

# INTERSTELLAR MEDIUM

- Stefano Bovino -

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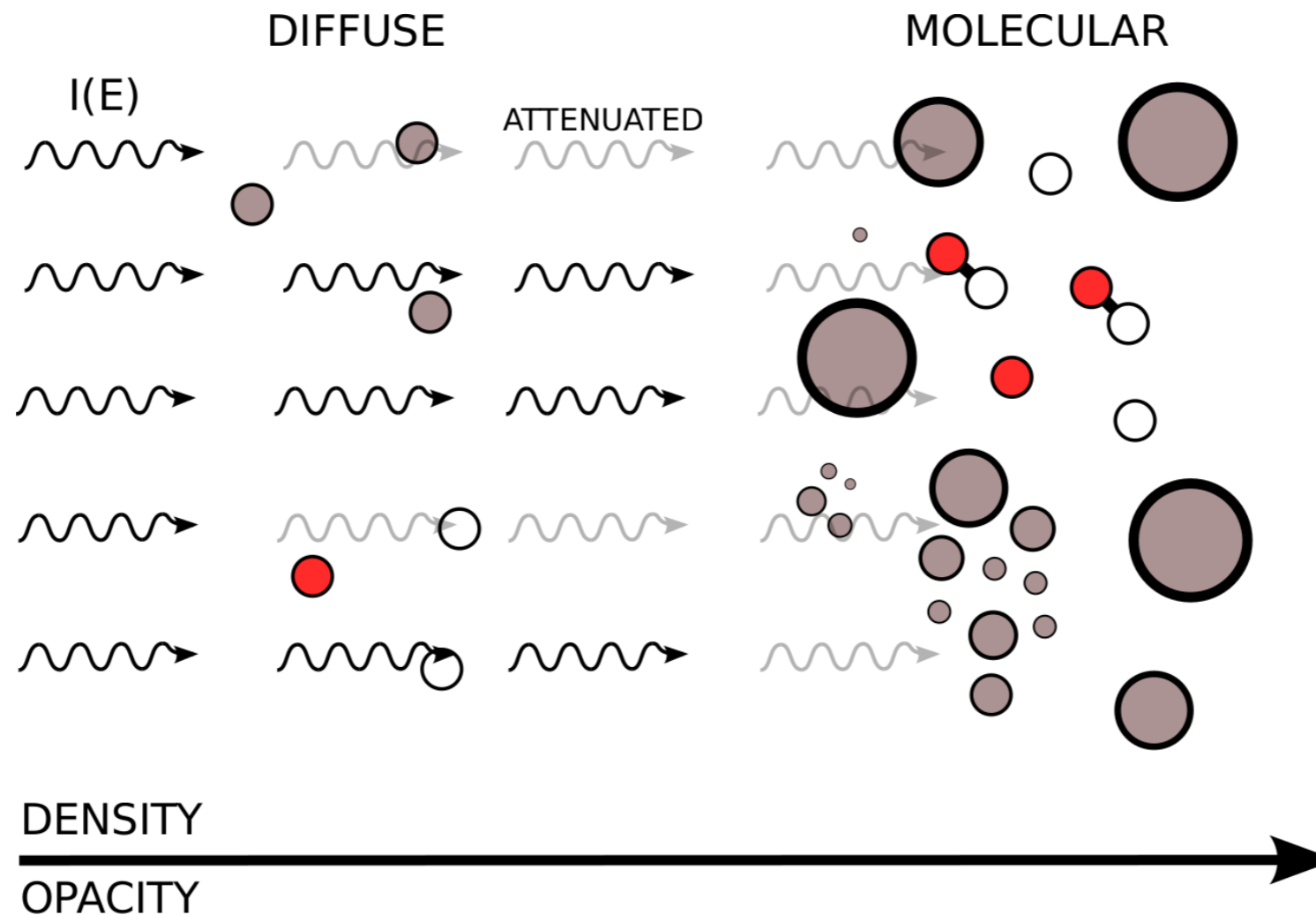
## Cosmic rays

## WHAT COSMIC RAYS ARE AND FROM WHERE THEY COME?

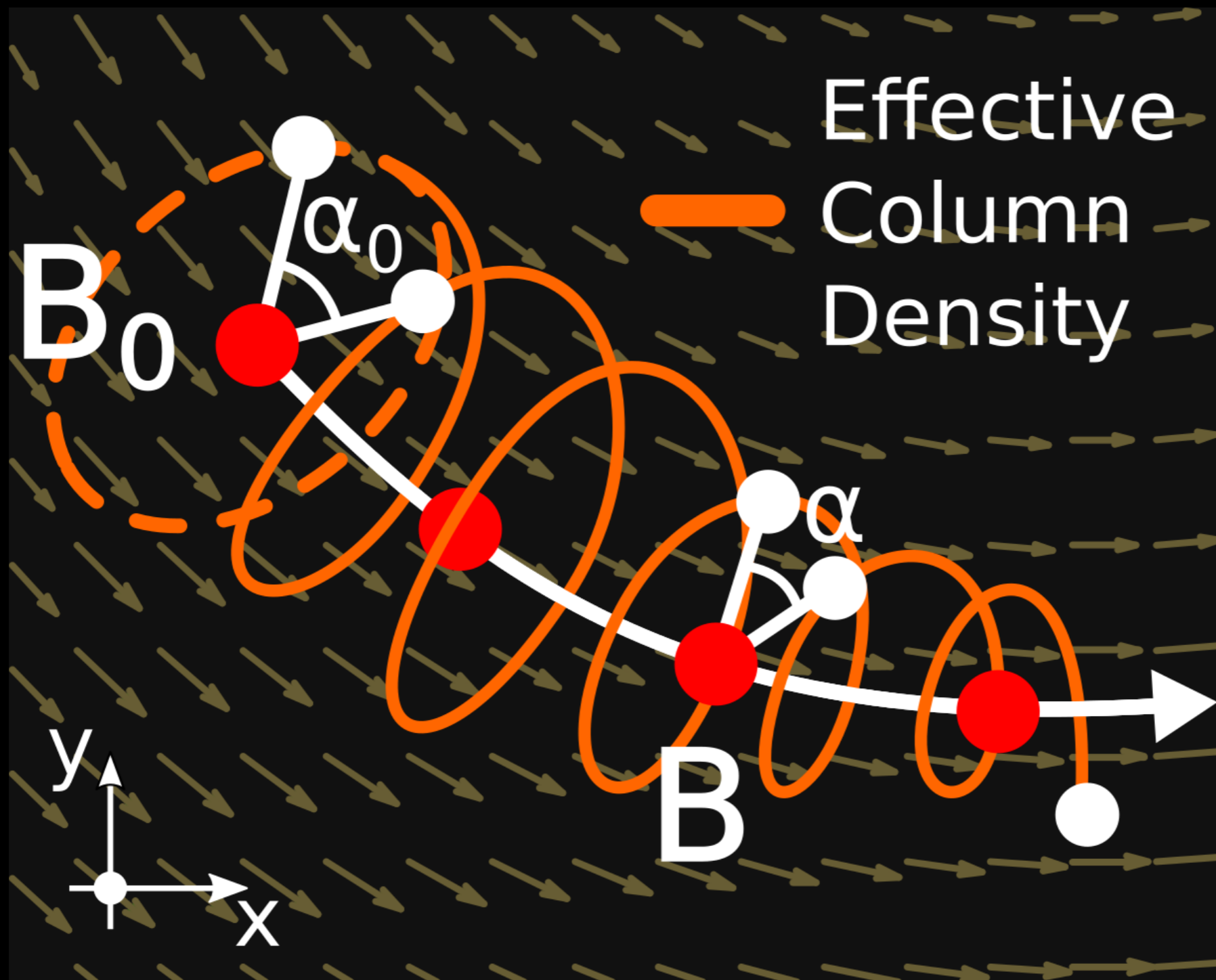
- ▶ Energetic charged particles ( $E > 100$  eV)
- ▶ Vast majority are protons, but also electrons, positrons and He-nuclei
- ▶ Non-thermal velocity distribution that exist in rough equipartition with the thermal and magnetic energies

Component		$u(\text{eV cm}^{-3})$	Note
Cosmic microwave background	$(T_{\text{CMB}} = 2.725 \text{ K})$	0.265	<i>a</i>
Far-infrared radiation from dust		0.31	<i>b</i>
Starlight ( $h\nu < 13.6 \text{ eV}$ )		0.54	<i>c</i>
Thermal kinetic energy	$(3/2)nkT$	0.49	<i>d</i>
Turbulent kinetic energy	$(1/2)\rho v^2$	0.22	<i>e</i>
Magnetic energy	$B^2/8\pi$	0.89	<i>f</i>
Cosmic rays		1.39	<i>g</i>

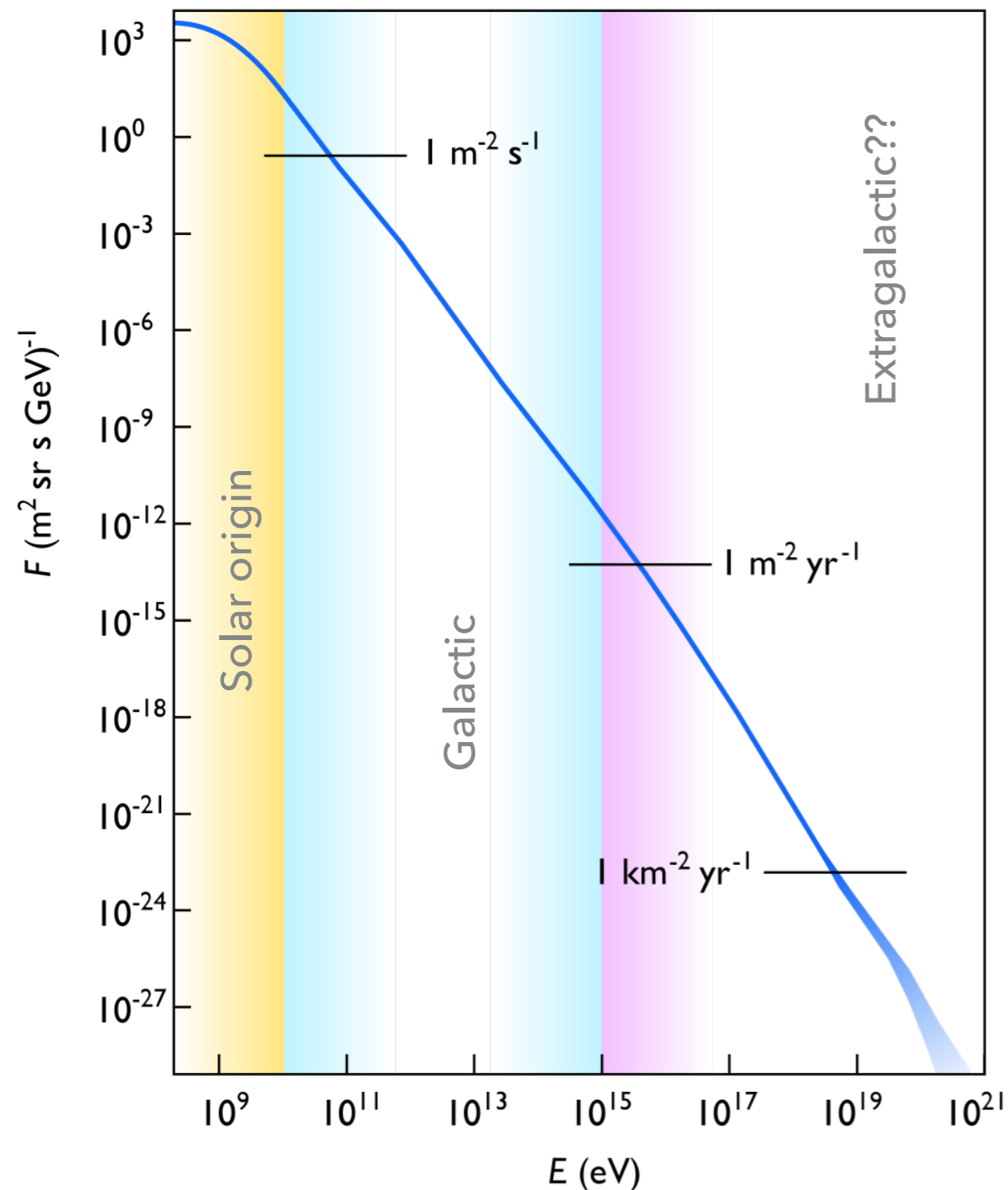
- ▶ Can penetrate through thick clouds
- ▶ Are principal source of ionization in MCs
- ▶ Contribute to the heating of the gas ( $\sim 10\text{-}20$  eV per ionization)
- ▶ Produce gamma-rays and light element isotopes via spallation
- ▶ Control the coupling of B with the gas (electrical resistivity)



