超新星遗迹伽玛射线辐射与LHAASO观测

南京大学天文与空间科学学院
陈　阳

宇宙线：2012年被《Science》列为8大天文学之谜

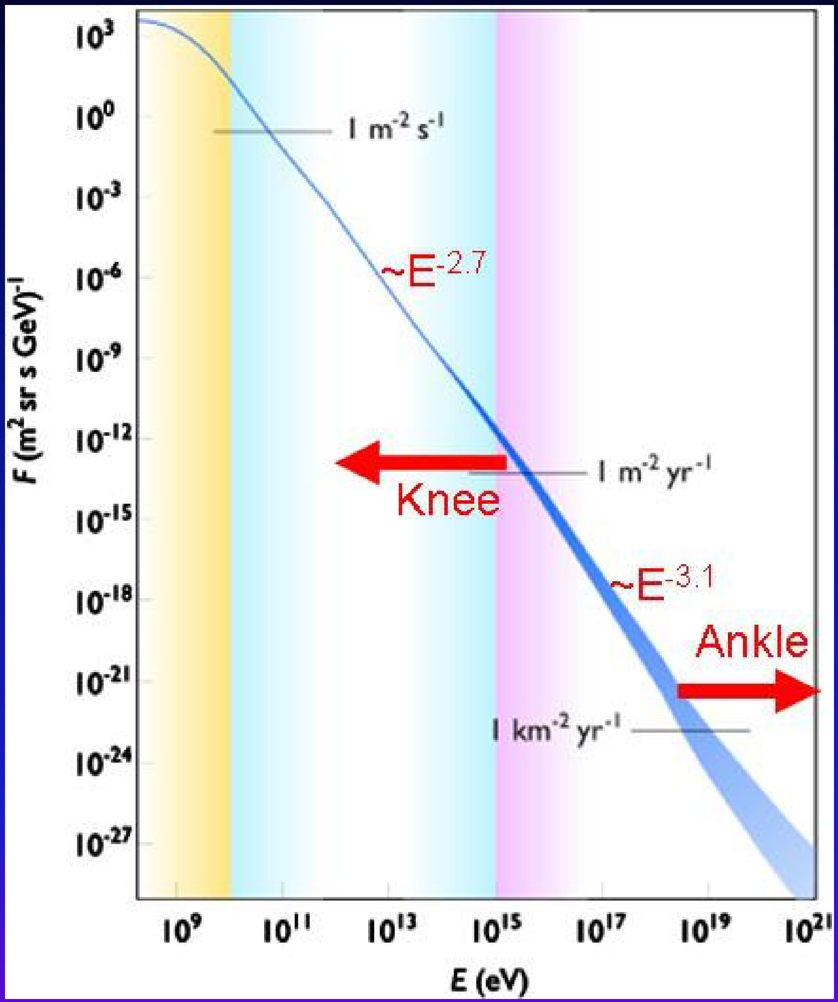
Science News Reports on the Top Mysteries

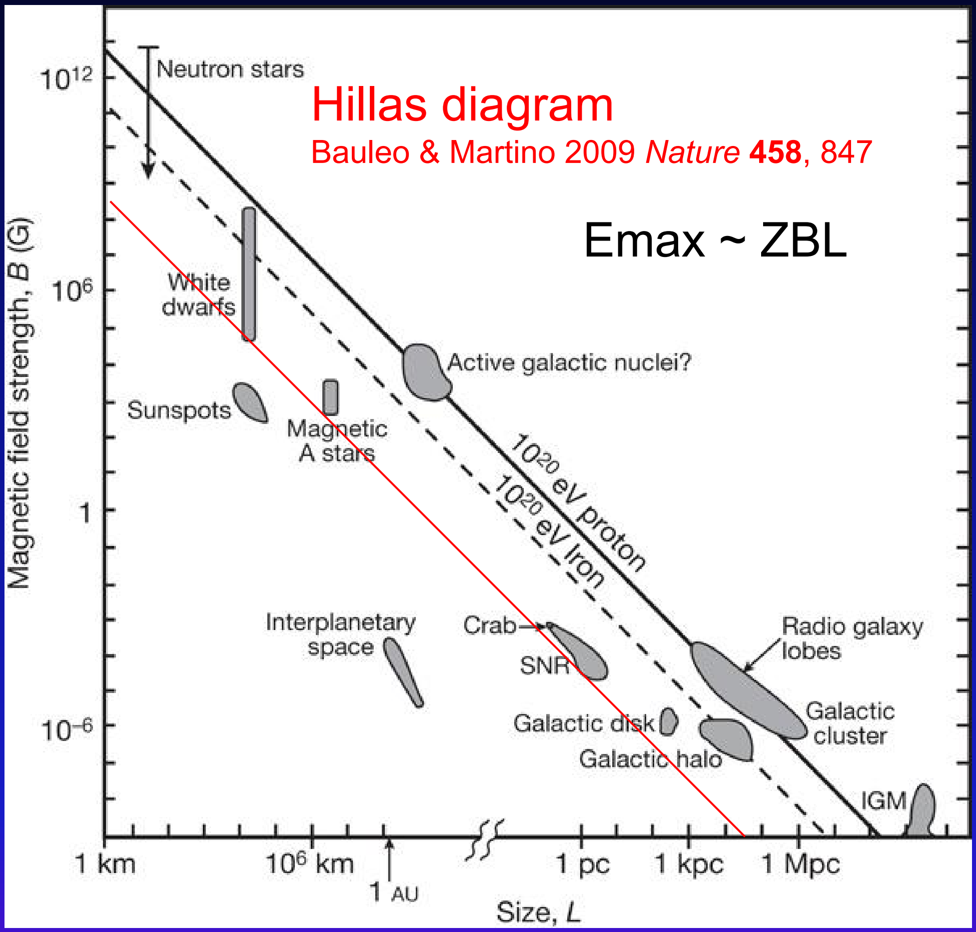
SCIENCE PODCAST

Interview with the Editor

Deputy News Editor Robert Coontz discusses the most confounding problems of astronomy.

Spectrum of CRs





- Above 'ankle': extragalactic
- Below 'knee': galactic origin (Gal.E.den. > SMC E.den)

Two great ideas in a single short paper

COSMIC RAYS FROM SUPER-NOVAE

BY W. BAADE AND F. ZWICKY

MOUNT WILSON OBSERVATORY, CARNEGIE INSTITUTION OF WASHINGTON AND CALIFORNIA INSTITUTE OF TECHNOLOGY, PASADENA

Communicated March 19, 1934

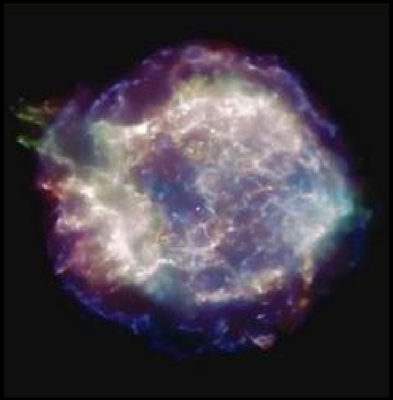
happenings in a super-nova now confronts us. With all reserve we advance the view that a super-nova represents the transition of an ordinary star into a *neutron star*, consisting mainly of neutrons. Such a star may possess a very small radius and an extremely high density. As neutrons can be packed much more closely than ordinary nuclei and electrons, the "gravitational packing" energy in a *cold* neutron star may become very large, and, under certain circumstances, may far exceed the ordinary nuclear packing fractions. A neutron star would therefore represent the most stable configuration of matter as such. The consequences of this hypothesis will be developed in another place, where also will be mentioned some observations that tend to support the idea of stellar bodies made up mainly of neutrons.

D. Conclusions.—From the data available on super-novae we conclude

(1) Mass may be *annihilated* in bulk. By this we mean that an assembly of atoms whose total mass is M may lose in the form of electromagnetic radiation and kinetic energy an amount of energy E_T which probably cannot be accounted for by the liberation of known nuclear packing fractions. Several interpretations of this result are possible and will be published in another place.

(2) The hypothesis that *super-novae emit cosmic rays* leads to a very satisfactory agreement with some of the major observations on cosmic rays.

