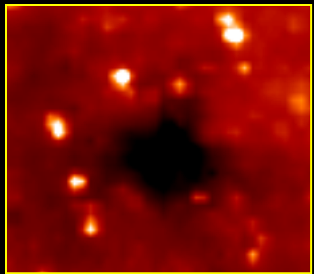
Phosphorus-bearing molecules in Solar-type Star Forming Regions

B. Lefloch
(IPAG, Grenoble)

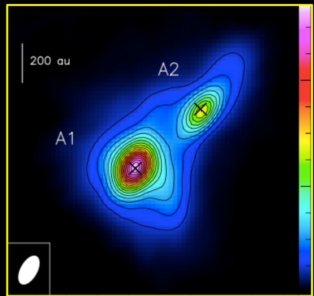
C. Codella, C. Vastel, S. Viti, I. Jiménez-Serra, L. Podio, C. Ceccarelli, R. Bachiller, N. Balucani

Why searching P-molecules in Solar-type SFRs ?

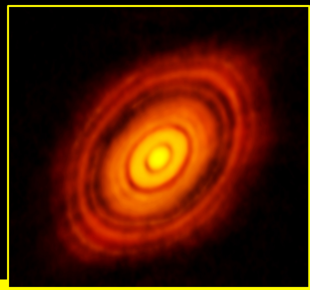
EVOLUTION



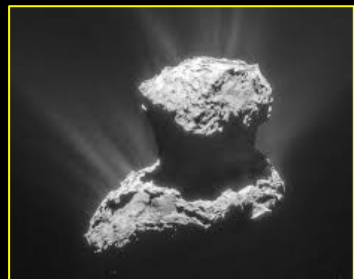
PRESTELLAR CORES



PROTOSTARS



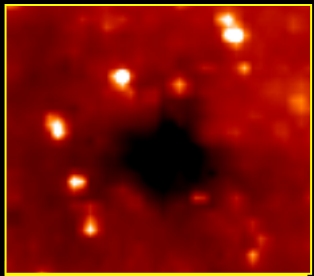
PROTOPLANETARY DISKS



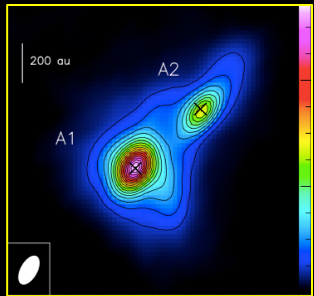
COMETS & ASTEROIDES

P-molecules in Solar-type SFRs : a "direct" link with cometary material

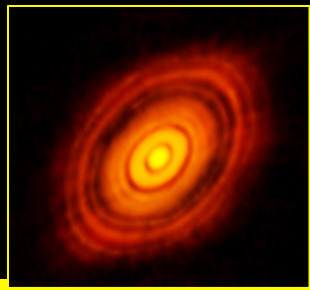
See Rivilla's talk yesterday on the high-mass SFRs
(Fontani et al. 2016, Rivilla et al. 2016, 2018)



PRESTELLAR CORES

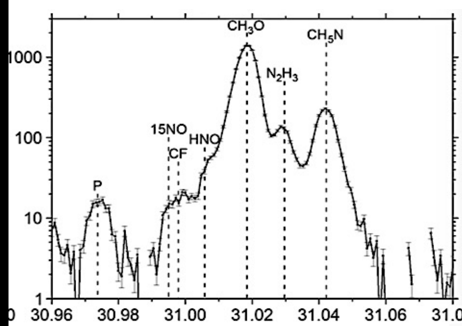


PROTOSTARS

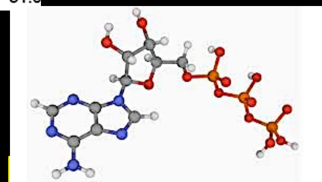


PROTOPLANETARY DISKS

Altwegg et al. (2016)



COMETS & ASTEROIDES



?

