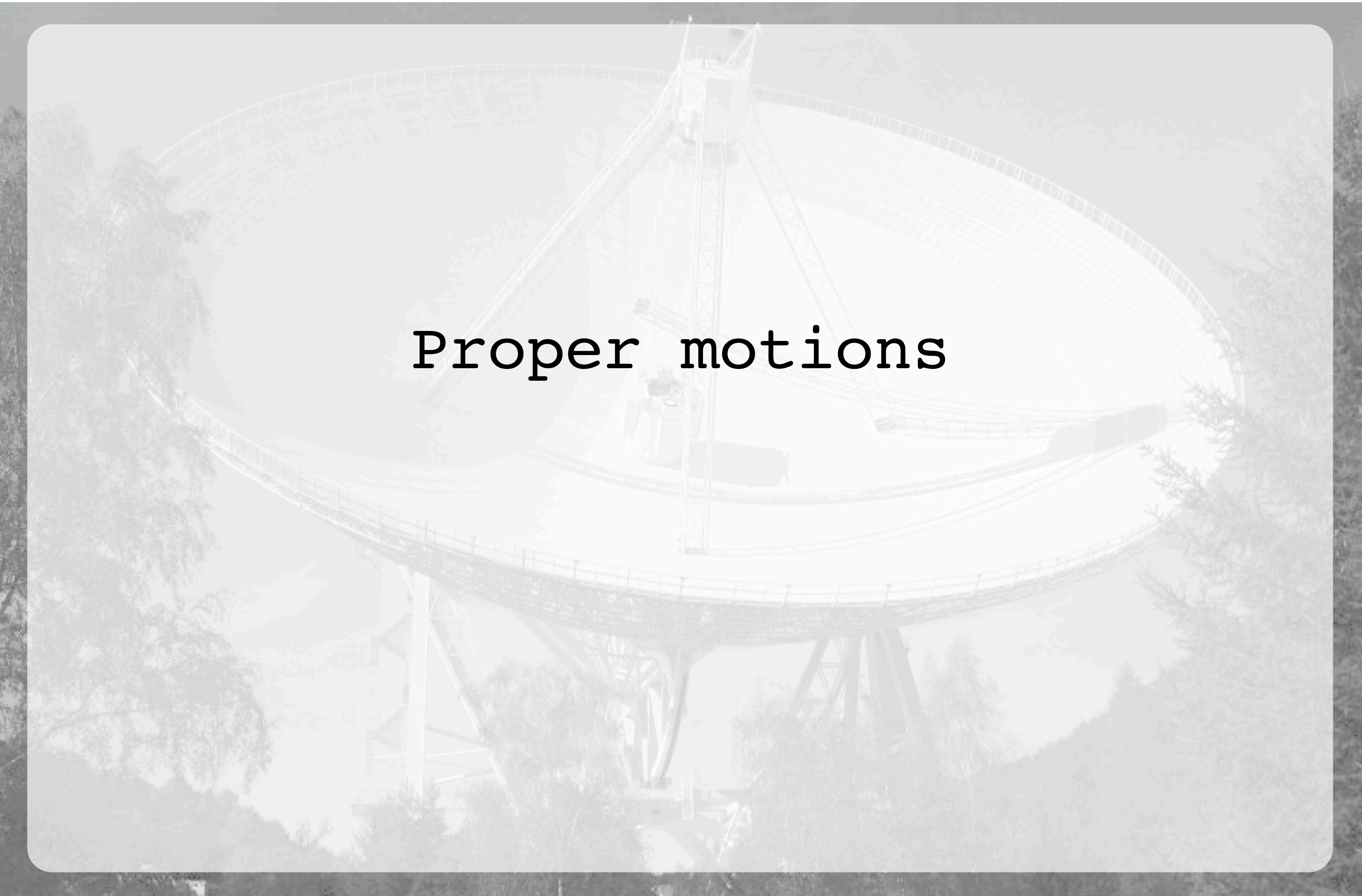


Again: Both provide different but complementary science

<u>VLBI / VLA</u>
- Harder technique
+ Measures flux and frequency and <u>sky-plane distribution</u>



