

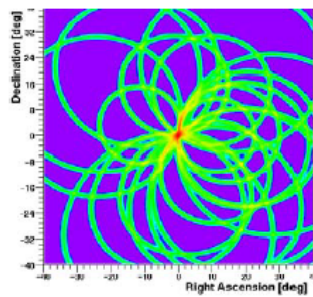
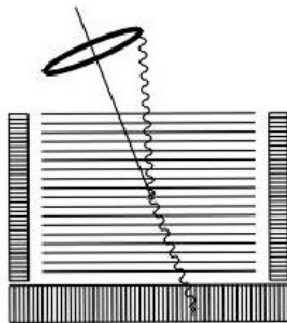
# Astrofisica Nucleare e Subnucleare

## “MeV” Astrophysics

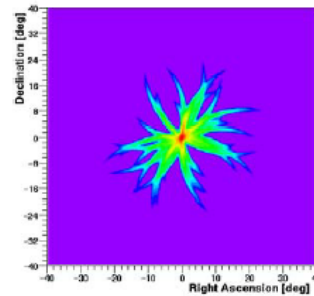
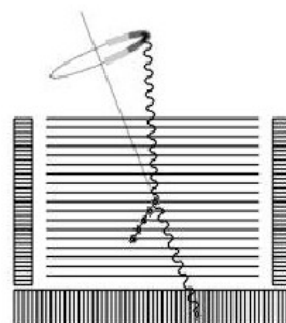
# Compton Imaging

## Coincidence Detector Schematics

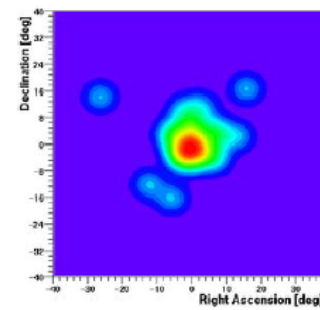
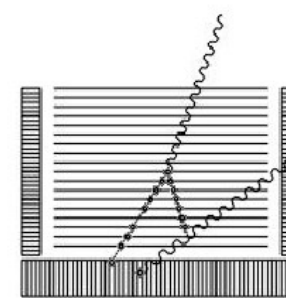
Classical Compton  
Event Circles  
(no electron tracking)



Reduced Compton  
circles of events  
with electron track



Direct imaging of pair-  
creation events





# Compton Imaging

## Sensitivities

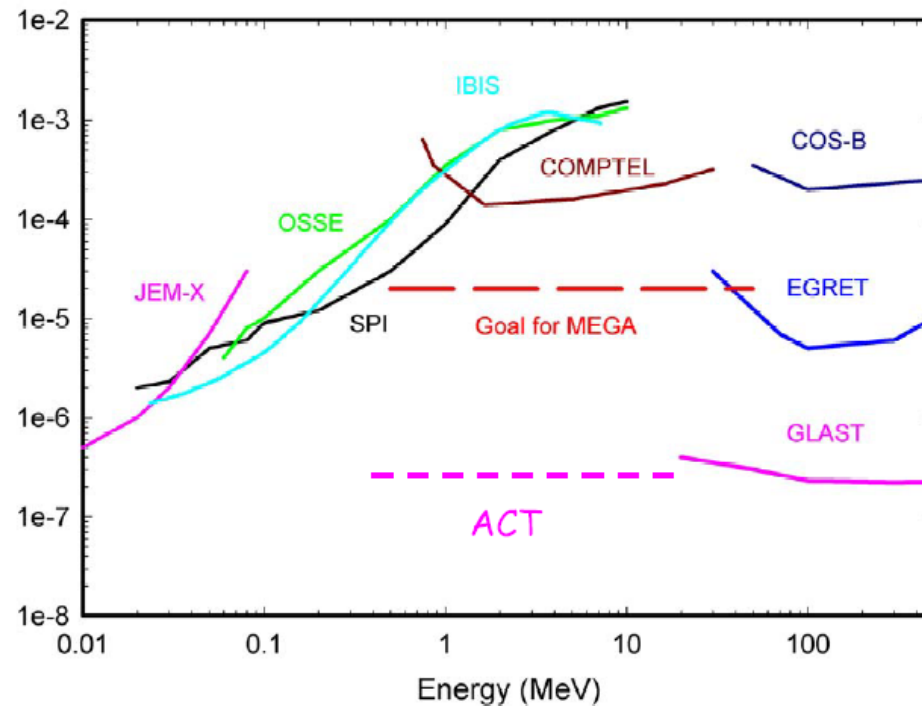
### Generations of $\gamma$ -ray Missions:

1. COMPTEL  $\leftrightarrow$  COS-B

2. MEGA (~2006)  $\leftrightarrow$  EGRET

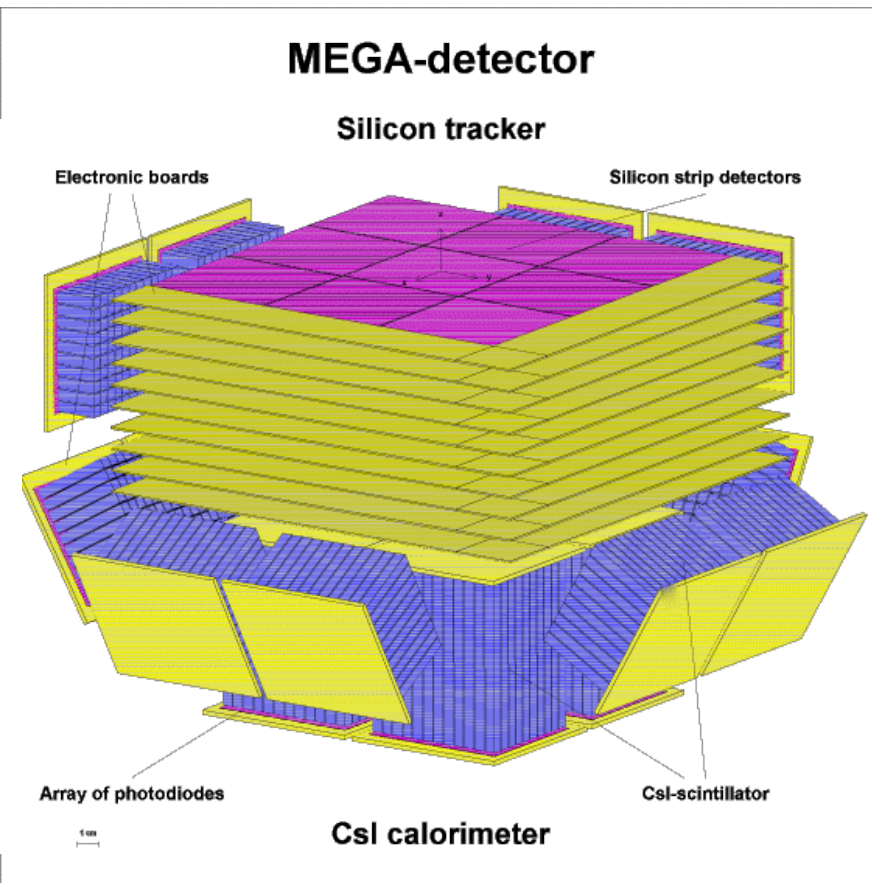
3. Advanced Compton  $\leftrightarrow$  GLAST  
(ACT, ~2012) (~2006)

Continuum Sensitivity \*  $E^2$   
[MeV cm<sup>-2</sup> s<sup>-1</sup>]  $T_{\text{obs}}=10^6$  s,  $\Delta E = E$



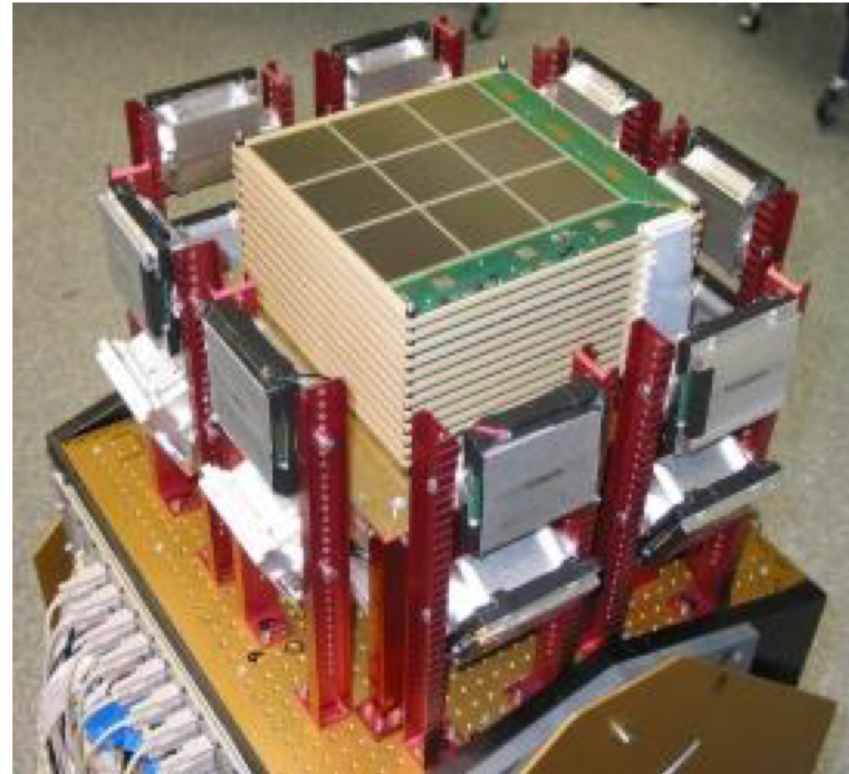
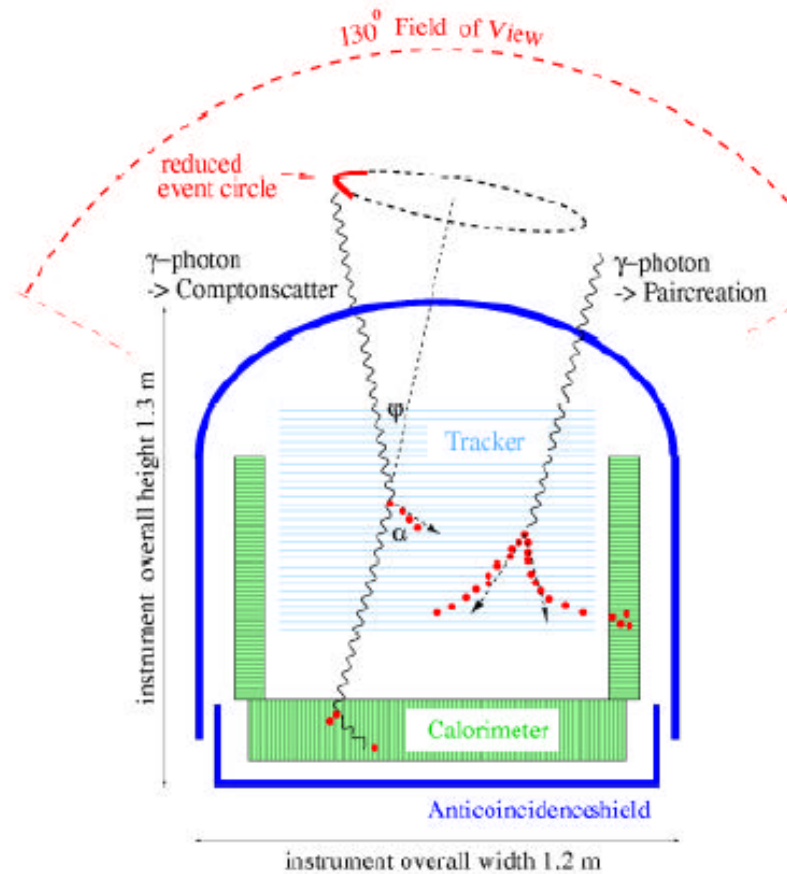
# MEGA

**MEGA** is planned as a telescope for **Medium Energy Gamma-Ray Astronomy** in the energy range between 400 keV and 50 MeV. In this energy range MEGA exploits the two dominating interaction mechanisms for gamma rays: Compton scattering and Pair creation. MEGA has two detectors: A tracker, consisting of double-sided silicon strip detectors, and a calorimeter, consisting of highly segmented CsI(Tl) bars. In the tracker the Compton and Pair interactions take place and the direction and energy of the participating electrons and positrons is measured. In the calorimeters the Compton scattered gamma rays are stopped and thus their energy and direction is determined.



<https://www2011.mpe.mpg.de/gamma/instruments/mega/www/mega.html>

# MEGA



<https://www2011.mpe.mpg.de/gamma/instruments/mega/www/mega.html>

# ACT project

<b>Energy Range</b>	0.2 - 30 MeV Compton mode
<b>Energy Resolution</b>	$\leq 10\text{keV FWHM @ } 1\text{ MeV}$
<b>Field of View</b>	$> 4\text{ steradian}$
<b>Angular Resolution</b>	1 deg
<b>Source Localization</b>	5 arcmin for bright sources
<b>Line Sensitivity in 1.0E6 sec</b>	$1.0\text{E-}7\text{ ph}/(\text{cm}^2\text{s})$ (narrow) $5.0\text{E-}7\text{ ph}/(\text{cm}^2\text{s})$ (broad)
<b>Continuum Sensitivity</b>	$1.0\text{E-}5\text{ ph}/(\text{cm}^2\text{sMeV})$ @ 0.5 MeV
<b>Polarization Sensitivity</b>	1%, $2.0\text{E-}3\text{ ph}/(\text{cm}^2\text{sMeV})$ 10%, $2.0\text{E-}4\text{ ph}/(\text{cm}^2\text{sMeV})$

These science requirements are expected to translate to an instrument with effective area on the order of 1000-3000 cm<sup>2</sup>, a position resolution in the detectors of 1mm<sup>3</sup>, energy resolution of 1% (0.5-2.0 MeV) or better, and possibly recoil electron tracking capabilities for electron energies  $< 0.5\text{ MeV}$ . The concept study will look at a variety of possible detector technologies for implementing such a Compton telescope. Candidate detectors include, but are not limited to, CZT strip detectors, Si strip detectors, Ge strip detectors, liquid Xe, and gaseous Xe (or Ar) microwell detectors.

<https://arxiv.org/abs/astro-ph/0608532>



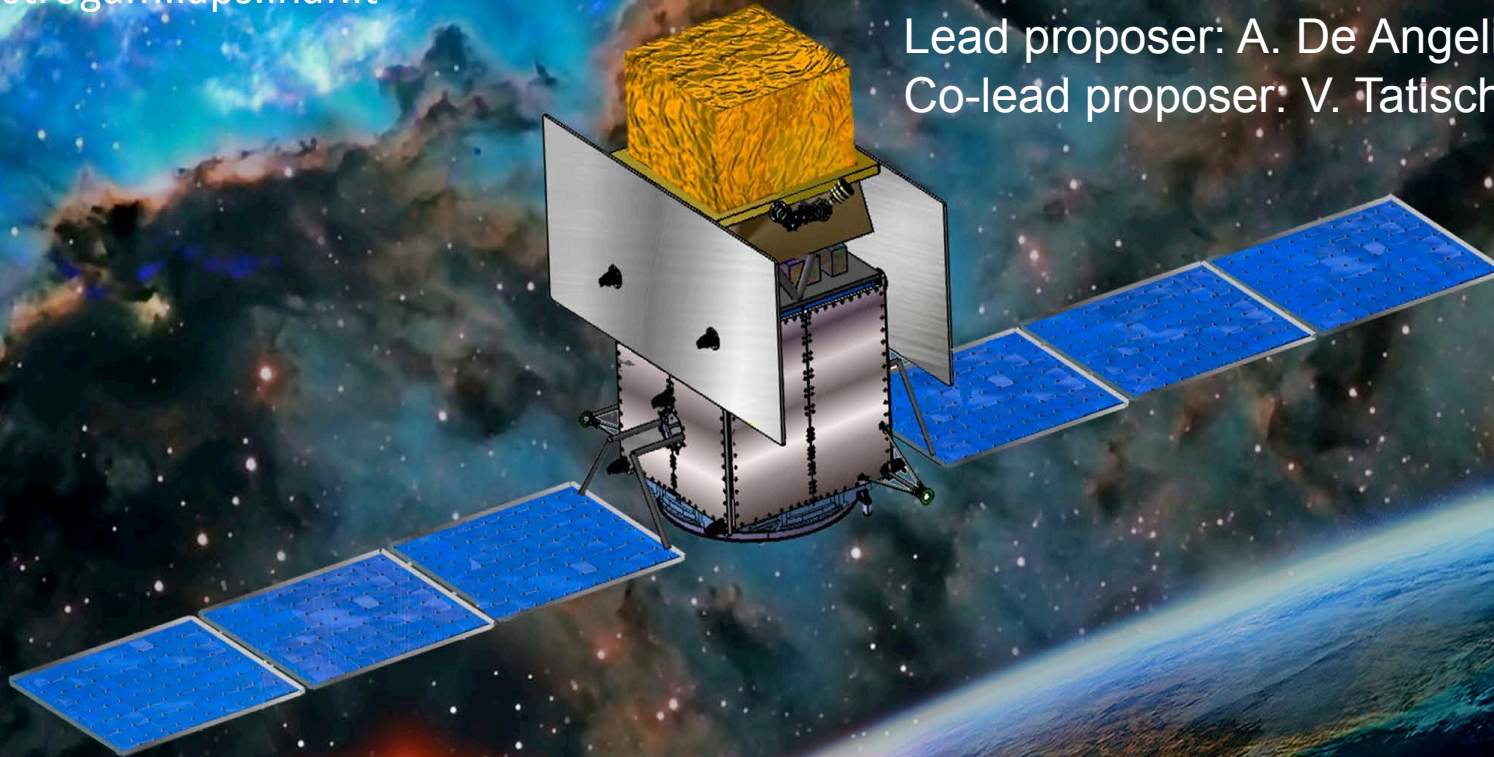
# e-ASTROGAM

at the heart of the extreme Universe

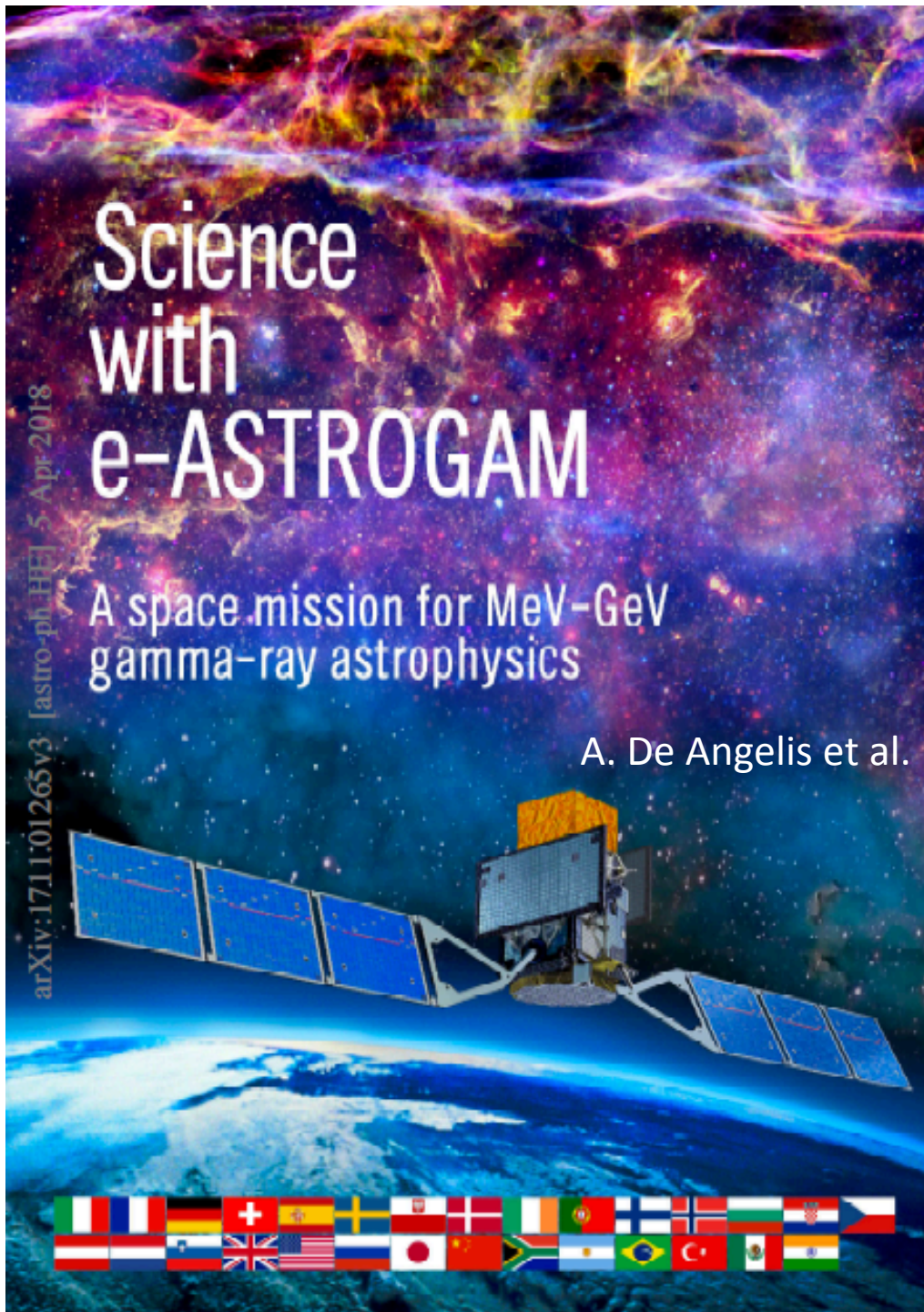
<http://eastrogam.iaps.inaf.it>

An observatory for gamma rays  
In the MeV/GeV domain

Lead proposer: A. De Angelis  
Co-lead proposer: V. Tatischeff







# Science with e-ASTROGAM

A space mission for MeV-GeV gamma-ray astrophysics

A. De Angelis et al.

A. De Angelis<sup>1,2,3,4</sup>, V. Tatischeff<sup>5</sup>, I. A. Grenier<sup>6</sup>, J. McEnery<sup>7</sup>, M. Mallamaci<sup>1</sup>, M. Tavani<sup>8,9,10</sup>, U. Oberlack<sup>11</sup>, L. Hanlon<sup>12</sup>, R. Walter<sup>13</sup>, A. Argan<sup>14</sup>, P. Von Ballmoos<sup>15</sup>, A. Bulgarelli<sup>16</sup>, A. Bykov<sup>17</sup>, M. Hernanz<sup>18</sup>, C. Kanbach<sup>19</sup>, I. Kuvvetli<sup>20</sup>, M. Pearce<sup>21</sup>, A. Zdziarski<sup>22</sup>, J. Conrad<sup>23</sup>, G. Chioselli<sup>24</sup>, A. Harding<sup>7</sup>, J. Isern<sup>25</sup>, M. Leising<sup>26</sup>, P. Longo<sup>27,28</sup>, C. Madejski<sup>29</sup>, M. Martinez<sup>30</sup>, M. N. Mazziotta<sup>31</sup>, J. M. Paredes<sup>32</sup>, M. Pohl<sup>33</sup>, R. Rando<sup>1,34</sup>, M. Razzano<sup>35,36</sup>, A. Abouan<sup>34,2</sup>, M. Ackermann<sup>37</sup>, A. Addazi<sup>38</sup>, M. Ajello<sup>39</sup>, C. Alberus<sup>40</sup>, J. M. Alvarez<sup>40</sup>, G. Ambrosi<sup>41</sup>, S. Antón<sup>42,43</sup>, L. A. Antonelli<sup>44</sup>, A. Babic<sup>45</sup>, B. Balbusstino<sup>1</sup>, M. Balbo<sup>13</sup>, I. Baldini<sup>35,36</sup>, S. Balman<sup>46</sup>, C. Bambi<sup>38,47</sup>, U. Barres de Almeida<sup>48</sup>, J. A. Barrio<sup>49</sup>, R. Bartels<sup>50</sup>, D. Bastieri<sup>34,1,51</sup>, W. Bednarek<sup>52</sup>, D. Bernard<sup>53</sup>, E. Bernardini<sup>54,37</sup>, T. Bernaboni<sup>13</sup>, B. Bertucci<sup>41,55</sup>, A. Biland<sup>56</sup>, E. Bissaldi<sup>57,31</sup>, M. Boettcher<sup>58</sup>, V. Bonvicini<sup>28</sup>, V. Bosch-Ramon<sup>55</sup>, E. Bottacini<sup>1,34</sup>, V. Bozhilov<sup>59</sup>, T. Bretz<sup>60</sup>, M. Brancibini<sup>61,62</sup>, V. Brdar<sup>63</sup>, T. Brtingmann<sup>64</sup>, A. Broga<sup>11</sup>, C. Budtz-Jørgensen<sup>65</sup>, G. Busetto<sup>34</sup>, S. Buson<sup>7</sup>, M. Buzzo<sup>41,55</sup>, A. Caerianiga<sup>24</sup>, S. Camera<sup>65,66,67,68</sup>, R. Campana<sup>69</sup>, P. Caravita<sup>69</sup>, M. Cardillo<sup>8</sup>, P. Carlson<sup>21</sup>, S. Celentini<sup>70</sup>, M. Cermeño<sup>29</sup>, A. Chen<sup>71</sup>, C. C. Cheung<sup>72</sup>, E. Churazov<sup>73,74</sup>, S. Ciprini<sup>44,41</sup>, A. Coc<sup>5</sup>, S. Colafrancesco<sup>71</sup>, A. Coleiro<sup>75,76</sup>, W. Collmar<sup>77</sup>, P. Coppi<sup>78</sup>, R. Curado da Silva<sup>79</sup>, S. Cutini<sup>44,41</sup>, F. D'Ammando<sup>80</sup>, B. De Lotto<sup>81</sup>, D. de Martino<sup>82</sup>, A. De Rosa<sup>8</sup>, M. Del Santo<sup>83</sup>, L. Delgado<sup>18</sup>, R. Diehl<sup>77</sup>, S. Dietrich<sup>84</sup>, A. D. Dolgov<sup>85,86</sup>, A. Dominguez<sup>49</sup>, D. Dominis Prestes<sup>87</sup>, I. Donnarumma<sup>8</sup>, D. Dornier<sup>88</sup>, M. Doro<sup>1,34</sup>, M. Dutra<sup>89</sup>, D. Elsaesser<sup>90</sup>, M. Fabrizio<sup>44,91</sup>, A. Fernández-Barral<sup>1</sup>, V. Fioretti<sup>10</sup>, L. Foffano<sup>34,1</sup>, V. Formato<sup>41</sup>, N. Fornengo<sup>65,66</sup>, L. Foschini<sup>24</sup>, A. Franceschini<sup>34</sup>, A. Franczkowiak<sup>37</sup>, S. Funk<sup>62</sup>, P. Fuschino<sup>16</sup>, D. Gaggero<sup>52</sup>, C. Galassi<sup>24</sup>, F. Gargano<sup>31,57</sup>, D. Gasparrini<sup>44,41</sup>, R. Gehrz<sup>92</sup>, P. Giannicola<sup>91</sup>, N. Giglietto<sup>57,31</sup>, P. Giommi<sup>94</sup>, F. Giordano<sup>31</sup>, M. Giroletti<sup>80</sup>, C. Ghislandi<sup>24,95</sup>, N. Godinovic<sup>96</sup>, C. Gouffin<sup>97</sup>, J. E. Grove<sup>98</sup>, C. Harnsdoerfer<sup>5</sup>, D. H. Hartmann<sup>26</sup>, M. Hayashida<sup>99</sup>, A. Hryczak<sup>64</sup>, P. Jean<sup>15</sup>, T. Johnson<sup>100</sup>, J. José<sup>101</sup>, S. Kaufmann<sup>102</sup>, B. Kheif<sup>103</sup>, J. Kiener<sup>5</sup>, J. Knöbbseder<sup>15</sup>, M. Kole<sup>123</sup>, J. Kopp<sup>104</sup>, V. Kozhuharov<sup>29</sup>, C. Labanti<sup>16</sup>, S. Lalkovski<sup>29</sup>, P. Laurent<sup>105</sup>, O. Limoustin<sup>106</sup>, M. Linares<sup>101</sup>, E. Lindfors<sup>107</sup>, M. Lindner<sup>107</sup>, S. Lombardi<sup>64,91</sup>, F. Loparco<sup>31,57</sup>, R. López-Coto<sup>1</sup>, M. López-Moya<sup>49</sup>, B. Lott<sup>108</sup>, P. Lubrano<sup>41</sup>, D. Malyshev<sup>110</sup>, N. Mankuzhiyil<sup>111</sup>, K. Mannheim<sup>88</sup>, M. J. Marcha<sup>112</sup>, A. Marengo<sup>38</sup>, B. Marcote<sup>113</sup>, M. Mariotti<sup>1</sup>, M. Maraschi<sup>114</sup>, S. McBreen<sup>12</sup>, S. Mergott<sup>69</sup>, A. Merle<sup>115</sup>, R. Mignani<sup>116,117</sup>, G. Minervini<sup>8</sup>, A. Morssev<sup>118</sup>, A. Morselli<sup>10</sup>, F. Moura<sup>79</sup>, K. Nakazawa<sup>119</sup>, L. Nava<sup>24,28,120</sup>, D. Nieto<sup>49</sup>, M. Orienti<sup>80</sup>, M. Orto<sup>121,2</sup>, E. Orlando<sup>29</sup>, P. Orlandi<sup>122</sup>, S. Palano<sup>2</sup>, R. Paoletti<sup>35</sup>, A. Papitto<sup>31</sup>, M. Pasquato<sup>2</sup>, B. Patricelli<sup>123,35</sup>, M. A. Pérez-García<sup>39</sup>, M. Perse<sup>123</sup>, G. Piano<sup>8</sup>, A. Pichel<sup>124</sup>, M. Pimenta<sup>4</sup>, C. Pittori<sup>44,91</sup>, T. Porter<sup>29</sup>, J. Poutanen<sup>107</sup>, E. Prandini<sup>34,1</sup>, N. Prantzos<sup>125</sup>, N. Produit<sup>13</sup>, S. Profumo<sup>126</sup>, P. S. Quastrol<sup>127</sup>, S. Rainó<sup>21,57</sup>, A. Rakhov<sup>64</sup>, M. Regis<sup>45,66</sup>, I. Reichardt<sup>128</sup>, Y. Ripphaell<sup>129,130</sup>, J. Rieco<sup>30</sup>, W. Rodejohann<sup>63</sup>, C. Rodríguez-Fernández<sup>10</sup>, M. Rosati<sup>131</sup>, L. Rosi<sup>132</sup>, A. Rovero<sup>124</sup>, R. Ruffini<sup>133</sup>, G. Sala<sup>101</sup>, M. A. Sánchez-Conde<sup>134</sup>, A. Santangelo<sup>135</sup>, P. Saz Parkinson<sup>136,137</sup>, T. Sbarrato<sup>95</sup>, A. Shearer<sup>138</sup>, R. Shellard<sup>48</sup>, K. Short<sup>20</sup>, T. Siegert<sup>77</sup>, C. Sigutta<sup>63,139</sup>, P. Spinnelli<sup>21</sup>, A. Stamerra<sup>140</sup>, S. Starrfield<sup>141</sup>, A. Strong<sup>77</sup>, I. Strümkne<sup>142</sup>, F. Tavecchio<sup>24</sup>, R. Tavera<sup>24</sup>, T. Terzić<sup>87</sup>, D. J. Thompson<sup>7</sup>, O. Tibolla<sup>102</sup>, D. F. Torres<sup>143,144,145</sup>, R. Turolla<sup>34</sup>, A. Ulyanov<sup>12</sup>, A. Ursi<sup>8</sup>, A. Vacchi<sup>81</sup>, J. Van den Abeele<sup>64</sup>, G. Vankova-Kirilova<sup>58</sup>, C. Venter<sup>58</sup>, F. Verrecchia<sup>44,91</sup>, P. Vincini<sup>146</sup>, X. Wang<sup>147</sup>, C. Weniger<sup>20</sup>, X. Wu<sup>123</sup>, G. Zaharijatic<sup>148</sup>, L. Zampieri<sup>2</sup>, S. Zane<sup>149</sup>, S. Zimmer<sup>150,13</sup>, A. Zoglauer<sup>151</sup> and the e-ASTROGAM collaboration

White Book published in arXiv/JHEAP  
Wide interest from the scientific community



Home

Science

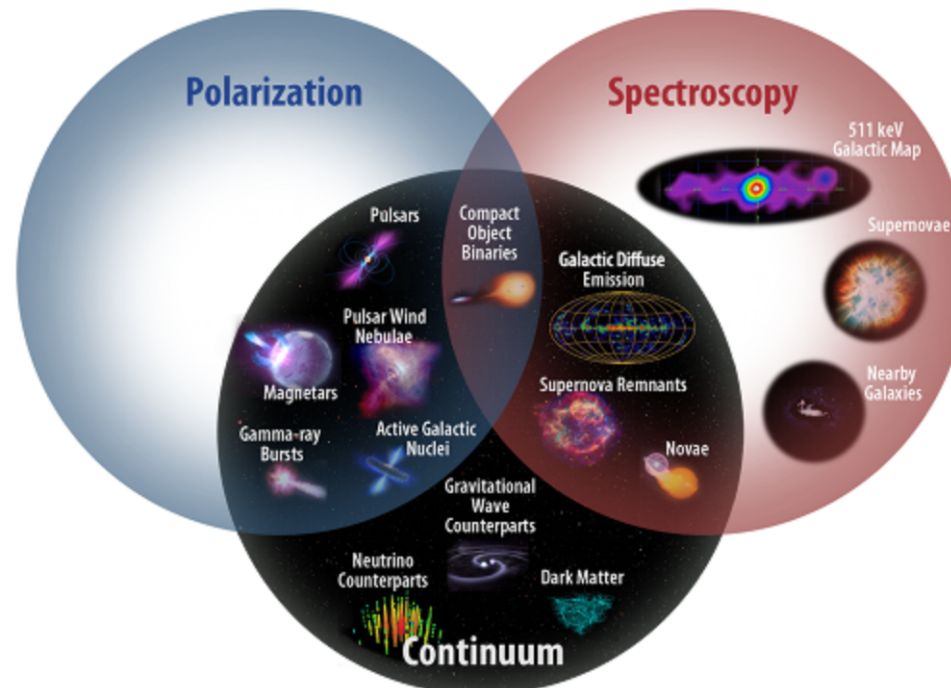
Technical

Team

Talks and News

Internal

AMEGO, the All-sky Medium Energy Gamma-ray Observatory, is an [Astrophysics Probe mission concept](#) designed to explore the MeV sky.





# AMEGO



## AMEGO Science

### *Understanding Extreme Environments*

#### Astrophysical Jets

*Understand the formation, evolution, and acceleration mechanisms in astrophysical jets*

#### Compact Objects

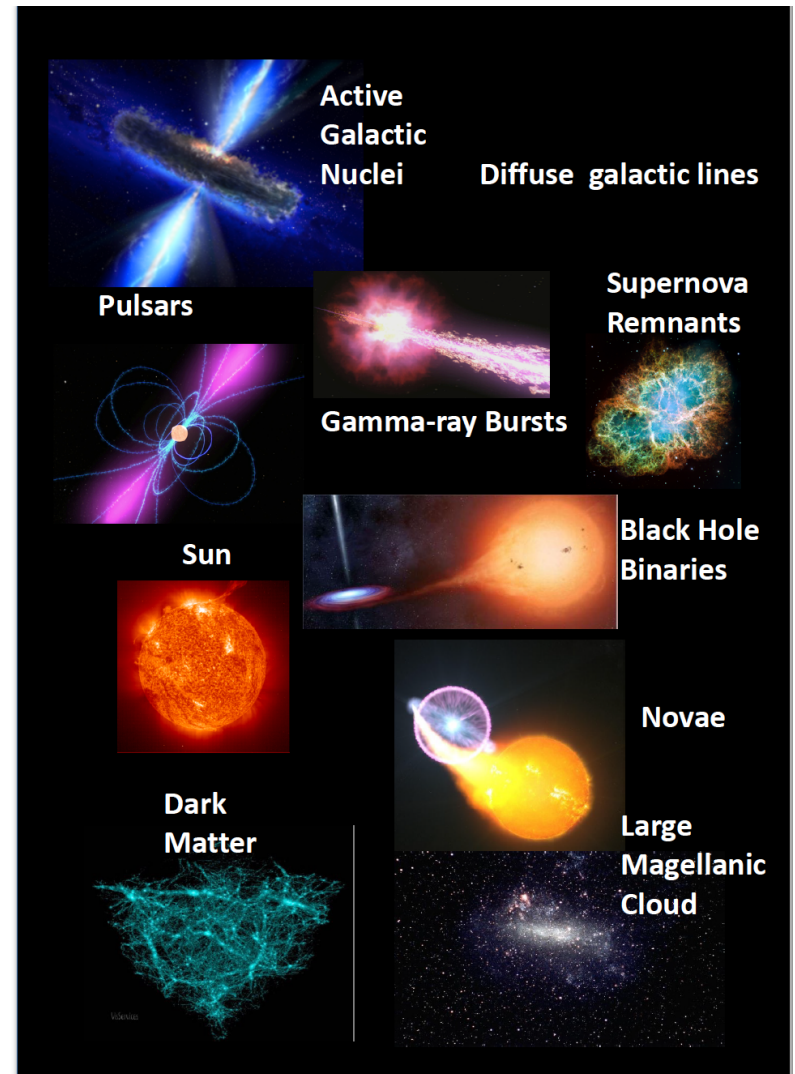
*Identify the physical processes in the extreme conditions around compact objects*

#### Dark Matter

*Test models that predict dark matter signals in the MeV band*

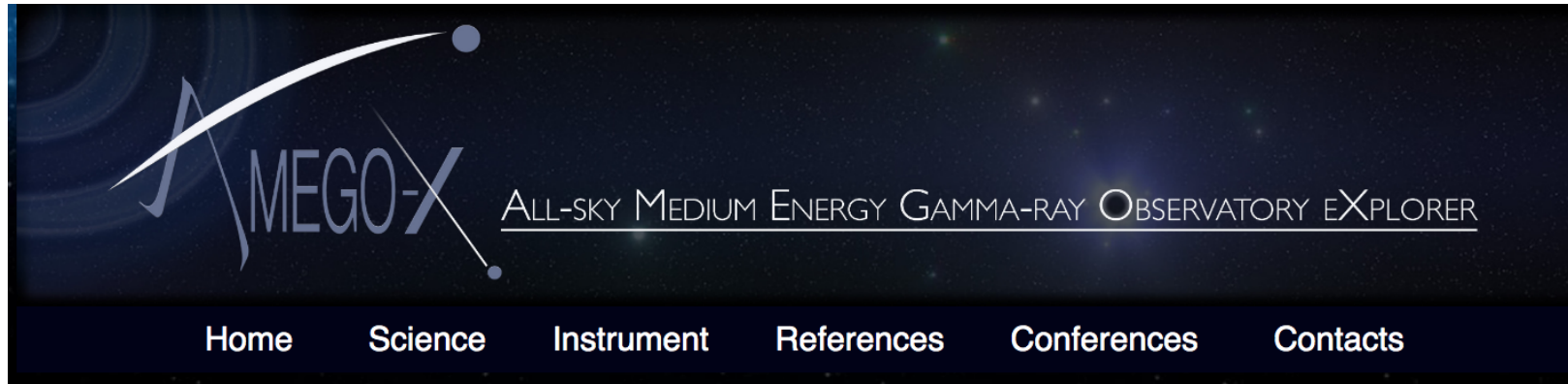
#### MeV Spectroscopy

*Measure the properties of element formation in dynamic systems*





# AMEGO-X



## About AMEGO-X

AMEGO-X, the All-sky Medium-Energy Gamma-ray Observatory eXplorer, is a multimessenger astronomy mission concept proposed to the 2021 [MIDEX Announcement of Opportunity](#), to be launched no later than Dec. 2028.