The IRAM-30m Large Project ASAI (Astrochemical Survey At IRAM)

Sources	Coordinates (J2000)	d (pc)	Lum. ($L_\odot$)	3 mm (mK)	2 mm (mK)	1.3 mm (mK)	$\delta\nu$ (kHz)	Comment
TMC1	$04^h41^m41.90^s$ $+25°41'27.1''$	140	–	–	4.2–4.2	–	48.8, 195.3	Early prestellar core
L1544	$05^h04^m17.21^s$ $+25°10'42.8''$	140	–	2.1–7.0	–	–	48.8	Evolved prestellar core
B1b	$03^h33^m20.80^s$ $+31°07'34.0''$	230	0.77	2.5–10.6(*)	4.4–8.0	4.2–4.6	195.3	First Hydrostatic Core
L1527	$04^h39^m53.89^s$ $+26°03'11.0''$	140	2.75	2.1–6.7(*)	4.2–7.1	4.6–4.1	195.3	Class 0 WCCC
IRAS4A	$03^h29^m10.42^s$ $+31°13'32.2''$	260	9.1	2.5–3.4	5.0–6.1	4.6–3.9	195.3	Class 0 Hot Corino
L1157mm	$20^h39^m06.30^s$ $+68°02'15.8''$	250	3	3.0–4.7	5.0–6.5	3.8–3.5	195.3	Class 0
SVS13A	$03^h29^m03.73^s$ $+31°16'03.8''$	260	34	2.0–4.8	4.2–5.1	4.6–4.3	195.3	Class I
AB Aur (†)	$04^h55^m45.84^s$ $+30°33'33.04''$	145	–	4.6–4.3	4.8–3.9	2.1–4.3	195.3	protoplanetary disk
L1157-B1	$20^h39^m10.20^s$ $+68°01'10.5''$	250	–	1.1–2.9	4.6–7.2	2.1–4.2	195.3	Outflow shock spot
L1448-R2	$03^h25^m40.14^s$ $+30°43'31.0''$	235	–	2.8–4.9	6.0–9.7	2.9–4.9	195.3	Outflow shock spot

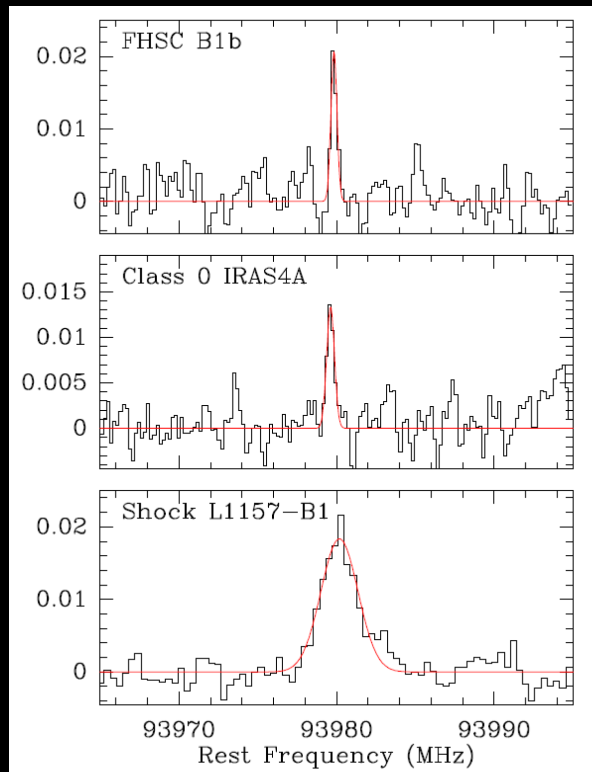
Unbiased spectral surveys covering the full 3, 2, 1 and 0.8 mm bands of ten of Solar-type SFRs (Lefloch et al. 2018)

JUST PERFECT TO OBTAIN THE CENSUS OF P-BEARING MOLECULES

RESULTS
ONLY DETECTED PN and PO

Source	Type	PN	PO
TMC1	Early Prestellar Core	-	-
L1544	Late Prestellar Core	-	-
B1b	Early Class 0 (FHSC)	Y	-
IRAS4A	Class 0 (hot corino)	Y	-
L1157-mm	Class 0 (WCCC)	-	-
L1527	Class 0/I (WCCC)	-	-
SVS13A	Class I (hot corino)	-	-
L1157-B1	Shock	Y	Y
L1448-R2	Shock	-	-