Proper motions

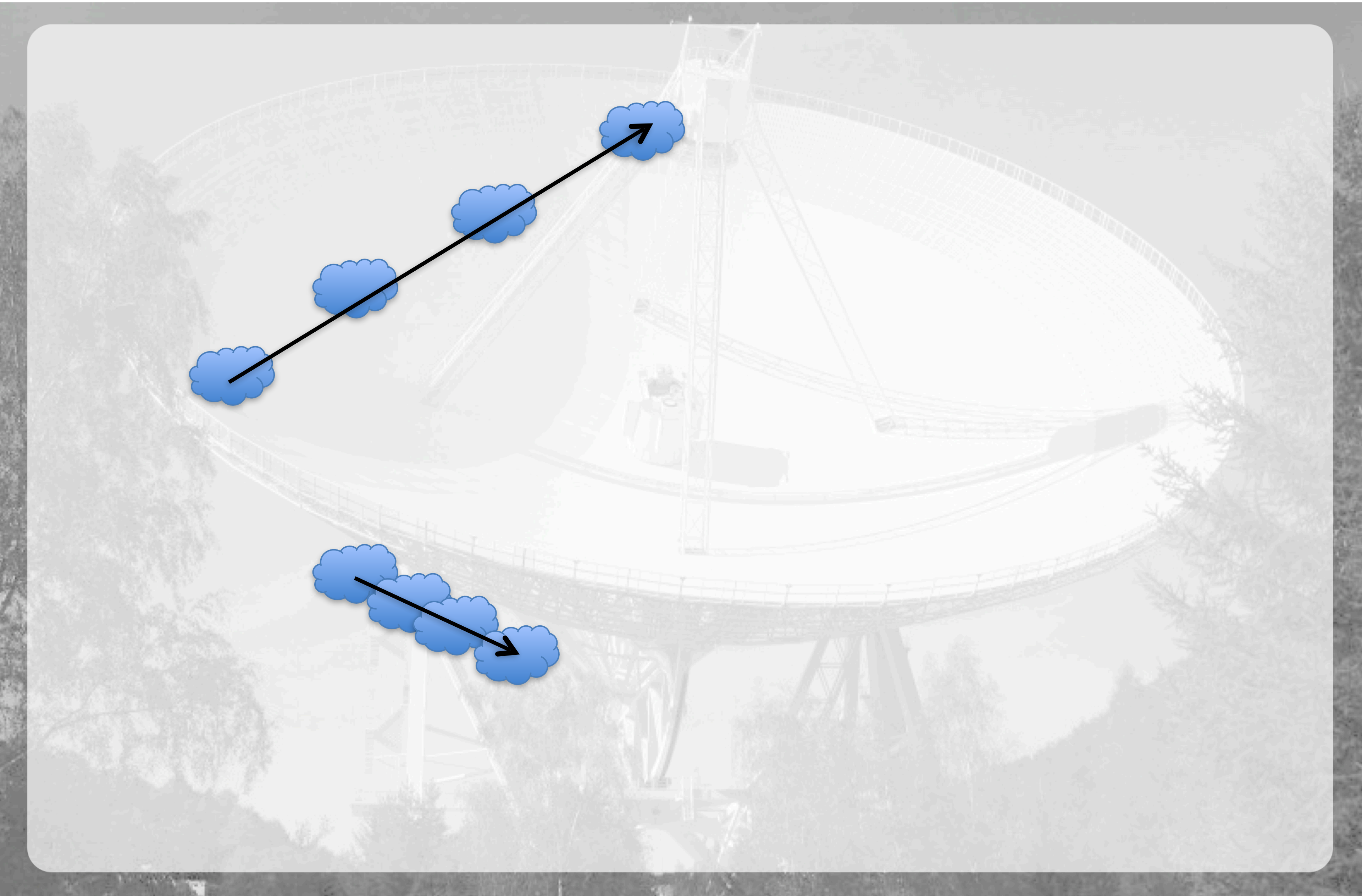


Multi-epoch VLBI observations

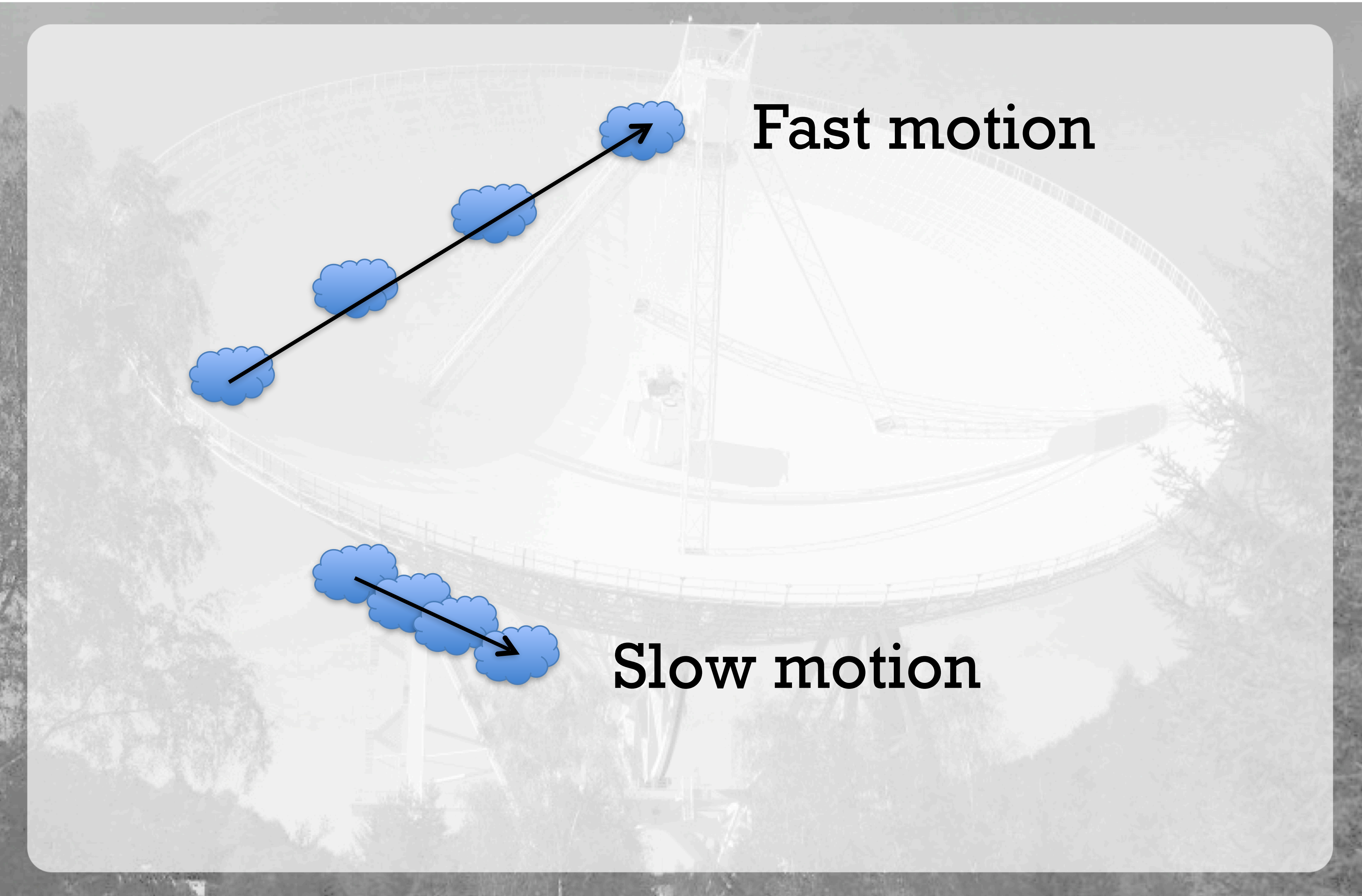
