

# The Cosmic Ray Key Science Project

## First results and future needs

Jörg P. Rachen for the

### LOFAR Cosmic Ray Key Science Project:

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ASTRON



university of  
 groningen



Vrije  
Universiteit  
Brussel



## Journal papers published:

Schellart+, *A&A* 560, A98 (2013): **Detecting cosmic rays with the LOFAR radio telescope**

Schellart+, *NIMPA* 742, 115 (2014): **Recent results** from cosmic-ray measurements with LOFAR

Schellart+, *JCAP* 10, 014 (2014): **Polarized radio emission** from extensive air showers measured with LOFAR

Buitink+, *PRD* 90, 082003 (2014): Method for **high precision reconstruction of air shower  $X_{\max}$**  using two-dimensional radio intensity profiles

Thoudam+, *NIMPA* 767, 339 (2014): **LORA** – A **scintillator array for LOFAR** to measure extensive air showers

Nelles+, *APh* 60, 13 (2015): A parameterization for the radio emission of air showers as predicted by **CoREAS simulations** and **applied to LOFAR measurements**

Corstanje+, *APh* 61, 22 (2015): The **shape of the radio wavefront** of extensive air showers as measured with LOFAR

Schellart+, *PRL* 114, 165001 (2015): **Probing Atmospheric Electric Fields in Thunderstorms** through Radio Emission from Cosmic-Ray-Induced Air Showers

Nelles+, *APh* 65, 11 (2015): Measuring a **Cherenkov ring in the radio emission** from air showers **at 110-190 MHz** with LOFAR

Nelles+, *JCAP* 5, 018 (2015): The **radio emission pattern of air showers** as measured with LOFAR – a tool for the reconstruction of the energy and the shower maximum

***..... plus about 10 conference presentations!***



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## Papers to be published soon:

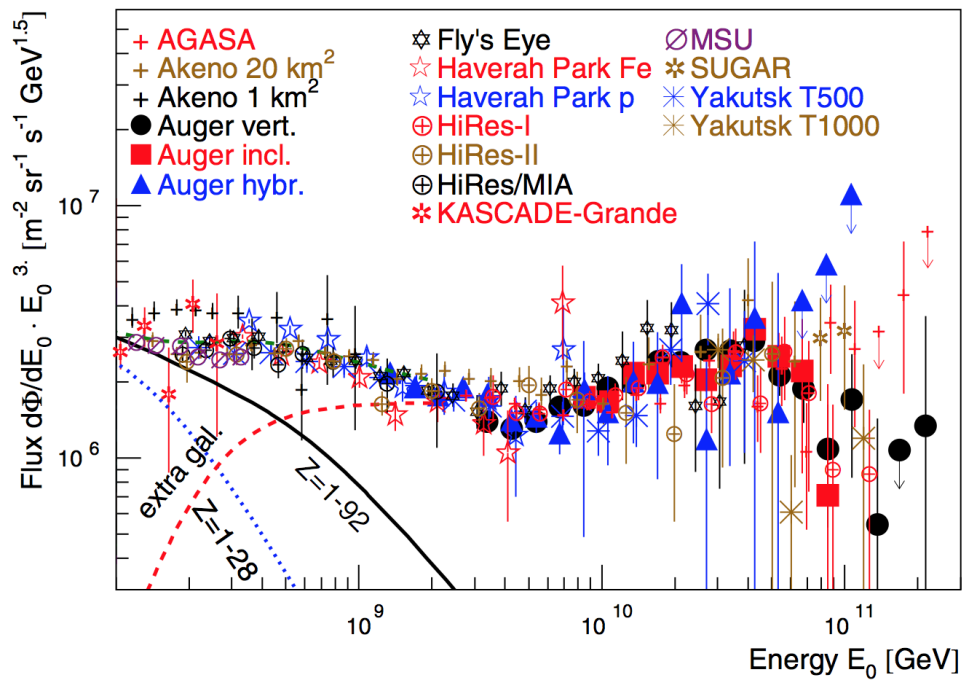
Thoudam+: **Measurement of the cosmic-ray energy spectrum** above  $10^{16}$  eV **with the LOFAR Radboud Air Shower Array.**