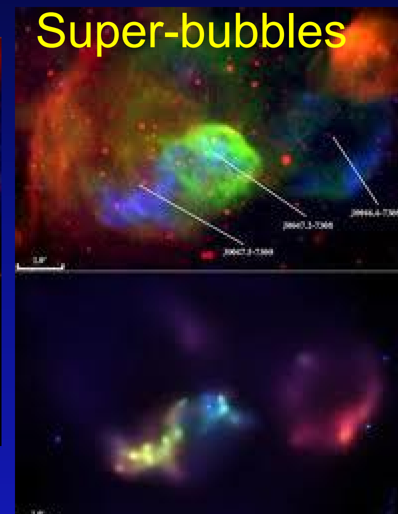
Baade & Zwicky (1934) :
SN → CRs & NS

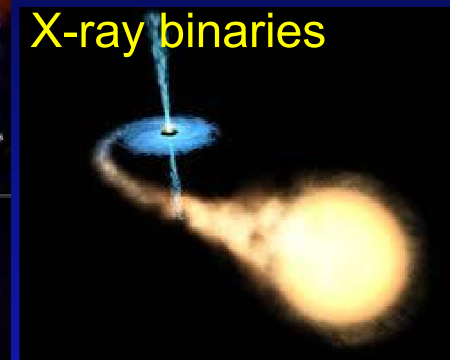


Galactic acceleration sources

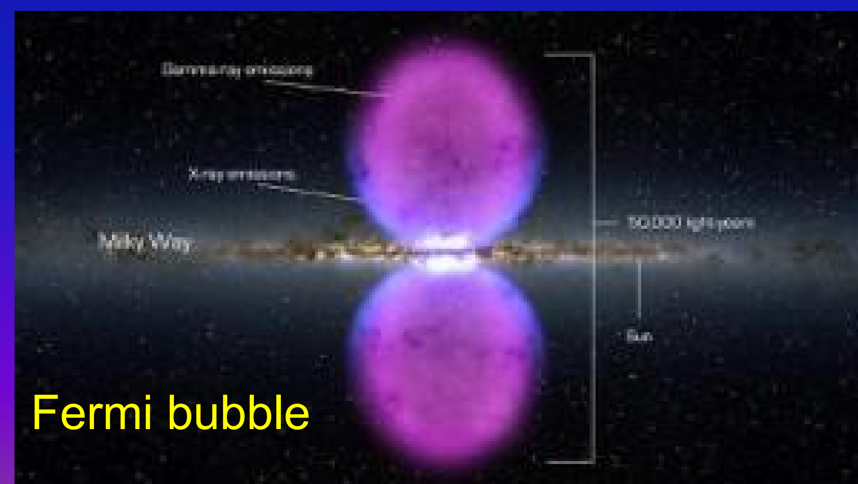

Supernova remnants


Pulsar wind nebulae


Super-bubbles

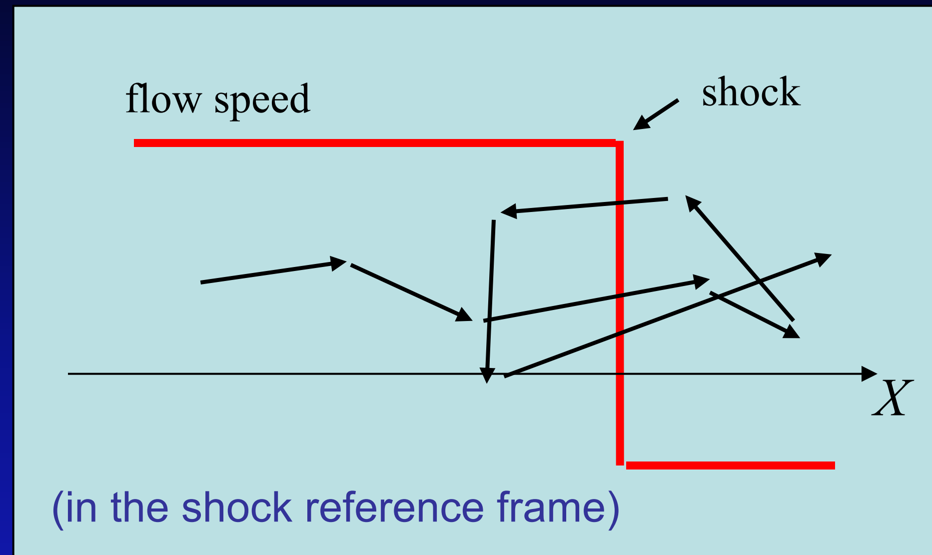

X-ray binaries


Galactic center

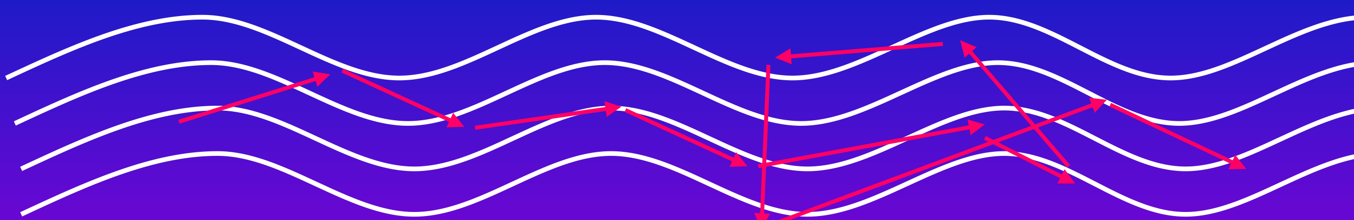


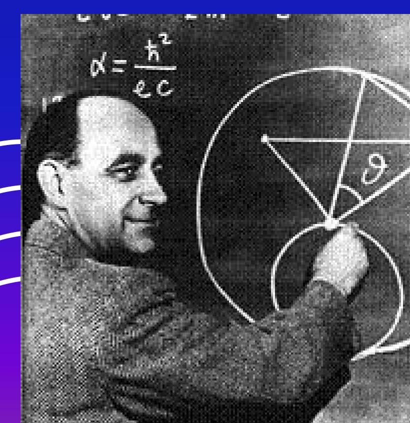
Fermi bubble

SNR shock wave enables Diffusive shock acceleration (DSA)

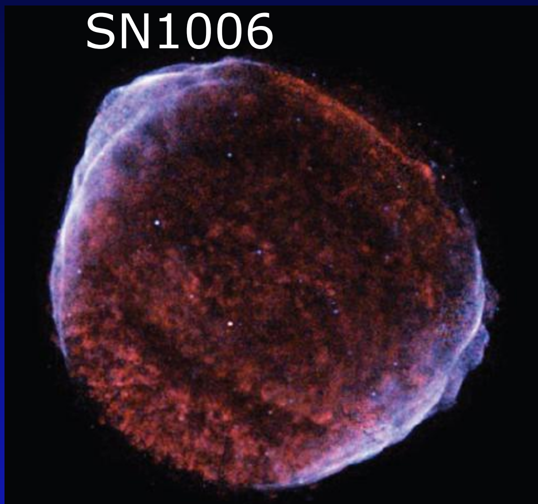


- Fermi acceleration
  - Converging flows
  - Particle diffusion (How possible, in a collisionless plasma?)
- Scattering on MHD waves





Evidence for rel. e's: Synchrotron X-rays from Shell-type SNRs

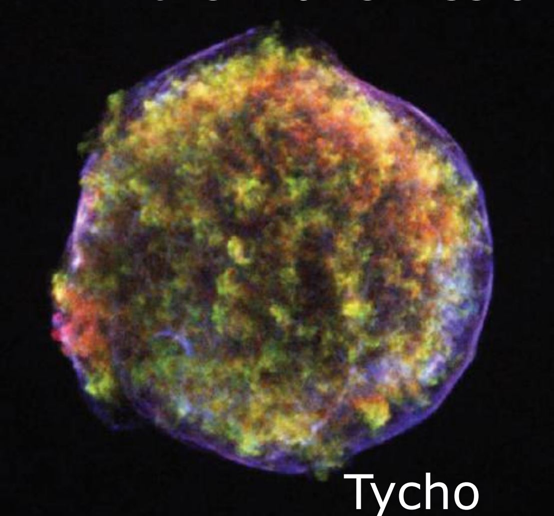

SN1006

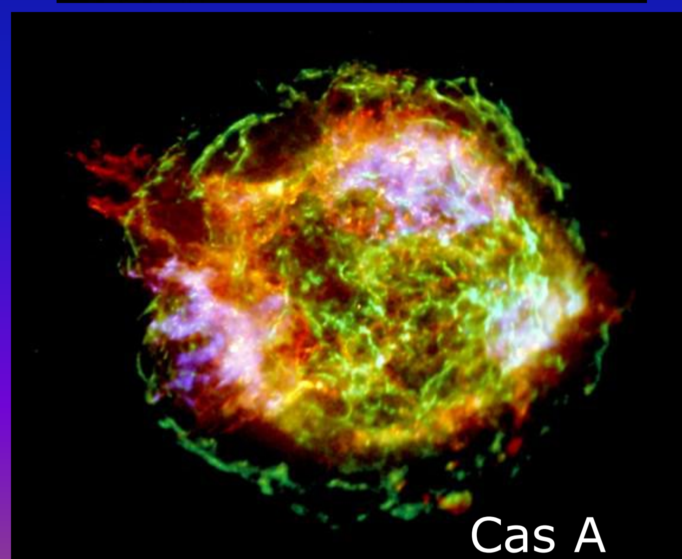

Kepler

- Power-law filaments;
- Up to

$E_e \sim 10^{14}$ eV (100 TeV)

Outer thin filaments: accelerated relativistic particles (non-thermal emission)

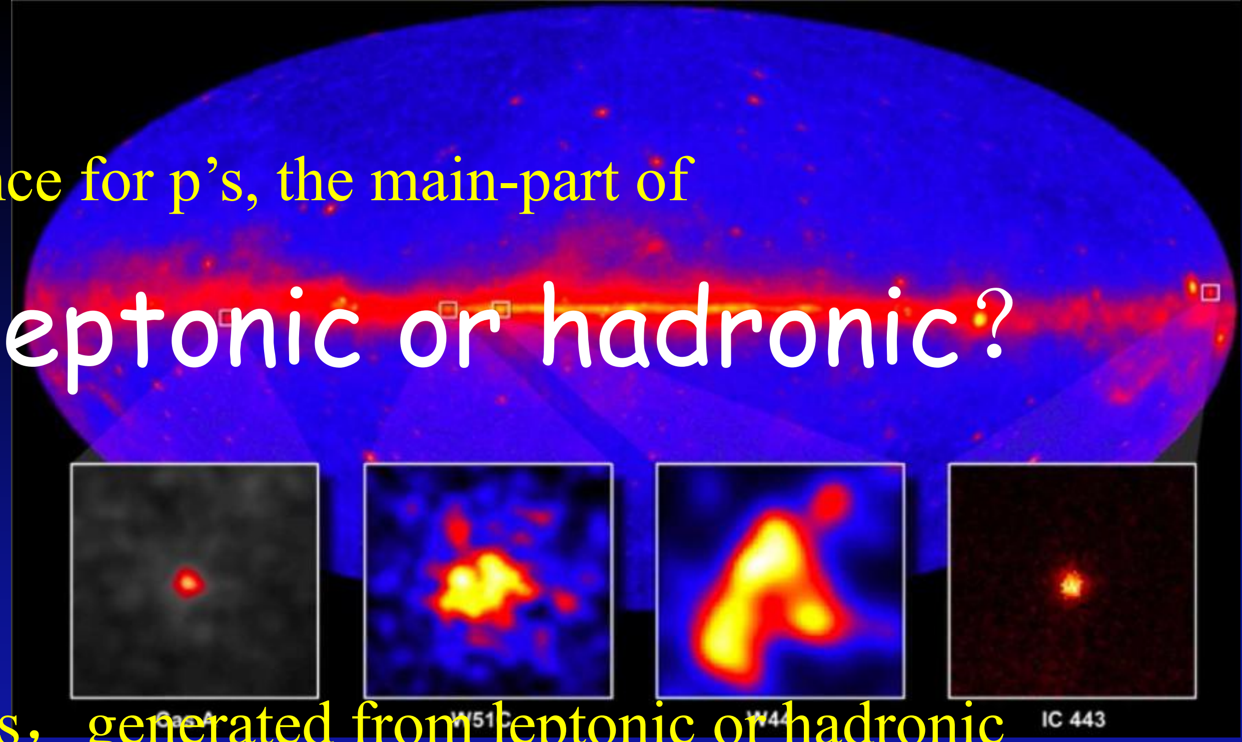

Tycho


Cas A

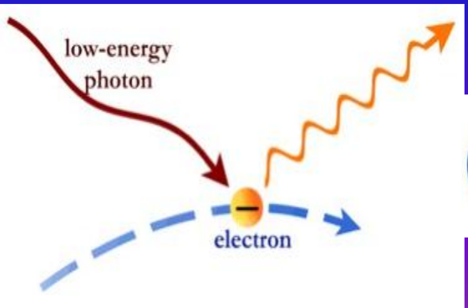
Synchrotron radiation

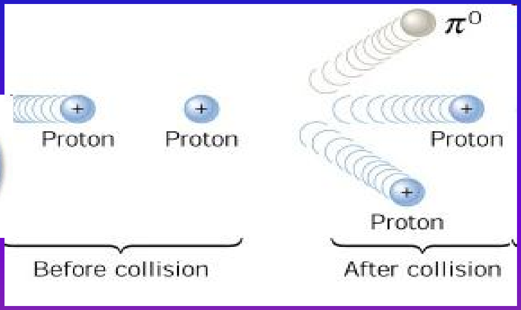
- However, evidence for p's, the main-part of CRs?

γ-rays: leptonic or hadronic?