- ▶ CRs coupled to magnetic fields which permeate the ISM (scatter on magnetic fields)
- ▶ Cosmic ray pressure as a source of galactic outflows (Feedback)



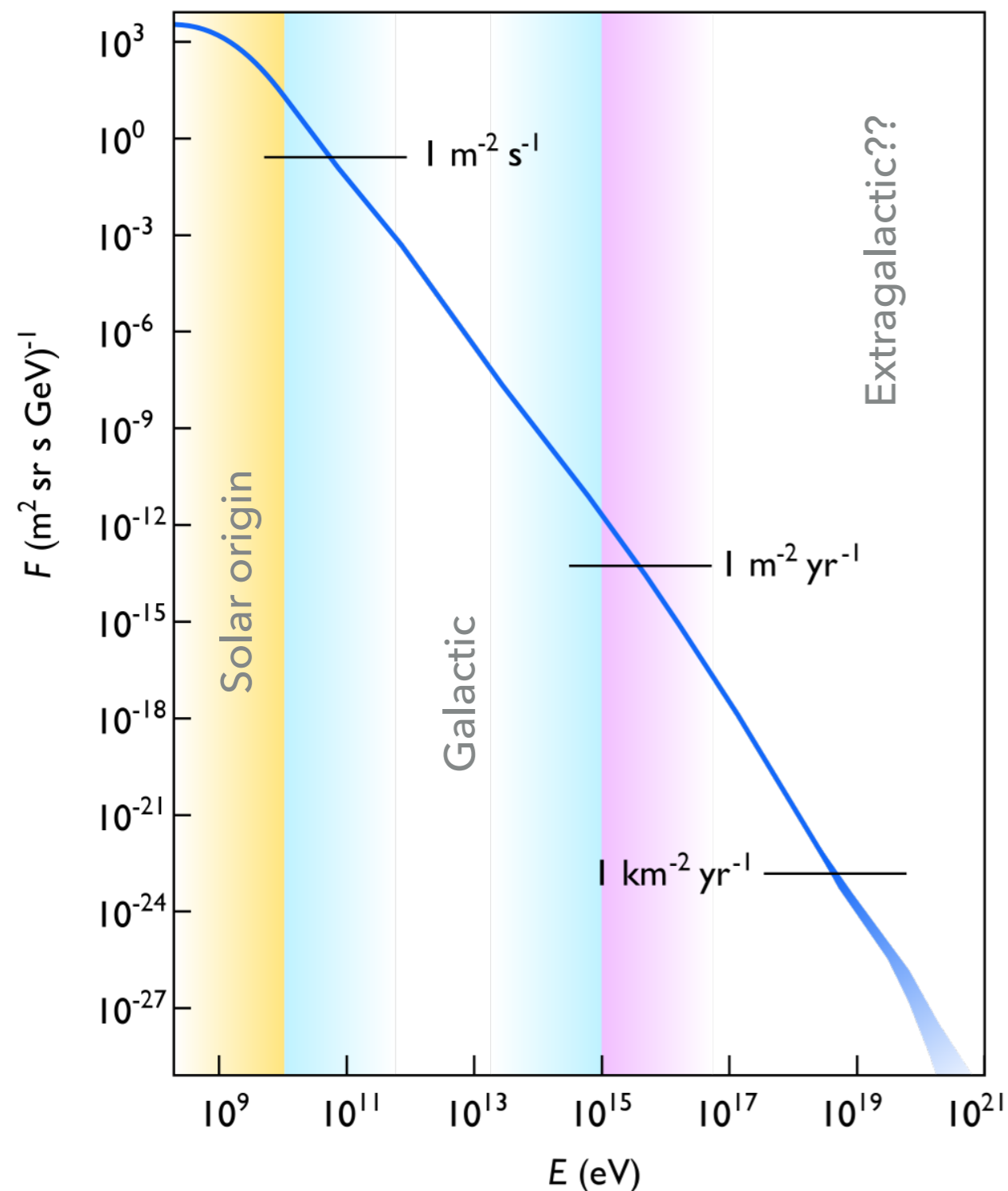
# COSMIC RAYS SPECTRUM



- ▶ Power-law
- ▶ Below  $10^9$  eV difficult to measure: low-energy particles deflected by solar winds (modulation)
- ▶ Produced by SNRs for  $E < 10^7$  GeV
- ▶  $E > 10^7$  GeV extragalactic (SMBHs, AGN)

$$F \propto E^{-2.7}$$

# HOW DO WE PROBE COSMIC RAYS?



## DIRECTLY

- ▶ Synchrotron radiation e-B interaction (see Larmor formula) probed via Chandra for instance
- ▶ High-energy part via Fermi-LAT, directly or indirectly (gamma-ray)
- ▶ Range 20 GeV - 1 TeV

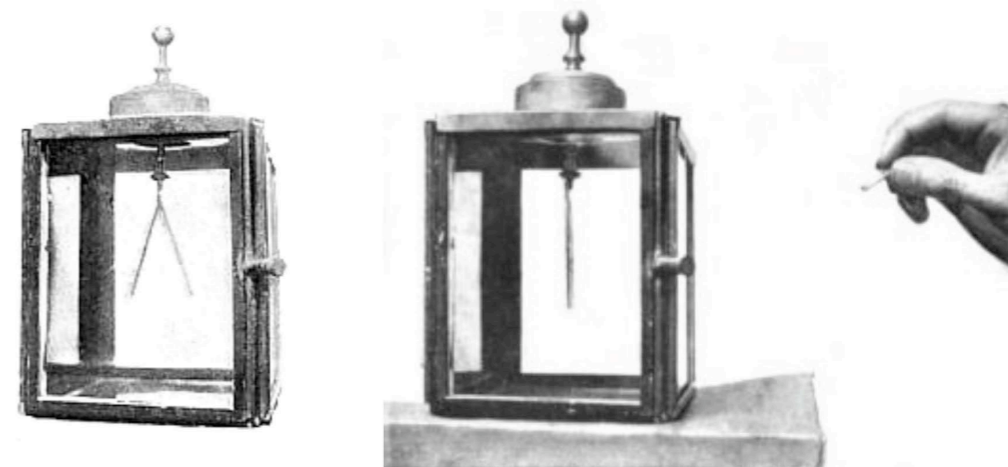
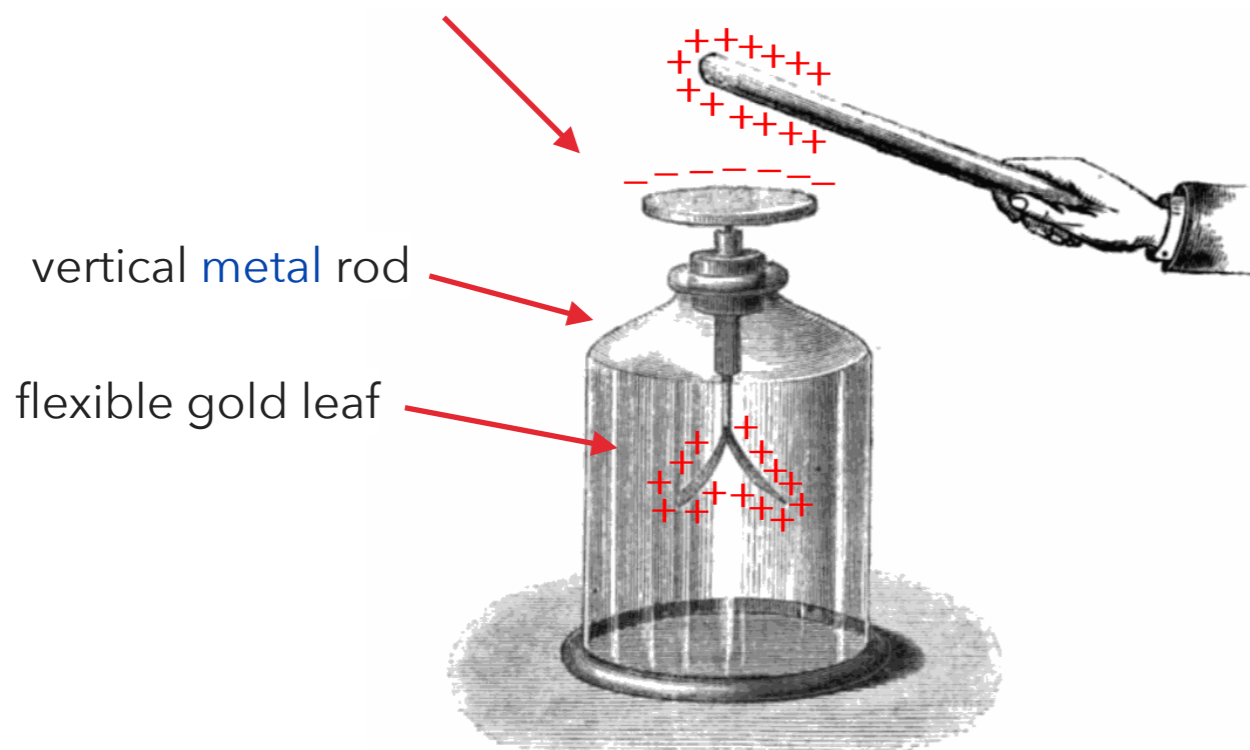
## LONG STORY

ALL STARTED IN 1785 WITH COULOMB

# HOW DOES AN ELECTROSCOPE WORK?

- ▶ used to detect the presence of electric charge
- ▶ due to the Coulomb electrostatic force on it

Negative charge usually given to the electroscope



**It will discharge when ions in the air remove electrons from it**

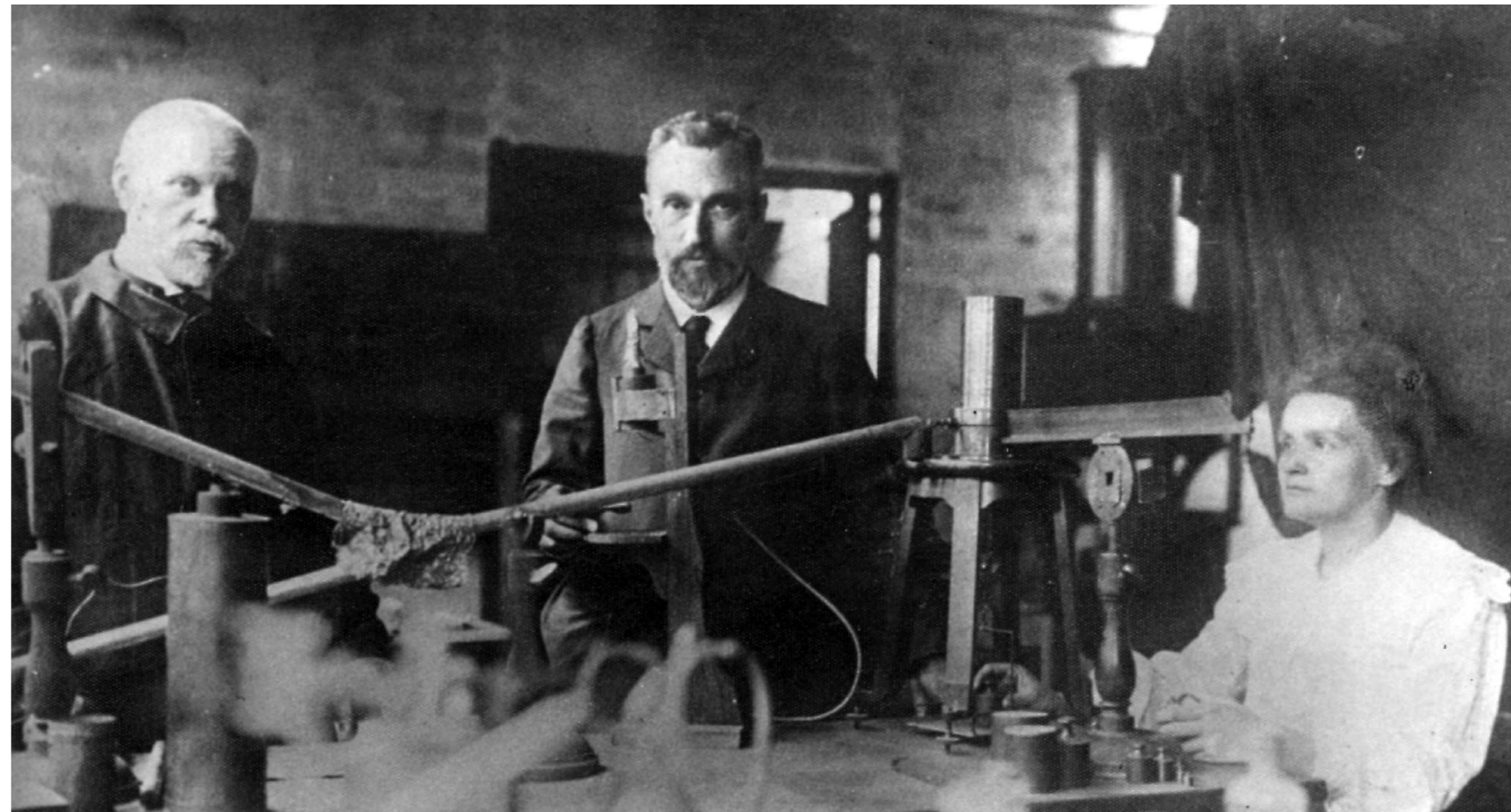
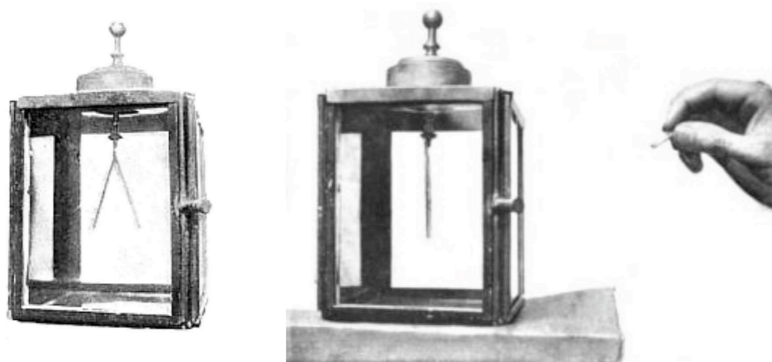