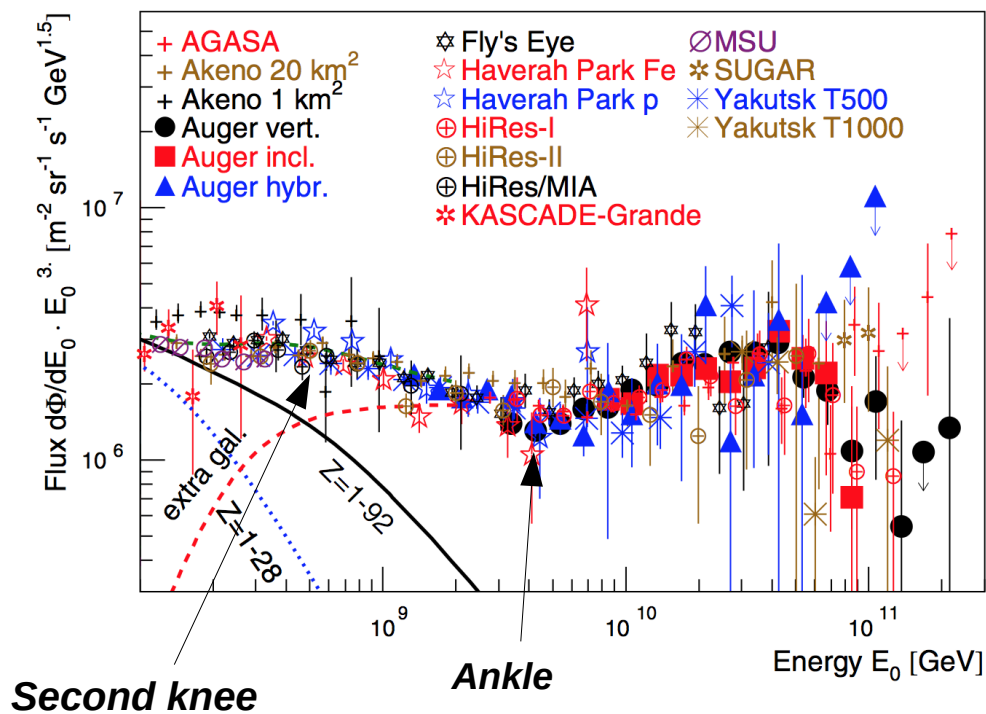
Nelles+: **Calibrating the absolute amplitude scale** for air showers measured at LOFAR.

Corstanje+: **Timing calibration** and spectral cleaning of LOFAR time series data.

Buitink+: **Radio emission from extensive air showers at 110-190 MHz**. To be submitted to **Nature**.

Trinh+: Influence of **Atmospheric Electric Fields** on Radio-wave Emission from Cosmic-Ray Induced Air Showers.

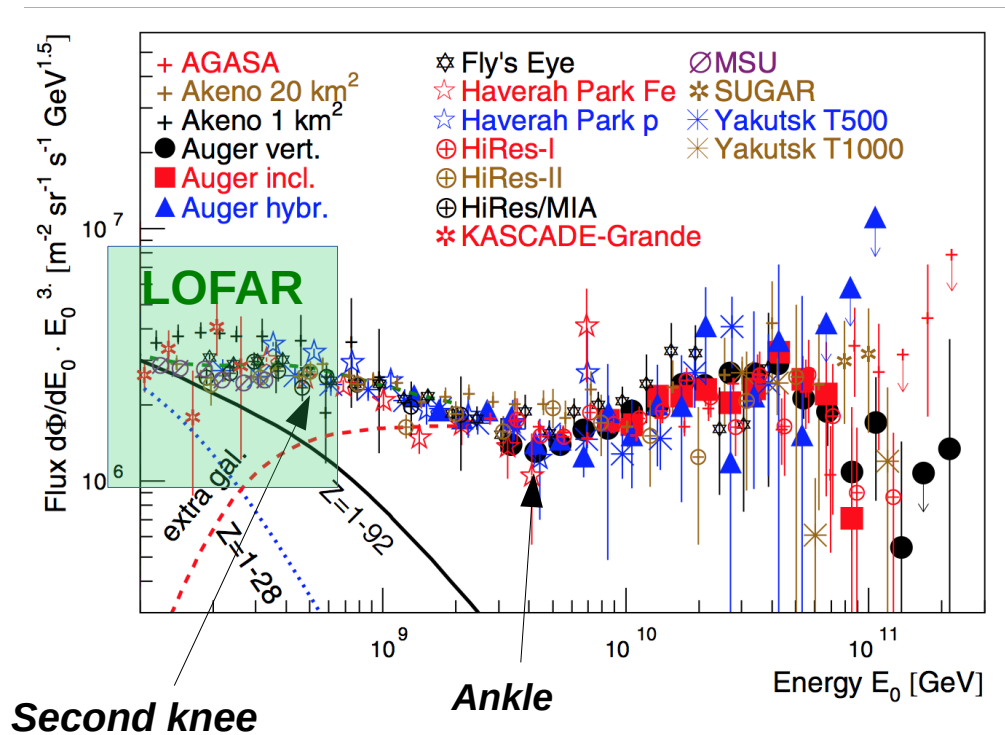




## VHECR: sub-second-knee to ankle

- Spectral features + composition changes
- Transition from galactic to extragalactic
- Key question for the origin of cosmic rays
- Implications for large scale Galactic Magnetic Field