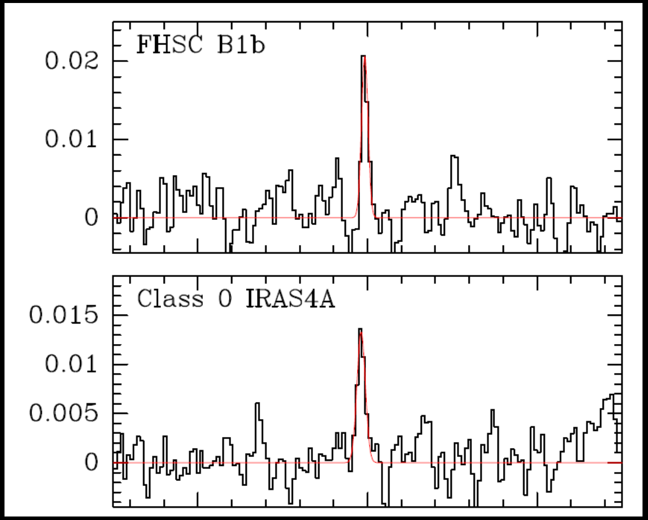
PN J=2-1



Lefloch et al. (2018)

PN in PROTOSTARS
B1b & NGC1333-IRAS4A

- WEAK LINE EMISSION
- FWHM ~ 1 km/s
- ONLY LOW-EXCITATION TRANSITIONS J=2-1 and J=3-2 (E_{UP}= 13.5K) ARE DETECTED



Lefloch et al. (2018)

→ PN TRACES THE COLD ENVELOPE

Non-LTE modeling

B1b: T=13 K → **[PN] ≈ $4x10^{-13}$**

IRAS4A: T=35 K → **[PN] ≈ $2x10^{-13}$**

PN in PROTOSTARS
OPEN QUESTIONS

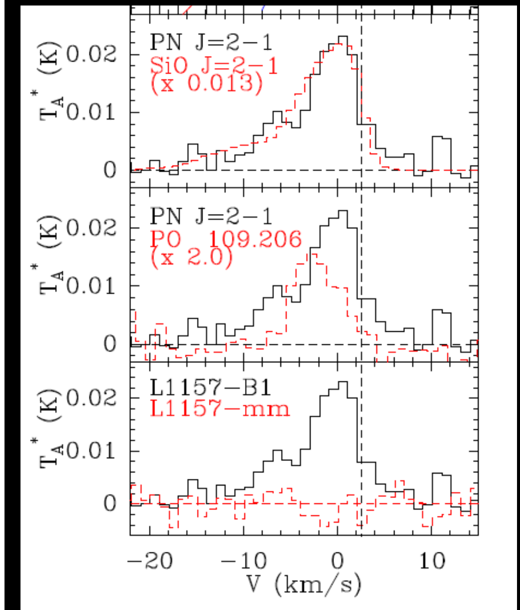
- WHY ONLY PN DETECTED IN PROTOSTARS ?
- WHY PN IS ONLY DETECTED IN COLD GAS AROUND PROTOSTARS ?
- WHERE IS THE MAJOR RESERVOIR OF P ?