# A BIT OF HISTORY OF COSMIC RAYS: IT STARTED WITH RADIOACTIVITY

- ▶ Some elements are able to spontaneously emit charged particles
- ▶ These can in turn cause discharge of the electroscopes
- ▶ The discharge rate was used to measure radioactivity
- ▶ The dominant opinion was that all the high-energy radiation was coming from the soil

## H. Becquerel & P. Curie & M. Curie

**1896-1898**

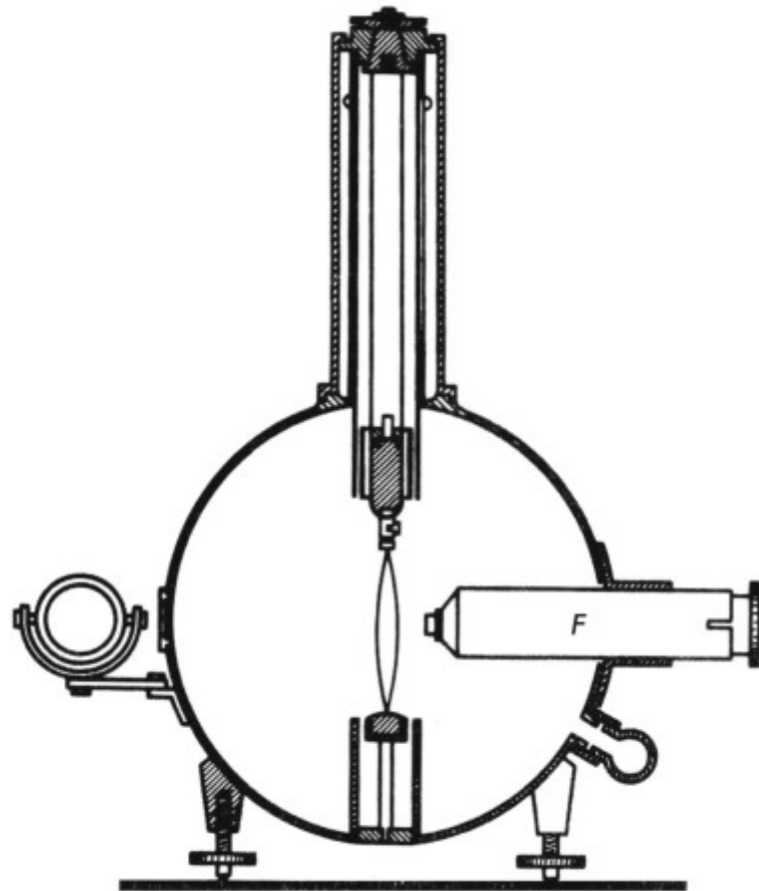


## COMMON IDEA

- ▶ Ionization is generated by radioactive materials on the Earth's crust.
- ▶ Calculations showed that this radiation should have then decreased with height
- ▶ Electroscopes at that time were difficult to transport and not very sensitive

## A BIT OF HISTORY OF COSMIC RAYS: FATHER WULF

- ▶ Theodor Wulf, German Jesuit Priest
- ▶ Built a accurate electroscope in 1908-1909
- ▶ Sensitivity of 1 V and transportable



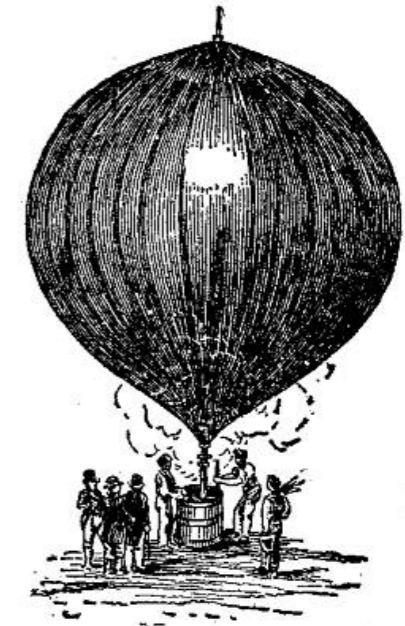
## FATHER WULF EXPERIMENT (1909–1910)

- ▶ Idea: measure radioactivity on top of Eiffel Tower (~300 m)
- ▶ He did it during an Easter holiday
- ▶ Expected reduction (if the radiation comes only from the soil) but results not conclusive

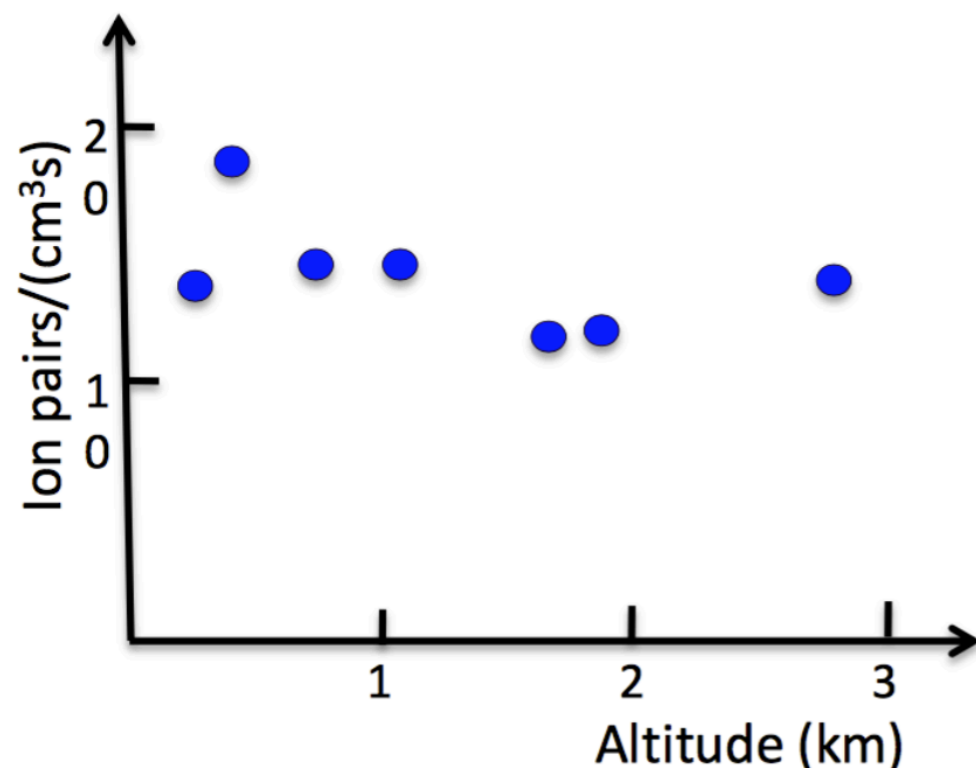


# BALLOON EXPERIMENTS: ALBERT GOCKEL

- ▶ Idea: improving Wulf's measurements going higher
- ▶ 1909: first balloon experiments (Berwitz and Gockel)
- ▶ Up to 4000 m, Gockel found that radiation did not decrease with altitude



Gockel concluded that: **penetrating radiation in the atmosphere independent on radioactive source**



Die erhaltenen Resultate würden in Übereinstimmung stehen mit dem, was auch Pacini<sup>1)</sup> aus seinen Beobachtungen auf dem Meere und Mache<sup>2)</sup> aus denen in Innsbruck folgert, daß nämlich ein nicht unbedeutlicher Teil der durchdringenden Strahlung unabhängig ist von der direkten Wirkung der in den obersten Erdschichten enthaltenen aktiven Substanz. Befriedigend stimmen mit meinen Resultaten auch die von Wulf<sup>3)</sup> auf dem Eiffelturm erhaltenen überein, besonders

1) Gockel cites the results of Pacini

# DOMENICO PACINI: FUNDAMENTAL CONTRIBUTION (NOT RECOGNIZED)

- ▶ Meteorologist in Rome, and professor in Bari
- ▶ June 1911: bringing an electroscope 3 m deep in the sea
- ▶ Experiment repeated at the Lake of Bracciano

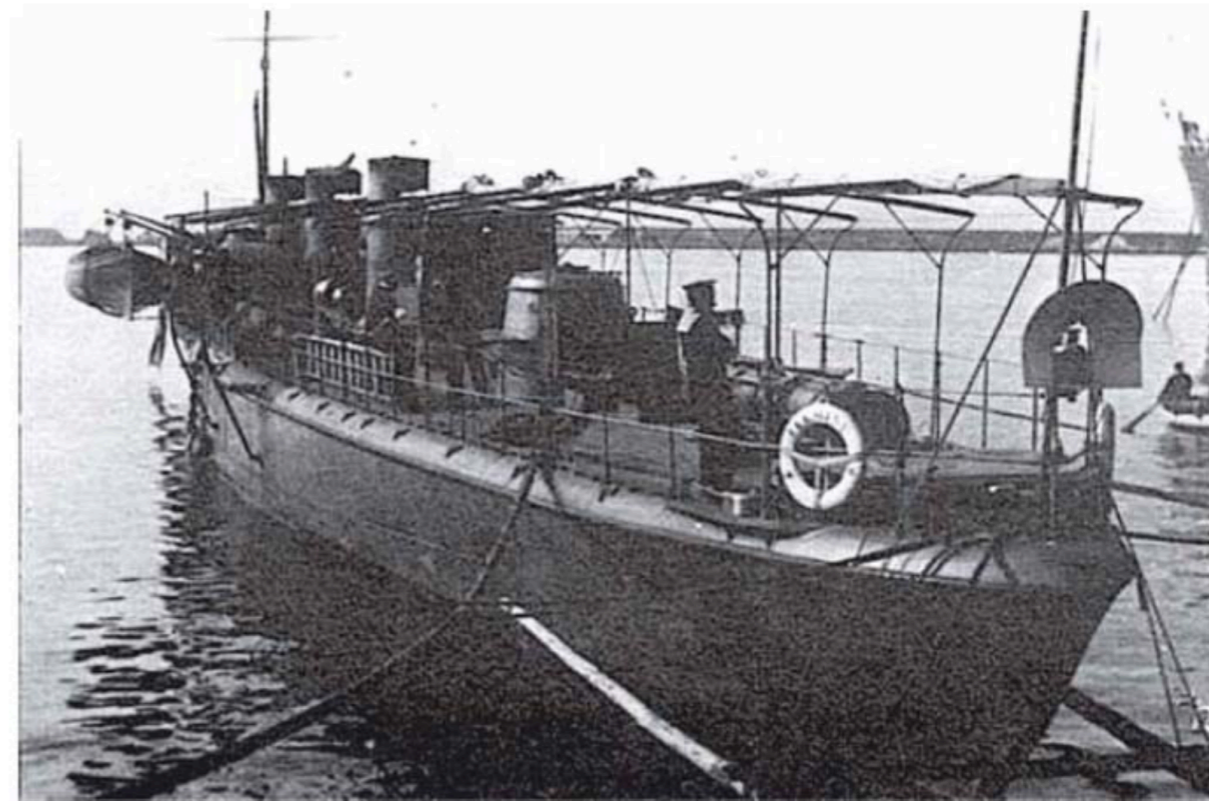


Fig. 4. The cacciatorpediniere "Fulmine", used by Pacini for his measurements on the sea (courtesy of the Marina Militare Italiana).