- Extended γ-rays, generated from leptonic or hadronic interaction? Their ratio?
  - Leptonic: Inverse Compton, non-thermal bremsstrahlung
  - Hadronic: p-p collision → π^0 decay





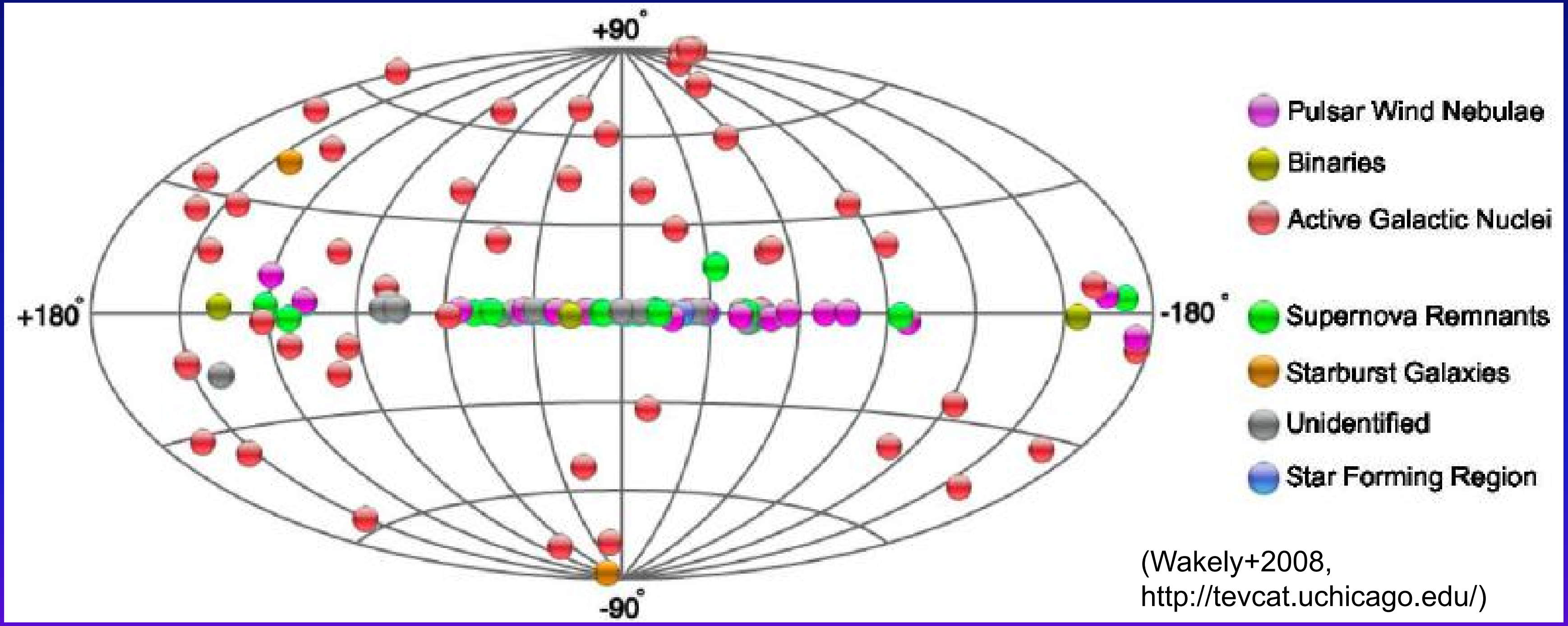
IC scattering

Proton-proton collision

Map of TeV Sources

> 20 SNRs

by Apr. 2015



(Wakely+2008, http://tevcat.uchicago.edu/)

mostly associated with molecular clouds

Name	RA	Dec	Type	Date	Dist	Catalog
			Shell			Default Catalog
Tycho	00 25 27	+64 10 50	Shell	2010.05	3.5 kpc	Default Catalog
IC443	06 16 51	+22 30 11	Shell	2007.05	1.5 kpc	Default Catalog
RX J0852.0-4622	08 52 00	-46 22 00	Shell	2005.02	0.2 kpc	Default Catalog
RCW 86	14 42 42.96	-62 26 41.6	Shell	2008.10	2.5 kpc	Default Catalog
SN 1006 SW	15 02 03.2	-41 07 05	Shell	2008.12	2.2 kpc	Default Catalog
SN 1006 NE	15 04 03.4	-41 48 11	Shell	2008.12	2.2 kpc	Default Catalog
RX J1713.7-3946	17 13 33.6	-39 45 36	Shell	2000.02	1 kpc	Default Catalog
CTB 37B	17 13 57.6	-38 12 00	Shell	2006.01	13.2 kpc	Default Catalog
HESS J1731-347	17 32 03	-34 45 18	Shell	2007.07		Default Catalog
SNR G106.3+02.7	22 27 59	+60 52 37	Shell	2009.07	0.8 kpc	Default Catalog
Cassiopeia A	23 23 13.8	+58 48 26	Shell	2001.04	3.4 kpc	Default Catalog

1-11

Name	RA	Dec	Type	Date	Dist	Catalog
			SNR/Molec. Cloud			Default Catalog
CTB 37A	17 14 19	-38 34 00	SNR/Molec. Cloud	2008.11	7.9 kpc	Default Catalog
SNR G349.7+00.2	17 17 57.8	-37 26 39.6	SNR/Molec. Cloud	2013.07	11.5 kpc	Default Catalog
HESS J1745-303	17 45 02.4	-30 22 12	SNR/Molec. Cloud	2006.01		Default Catalog
HESS J1800-240B	18 00 26.4	-24 02 20.4	SNR/Molec. Cloud	2008.04	2 kpc	Default Catalog
W 28	18 01 42.2	-23 20 06.0	SNR/Molec. Cloud	2008.04	2 kpc	Default Catalog
HESS J1800-240A	18 01 57.8	-23 57 43.2	SNR/Molec. Cloud	2008.04	2 kpc	Default Catalog
W 51	19 22 55.2	+14 11 27.6	SNR/Molec. Cloud	2008.10	4.3 kpc	Default Catalog

1-7

Name	RA	Dec	Type	Date	Dist	Catalog
			SNR/Molec. Cloud			Newly Announced
LMC N132D	05 25 02.20	-69 38 39.0	SNR/Molec. Cloud	2014.10		Newly Announced
SNR G318.2+00.1	14 57 46	-59 28 00	SNR/Molec. Cloud	2010.12		Newly Announced
W 49B	19 11 06.63	09 05 34.0	SNR/Molec. Cloud	2010.12		Newly Announced

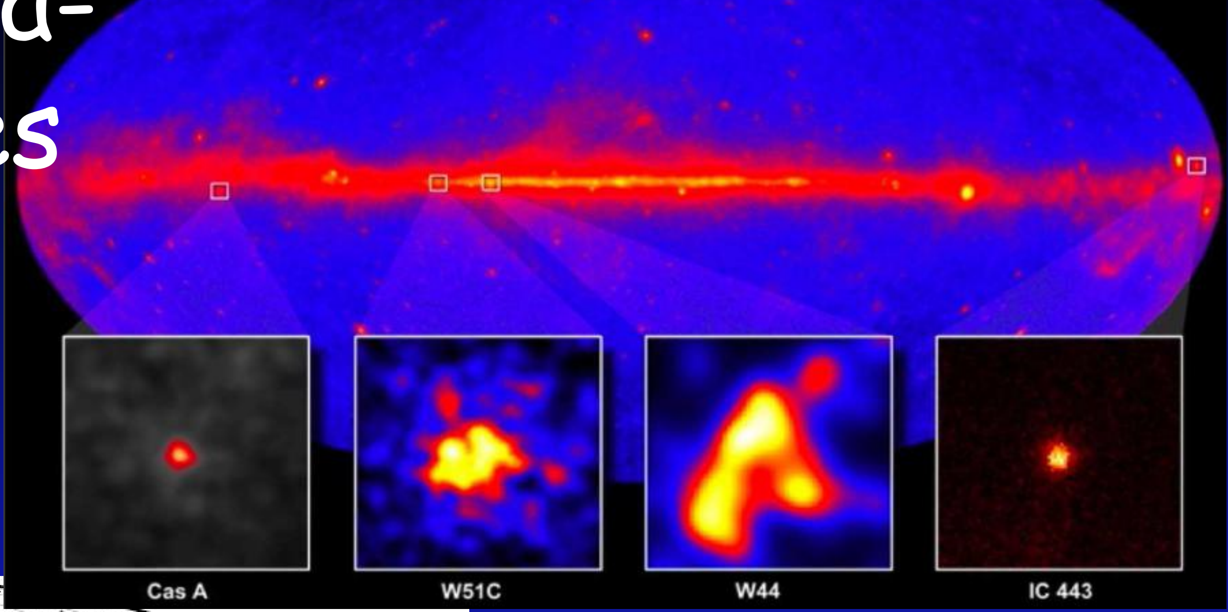
1-3

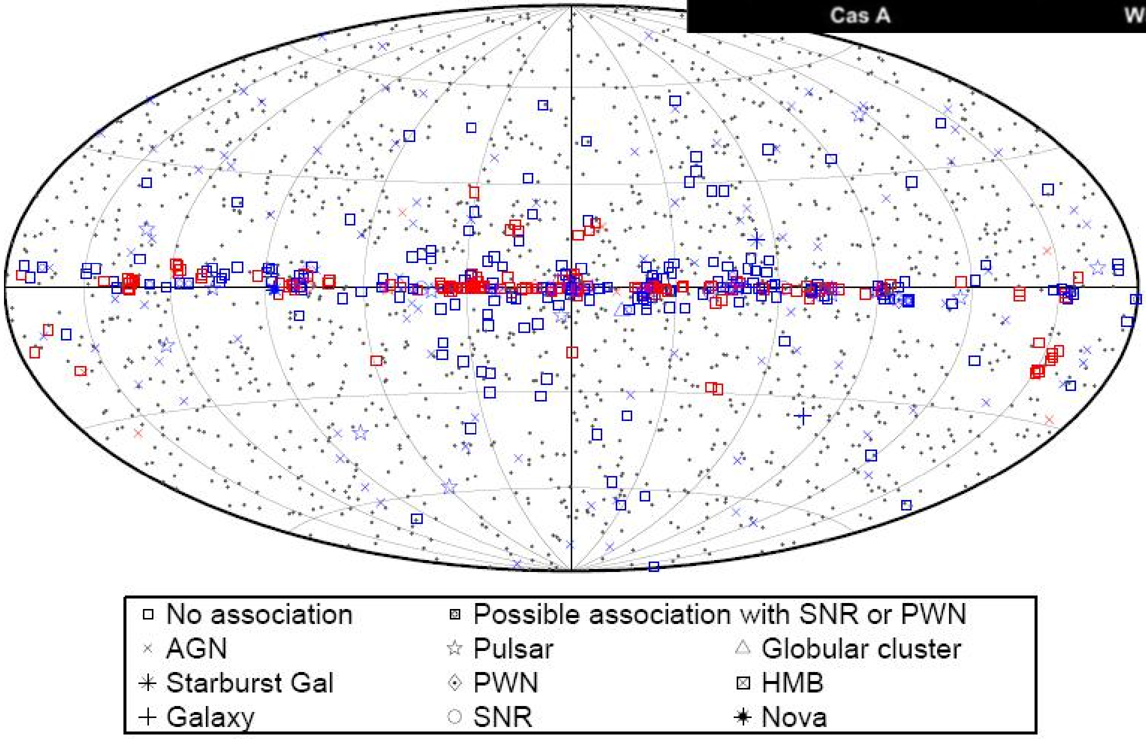
Name	RA	Dec	Type	Date	Dist	Catalog
			Composite SNR			Default Catalog
SNR G015.4+00.1	18 18 04.8	-15 28 01	Composite SNR	2011.12	4.8 kpc	Default Catalog

1-1

Fermi gamma-rays sources

Fermi-LAT allsky map of the gamma-ray sky (Knödlseder et al. 2010)





2FGL (2012): 89 sources overlap with SNRs

3FGL (2015)

Description	Identified Designator	Identified Number	Associated Designator	Associated Number
Pulsar, identified by pulsations	PSR	137	...	...
Pulsar, no pulsations seen in LAT yet	...	...	psr	29
Pulsar wind nebula	PWN	9	pwn	2
Supernova remnant	SNR	12	snr	11
Supernova remnant / Pulsar wind nebula	...	...	spp	51
Globular cluster	GLC	0	glc	15
High-mass binary	HMB	3	hmb	0
Binary	BIN	1	bin	0
Nova	NOV	1	nov	0
Star-forming region	SFR	1	sfr	0
Compact Steep Spectrum Quasar	CSS	0	css	1
BL Lac type of blazar	BLL	18	bll	642
FSRQ type of blazar	FSRQ	38	fsrq	447
Non-blazar active galaxy	AGN	0	agn	3
Radio galaxy	RDG	3	rdg	13
Seyfert galaxy	SEY	0	sey	1
Active galaxy of uncertain type	AGU	5	agu	578
Normal galaxy (or part)	GAL	2	gal	6
Starburst galaxy	SBG	0	sbg	4
Narrow line Seyfert 1	NLSY1	2	nlsy1	3
Soft spectrum radio quasar	SSRQ	0	ssrq	3
Total	...	232	...	1809
Unassociated				992

total: 232+1809+992 = 3033

SNRs (>30, actually)