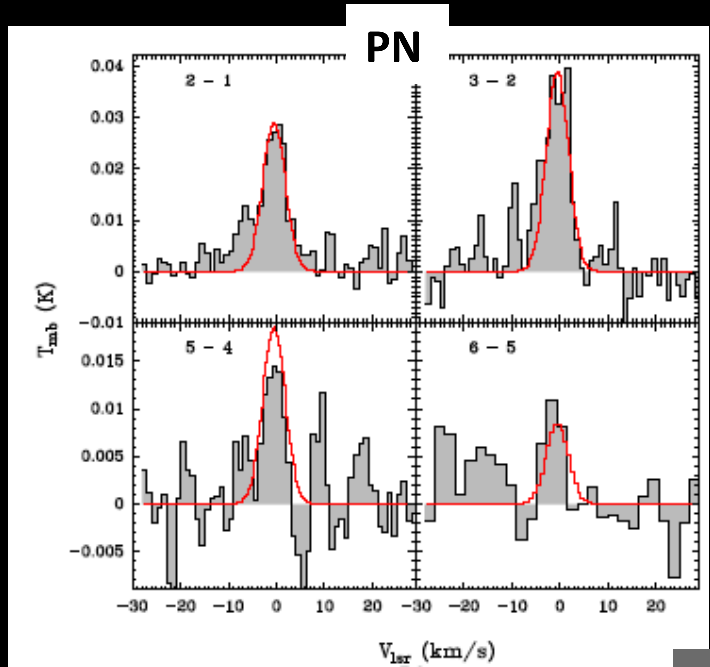
➔ NEW P-BEARING CHEMISTRY UNDER STUDY 🡐

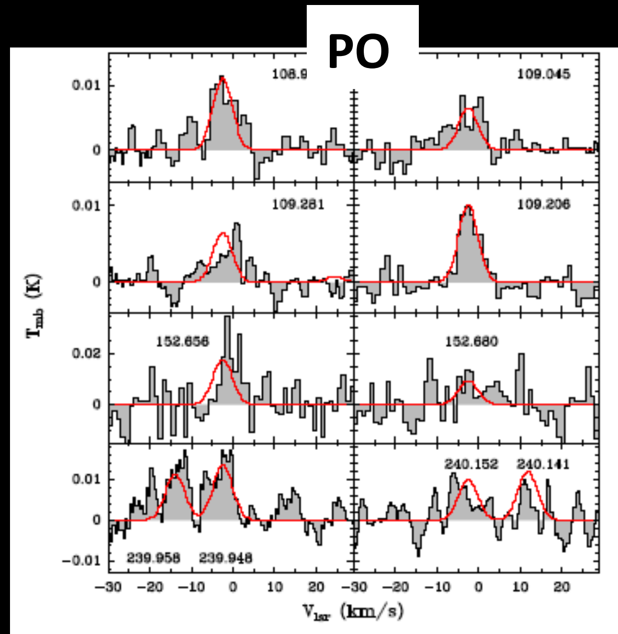
P- Chemistry in L1157-B1

First detection of PO and PN in Sun-like star forming region L1157

Emission from molecular-rich shock B1







Lefloch et al. (2016)

PO and PN are produced in the shock
They are tracing different layers

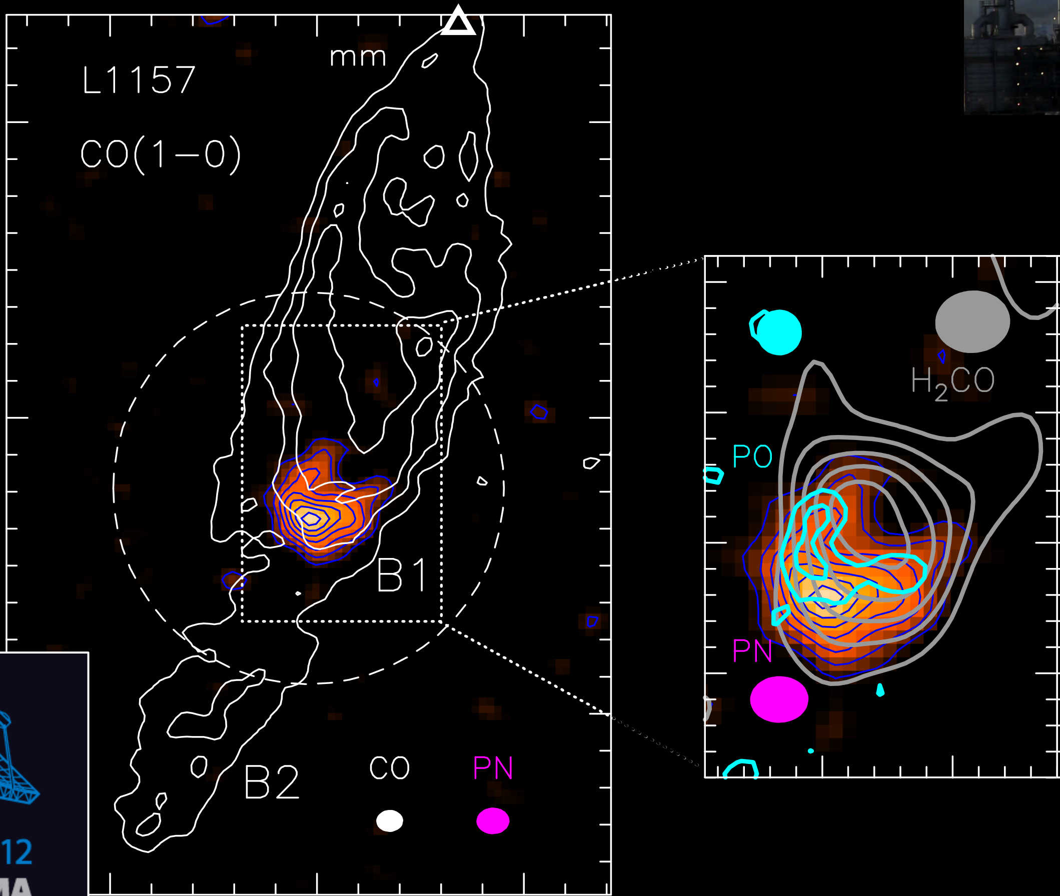
X(PO) = 2.5×10^{-9} : PO/PN= 3
Phosphorus depleted by 100