Multi-epoch VLBI observations

Multi-epoch VLBI observations

Multi-epoch VLBI observations



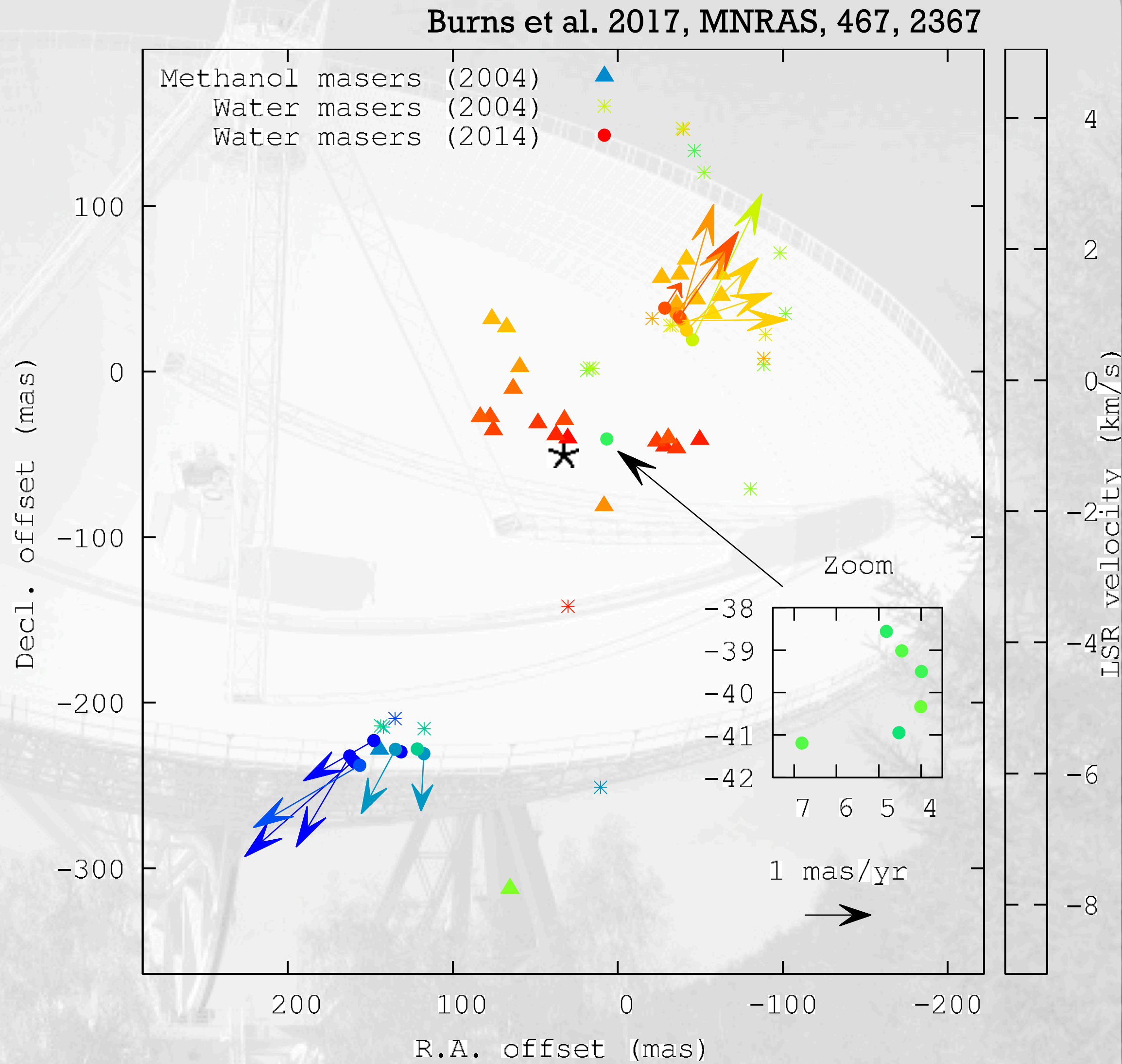