- Identifications (12 extended sources):

2FGL (6): IC 443, W28, W30, W44, W51C, Cygnus Loop (W78)

new (6): S147, Puppis A, Vela Jr., RX J1713.7-3946, Gamma Cygni (W66), HB21

- Associations (12):

Tycho, Cas A, Kes 17, CTB 33 (G337.0-0.1), CTB 37A,
G349.7+0.2, MSH 17-39, W41, 3C 391, W49B, CTB 109, SN1006

G296.5+10.0, G166.0+4.3, HB9 (G160.9+2.6)	Araya, M. (2013, 2014, MNRAS)
Kes 79	Auchettl, K. et al., (2014, ApJ, 783, 32)
RCW 103, Kes 27, SN1006	Xing, Y. et al. (2014, 2015, ApJ)
RCW 86	Yuan, Q. et al. (2014, ApJ, 785, L22)
Kes 41	Liu, B. et al. (2015, ApJ, 809, 102)
G338.3-00.0, G338.5+00.1	Lemoine-Goumard et al. (2014, ApJ, 794, 16)
3C397	Clark, C.J. et al. (2015, ApJL, arxiv:1508.00779)

The products of pp collision

$$p + p \rightarrow p + p + a(\pi^+ + \pi^-) + b\pi^0$$

$$p + p \rightarrow p + n + \pi^+ + a(\pi^+ + \pi^-) + b\pi^0$$

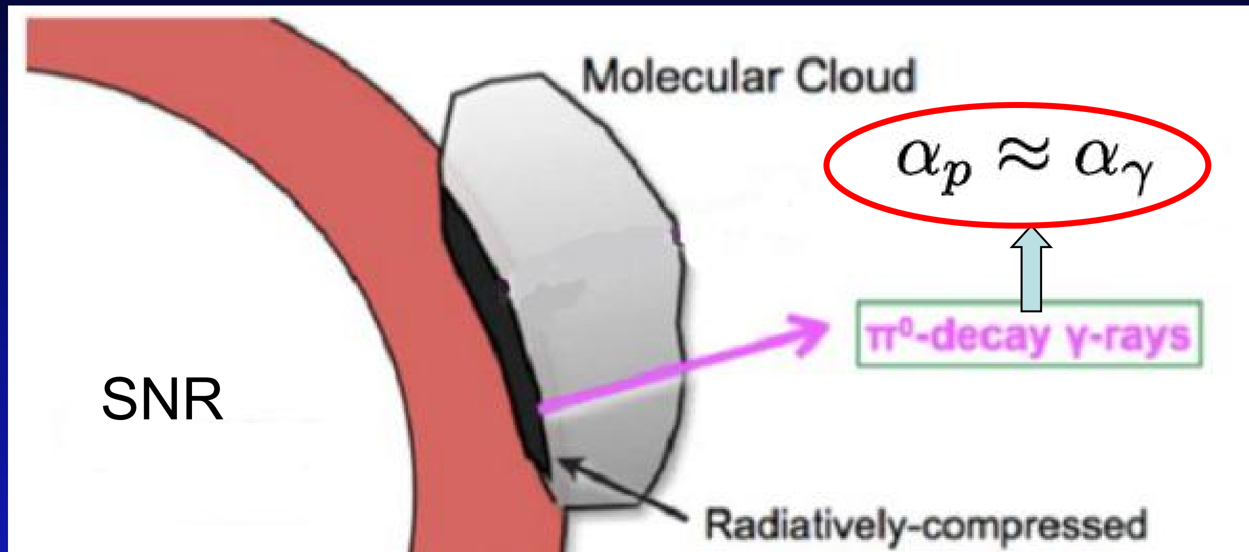
$$p + p \rightarrow n + n + 2\pi^+ + a(\pi^+ + \pi^-) + b\pi^0$$

(a and b: integers)

$$n(\pi^0) \sim n(\pi^+) \sim n(\pi^-)$$

Best target: molecular clouds!

MCs near SNRs: a probe for accelerated CR protons



I. In situ interaction

A. New CRs are produced in the SNRs

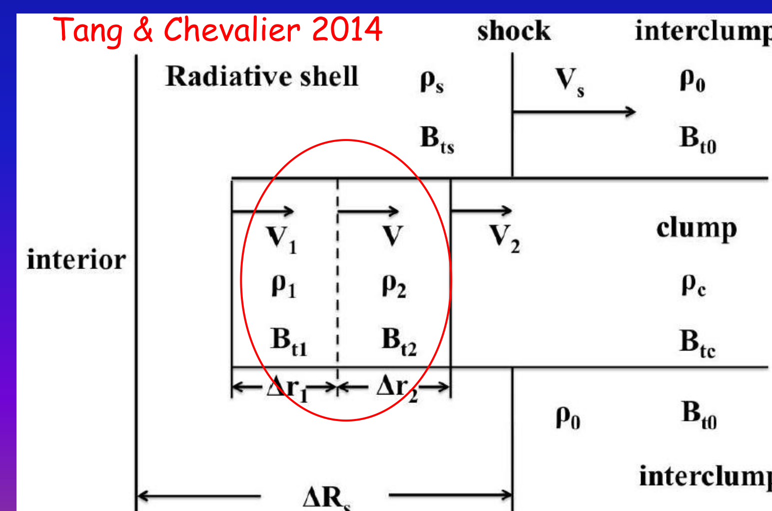
Inoue et al. 2010; Fang & Zhang 2010

Malkov et al. 2011

B. pre-exsiting CRs (compressed/reaccelerated) with 'crushed' MCs

Blandford & Cowie 1982 ; Uchiyama et al. 2010

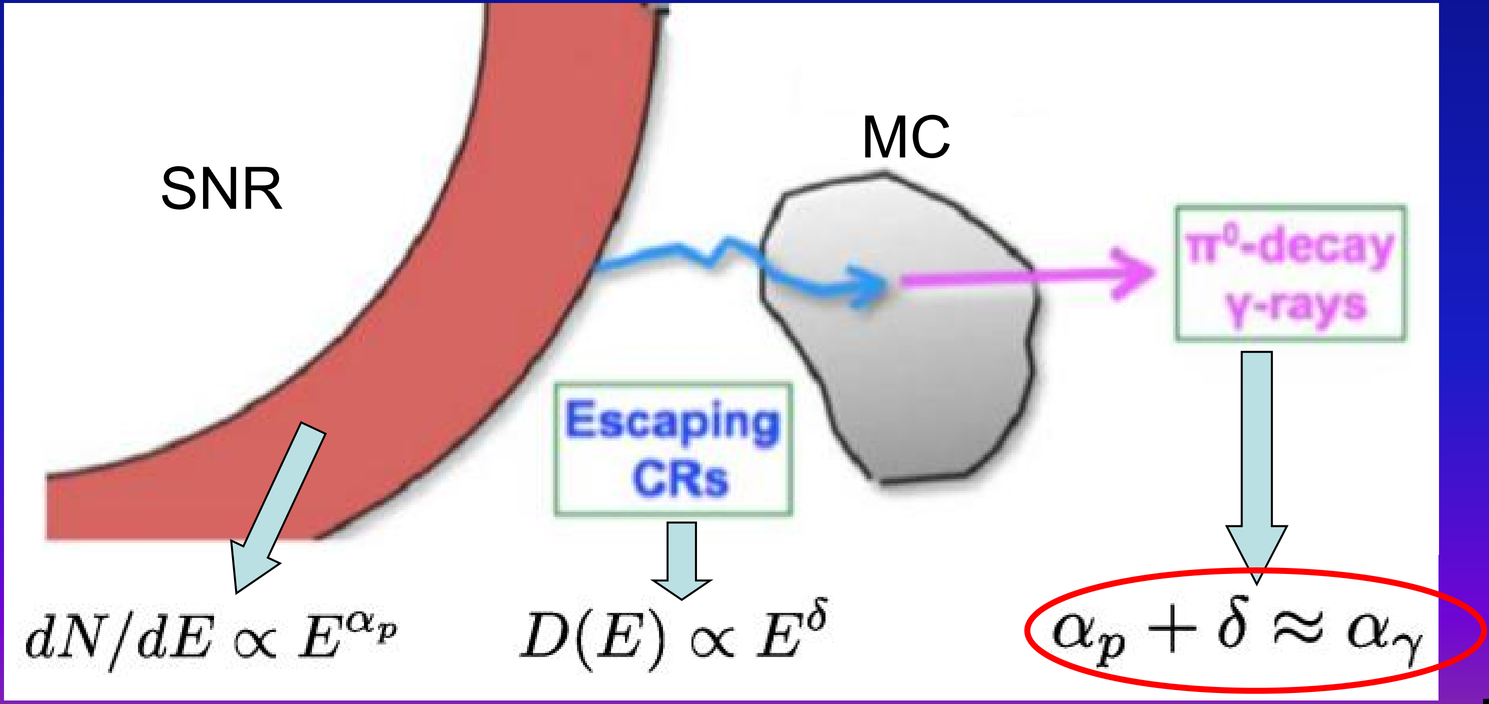
Tang & Chevalier 2014; …



MCs near SNRs: a probe for accelerated CR protons

II. Illumination by escaped protons

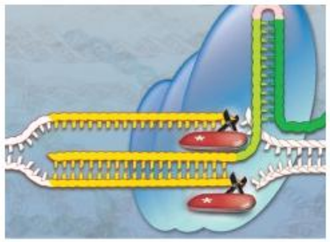
Aharonian & Atoyan 1996
Gabici et al. 2009
Li, H. & Chen, Y. 2010, 2012
Ohira et al. 2011



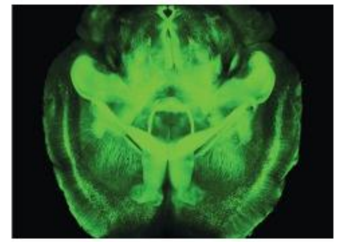
【Science】2013年度十大科学突破

Runners Up

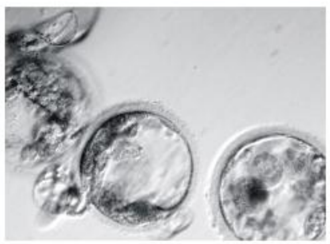
Genetic Microsurgery for the Masses



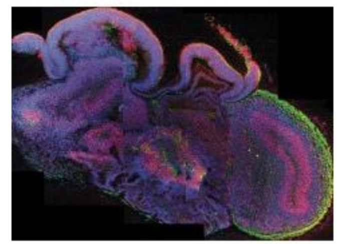
CLARITY Makes It Perfectly Clear



Human Cloning at Last



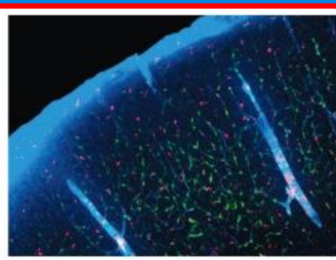
Dishing Up Mini–Organs



Cosmic Particle Accelerators Identified

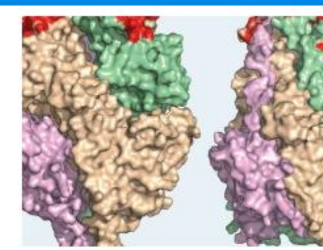
Newcomer Juices Up the Race to Harness Sunlight