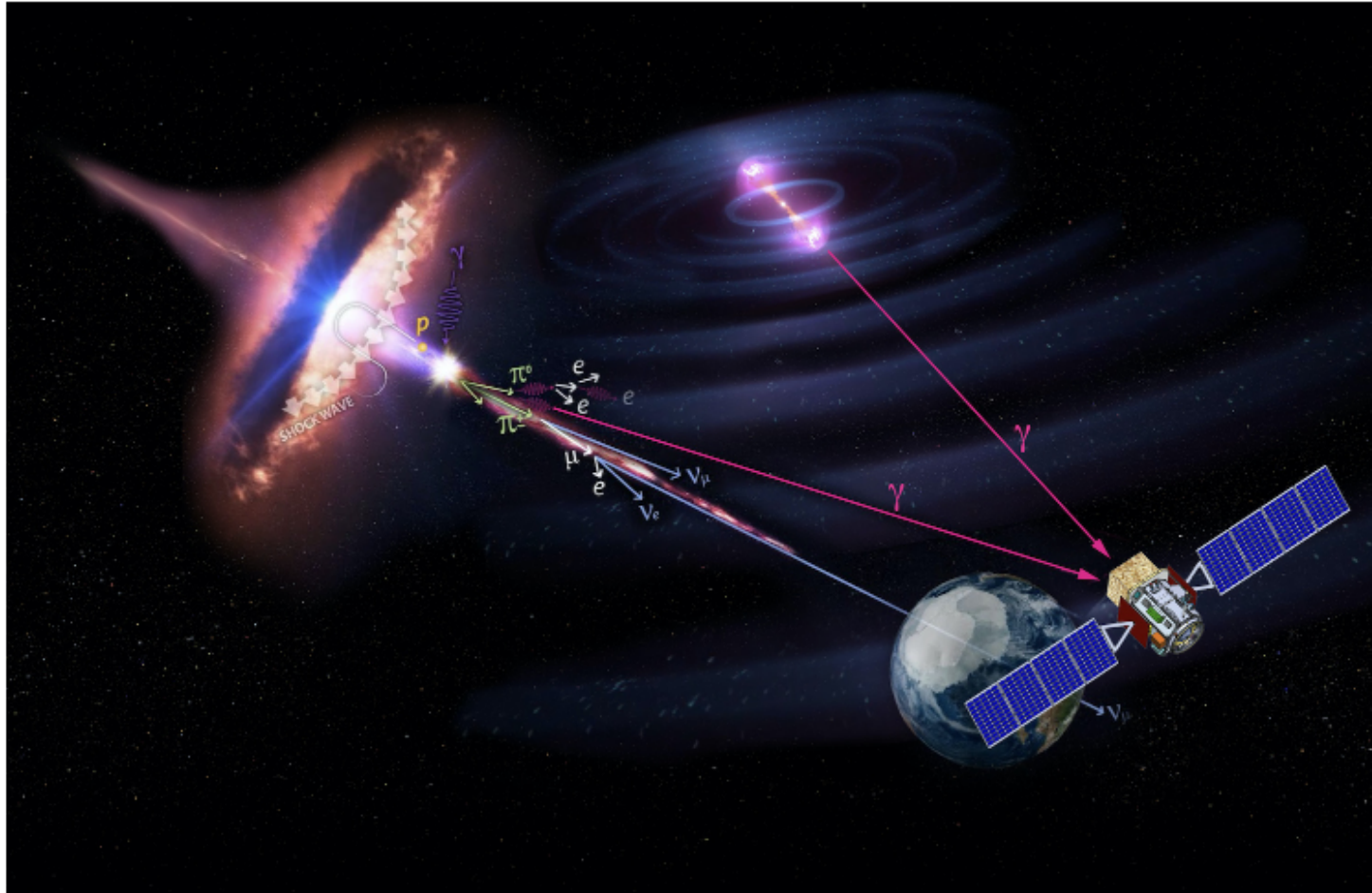
Multimessenger astrophysics (*New Messengers New Physics*) is a priority theme of the [Astro2020 Decadal Survey report](#), and the highest priority for space missions on small and medium scale platforms. This science is poised to revolutionize our understanding of the extreme universe. Data from AMEGO-X will answer the following questions pertaining to all cosmic messengers:

- Do supermassive black holes accelerate cosmic rays and produce neutrinos?
- How do binary neutron star mergers produce relativistic jets and what is the structure of those jets?
- Where are the cosmic rays accelerated in our Galaxy?

To answer these questions, AMEGO-X will be sensitive to gamma-ray photons in the energy range from about 100 keV to 1 GeV and transient events down to about 25 keV. During its three-year baseline mission, AMEGO-X will observe nearly the entire sky every two orbits, building up a sensitive all-sky map of gamma-ray sources and emission. Want to learn more? Check out the list of [publications](#) or see when and where to find us at upcoming [conferences](#).

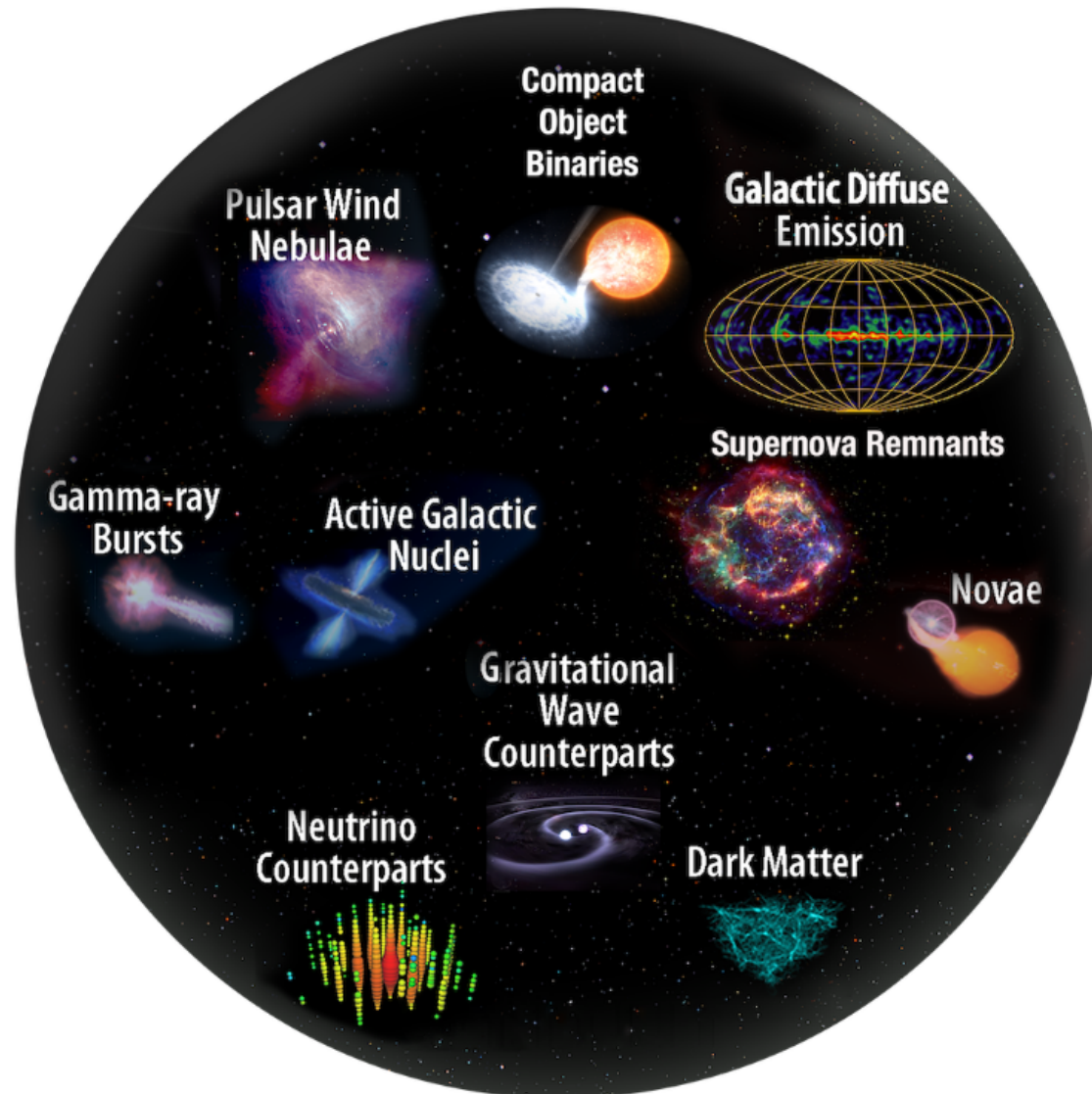
<https://asd.gsfc.nasa.gov/amego-x/index.html>

# AMEGO-X



Multimessenger Astrophysics

# AMEGO-X



Continuum Astrophysics

# COSI

## COSI

THE COMPTON SPECTROMETER AND IMAGER

[HOME](#)

[SCIENCE](#)

[INSTRUMENT](#) ▾

[BALLOON](#) ▾

[MORE](#) ▾



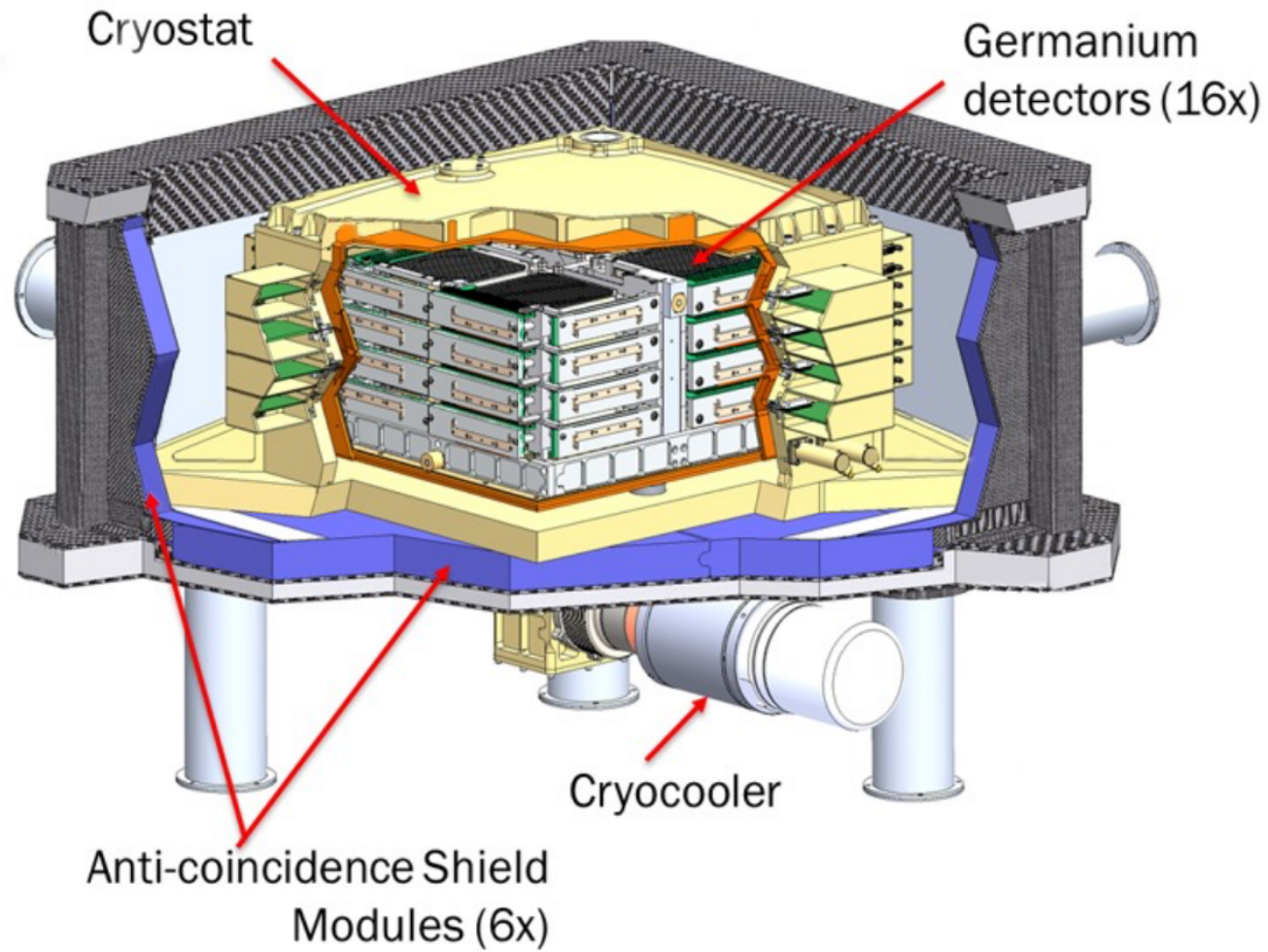
HOME

A detailed 3D rendering of the COSI satellite is centered in the image. The satellite has a complex, multi-faceted structure with several large, dark, rectangular panels extending from its sides, likely solar panels or detector components. It is set against a vibrant background of a starry night sky with colorful nebulae in shades of blue, purple, and pink. A semi-transparent dark grey horizontal bar is overlaid across the middle of the image, containing the word 'HOME' in large, white, bold, sans-serif capital letters.

<https://cosi.ssl.berkeley.edu/>



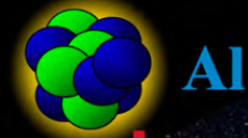
# COSI



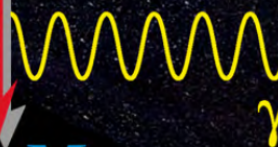
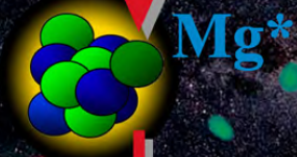
<https://cosi.ssl.berkeley.edu/>

Astrofisica Nucleare e Subnucleare  
MeV gamma astrophysics and Nuclear  
Astrophysics

# Observing cosmic nuclei through $\gamma$ ray spectroscopy



Proton  $\rightarrow$  Neutron



Roland Diehl

(MPE Garching, Germany)

with

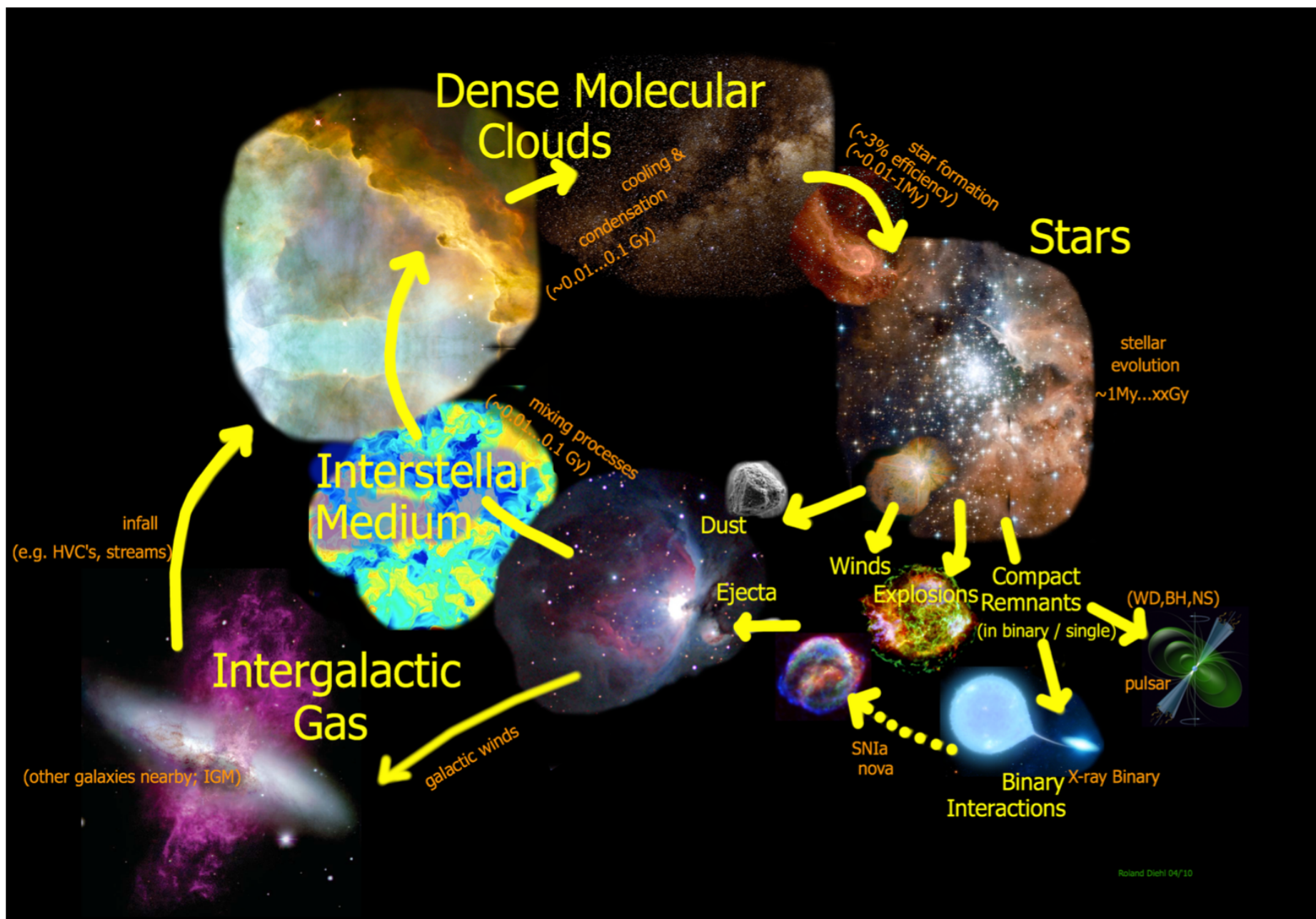
Thomas Siegert, Christoph Weinberger, Moritz Pleintinger,  
Daniel Kröll, Jochen Greiner, Xiaoling Zhang (MPE),  
Martin Krause, Karsten Kretschmer, Keiichi Maeda, and  
many others at other institutions

Russbach school 2019

*Instrument, Lessons & Puzzles*



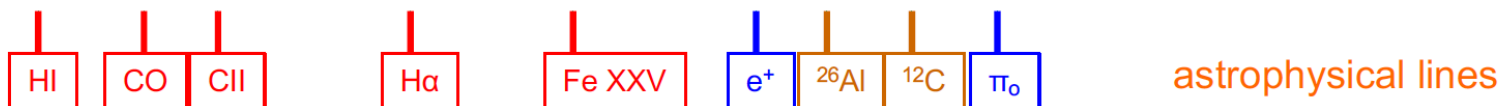
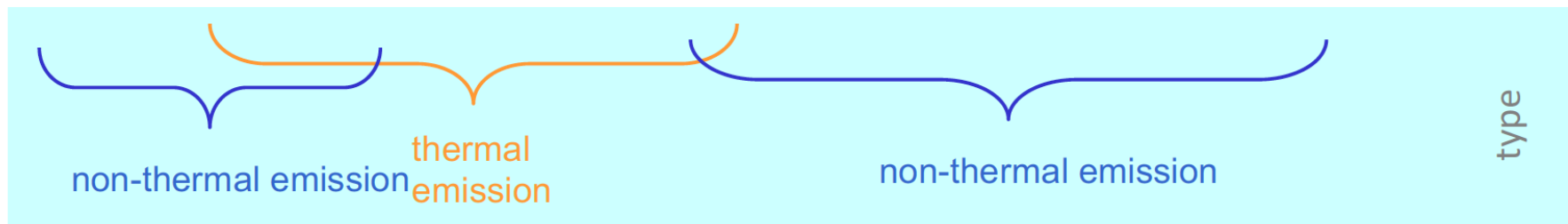
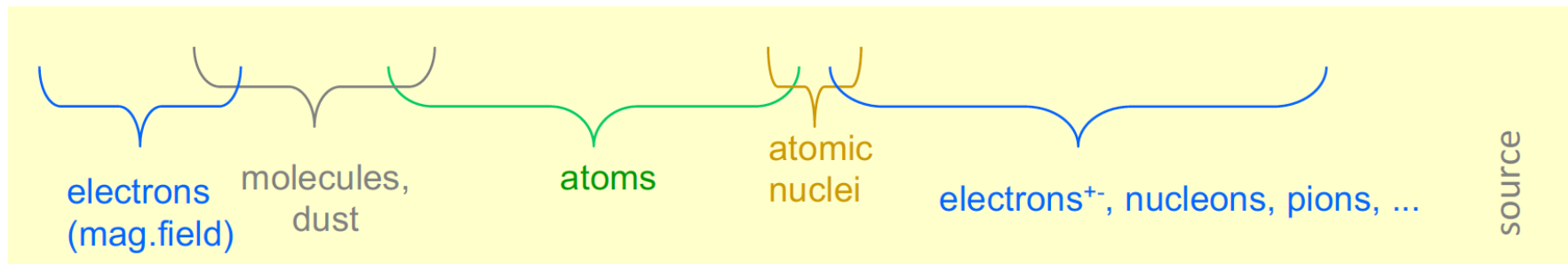
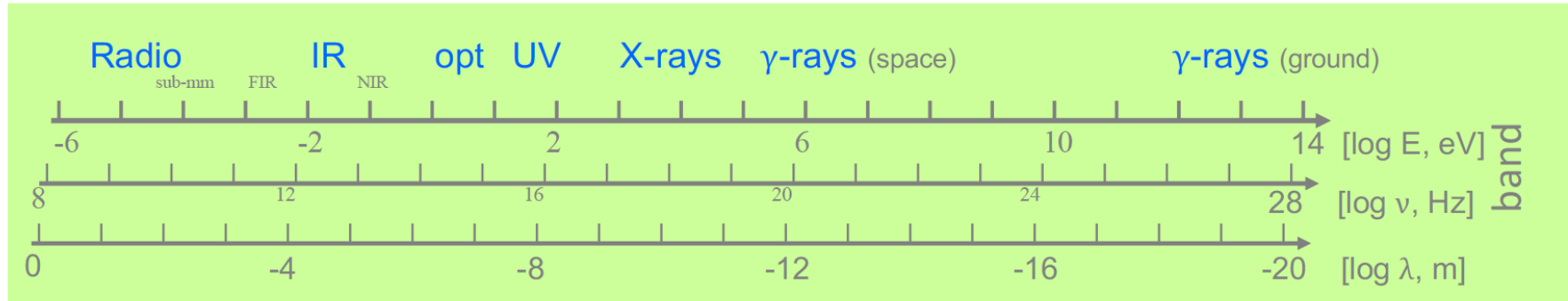
# How Stars Shape Galaxies







# Line Spectroscopy across the Electromagnetic Spectrum



# Radioisotope Gamma-Ray Lines and their Messages

Isotope	Mean Lifetime	Decay Chain	$\gamma$ -Ray Energy (keV)
${}^7\text{Be}$	77 d	${}^7\text{Be} \rightarrow {}^7\text{Li}^*$	478
${}^{56}\text{Ni}$	111 d	${}^{56}\text{Ni} \rightarrow {}^{56}\text{Co}^* \rightarrow {}^{56}\text{Fe}^* + e^+$	158, 812; 847, 1238
${}^{57}\text{Ni}$	390 d	${}^{57}\text{Co} \rightarrow {}^{57}\text{Fe}^*$	122
${}^{22}\text{Na}$	3.8 y	${}^{22}\text{Na} \rightarrow {}^{22}\text{Ne}^* + e^+$	1275
${}^{44}\text{Ti}$	89 y	${}^{44}\text{Ti} \rightarrow {}^{44}\text{Sc}^* \rightarrow {}^{44}\text{Ca}^* + e^+$	78, 68; 1157
${}^{26}\text{Al}$	$1.04 \cdot 10^6 \text{y}$	${}^{26}\text{Al} \rightarrow {}^{26}\text{Mg}^* + e^+$	1809
${}^{60}\text{Fe}$	$3.8 \cdot 10^6 \text{y}$	${}^{60}\text{Fe} \rightarrow {}^{60}\text{Co}^* \rightarrow {}^{60}\text{Ni}^*$	59, 1173, 1332
$e^+$	$\dots \cdot 10^5 \text{y}$	$e^+ + e^- \rightarrow \text{Ps} \rightarrow \gamma\gamma..$	511, <511

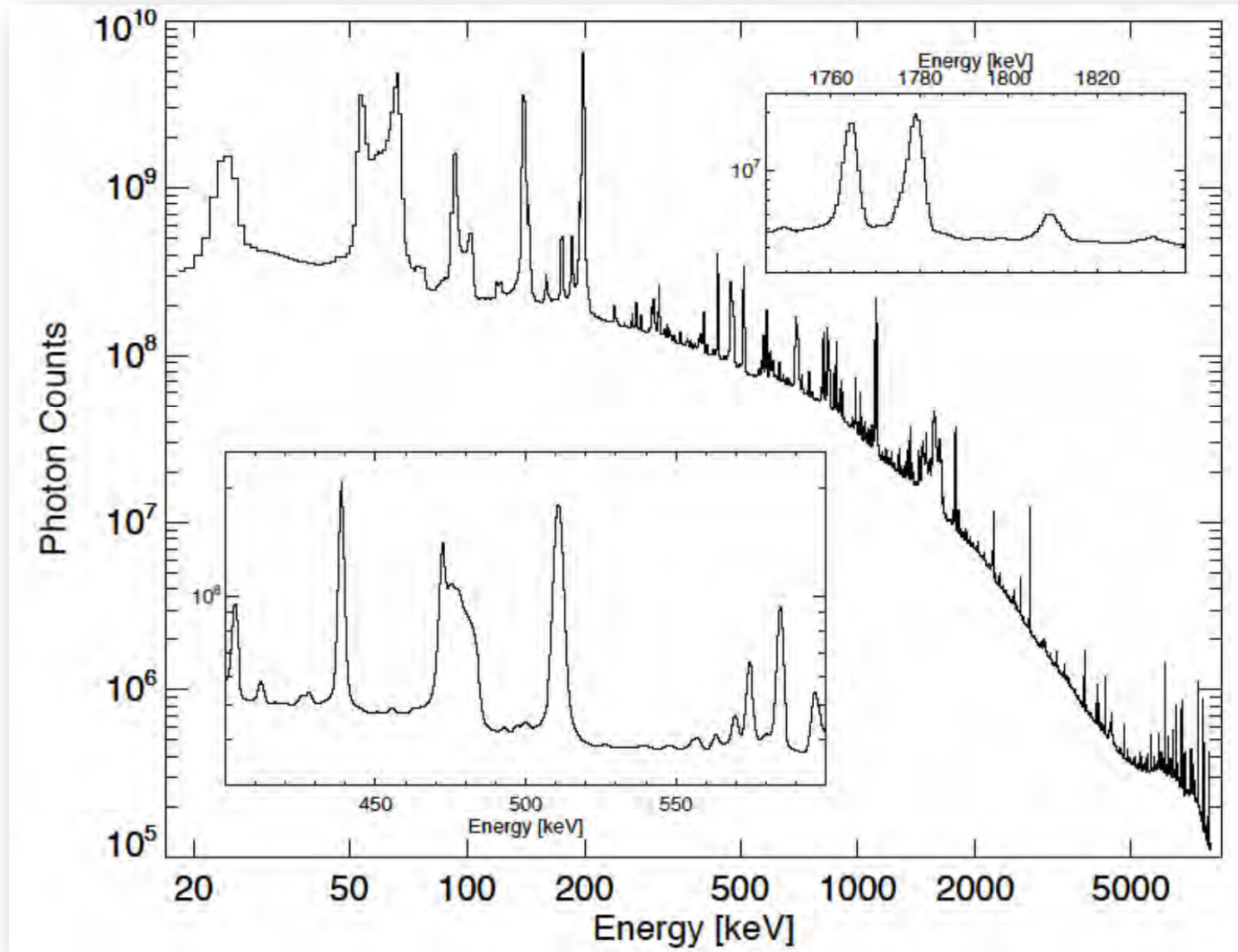
individual object/event

cumulative from many events



# Dominance of instrumental background

SPI Ge detector spectra



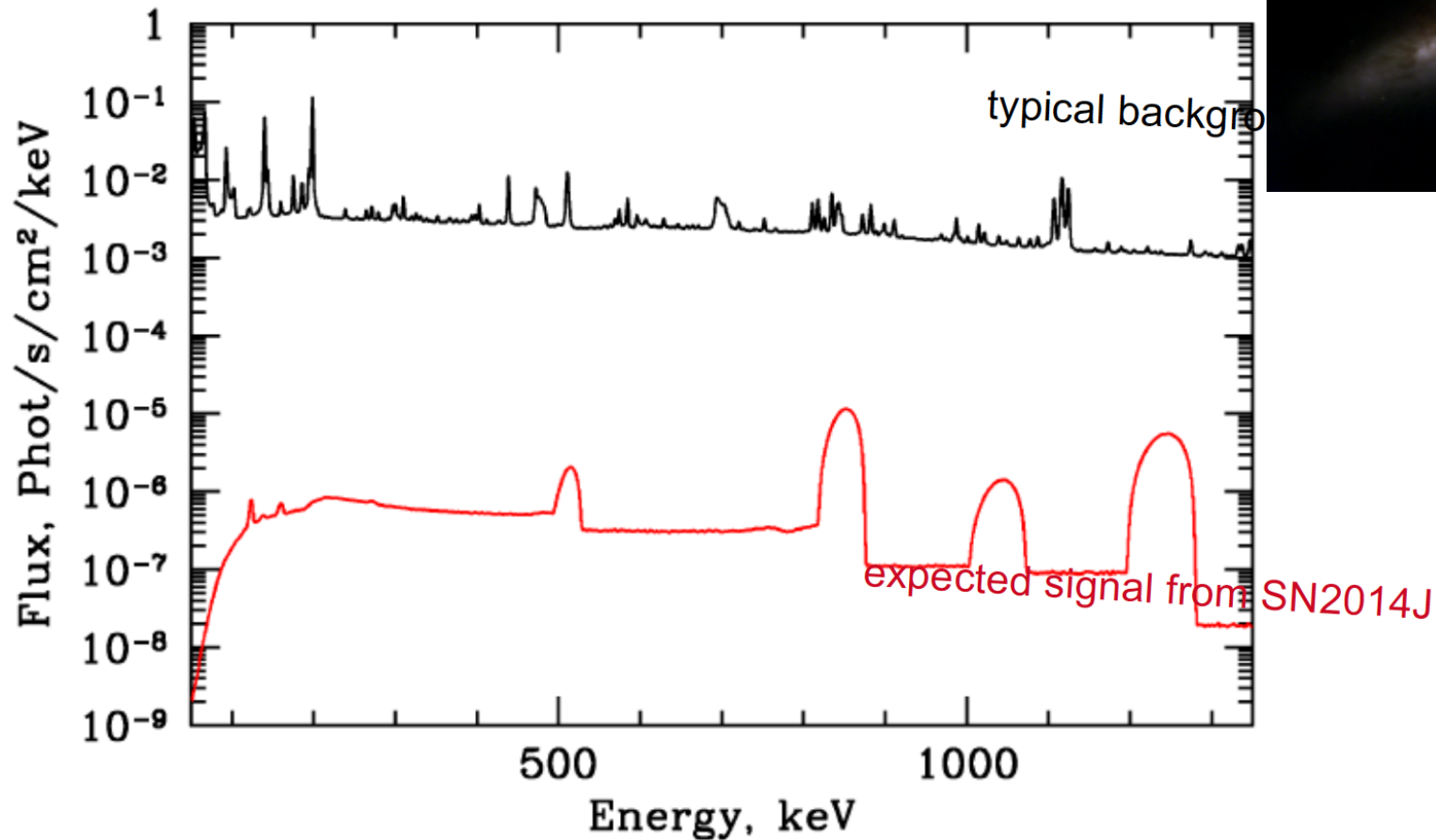


# The Challenge of Finding SN2014J Gamma-Rays



★ Current Gamma-Ray Telescopes Have Large Intrinsic Background

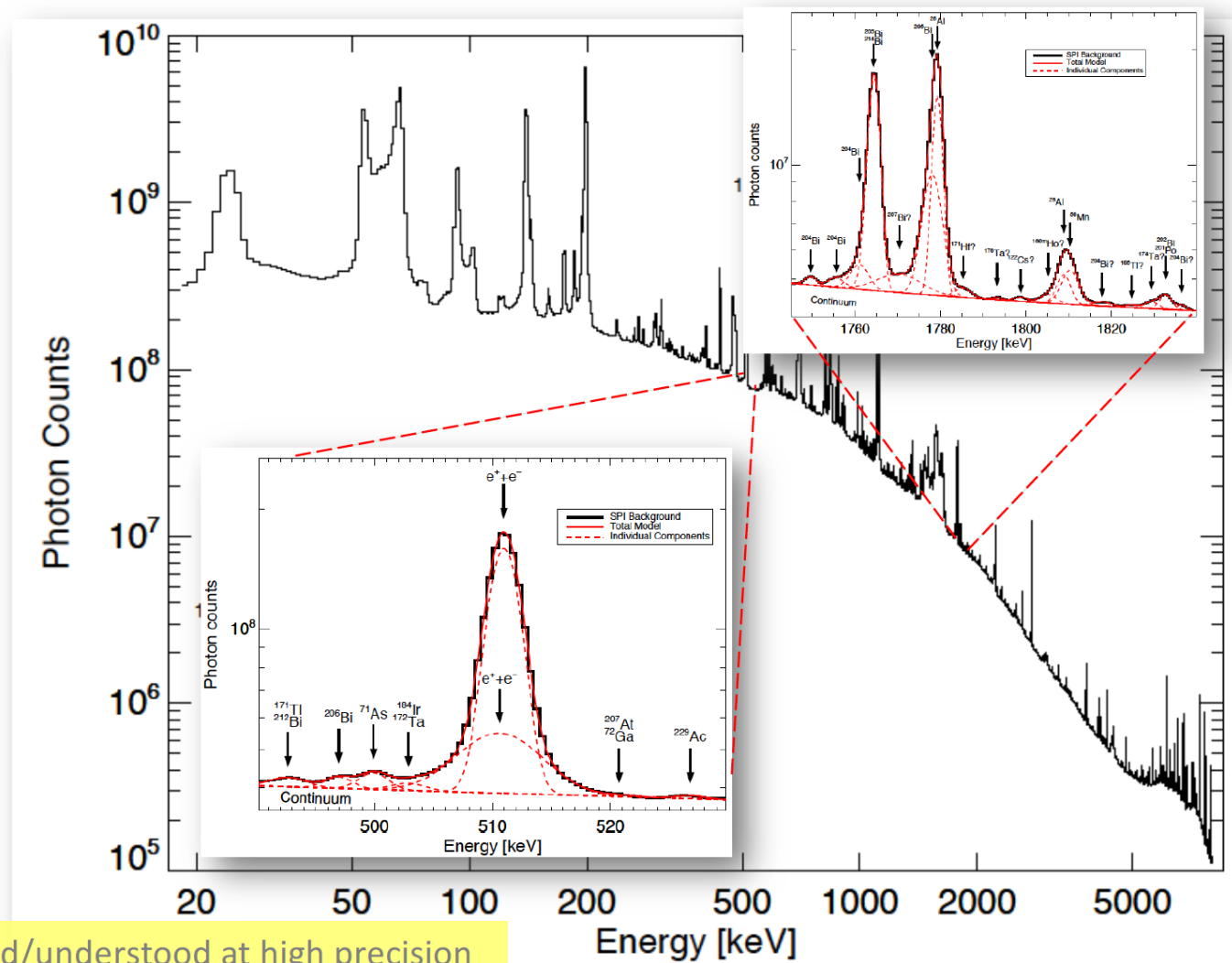
☞ Cosmic Ray Activation of Spacecraft and Instrument





# Dominance of instrumental background

## SPI Ge detector spectra



Modelled/understood at high precision



# Gamma ray spectroscopy with SPI



...it works!