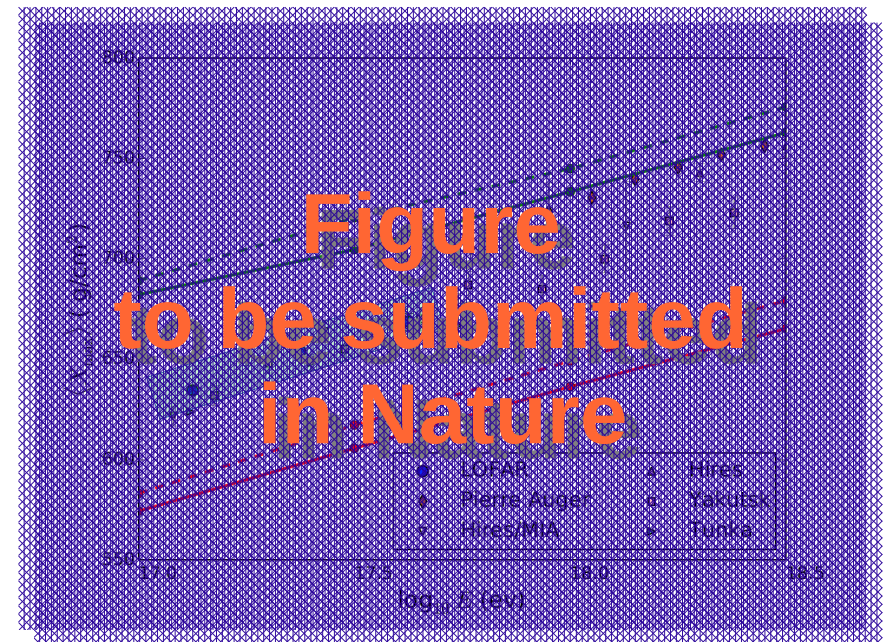


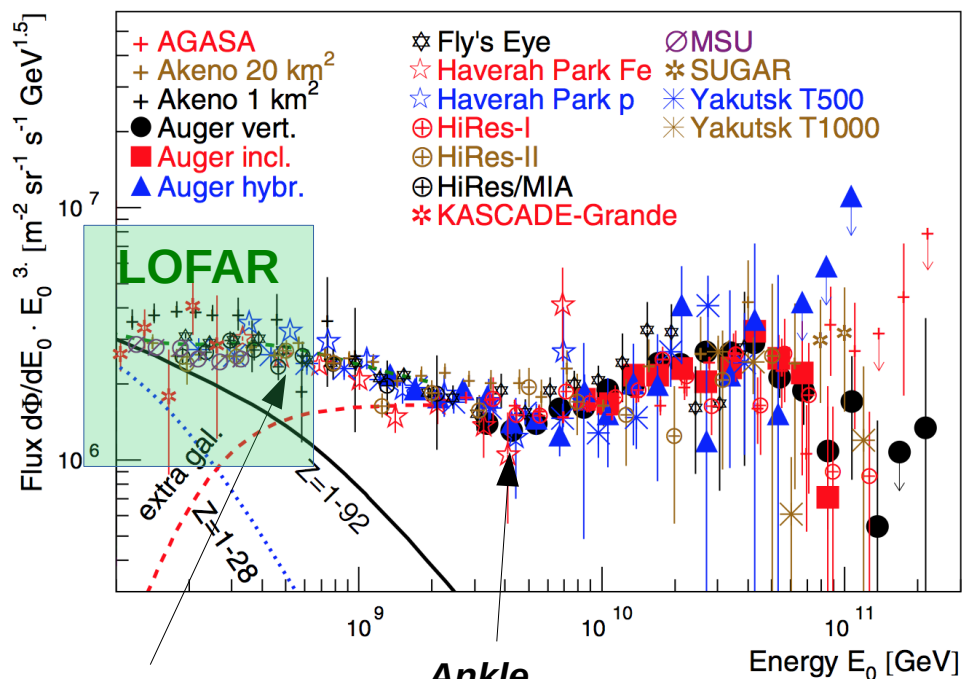
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## LOFAR VHECR data:

- Confirm **light** composition **below** the second knee
- Show no significant change in composition