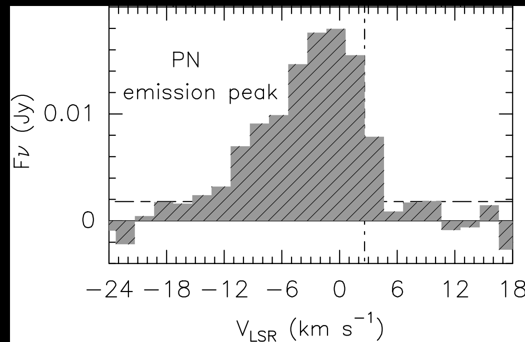
PH_3 is undetected $X(PH_3) \leq 10^{-9}$

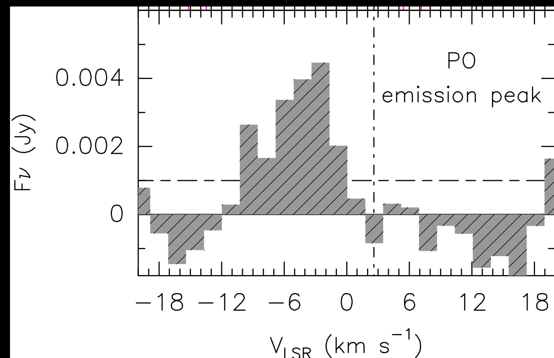
Yes, we are tracing shocks!