★  $^{26}\text{Al}$  line 1808.6 keV

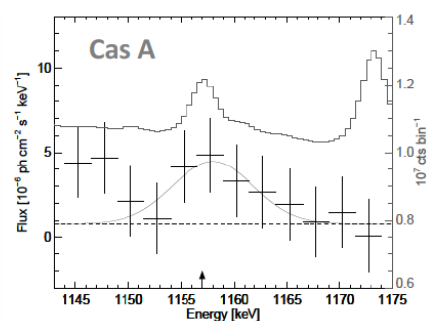
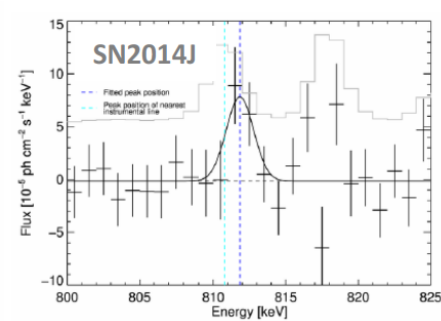
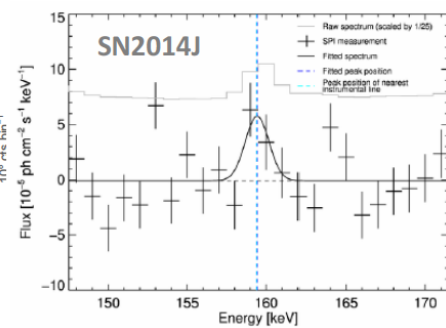
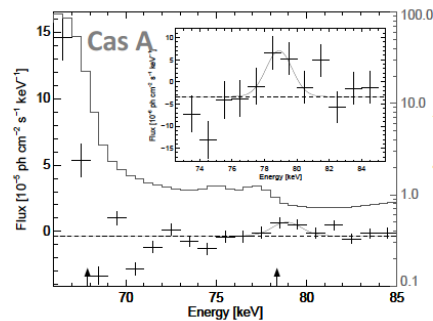
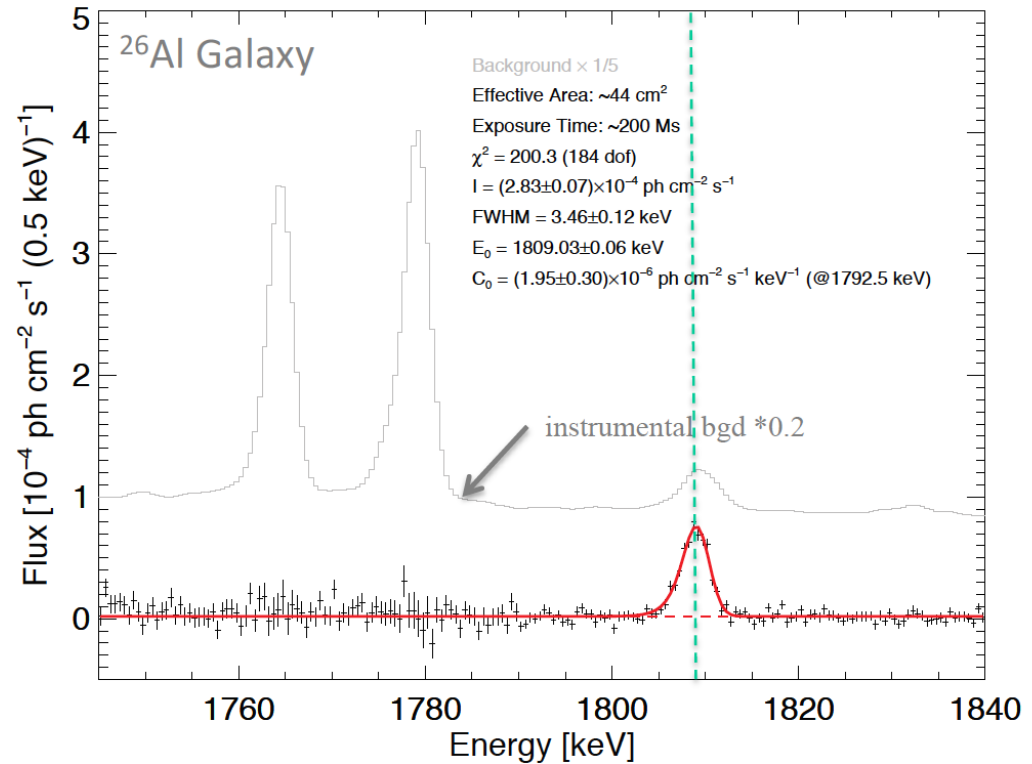
★ instrumental lines

👉 1810 keV

👉 1779 keV

👉 1764 keV

★ ...also: SN  $^{56}\text{Ni}$ ,  $^{44}\text{Ti}$



# Nucleosynthesis

## Basic Understanding of SNe Ia

### What we know....:

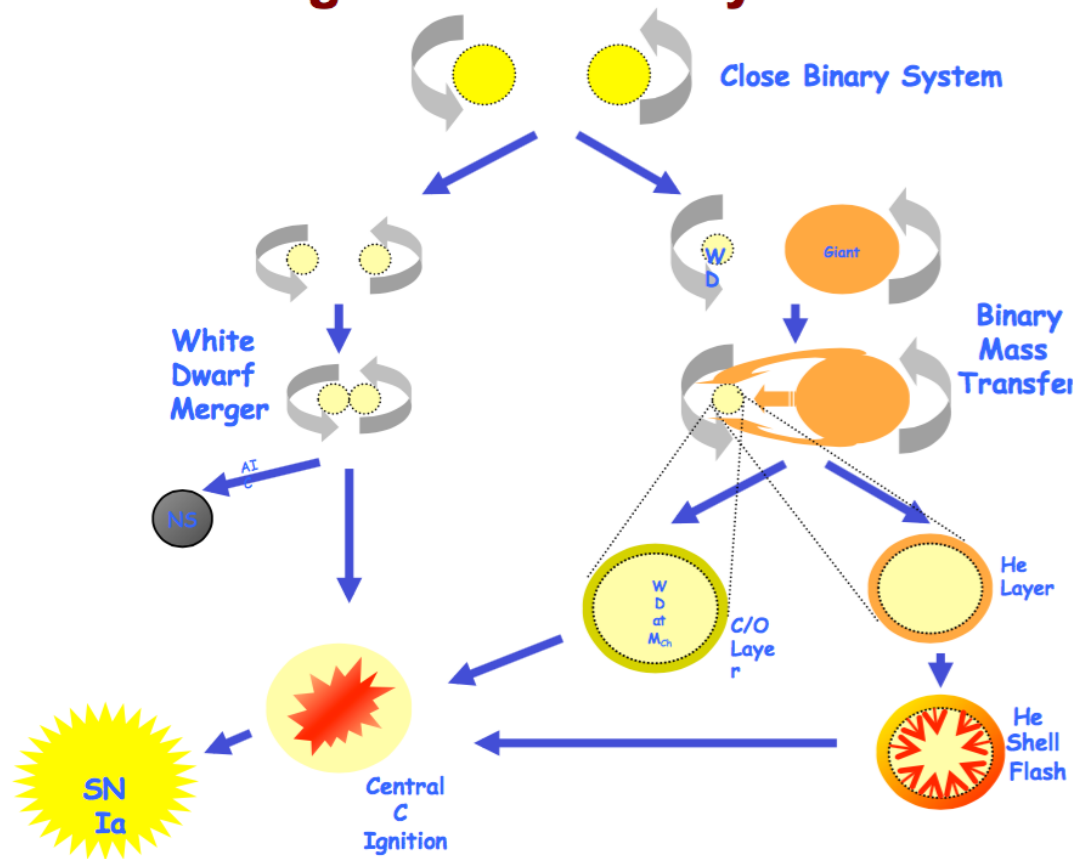
- WD in binary system accretes hydrogen
- when Chandrasekhar mass is reached, WD collapses, explosively ignites Carbon, and is destroyed completely
- SNe Ia are very good *standard* candles: same maximum luminosity
- Powered by the decay of  $^{56}\text{Ni} \rightarrow ^{56}\text{Co} \rightarrow ^{56}\text{Fe}$   
 $\sim 0.6 M_{\text{sun}} = 10^{43}$  erg/s at peak  
this explains the light curves (temporal evolution of photometry)
- produces velocities  $\sim 0.1c$
- Lack H/He, show strong intermediate mass and iron peak elements
- They occur in all types of galaxies

### ...and what we don't:

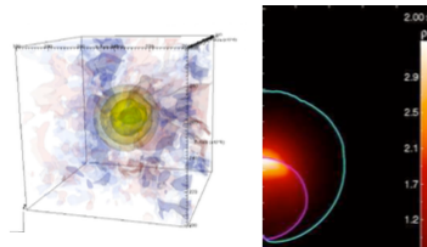
- Evolution with redshift
- Asphericities

- **SN Ia Diversity**

👉 **Progenitor Diversity?**



★ **Ignition Physics?**





# Nucleosynthesis

## Modeling the SNe Ia

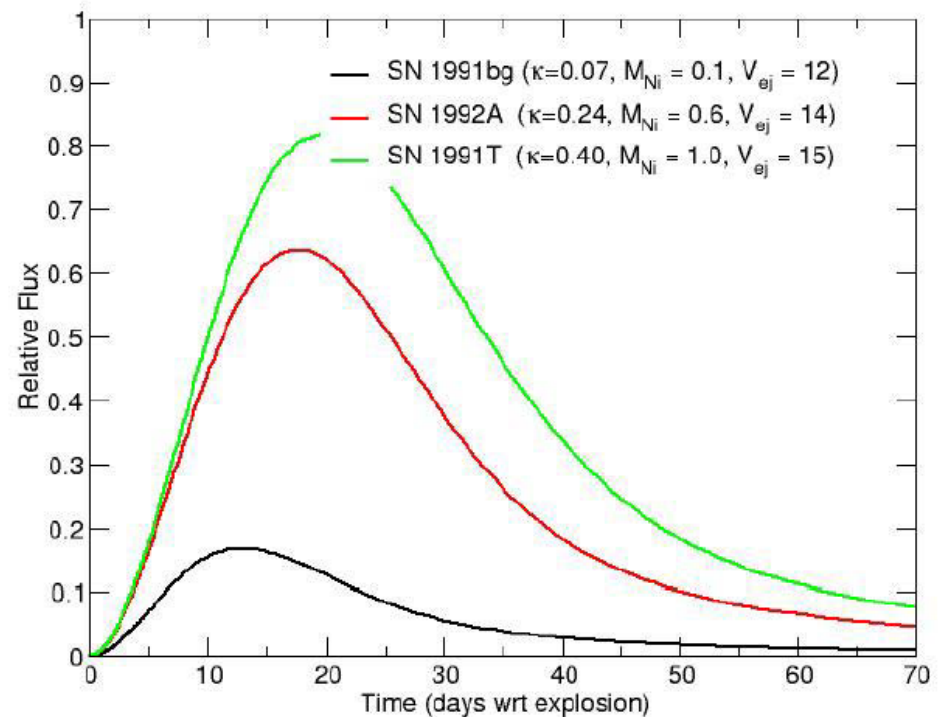
Simple relationship: More  $^{56}\text{Ni}$   $\rightarrow$  Higher Temperatures  $\rightarrow$  Higher Opacities

= Brighter/Broader SNe Ia

The higher opacities allow to trap the radiation more effectively and release it later making for broader light curves.

Parameters for modelling SN Ia light curve:

- $^{56}\text{Ni}$  mass
- Opacity
- Kinetic Energy

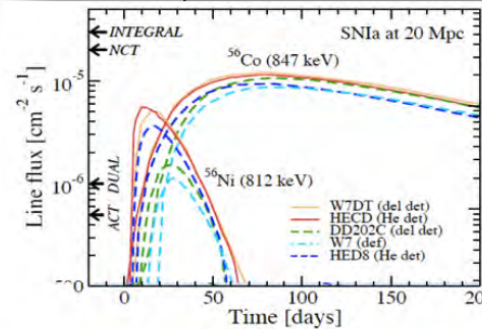
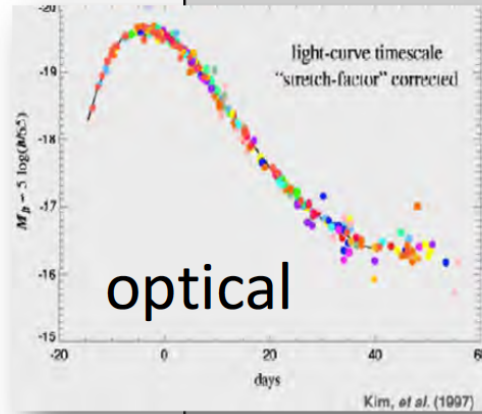




# $^{56}\text{Ni}$ radioactivity $\rightarrow \gamma$ -Rays, $e^+ \rightarrow$ leakage/deposit



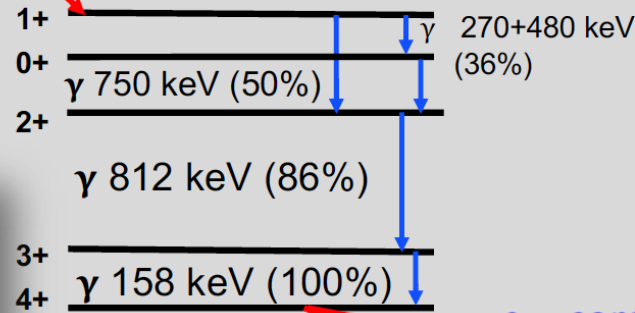
**SN Ia**



$0^+$   
 $\tau = 8.8 \text{ d}$

**$^{56}\text{Ni}$**

$e^-$ -capture (98%)



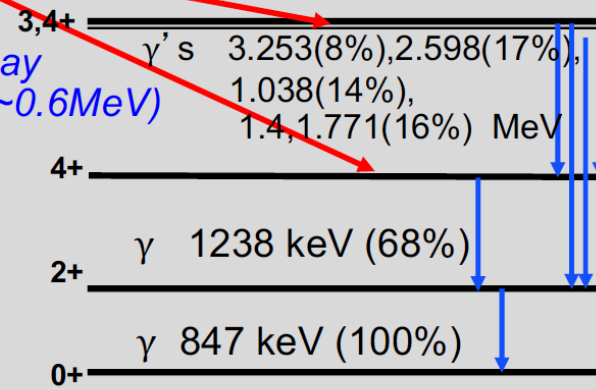
$\rightarrow$  talk Nando Patat

**$^{56}\text{Co}$**

$\beta^+$  - decay  
(19%,  $E \sim 0.6 \text{ MeV}$ )

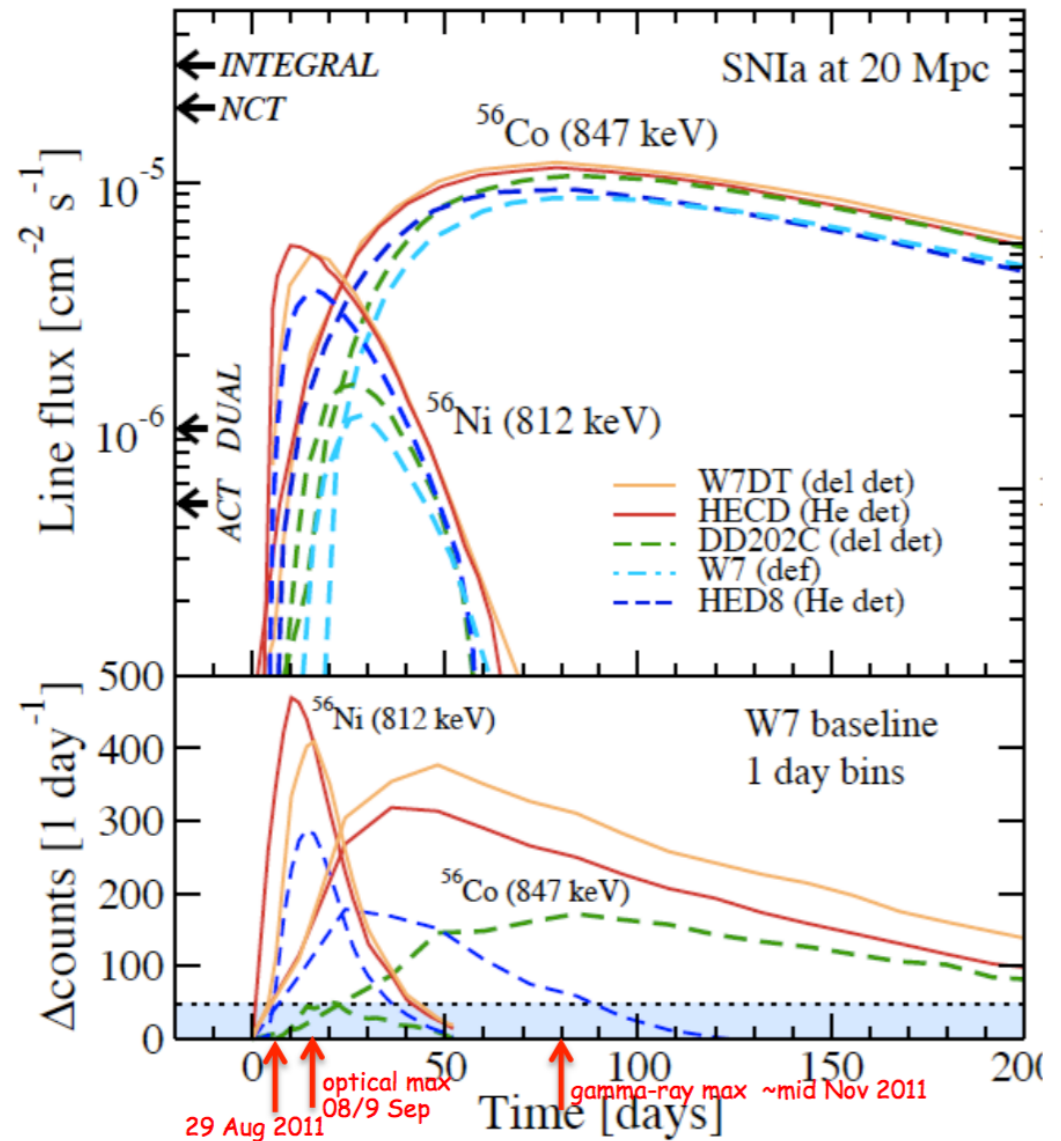
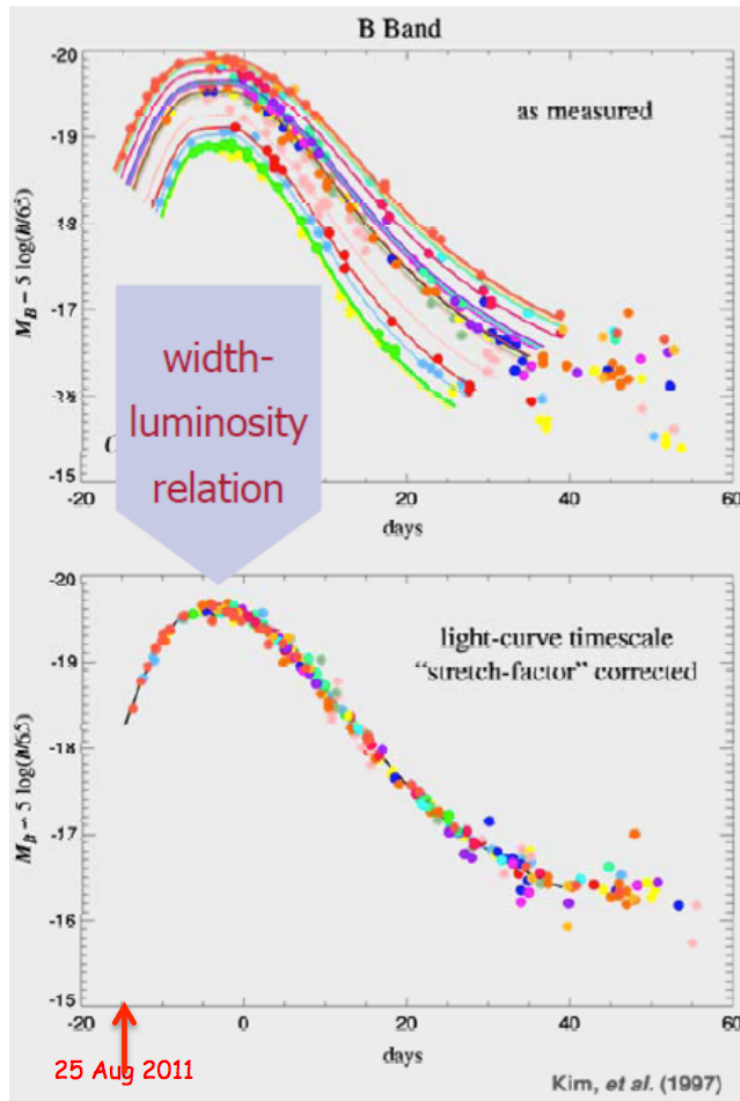
$\tau = 111.3 \text{ d}$

$e^-$  - capture (81%)



**$^{56}\text{Fe}$**

# SN Ia Models and Radioactivity Gamma-Rays

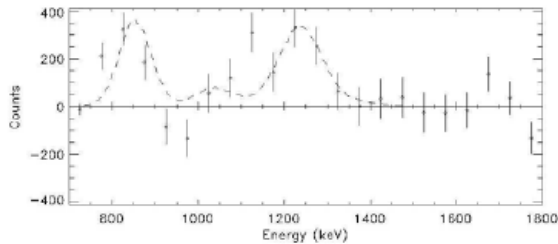


- **SN 2011fe in M101 is a Chance to Gamma-Calibrate SN Ia Models** (d~6.4 Mpc)
  - ☆ Phillips Relation, Light Transport Codes from Gamma to X/UV/OPT/IR

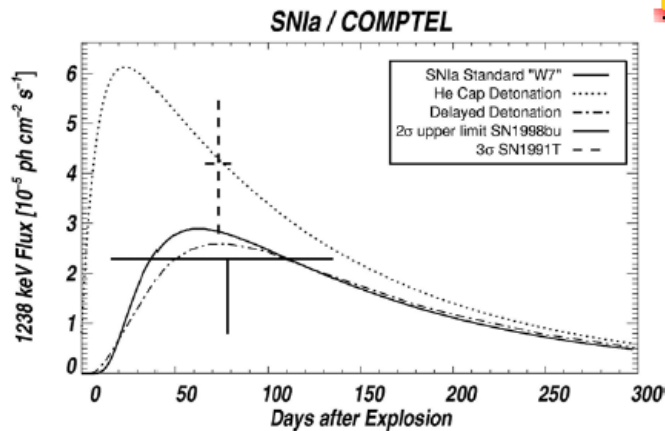
# Nucleosynthesis



## Gamma-Rays from Supernovae Ia



- Rarely SNIa  $^{56}\text{Ni}$  Decay Gamma-Rays are Above Instrumental Limits ( $\sim 10^{-5} \text{ ph cm}^{-2} \text{ s}^{-1}$ )
  - $\sim 2$  Events / 9 Years CGRO
  - $\sim 1$  Event / Year INTEGRAL Mission?



### COMPTEL

- ☞ Signal from SN1991T ( $3\sigma$ ) (13 Mpc)
- ☞ Upper Limit for SN1998bu (11 Mpc)

- ★ The  $^{56}\text{Ni}$  Power Source:  $0.5 M_{\odot}$  of  $^{56}\text{Ni}$  ??
- ★ Which Burning Profile and Mixing ?



# SN2014J data Jan – Jun 2014: 847 keV <sup>56</sup>Co line



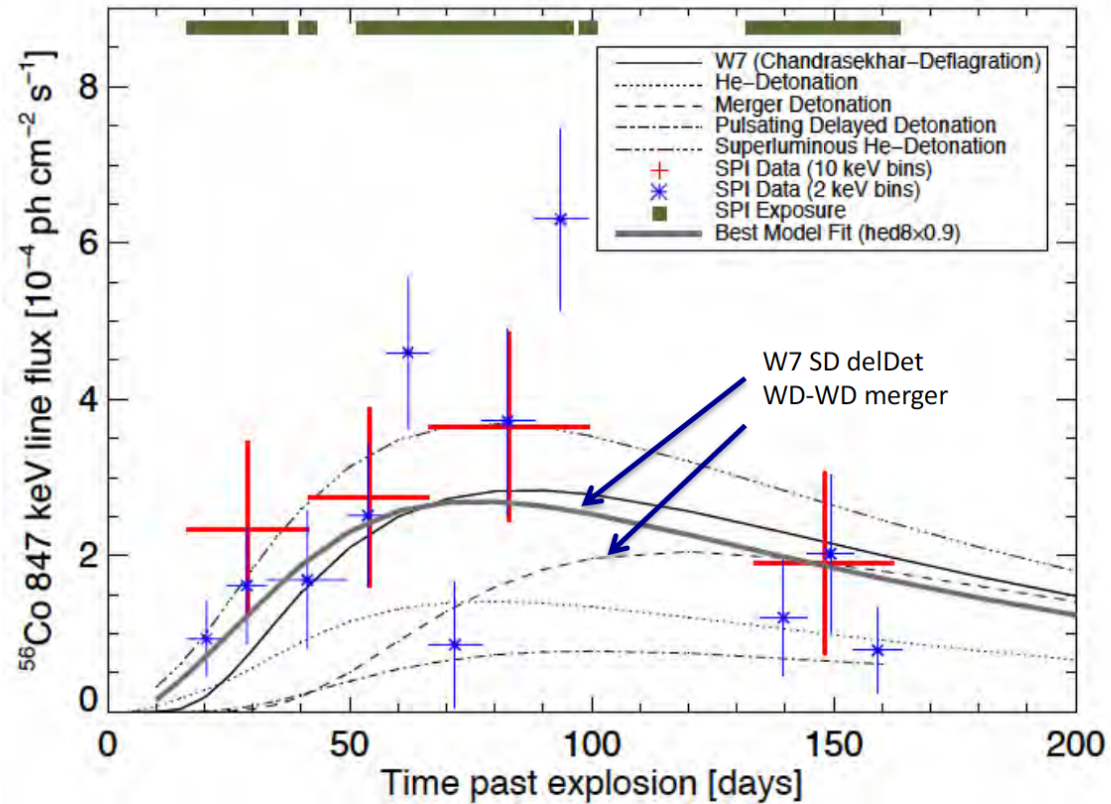
★ Track emergence of gamma rays i.e. fading energy deposit

→ Calibration of optical emission against <sup>56</sup>Ni amount!

★ <sup>56</sup>Ni mass (fitted): 0.49 +/- 0.09 M<sub>⊙</sub>

(cmp from empirical law) → 0.42 +/- 0.05 M<sub>⊙</sub>

(from models) → 0.5 +/- 0.3 M<sub>⊙</sub>



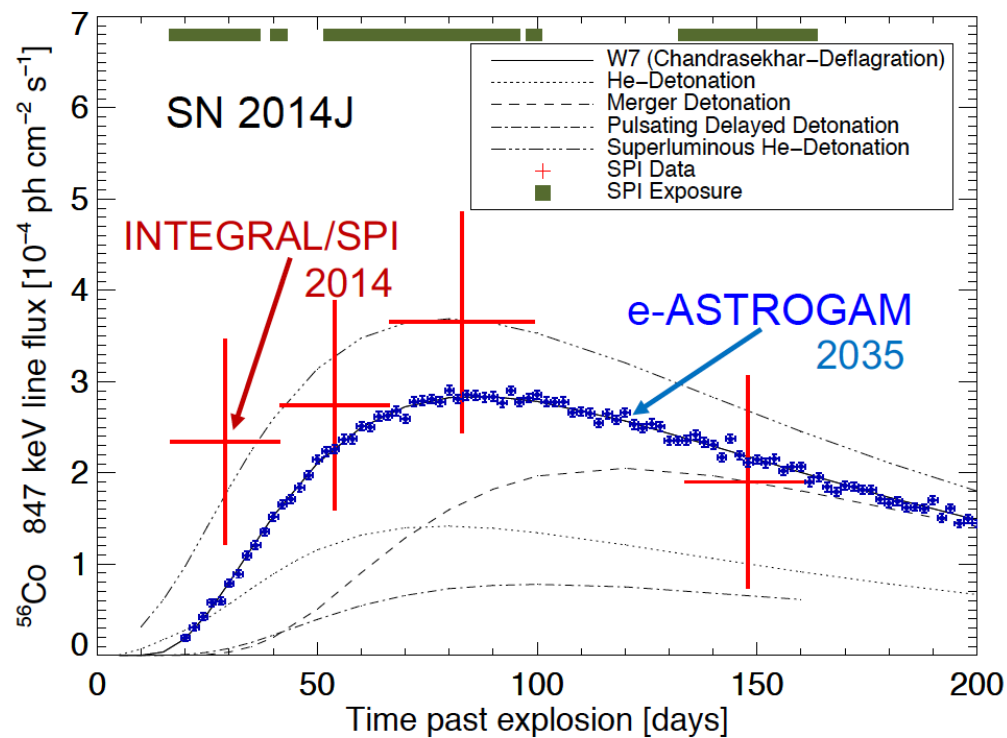




# If we had a new gamma-ray telescope mission...



...we would have THIS:

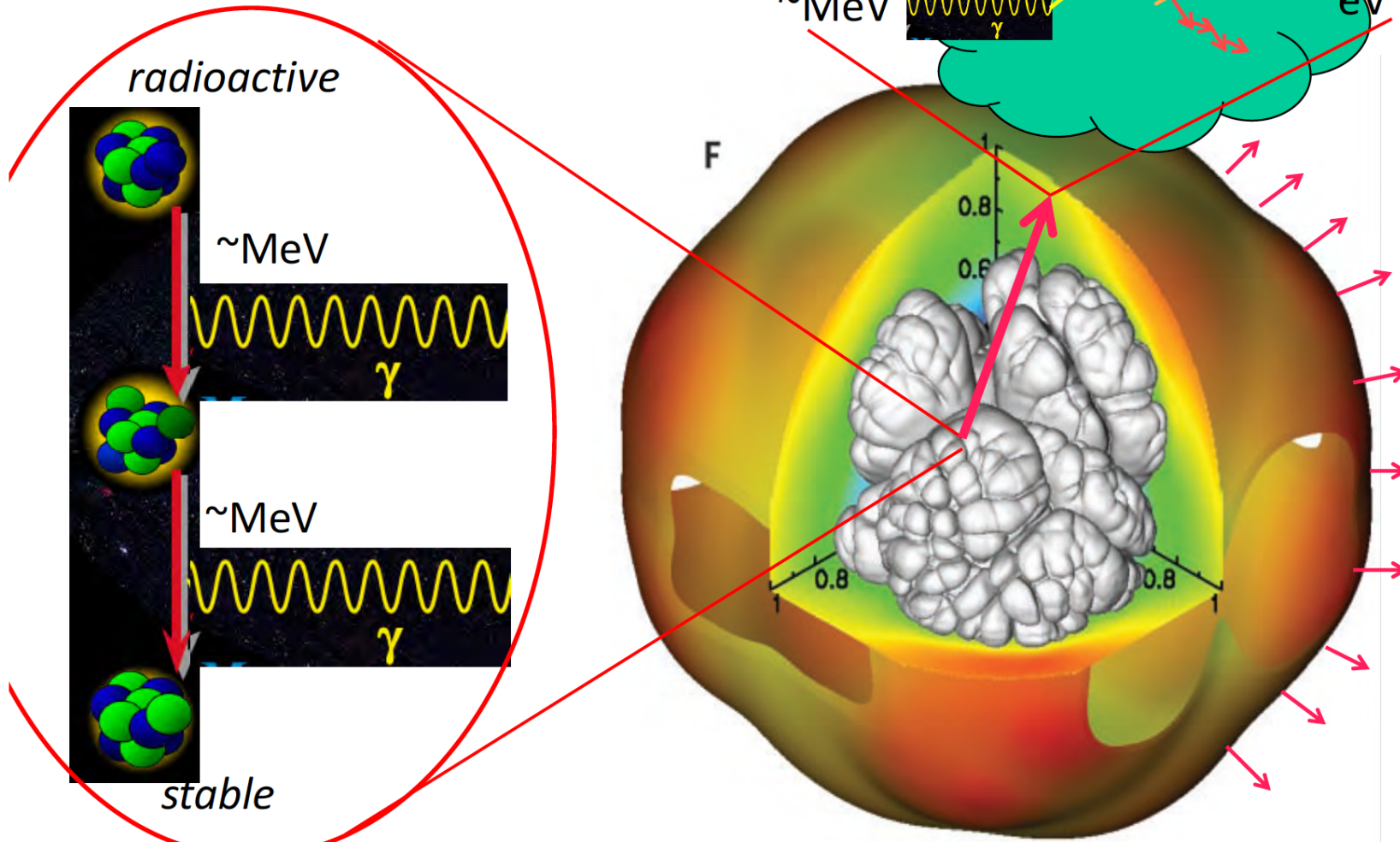




# Light from Explosions



- Radiation Transport:

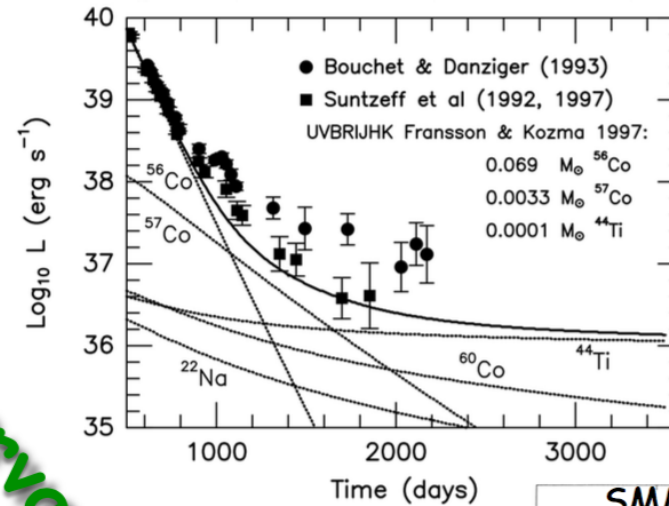
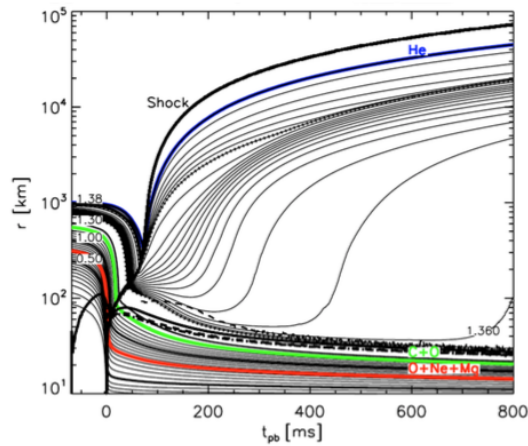


# Aspects of a Core-Collapse Supernova

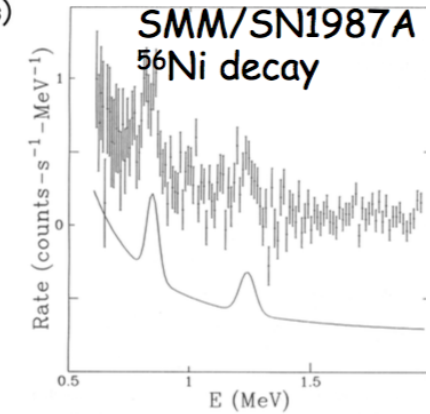
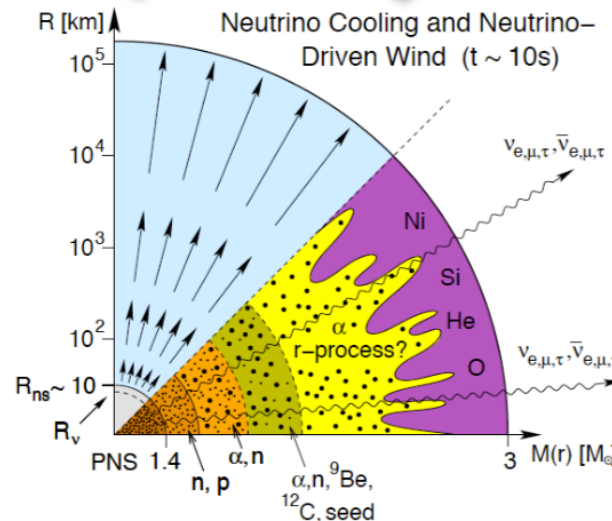
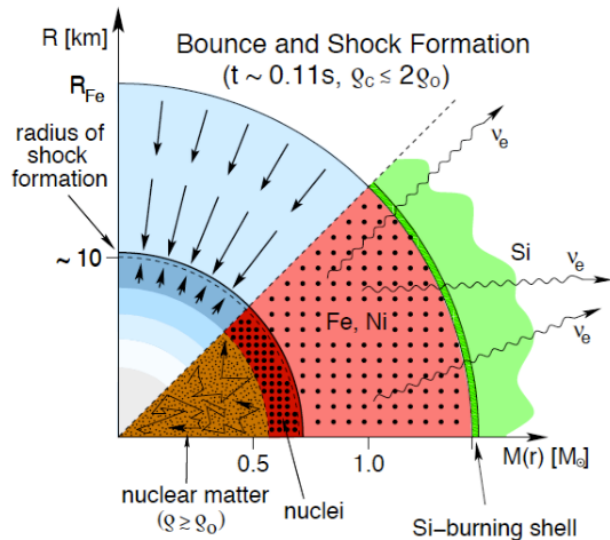
- **Nuclear Energy Conversions +...**