To Sleep, Perchance to Clean

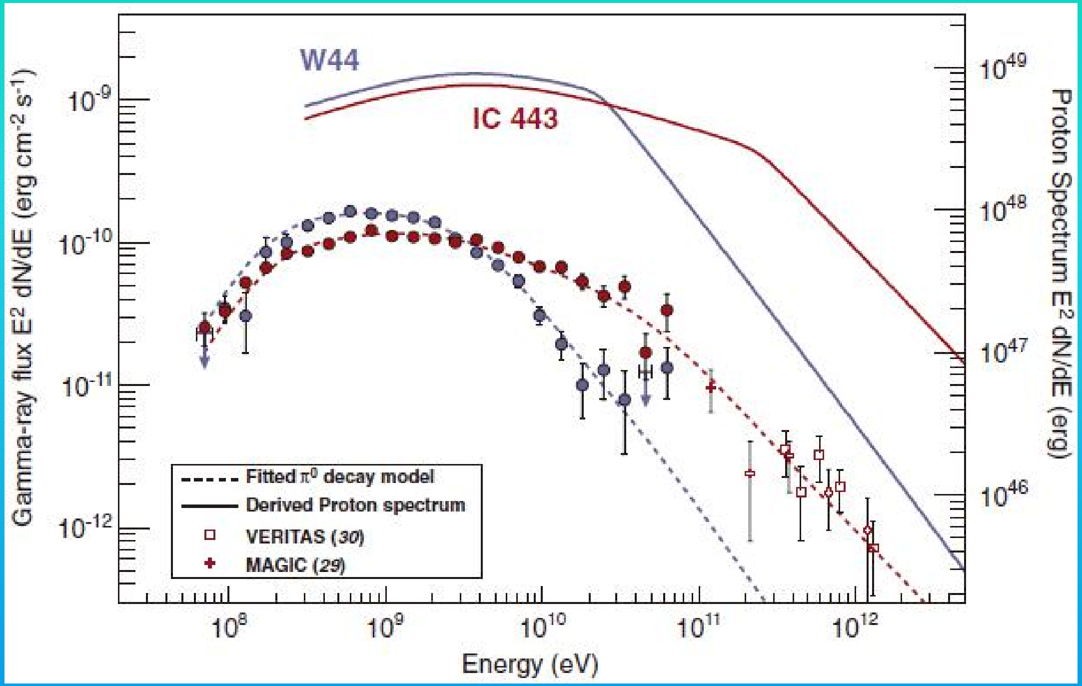


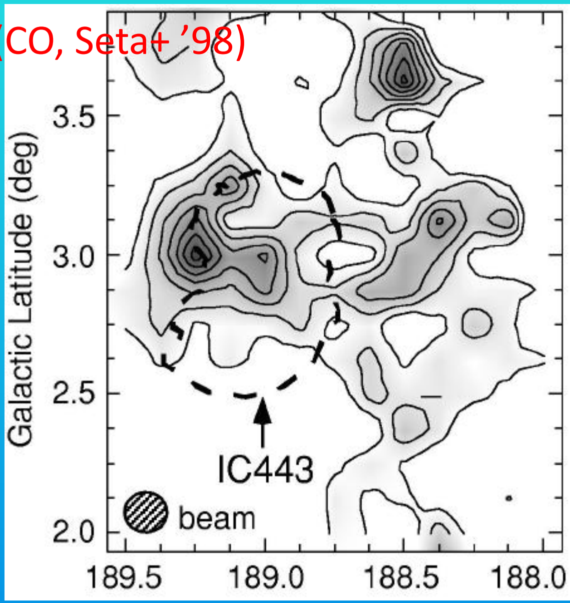
Your Microbes, Your Health

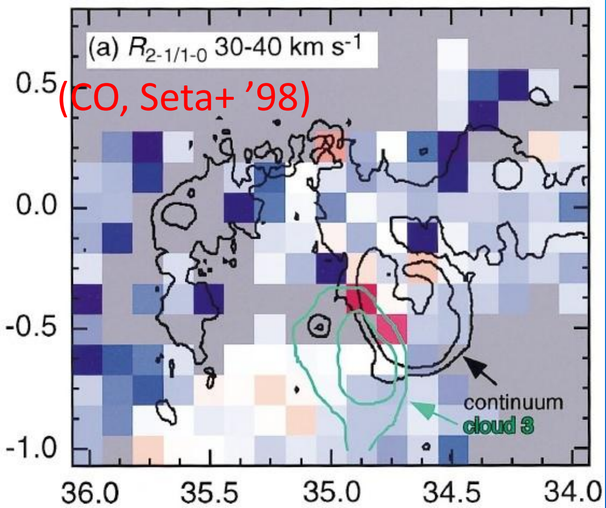
In Vaccine Design, Looks Do Matter

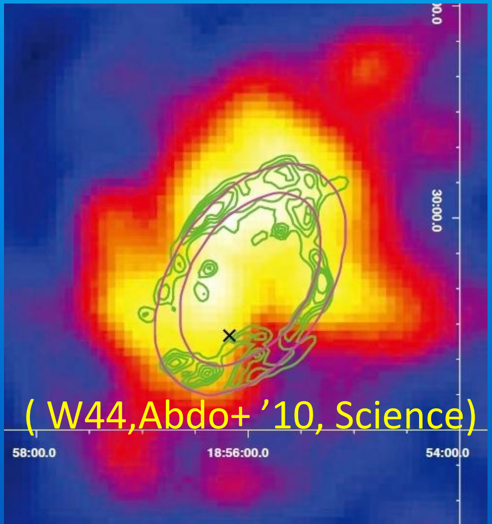


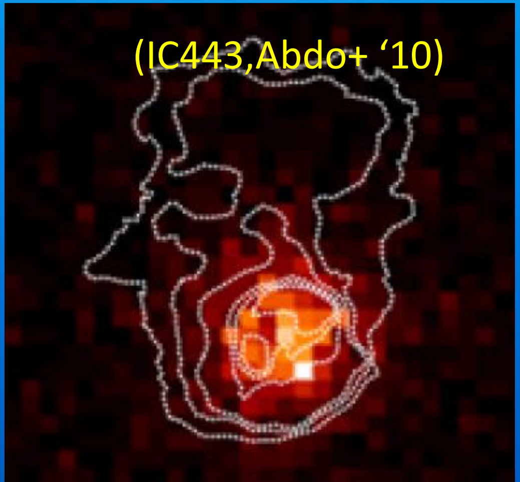
Fermi (Ackermann, M. et al. 2013, Science): W44 & IC443
AGILE (Giuliani, A. et al. 2011, ApJ, 742, L30): W44





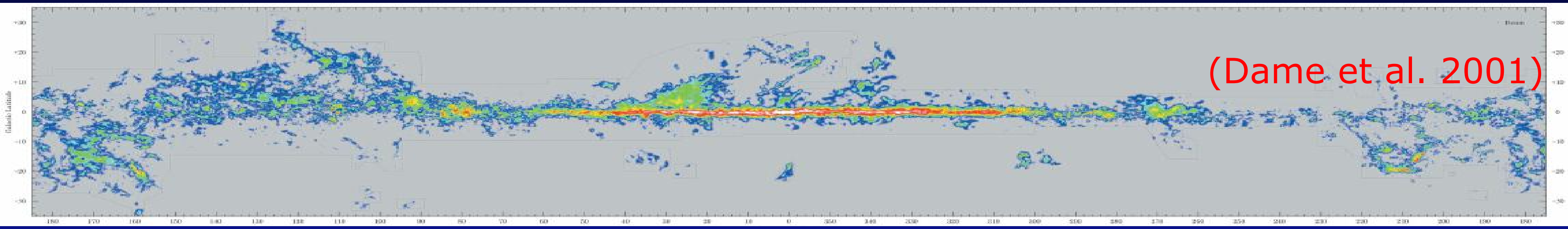




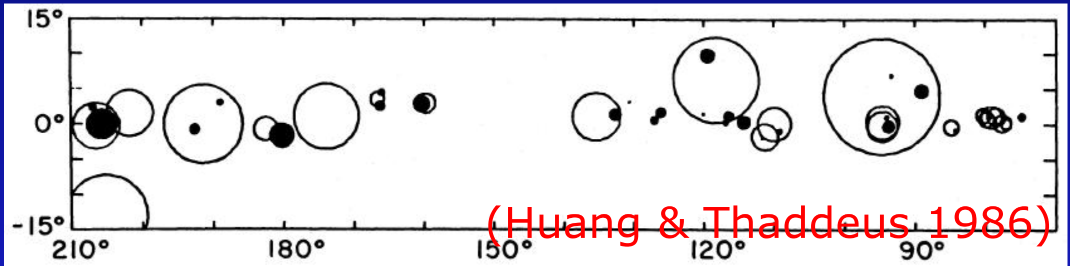


SNRs in molecular environment

- Molecular gas takes up 1/2 mass of ISM



- Most core-collapse SNe are located close to GMCs -- their birth places (e.g. Huang & Thaddeus 1986)



- Among >~270 Galactic SNRs, which are interacting with MCs?

Green + (1997): 1720MHz OH masers, 17 SNRs

Seta + (1998): CO or H_2 along LOS towards ~20 SNRs, no direct evidence

Jiang, Chen + (2010): A detailed summary from literature,

≥ 34 interacting SNRs, possibly up to 70

with 6 kinds of evidence summarized

Criterions & list of SNR-MC association

64 (Jiang, Chen+ 2010) + 6 (Jeong+ 2012)

Name	Other Name	Type[a]	Evidence[b]	Reference[c]	Group[d]	γ-ray detection[e] (Reference[f]
G0.0+0.0	Sgr A East	TC	OH maser, CS MA & LB, H_2	1, 2, 3, 4, 5	Y	HESS(67)
G1.05–0.1	Sgr D SNR	S	OH maser	2, 6	Y	
G1.4–0.1		S	OH maser	2, 6	Y	
G5.4–1.2	Milne 56	C?	OH maser	7	Y	
G5.7–0.0		?	OH maser	7	Y	HESS(68)
G6.4–0.1	W28	TC	OH maser, CO MA & LB, H_2 MA, NIR	2, 8, 9, 10	Y	EGRET(69), HESS(68)
G8.7–0.1	W30	TC	OH maser	7	Y	HESS(70)
G9.7–0.0		S	OH maser	7	Y	
G16.7+0.1		C	OH maser, CO MA	2, 11, 12	Y	
G18.8+0.3	Kes 67	S	CO MA & LB, CO ratio	13, 14	Y	
G21.8–0.6	Kes 69	TC	OH maser, CO MA & LB, HCO^+, H_2	2, 11, 15, 16	Y	
G29.7–0.3	Kes 75	C	CO MA & LB	17	Y	
G31.9+0.0	3C 391	TC	OH maser, molecular MA & LB, H_2, NIR	2, 18, 19, 20	Y	
G32.8–0.1	Kes 78	S	OH maser	21	Y	
G34.7–0.4	W44	TC	OH maser, molecular LB, H_2 MA, NIR, CO ratio	2, 8, 10, 22	Y	EGRET(69)
G39.2–0.3	3C 396	C	H_2 & NIR MA, CO MA & LB	16, 23, 24	Y	
G41.1–0.3	3C 397	TC	CO MA & LB	25	Y	
G49.2–0.7	W51	TC	OH maser, CO MA & LB, HCO^+ LB	2, 11, 26	Y	HESS(71), Milagro(72)
G54.4–0.3	HC40	S	CO MA & LB, IR MA	27, 28	Y	
G89.0+4.7	HB21	TC	CO MA & LB, CO ratio, H_2, NIR	29, 30, 31	Y	
G109.1–1.0	CTB 109	S	CO MA & LB	32	Y	
G189.1+3.0	IC 443	TC	OH maser, CO ratio, H_2, molecular MA & LB	2, 8, 22, 33, 34, 35	Y	EGRET(69), MAGIC(73) Milagro(72), VERITAS(74) AGILE(75)
G304.6+0.1	Kes 17	S	H_2, IR MA & colors	16, 28	Y	
G332.4–0.4	RCW 103	S	IR MA & colors, NIR, H_2 & HCO^+ MA	28, 36, 37	Y	
G337.0–0.1	CTB 33	S	OH maser	18	Y	
G337.8–0.1	Kes 41	S	OH maser	21	Y	
G346.6–0.2		S	OH maser, H_2, IR colors	21, 16, 28	Y	
G347.3–0.5		S?	CO MA & LB	38	Y	CANGAROO(76) HESS(77), Fermi(78)
G348.5–0.0		S?	OH maser, H_2, IR MA	2, 16, 28	Y	
G348.5+0.1	CTB 37A	S	OH maser, CO MA	2, 12, 18	Y	HESS(79)
G349.7+0.2		S	OH maser, CO MA & LB, CO ratio, H_2, IR MA	2, 18, 13, 16, 28	Y	
G357.7+0.3	Square Nebula	S	OH maser	2, 6	Y	
G357.7–0.1	MSH 17–39	TC	OH maser, CO & H_2 MA	2, 18, 39	Y	
G359.1–0.5		TC	OH maser, CO & H_2 MA	2, 40, 41, 42	Y	HESS(80)

