Complex propagation of explosion-generated infrasound revealed by the large-scale AlpArray seismic network

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and the AlpArray Working Group

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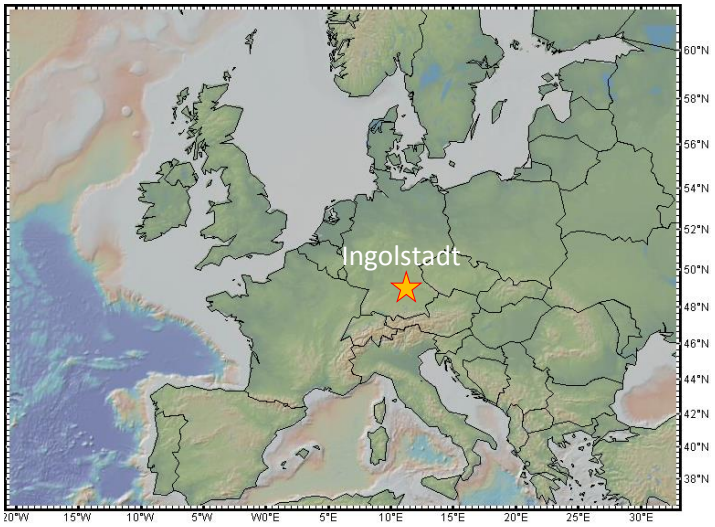
Ingolstadt explosion – Incident & dataset



- **Explosion** on **oil refinery** site in the morning (~ 3:11 UTC / 5:11 local time) of Sept. 1st 2018
- The **blast was audible** in Ingolstadt (10 km distance)
- Newspaper report **broken doors & windows** at **more than 1 km distance**
- **Hot petrol** escaped through crack from **highly pressurized** reactor. Explosion **above ground**.

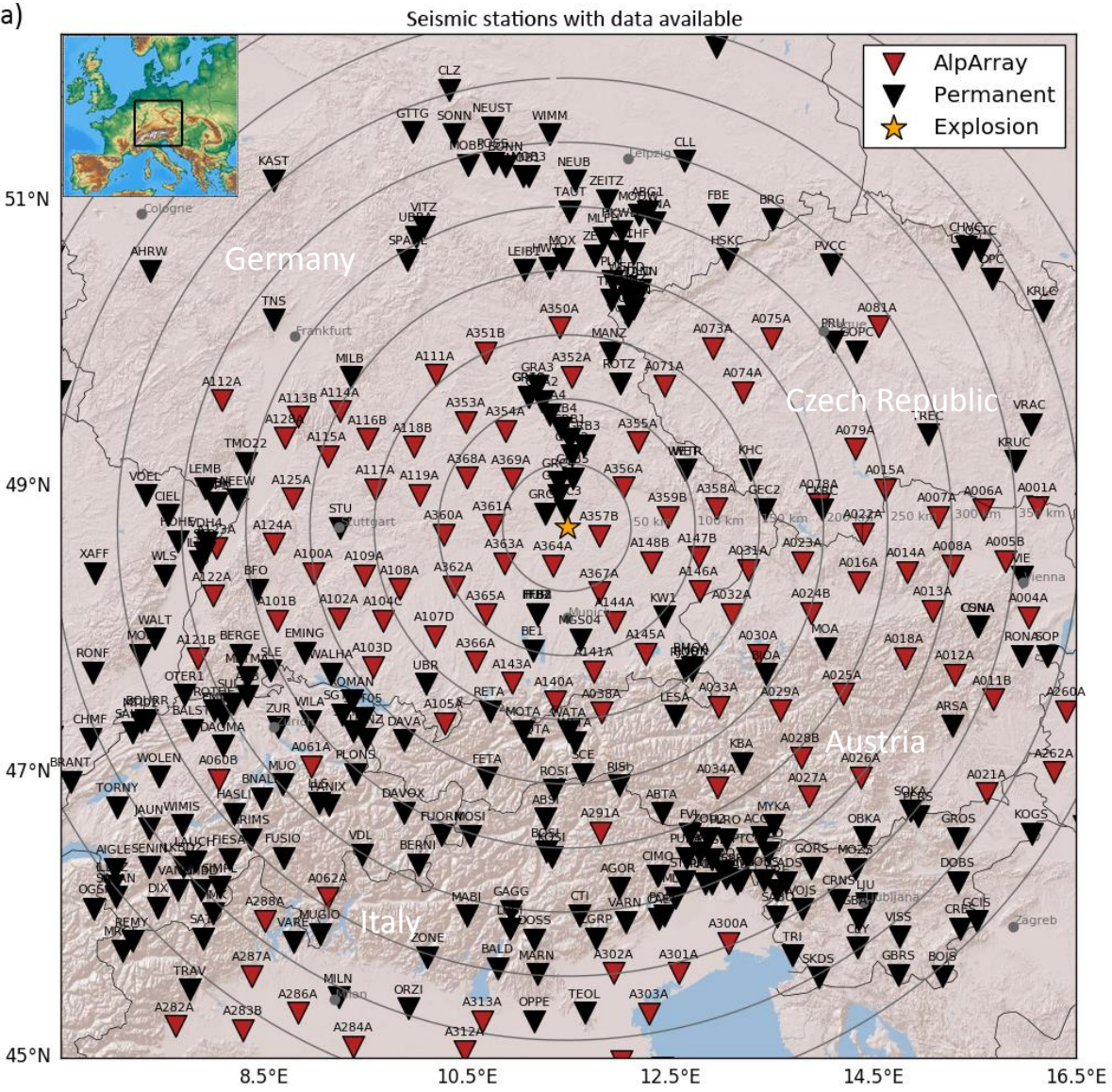
b)

c)

d)

Ingolstadt explosion – Incident & dataset

a)

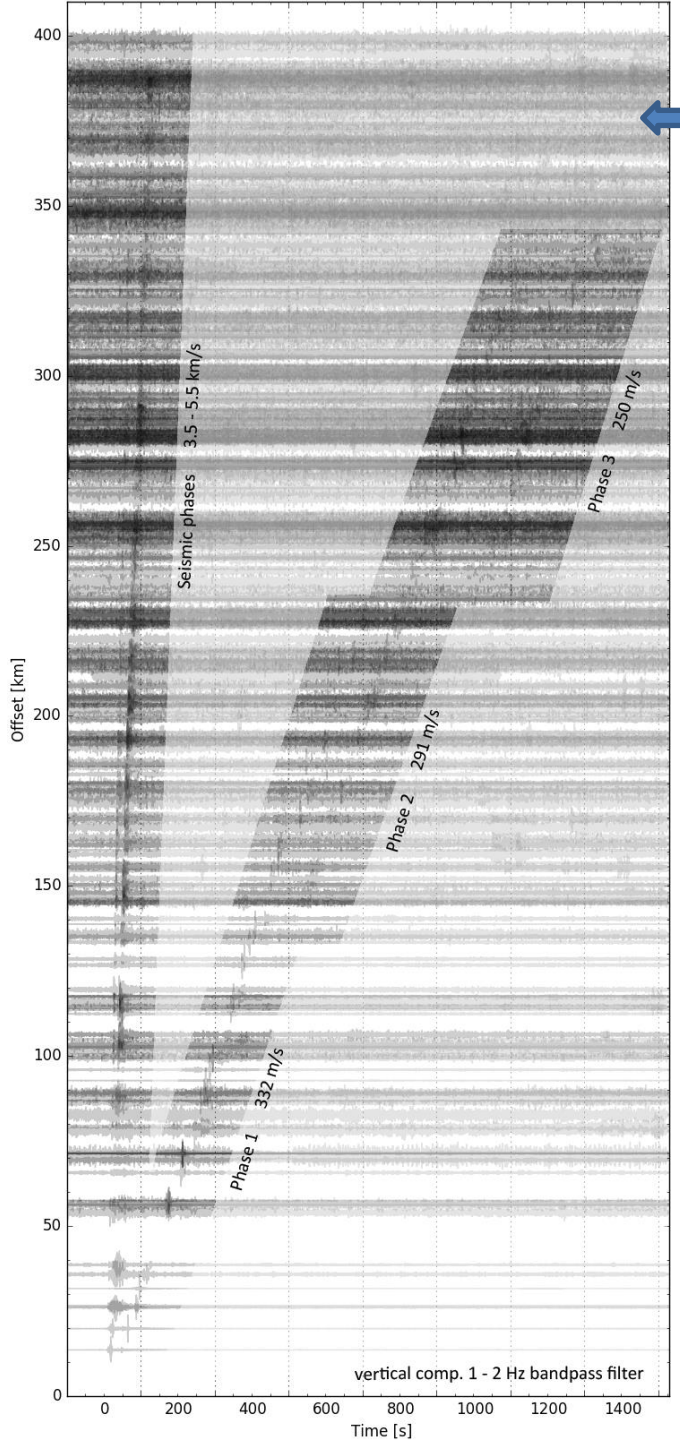


b)

c)

d)

400 seismic broadband stations (temporary & permanent) operating within 400 km radius



Record section of **all available data** (**vertical** comp.)

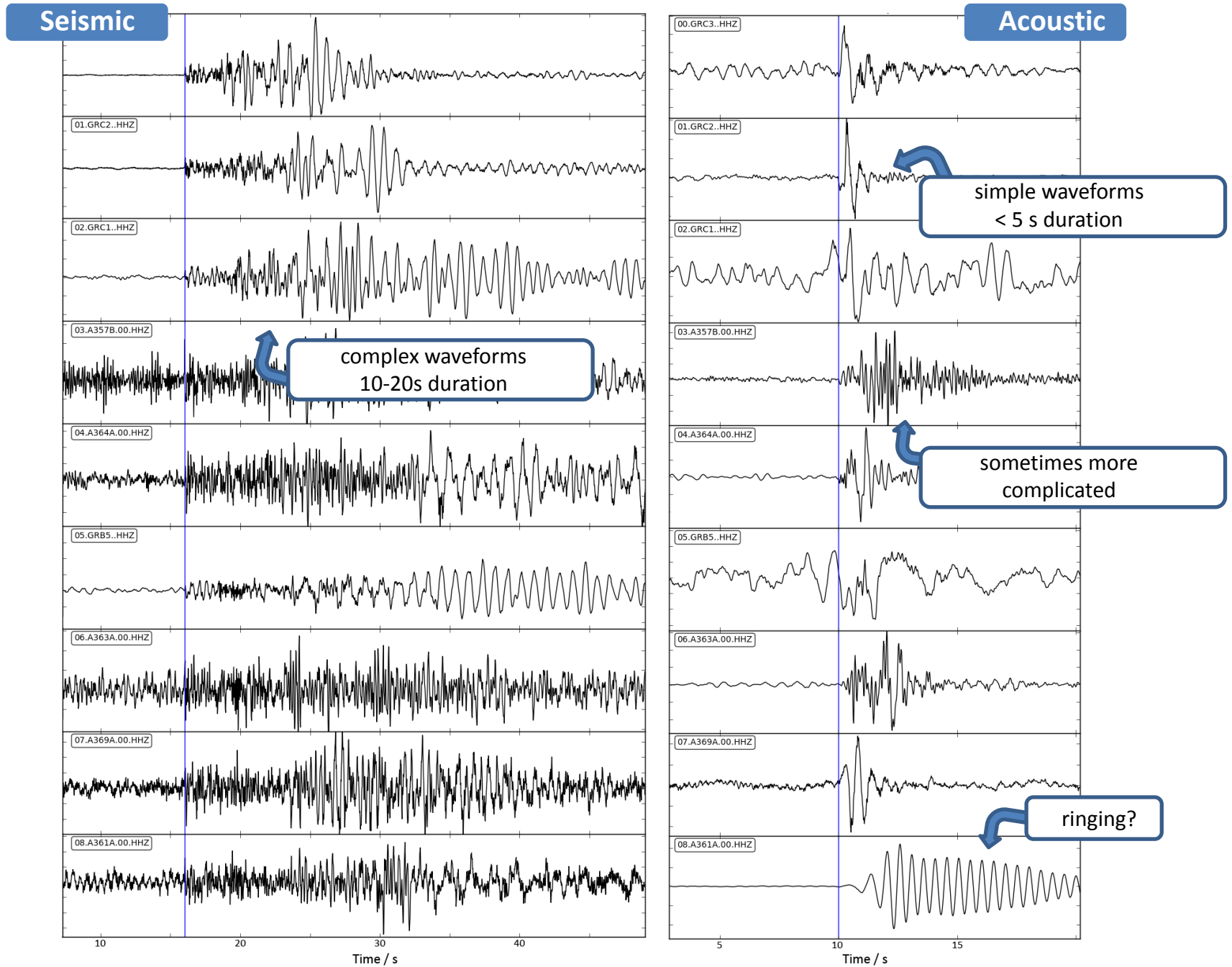
(no pre-selection, 1-2 Hz bandpass, individual scale)

- **Seismic phases** (P+S/Rg) clearly visible
  (Vp ~ 5.5 - 5.9 km/s Vs ~ 3.5 km/s)
- **Seismic amplitudes** correspond to local **Magnitude**
  M_l = 2.0 (ISC bulletin, event 61268997717)
- Three separate **acoustic phases**:

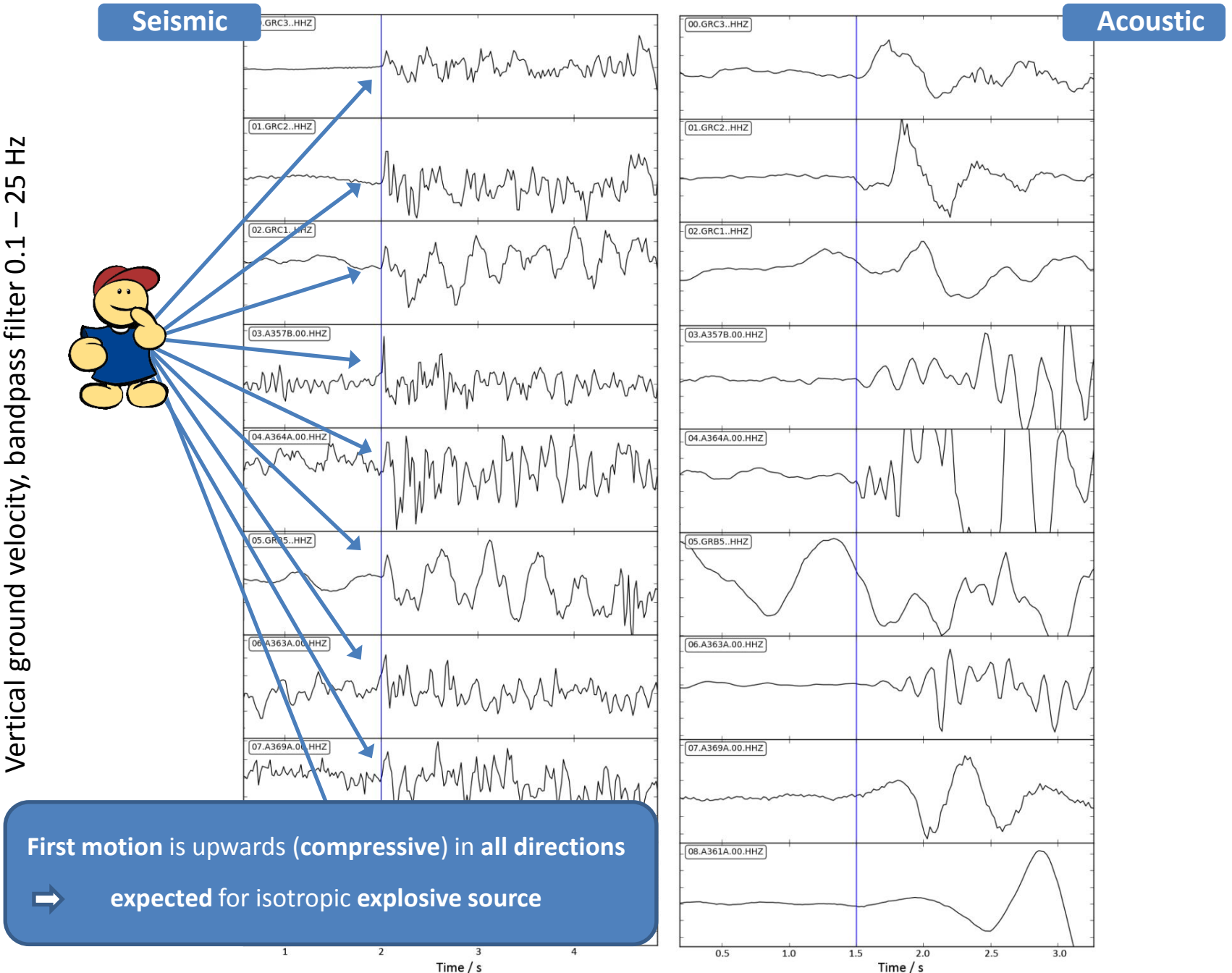
	Distance	*Celerity* (= distance / travel time)
Phase 1	10-200 km	310-340 m/s
Phase 2	150-325 km	270-300 m/s
Phase 3	250-350 km	240-260 m/s

84 positive **acoustic detections** within **350 km distance**
(for SnR > 3)

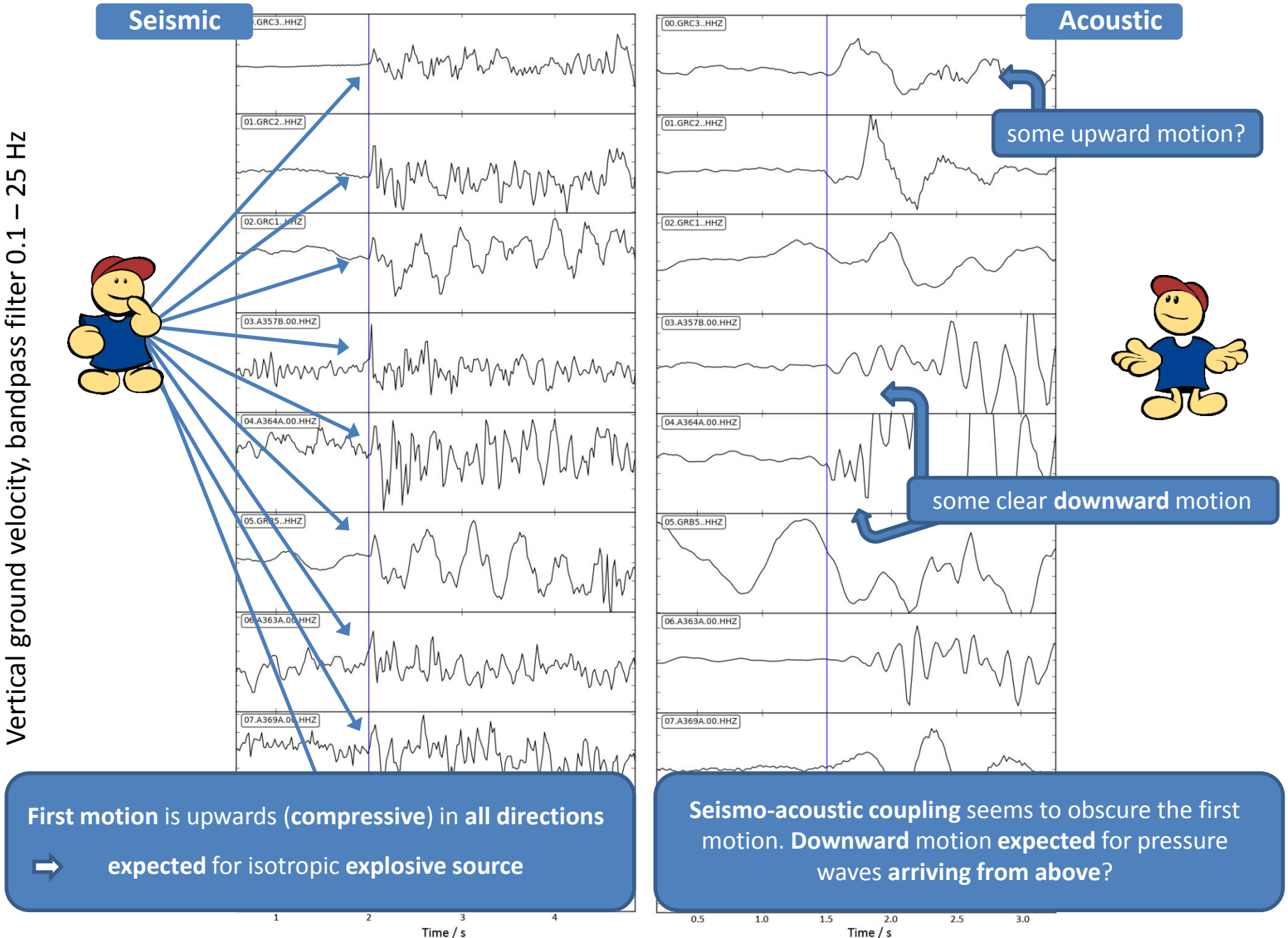
Ingolstadt explosion – Waveforms: seismic vs acoustic



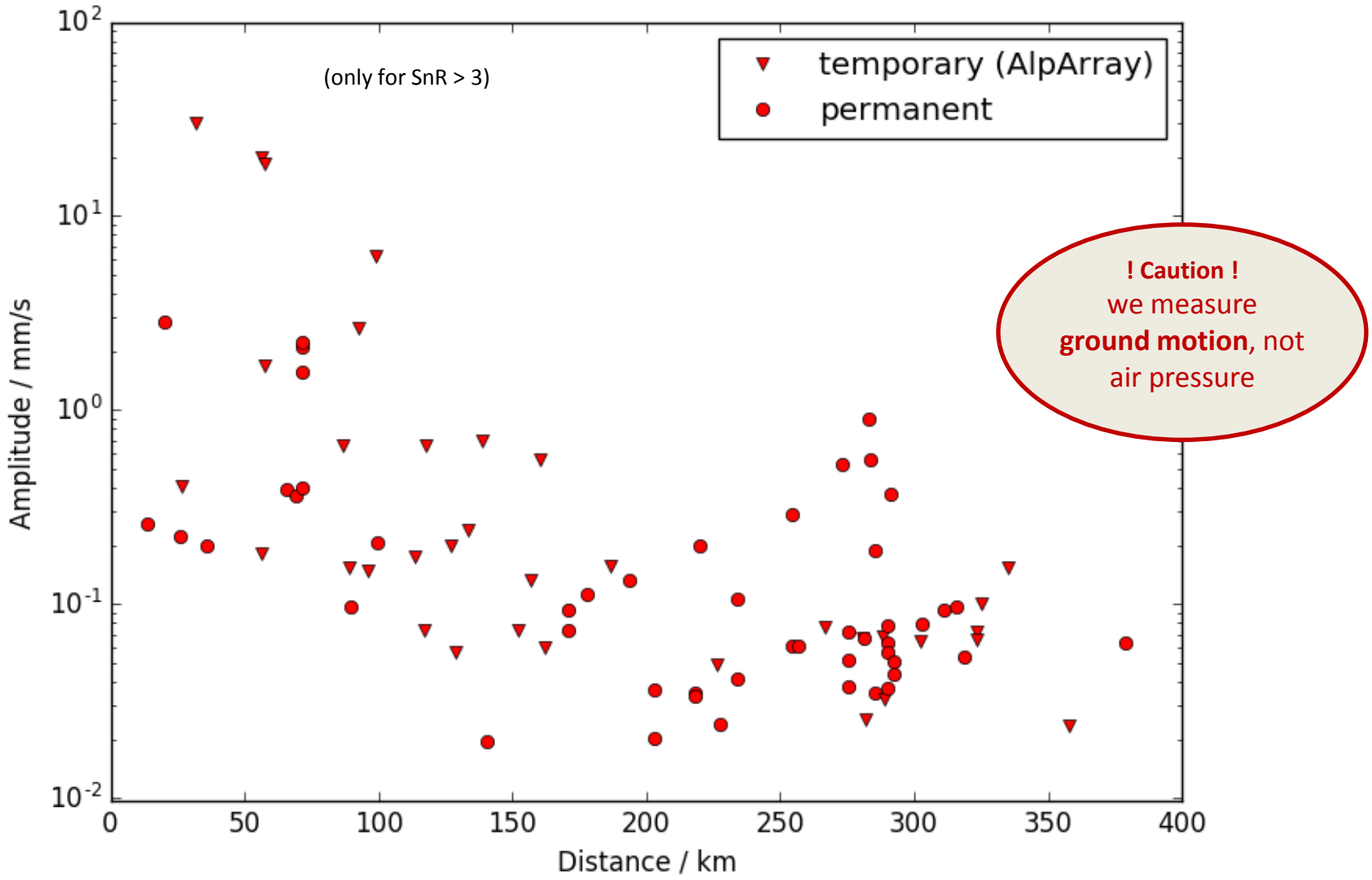
Ingolstadt explosion – Waveforms: seismic vs acoustic – close-up



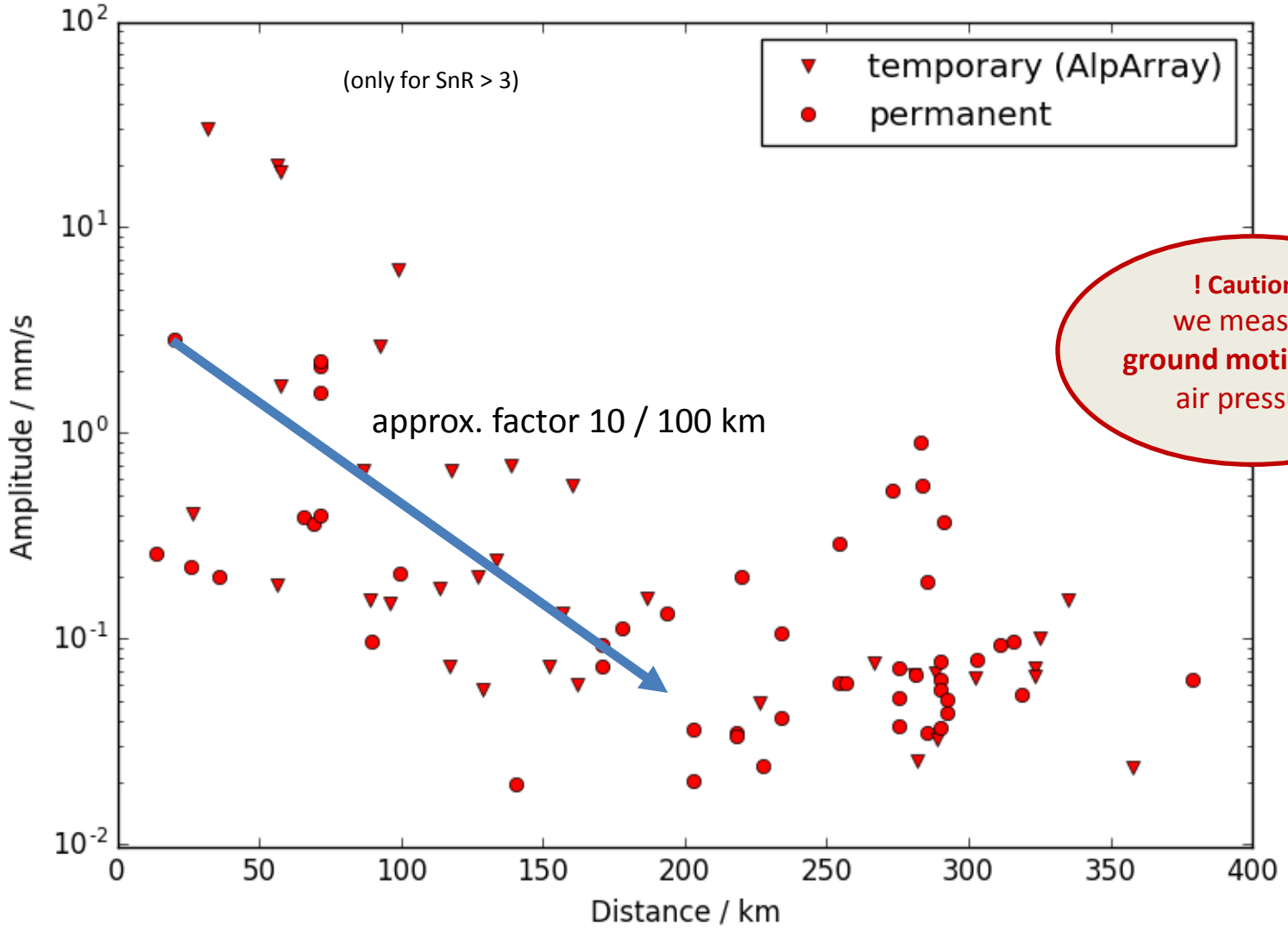
Ingolstadt explosion – Waveforms: seismic vs acoustic – close-up