- ☆ **Dynamics of Explosions**

- ☆ **Structure of Stars**

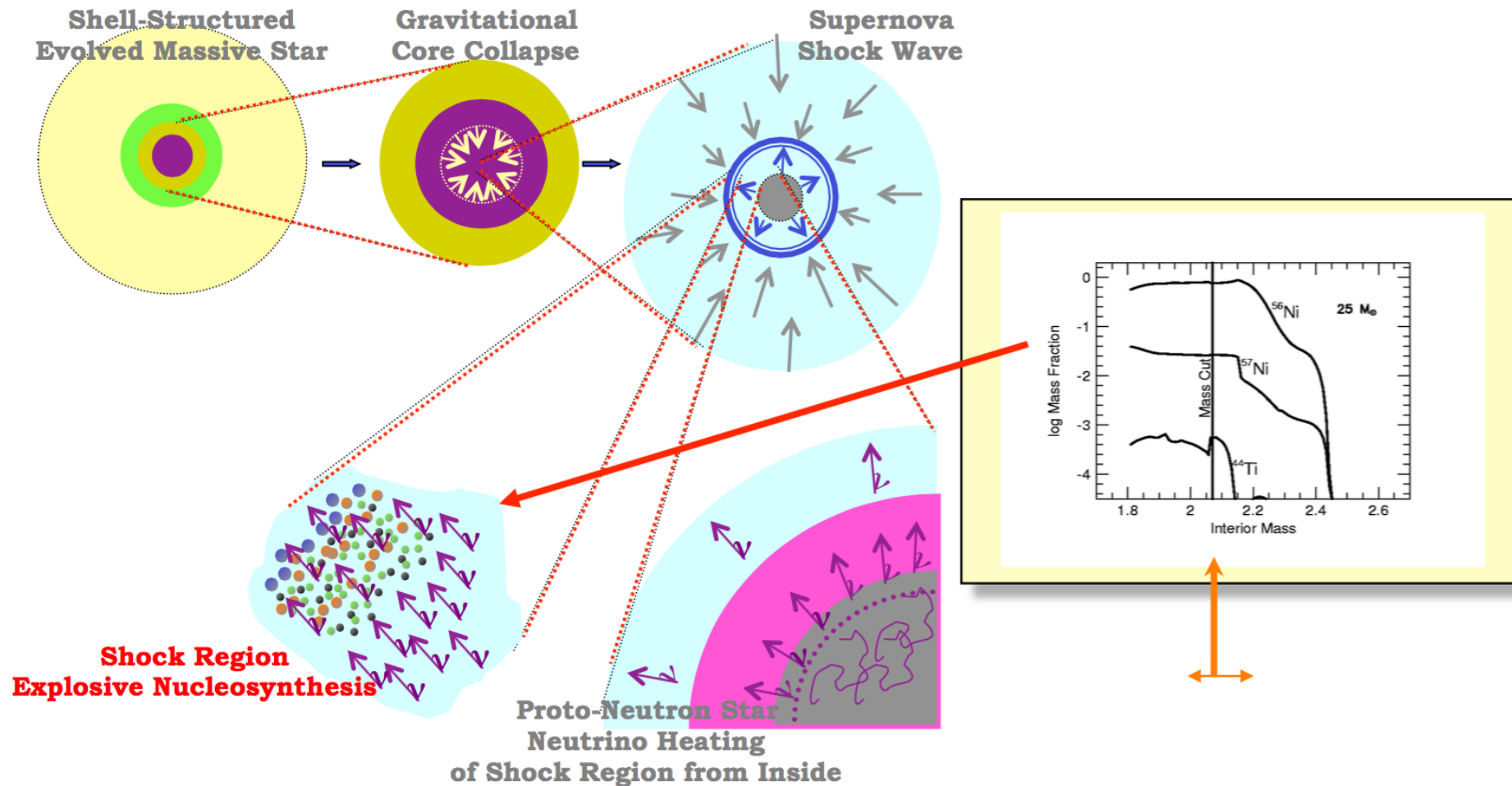


Observations  
Models





# Nucleosynthesis in CC-Supernova Models and $^{44}\text{Ti}$

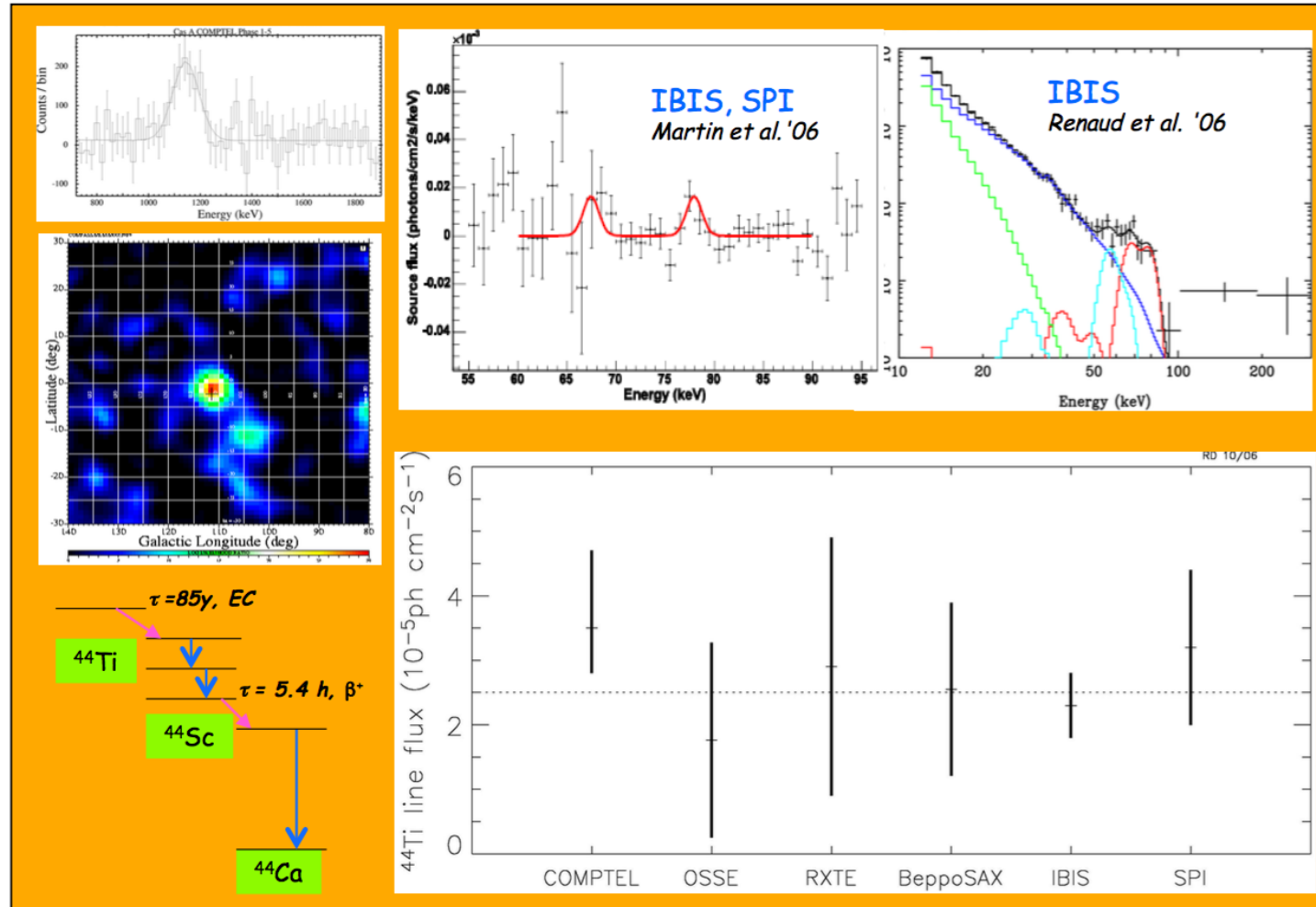


- $^{44}\text{Ti}$  Produced at  $r < 10^3$  km from  $\alpha$ -rich Freeze-Out,  
=> Unique Probe (+Ni Isotopes)

# $^{44}\text{Ti}$ $\gamma$ -rays from Cas A

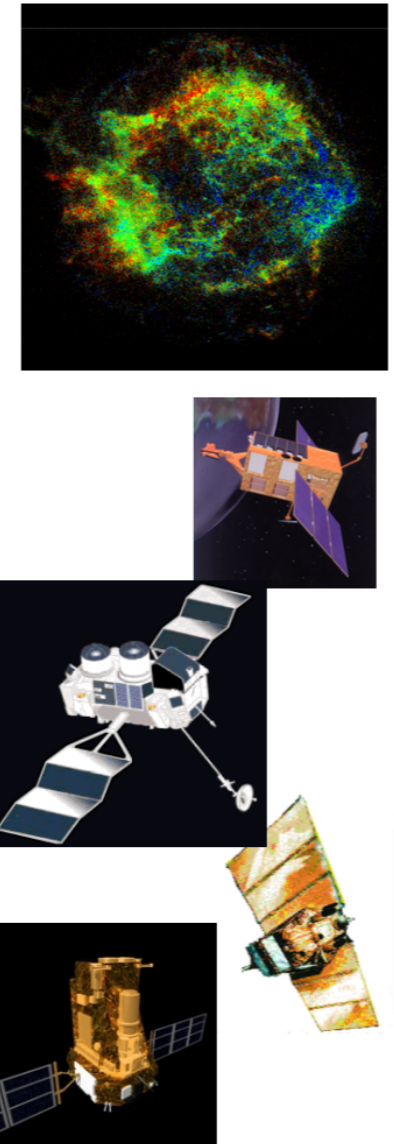
$\tau=85\text{y}$  (Ahmad et al. 2006)

89 y |  $^{44}\text{Ti} \rightarrow ^{44}\text{Sc}^* \rightarrow ^{44}\text{Ca}^* + e^+$  | 78, 68; 1157



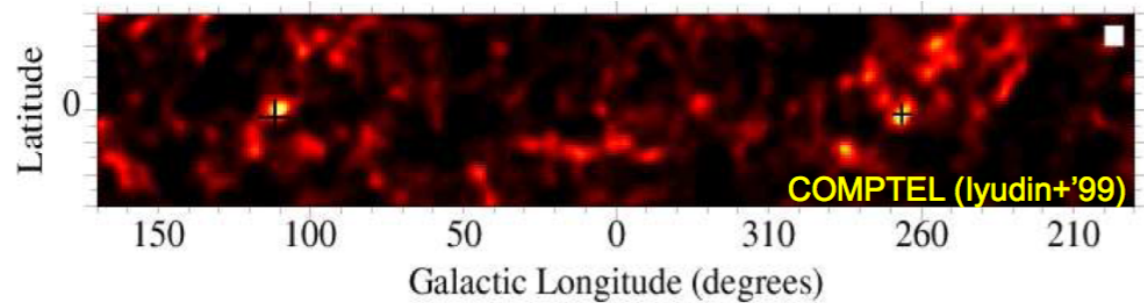
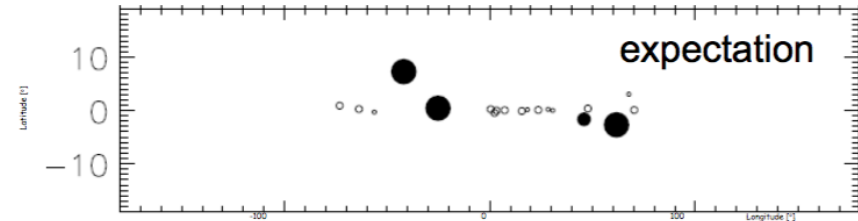
**$^{44}\text{Ti}$  Ejected Mass**

**$\sim 0.8-2.5 \cdot 10^{-4} M_{\odot}$**



# Are Core Collapse Supernovae $^{44}\text{Ti}$ Sources?

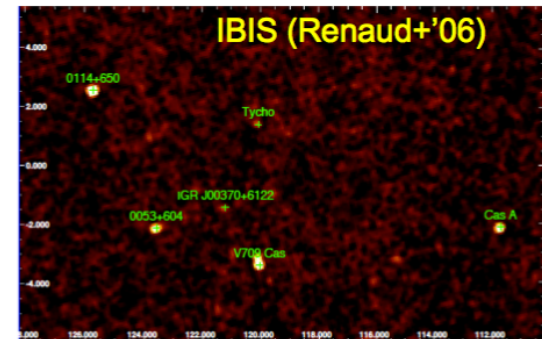
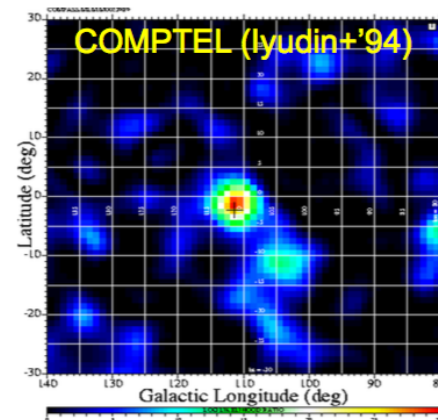
- ☆ Sky Regions with Most Massive Stars are  $^{44}\text{Ti}$  Source-Free (COMPTEL, INTEGRAL)



- ☆ Cas A is the ONLY Source Seen in our Galaxy

☆  $^{44}\text{Ti}$  is from Rare Events??

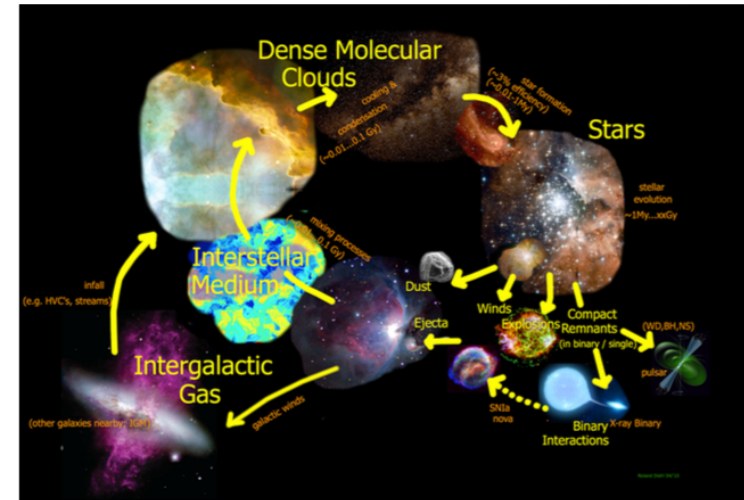
⇒ The et al. 2006



# Massive-Star Interiors

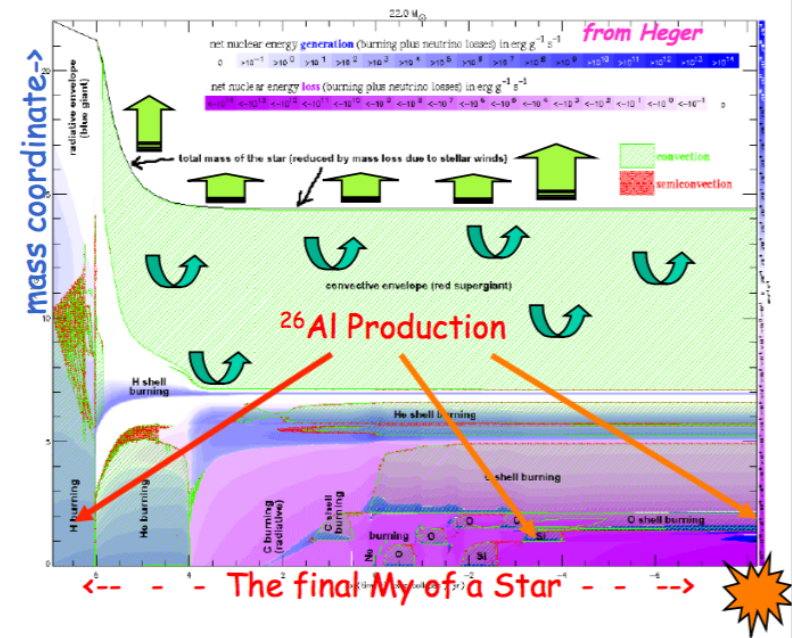
## ★ Massive Stars are:

- 👉 Key Producers of Cosmic 'Metals'
- 👉 Key Agents for Cosmic Evolution in Galaxies



## ★ How does the Interior Structure Evolve in Late Stages?

- 👉 Which "Shells" are Active?
- 👉 Which Nuclei are Produced? (ejected?)
- 👉 What are the Time Scales?
- 👉 How does all this Depend on Rotation?
- 👉 How does all this Depend on Metallicity?



Main Sources of  $^{44}\text{Ti}$ ,  $^{26}\text{Al}$ ,  $^{60}\text{Fe}$



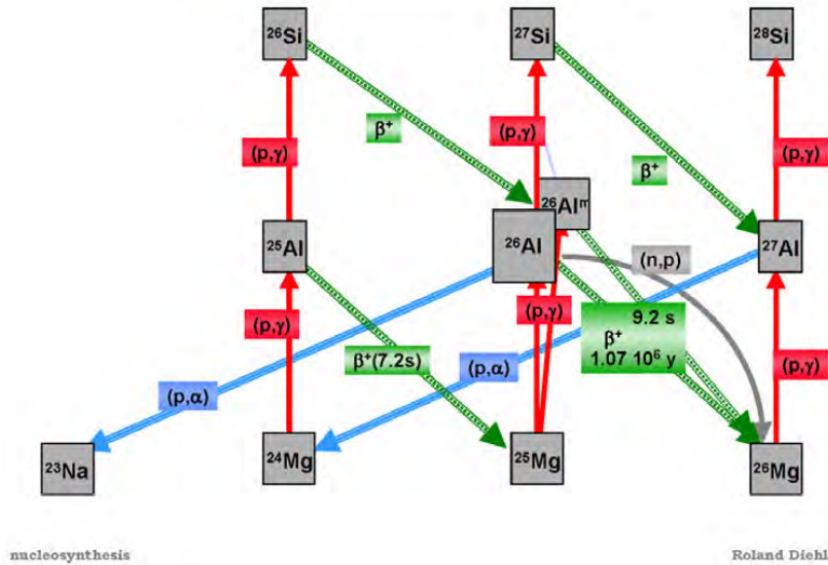


# Nuclear reactions to produce $^{26}\text{Al}$ , $^{60}\text{Fe}$

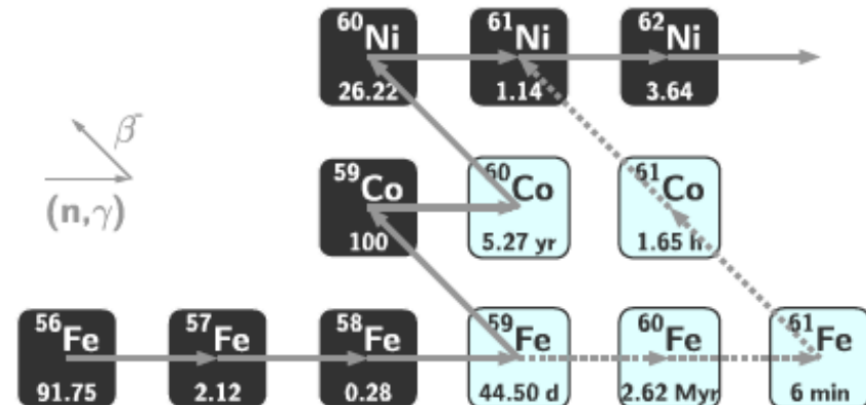


- The Na-Al-Mg cycle: p captures (H burning, +...)

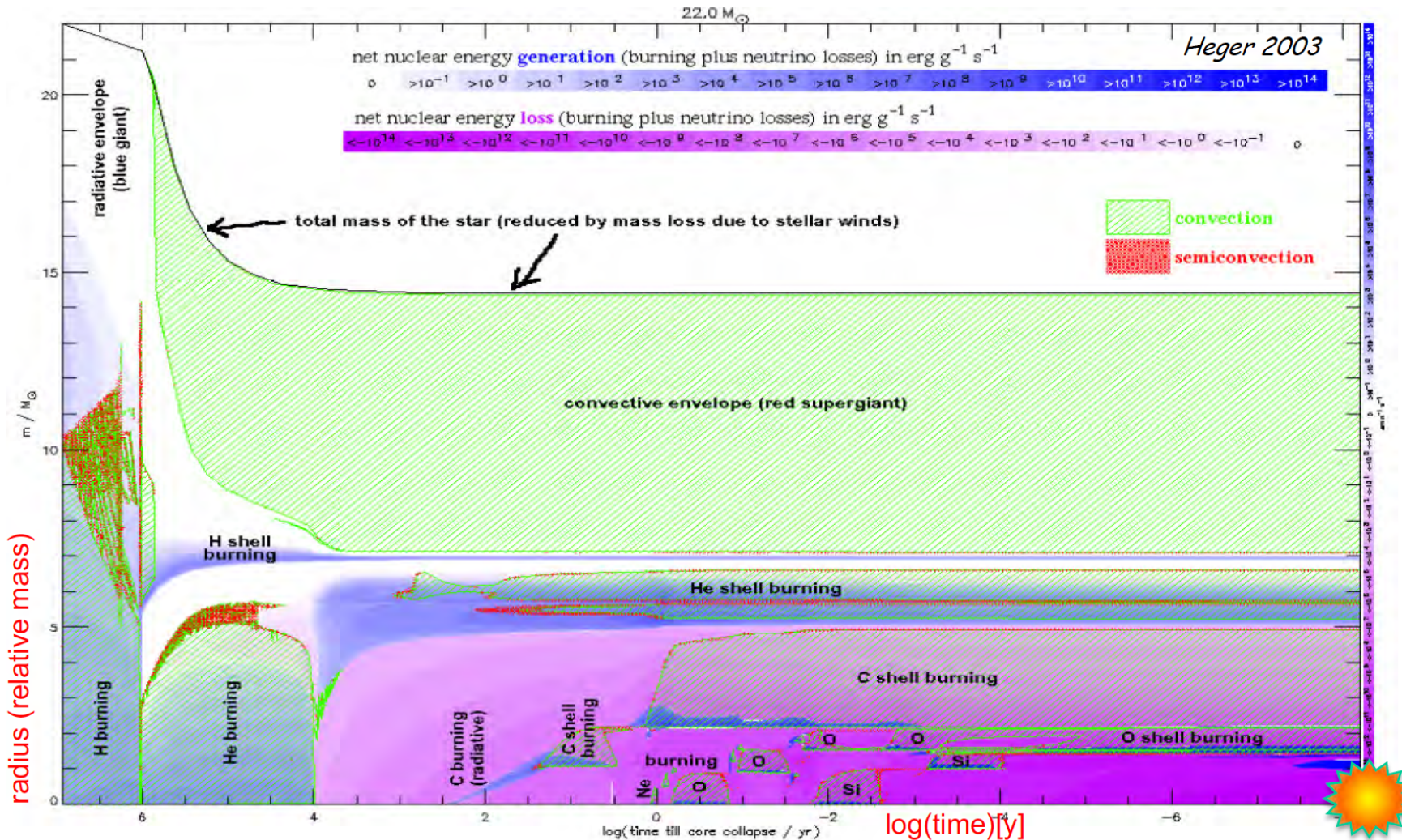
$^{26}\text{Al}$  Nucleosynthesis: Example of a Cosmic Reaction Network, Common for Intermediate-Mass Isotopes



- Neutron capture on Fe in massive-star shells



- Stars evolve into a complex interior structure

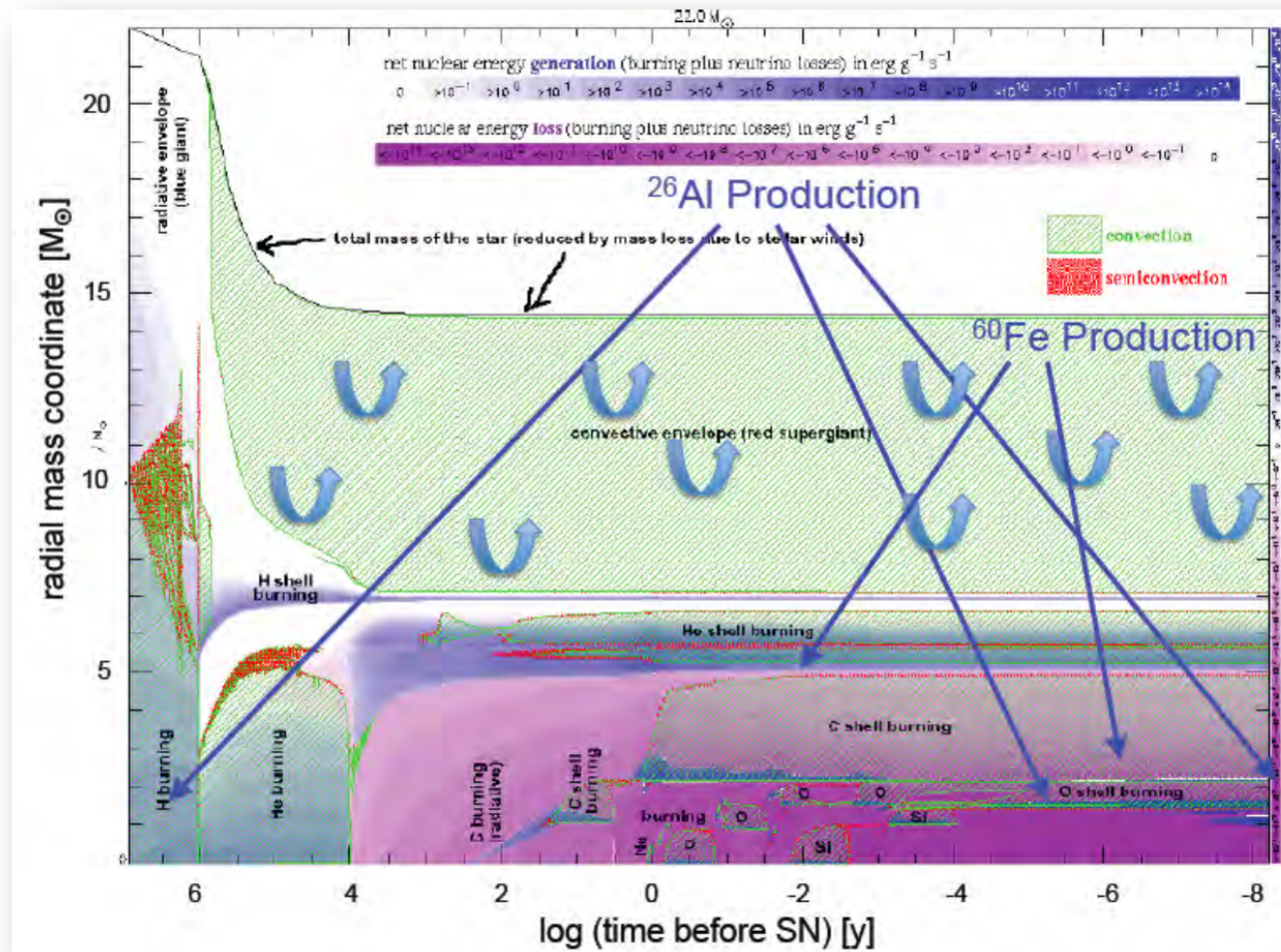




## Massive-Star Interiors

(adapted from Heger)

- ☆ Hydrostatic fusion
- ☆ WR wind release
- ☆ Late Shell burning
- ☆ Explosive fusion
- ☆ Explosive release



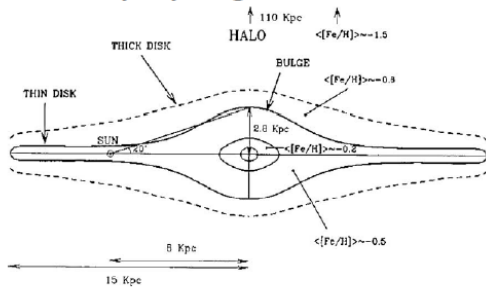


# Using the $^{26}\text{Al}$ Line to Characterize the Galaxy's SN Activity



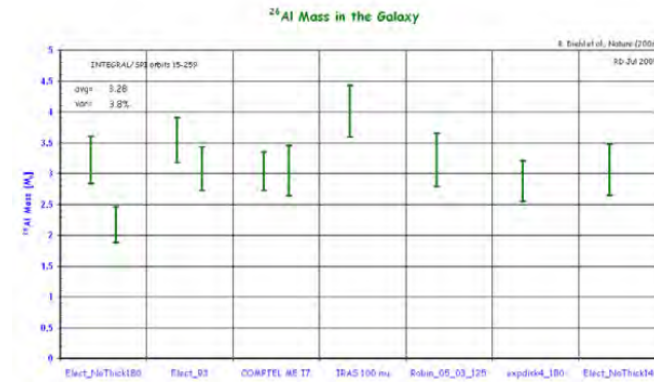
Measured Gamma-Ray Flux\*  
Galaxy Geometry

\*) better account for foreground emission



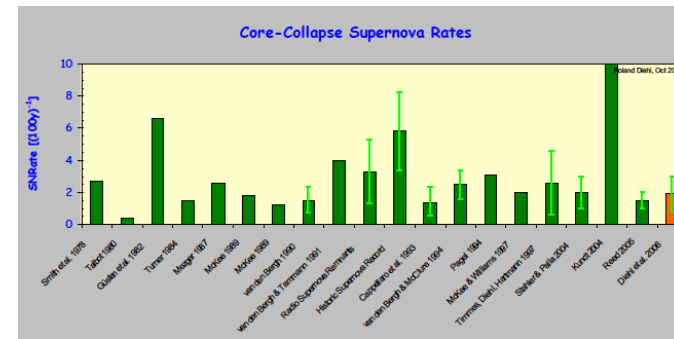
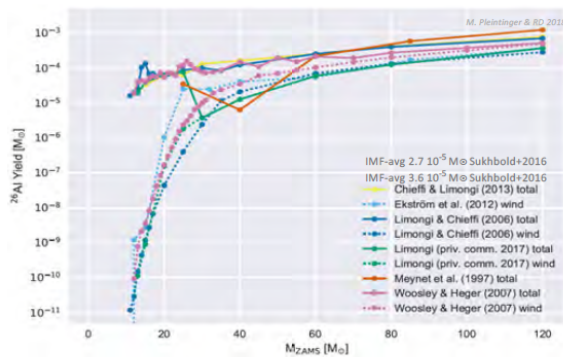
➤  $^{26}\text{Al}$  Mass in Galaxy =  $2.0 (\pm 0.3) M_{\odot}$

- Diehl et al., Nature 2006
- Diehl et al., A&A 2010\*
- Diehl et al., in prep. (2019)\*



$^{26}\text{Al}$  Yields per Star  
Stellar Mass Distribution

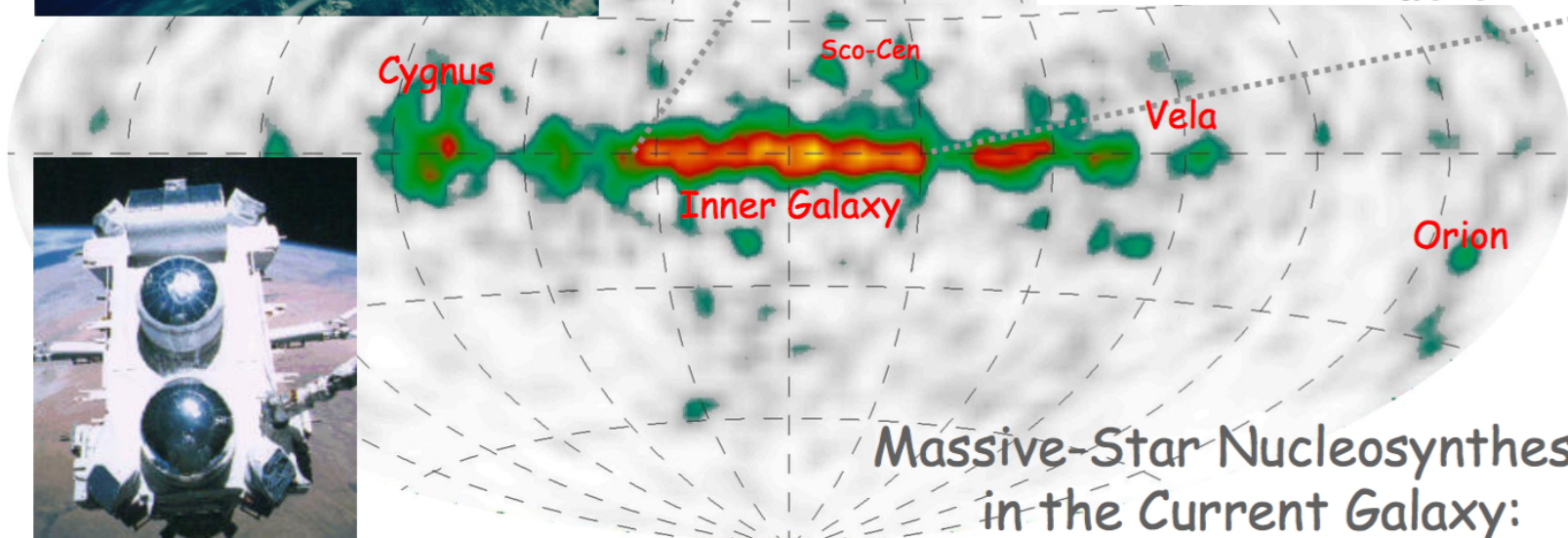
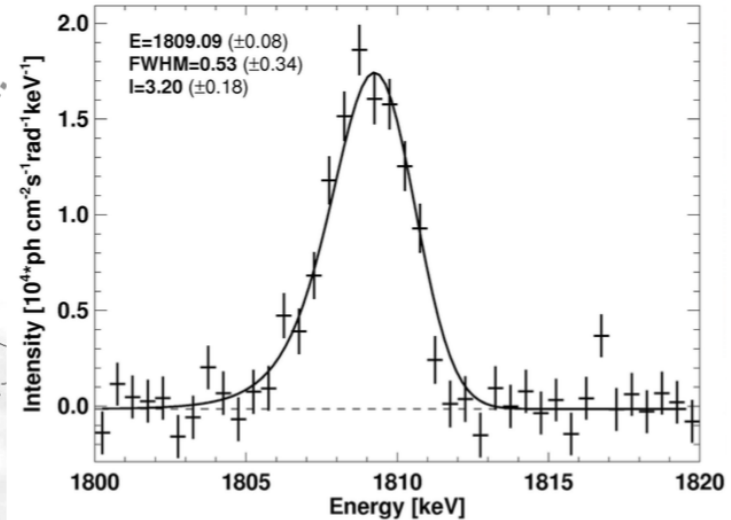
✓ cc-SN Rate =  $1.3 (\pm 0.6)$  per Century



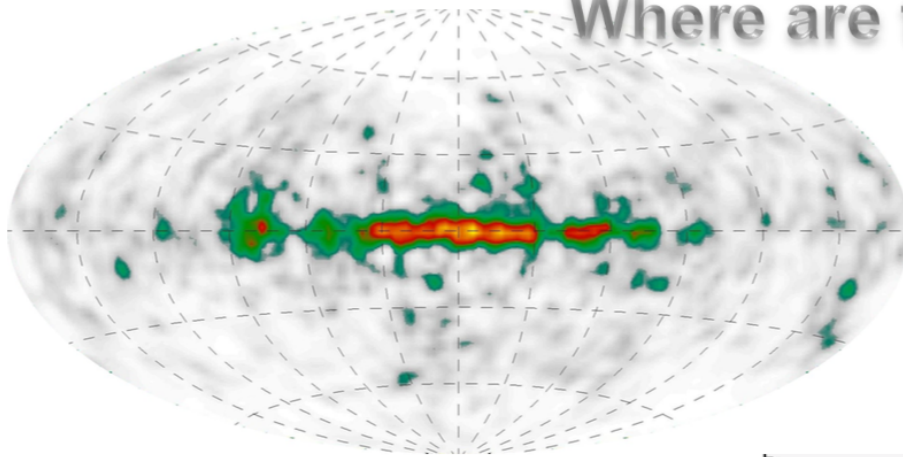
✓ Star Formation Rate =  $2.8 M_{\odot}/\text{yr}$



# $^{26}\text{Al}$ in our Galaxy: $\gamma$ -ray Image and Spectrum



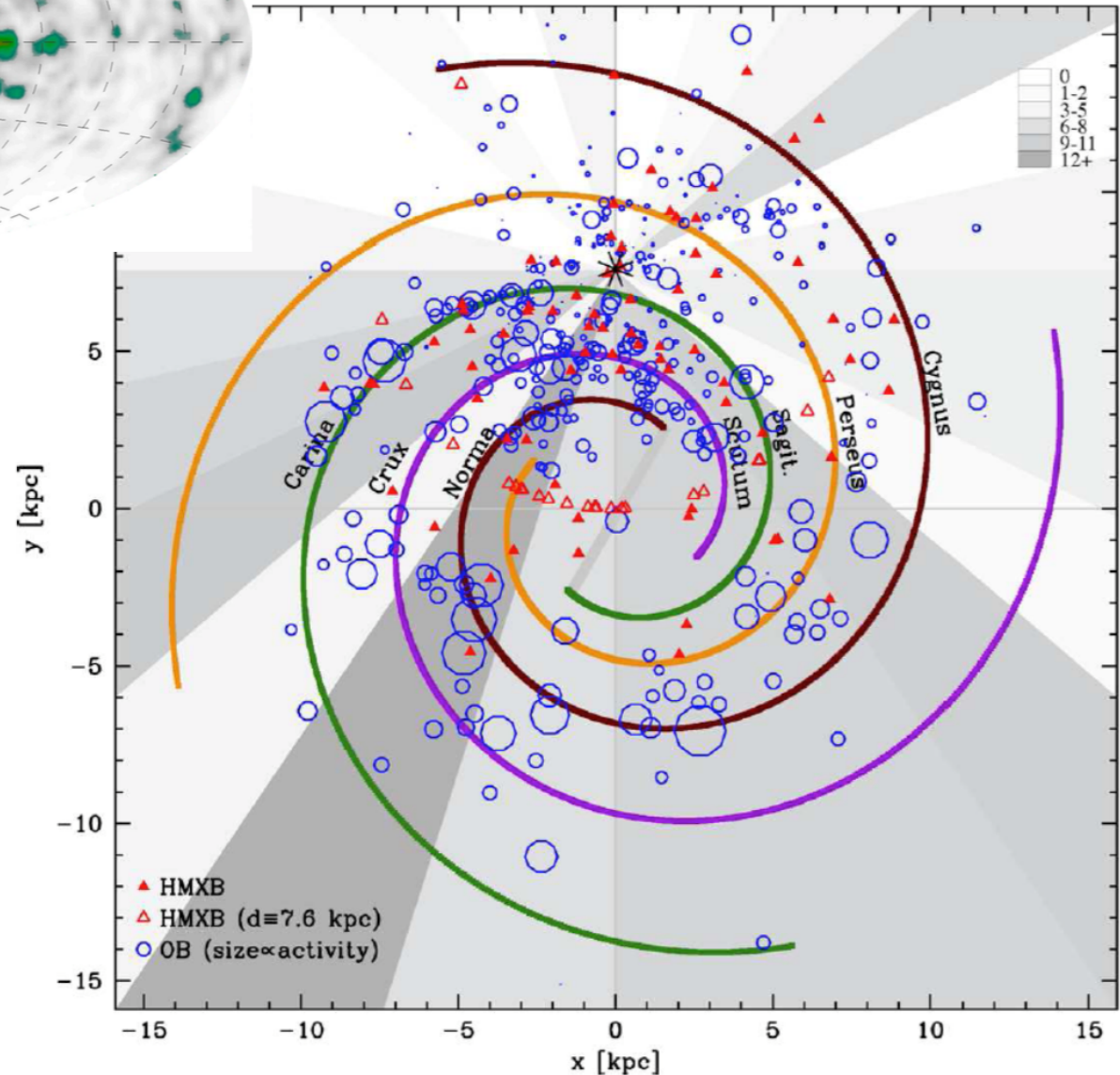
# Where are the Candidate Sources?