The NOEMA images

PN J=2-1 94 GHz and PO $^2\Pi_{½}$ J=5/2 – 3/2 109 GHz
4’’ resolution



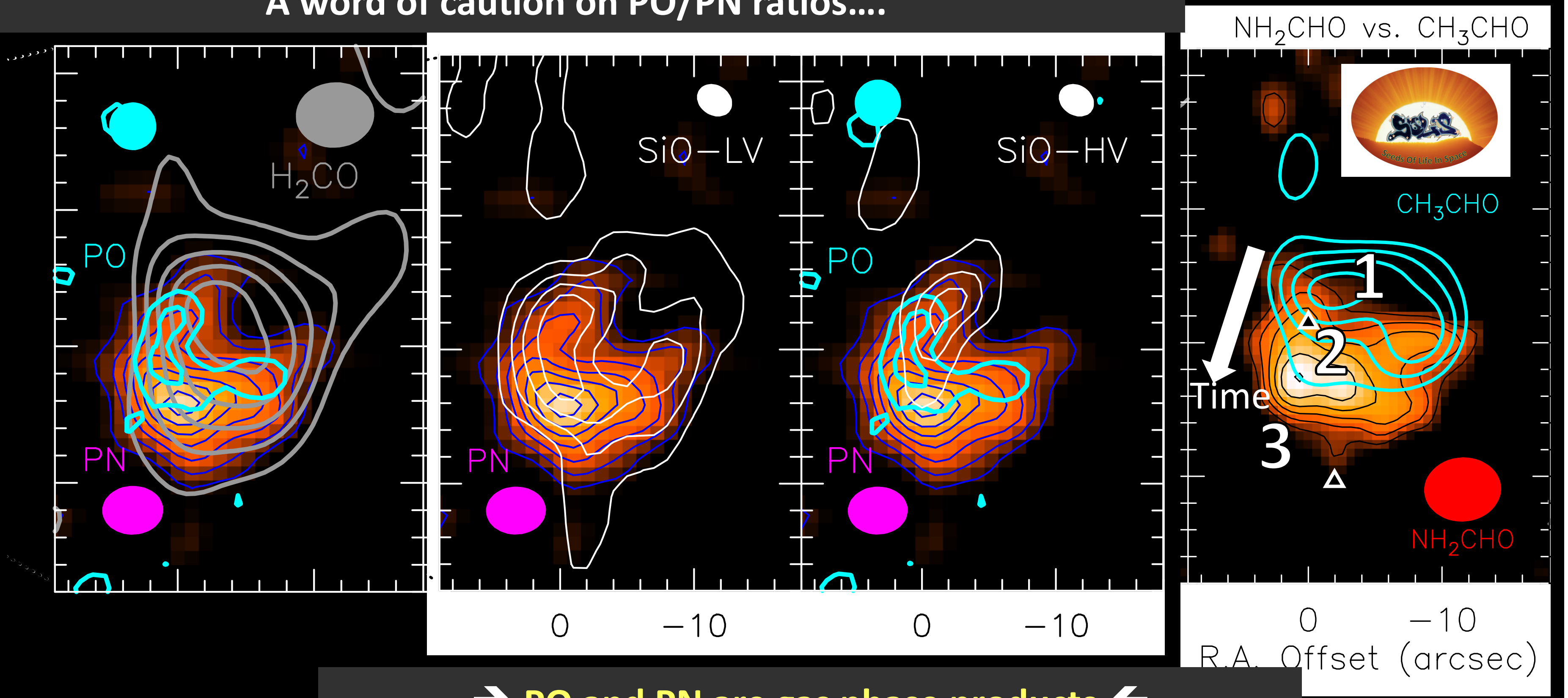




x12
NOEMA
NOrthern Extended
Millimeter Array

Shock's Anatomy

PN and PO are tracing the apex of the outflow cavity
Overall agreement with SiO
Spatial shift: PO peaks upstream of PN
A word of caution on PO/PN ratios….



➔ PO and PN are gas phase products ➔
They are both present in the early phase of the shock then PO disappears earlier than PN

Lefloch et al. : Wilhelm u

Shock Modelling

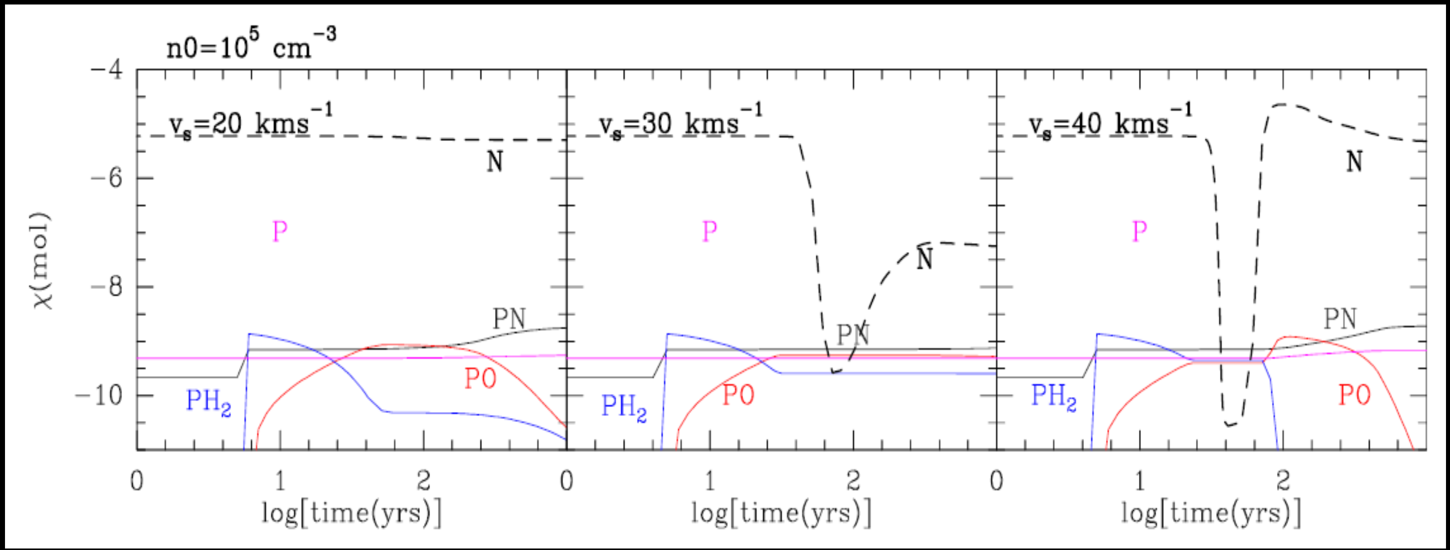
UCL_CHEM (Viti et al. 2011) + Parametric shock code
(Jimenez-Serra et al. 2008)