Ingolstadt explosion – Regional infrasound attenuation



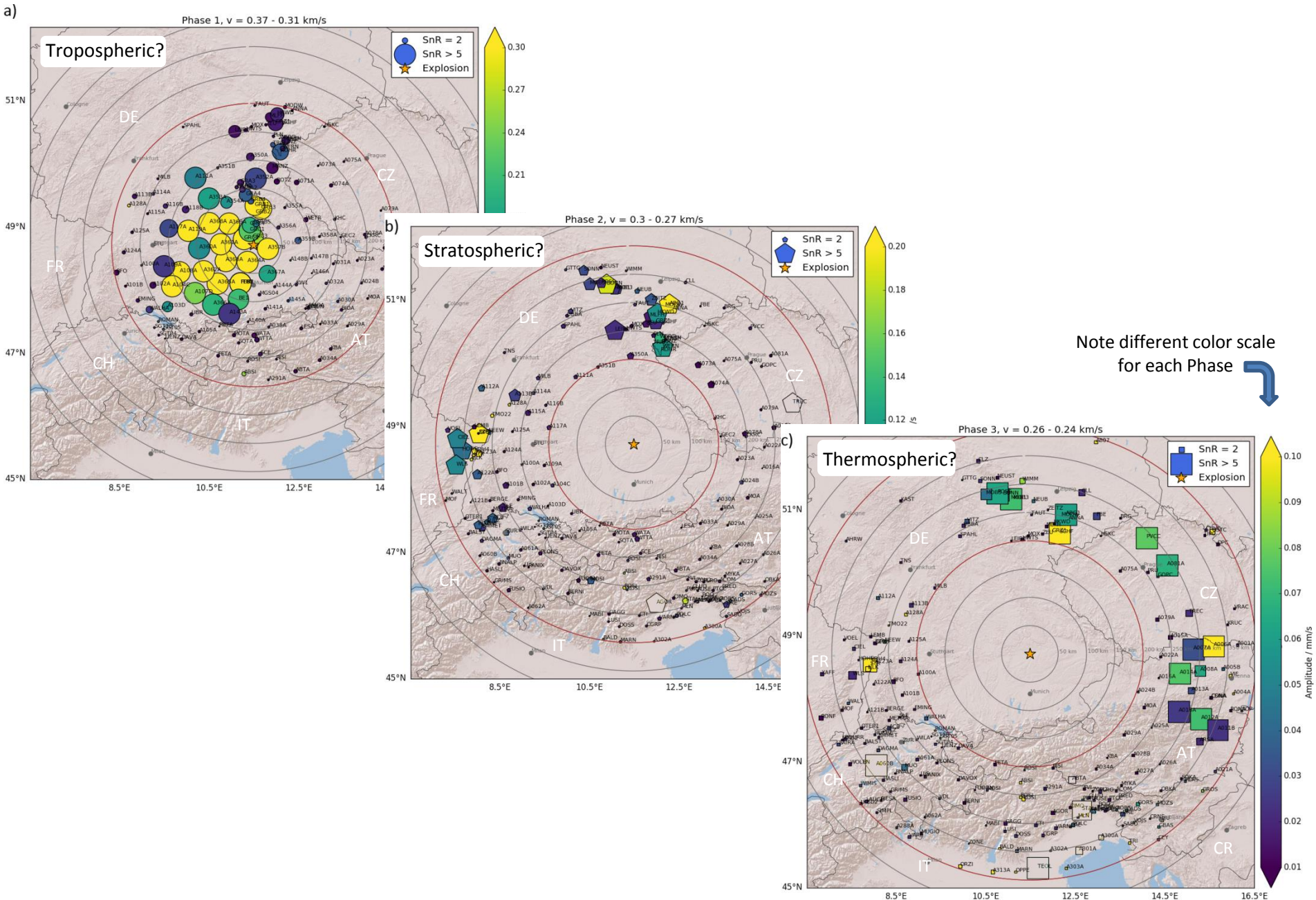
Ingolstadt explosion – Regional infrasound attenuation



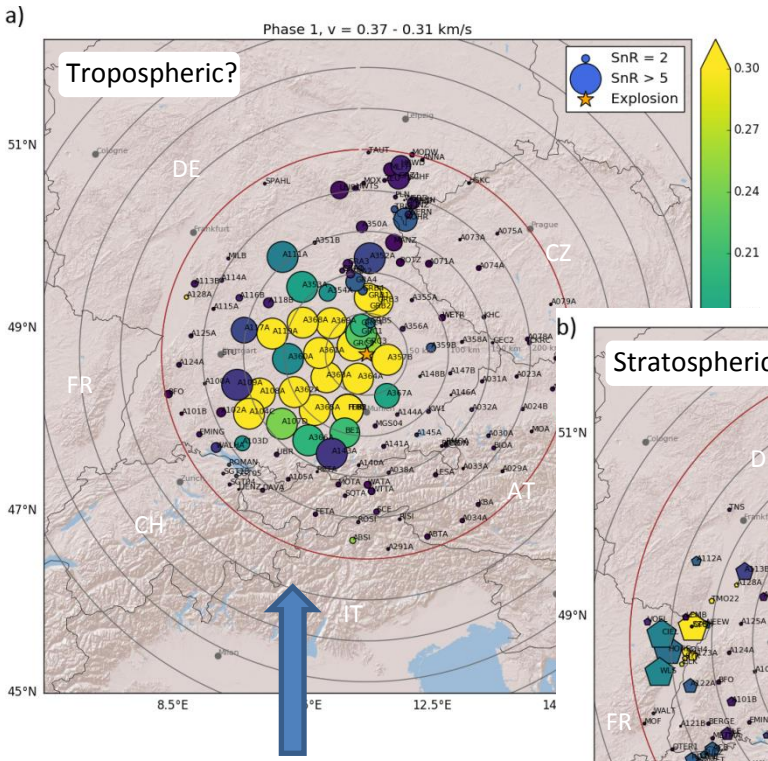
! Caution !
we measure **ground motion**, not air pressure

Within 200 km from the source amplitudes are attenuated approx. one order of magnitude per 100 km
→ Potentially allows **insight** into infrasound **attenuation** inside **tropospheric ducts ?**

Ingolstadt explosion – Spatial distribution of seismo-acoustic detections

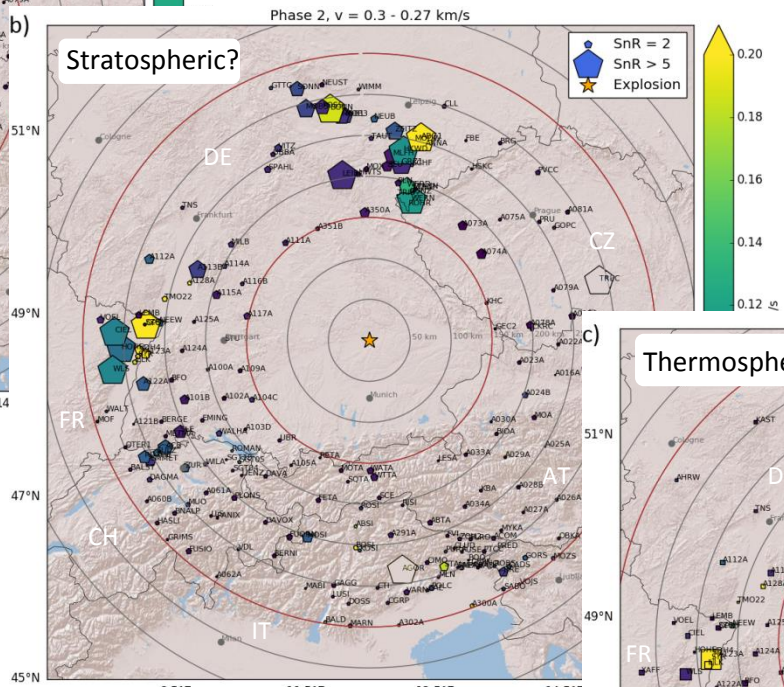


Ingolstadt explosion – Spatial distribution of seismo-acoustic detections

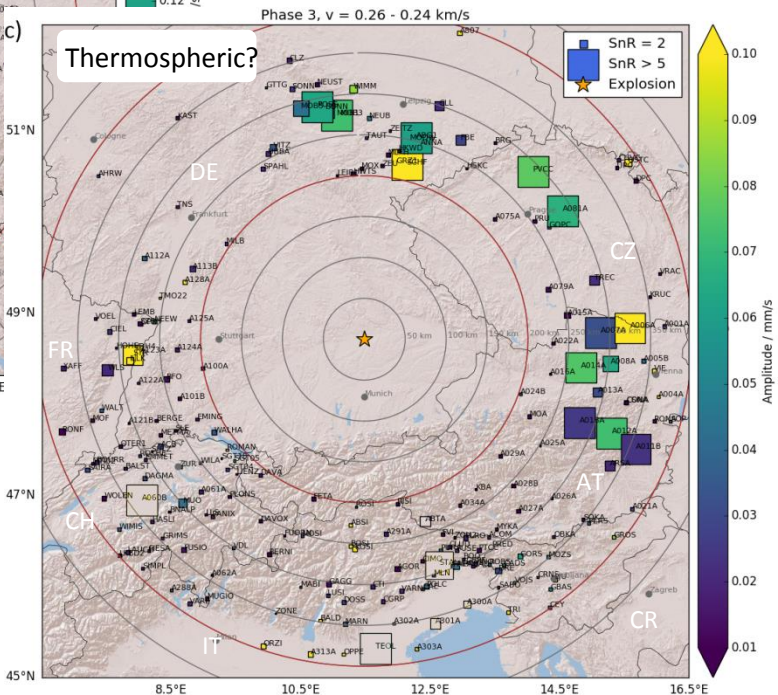


Phase 1 observed mainly in directions NW – SW of explosion

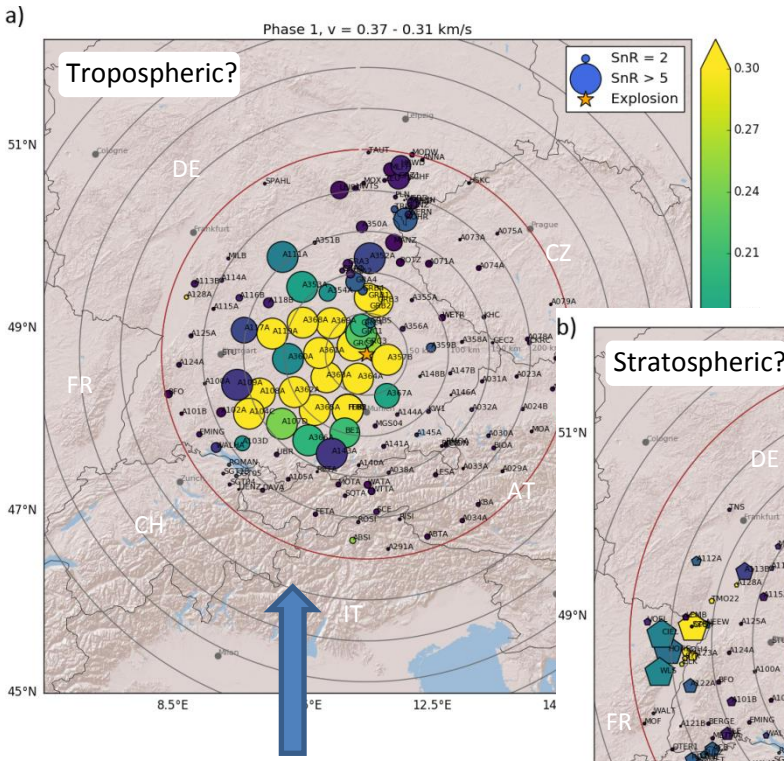
Several detection in narrow corridor towards N



Note different color scale for each Phase



Ingolstadt explosion – Spatial distribution of seismo-acoustic detections

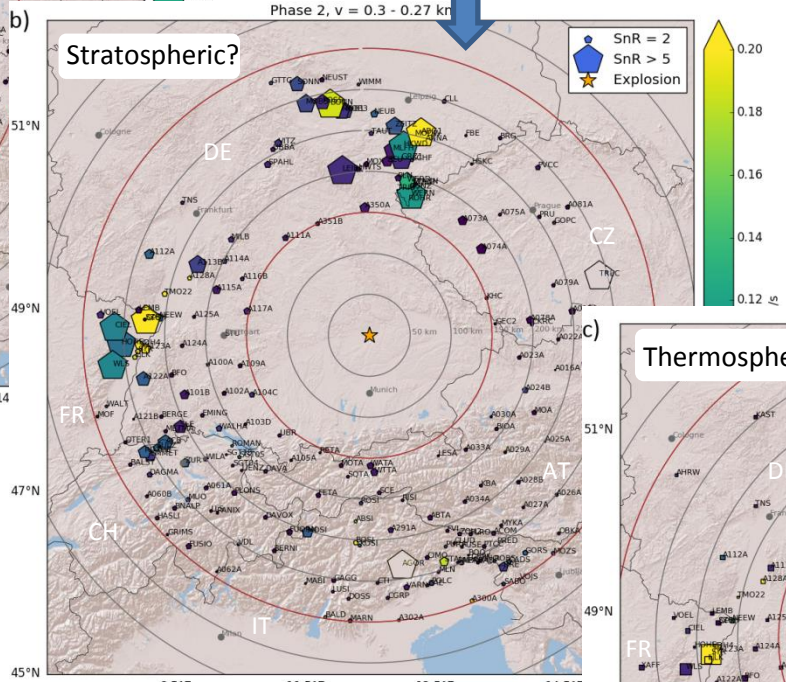


Phase 1 observed mainly in directions NW – SW of explosion

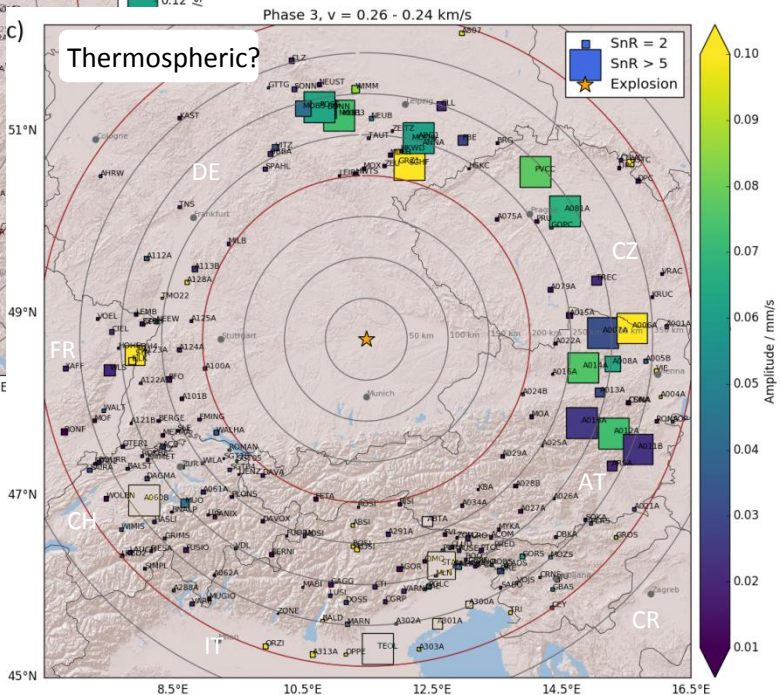
Several detection in narrow corridor towards N