★ OB Associations,  
Massive Binaries, ...

👉 We Need to  
Account for  
Incomplete  
Knowledge:

- Biases in Time
- Biases in Radiation
- Biases in Space

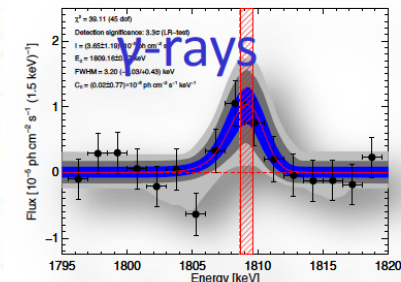
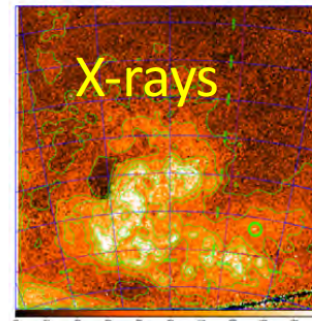
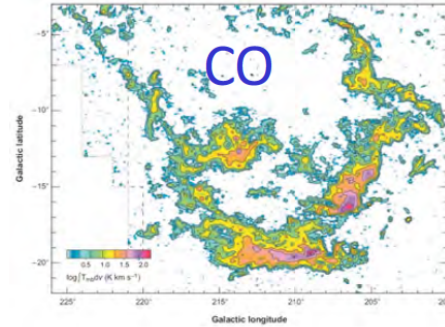
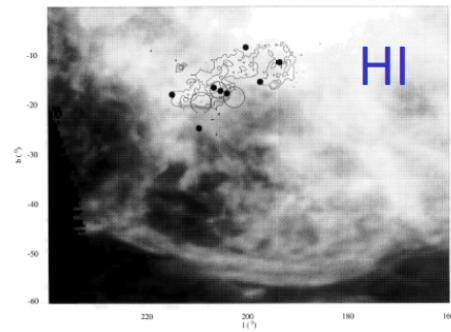
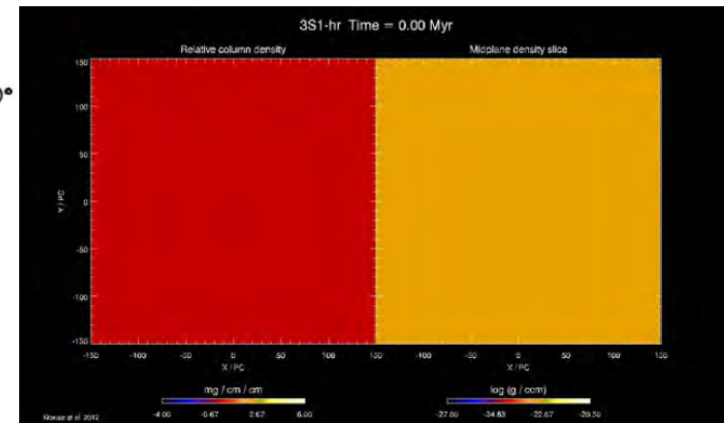
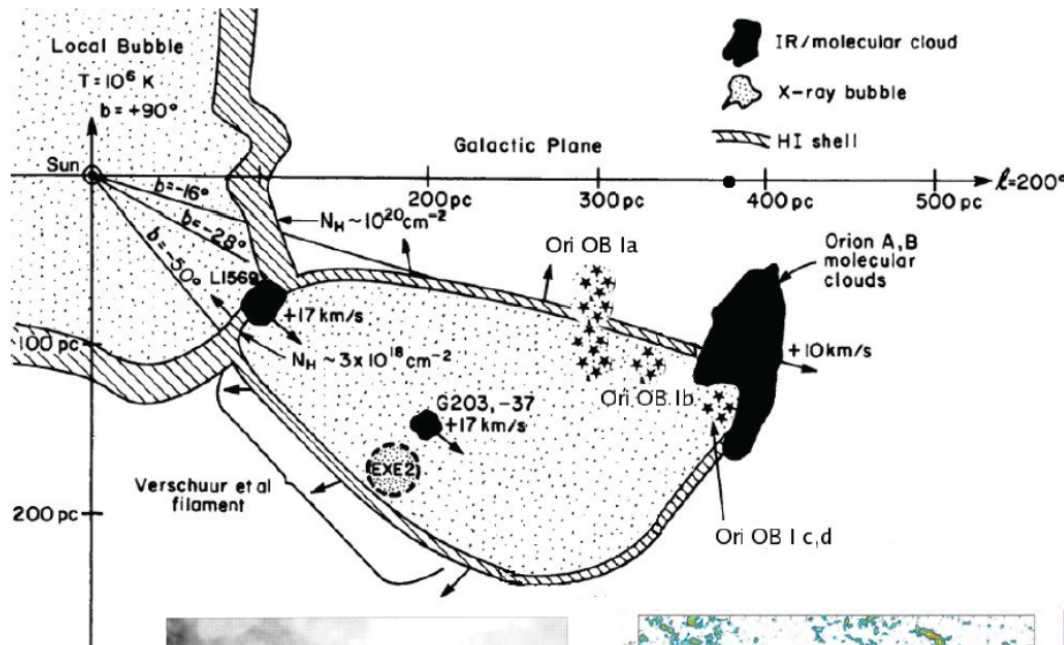




# Nucleosynthesis Ejecta and the Dynamic ISM

ISM is Driven by Stars and Supernovae → Ejecta in (Super-)Bubbles

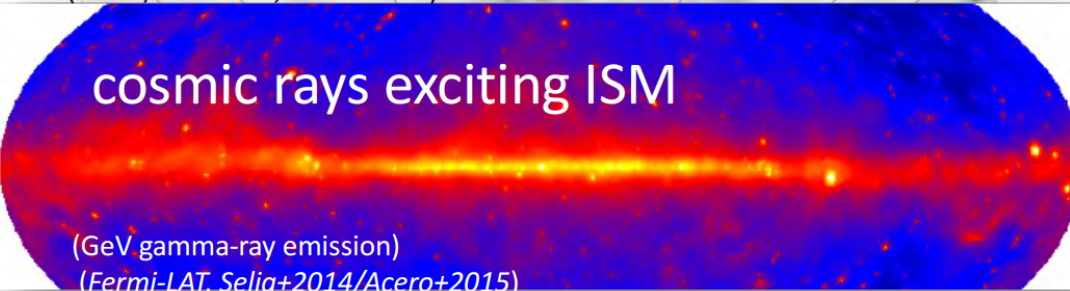
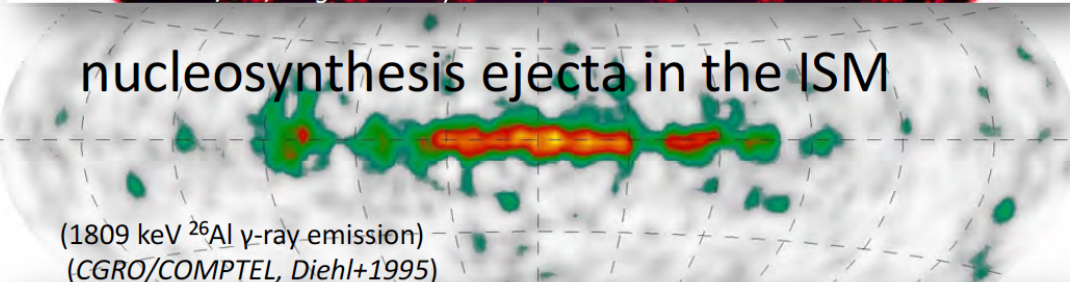
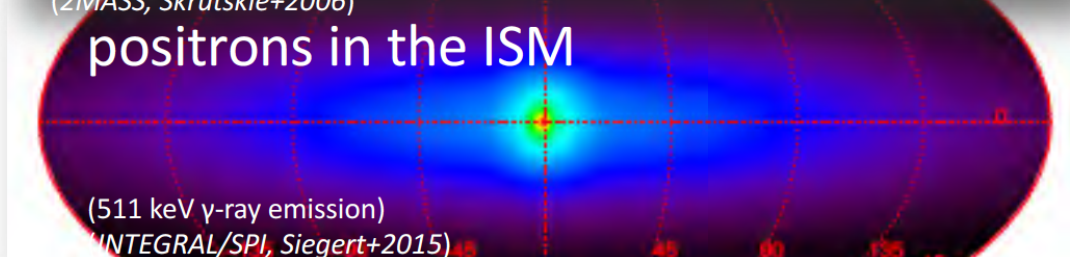
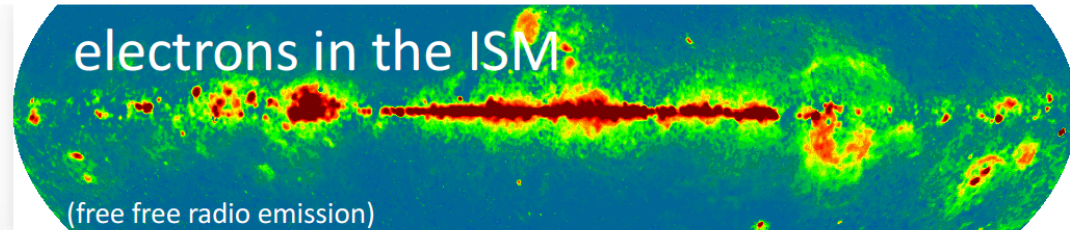
★ Study Multi-Messenger Observations, also through Simulations (here: Orion Region)





## $^{26}\text{Al}$ Radioactivity: Special Messengers

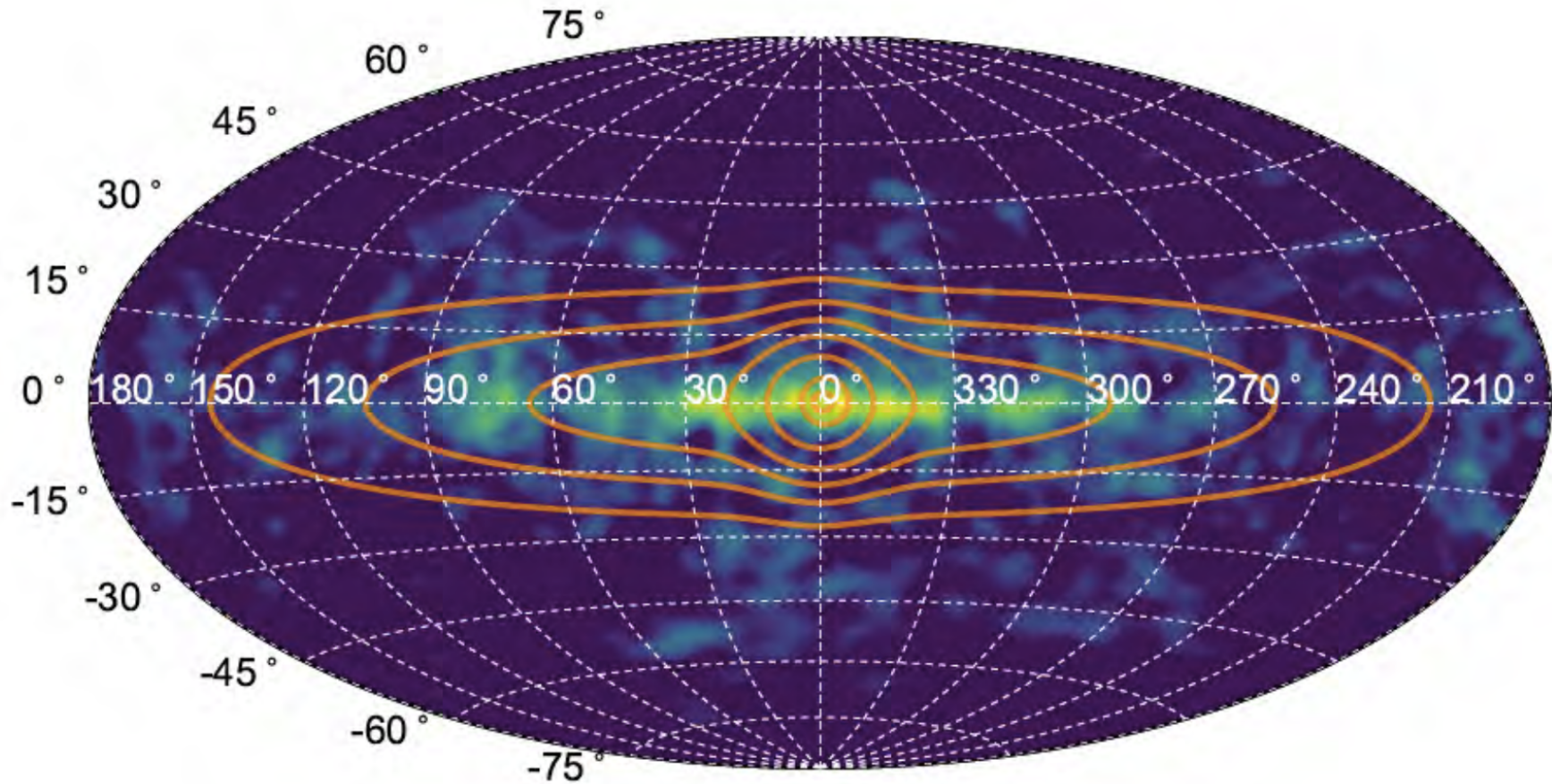
- Radioactivity provides a clock
- $^{26}\text{Al}$  radioactivity gamma rays trace nucleosynthesis ejecta over  $\sim$ few Myrs
- Radioactive emission is independent of density, ionisation states, ...





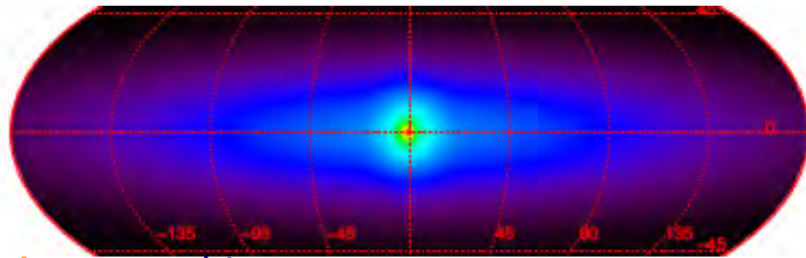


# $^{26}\text{Al}$ radioactivity versus positron annihilation

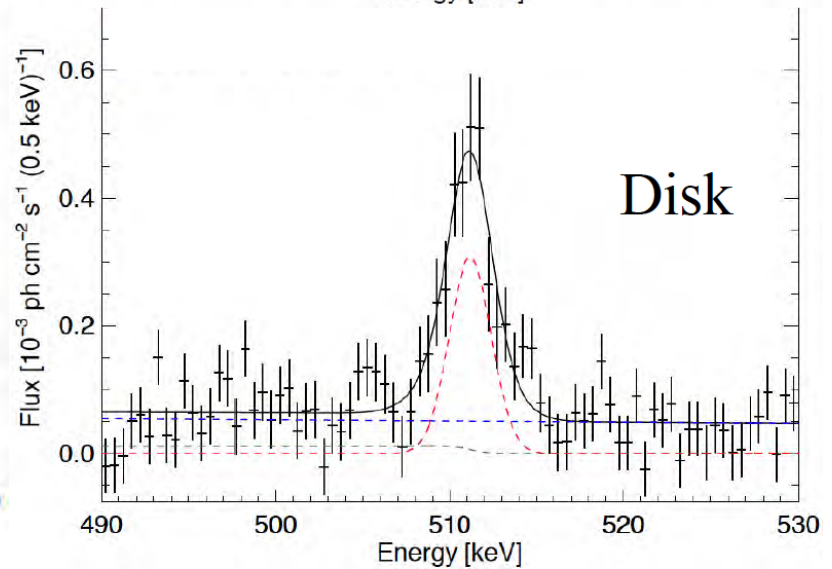
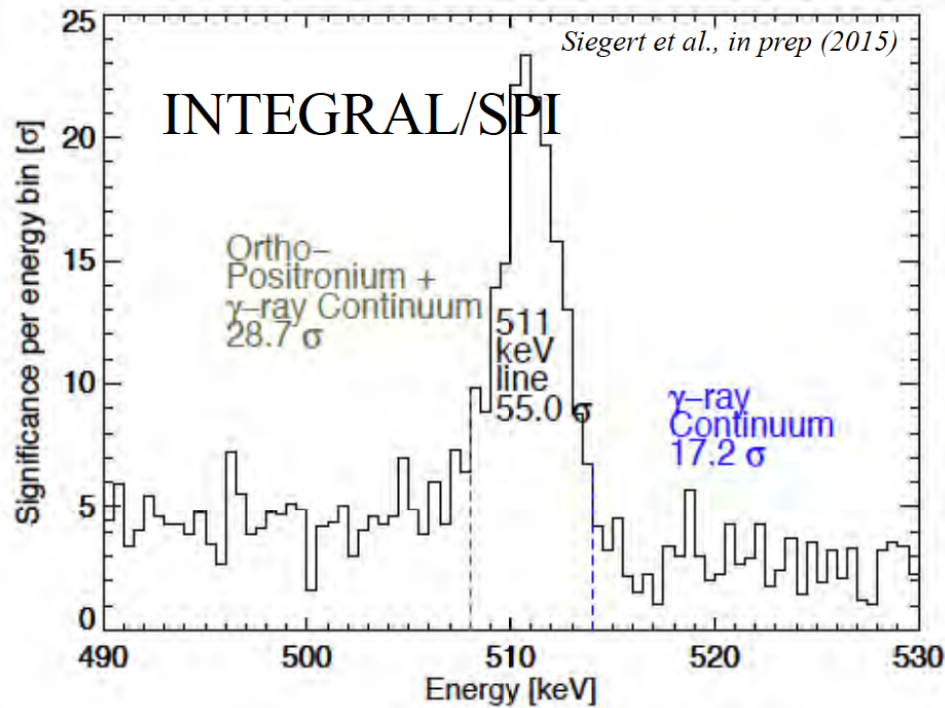
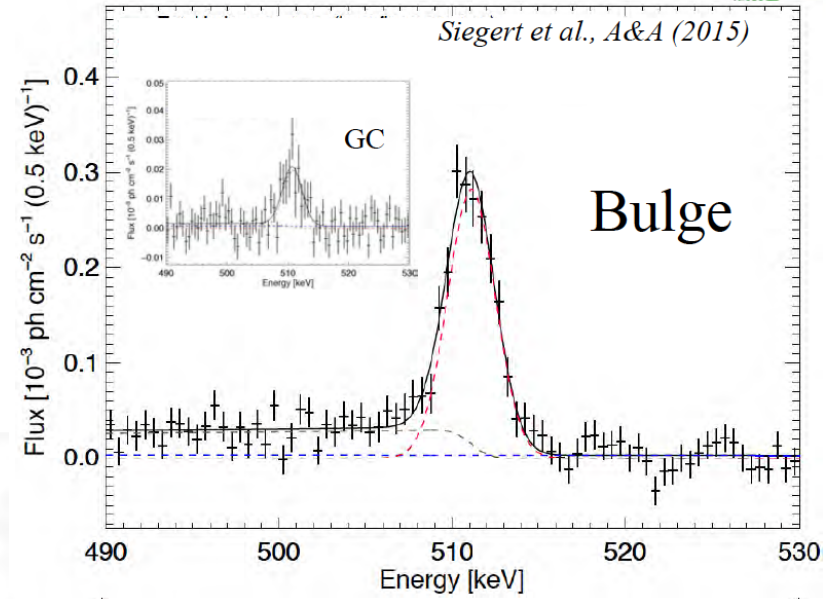




# Insights from spectral details?



★ Derive/discriminate spectra from different regions





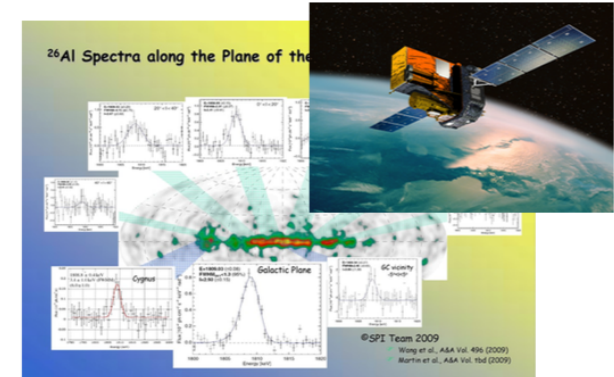
# Lessons from Cosmic Radioactivities Summary

## ★ Radioactivity provides a unique / different astronomical tool

- ☞ Intensity change only due to radioactive decay
- ☞ Thermodynamic gas state unimportant

## ★ Supernova interiors can be explored

- ☞ SNIa brightness evolution and  $^{56}\text{Ni}$  yield calibration
- ☞ Core collapse evolution into an explosion with  $^{56}\text{Ni}$  and  $^{44}\text{Ti}$  production

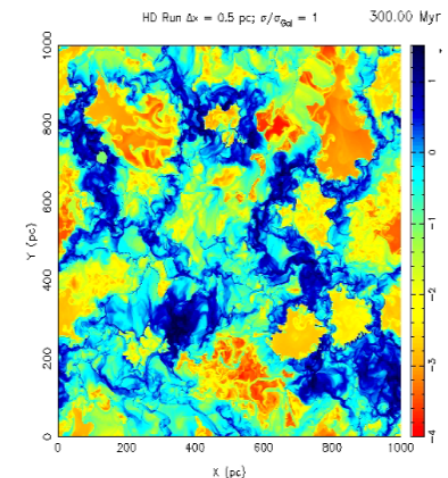


## ★ Massive-star shell structure and evolution can be explored

- ☞  $^{26}\text{Al}$  production in core H burning and late shell burning
- ☞  $^{60}\text{Fe}$  production in C and He shells

## ★ Chemical evolution uncertainties can be explored

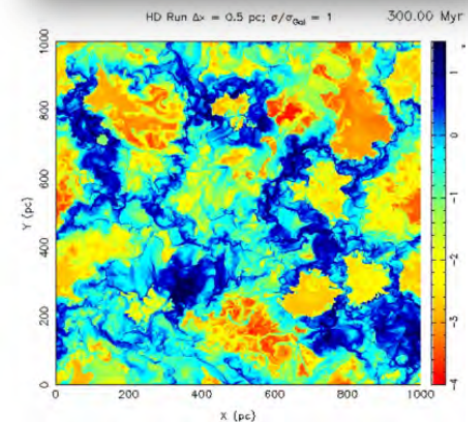
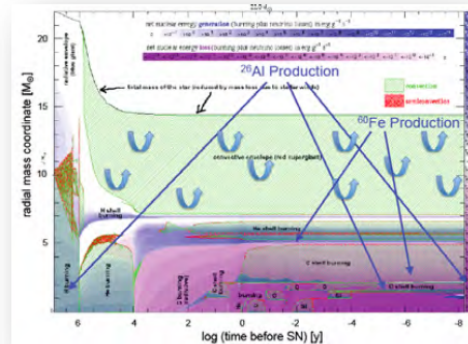
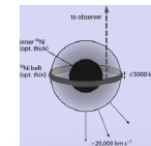
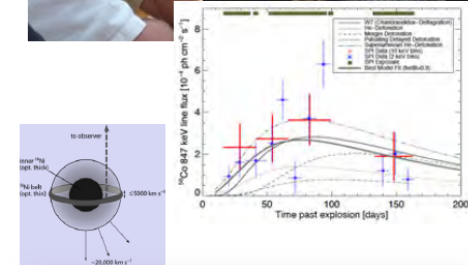
- ☞ ISM state and dynamics around massive-star regions
- ☞ Nucleosynthesis ejecta recycling times





# Cosmic Radioactivities Summary

- ★ Radioactivity  $\gamma$ -rays provide a unique / different view
  - ☞ Yield constraints for SNe and Novae, Independent of complexity from unfolding of the explosion
  - ☞ Radioactivity traces diluted ejecta at late phases
- ★ SNIa  $^{56}\text{Ni}$  and how the explosion generates SN light
  - ☞ SN2014J reveals its  $^{56}\text{Ni}, ^{56}\text{Co}$  irregularly  $\rightarrow$  3D effects?
- ★ ccSupernova  $^{44}\text{Ti}$  demonstrates SN asymmetries
  - ☞ Only Some SN Eject  $^{44}\text{Ti}$ , but then much, and clumpy
- ★ Massive-star shell structure & evolution tests:  $^{26}\text{Al}, ^{60}\text{Fe}$ 
  - ☞  $^{26}\text{Al}$  as a tool: understand groups of massive stars (Mys)
  - ☞ How much  $^{60}\text{Fe}$  from n captures in C and He shells?
- ★ ISM in the Galaxy: Role of superbubbles;  $e^+$  sources
  - ☞  $^{26}\text{Al}$  spreads into large (super)bubbles
  - ☞  $e^+$  sources are a variety & puzzle; incl  $\mu\text{QSOs}$





Astrofisica Nucleare e Subnucleare  
Dark Matter Searches



## ISAPP2013 Stockholm

from 29 July 2013 to 06 August 2013

Djurönäset Conference Centre, Stockholm region

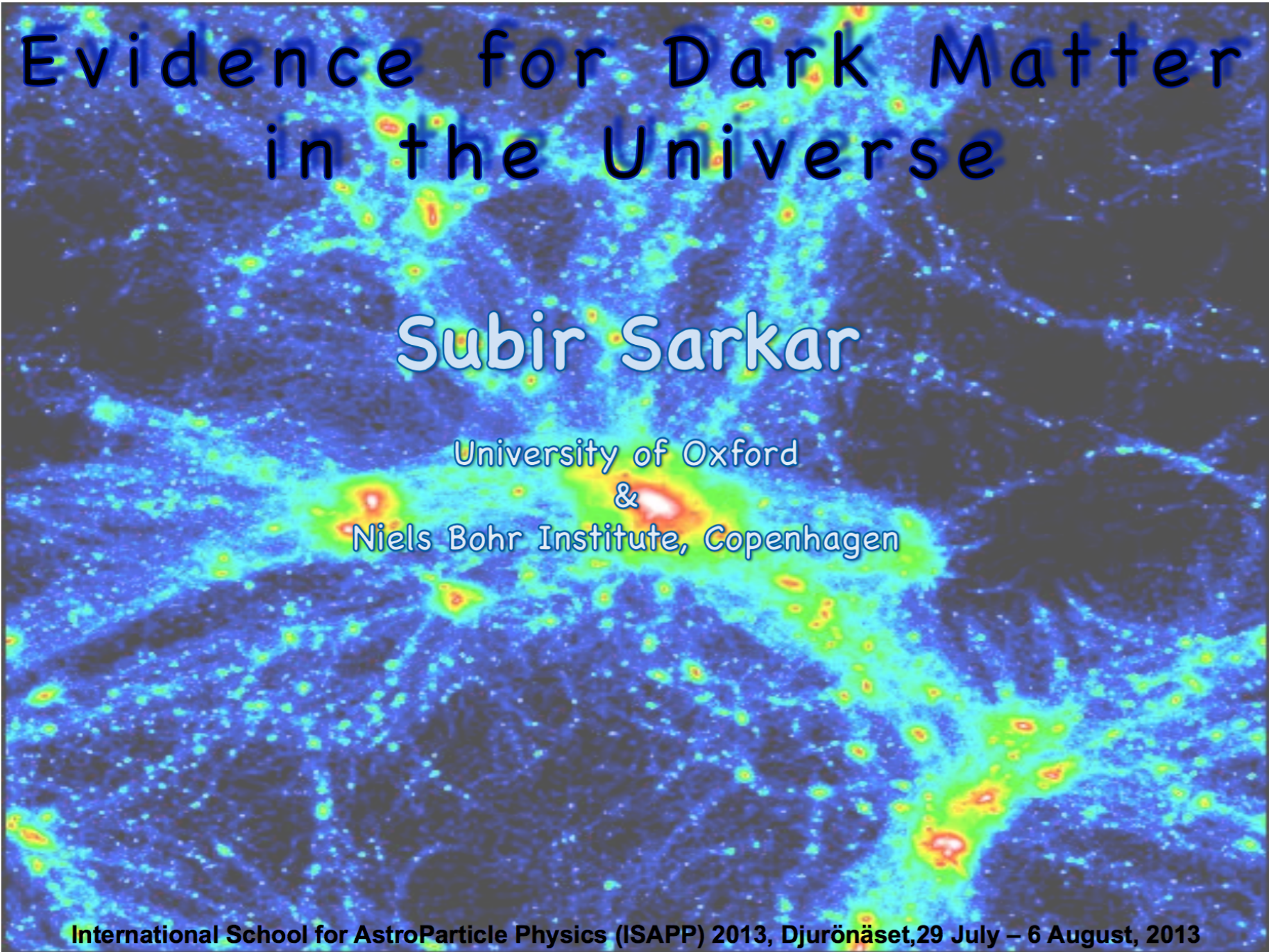


- Overview
- Presentation slides and additional material
- Schedule
- Circular #1
- Circular #2
- Local Organizing Committee
- Posters
- Poster listing
- Group picture
- Photo gallery
- List of participants

[Home](#)

### The International School for AstroParticle Physics (ISAPP) 2013, Djurönäset: Dark Matter Composition and Detection, July 29 to August 6, 2013



A Cosmic Microwave Background (CMB) fluctuation map showing temperature variations across the sky. The map uses a color scale from blue (cooler) to red (warmer), with a prominent horizontal band of higher temperature (yellow and red) in the center. The background is dark blue with scattered smaller fluctuations.

# Evidence for Dark Matter in the Universe

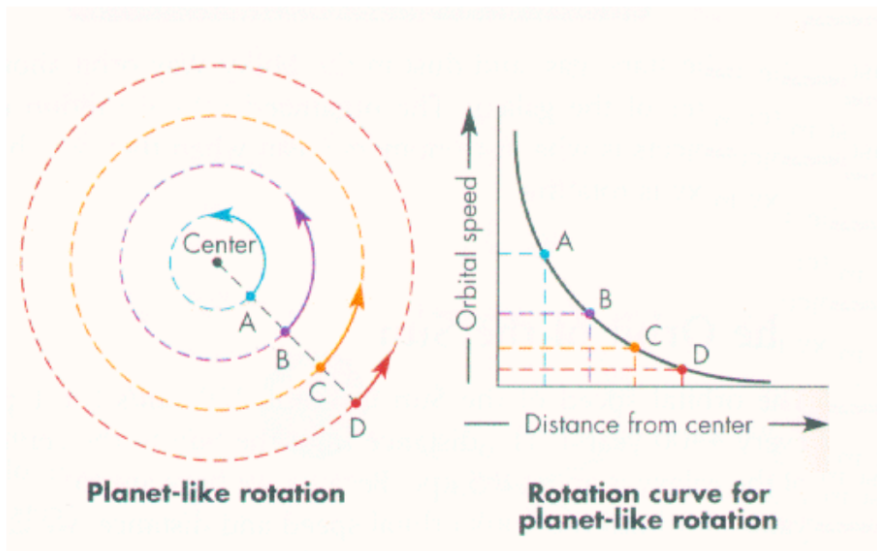
Subir Sarkar

University of Oxford  
&  
Niels Bohr Institute, Copenhagen

International School for AstroParticle Physics (ISAPP) 2013, Djurönäset, 29 July – 6 August, 2013



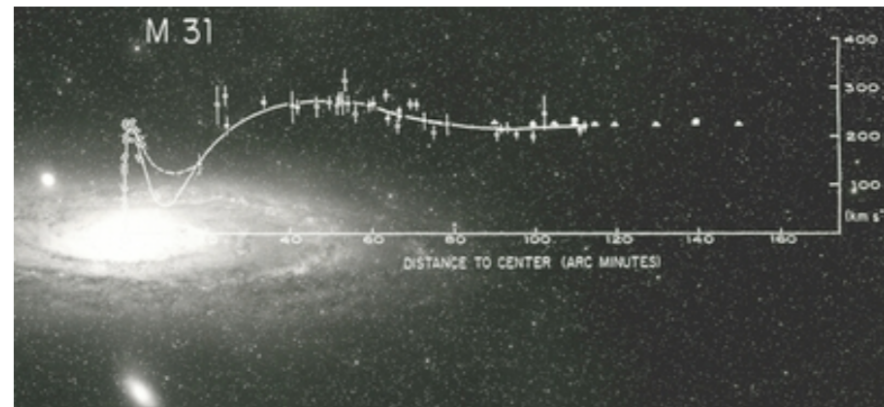
## The modern saga of dark matter starts with the rotation curves of spiral galaxies



At large distances from the centre, beyond the edge of the visible galaxy, the velocity would be expected to fall as  $1/\sqrt{r}$  if most of the matter is contained in the optical disc

$$v_{\text{circ}} = \sqrt{\frac{G_N M(< r)}{r}}$$

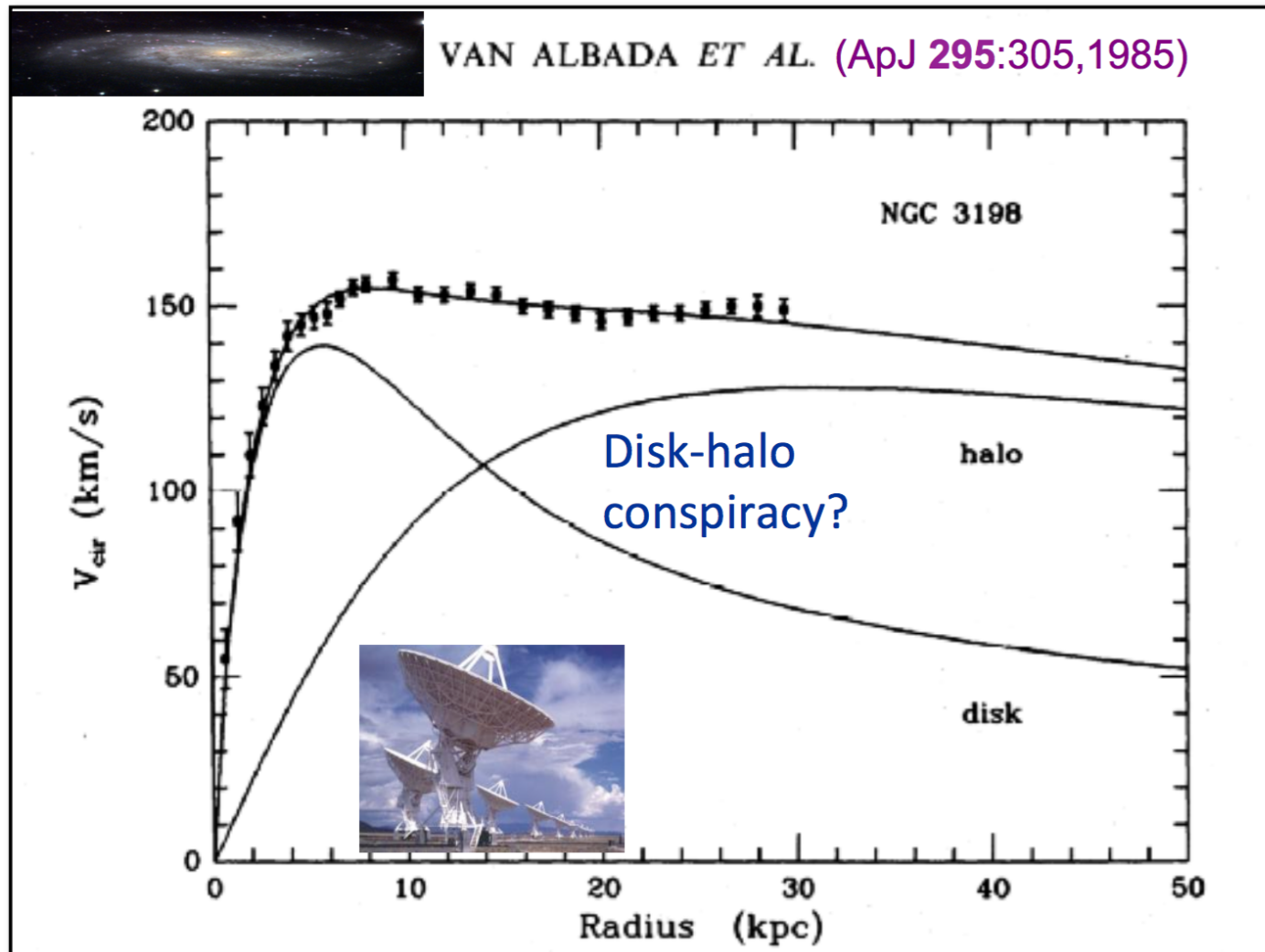
... but Rubin & Ford (ApJ 159: 379,1970) observed that the rotational velocity remains  $\sim$ constant in Andromeda, implying the existence of an **extended dark halo** (earlier Babcock 1939, later Roberts & Whitehurst 1975, Bosma 1978)



$$v_{\text{circ}} \sim \text{constant} \quad \Rightarrow \quad M(< r) \propto r \quad \Rightarrow \quad \rho \propto 1/r^2$$



The really compelling evidence for extended halos of dark matter came from observations in the 1980's of 21-cm line emission from neutral hydrogen (orbiting around Galaxy at  $\sim$ constant velocity) well *beyond* the visible disk



**Cored isothermal sphere:**  $\rho_{\text{isothermal}} = \frac{\rho_s}{\left(1 + \frac{r}{r_s}\right)^2}$

**Navarro-Frenk-White profile:**  
(indicated by CDM simulations)  $\rho_{\text{NFW}} = \frac{\rho_s}{\frac{r}{r_s} \left(1 + \frac{r}{r_s}\right)^2}$

**Burkert profile:**  
(fits observations better)  $\rho_{\text{Burkert}} = \frac{\rho_s}{\left(1 + \frac{r}{r_s}\right) \left[1 + \left(\frac{r}{r_s}\right)^2\right]}$

**Hernquist profile:**  $\rho_{\text{Hernquist}} = \rho_s \left(\frac{r}{r_s}\right)^{-\gamma} \left[1 + \left(\frac{r}{r_s}\right)^\alpha\right]^{\frac{\gamma-\beta}{\alpha}}$

where  $r_s$  is a characteristic scale and  $\alpha$  controls the sharpness of the transition from the inner slope  $\lim_{r \rightarrow 0} d \ln(\rho) / d \ln(r) = -\gamma$  to the outer slope  $\lim_{r \rightarrow \infty} d \ln(\rho) / d \ln(r) = -\beta$