Multi-epoch VLBI observations



Multi-epoch VLBI observations

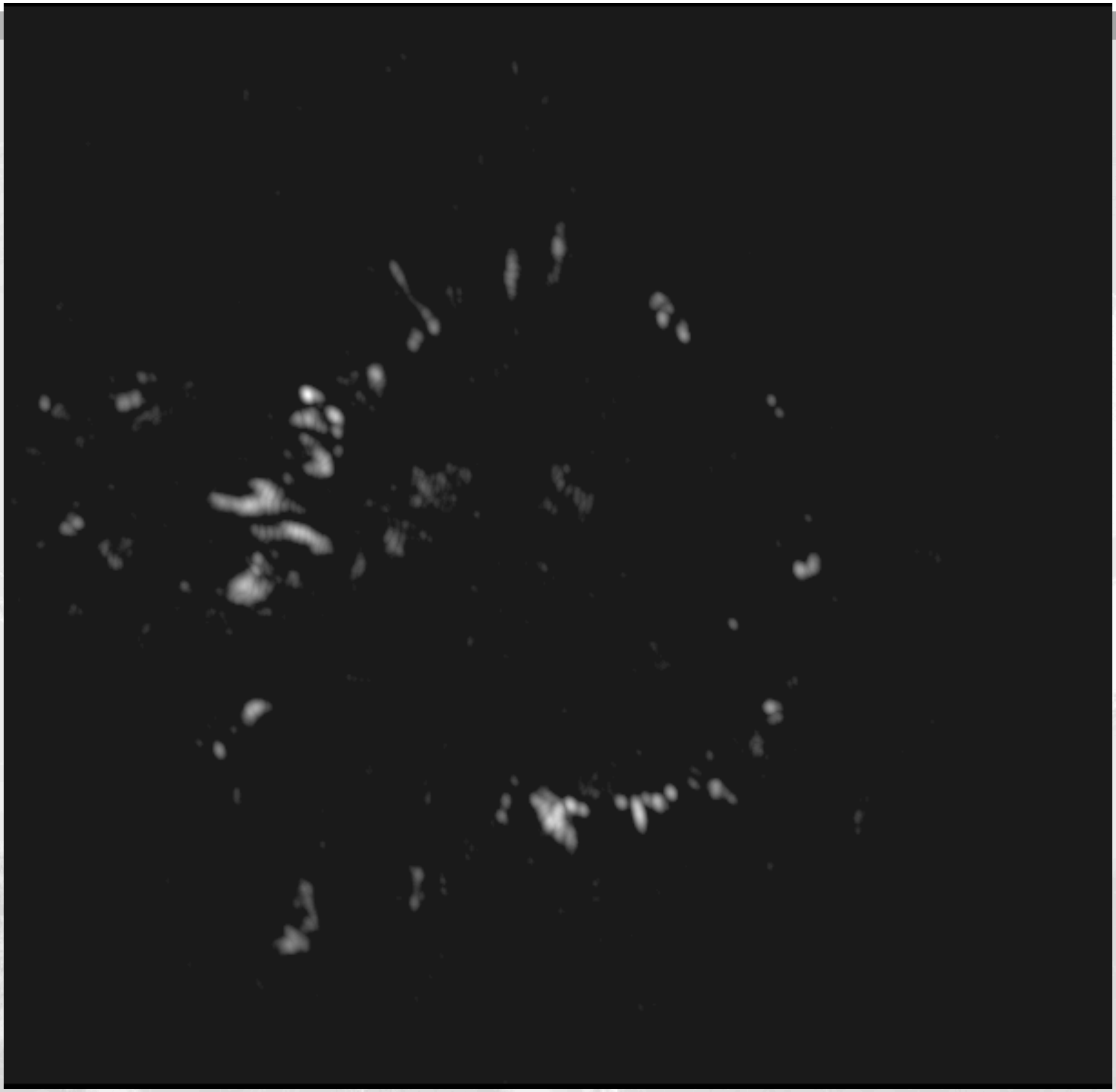
Fast motion

Slow motion