Phase 2 observed in N directions and W – SW of explosion

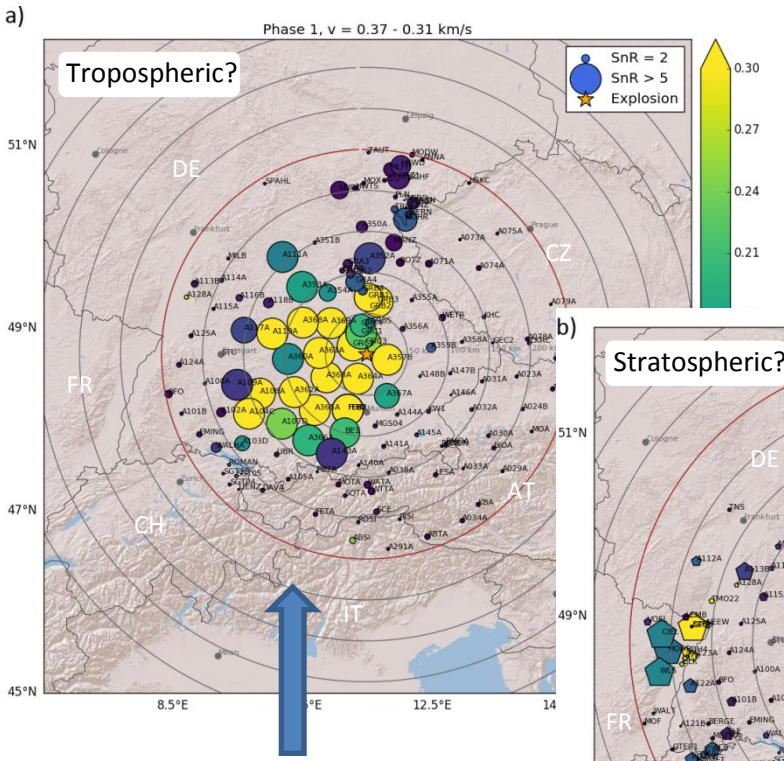
Note the station gap towards NW and NE



Note different color scale for each Phase



Ingolstadt explosion – Spatial distribution of seismo-acoustic detections

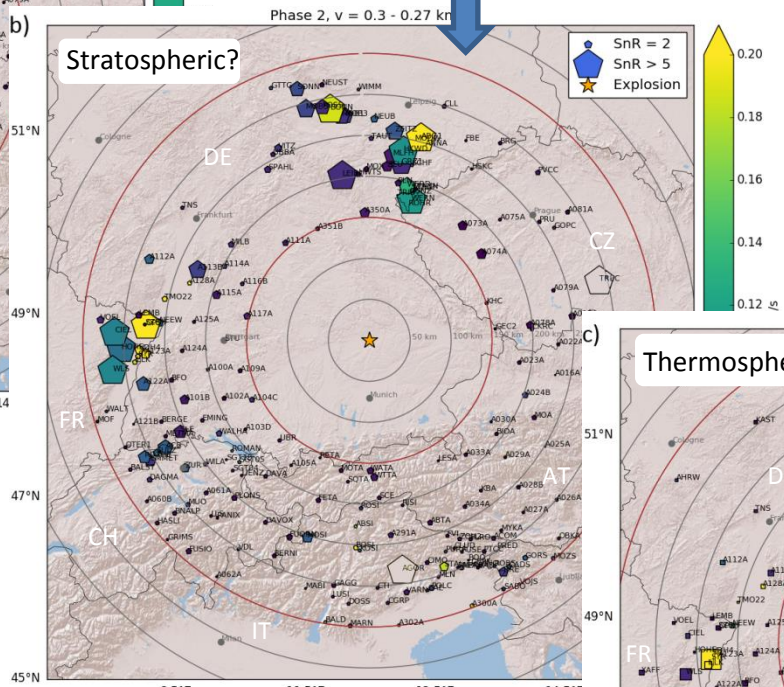


Phase 1 observed mainly in directions NW – SW of explosion

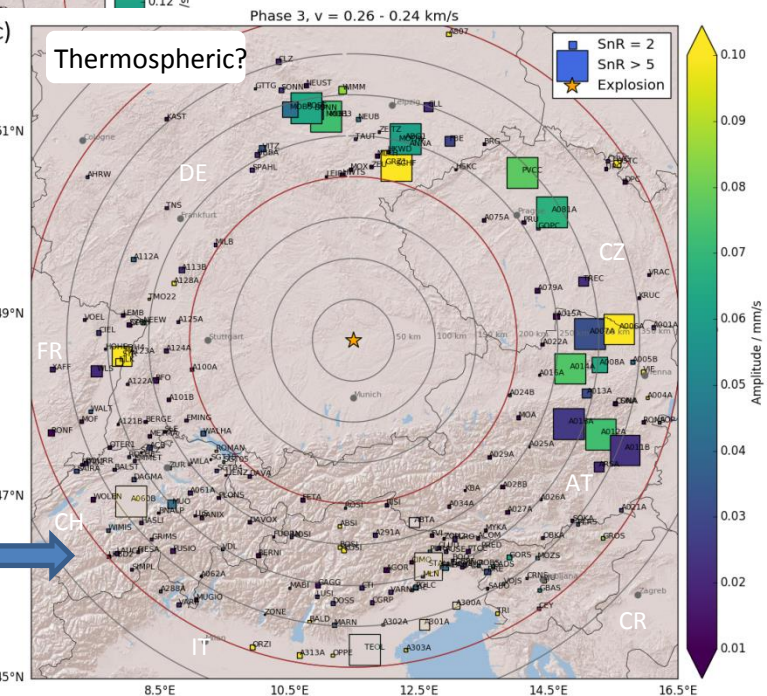
Several detection in narrow corridor towards N

Phase 2 observed in N directions and W – SW of explosion

Note the station gap towards NW and NE



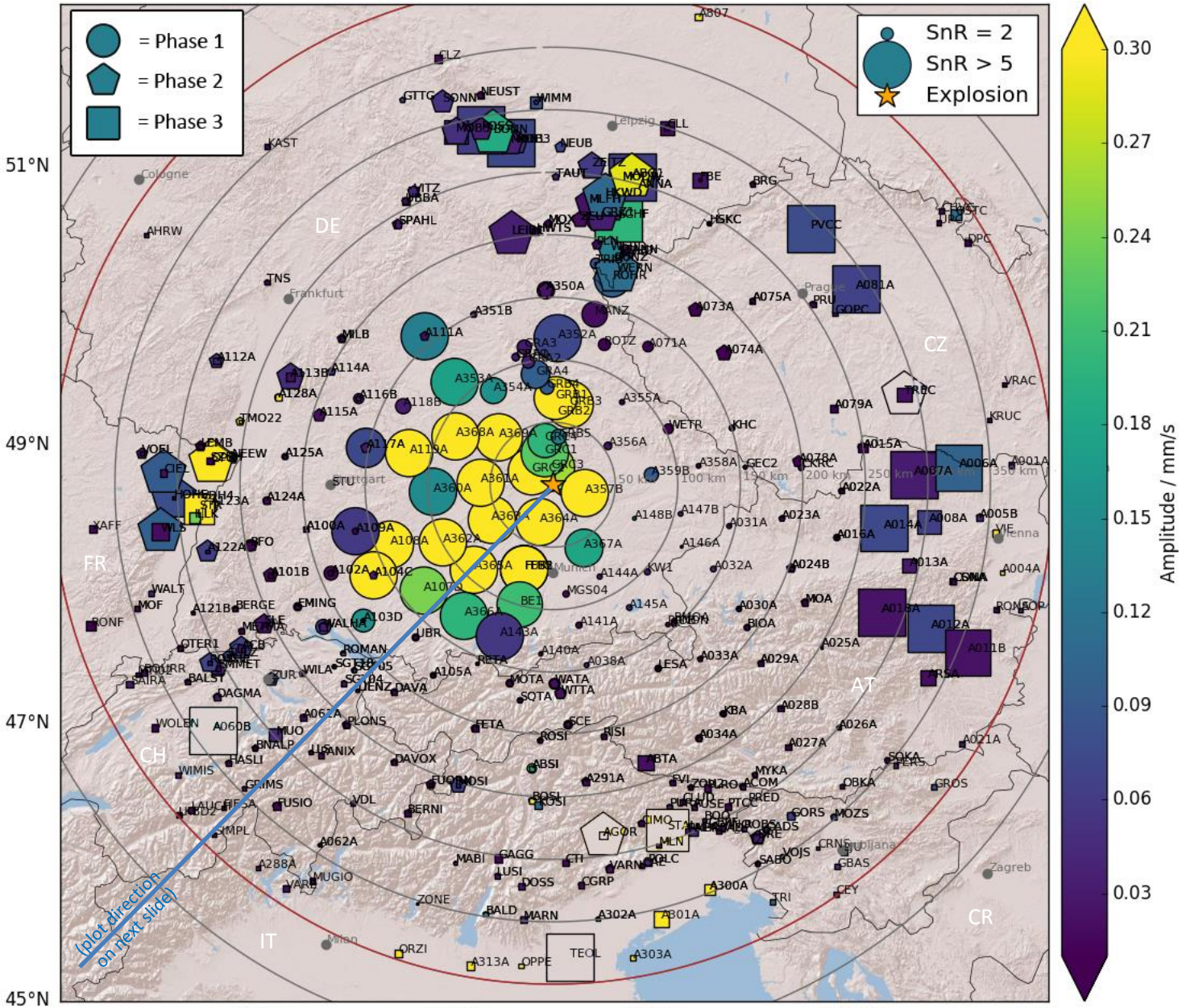
Note different color scale for each Phase



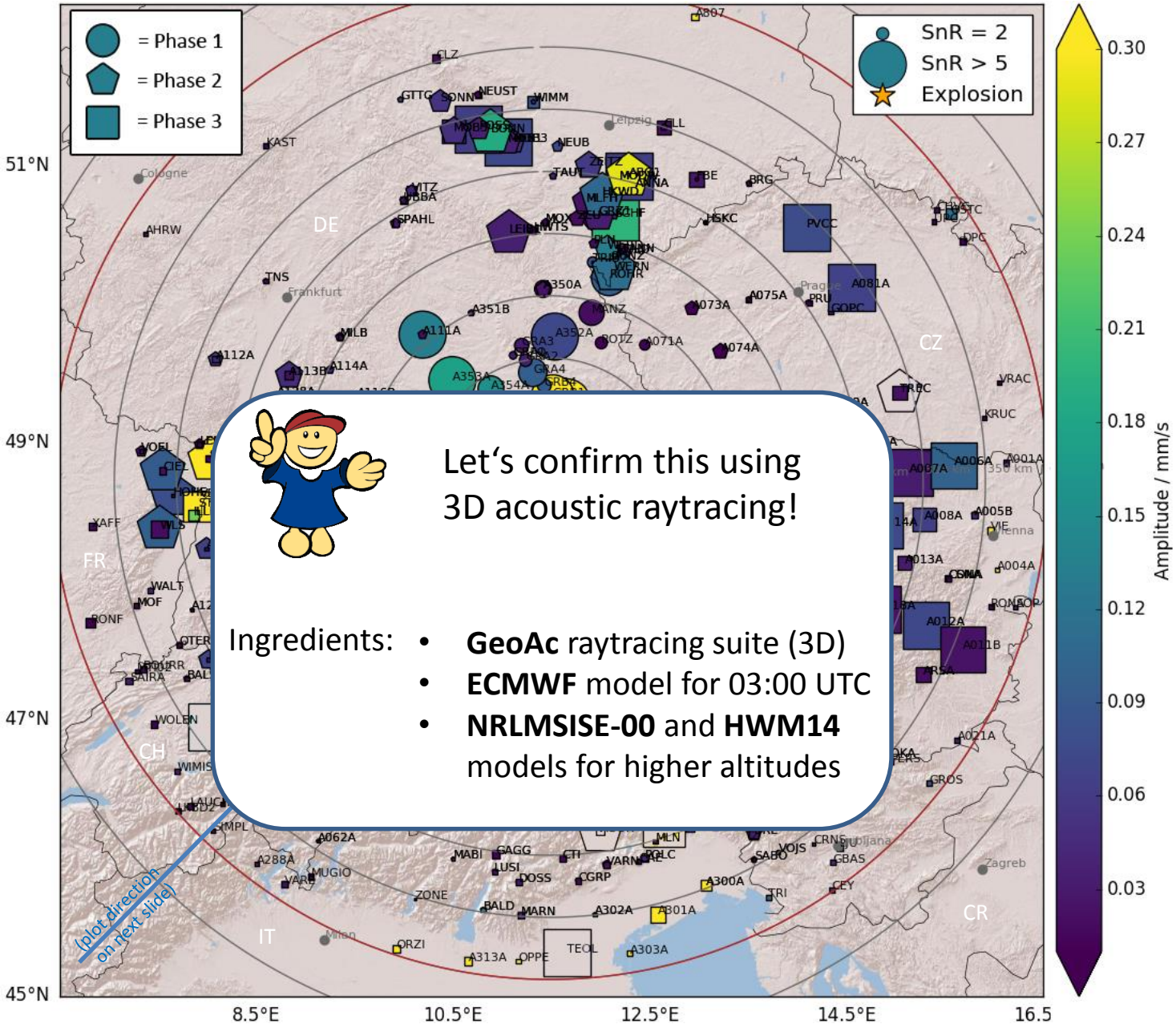
Phase 3 detected in wide azimuth range from N – SE