... e.g. the NFW profile corresponds to choosing  $\alpha = 1, \beta = 3, \gamma = 1$ , whereas a cored isothermal profile corresponds to choosing  $\alpha = 1, \beta = 2, \gamma = 0$ , and a Moore profile is obtained by setting  $\alpha = 1.5, \beta = 2, \gamma = 1.5$  *et cetera*

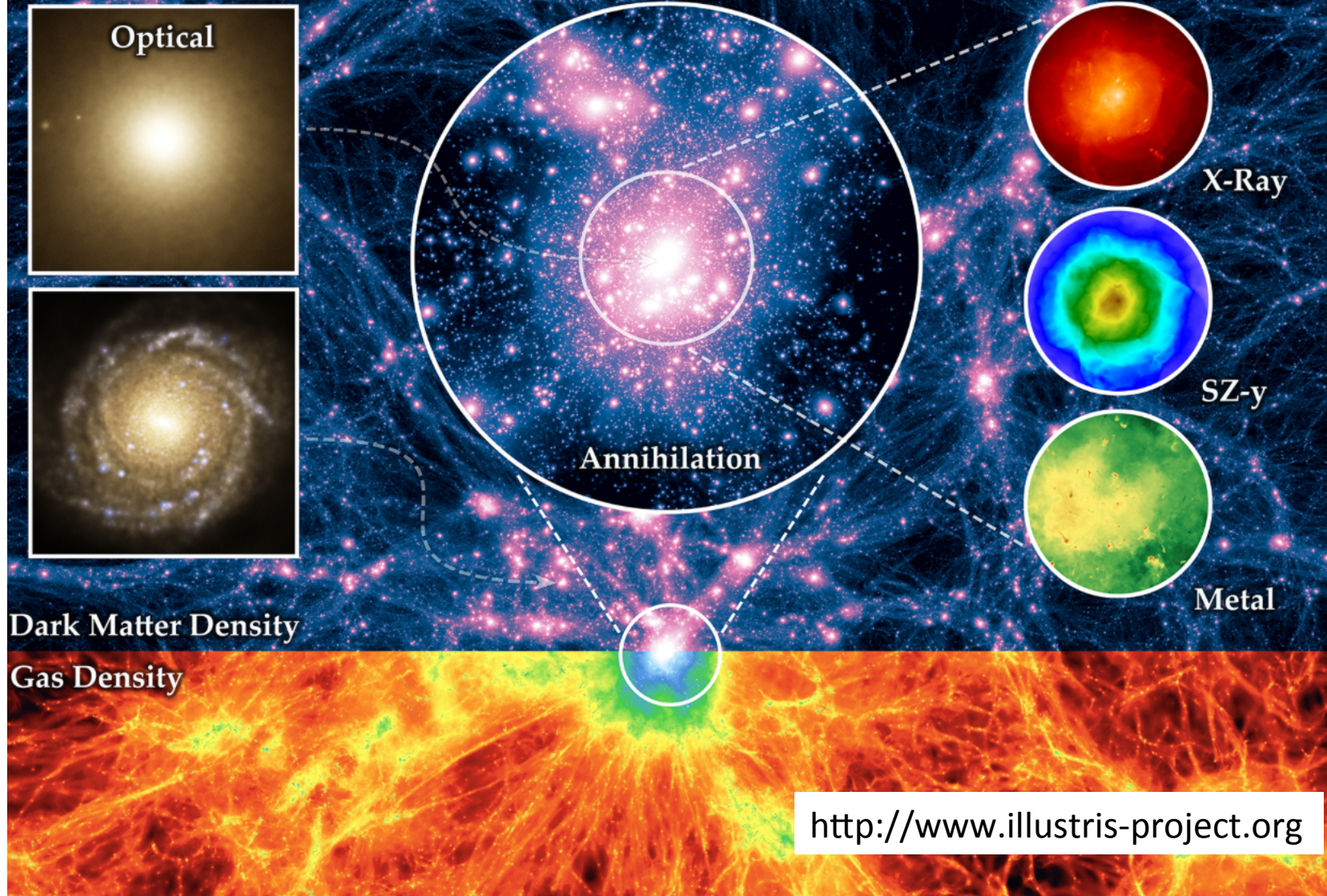
**Einasto profile:**  $\rho_{\text{Einasto}} = \rho_s \exp \left\{ -d_n \left[ \left(\frac{r}{r_s}\right)^{1/n} - 1 \right] \right\}$

where  $d_n$  is defined such that  $\rho_s$  is the density at the radius  $r_s$  which encloses half the total mass



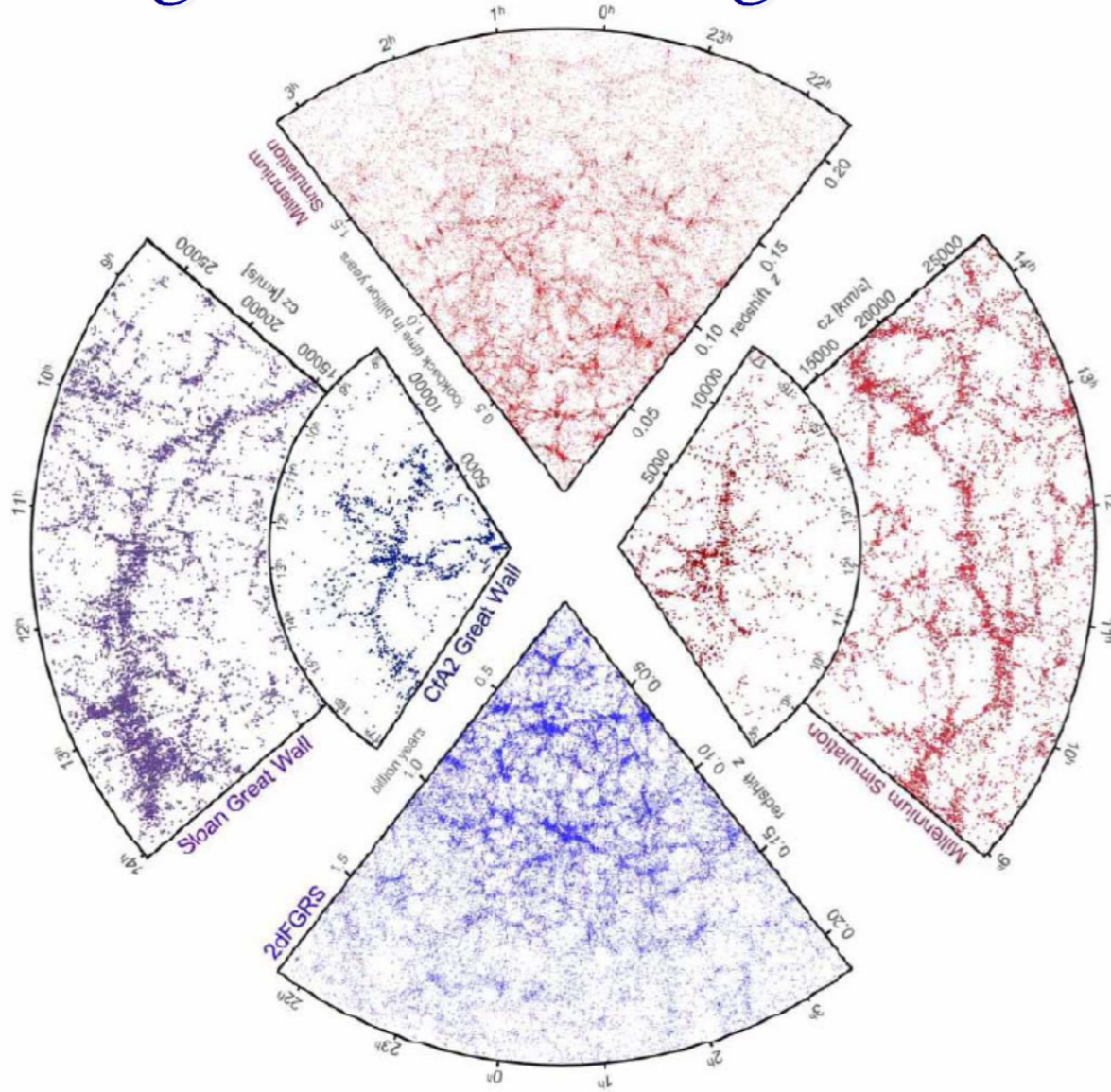
# The Illustris Simulation

M. Vogelsberger · S. Genel · V. Springel · P. Torrey · D. Sijacki · D. Xu · G. Snyder · S. Bird · D. Nelson · L. Hernquist





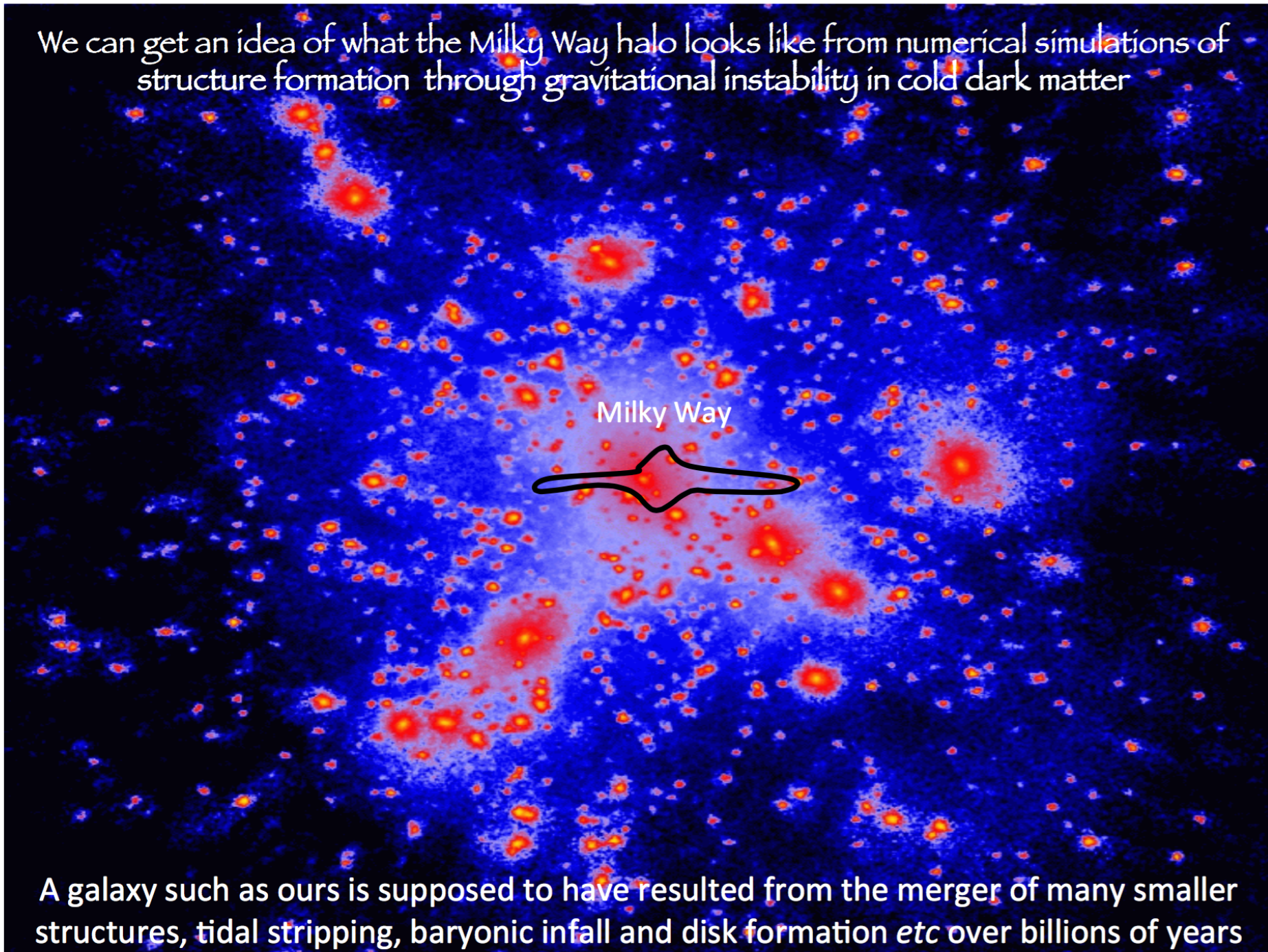
Such numerical simulations provide a pretty good match to the observed large-scale structure of galaxies in the universe



Springel, Frenk & White, Nature 440:1137,2006



We can get an idea of what the Milky Way halo looks like from numerical simulations of structure formation through gravitational instability in cold dark matter

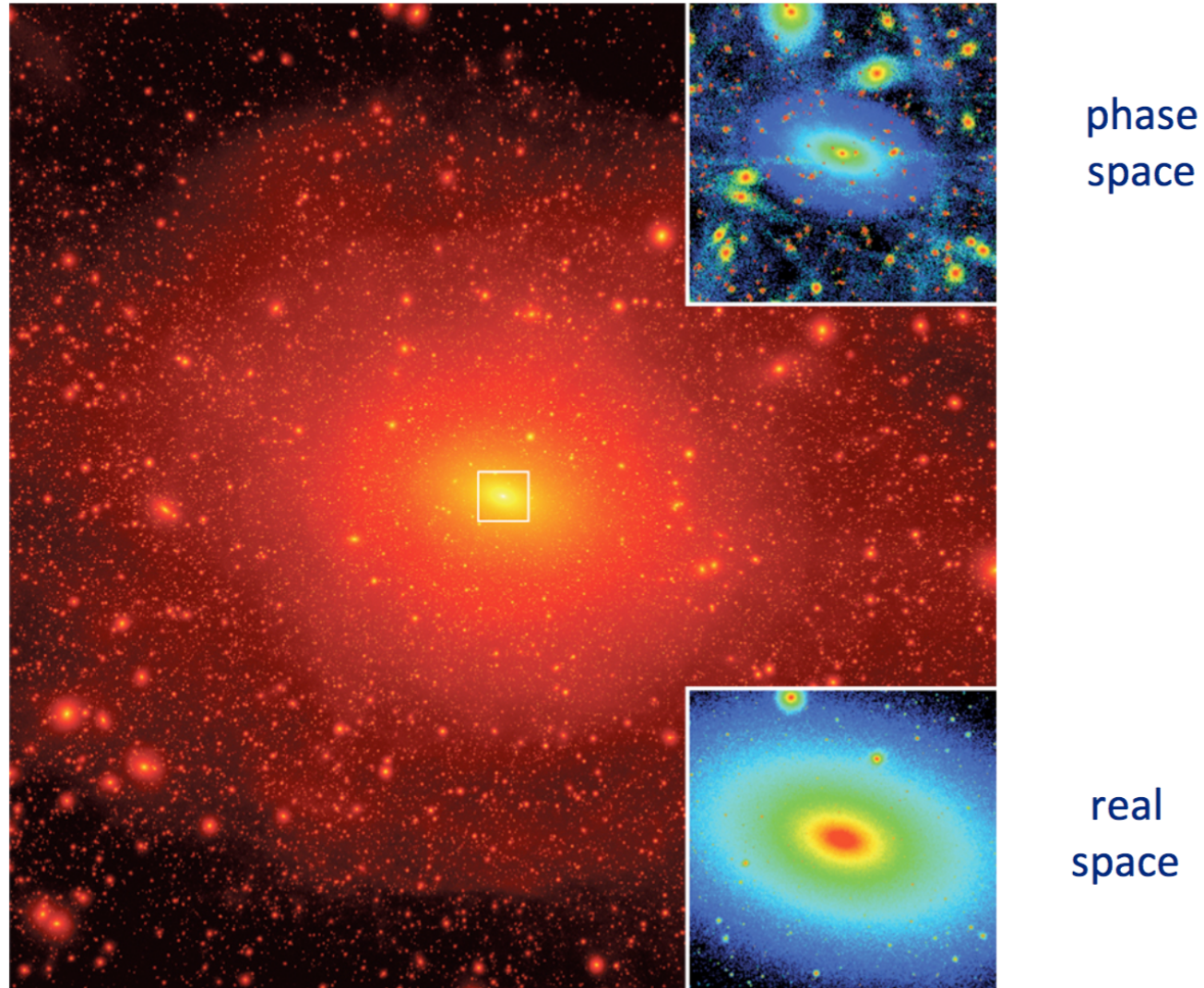


A galaxy such as ours is supposed to have resulted from the merger of many smaller structures, tidal stripping, baryonic infall and disk formation etc over billions of years



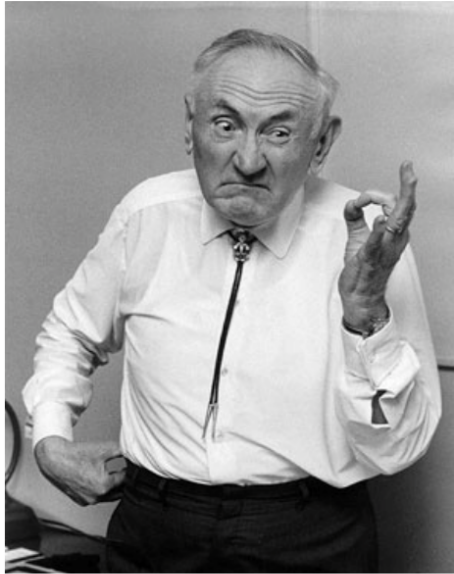
So the phase space structure of the dark halo is pretty complicated ...

Via Lactea II projected dark matter (squared-) density map



Diemand, Kuhlen, Madau, Zemp, Moore, Potter & Stadel, Nature **454**:735,2008





Fritz Zwicky (1933) measured the velocity dispersion in the Coma cluster to be as high as 1000 km/s

$$\Rightarrow M/L \sim O(100) M_{\odot}/L_{\odot}$$

“... If this overdensity is confirmed we would arrive at the astonishing conclusion that dark matter is present (in Coma) with a much greater density than luminous matter”

Virial Theorem:

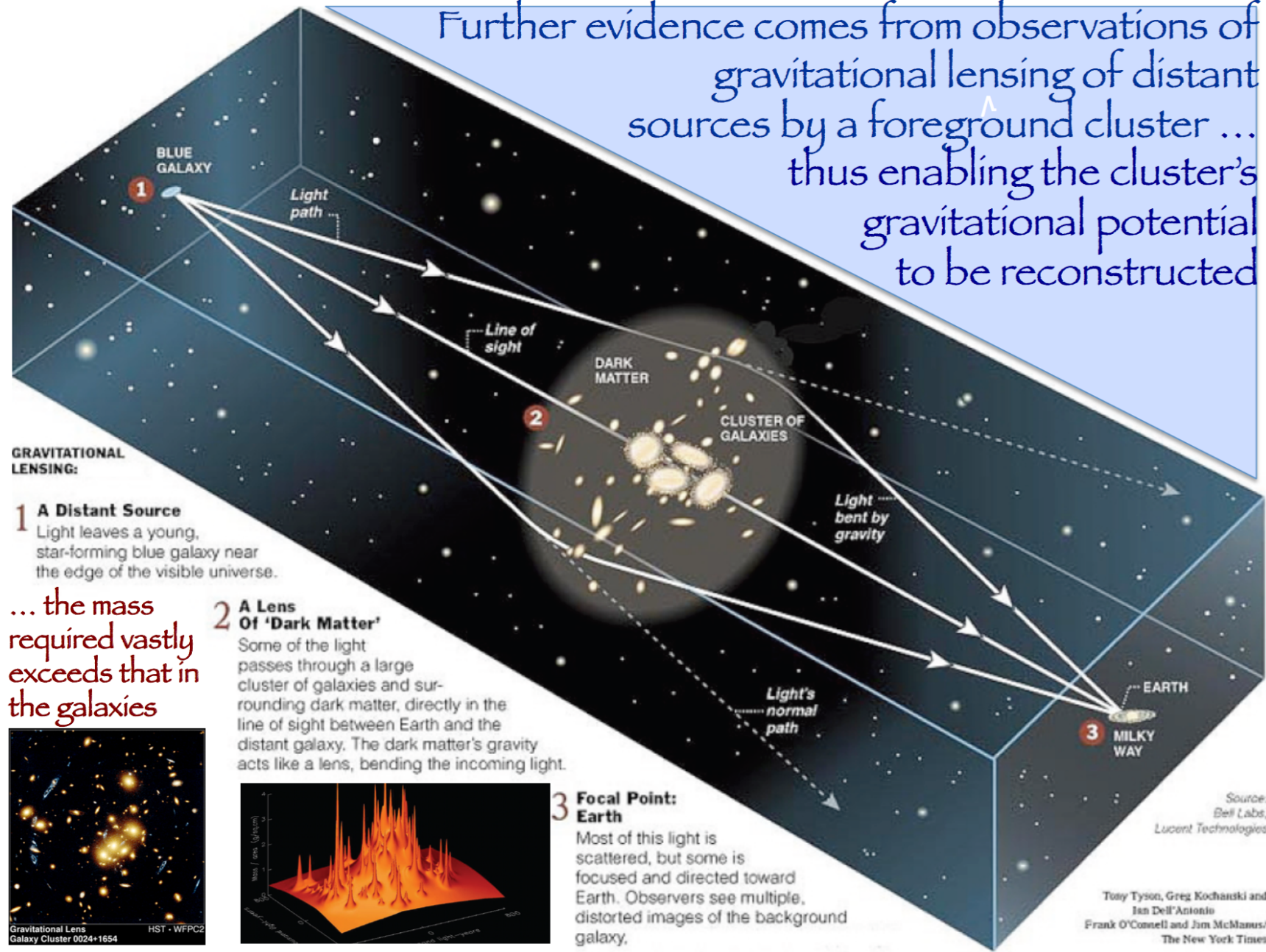
$$\langle V \rangle + 2\langle K \rangle = 0$$

$$V = -\frac{N^2}{2} G_N \frac{\langle m^2 \rangle}{\langle r \rangle}, \quad K = N \frac{\langle mv^2 \rangle}{2}$$

$$M = N \langle m \rangle \sim \frac{2 \langle r \rangle \langle v^2 \rangle}{G_N} \gg \sum m_{\text{galaxies}}$$



Further evidence comes from observations of gravitational lensing of distant sources by a foreground cluster ... thus enabling the cluster's gravitational potential to be reconstructed



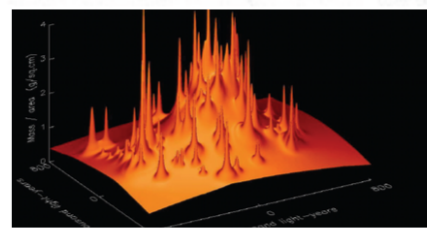
**GRAVITATIONAL LENSING:**

**1 A Distant Source**  
Light leaves a young, star-forming blue galaxy near the edge of the visible universe.

... the mass required vastly exceeds that in the galaxies



**2 A Lens Of 'Dark Matter'**  
Some of the light passes through a large cluster of galaxies and surrounding dark matter, directly in the line of sight between Earth and the distant galaxy. The dark matter's gravity acts like a lens, bending the incoming light.



**3 Focal Point: Earth**  
Most of this light is scattered, but some is focused and directed toward Earth. Observers see multiple, distorted images of the background galaxy.

Source: Bell Labs, Lucent Technologies

Tony Tyson, Greg Kochanski and Jan Dell'Antonio  
Frank O'Connell and Jim McManus/  
The New York Times



The Chandra picture of the ‘bullet cluster’ (1E 0657-558) shows that the X-ray emitting baryonic matter is *displaced* from the galaxies and the dark matter (inferred through gravitational lensing) ... convincing evidence of dark matter?

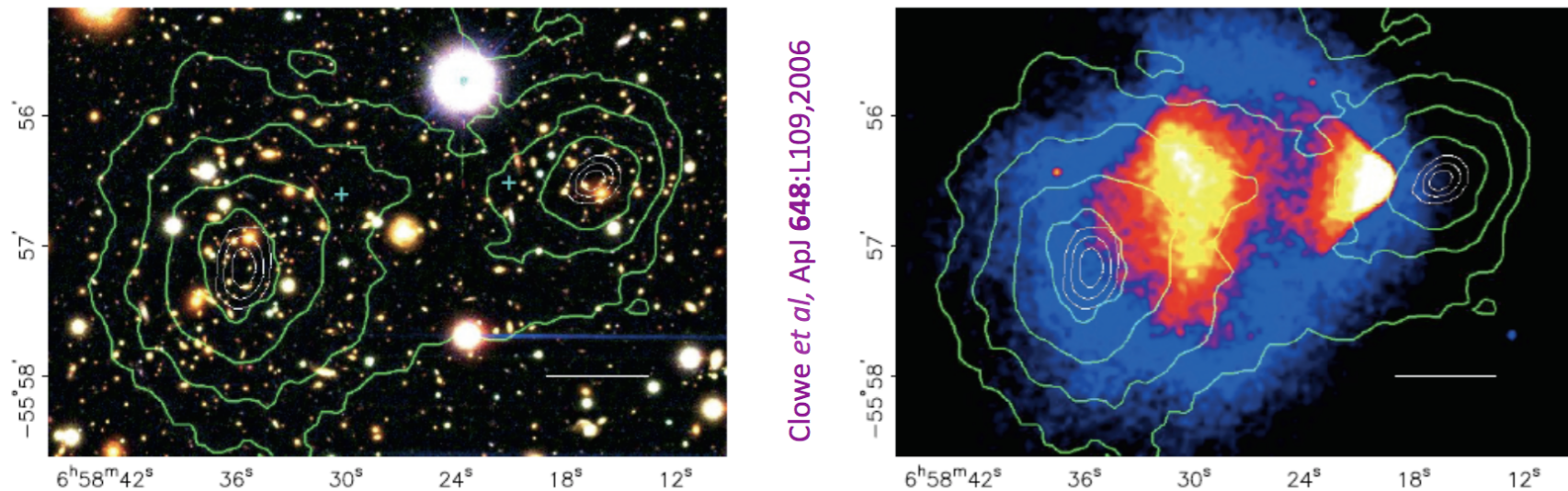


FIG. 1.—*Left panel:* Color image from the Magellan images of the merging cluster 1E 0657–558, with the white bar indicating 200 kpc at the distance of the cluster. *Right panel:* 500 ks *Chandra* image of the cluster. Shown in green contours in both panels are the weak-lensing  $\kappa$  reconstructions, with the outer contour levels at  $\kappa = 0.16$  and increasing in steps of 0.07. The white contours show the errors on the positions of the  $\kappa$  peaks and correspond to 68.3%, 95.5%, and 99.7% confidence levels. The blue plus signs show the locations of the centers used to measure the masses of the plasma clouds in Table 2.



**The standard model** is the THEORY of elementary particles and their interactions (excluding gravity). It is a **renormalizable relativistic quantum field theory with a gauge symmetry, part of it spontaneously broken by the “Higgs mechanism”**, and the following particles

mass →	$\approx 2.3 \text{ MeV}/c^2$	$\approx 1.275 \text{ GeV}/c^2$	$\approx 173.07 \text{ GeV}/c^2$	0	$\approx 126 \text{ GeV}/c^2$
charge →	2/3	2/3	2/3	0	0
spin →	1/2	1/2	1/2	1	0
	<b>u</b> up	<b>c</b> charm	<b>t</b> top	<b>g</b> gluon	<b>H</b> Higgs boson
<b>QUARKS</b>	$\approx 4.8 \text{ MeV}/c^2$	$\approx 95 \text{ MeV}/c^2$	$\approx 4.18 \text{ GeV}/c^2$	0	
	-1/3	-1/3	-1/3	0	
	1/2	1/2	1/2	1	
	<b>d</b> down	<b>s</b> strange	<b>b</b> bottom	<b><math>\gamma</math></b> photon	
	$0.511 \text{ MeV}/c^2$	$105.7 \text{ MeV}/c^2$	$1.777 \text{ GeV}/c^2$	$91.2 \text{ GeV}/c^2$	
	-1	-1	-1	0	
	1/2	1/2	1/2	1	
	<b>e</b> electron	<b><math>\mu</math></b> muon	<b><math>\tau</math></b> tau	<b>Z</b> Z boson	
<b>LEPTONS</b>	$< 2.2 \text{ eV}/c^2$	$< 0.17 \text{ MeV}/c^2$	$< 15.5 \text{ MeV}/c^2$	$80.4 \text{ GeV}/c^2$	
	0	0	0	$\pm 1$	
	1/2	1/2	1/2	1	
	<b><math>\nu_e</math></b> electron neutrino	<b><math>\nu_\mu</math></b> muon neutrino	<b><math>\nu_\tau</math></b> tau neutrino	<b>W</b> W boson	
				<b>GAUGE BOSONS</b>	

## Problems of the SM

So far the SM has been enormously successful, proven to be right in the 100's of experimental tests (maybe too successful at this point). But we believe it cannot be the last word.

- It does not include **gravitational interactions**
- Has many (too many?) **free parameters**: 20 for massless neutrinos + 7(9) for Dirac (Majorana) neutrinos. It does not explain why the electric charge of quarks is exactly related to that of electrons, so that **atoms are neutral** (in the SM this is an accident). There is no explanation of why there are **3 generations** of repeated fermions and of their mass hierarchy.
- There is no explanation of **neutrino masses**.
- No solution for the **“strong CP problem”** (due to a term  $\theta F_{\mu\nu} \widetilde{F}^{\mu\nu}$  in the QCD Lagrangian -only viable solution so far is to add a global Peccei-Quinn symmetry)

- There are no cold or warm **Dark Matter** particle candidates (so the bulk of the dark matter cannot be accounted for within the SM)
- There is no explanation of the **Dark Energy**
- Problem of **stability of the Higgs mass if there is any physical scale  $\Lambda$  where new physics arises**. The tree-level (bare) Higgs mass, the one which appears in the Lagrangian we dealt with, receives quadratically-divergent corrections from one loop diagrams,  $M_H^2 = (M_H^2)_{bare} + O(\lambda, g^2, h^2)\Lambda^2$ , which take the corrected mass to  $O(\Lambda)$ , much larger than measured

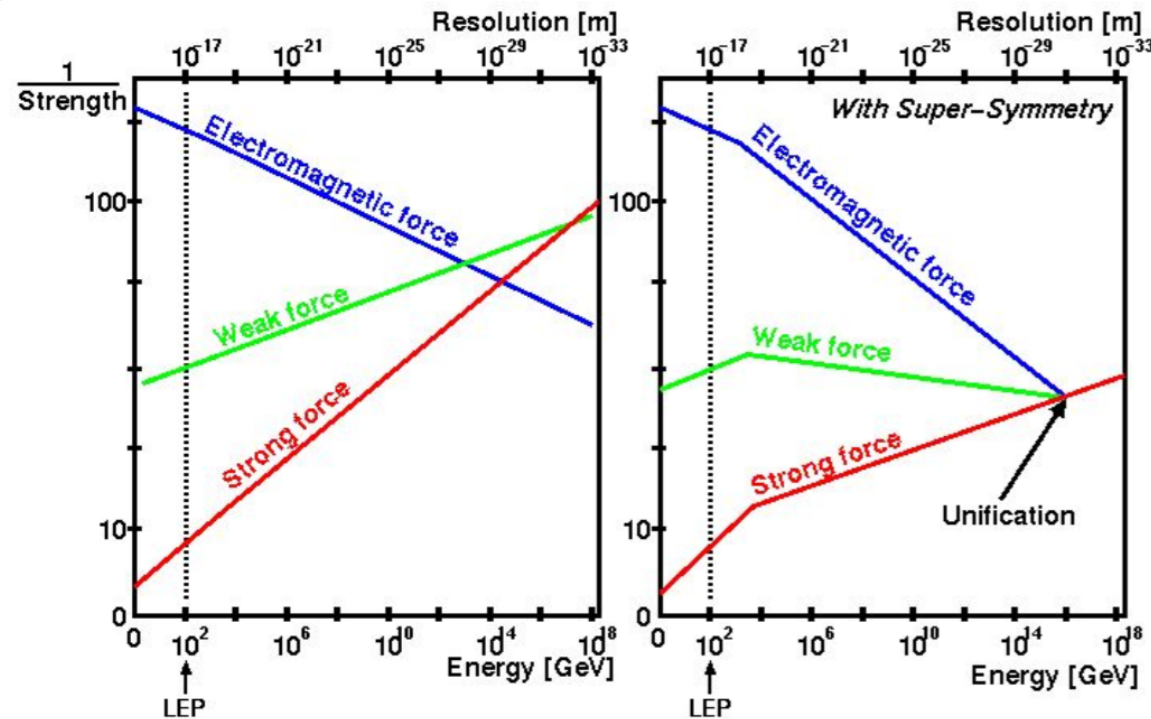
(Solutions: TeV scale supersymmetry (so far not found by the LHC) where there is cancellation of fermionic and bosonic contributions to the loop, Little Higgs models, where the Higgs is light because it is almost a Goldstone boson... all already constrained by the LHC)



## Ideas to go beyond the SM

- More symmetry

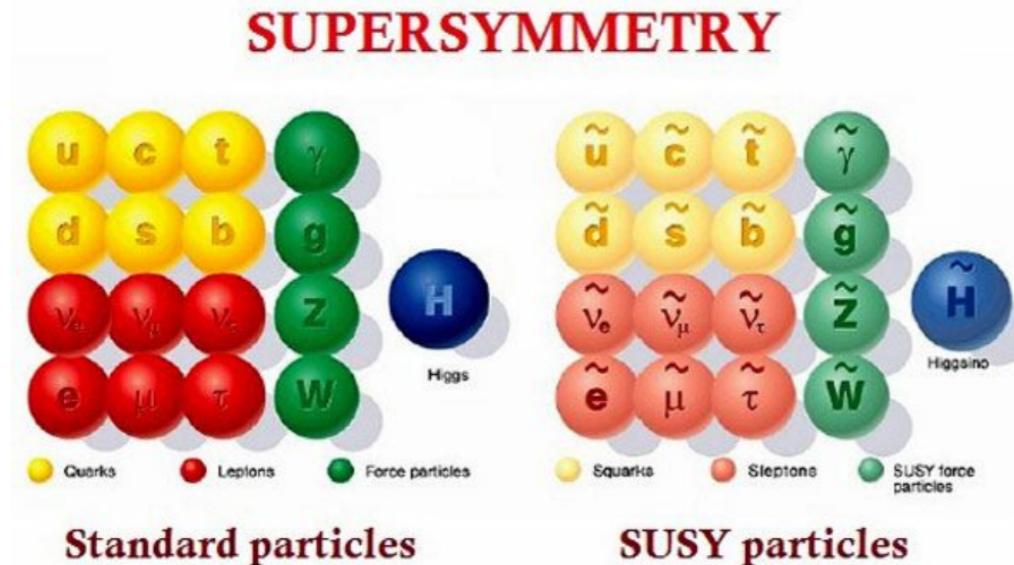
Grand Unified Theories (GUT), unifications of electroweak and strong interactions at high energies?



## Ideas to go beyond the SM

- More symmetry

Supersymmetry (SUSY): Symmetry between bosons and fermions (need to duplicate all the particles of the SM, and at least an additional Higgs doublet)!