34 confirmed

Evidence:

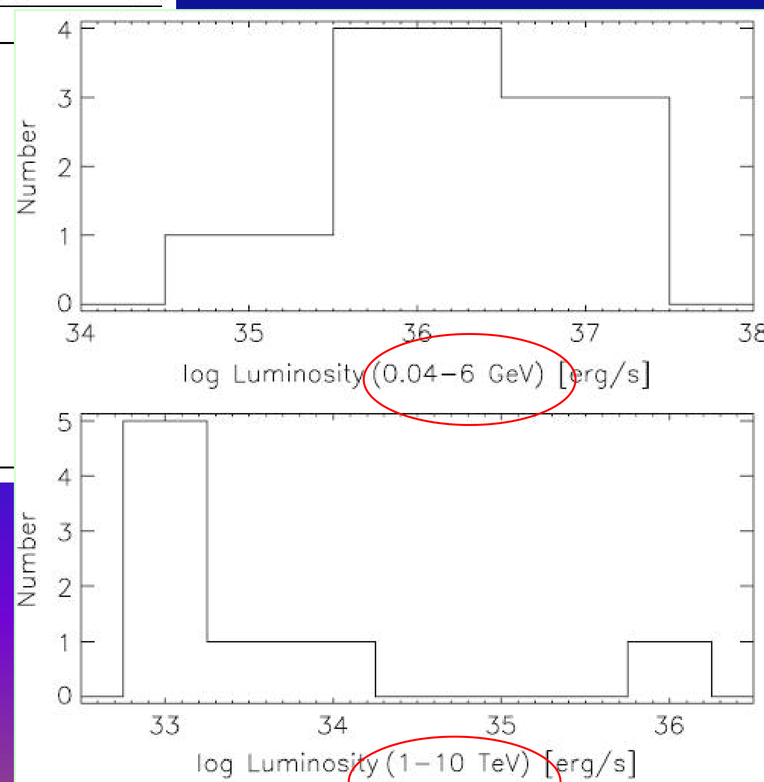
1. 1720MHz OH masers
2. Molecular line broadening (LB)
3. High line ratio, e.g CO2-1/CO1-0
4. NIR [FeII], vibrational /rotational H_2
5. Specific (Spitzer) IR colors
6. Morphology agreement (MA) of spatial features

γ-ray SNRs -- OH masers correlation

Known SNR Masers and Coincident γ-ray Sources

l	b	SNR	Diameter (′)	Distance (kpc)	L_{GeV} (erg s^{-1})	α_{GeV}	L_{TeV} (erg s^{-1})	α_{TeV}	Ref.
Group A									
6.4	−0.1	W28	42	2.0	4.8e35	2.1	1.5e33	2.7	1,2
34.7	−0.4	W44	30	2.5	4.1e35	1.9	...	−...	1
49.2	−0.7	W51 C	30	6	1.7e36	...	1.5e33	...	3,4
189.1	+3.0	IC 443	50	1.5	1.0e35	2.0	1.2e33	3.1	1,5,6
Group B									
0.0	+0.0	SgrA East	2.5	8.5	1.2e37	1.7	1.3e36	2.2	
5.7	−0.0		9	3.2	...	...	0.8e33	2.3	2
8.7	−0.1	W30	45	3.9	...	...	1.7e34	2.7	
337.8	−0.1	Kes 41	5	12.3	4.2e36	2.5	...	...	
348.5	+0.1	CTB 37A	10	11.3	3.5e36	2.3	5.3e33	2.3	7
359.1	−0.5		10	5.0	1.2e36	2.2	7.5e32	2.7	8
Group C									
1.0	−0.1	Sgr D SNR	8	8.5					
1.4	−0.1		10	8.5					
5.4	−1.2	Duck	35	5.2					
9.7	−0.0		11	4.7					
16.7	+0.1		4	2/14					
21.8	−0.6	Kes 69	20	5.2					
31.9	−0.0	3C 391	8	9					
32.8	−0.1	Kes 78	20	5.5/8.5					
337.0	−0.1	CTB 33	3	11					
346.6	−0.2		8	11					
348.5	−0.0		10	13.7					
349.7	+0.2		2	>11					
357.7	+0.3	Square	24	6.4					
357.7	−0.1	Tornado	5	>6					

Hewitt et al. (2009)



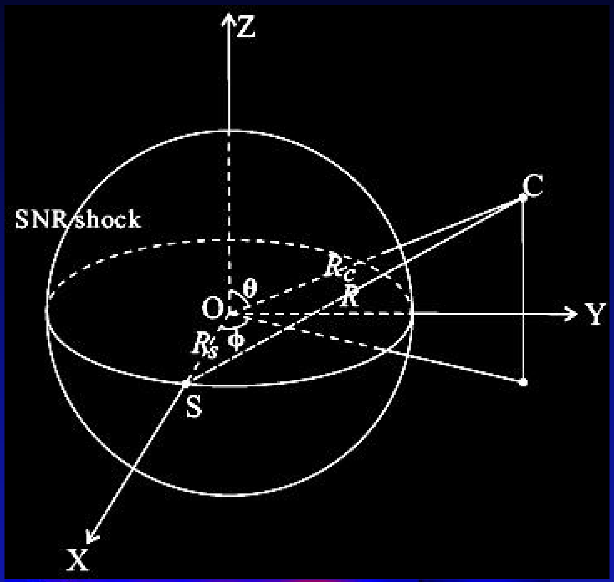
Π^0 break后，还需大量的工作……

- < GeV，其它更多的“interacting SNRs”都有“Π^0 break” 吗？

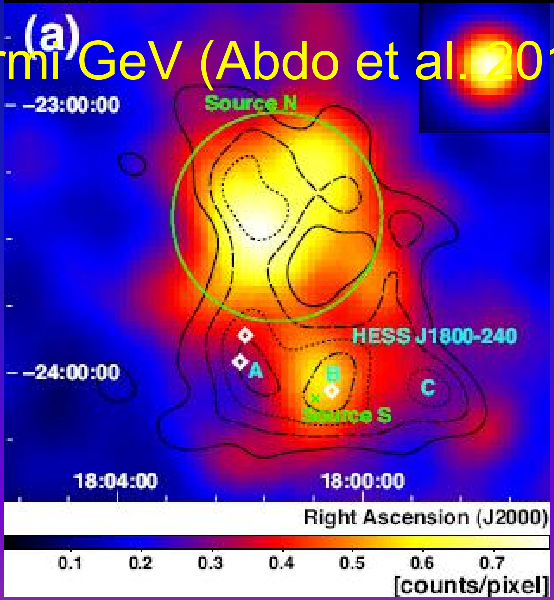
- > GeV，伽玛射线谱的形态、走势（特别是到10^14 eV）？决定性的辐射机制?