Note station gap towards NW and NE

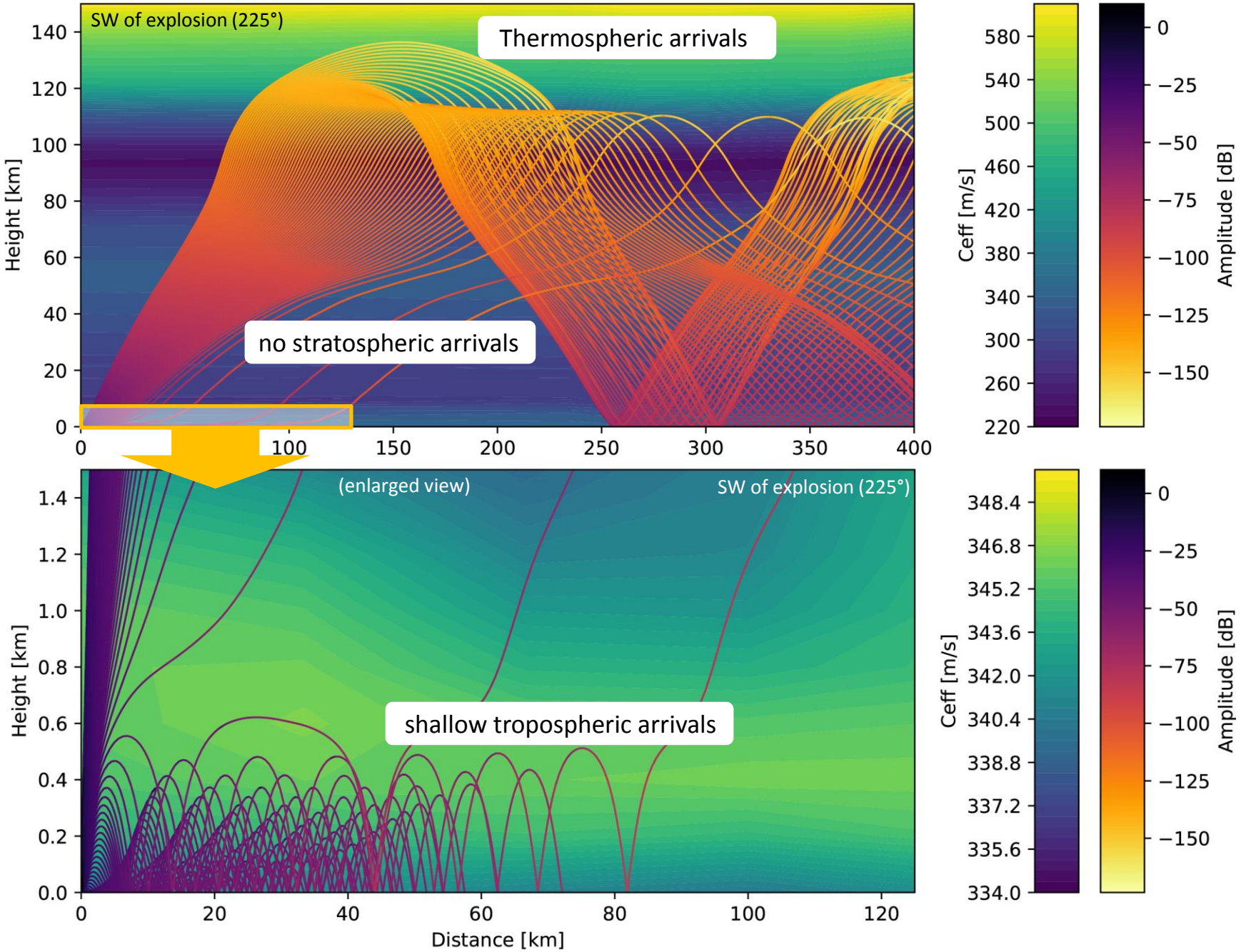
Ingolstadt explosion – Spatial distribution of seismo-acoustic detections



Ingolstadt explosion – Spatial distribution of seismo-acoustic detections



Ingolstadt explosion – Acoustic raytracing results (GeoAc raytracing suite, Blom & Waxler 2012)



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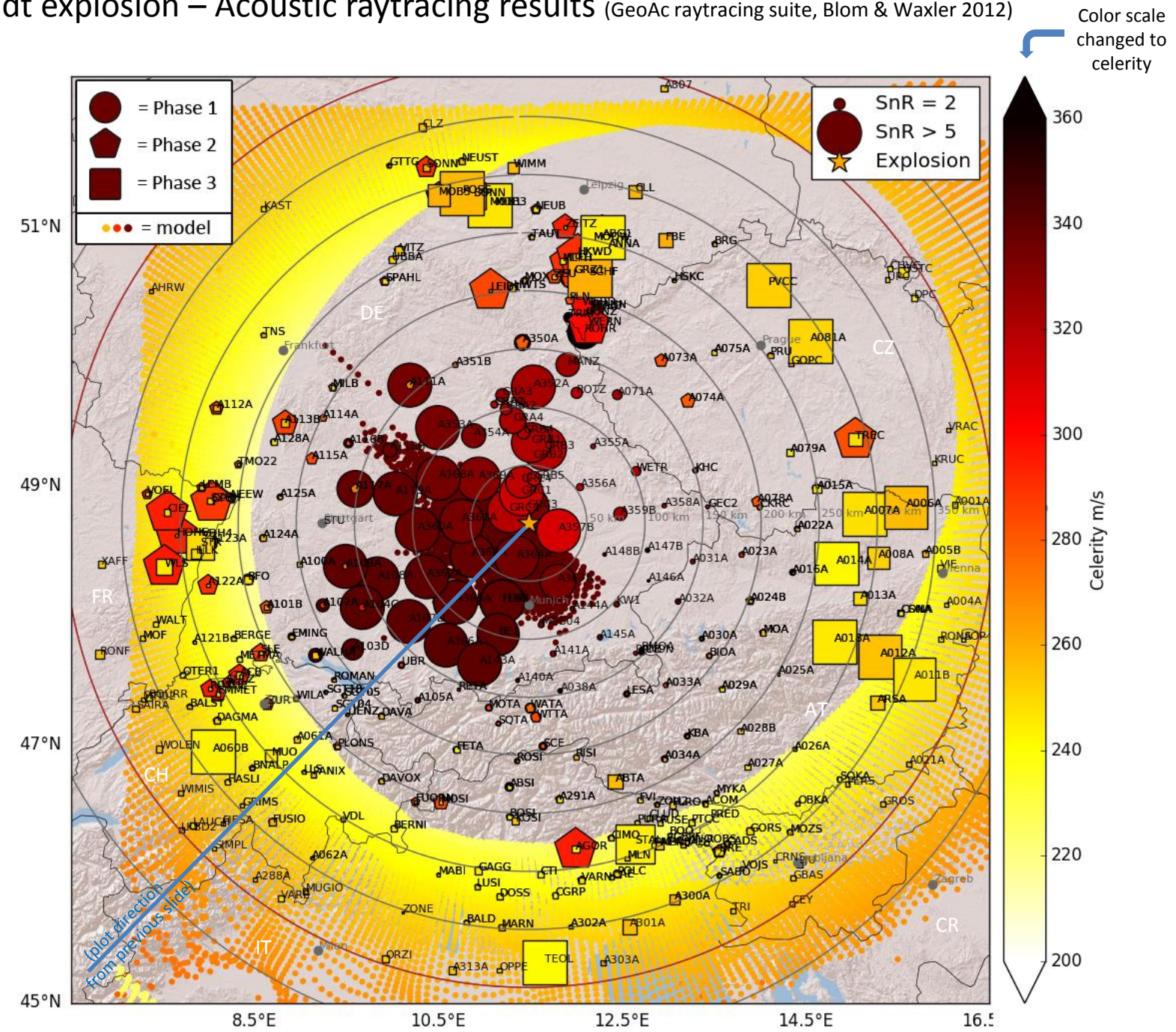
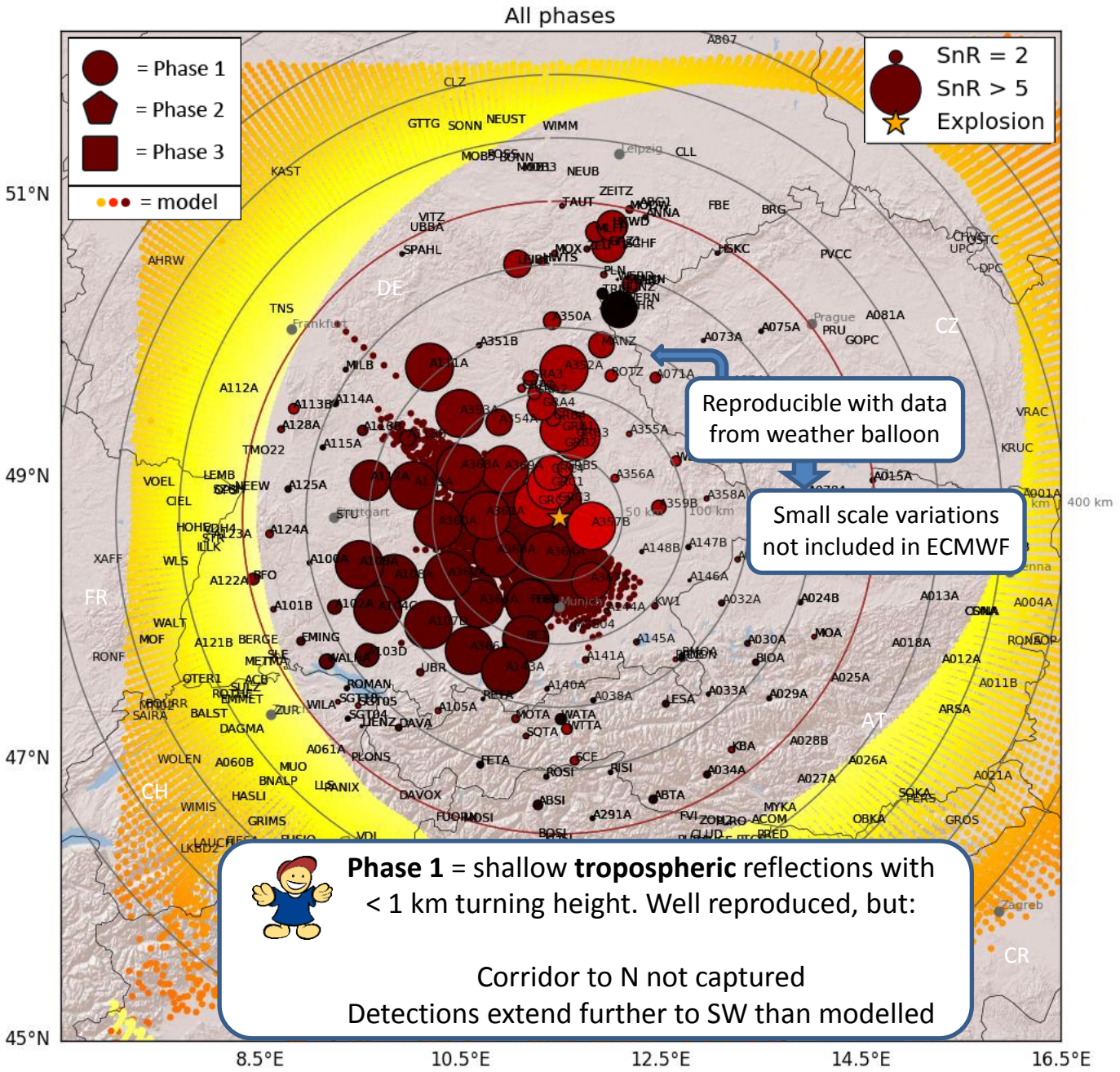
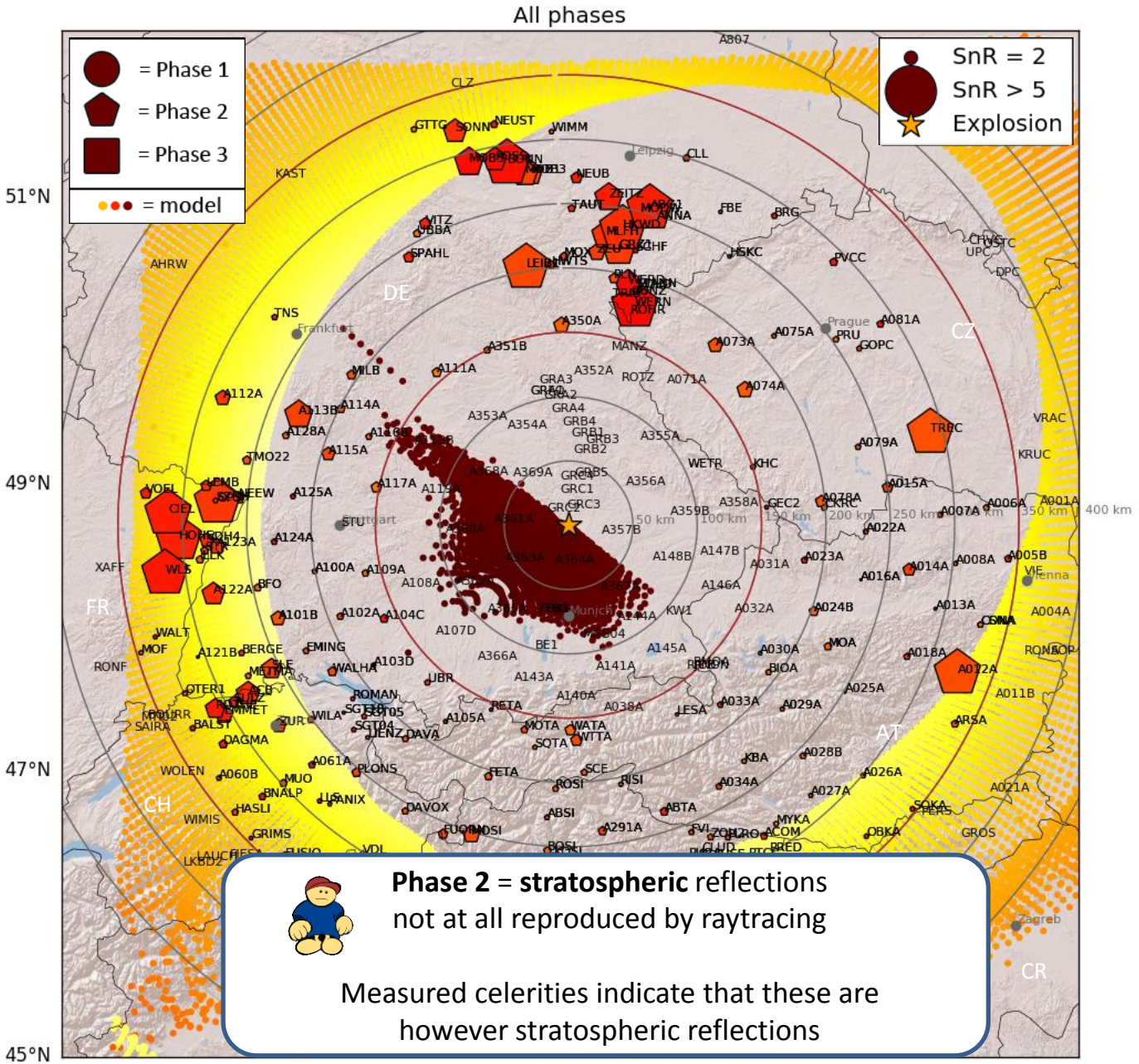