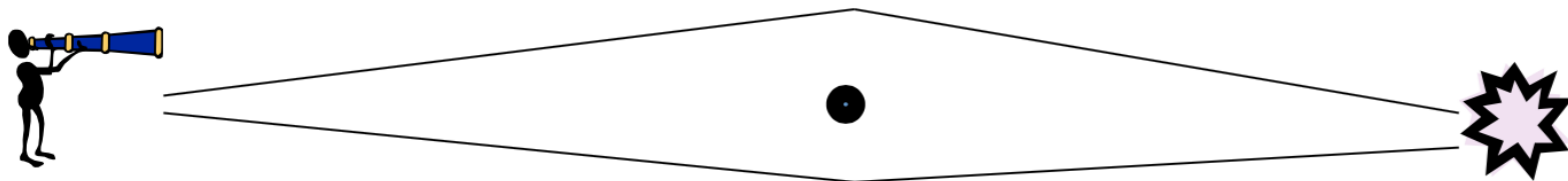
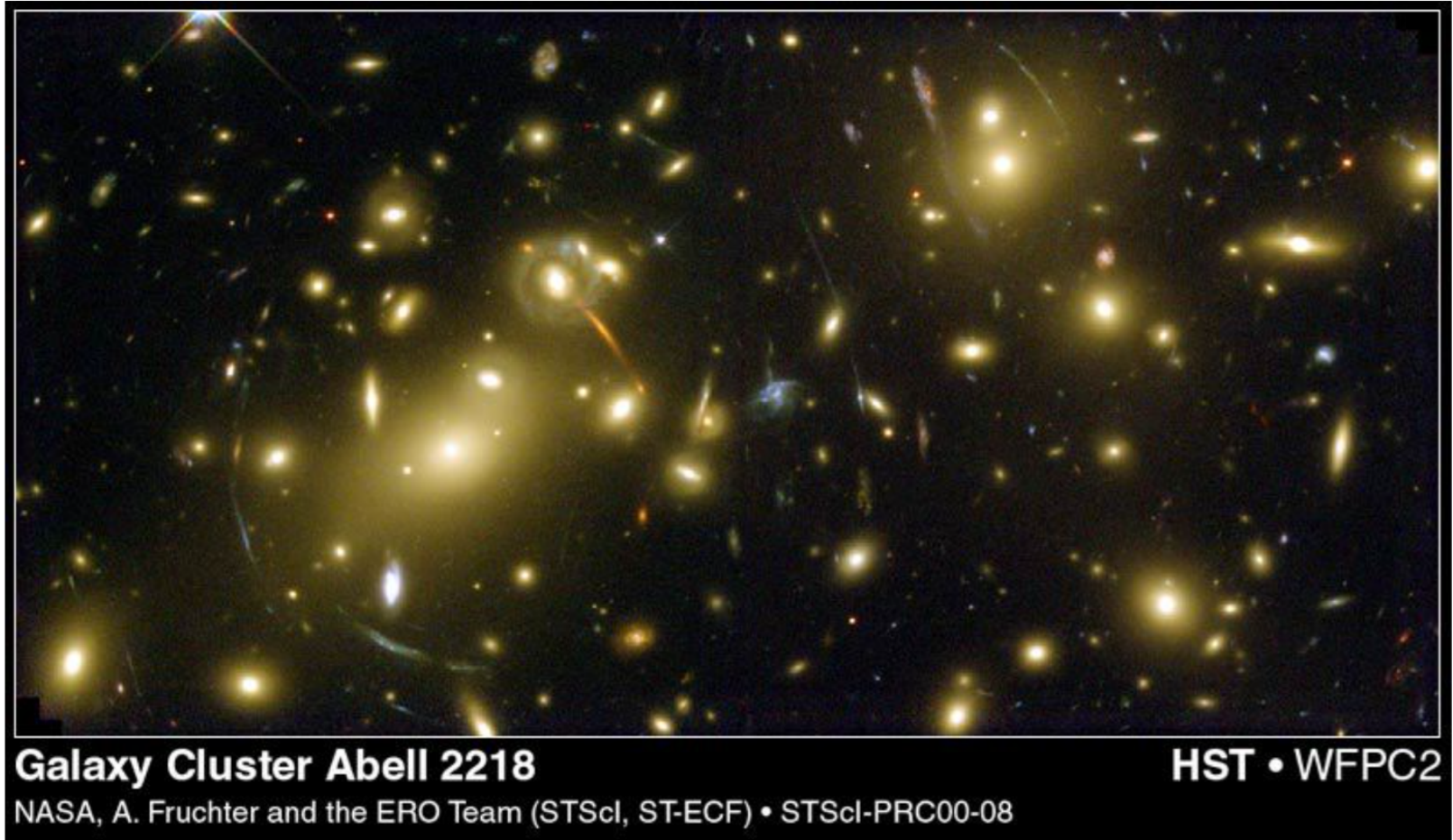
# Astrophysics and Cosmology for Particle Physicists

Marc Kamionkowski  
Johns Hopkins University

<https://arxiv.org/abs/0907.1912>

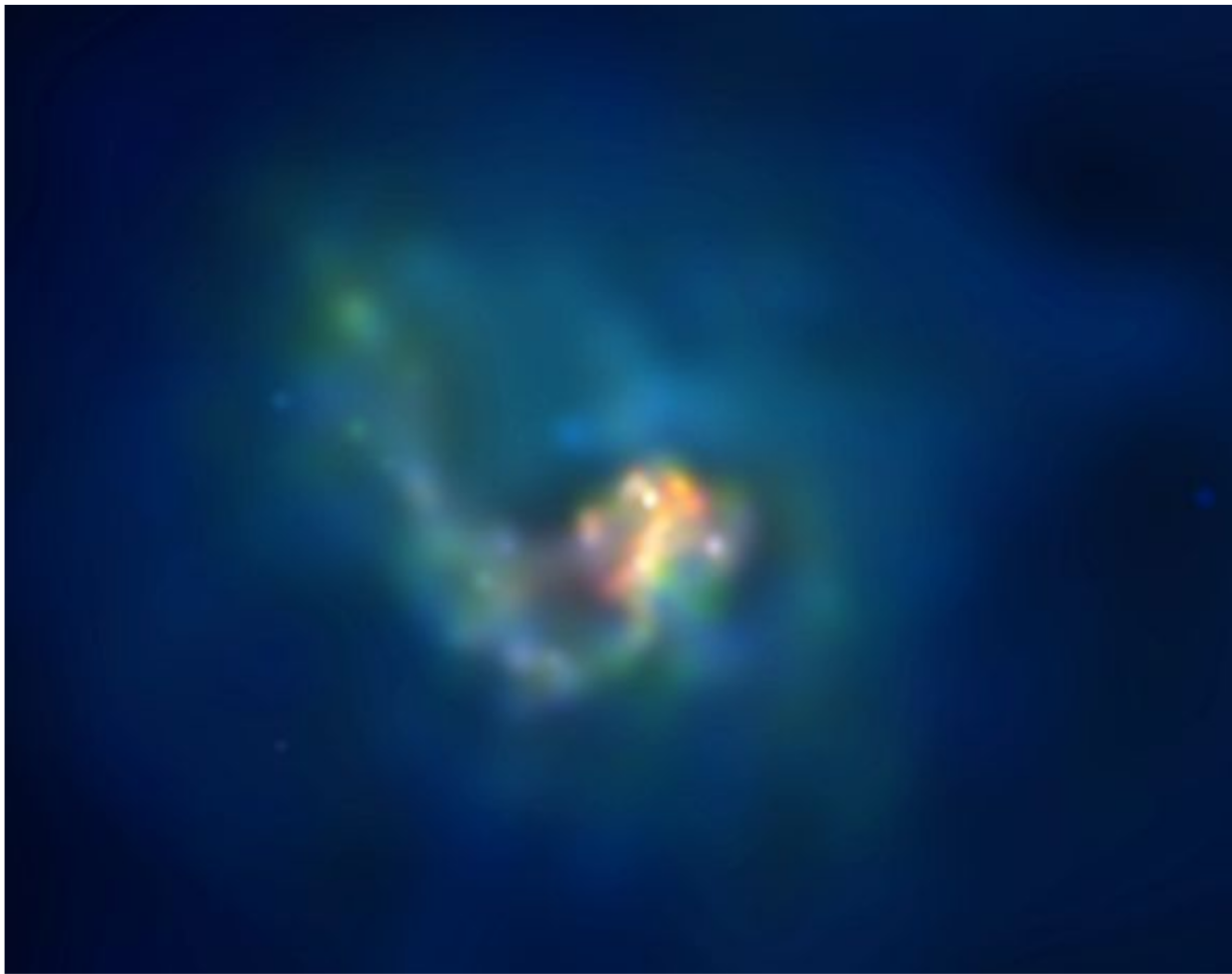


# Lensing effect of dark matter



X-ray clusters: Gas in hydrostatic eq

$$dP/dr = -G\rho_{\text{tot}}(r)m_b(r)/r^2$$



$M_{\text{total}} \gg M_{\text{baryons}}$  in clusters

## Dark matter properties:

- Must have no (or no more than very weak) coupling to photons
- Cross section for self-scattering must be  $<10^{-24} \text{ cm}^2$
- Interactions with baryons must be very weak



# Could dark matter be neutrino?

No!

Quantum mechanics:  $\Delta x \Delta p > \hbar$

$$\Delta x \sim n_\nu^{-1/3} \sim (\rho_0/m_\nu)^{-1/3}$$

$$\Delta p \sim m_\nu v \quad (v \sim 300 \text{ km/sec})$$

$$\rightarrow m_\nu > 50 \text{ eV}$$

But

$$m_\nu < 10 \text{ eV} \quad \text{if} \quad \Omega_\nu h^2 < 0.1$$

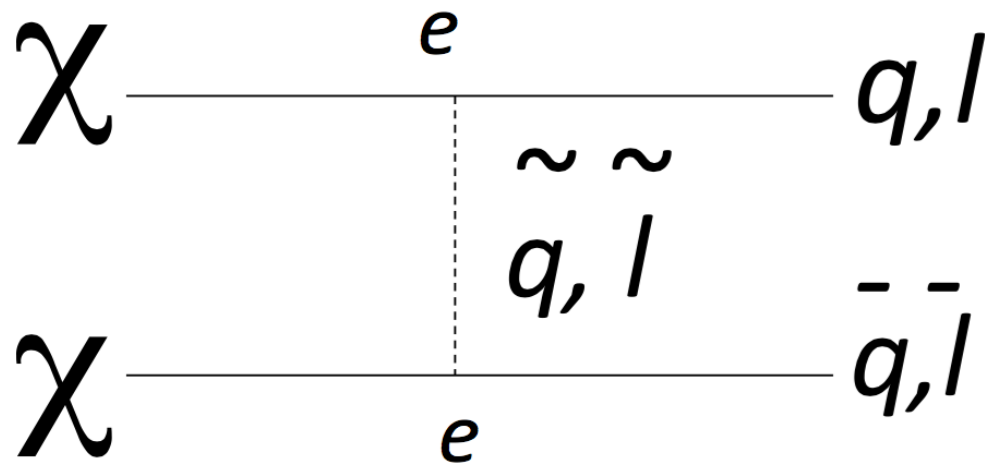
Supersymmetric models:

WIMP (weakly-interacting massive particle) is  
*neutralino* = (photino + Z-ino + higgsino)

$$\tilde{\chi} = \xi_{\gamma} \tilde{\gamma} + \xi_Z \tilde{Z} + \xi_h \tilde{h}$$

Mass  $m_{\tilde{\chi}} \sim 10\text{s} - 1000\text{s GeV}$   
Spin=1/2 (Majorana fermion)

# WIMP interactions:



$$\alpha \sim \frac{1}{137}$$

Cross Section:  $m_{\tilde{q}} \sim 100 \text{ GeV}$

$$\sigma \sim \frac{\alpha^2}{m_{\tilde{q}}^2} \sim 10^{-8} \text{ GeV}^{-2} \sim 10^{-36} \text{ cm}^2$$



# WIMP Freezeout

Annihilation Rate

Expansion Rate

$$\Gamma(\chi\chi \leftrightarrow q\bar{q}, l\bar{l}, \dots) = n_\chi \langle \sigma |v| \rangle \quad H = \left( \frac{8\pi G\rho}{3} \right)^{1/2} \propto T^2$$

**Early Times:**

$$k_B T \gg m_\chi c^2$$

$$n_\chi \propto T^3$$

$$\Gamma \gg H$$

Equilibrium Holds

**Late Times:**

$$k_B T \ll m_\chi c^2$$

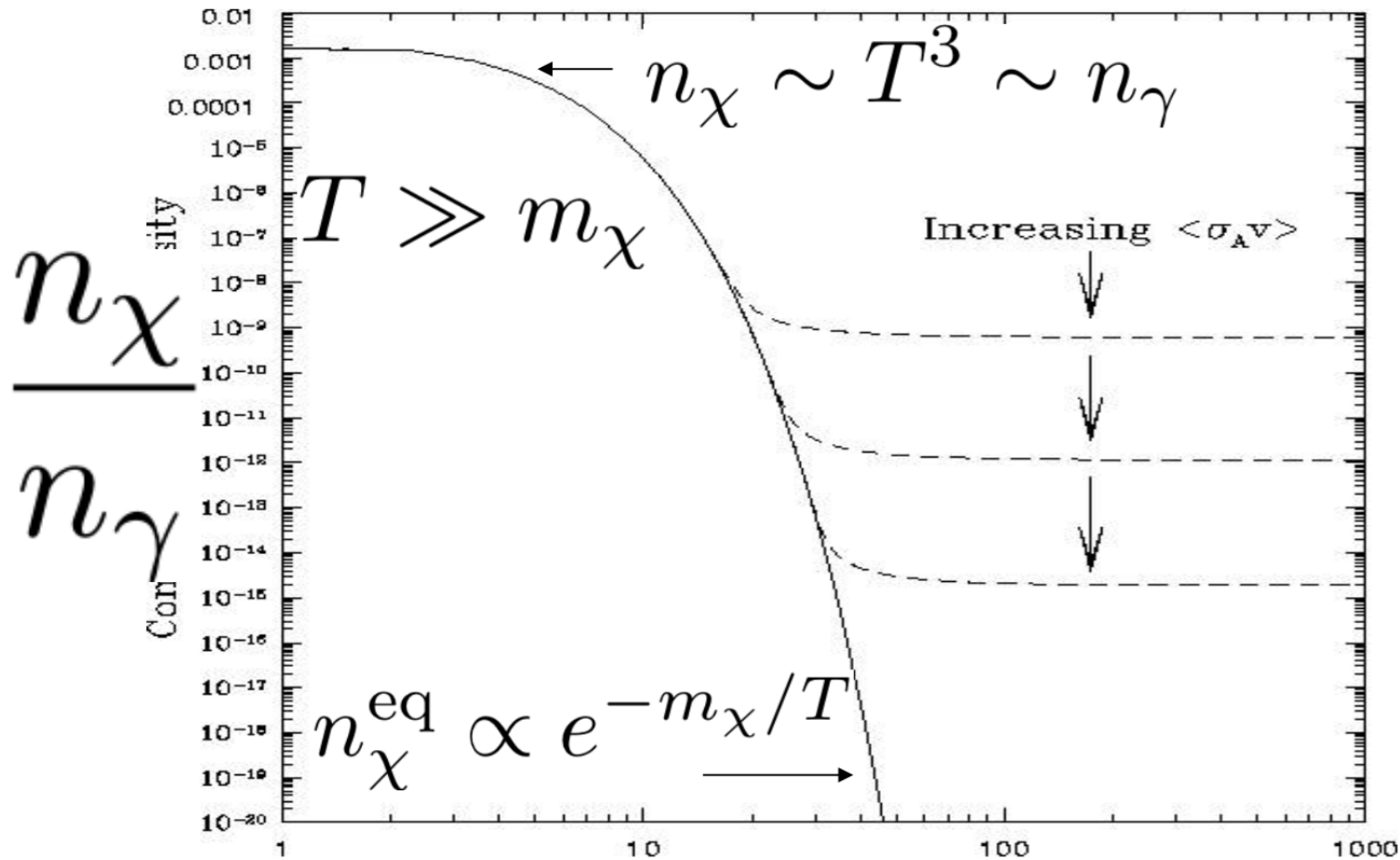
$$n_\chi^{\text{eq}} \propto e^{-m_\chi/T}$$

$$\Gamma \ll H$$

Annihilations can  
not occur

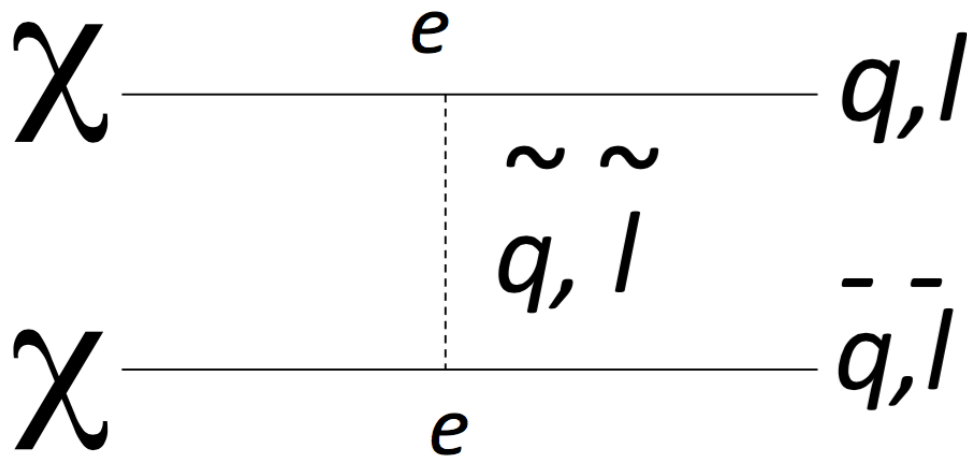
“Freezeout” at  $\Gamma(T_f) = H(T_f)$

Afterwards, comoving WIMP # constant



## Freezeout Calculation:

$$\Omega_\chi h^2 \simeq 0.1 \left( \frac{\langle \sigma v \rangle}{3 \times 10^{-26} \text{ cm}^3 \text{ sec}^{-1}} \right)^{-1}$$



$$\sigma \sim \frac{\alpha^2}{m_\chi^2}$$



$$\Omega_\chi h^2 \sim m_\chi^2 \quad \text{from} \quad \langle \sigma v \rangle \sim m_\chi^{-2}$$

$$\langle \sigma v \rangle \lesssim m_\chi^{-2} \quad \text{with} \quad \Omega_\chi h^2 \lesssim 0.1$$

leads to WIMP-mass limit,

$$m_\chi \lesssim 100 \text{ TeV}$$

Griest&MK 1991

# Direct detection:

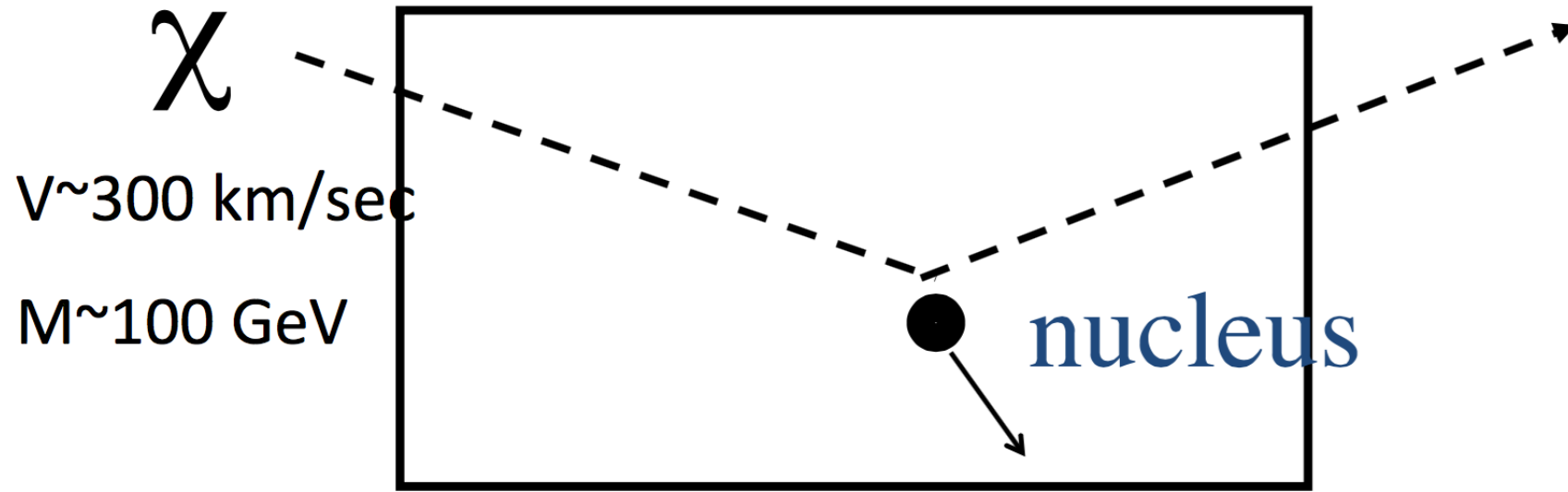
QCD

nuclear physics

$$\chi q \longrightarrow \chi n \longrightarrow \chi N$$

$$\sigma_{\text{WIMP-nucleus}} \sim 10^{-36} \text{ cm}^2$$

E.g., Ge or Xe detector



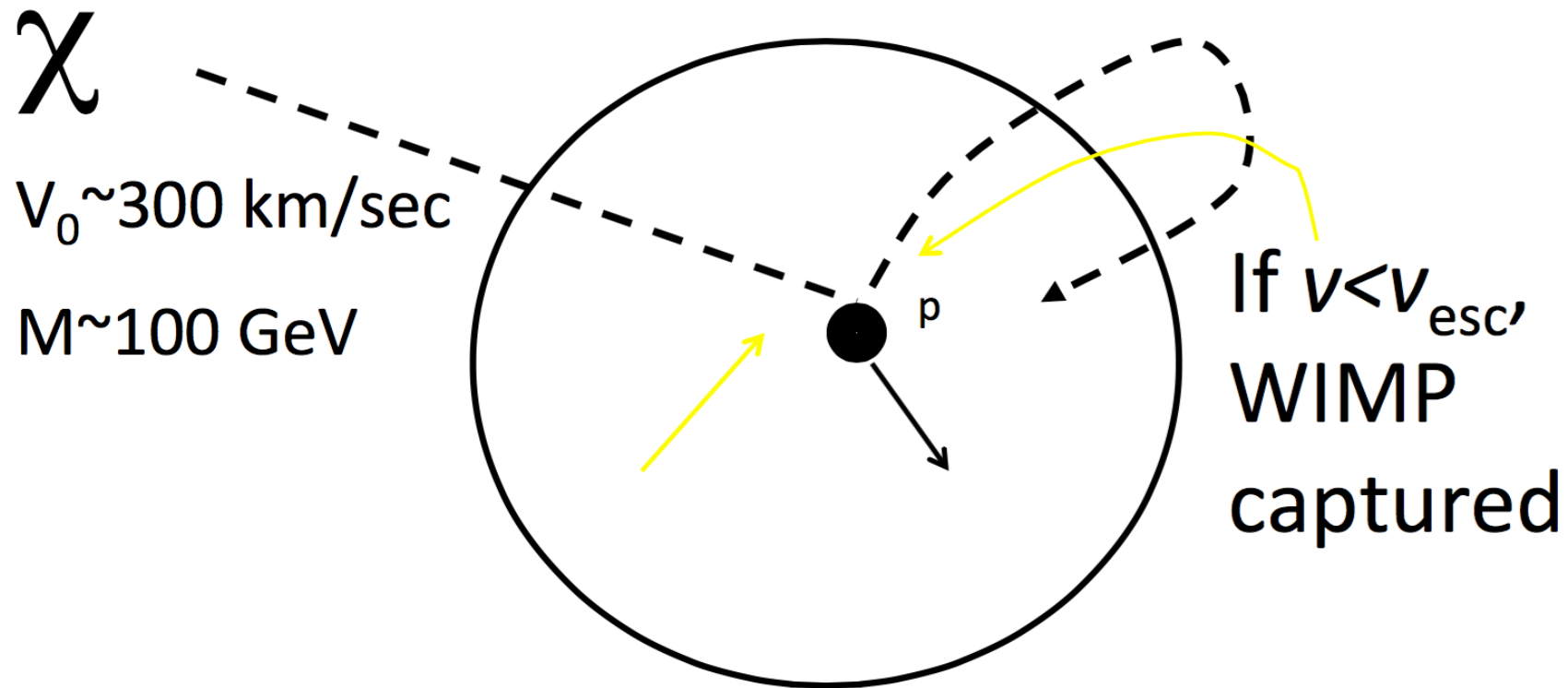
$$E_{recoil} \sim (1/2)mv^2 \sim 50 \text{ keV}$$

Rate:

$$\begin{aligned} n\sigma v N_{\text{nuclei}} &\sim (10^{-36} \text{ cm}^2) \left( \frac{0.4 \text{ GeV/cm}^3}{100 \text{ GeV}} \right) (3 \times 10^7 \text{ cm/sec}) \left( \frac{6 \times 10^{23} \text{ kg}^{-1}}{A} \right) \\ &\sim \text{few kg}^{-1} \text{ yr}^{-1} \end{aligned}$$



# Indirect Detection: Energetic neutrinos from WIMP annihilation in Sun/Earth



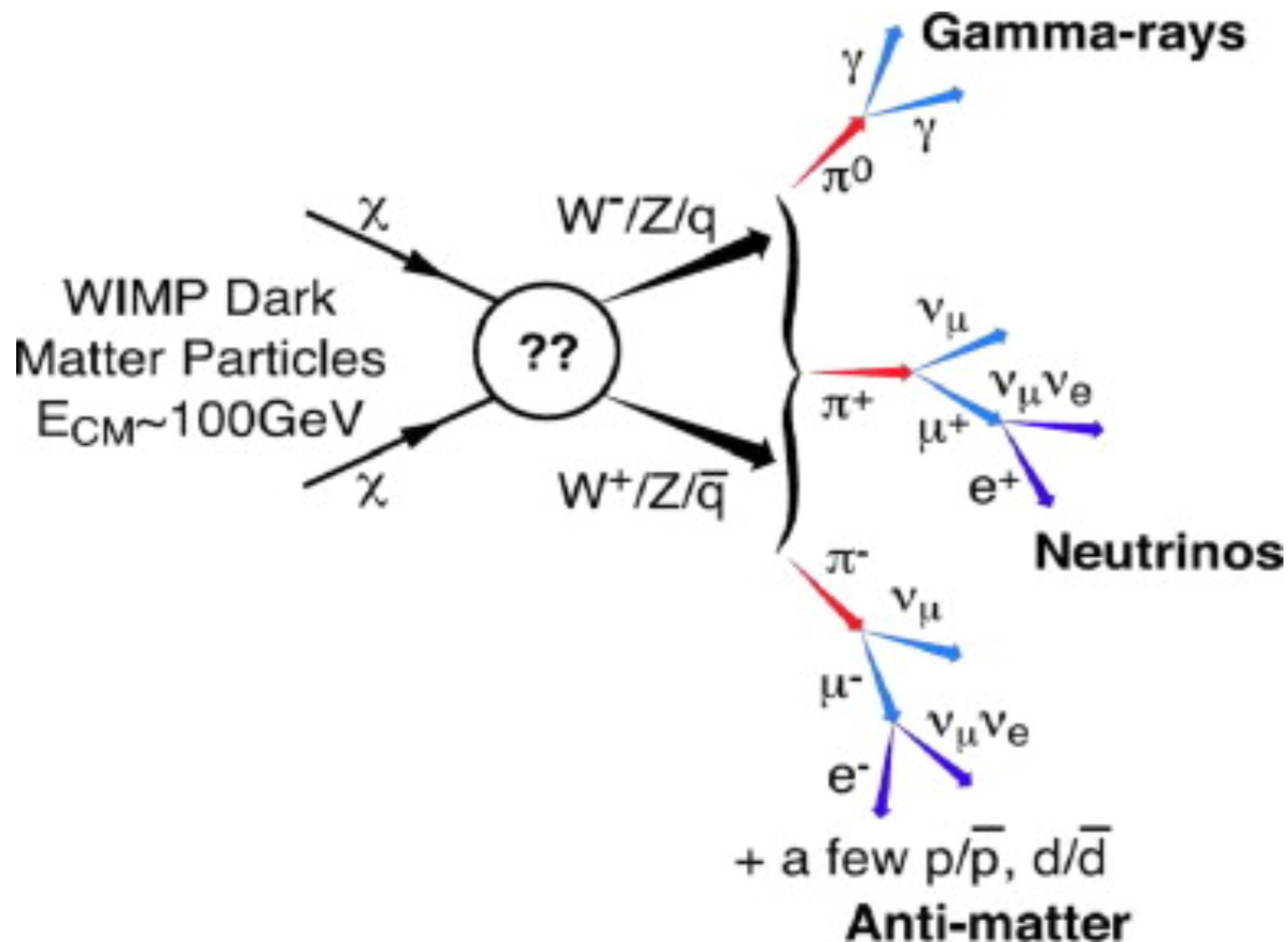
Inside Sun and/or Earth:

$$\chi\chi \rightarrow (W^+W^-, Z^0Z^0, q\bar{q}, l\bar{l}, \dots) \rightarrow \nu\bar{\nu}$$

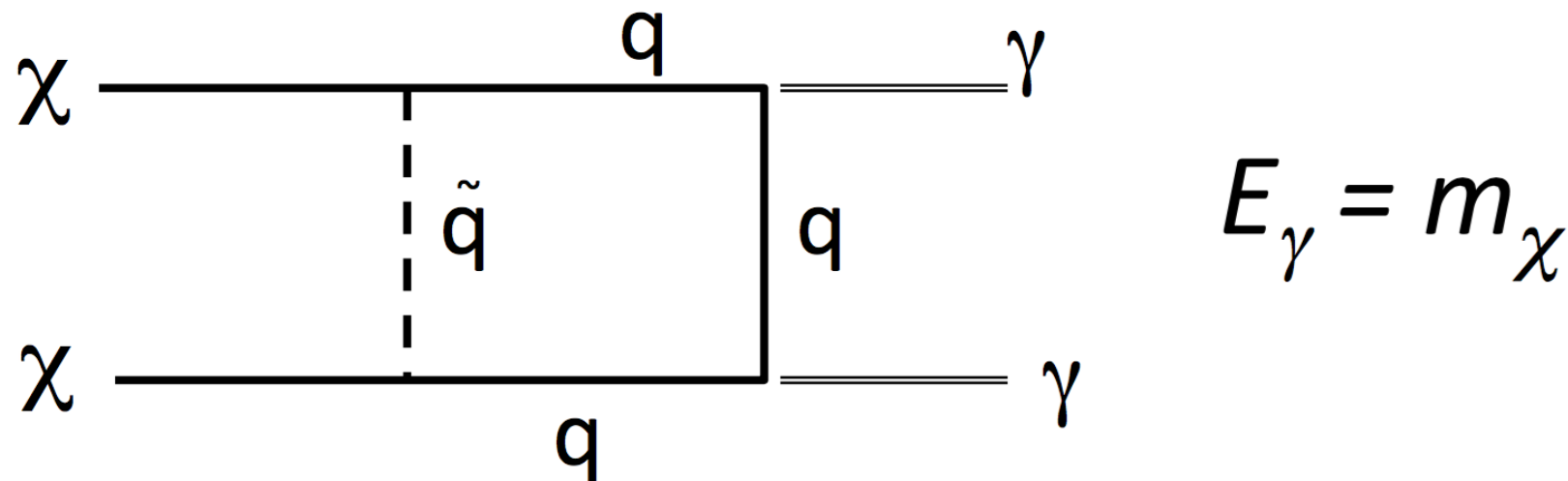
$$E_\nu \sim (1/10 - 1/2)m_\chi \sim 10 - 1000s \text{ GeV}$$

Neutrinos sought in, e.g., MACRO, IMB,  
Super-Kamiokande, IceCube.....

# Indirect detection: Exotic cosmic rays from WIMP annihilation in Galactic halo



# Indirect Detection: Gamma-rays from WIMP annihilation in Galactic halo



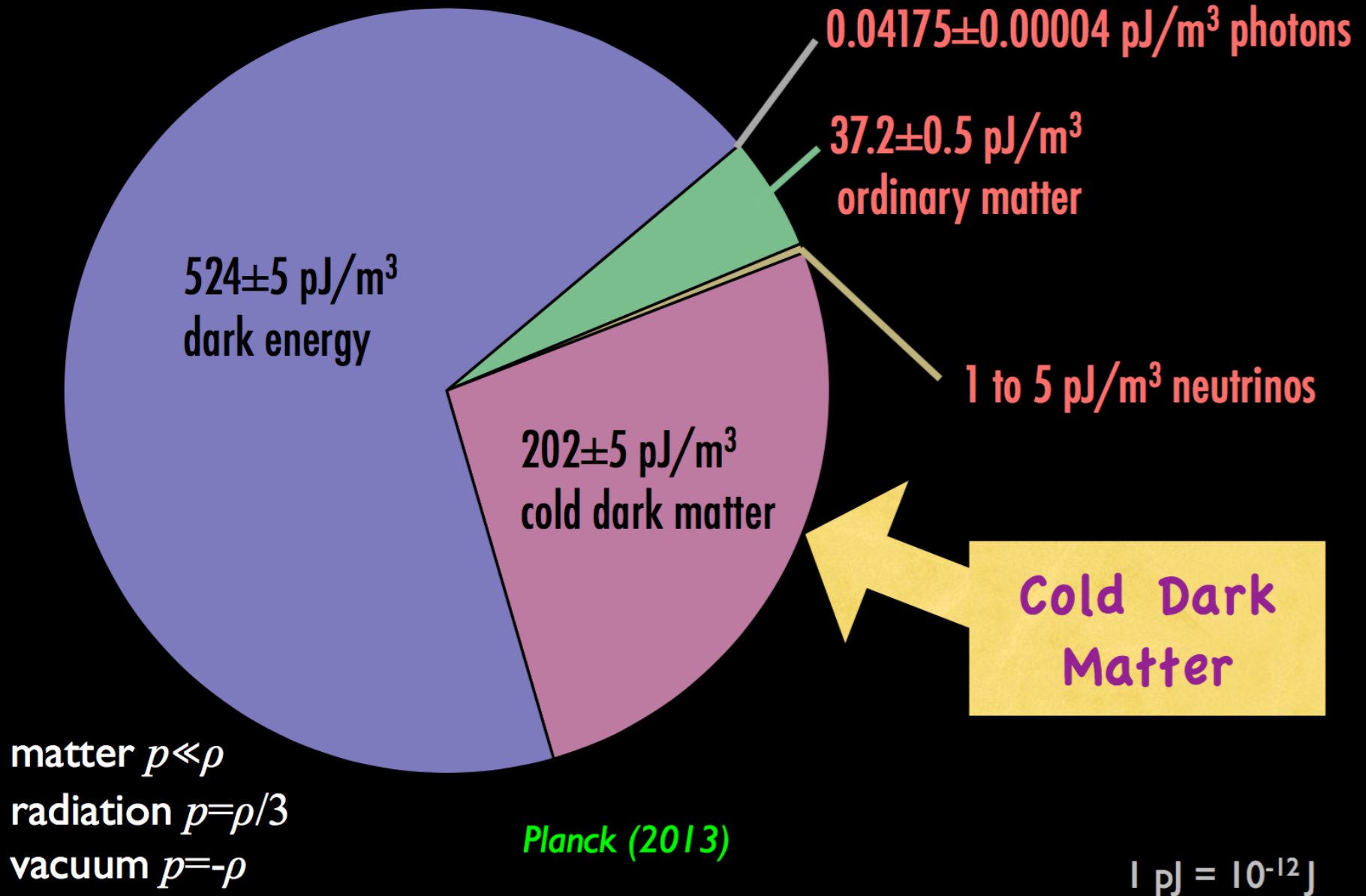
Can be sought in Fermi, air Cherenkov telescopes (e.g, CTA)



# **Particle Physics Models for Dark Matter**

*Paolo Gondolo*  
*University of Utah*

# The observed content of the Universe



# What particle model for dark matter?

- It should have the cosmic cold dark matter density
- It should be stable or very long-lived ( $\gtrsim 10^{24}$  yr)
- It should be compatible with collider, astrophysics, etc. bounds
- Ideally, it would be possible to detect it in outer space and produce it in the laboratory
- For the believer, it would explain any claim of dark matter detection (annual modulation, positrons, gamma-ray line, etc.)

# Cold dark matter, *not* modified gravity

## The Bullet Cluster

*Symmetry argument: gas is at center, but potential has two wells.*



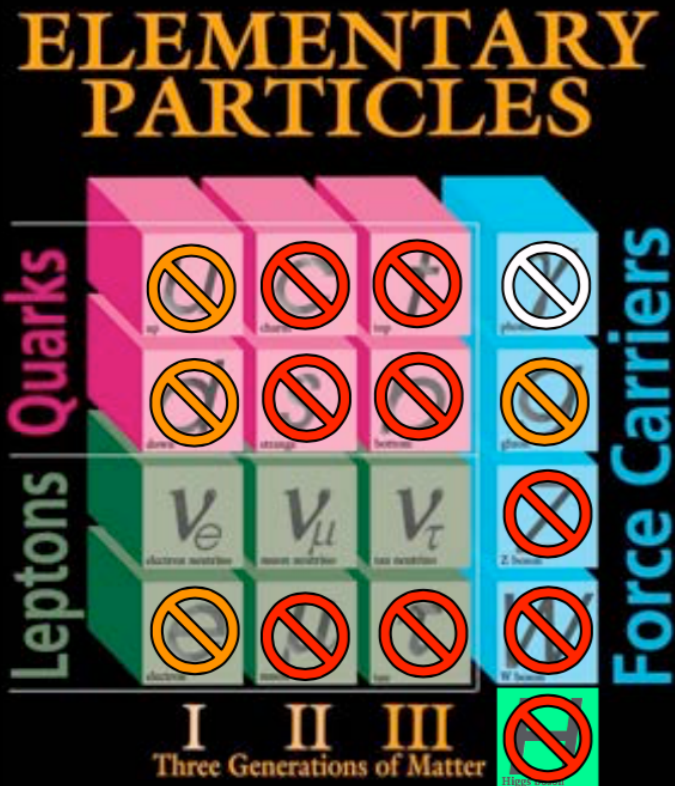
Galaxies in optical  
(Hubble Space  
Telescope)

Gravitational potential  
from weak lensing

X-ray emitting hot gas  
(Chandra)



# Which particle is cold dark matter?



is the particle of light

couples to the plasma

disappears too quickly

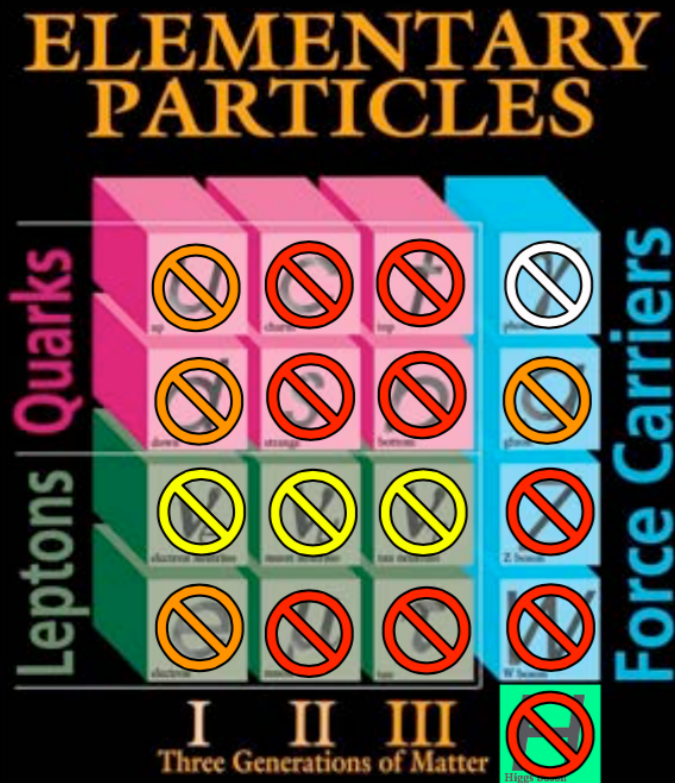
## Known active neutrinos

- Neutrino oscillations (largest  $\Delta m^2$  from SK+K2K+MINOS) place a lower bound on one of the neutrino masses,  $m_\nu > 0.048 \text{ eV}$
- Cosmology (CMB+LRG+ $H_0$ ) places an upper bound on the sum of the neutrino masses,  $\sum m_\nu < 0.44 \text{ eV}$
- Therefore neutrinos are *hot dark matter* ( $m_\nu \ll T_{\text{eq}} = 1.28 \text{ eV}$ ) with density  $0.0005 < \Omega_\nu h^2 < 0.0047$

*Detecting this Cosmic Neutrino Background (CNB) is a big challenge*

***Known neutrinos are hot dark matter***

# Which particle is cold dark matter?



 is the particle of light

 couples to the plasma

 disappears too quickly

 is hot dark matter

***No known particle can be cold dark matter!***

# Particle dark matter

## Thermal relics

in thermal equilibrium in the early universe

neutrinos, neutralinos, other WIMPs, ....

## Non-thermal relics

never in thermal equilibrium in the early universe

axions, WIMPZILLAs, solitons, ....