Second knee

Ankle

## VHECR: sub-second-knee to ankle

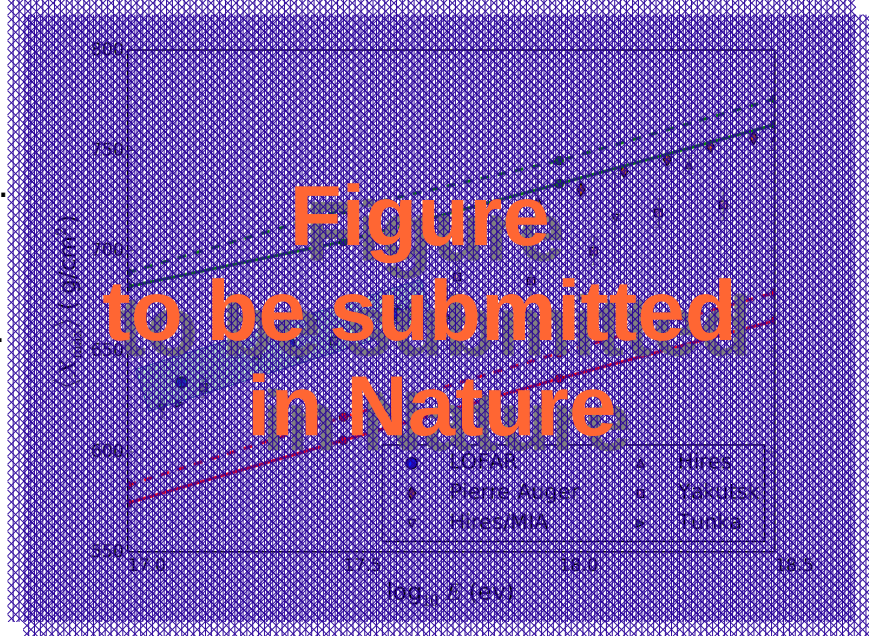
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