……

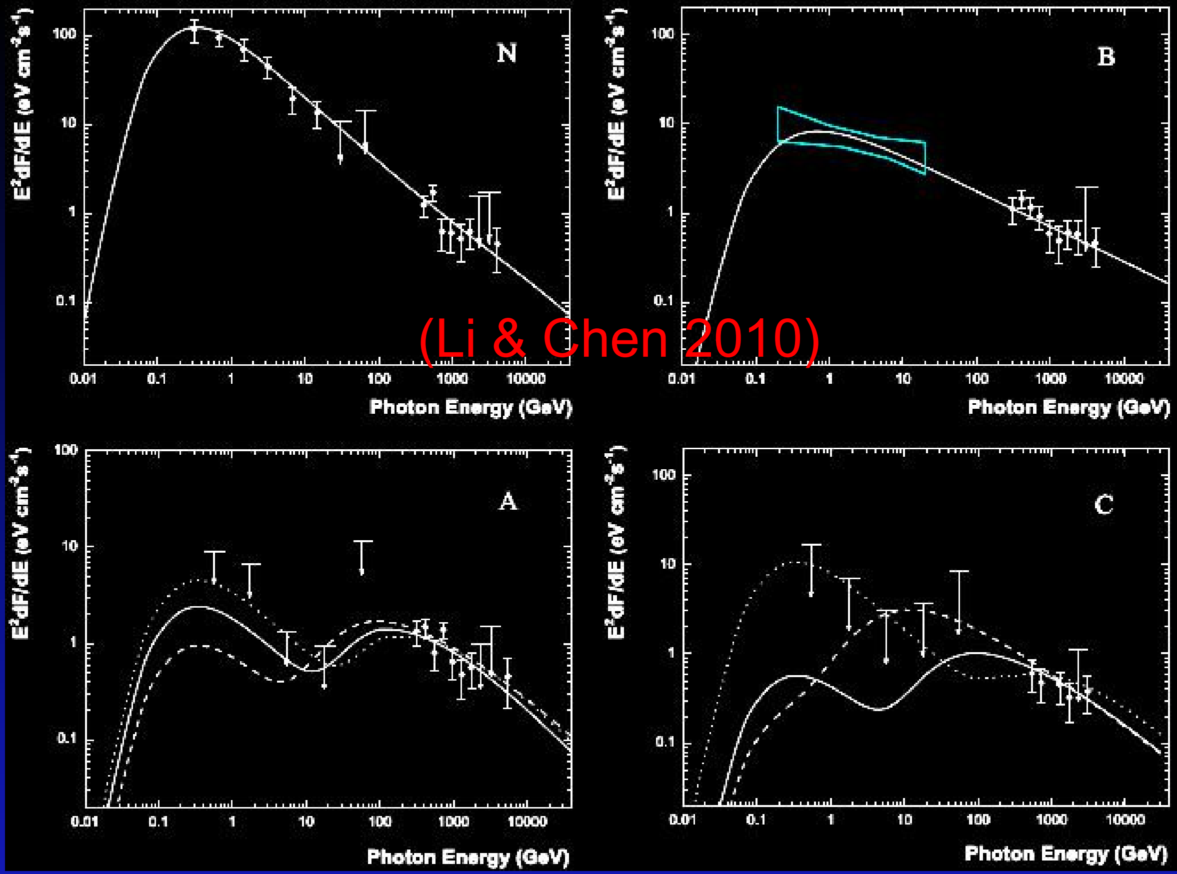
W28



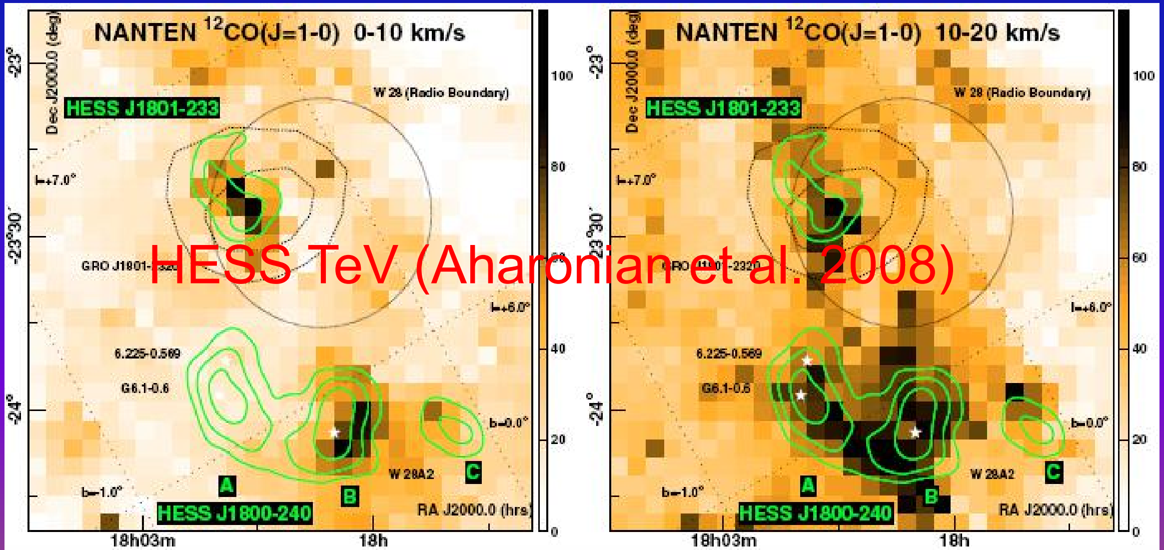
Fermi GeV (Abdo et al. 2010)



(Li & Chen 2010)

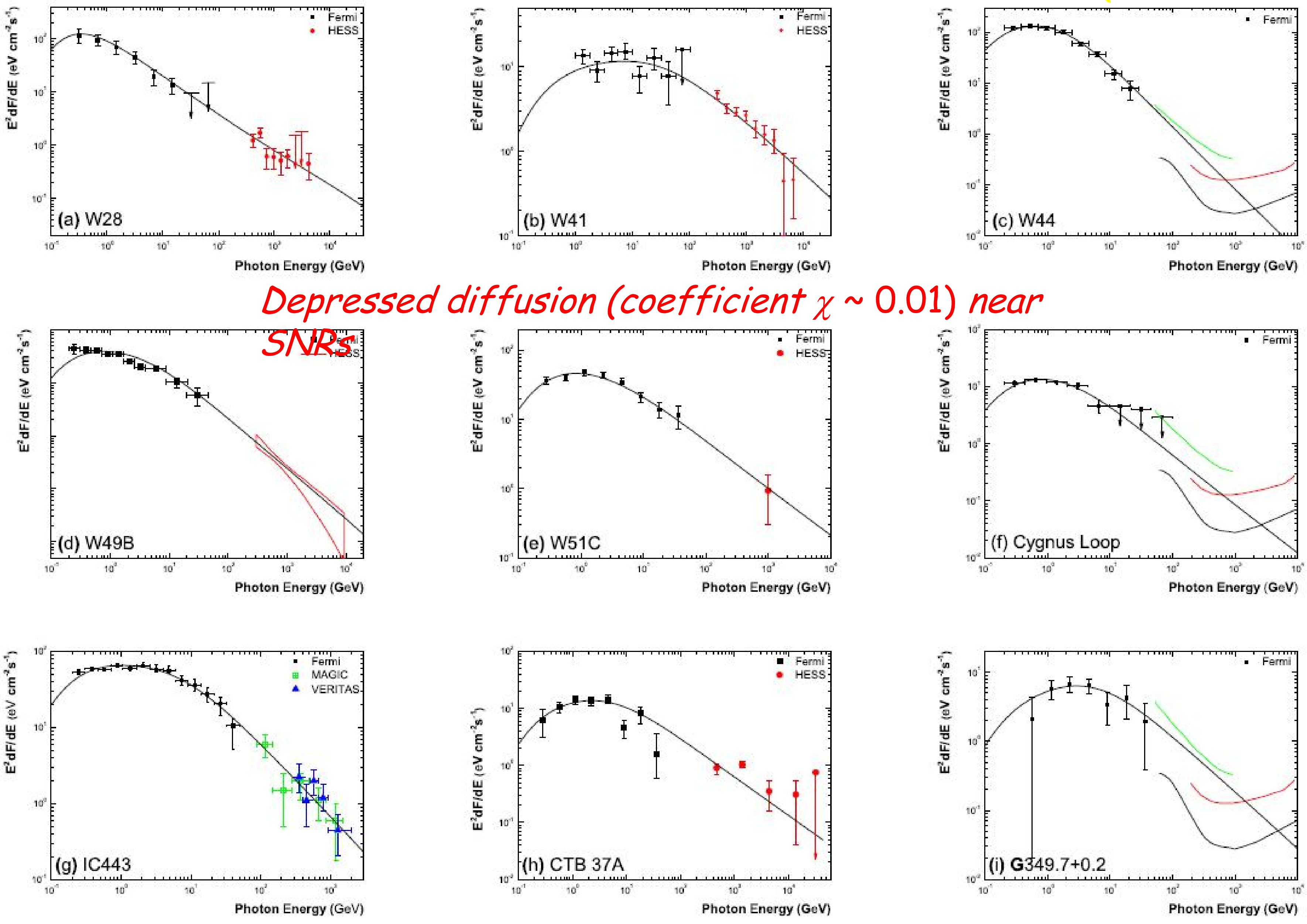


HESS TeV (Aharonian et al. 2008)



9 SNRs interacting with MCs

(Li & Chen 2012)