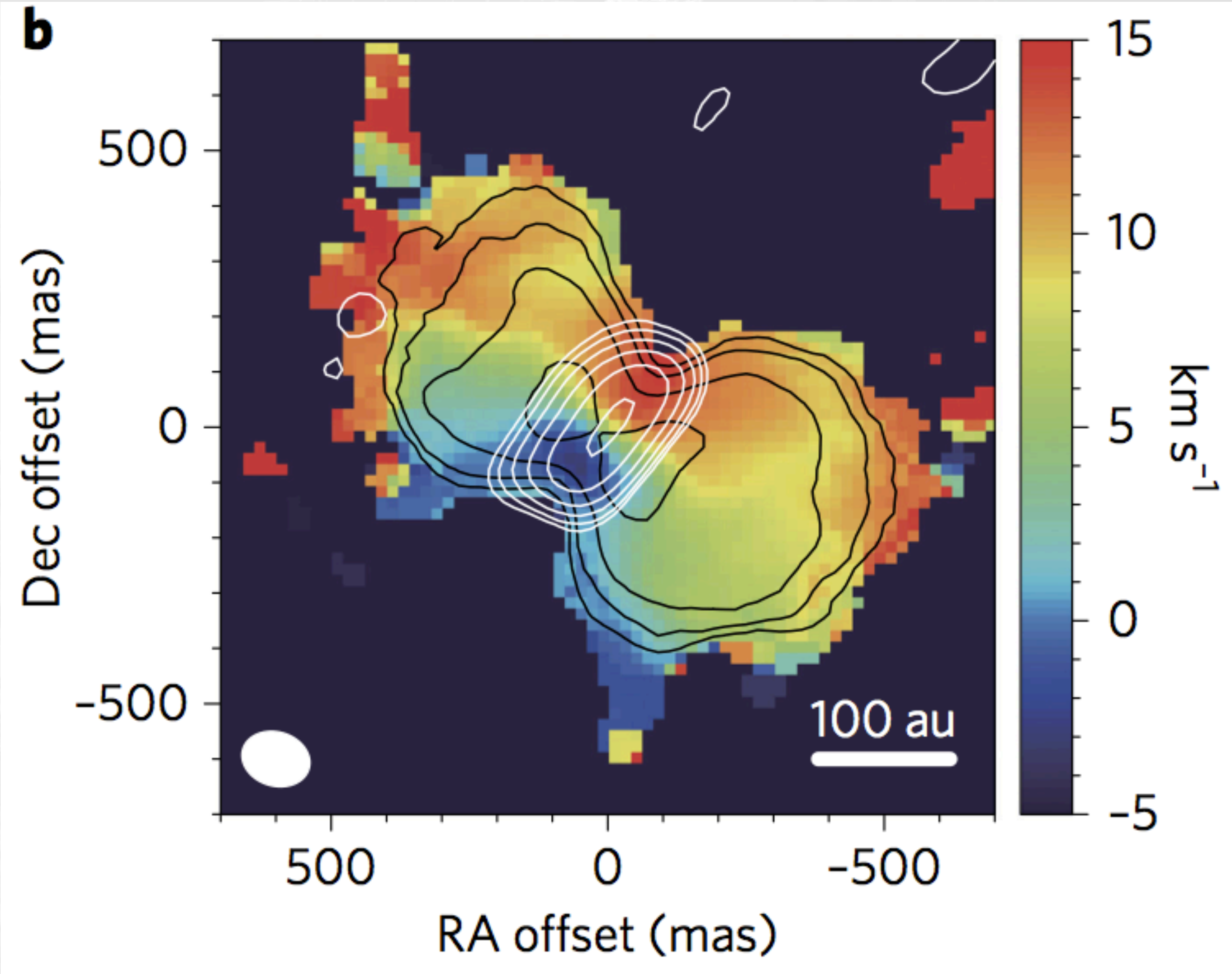


Multi-epoch observations taken to the extreme

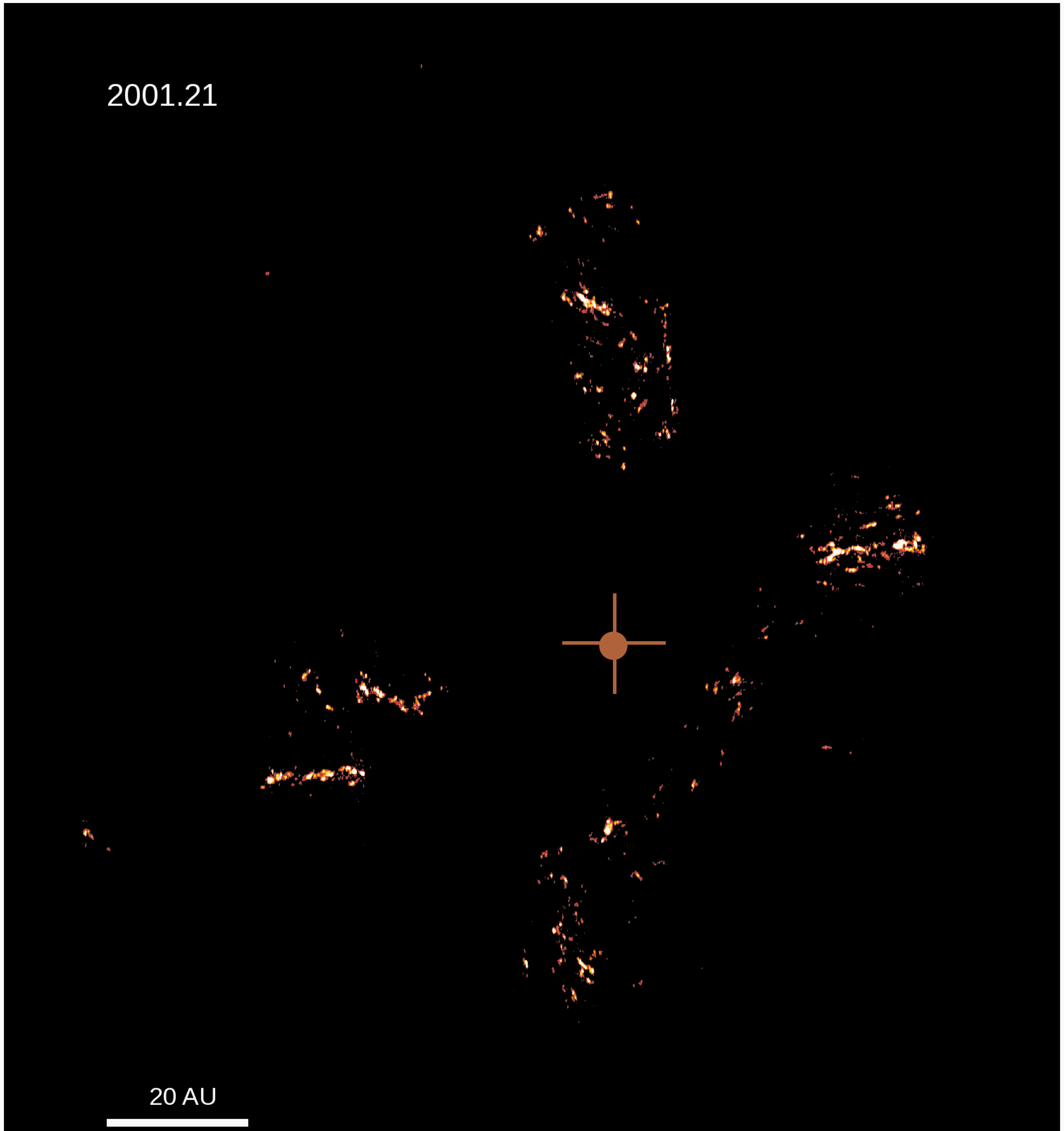