# DOMENICO PACINI: FUNDAMENTAL CONTRIBUTION (NOT RECOGNIZED)

- ▶ Published: "Penetrating radiation at the surface of and in water"
- ▶ 20% reduction of the radioactivity



Coll' apparecchio alla superficie del mare si ebbe una perdita oraria di Volta:

13,2 — 12,2 — 12,1 — 12,6 — 12,5 — 13,5 — 12,1 — 12,7

media 12,6 equivalente a ioni 11 per  $\text{cm}^3$  al 1".

Coll' apparecchio immerso:

10,2 — 10,3 — 10,3 — 10,1 — 10,0 — 10,6 — 10,6.

media 10,3 equivalente a ioni 8,9 per  $\text{cm}^3$  al 1".

La differenza fra questi due valori è di ioni 2,1.

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## PACINI CONCLUSIONS

“The explanation appears to be, due to the absorbing power of water and the minimum amount of radioactive substances in the sea, that radiation coming from the outside is absorbed when the apparatus is immersed. (Nuovo Cim., February 1912)”

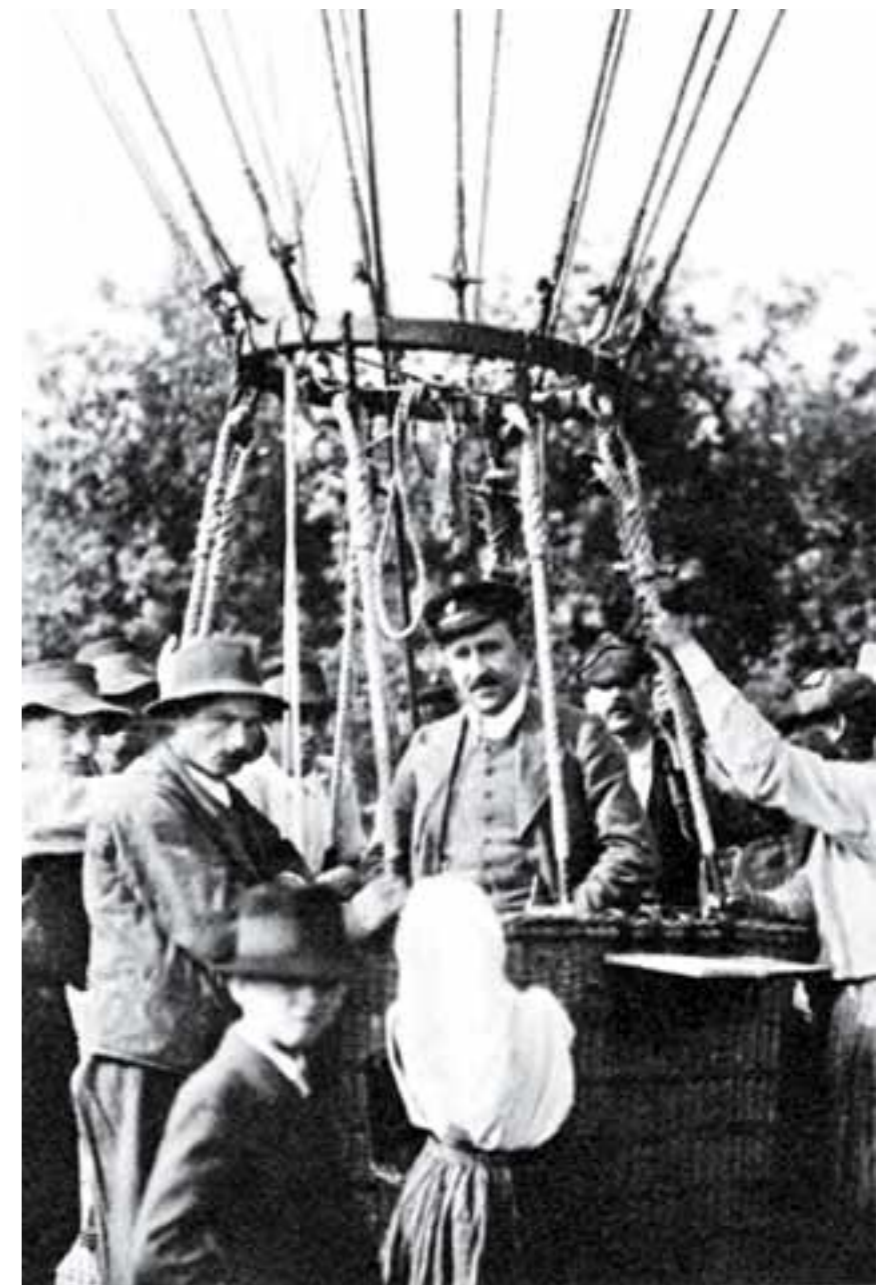
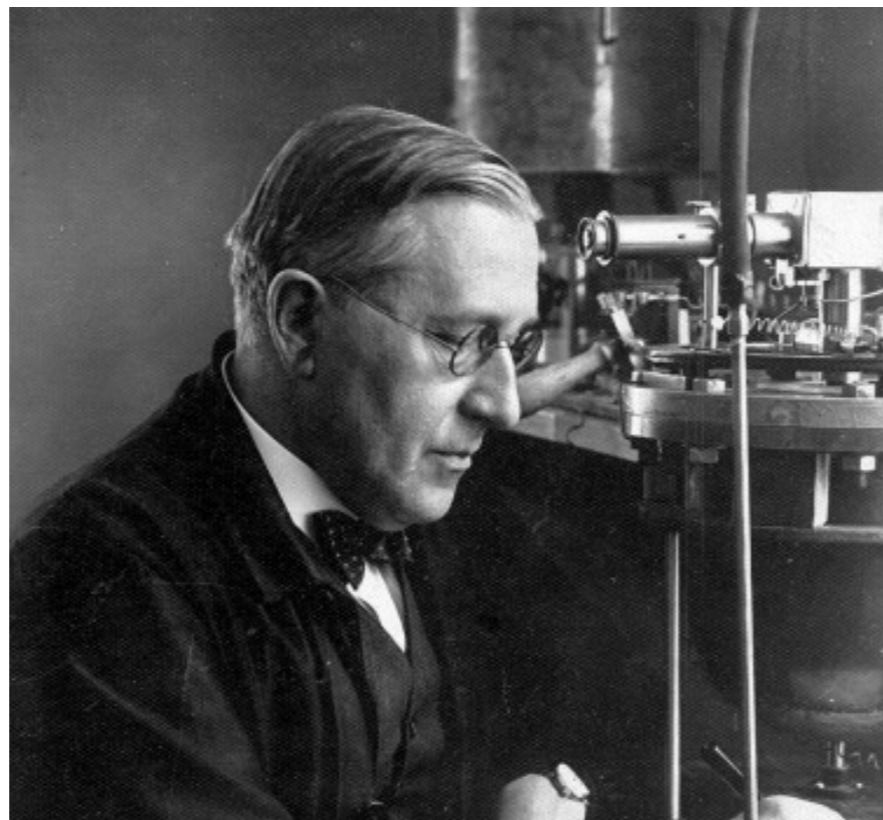
Pacini concludes that *“a sizable cause of ionization exists in the atmosphere, originating from penetrating radiation, independent of the direct action of radioactive substances in the ground.”*

Pacini’s experiment marked the beginning of the underwater technique for CR studies



## VICTOR HESS (1911–1912): NEW RESULTS

- ▶ Austrian scientist working in Wien and Graz
- ▶ Started using the Wulf's electroscope
- ▶ Expected reduction but results not conclusive
- ▶ 2 ascensions up to 1300 m in 1911



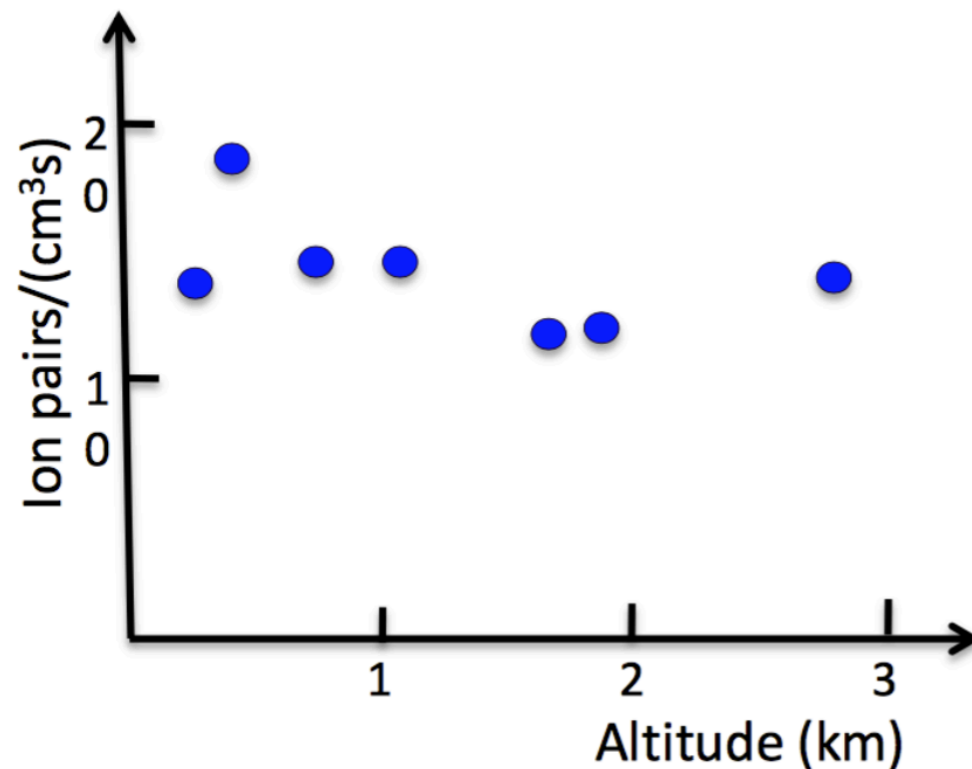
## VICTOR HESS (1911-1912): FINAL FLIGHTS

- ▶ April-August 1912: 7 flights
- ▶ Reached 5200 m

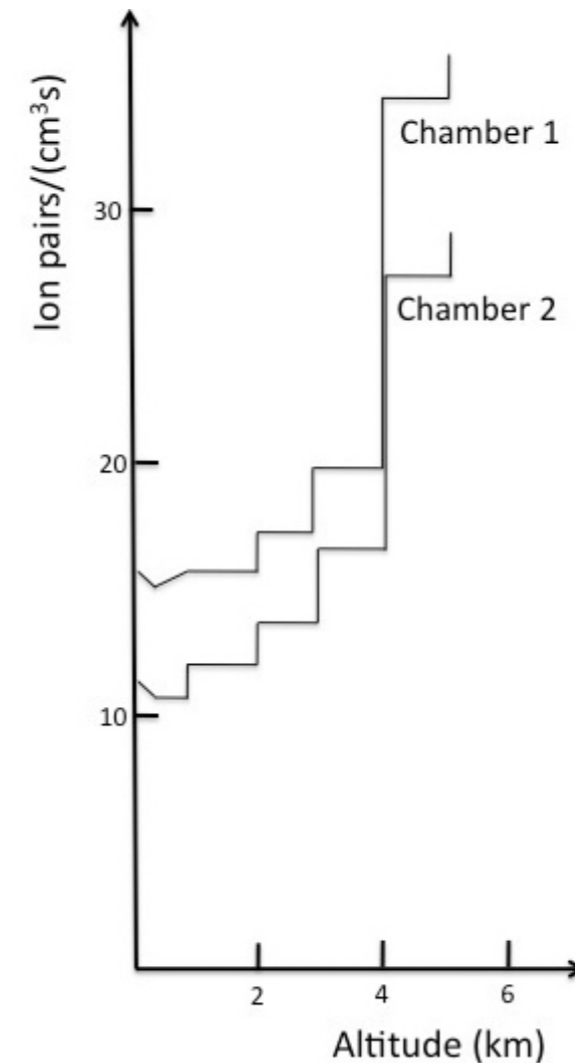


## VICTOR HESS (1911-1912): RESULTS

- ▶ After passing a minimum he found increase of ionization
- ▶ conclusions: radiation has extra-terrestrial origin