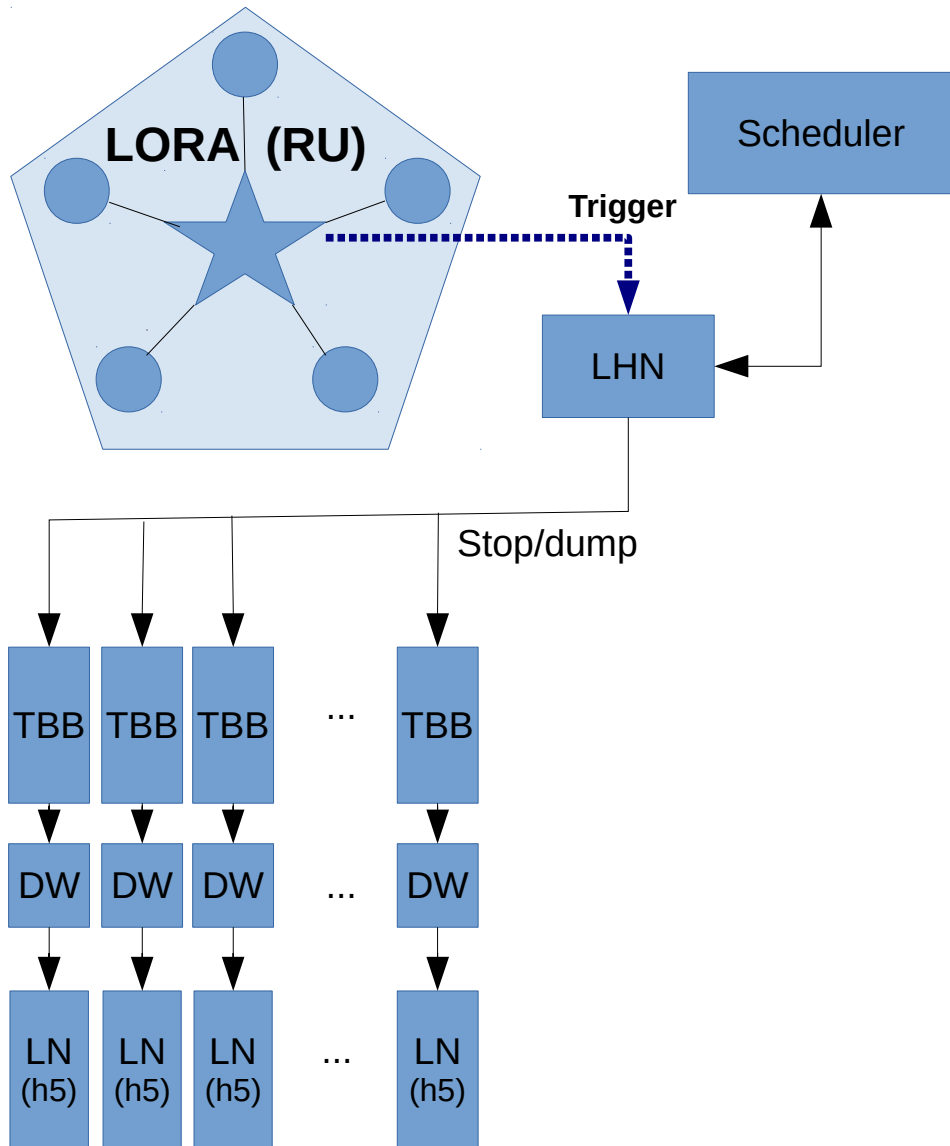
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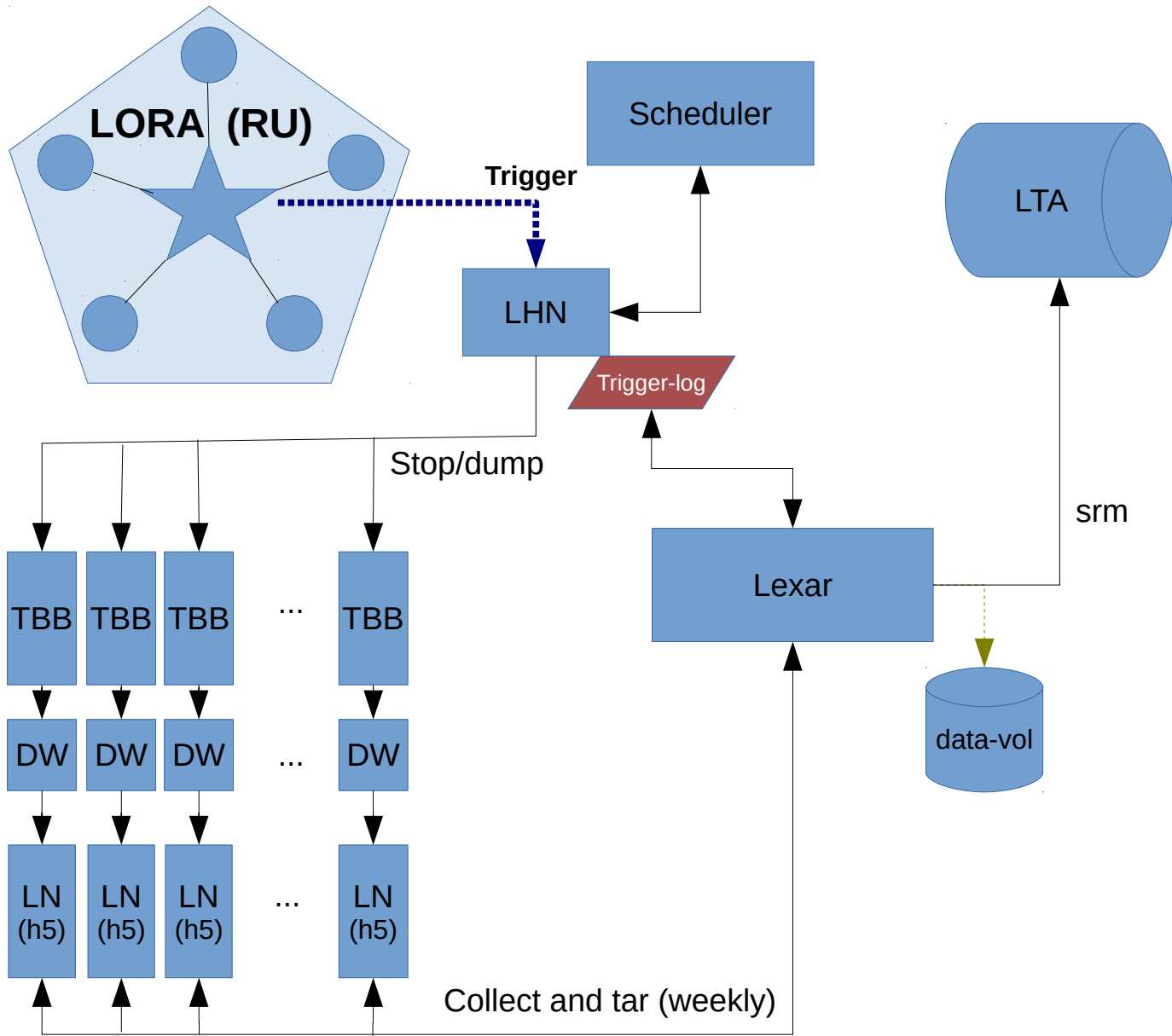
## Light what? Proton, Helium, or... ???