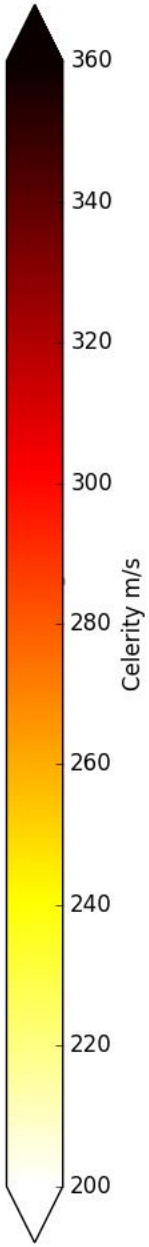
Ingolstadt explosion – Acoustic raytracing results / Phase 1



Ingolstadt explosion – Acoustic raytracing results / Phase 2



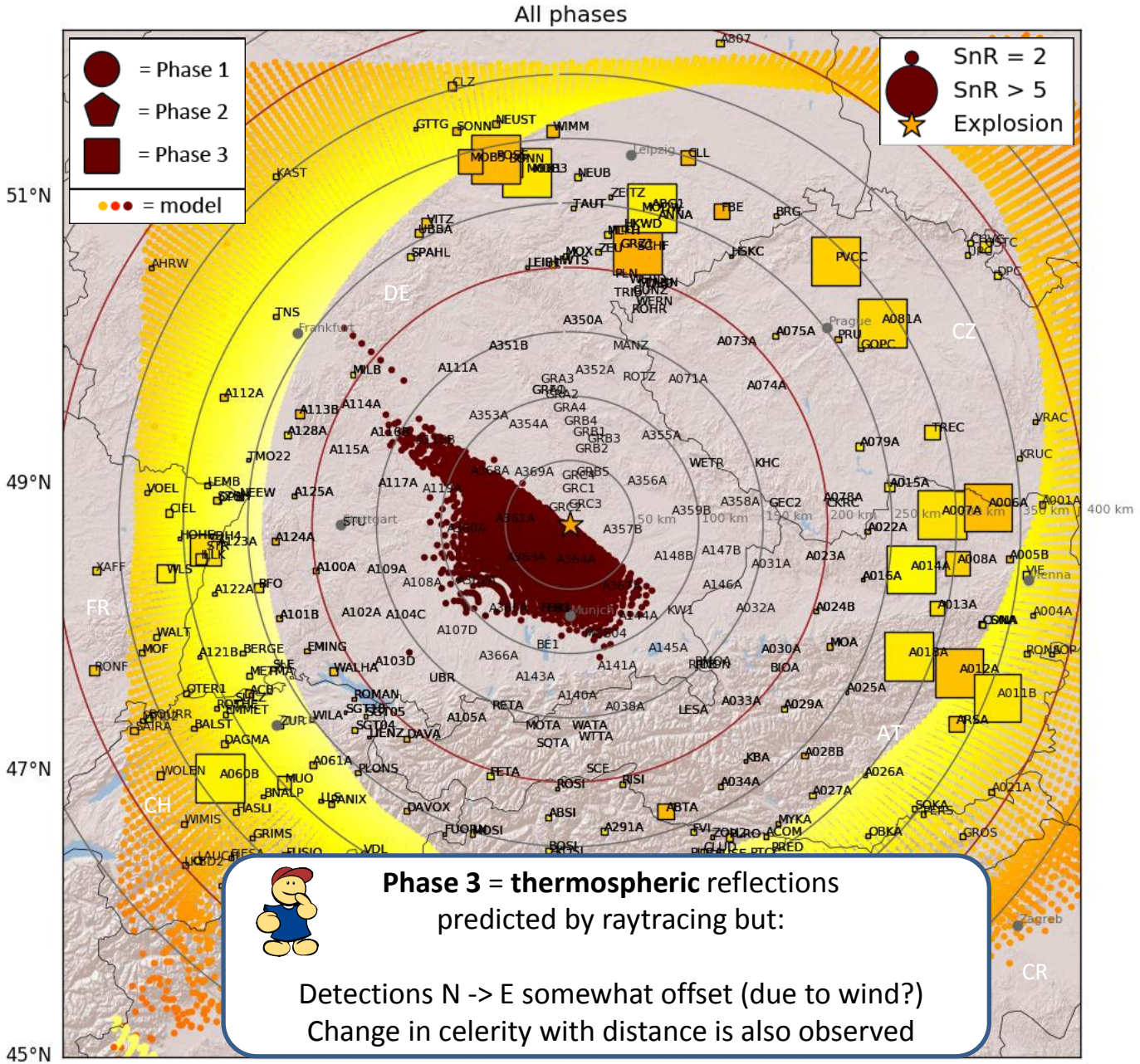
Color scale changed to celerity



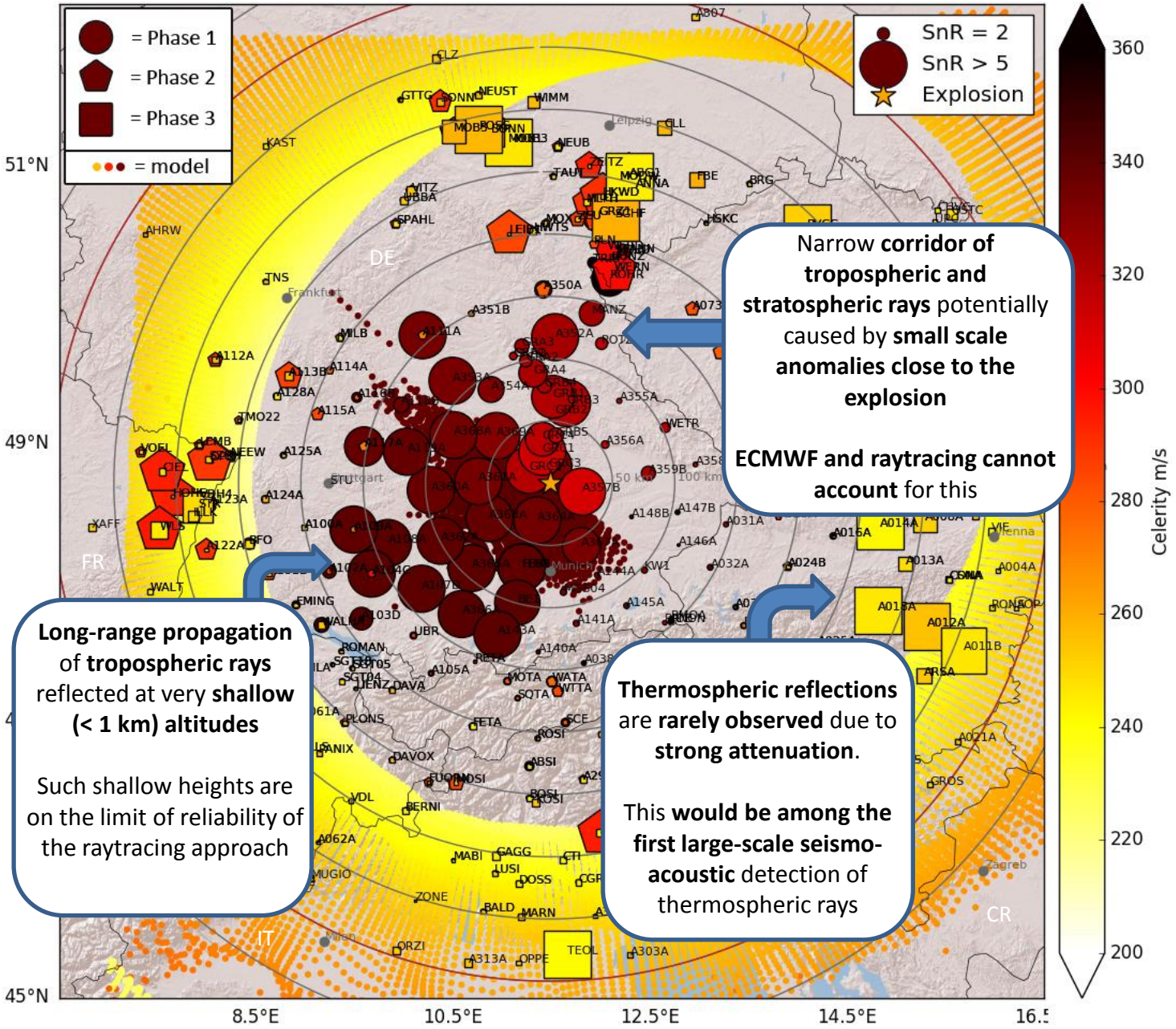
Phase 2 = **stratospheric** reflections not at all reproduced by raytracing

Measured celerities indicate that these are however stratospheric reflections

Ingolstadt explosion – Acoustic raytracing results / Phase 3

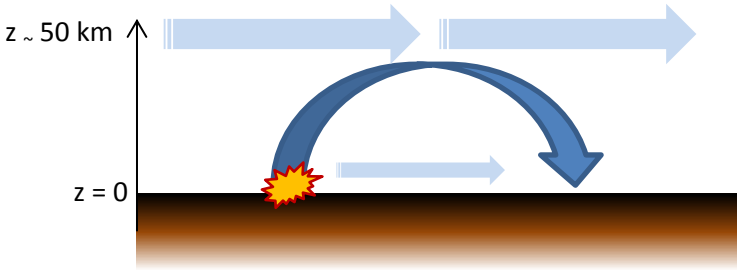


Ingolstadt explosion – Interpretation of modelling results



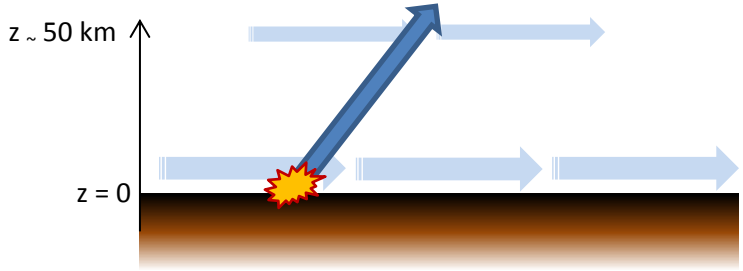
Ingolstadt explosion – Absence of stratospheric reflections

- Effective sound speed ratio: if $\frac{C_{eff}\ (strato)}{C_{eff}\ (ground)} > 1$ stratospheric reflections are expected