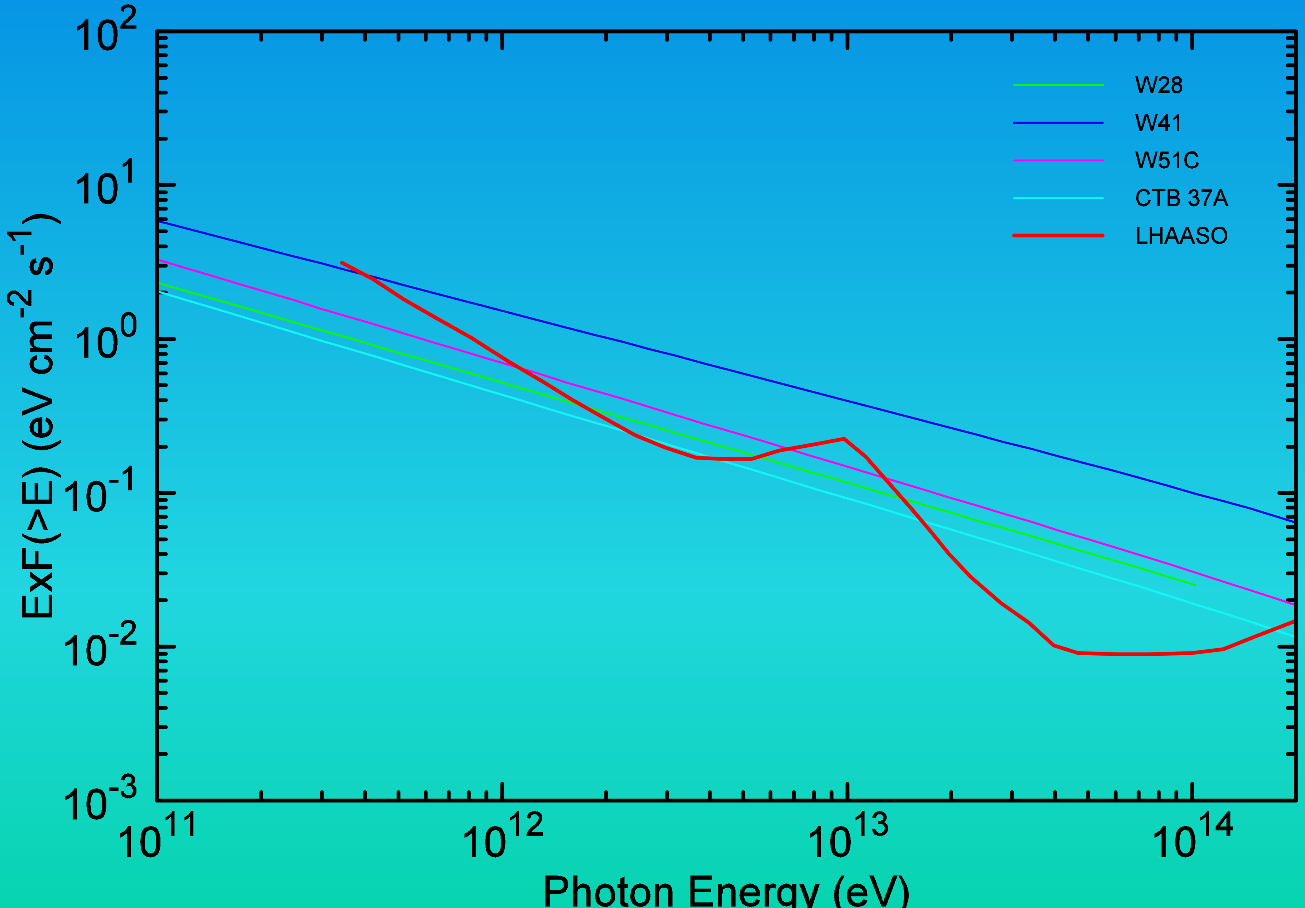


Depressed diffusion (coefficient χ ~ 0.01) *near SNRs*

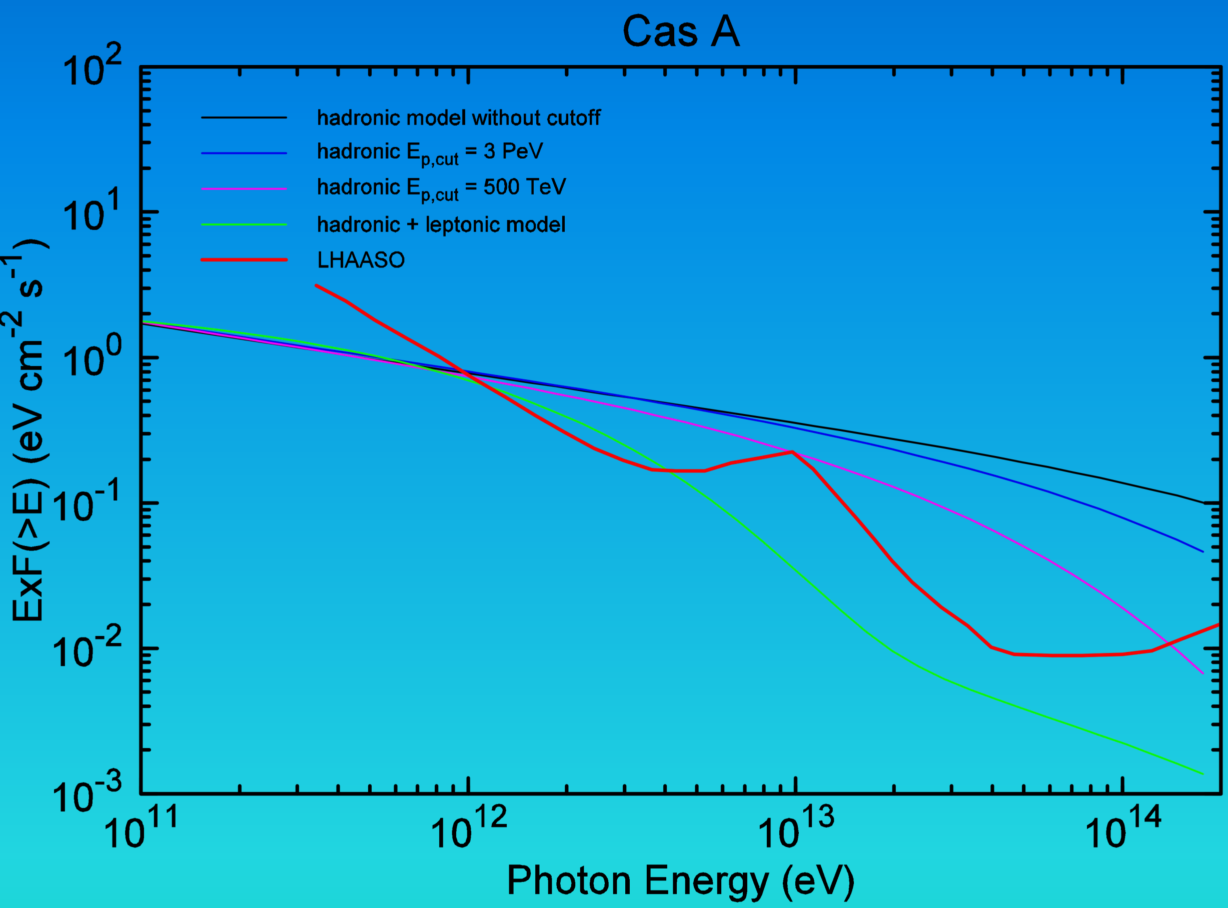
高能能谱截断？

- No energy cutoff at >10 TeV for known TeV SNRs. Any higher? Sign of E_{max}?

- “Accumulative diffusion model” predicts for 4 SNRs:

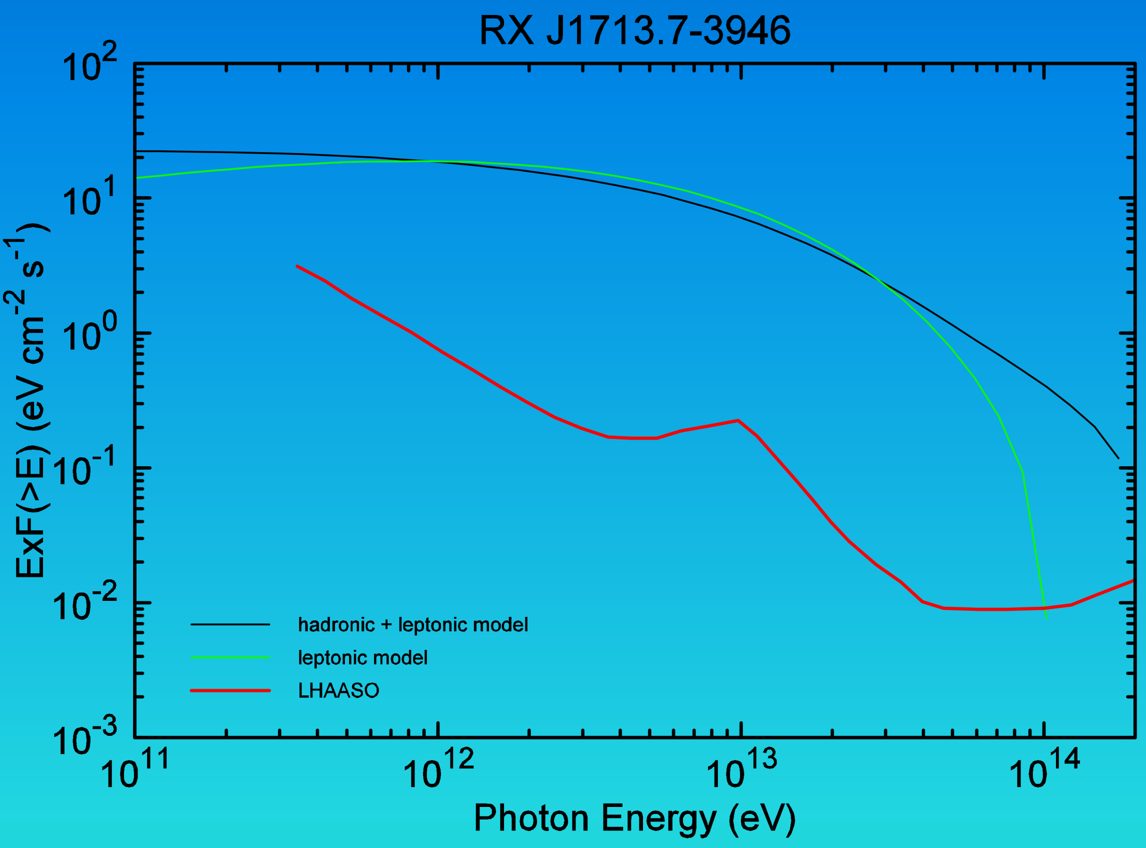


年轻SNR的质子能谱？



- GeV-TeV强子辐射 ➔ Γ=2.3，黑线
- 射电同步 ➔ Γ=2.6，绿线

γ-ray SNR原型：RXJ1713-3946

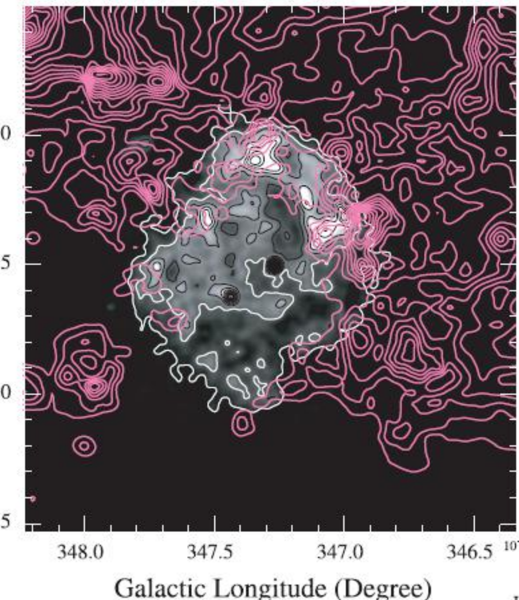


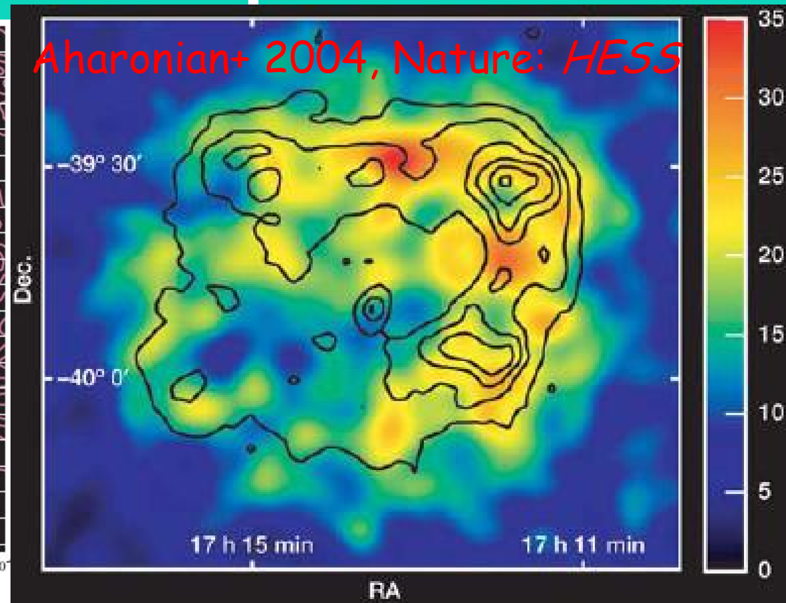
- 强-轻子混合模型，黑线 （Zhang & Chen 16）
- 轻子模型：绿线

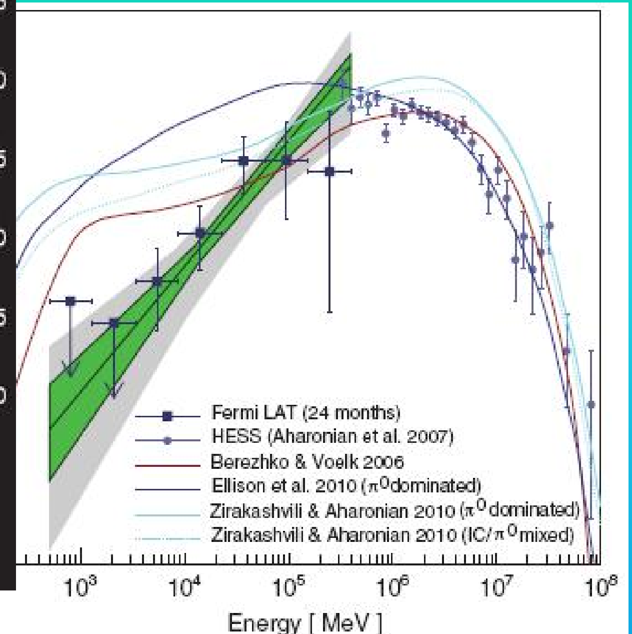
小结

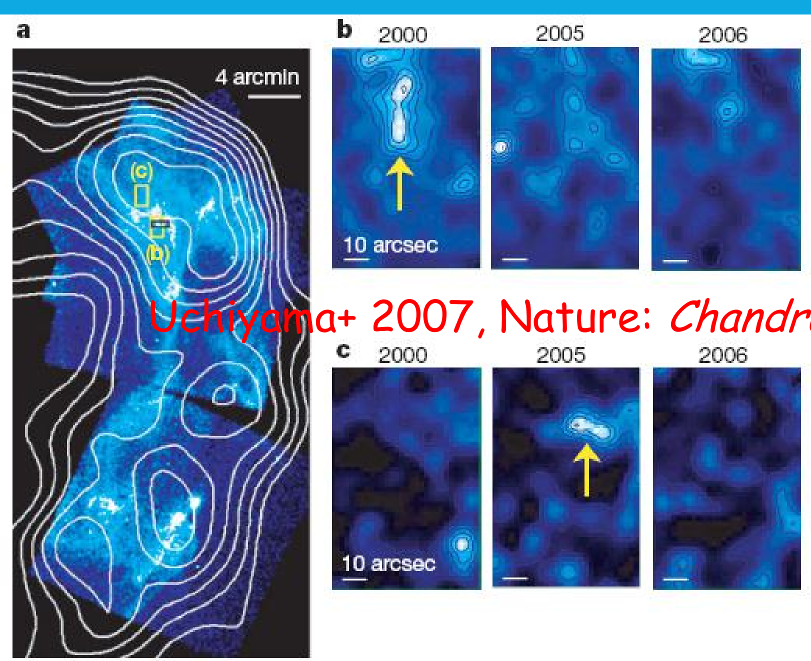
- 北天SNR普测，特别对SNR-MC系统
- 区分轻强子作用
- 探索高能粒子高端能量截断

Hadronic vs. leptonic: RX J1713-3946









- 小尺度1年快速光变，B~10^3 uG，synchrotron强，电子能量不足IC，不利于轻子说。
- 但1年光变也可能是局部磁场快速变化导致。