**Gockel's results**



**Hess's results**

# PACINI-HESS: SCIENCE AT WORK

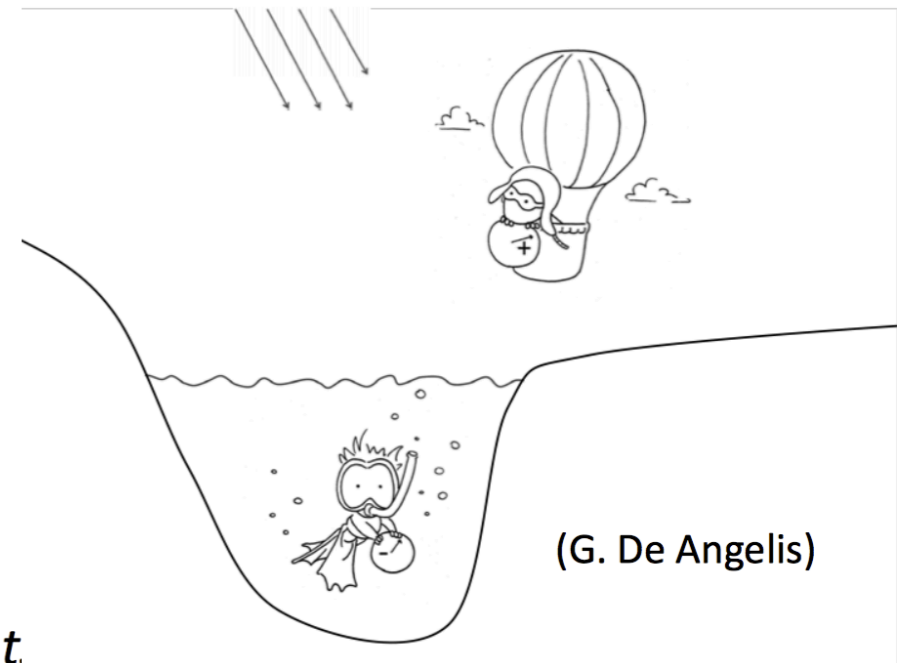
## Exchange of letters between Pacini and Hess

Pacini to Hess, March 1920: ... *[in your] paper entitled 'The problem of penetrating radiation of extraterrestrial origin' ... the Italian measurement ..., which take priority [for] the conclusions that you ... draw, are missing; and I am so sorry about this, because in my own publications I never forgot to mention and cite anyone...*

Hess to Pacini, March 1920: ... *My short paper ... is a report of a public conference, and therefore has no claim of completeness...*

Pacini to Hess, April 1920: *[...but] several authors are cited whereas I do not see any reference to my relevant measurements ... performed underwater in the sea and in the Bracciano Lake, that led me to the same conclusions that the balloon flights have later confirmed. ...*

Hess to Pacini, May 1920: ... *I am ready to acknowledge that certainly you had the priority in expressing ... in 'Nuovo Cimento', February 1912, the statement that a non terrestrial radiation of 2 ions/cm<sup>3</sup>/s at sea level is present. However, the demonstration of the existence of a new source of penetrating radiation from above came from my balloon ascent to a height of 5000 meters on August 7 1912, in which I have discovered a huge increase in radiation above 3000 meters. ...*



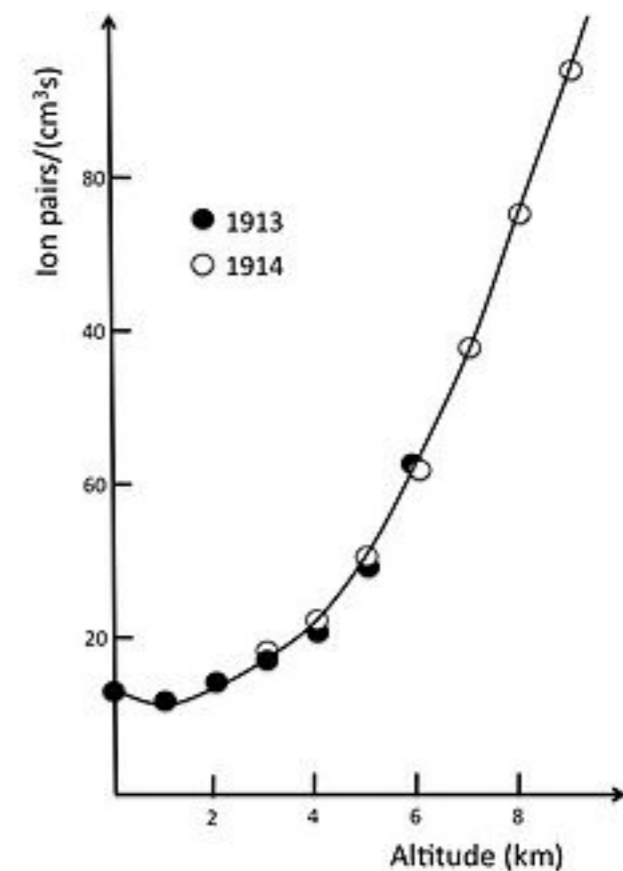
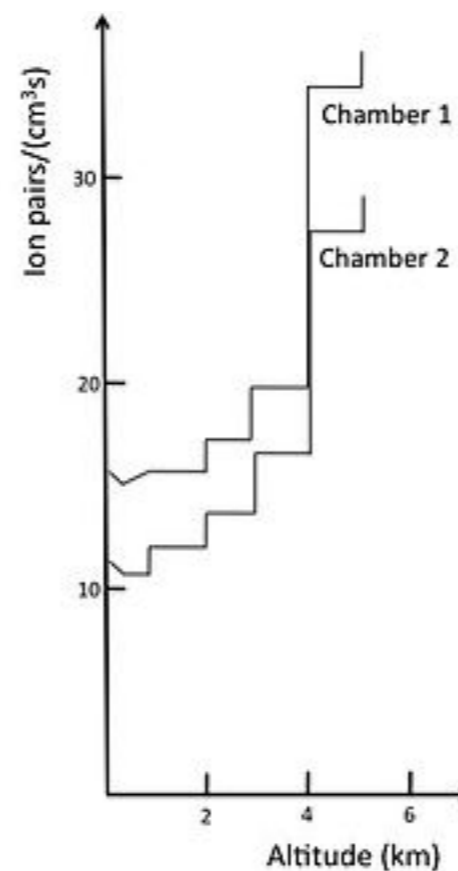
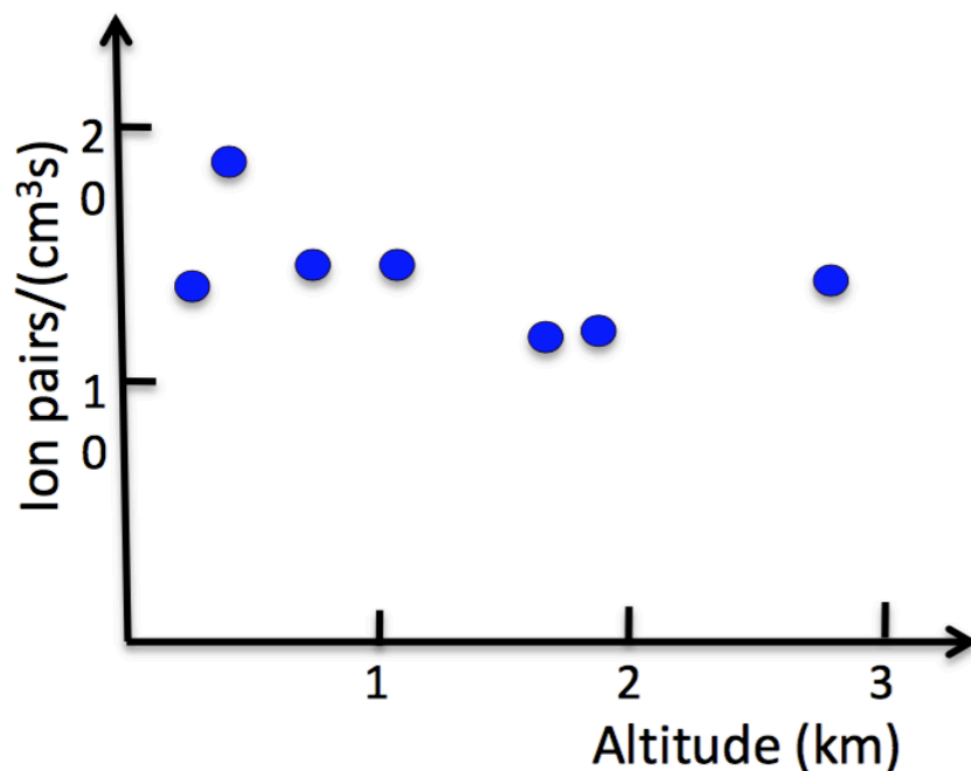
Hess and Eugster writes about the contribution of Pacini:

*"The first who expressed some doubts as to the correctness of this view was D. Pacini, who, in 1910, from measurements over sea and on shores at Livorno concluded that part of the observed ionization might be due to sources other than the known radioactive substances."*

Pacini, who died in 1934, was never nominated for the Nobel Prize. Hess was first nominated in 1931 and received the prize in 1936.

# WERNER KOLHÖRSTER (1913-1914)

- ▶ Confirmed Hess's results
- ▶ Did a number of flights up to 9200 m
- ▶ He found an increase of ionization up to 10x at sea level



USA ARRIVED LATE BUT CLAIM THE  
DISCOVERY (WAR TIME)

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**MILLIKAN AND CO**

# MILLIKAN CONTRADICTION!

In the early 1920's the existence of hohenstrahlung was questioned.

Otis and Millikan Phys Rev 23 778 (1924)

62. The source of the penetrating radiation found in the earth's atmosphere. RUSSELL M. OTIS and R. A. MILLIKAN, California Institute of Technology.—Assuming, following Kolhorster's 1923 conclusions, a penetrating radiation of cosmic origin which produces 2 ions/cc/sec. at sea level and has an absorption coefficient per cm in water of  $2.5 \times 10^{-3}$ , we find that this radiation would produce 9 ions/cc/sec. on top of Pike's Peak (14100 ft). Inside our completely enclosing lead shield, 5 cm thick, it should produce 7.8 ions/cc/sec. The ionization in our apparatus contributed by the walls and the lead shield was found to be at least 7 ions/cc/sec., so that if there were no local radiation on Pike's Peak, the lowest obtainable value of the ionization in our shielded vessel should have been 14.8 ions/cc/sec. We observed as low as 11. We conclude, therefore, that there exists no such penetrating radiation as we have assumed. Second,

we found as a result of a snow-storm on the mountain as large a percentage change (about 10 per cent) in the ionization inside our 5 cm lead shield as outside it. We interpret this result also as meaning that the whole of the penetrating radiation is of local origin. How such quantities of radioactive material get into the upper air is as yet unknown.