Reflection

$$\frac{C_{eff}\ (strato)}{C_{eff}\ (ground)} > 1$$

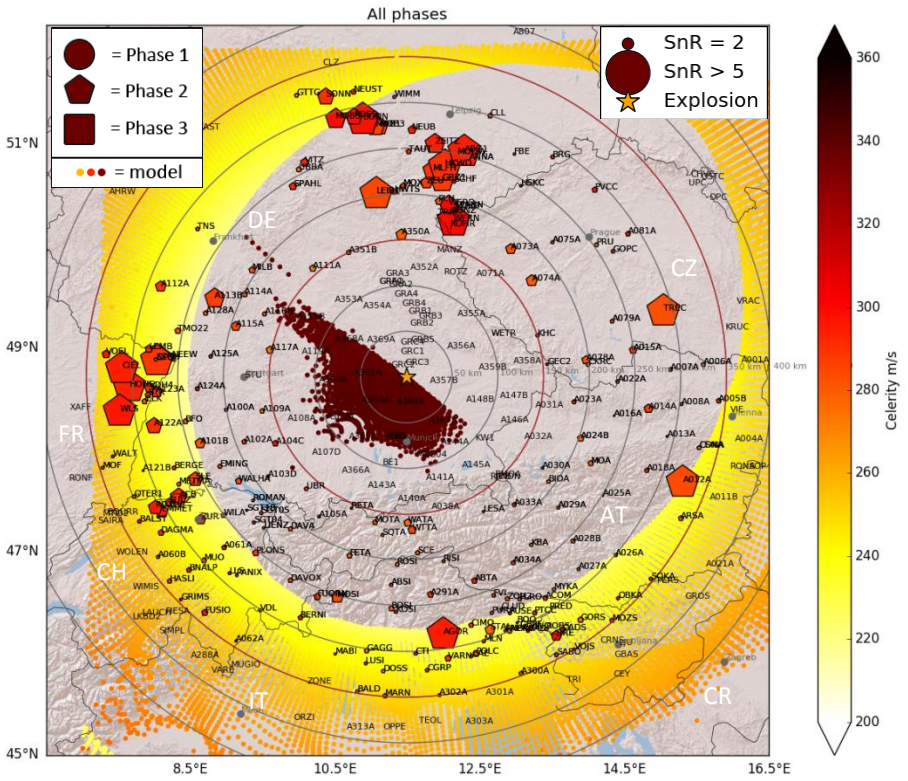


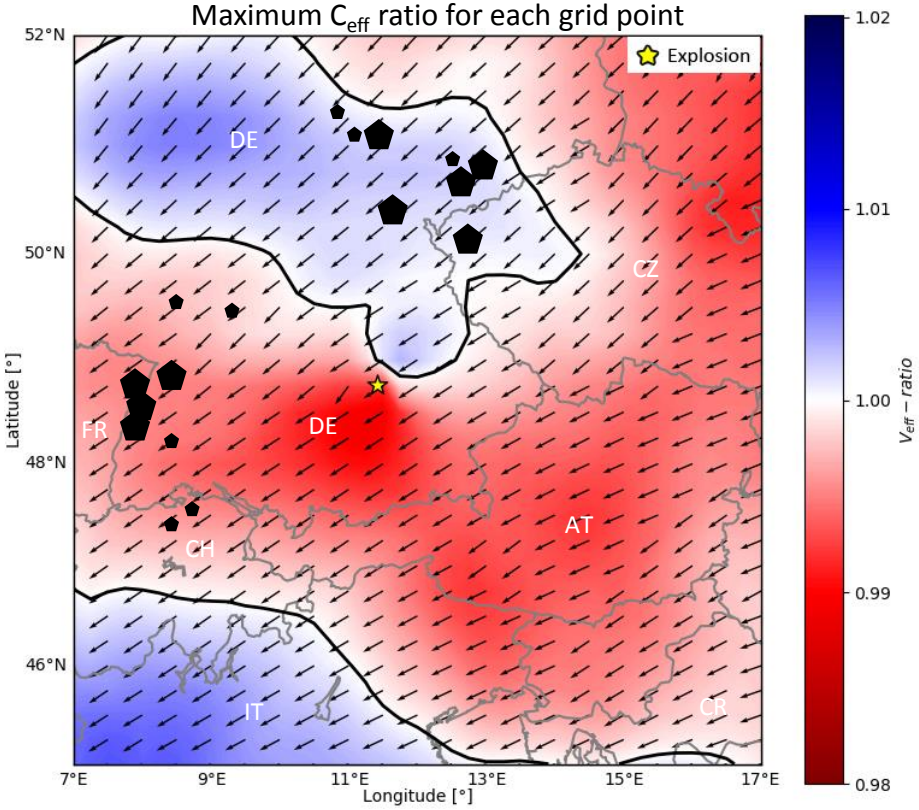
No reflection

$$\frac{C_{eff}\ (strato)}{C_{eff}\ (ground)} < 1$$

Ingolstadt explosion – Absence of stratospheric reflections

- Effective sound speed ratio: if $\frac{C_{eff}\ (strato)}{C_{eff}\ (ground)} > 1$ stratospheric reflections are expected





Why do we still see stratospheric arrivals?

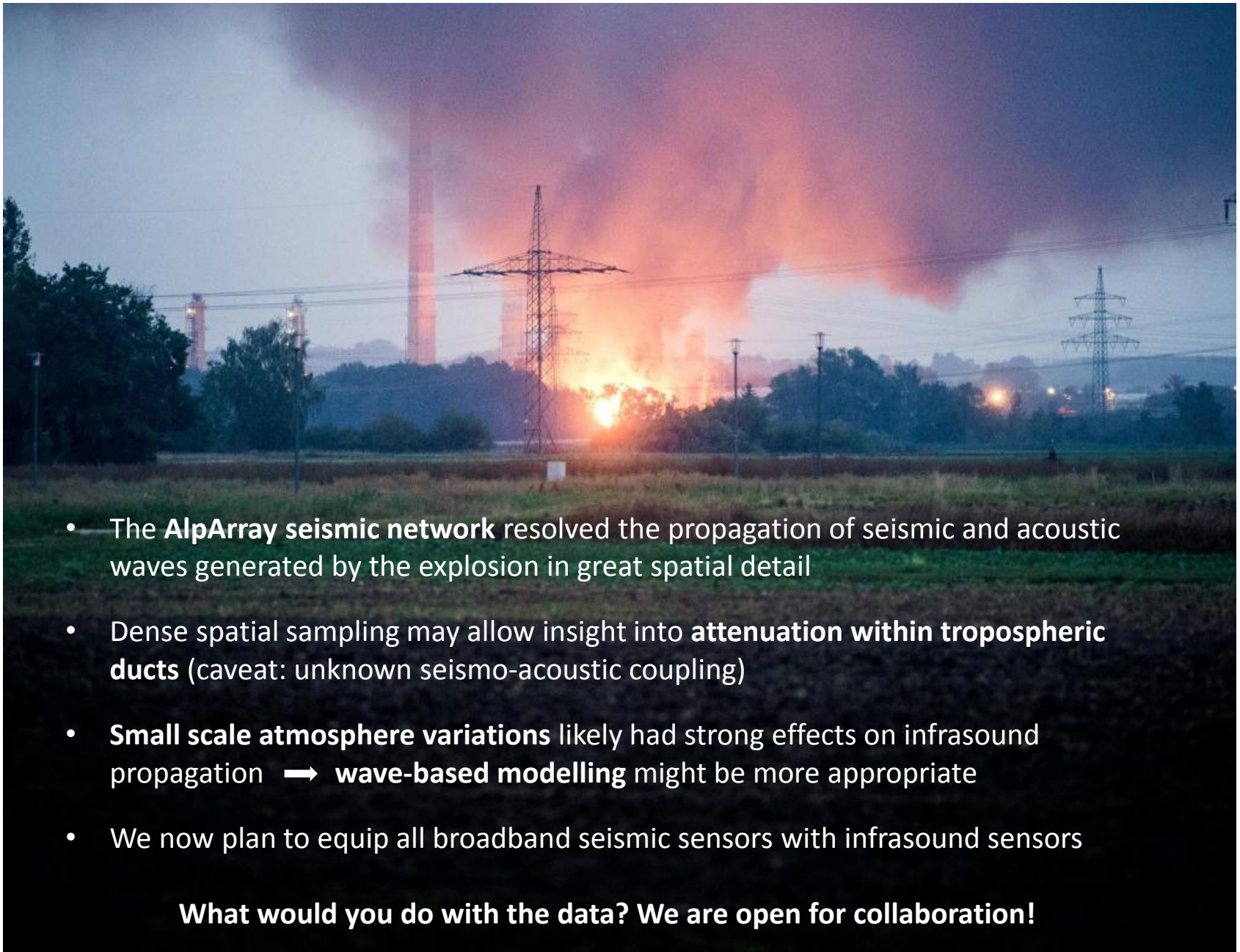
= stratospheric reflections expected

= no stratospheric reflections expected

= measured stratospheric detections

= wind direction

Ingolstadt gas explosion – summary



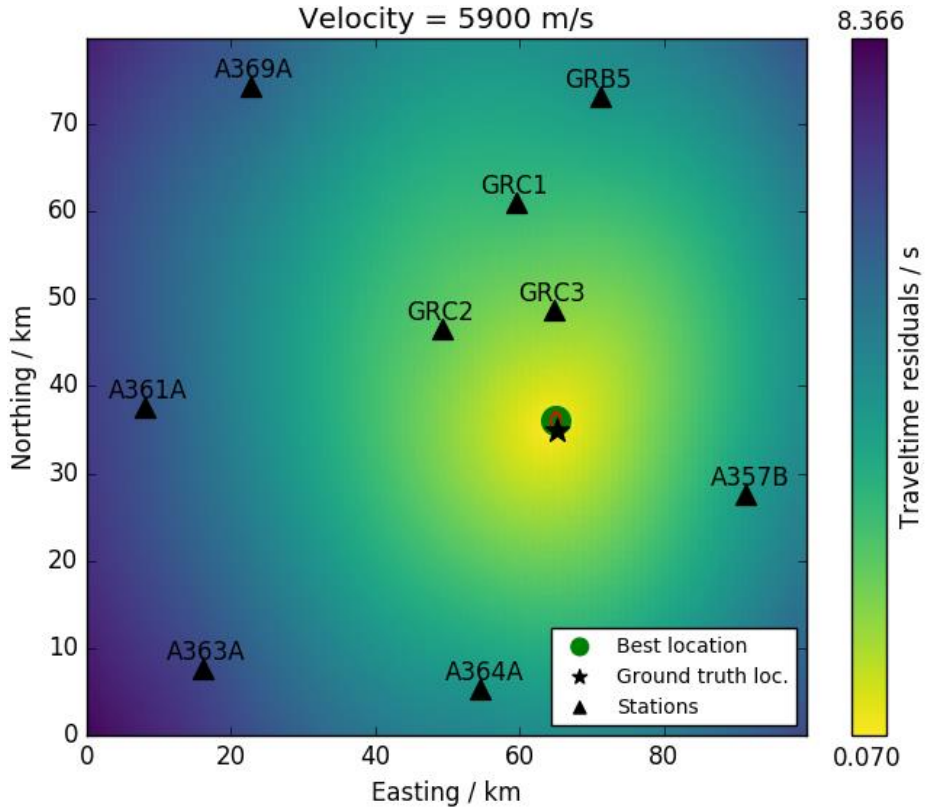
- The **AlpArray seismic network** resolved the propagation of seismic and acoustic waves generated by the explosion in great spatial detail
- Dense spatial sampling may allow insight into **attenuation within tropospheric ducts** (caveat: unknown seismo-acoustic coupling)
- **Small scale atmosphere variations** likely had strong effects on infrasound propagation ➞ **wave-based modelling** might be more appropriate
- We now plan to equip all broadband seismic sensors with infrasound sensors

What would you do with the data? We are open for collaboration!

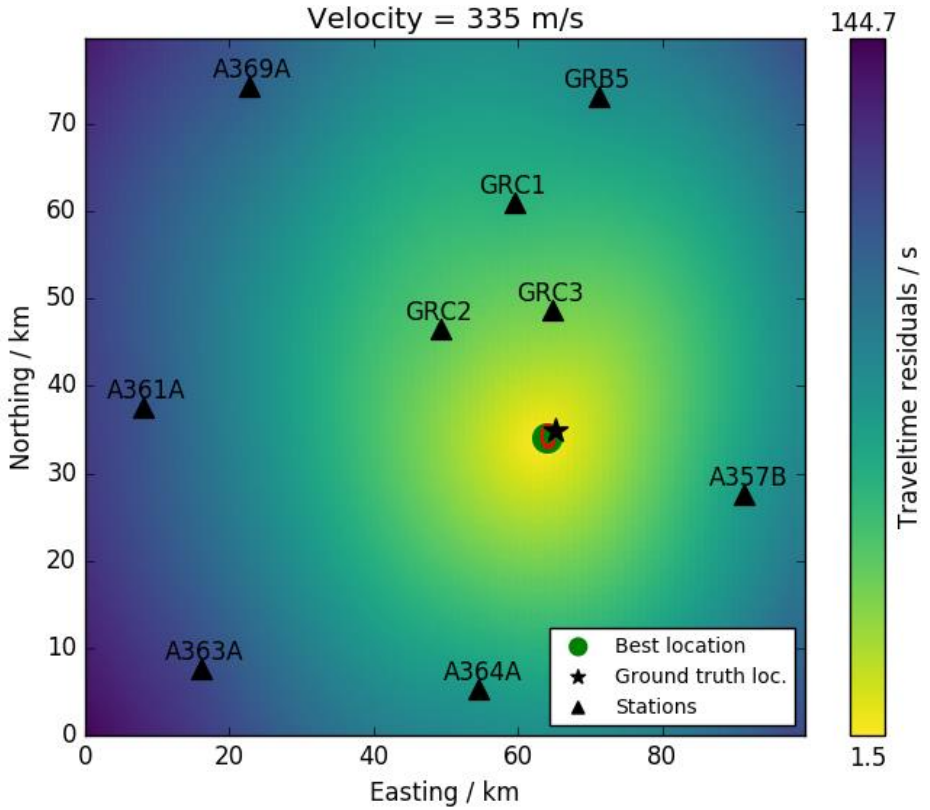
Ingolstadt explosion – Location: seismic vs acoustic

use **first onset** times to **locate** the event via **grid search** (minimize travel time residuals between measured & expected arrivals)