Step 1 : pre-shock gas conditions.

Main assumption: P is depleted and hydrogenated on the dust grains: PH, PH_2, PH_3 (Charnley & Millar 1994)

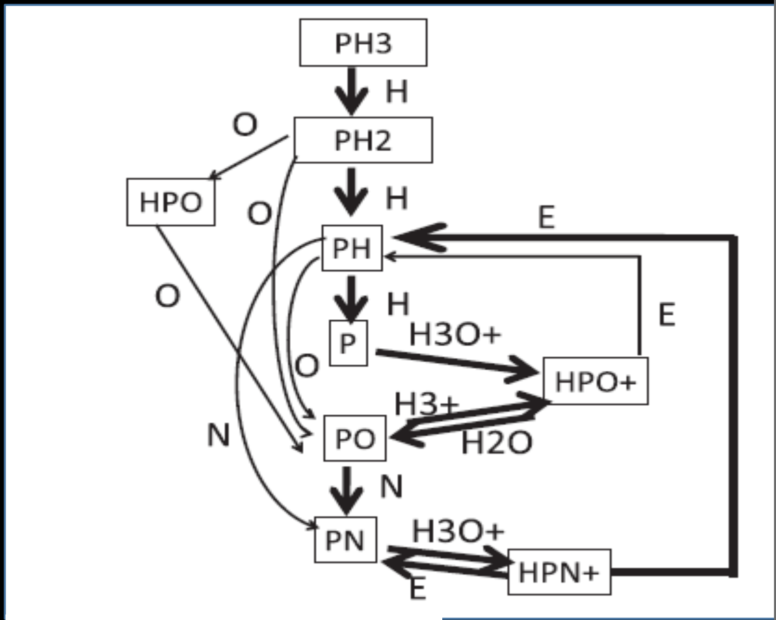
Step 2: chemical gas and dust evolution across the shock.

→ density n0, shock velocity, X_i[P], duration of pre-shock phase



Good fits when the pre-shock density is at least 10^5 cm^{-3}

P and N CHEMISTRY



Aota & Aikawa 2012

ISM P CHEMISTRY IS POORLY EXPLORED

↓

ADDITIONAL/ALTERNATIVE ROUTES OF PN FORMATION UNDER STUDY (Balucani et al. in prep)

Work in progress to simultaneously model N/NO and P/PN chemistry….
(see also Codella et al. 2017 on NO in shocks)

Conclusions and Prospects

Few P-bearing species have been detected for the first time in solar-type star forming regions thanks to ASAI : PN and PO

Is Phosphorus depleted by about 2 orders of magnitude ?

PN detected towards cold envelopes surrounding hot-corinos

PO and PN are both present in the early phase of shocks: PO looks to disappear earlier than PN

Preliminary chemical model analysis: PO and PN are produced in shocks from gas phase reactions

➔ MORE WORK IS NEEDED TO MODEL THE P + N CHEMISTRY (E.G. UNDERSTAND THE ROLE AND FATE OF PH_3)