A. De Angelis 2012 22

**1924: No penetrating radiation exists**

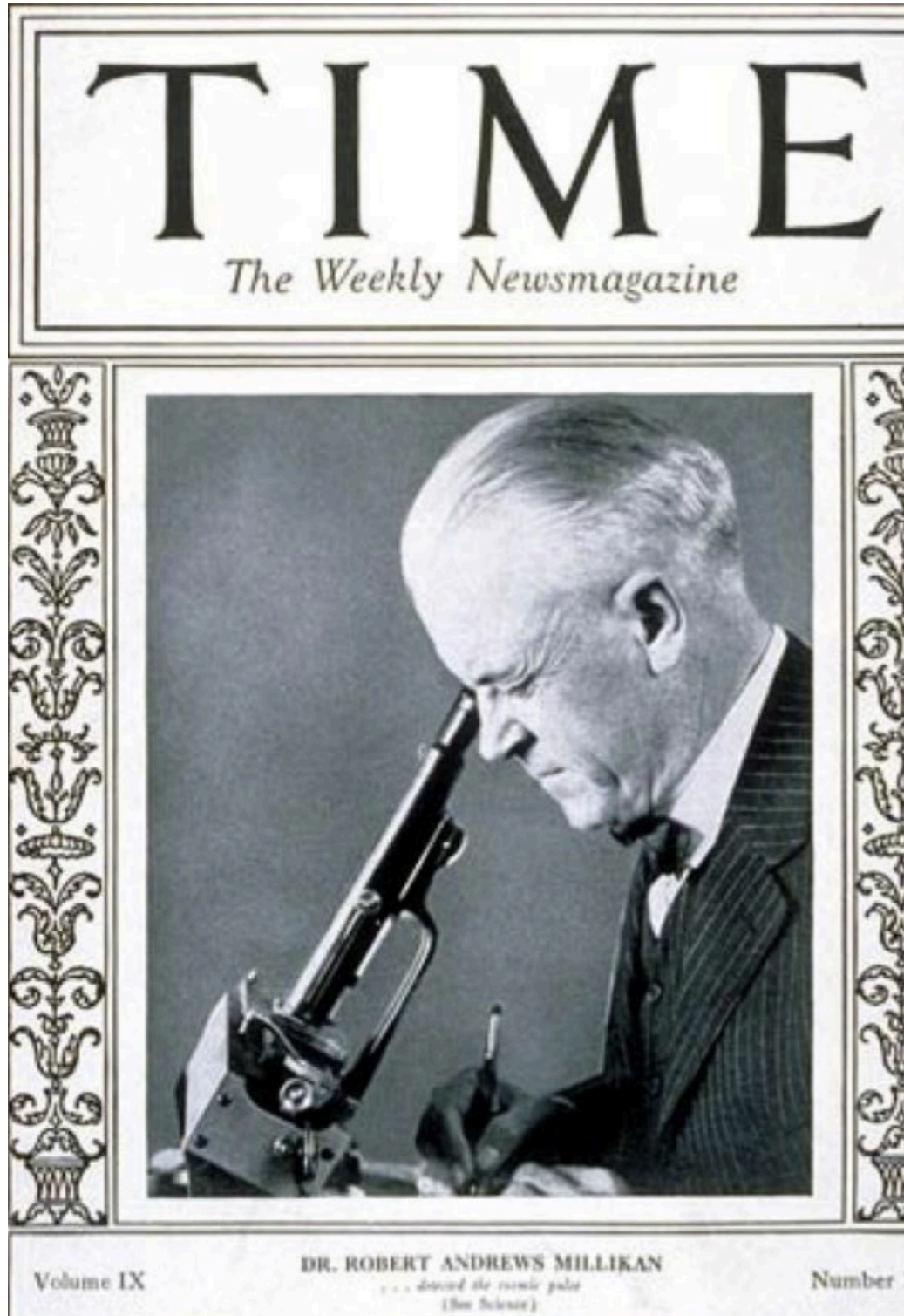
**1928: evidence claimed**

Nature (suppl) 121, 19, (1928)  
Lecture at Leeds University

These facts, combined with the further observation made both before and at this time, that within the limits of our observational error the rays came in equally from all directions of the sky, and supplemented finally by the facts that the observed absorption coefficient and total cosmic ray ionisation at the altitude of Muir Lake predict satisfactorily the results obtained in the 15.5 km. balloon flight, *all this constitutes pretty unambiguous evidence that the high altitude rays do not originate in our atmosphere, very certainly not in the lower nine-tenths of it, and justifies the designation 'cosmic rays,'* the most descriptive and the most appropriate name yet suggested for that portion of the penetrating rays which come in from above. We shall discuss just how unambiguous the evidence is at this moment after having presented our new results.



## MILLIKAN SURFING THE WAVE (1926)!



- ▶ Measurements of radiation depths in lake at high-altitudes
- ▶ Pacini's results reproduced
- ▶ He cloned the term "cosmic rays"
- ▶ This became a success of USA science
- ▶ Never mentioned Hess or Pacini pioneering works



# Popular Science MONTHLY

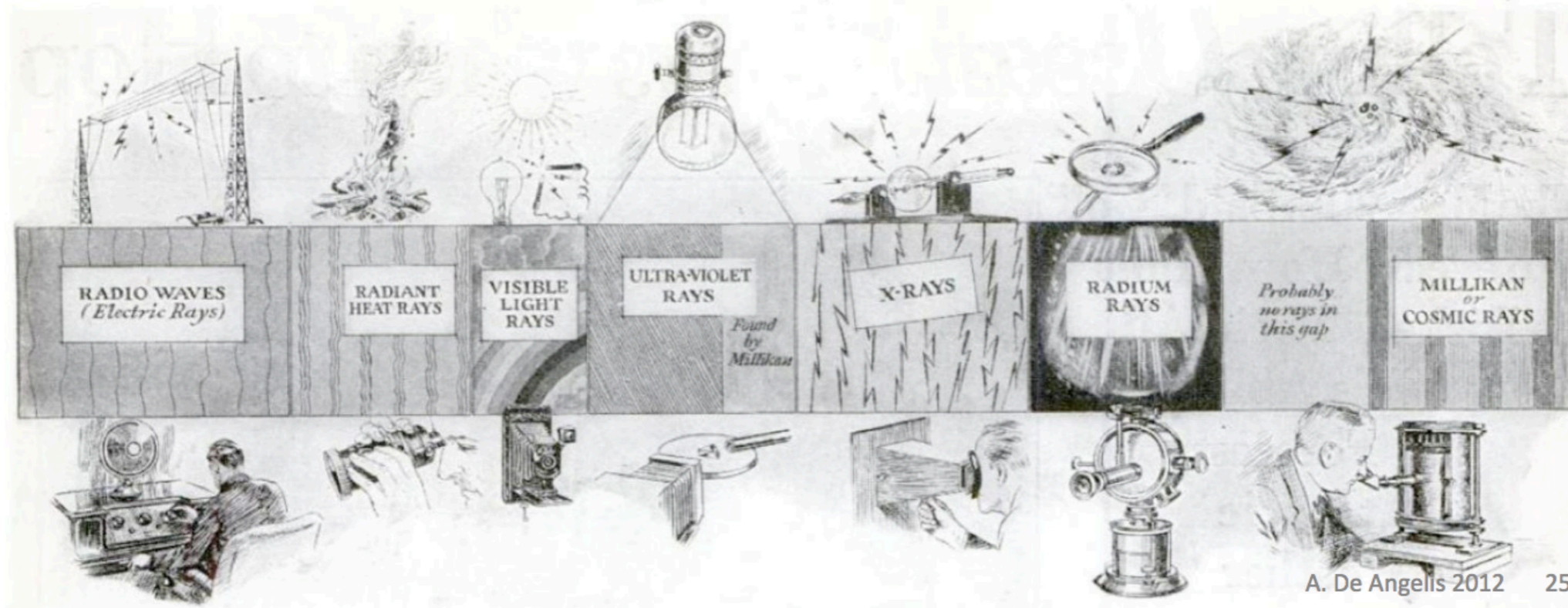


JULY, 1928

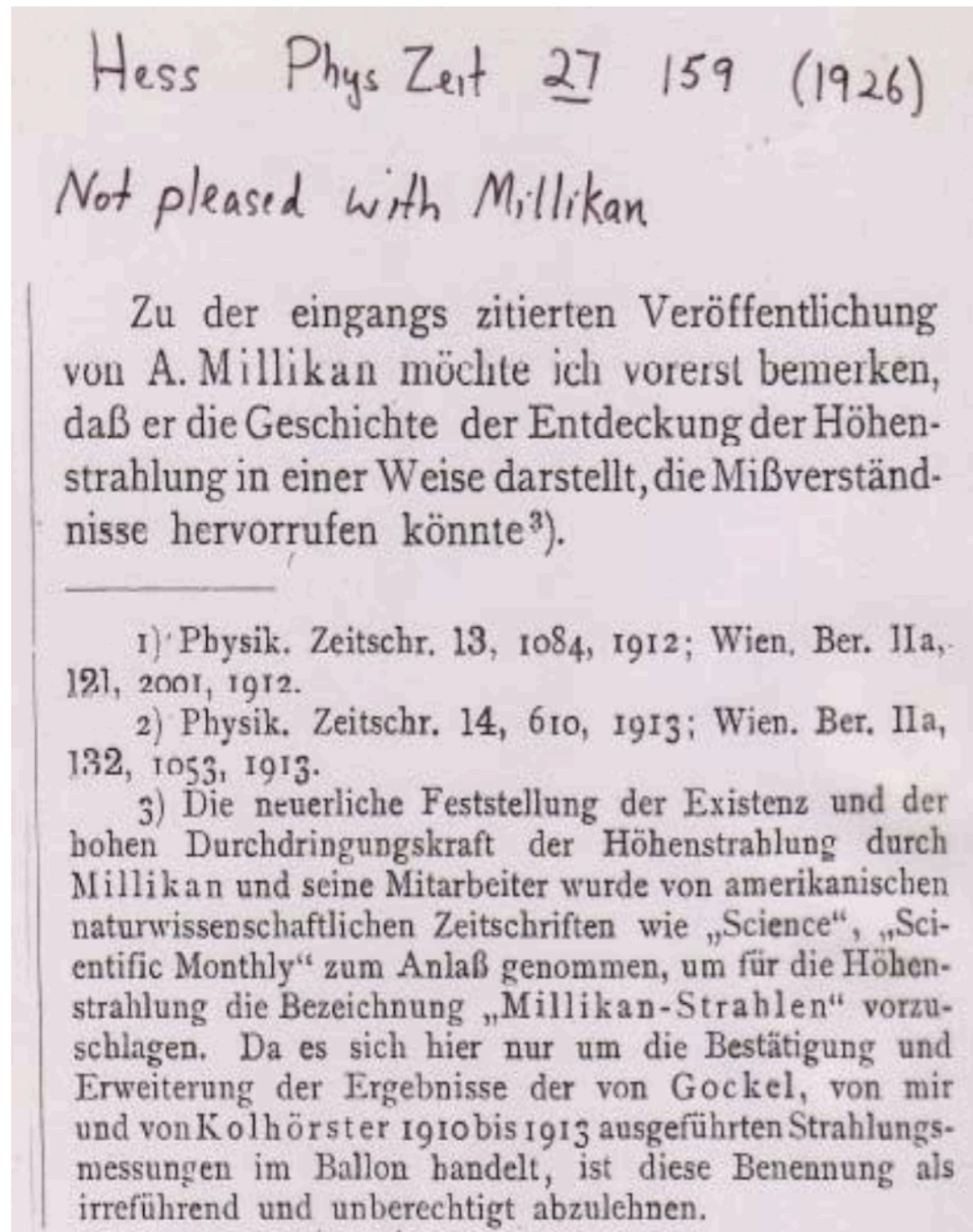
SUMNER BLOSSOM *Editor*

VOL. 113, NO. 1

## Super-Rays Reveal Secret of Creation



## HESS'S REACTION (1926)



Hess: Physik. Zeitschr. 27, 159, (1926)

As concerns the publication of Millikan, cited above, I would like to remark that he tells a story of the discovery of hohenstrahlung that could be easily misunderstood.

3) The recent determination by Millikan and his colleagues of the high penetrating power of hohenstrahlung has been an occasion for American scientific journals such as “Science” and “Scientific Monthly” to introduce the term “Millikan Rays”. Millikan’s work is only a confirmation and extension of the results obtained by Gockel, by myself, and by Kolhörster from 1910 to 1913 using balloon borne measurements of the rays. To refuse to acknowledge our work is an error and unjustified.

## 1936: The Nobel prize to Hess (& Anderson)

Hess was awarded the 1936 Nobel Prize in physics, shared with Anderson. Hess was nominated by Clay, Compton:

- *The time has now arrived, it seems to me, when we can say that the so-called cosmic rays have their origin at remote distances from the Earth [...] and that the use of the rays has by now led to results of such importance that they may be considered a discovery of the first magnitude. [...] It is, I believe, correct to say that Hess was the first to establish the increase of the ionization observed in electroscopes with increasing altitude; and he was certainly the first to ascribe with confidence this increased ionization to radiation coming from outside the Earth*