Seismic

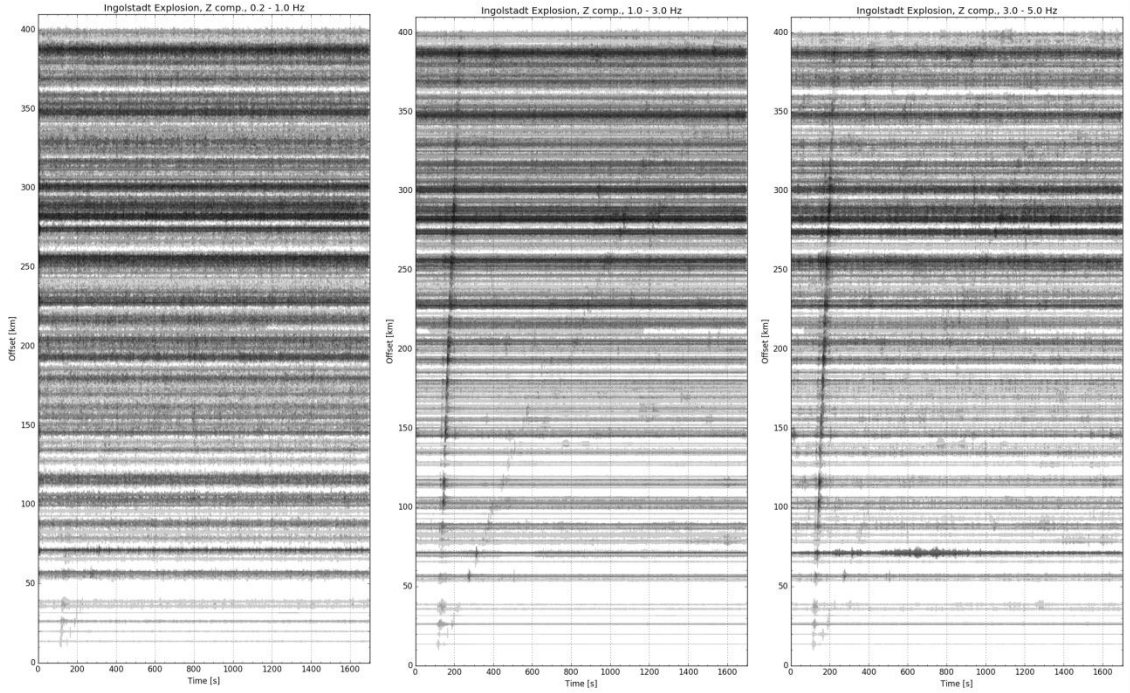


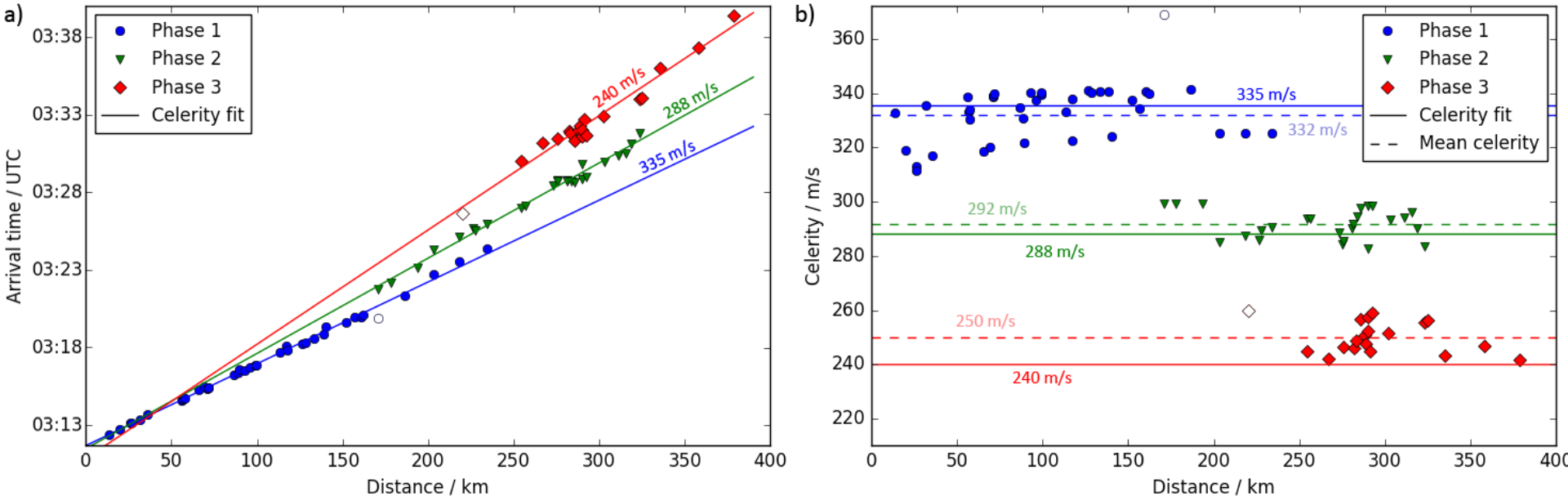
Acoustic

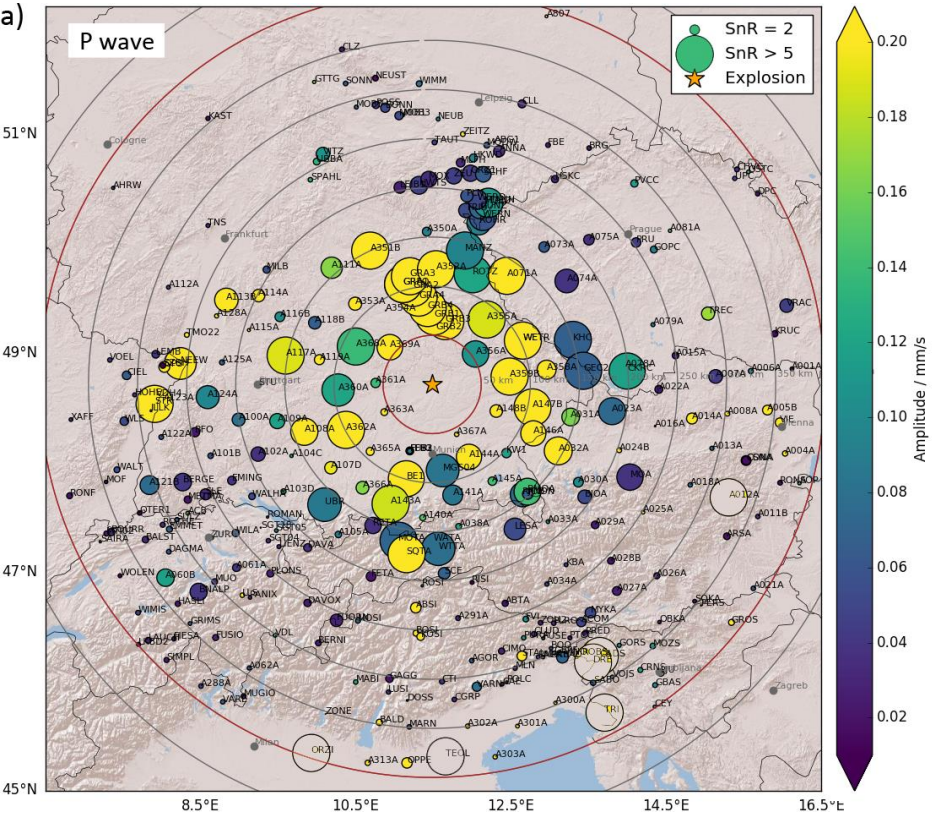


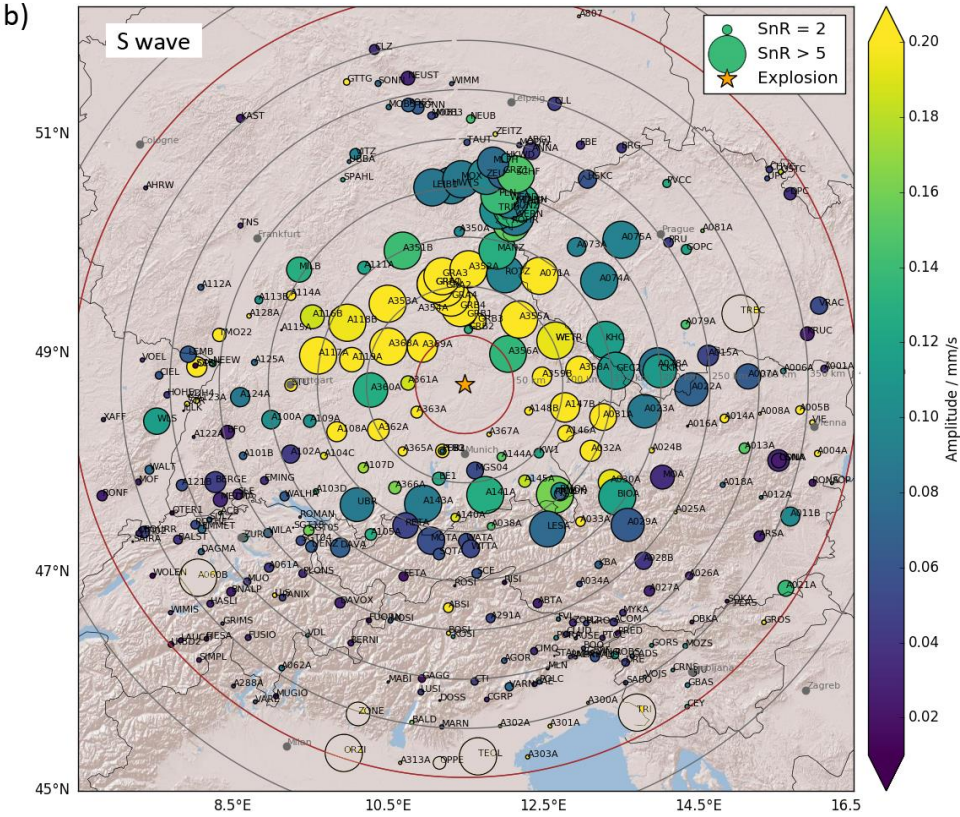
= 10% variation ellipse (< 1km diameter for seismic & acoustic)
seismic and acoustic location are of similar quality

Origin time (seismic & acoustic) = 03:11:45 UTC +/- 1s (in agreement with ISC entry and ground truth video records)


Ingolstadt Explosion, Z comp., 0.2 - 1.0 Hz
Ingolstadt Explosion, Z comp., 1.0 - 3.0 Hz
Ingolstadt Explosion, Z comp., 3.0 - 5.0 Hz
Ingolstadt Explosion, Z comp., 5.0 - 7.0 Hz
Ingolstadt Explosion, Z comp., 7.0 - 10.0 Hz
Ingolstadt Explosion, Z comp., 10.0 - 15.0 Hz
Offset [km]
Time [s]
0
50
100
150
200
250
300
350
400
0
200
400
600
800
1000
1200
1400
1600


a)
Phase 1
Phase 2
Phase 3
Celerity fit
240 m/s
288 m/s
335 m/s
Arrival time / UTC
03:38
03:33
03:28
03:23
03:18
03:13
0
50
100
150
200
250
300
350
400
Distance / km
b)
Phase 1
Phase 2
Phase 3
Celerity fit
Mean celerity
335 m/s
332 m/s
292 m/s
288 m/s
250 m/s
240 m/s
Celerity / m/s
360
340
320
300
280
260
240
220
Distance / km

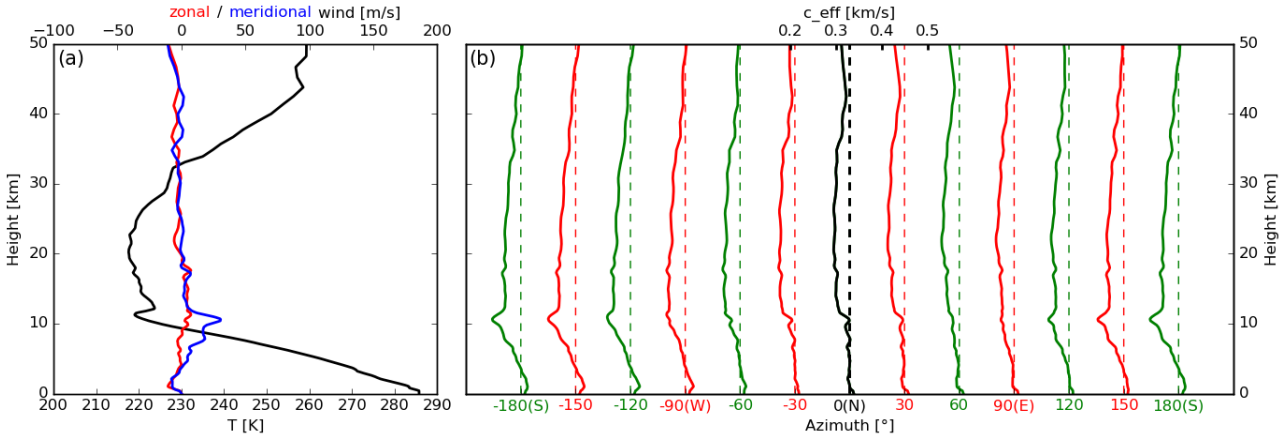

a)
P wave
SnR = 2
SnR > 5
Explosion
Amplitude / mm/s
0.20
0.18
0.16
0.14
0.12
0.10
0.08
0.06
0.04
0.02
51°N
49°N
47°N
45°N
8.5°E
10.5°E
12.5°E
14.5°E
16.5°E


b)
S wave
SnR = 2
SnR > 5
Explosion
Amplitude / mm/s
0.20
0.18
0.16
0.14
0.12
0.10
0.08
0.06
0.04
0.02
51°N
49°N
47°N
45°N
8.5°E
10.5°E
12.5°E
14.5°E
16.5

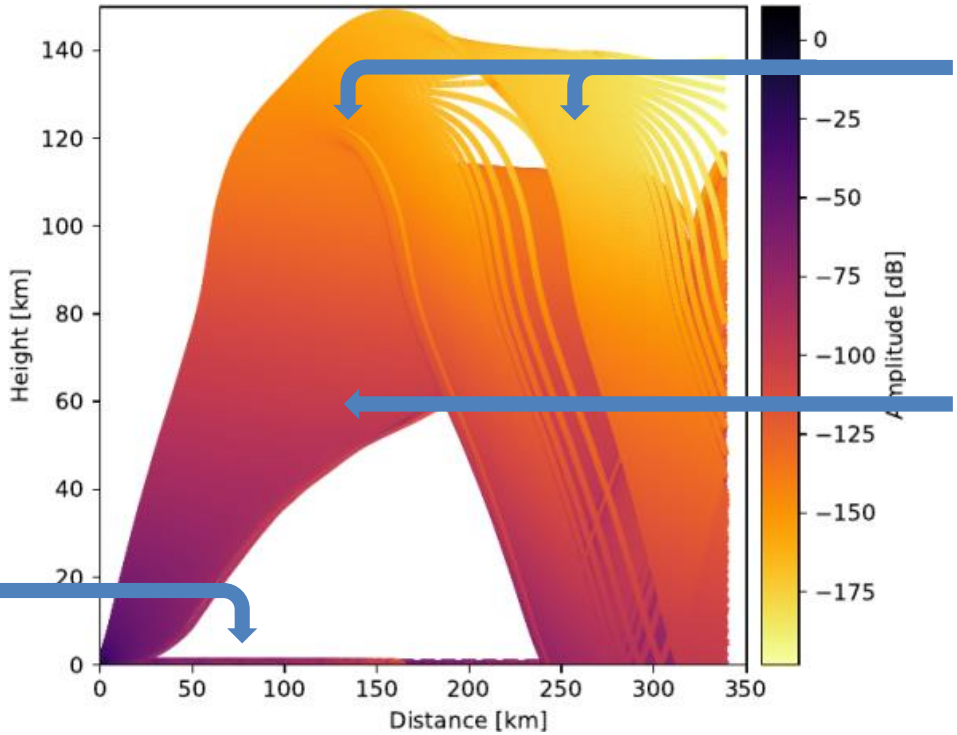
Ingolstadt explosion – Acoustic raytracing results

Wind + Temperature from ECMWF
(higher altitude extension not shown)

Effective wind speed with respect to explosion site



GeoAc raytracing suite
[Blom & Waxler, 2012]



Thermospheric reflections
from > 100 km altitude

No stratospheric reflections

Long range tropospheric
duct with very shallow
(< 1 km) turning heights

[Beware: this is based on
Simplified 1D modelling]