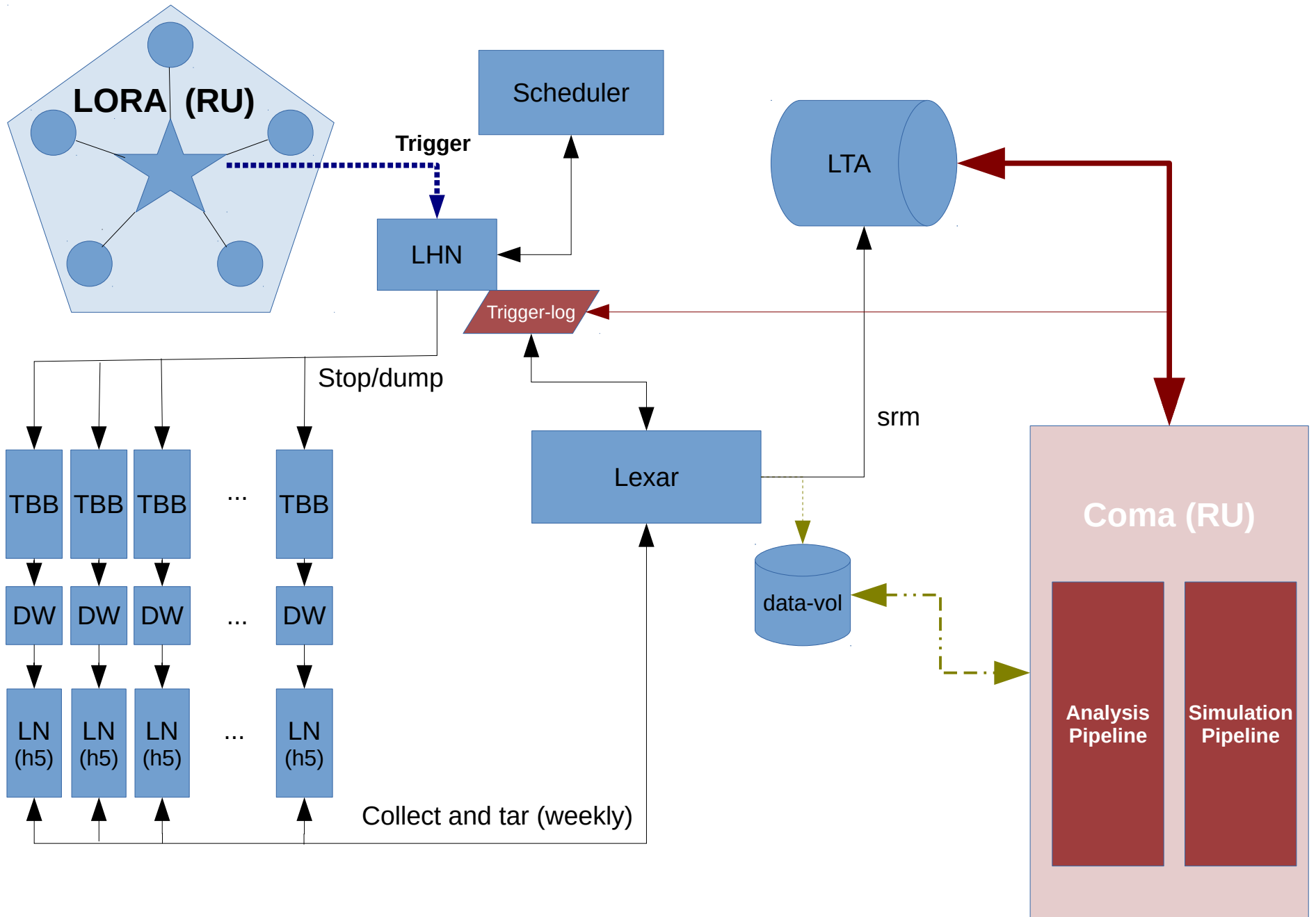
- Current analysis based on ~100 well selected LBA events.
- With **~1000 similar quality events** we will:
  - Apply multi-component fits, i.e. distinguish p, He, C/N/O and Fe.
  - Measure composition gradients.
  - Significantly constrain models of VHECR origin.
- For this we need ....
  - Improve LORA trigger rate (up to factor of 3).
  - **At least another 5 years of stable operation.**