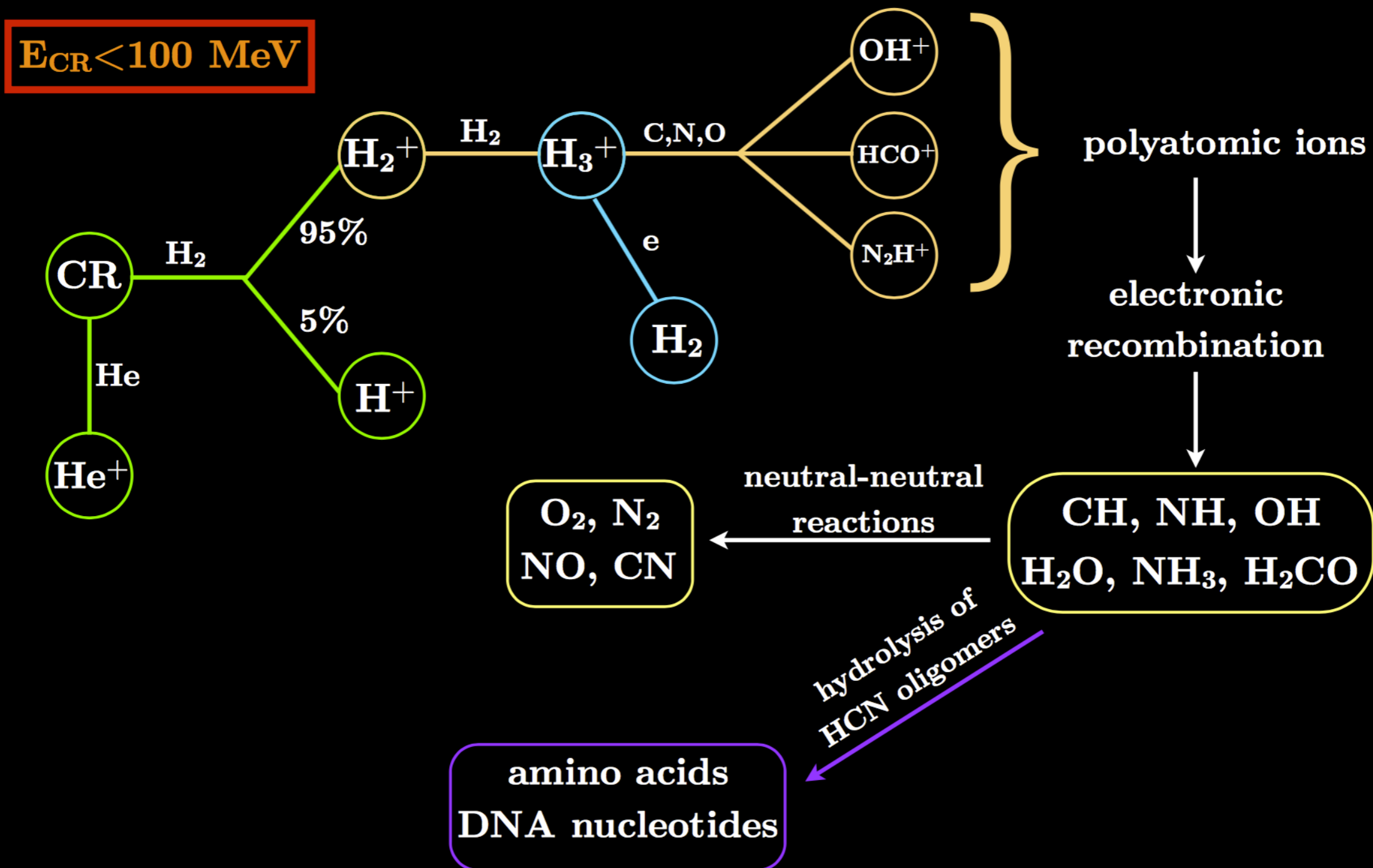


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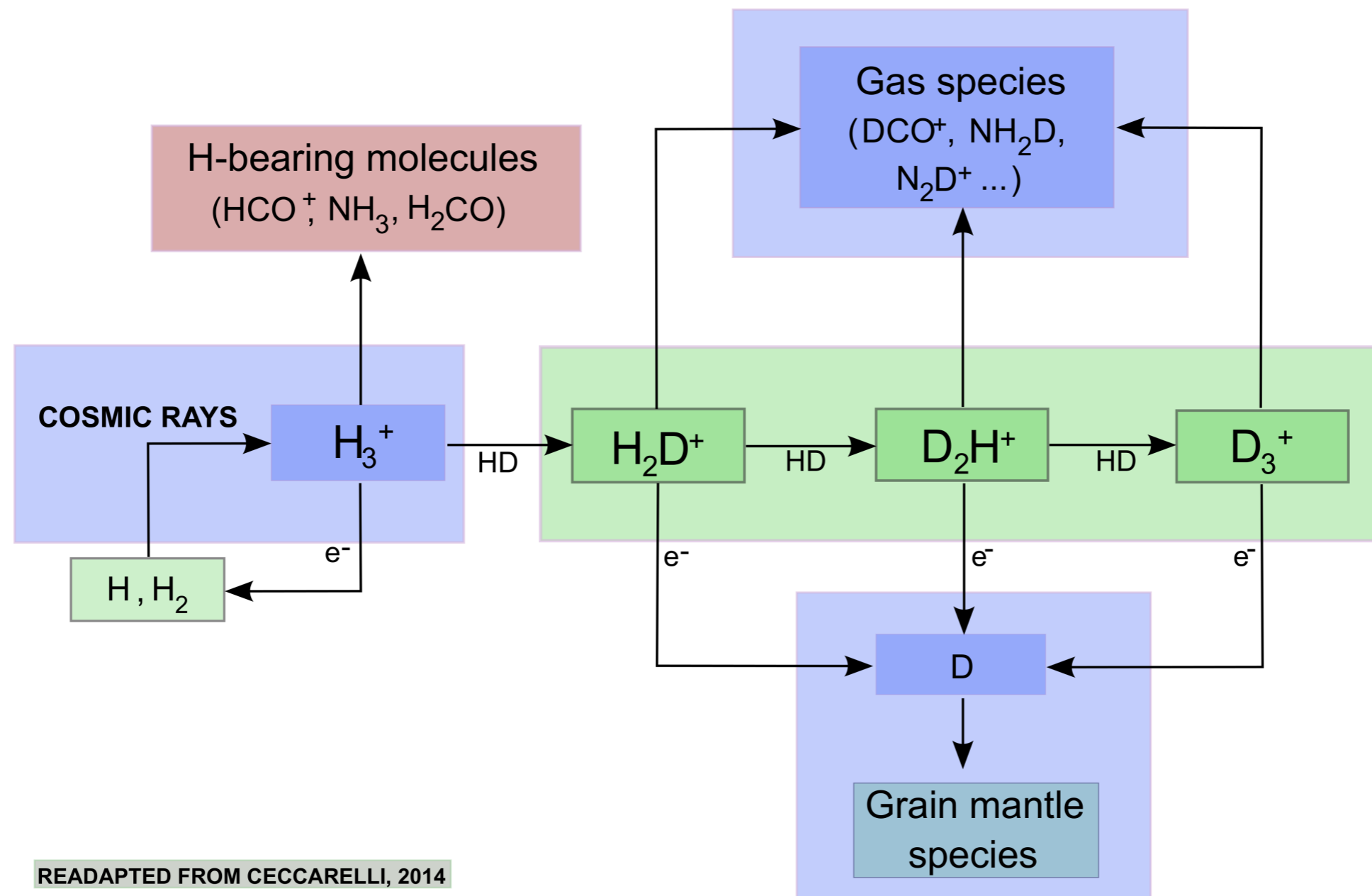
## PHYSICS OF COSMIC RAYS DEVELOPED FURTHER

- ▶ Cosmic rays are important in particle physics, astrophysics, astrochemistry!
- ▶ Particularly in astrochemistry they drive ions-neutral reactions in MCs
- ▶ Low-energy CRs determine ionization of species in the ISM
- ▶ Unfortunately the CRIR is still an uncertain parameter

# COSMIC RAYS CHEMISTRY



# EXAMPLES: DEUTERATION CHEMISTRY



READAPTED FROM CECCARELLI, 2014

## SO FAR IN ASTROCHEMICAL MODELS

- ▶ We need the cosmic-rays ionization rate (CRIR)
- ▶ Fundamental for the interpretation of observations
- ▶ Important in non-ideal MHD
- ▶ Normally a constant CRIR is assumed

$$\zeta_{CR} \sim 10^{-17} [\text{s}^{-1}]$$



## SOME IMPORTANT CONSIDERATION (SEE INDRIOLO+2013)

- ▶ Different ways to define CRIR
- ▶ Primary ionization rate (ionization rate of H due only to protons and heavy nuclei)  $\zeta_p$
- ▶ Total ionization rate of H  $\zeta_H$
- ▶ Total ionization rate of H<sub>2</sub>  $\zeta_{H_2}$

$$\zeta_H = 1.5\zeta_p$$

$$\zeta_{H_2} = 2.3\zeta_p$$

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## PROPERLY MODELING THE COSMIC RAYS (CONT'D)

- ▶ The idea is that we could consider variation and effect of column density on the CRIR
- ▶ And the magnetic field coupling
- ▶ But unfortunately this is pretty expensive, it requires propagation of CRs which is similar to RT
- ▶ See Padovani&Galli 2011,2013, and Padovani+2009

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# MEASUREMENTS

# COSMIC-RAYS MEASUREMENTS (NEUFELD'S TALK)

Table 1 Classification of Interstellar Cloud Types

	Diffuse Atomic	Diffuse Molecular	Translucent	Dense Molecular
Defining Characteristic	$f_{\text{H}_2}^n < 0.1$	$f_{\text{H}_2}^n > 0.1$ $f_{\text{C}^+}^n > 0.5$	$f_{\text{C}^+}^n < 0.5$ $f_{\text{CO}}^n < 0.9$	$f_{\text{CO}}^n > 0.9$
$A_V$ (min.)	0	$\sim 0.2$	$\sim 1-2$	$\sim 5-10$
Typ. $n_{\text{H}}$ ( $\text{cm}^{-3}$ )	10-100	100-500	500-5000?	$> 10^4$
Typ. T (K)	30-100	30-100	15-50?	10-50
Observational Techniques	UV/Vis HI 21-cm	UV/Vis IR abs mm abs	Vis (UV?) IR abs mm abs/em	IR abs mm em

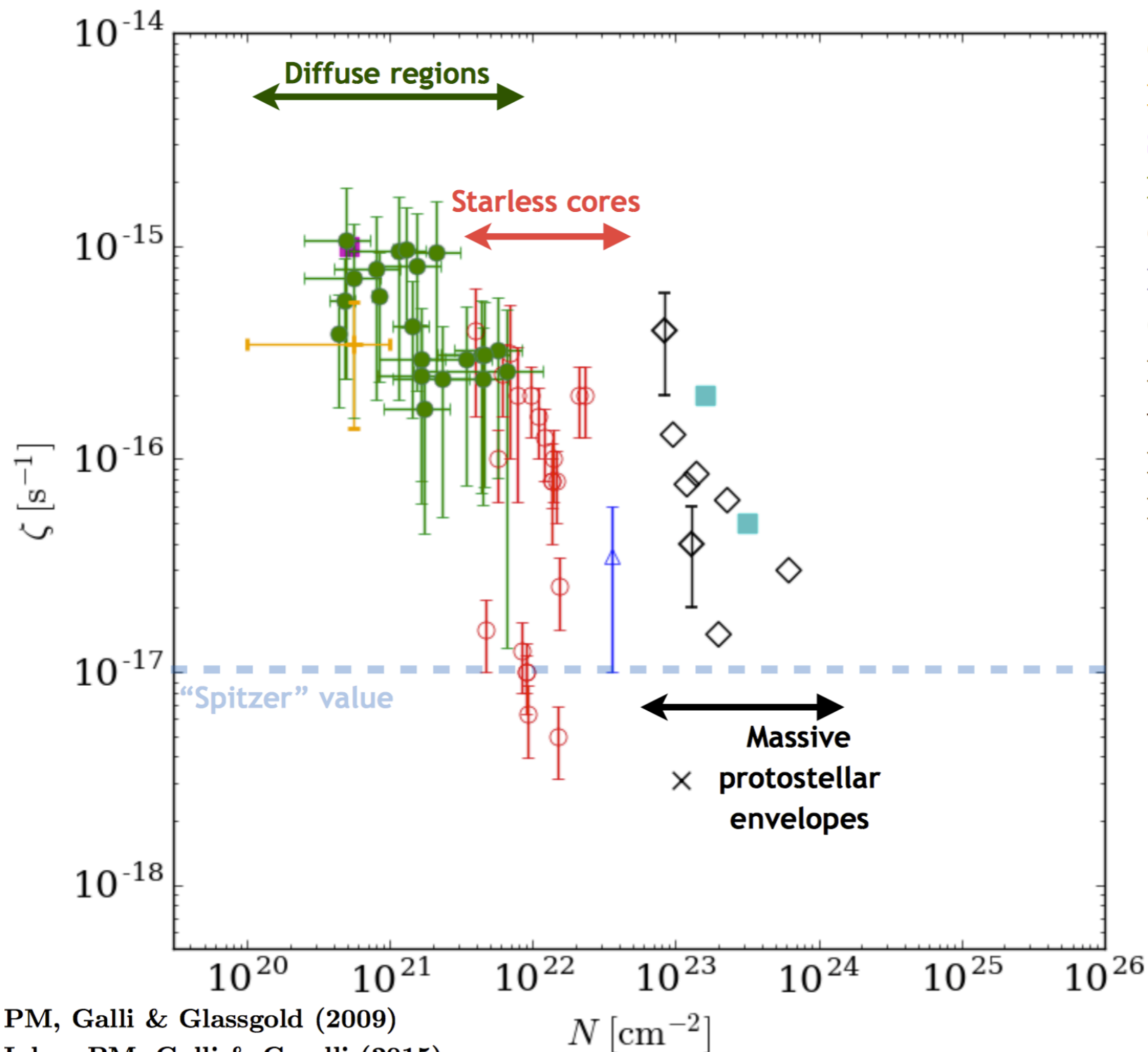
**From  $\text{OH}^+$ ,  $\text{H}_2\text{O}^+$  and  $\text{ArH}^+$**   
 $\zeta_p(\text{H}) = 2.2 \pm 0.3 \times 10^{-16} \text{ s}^{-1}$