# Particle dark matter

## Hot dark matter

- relativistic at kinetic decoupling (start of free streaming)
- big structures form first, then fragment

light neutrinos

## Cold dark matter

- non-relativistic at kinetic decoupling
- small structures form first, then merge

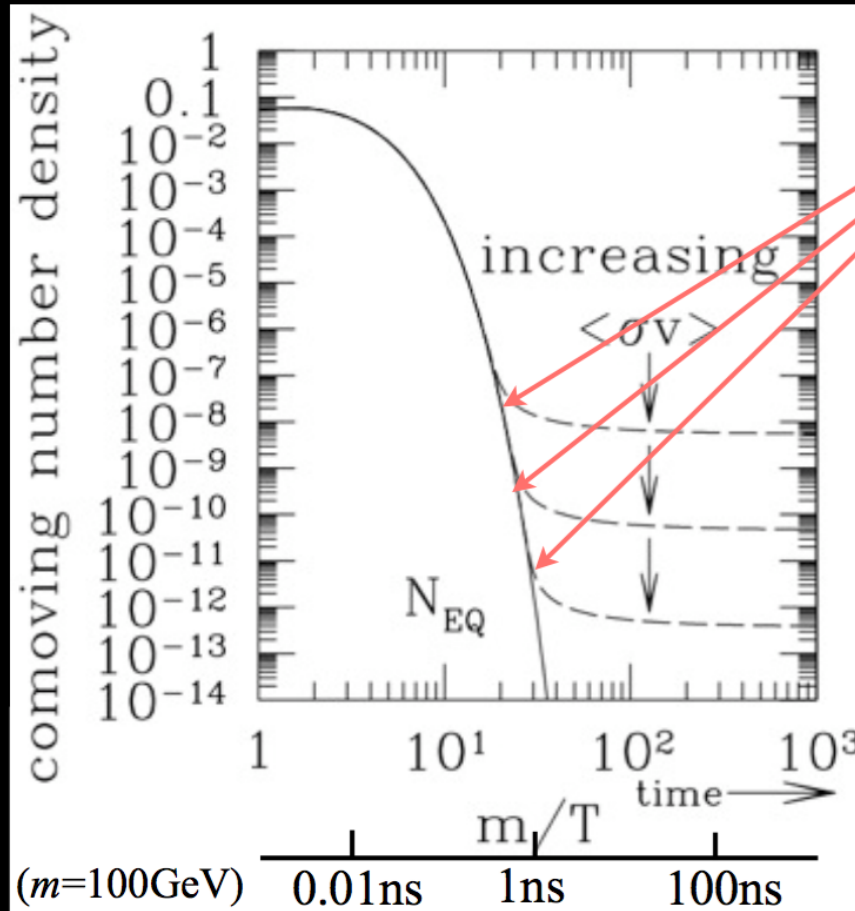
neutralinos, axions, WIMPZILLAs, solitons

## Warm dark matter

- semi-relativistic at kinetic decoupling
- smallest structures are erased

sterile neutrinos, gravitinos

# Cosmic density of heavy active neutrinos



freeze-out

$$\Gamma_{\text{ann}} \equiv n \langle \sigma v \rangle \sim H$$

annihilation rate

expansion rate

$$\Omega_{\chi} h^2 \simeq \frac{3 \times 10^{-27} \text{ cm}^3/\text{s}}{\langle \sigma v \rangle_{\text{ann}}}$$

$$\Omega_{\chi} h^2 = \Omega_{\text{cdm}} h^2 \simeq 0.1143$$

$$\text{for } \langle \sigma v \rangle_{\text{ann}} \simeq 3 \times 10^{-26} \text{ cm}^3/\text{s}$$

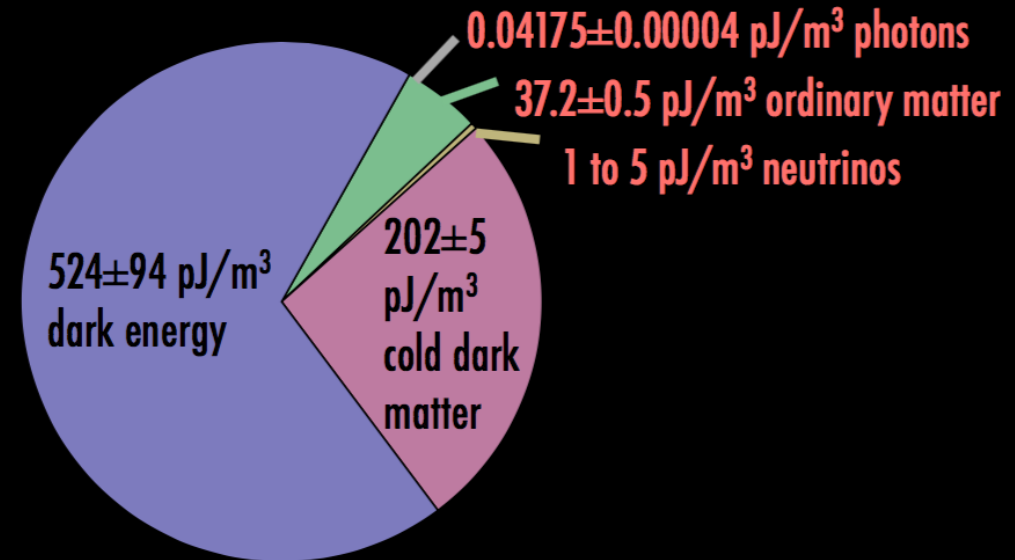
*This is why they are called Weakly Interacting Massive Particles (WIMPlless candidates are WIMPs!)*

# The Magnificent WIMP

(Weakly Interacting Massive Particle)

- One naturally obtains the right cosmic density of WIMPs

*Thermal production in hot primordial plasma.*



- One can experimentally test the WIMP hypothesis

*The same physical processes that produce the right density of WIMPs make their detection possible*

# The magnificent WIMP

To first order, three quantities characterize a WIMP

- Mass  $m$

- Simplest models relate mass to cosmic density:  $1 - 10^4 \text{ GeV}/c^2$

- Scattering cross section off nucleons  $\sigma_{\chi N}$

- Usually different for protons and neutrons

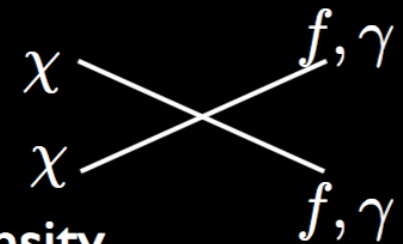


- Spin-dependent or spin-independent governs scaling to nuclei

- Annihilation cross section into ordinary particles

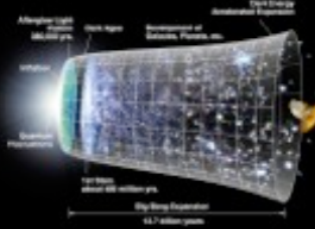
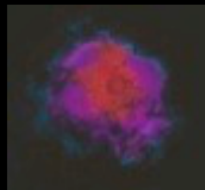
- $\sigma \approx \text{const}/v$  at small  $v$ , so use  $\sigma v$

- Simplest models relate cross section to cosmic density





Indirect detection

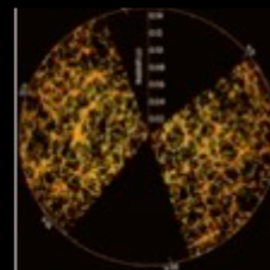


Cosmic density

Annihilation



Direct detection



Scattering

Large scale structure

The power of the WIMP hypothesis

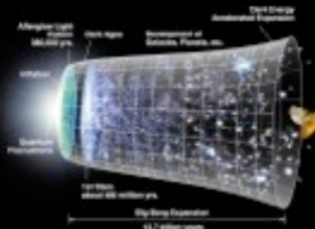
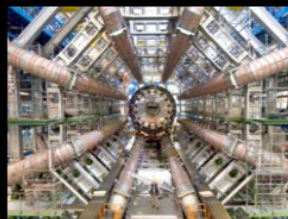
$\chi$

$f$

$f$

Production

Colliders



Cosmic density

# Supersymmetry

A supersymmetric transformation  $Q$  turns a bosonic state into a fermionic state, and viceversa.

$$Q|\text{Boson}\rangle = |\text{Fermion}\rangle$$

$$Q|\text{Fermion}\rangle = |\text{Boson}\rangle$$

$$\{Q_\alpha, Q_{\dot{\alpha}}^\dagger\} = P_\mu \sigma_{\alpha\dot{\alpha}}^\mu, \{Q_\alpha, Q_\beta\} = \{Q_{\dot{\alpha}}^\dagger, Q_{\dot{\beta}}^\dagger\} = 0, [P^\mu, Q_\alpha] = [P^\mu, Q_{\dot{\alpha}}^\dagger] = 0$$

*A supersymmetric theory is invariant under supersymmetry transformations*

- bosons and fermions come in pairs of equal mass
- the interactions of bosons and fermions are related

# Supersymmetric dark matter

Neutralinos (the most fashionable/studied WIMP)

*Goldberg 1983; Ellis, Hagelin, Nanopoulos, Olive, Srednicki 1984; etc.*

Sneutrinos (also WIMPs)

*Falk, Olive, Srednicki 1994; Asaka, Ishiwata, Moroi 2006; McDonald 2007; Lee, Matchev, Nasri 2007; Deppisch, Pilaftsis 2008; Cerdeno, Munoz, Seto 2009; Cerdeno, Seto 2009; etc.*

Gravitinos (SuperWIMPs)

*Feng, Rajaraman, Takayama 2003; Ellis, Olive, Santoso, Spanos 2004; Feng, Su, Takayama, 2004; etc.*

Axinos (SuperWIMPs)

*Tamvakis, Wyler 1982; Nilles, Raby 1982; Goto, Yamaguchi 1992; Covi, Kim, Kim, Roszkowski 2001; Covi, Roszkowski, Ruiz de Austri, Small 2004; etc.*

# Neutralino dark matter

Process	Diagrams			
	s	t	u	p
$\chi_i^0 \chi_j^0 \rightarrow B_m^0 B_n^0$	$H_{1,2,3}^0, Z$	$\chi_k^0$	$\chi_l^0$	
$\chi_i^0 \chi_j^0 \rightarrow B_m^- B_n^+$	$H_{1,2,3}^0, Z$	$\chi_k^+$	$\chi_l^+$	
$\chi_i^0 \chi_j^0 \rightarrow f \bar{f}$	$H_{1,2,3}^0, Z$	$\tilde{f}_{1,2}$	$\tilde{f}_{1,2}$	
$\chi_i^+ \chi_j^0 \rightarrow B_m^+ B_n^0$	$H^+, W^+$	$\chi_k^0$	$\chi_l^+$	
$\chi_i^+ \chi_j^0 \rightarrow f_u \bar{f}_d$	$H^+, W^+$	$\tilde{f}'_{d1,2}$	$\tilde{f}'_{u1,2}$	
$\chi_i^+ \chi_j^- \rightarrow B_m^0 B_n^0$	$H_{1,2,3}^0, Z$	$\chi_k^+$	$\chi_l^+$	
$\chi_i^+ \chi_j^- \rightarrow B_m^+ B_n^-$	$H_{1,2,3}^0, Z, \gamma$	$\chi_k^0$		
$\chi_i^+ \chi_j^- \rightarrow f_u \bar{f}_u$	$H_{1,2,3}^0, Z, \gamma$	$\tilde{f}'_{d1,2}$		
$\chi_i^+ \chi_j^- \rightarrow \bar{f}_d f_d$	$H_{1,2,3}^0, Z, \gamma$	$\tilde{f}'_{u1,2}$		
$\chi_i^+ \chi_j^+ \rightarrow B_m^+ B_n^+$		$\chi_k^0$	$\chi_l^0$	
$\tilde{f}_i \chi_j^0 \rightarrow B^0 f$	$f$	$\tilde{f}_{1,2}$	$\chi_l^0$	
$\tilde{f}_d \chi_j^0 \rightarrow B^- f_u$	$f_d$	$\tilde{f}_{u1,2}$	$\chi_l^+$	
$\tilde{f}_u \chi_j^0 \rightarrow B^+ f_d$	$f_u$	$\tilde{f}_{d1,2}$	$\chi_l^+$	
$\tilde{f}_d \chi_j^+ \rightarrow B^0 f_u$	$f_u$	$\tilde{f}_{d1,2}$	$\chi_l^+$	
$\tilde{f}_u \chi_j^+ \rightarrow B^+ f_u$		$\tilde{f}_{d1,2}$	$\chi_l^0$	
$\tilde{f}_d \chi_j^+ \rightarrow B^+ f_d$	$f_u$		$\chi_l^0$	
$\tilde{f}_u \chi_j^- \rightarrow B^0 f_d$	$f_d$	$\tilde{f}_{u1,2}$	$\chi_l^+$	
$\tilde{f}_u \chi_j^- \rightarrow B^- f_u$	$f_d$		$\chi_l^0$	
$\tilde{f}_d \chi_j^- \rightarrow B^- f_d$		$\tilde{f}_{u1,2}$	$\chi_l^0$	
$\tilde{f}_d \tilde{f}_{d_j}^* \rightarrow B_m^0 B_n^0$	$H_{1,2,3}^0, Z, g$	$\tilde{f}_{d1,2}$	$\tilde{f}_{d1,2}$	$p$
$\tilde{f}_d \tilde{f}_{d_j}^* \rightarrow B_m^- B_n^+$	$H_{1,2,3}^0, Z, \gamma$	$\tilde{f}_{u1,2}$		$p$
$\tilde{f}_d \tilde{f}_{d_j}^* \rightarrow f_d'' \bar{f}_d'''$	$H_{1,2,3}^0, Z, \gamma, g$	$\chi_k^0, \tilde{g}$		
$\tilde{f}_d \tilde{f}_{d_j}^* \rightarrow f_u'' \bar{f}_u'''$	$H_{1,2,3}^0, Z, \gamma, g$	$\chi_k^+$		
$\tilde{f}_d \tilde{f}_{d_j}^* \rightarrow f_d f_d'$		$\chi_k^0, \tilde{g}$	$\chi_l^0, \tilde{g}$	
$\tilde{f}_u \tilde{f}_{d_j}^* \rightarrow B_m^+ B_n^0$	$H^+, W^+$	$\tilde{f}_{d1,2}$	$\tilde{f}_{u1,2}$	$p$
$\tilde{f}_u \tilde{f}_{d_j}^* \rightarrow f_u'' \bar{f}_d'''$	$H^+, W^+$	$\chi_k^0, \tilde{g}$		
$\tilde{f}_u \tilde{f}_{d_j}^* \rightarrow f_u'' f_d'''$		$\chi_k^0, \tilde{g}$	$\chi_l^+$	

## Cosmic density

Thousands of annihilation (and coannihilation) processes

Use publicly-available computer codes, e.g. DarkSUSY, micrOMEGAs



# ***Direct Dark Matter Searches***

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- 0- Context
- 1- Elastic scattering rates
- 2- Detection principle: signal and backgrounds
- 3- Review of current experiments

J. Gascon  
UCB Lyon 1, CNRS/IN2P3/IPNL

## Recommended reading

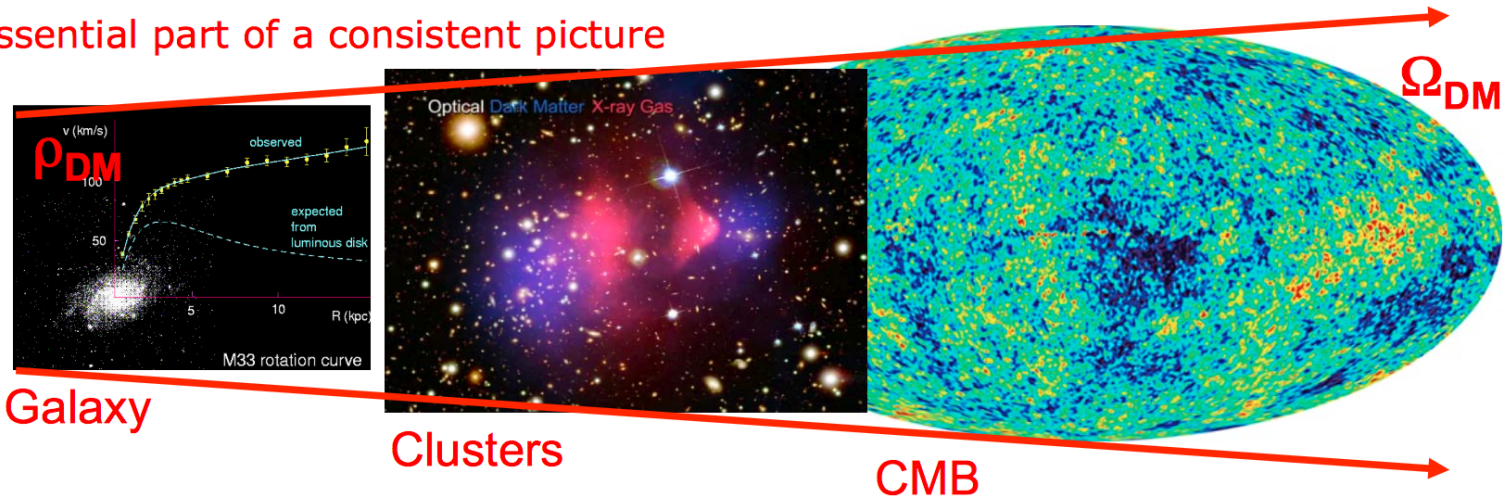
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- *Particle Dark Matter : observations, models and searches*, G. Bertone (dir.), Cambridge University Press, 2010.
  - *Recent and complete review of direct dark matter searches*
  
- *Supersymmetric Dark Matter*, G. Jungman, M. Kamionkowski and K. Griest, Phys. Rep. **267**, 195 (1996).
  - *First comprehensive reviews on all aspects of supersymmetric dark matter and its detection*
  
- *Particle Dark Matter: Evidence, Candidates and Constraints*, G. Bertone, D. Hooper, and J. Silk, Phys. Rep. **405**, 279 (2005).
  - *A more recent reviews on dark matter and its detection*
  
- *Review of mathematics, numerical factors, and corrections for dark matter experiments based on elastic nuclear recoils*, J. D. Lewin and P. F. Smith, Astropart. Phys. **6**, 87 (1996).
  - *Complete – and easy to follow – presentation of all ingredients needed to calculate experimental recoil spectra in a given detector for a given WIMP model. Must-read for all.*
  
- Particle Data Group: sections *Cosmology, Dark Matter et Detectors for non-accelerators physics*
  - <http://pdg.lbl.gov/>

## Cold Dark Matter in the Universe

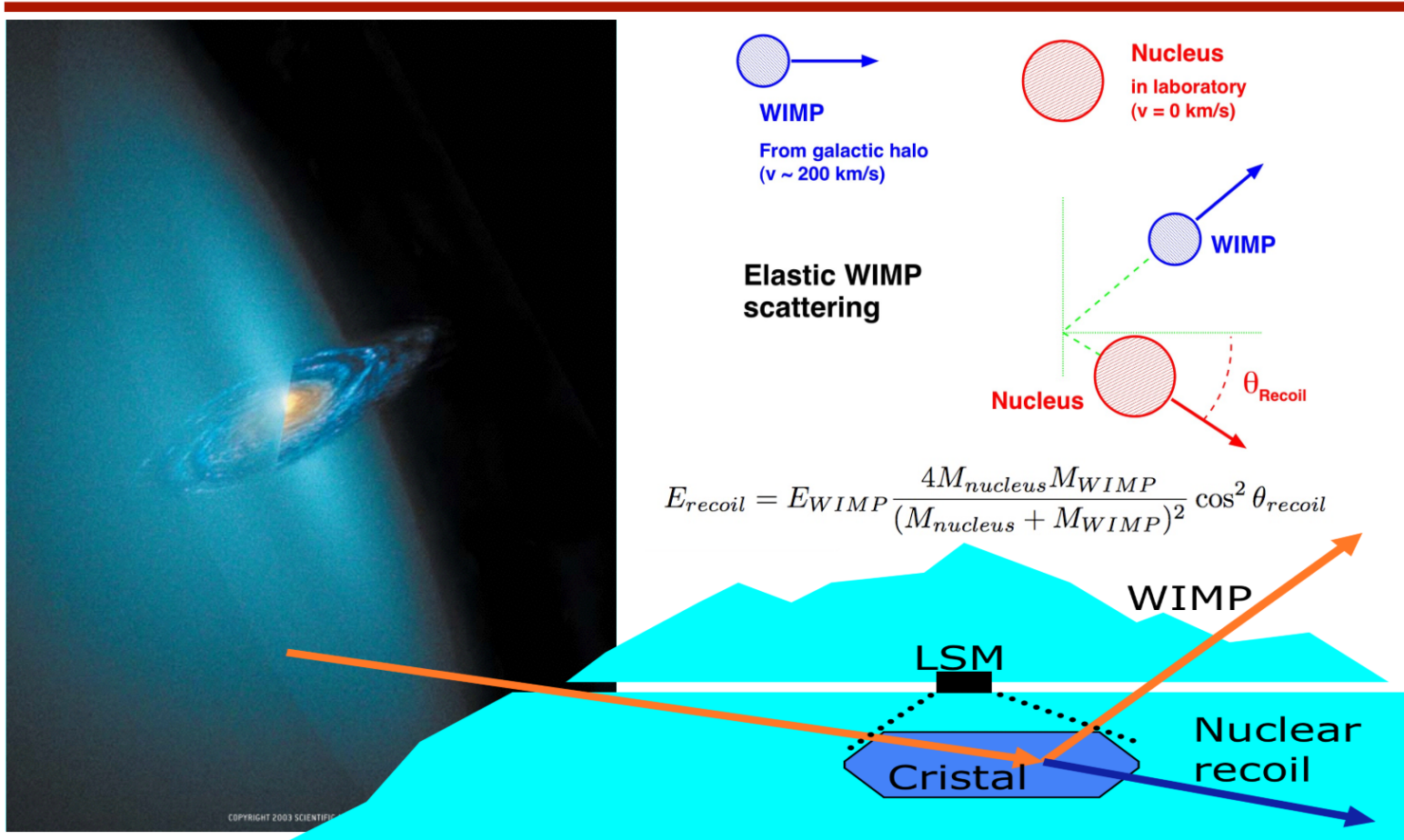
- Cold Dark Matter present at all scales in the Universe...

Essential part of a consistent picture



- Searched as a new particle at LHC
- Searched via the remains of its decay in cosmic rays ( $\gamma$ ,  $\nu$ ,  $e^+$ , antimatter)
- ... *Direct search: collision of WIMPs from our galactic halo on target nuclei in a laboratory on Earth*
  - Proof that Dark Matter is present in our environment
  - After discovery: observatory for WIMP velocity distribution in our environment?
  - Sensitive to local WIMP density  $\rho_{DM}$  (not to the cosmological density  $\Omega_{DM}$ )

## Direct search schematics



Observables: Event rate,  $E_{recoil}$ ,  $\theta_{recoil}$  (recoil range is related to  $E_{recoil}$ )



PHYSICAL REVIEW D

VOLUME 31, NUMBER 12

15 JUNE 1985

### Detectability of certain dark-matter candidates

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(Received 7 January 1985)

We consider the possibility that the neutral-current neutrino detector recently proposed by Drukier and Stodolsky could be used to detect some possible candidates for the dark matter in galactic halos. This may be feasible if the galactic halos are made of particles with coherent weak interactions and masses  $1-10^6$  GeV; particles with spin-dependent interactions of typical weak strength and masses  $1-10^2$  GeV; or strongly interacting particles of masses  $1-10^{13}$  GeV.

### Method suggested in 1985 (28 years ago!) by Goodman + Witten

- Predict rates between 4 and 1400 events/kg/day for heavy  $\nu$ .  
 $M_\nu = 100 \text{ TeV} \leftarrow$        $\rightarrow M_\nu = 100 \text{ GeV}$
- As early as 1987, first significant constraints (*exclusion of a heavy  $\nu$* ) with ionization Ge and Si detectors: sensitivity to  $\sim$  few evts/kg/day
  - Ge: S. P. Ahlen, et al., Phys. Lett. B 195 (1987) 603
  - Ge: D. O. Caldwell, et al., Phys. Rev. Lett., 61 (1988) 510
  - Si: D. O. Caldwell, et al., Phys. Rev. Lett. 65 (1990) 1305
- To do better, need better rejection of radioactive backgrounds
  - Competition between techniques: Pulse-shape discrimination in NaI? Phonon+ Ionization detectors [*Shutt et al, PRL 69 (1992) 3531*]? CsI? Liquid Ar? 2-phase Xenon? Bubbles? Etc ...

## *Basic questions*

---

- Direct Dark Matter searches are simple: just look at a large number of nuclei and see if any of them recoils due to a hit-and-run collision with a WIMP, but...
- How many such events can we expect per unit time and per number of target nuclei?
- How big is the kinetic energy involved in such collisions?
- What is the fake rate and how can we reject it?

## Scattering probability

---

- Collision rate (per unit time) R:

$$R = \varphi \sigma_A N_{\text{target}}$$

$$\varphi = \text{WIMP flux (WIMP/cm}^2\text{/s)} = (\rho_W/M_W) v$$

$\sigma_A$  = cross-section for the elastic scattering of a WIMP on a nucleus  
(cm<sup>2</sup>, barn or picobarn) 1 pb = 10<sup>-36</sup> cm<sup>2</sup>

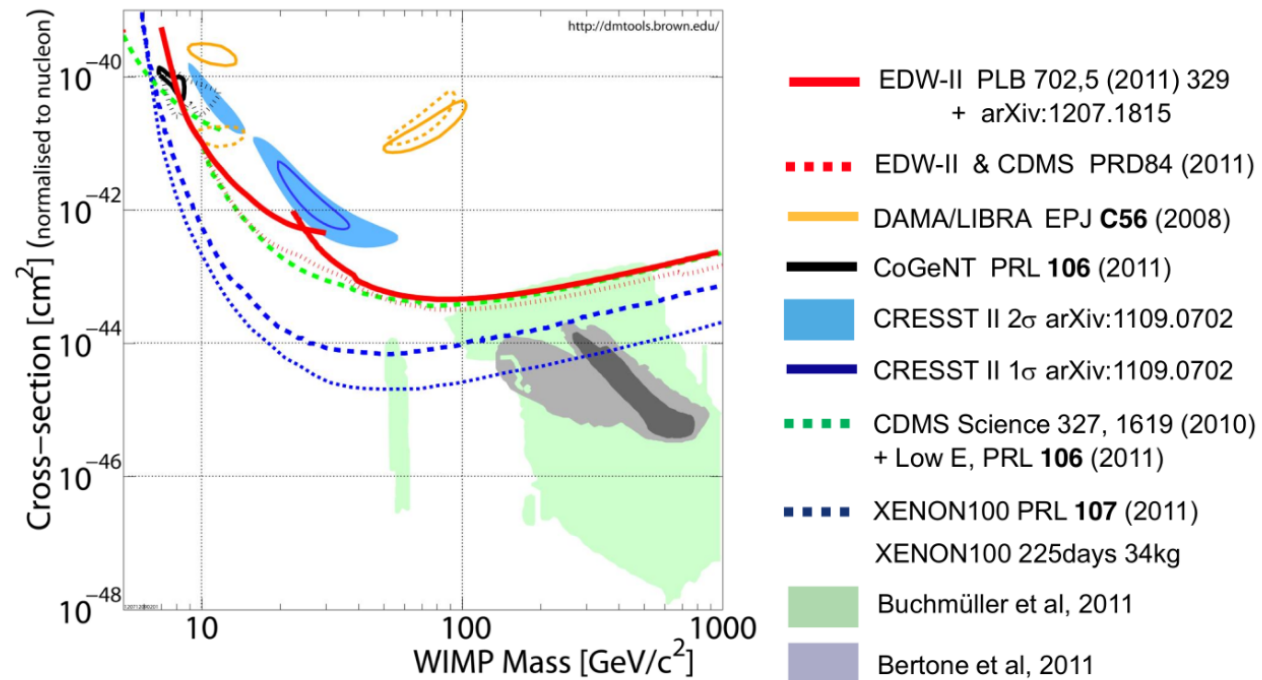
$N_{\text{target}}$  = number of target nuclei exposed to the flux  $\varphi$

→ Need massive detectors ( $N_{\text{target}}$ )

## The search domain

- We don't know (yet) what is the mass of the WIMPs
- We don't know (yet) what is the cross-section for WIMP-nucleus scattering
- Generic searches for ALL WIMPs masses  $M_W$  and ALL cross-section  $\sigma$ .
- A given experiment will be able to probe a certain region of  $(M_W, \sigma)$ :

“exclusion plots”





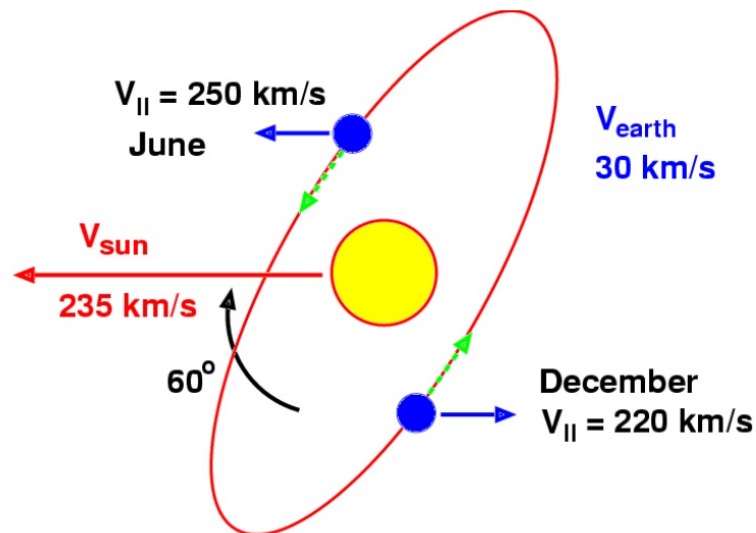
## Flux: WIMP velocity distributions

---

- Exact calculation extremely difficult
  - N-body calculation,  $N=\infty$ , Gravity range =  $\infty$
  - No dissipation: WIMPs don't "stick" together as ordinary matter
- Equilibrium: Kinetic energy  $\sim$  -Potential energy/2
- Simplest (crudest) case: spherical isothermal halo
  - Maxwellian velocity distribution: 
$$\frac{dP(v)}{v^2 dv} = \frac{1}{(\pi v_0^2)^{3/2}} \exp\left(-\frac{v^2}{v_0^2}\right)$$
  - $v_0 \sim 220$  km/s (  $v_{\text{rms}} = \text{sqrt}(3/2)v_0 = 270$  km/s )
  - Truncated to escape velocity from Galaxy (  $v_{\text{esc}} \sim 544$  km/s )
- More realistic halo model: heated debate
  - Central cusp? clumps? triaxial? caustics? tidal flows? Comoving?
  - Direct search mostly sensitive to *average*  $v^2$  (if not too clumpy)

## Sun and Earth velocities

- Sun around the galaxy:  $\sim 235$  km/s
- $\exp(-v^2/v_0^2) \rightarrow \exp(-|\vec{v} + \vec{v}_{||}|^2/v_0^2)$  (energy boost)
- Earth around the sun: 30 km/s ( $\sim 60^\circ$  to Galactic plane)



$$f(\mathbf{v}) =$$

$$f(\mathbf{v}; V_o, V_{\text{escape}}, V_{\text{sun}}, V_{\text{earth}})$$

- Annual modulation of  $\pm 7\%$  of  $v_{||} \rightarrow \sim \pm 3\%$  on WIMP flux
- Modulation more sensitive to detailed halo model

- For  $M_{\text{WIMP}} \sim 100 \text{ GeV}/c^2$  and  $v_{\text{WIMP}} \sim 200 \text{ km/s}$ :
- $(v_{\text{WIMP}}/c) = 0.7 \%$

*Good news #1: non relativistics! Use Newtonian kinematics...*

- $M_{\text{WIMP}} = 10^{+8} \text{ keV}/c^2$
- $E_{\text{kinetic}} = \frac{1}{2} M_{\text{WIMP}} (v/c)^2 = 22 \text{ keV}$

*Good news #2: a single 22 keV deposit is detectable in (good) conventional detectors used in nuclear physics*

- Momentum =  $pc = \text{sqrt}(2 M_{\text{WIMP}} v_{\text{WIMP}} c) \sim 66 \text{ MeV}$
- Associated wavelength  $\lambda = h/p \sim 20 \text{ fm}$  : larger but comparable to nuclear radii (2-7 fm)

*~Good news #3: we can first consider the whole nucleus as a "point-like" particle but will need to consider quantum physics corrections*

## Total scattering rate (1)

---

- We want a rate  $R$  per unit time and per kilograms, for a target of atomic mass  $A$  (in a.m.u.=g/mol).

$$R = ( 1000 N_0/A ) \sigma_0 \phi \quad (N_0 = 6.022 \times 10^{23})$$

- The flux is due to  $n_0$  WIMP per volume,  $n_0 = \rho_{\text{WIMP}}/M_{\text{WIMP}}$
- $\sigma_0 =$  scattering cross-section on a *nucleus*:.

- Must integrate over the velocity distribution. Contribution  $dR$  from the flux  $n_0 v dP(v)$  of WIMPs with velocity  $v$ :

$$dR = ( N_0/A ) \sigma_0 n_0 v dP(v)$$

- Total rate is thus obtained by averaging  $v$  over  $P(v)$

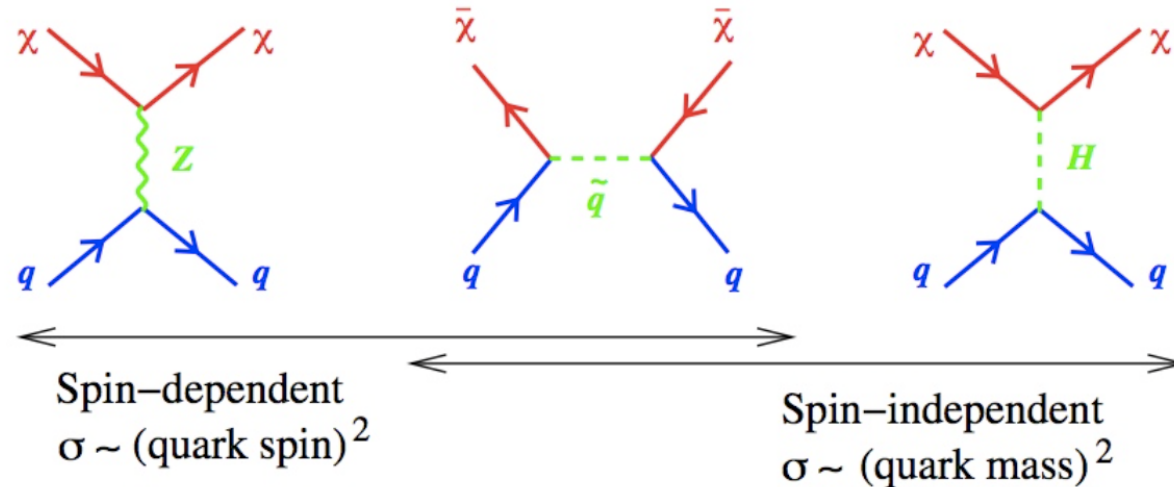
$$R = ( N_0/A ) \sigma_0 n_0 \langle v \rangle$$



- Now that we know how to handle the WIMP flux in our calculation, let's turn to the cross-section
- So far  $\sigma_0$  was a cross-section for the scattering on a *nucleus* with  $A$  nucleons, of radius  $r \ll h/p_{\text{WIMP}}$
- Fundamental particle physics theories (for example: the WIMP is a neutralino  $\chi$ ) begin with a prediction for a scattering cross-section on a *quark*
  - *Hadronic physics* will give what is the relation between this cross-section and the cross-section on a *nucleon* (n or p)
  - *Nuclear physics* will give what is the relation of this second cross-section with the one for a nucleus containing  $Z$  protons and  $(A-Z)$  neutrons

## From the quark to a nucleon (1)

- $\chi$ -nucleon scattering cross-section can be calculated within SUSY



- Separation spin dependent (SD) / independent (SI): most general expression for most types of interactions, even beyond SUSY
- In a nucleus, spin of quarks add incoherently
  - Spin of most nucleons cancels out in most nucleus: incoherent sum
  - In a nucleus, quark masses add coherently
  - Strange quark content dominates! (ok, known to some precision)
  - Expect large coherence effects for SI (Good, that will help!)

## Summary of ingredients (1)

---

First three ingredients usually taken from the Lewin and Smith's prescriptions for comparing experiments.

### ■ $\rho_W$ , WIMP density in the laboratory

- Local measurements suggests  $\sim 0.4 \text{ GeV/cm}^3$  but adopted reference is 0.3
- Observed rate  $\propto \sigma_n \times \rho_W$

### ■ $f(v)$ , WIMP velocity distribution

- Dependence on average  $v_{\text{rms}}$ , not much on  $f(v)$  details (except: modulation)
- Adopted reference: Isothermal halo,  $v_{\text{rms}} = 270 \text{ km/s}$  ( $v_0 = 220 \text{ km/s}$ ),  $v_{\text{escape}} = 544 \text{ km/s}$ , + sun (235 km/s) and earth ( $0 \pm 15 \text{ km/s}$ ) velocities.

### ■ $\sigma_A/\sigma_n$ , nucleon-to-nucleus scaling of scattering cross-section

- Nuclear form factors matter (from  $\sim 0.2$  to 1).
- $A^2 \mu^2$  scaling (spin-indep. case) dominates for  $A > 30$  in MSSM.
- $A < 30$ , non-MSSM WIMPs: spin-dependent may dominate. No large gains from scaling, more model-dependence, poor rates.

## Summary of ingredients (2)

---

- Last two ingredients usually left as free parameters of the searches:
- $M_W$  , WIMP mass
  - Taken from SuperSYmmetric (or other) Model prediction
  - Method works from a few GeV/c<sup>2</sup> to >10 TeV/c<sup>2</sup>
  - Typical SUSY range: from 50 GeV/c<sup>2</sup> to 1 TeV/c<sup>2</sup>
- $\sigma_n$ , WIMP-nucleon cross-section
  - Taken from SuperSYmmetric (or other) prediction
  - Method *could maybe* work down to 10<sup>-11</sup> pb
  - Typical SUSY range: 10<sup>-6</sup> to 10<sup>-11</sup> pb (kg.day -> ton.year)
- Generic search: test all values of ( $M_W$  ,  $\sigma_n$  )