Maser movie: AGB



Maser movie: Orion S.I



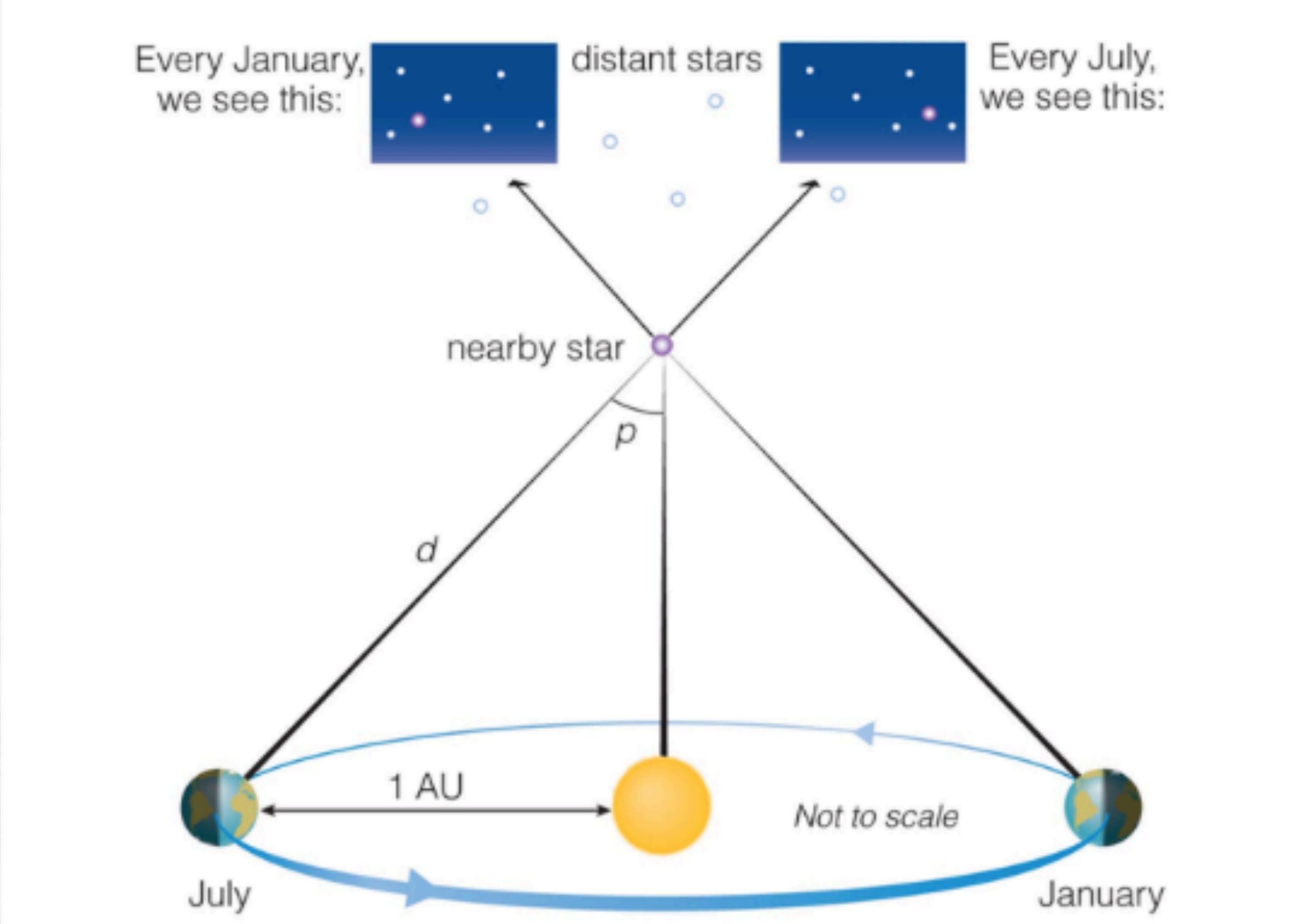
Maser movie: Orion S.I



Questions?