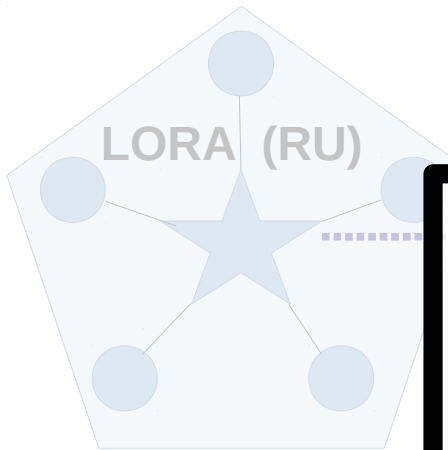




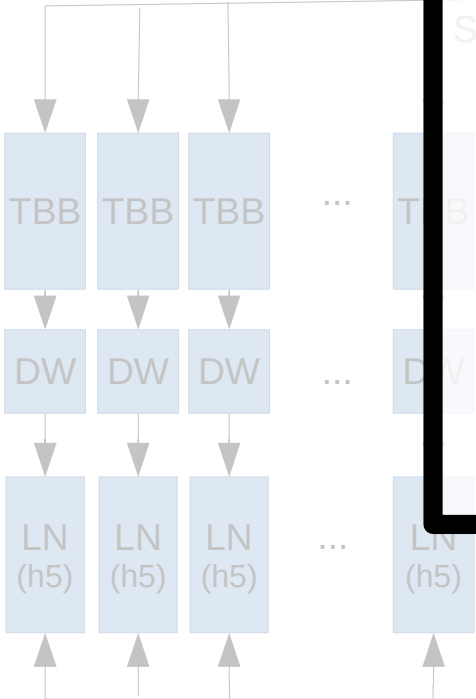




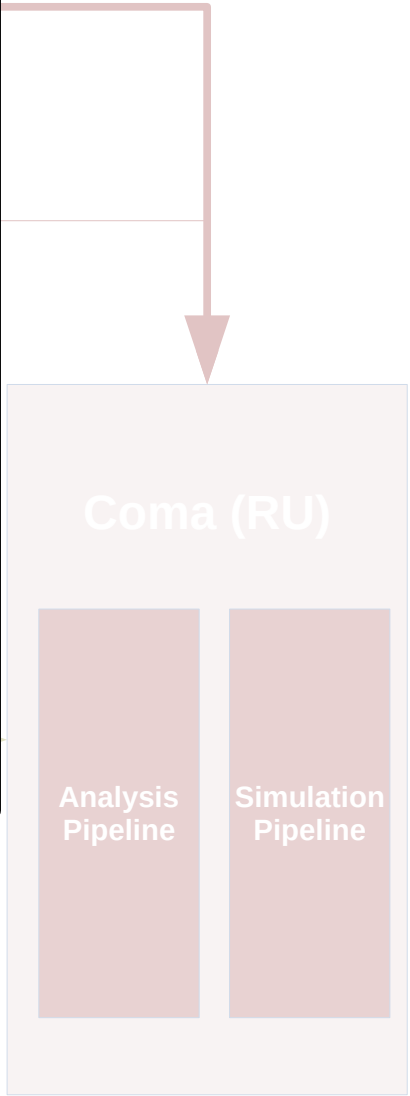


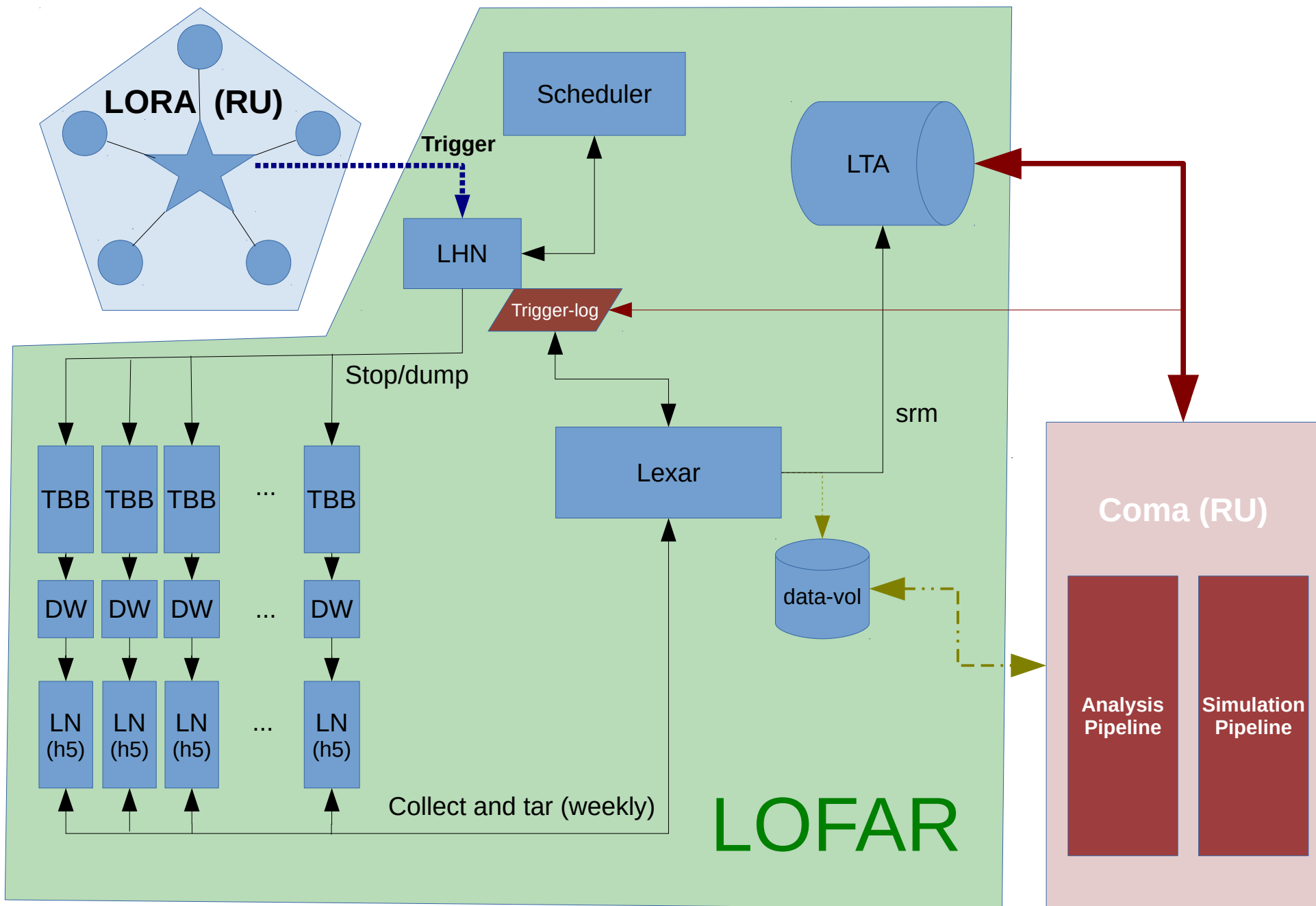


Scheduler

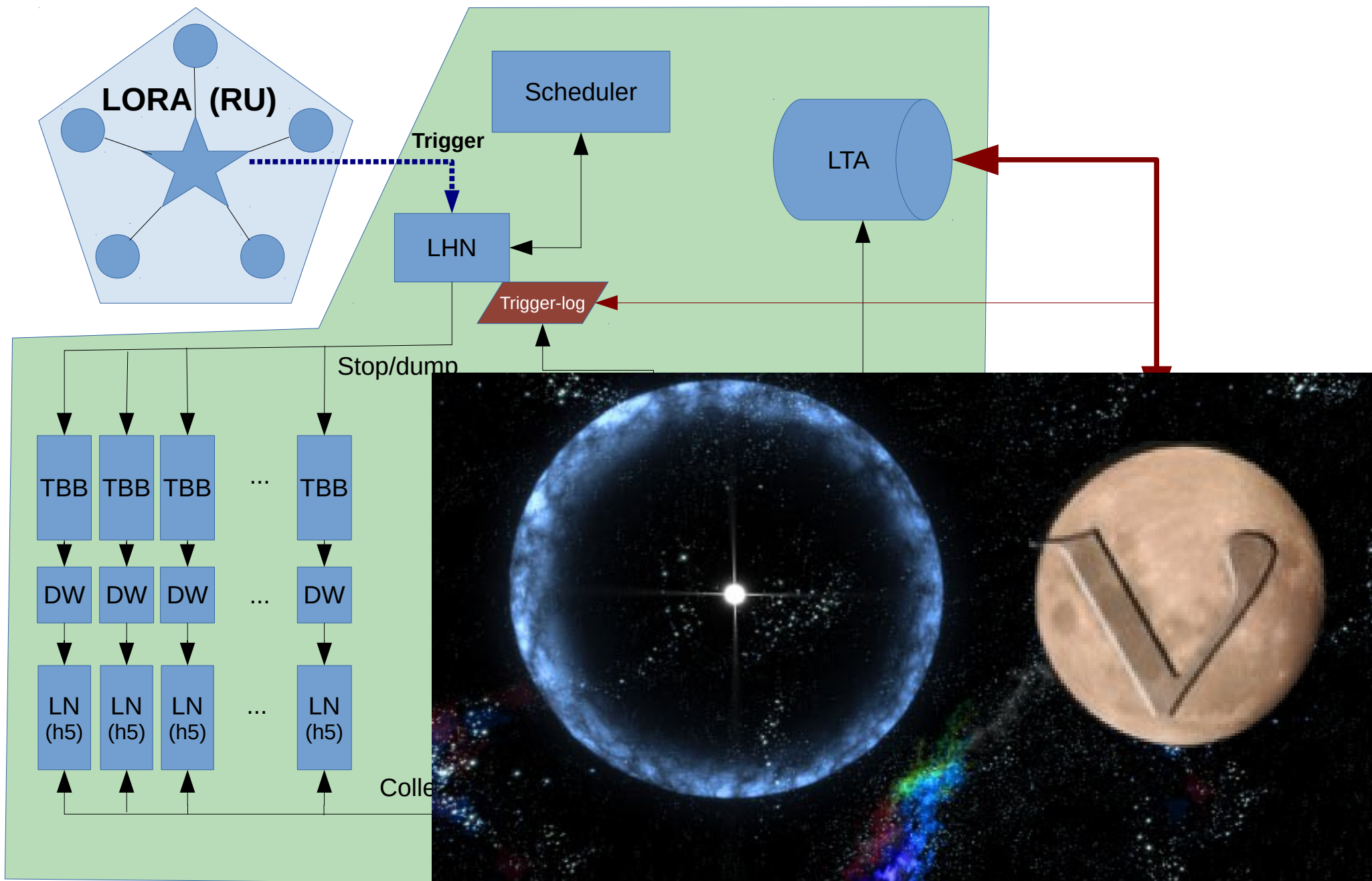


Collect and tar (weekly)









Also relevant for EHE neutrino (NuMoon) and Fast Radio Burst searches with LOFAR

# Summary

- CRKSP shows high scientific productivity
  - 10 journal papers published, more follow soon
  - **Featured Phys. Rev. Letter, Nature paper to be submitted**
  - High visibility at conferences (ARENA, ICRC, TAUP, ...)
- Radio observation technique shown to work and compete with other techniques of VHECR observation.
- Data provide relevant information on the galactic to extragalactic transition of cosmic rays.
- Interesting ancillary science (e.g., thunderstorms) and technical info for LOFAR (e.g., antenna calibration).
- At least five more years of operation needed to provide top science results.
- **Integration of VHECR software into LOFAR system essential for successful continuation.**