**From H and C RRL**  
 $\zeta_p(\text{H}) = 8 \times 10^{-17} \text{ s}^{-1}$

**From  $\text{H}_3^+$**   
 $\zeta_p(\text{H}) = 2.3 \pm 0.6 \times 10^{-16} \text{ s}^{-1}$   
 (with marginal evidence for decline with  $A_V(\text{tot})$ )

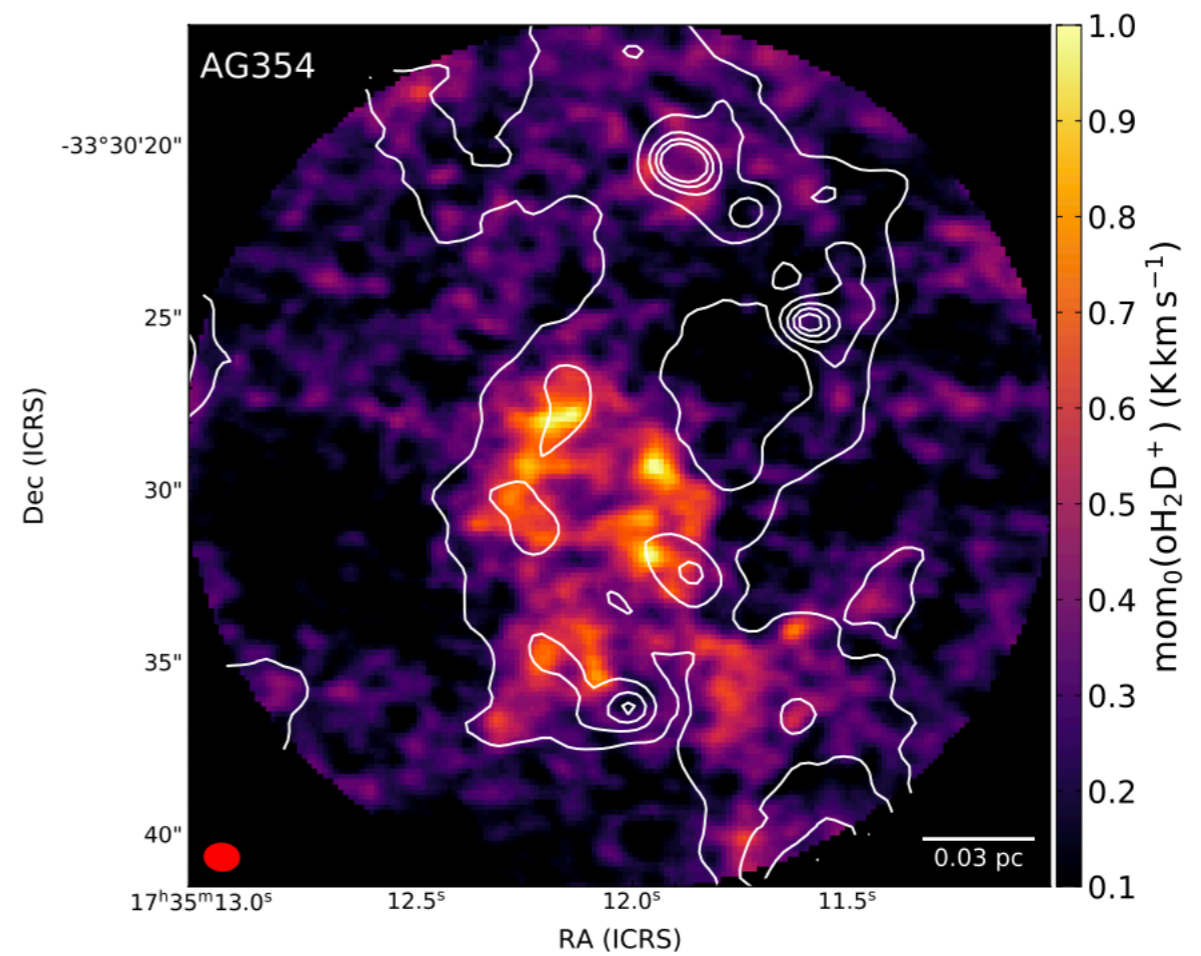
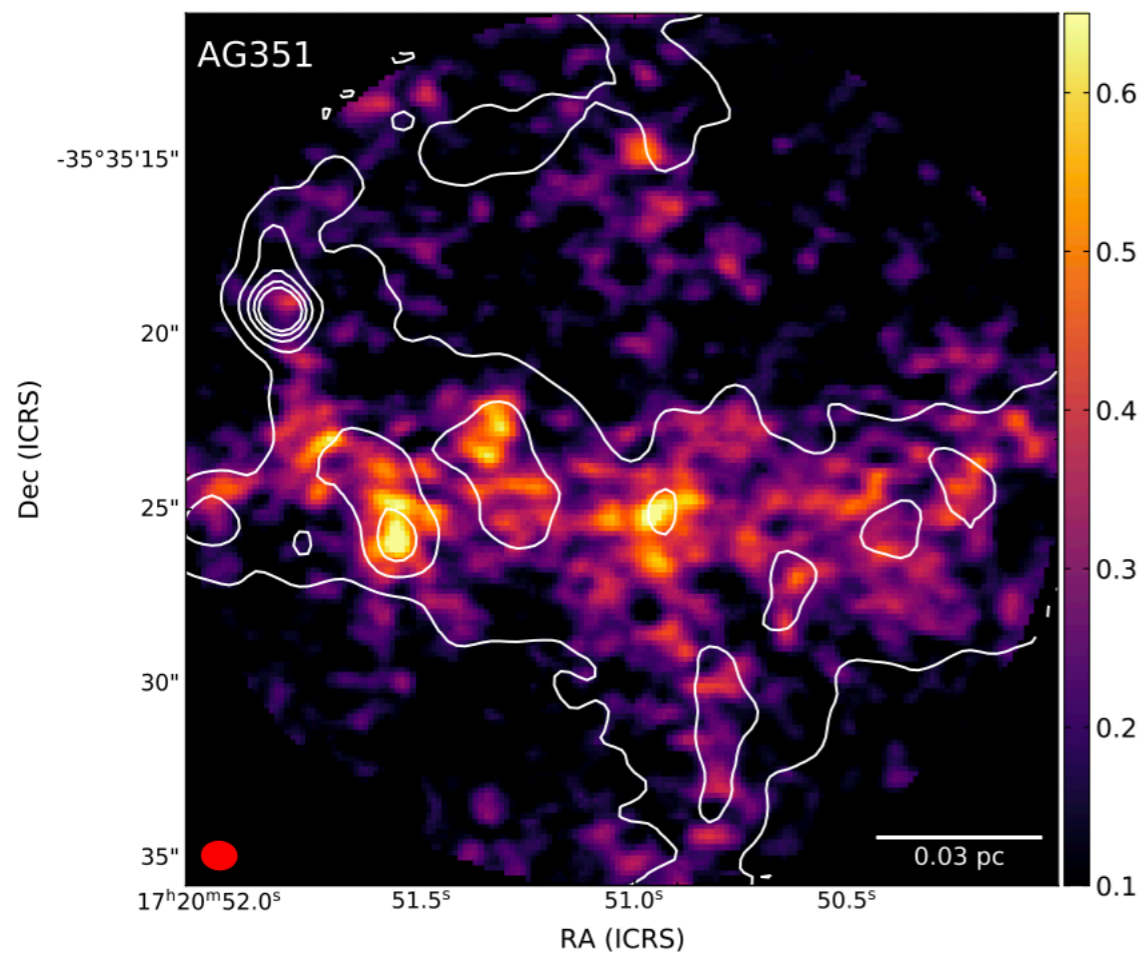
**From  $\text{HCO}^+$  (van der Tak & van Dishoeck 2000)**  
 $\zeta_p(\text{H}) = 1.1 \times 10^{-17} \text{ s}^{-1}$

# SUMMARY OF OBSERVATIONS (PADOVANI+)

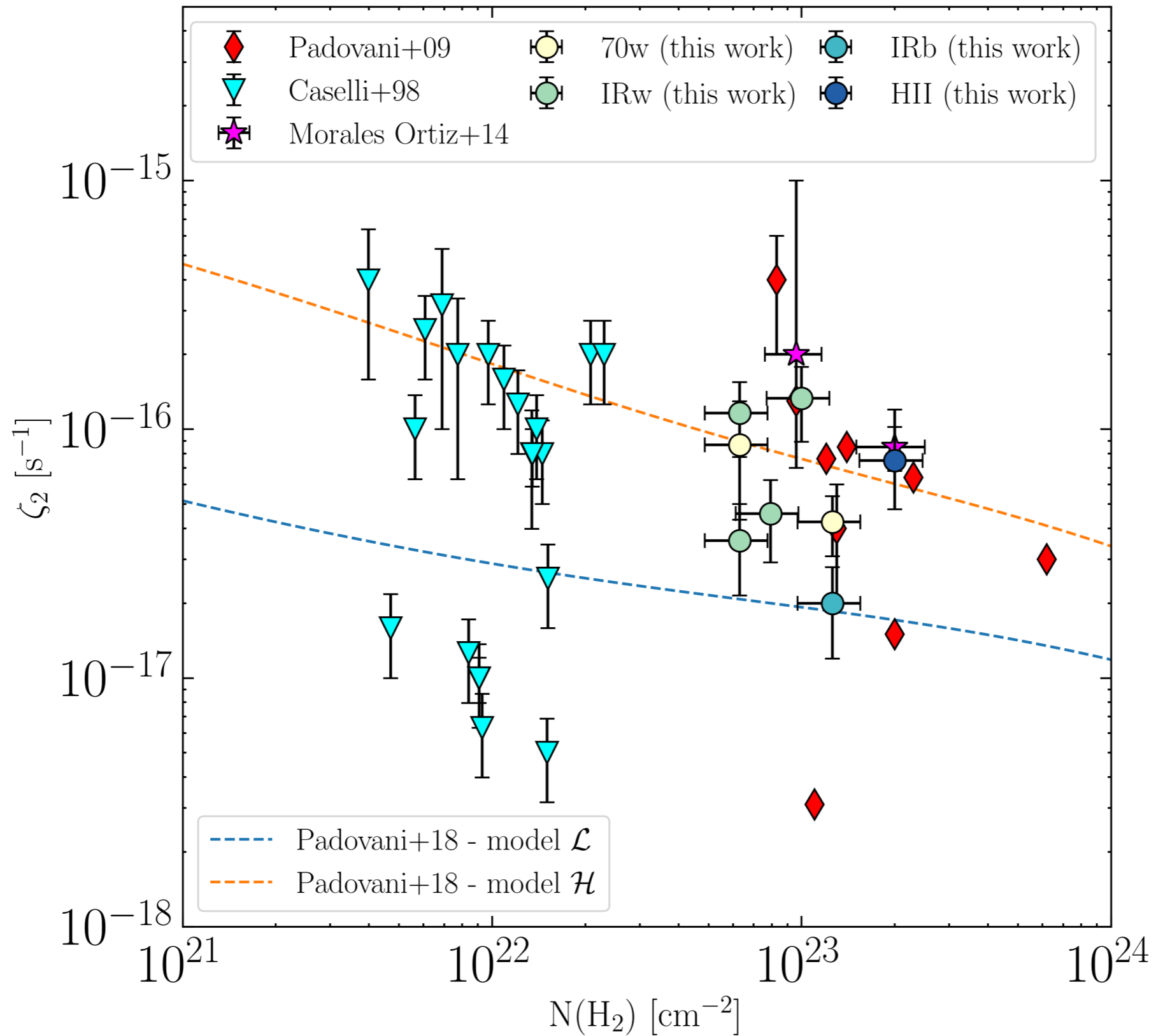


Gerin+ (2010)  
 Neufeld+ (2010)  
 Shaw+ (2008)  
 Indriolo+ (2012)  
 Caselli+ (1998)  
 Maret & Bergin (2007)  
 Ceccarelli+ (2004)  
 Boisanger+ (1996)  
 van der Tak+ (2000)  
 Doty+ (2002)  
 Hezareh+ (2008)

$$R_D \equiv \frac{n(\text{DCO}^+)}{n(\text{HCO}^+)} = \frac{1}{3} \frac{n(\text{H}_2\text{D}^+)}{n(\text{H}_3^+)}$$



Obtained from deuterated species of  $\text{H}_3^+$  ( $\text{H}_2\text{D}^+$ )



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# SUMMARY

- ▶ Gas-phase chemistry is driven by fast ion-neutral reactions
- ▶ This requires a mechanism of ionization
- ▶ UV radiation (diffuse gas) and cosmic-rays (dense gas) provide with the necessary ions
- ▶ Both radiation and cosmic-rays also heat the gas
- ▶ Cosmic-rays are fundamental for the understanding of observational signatures
- ▶ Some processes generate secondary electrons which can induce further ionization
- ▶ CRIR still uncertain and inaccurate in models!