Using masers to map the Galaxy

Annual parallax



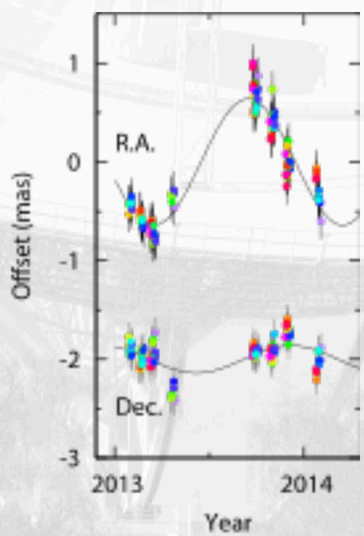
Multi-epoch observations

Astrometry (~1 year)

Make a fit

Linear component

- **Proper motion**

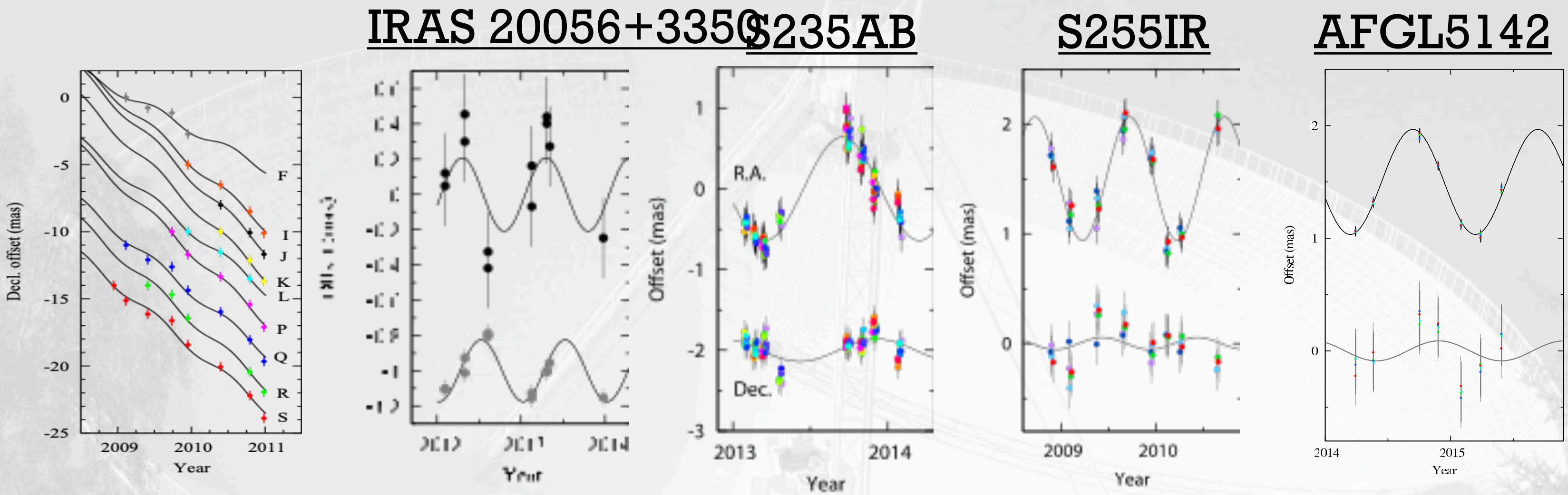


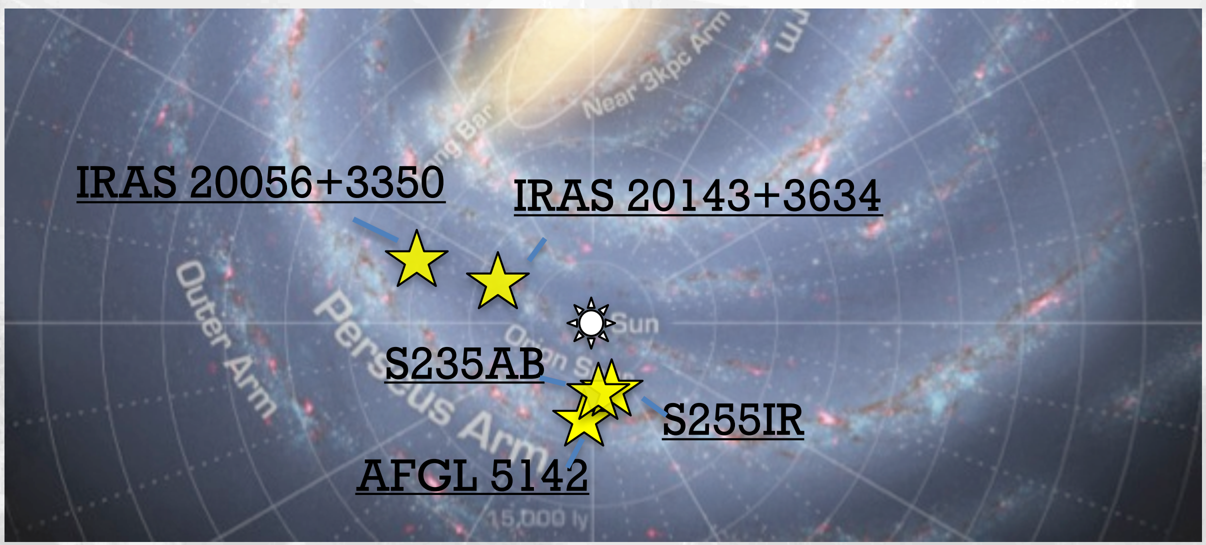
Sinusoidal component

- **Annual parallax**

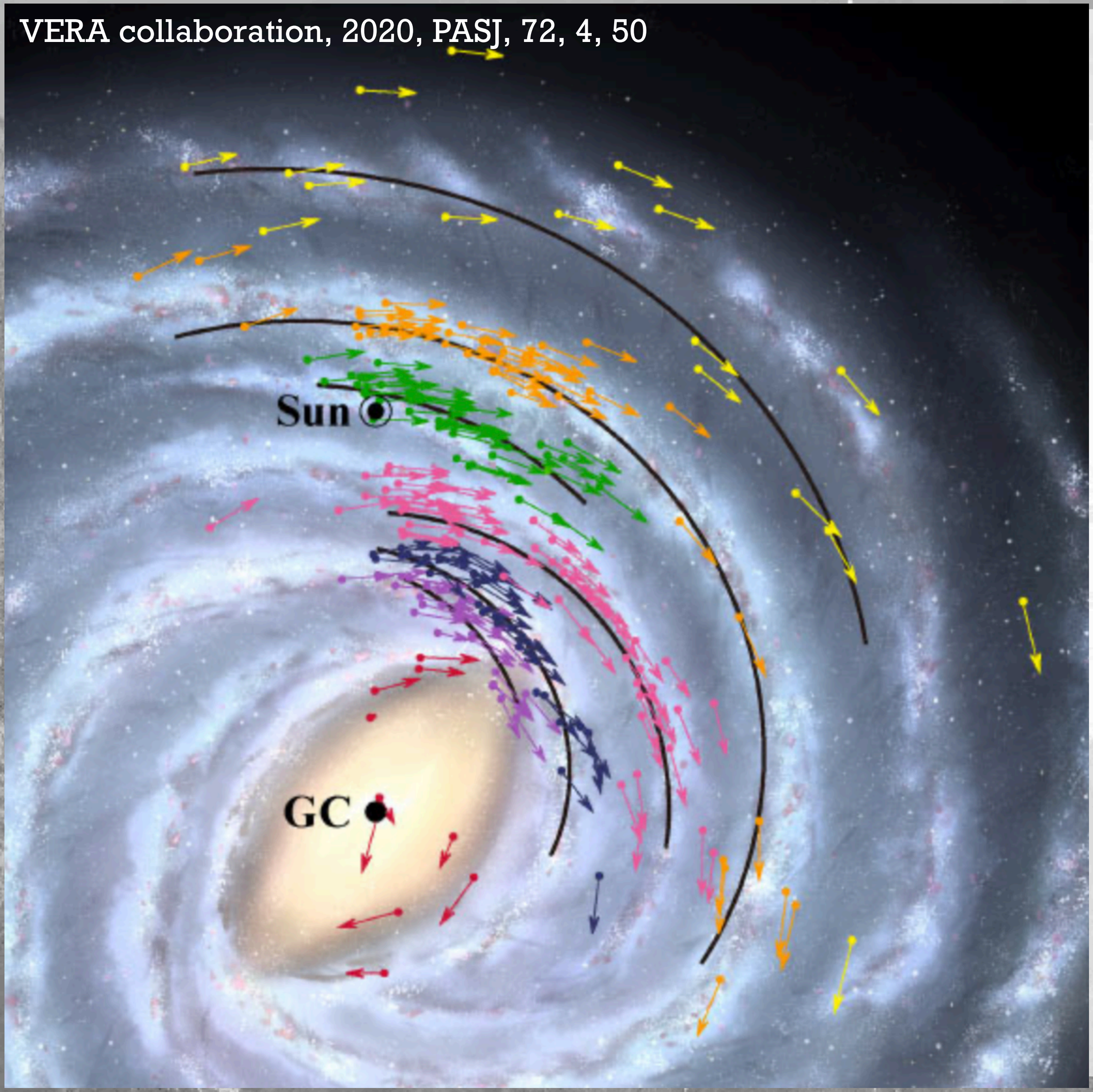
↓

Distance ✓


IRAS 20056+3350
S235AB
S255IR
AFGL5142
Decl. offset (mas)
Year
F
I
J
K
L
P
Q
R
S
2009
2010
2011
R.A.
Dec.
Offset (mas)
2013
2014
2015


IRAS 20056+3350
IRAS 20143+3634
S235AB
S255IR
AFGL 5142
Sun
Outer Arm
Perseus Arm
Near 3kpc Arm
15,000 ly

VLBI maser parallaxes circa 2021



Galactic structure by direct distance measurement

Map the Spiral Arms

Distance to Galx. center